The Abdus Salam
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SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
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Perspectives in LHC Physics

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These are preliminary lecture notes, intended only for distribution to participants.

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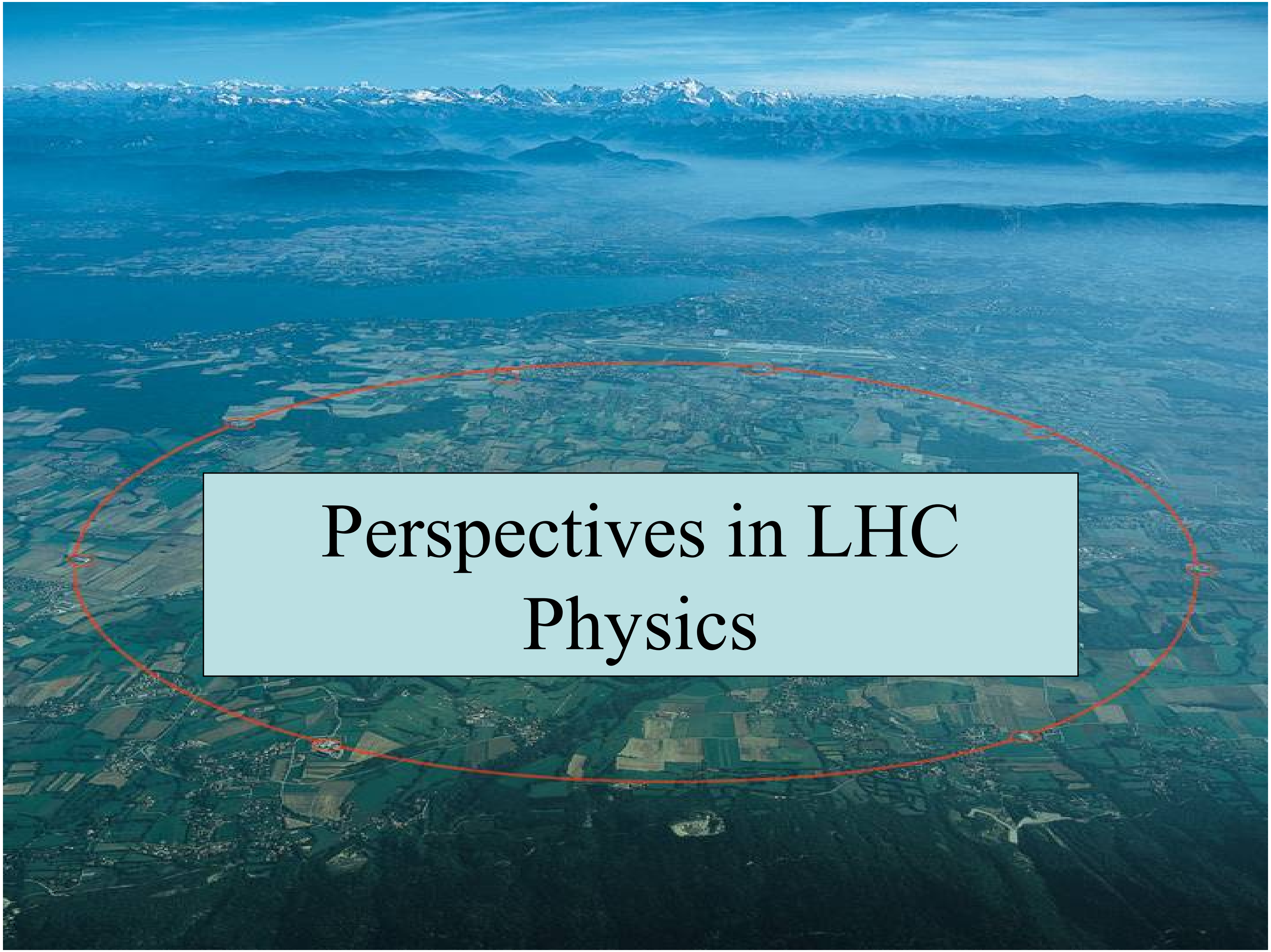
Perspectives in LHC Physics



Summary of the Standard Model of Particle Physics

- Particles and SU(3) X SU(2) X U(1) quantum numbers:

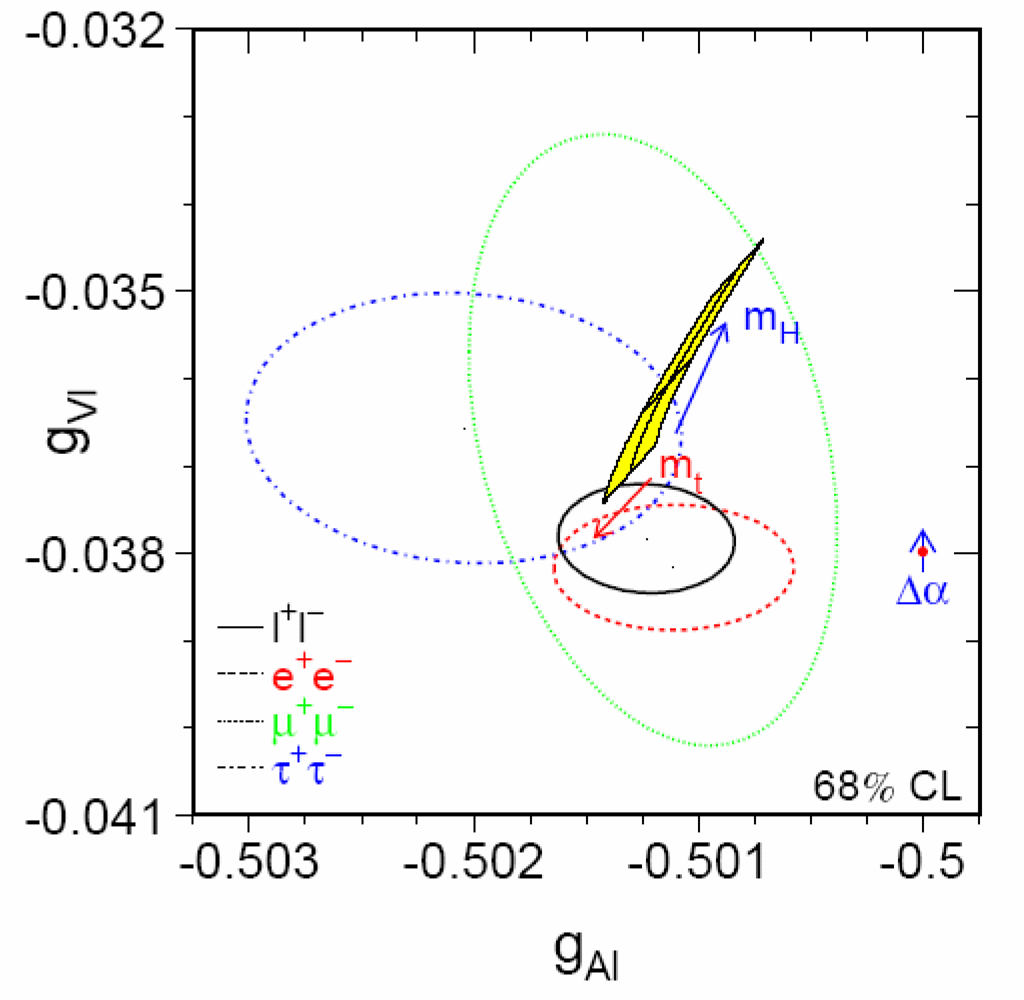
L_L E_R	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$ $e^-_R , \mu^-_R , \tau^-_R$	$(\mathbf{1},\mathbf{2},\text{-}1)$ $(\mathbf{1},\mathbf{1},\text{-}2)$
Q_L U_R D_R	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$ u_R , c_R , t_R d_R , s_R , b_R	$(\mathbf{3},\mathbf{2},+1/3)$ $(\mathbf{3},\mathbf{1},+4/3)$ $(\mathbf{3},\mathbf{1},\text{-}2/3)$

- Lagrangian:

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\ \mu\nu} && \text{gauge interactions} \\ &+ i\bar{\psi}\ \not{D}\psi + h.c. && \text{matter fermions} \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions} \\ &+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential} \end{aligned}$$

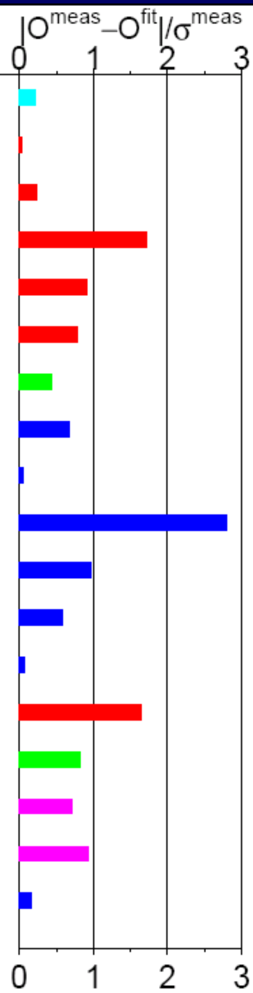
Precision Tests of the Standard Model

Lepton couplings



Pulls in global fit: Summer 2006

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



Status of the Standard Model

- Perfect agreement with all *confirmed* accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a Higgs boson*
- Agreement seems to require *a relatively light Higgs boson* weighing $< \sim$ 200 GeV
- Raises many unanswered questions:

  mass? flavour? unification?

Open Questions beyond the Standard Model

- What is the origin of particle masses?

  due to a Higgs boson? + other physics?

  solution at energy < 1 TeV (1000 GeV)

  LHC
- Why so many types of matter particles?

  matter-antimatter difference?

  LHC
- Unification of the fundamental forces?

  at very high energy ~ 10^{16} GeV?

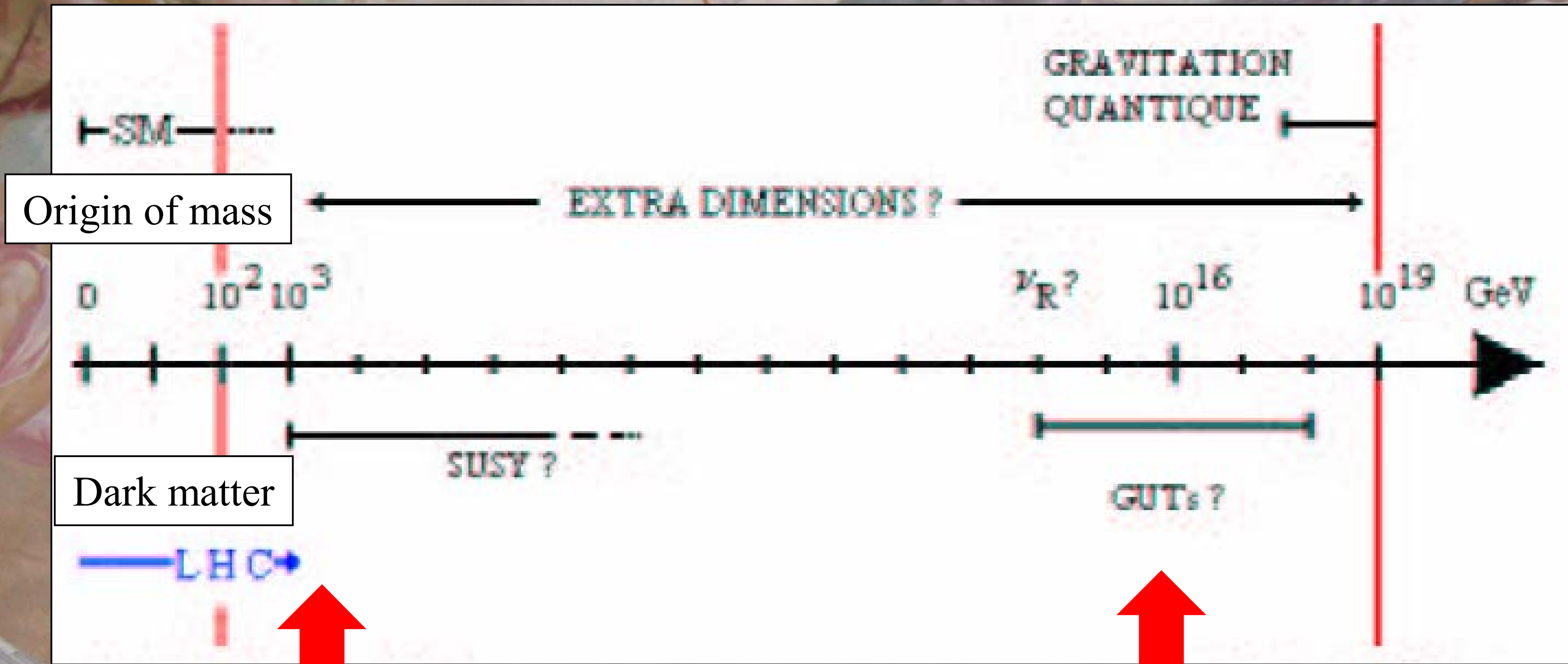
  probe directly via neutrino physics, indirectly via masses, couplings

  LHC
- Quantum theory of gravity?

  (super)string theory: extra space-time dimensions?

  LHC

At what Energy is the New Physics?



A lot accessible directly to the LHC

Some accessible only indirectly: Astrophysics and cosmology?

Some particles have mass, some do not

Where do the masses come from?

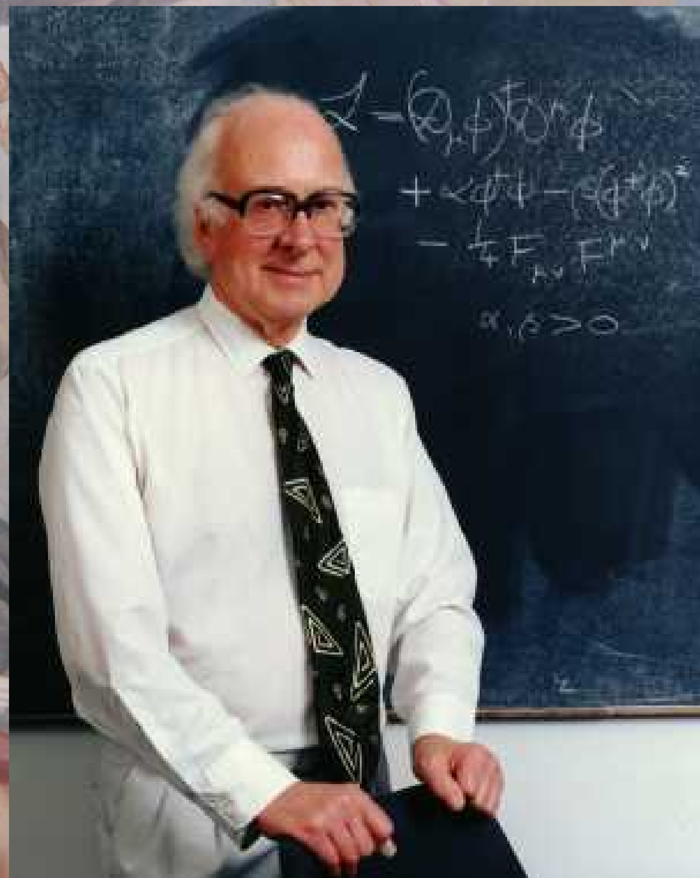
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass



Are masses due to Higgs boson?
(yet another particle)

The Higgs-Brout-Englert Mechanism

- Postulated effective scalar-field potential:

$$V[\phi] = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

- Minimum energy at non-zero value:

$$\phi_0 = < 0|\phi|0 > = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ +v \end{pmatrix} \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

- Non-zero masses: $M_f = y_f \frac{v}{\sqrt{2}}$ $M_W = \frac{g\,v}{2}$
- Components of scalar field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x)) e^{i\pi(x)}$
- π massless, eaten by W, Z, give them masses
- σ massive: the ‘Higgs’ boson: $m_H^2 = 2\mu^2 = 2\lambda v$

Constraints on the Higgs Mass

- Masses, other quantities sensitive via quantum loop corrections: $$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$
- Δr sensitive to top, Higgs masses:

$$\frac{3G_F}{8\pi^2\sqrt{2}}m_t^2 \qquad \frac{\sqrt{2}G_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+\ldots\right),\ M_H >> m_W$$

- Preferred Higgs mass: **$m_H = 85^{+39}_{-28}$ GeV**
- Compare with lower limit from direct searches:

