the Standard Model: alchemy and astrology

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Outline

- inputs and outputs
- disturbing features
- the right way to think about SM tests
- what we don’t understand about the SM
- discovering the SM at the LHC

what is the Standard Model?

- let's separate the theoretical <u>inputs</u> of the SM from its <u>derived</u> properties
- this is an ahistorical exercise
- and experts may differ on how to make this separation

SM theoretical inputs (I)

-
- All interactions are local
- Quantum mechanics is correct, at least up to energy scales > 1 TeV (length scales down to $\mathbf{10^{-17}}$ cm)
- Special relativity (actually 4d Poincare invariance) is correct on these same scales

these assumptions imply that particle physics is completely described by (effective) quantum field theory

SM theoretical inputs (II)

- There are gauge forces, mediated (at least at large $\mathbf{Q^2}$) by exchanges of gauge bosons
- The gauge group is $\mathbf{SU(3)_c \times SU(2)_w \times U(1)_Y}$
- Gravity is ignored

SM theoretical inputs (III)

- The fundamental matter constituents are 2-component Weyl fermions. They come in 5 varieties:

label	$\mathbf{SU(3)_c}$	$\mathbf{SU(2)_w}$	$\mathbf{U(1)_Y}$
$\mathbf{Q_i}$	triplet	doublet	1/3
$\mathbf{U_i}$	triplet	singlet	4/3
$\mathbf{D_i}$	triplet	singlet	-2/3
$\mathbf{L_i}$	singlet	doublet	-1
$\mathbf{E_i}$	singlet	singlet	-2

There are 3 copies (generations) of this matter content
And a Higgs scalar with the same charges as $\mathbf{L_i}$

SM theoretical inputs (IV)

-
- $\mathbf{SU(3)_c \times SU(2)_w \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{em}}$ via the Higgs mechanism
- This same Higgs also has direct Yukawa couplings to pairs of fermions. These pairs have the same color charges but different hypercharges and weak charges, e.g.

$$\lambda_{\mathbf{ij}}\, \mathbf{H L_i E_j}$$

SM theoretical inputs (V)

- Only include operators up to dimension four

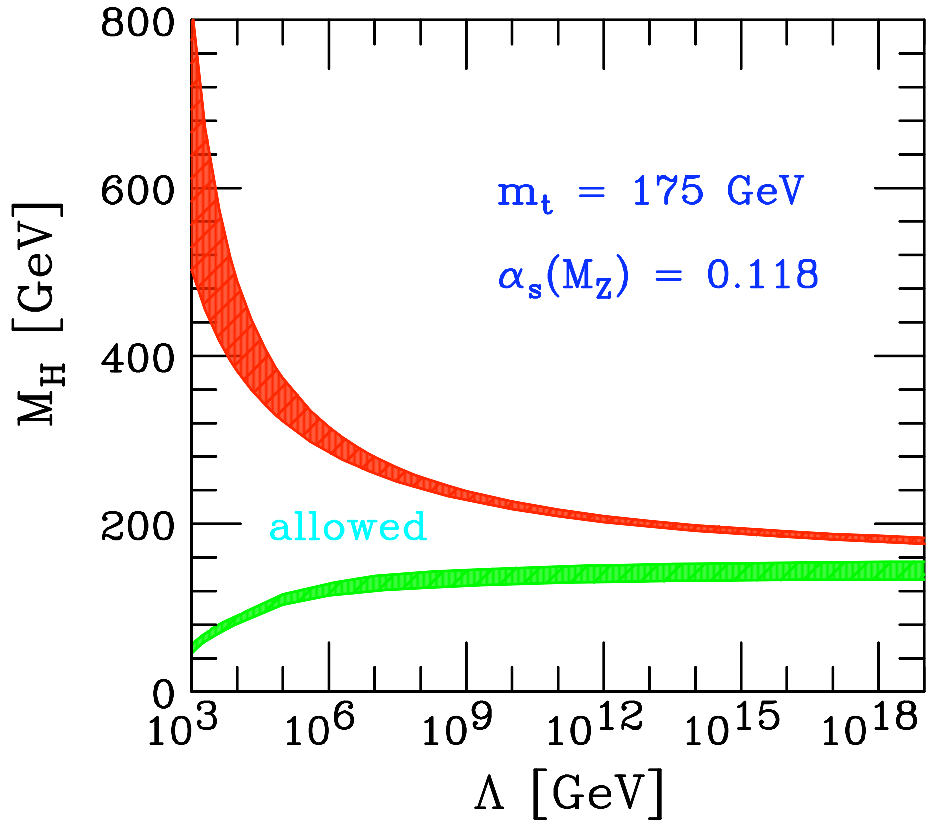
(The historical motivation for this was to make the theory renormalizable. This motivation is no longer compelling, but this remains an important input)

SM derived properties (I)

- Particle masses are derived from dynamics and dimensionless couplings
- There is one input mass scale at the classical level: the Higgs mass-squared parameter $-\mathbf{m_H^2}$
- Together with the Higgs quartic self-coupling parameter λ , this determines v=246 GeV and the Higgs boson mass

SM derived properties (II)

- The theory has no explicit cut-off dependence (i.e. it is renormalizable)
- At the quantum level the dimensionless couplings run
- This introduces a new low energy mass parameter $\mathbf{\Lambda_{QCD}}$
- If the Higgs particle has mass > about 180 GeV, also introduces a new mass scale $\mathbf{\Lambda_{LP}}$ where the running Higgs quartic coupling λ hits a Landau pole and the SM breaks down:



Hambye and Riesselmann

SM derived properties (III)

There are "accidental" global symmetries:

- B and L (but B+L broken nonperturbatively)
- chiral symmetries for quarks and leptons (but quark chiral symmetry broken by QCD condensate)
- a huge $[\mathbf{U(3)}]^{\mathbf{5}}$ flavor symmetry broken by the (mostly small) Yukawa couplings

SM derived properties (IV)

