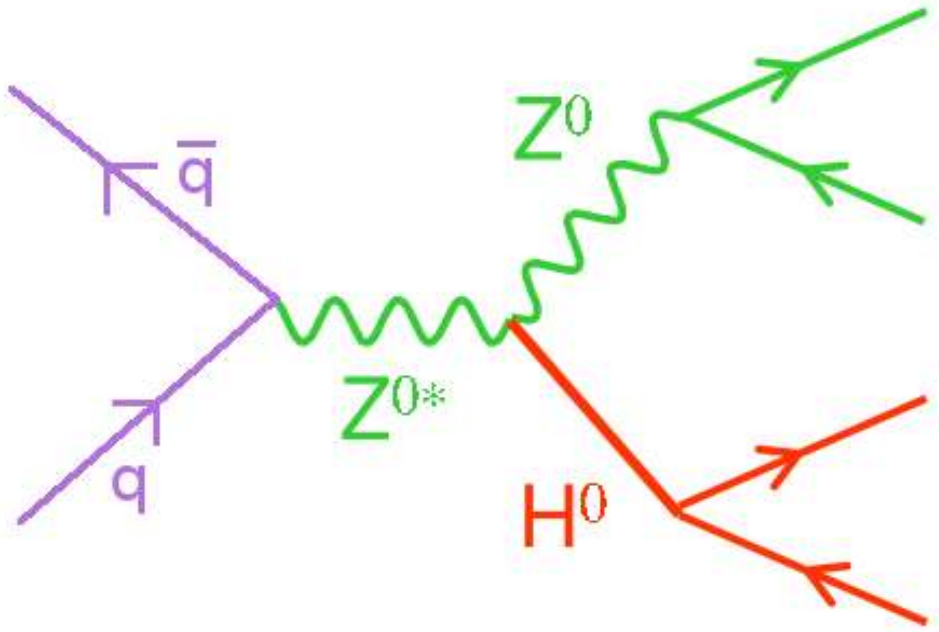
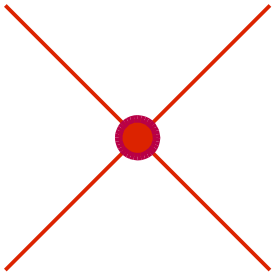
New Physics at the Large Hadron Collider



Andy Buckley,
High Energy Physics Group,
Cavendish Laboratory, Cambridge

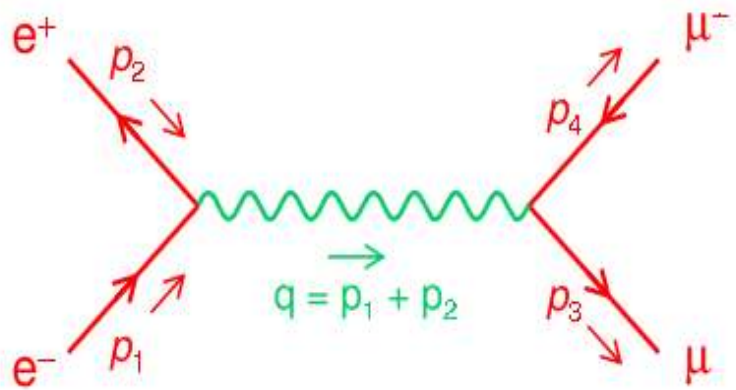
First things first...

- Particle physics (a.k.a. HEP) is the study of fundamental “entities” and their interactions. “Particle” is a convenient label, but what we're really dealing with are *matter fields*.
- The starting points for the subject are Maxwell's electromagnetic unification, Einstein's special relativity and quantum mechanics.
- The first glimpse into modern particle physics is arguably the discovery of weak nuclear decay: missing energy led to the invention/discovery of the neutrino.
- But UV problems with Fermi 4-pt weak force theory: diverges at high energies.



