The Search for the Higgs Boson

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September 15, 2008

University of Stockholm
Experimental High-Energy Physics Seminar

What is the Higgs Boson?

The Standard Model

The Standard Model (SM) of Particle Physics…

- **So far extremely successful at describing nature's fundamental particles and their interactions**

3 Generations of Matter

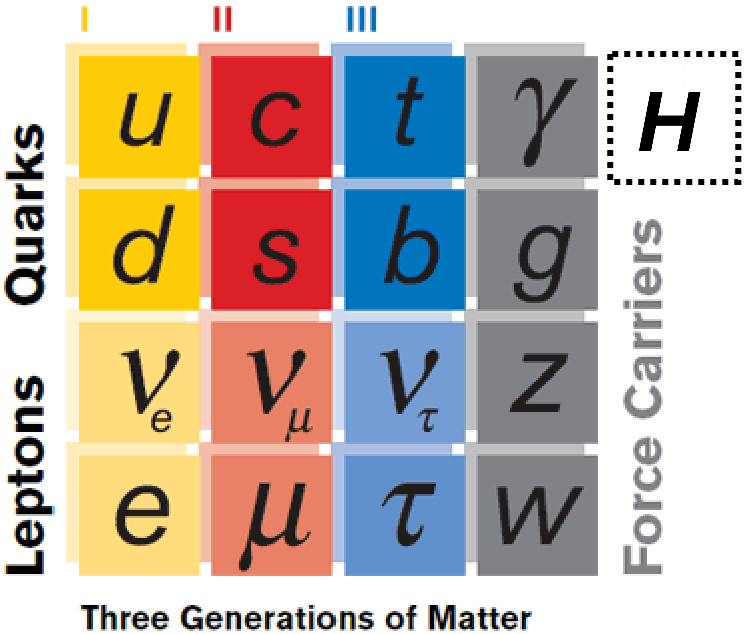
- **Quarks and Leptons**

3 Forces

- **Electromagnetic, Weak, Strong**
- **Forces carried by:** $\gamma,\, W^{\pm}/Z,\, g$

…one missing piece

- **The mechanism believed to be responsible for the origin of mass, predicts a single neutral particle.**

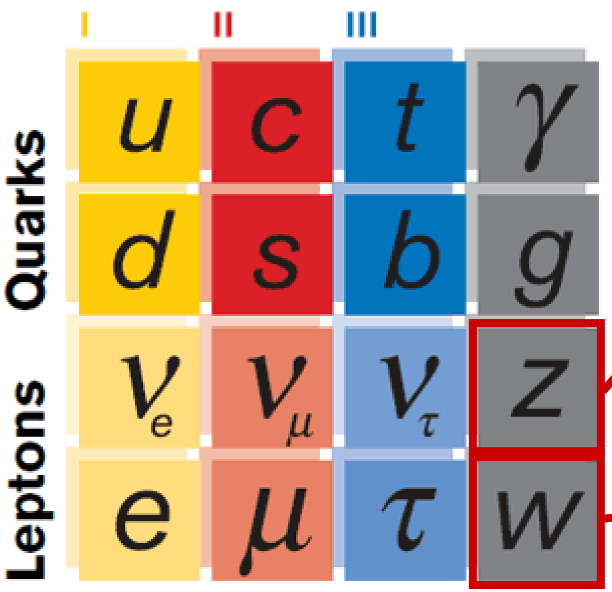


The Higgs boson has eluded experimentalists for decades

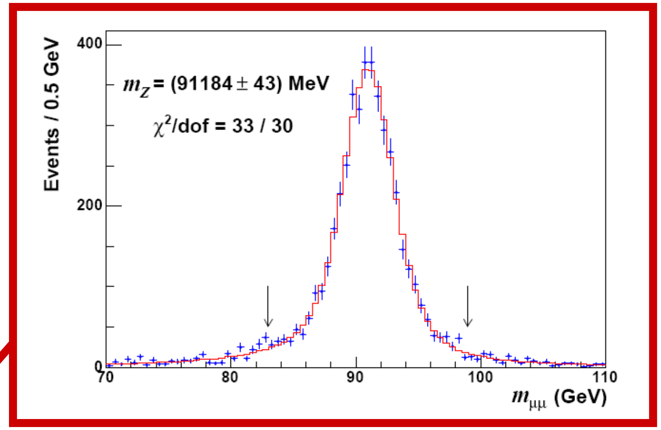
The Origin of Mass

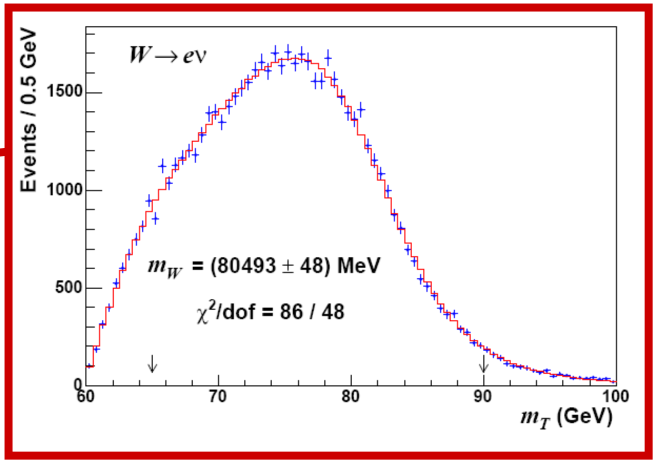
The SM says that all of the carriers of the Electromagnetic and Weak forces must have the same "symmetric" mass, of zero

- **These force carriers are the γ and $W^{\pm}/Z$, respectively**
- **We know from experiment that the Weak force carriers have a non-zero mass**
- **The symmetry is broken**



Three Generations of Matter





Discovered by the UA1 and UA2 Experiments at CERN in 1983

T. Aaltonen *et al.* arXiv:0708.3642

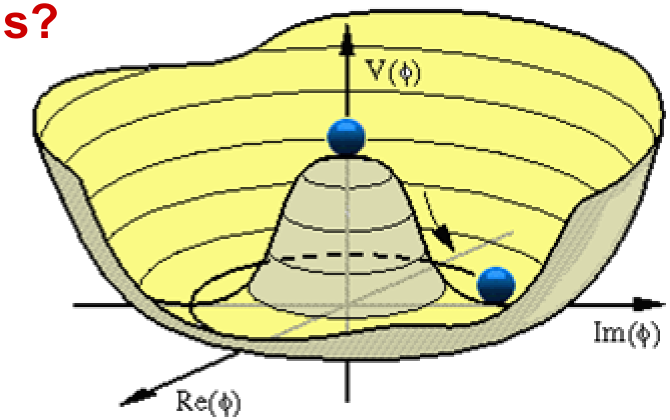
The Origin of Mass

What breaks the symmetry of the Weak Interactions?

- **In the theory, postulate a Higgs Field** ϕ
  and a potential energy function:

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

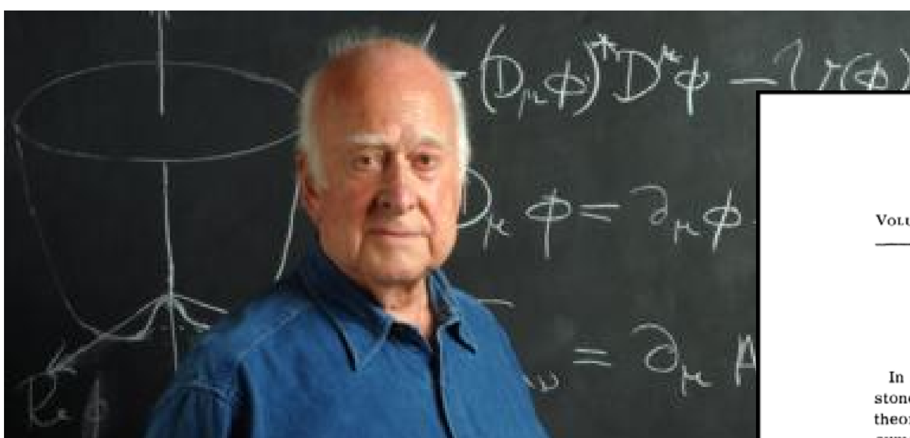
- **Assume minimum is not at** $\phi = 0$ **but,**
  some non-zero value: ϕ_0



Analogy to a ball rolling down a hill

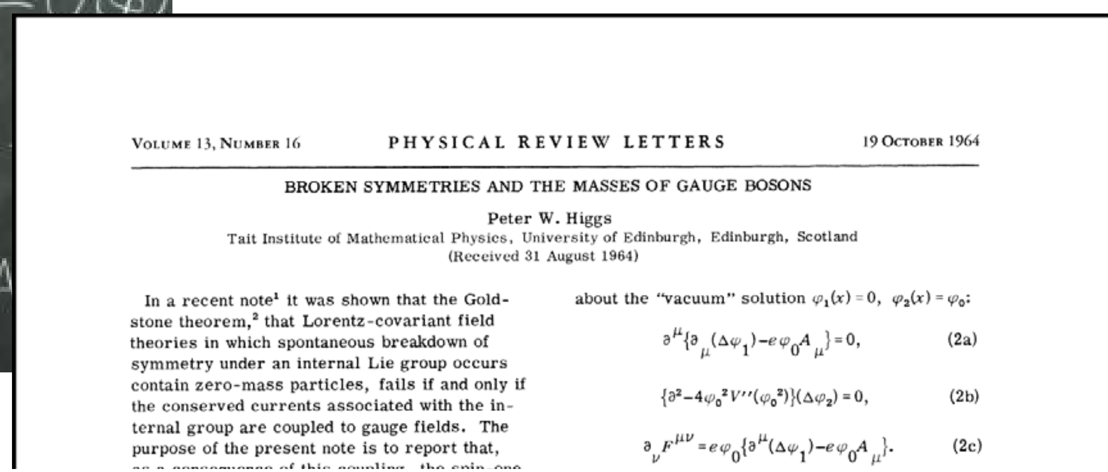
- **Direction that the ball rolled down has now been singled out from all other directions; the symmetry has been spontaneously broken**

Through the Higgs Mechanism, particles obtain an “effective mass”



Peter Higgs

1964



VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that,

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \quad (2a)$$

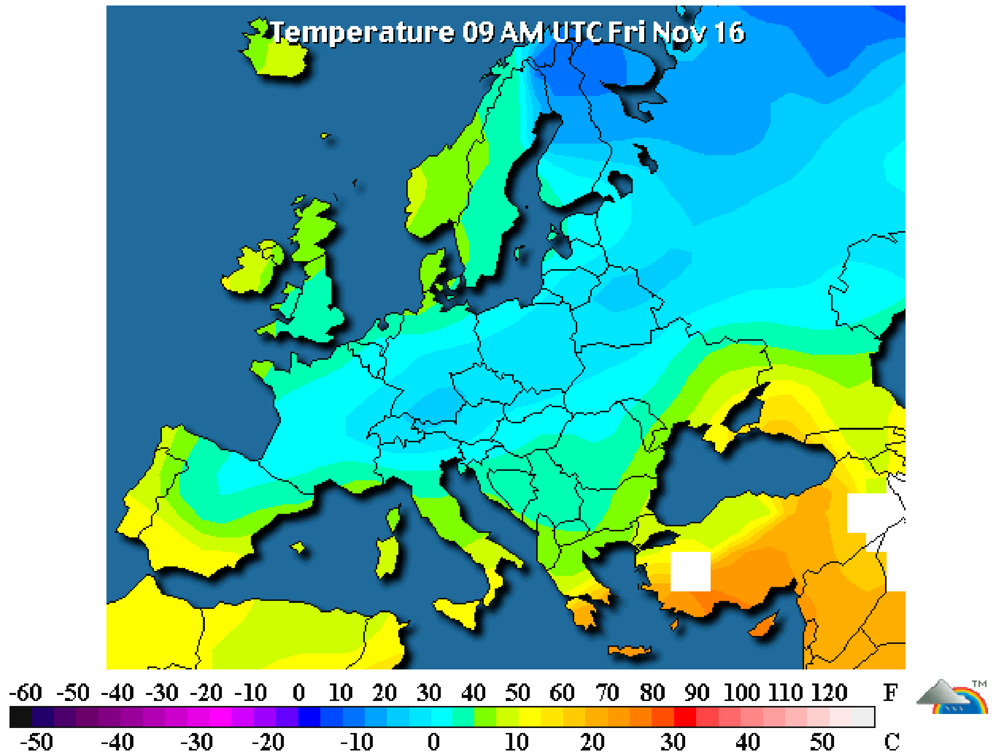
$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \quad (2b)$$

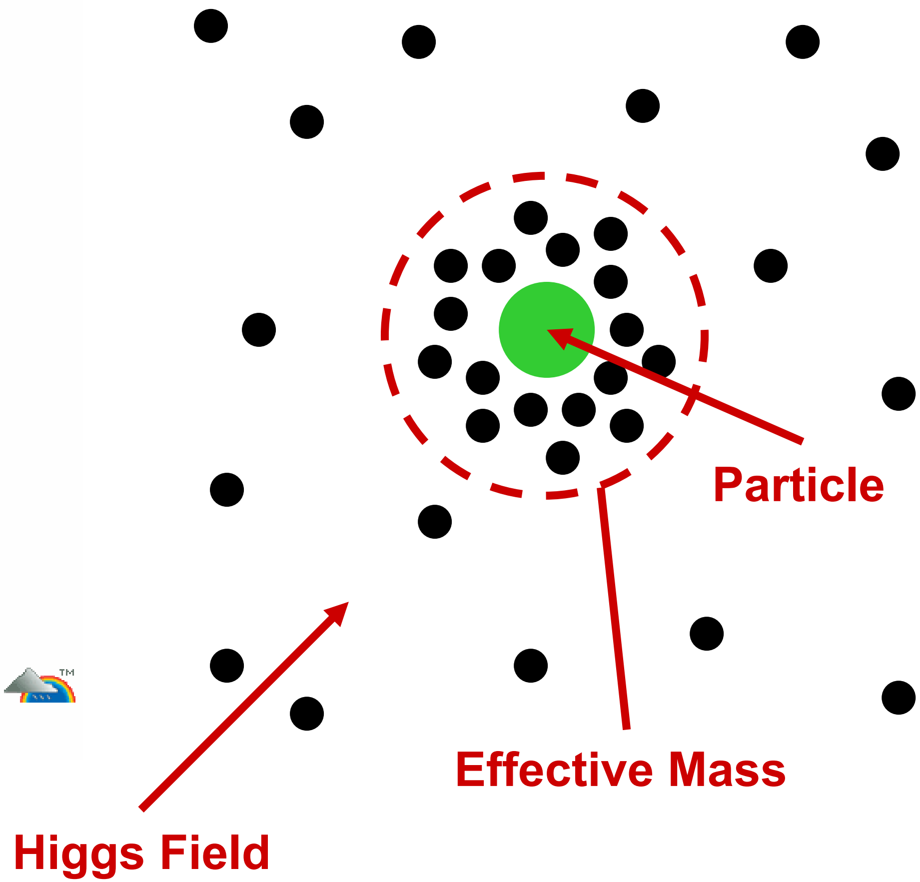
$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \quad (2c)$$

The Higgs Field

The Higgs Field is a scalar field (think of a temperature map)

- **Particles obtain an "effective mass" by interacting with the Higgs field of empty space**





What we know about the Higgs

From Theory… the exact Higgs mass is unknown

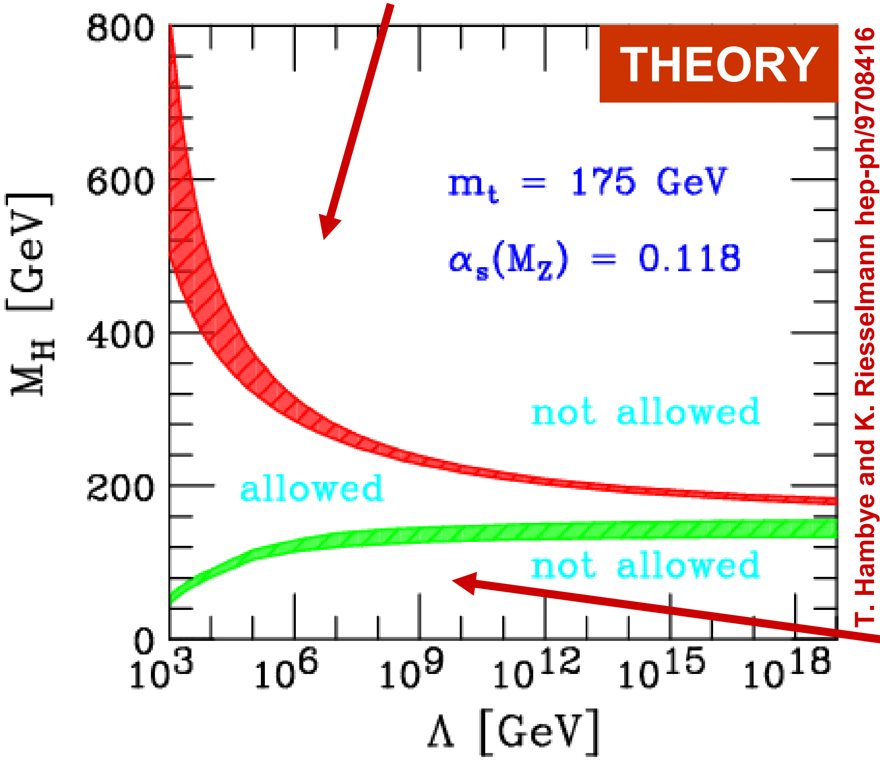
- **If SM is valid up to the Plank Scale ~10^{19} GeV then M_H is in a limited range:**

$$130\ \mathrm{GeV}/c^2 \lesssim M_H \lesssim 180\ \mathrm{GeV}/c^2$$

- **If there is new physics ~10^3 GeV:**

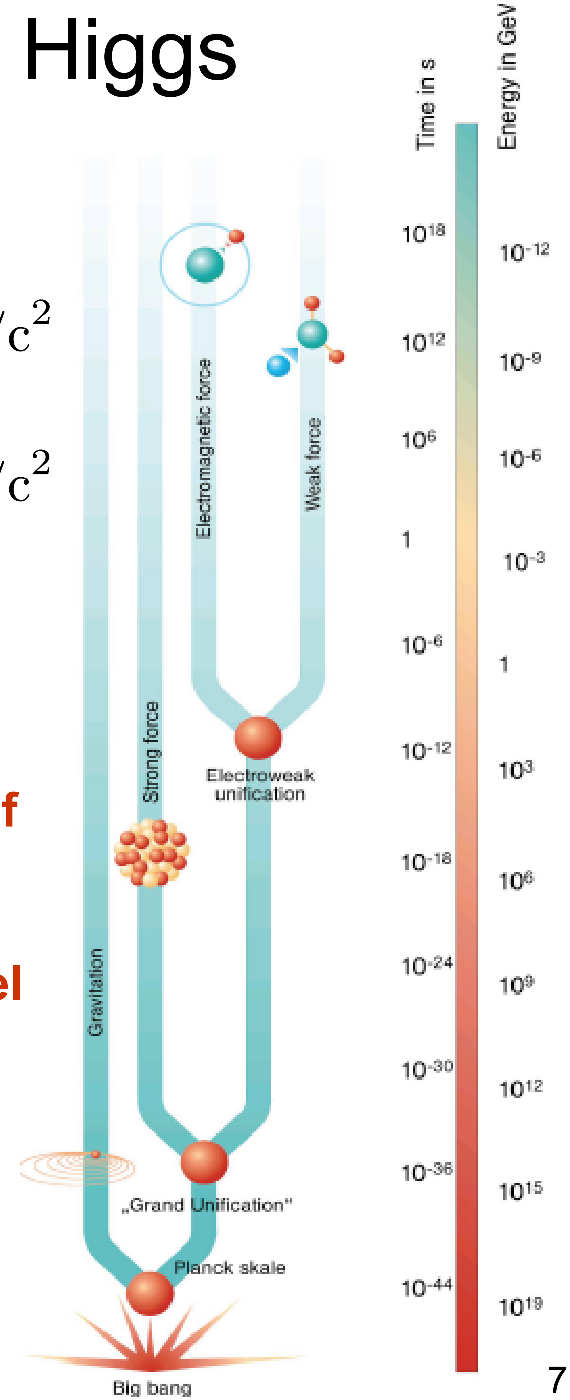
$$50\ \mathrm{GeV}/c^2 \lesssim M_H \lesssim 800\ \mathrm{GeV}/c^2$$

SM Higgs Sector no longer meaningful for this Λ



Vacuum stability

Λ is the scale of new physics beyond the Standard Model



What we know about the Higgs

From Experiments of the past…

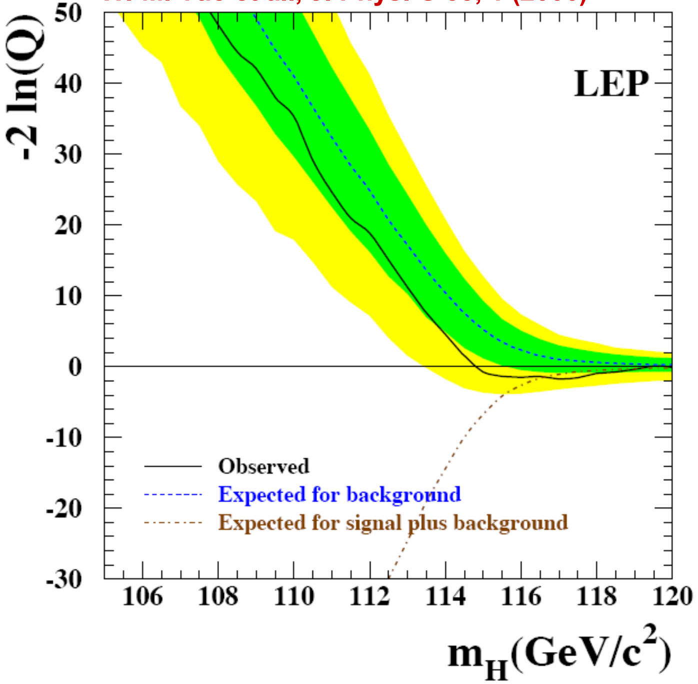
Higgs searches at the Large Electron-Positron Collider (LEP) at CERN

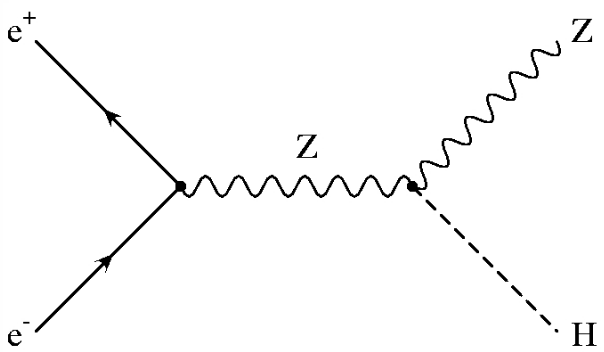
- **Collider ran from 1989 through 2000**
- **In 2000, center-of-mass energy was 200 - 210 GeV**
- **Four detectors: ALEPH, DELPHI, L3 and OPAL**

Present Limit from direct searches at LEP:

$$M_H > 114.4\ \mathrm{GeV/c^2}, \mathrm{CL} = 95\%$$

W.-M. Yao et al., J. Phys. G 33, 1 (2006)





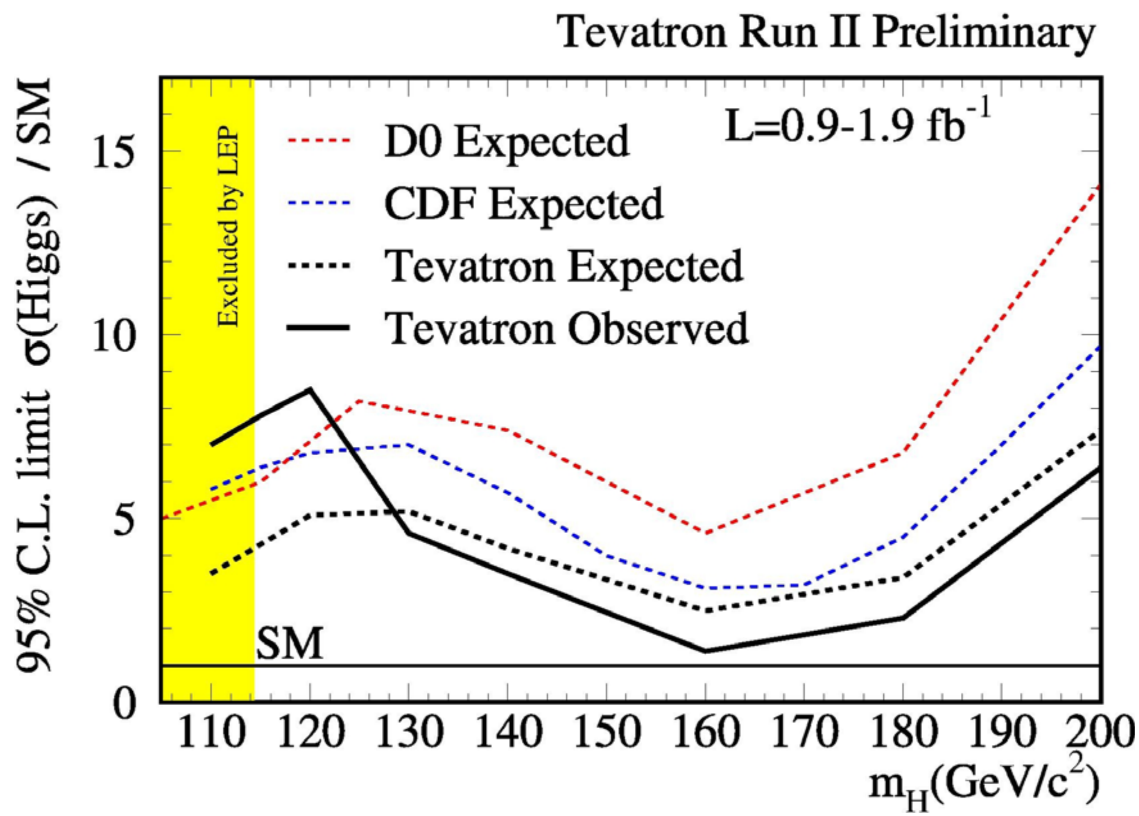
What we know about the Higgs

From Experiments of the present…

Very aggressive searches at the CDF and D-Zero Experiments

- **Proton anti-proton collider near Chicago, USA**
- **Running with a center-of-mass energy of 1.96 TeV**
- **Now looking into roughly 3 fb^{-1} of data, but no sign of the Higgs yet**
- **Running through 2010 is on the table; could provide a total of 8 – 10 fb^{-1}**

Fermilab

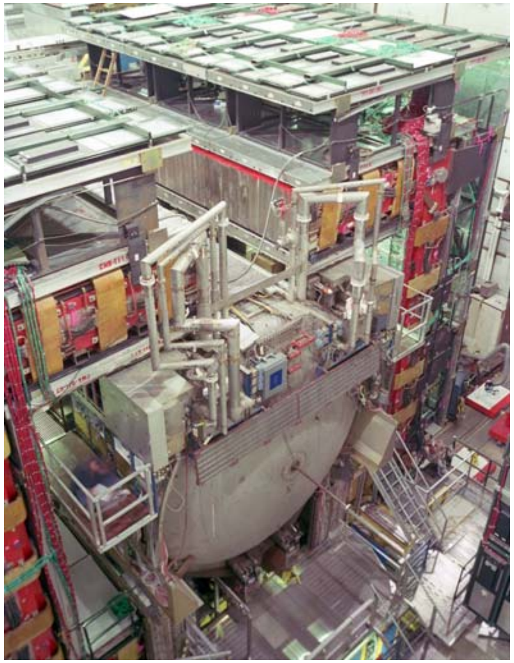


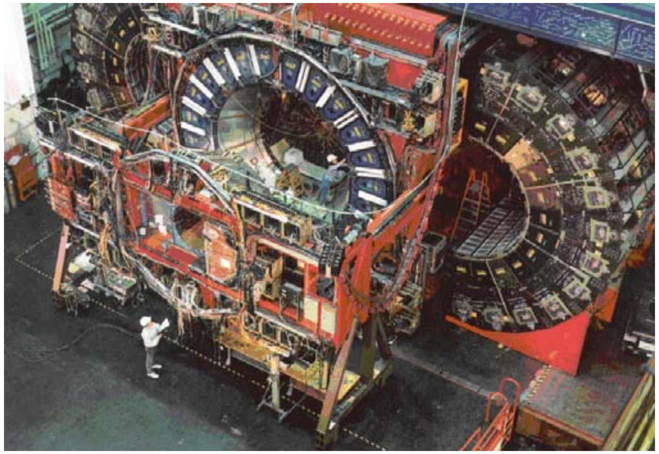
*Note: 1 barn (b) = 10^{-28} m^2

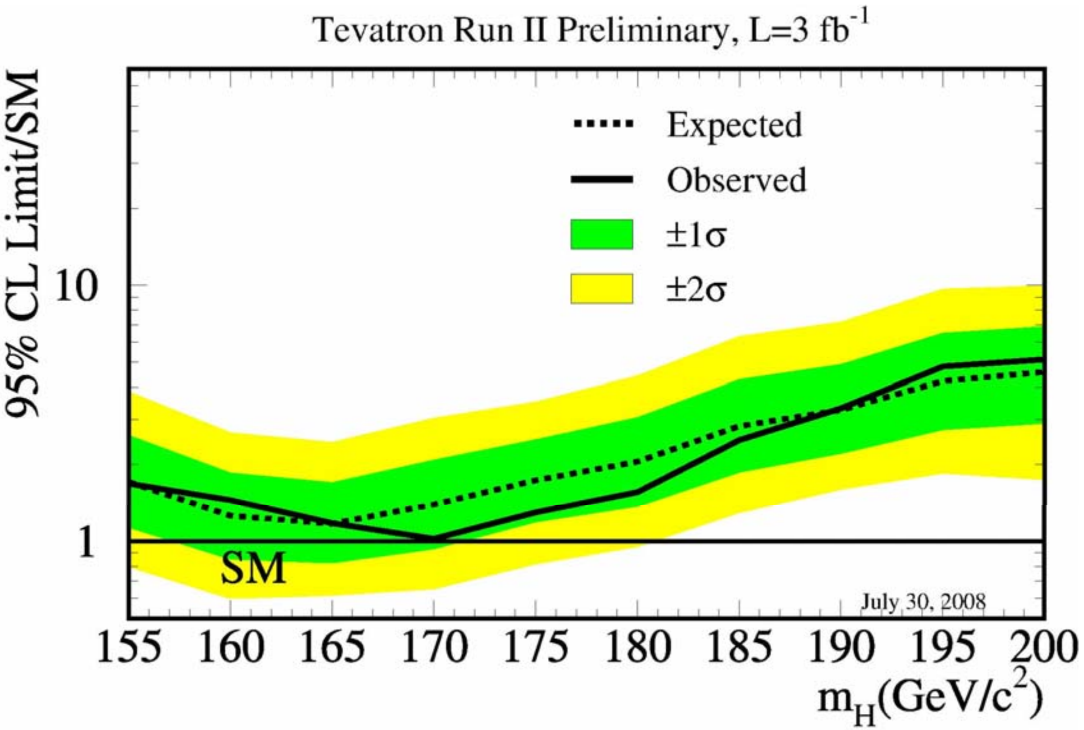
What we know about the Higgs

ICHEP 2008 combined result from CDF and D-Zero [155, 200 GeV]

