Some theoretical aspects to $p\, p$ collisions

presented by Alan S. Cornell
National Institute for Theoretical Physics;
School of Physics, University of the Witwatersrand
South Africa

NITheP
National Institute for Theoretical Physics

Introduction

In this node of NITheP we are concerned with high energy physics, such as string theory or particle physics (that is, the study of the elementary constituents of matter, and the interactions between them).

To date, all observed particles, and their interactions, can be described by the standard model, where ...

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

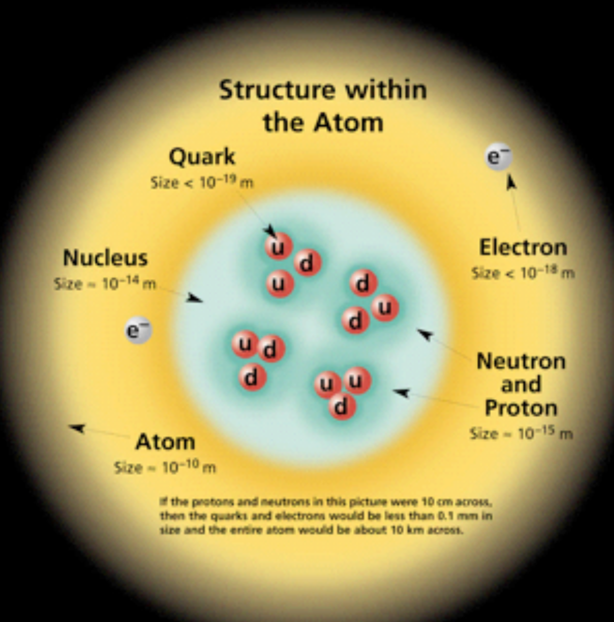
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

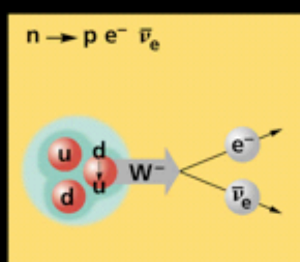
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

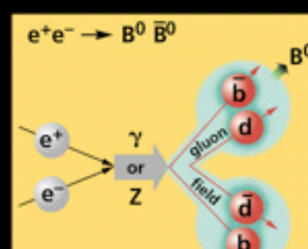
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

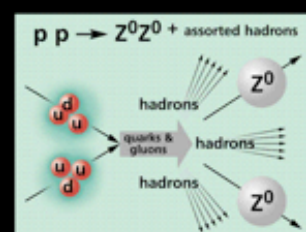
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as *Z* bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

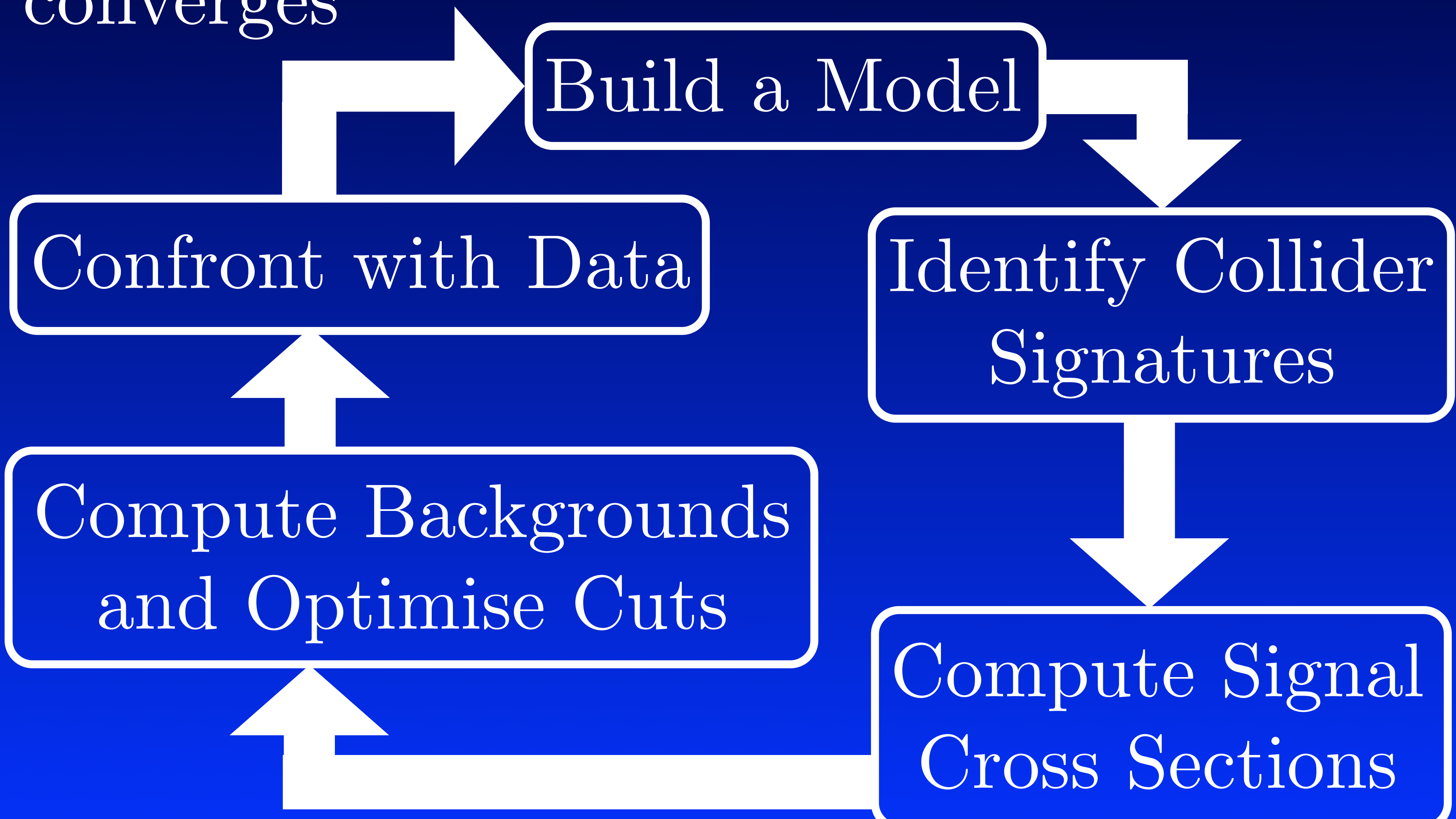
The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

