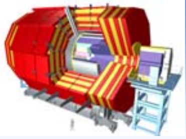
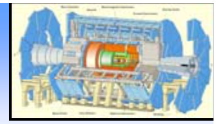
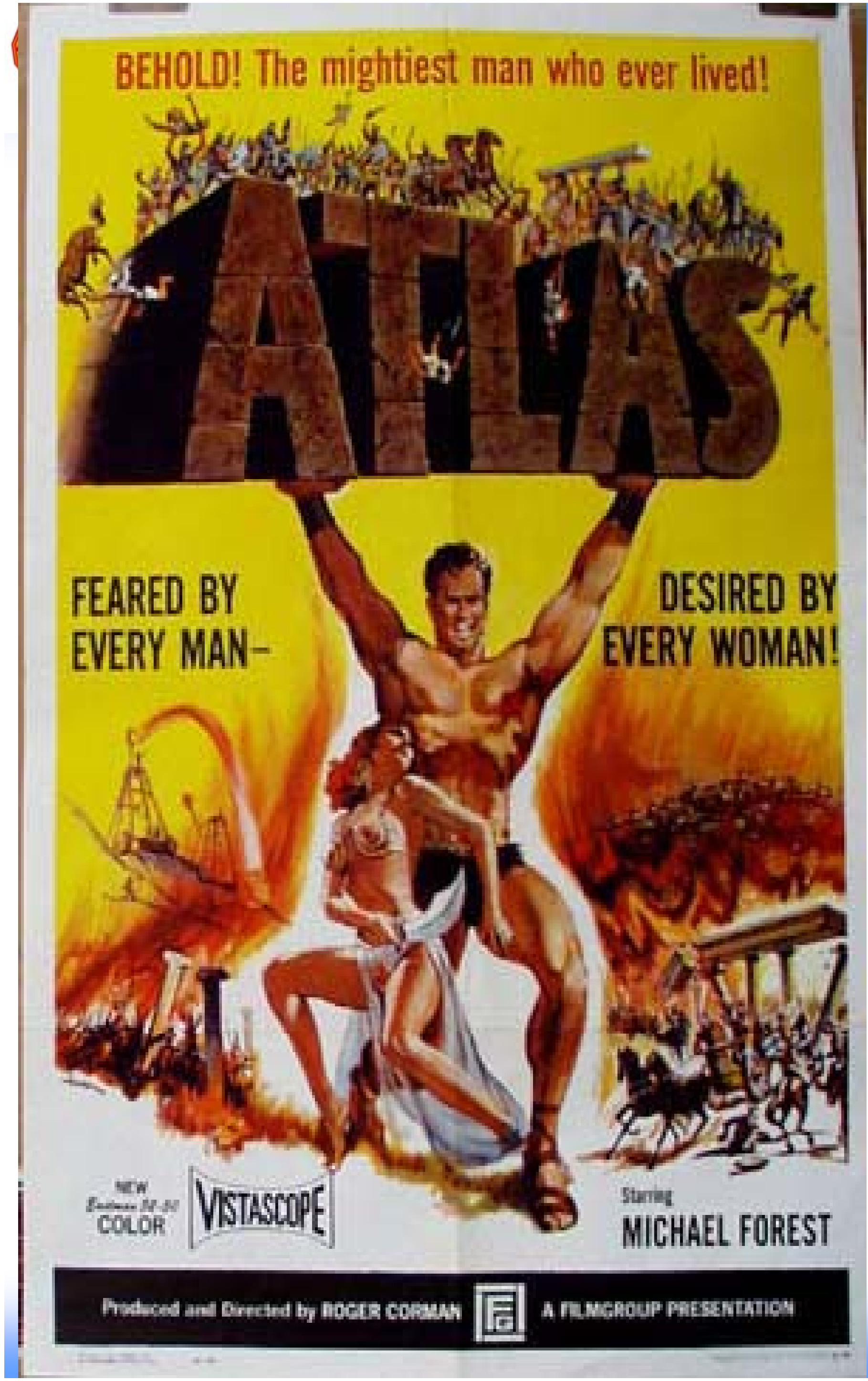




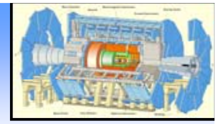
The Road to Discovery

Andy Parker

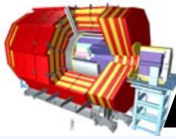
Cambridge University



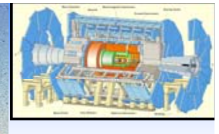
Disclaimer



- I shall use more ATLAS plots to illustrate LHC physics, because it is the experiment I know best.
- Both general purpose detectors - ATLAS and CMS - have very similar physics performance.
- Not every study of LHC physics potential is covered… apologies to those not mentioned.

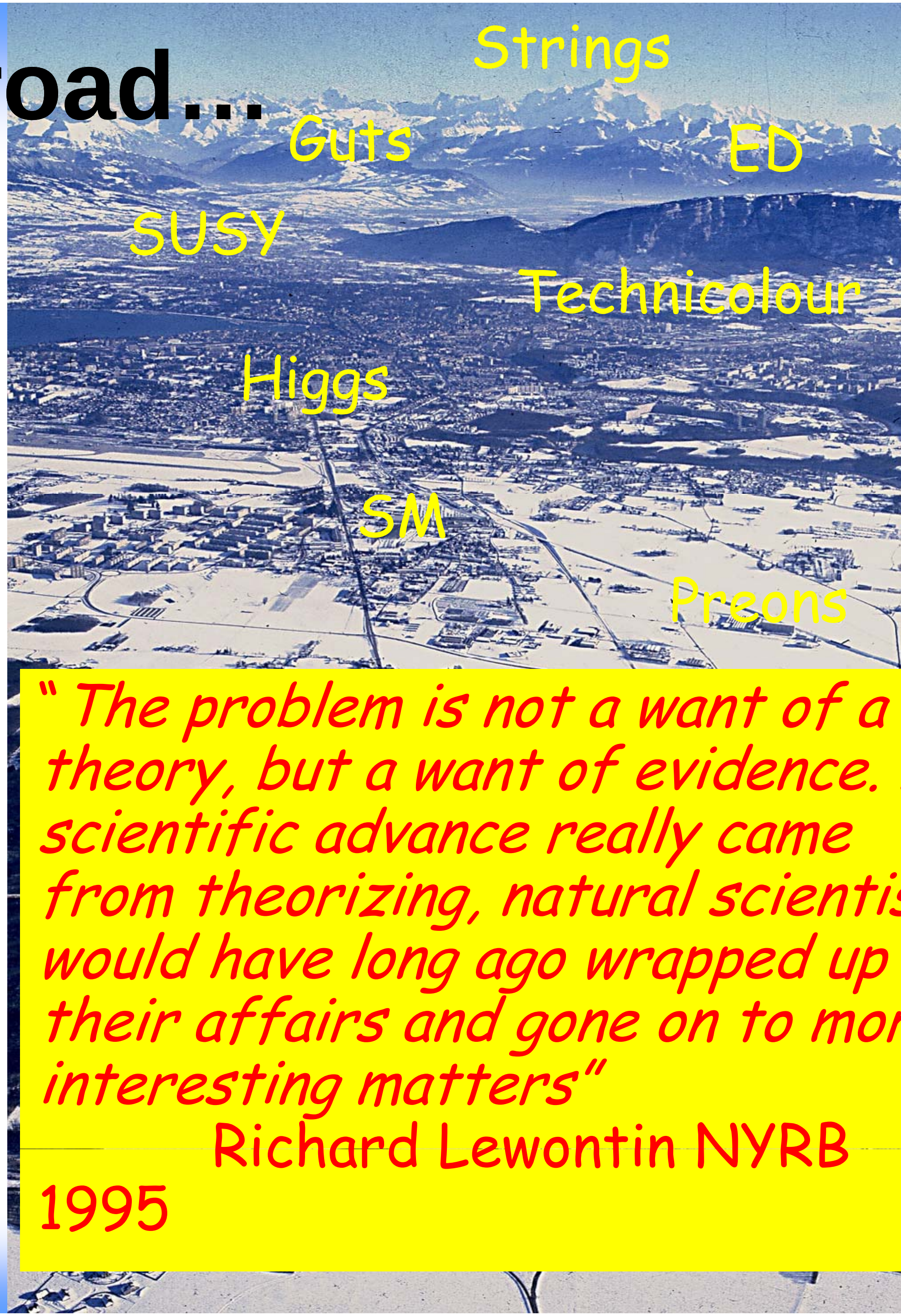


Along the road…



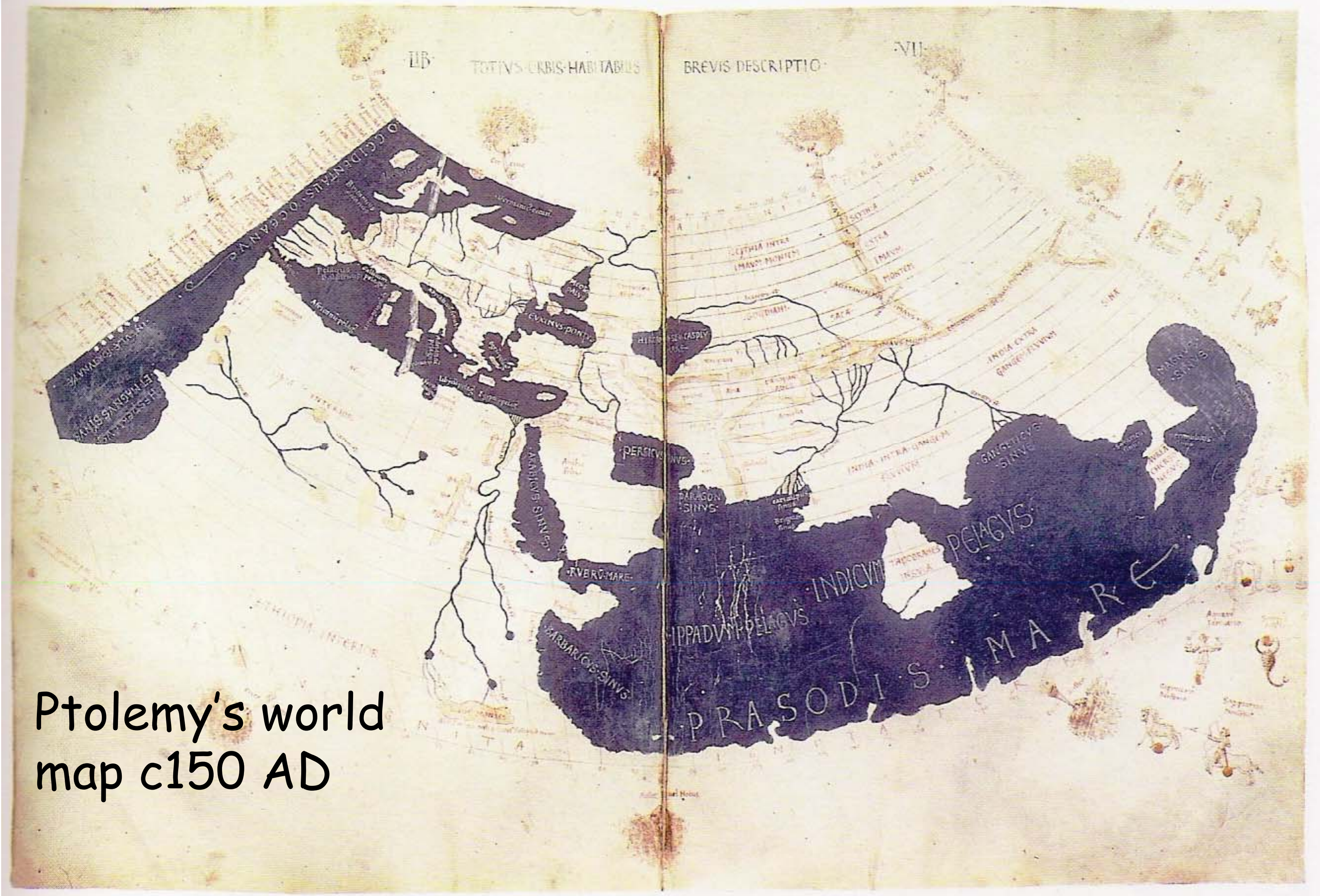
- Preparations - SM Physics, tools, problems
- The local road - hunting the Higgs
- The far horizon - SUSY
- The hidden road - Extra Dimensions

Thanks to Fabiola Gianotti and many authors of notes etc used in these lectures



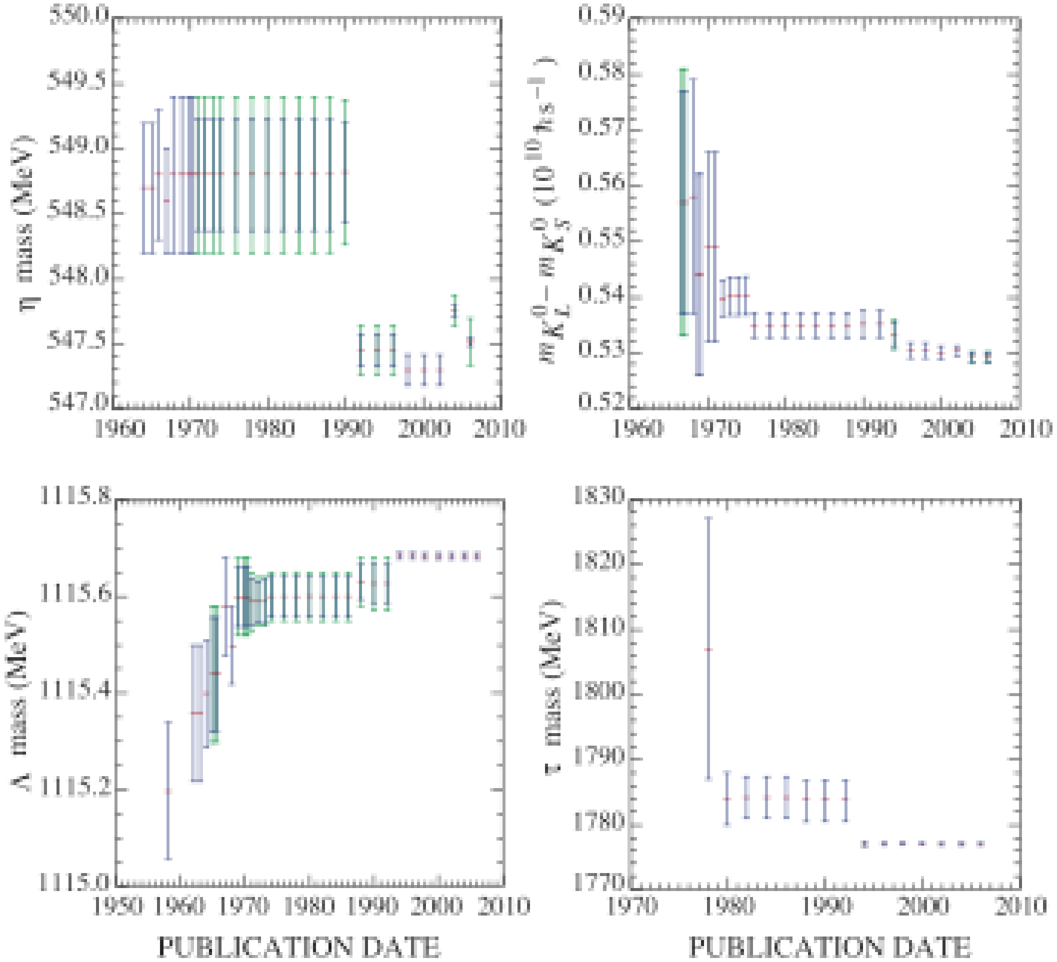
"The problem is not a want of a theory, but a want of evidence. If scientific advance really came from theorizing, natural scientists would have long ago wrapped up their affairs and gone on to more interesting matters"
Richard Lewontin NYRB 1995

Beware of conventional wisdom



Ptolemy's world map c150 AD

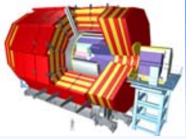
Beware of last result…



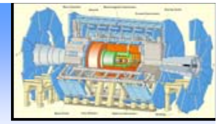
Measurements vs publication date (PDG)

Blind analysis? Not in first phase

Use later, larger sample to control bias.



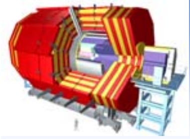
Statistical Analysis of Discoveries



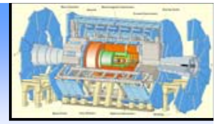
- From Fred James, CERN Academic Training Programme 1986: “The statistics of small samples - Bayesian and Classical Approaches”

- What should a physicist publish?

- Required:
1. Number of observed events
2. Calculated background
3. Conversion from events to physical units
- Optional:
- An upper limit using any rule, but tell us which rule you use.

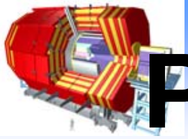


Confidence limits

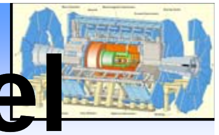


- S, B and relevant conversion factors (eg luminosity, inverse tonne-years…) contain all the information about the experiment and can be combined with other experiments.
- Confidence limits are a matter of controversy, even among experts, and in general cannot be combined.