- **Exclude 170 GeV/c² @ 95% CL**





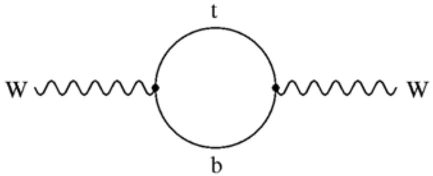


Fermilab

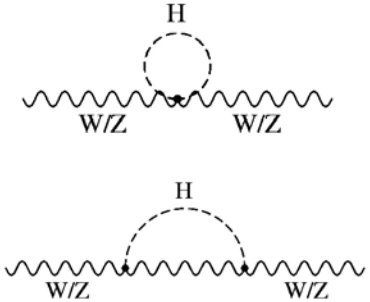
What we know about the Higgs

From other experimental measurements…

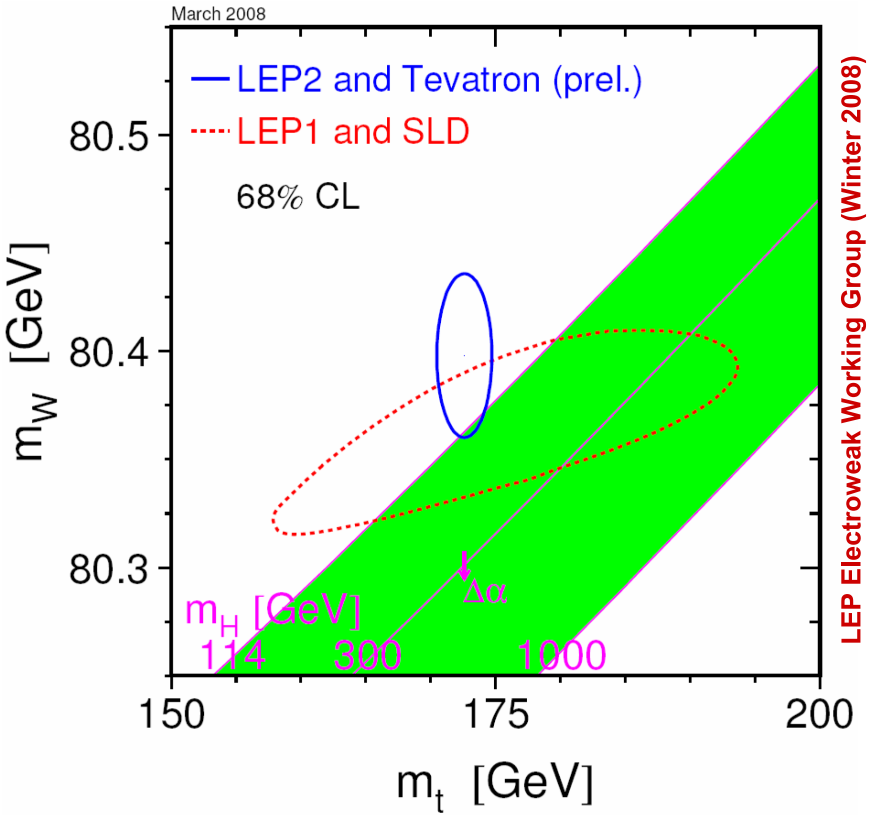
- **Precision Electroweak measurements are indirectly sensitive to the Higgs mass through radiative corrections**



$$\delta_t \propto M_t^2$$



$$\delta_H \propto \ln\left(\frac{M_H}{M_W}\right)$$



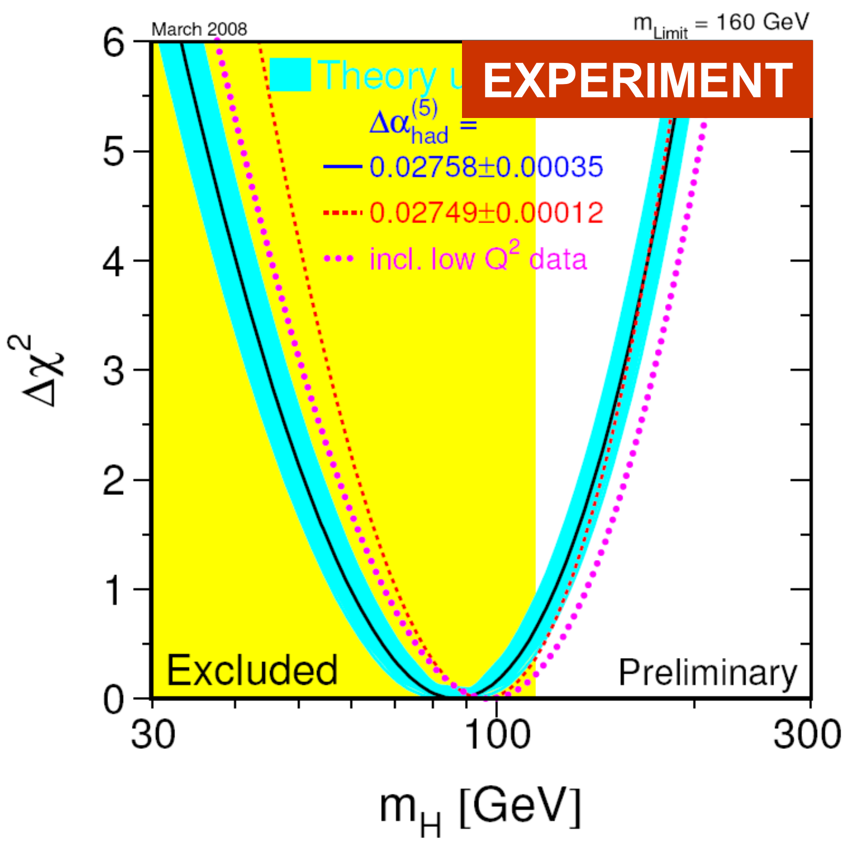
m_W = 80.398 +/- 0.025 GeV

m_t = 172.8 +/- 1.4 GeV

What we know about the Higgs

All experimental data to date favors a light Higgs

- **SM: $M_H = 87^{+36}_{-27}$ GeV; $M_H < 160$ GeV @ 95% CL**
- **LEP Direct Limit: $M_H > 114.4$ GeV @ 95% CL**



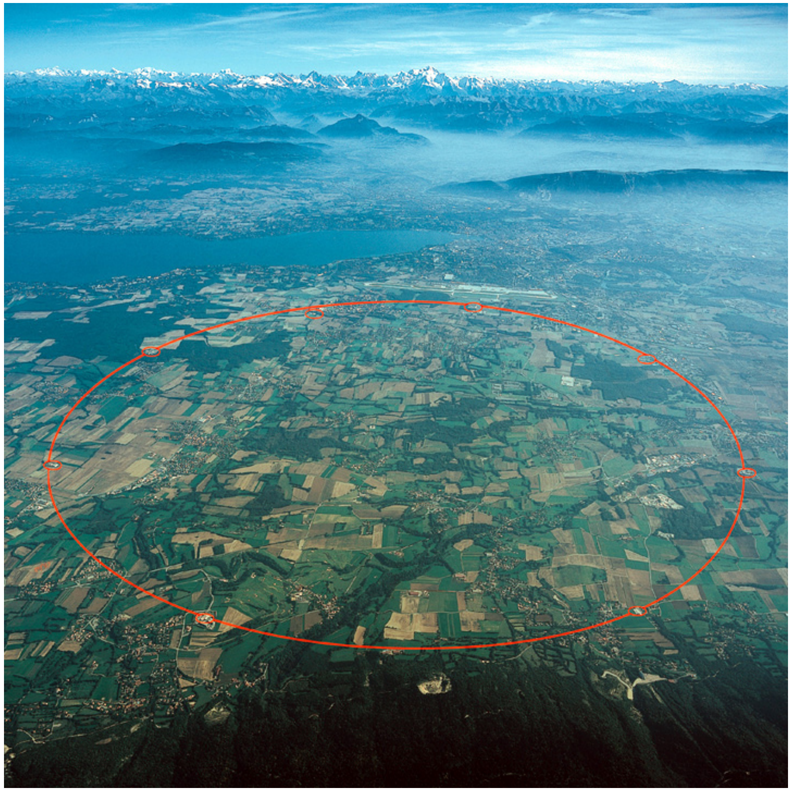
Fit to Electroweak data performed by the LEP Electroweak Working Group (Winter 2008)

The Large Hadron Collider (LHC)

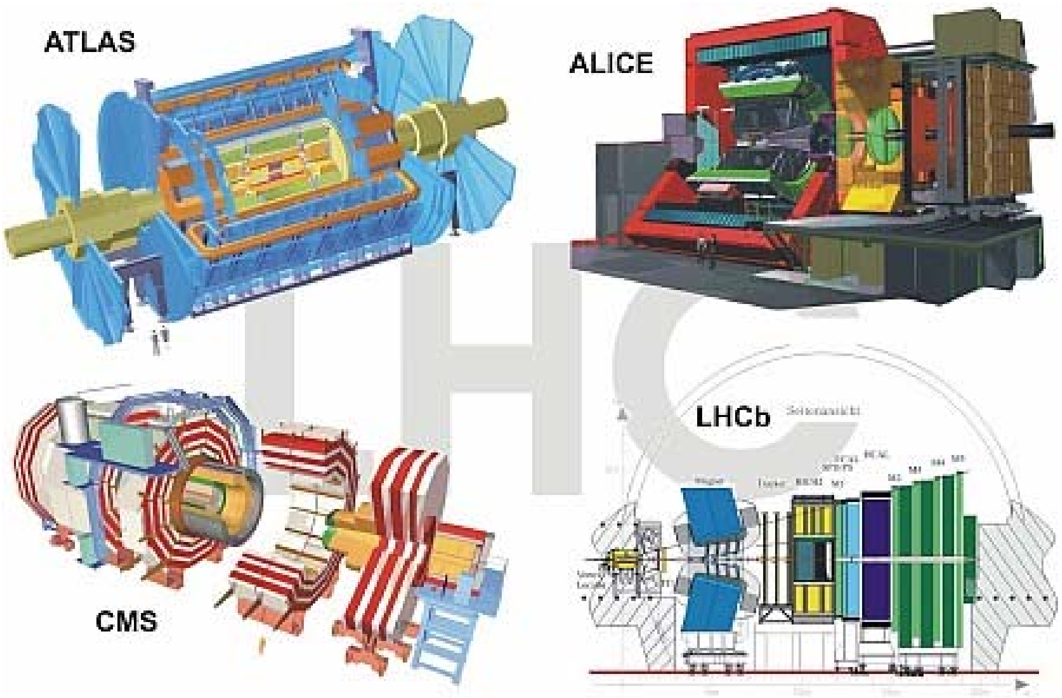
The Primary Objective of the LHC

Elucidate the mechanism responsible for Electroweak Symmetry Breaking

- **Particle accelerator located at CERN (Geneva, Switzerland)**
- **26.7 km circumference**
- **pp collider at $\sqrt{s} = 14$ TeV**
- **Instantaneous luminosity of $\sim 10^{33} - 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$**
- **40 MHz bunch-crossings with a "pile-up" of 2-20 inelastic collisions per crossing**
- **First circulating beam September 10, 2008 / Full-energy running in 2009**



High p_T **Heavy Ion**

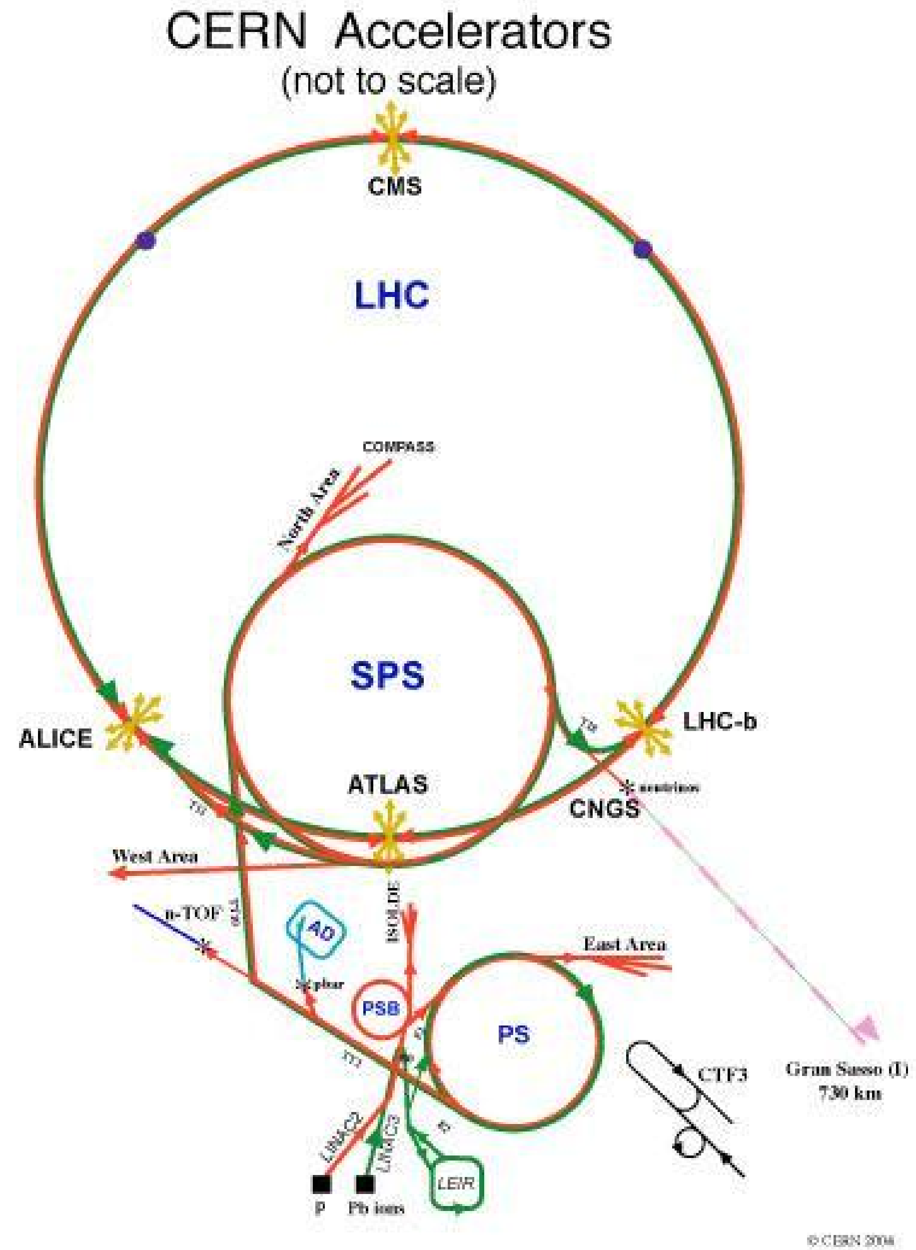


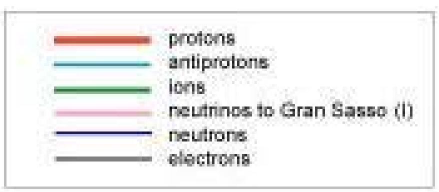
High p_T **b Physics**

The Large Hadron Collider

Housed in the former LEP tunnel

- Dipole field at 7 TeV is 8.33 T
- ~350 MJ per beam!
- Ultimately ~2800 bunches
- Vacuum 10^{-13} atm (~6500 m^3 pumped)
- 1232 Dipoles (operate at 1.9 K)
- 858 Quadrupoles
- Typical store lasts ~10 hours
- Can also be used for ion running (Pb)
- Final price tag estimated at 4G EUR



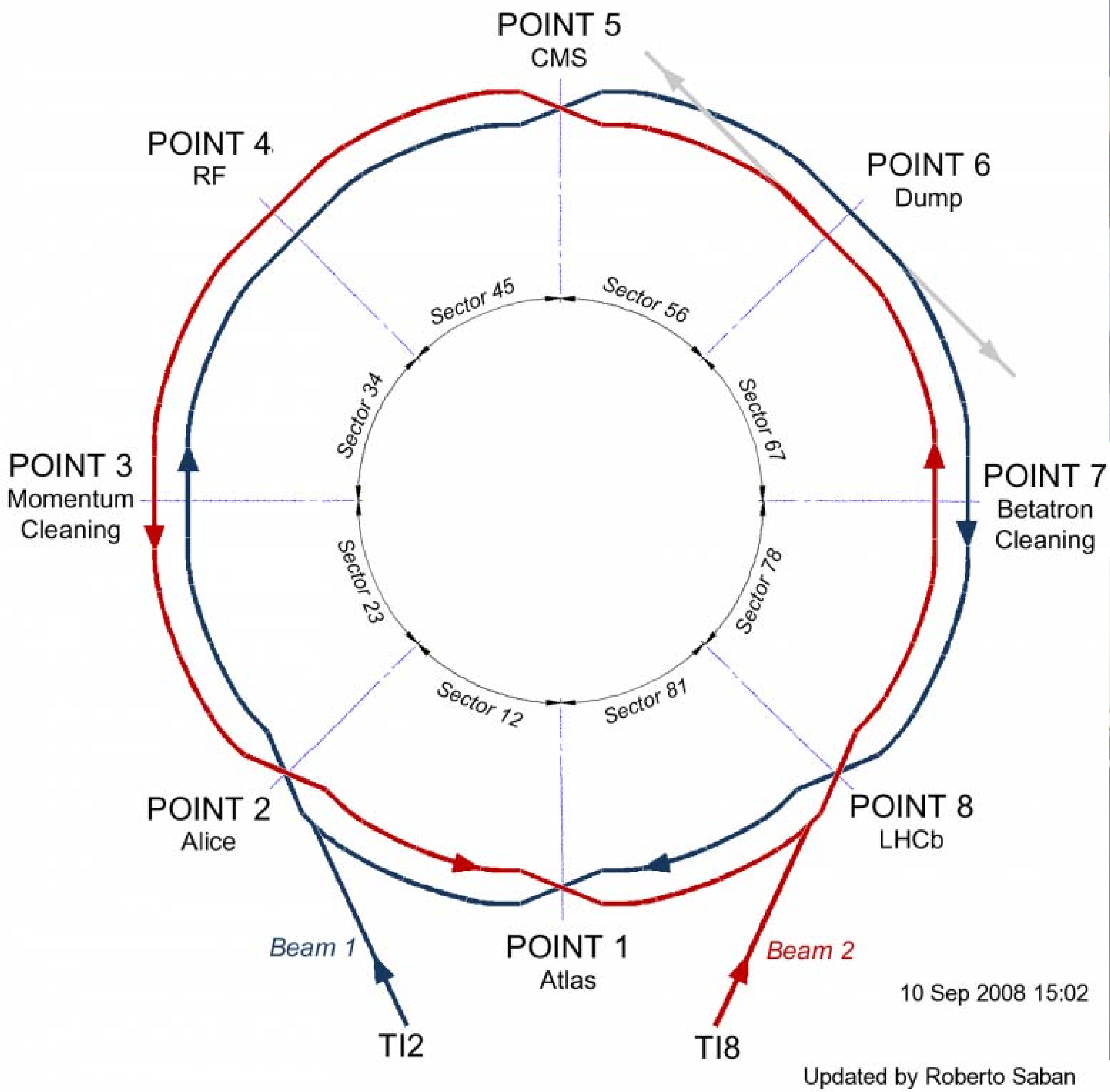


LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

September 10, 2008

First circulating beam!

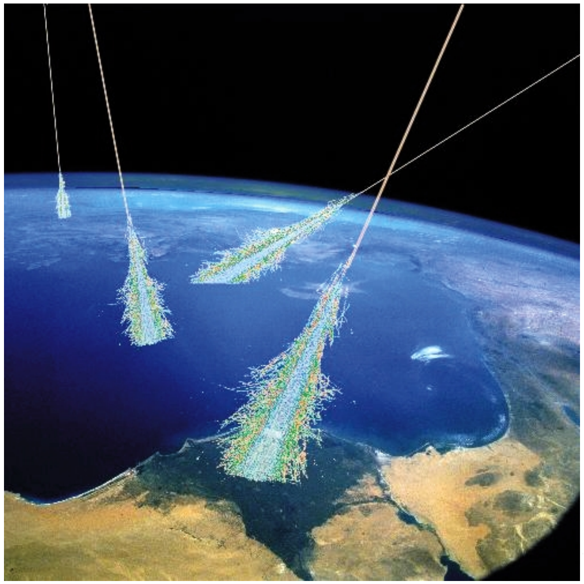
- **450 GeV Beam 1 (clockwise) ~10:30**
- **450 GeV Beam 2 (counter-clockwise) ~15:00**



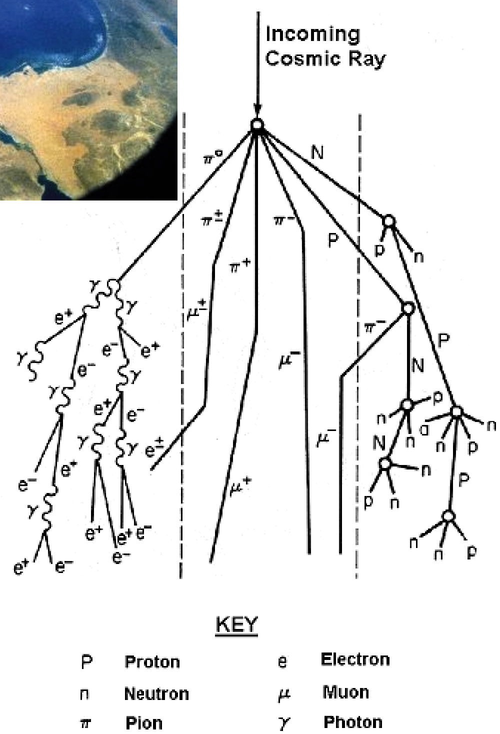
An Unexpected Event?

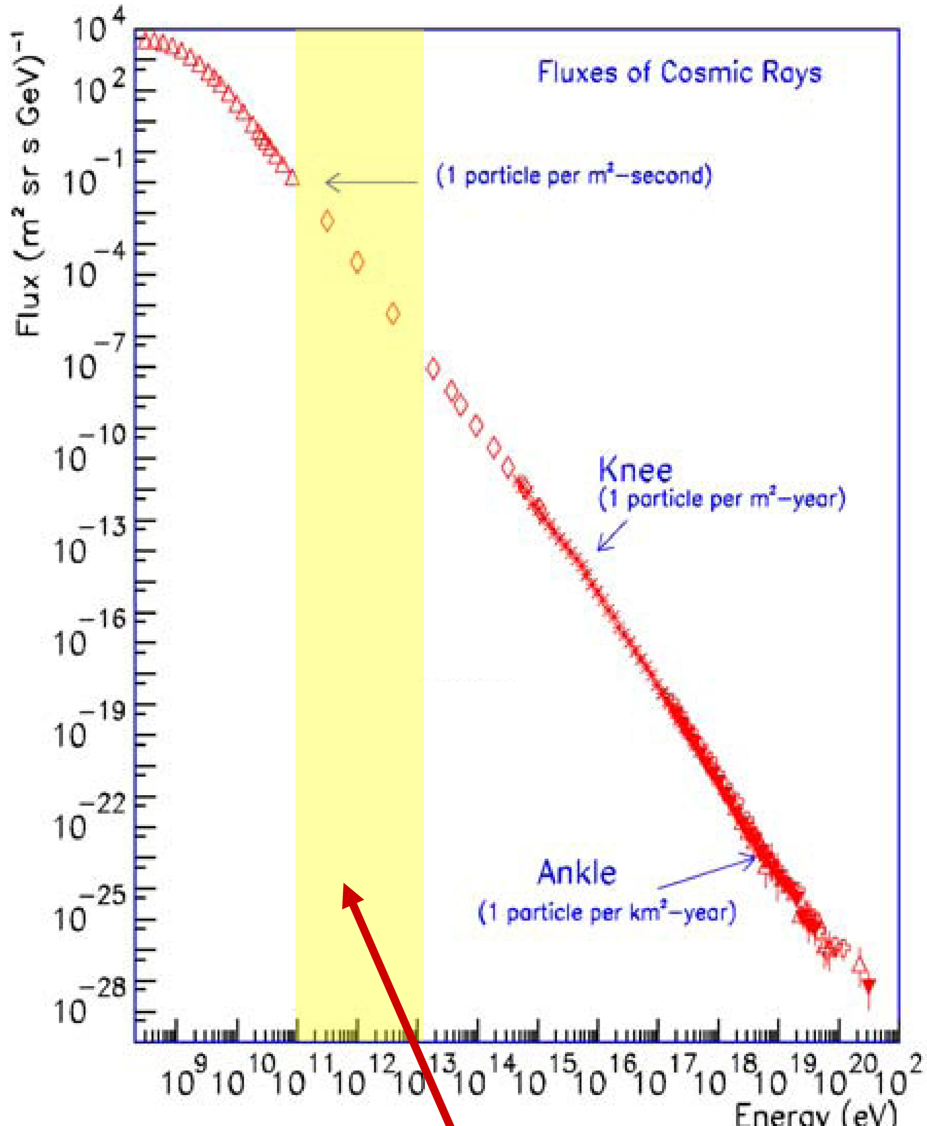
The media likes to get carried away… Will a Black Hole swallow the Earth?