  $m_H > 114$ GeV

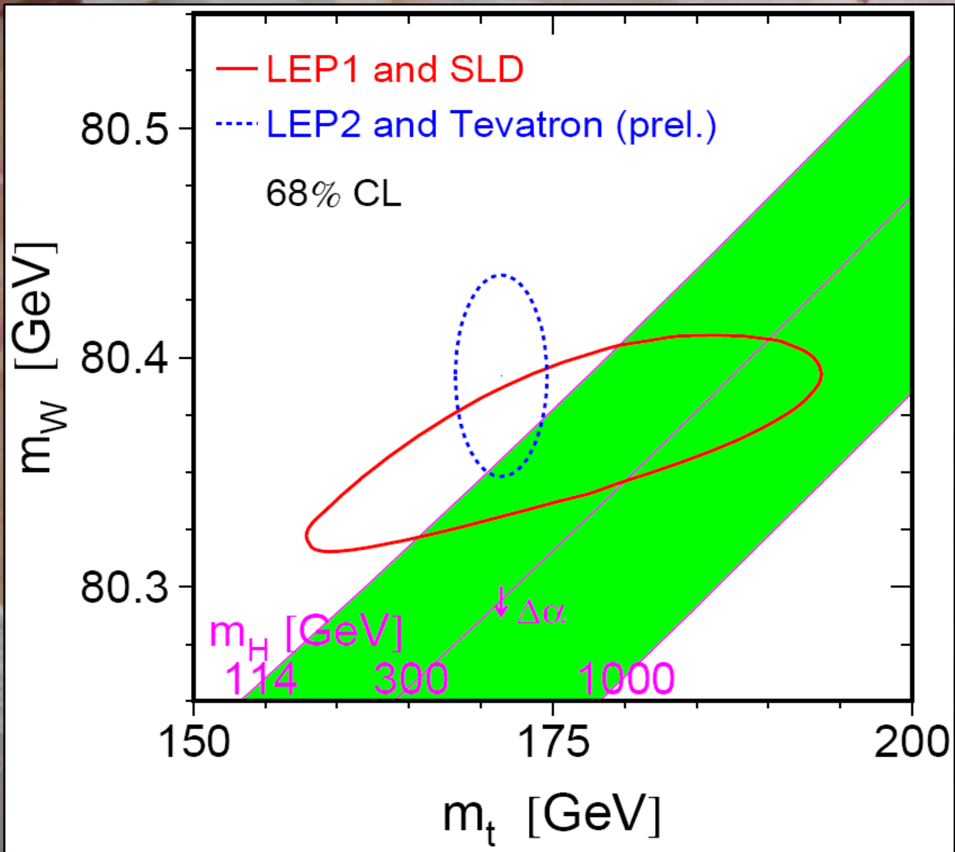
- Combined limit < 199 GeV @ 95% c.l.

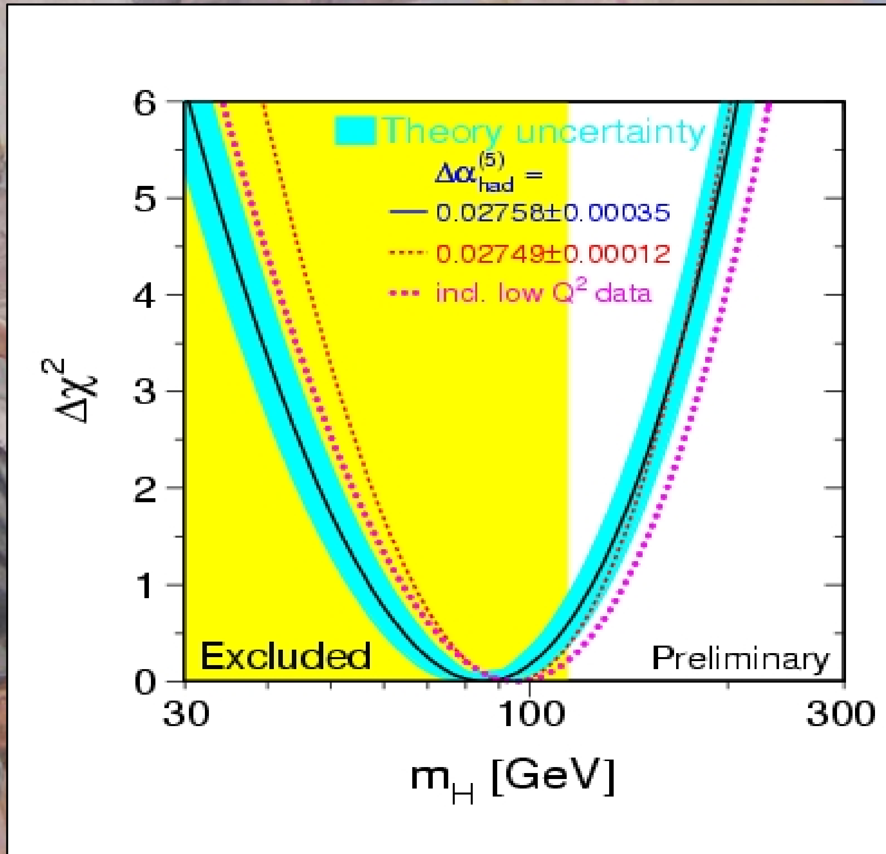
Summer 2006

Indications on the Higgs Mass

Sample observable:
W mass @ LEP & Tevatron

Combined information on Higgs mass

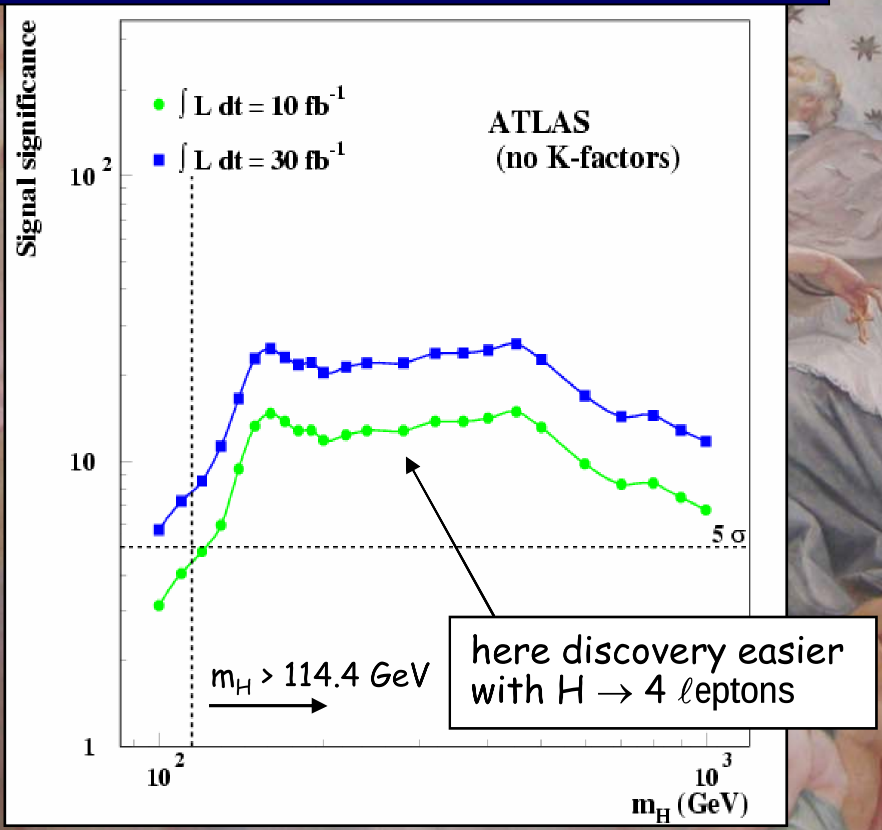




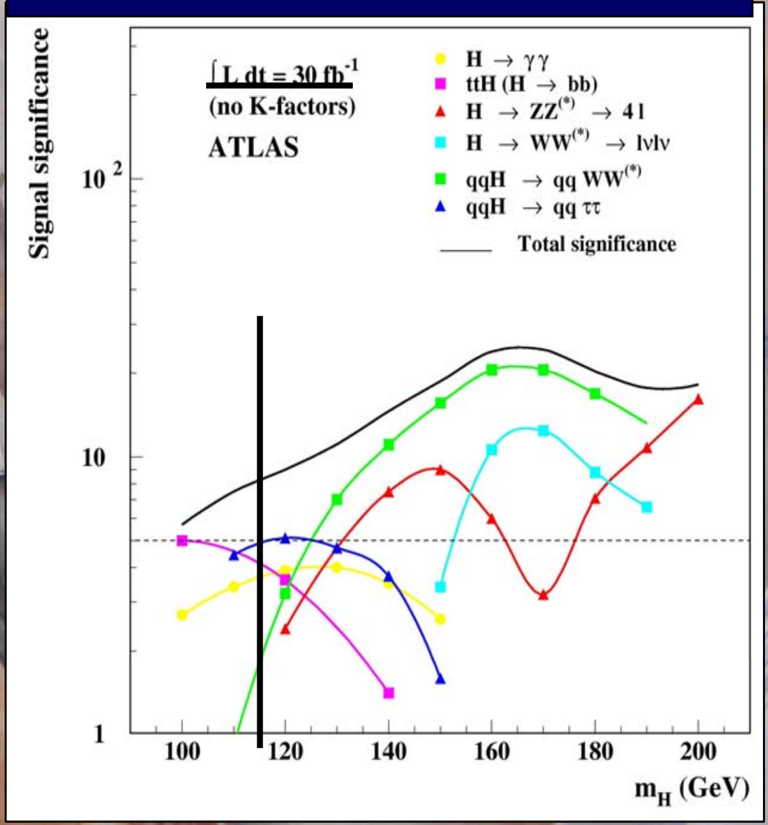
m_W, m_t both reduced by ~ ½ σ

Higgs Detection at the LHC

The Higgs may be found quite quickly …



… in several different channels



Theorists getting Cold Feet

- Composite Higgs model?
  fermion masses? precision electroweak data?
- Interpretation of EW data?
  consistency of measurements? Discard some?
- Higgs + higher-dimensional operators?
  corridors to higher Higgs masses?
- Little Higgs models?
  extra `Top', gauge bosons, `Higgses'
- Higgsless models?
  strong WW scattering, extra D?

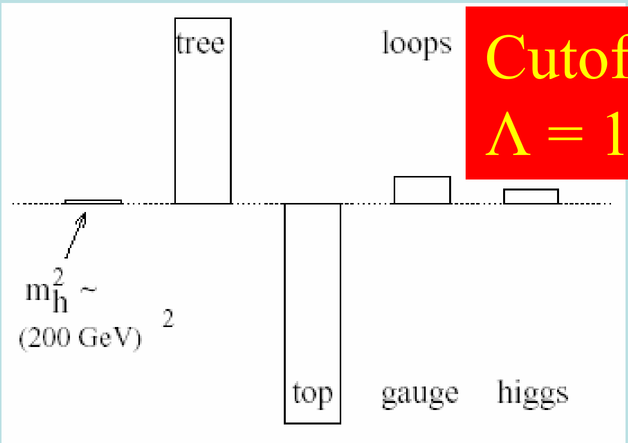
Kraml et al: hep-ph/0608079

Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- Quantum loop problems



Cutoff
Λ = 10 TeV

- Cut-off $\Lambda \sim$ 1 TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

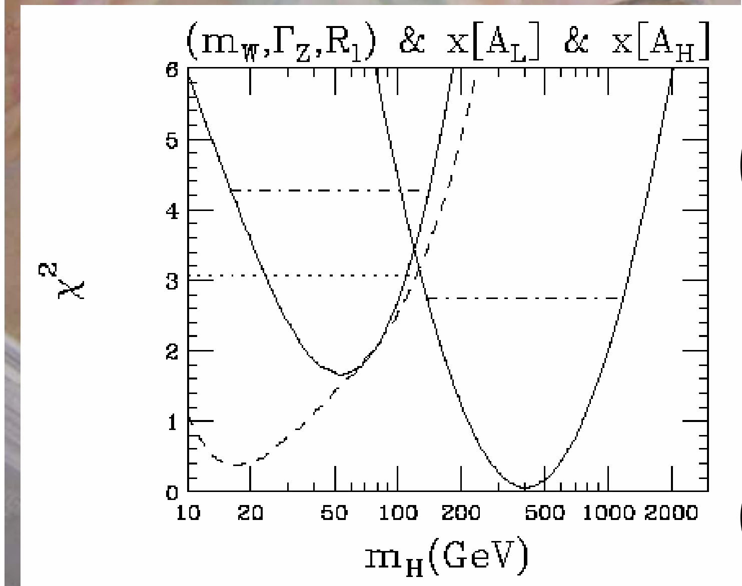
- New technicolour force? inconsistent with precision electroweak data?

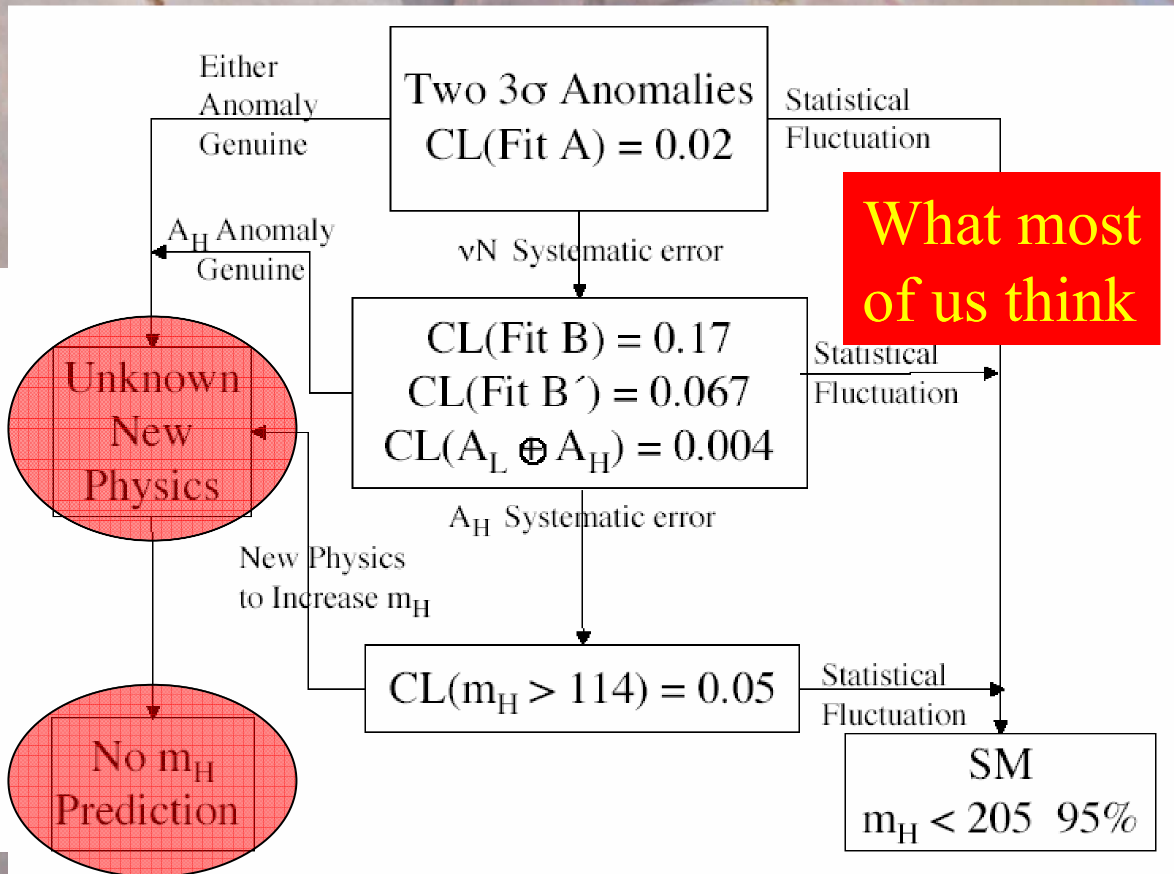
Heretical Interpretation of EW Data

Do all the data tell the same story?

e.g., A_L vs A_H

What attitude towards LEP, NuTeV?





What most of us think

Higgs + Higher-Order Operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^p} \mathcal{O}_i^{(4+p)}$$

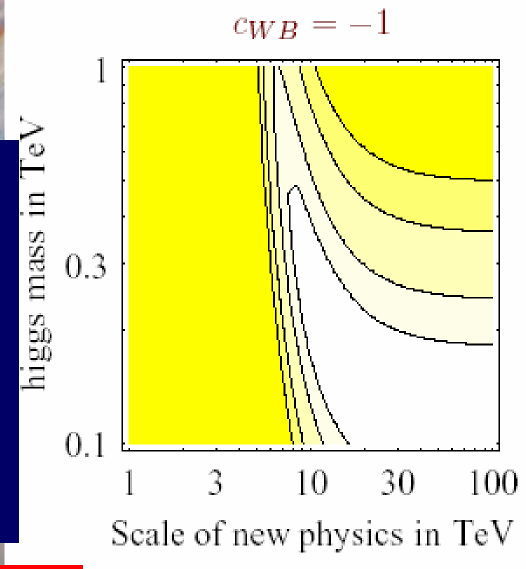
Corridor to heavy Higgs?