I shall now be more concerned with **phenomenology**, that is, the search for new phenomena, where we iterate this loop until it converges

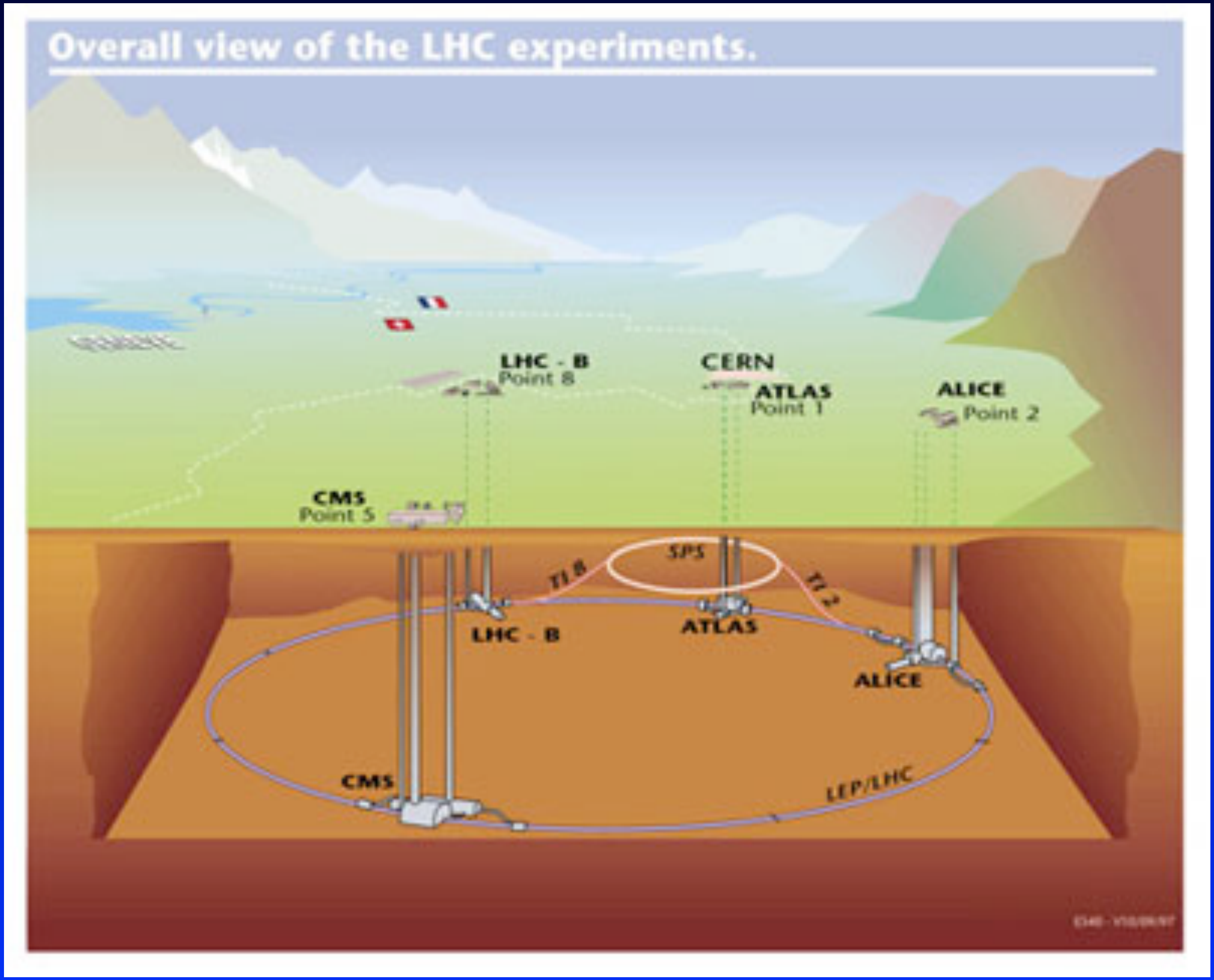


This search can be through the making of predictions for theories Beyond the SM:

- By searching for new particles, or other signatures of new physics.
- Or by trying to explain any observed discrepancies with the SM with BSM theories.

Ultimately all phenomenology is connected with experiments.

The Large Hadron Collider



As you should all know, the LHC, collides protons with a collision energy potentially up to 14 TeV.

In this collider, two beams, each containing 2808 bunches of 1.15×10^{11} protons (where each bunch is spaced 25ns, or 7.5m, apart) will be crossed at each of the detectors spaced around the ring.

When two bunches meet, there will be about 23 proton-proton collisions, with about 1500 particles “born”.

Where can we search for new physics?