I think we're safe…



~4.5 Billion Years





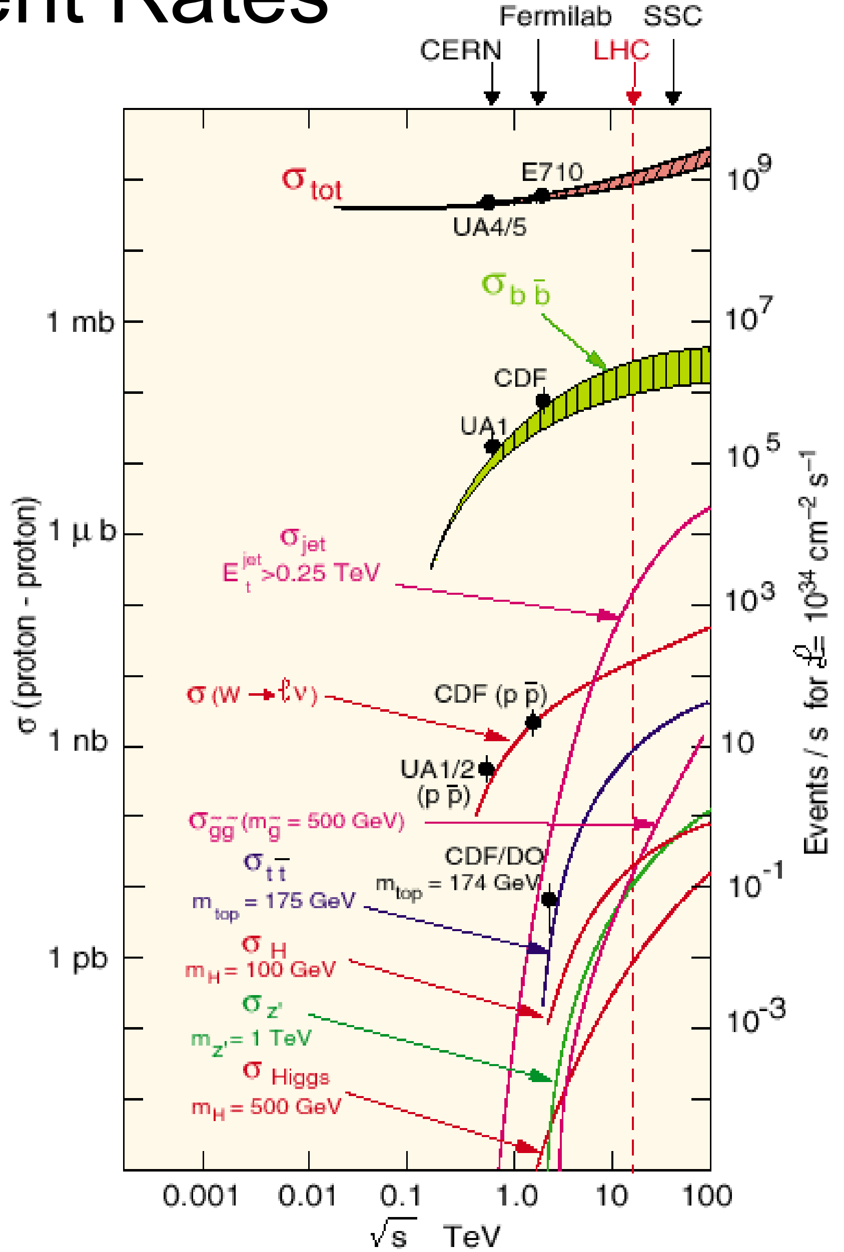
Earth-based Accelerators

Expected Event Rates

ATLAS with LHC at $\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Process	Events / s	Events in 10 fb^{-1}
W→eν	15	10^8
Z→ee	1.5	10^7
ttbar	1	10^9
bbbar	10^6	10^{12}-10^{13}
H (m=130)	0.02	10^5

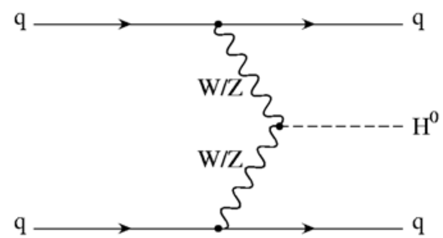
Many of these processes become backgrounds to Higgs searches…
…more on this later



Center of mass energy

Higgs production at the LHC

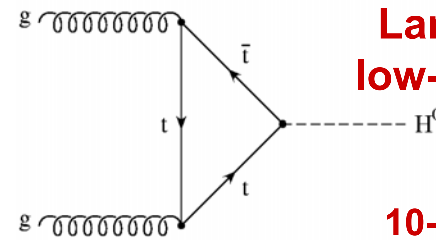
Vector Boson Fusion



The two "spectator" quarks make for a very distinct final state

<10% unc. NLO

Gluon-gluon Fusion

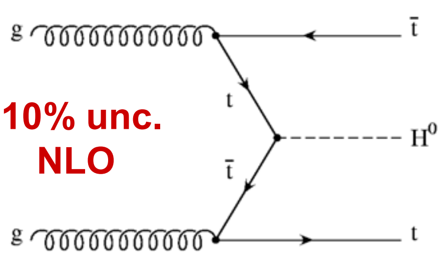


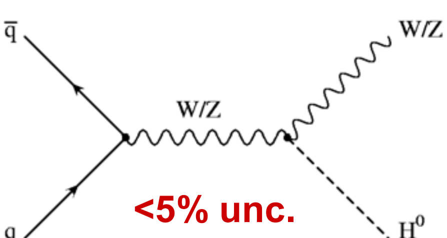
Large backgrounds for low-mass Higgs searches

10-20% unc. NNLO

Associated Production

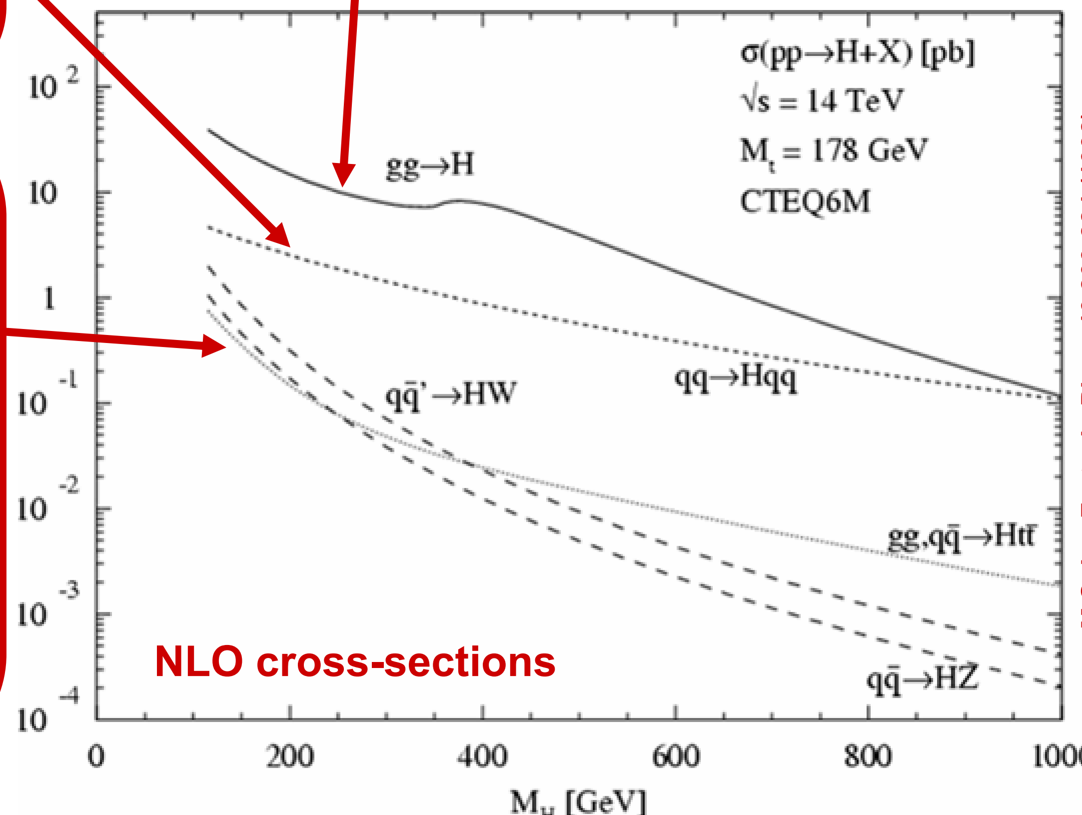
~10% unc. NLO





<5% unc. NNLO

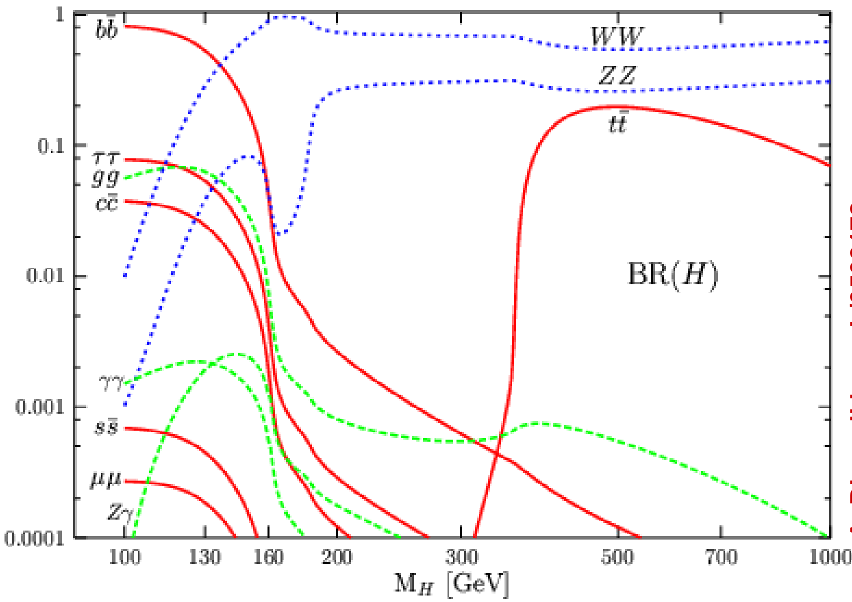
Allows for triggering regardless of Higgs decay mode



NLO cross-sections

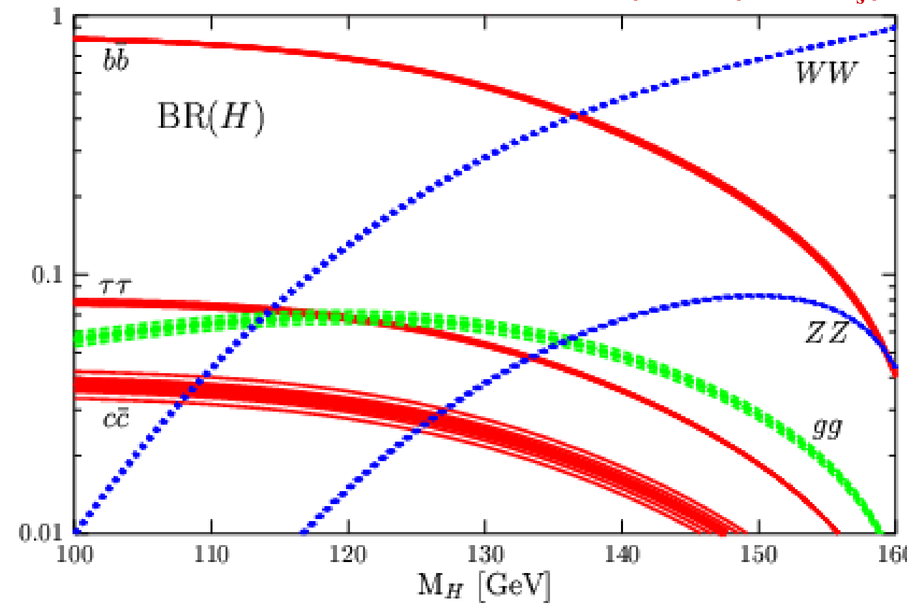
M.Spira, Fortsch. Phys. 46 203-284 (1998)

SM Higgs discovery final states



A. Djouadi hep-ph/0503172

Includes quark mass uncertainties (t, b, c) and $\alpha_s(M_Z)$



At low mass ($M_H < 2M_Z$)

- **Dominant decay through bb; enormous QCD background, suppressed in ttH**
- **H→ττ accessible through Vector Boson Fusion (VBF)**
- **H→WW$^{(*)}$ accessible through gluon-gluon fusion and VBF**
- **H→γγ has a low BR (decays through top and W loops); but due to excellent γ/jet separation and γ resolution is still very significant**
- **H →ZZ*→4l also accessible**

For higher masses

- **H→WW and H→ZZ→4l final-states**

The ATLAS Experiment

The ATLAS Experiment

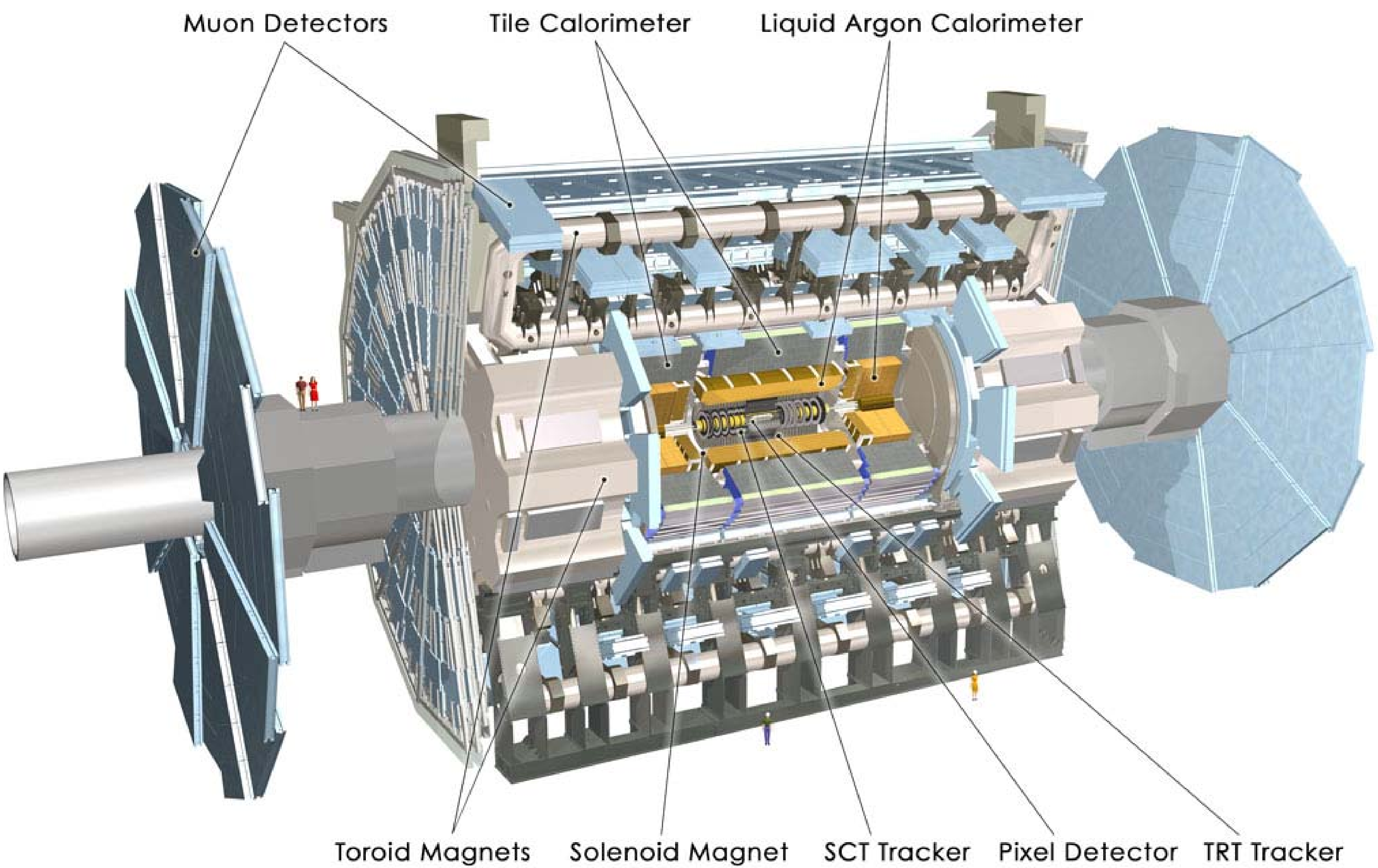
A Toroidal LHC ApparatuS (ATLAS)

- Collaboration formed in 1992
- As of April 2007: 37 Countries, 167 Institutions, ~2000 Members
- The largest collider detector ever built

The ATLAS Experiment

General purpose experiment at the LHC

- **Not just poised for finding and studying Higgs: Top, Exotics, SUSY, etc.**
- **Length ~40 m, Radius ~10 m, Weight ~7k tons, Channels ~10^8**



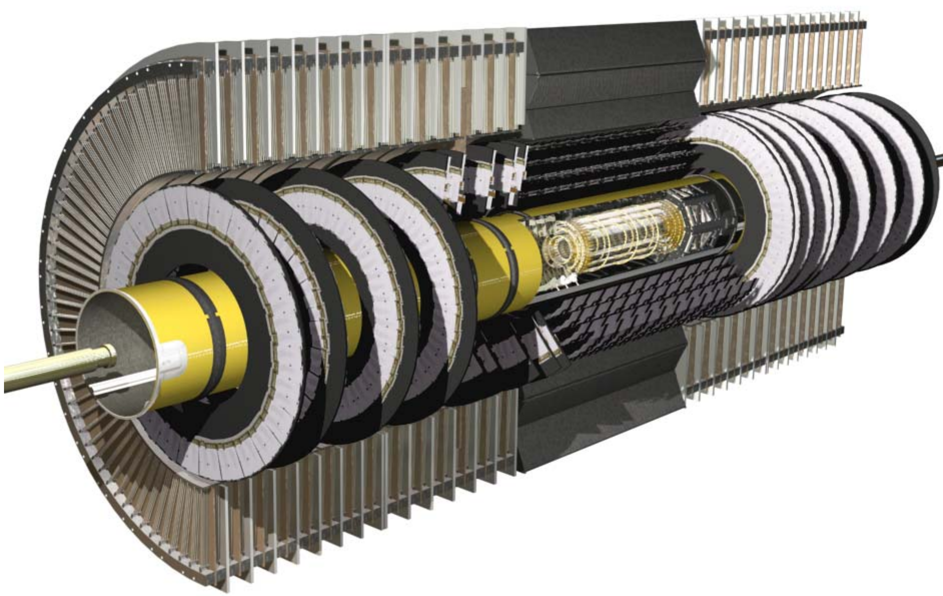
The ATLAS Experiment

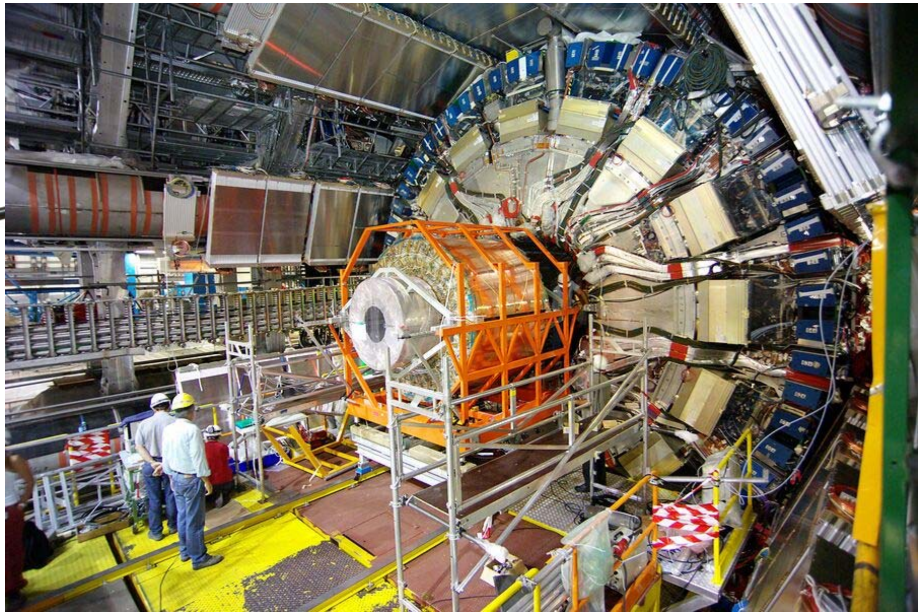
The Inner Tracker

- **Comprised of the silicon Pixel Detector (50 x 400 µm), Semiconductor Tracker (silicon strips 80 µm pitch), Transition Radiation Tracker (straw tracker)**
- **Residues inside of the central solenoid (magnetic field of 2 Tesla)**

$$\frac{\delta p_T}{p_T} \simeq 5 \times 10^{-4} \oplus 0.01$$

Silicon ROD





The ATLAS Experiment

Electromagnetic Calorimeter

- **Pb and liquid Ar**

$$\frac{\delta E}{E} = \frac{0.1}{\sqrt{E}}$$

Hadronic Calorimeter

- **Fe + scintillator and Cu + liquid Ar**

$$\frac{\delta E}{E} = \frac{0.5}{\sqrt{E}} \oplus 0.03 \quad |\eta| < 3$$

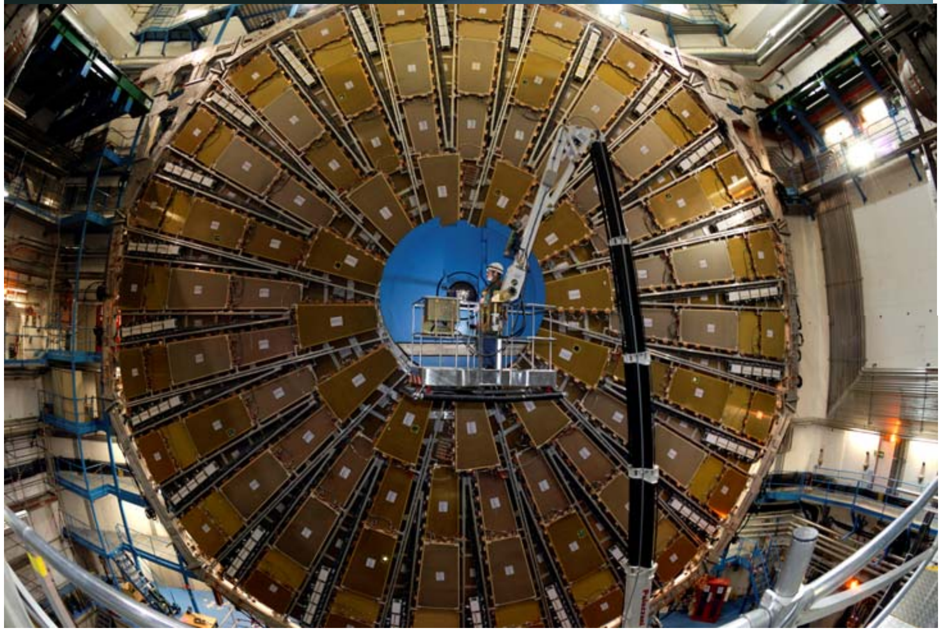
$$\frac{\delta E}{E} = \frac{1}{\sqrt{E}} \oplus 0.07 \quad |\eta| \geq 3$$

Stockholm University

Muons

- **Monitored Drift-Tube chambers**
- **Cathode Strip Chambers**
- **Resistive Plate Chambers**
- **Thin Gap Chambers**

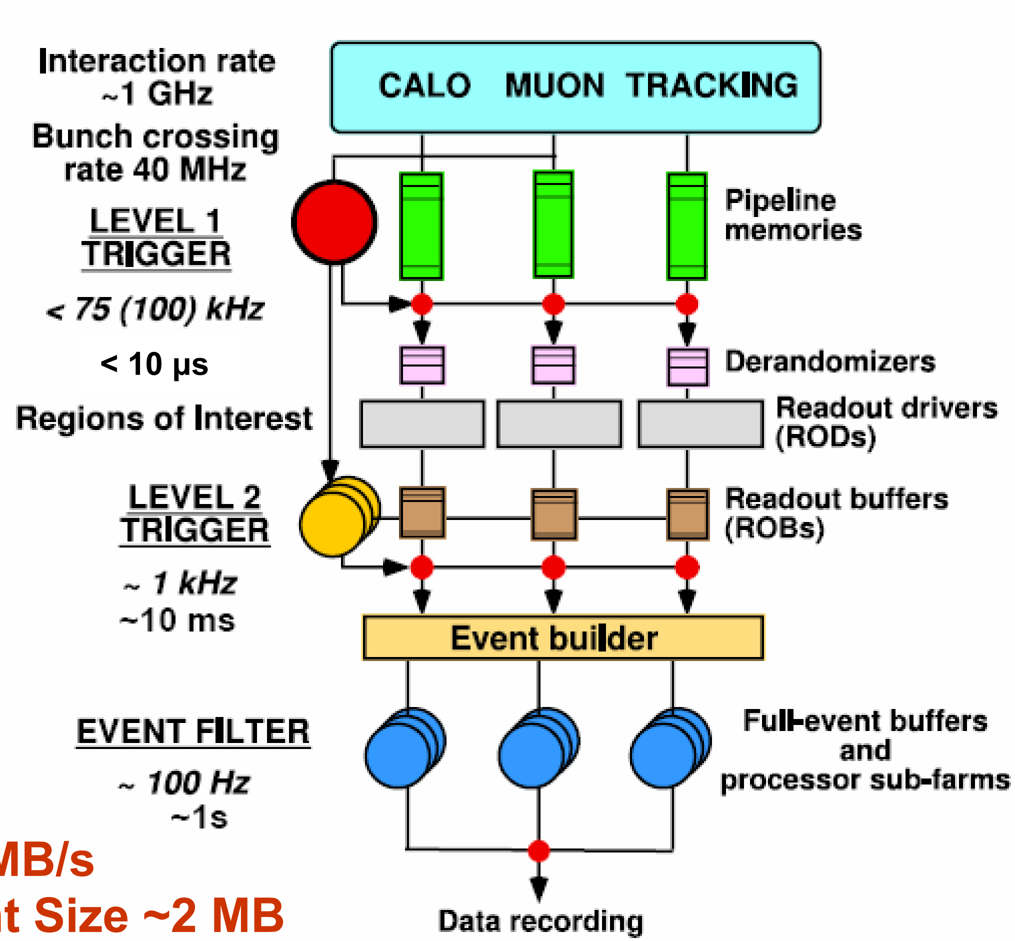
$$\frac{\delta p_T}{p_T} \simeq 0.1 \text{ at } 1 \text{ TeV}$$



The ATLAS Experiment

Trigger and Data Acquisition System:

- **Level-1 is hardware, Level-2 confined to "Regions of Interest", Event Filter has the ability to access the entire event**



Level 1

Level 2

Level 3
(Event Filter)

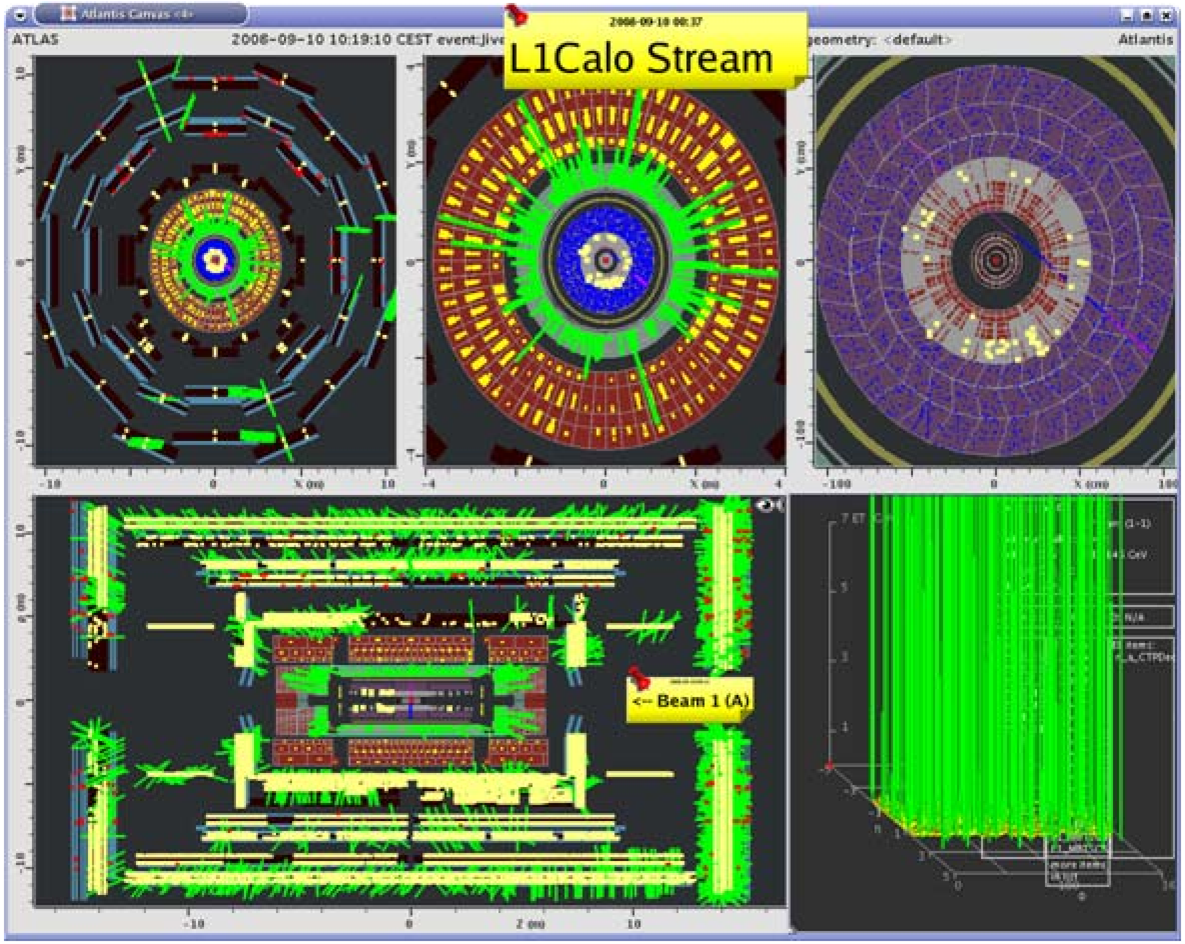
High-Level
Trigger

~100 MB/s
Average Event Size ~2 MB
~1 PB/year (petabyte = 10^{15} bytes!)