Precision EW data suggest they are small: why?

Dimension six operator	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^+ \sigma^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.0	13
$\mathcal{O}_H = \lvert H^+ D_\mu H \rvert^2$	4.2	7.0
$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu \sigma^a L)^2$	8.2	8.8
$\mathcal{O}_{HL} = i(H^+ D_\mu H)(\bar{L}\gamma_\mu L)$	14	8.0

95% lower bounds on Λ/TeV

But conspiracies are possible: m_H could be large, even if believe EW data …?



Do not discard possibility of heavy Higgs

Little Higgs Models

- Embed SM in larger gauge group
- Higgs as pseudo-Goldstone boson
- Cancel top loop

$$\delta m^2_{H,top}(SM) \sim (115GeV)^2 (\frac{\Lambda}{400GeV})^2$$

with new heavy T quark $m_T > 2\lambda_t f \sim 2f$ $f > 1$ TeV

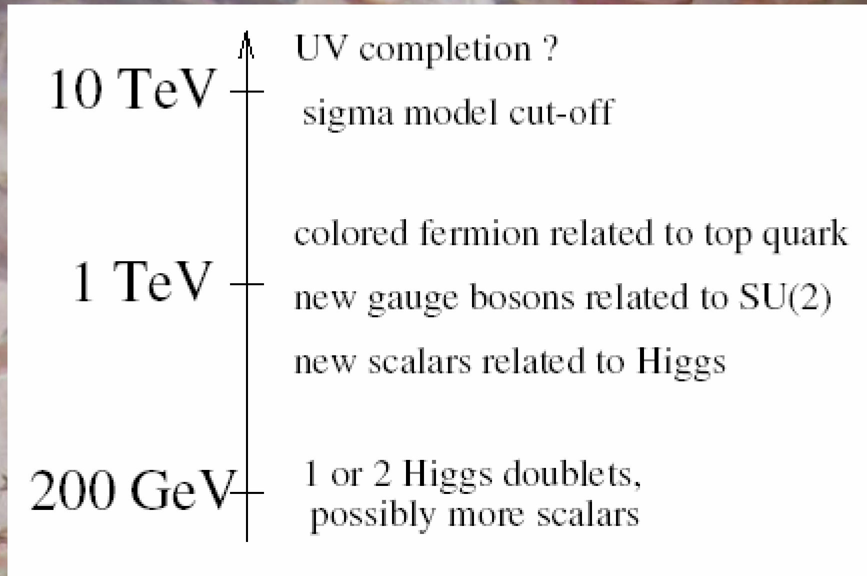
$$\delta m^2_{H,top}(LH) \sim \frac{6G_F m_t^2}{\sqrt{2}\pi^2} m_T^2 log \frac{\Lambda}{m_T} \gtrsim 1.2 f^2$$

- New gauge bosons, Higgses
- Higgs light, other new physics heavy

$M_T < 2$ TeV $(m_h / 200 \text{ GeV})^2$
$M_{W'} < 6$ TeV $(m_h / 200 \text{ GeV})^2$
$M_{H++} < 10$ TeV

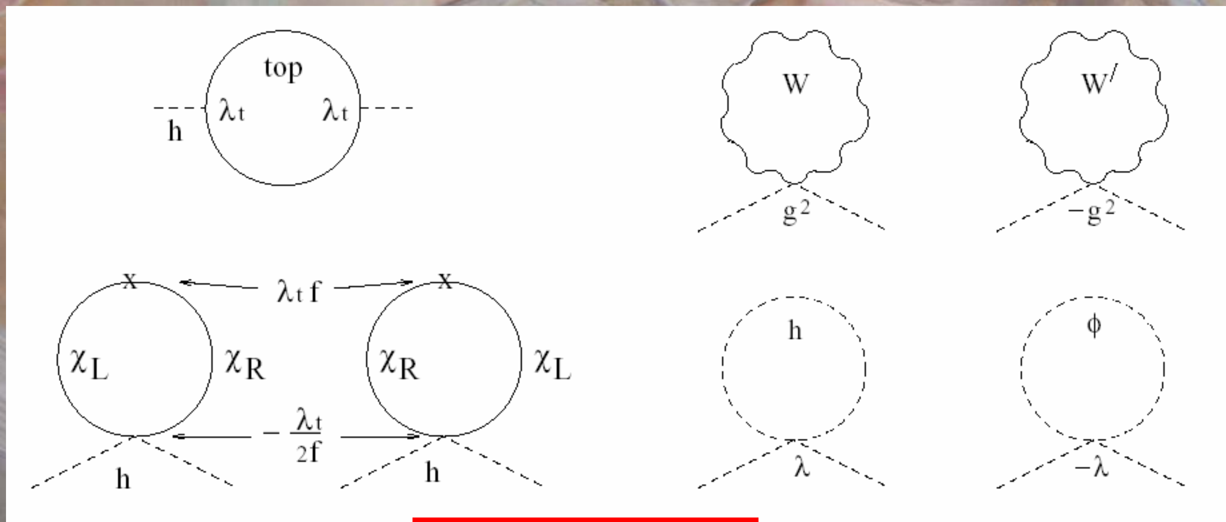
Not as complete as susy: more physics > 10 TeV

Generic Little Higgs Models

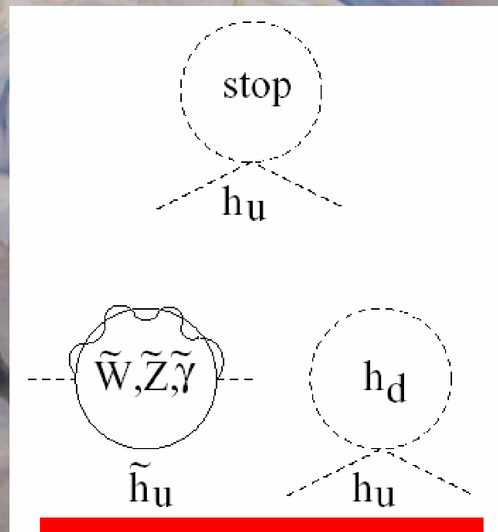


(Higgs as pseudo-Goldstone boson of larger symmetry)

Loop cancellation mechanism



Little Higgs



Supersymmetry

Higgsless Models?

- Four-dimensional versions:

  Strong WW scattering @ TeV, incompatible with precision data?

- Break EW symmetry by boundary conditions in extra dimension:

  delay strong WW scattering to ~ 10 TeV?

  Kaluza-Klein modes: m_{KK} > 300 GeV?

  compatibility with precision data?

- Warped extra dimension + brane kinetic terms?

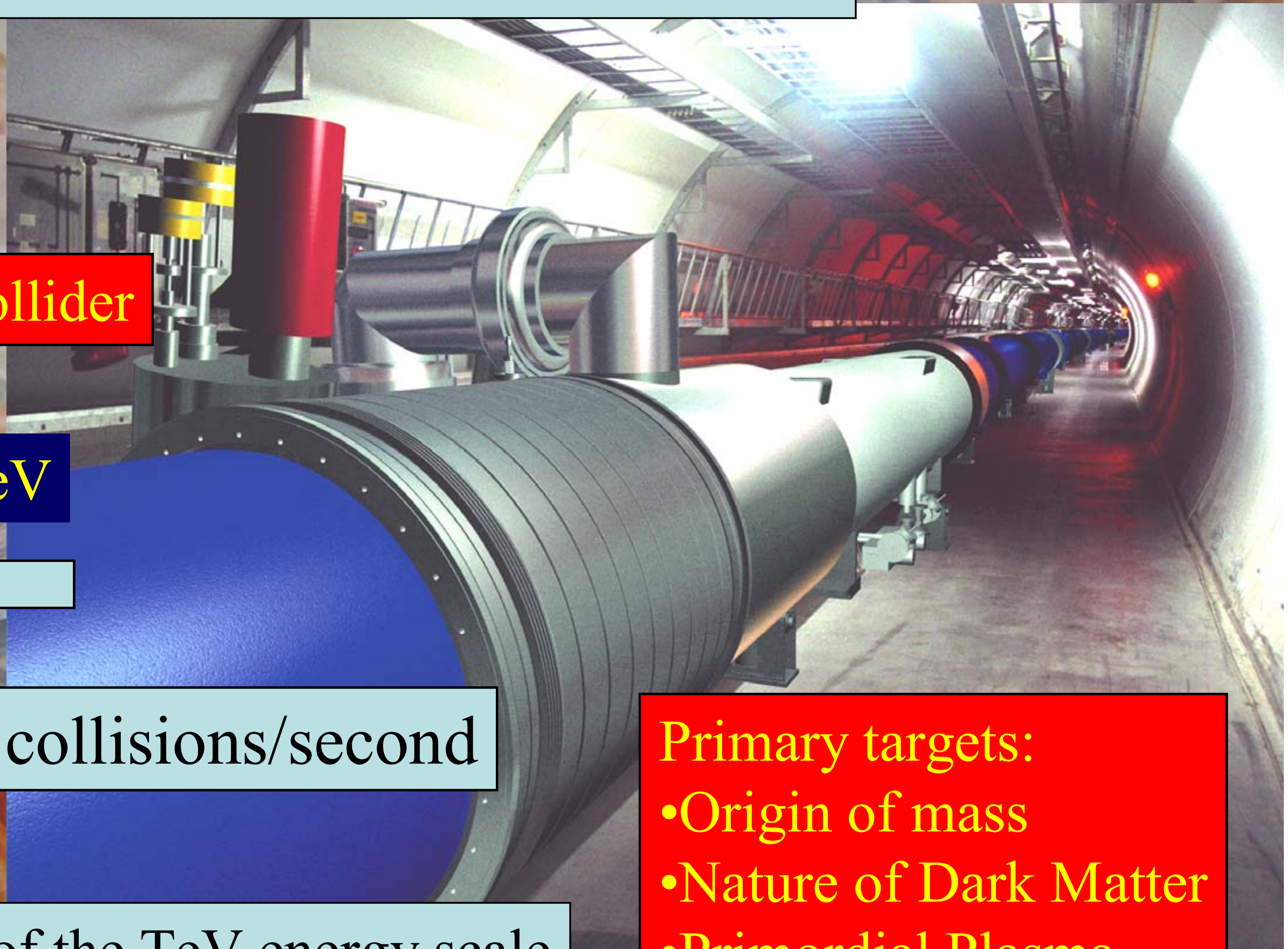
Lightest KK mode @ 300 GeV, strong WW @ 6-7 TeV

Haiku by Matsuo Basho

In a way,
it was quite fun
not to see Mount Fuji
in foggy rain

- **Interesting for theorists**
- **But the politicians would rather we found the Higgs**

The Large Hadron Collider (LHC)



Proton- Proton Collider

7 TeV + 7 TeV

1,000,000,000 collisions/second

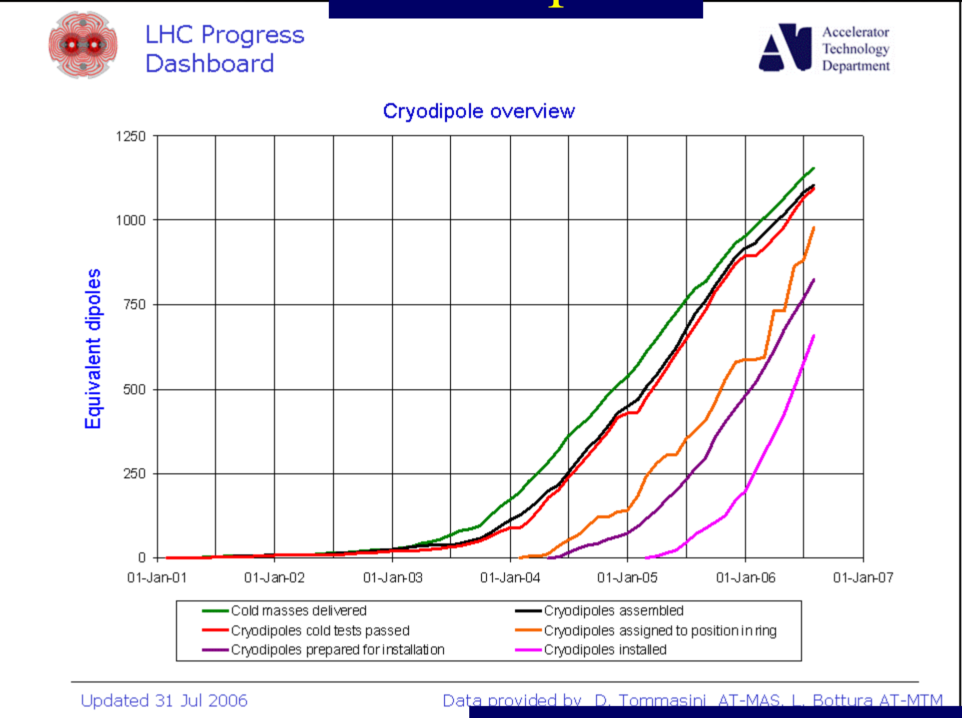
First exploration of the TeV energy scale

Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

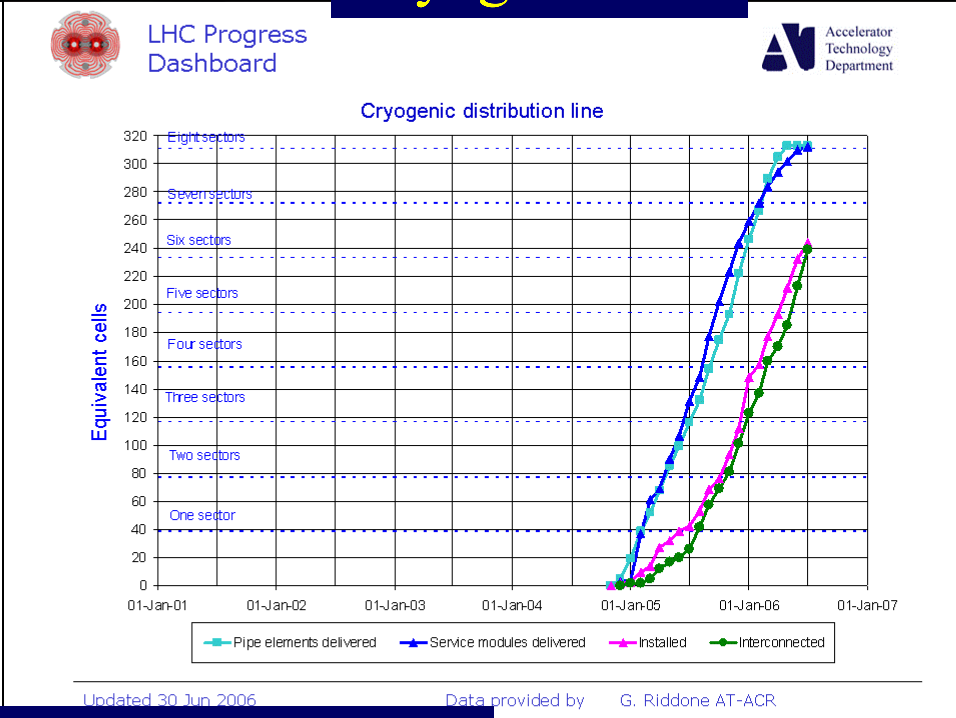
Underground

LHC Progress Dashboard

Main dipoles



Cryogenic line



Accelerator to be completed in Summer 2007,

First collisions November 2007

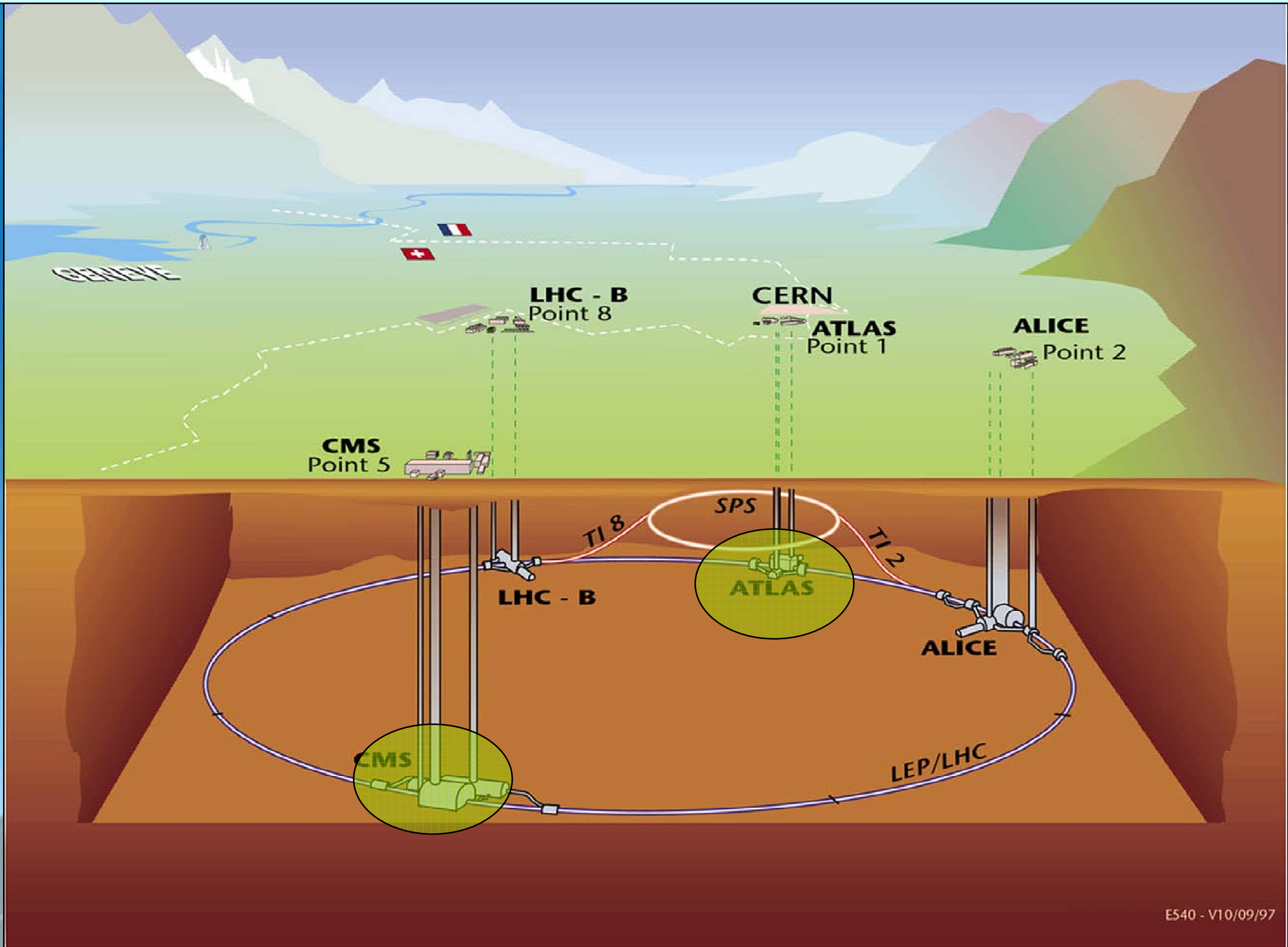
Remaining LHC Milestones

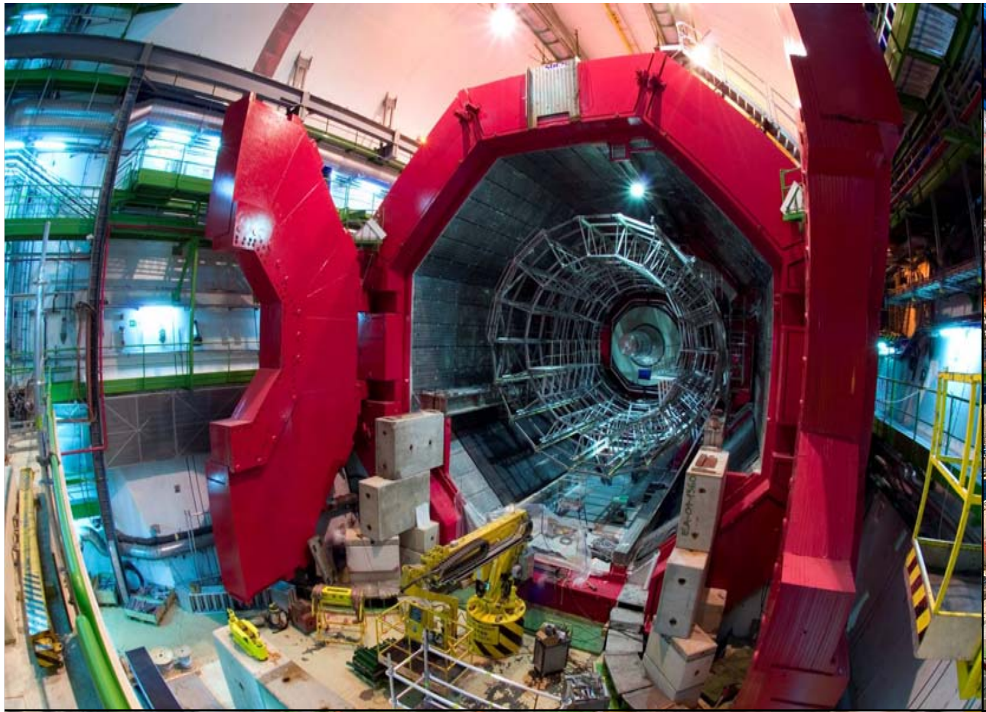
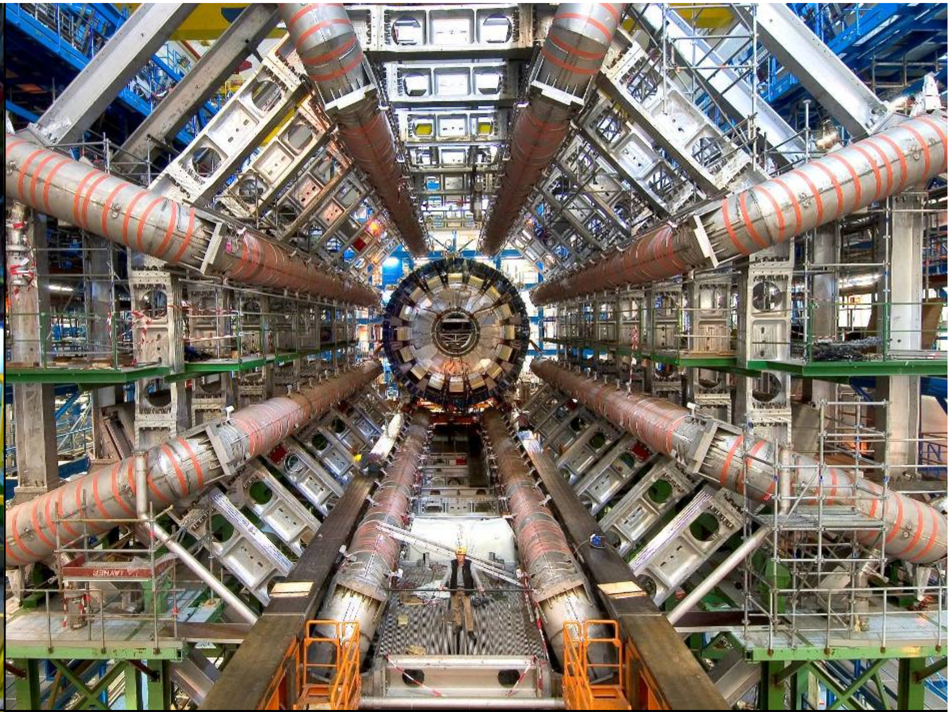
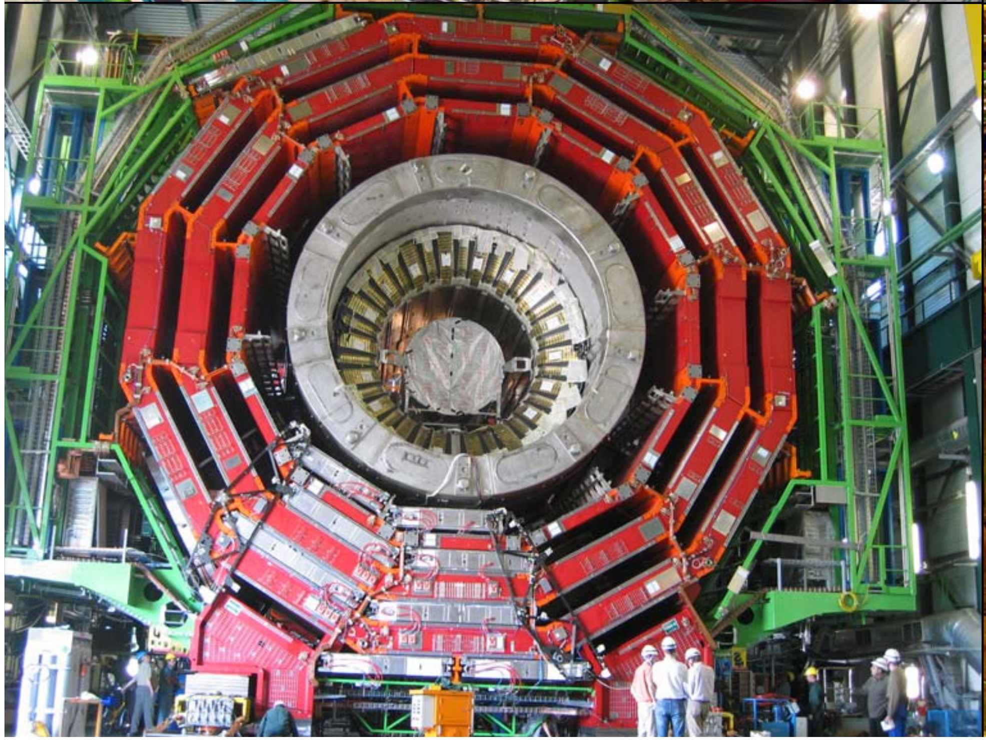
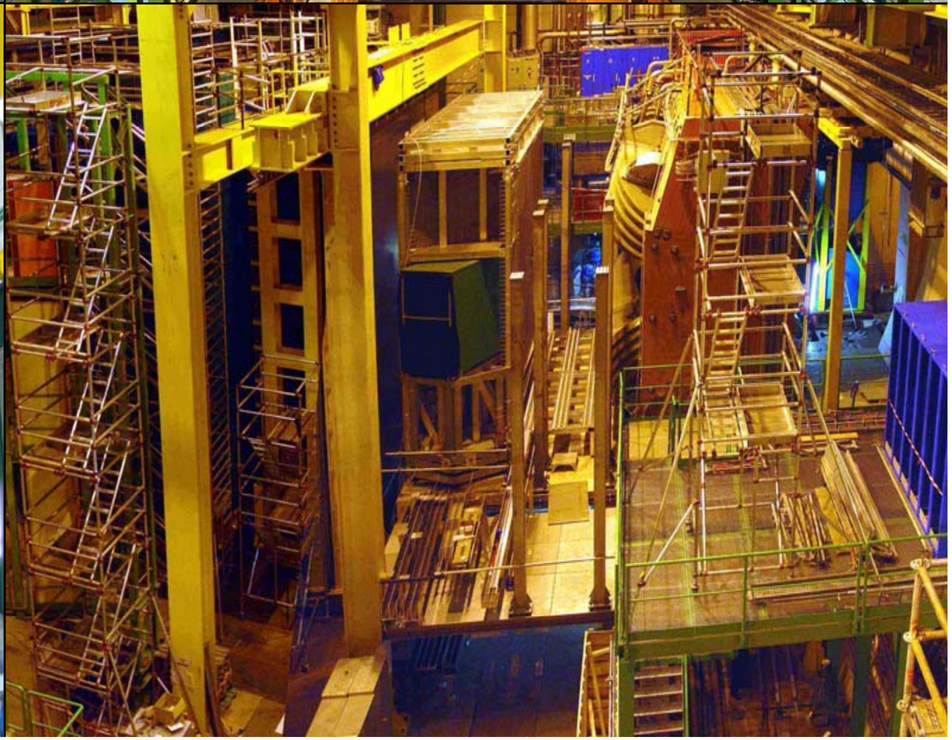
Last magnet delivered	October 2006
Last magnet tested	December 2006
Last magnet installed	March 2007
Machine closed	August 2007
First collisions	November 2007

Machine commissioning

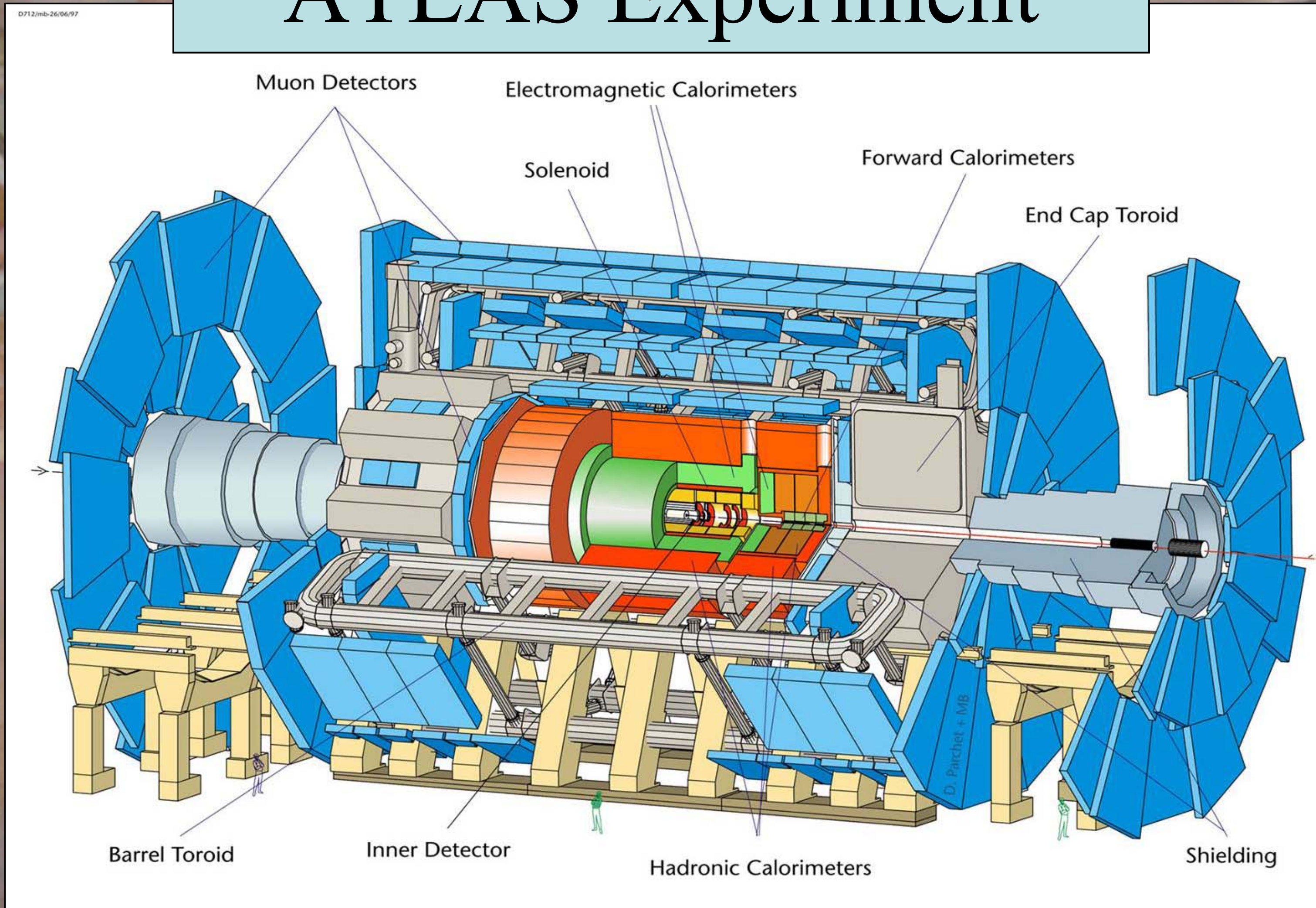
- Sectors 7-8 and 8-1 will be fully commissioned up to 7 TeV in 2006-2007. If we continue to commission the other sectors up to 7 TeV, we will not get circulating beam in 2007
- The other sectors will be commissioned up to the field needed for de-Gaussing.
- **Initial operation will be at 900 GeV (CM) with a static machine (no ramp, no squeeze) to debug machine and detectors**
- Full commissioning up to 7 TeV will be done in the winter 2008 shutdown