Parkers postulate: if you are arguing about statistics, it isn't a discovery



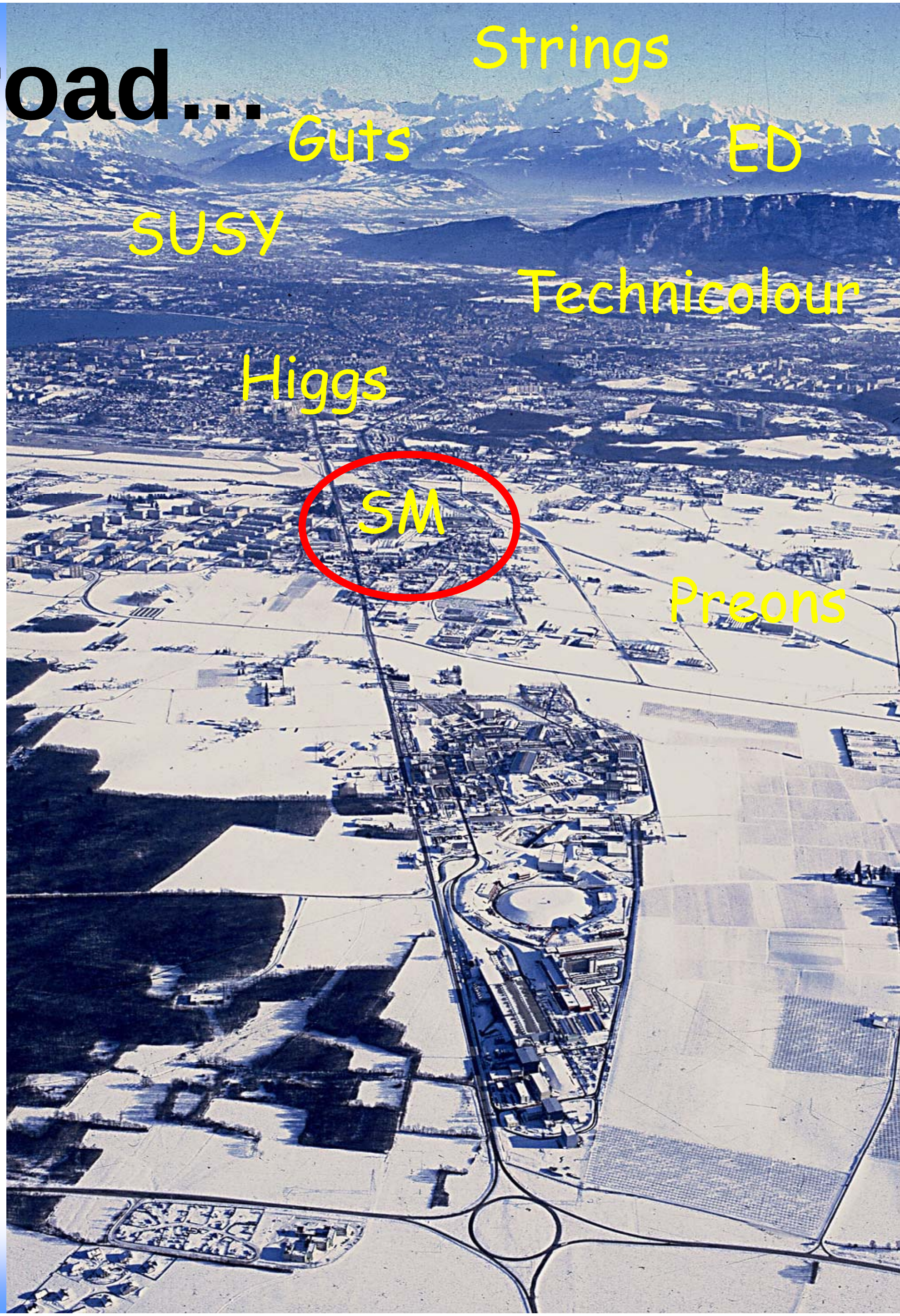
Problems in the Standard Model



- 19 free parameters: m_e, m_μ, m_τ , m_u, m_d, m_s, m_c, m_b, m_t, e, G_F, θ_W, α_s, A, λ, ρ, η, m_H, θ_{CP}
- Why SU(3)xSU(2)xU(1)?
- Why 3 generations?
- Why $Q_e=Q_p$?
- Is the Higgs mechanism responsible for masses?
- What is the origin of CP violation?
- Are B and L really conserved? (no underlying symmetry)
- What is dark matter?
- How can we include gravity?
- The Hierarchy problem….

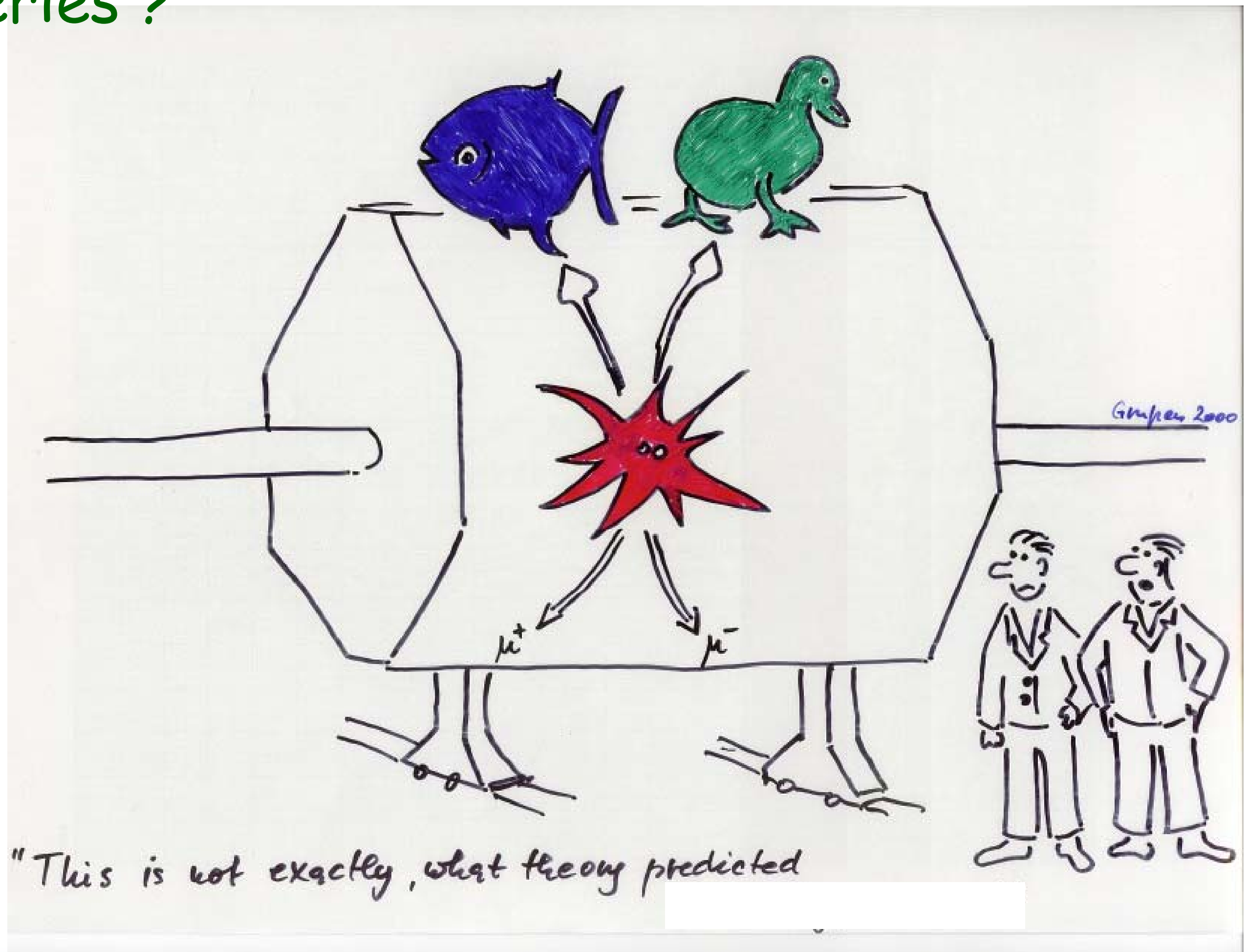
Along the road…

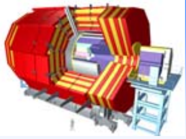
Starting line…



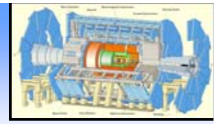
Startup physics

- Understand detector and Standard Model physics
- Discoveries ?





First physics run 2008



($\sqrt{s}$ = 14 TeV) ….

1 fb^{-1} (100 pb^{-1}) ≡ 6 months (few days) at L= 10^{32} $cm^{-2}s^{-1}$ with 50% data-taking efficiency
→ may collect a few fb^{-1} per experiment by end 2008

Channels (examples …)	Events to tape for 100 pb^{-1} (per expt: ATLAS, CMS)	Total statistics from some of previous Colliders
$W \to \mu\nu$	~ 10^6	~ 10^4 LEP, ~ 10^6 Tevatron
$Z \to \mu\mu$	~ 10^5	~ 10^6 LEP, ~ 10^5 Tevatron
$tt \to W b W b \to \mu\nu + X$	~ 10^4	~ 10^4 Tevatron
QCD jets p_T > 1 TeV	> 10^3	---
$\tilde{g}\tilde{g}$ m = 1 TeV	~ 50	---

With these data:

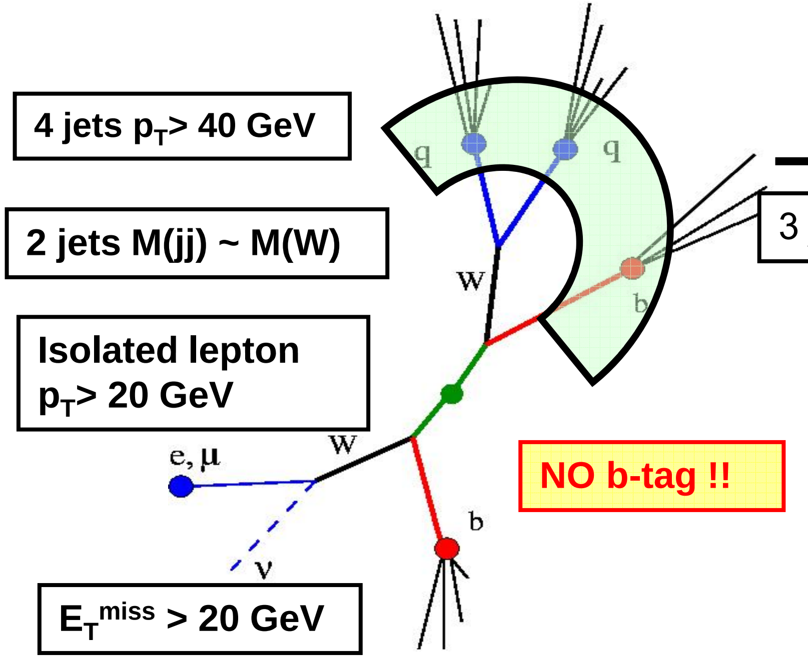
- Understand and calibrate detectors in situ using well-known physics samples
  e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $tt \to bl\nu\ bjj$ jet scale from $W \to jj$, b-tag performance, etc.
- Measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, QCD jets …
  (also because omnipresent backgrounds to New Physics)

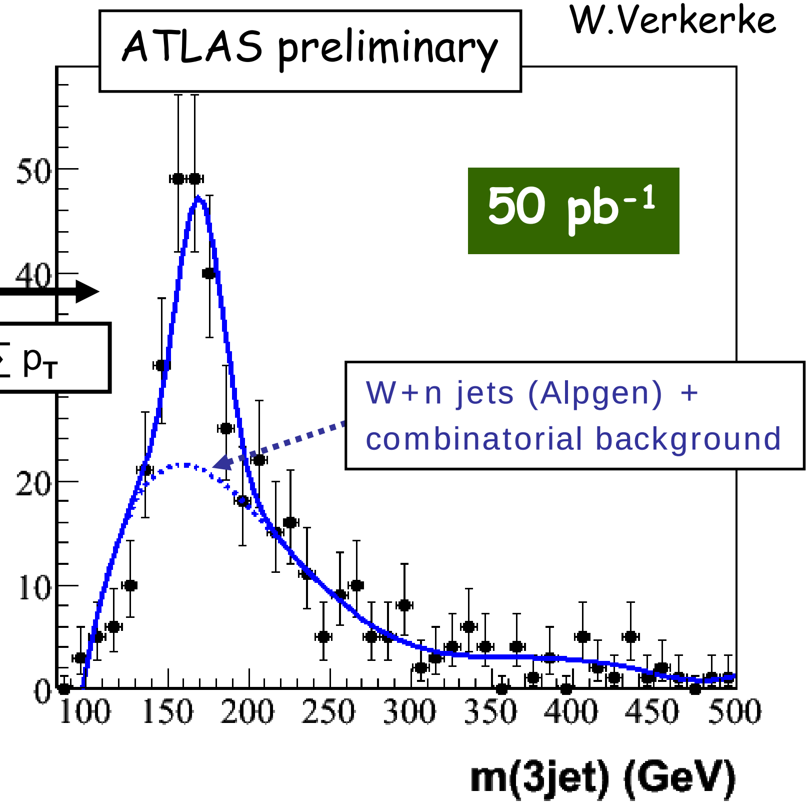
→ **prepare the road to discovery …… it will take time …**

Top events

Can we observe an early top signal with limited detector performance ?
And use it to understand detector and physics ?

$\sigma_{tt} \approx 250$ pb for $tt \to bW\,bW \to bl\nu\,bjj$





Top signal observable in early days with no b-tagging and simple analysis
(100 ± 20 evts for 50 pb^{-1}) → measure σ_{tt} to 20%, m to 10 GeV with ~100 pb^{-1} ?

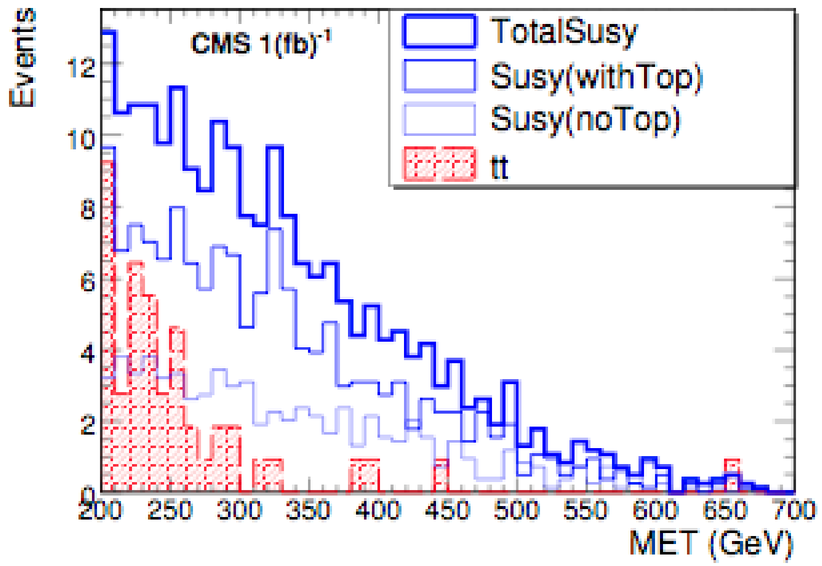
- **commission b-tagging, set jet E-scale using W → jj peak**
- **understand detector performance for e, μ, jets, b-jets, missing E_T, …**
- **understand / constrain theory and MC generators using e.g. p_T spectra**

Top signature for SUSY

CMS AN 2005/069

CMS analysis of low mass test point (CMS-LM1) with m_0=60 ,$m_{1/2}$=250 GeV

A_0=0, tan(β)=10, μ>0

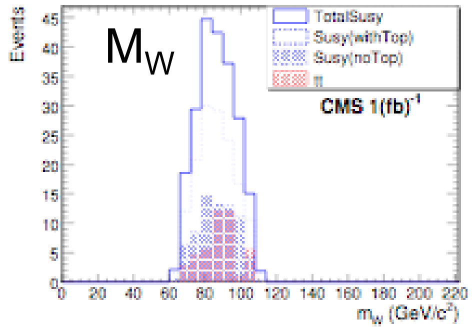


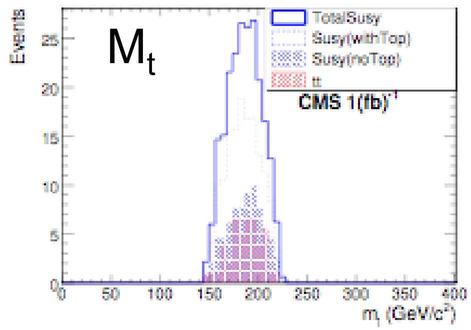
11σ signal with S/B=3

1 fb^{-1}

Search for excess of top events at high missing ET

Kinematic fit used to find top decays

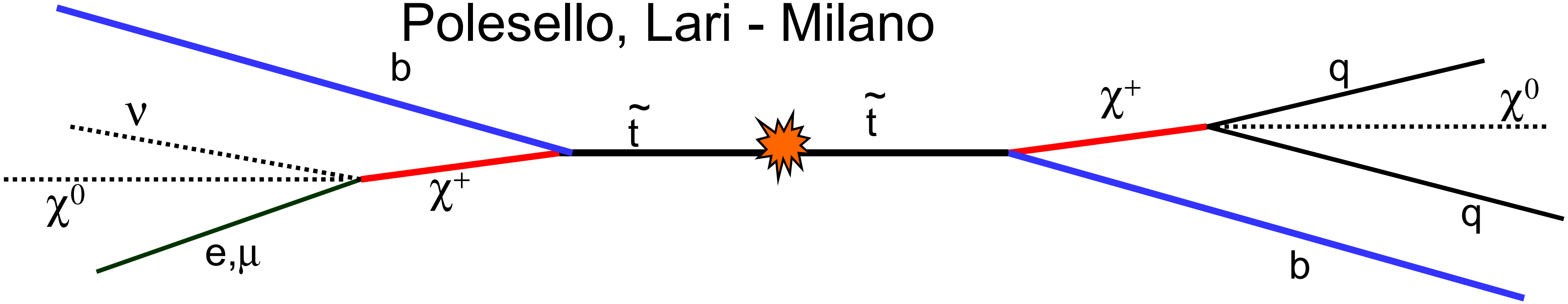




After all cuts SM ttbar is strongly suppressed

Light stop production

Polesello, Lari - Milano



- **Stop pair production:** 412 pb **(PROSPINO, NLO)**
- **Dominant (~100%) stop decay: $\tilde{t} \to \tilde{\chi}^+ b \to \tilde{\chi}^0_1 W^* b$**
- **Final state is very similar to top pair production events.**

