A Theorist's Take on LHC

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Universität Heidelberg

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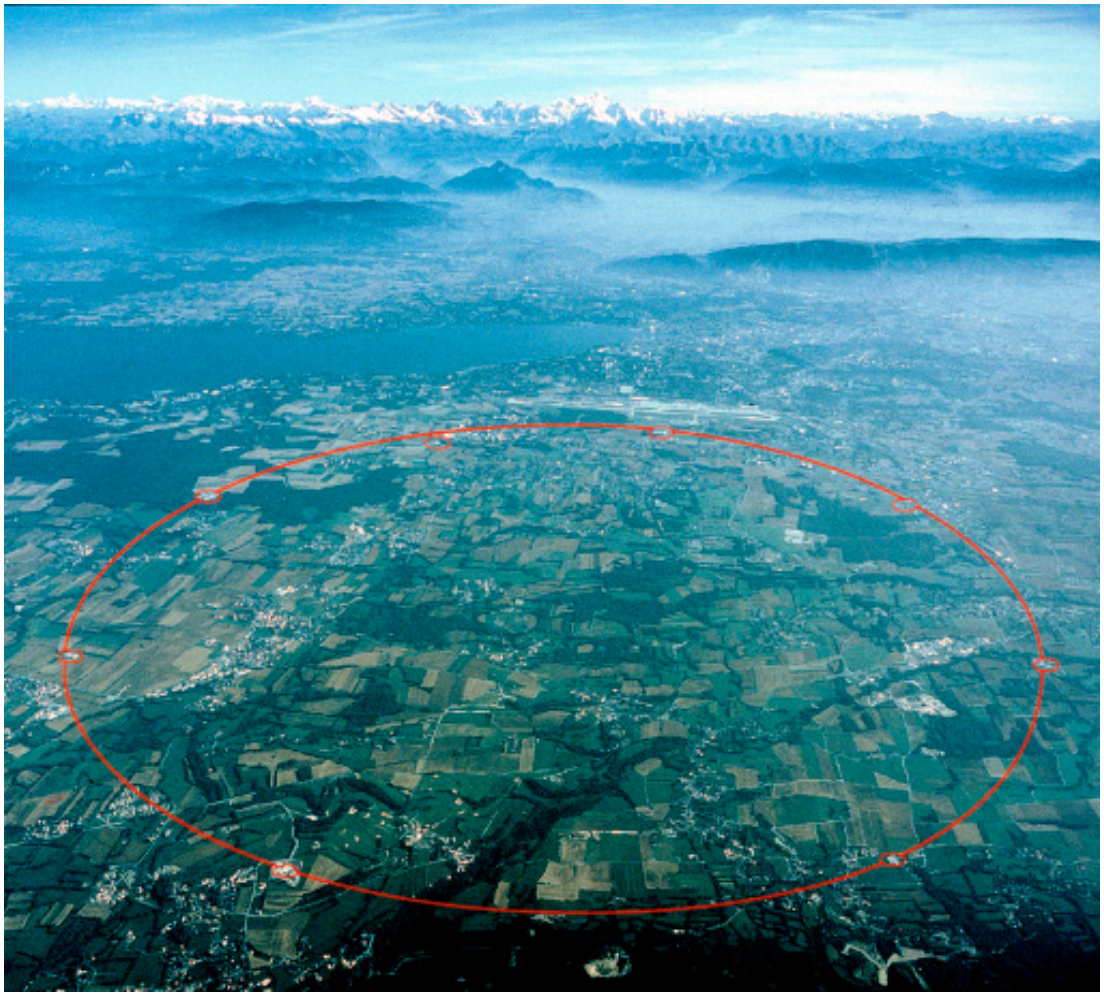
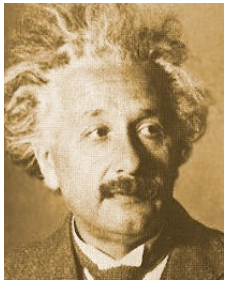
The LHC



The LHC


Golders Green
Hampstead
Hampstead Heath
Gospel Oak
Tufnell Park
Upper Holloway
Finsbury Park
Neasden
Dollis Hill
Willesden Green
Kilburn
Finchley Road & Frognal
Belsize Park
Kentish Town West
Kentish Town
Arsenal
Holloway Road
Brondesbury Park
West Hampstead
Chalk Farm
Camden Road
Caledonian Road
Highbury & Islington
Canonbury
Finchley Road
Camden Town
Swiss Cottage
St. John's Wood
Mornington Crescent
King's Cross St. Pancras
Caledonian Road & Barnsbury
Brondesbury
Kilburn High Road
South Hampstead
Great Portland Street
Euston
Angel
Paddington
Edgware Road
Baker Street
Warren Street
Euston Square
Farringdon
Old Street
Liverpool Street
Shoreditch
Edgware Road
Marylebone
Regent's Park
Russell Square
Barbican
Bayswater
Holland Park
Notting Hill Gate
Lancaster Gate
Bond Street
Oxford Circus
Goodge Street
Holborn
Chancery Lane
Moorgate
Aldgate East
Queensway
Marble Arch
Tottenham Court Road
St. Paul's
Bank
Aldgate
Covent Garden
Cannon Street
High Street Kensington
Hyde Park Corner
Green Park
Piccadilly Circus
Leicester Square
Mansion House
Monument
Tower Hill
Tower Gateway
Knightsbridge
Charing Cross
Blackfriars
River Thames
Gloucester Road
Sloane Square
St. James's Park
Temple
Rotherhithe
Earl's Court
South Kensington
Victoria
Westminster
Embankment
London Bridge
Bermondsey
Canada Water
Fulham Broadway
Waterloo
Surrey Quays
Pimlico
Southwark
Borough
Lambeth
East London line is closed for major line extension work to become part of the London Overground network.