Overall View of the Large Hadron Collider (LHC)



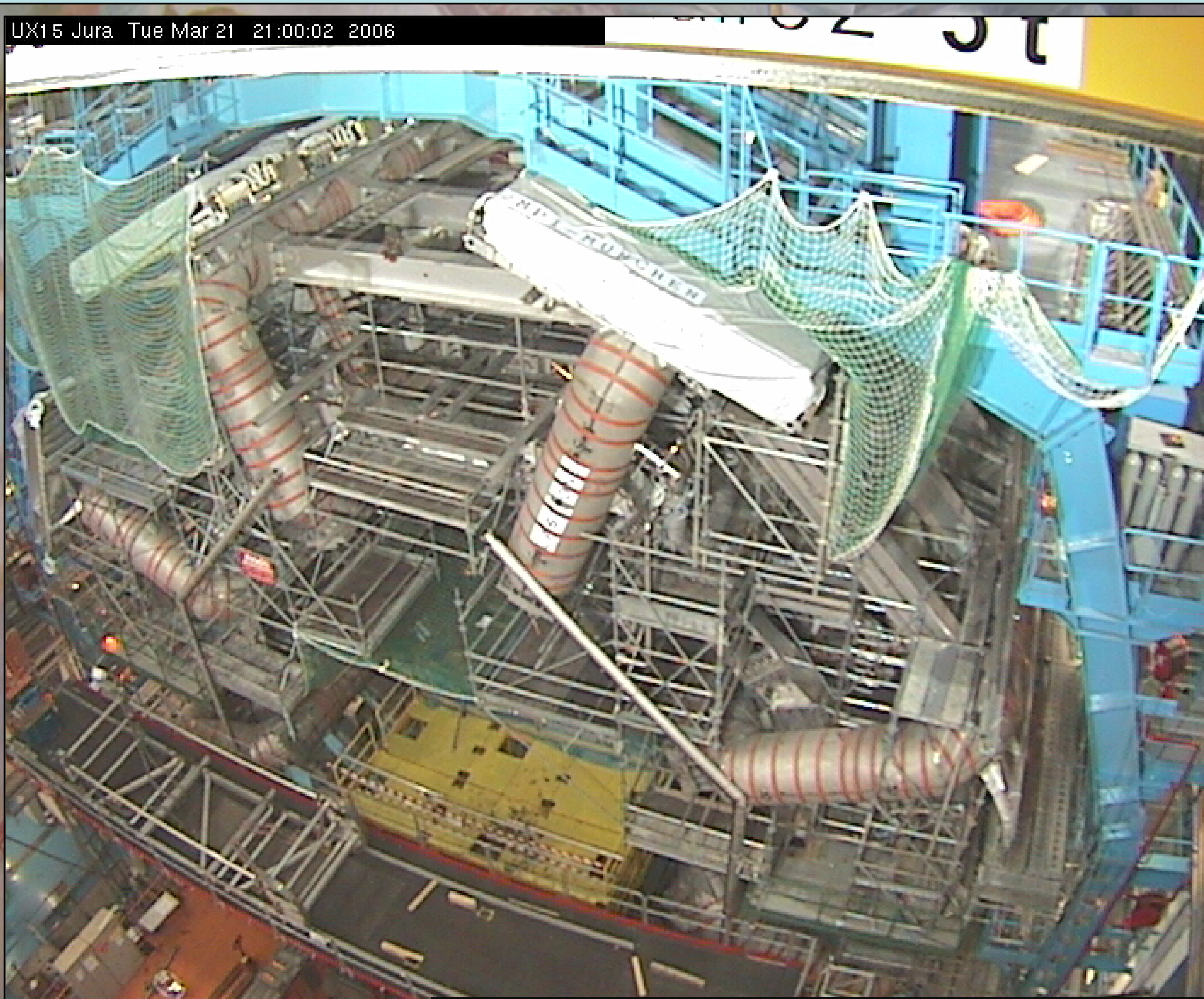





ATLAS Experiment

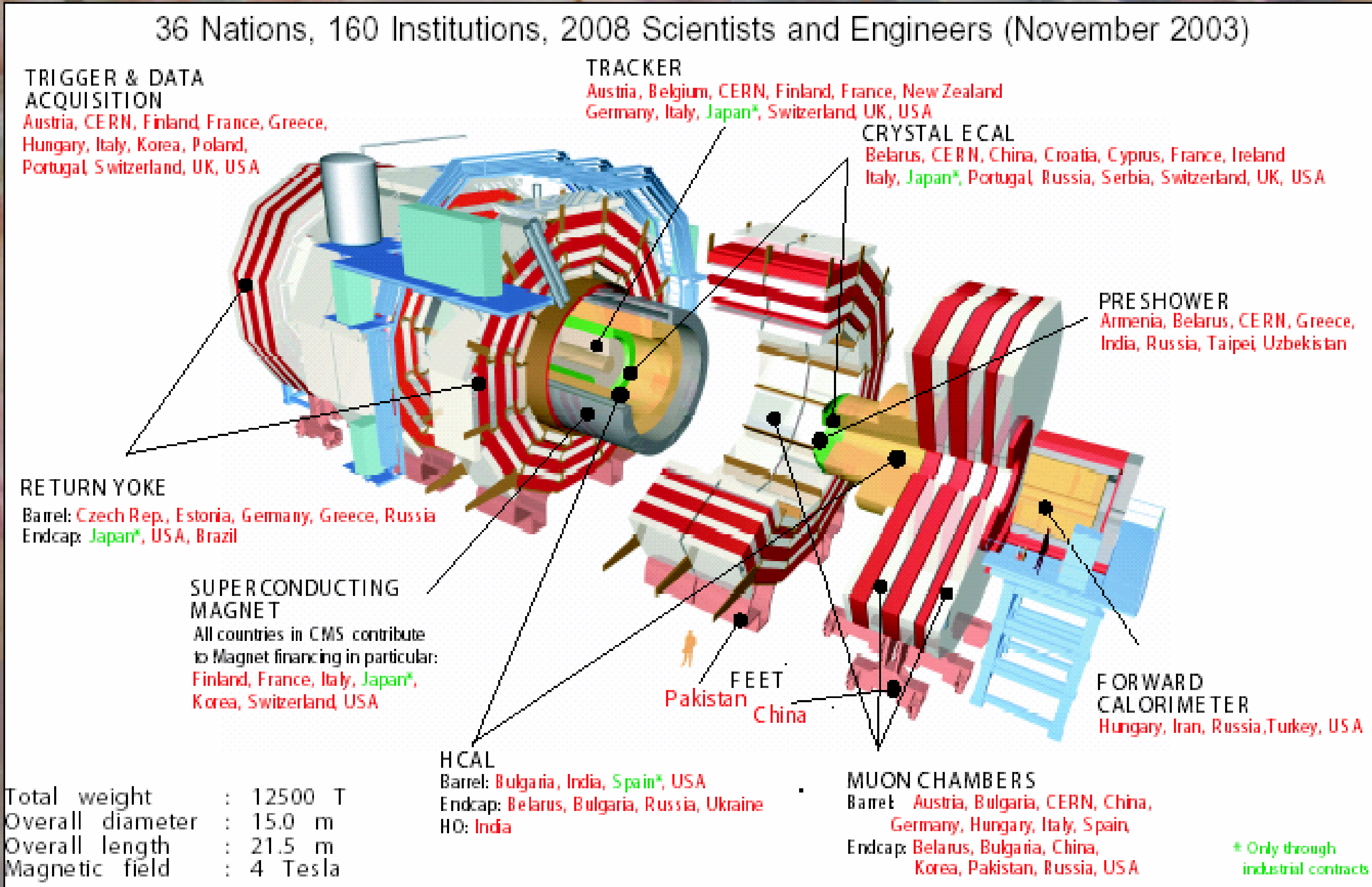


Diameter	***25 m***
Barrel toroid length	***26 m***
End-cap end-wall chamber span	***46 m***
Overall weight	***7000 Tons***

ATLAS Cavern Webcam



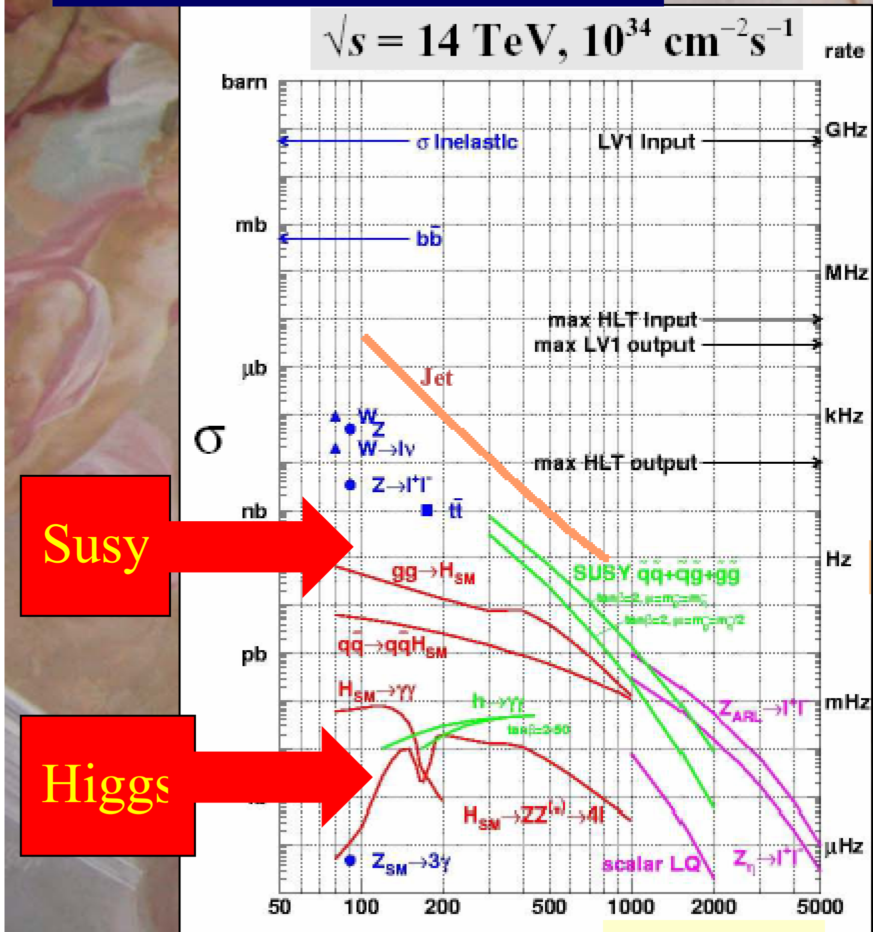
CMS Experiment



The CMS Cavern

The LHC Physics Haystack(s)

Interesting cross sections



- Cross sections for heavy particles
  $\sim 1/(1\ \text{TeV})^2$
- Most have small couplings $\sim \alpha^2$
- Compare with total cross section
  $\sim 1/(100\ \text{MeV})^2$
- Fraction ~ 1/1,000,000,000,000
- Need ~ 1,000 events for signal
- Compare needle
  $\sim 1/100{,}000{,}000\ \text{m}^3$
- Haystack $\sim 100\ \text{m}^3$
- Must look in ~ 100,000 haystacks

Huge Statistics thanks to High Energy and Luminosity

Event rates in ATLAS or CMS at L = 10^{33} cm^{-2} s^{-1}

Process	Events/s	Events per year	Total statistics collected at previous machines by 2007
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$	10^6	10^{12} - 10^{13}	10^9 Belle/BaBar ?
H m=130 GeV	0.02	10^5	?
$\tilde{g}\tilde{g}$ m= 1 TeV	0.001	10^4	---
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3	---

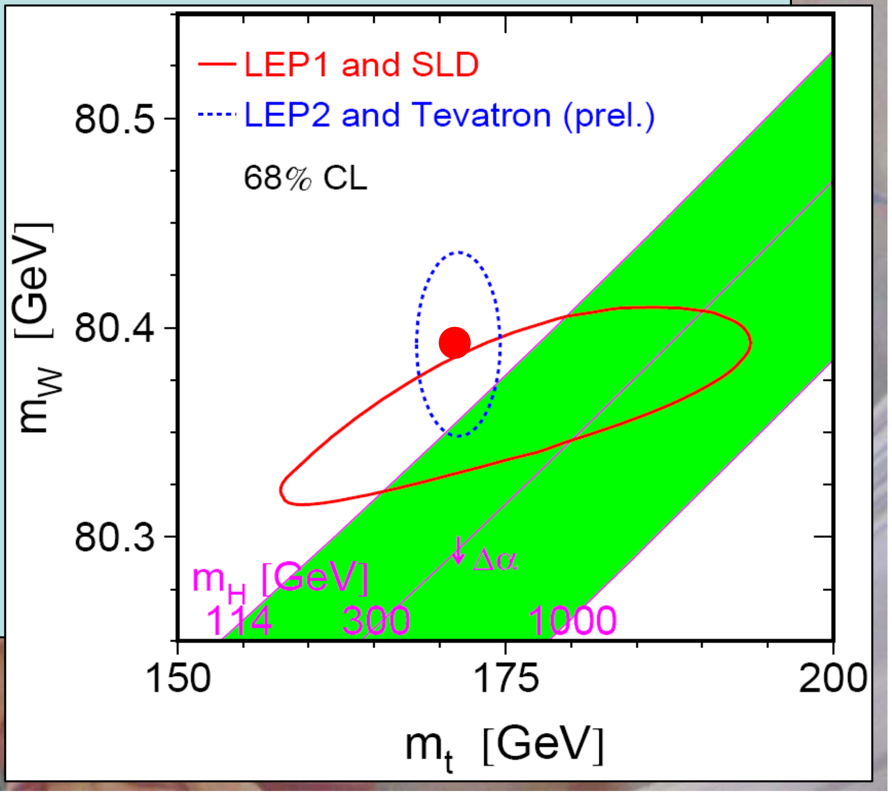
LHC is a factory for anything: top, W/Z, Higgs, SUSY, etc….
mass reach for discovery of new particles up to m ~ 5 TeV

Entry-level LHC Physics

- Measure and understand minimum bias
- Measure jets, start energy calibration
- Measure W/Z, calibrate lepton energies
- Measure top, calibrate jet energies & missing E_T
- First searches for Higgs:
  - Combine many signatures
  - need to understand detector very well
- First searches for SUSY, etc.

Standard Model @ LHC

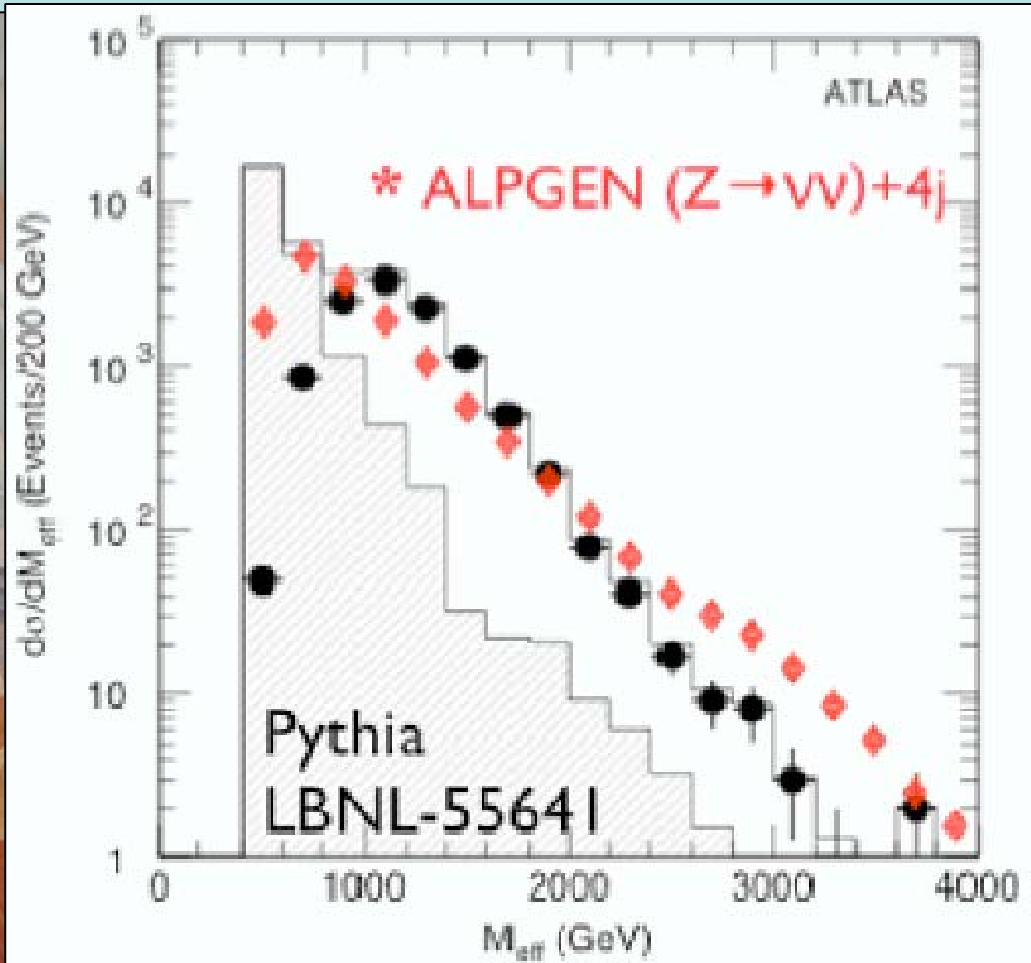
- Jet multiplicity distributions from data:
  - to fix normalization for Monte Carlos
- W, Z: theory uncertainties will dominate
- Hope $\delta m_W < 10$ MeV
  - 5 MeV possible?
  - remember LEP!
- Hope $\delta m_t < 1$ GeV
  - underlying event, jet E
  - eventually ± 0.5 GeV?