- There are FCCC at tree level
- There are no FCNC at tree level, and a GIM suppression at loop level
- All quark flavor violation is parametrized by the CKM matrix
- There are two sources of CPV (not including neutrinos): one (not small) phase in the CKM matrix, and one (very small) angle in QCD

disturbing features (I): the hierarchy problem

- SM avoids 1-loop breaking of $\mathbf{SU(2)_w \times U(1)_Y}$ <u>only</u> because the fermions come in 3 copies of the charges of a 16 of SO(10)
- And the gauge couplings <u>almost</u> unify at a superheavy scale
- So why isn't $\mathbf{|m_H| \sim M_{GUT}}$?
- Gravity exists, naively becomes strong at $\sim \mathbf{M_{Planck} = 10^{19}}$ GeV
- So why isn't $\mathbf{|m_H| \sim M_{Planck}}$?
- For most of the possible range of mass of the Higgs particle, the SM breaks down at a heavy scale $\mathbf{M_{LP}}$ (or $\mathbf{M_{VI}}$)
- So why isn't $\mathbf{|m_H| \sim M_{LP}}$?

disturbing features (II): flavor

- The top Yukawa, in units of $\frac{\mathbf{v}}{\sqrt{\mathbf{2}}}$, is 1.0 (!)
- But e.g. the electron Yukawa is $\sim \mathbf{10^{-6}}$
- The CKM matrix also has a hierarchical structure:

$$\mathbf{V_{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda^2 & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Could say: these are just free parameters so who cares?
- Could say: these are set by initial conditions + anthropic arguments (Cogito, ergo $\mathbf{m_e = 0.5109989}$ MeV)
- But the most straightforward conclusions are:
  - SM has too few degrees of freedom (Yukawas should be promoted to fields)
  - or SM has too many degrees of freedom (quarks are not fundamental)

disturbing features (III): why no higher dimension operators?

- After 25 years, would have expected that at some point data would favor adding some higher dimension operators to the original SM
- Just some dim=5,6,... operator constructed out of SM fields, introducing one more mass scale, and <u>at most</u> breaking the “accidental” symmetries
- But this has not happened, with one possible exception

3 classes of (acceptable) higher dimension operators:

- Those which violate B and/or L
- Those which violate the approximate flavor symmetries of the SM
- Those which conserve B and L and are MFV (Minimal Flavor Violating)

B and/or L violating operators

- Proton decay and LFV data tell us that dim=6 operators of this type either don't exist or are suppressed by a superheavy mass scale
- So B and L are not so accidental?
- The discovery of neutrino masses, if they turn out to be Majorana, favor adding a dim=5 operator to the SM:

$$\mathcal{O}_{\mathbf{5}} = \frac{\mathbf{f}}{\mathbf{\Lambda}}(\mathbf{L}^{\mathbf{T}}\mathbf{C}\,\mathbf{i}\tau_{\mathbf{2}}\vec{\tau}\,\mathbf{L})(\mathbf{H}^{\mathbf{T}}\,\mathbf{i}\tau_{\mathbf{2}}\vec{\tau}\,\mathbf{H})$$

$$\mathbf{m}_{\nu} \simeq \frac{\mathbf{f}}{\mathbf{\Lambda}}\,\mathbf{v}^{\mathbf{2}}$$

thus e.g. $\mathbf{f} = \mathbf{1},\ \mathbf{m}_{\nu} \simeq \mathbf{0.3}\ \mathrm{eV}\ \Rightarrow \mathbf{\Lambda} \simeq \mathbf{3} \times \mathbf{10}^{\mathbf{14}}\ \mathrm{GeV}$

operators with general quark flavor violation

- The B factories, Tevatron expts, etc have been looking for these for a long time now
- They don’t see any yet
- Some FCNC operators, if they exist, have to be suppressed by scales as high as 1000 TeV (!)
- Starting to look like CKM is the <u>only</u> source of quark flavor violation? Why?

how about harmless dim=6 four-fermion operators that are flavor diagonal?

$\Lambda^+_{LL}(eeee)$	$>$ 8.3 TeV,	$\Lambda^+_{LL}(eecc)$	$>$ 1.0 TeV,
$\Lambda^-_{LL}(eeee)$	$>$ 10.3 TeV,	$\Lambda^-_{LL}(eecc)$	$>$ 2.1 TeV,
$\Lambda^+_{LL}(ee\mu\mu)$	$>$ 8.5 TeV,	$\Lambda^+_{LL}(eebb)$	$>$ 5.6 TeV,
$\Lambda^-_{LL}(ee\mu\mu)$	$>$ 6.3 TeV,	$\Lambda^-_{LL}(eebb)$	$>$ 4.9 TeV,
$\Lambda^+_{LL}(ee\tau\tau)$	$>$ 5.4 TeV,	$\Lambda^+_{LL}(\mu\mu qq)$	$>$ 2.9 TeV,
$\Lambda^-_{LL}(ee\tau\tau)$	$>$ 6.5 TeV,	$\Lambda^-_{LL}(\mu\mu qq)$	$>$ 4.2 TeV,
$\Lambda^+_{LL}(\ell\ell\ell\ell)$	$>$ 9.0 TeV,	$\Lambda(\ell\nu\ell\nu)$	$>$ 3.10 TeV
$\Lambda^-_{LL}(\ell\ell\ell\ell)$	$>$ 7.8 TeV,	$\Lambda(e\nu qq)$	$>$ 2.81 TeV
$\Lambda^+_{LL}(eeuu)$	$>$ 23.3 TeV,	$\Lambda^+_{LL}(qqqq)$	$>$ 2.7 TeV,
$\Lambda^-_{LL}(eeuu)$	$>$ 12.5 TeV,	$\Lambda^-_{LL}(qqqq)$	$>$ 2.4 TeV,
$\Lambda^+_{LL}(eedd)$	$>$ 11.1 TeV,	$\Lambda^+_{LL}(\nu\nu qq)$	$>$ 5.0 TeV,
$\Lambda^-_{LL}(eedd)$	$>$ 26.4 TeV,	$\Lambda^-_{LL}(\nu\nu qq)$	$>$ 5.4 TeV,

PDG 2004

how about harmless dim=6 "oblique" operators?