The LHC



Einstein: beam energy to particle mass $E = mc^2$

- smash 4 TeV protons onto 4 TeV protons [energy unit GeV: proton mass]
  produce anything that interacts with quarks and gluons
  search for it in decay products
  repeat every 25 ns
- huge detectors, actual data, commuting to CERN $\longrightarrow$ experiment
  field theory, strong opinions, working in villas $\longrightarrow$ theory

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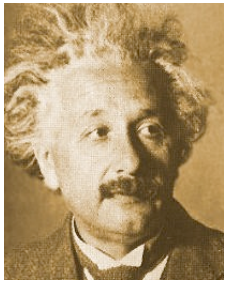

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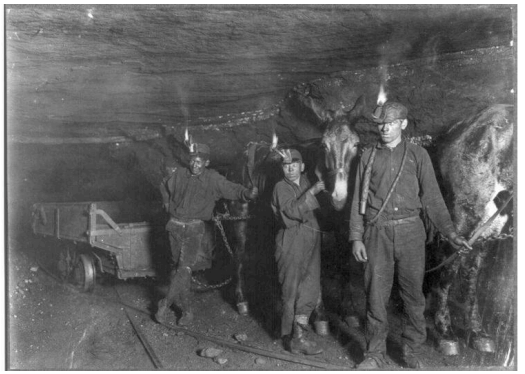
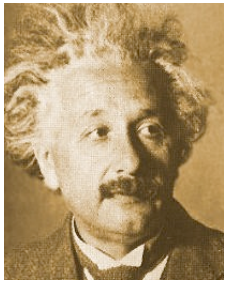


life as a theorist

The LHC



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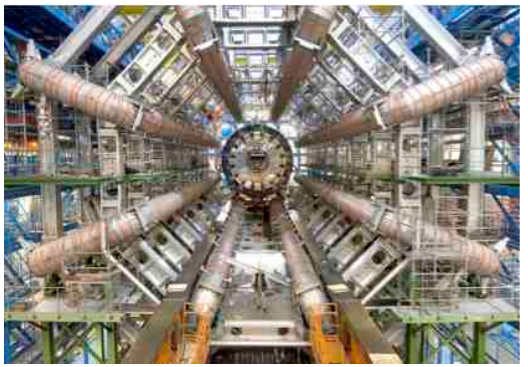

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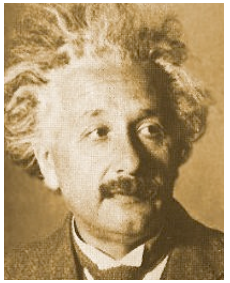

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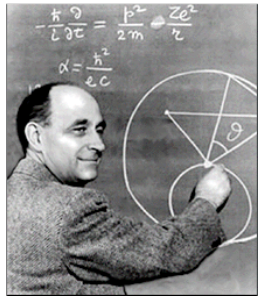
Things you never dared to ask...

- $N_{\text{events}} = \sigma \cdot \mathcal{L}$ ['cross section [fb] times luminosity [1/fb]']
- signal: everything new, exciting and rare
  background: yesterday's signal
- Standard Model w/o Higgs: background theory
  QCD: evil background theory
- jet: everything except for leptons/photons
  crucial: what makes a jet $[q, g, b, \tau, W, H, t]$
- always statistics: $\sigma_{b\bar{b}} \sim 10^7 \sigma_H$

$\Rightarrow$ discovery $\#\sigma \sim N_S/\sqrt{N_B} > 5$

Standard–Model

Climbing up energy scales



- Fermi 1934: weak interactions $[n \to p e^- \bar{\nu}_e]$
  (2 $\to$ 2) amplitude $\mathcal{A} \propto G_F E^2$
  probability/ unitarity violation $[E < 600\ \text{GeV}]$
  pre-80s effective theory

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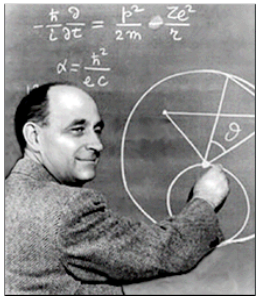

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  Fermi's theory for $E \ll M$
  unitary fermion amplitude $\mathcal{A} \propto g^2 E^2/(E^2 - M^2)$
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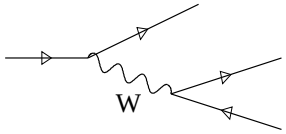

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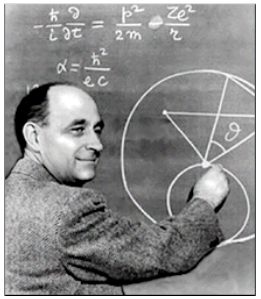

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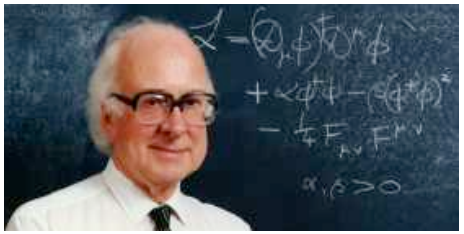

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  completely unitary
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  fundamental weak-scale scalar

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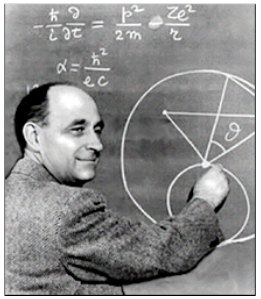

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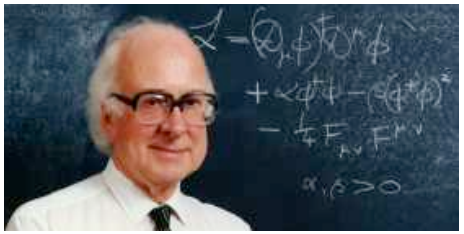