Looking for New Physics @ LHC

- Need to understand SM first:
  - calibration, alignment, systematics
- Searches for specific scenarios, e.g., SUSY, vs signature-based searches, e.g., monojets?
- **False dichotomy!**
- How to discriminate between models?
  - missing energy: SUSY vs UED?
    - higher excitations, spin correlations, spectra, …

New Calculations may provide Shocks



Standard Model background comparable to SUSY signal:

Can be normalized and subtracted using Z → ee, μμ

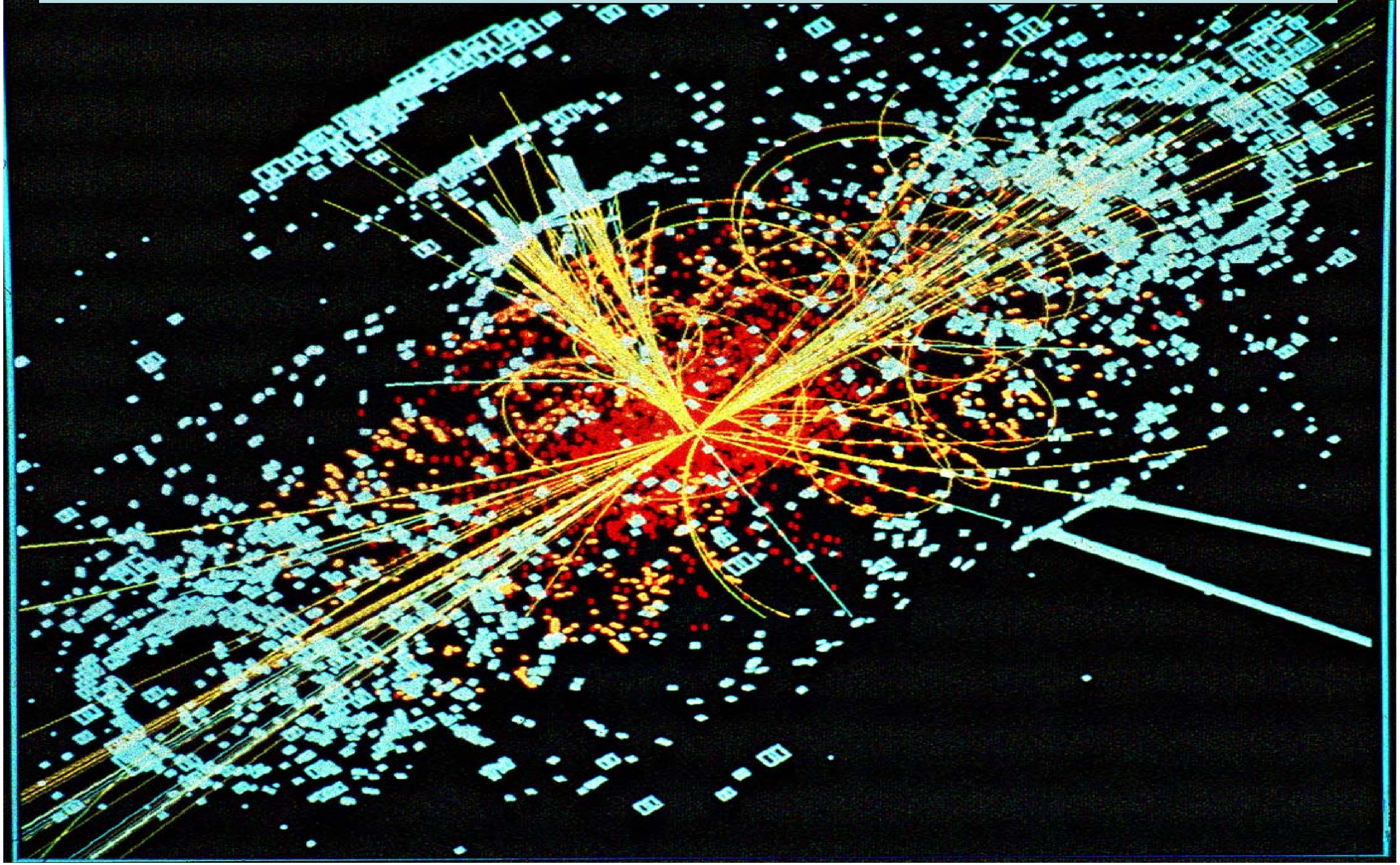
Still Much Homework for Theorists

Still many processes uncalculated

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

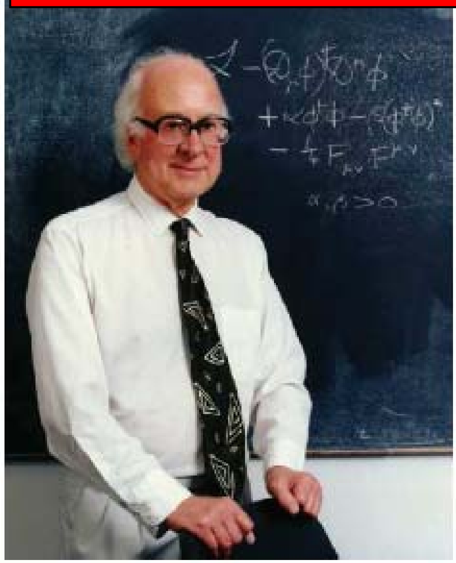
Powerful new QCD techniques: SUSY, twistors

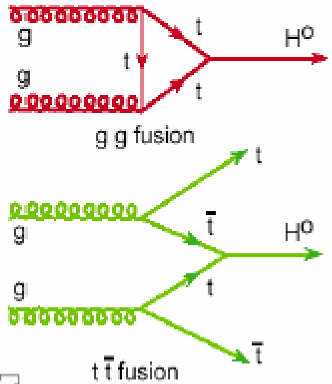
A Simulated Higgs Event in CMS



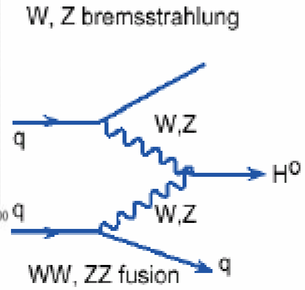
A la recherche du Higgs perdu …

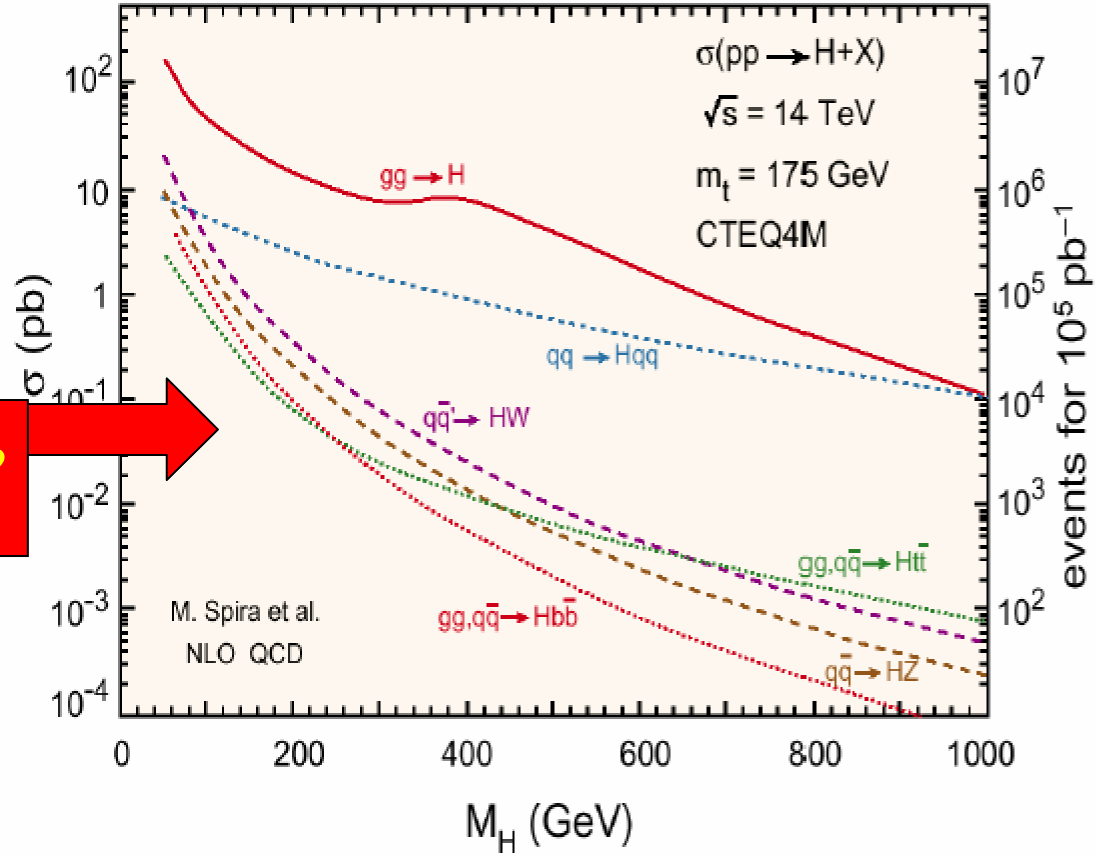
Higgs Production at the LHC

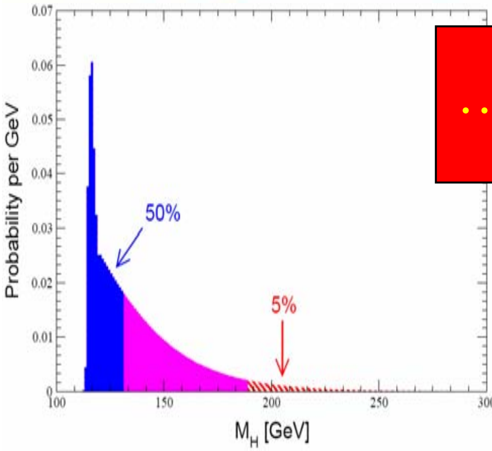




… not far away?