- These are purely electroweak, flavor diagonal, and only affect the W and Z vacuum polarization, e.g.

$$\mathcal{O}_{\mathbf{WB}} \propto (\mathbf{H}^\dagger \tau^{\mathbf{a}} \mathbf{H}) \mathbf{W}^{\mathbf{a}}_{\mu\nu} \mathbf{B}_{\mu\nu} \qquad \mathcal{O}_{\mathbf{BB}} \propto (\partial_\rho \mathbf{B}_{\mu\nu})^{\mathbf{2}}$$

$$\mathcal{O}_{\mathbf{H}} = |\mathbf{H}^\dagger \mathbf{D}_\mu \mathbf{H}|^{\mathbf{2}} \qquad \mathcal{O}_{\mathbf{WW}} \propto (\mathbf{D}_\rho \mathbf{W}^{\mathbf{a}}_{\mu\nu})^{\mathbf{2}}$$

- If present, they would give the leading contributions to the S,T,Y,W parameters

Barbieri, Pomarol, Rattazzi, Strumia

- But, barring conspiracies, electroweak data says that they are all suppressed by multi-TeV scales (!)

the little hierarchy problem

- This is particularly disturbing when we think about Higgs naturalness
- The leading corrections to the Higgs mass-squared parameter from SM loops are:

$$\delta \mathbf{m_H^2} = \frac{\mathbf{6G_F}}{\sqrt{\mathbf{2}}\pi^{\mathbf{2}}}(\mathbf{m_t^2} - \mathbf{1/2\,m_W^2} - \mathbf{1/4\,m_Z^2} - \mathbf{1/4\,m_H^2}) \int^{\mathbf{\Lambda}} \mathbf{EdE}$$

- Thus e.g. just from the top loop we have:

$$\delta \mathbf{m_H^2(top)} \sim (\mathbf{115}\ \mathrm{GeV})^{\mathbf{2}} \left(\frac{\mathbf{\Lambda}}{\mathbf{400}\ \mathrm{GeV}} \right)^{\mathbf{2}}$$

the wrong way to think about SM tests

- SM tests are boring unless they fail
- SM tests never fail (in a clear-cut way)
- So SM tests are always boring

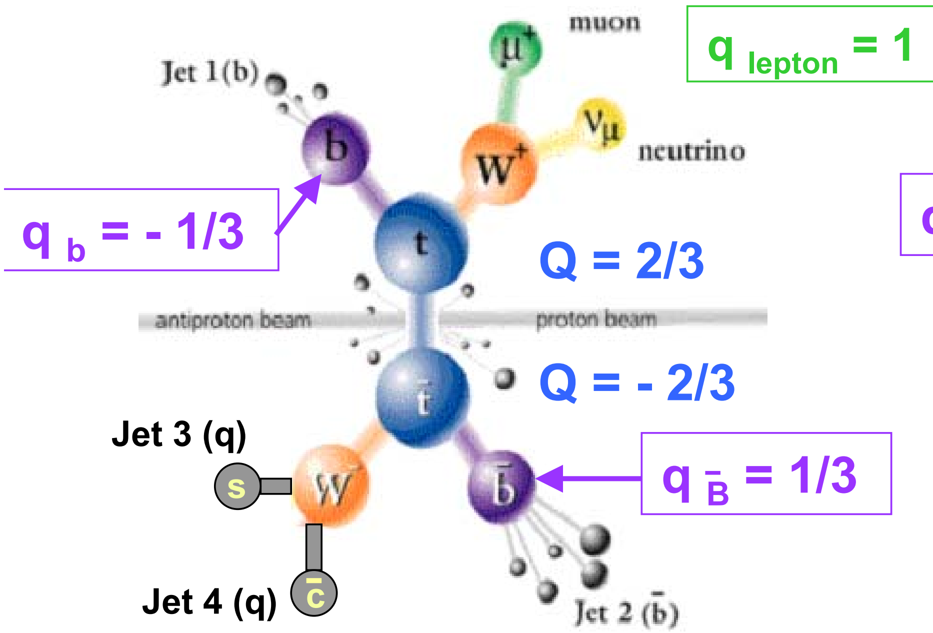
the right way to think about SM tests

- The SM predicts a wealth of new particle physics phenomena
- If you observe any of these phenomena for the first time in an experiment, you have made a discovery
- When you observe the phenomena in more detail, you force the theorists to develop a more concrete understanding of what the SM really is
- Thus e.g. the LEP experiments were both exciting and important, even though/if they “only” saw SM physics

An example: top physics

- Even though we “knew” it had to exist, the Tevatron production of top was an important discovery
- The observation of virtual top in EW precision data was also an important discovery
- Recently Tevatron experiments have discovered that this thing we call “top” (a strongly pair-produced heavy state that decays promptly to W+b jet) really has charge +2/3
- And they have discovered this thing we call top really has spin 1/2

Standard Model Top Quark

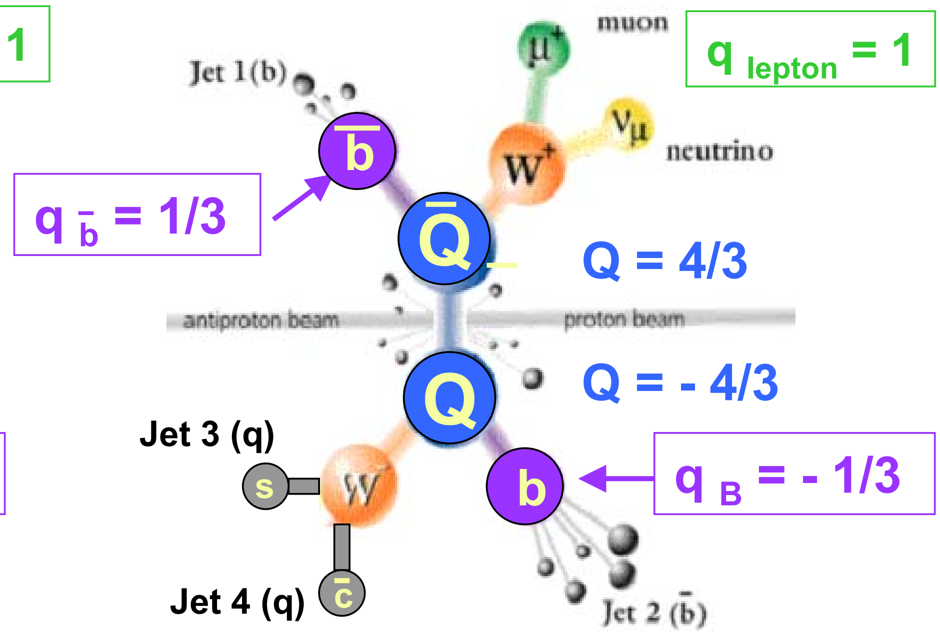


$Q_1 = 2/3,\ Q_2 = 2/3$

- One high P_T lepton: $P_T > 15$ GeV
- Missing transverse energy: $E_T > 15$ GeV
- Four or more jets: $P_T > 15$ GeV

Each scenario has two bottom quarks!