First things first... (2)

- Development of underlying theory by Feynman *et al*: boson mediation removes UV divergence. "Feynman diagram" description of process:



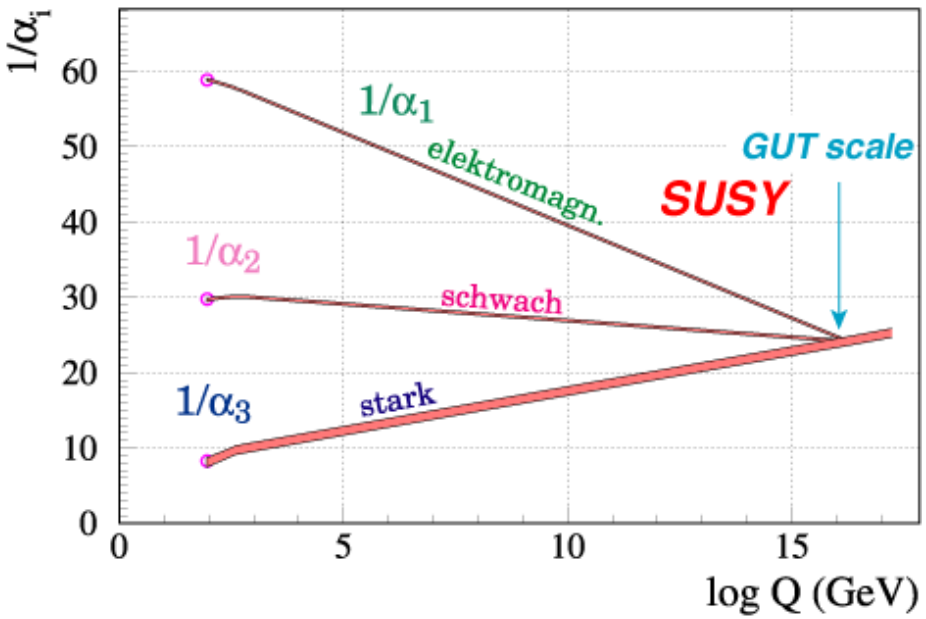
- EM as the QED quantum field theory. U(1) gauge group: the simplest *gauge field theory*.
- The weak force and strong nuclear force can also be described as GFTs: weak force is SU(2) of ~"weak isospin"; strong is SU(3) of "colour". Weak field isn't actually weak, just heavy!

Electroweak unification

- More unification of fields in the 70s: Glashow, Salam and Weinberg propose unifying the EM and weak fields.
- “Weak isospin” and “hypercharge” are mixed to give 3 massive gauge bosons, the W^+, W^- and Z^0 and one massless boson, representing the photon. The physical Z^0 and γ are mixtures of the fundamental fields.
- The acquisition of mass breaks the EW symmetry: since this spontaneous symmetry breaking (SSB) is mediated by the Higgs field, it is called the Higgs mechanism. It's the only consistent way to give mass to particles.

Renormalisation

- t'Hooft and Veltman showed that gauge theories need SSB to be physical. Involves accounting for all self-interactions of fields (cf. ignored electron self-interation in classical EM) – technical procedure called renormalisation.
- Absorb the divergent parts into physical quantities like mass, charge and gauge coupling: introduce scale-dependance.



Renormalisation (2)

- Not everyone believes/likes renormalisation!

ALRIGHT RUTH, I ABOUT GOT THIS ONE RENORMALIZED.

The Standard Model

- "Standard Model of Fundamental Interactions" has gauge structure $SU(3)_C \otimes SU(2)_I \otimes U(1)_Y$
- Standard model particle content *:
  leptons: (e, ν_e), (μ, ν_μ), (τ, ν_τ)
  quarks: (d, u), (s, c), (b, t)
  bosons: γ, Z^0, W^+, W^- ; and 8 "gluons"
- Some problems: heirarchy problem, Higgs undiscovered (others?) ... but it works in formidable agreement with precision expts.
- SLC/UA2/LEP studies of EW unification were *the* HEP triumph of the last 20 years.