September 10, 2008

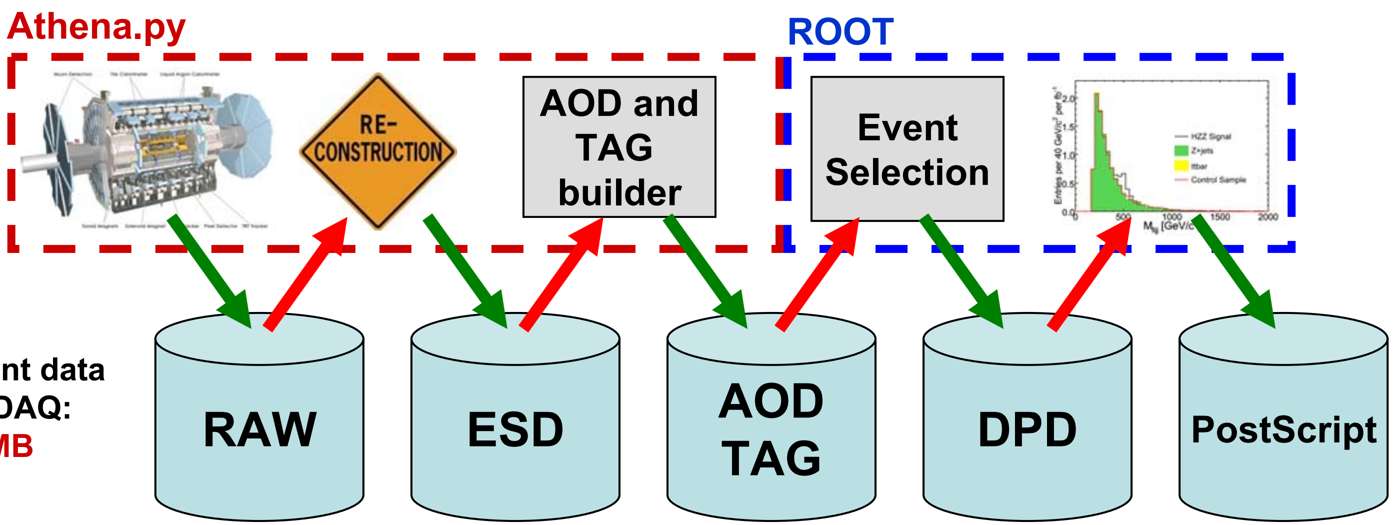
First beam event in ATLAS!

- **ATLAS has been told to expect 900 GeV collisions THIS WEEK**

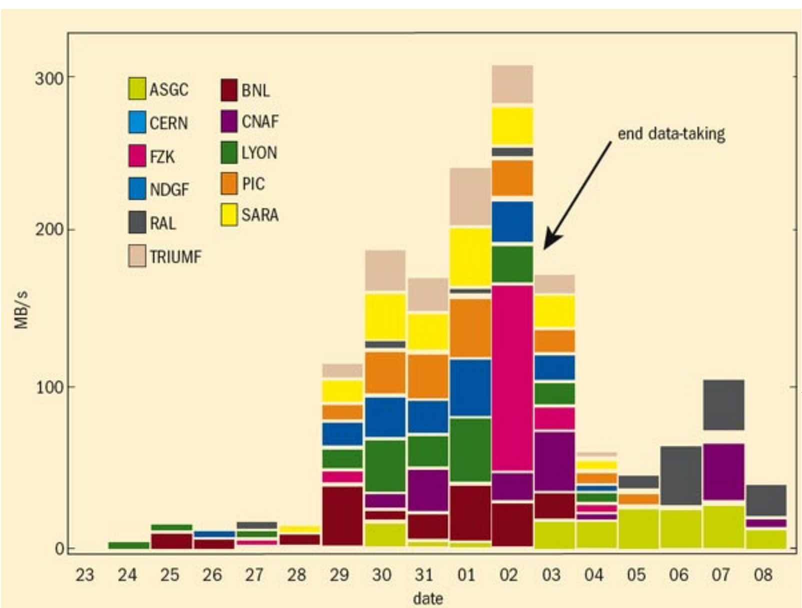


ATLAS Data-taking Chain

First test of the end-to-end data-taking chain took place in September 2007



RAW Event data from TDAQ: ~2 MB



ESD (Event Summary Data):
output of reconstruction (calo cells, track hits, ..): ~1 MB

AOD (Analysis Object Data):
physics objects for analysis (e,γ,m,jets, …): ~100 kB

TAG (Event Level Metadata):
Reduced set of information for event selection: ~1 kB

DPD (Derived Physics Data): equivalent of old ntuples: ~10 kB

Flow of data from CERN Tier 0 to Tier 1 sites all over the world.

For data processing and analysis, the GRID is an absolute necessity

Strategy and Start-up

The LHC has ushered in a new era…

- **10 TeV running Fall 2008**
- **Few ~100 pb^{-1} by the year's end**
- **Both ATLAS and CMS have already recorded beam data!**

LHC The first five years?

2008	~100 pb^{-1}	10^{31} cm^{-2} s^{-1}
2009	~1 fb^{-1}	10^{32} cm^{-2} s^{-1}
2010	~10 fb^{-1}	2 x 10^{33} cm^{-2} s^{-1}
2011	~30 fb^{-1}	2 x 10^{33} cm^{-2} s^{-1}
2012	~100 fb^{-1}	2 x 10^{34} cm^{-2} s^{-1}

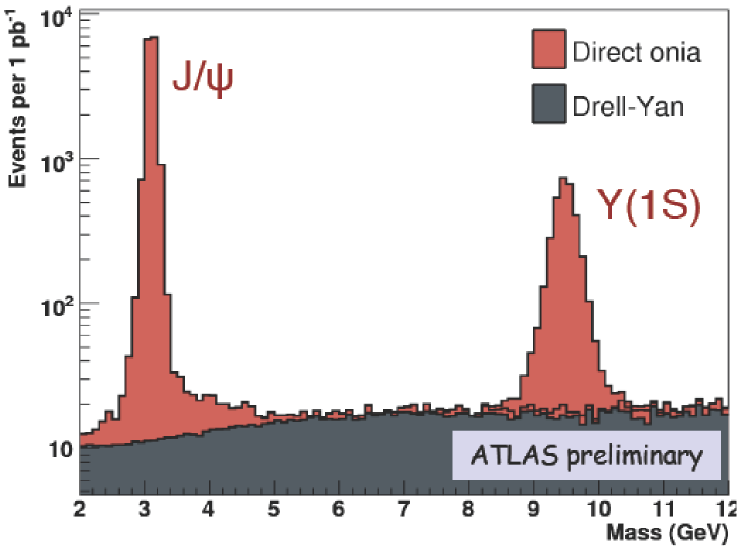
Understand the detectors…

- **Diagnose hot or dead channels**
- **Tally up dead material**
- **Tracking detector alignment**
- **Tune the detector simulations to better match ATLAS and CMS**

…do Standard Model measurements

- **Examine our standard candles**
- **Demonstrate the ability to measure Ws, Zs and top quarks (b-jet identification)**

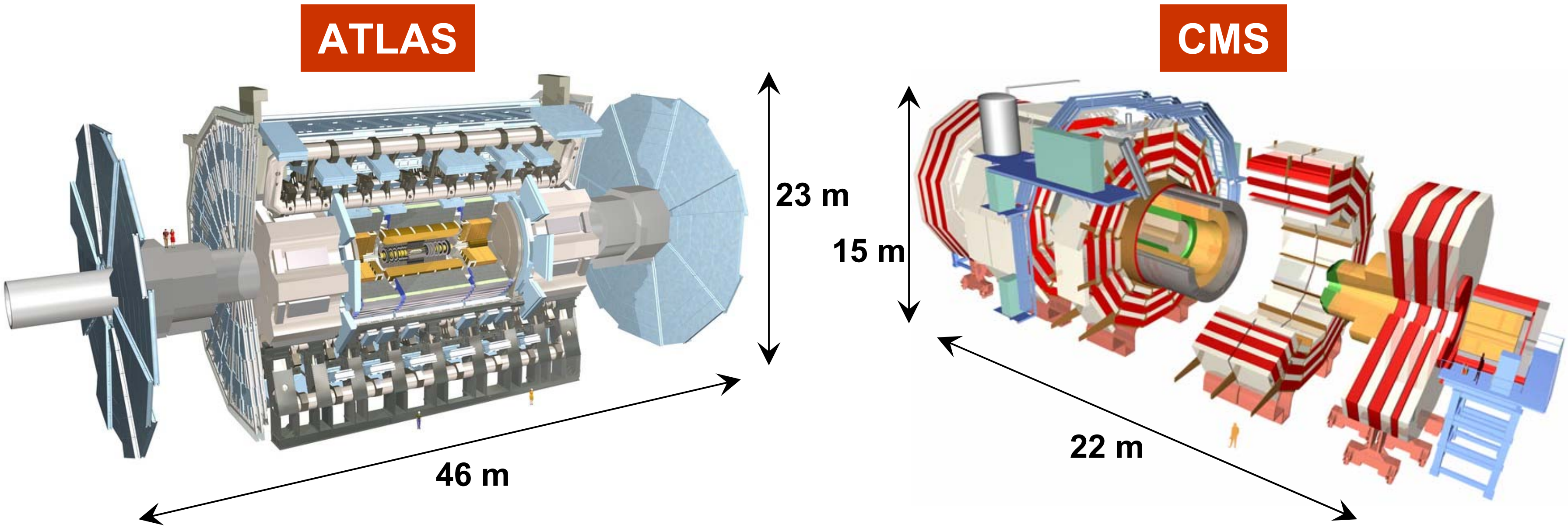
…then search for the Higgs



1 pb^{-1} = 3 days at 10^{31} cm^{-2} s^{-1}

The ATLAS and CMS Experiments

Both designed to search for the Higgs over a wide mass range



Hermetic calorimetry

- Exceptional measurement of missing transverse energy, jets to high eta

Exceptional particle identification

- Muons Efficiency ~90% Jet Rejection ~10^5
- Electrons Efficiency ~80% Jet Rejection ~10^5
- Photons Efficiency ~80% Jet Rejection ~10^3
- b-Jet ID Efficiency ~60% Light Jet Rejection ~10^2
- Tau ID Efficiency ~50% Jet Rejection ~10^2

Electron, muon and photon energy and momentum resolution of ~2-3%

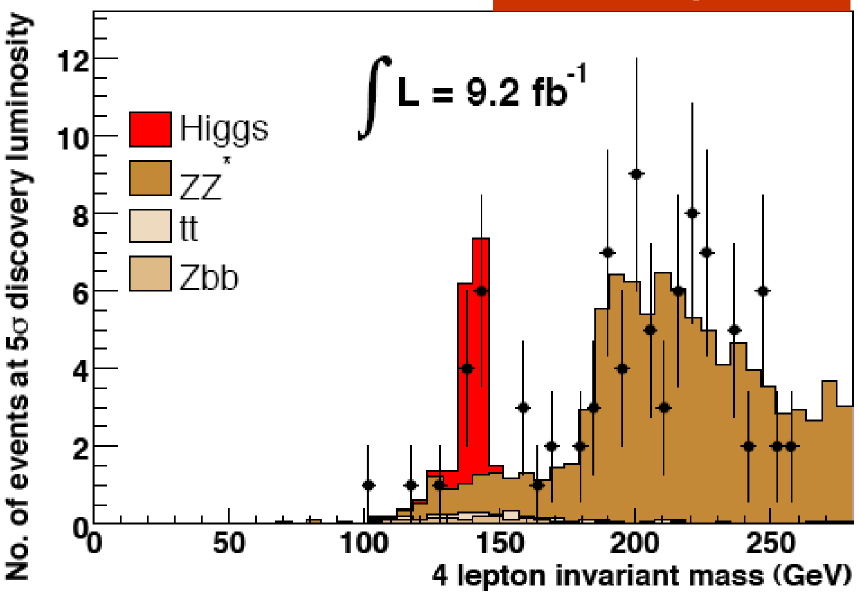
Higgs Discovery Final States

$H \rightarrow ZZ^{(*)} \rightarrow 4\,l$

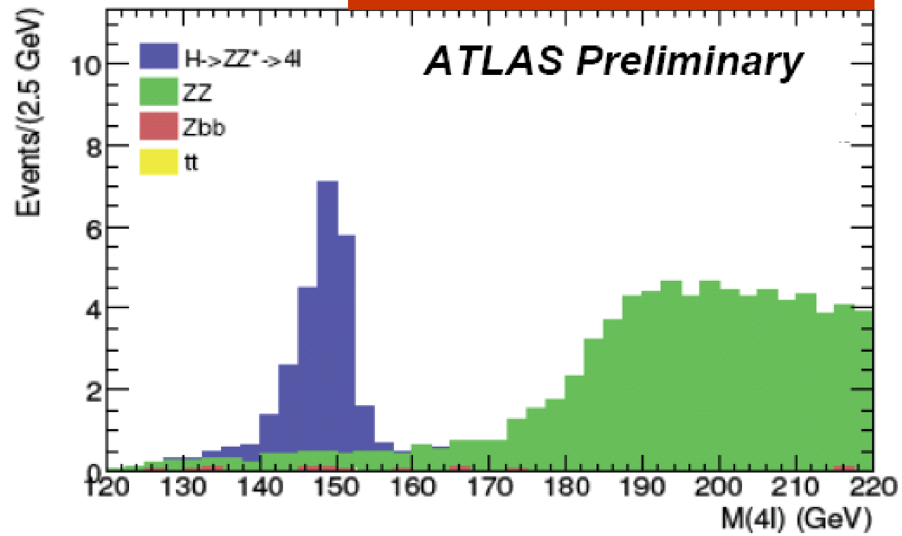
The "Golden Mode"

- **Very clean signal (looking for final states with 4e, 4μ, 2e2μ)**
- **Excellent mass resolution (1.5 – 2 GeV for M_H = 130 GeV)**
- **Powerful analysis in a wide mass range**

CMS 2e2μ at 5σ



ATLAS CSC 2008 10 fb^{-1}

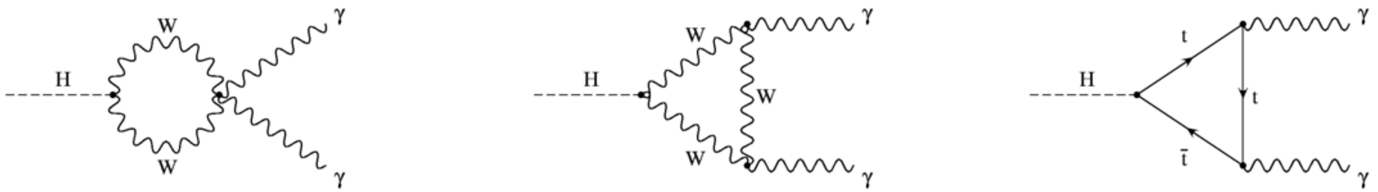


Experimental issues:

- **Zbb and tt rejection (leptons non-isolated, with activity around the leptons in the calorimeter and tracker; high impact parameter significance)**
- **qq→ZZ known at NLO; gg→ZZ is added as 30% of LO qq→ZZ (gg2ZZ not used yet)**

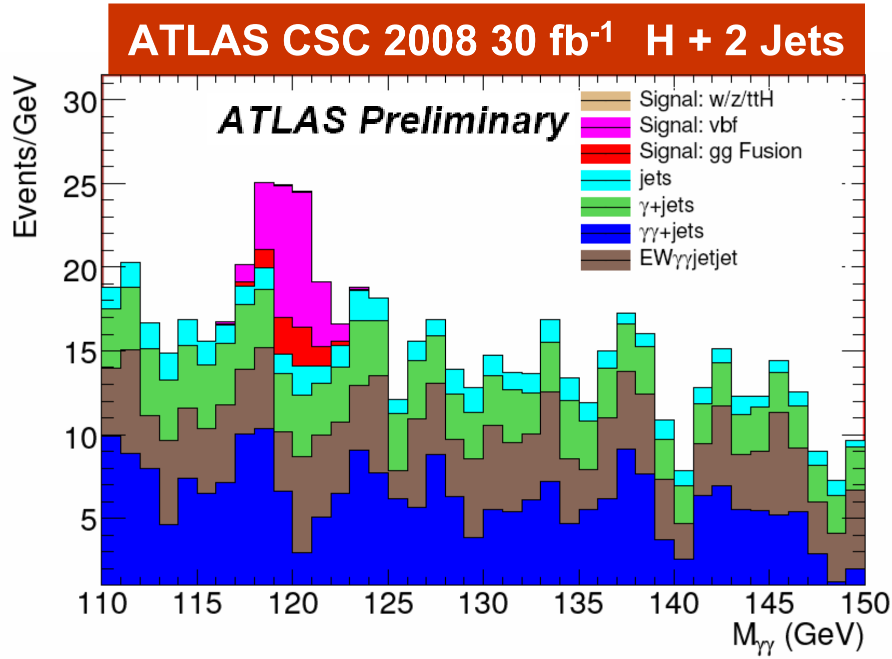
$H \rightarrow \gamma\gamma$

Final state produced through W, top and bottom loops



Powerful for low masses

- Significance of 6 – 8σ with 30 fb^{-1}
- Excellent mass resolution (~1.5 – 2 GeV)



Experimental issues

- Electromagnetic calorimeter calibration
- Requires excellent γ/jet separation
- Conversion recovery

Recent developments

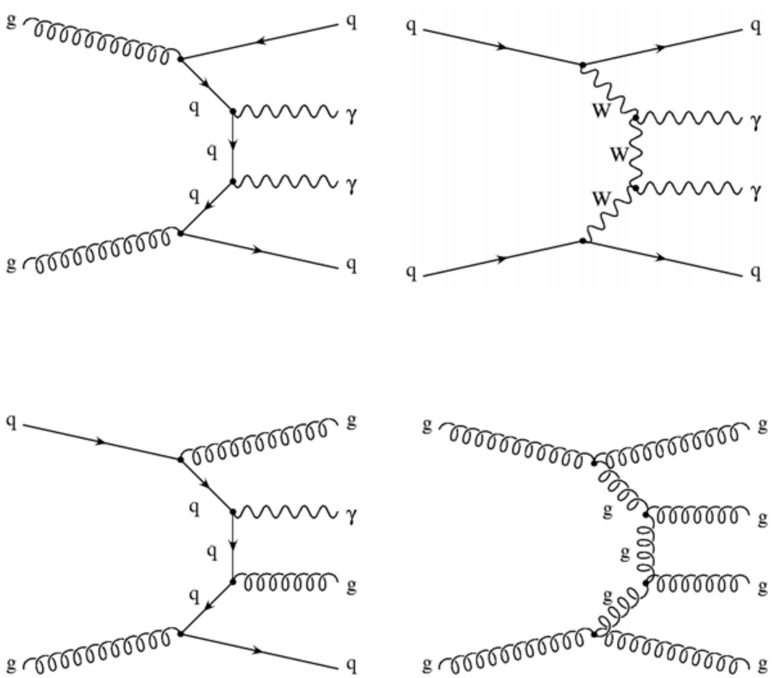
- Split events into categories (by jet multiplicity, energy ratios and η region)
- Inclusive, 1 and 2-jet analyses; combine to increase significance
- Use of fits and a Likelihood Ratio for discovery, systematics

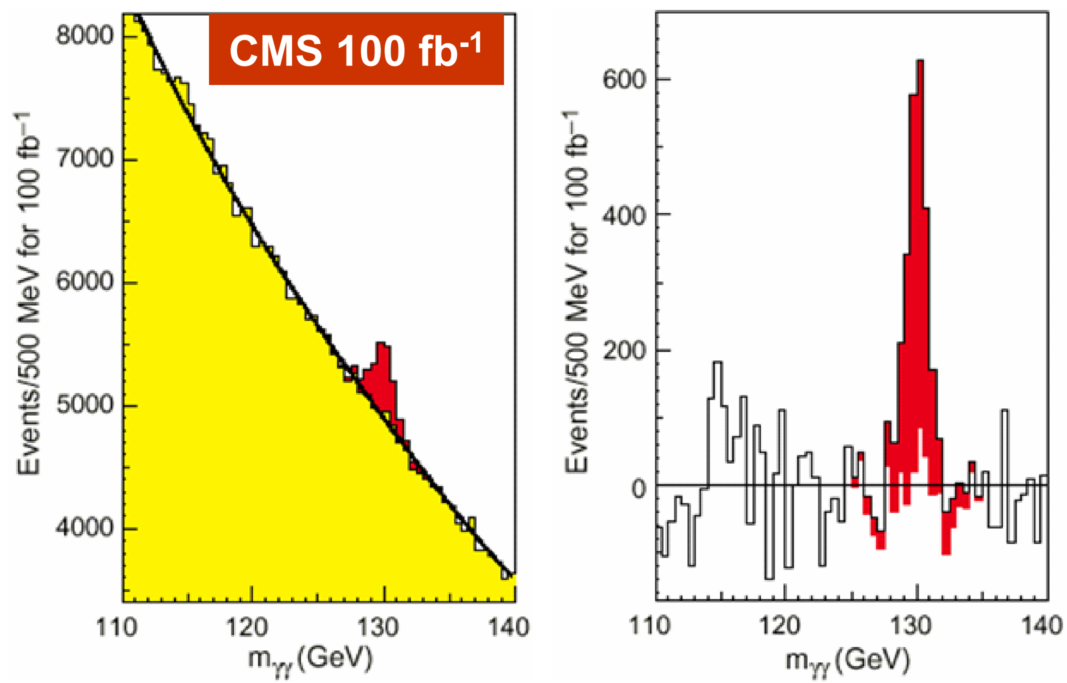
$H \rightarrow \gamma\gamma$

Diphoton background now calculated at NLO

- **Agrees with the data from the Tevatron**

Backgrounds can be taken from the sidebands…





Signal with background

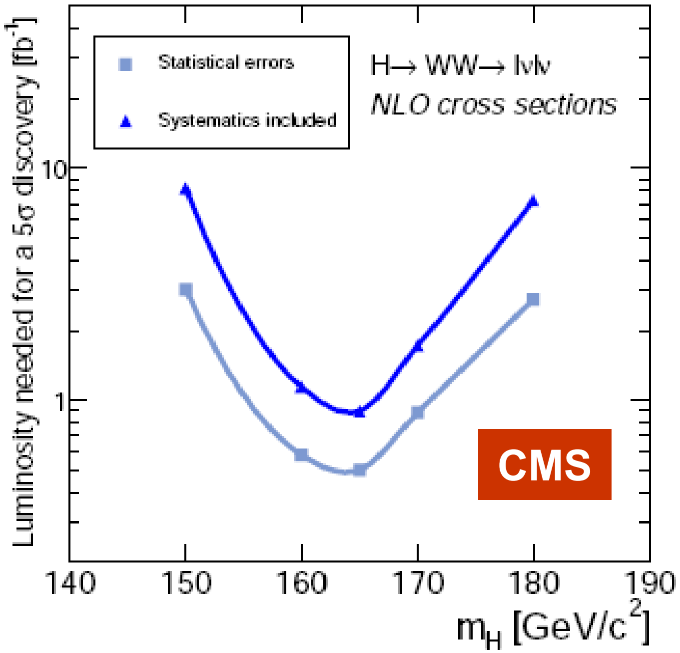
Signal after background subtraction

Inclusive Analysis

$H \to WW \to 2l2\upsilon$

Unlike other channels, full mass reconstruction is not possible

- **Essentially a counting experiment**
- **Accurate background estimate is critical**

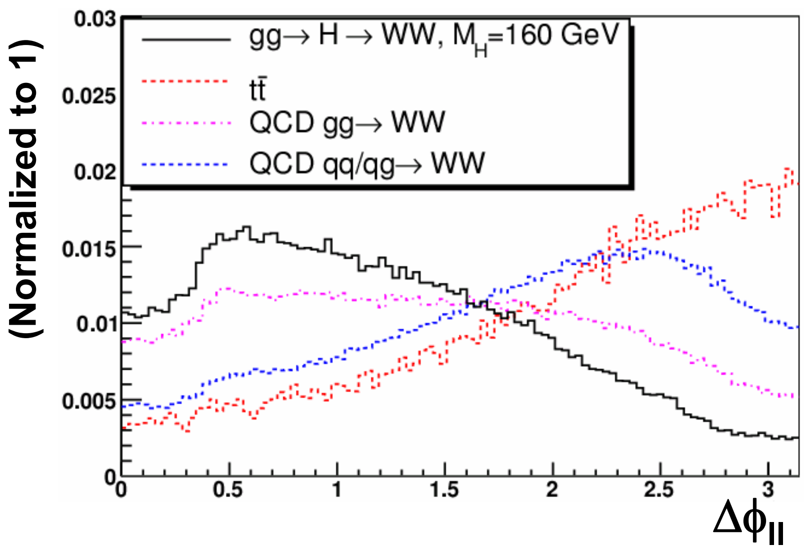


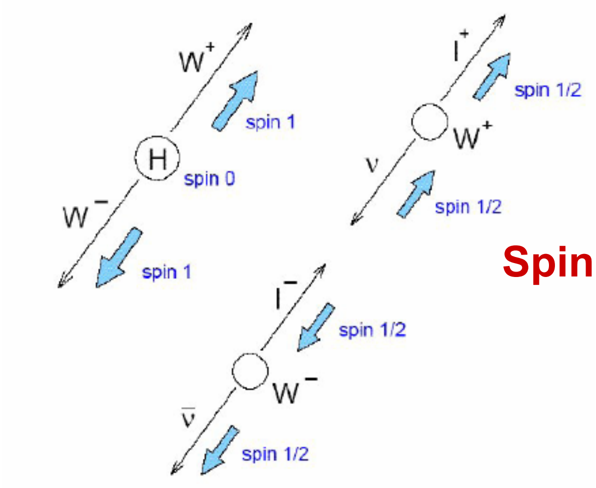
Most significant ~160 GeV

- **BR(H→WW) > 95%**

Dominant backgrounds

- **ttbar (suppressed with a jet veto)**
- **WW (exploit spin correlations)**





Spin correlations

Forward Jet Tagging and the Central Jet Veto

We can get the upper-hand in the VBF channels

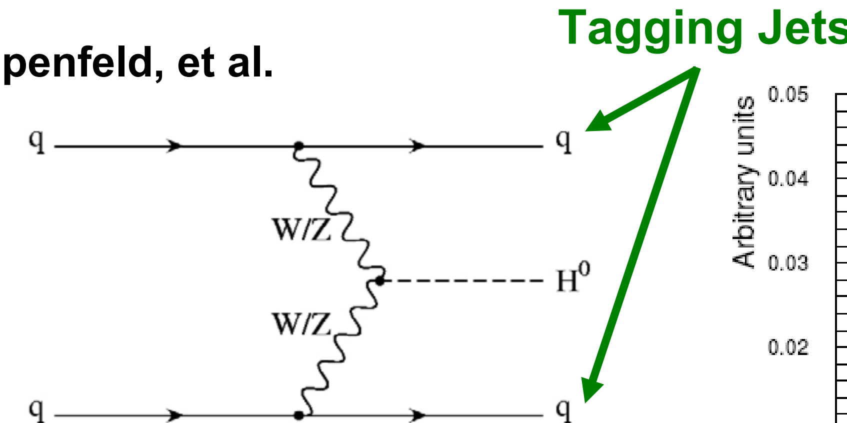
Forward Jet Tagging

- **D. Rainwater, D. Zeppenfeld, et al.**

$$\eta_{j1} \cdot \eta_{j2} < 0$$

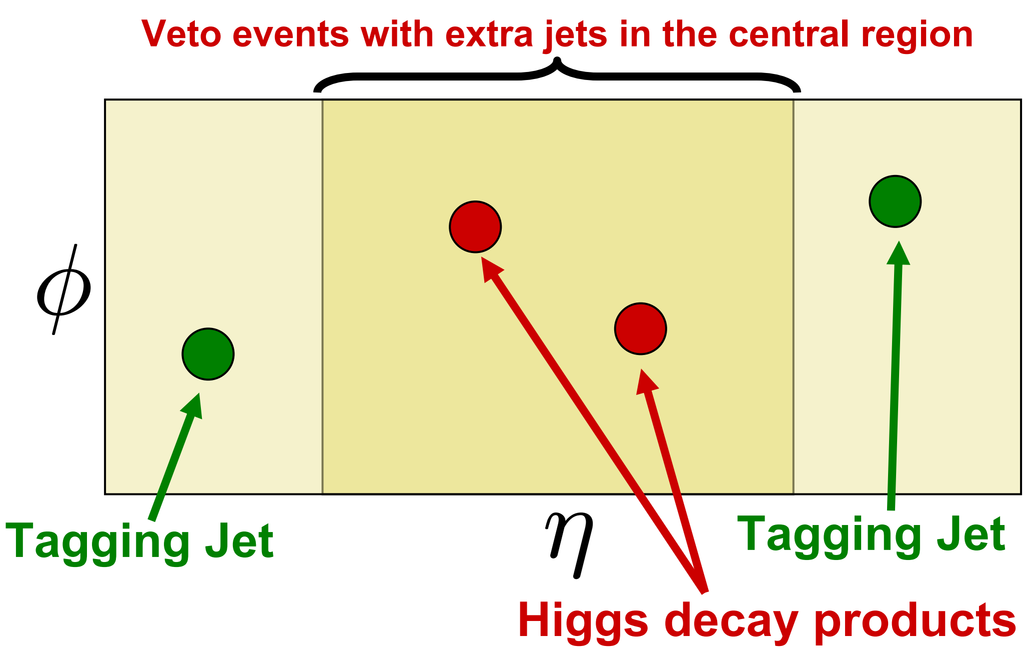
$$|\Delta\eta_{jj}| > 3.5 - 4$$

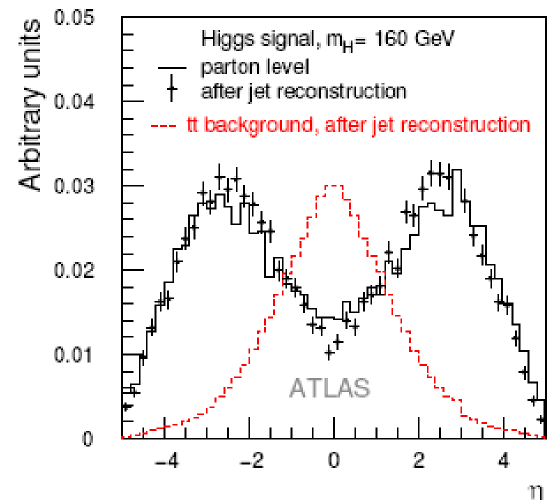
$$m_{jj} > 500 - 700 \text{ GeV}$$



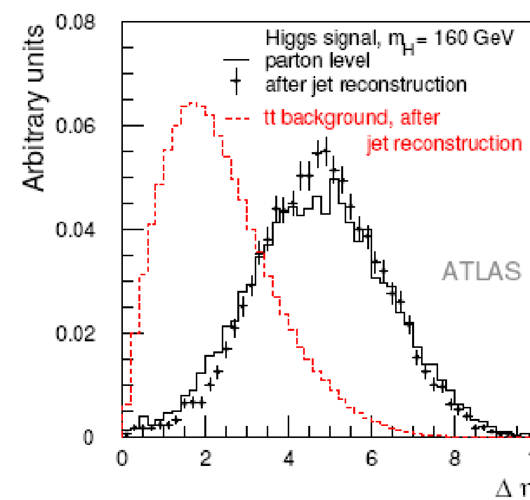
Central Jet Veto

- **V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)**





S. Asai et al., ATL-PHYS-2003-005



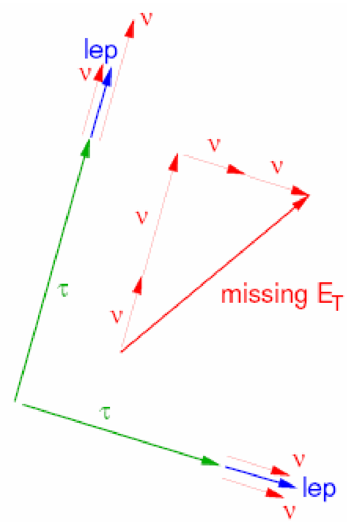
VBF H → ττ

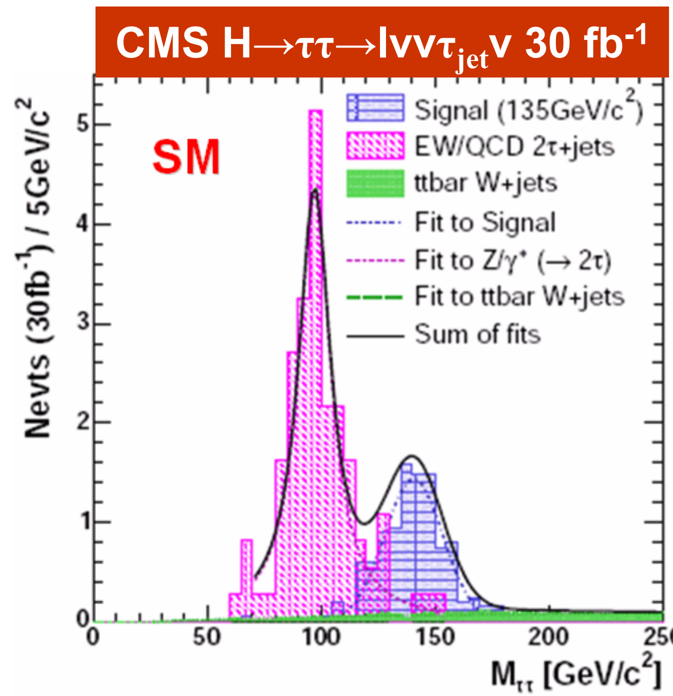
A very significant channel for low masses