Exotic Top Quark



$Q_1 = 4/3,\ Q_2 = 4/3$

PRD 59, 091503 & PRD 61, 037301

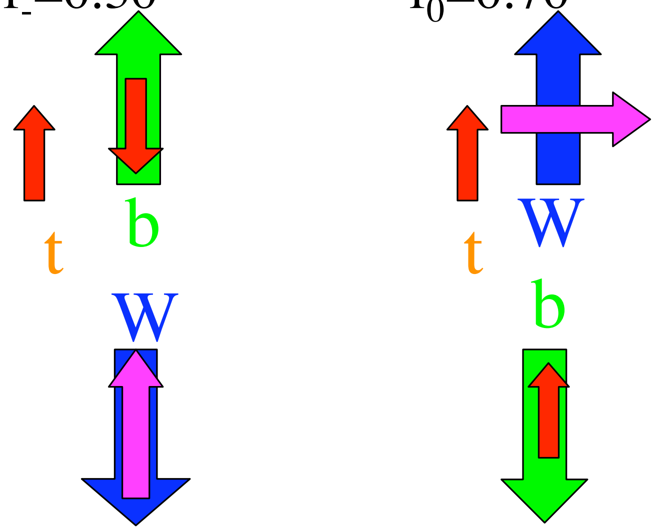
Form two observables:

$$Q_1 = |\ \ q_{lepton} + q_b\ (q_{\bar{b}})\ |$$
$$Q_2 = |\ -q_{lepton} + q_{\bar{B}}\ (q_B)\ |$$

W Boson Helicity

- Helicity is the projection of a particle's spin onto it's direction of motion
- In the standard model the top quark decays to a W boson and b quark via V-A interaction
- There are the three possible W boson helicity states

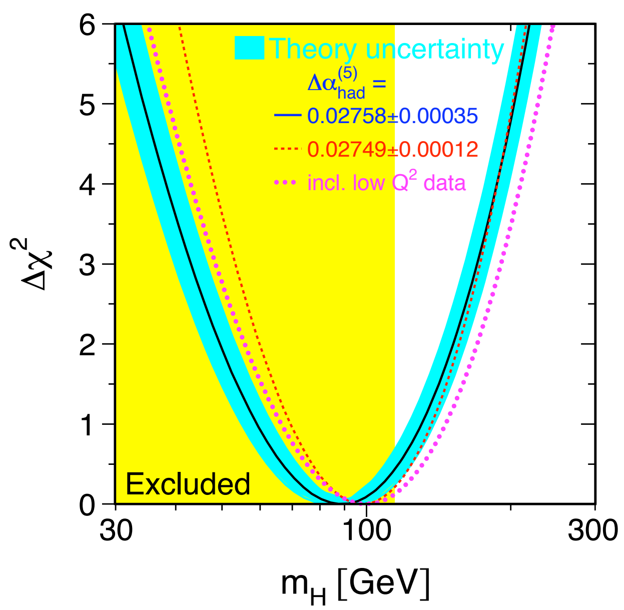
Negative Helicity	Longitudinal Helicity	Positive Helicity
$f_-=0.30$	$f_0=0.70$	$f_+=3.6\text{x}10^{-4}$



Note if "top" had spin 3/2, we would predict $f_+ = 1.0$

the virtual virtual Higgs

- Plots like this give the impression that we are already seeing the Higgs in (logarithmic) radiative corrections, just as we see top in (quadratic) radiative corrections



- Let's have a closer look at what is actually done in these fits
- E.g. the LEPI+SLD+W mass combined analysis from hep-ex/0509008
- They use this data to fit the purely electroweak quasi-observables $\epsilon_{\mathbf{1}},\ \epsilon_{\mathbf{2}},\ \epsilon_{\mathbf{3}},\ \epsilon_{\mathbf{b}}$ of Altarelli, Barbieri, Caravaglios, Jadach (these are simply related to S,T,U, $\delta_{\mathbf{b}}$)
- From their Table E.1:

$$\epsilon_{\mathbf{1}} = \mathbf{0.0054 \pm 0.0010}$$

$$\epsilon_{\mathbf{2}} = \mathbf{-0.0089 \pm 0.0012}$$

$$\epsilon_{\mathbf{3}} = \mathbf{0.00534 \pm 0.00094}$$

$$\epsilon_{\mathbf{b}} = \mathbf{-0.0050 \pm 0.0016}$$

- To leading order in purely EW radiative corrections, we can extract the virtual top from, e.g., $\epsilon_{\mathbf{b}}$:

$$\mathbf{m_t^2 = -4\pi^2 \epsilon_b \frac{\sqrt{2}}{G_F}}$$

$$\Rightarrow \mathbf{m_t = 155}\ \mathrm{GeV} \pm \mathbf{25}\ \mathrm{GeV}$$

- Obviously we do see virtual top in the EW data

- To leading order in purely EW radiative corrections, two linear combinations of the fit parameters are dominated by the logarithmic Higgs contribution:

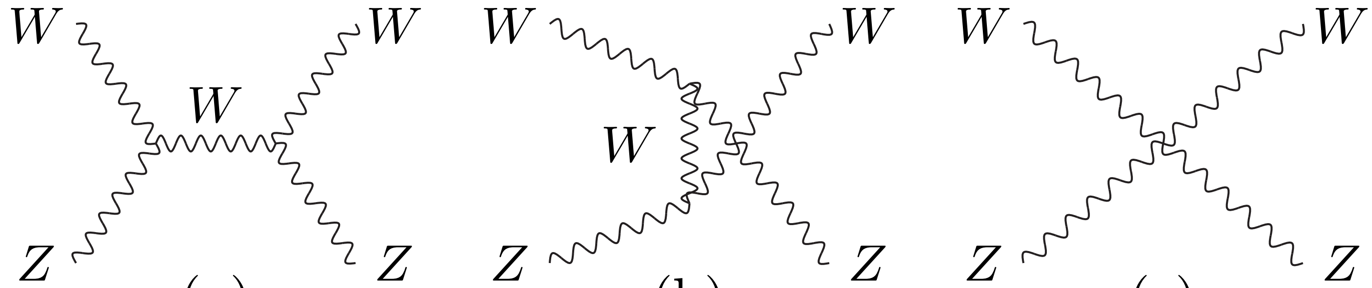
$$\mathbf{3\epsilon_3 - \epsilon_2 \propto \ln\frac{m_H}{m_Z} = -0.002 \pm 0.004}$$

$$\mathbf{2\epsilon_1 + 3\epsilon_b \propto \ln\frac{m_H}{m_Z} = -0.004 \pm 0.005}$$

- So we do not see a virtual Higgs contribution in the EW data (!)