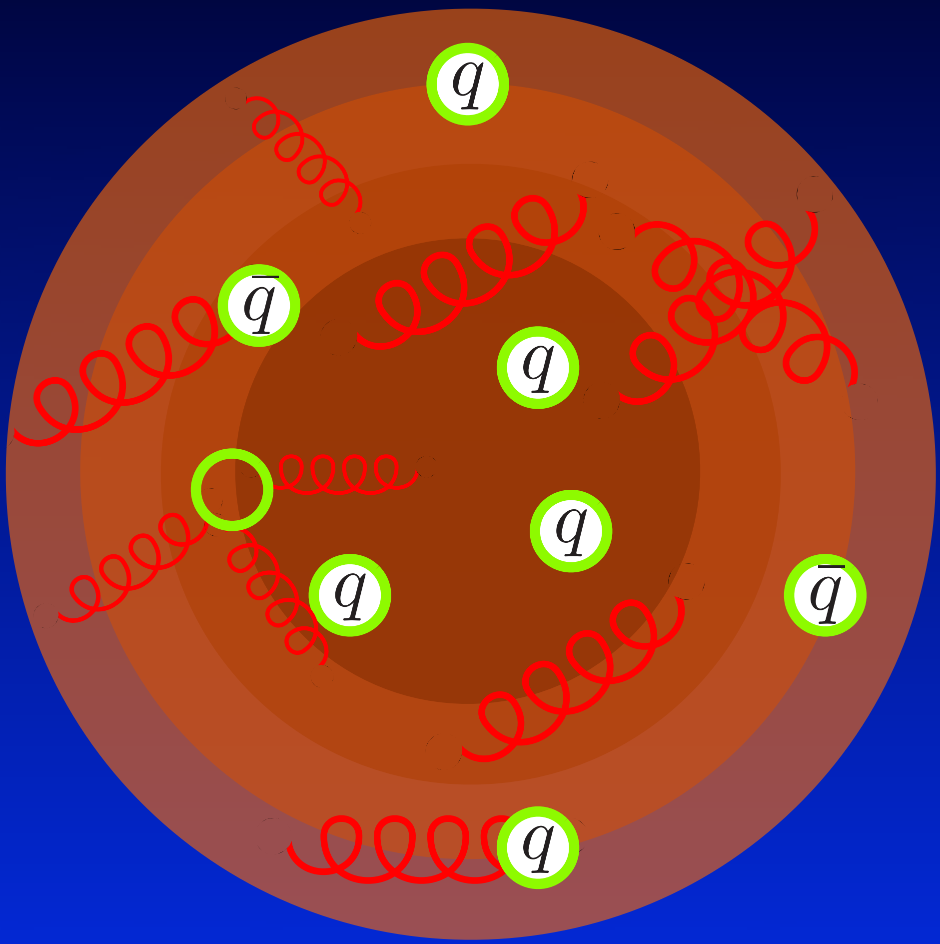
Armed now with these experiments, how and where do we look for new physics?

- At energies beyond the current range of accepted theories,
- or, looking at where our theories are most poorly understood

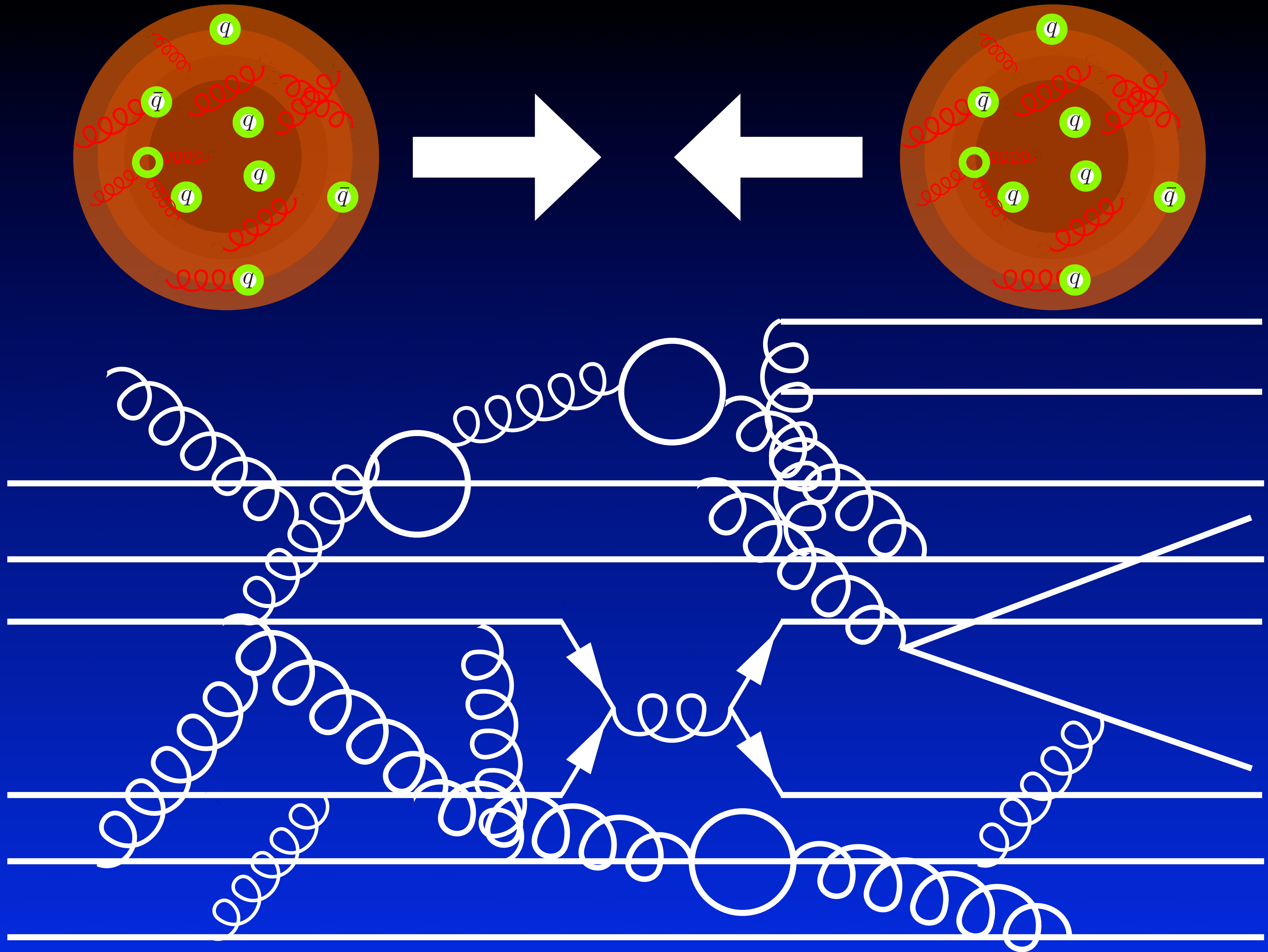
As the LHC will collide protons, what does a proton really look like?