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  completely unitary
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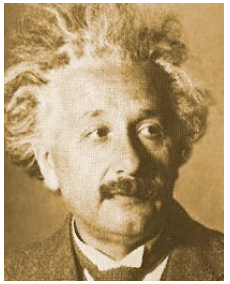
- 't Hooft & Veltman 1971: renormalizability
  no $1/M$ couplings allowed
  theory valid to high energy
  Standard Model with Higgs fundamental

Standard–Model effective theory

Theory perspective

- massless $SU(3)$ and $U(1)$ gauge bosons
  massive W, Z bosons
- weak-scale Higgs scalar
- generation mixing of quark and lepton fermions
- Lagrangian $\mathcal{L} \supset -m_W^2 W_\mu W^\mu - m_f \bar{\Psi}\Psi + gH\bar{\Psi}\Psi \overset{?}{+} \frac{g'}{\Lambda} H W_{\mu\nu} W^{\mu\nu}$

$\Rightarrow$ renormalizable $\Leftrightarrow$ valid to high scales $\Leftrightarrow$ fundamental



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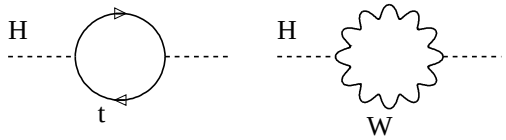
Experimental perspective

- dark matter? [solid evidence for low–scale new physics!?]
- quark mixing — flavor physics? [new operators above 10^4 GeV?]
- neutrino masses and mixing? [see-saw at 10^{11} GeV?]
- matter–antimatter asymmetry? [universe mostly matter?]
- gauge coupling unification? [experimental fact]
- gravity missing? [negligible at LHC]

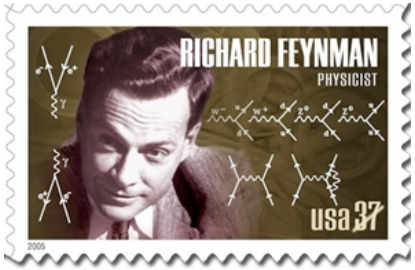
$\Rightarrow$ cut-off unavoidable

Standard–Model and beyond



Theory problems

– Heisenberg: quantum corrections to Higgs mass... $[\Delta t\, \Delta E < 1]$



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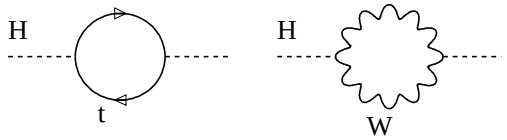

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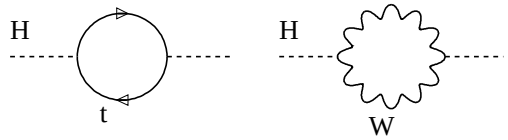
- Heisenberg: quantum corrections to Higgs mass lead to effective theory desaster

$$m_H^2 \longrightarrow m_H^2 - \frac{g^2}{(4\pi)^2}\,\frac{3}{2}\,\frac{\Lambda^2}{m_W^2}\left[m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right] + \cdots$$

- Higgs mass pulled to cut-off Λ [where Higgs at Λ does not work]

$\Rightarrow$ hierarchy problem — Higgs scalar needs stabilization

Standard–Model and beyond



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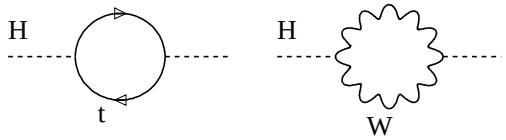
Starting from data which...

- easy solution: counter term — but unethical tuning
- or new physics at TeV scale: supersymmetry
  extra dimensions
  little Higgs
  composite Higgs, TopColor
  YourFavoriteNewPhysics...

$\Rightarrow$ beautiful concepts, not sure if true

Standard–Model and beyond



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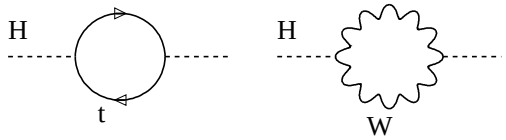

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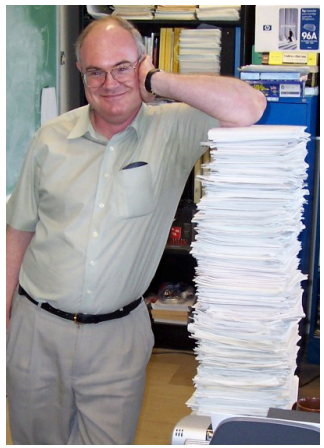

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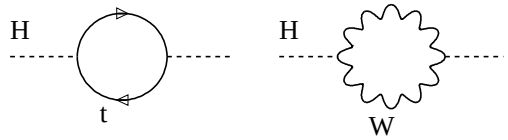

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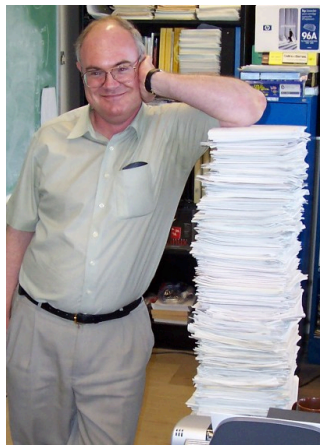
$\Rightarrow$ Higgs discovery waiting since Fermi!