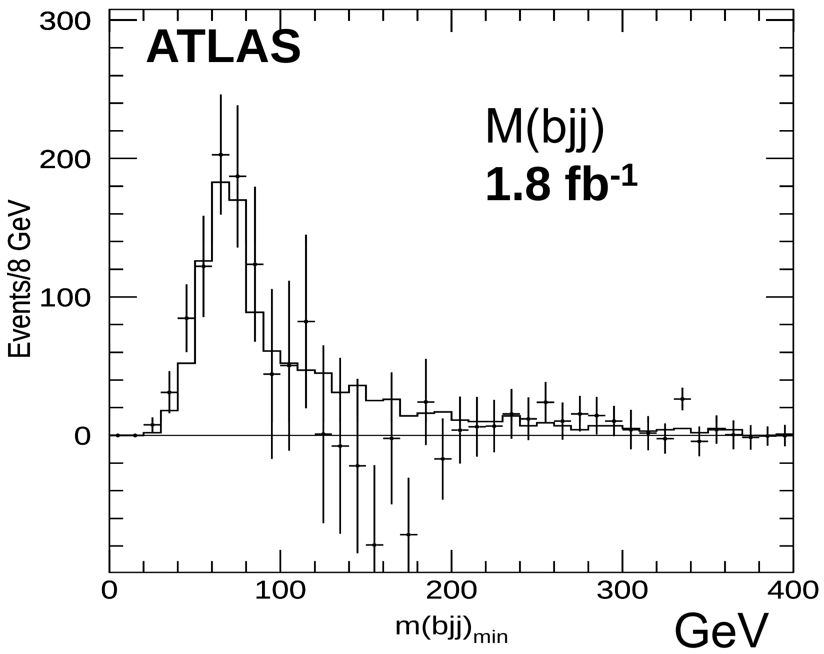
- 4 jets, 2 of which b-jets, one isolated lepton, missing energy
- All of them **softer** (on average) than in top pair production
- Invariant mass combinations will not check out with top, W masses

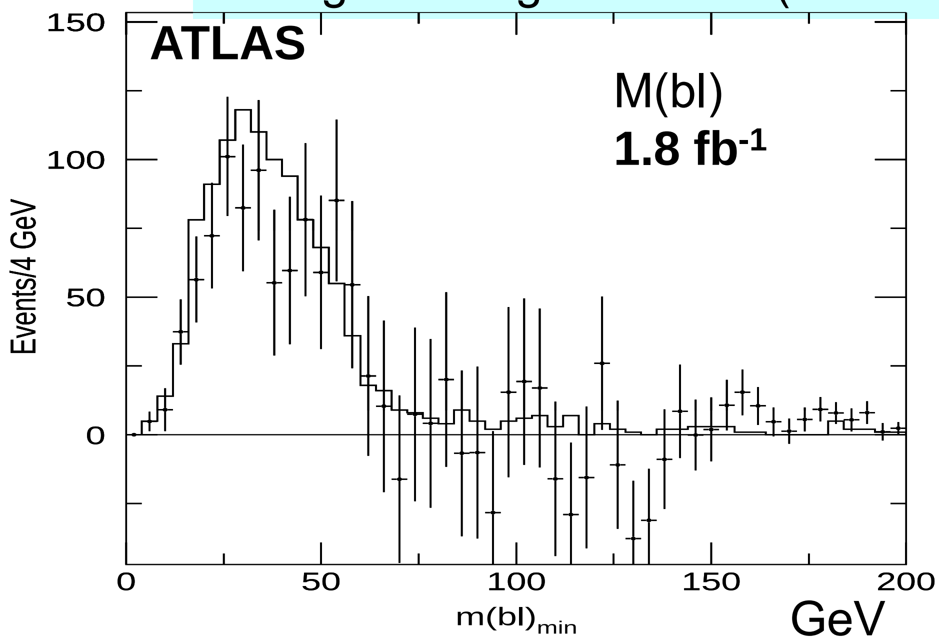
- **Also potentially accessible at LHC, but not discussed here:**
  - **Gluino pair production. Gluino decays (100%) into t t**
  - **Chargino/neutralino direct production**

top background subtraction

- **Top background subtracted from using simulated data**
- **Wbbjj subtracted using MC Truth**
  - **Expect that in practice, a combination of Montecarlo and Zbbjj data will be used to estimate this background.**

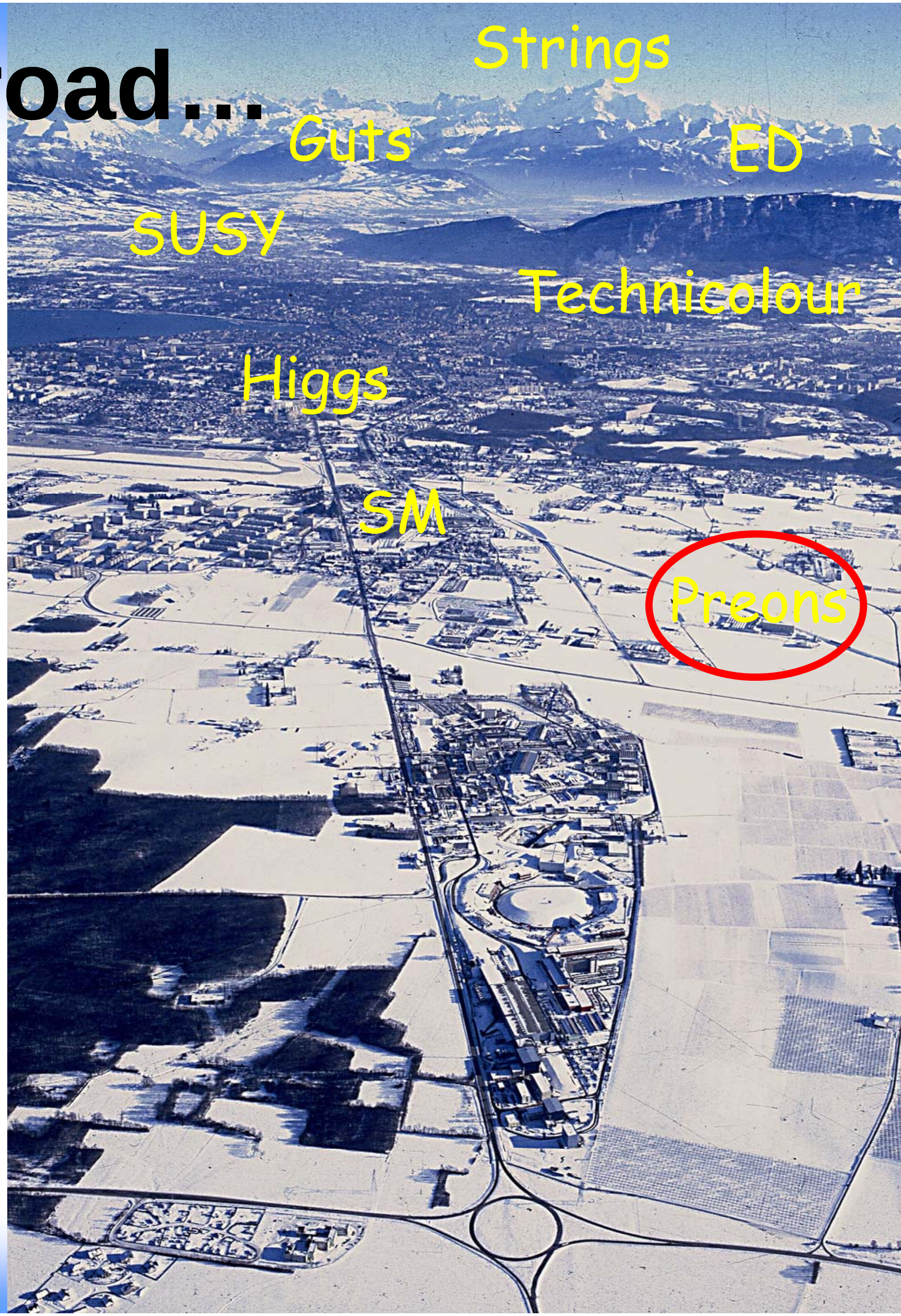
Points: simulated data
Histograms: signal events (MC truth)



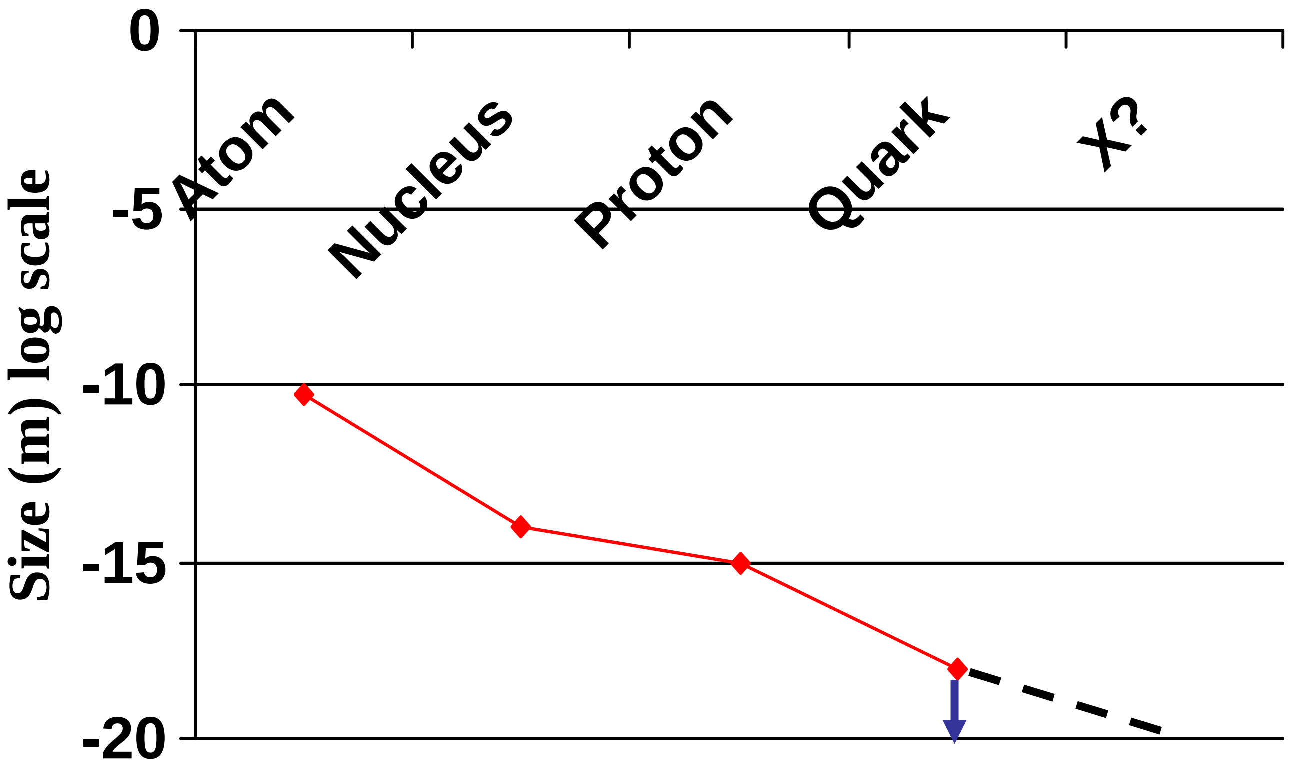


Along the road…

A detour?

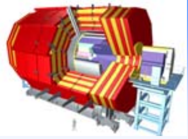


Compositeness

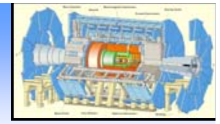


Perhaps all the usual theory is nonsense? If the particles we observe now are not fundamental, we have no reason to extrapolate to a final theory.

New substructure every few orders of magnitude in size…why not this time?



Why not compositeness?

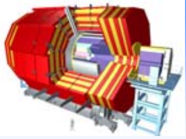


Advantages

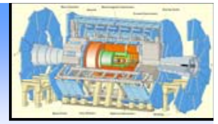
- It agrees with past experience
- Can create SM particles from bound states of just two "preons"
- If Higgs is composite, there are no scalar fields, and Higgs mass problems don't arise.
- Can expect excitations of bound states to be detected.
- Explain 3 family structure as excitations

Disadvantages

- Difficult to form correct mass spectrum with reasonable binding potential
- Postpones fundamental questions to next level



Preon model



Start with two preons:

T	charge 1/3	Coloured
V	charge 0	Anticoloured

No satisfactory dynamics for binding preons!

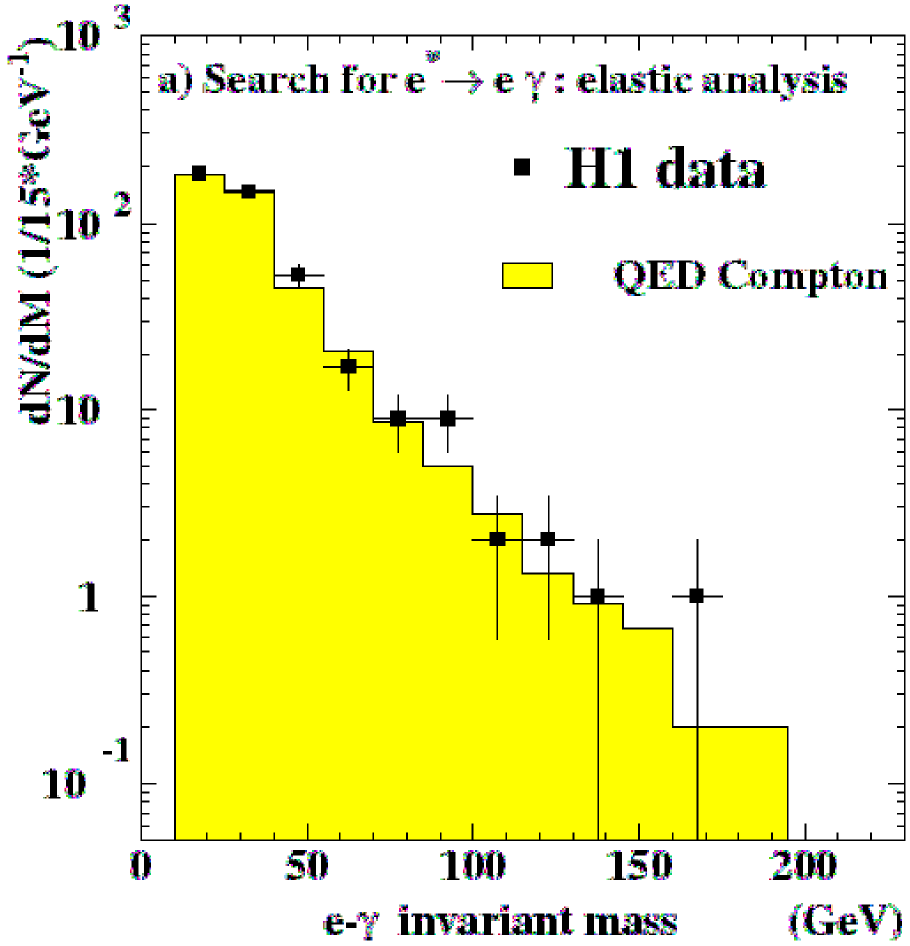
Make SM particles:

Charged leptons	TTT Colour singlet
Neutrinos	VVV Colour singlet
Quarks	TTV VVT

But: need to make T,V very heavy and very tightly bound to explain mass range from <10eV to 174 GeV.

Searching for compositeness

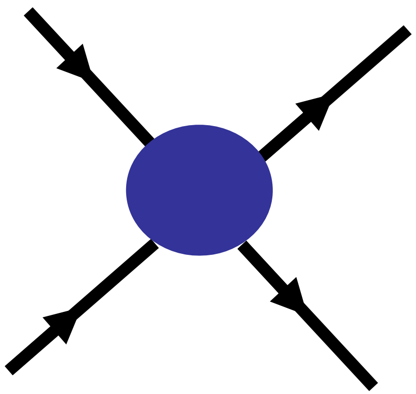
- Compositeness implies a new very strong interaction between the constituents of quarks and leptons
- Search for "contact interaction" at short range, or for excited states of quarks or leptons.



No signal for lepton excitations yet

Contact interactions

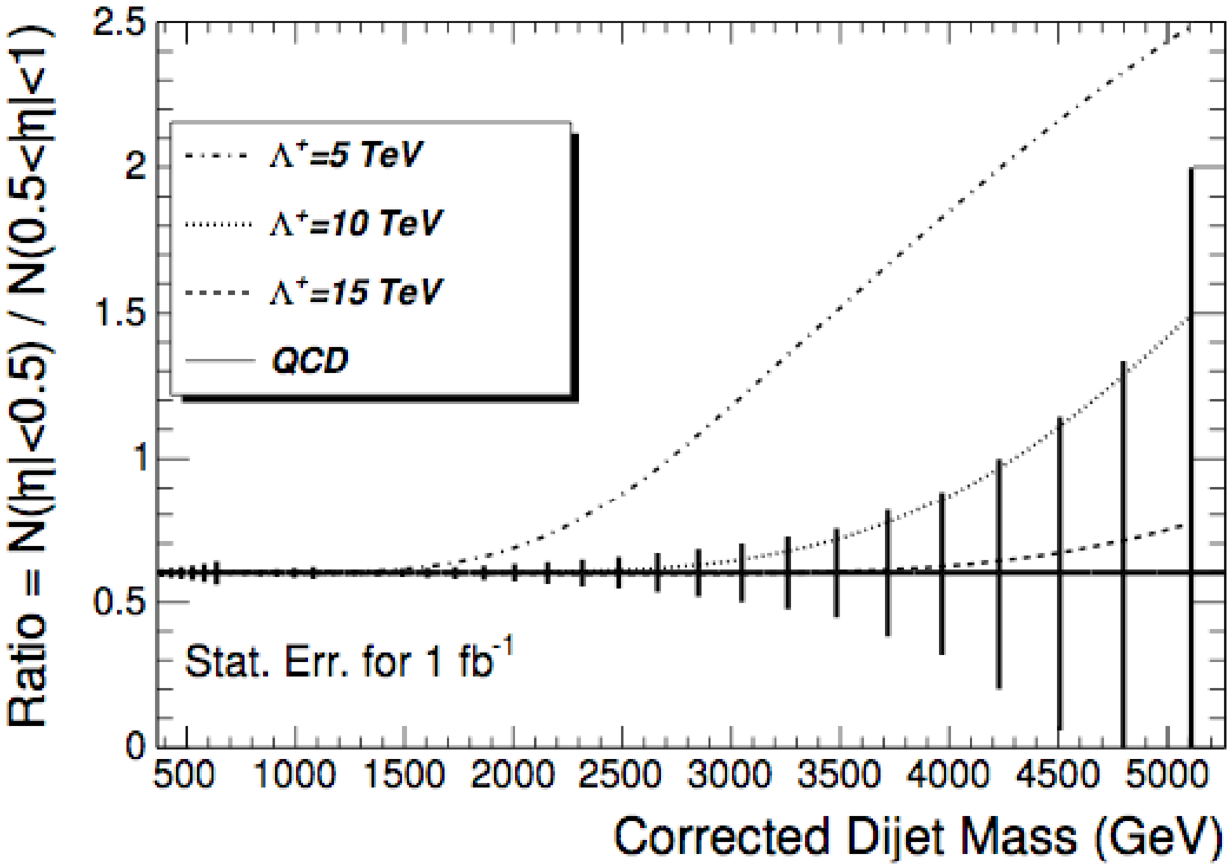
$$L_{qq} = A\left(\frac{g^2}{2\Lambda_{LL}^2}\right)\bar{q}_L\gamma^\mu q_L\bar{q}_L\gamma_\mu q_L$$



Coupling g and scale Λ_{LL} .
A is ±1 - sign of interference with QCD.