Actually, QCD tells us it will look a little something like this!

$$r \sim \frac{1}{\Lambda_{QCD}} \sim 10^{-15} m$$



So you can imagine what will happen when we collide two protons!

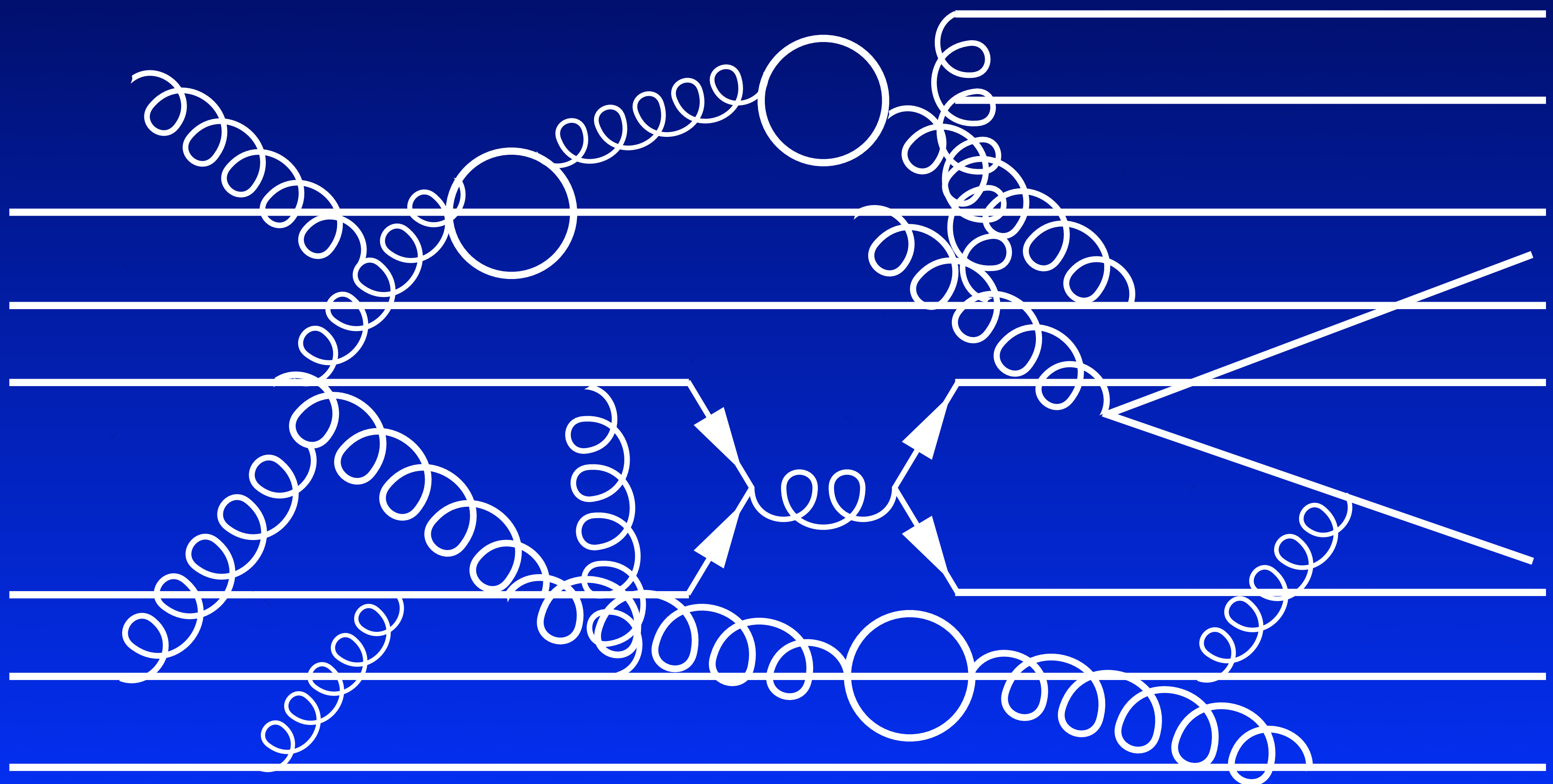


Well, a fairly low order guess would be something like this!