[*] Give or take an (important) technicality about chiral fields

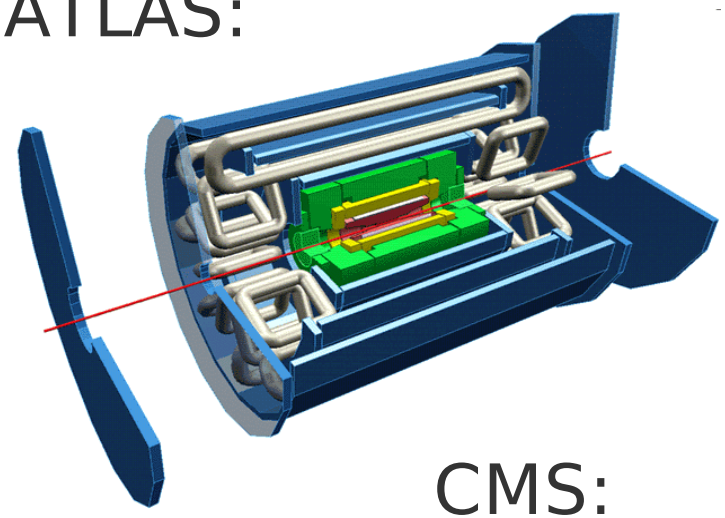
The Large Hadron Collider

- LHC is being built at the CERN lab in Geneva (www.cern.ch), using the existing LEP tunnel:

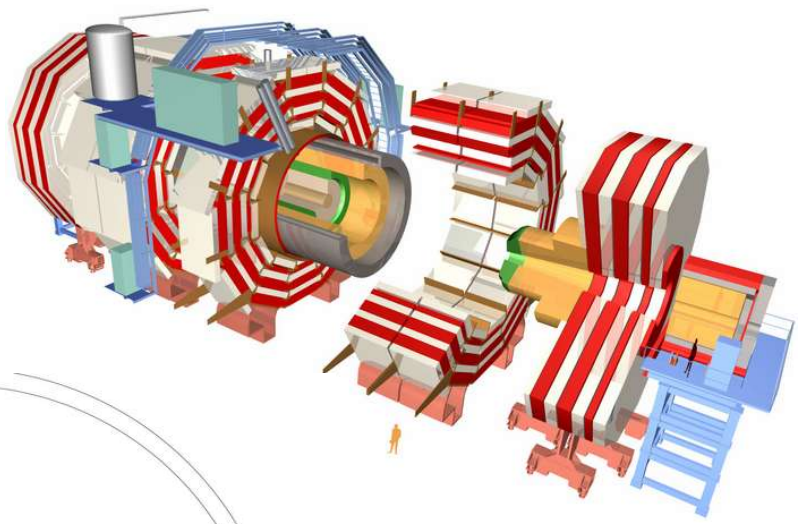
- 14 TeV centre of mass energy (2 TeV effective interaction energy) in pp collisions.
- 4 new detectors: ATLAS, CMS, LHCb, Alice

LHC Detector Experiments

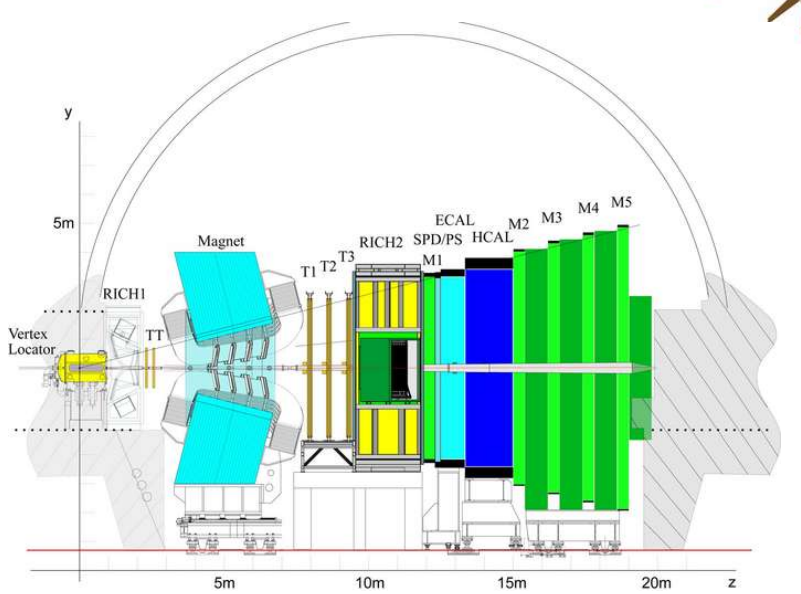
ATLAS:



CMS:



LHCb:

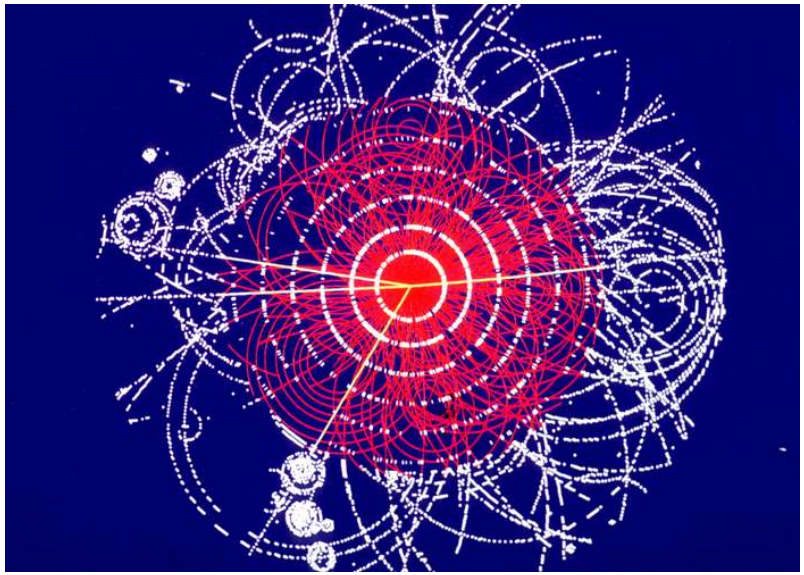


Physics at the LHC

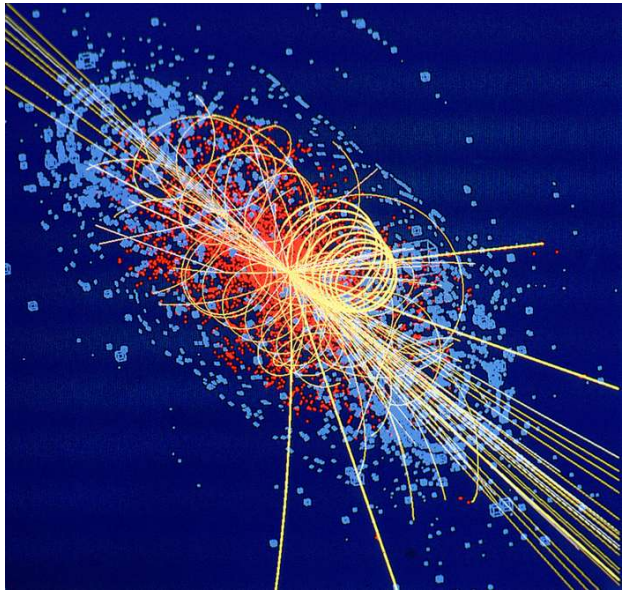
- Apologies to e.g. neutrino experiments!
- ATLAS and CMS are general-purpose experiments for *discovery* of Higgs and “SUSY”.
- LHCb is a precision flavour physics and “hadronic CP violation” experiment.
- Alice will study quark-gluon plasma.
- Primary LHC aims are to discover and constrain the Higgs boson(s)' properties and investigate the particle content of the trans-TeV region
- New physics: supersymmetry? extra dimensions? GUTs? composite Higgs?

Higgs Decays in ATLAS & CMS

ATLAS:



CMS:



Supersymmetry

- Bosons and fermions: integer and half-integer values of “spin” quantum number.
- $\Delta S = {}^{1}/_{2}$ superpartners: new discrete symmetry. Every particle has a superpartner “sparticle”.
- Motivation: fermionic and bosonic *loops* contribute with opposite sign at high energy ⇒ natural cancellation. SUSY also corrects the “running” of gauge couplings to indicate successful GUT unification. *It's also required* by string theory.
- SUSY is manifestly *broken* since $m_p \neq m_{sp}$: breaking mechanism from “hidden sector”.

Supersymmetry (2)

- Canonical breaking scenario is supergravity: breaking is transmitted via graviton interactions (gravity in unification...woo!)
- Minimal scenario is MSSM: no flavour violation. Get 5 Higgs bosons. Predict mass spectra of superpartners.
- Problem is that in breaking we introduce ~120 new parameters. More fine tuning to avoid!
- Link to cosmology: the lightest SUSY particle is stable and can provide a good dark matter candidate!