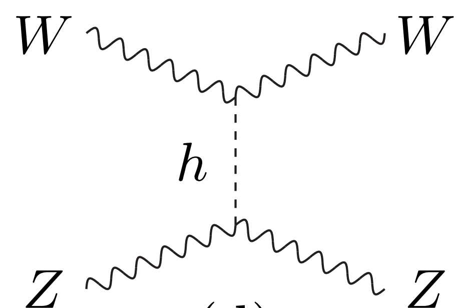
- Since we also do not see any clear non-SM effect, one can speculate that $\mathbf{m_H \simeq m_Z \simeq m_W}$

Higgs particle, TeV cutoff, or ?



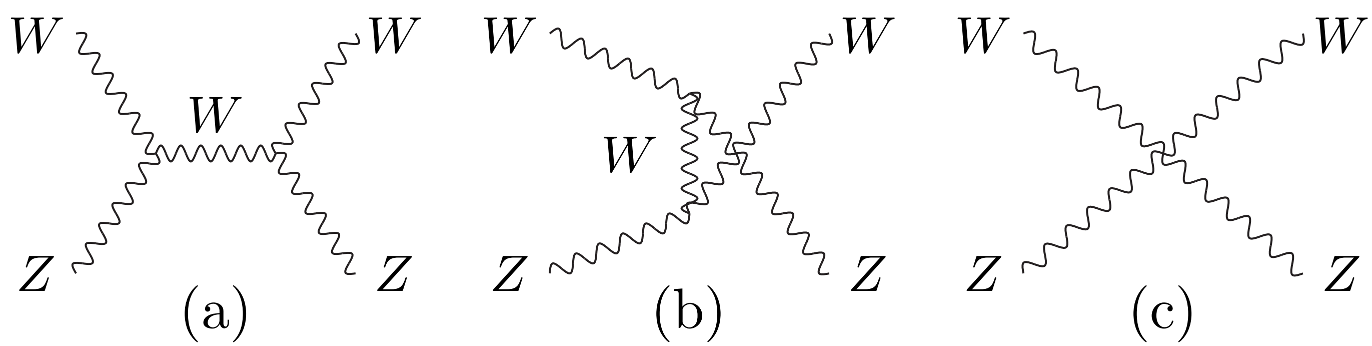
(a) (b) (c)

these diagrams give amplitudes that grow like $\mathbf{E^4}$ and $\mathbf{E^2}$, violating unitarity a little above a TeV

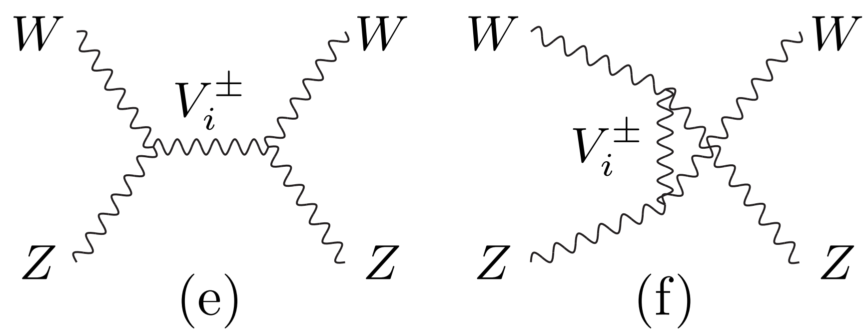


(d)

adding this Higgs diagram magically cancels the $\mathbf{E^4}$ and $\mathbf{E^2}$ behavior



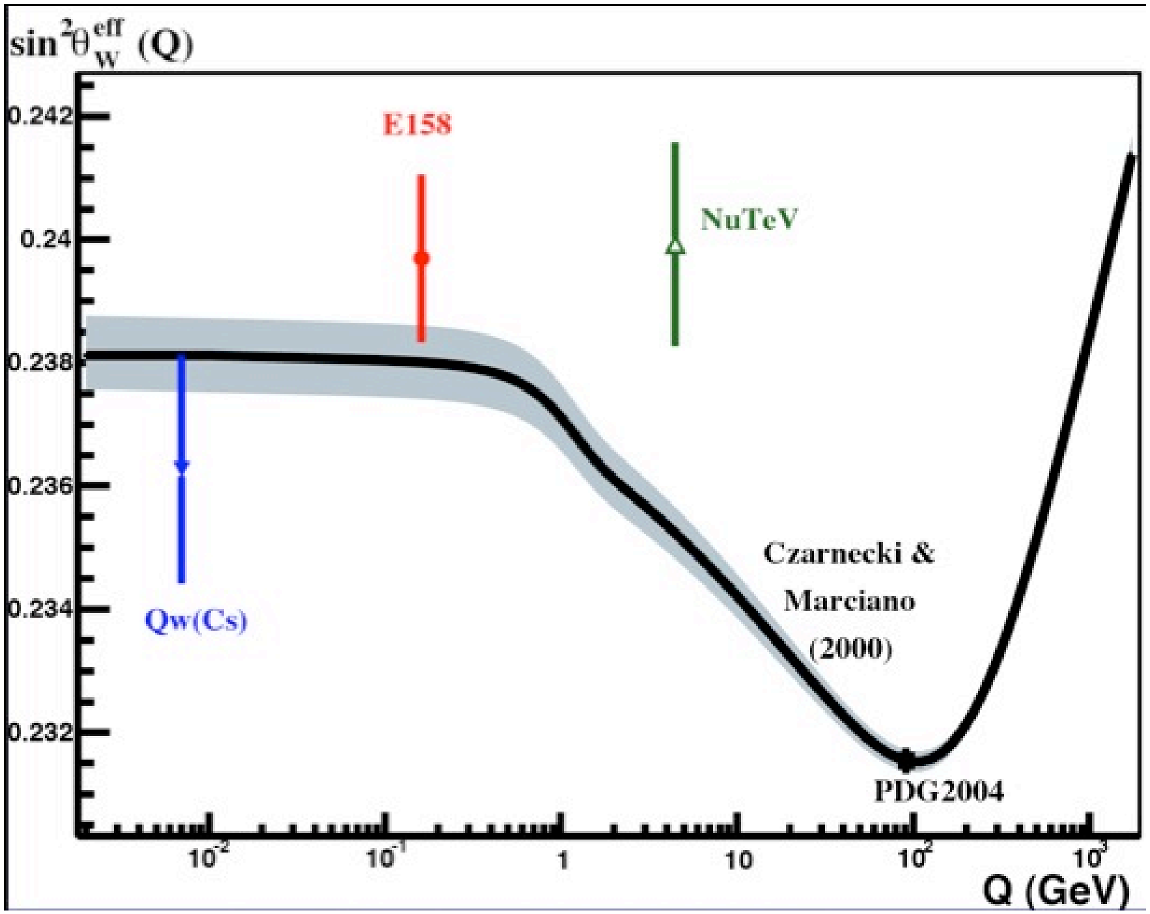
but Higgless models exist in which (weakly coupled) Kaluza-Klein gauge bosons do the same job (!)