- Important for studying the coupling of Higgs to leptons
- Three final states lepton-lepton, lepton-hadron, hadron-hadron
- Triggers for the fully hadronic mode are under investigation

Mass reconstruction via the collinear approximation

- Approximation breaks down when the two taus are back-to-back
- Mass resolution limited by missing transverse energy (~8 – 10 GeV)





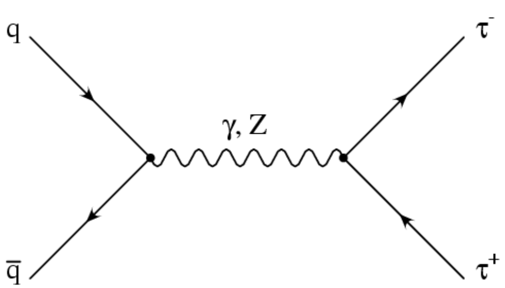
Experimental issues:

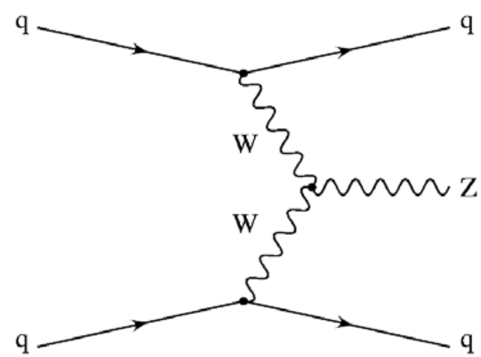
- Tau tagging (Likelihood, Neural Net methods)
- Z+jets background (especially for low masses)
- tt rejection (b-jet ID and veto for lepton-lepton)

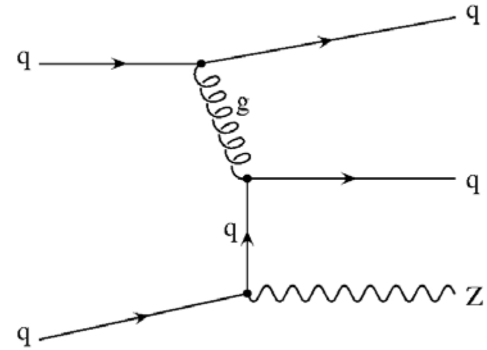
VBF H → ττ

Data-driven control samples are being explored for many backgrounds

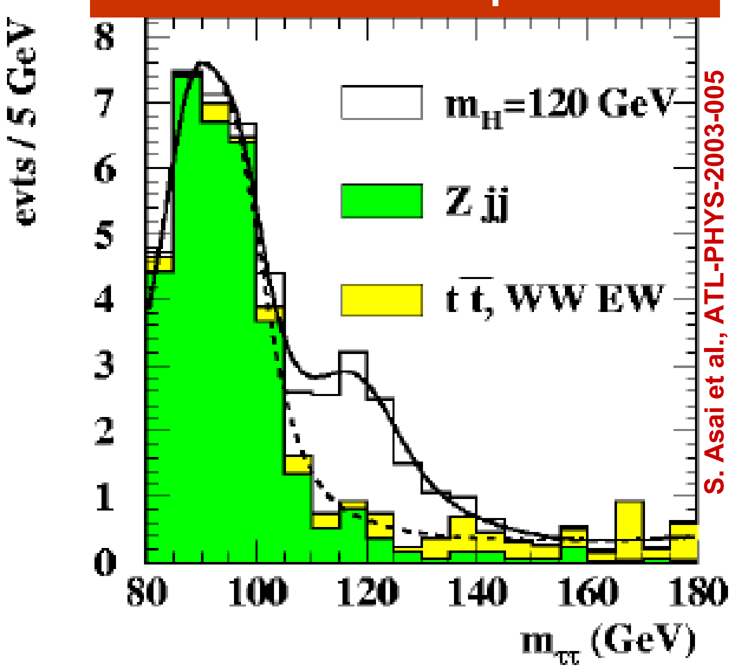
- **The relative contributions from different jet multiplicities are not known**
- **Unknowns related to critical analysis cut-specific variables exist**







ATLAS H→ττ→eννμνν 30 fb^{-1}



For the dominant background, collect Z→μμ and Z→ee events from data and use TAUOLA to decay the leptons to taus

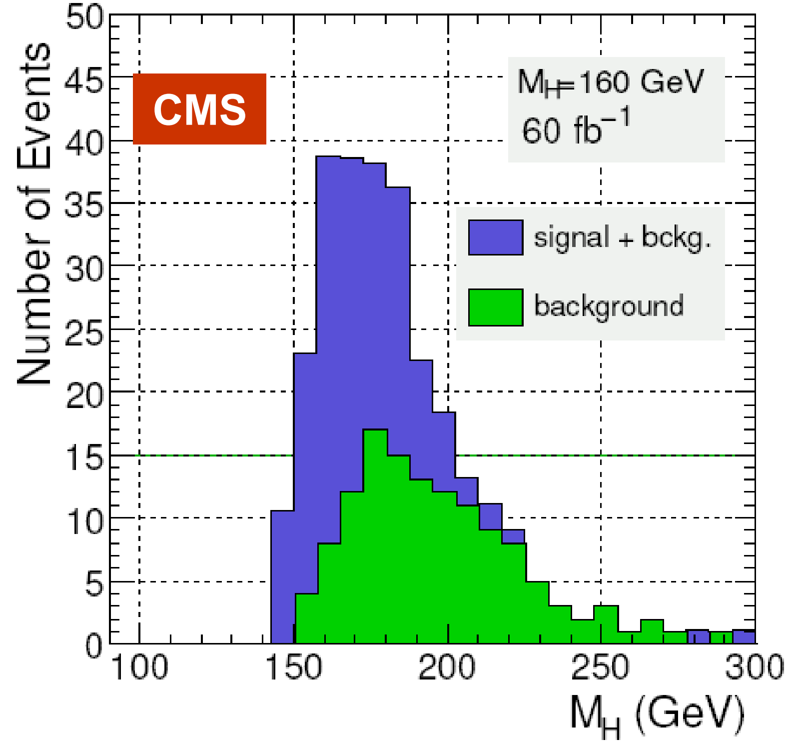
In this way we can emulate each of the lepton-lepton, lepton-hadron and hadron-hadron final states

Obtain both the background shape and normalization from data

VBF H → WW → lυqq

One of the best channels for intermediate and high Higgs masses

- **A VBF analysis reaping the benefits of the CJV and Tagging Jets selection**



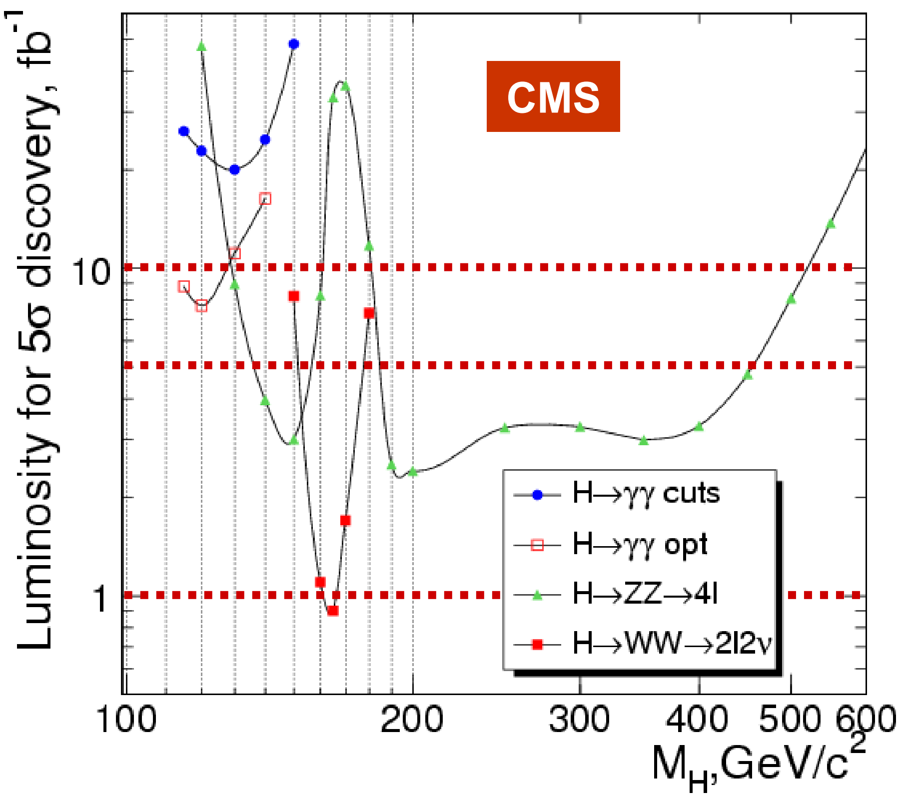
Event Selection

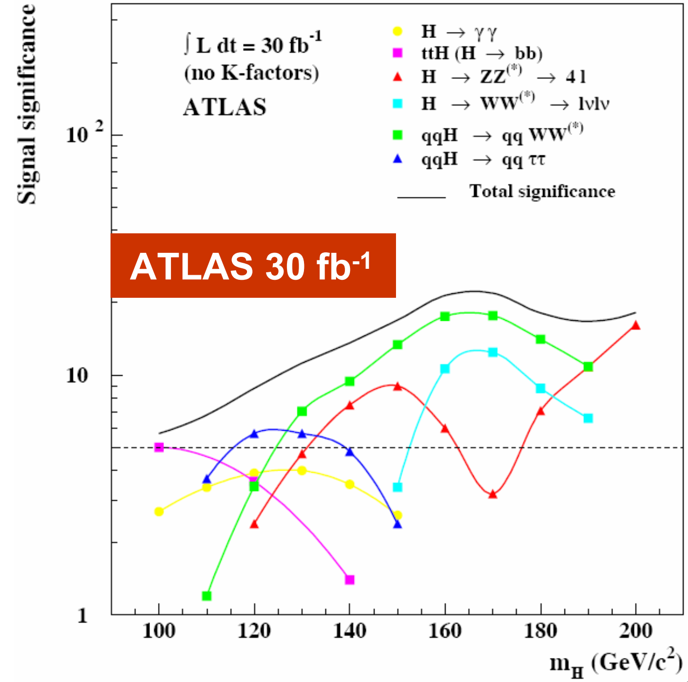
- **VBF tagging jets selection**
- **Central Jet Veto**
- **Isolated lepton**
- **4 jets**
- **Large missing transverse energy**

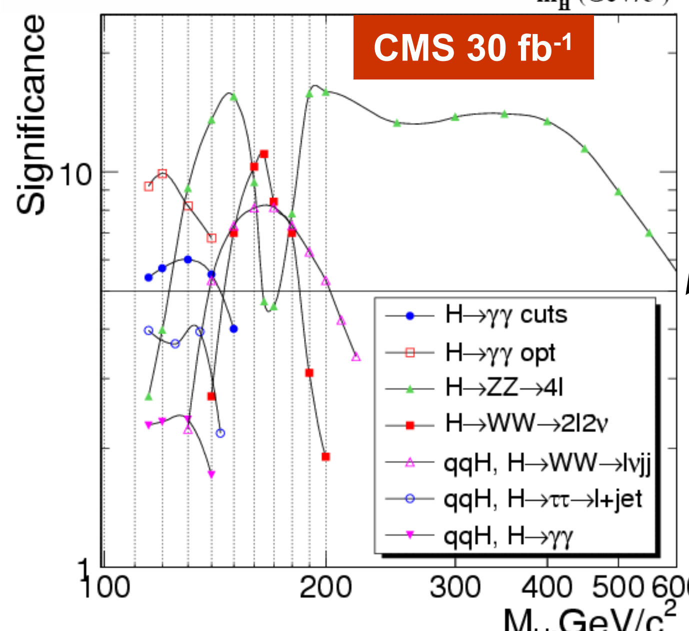
Mass reconstruction possible

- **Backgrounds: ttbar, W+jets, WW+jets**
- **Exploring data-driven approaches for obtaining background shapes**

SM Higgs Discovery Potential



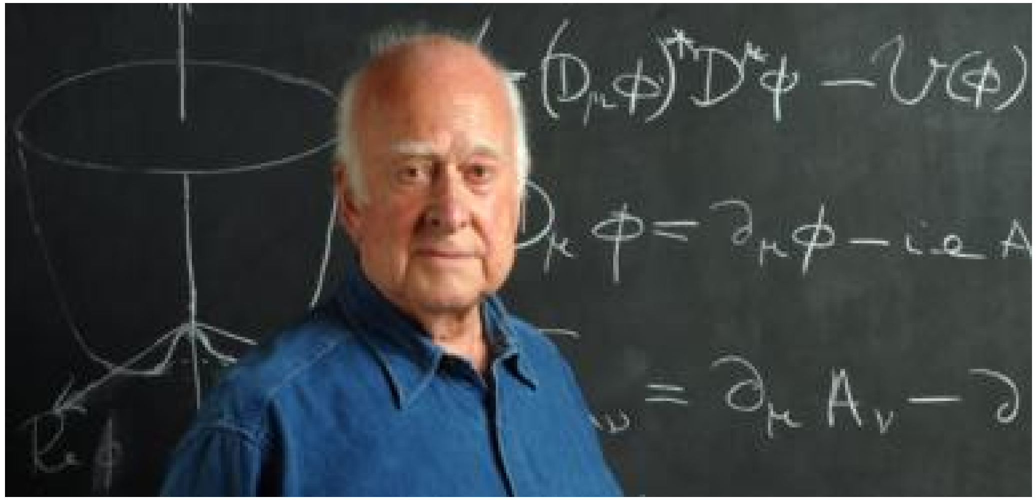




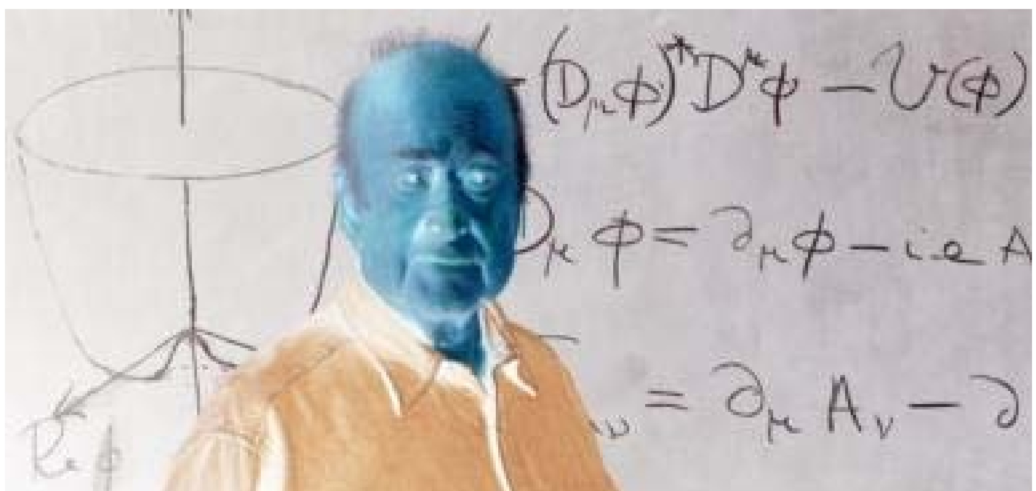
Signal significance of 5σ

Luminosity for SM Higgs discovery or exclusion

- **~few 100 pb^{-1}, some exclusion @ 95% CL**
- **~1 fb^{-1}, 5σ discovery if M_H ~160 - 170 GeV**
- **~10 fb^{-1}, discovery over a broad mass range**

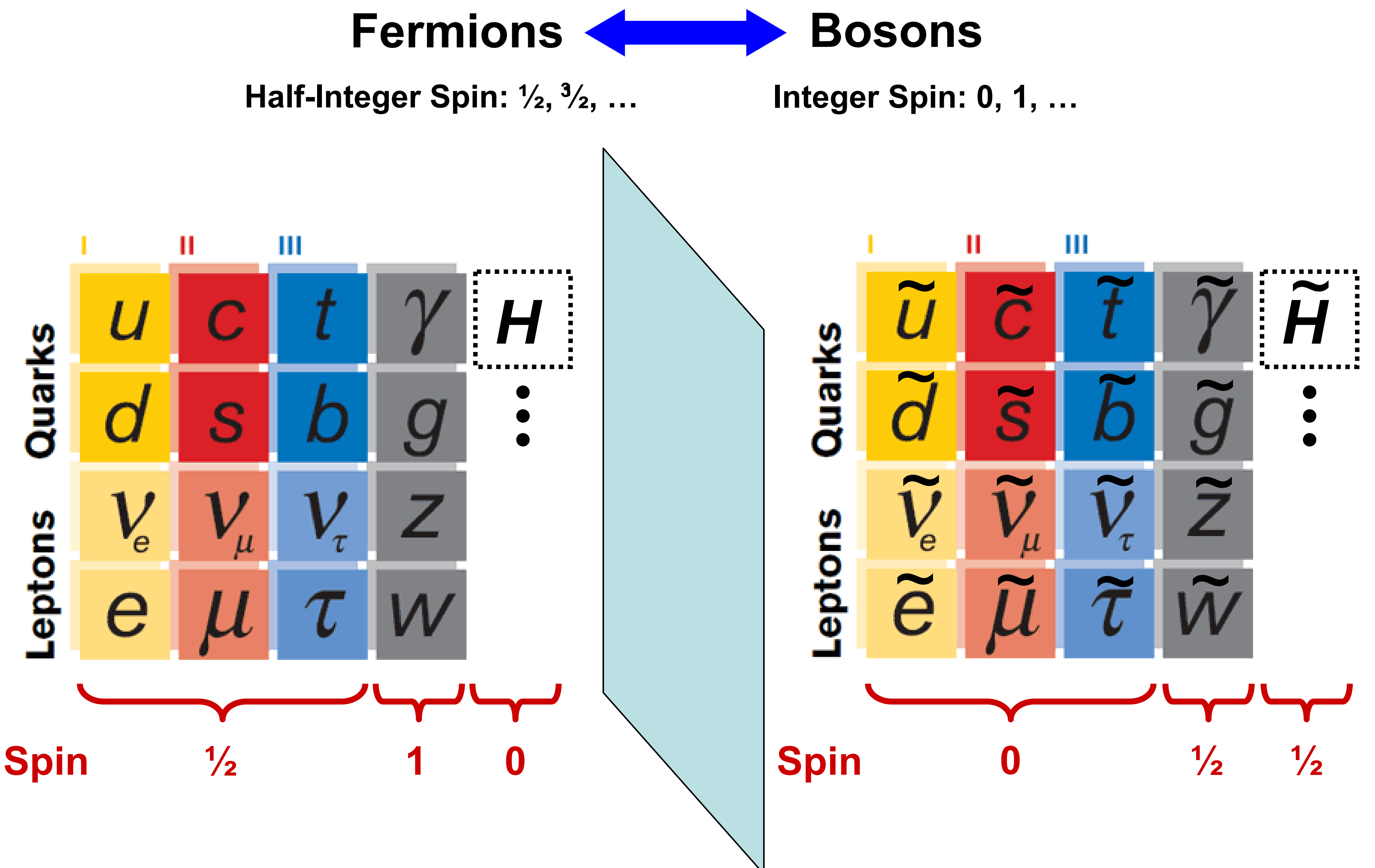


Supersymmetric Higgs(es)



Supersymmetry

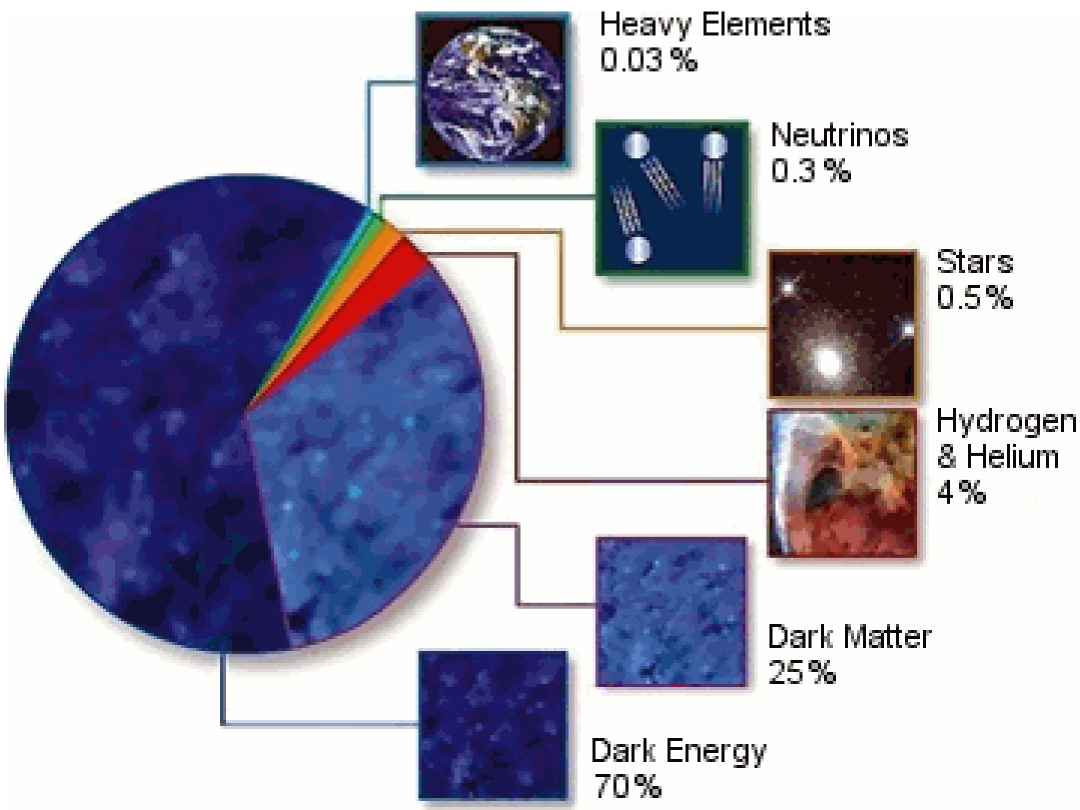
Every particle has a "super-partner" particle

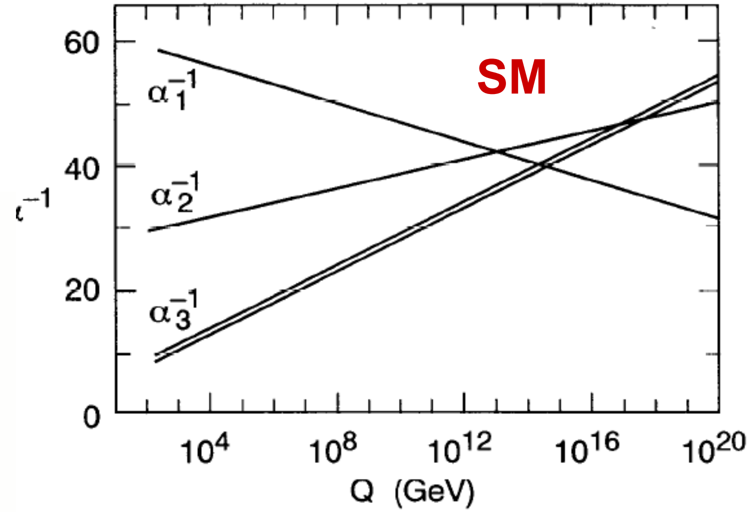


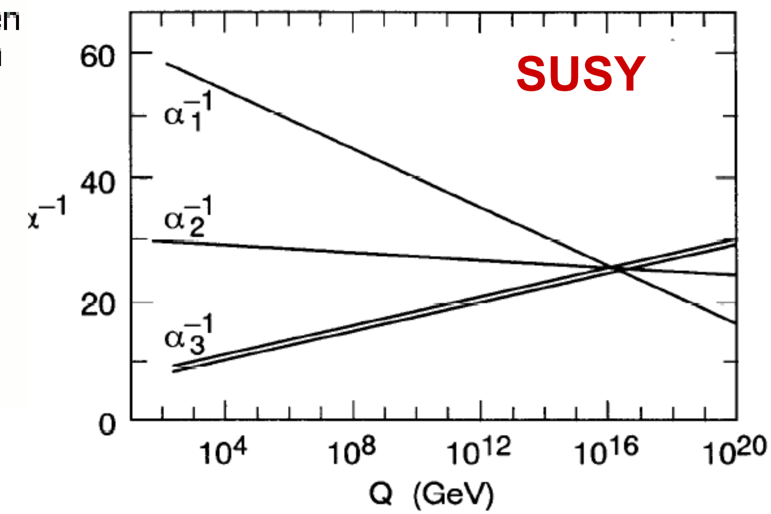
Motivation for SUSY

Motivation for Supersymmetry

- **Naturalness (Hierarchy Problem)**
- **Unification of the forces (gauge couplings)**
- **Provides a candidate for Dark Matter**







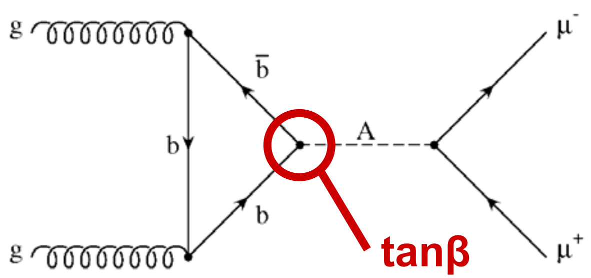
MSSM Higgs at the LHC

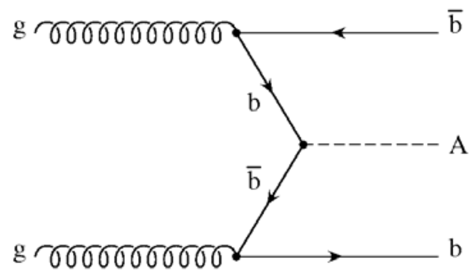
Minimal Supersymmetric extension to the SM: (A, H, h, H±)