Things we see plenty: jets

Need to count them [e.g. for Higgs searches]

– Peskin & Schroeder: soft photons with Poisson scaling

$$R_{(n+1)/n} \equiv \frac{\sigma_{n+1}}{\sigma_n} = \frac{\bar{n}}{n+1}$$

1. radiation matrix element $\bar{n}^n$
   photons fine, gluons tricky
2. phase space $1/n!$
   only combinatorics, matrix element ordered
3. normalization $e^{-\bar{n}}$

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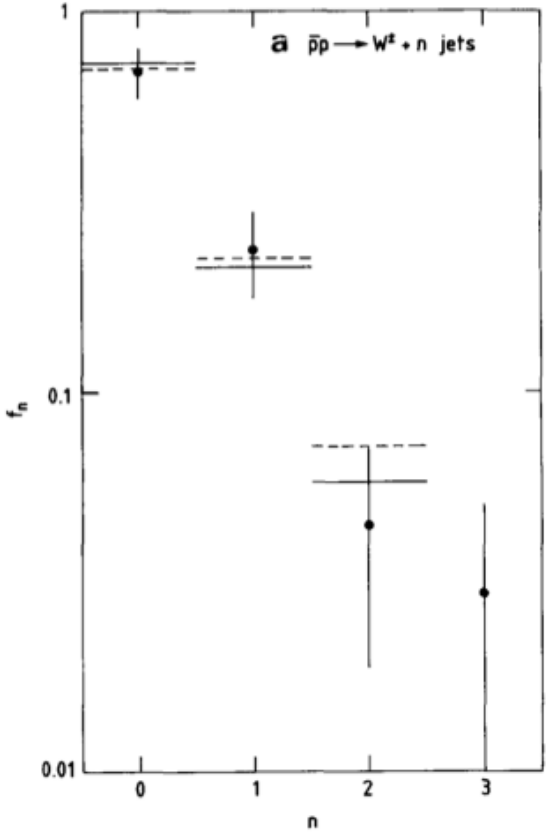

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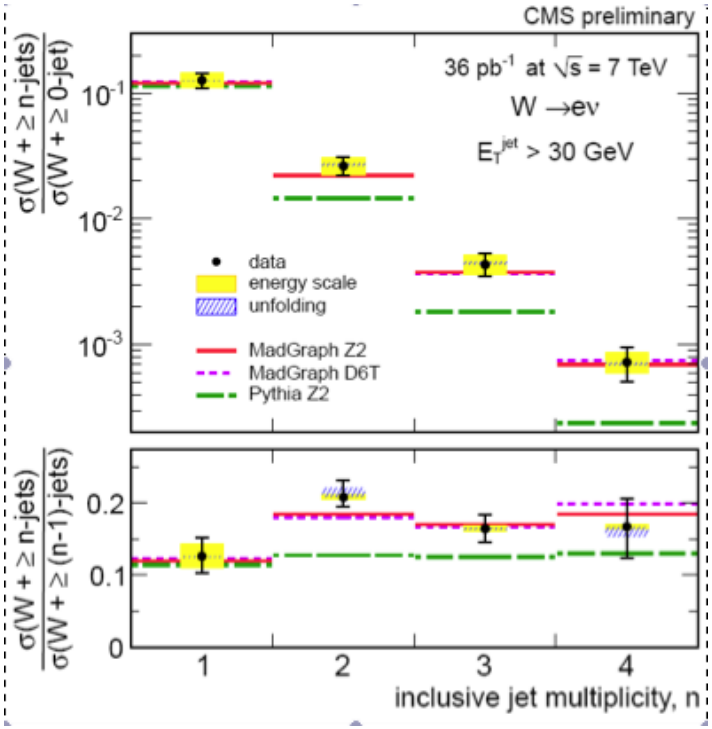

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Modern QCD simulations

- inclusive: staircase scaling
  after cuts: Poisson scaling
- W, Z, γ+jets and QCD jets the same
- mostly an effect of gluon self coupling?

$\Rightarrow$ there still exist QCD puzzles


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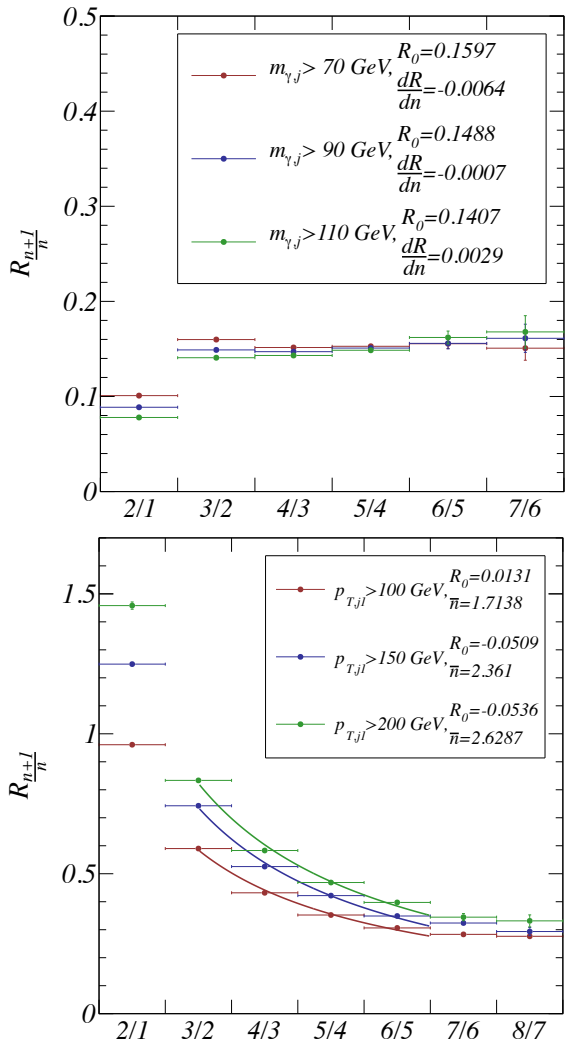
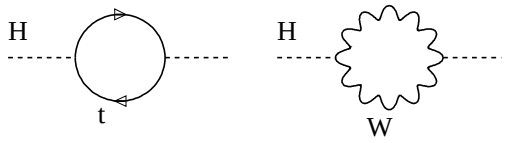