- Contact interaction parameterizes ignorance of true process, as a single 4 fermion vertex - analagous to Fermi theory for weak interactions, where energy scale << $M_{W.}$
- Expect deviations from QCD at high mass, and in angular distributions

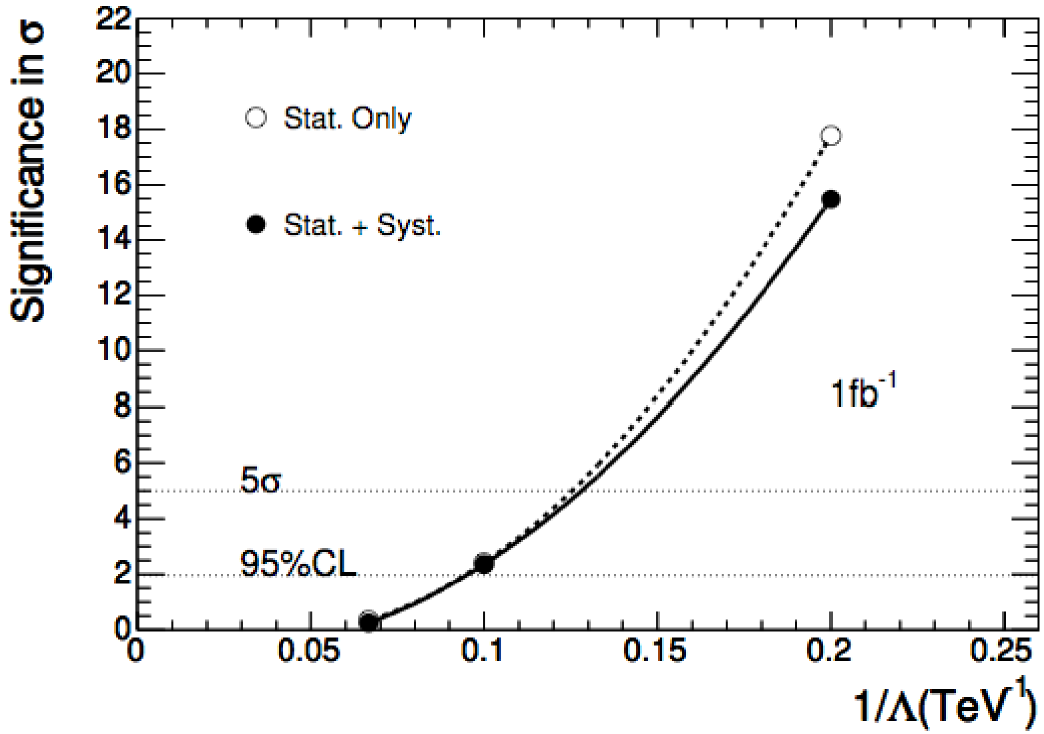
CMS dijet search



- Use dijet ratio over two different eta ranges, as fcn of mass.
- Sensitive to angular distribution as well as deviations at high mass.

Jet energy scale, and parton distribution systematics cancel in ratio

CMS dijet search reach

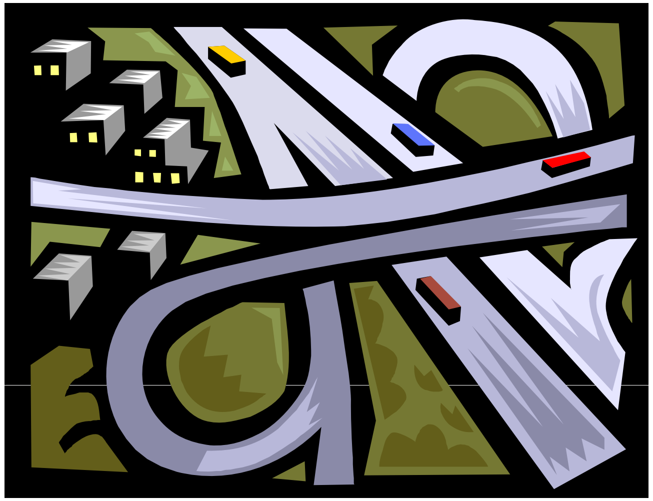


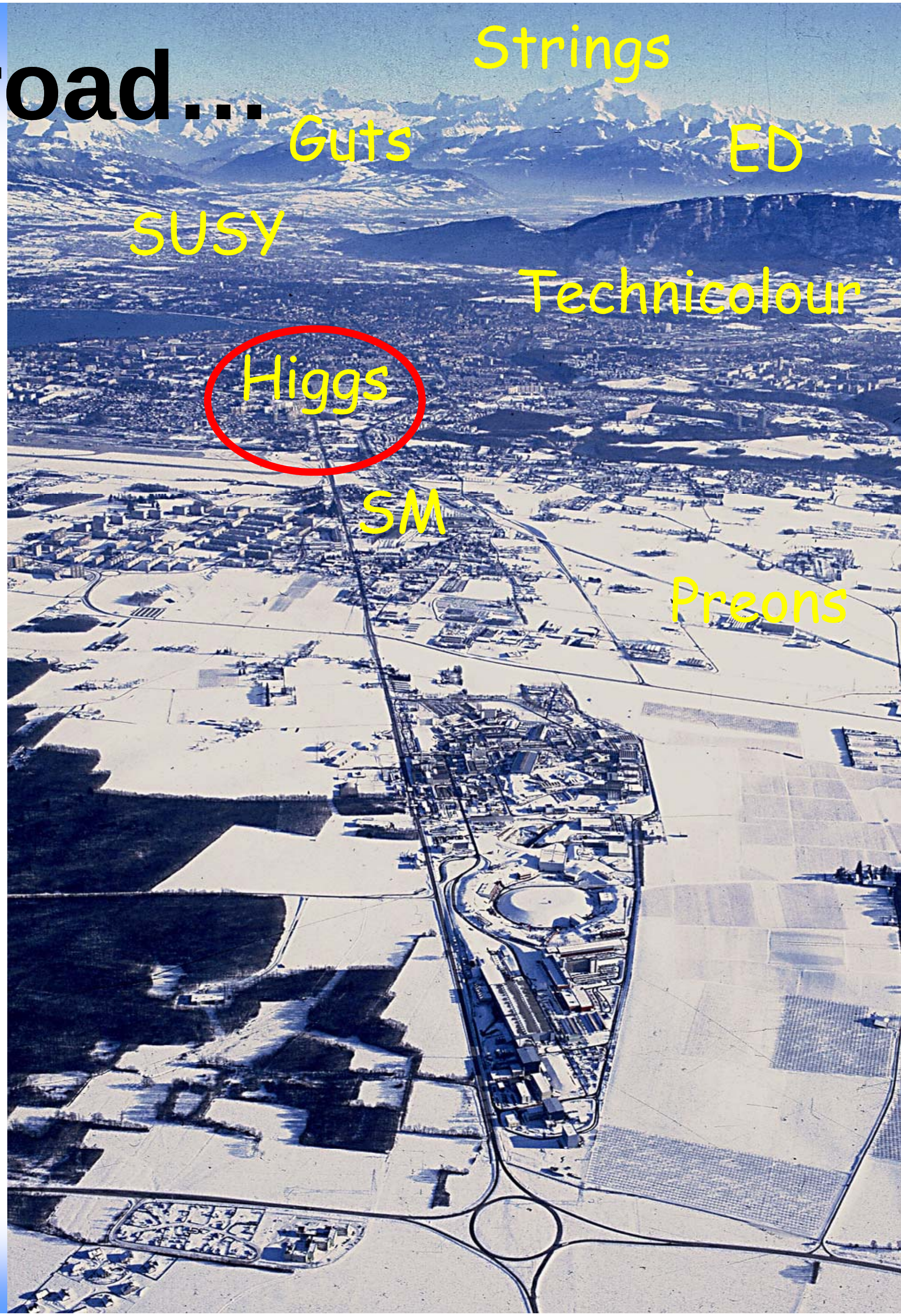
Sensitive to mass scale of order 10 TeV with 1 fb-1

Luminosity	95% CL Excluded Scale			5σ Discovered Scale		
	100 pb^{-1}	1 fb^{-1}	10 fb^{-1}	100 pb^{-1}	1 fb^{-1}	10 fb^{-1}
Λ^+ (TeV)	<6.2	<10.4	<14.8	<4.7	<7.8	<12.0

Along the road…

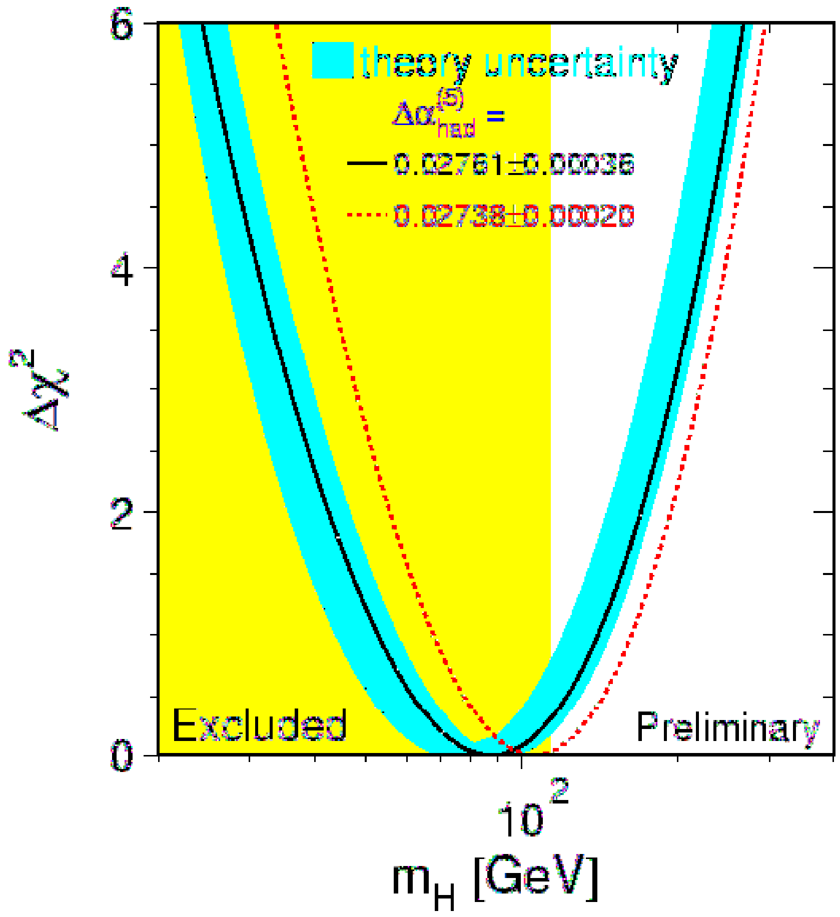
Back to the highway…





Higgs searches

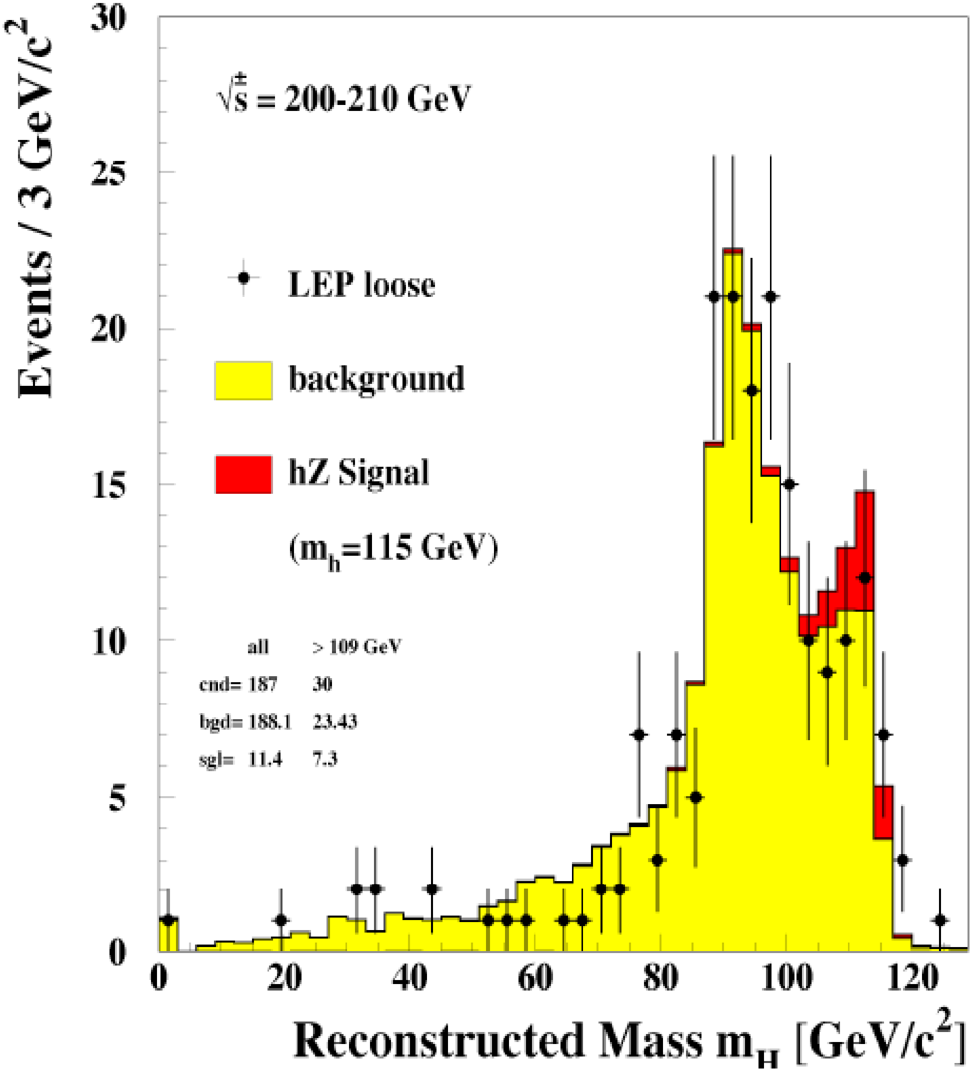
Fit to all precision electroweak data gives χ^2 as function of Higgs mass (assuming Higgs exists).



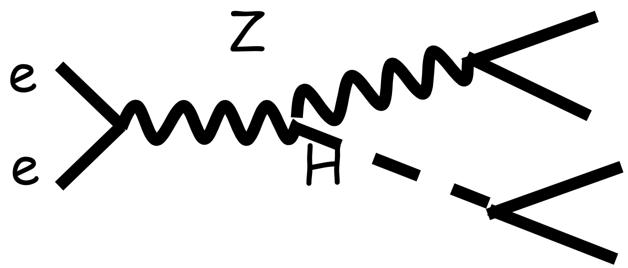
- In SM framework, Higgs mass is well constrained.
- Only a matter of time!
- In SUSY models, very difficult to raise lightest higgs mass

Preferred mass is 85 GeV (excluded by direct search), 95% confidence limit < 199 GeV.

LEP searches

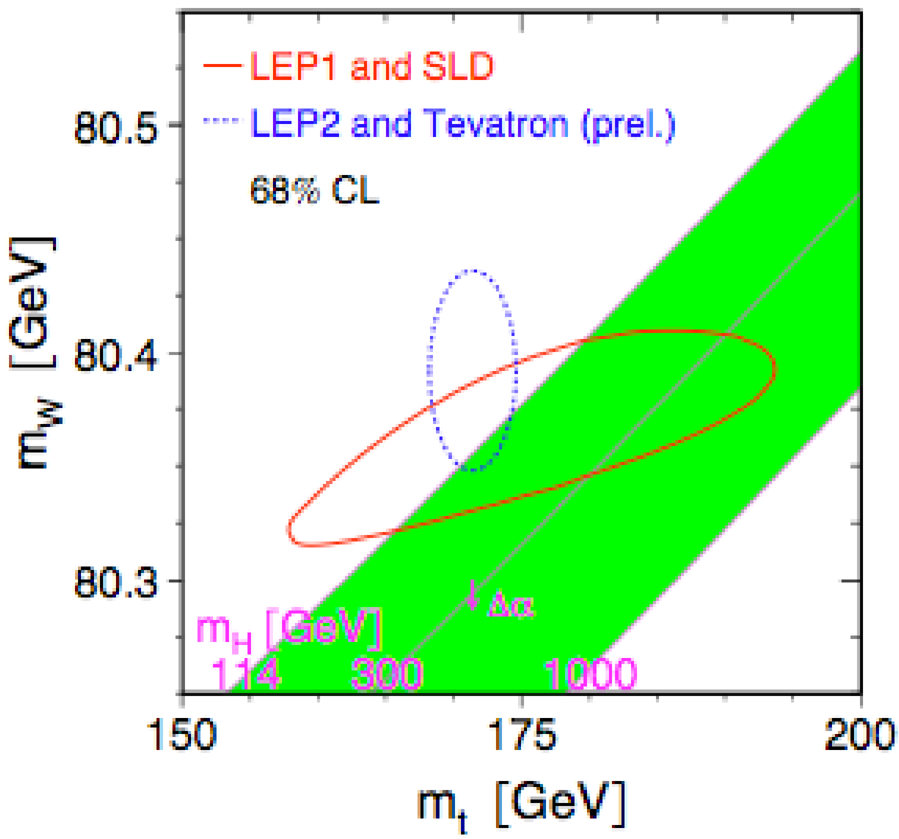


LEP



- Hint of a signal at m_H=115 GeV, in the dominant HZ -> 4 jet channel, but not statistically significant.