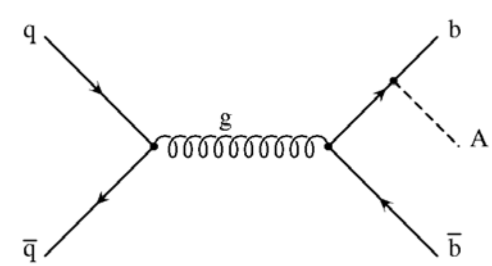
- As one example here, consider A / H →μμ
- Not visible in the SM
- Enhanced in the MSSM by ~$\tan^2\beta$; excellent mass resolution as opposed to ττ

Direct and associated production

Enhanced for large tanβ







Divide μμ analysis into two uncorrelated channels

Initial event selection:

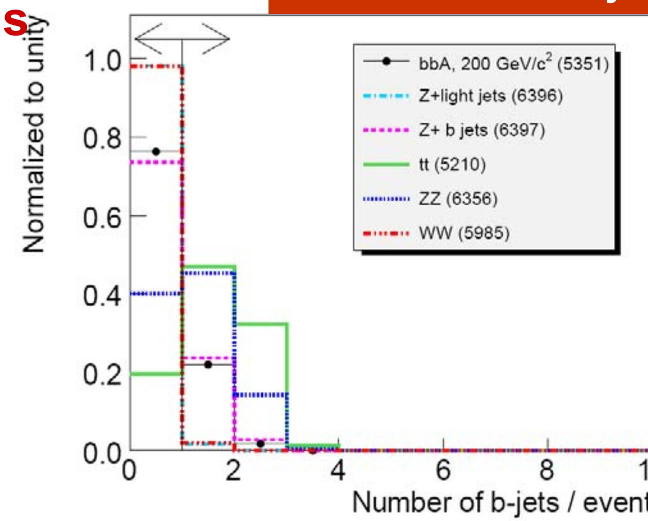
- Di-muon selection, low event MET, b-tag

0 b-jet

≥1 b-jet

- Acoplanarity, sum pT of all jets

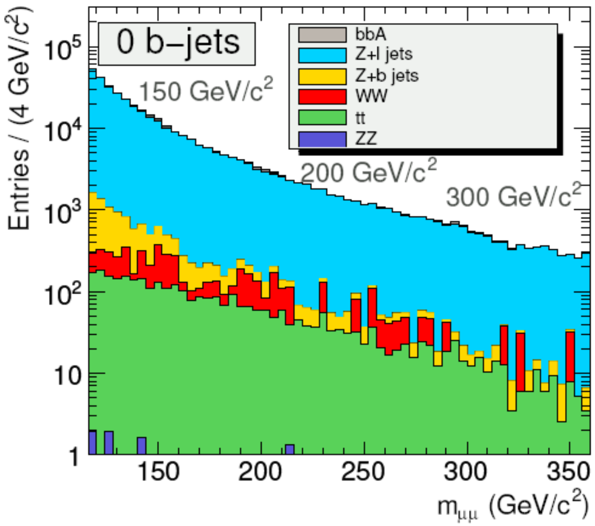
ATLAS Preliminary

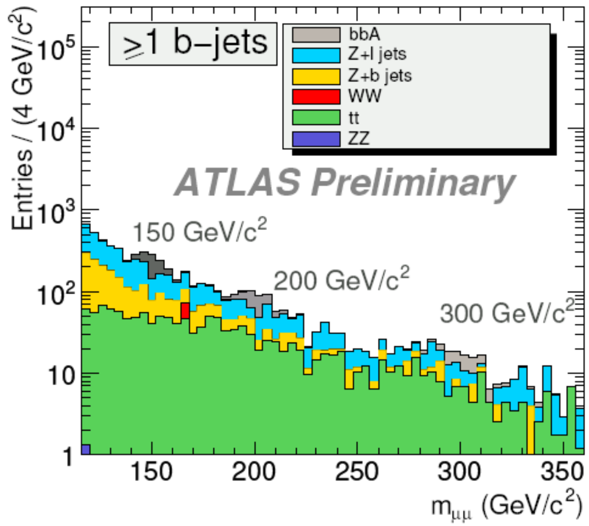


MSSM Higgs at the LHC

Combine the 0 and ≥ 1 b-jet analyses to increase the significance

- **A very similar analysis has been explored for the $\tau\tau$ channel**

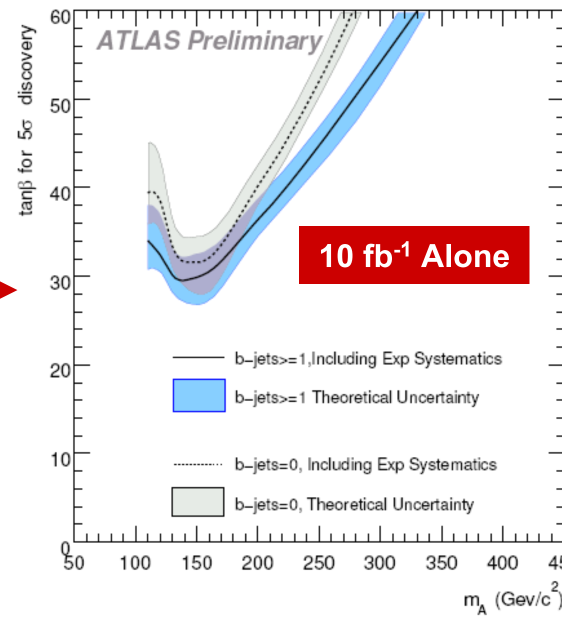


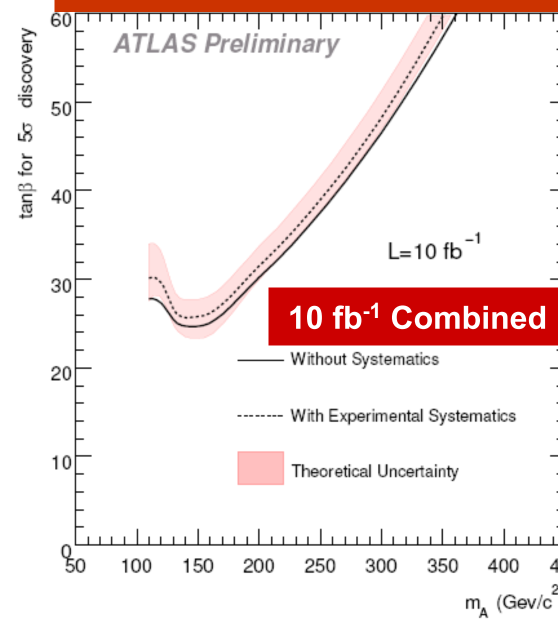


Reconstructed Invariant mass

ATLAS CSC 2008 10 fb^{-1}

tanβ for a 5σ Discovery

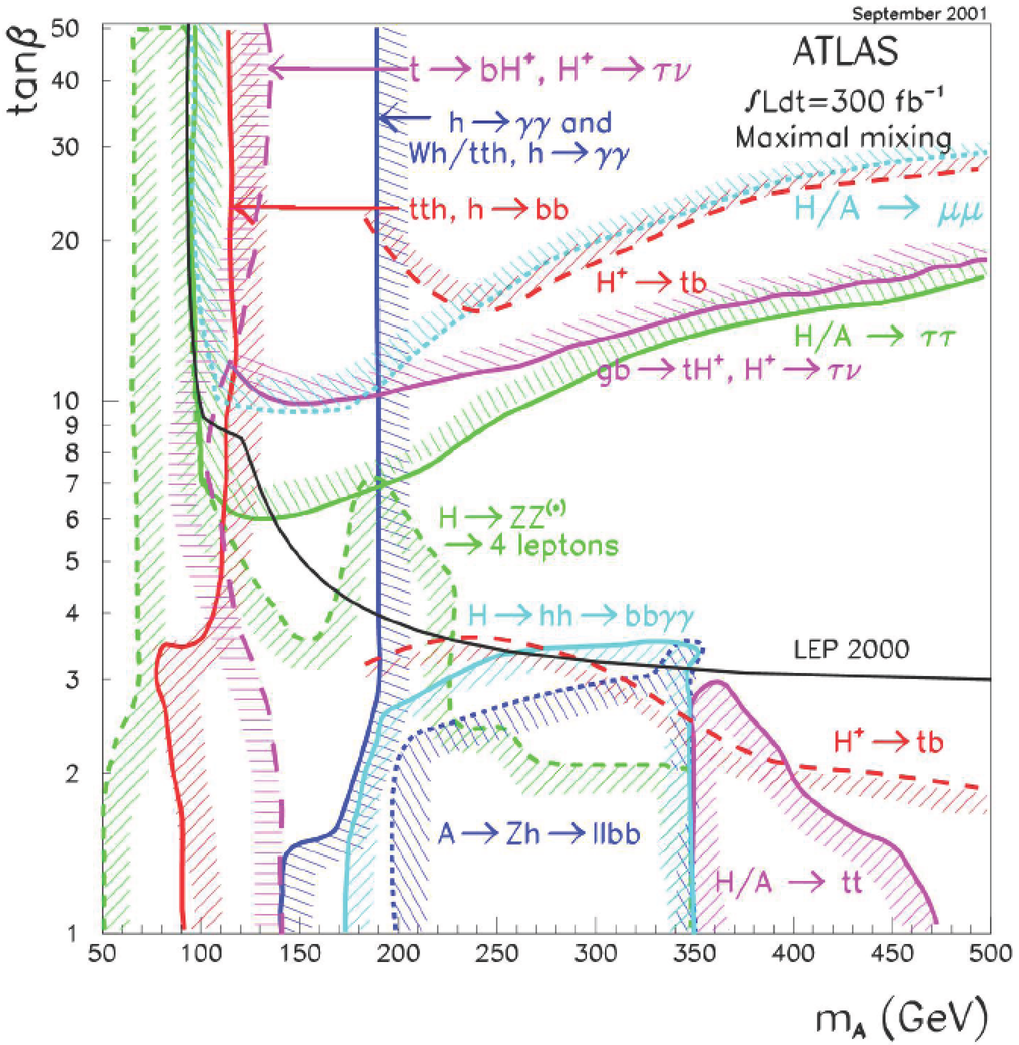




MSSM Higgses with ATLAS

The complete region of the m_A – tanβ parameter space should be accessible to ATLAS

- **mA = 50 – 500 GeV**
- **Tanβ = 1 - 50**

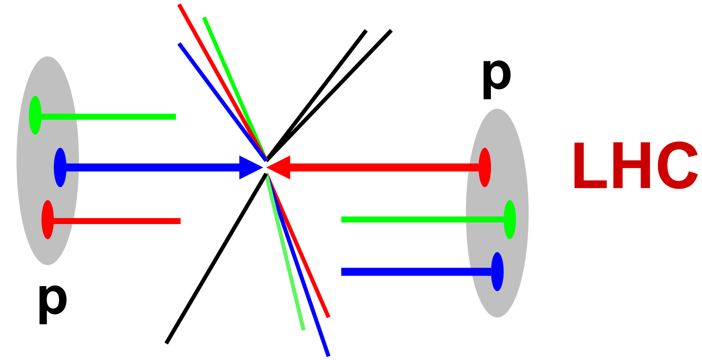


Is it really the Higgs?

Is it really the Higgs?

Properties that we will want to measure to confirm a Higgs discovery:

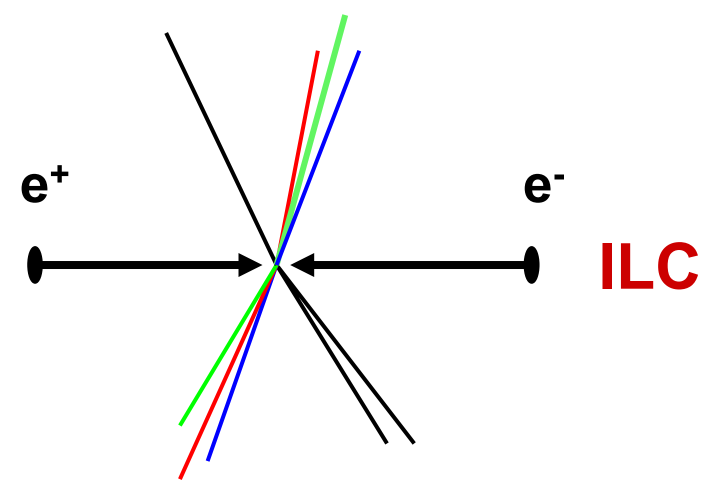
- **What is the mass and width?**
- **Does it have charge?**
- **What are the production processes and cross-sections?**
- **What are the branching-ratios?**
- **What are the couplings?**
- **What is its spin?**



Reasonably good precision from the LHC ~10-20% level
Get precise measurements from a high-energy e+e- collider ~1% level

The advantages of an e+e- collider:

- **They're elementary particles**
- **Able to collide them with well defined energy and angular momentum**
- **Collisions at the full center-of-mass energy**
- **"Democratic" particle production**
- **Possible to fully reconstruct the events**



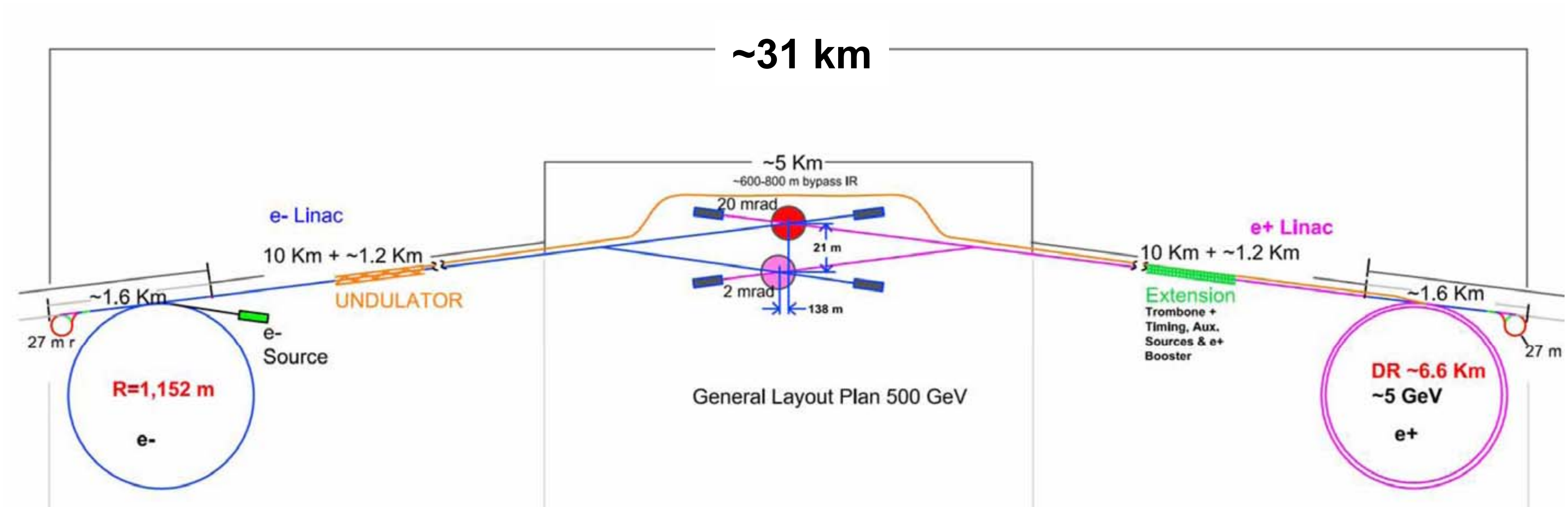
The International Linear Collider (ILC)

Already a huge international effort of R&D on this accelerator

- Global design effort well underway

Parameters for the ILC (derived from the scientific goals)

- Center-of-mass energy adjustable from 200 – 500 GeV (extendible to 1 TeV)
- Total integrated luminosity of 500 fb^{-1} in 4 years
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%



Cost: ~6.6 Billion USD

Location: One of three possible sites

- Locations in the Americas, Europe and Asia: Fermilab, CERN and Japan

Timescale: Commissioning sometime beyond 2020?

Conclusions

Conclusions

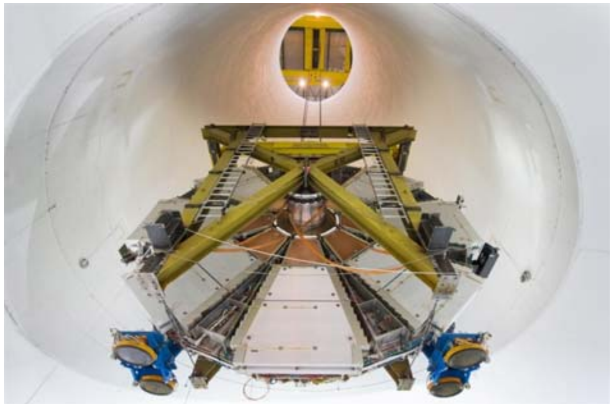
If it is there, ATLAS and CMS are in a good position to find the Higgs…

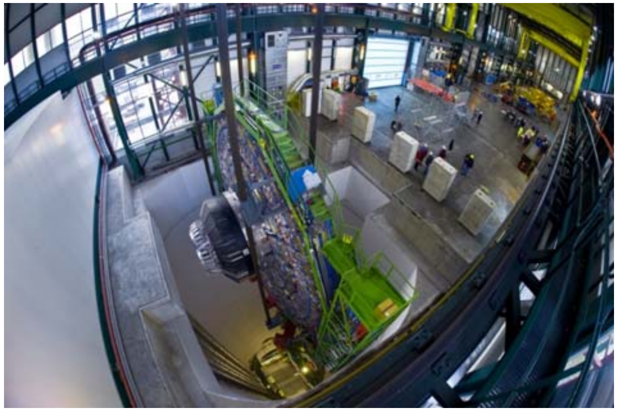
- **Unless it is discovered first at the Tevatron**
- **For a SM Higgs ATLAS and CMS need ~1 – 30 fb^{-1}**
- **How long will it take to get that much integrated luminosity from the LHC?**
- **How quickly will we understand the detectors?**

Post-discovery questions that would need be answered…

- **Is it the simple Standard Model Higgs?**
- **Does it have the expected couplings to various particle types?**
- **Are there more Higgs particles (à la Supersymmetry)**
- **Higgs discovery also raises the “hierarchy” problem**

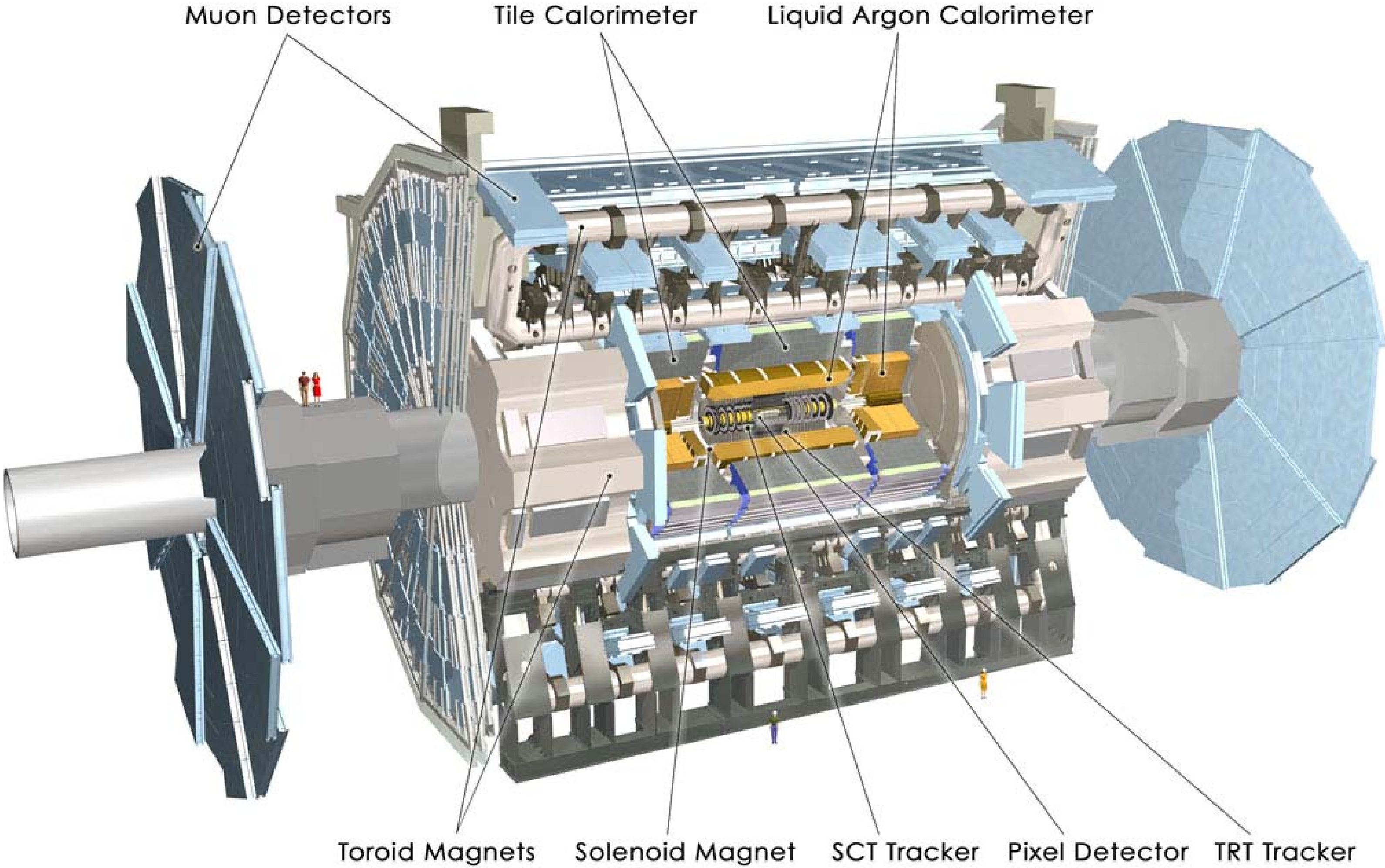
The LHC era has now begun… ATLAS and CMS will address these questions.



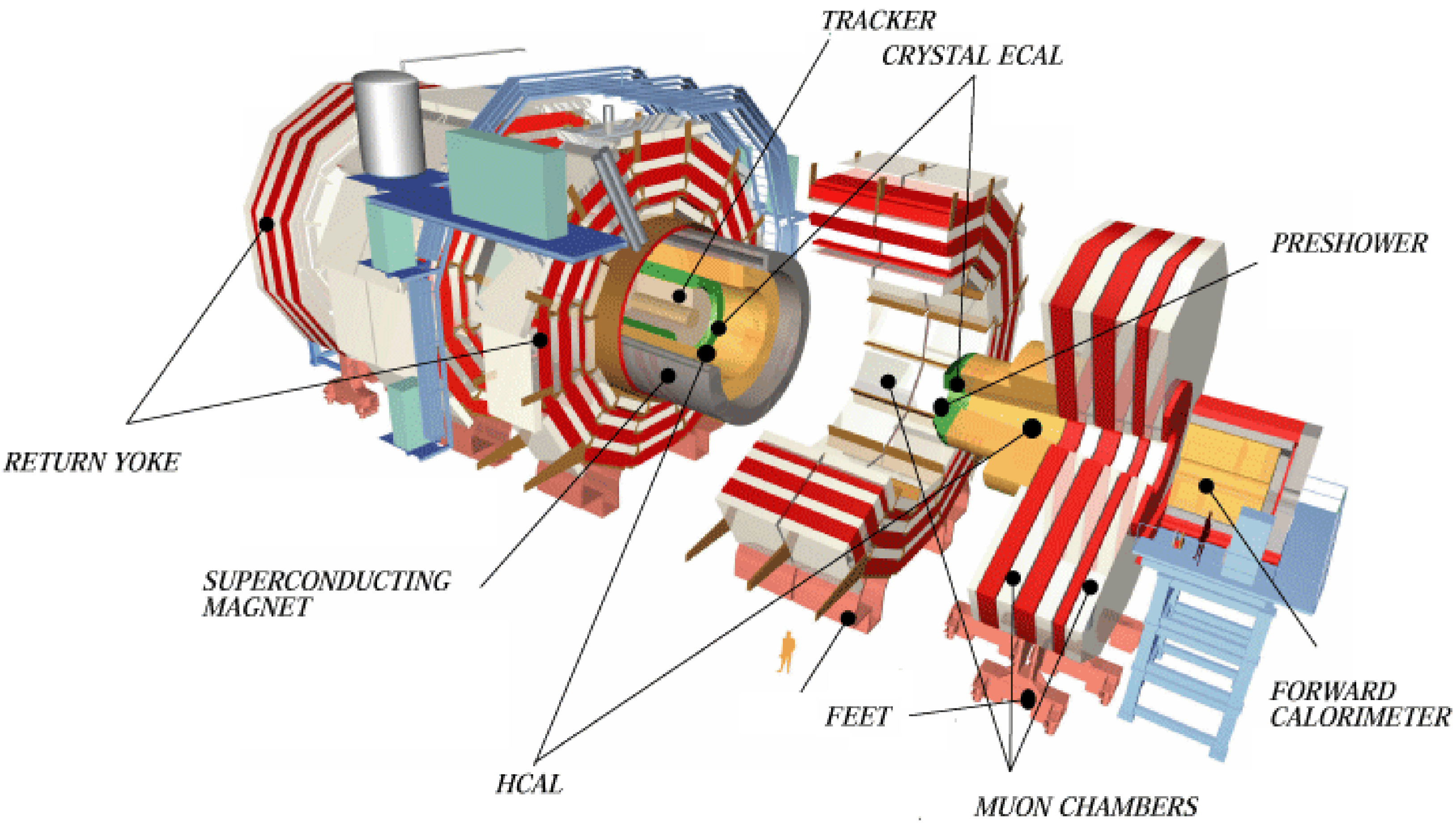


Backup Slides

The ATLAS Experiment



The CMS Experiment



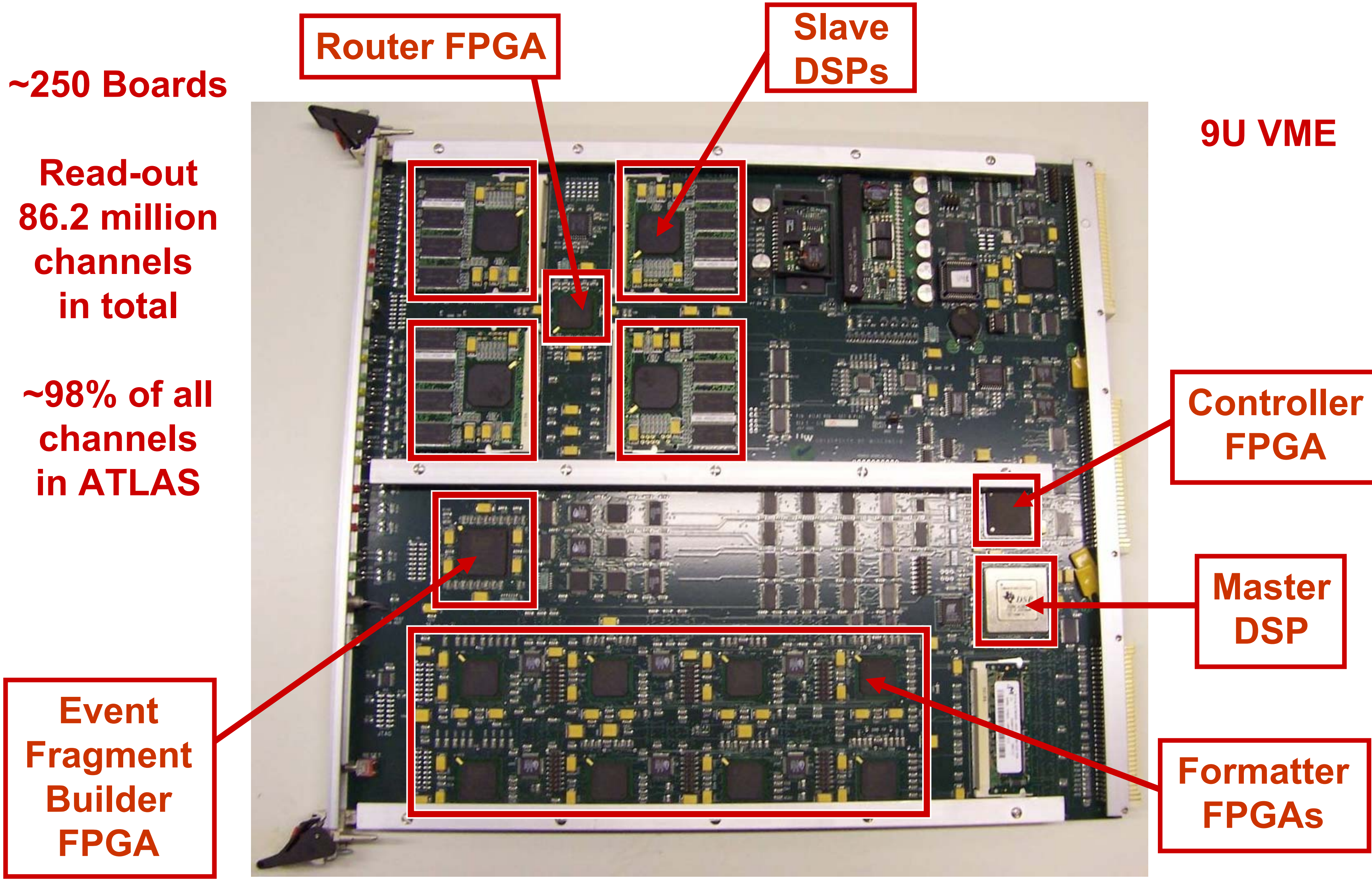
The Silicon Read-Out Driver (ROD)