Things we'd like to see: supersymmetry



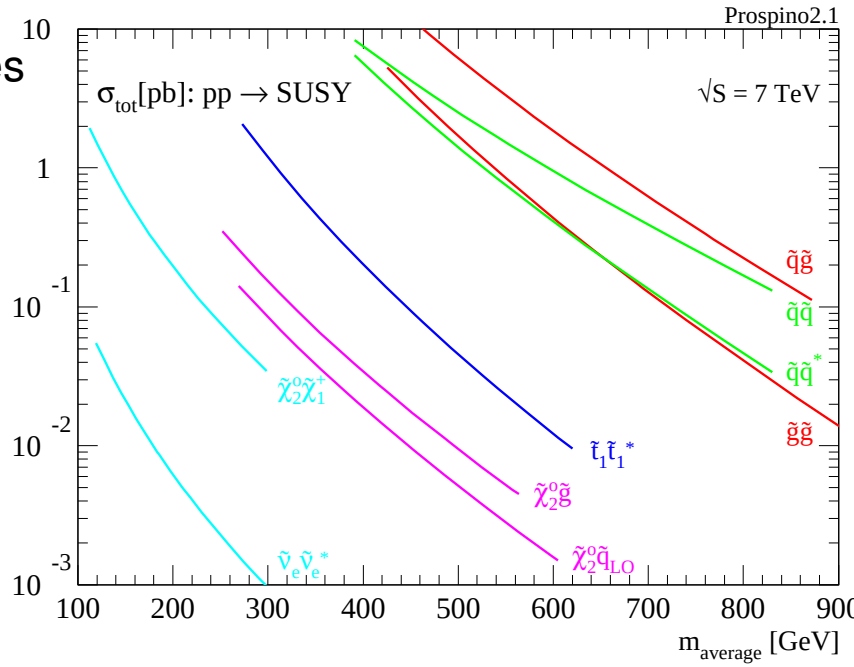
The best theorists can do: supersymmetry

- partner for each Standard Model particle
- cancellation because of different spins
- assume dark matter, stable lightest partner

$\Rightarrow$ LHC: model for WIMP dark matter

Production processes

- produce strongly interacting particles
  cascade decay to DM candidate



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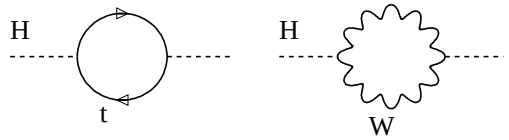

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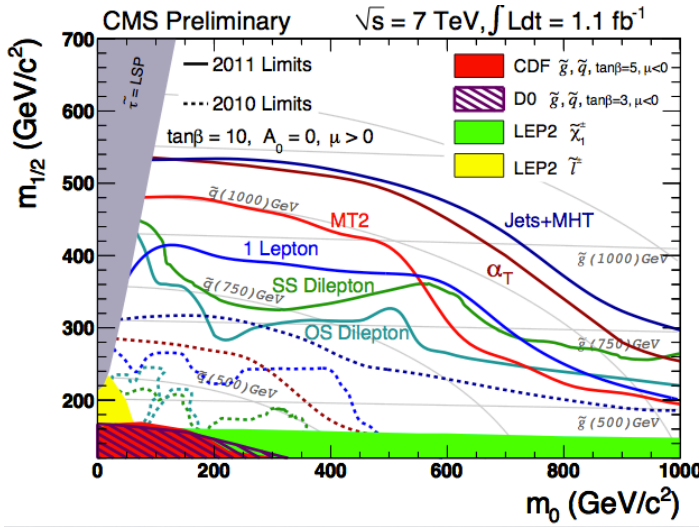

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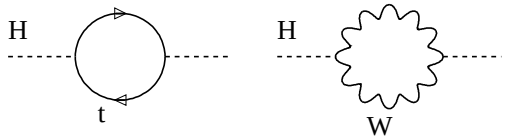

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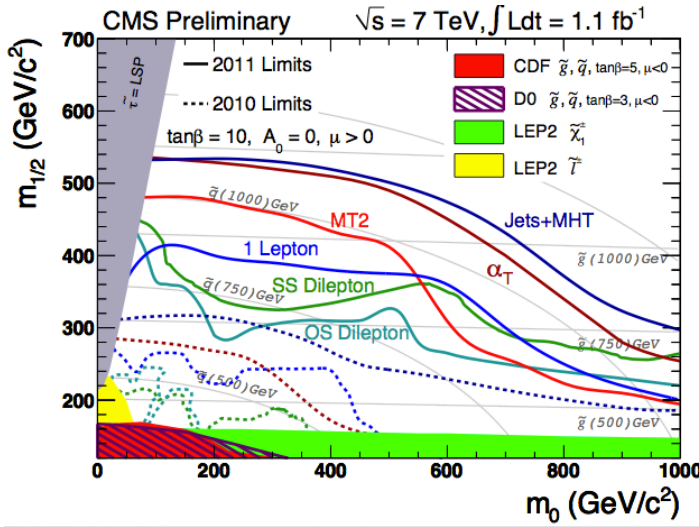
$\Rightarrow$ but only one signature and still early



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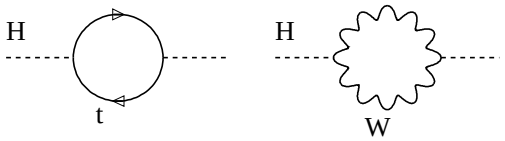