Higgs mass from t and W



Data favours a light Higgs

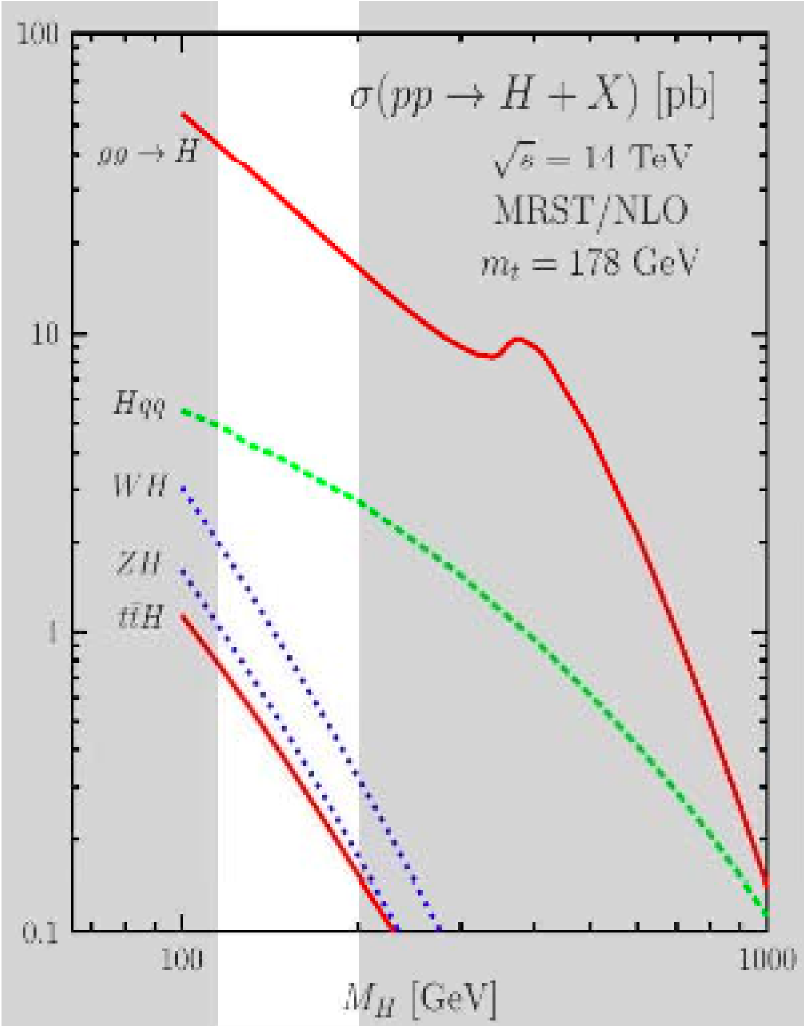
Tevatron top working group gives

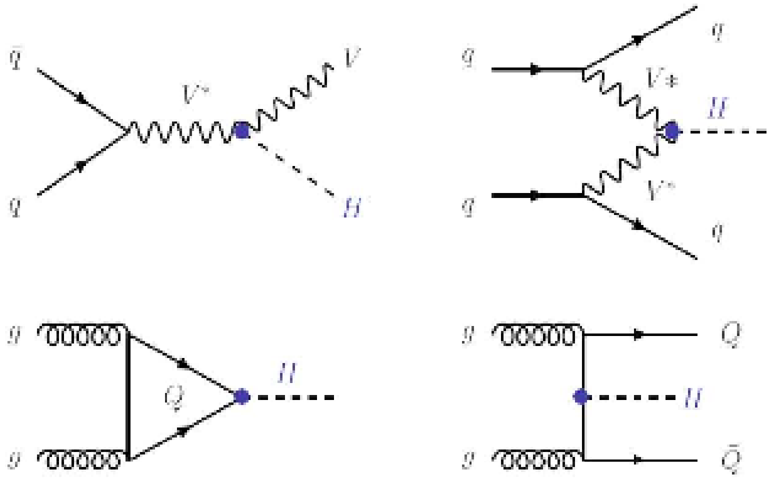
M_t=170.9+-1.8 GeV

Limited by systematics, dominated by jet energy scale. Expect to reach <1% precision.

hep-ex/0703034

Higgs production at LHC



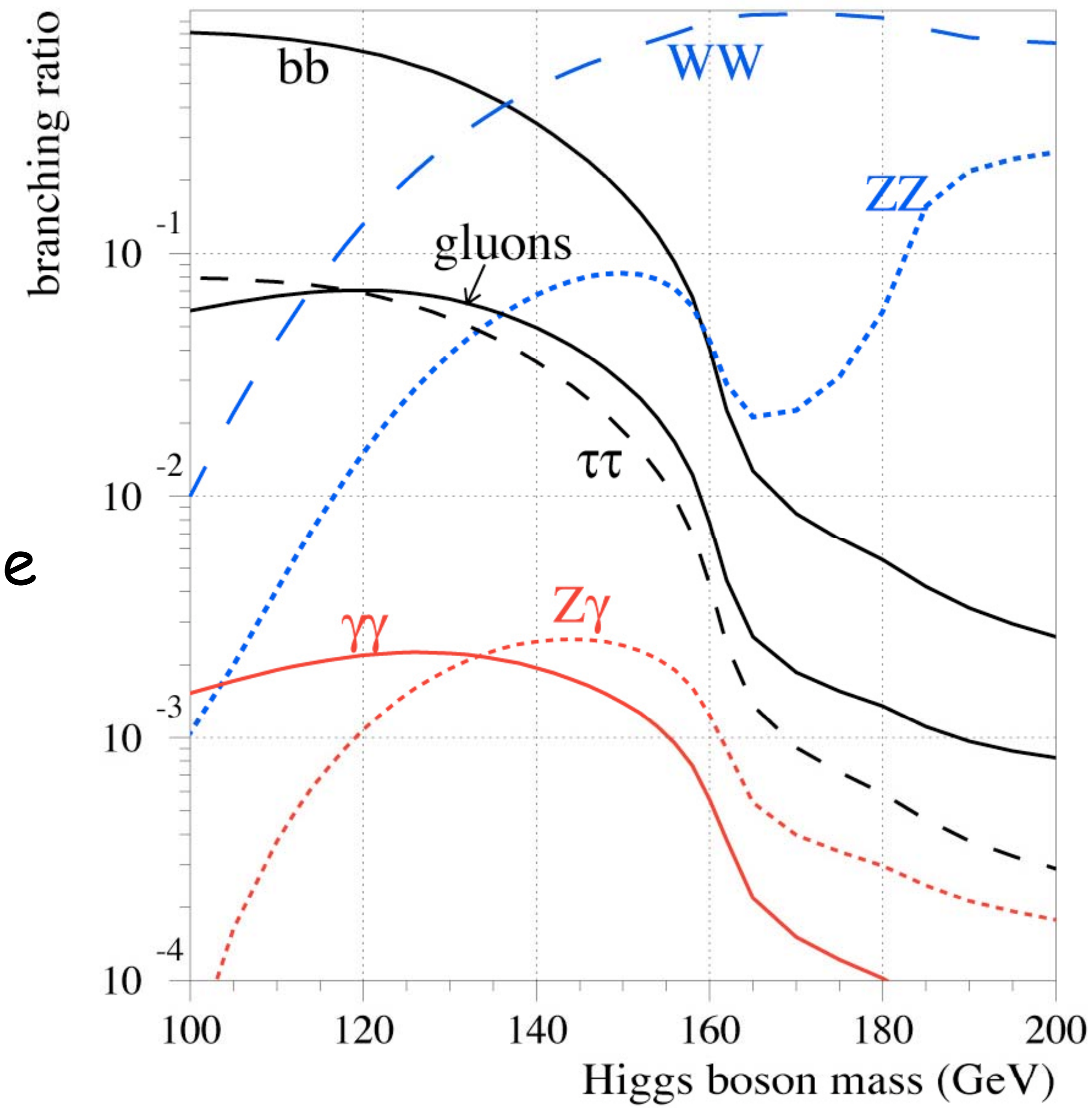


M_H=115 GeV σ=52 pb

M_H=200 GeV σ= 20 pb

NLO differs from LO by up to 2x

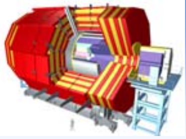
Light Higgs decays



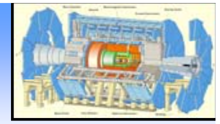
Log scale

No obvious clean channel for M_h<130 GeV

BR(WW)=98% at ~160 GeV



Higgs signatures at LHC



Higgs couples to heavy particles:

H->ZZ->4l Golden channel

120 <m_H<700 GeV

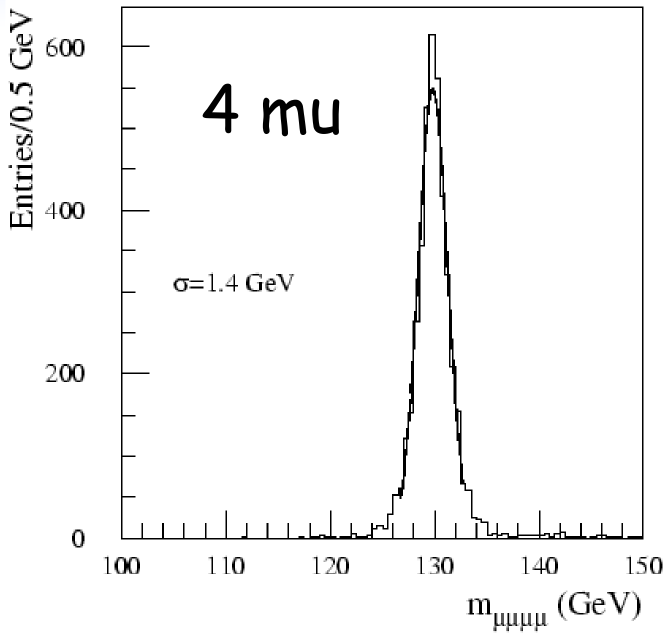
H->ZZ->ll$\nu\nu$ m_H > 700 GeV

H->bb m_H <160 GeV

H->$\gamma\gamma$ m_H <150 GeV

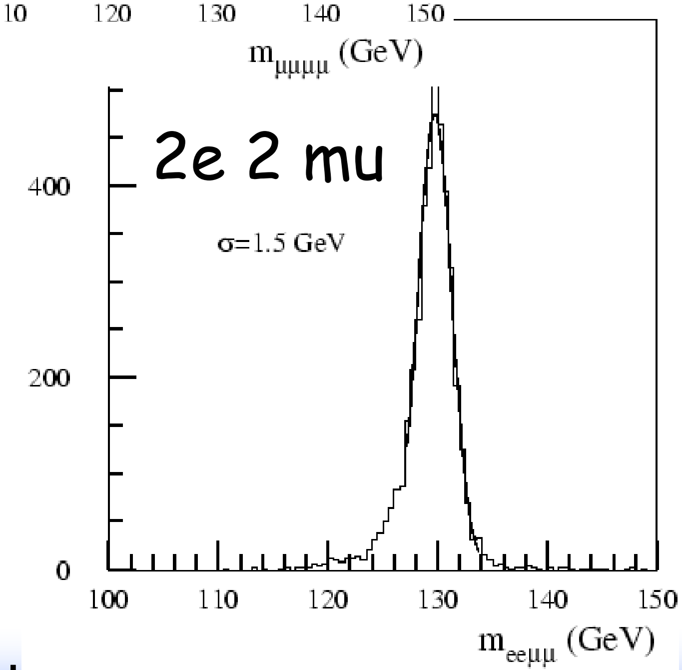
- LEP limit m_H > 114 GeV
- m_H <1 TeV from theory
- Need to detect high leptons (electrons and muons)
- Need to detect missing energy from ν's
- Need to find b jets using short lifetime (1.6ps, ct=0.5mm)
- Need to detect narrow resonance in $\gamma\gamma$ on large background

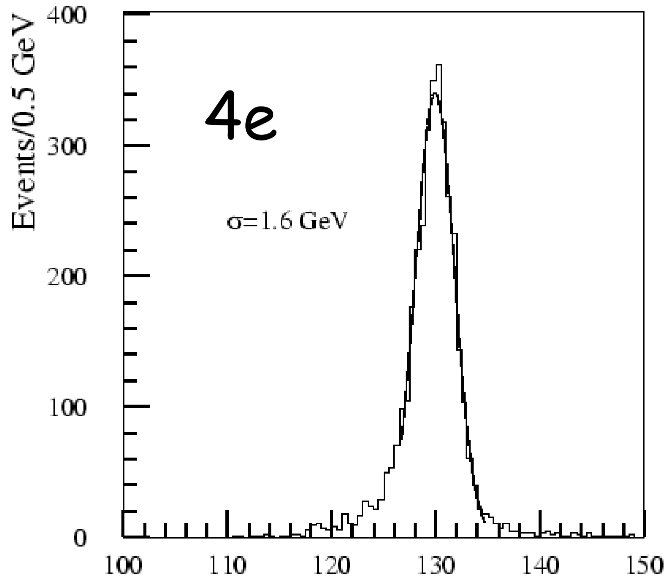
H-> 4 leptons



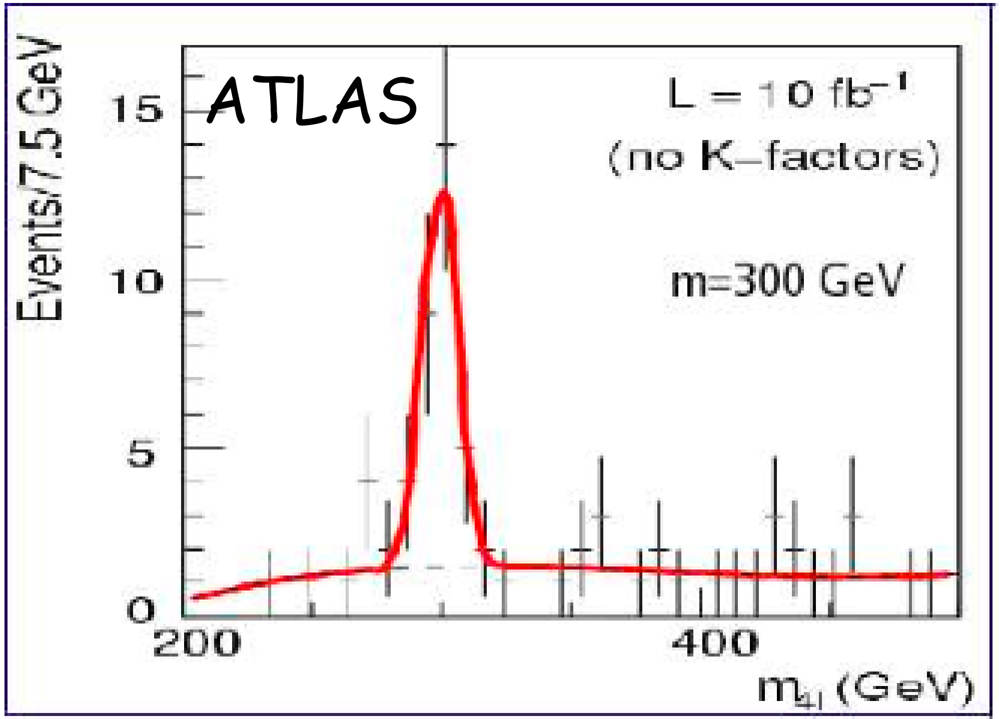
Higgs mass reconstructed in 4 lepton channels

Potentially excellent resolution. Note brem tail for e's





H->4l background

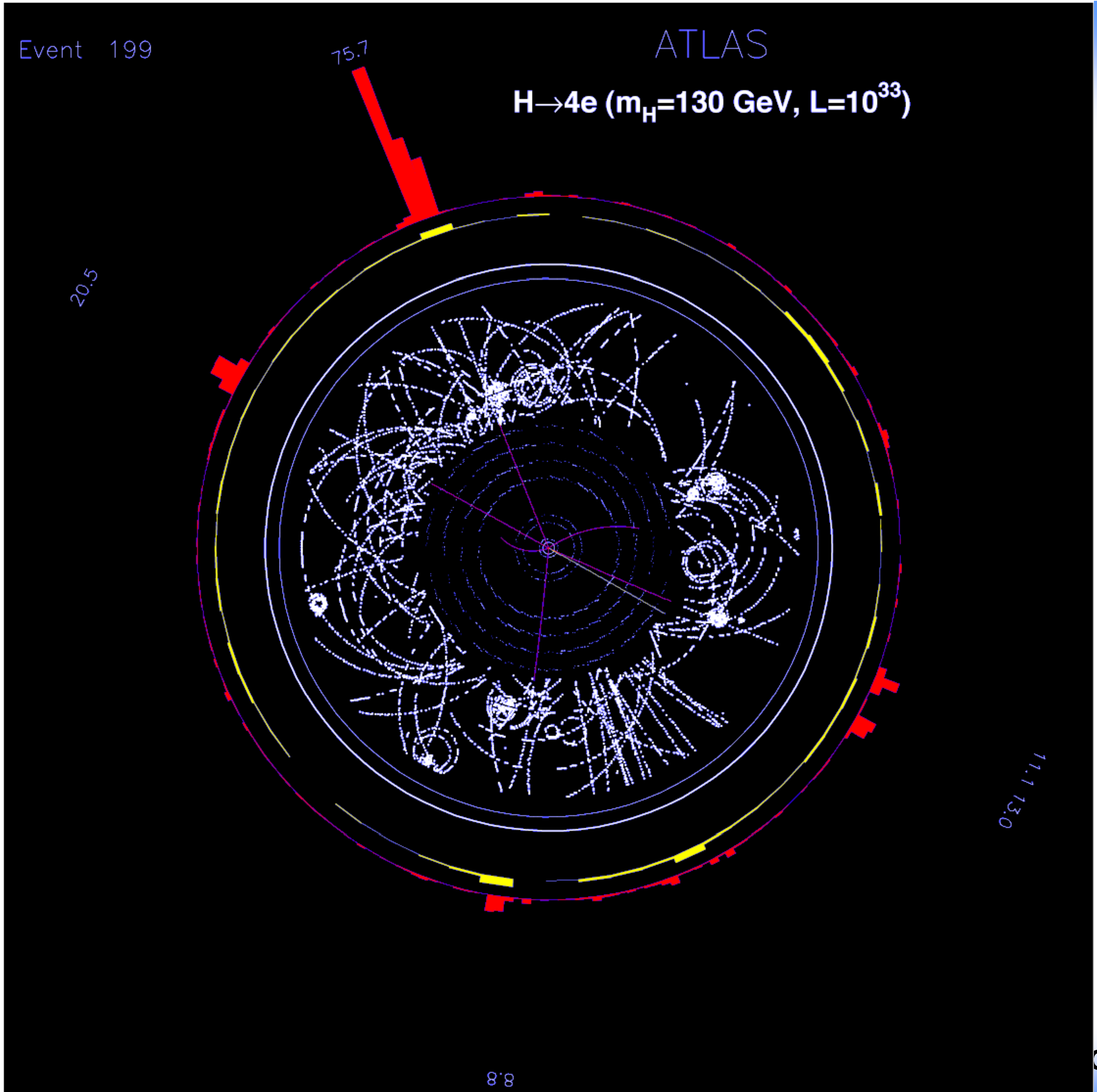


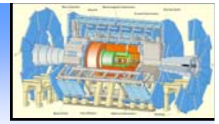
Irreducible background from ZZ*

Other backgrounds from t tbar and Z b bbar

Background level is low, and can be estimated from sidebands, with error dominated by statistics.

