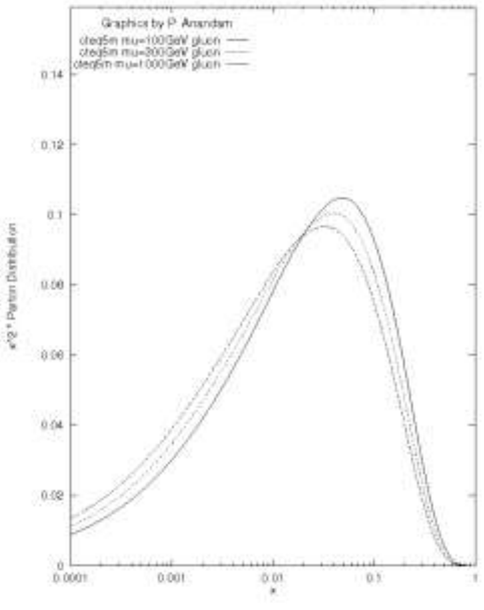
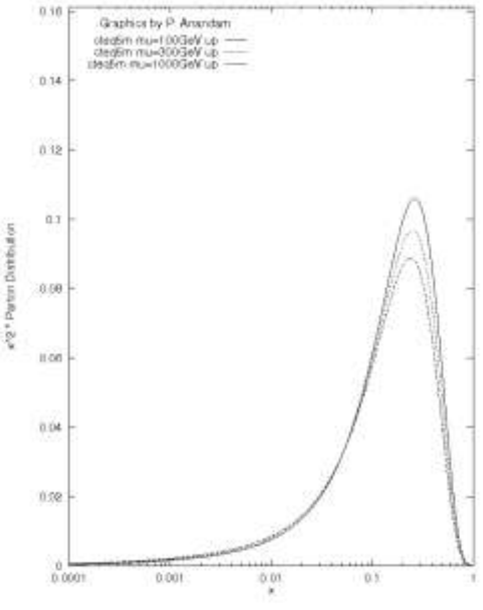
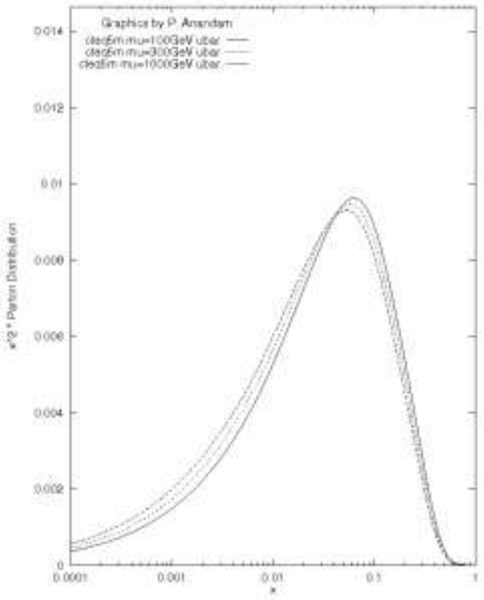

Graphics by P. Anandam
cteq5m mu=100GeV gluon
cteq5m mu=300GeV gluon
cteq5m mu=1000GeV gluon
x^2 * Parton Distribution
x
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.0001
0.001
0.01
0.1
1


Graphics by P. Anandam
cteq5m mu=100GeV up
cteq5m mu=300GeV up
cteq5m mu=1000GeV up
x^2 * Parton Distribution
x
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.0001
0.001
0.01
0.1
1


Graphics by P. Anandam
cteq5m mu=100GeV ubar
cteq5m mu=300GeV ubar
cteq5m mu=1000GeV ubar
x^2 * Parton Distribution
x
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.0001
0.001
0.01
0.1
1

Jet evolution

Scattering occurs at scale $Q_0^2 \gg \Lambda^2$. makes quark with virtuality q^2, with $0 < q^2 < Q^2$.

Now the quark emits collinear and soft radiation as before, with small changes.

- The initial quark is more off-shell than the final one; $|q^2|$ *decreases*
- We don't just measure one particle now: the soft gluon radiation is measured too, as soft jets.
- Therefore we must evolve also the emitted particles in this case – a **parton shower**

Collinear emission follows the same equations as before (at leading order.)