As such, many of the fundamental constants in QCD are poorly understood.

Therefore, using techniques such as factorisation, a closer look at specific processes may lead to some new physics

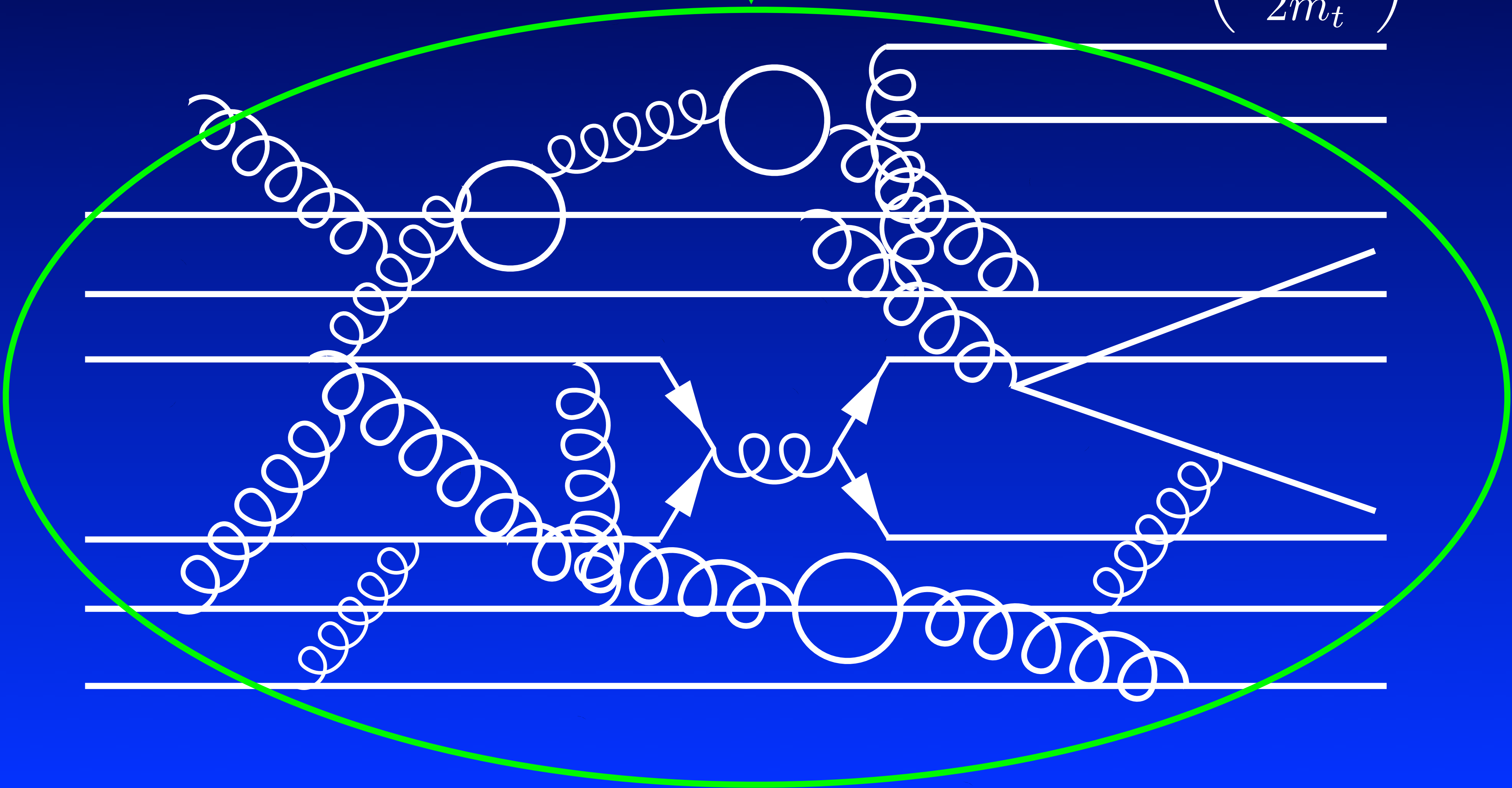
$$\begin{aligned}\sigma\Big(p(P_1) \quad &+ \quad p(P_2) \to t\bar{t} + X\Big) \\ &= \int_0^1 dx_1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma\Big(q_f(x_1 P) + \bar{q}_f(x_2 P) \to t\bar{t}\Big) \\ &\qquad + \mathcal{O}\left(\frac{\Lambda_{QCD}}{2m_t}\right)\end{aligned}$$



$$\sigma\Big(p(P_1) \quad + \quad p(P_2) \to t\bar{t} + X\Big)$$

$$= \quad \int_0^1 dx_1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma\Big(q_f(x_1 P) + \bar{q}_f(x_2 P) \to t\bar{t}\Big)$$