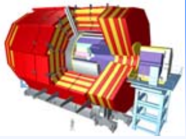
Selection efficiency is not as high as might expect.



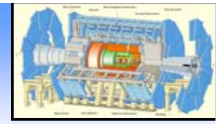


H -> 4e event. One electron emits high energy photon in beam pipe. Only electron tracks shown in ID.

(L=10^{33} cm^{-2} s^{-1})



CMS results M_h=140 GeV



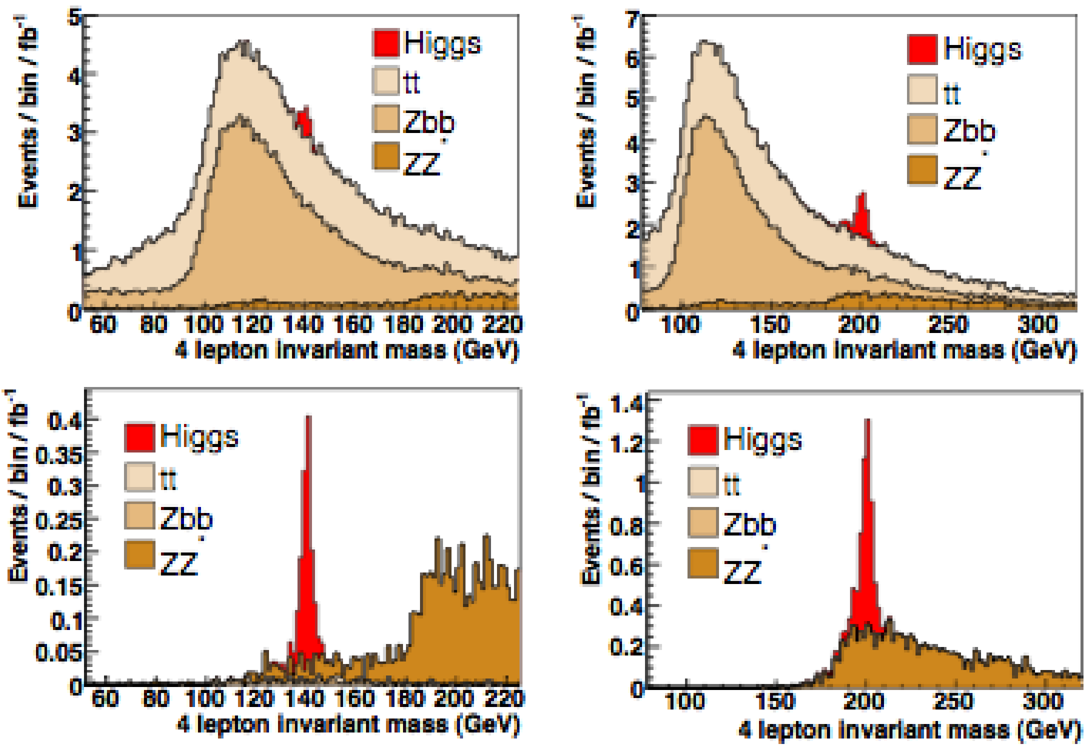
- **CMS TDR signal and background 4 lepton final state**
- **12 signal, 2 background expected with 10 fb^{-1}. Cuts lose 90% of signal.**
  Preselection: electrons pT>5 GeV, η<2.5, muons pT>3 GeV, η<2.4

Table 10.3: Production cross-section (NLO), cross-section times branching ratio, cross-section times branching ratio times pre-selection efficiency and cross-section times branching ratio times efficiency after each stage of the online and offline event selection, for m_H=140 GeV/c^2, for signal and backgrounds. All values in fb, except for expected number of events. Uncertainties are statistical only.

	Signal	$t\bar{t}$	$Zb\bar{b}$	ZZ^*/γ^*
Production cross-section (NLO)	33.6×10^3	840×10^3	555×10^3	28.9×10^3
$\sigma\times$BR(4 lepton final state)	11.6	-	-	367.5
Pre-selection: $\sigma\times\mathrm{BR}\times\epsilon$	3.29±0.04	743±2	390±1	37.0±0.4
Level-1 trigger	3.24±0.04	707±2	360±1	36.3±0.4
High Level trigger	2.91±0.03	282±1	237±1	32.5±0.4
$e^+e^-\mu^+\mu^-$ reconstructed	2.23±0.03	130±1	141±1	24.1±0.3
Vertex and impact parameter cuts	2.01±0.03	18.9±0.3	18.4±0.2	21.5±0.3
Isolation cuts	1.83±0.03	1.34±0.07	5.8±0.1	20.0±0.3
Lepton p_T cuts	1.61±0.03	0.40±0.04	0.56±0.03	17.6±0.3
Z mass window cuts	1.35±0.02	0.20±0.03	0.23±0.02	13.8±0.3
Higgs mass window cuts	1.17±0.02	0.02±0.01	0.025±0.007	0.15±0.03
Expected events for $\int\mathcal{L}=10\ \mathrm{fb}^{-1}$	11.7±0.2	0.2±0.1	0.25±0.07	1.5±0.3

CMS Higgs selection

M_H=140 GeV M_H=200 GeV



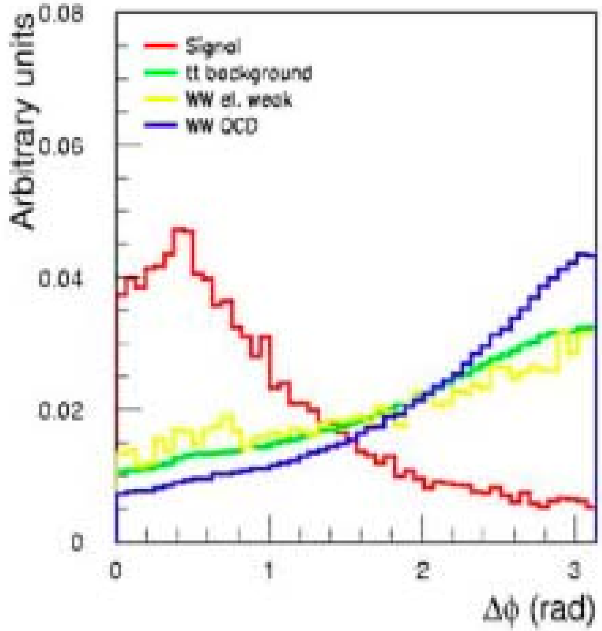
Before selection

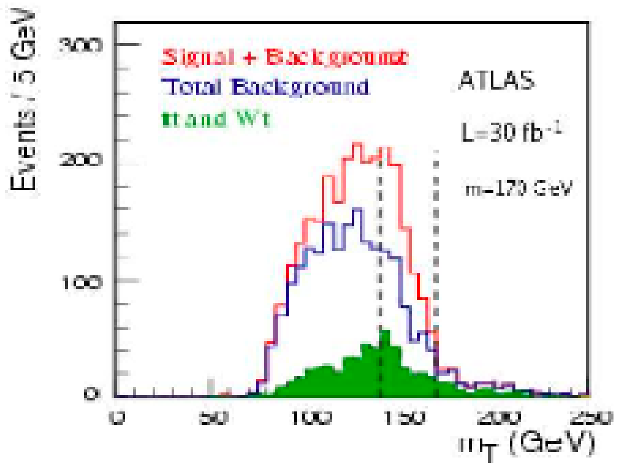
After selection

Figure 10.6: Invariant mass of the four reconstructed leptons before (top) and after (bottom) the application of the offline selection, for signal events for $m_H = 140\,\mathrm{GeV}/c^2$ (left) and $m_H = 200\,\mathrm{GeV}/c^2$ (right), and for the three background processes.

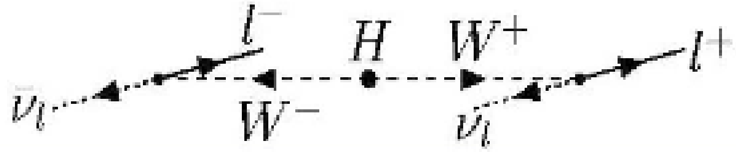
H-> WW

ATLAS





Valuable additional channel at 2 M_W

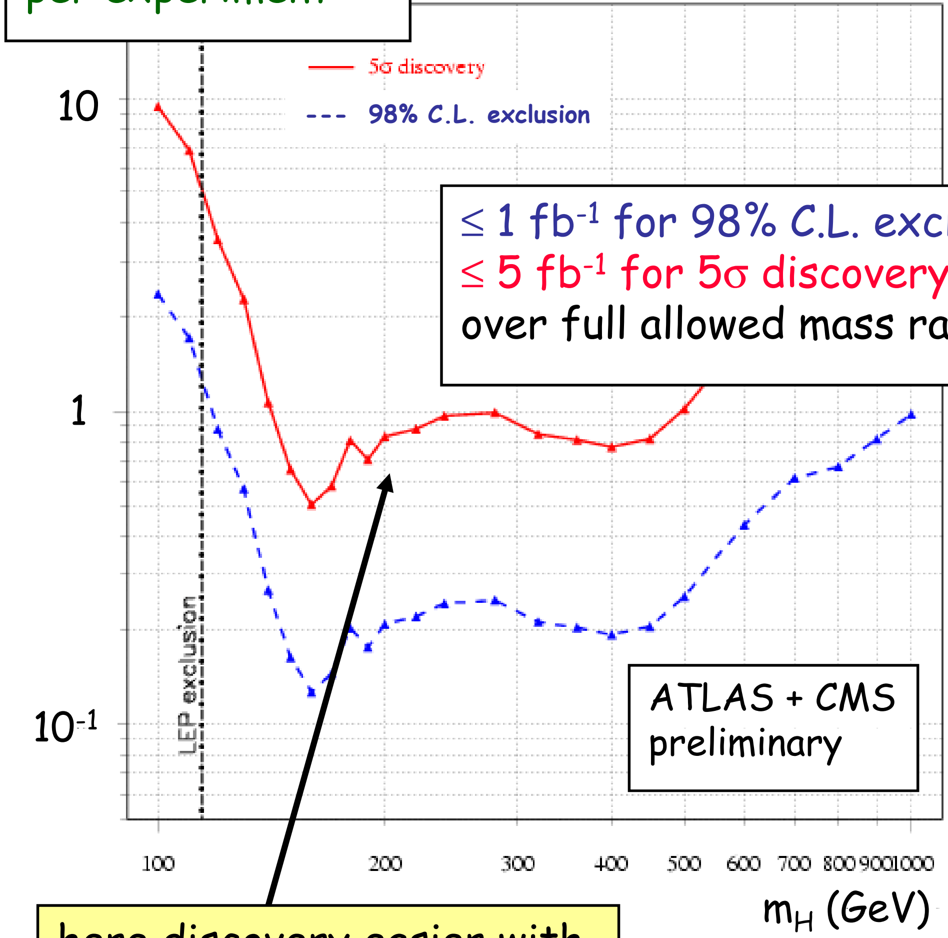


Parity violation creates correlation between leptons -> use to reject tt, WW, WZ backgrounds.

Signal found in transverse mass plot - no mass peak

SM Higgs

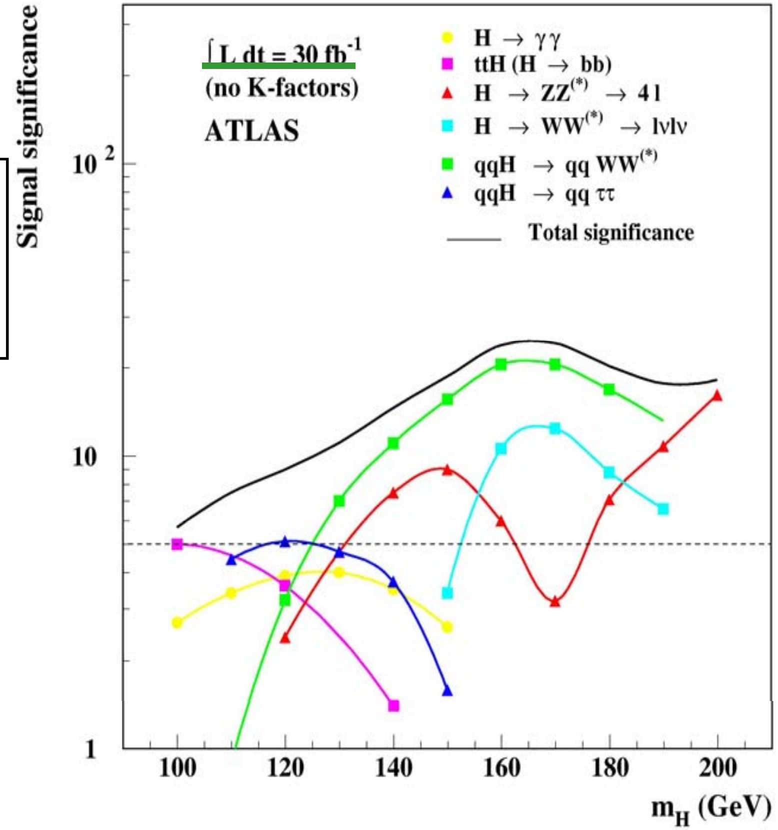
Needed ∫Ldt (fb^{-1}) per experiment



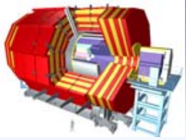
≤ 1 fb^{-1} for 98% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery
over full allowed mass range

ATLAS + CMS preliminary

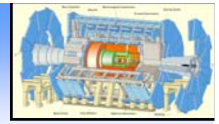
here discovery easier with gold-plated H → ZZ → 4l
→ **in first year ?**



H → 4l : narrow mass peak, small background
H → WW → lνlν (dominant at the Tevatron): counting channel (no mass peak)



Light Higgs

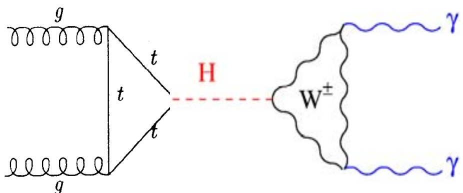


More difficult ....

m_H ~ 115 GeV 10 fb^{-1} : $S/\sqrt{B} \approx 4$ ATLAS

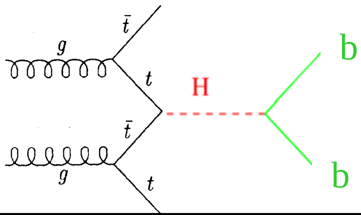
3 (complementary) channels with similar (small) significances:

$H \rightarrow \gamma\gamma$



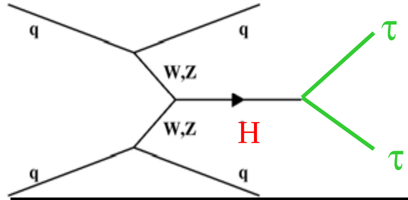
S=130, B=4300, $S/\sqrt{B}$=2

$ttH \rightarrow ttbb \rightarrow bl\nu bjjbb$



S=15, B=45, $S/\sqrt{B}$=2.2

$qqH \rightarrow qq\tau\tau$



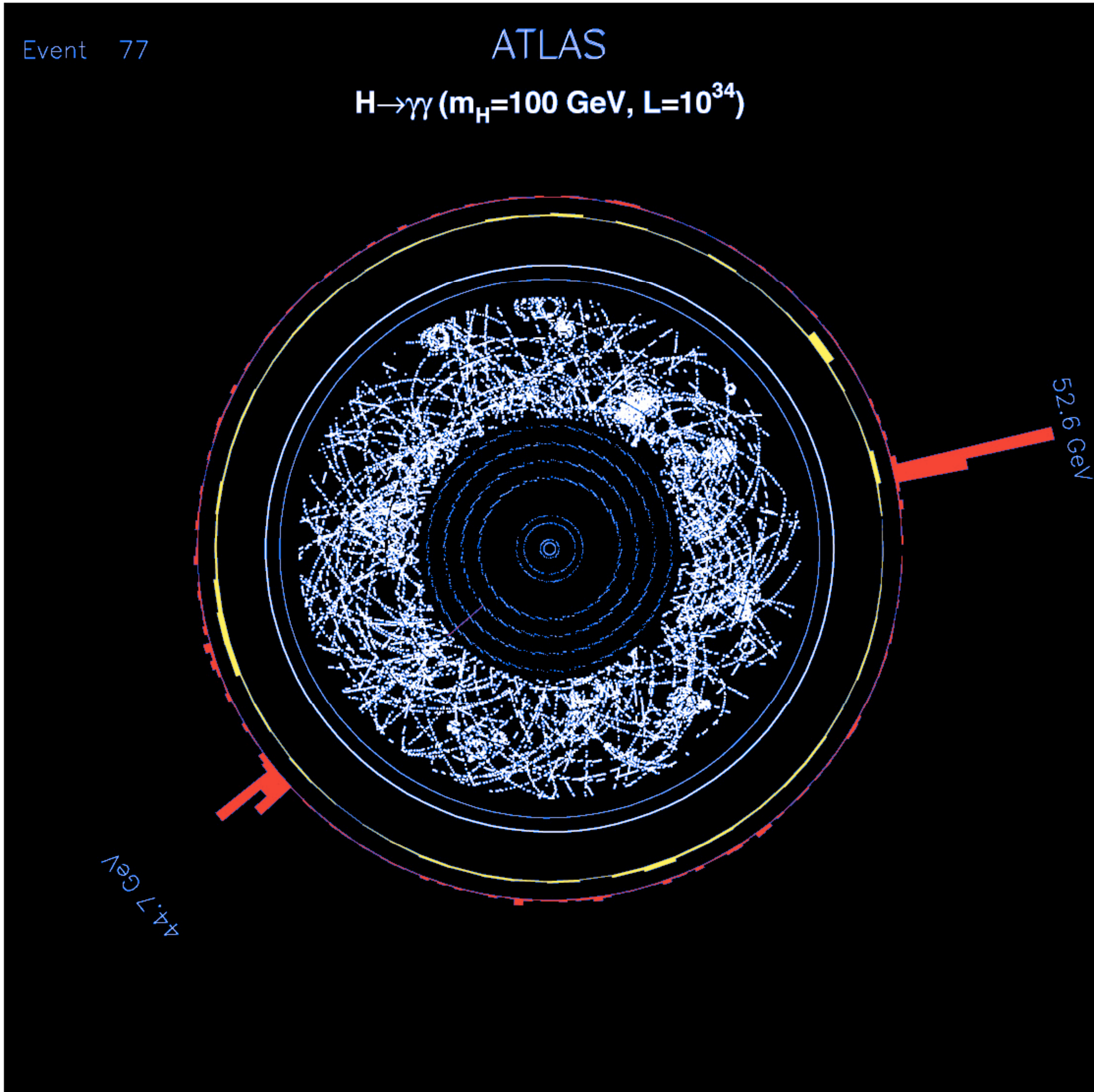
S=10, B=10, $S/\sqrt{B}$=2.7

- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - -- ECAL crucial for $H \rightarrow \gamma\gamma$ (in particular response uniformity) : σ/m ~ 1% needed
  - -- b-tagging crucial for ttH : 4 b-tagged jets needed to reduce combinatorics
  - -- efficient jet reconstruction over $|\eta| < 5$ crucial for $qqH \rightarrow qq\tau\tau$: forward jet tag and central jet veto needed against background

K-factors ≡ σ(NLO)/σ(LO) ≈ 2
for $H \rightarrow \gamma\gamma$ NOT included (conservative)

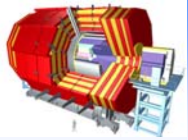
All three channels require very good understanding of detector performance and background control to 1-10% → convincing evidence likely to come later than 2008 ...

Note: WH→ lνbb (dominant at the Tevatron) provides less sensitivity than ttH at LHC



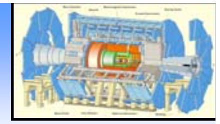
H -> γγ event. One photon converts to e^+e^- in ID material. Note high number of low momentum tracks

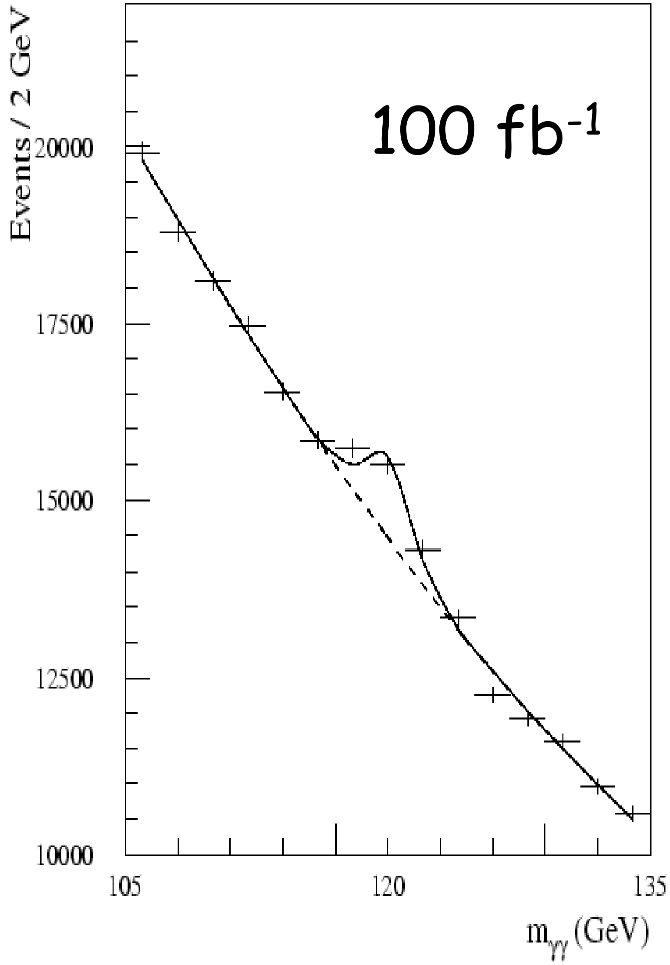
($L=10^{34}$ cm^{-2} s^{-1})

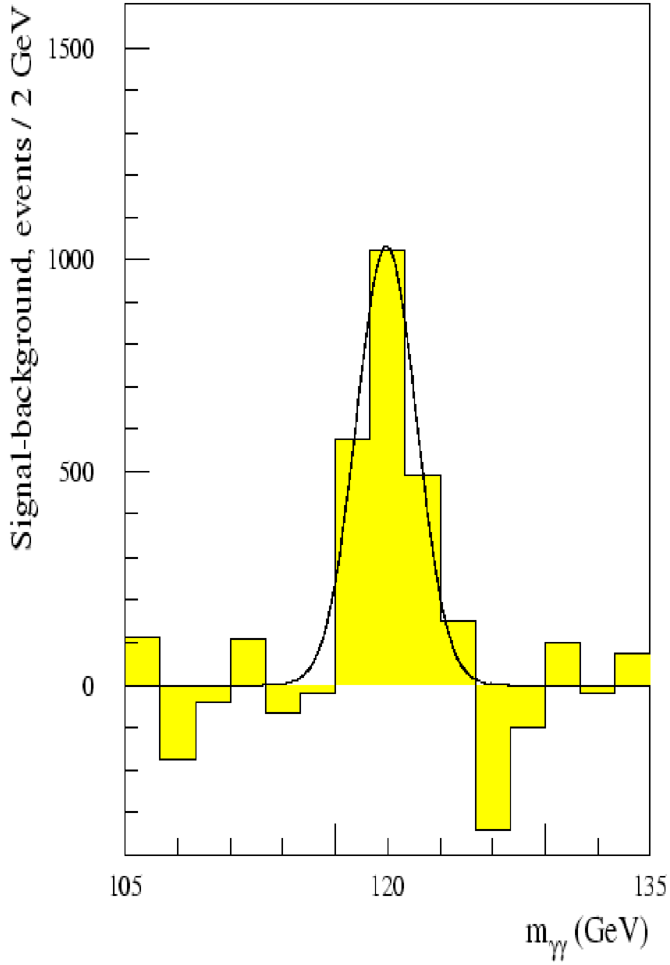


ATLAS TDR

H-> $\gamma\gamma$



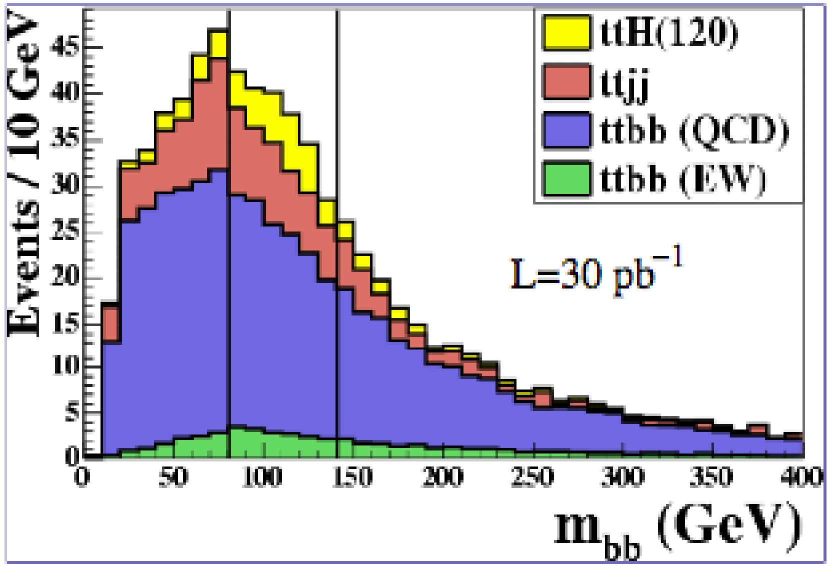




Extremely challenging for EM calo resolution and uniformity. Need $\sigma(m)/m \sim 1\%$ to see peak

Real $\gamma\gamma$ background 125 fb/GeV. Also fakes from jets.
$\sigma(\gamma j)$ = 800x $\sigma(\gamma\gamma)$ and $\sigma(jj)$ = 2x10^6x $\sigma(\gamma\gamma)$

ttH->bb



$$t \to \ell \nu b$$

$$\bar{t} \to jj\bar{b}$$

$$H \to b\bar{b}$$

6 jets, lepton and missing energy

Direct H->bb impossible because of QCD background.

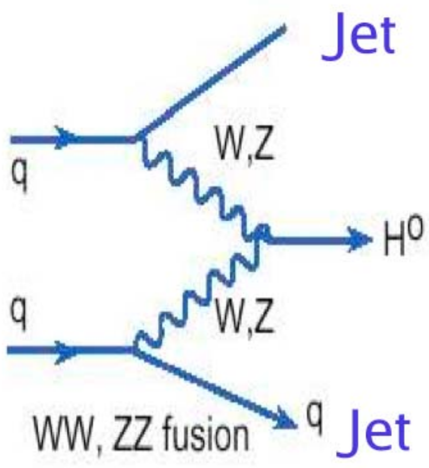
Use associated production with ttbar to suppress backgrounds.

Trigger on lepton from top decay.

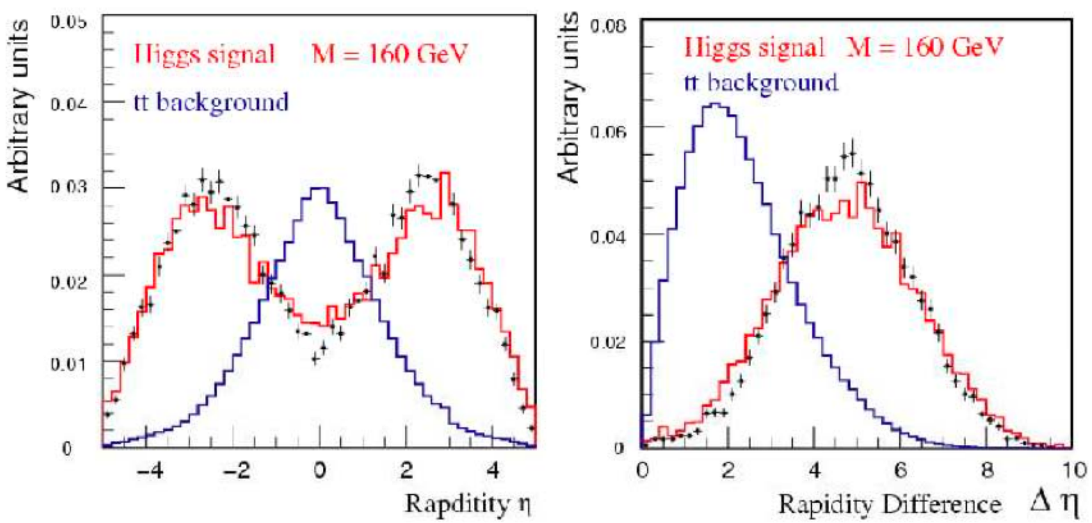
Physics background from QCD non-resonant ttbb and ttjj

Very challenging channel - not for first physics

Vector boson fusion



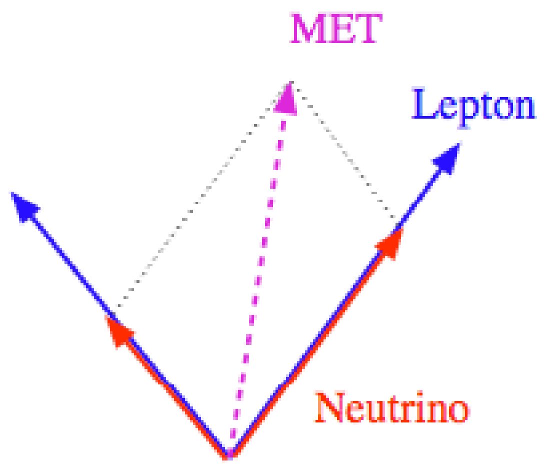
VBF process gives two "tag" jets at high rapidity. Allows background suppression and access to H-> WW and ττ modes.



J1 > 40 GeV
J2 > 20 GeV
$\Delta\eta > 3.8$
No central jet

H in η gap

VBF H-> ττ



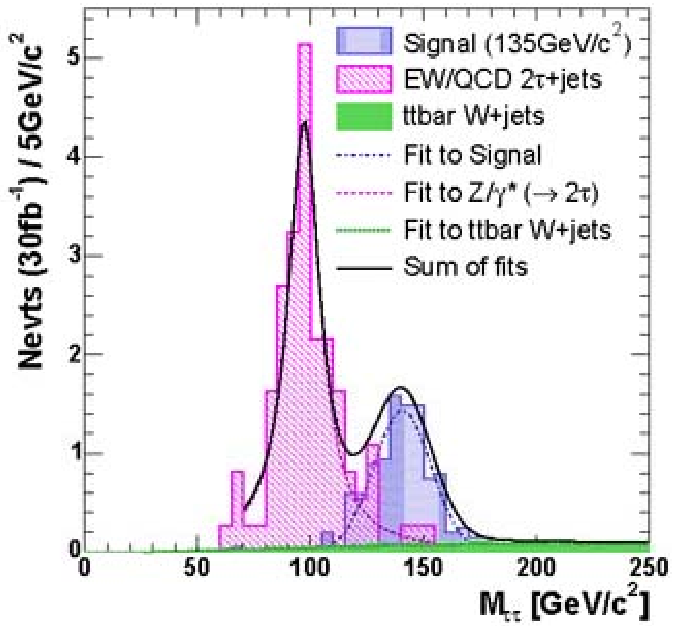
ν and visible decay products ~colinear for fast τ

Use missing pT to infer mass.