- Emission at large q^2 has large k_T and is visible as final-state radiation ("FSR")
- Lower-q^2 emission is increasingly collinear and **forms the quark's jet.**
- But to describe final state, need to model emission fully as a classical probabilistic branching process.
- Same approach if want to describe ISR in detail: needed for simulating events.

That this is possible (at a certain approximation) is a non-trivial, key result, allowing event simulation with pdfs and jets! (PYTHIA, HERWIG, SHERPA, ARIADNE...)

But not exact. Extend to arbitrary orders in perturbation theory? [Active research area.]

Why doesn't soft emission destroy the jet structure and throw hadrons everywhere?

DIPOLES! and $N_c^2 \gg 1$!

Gluon emission from quark

$$c_1 \to (c_1\bar{c}_2)c_2 \to (c_1\bar{c}_2)(c_2\bar{c}_3)c_3 \to \ldots$$

- For $N_c^2 \gg 1$ colors are independent; forces between c and $\bar{c}'$ large only if $c = c'$.
  - Therefore no interference between non-adjacent legs.
- The $\bar{c}_2$ and c_2 charges form a dipole. Soft emission will only occur *inside!*
  - Compare $\vec{E}$ field of e^+e^- pair with small opening angle ϕ
  - Interference between emission off e^+ and e^- is destructive for $\theta > \phi$
- Called "angular ordering" – each emission at smaller angle than the previous one (on average).

Therefore when a new gluon is emitted

$$(c_1\bar{c}_2)(c_2\bar{c}_3)c_3 \to (c_1\bar{c}_4)(c_4\bar{c}_2)(c_2\bar{c}_3)c_3 \to \ldots\ldots$$

the gluon is both "inside" in color-space and "inside" in physical angular space.

This correlation between the color-space configuration and the momentum-space configuration builds a string!

This is the string which arose in my heuristic argument for hadronization.

- Pre-exists *before* confinement
- begins to fracture into colorless pieces through $g \to q\bar{q}$ processes that occur along it.
- these processes split the string into gauge-invariant string-segments
- these segments are small in physical space and so have invariant mass $\sim \Lambda$, not Q
- they turn into hadrons, with mass not much larger than Λ, which decay to πs etc.

This pre-clustering is crucial for jet survival! And it goes like N_f/N_c.

The string is cut into little string bits before it has time to drag on itself.

Summary

- At small $\alpha_s N_c$ jets **always** form: perturbatively, through quasi-scale-invariant process.
- This is called the "parton shower": resummation of many graphs
- But at large N_c jets might be entirely lost during hadronization.
- Fortunately for LHC, N_f/N_c big enough, hadronization lets the jets through, with $p^\mu_{jet} \sim p^\mu_q$.
- Critical link between the observed hadronic physics and the high-energy quarks and gluons.
- Without this, we could not reconstruct hadronic decays of W, t, $\tilde{g}$, etc.

Further reading on all aspects of collider QCD:

Best LHC-QCD/SM lectures available: M.L.Mangano, home.cern.ch/mlm

QCD book with technical details: *QCD and Collider Physics*, Ellis, Stirling and Webber

What Lies Beyond the Standard Model?

Non-minimal Higgs Sector

In the SM

- Higgs is produced (from highest rate to lowest rate) in
  - $gg \to h$ via loops of colored particles (mainly t in the SM, sensitive to new physics)
  - $qq \to hqq$ via intermediate W, Z bosons: Vector Boson Fusion (VBF) [tests WWh, ZZh coupling]
  - $q\bar{q} \to Wh, Zh$ [tests WWh, ZZh coupling]

  Note any scalar can have the first coupling (if it interacts with quarks directly, or with any other unknown colored particle) but recall that **only a scalar with an EWSB vev** can have the last two couplings!

- Higgs decays
  - Light Higgs is narrow and decays to $b\bar{b}, \tau^+\tau^-, gg, \gamma\gamma, \ldots$.
  - Heavy Higgs is wider and decays to W^+W-, ZZ (and only a bit of $t\bar{t}$.)