Birkedal and Matchev

these models are generically disfavored by EW data, but they show that the SM picture of weakly coupled EWSB is not unique

the right way to think about discrepancies

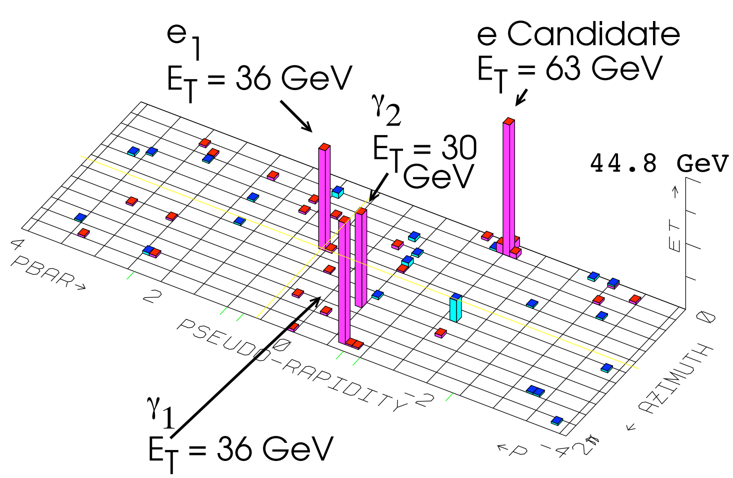


1. Be selective about what ambulances to chase
2. Improve the SM analysis

3. Answer the most important question:

If this is a real BSM effect, what else should we see?

$ee\gamma\gamma\not{E}_T$ Candidate Event



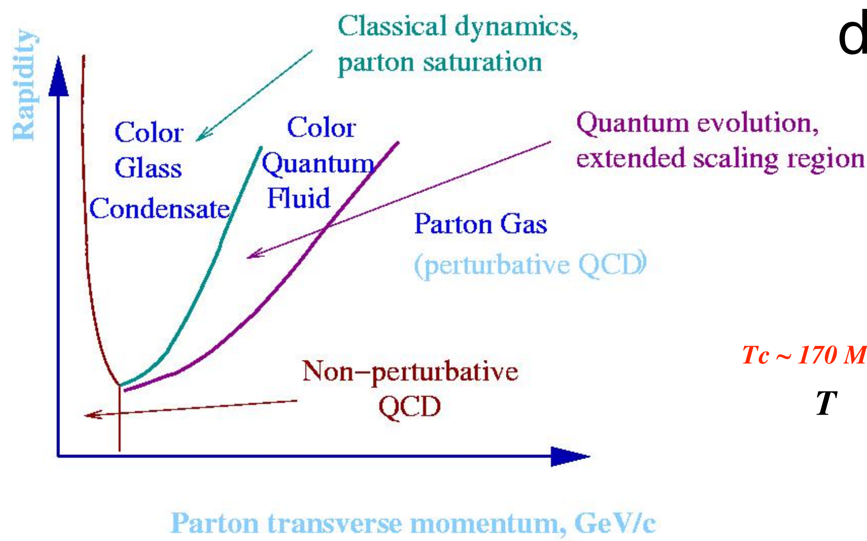
$\not{E}_T$ = 55 GeV

what we don’t understand about the SM

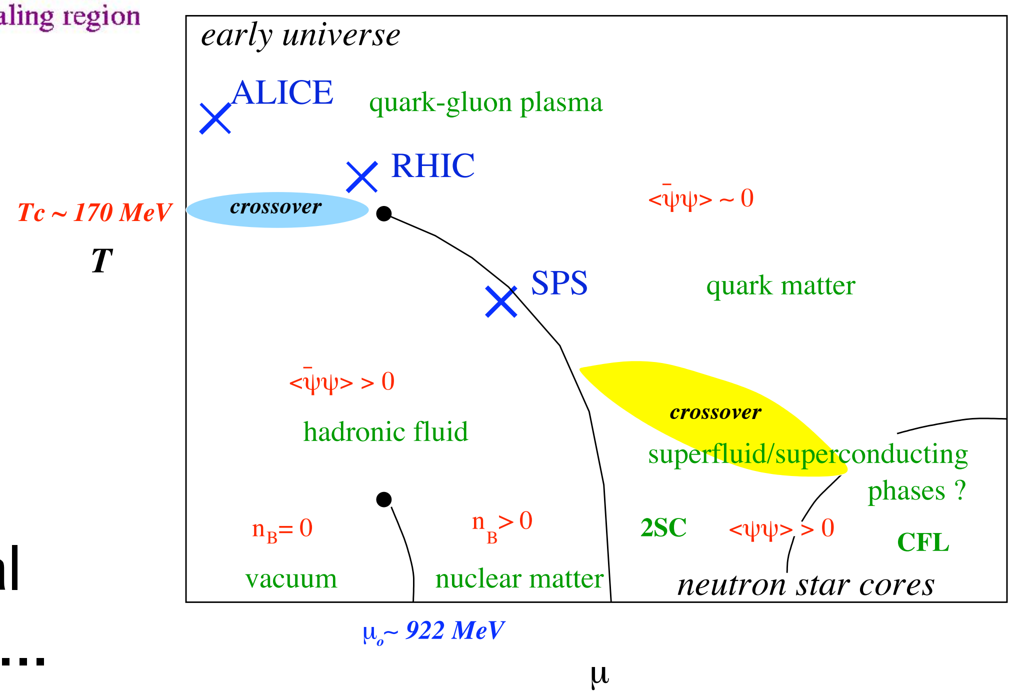
- Where it comes from
- For the electroweak theory, we still need a better understanding of the electroweak phase transition, which is important for understanding baryogenesis
- For QCD, there are many, many things that we still do not understand....

small x, gluon saturation, Color Glass Condensate, breakdown of factorization, ...