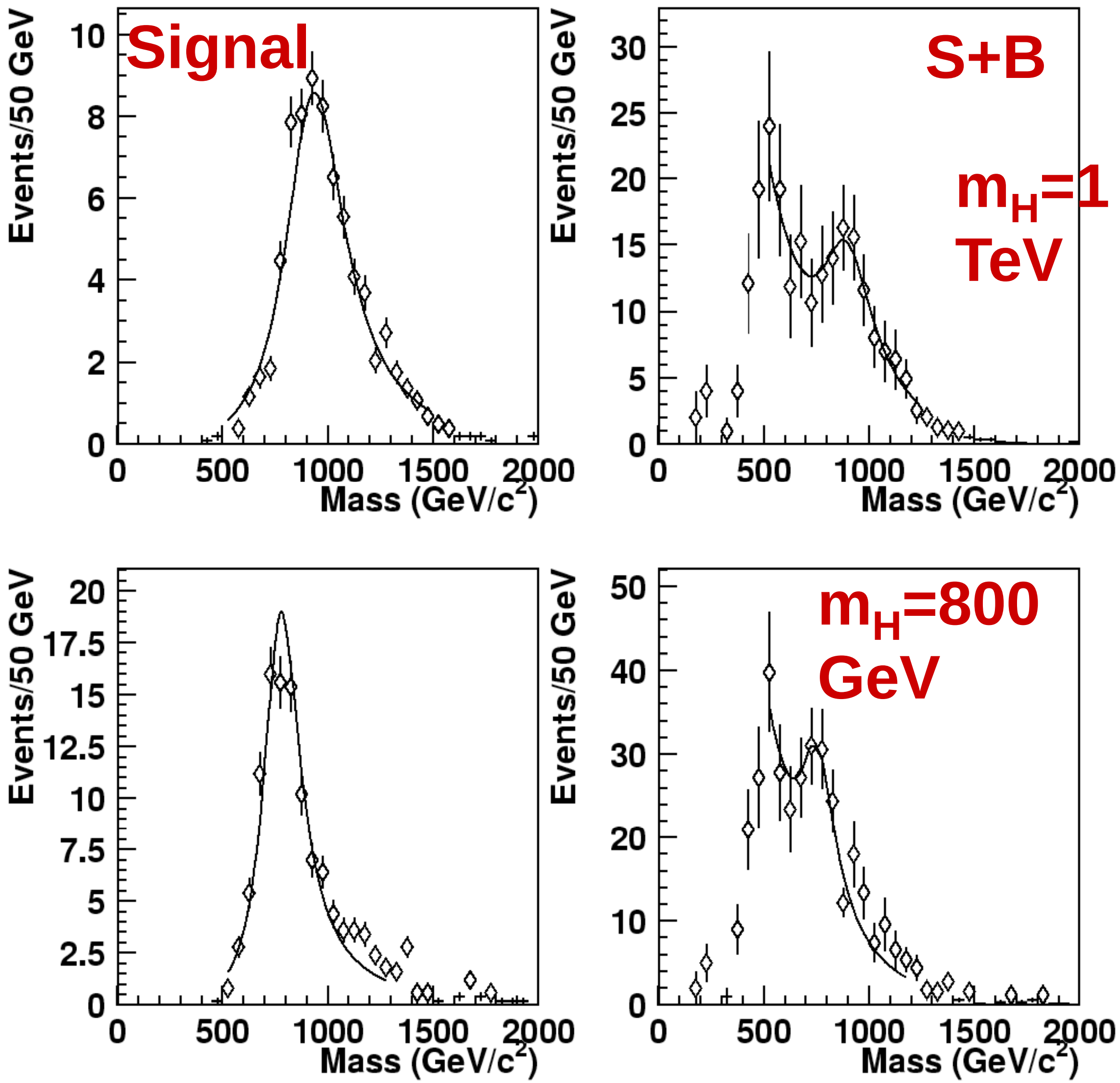
Dominant background from 2τ+jets (QCD and EW processes)

CMS 30 fb^{-1}

Selection	cross section, σ [fb] (% from previous cut)				
	signal	background			
	M_H=135	EW 2τ+2j	QCD $\tau\tau$+2/3j	W+3/4j	tt →WbWb
Starting σ	82.38	299.	1615.	14.45×10^3	86×10^3
Level-1	46.50 (56.5)	179.8 (60.1)	543.8 (33.7)	9186. (63.6)	71.39×10^3 (83.0)
L1+HLT	24.60 (52.9)	58.81 (32.7)	201.3 (37.0)	6610. (71.9)	55.42×10^3 (77.6)
lepton ID	23.34 (94.9)	50.67 (86.2)	187.4 (93.1)	6549. (99.1)	54.08×10^3 (97.6)
lepton p_T	23.16 (99.3)	49.13 (97.0)	185.6 (99.0)	6543. (99.9)	53.54×10^3 (99.0)
τ-jet ID	8.276 (35.7)	10.49 (21.3)	39.64 (21.4)	(0.21)	5.056×10^3 (9.4)
τ-jet p_T	6.422 (77.6)	7.360 (70.2)	24.25 (61.2)	-	3.215×10^3 (63.6)
Valid mass	4.461 (69.5)	4.232 (57.5)	14.49 (59.8)	(17.4)	848.6 (26.4)
VBF cuts	0.545 (12.2)	0.391 (9.2)	1.666 (11.5)	(11.0)	2.738 (0.3)
M_T(lep,E_T^{miss})	0.423 (77.6)	0.322 (82.4)	1.382 (83.0)	(30.5)	0.942 (34.4)
Central Jet Veto	0.344 (81.3)	0.230 (71.4)	0.555 (39.7)	(28.9)	0.224 (23.8)
N events at 30 fb^{-1}	10.3	6.9	16.6	1.5*	6.7

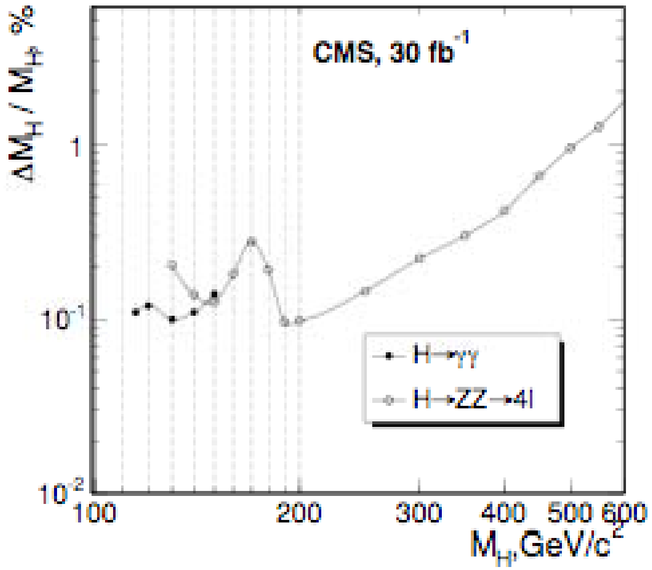


H -> WW -> $l\nu jj$ at high mass



- Good rate at high mass
- Requires excellent calorimeter coverage to measure n, and good energy resolution to resolve jet pair mass

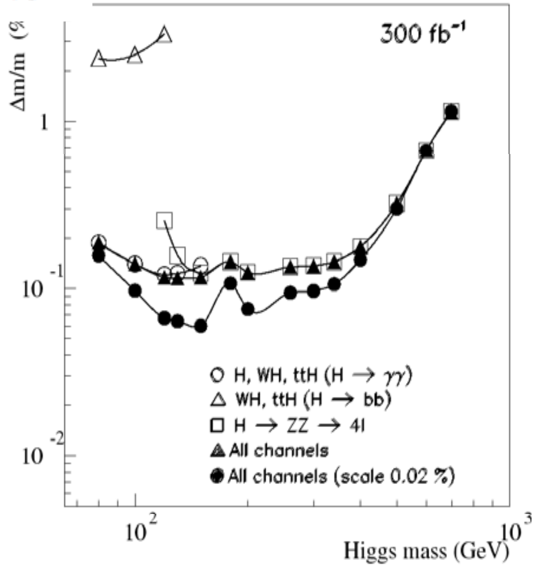
Higgs Parameters

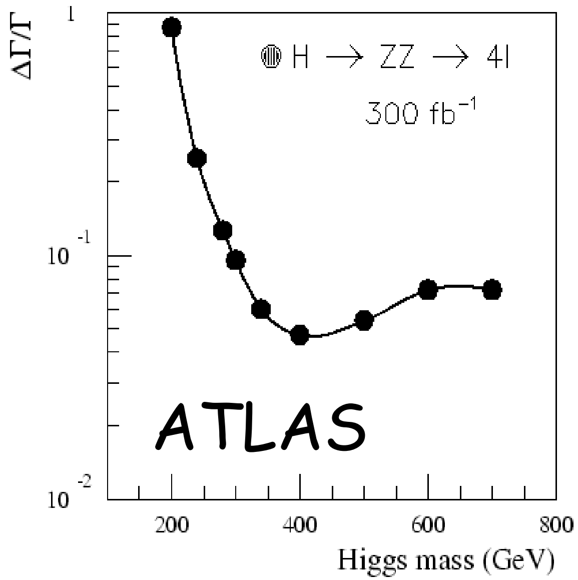


To prove state is Higgs, need to measure spin and CP as well.

- Higgs mass measured to 0.1% with 30 fb^{-1} - CMS

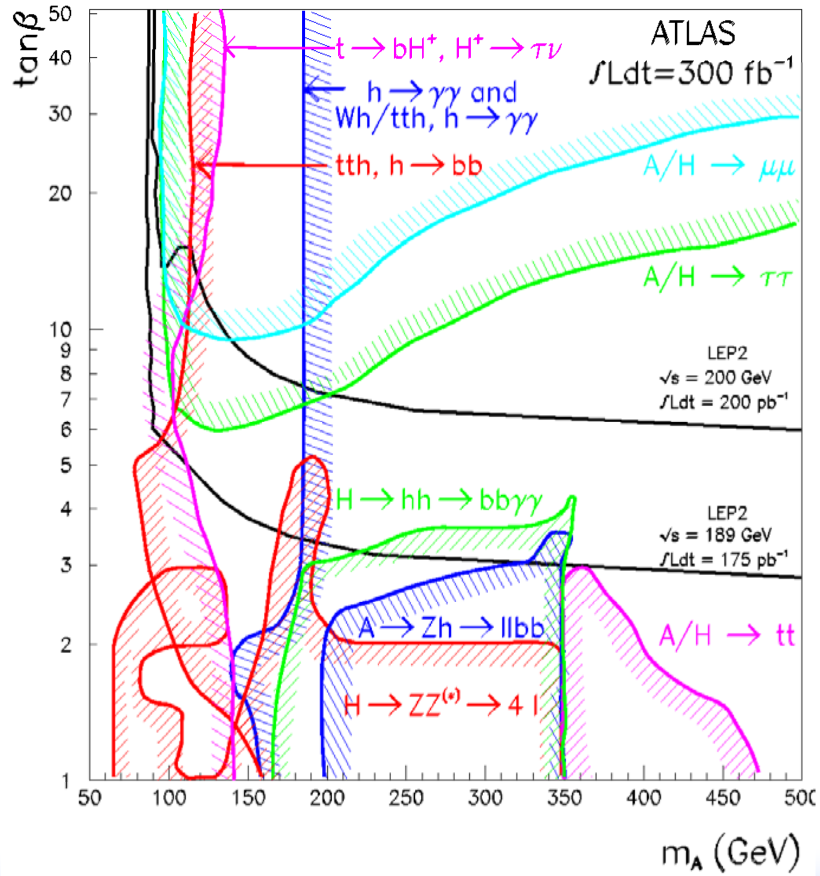
Higgs mass and width with 300 fb^{-1} - ATLAS

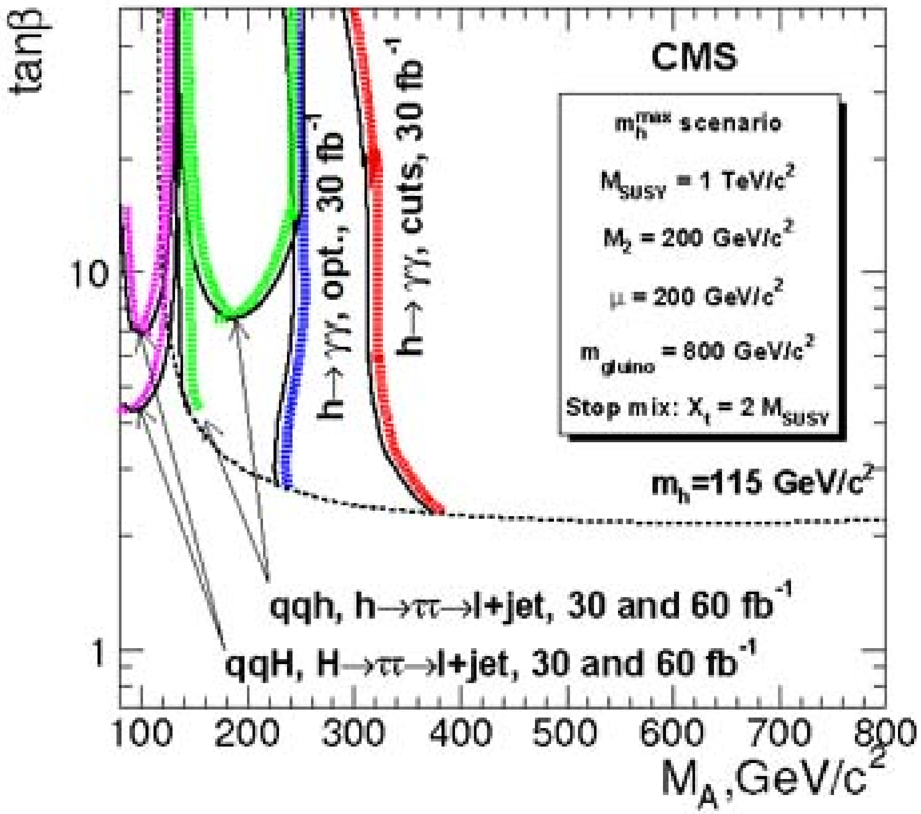




Susy higgs discovery potential

CMS Initial 5σ discovery reach

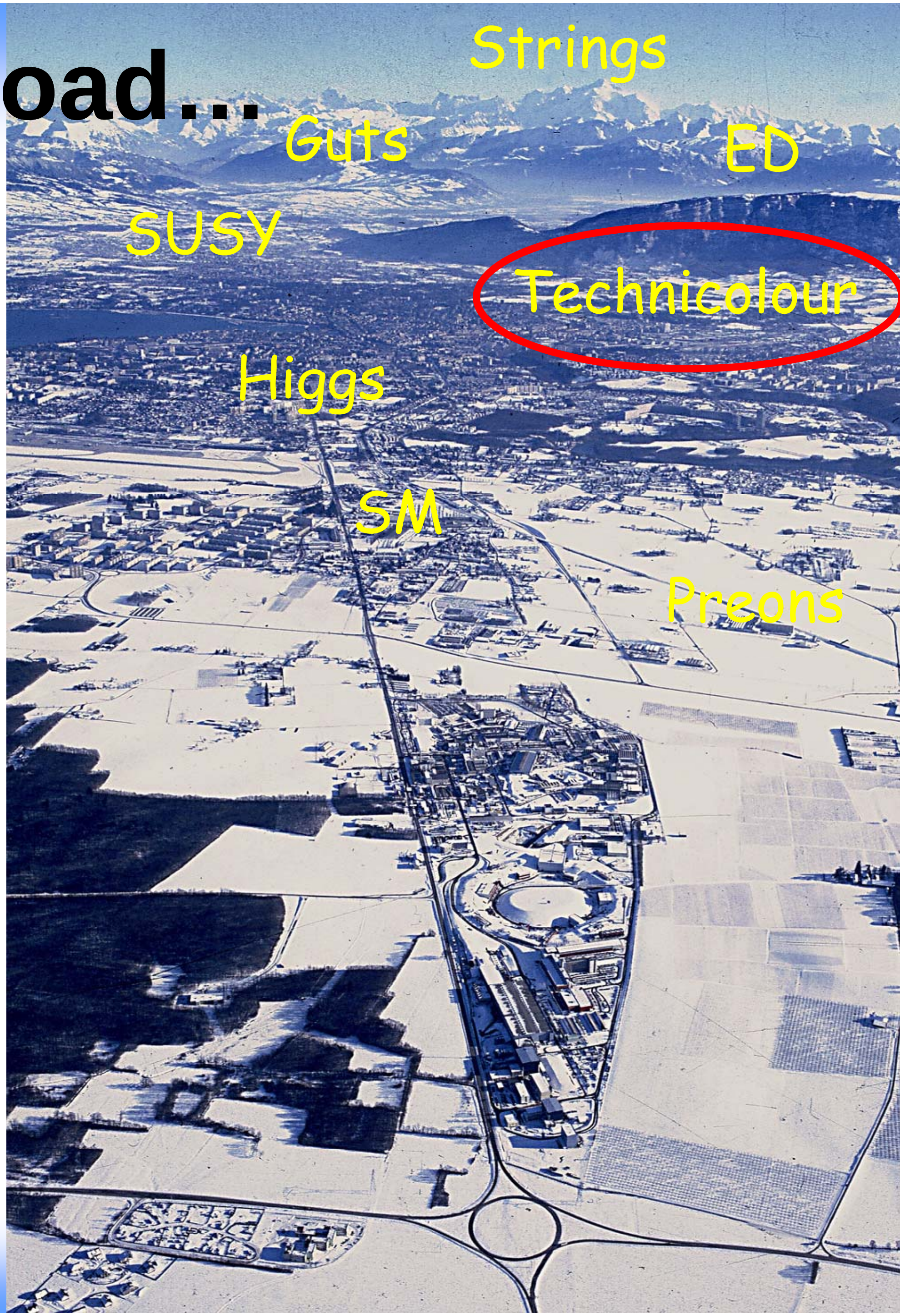


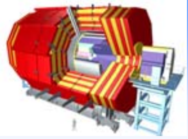


ATLAS final exclusion zones

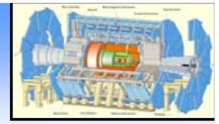
Along the road...

Another way to get massive...





Technicolour



Use new strong interaction between technifermions to break EW symmetry dynamically, at scale Λ_{TC}=weak vev =246 GeV

Technipions provide scalar to play role of Higgs boson.

Other bound states produced as resonances at LHC:

technirho - ρ_{TC}

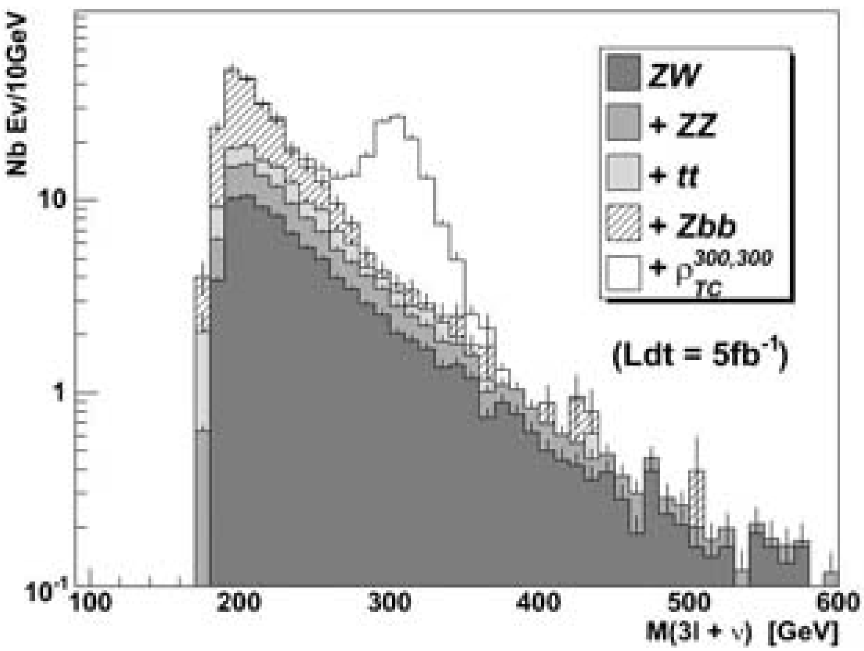
techniomega - ω_{TC}

Models have problems with FCNCs, and top mass - less popular than Higgs/SUSY - but remember problems in nuclear and strong interactions have never been solved!

Searches look for decays of these resonances.

Technicolour

CMS



Search for
ρ_{TC}-> WZ -> 3l+ν

Very clean signature, backgrounds from SM IVB processes.

5σ discovery possible with 4fb^{-1}

BACK-UP SLIDES