Beyond the SM? Without being too specific,

- There can be multiple neutral and charged Higgs bosons in the Higgs sector, with different masses, production rates and decay modes.
- The Higgs production and decay mechanisms can be affected
  - the WWh, ZZh coupling can be shared among several bosons, each of which has a vev smaller than v.
  - the ggh and $\gamma\gamma h$ couplings can be bigger or smaller
  - the $bbh, \tau\tau h$ couplings are easily affected
  - even the $\mu^+\mu^- h$ coupling can become large enough to be important.
  - the dominant decay of the most easily produced Higgs bosons can be to pairs of light, rarely produced scalars (e.g. $h \to aa$, where a is a CP-odd scalar decaying to light SM fermions.)
  - the Higgs may be often produced in the decay of heavy new particles, which (if colored) may be copious, and their production easy to identify.
  - the Higgs may decay invisibly almost all of the time

So discovery of the Higgs can be a lot easier or a lot harder.

But in any case, experimental life is a lot harder! *There is a huge range of possibilities, and a huge range of analysis strategies that must be pursued!!*

In SM and most SUSY, if $m_h < 140$ GeV $h \to b\bar{b}$ is common; otherwise $h \to WW, ZZ$.

Consider the **Minimally Non-minimal Standard Model:** SM plus one real scalar S

$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \eta S^2|H|^2 + M_s^2 S^2 + \kappa S^4$$

For some choices of parameters $\langle H\rangle = v$, $\langle S\rangle = 0$. Write $H = v + h$, find (dropping 2s)

$$V(h,S) = m_h^2 h^2 + m_s^2 S^2 + 2\eta v h S^2 + \text{quartic terms}$$

- If $m_h > 2m_s$, then $h \to SS$ decay becomes possible!
- if $\eta v^2 \gg m_b m_h$, the rate could be $\sim 100\%$!
- Z_2 symmetry $S \to -S$ unbroken; S is stable and invisible!

Now our Higgs boson is invisible; all visible decays reduced by large common factor.

Lesson: One new particle can ruin your whole day.

Alternatively, for other choices of parameters $\langle S\rangle \equiv v' \neq 0$. Let $S = v + s$.

In that case there is a non-zero hs term in the Lagrangian in addition to m_h, m_s —

Therefore the mass eigenstates are mixtures of h and s!

In turn, that means that there are two scalars

$$\phi_1 = h\cos\theta + s\sin\theta \; ; \phi_2 = -h\sin\theta + s\cos\theta$$

- The lighter ϕ may decay like light SM-h, maybe $\phi_1 \to b\bar{b}$
- The heavier ϕ may decay like heavy SM-h, maybe $\phi_2 \to ZZ$
- Or maybe (through hss, hhs terms) $\phi_2 \to \phi_1\phi_1 \to b\bar{b}\; b\bar{b}$

With one new particle, significantly altered pheno; possibly a completely new signature.

One more possibility; perhaps the Z_2 symmetry $S \to -S$ is explicitly broken, by tiny effects.
Note: Not fine-tuned! small sym.breaking effects common, protected against quantum corrections.
This would allow a tiny $S|H|^2$ term, which would induce Sh mixing even with $\langle S\rangle = 0$.

- The hSS term allows $h \to SS$, possibly with 100% branching fraction.
- The tiny mixing allows $S \to b\bar{b}$ with a very long lifetime.

Now the S may decay anywhere

- Outside the detector (invisible Higgs)
- Promptly (difficult $b\bar{b}b\bar{b}$ signal)
- Right in the middle of the tracking volume.

This last has no SM background but a huge detector background from secondary interactions.

Tevatron analysis took ¿2 years; constraints still weak. *And signature has very low trigger rate at the LHC!*

Imagine the range of possibilities if we allow 2 (or 5!) new particles.
Should we investigate all these possibilities?! Infinite task, unmotivated models...

You've heard of Occham's Razor – an elegance criterion. I hereby present:

Strassler's Machete: a usefulness criterion.
A theory is important experimentally if it predicts a non-obvious signature which has not been previously (or sufficiently) considered, could be observed, and is unlikely to be discovered by accident using existing methods.

Lecture 5

Models beyond the SM, mainly driven by the hierarchy problem.