~250 Boards

Read-out 86.2 million channels in total

~98% of all channels in ATLAS

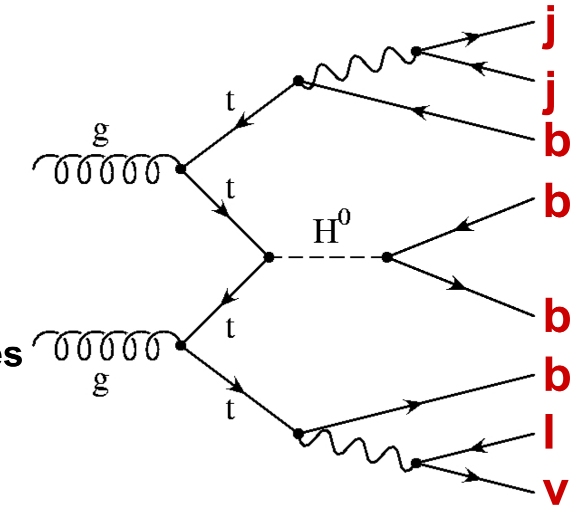
9U VME

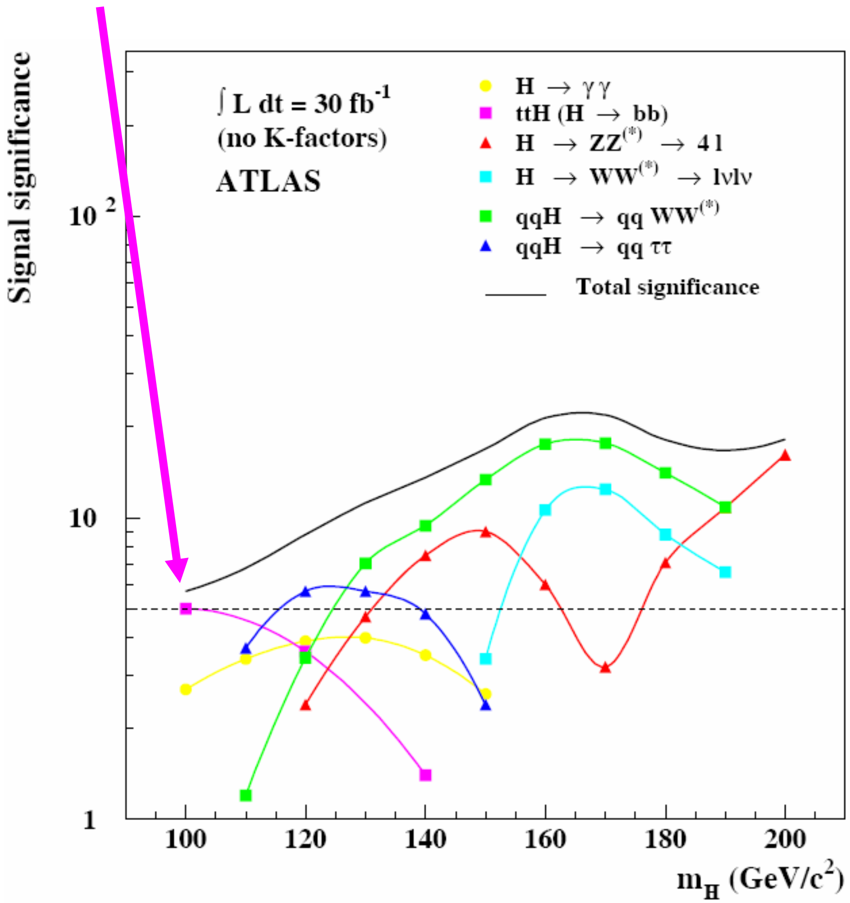


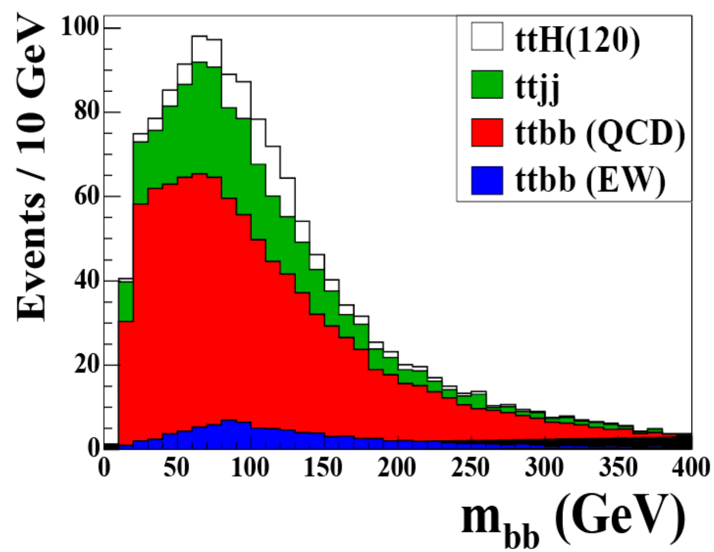
ttH(H→bb)

A very complex final state

- Good discovery channel at low masses
- Determination of the Yukawa coupling
- Dominant backgrounds tt+jets production
- Also considering fully-hadronic and dilepton final states







J. Cammin and M. Schumacher, ATL-PHYS-2003-024

Experimental issues:

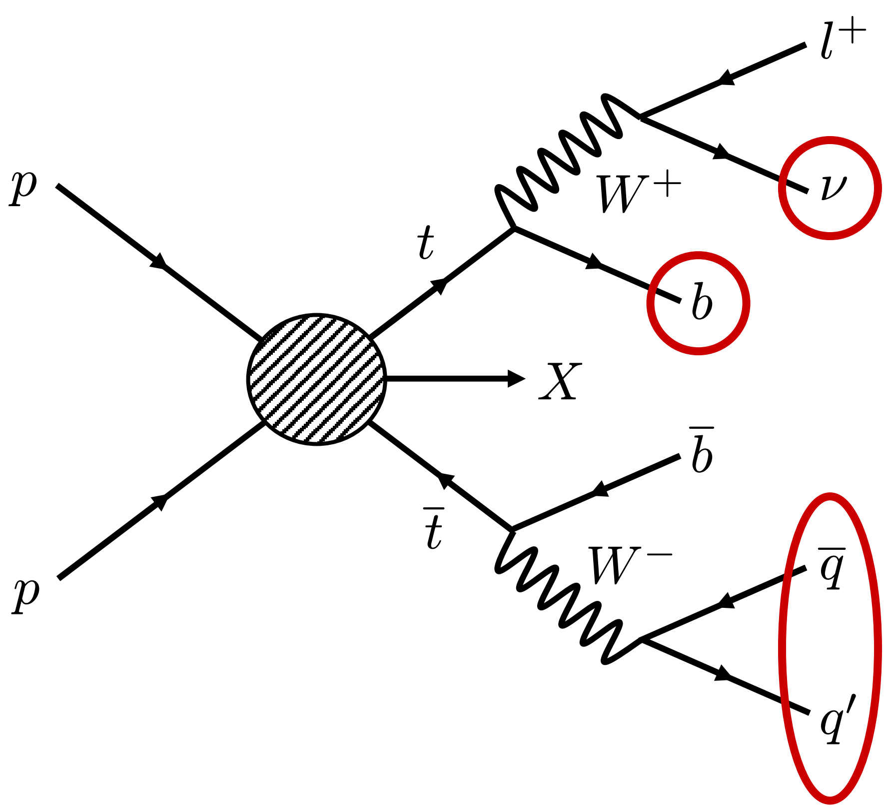
- b-tagging (efficiency $\sim\varepsilon_b^4$)
- Good understanding of background shape at turn-over

Calibration using Standard Candles

We will have a huge number of Ws and Zs in early running

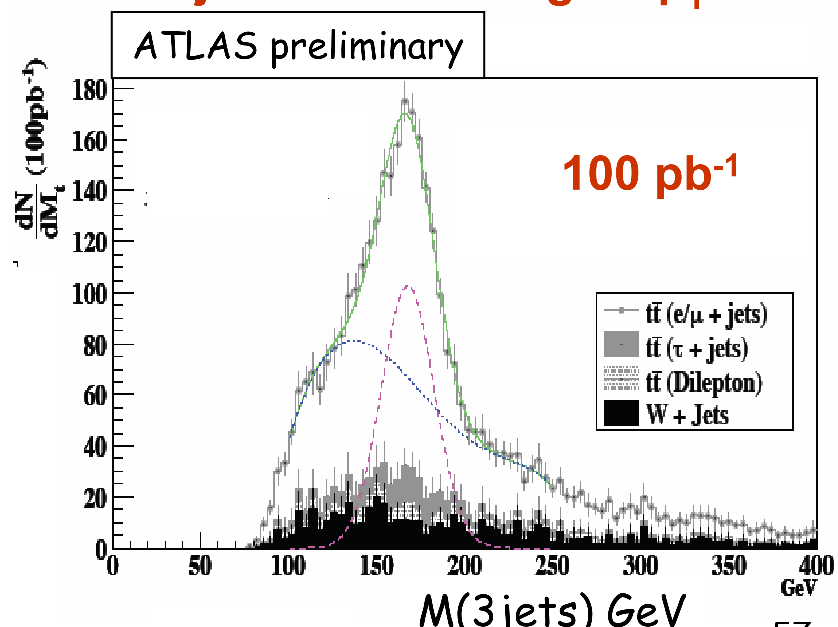
But, ttbar events are also very well suited for this purpose

- **Mass very well known from the Tevatron (~few GeV)**
- **A large number of ttbar events very early on (~1k events in 30 pb^{-1})**
- **Final state gives us an ideal sample to exercise b-jet identification, calibrate the jet energy scale (using $W \rightarrow jj$) and tune our Monte Carlo generators (e.g. from the p_T spectra)**



σ_{ttbar} (ttbar → Wb Wb→blν bjj) ~250 pb

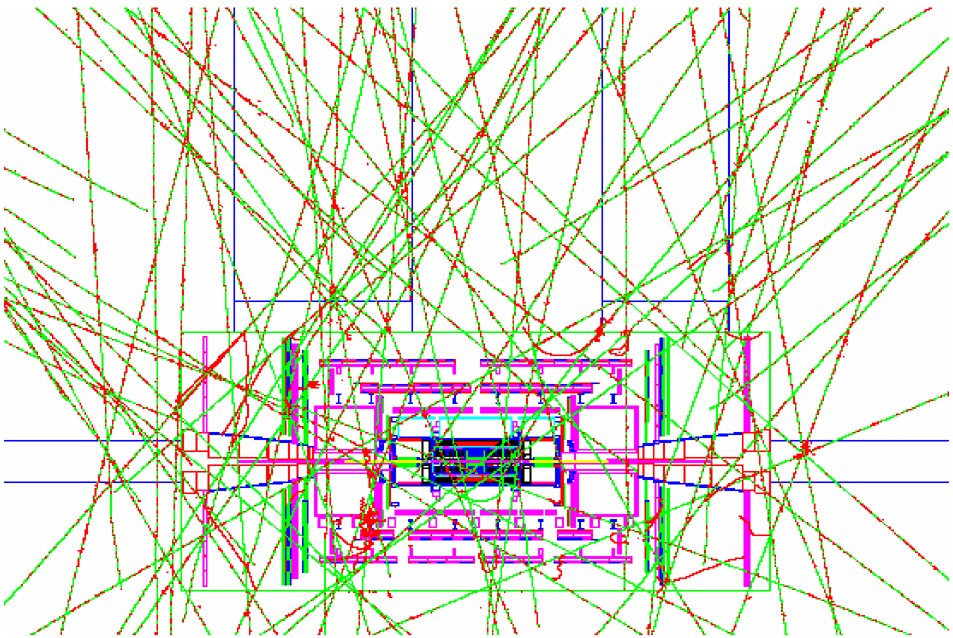
Invariant mass of the three jets with the largest p_T

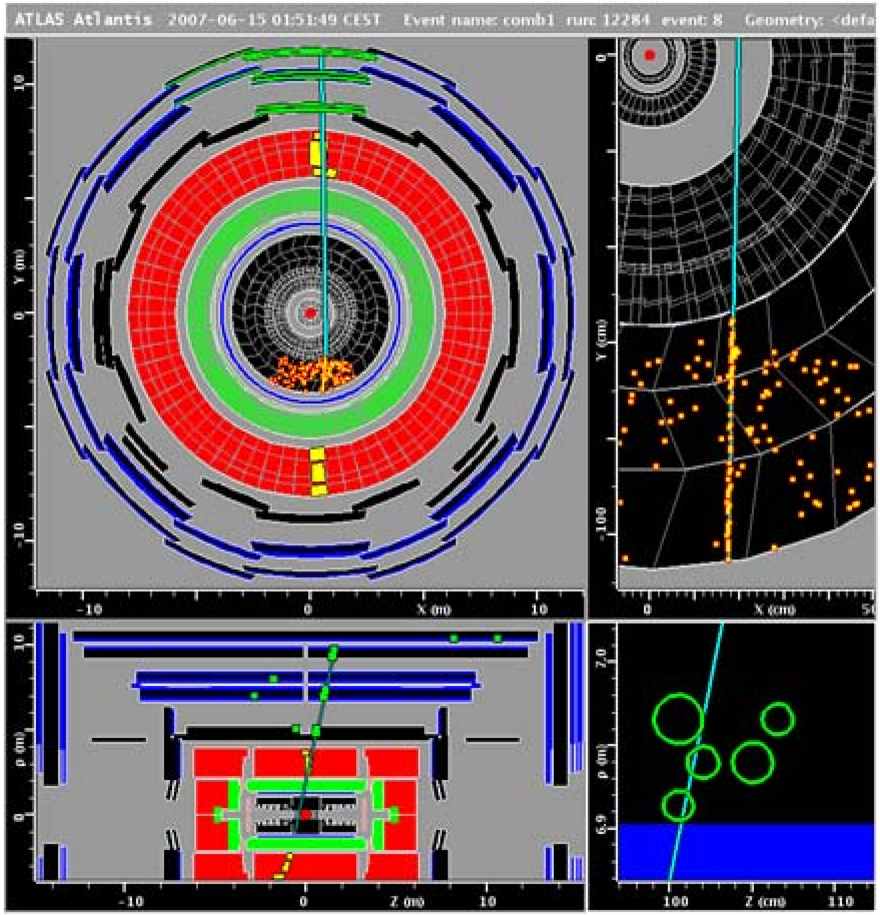


ATLAS Cosmic-ray Data-taking

ATLAS is already taking data…

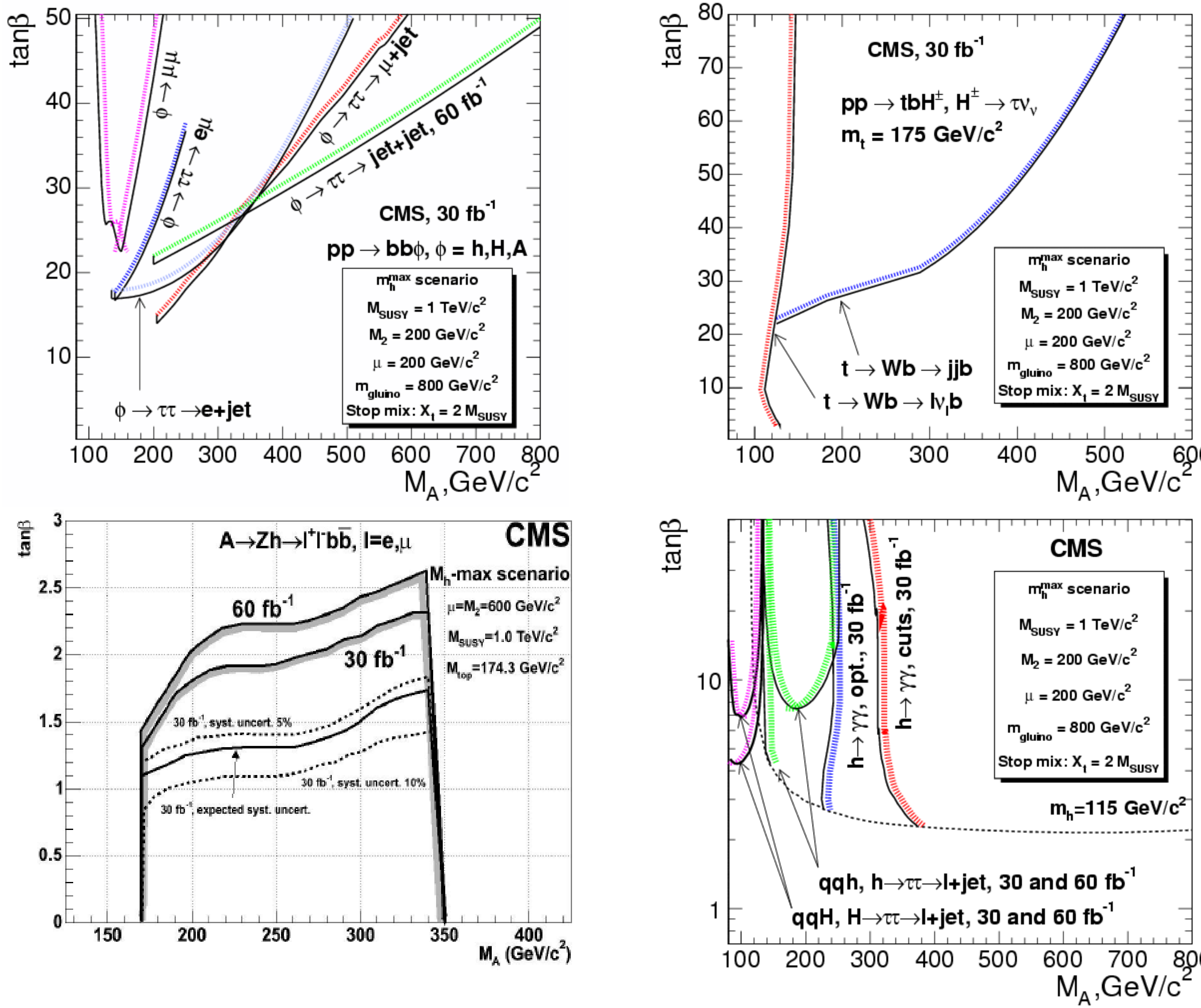
- **We get a constant delivery of cosmic rays for free**
- **Typical trigger rate is 1 – 200 Hz**





MSSM Higgs at the LHC

Summary of CMS reach in M_A tan β



VBF H $\to \tau\tau$

Decay modes	TAUOLA-CLEO
$\tau \to e\nu_e\ \nu_\tau$, $\tau \to \mu\nu_\mu\ \nu_\tau$	17.8 % 17.4 %
$\tau \to h^\pm neutr.\nu_\tau$	49.5 %
$\tau \to \pi^\pm\nu_\tau$	11.1 %
$\tau \to \pi^0\pi^\pm\nu_\tau$ $\tau \to \pi^0\pi^0\pi^\pm\nu_\tau$ $\tau \to \pi^0\pi^0\pi^0\pi^\pm\nu_\tau$	25.4 % 9.19 % 1.08 %
$\tau \to K^\pm neutr.\nu_\tau$	1.56 %
$\tau \to h^\pm h^\pm h^\pm neutr.\nu_\tau$	14.57 %
$\tau \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau$ $\tau \to \pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$ $\tau \to \pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$ $\tau \to \pi^0\pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	8.98 % 4.30 % 0.50 % 0.11 %
$\tau \to K^0_S X^\pm\nu_\tau$	0.90 %
$\tau \to (\pi^0)\pi^\pm\pi^\pm\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.10 %
other modes with K	1.30 %
others	0.03 %

Note: All cross-sections are shown in fb

S. Asai et al., ATL-PHYS-2003-005

	signal (fb)		background (fb)					
	VV	gg	$t\bar{t}$ + jets	WW + jets		γ^*/Z + jets		Total
				EW	QCD	EW	QCD	
Lepton acceptance	5.55		2014.	18.2	669.8	11.6	2150.	4864.
+ Forward Tagging	1.31		42.0	9.50	0.38	2.20	27.5	81.6
+ P_T^{miss}	0.85		29.2	7.38	0.21	1.21	12.4	50.4
+ Jet mass	0.76		20.9	7.36	0.11	1.17	9.38	38.9
+ Jet veto	0.55		2.70	5.74	0.05	1.11	4.56	14.2
+ Angular cuts	0.40		0.74	1.20	0.04	0.57	3.39	5.94
+ Tau reconstruction	0.37		0.12	0.28	0.001	0.49	2.84	3.73
+ Mass window	0.27	0.01	0.03	0.02	0.0	0.04	0.15	0.24
$H \to \tau\tau \to e\mu$	0.27	0.01	0.03	0.02	0.0	0.04	0.15	0.24
$H \to \tau\tau \to ee$	0.13	0.01	0.01	0.01	0.0	0.02	0.07	0.11
$H \to \tau\tau \to \mu\mu$	0.14	0.01	0.01	0.01	0.0	0.02	0.07	0.11

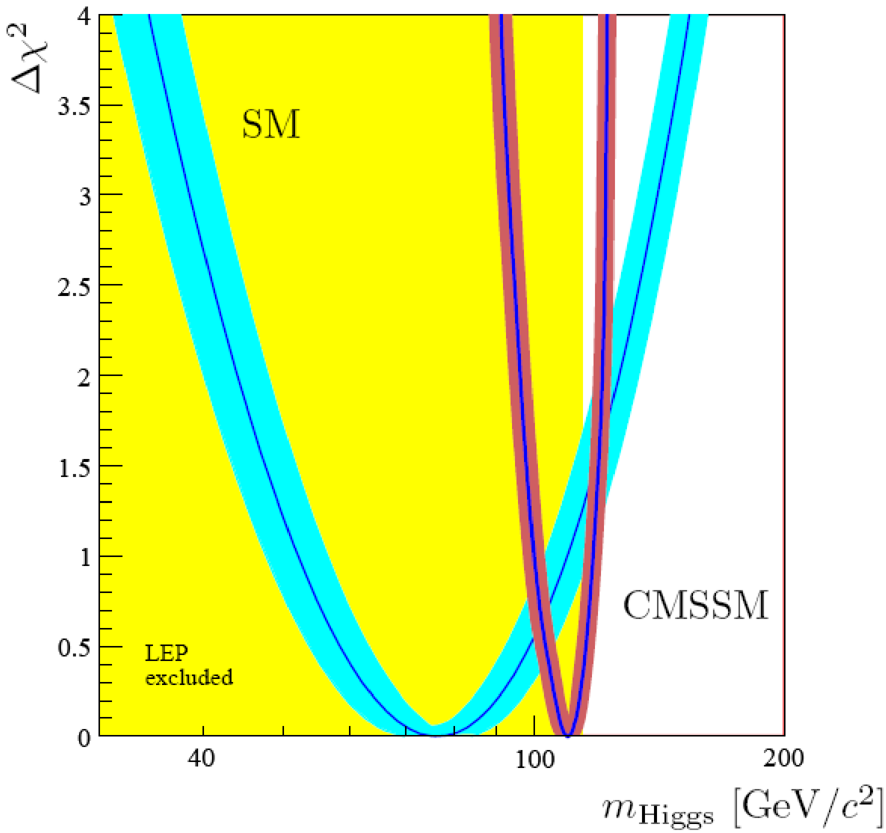
CMSSM

Constrained MSSM

- **O. Buchmueller et al., arXiv:0707.3447v2 [hep-ph]**
- **CMSSM: M_h = 110 (+8)(-10) ± 3 (theo.) GeV**
- **Includes CDM, flavor physics and a_μ experimental data**

CMSSM parameter	Preferred value
M_0	(85^{+40}_{-25}) GeV/c^2
$M_{1/2}$	(280^{+140}_{-30}) GeV/c^2
A_0	(-360^{+300}_{-140}) GeV/c^2
$\tan\beta$	10^{+9}_{-4}
sgn(μ)	+1 (fixed)

Table 2
Values of the CMSSM parameters at the globally preferred χ^2 minimum, and corresponding 1-sigma errors. The lower limit of Eq. 2 is included.



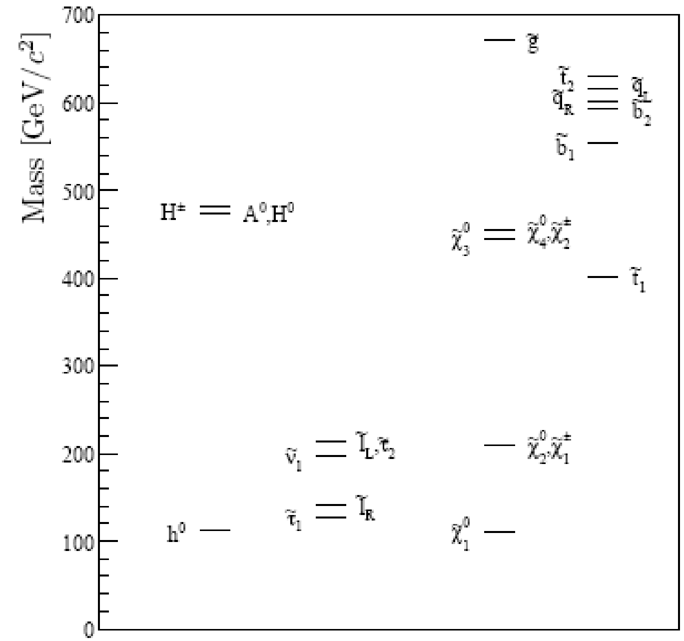
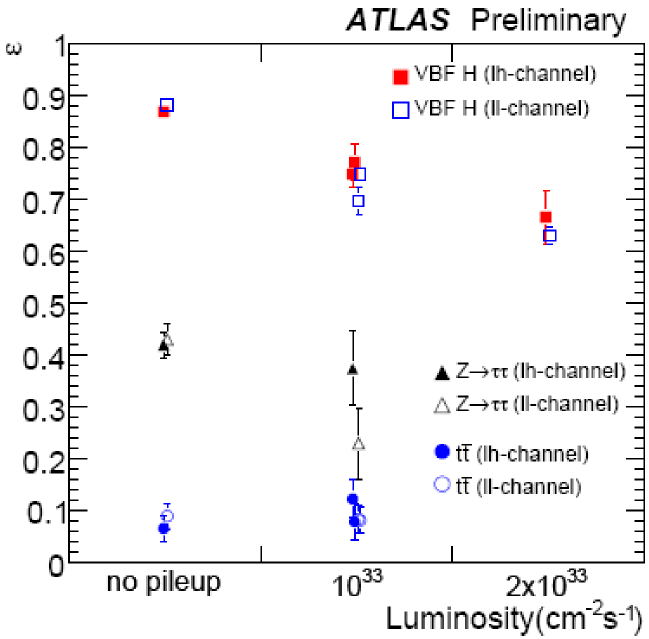


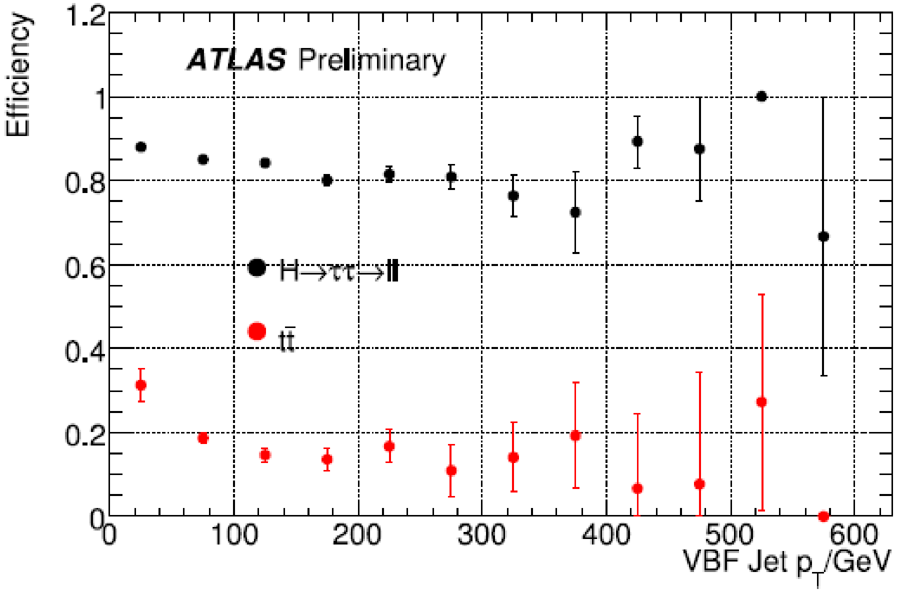
Figure 2. Mass spectrum of super-symmetric particles at the globally preferred χ^2 minimum. Particles with mass difference smaller than 5 GeV/c^2 have been grouped together.

chi² / ndf = 17.34 / 14

Central Jet Veto and Pile-up



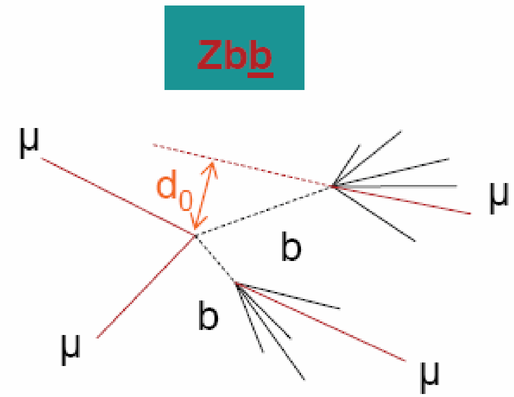
(a)



(b)

Figure 7: (a) Central Jet Veto performance in the presence of varying levels of pileup for signal and background samples. (b) Performance of the b-jet tagging as a function of the forward jet p_T in the events, where the $t\bar{t}$ processes is analyzed.