Extra Dimensions

- Extra dimensions first proposed in 1919 by Kaluza and Klein: 5D extension to EM unification to incorporate gravity (it almost works, too!)
- More recently it's been a “hot” area of research in the context of the heirarchy problem and “M-theory”: e.g. Randall-Sundrum models.
- With extra dimensions, if gravity can propagate in the bulk its effect is diluted.
- Exponentially-warped extra spatial dimension enhances volume factor and is a valid soln of Einstein's field eqns!

Extra Dimensions (2)

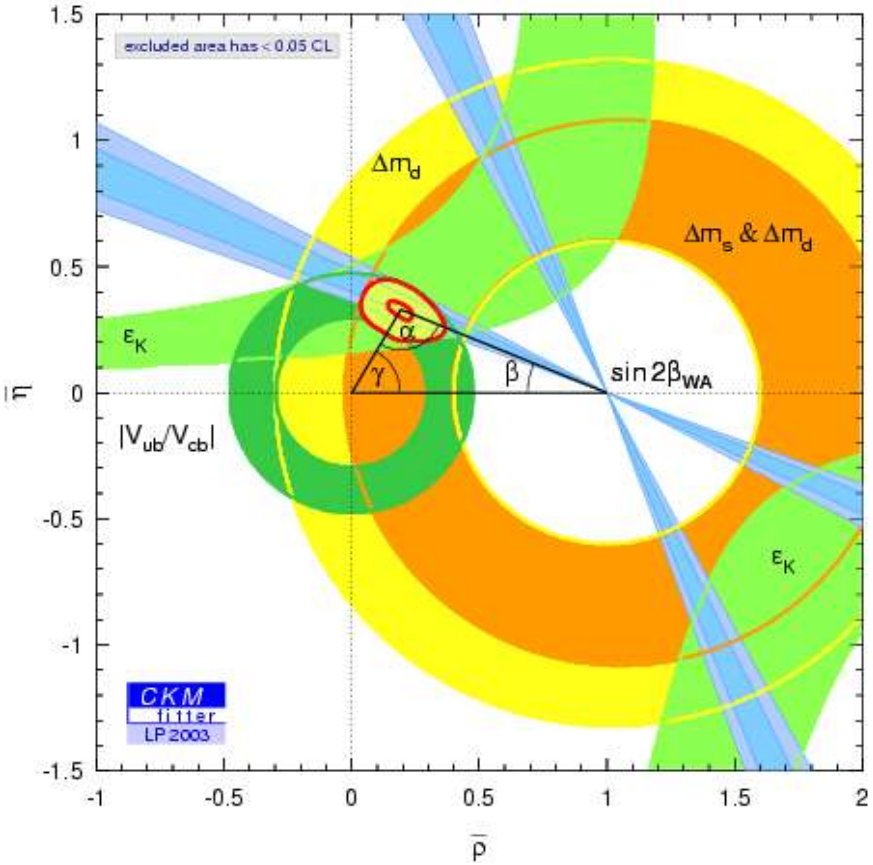
- XD allows for production of microscopic black holes at colliders! Assumed to rapidly decay via Hawking radiation (cf. cosmic rays) but no certainty!
- pT missing: Noether connection to breaking of y-direction translational invariance by branes.
- Quite silly, but also fun!

CP violation

- CP (charge-parity) is an approximately-conserved “mirror symmetry” in nature.
- Connection to cosmology via Sakharov conditions (though not really in hadronic sector): also leptonic, exotic and strong CP.
- Observed direct and mixing CPv in K_S/K_L decays at CPLEAR/NA48/etc.
- LHCb will investigate CP violation in weak hadronic decays of B mesons (quark-antiquark bound states containing b quarks).

CP violation (2)

- CKM mechanism and unitarity: mixing of quark “weak” and “mass” reps. in CC interactions.
- Unitarity triangle for B decays: constrain the triangle(s) to explore new physics.
- Decays with “penguin” diagrams are important since high-mass particles can propagate in loops (cf. Heisenberg uncertainty).



Conclusions

- Lots of interesting things to explore at the LHC! (as well as ν-expts, Super-B factories, LCs...).
- We're finding some very deep and powerful things about how the universe works at a fundamental level.
- This isn't just HEP: it's *fundamental physics* --- weak decays, Higgs physics are “everyday occurences”.
- Also have technological offshoots, which is how all this is justified!
- And we still don't know WHY! (i.e. we've not put ourselves out of a job just yet)