Let me look again at the hierarchy problem.
Higgs has mass-squared term $\sim (100 \text{ GeV})^2$; Yukawa couplings range from $\sim 10^{-5}$ to ~ 1.

$$\mathcal{L} = \mu^2 H H^\dagger + y_i F H f + \dots$$

The hierarchy problem can be phrased as a tension between these two.

- The mass-squared term wants the Higgs to be composite (or otherwise non-perturbative)
  - If the Higgs is a fundamental field, then $\mu^2 \ll M_{max}^2$ is unnatural.
  - If the Higgs is a composite object at scale Λ_{UV}, then $|\mu^2| \sim \Lambda_{UV}^2$ is natural.
    - Note this is true of scalar hadrons in QCD
  - More generally: if Higgs is strongly interacting and $\dim(H) \gg 1$ well above 1 TeV, such that $\dim(H^\dagger H) > 4$, then at high scales $\dim(\mu^2) < 0$ and runs to smaller values in the IR. Eventually strong dynamics ends near 1 TeV, where $\dim(H) \to 1$ and $\mu^2 \sim$ TeV^2.
- But the Yukawa couplings want the reverse:
  - If the Higgs is a fundamental field, then the Yukawa couplings are dimensionless and can be of order 1.
  - If Higgs composite, then Yukawa interactions have dimension > 4 above Λ_{UV} and natural size of the couplings is then of order Λ_{UV}/M_{Planck} to a positive integer power.
  - More generally: if the Higgs has a substantial anomalous dimension, then the natural size of Yukawa couplings is of order Λ_*/M_{Planck} to a substantial positive power.

Note that most of the Yukawa couplings are small, so actually a composite or strongly interacting Higgs might even be ok were it not for $y_t \sim 1$.

Approaches:

- Supersymmetry: Contributions to μ^2 vanish in the SUSY limit ;SUSY is broken at TeV scale.
- Technicolor: Higgs is composite (and possibly top as well) at 1 TeV.
- Warped Extra Dimensions: AdS/CFT dual to models in which (some) SM fields are composite. [Some working models dual to technicolor.]
- Little Higgs: Higgs is PNGB, composite at 10 TeV; mass suppressed below 1 TeV by "collective symmetry breaking".
- Anomalous Dimensions: [idea, but no realistic models] H and SM fermions charged at high energy under a strong gauge group, $H^\dagger H$ operator has a large anomalous dimension while FHf operators do not.
- Large-Volume Flat Extra Dimensions: $M_{Max} = 1$ TeV: Quantum Gravity (String Theory?) at TeV scale.
- Standard Model Plus Denial: **There Is No Hierarchy Problem.** Selection effect? Misunderstanding of QFT with gravity? Something else?

Supersymmetry

- Every particle has a sparticle partner of opposite statistics
- Requires at least two Higgs $SU(2)$ doublets
- Solves the hierarchy problem naturally
  - Higgs h^0 is fundamental scalar
  - Cancellations — positive and negative contributions from bosons and partner fermions — to Higgs mass
  - Failure to cancel is of order the mass splittings within supermultiplets so new particles at or below 1 TeV

The minimal model still has over 50 new particles and over 100 new parameters. And why minimal?

But

- SUSY must be broken — how?
- SM particles must learn about the breaking — how?
  - directly, by participation
  - indirectly, through "gauge mediation"
  - indirectly, through Planck-suppressed effects — "gravity mediation" [misnomer]
  - indirectly, through anomaly — "anomaly mediation"
  - other possibilities...

In MSSM, R-parity is conserved (to avoid catastrophic baryon-number violation) so:

- SUSY particles must be produced in pairs
- A SUSY particle must decay to SM particles plus one other SUSY particle
- The lightest R-parity-odd particle (LSP) is stable.
- Therefore two LSPs are produced in every SUSY event!

Key issue for MSSM: the mass of the gravitino.
Call "LSMSP" the Lightest Standard Model Sparticle.

- Typical Gravity mediation: the LSMSP is the LSP
- Gauge mediation: the gravitino is the LSP, the LSMSP is NLSP

The difference has a huge effect on the phenomenology.

- Since R-parity is conserved in the MSSM, the LSP is stable.
- Light stable charged particles or colored particles would have been found already at colliders.
- Heavy stable charged particles would show up as unusual atoms and are excluded.