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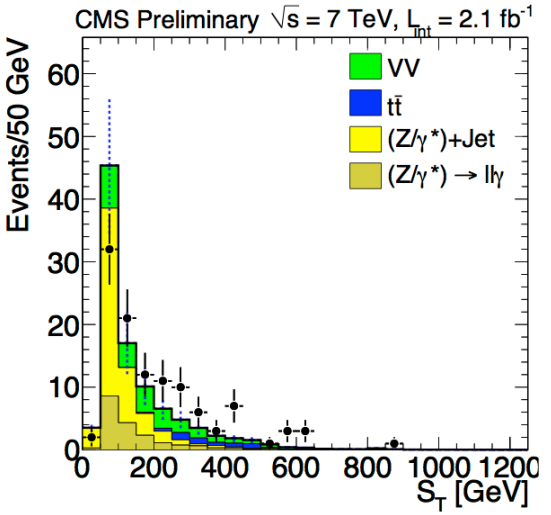

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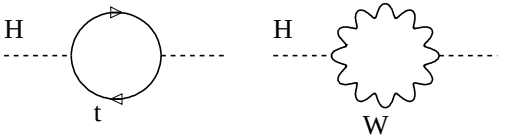

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Fat top jets: $t \to bW^+ \to bjj$ [HEPTopTagger]

- boost likely at LHC: $R^2_{bjj} \equiv \phi^2_{bjj} + y^2_{bjj} \sim (m_t/p_T)^2 \gtrsim 1.5^2$
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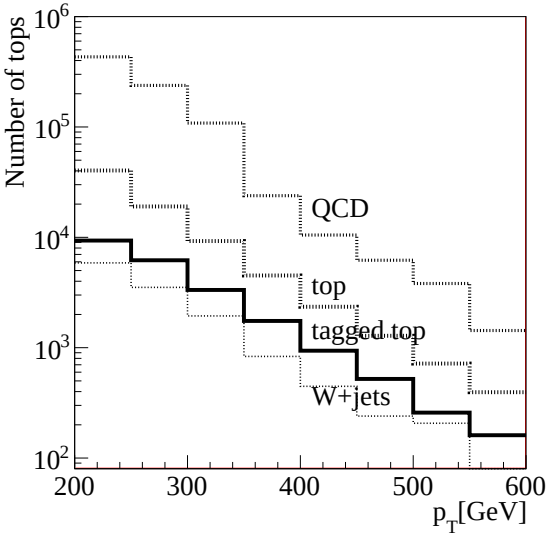

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  S: large m_{bb}, boost-dependent separation
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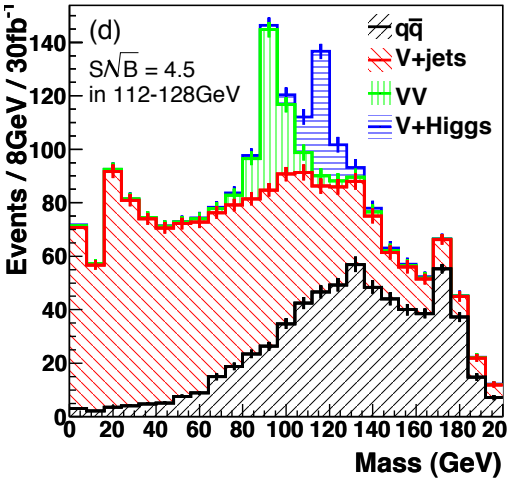

Things we might have seen: Higgs

Standard Model Higgs sector

- gives mass to photons, protons, and the universe!

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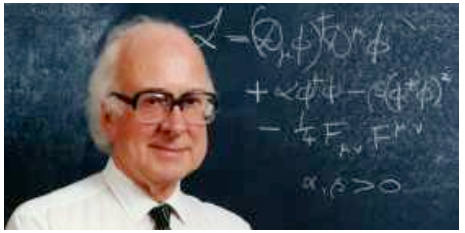

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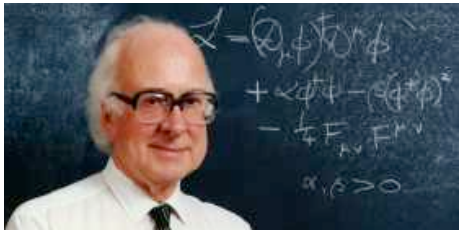

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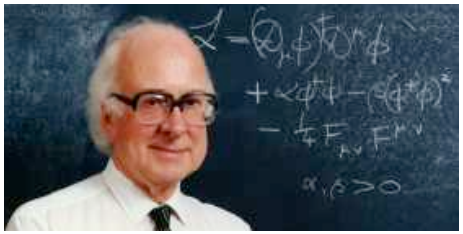

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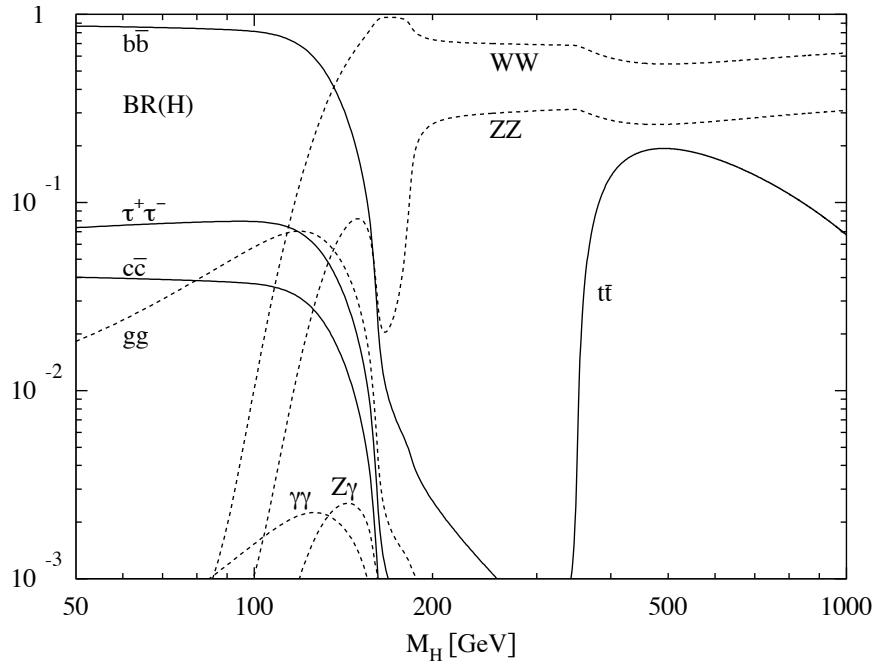