The phase diagram of high energy QCD

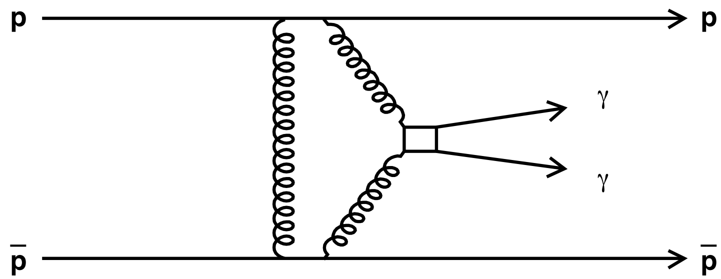


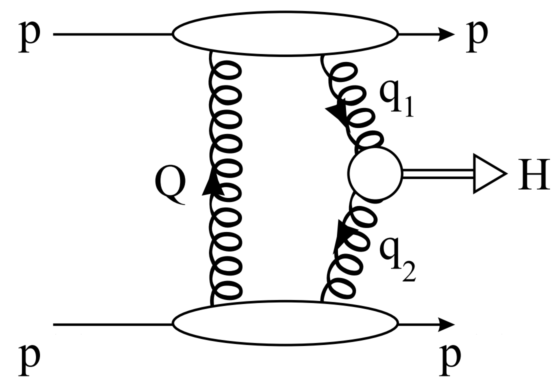
decomposing spin of the proton



quark deconfinement, sQGP=perfect fluid, critical line, high density phases, ...

Diffractive QCD





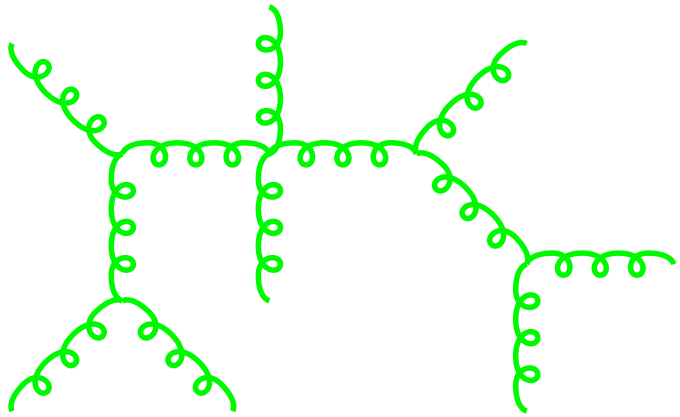
seen at Tevatron

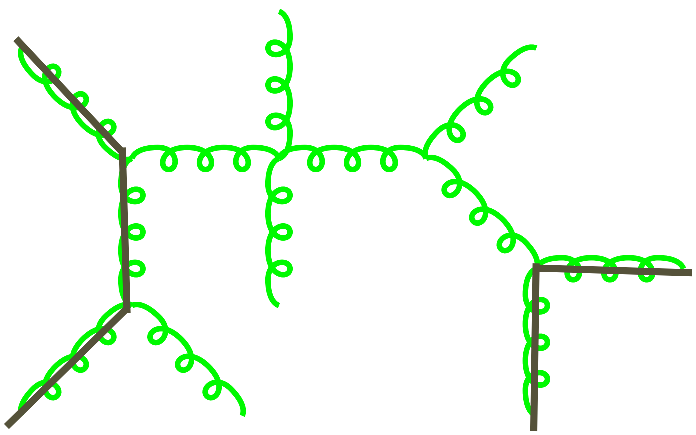
can we see this at LHC?

hidden symmetries of QCD

- QCD has hidden symmetries which lead to drastic simplifications of perturbative amplitudes
- The first hidden symmetry is essentially supersymmetry (!) and is well understood
- The second is connected to twistor space, and is not well understood
- These simplifications of pQCD may be of great practical importance for LHC

QCD knows about SUSY



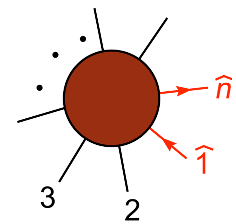


- tree level gluon diagrams don't care (naively) about conserving gluon helicity
- but diagrams with external gluinos conserve gluino helicity
- SUSY relates these amplitudes
- Leads to "accidental" simplifications of gluon amplitudes (Parke-Taylor)

Simple, general: Residue theorem + factorization

how amplitudes “fall apart” in degenerate kinematic limits

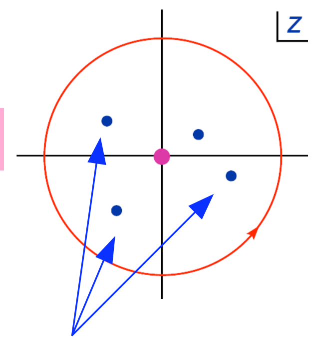
Inject complex momentum at leg 1, remove it at leg *n.*



$$k_1 = \lambda_1 \tilde{\lambda}_1 \;\to\; (\lambda_1 + z\lambda_n)\tilde{\lambda}_1 \quad\Rightarrow\quad A(0) \;\to\; A(z)$$