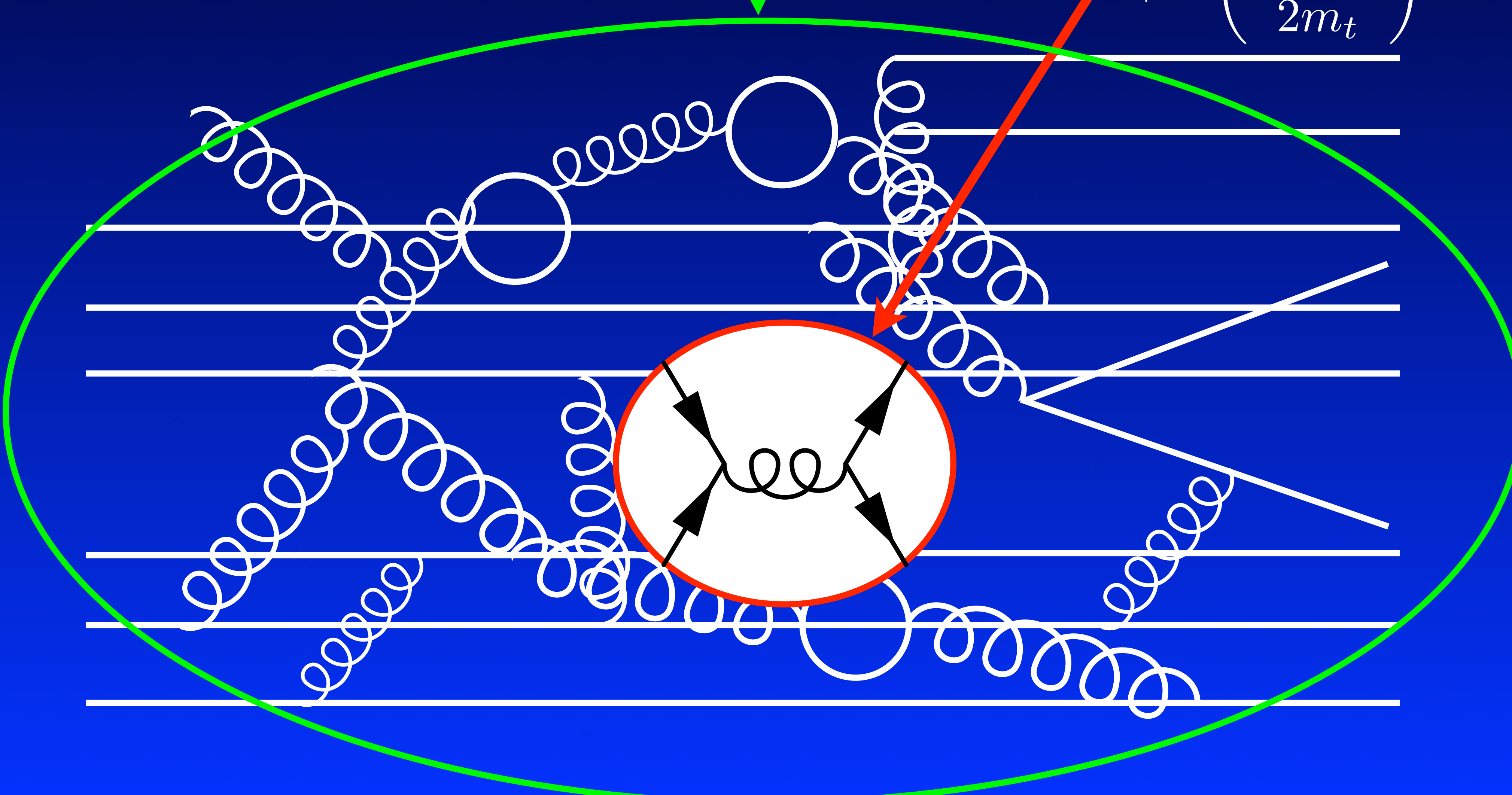
$$+\mathcal{O}\left(\frac{\Lambda_{QCD}}{2m_t}\right)$$



$$\sigma\big(p(P_1) \quad + \quad p(P_2) \to t\bar{t} + X\big)$$

$$= \quad \int_0^1 dx_1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma\big(q_f(x_1 P) + \bar{q}_f(x_2 P) \to t\bar{t}\big)$$

$$+\mathcal{O}\left(\frac{\Lambda_{QCD}}{2m_t}\right)$$



The SM Higgs

One place we can look closer in the SM is at the **Higgs boson**

In the SM though the EW gauge symmetry $SU(2) \times U(1)$ is fundamental, it is spontaneously broken at low energies.

The SM explanation for EWSB is to postulate a new particle, the **Higgs boson**. A spin-0 particle. Where the vacuum is thought to be filled with a Higgs condensate, which breaks the symmetry.

However, no elementary spin-0 particles are known to have previously existed!

A major problem is that a scalar mass is unstable with respect to radiative corrections.

In the SM $V(H) = \mu^2 H^\dagger H + \lambda(H^\dagger H)^2$, where $v^2 = \frac{\mu^2}{\lambda}$, $m_{h0}^2 = 2\mu^2$.

Such that after we renormalise these radiative corrections to the Higgs mass

$$m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Λ is the scale at which the loop integrals are cut off by **new physics**.

Note that "naturalness" arguments require $\Lambda \sim 1$ TeV (that is, we don't want the parameters to be too finely tuned), however, if a theory were to include gravity (whose energy scale is $M_{Pl} \sim 10^{19}$ GeV) we have a big problem with the hierarchies of the energies in our theory!

So what sorts of models have a light Higgs, which addresses this issue of naturalness?

- Theories with new particles related to the SM by symmetries. These provide new loop diagrams which cancel with the SM loops (for example, SUSY, Little Higgs models etc.)

- Theories where the Higgs is not elementary, but a bound state resolved at TeV scales (for example warped extra-dimensional models)

- Theories where point-like SM particles are resolved as TeV-scale strings (eg, large XD models)

Alternatively, we could look for models without a light Higgs, such as those which are strongly coupled at the TeV scale (eg, Technicolour or other Higgless models).

Or models that do not improve naturalness, but have other interesting features or unusual signatures (for example, unparticles etc.)

SUSY

In **supersymmetric** theories, we suppose the existence of a new symmetry that relates particles of one spin to another particle that differs by half a unit of spin and are known as **superpartners**.