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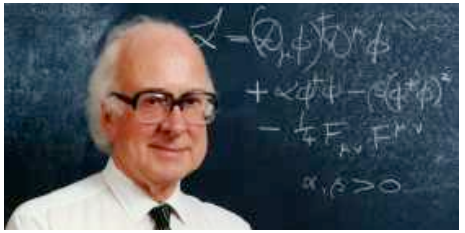

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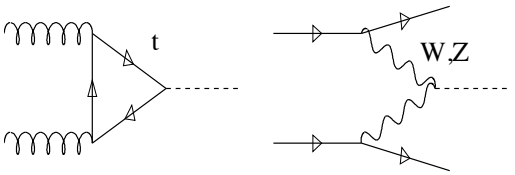

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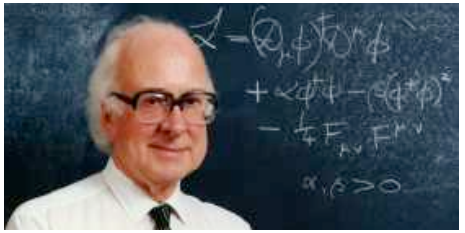

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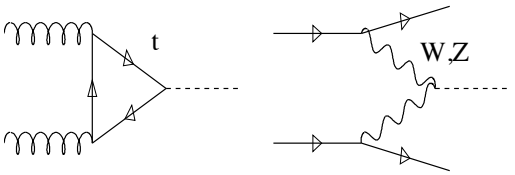

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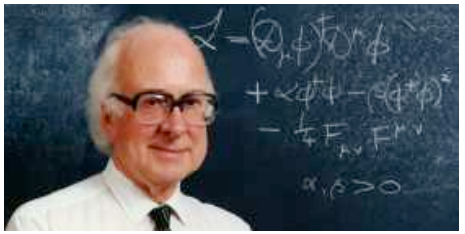

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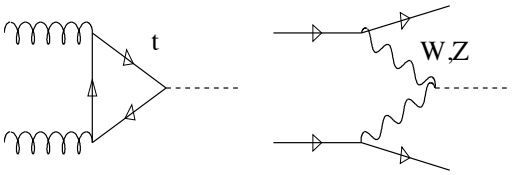

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- harder channels 2012-2015

  $pp \to H \to \tau\tau$ plus jets
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  etc...

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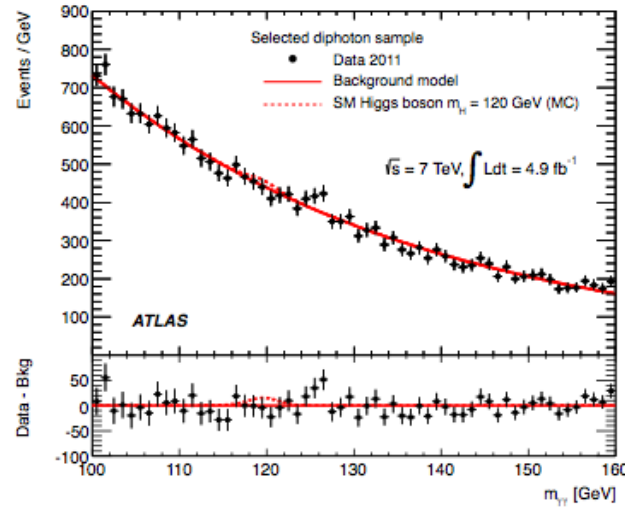

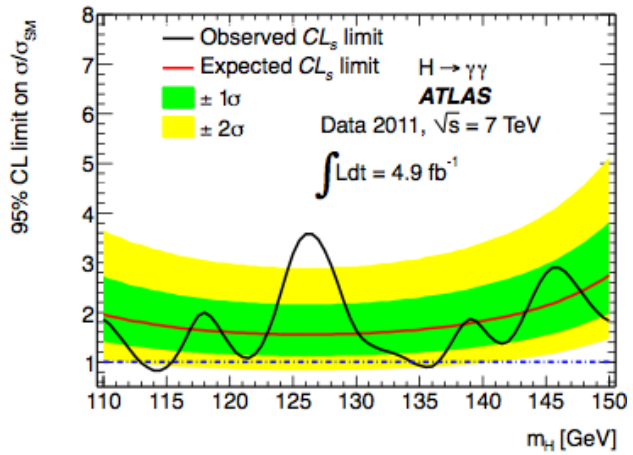

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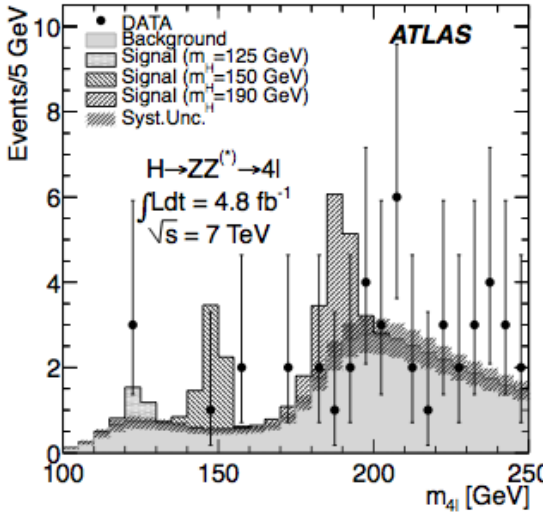