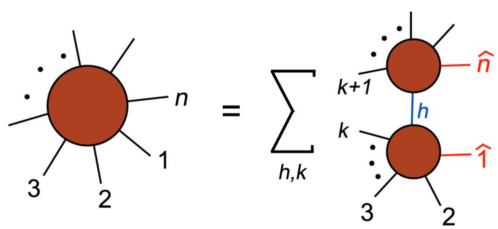
$$k_n = \lambda_n \tilde{\lambda}_n \;\to\; \lambda_n(\tilde{\lambda}_n - z\tilde{\lambda}_1)$$

degenerate limits ⇔ poles in z



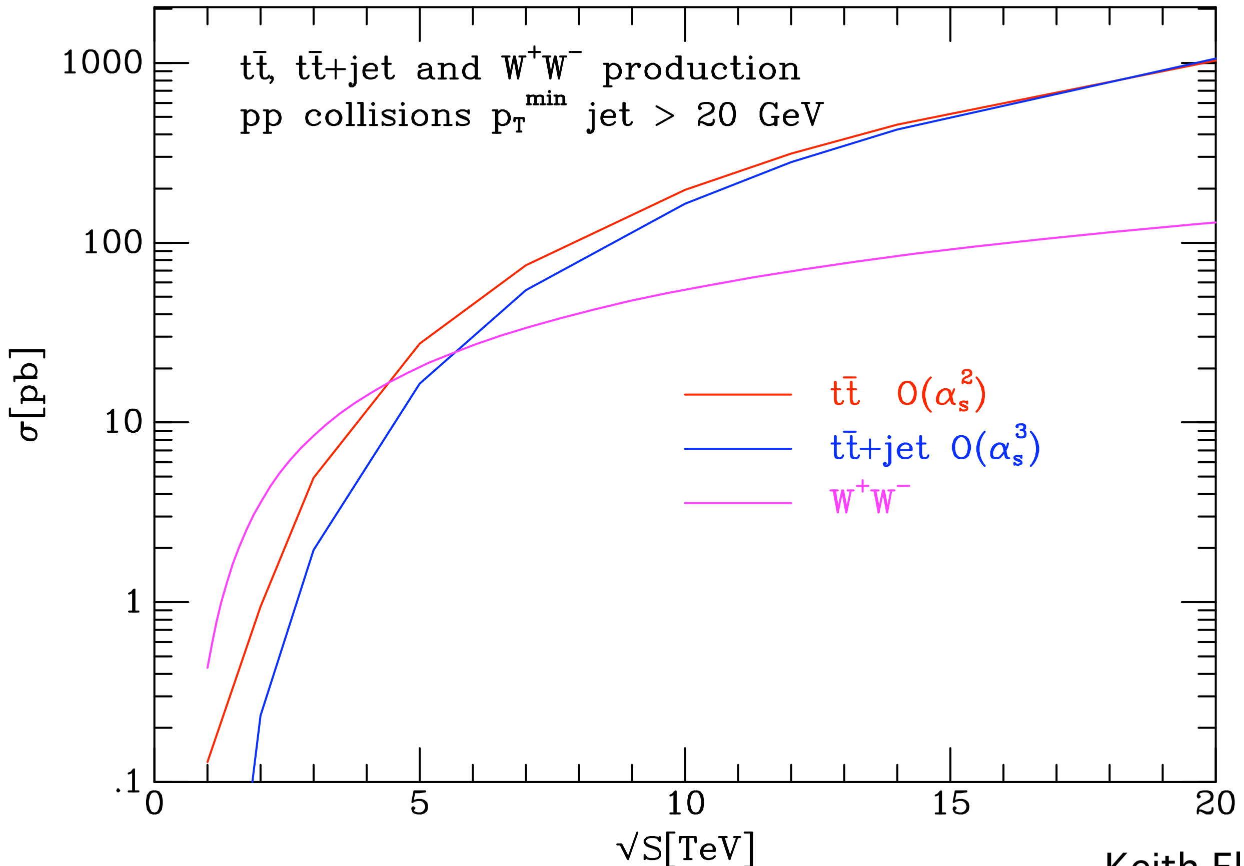
Cauchy: If $A(\infty) = 0$ then

residue at z_k
= [k^{th} term in relation]



discovering the SM at LHC

- Most of what we see at LHC will be SM physics, but in regimes which are very different from what we have seen before



Keith Ellis, Moriond QCD 06

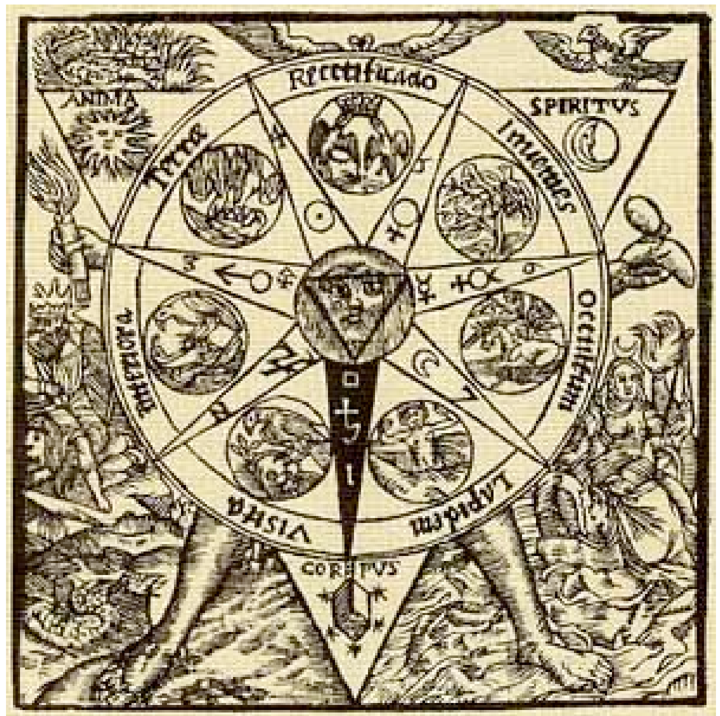
discovering the SM at LHC

- Theorists are working hard to calculate key processes at NLO and NNLO, and interface these results with showering MCs

Les Houches 2005 wishlist (short version)

1. $pp \to V\,V\,\mathrm{jet}$	$t\bar{t}H$, new physics
2. $pp \to H + 2\,\mathrm{jets}$	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2\,\mathrm{jets}$	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V + 2\,\mathrm{jets}$	VBF$\to H \to VV$
7. $pp \to V + 3\,\mathrm{jets}$	various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton

prediction:



10 years from now we will look back on
our current understanding of the SM
and laugh at how little we knew