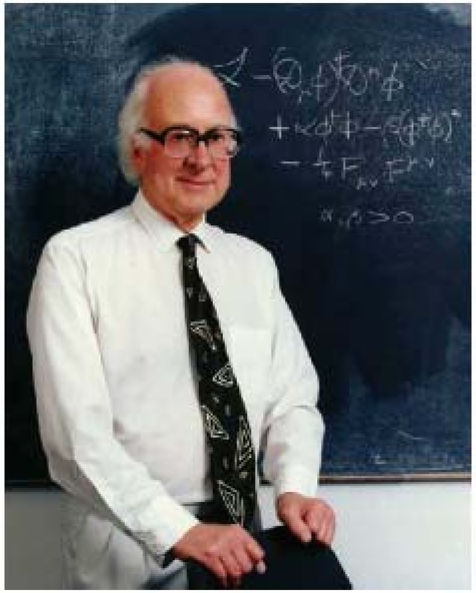




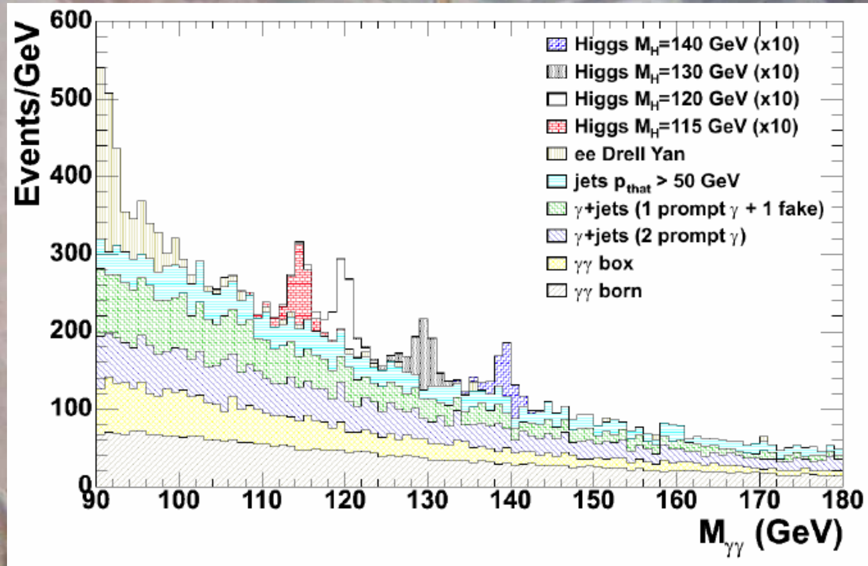
Combining direct,
Indirect information

A la recherche du Higgs perdu …

Some Sample Higgs Signals

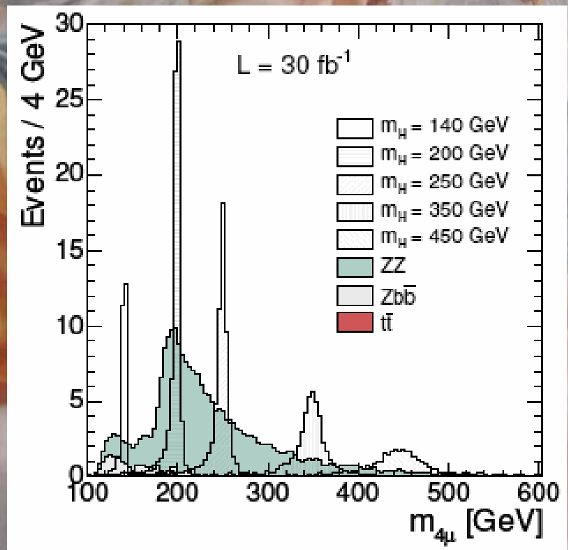


γγ

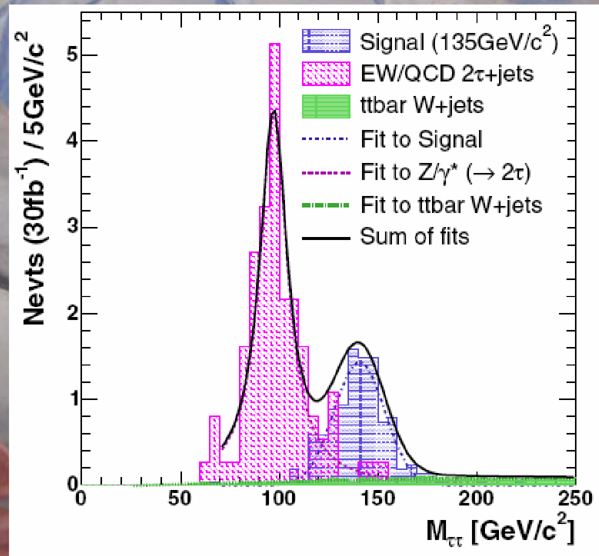


CMS

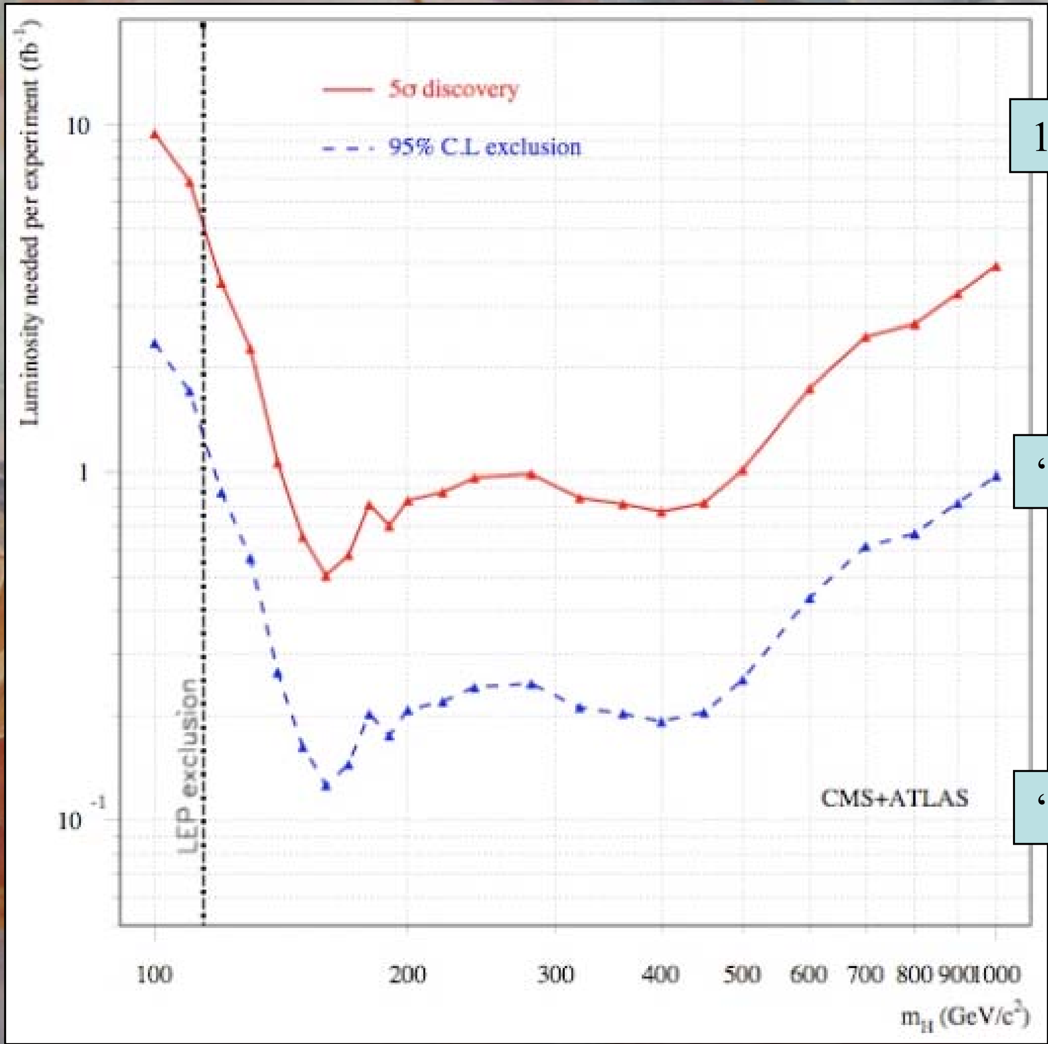
ZZ* -> 4 leptons



ττ



When will the LHC discover the Higgs boson?



1 'year' @ 10^{33}

'month' @ 10^{33}

'month' @ 10^{32}

What is Supersymmetry (Susy)?

- The last undiscovered symmetry?
- Could unify matter and force particles
- Links fermions and bosons

$$Q|Boson> \quad = |Fermion>$$
$$Q|Fermion> \quad = |Boson> .$$

- Relates particles of different spins

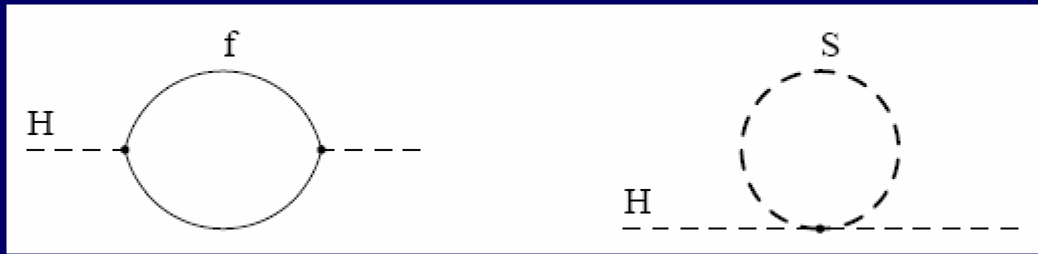
0 - ½ - 1 - 3/2 - 2

Higgs - Electron - Photon - Gravitino - Graviton

- Helps fix masses, unify fundamental forces

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

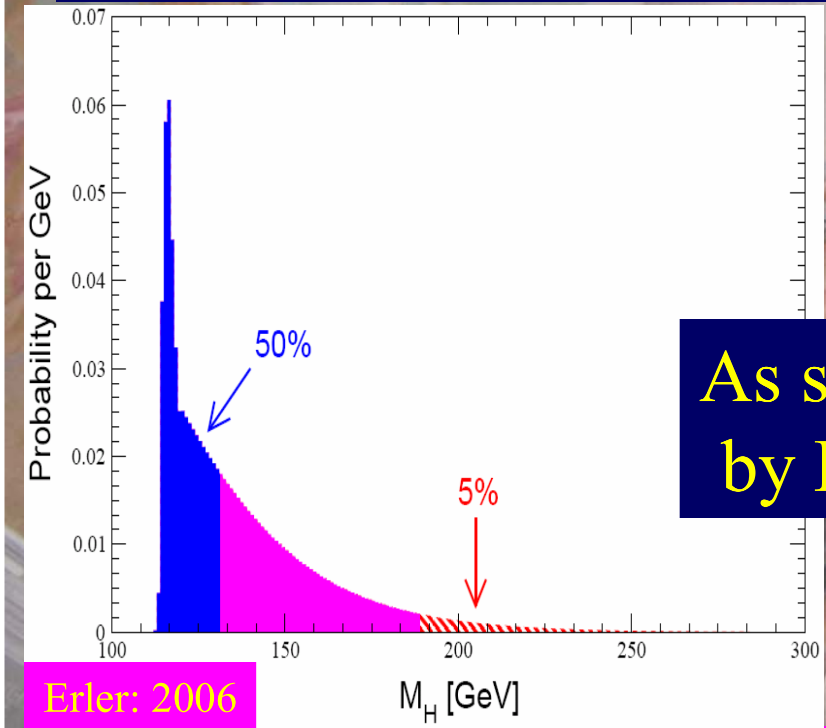
- Leading divergence cancelled if

$\lambda_S = y_f^2$ x 2 **Supersymmetry!**

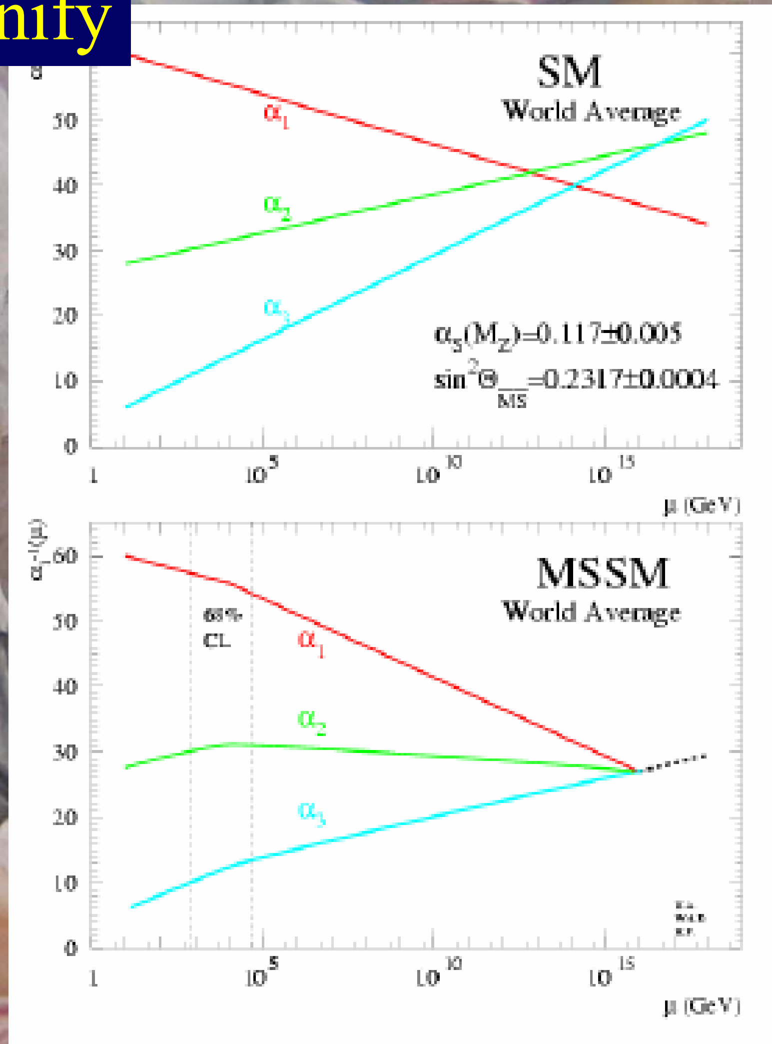
Other Reasons to like Susy

It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV



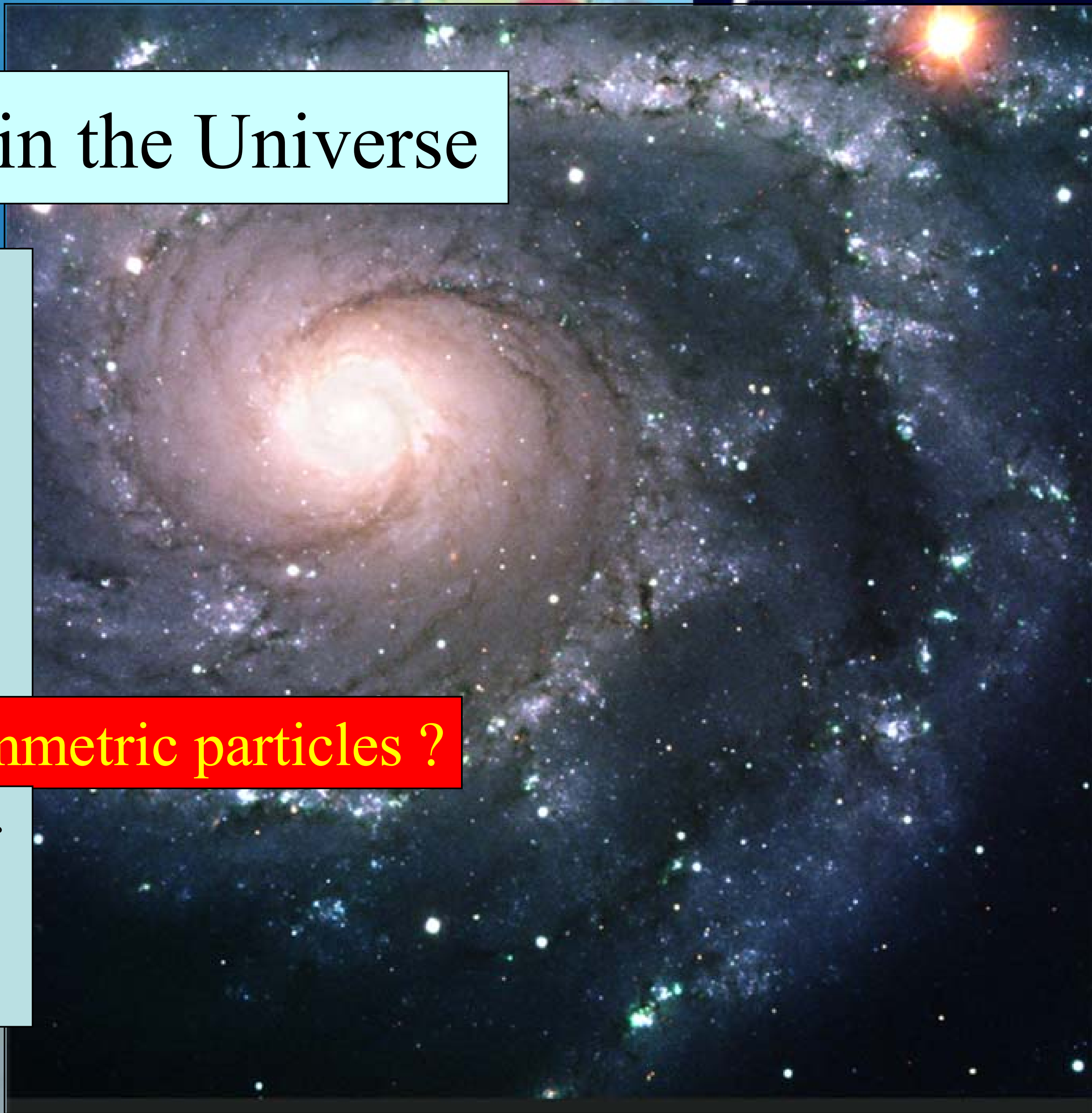
As suggested by EW data



Erler: 2006

JE, Nanopoulos, Olive + Santoso: hep-ph/0509331

Dark Matter in the Universe



Astronomers say that most of the matter in the Universe is invisible

Dark Matter

Lightest Supersymmetric particles ?

We shall look for them with the LHC

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles

- Lightest supersymmetric particle (LSP) stable

Fayet

Possible Nature of LSP

- No strong or electromagnetic interactions

  Otherwise would bind to matter

  Detectable as anomalous heavy nucleus

- Possible weakly-interacting scandidates

  Sneutrino

  (Excluded by LEP, direct searches)

  Lightest neutralino χ (partner of Z, H, γ)

  Gravitino

  (nightmare for astrophysical detection)