In other words, in a supersymmetric theory, for every type of boson there exists a corresponding type of fermion, and vice-versa.

To date there is no direct evidence that SUSY exists. Since superpartners of the particles of the SM have not been observed. SUSY, if it exists, must be a broken symmetry allowing the **sparticles** to be heavy.

If SUSY exists close to the TeV energy scale, it allows a solution of the hierarchy problem.

SUSY is also a feature of most versions of string theory, though it can exist in nature even if string theory is wrong.

In the Minimal supersymmetric SM, there are superpartners for each SM d.o.f., plus a **2nd Higgs doublet** and its superpartners.

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	-1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$ $\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$ $\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	(same) (same) $\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	-1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$ $\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$ $\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	(same) (same) $\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	-1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	-1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	-1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 3/2	-1 -1	$\tilde{G}$	(same) (same)

34 new particles waiting to be discovered!

MSSM, however, has some $\mathcal{O}(100)$ free parameters affecting spectrum, branching ratios, etc

Models of SUSY breaking predict some parameters (or relations among them), reducing the freedom

But many such models (eg. gravity mediation, gauge mediation etc.) each has strengths and weaknesses
$\Rightarrow$ WE NEED DATA!

Search strategies therefore need to be designed with this in mind. That is, we need to search 120-dimensional parameter spaces, as well as keeping experimental limitations in mind.

Generic SUSY predictions

In general we impose an extra discrete symmetry, R-parity, to avoid rapid p decay.

SM states are R-even, superpartners R-odd
$\Rightarrow$ lightest superpartner is stable

There are strong limits on charged relics in the universe
$\Rightarrow$ so we prefer a neutral LSP (also WIMP dark matter candidate!)

So a generic signature would be missing energy in every event with superpartner production

Also, NLSP may be stable on collider detector time scales
$\Rightarrow$ searches for charged object (eg. staus and R-hadrons) are also well motivated

So an inclusive search for stable (neutral or not) objects plus high-pT jets and/or leptons is the best model independent strategy.

Note that the observed Higgs presents significant problems for the MSSM, which implies that if SUSY is realised, it may well be a non-minimal version (which means extra scalars coupled to the Higgs sector etc.)

Quantum Gravity at TeV

At the Planck scale, the SM has to be embedded into a theory with quantum gravity

It is believed that that theory must be finite, that is, all divergences are cut-off at M_{Pl}

But if $M_{Pl} \sim 1$ TeV, there is no hierarchy problem!

So in the ADD model we considered the SM on a 4D brane inside a higher-dimensional space, with the extra- dimensions compactified with

$$R \sim M_{Pl}^{-1} \left(\frac{M_{Pl,4}}{M_{Pl}} \right)^{2/n} \gg M_{Pl}^{-1}$$

For $E < M_{Pl}$, we would have model-independent missing energy signatures due to graviton emission into the XDs.

But for $E \gg M_{Pl}$, the collision of two partons would form a black hole (and decay promptly)

Composite Higgs

But what if we were to now consider the Higgs as not being fundamental. Afterall, we have plenty of spin-0 mesons in the SM

In which case they are **composed** of spin-1 *quarks* bound by the strong force

Above the QCD confinement scale, the good degrees of freedom are quarks
$\Rightarrow$ no hierarchy problem!

This is an old idea, but it is difficult to build models, as this is
non-perturbative physics

New insight: **AdS/CFT duality**, some strongly coupled 4D models are dual to weakly coupled, calculable models with an extra-dimension

Warped (RS) Extra dimensions

The original RS model had the SM on the TeV brane $\Rightarrow$ solves the hierarchy problem

We also get new states: KK gravitons at the TeV scale with couplings

$$\mathcal{L} \sim \frac{1}{(\text{TeV})^2} T_{\mu\nu} G^{\mu\nu}_{KK}$$

It was subsequently realised that models with SM gauge fields and fermions **in the bulk** are more interesting

This provides a natural solution to

- **fermon mass hierarchy**,
- suppression of **FCNCs**,
- and the possibility of gauge coupling unification (as in the MSSM)

The good news is that all SM states now have **KK modes**

Though they **do not necessarily couple** to light quarks and leptons much.

Even worse, KK masses are large and becoming more constrained.

Note that the KK gluon is probably the easiest target at the LHC

Little Higgs Models

In this model, the basic idea is that the Higgs field is a pseudo-Goldstone boson of a global global symmetry which is broken at some higher scale.

Quadratic divergences in the Higgs mass are cancelled at one loop level with new particles

Higgs particle acquires mass radiatively at EW scale

Three-scale model:

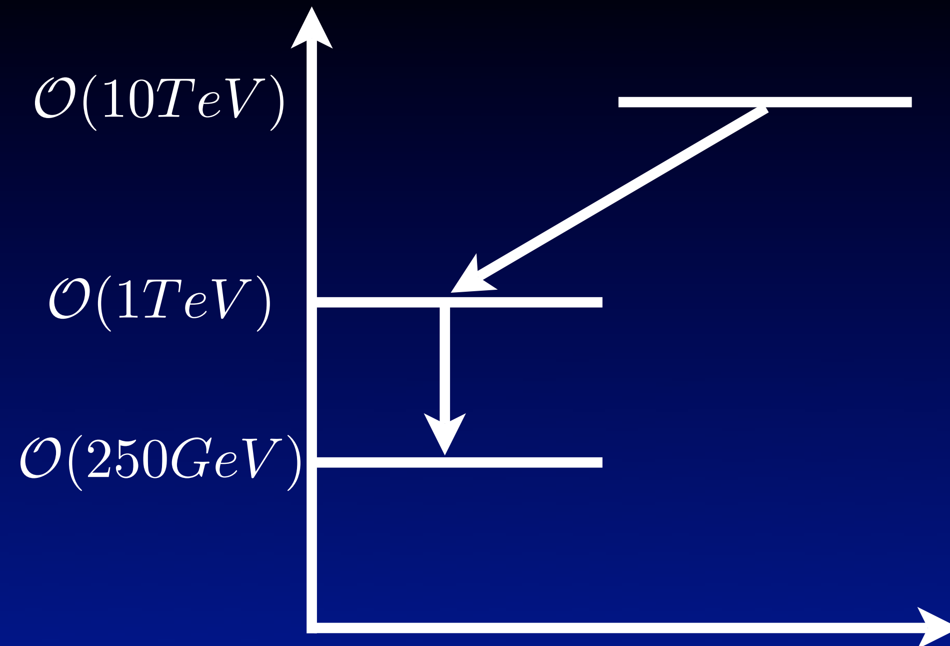
$v \sim f/4\pi,\ f \sim \Lambda/4\pi$

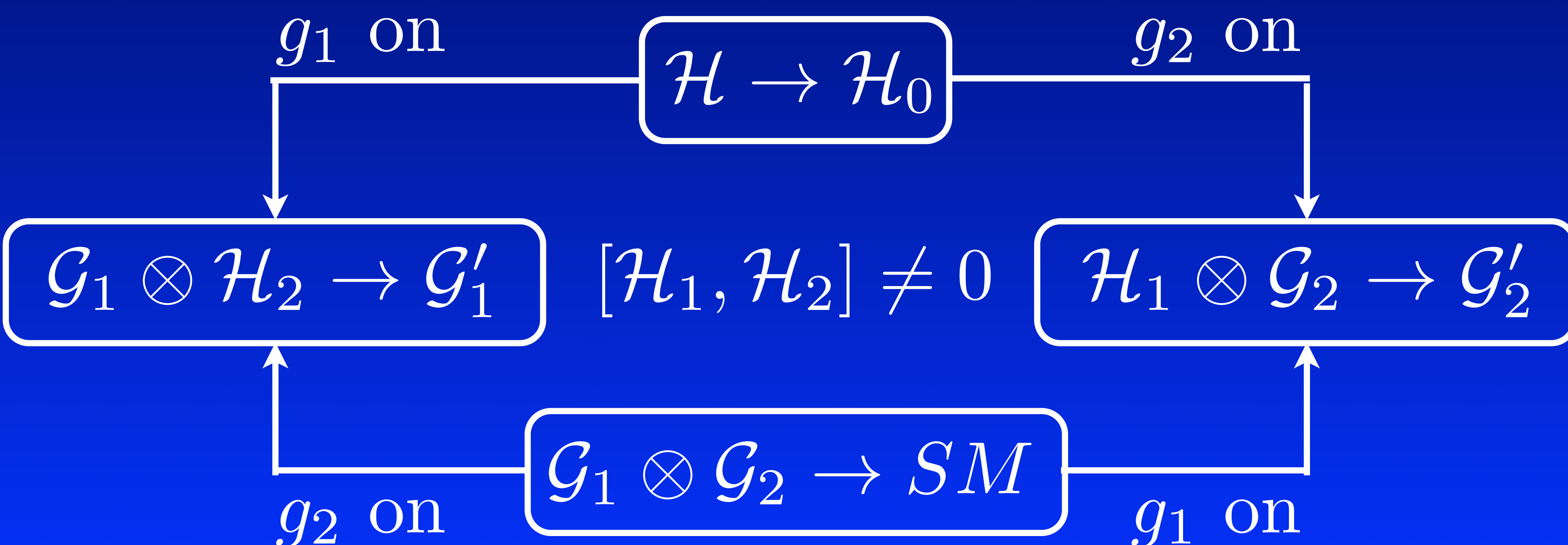
$v = 250$ GeV $\rightarrow \Lambda \sim 10$ TeV

Λ: Global symmetry breaking, new dynamics

f: Pseudo-Goldstone boson, extra bosons, new fermions

v: Higgs, SM gauge bosons and fermions





So in this model, we have an extended gauge sector ($\mathcal{G}_1 \otimes \mathcal{G}_2 \to \mathrm{SM}$)

An enlarged global symmetry (extended Higgs sector), and extended top sector

- So when we go from $\mathcal{H} \to \mathcal{H}_0$ some Goldstones are eaten $\to W_H,\ Z_H,\ A_H$
- Some heavy (mass $f \sim \Lambda/4\pi$) scalars
- Some light (mass $\sim g_1 g_2 \Lambda/16\pi^2$) scalars $\to$ **Higgs candidate**

1^{st} gen. LH models were disfavoured by precision EW data

So T-parity was introduced (*a la* R-parity), and LHT pass the precision test without significant fine-tuning

Note that the LHT has a T-odd particle which is stable, typically neutral (such as the *heavy photon*) and a good WIMP DM candidate

The symmetry structure introduces T-odd partners for each SM fermion

Conclusions

- Since the SM became accepted ($\sim$ 30 years ago), theorists have been able to provide very precise guidance for new physics searches
- This is not the case for BSM physics hunts as the number of ideas is finite, yet the implementation are essentially infinite with large numbers of free parameters

- As such **inclusive** (signature-based) searches are the best bet
- where the **model space** will evolve very quickly once there is some data!
- The mechanism which breaks the EW symmetry remains a fundamental,
- All natural models of EWSB predict new physics at the TeV scale