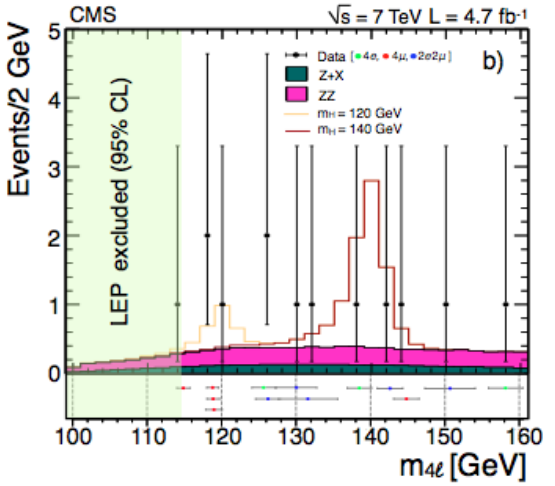

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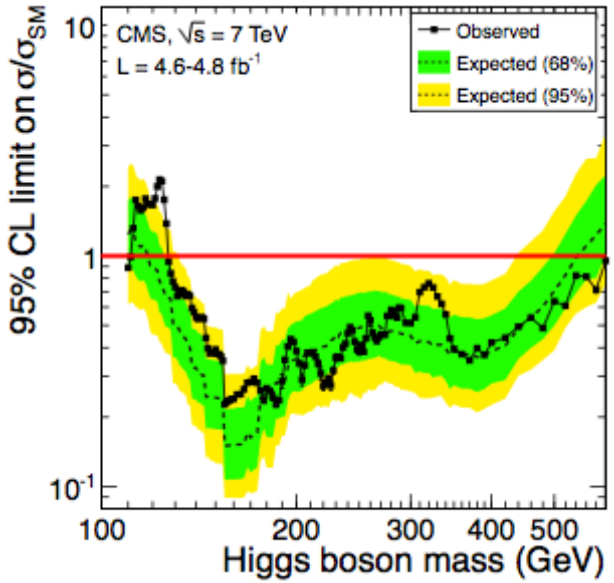

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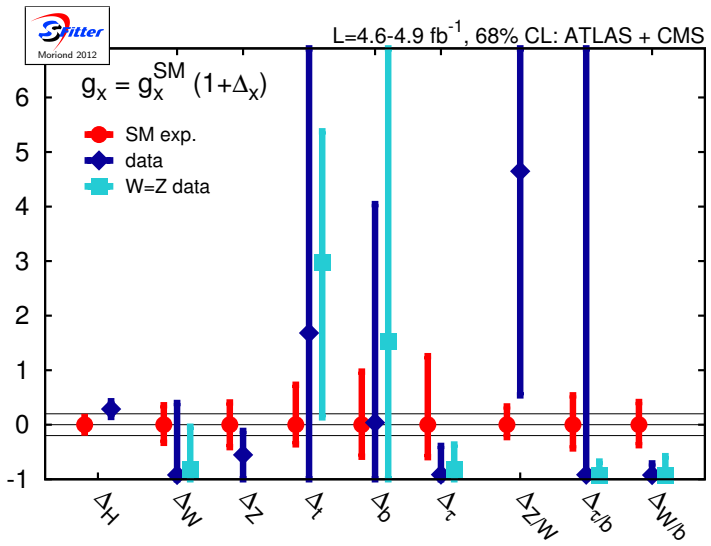

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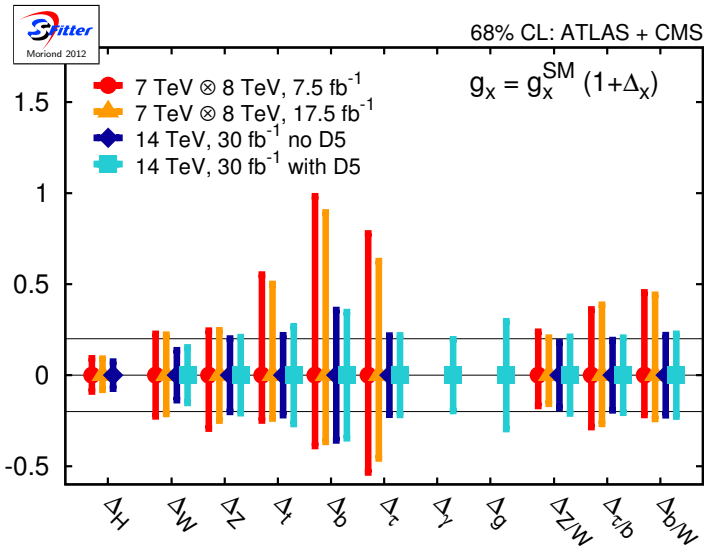

Exciting times...

...for LHC physicists

- many things (some of us/we) (would like to see/(might) have seen)

  plenty of QCD jets
  probably no new physics (yet)
  first fat jets
  maybe a Higgs boson

- new ideas always high in demand

$\Rightarrow$ analyses moving fast, keep your fingers crossed for 2012

New Physics at the LHC, David Morrissey, TP, and Tim Tait, Phys Rept, arXiv 0912.3259

Lectures on LHC Physics, TP, Springer Lecture Notes, arXiv:0910.4182