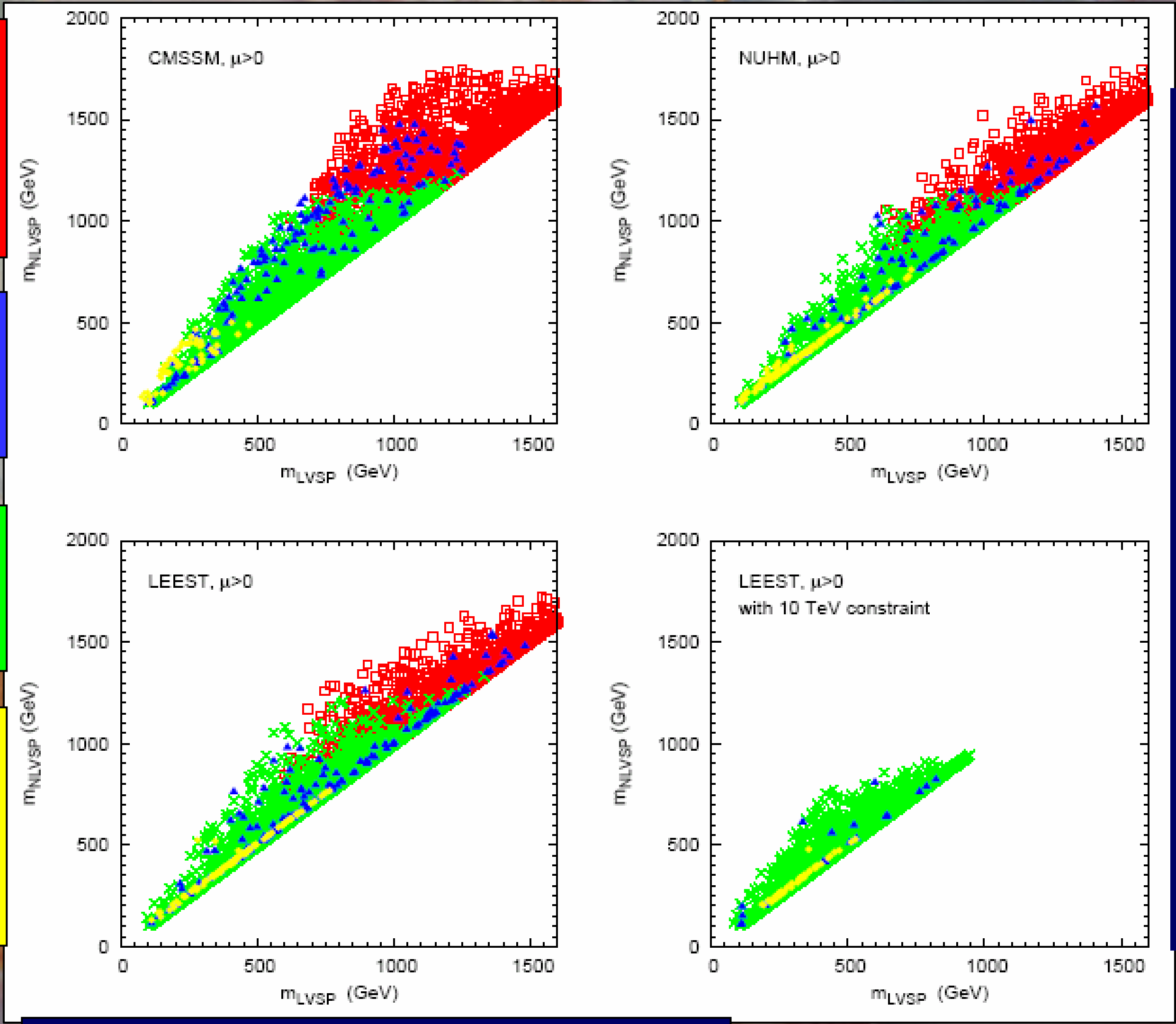
Sparticles may not be very light

Full Model samples

Provide Dark Matter

Detectable @ LHC

Dark Matter Detectable Directly

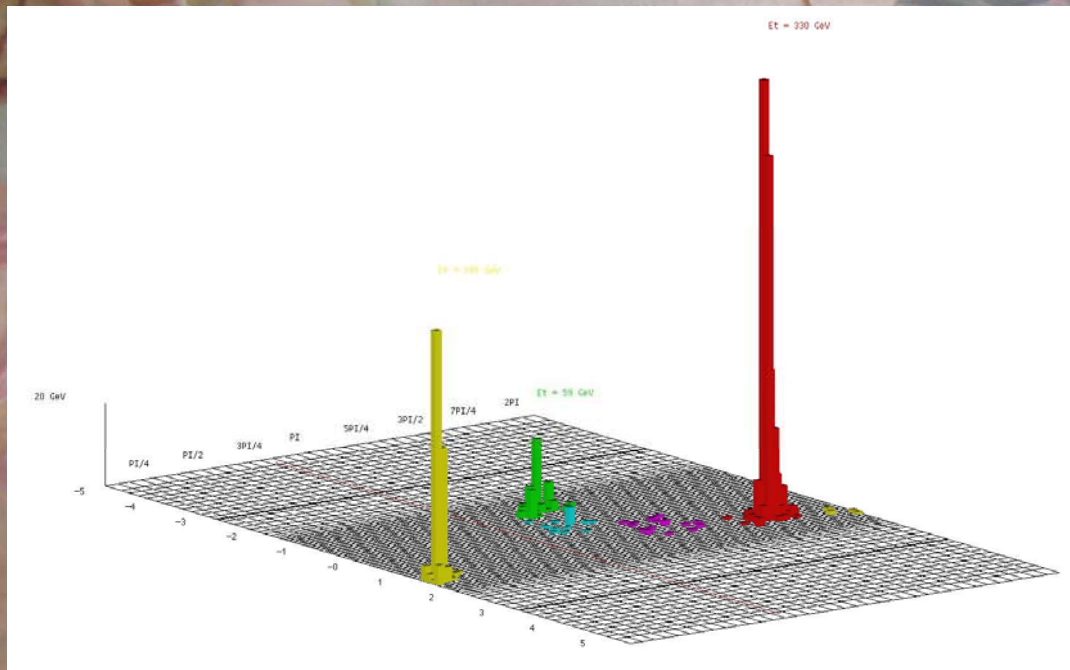


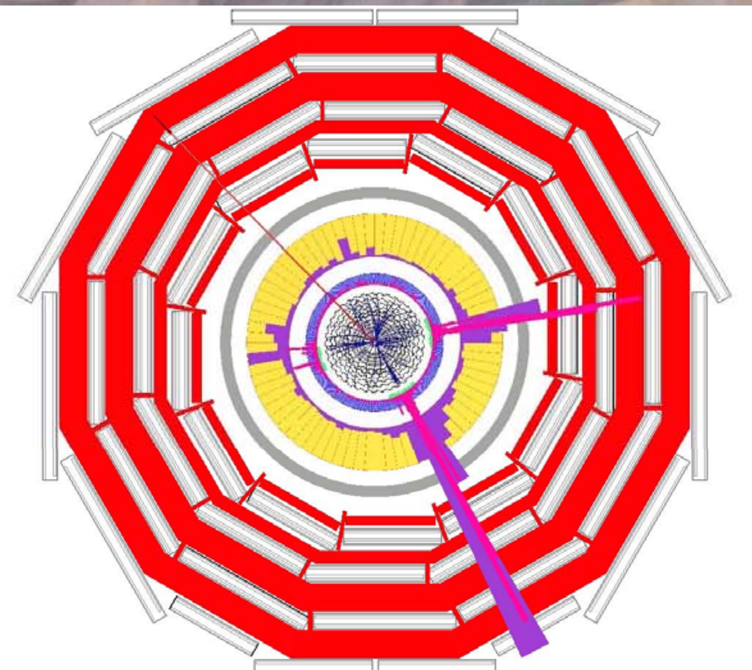
← Second lightest visible particle

Lightest visible sparticle →

JE + Olive + Santoso + Spanos

Classic Supersymmetric Signature

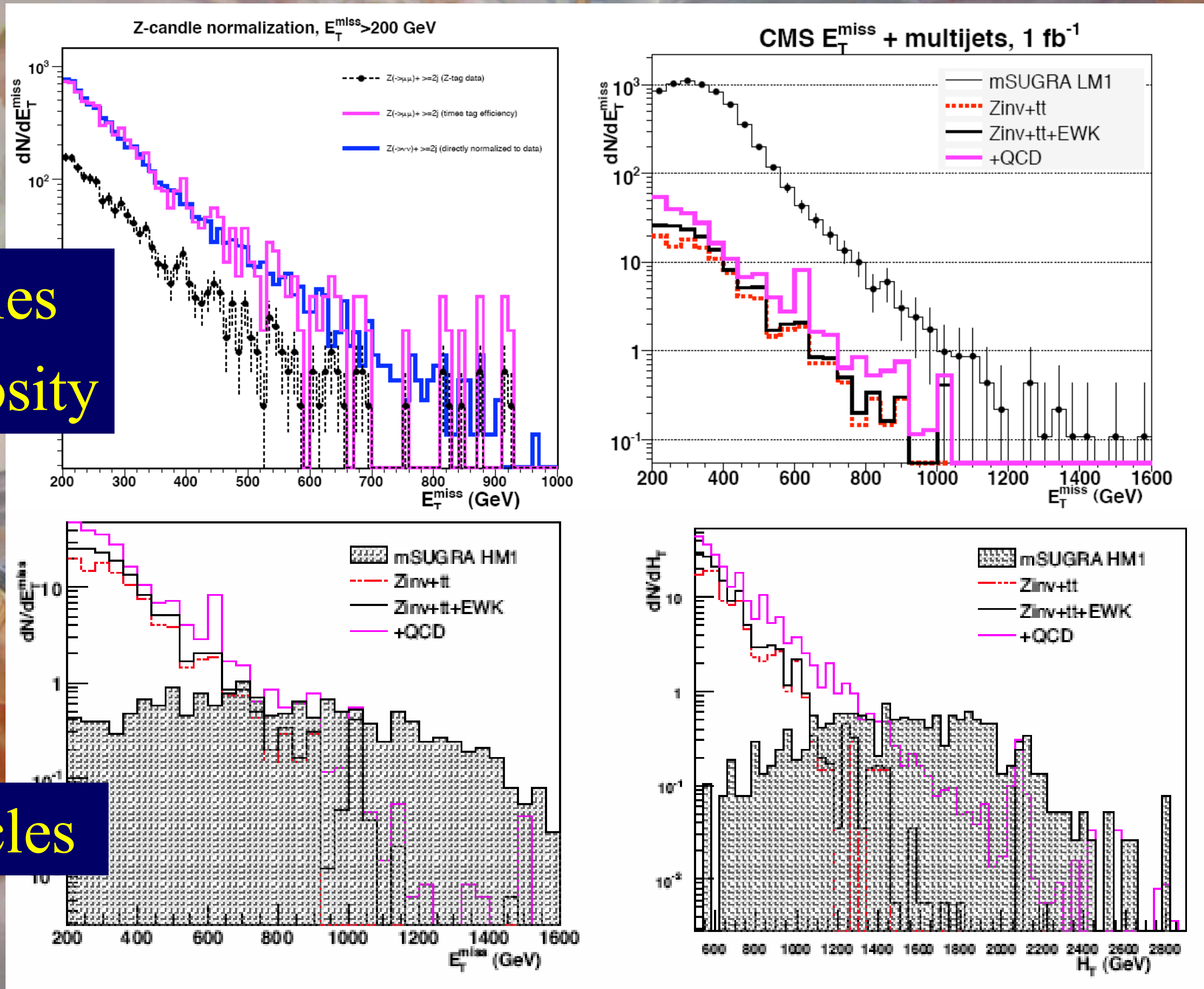




Missing transverse energy
carried away by dark matter particles

Search for Supersymmetry

Light sparticles @ low luminosity

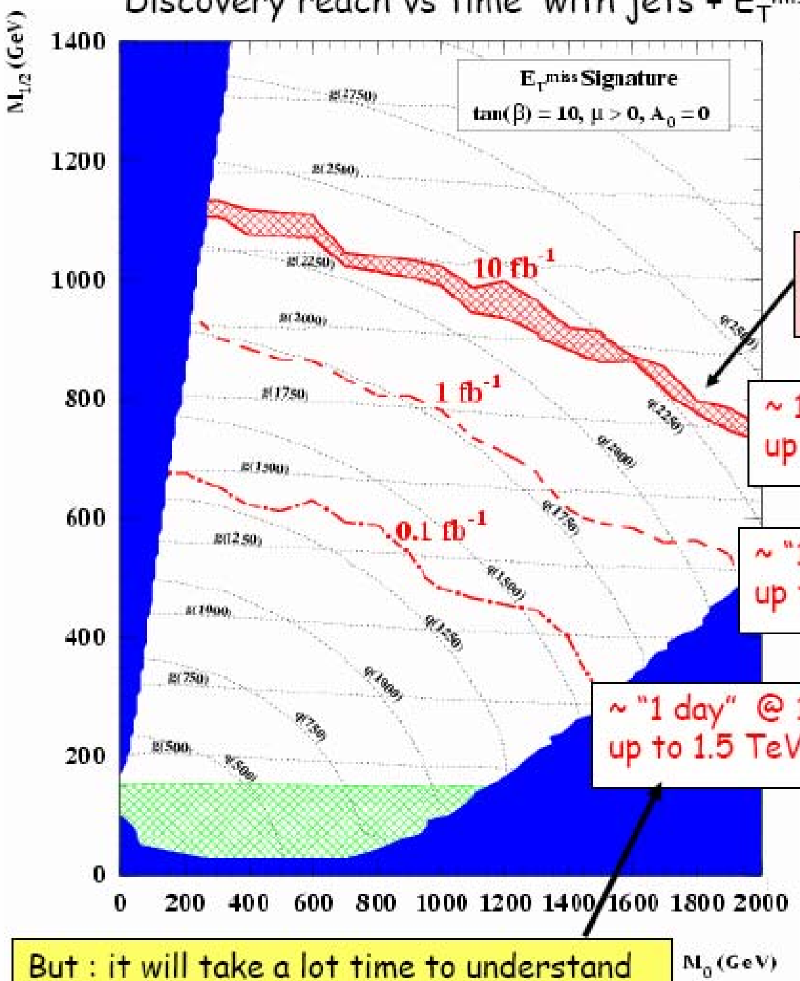


Heavy sparticles

How soon will we know?

Initial LHC Reach for Supersymmetry

Discovery reach vs time with jets + E_T^{miss} signature (most model-independent)



ATLAS
5σ discovery curves

band indicates factor ± 2 variation in background estimate

~ 100 days : up to 2.3 TeV

~ "10 days" : up to 2 TeV

~ "1 day" @ 10^{33}: up to 1.5 TeV

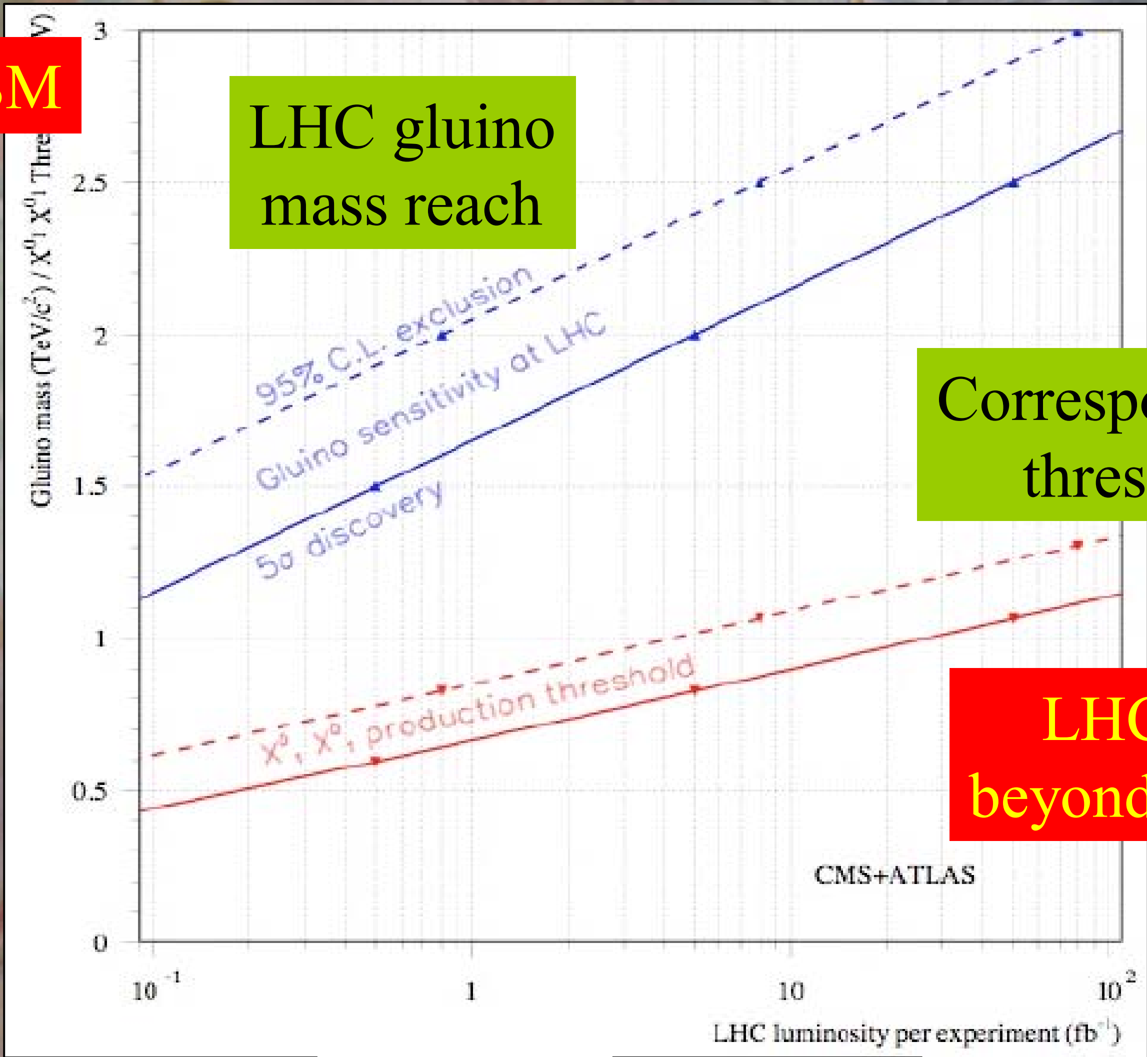
Discovery reach for squarks/gluinos

Time	mass reach
1 month at 10^{33}	~ 1.3 TeV
1 year at 10^{33}	~ 1.8 TeV
1 year at 10^{34}	~ 2.5 TeV
ultimate (300 fb^{-1})	~ 2.5-3 TeV

But : it will take a lot time to understand the detectors and the backgrounds ...

Implications of LHC Search for ILC

In CMSSM



Corresponding sparticle thresholds @ ILC

LHC already sees beyond ILC 'at turn-on'

'month' @ 10^{32}	'month' @ 10^{33}	1 'year' @ 10^{33}	1 'year' @ 10^{34}

Blaising et al: 2006

Summary

- The origin of mass is the most pressing in particle physics
- Needs a solution at energy < 1 TeV

  Higgs? Supersymmetry?

  LHC will tell!
- Lots of speculative ideas for other physics beyond the Standard Model

  Grand unification, strings, extra dimensions? …

  LHC may also probe these speculations

We do not know what the LHC will find

Its discoveries will set agenda for future projects