Impact Parameter



Displaced vertices present

in $Zb\bar{b}$ and $t\bar{t}$

Impact Parameter Significance ≡ d_0/σ_{d0}

Transverse impact parameter resolution

~15 μm for P_T = 20 GeV

Transverse primary vertex spread

~15 μm, taken into account

Isolation + Impact Parameter Criteria

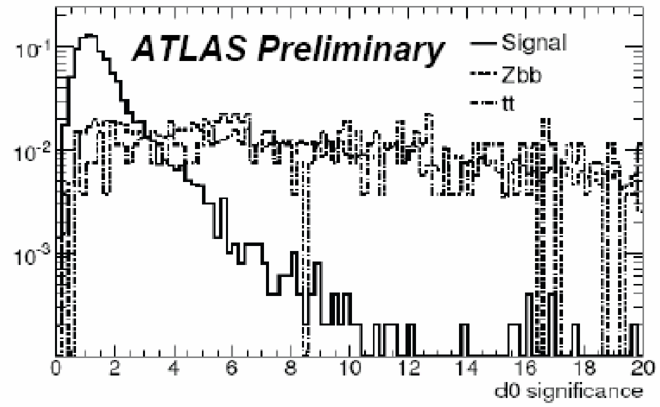
$O(10^2)$ Rejection for $Zb\bar{b}$

$O(10^3)$ Rejection for $t\bar{t}$

for signal efficiency O(80%)

Effect of pile-up on signal significance ≤5% *preliminary*

H(130 GeV) → ZZ^* → 4μ



Higgs Properties

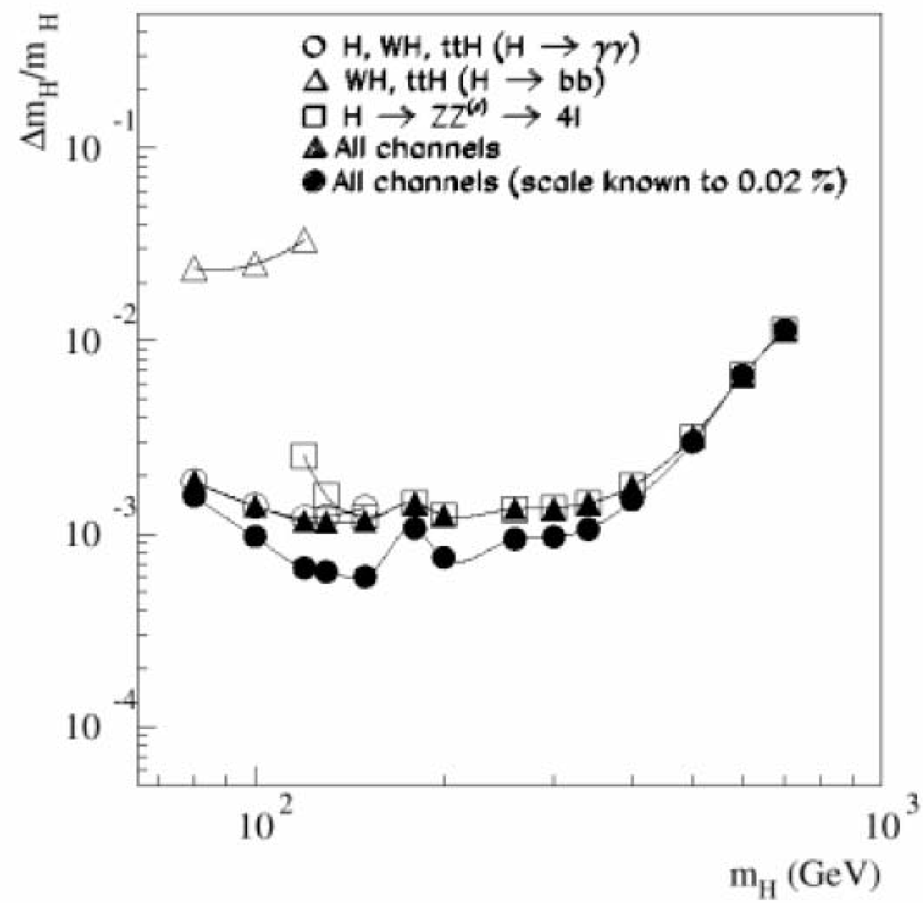
Higgs Properties: Mass

Mass

Favoured mass of SM Higgs
$113.5 < mH < 212$ GeV

In this range m_H can be measured to 0.1% using $\gamma\gamma$ and 4ℓ channels

Energy scale can be calibrated to 0.1% using $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$



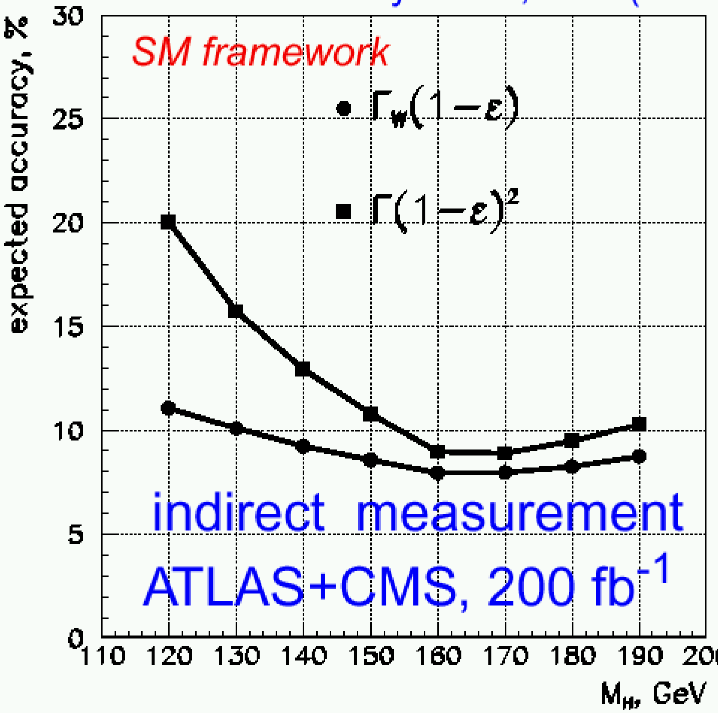
Higgs Properties: Width

- **precise measurement of width**

  qq->qqh. h->2γ,WW$^{(*)}$, 2τ together with gg->WW$^{(*)}$ allows indirect measurement of Higgs width

  D. Zeppenfeld, R. Kinnunen, A. Nikitenko

  E. Richter-Was. Phys.Rev., D62 (2000)



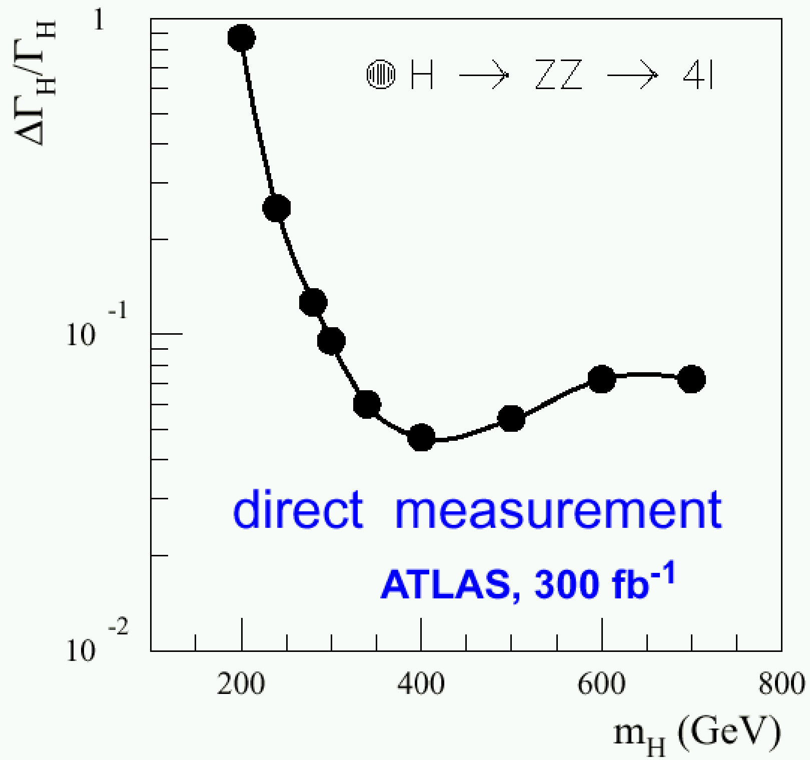
- **observation of other Higgs channels :**

  Wh with h->bb, h->$\gamma\gamma$

  tth with h->$\gamma\gamma$, WW

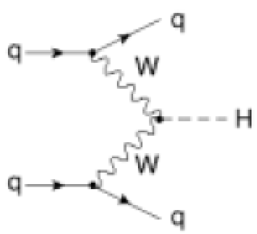
  qqh, with h->$\mu\mu$ (?)

- **self couplings; h->hh (?)**



Higgs Properties: Cross-sections

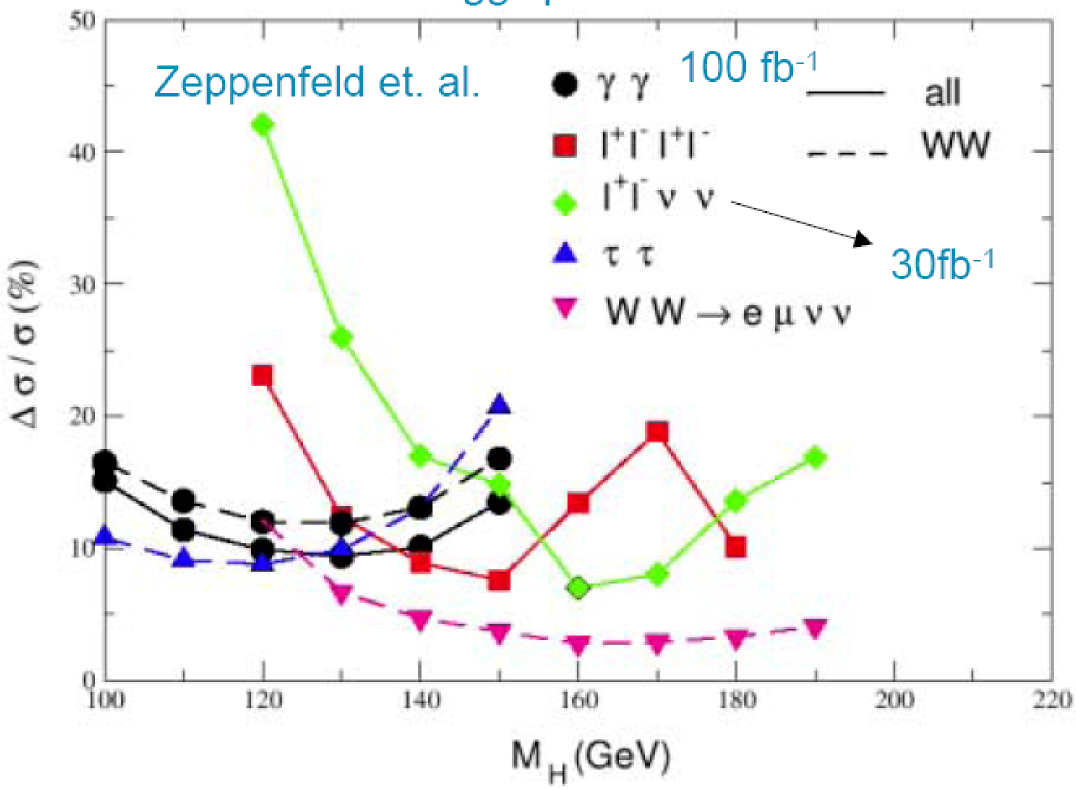
10% of σ in intermediate mass region comes from WW fusion
Identified by requiring forward tagging jets and no additional central jets



Errors
Statistical: 5 – 20%
$\gamma\gamma$ and 4ℓ well understood
Modes involving fwd jets more difficult to estimate

Corrected σ compared with perturbative QCD calculations
Known to NLO for all and NNLO for gg→H processes

Higgs production via WW fusion



Higgs Properties: Couplings and BRs

Use various Higgs production and decay modes
In ratios luminosity uncertainty largely cancels
Assuming 300 fb-1

$$\frac{\sigma.B(t\bar{t}H + WH \to \gamma\gamma)}{\sigma.B(t\bar{t}H + WH \to b\bar{b})} \Rightarrow \frac{BR(H \to \gamma\gamma)}{BR(H \to b\bar{b})}$$

$$\frac{\sigma.B(H \to \gamma\gamma)}{\sigma.B(H \to ZZ^*)} \Rightarrow \frac{BR(H \to \gamma\gamma)}{BR(H \to ZZ^*)}$$

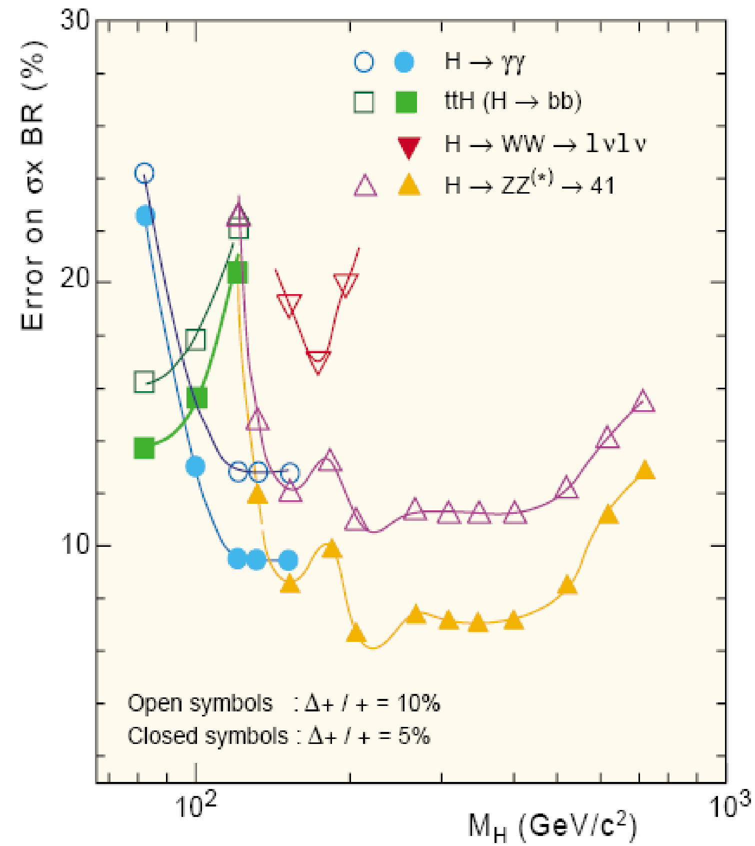
$$\frac{\sigma.B(t\bar{t}H \to \gamma\gamma / b\bar{b})}{\sigma.B(WH \to \gamma\gamma / b\bar{b})} \Rightarrow \frac{g^2_{Ht\bar{t}}}{g^2_{HWW}}$$

$$\frac{\sigma.B(H \to WW^* / W)}{\sigma.B(H \to ZZ^* / Z)} \Rightarrow \frac{g^2_{HWW}}{g^2_{HZZ}}$$

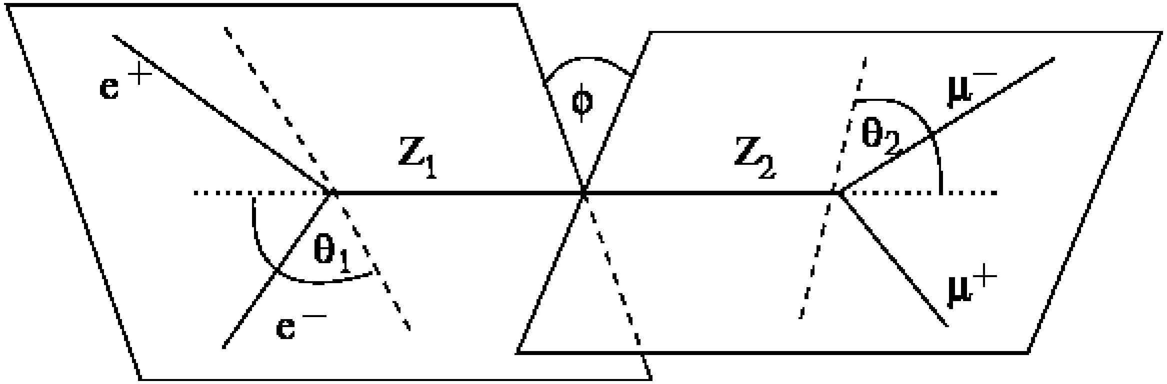
Higgs Properties: Branching Ratios

BR cannot be measured directly at the LHC
But possible to infer ratios of couplings from measured rates

Measure	Error	M_H range
$\frac{B(H \to \gamma\gamma)}{B(H \to b\bar{b})}$	30%	80–120
$\frac{B(H \to \gamma\gamma)}{B(H \to ZZ^*)}$	15%	125–155
$\frac{\sigma(t\bar{t}H)}{\sigma(WH)}$	25%	80–130
$\frac{B(H \to WW^{(*)})}{B(H \to ZZ^{(*)})}$	30%	160–180



Higgs Properties: CP



Azimutal angle ϕ between decay planes in the rest frame of Higgs

$$F(\phi) = 1 + \alpha \cos(\phi) + \beta \cos(2\phi)$$

Polar angle θ between lepton and the Z momentum in Z rest frame

$$G(\theta) = L \sin^2(\theta) + T(1+\cos^2(\theta)),\ R=(L-T)/(L+T)$$

M_{Z*} distribution for $M_H < 2\,M_Z$, $d\Gamma_H/dM_{Z*}^2 \sim \beta^n$ near threshold (n=1 in SM)

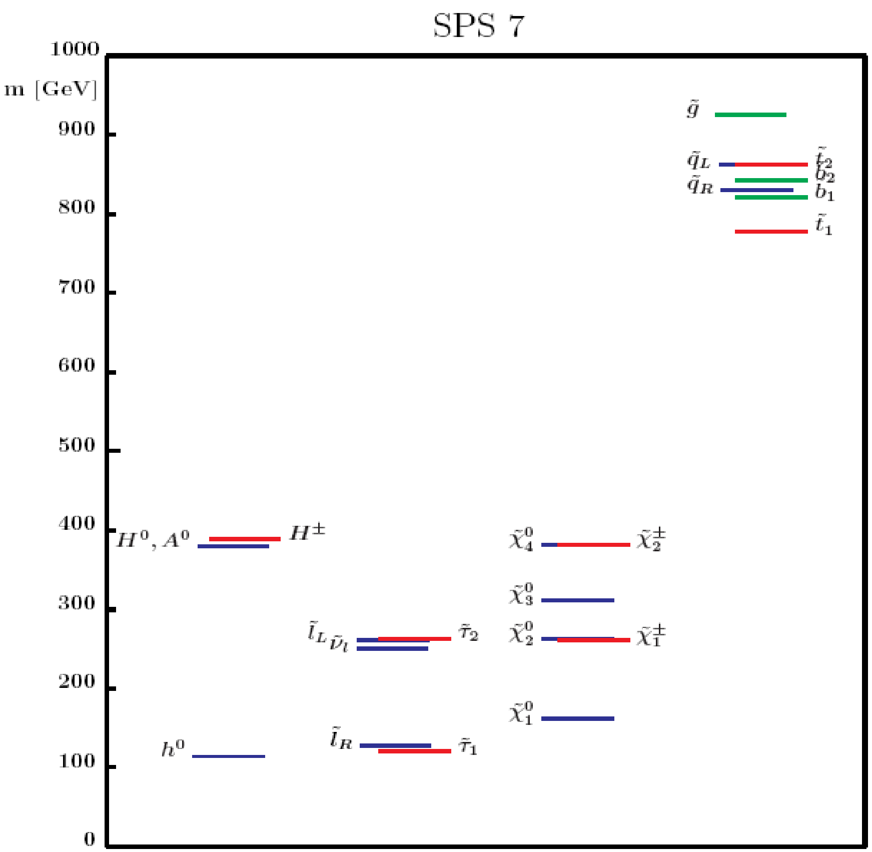
$$\beta^2=[1-(M_Z+M_{Z*})^2/M_H^2][1-(M_Z-M_{Z*})^2/M_H^2]$$

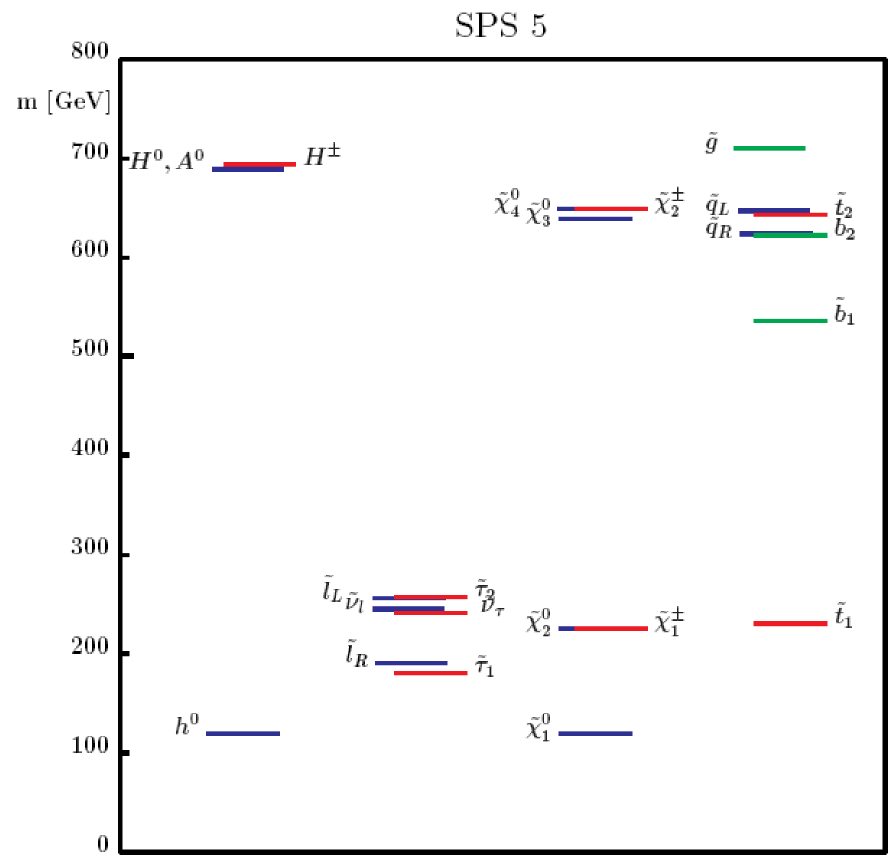
Resent ATLAS fast simulation study on sensitivity to $F(\phi)$ and $G(\theta)$
for exclusion of 0^-, 1^+, 1^- for $M_H > 2M_Z$: SN-ATLAS-2003-025

Higgs Channels

Five Higgses

From two of the Snowmass points and slopes:

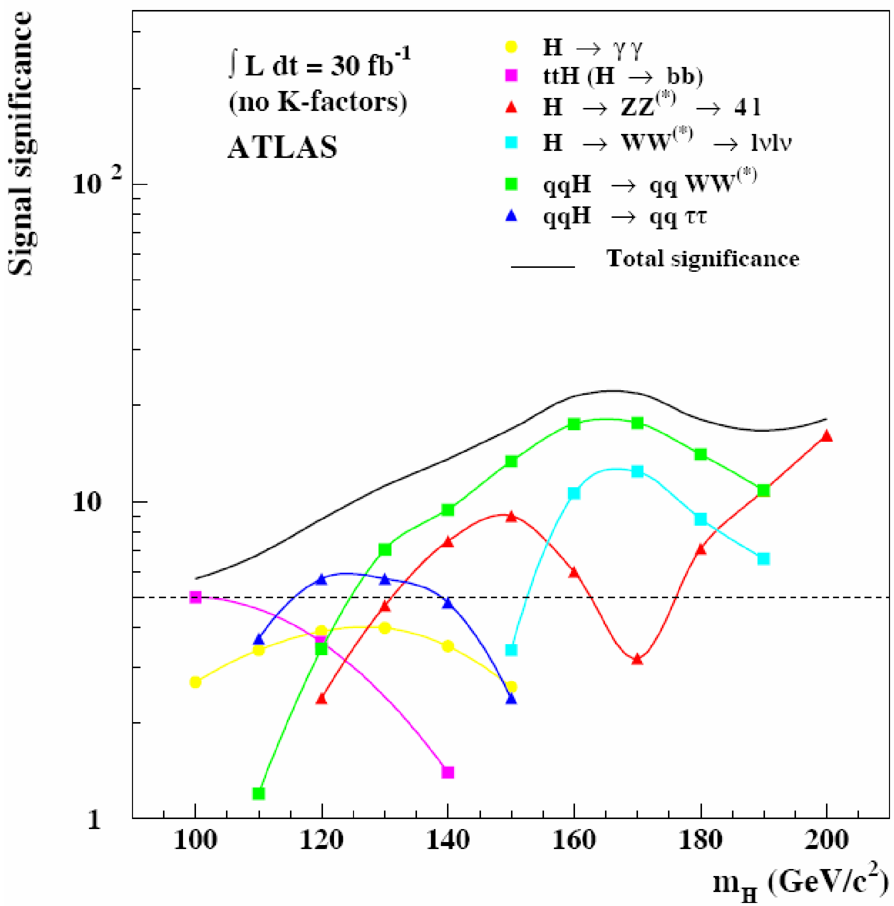


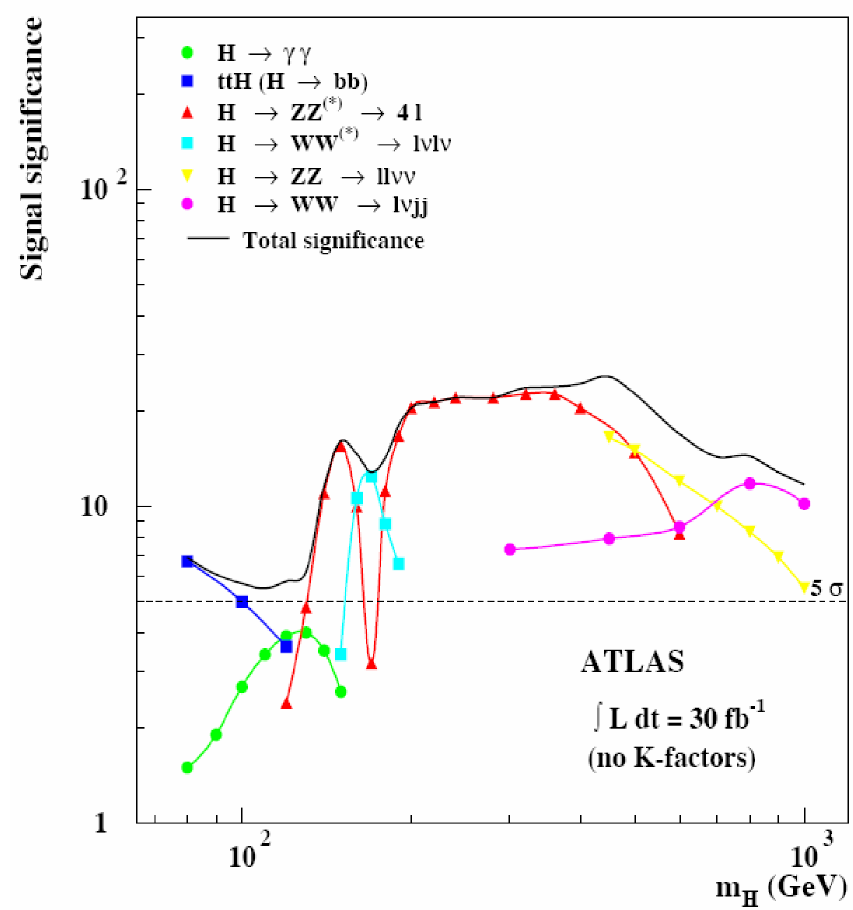


Standard Model Higgs at ATLAS

ATLAS is in a good position to study all of these final states

- **We'll come back to this…**





ATLAS-TDR, CERN/LHCC 99-14/15, May 1999

Tau ID in ATLAS

- **two algorithms:** calorimetry-based (*tauRec*) and track-based (*tau1p3p*)
- **Calorimetry:** collimated energy deposition, π^0s produced, isolation region, EM radius, EM fraction
- **Tracking:** low track multiplicity, isolation region, positive impact parameter, invariant mass and width of track system (3-prong)
- **Highlights from Data Preparation Perspective:**
  - τ-specific calibrations need to be understood
  - tracking objects associated with calo objects: good sensitivity to detector performance

Tau ID in ATLAS

Track based approach

identify "good quality" hadronic track, $p_T > 9$ GeV,
find nearby "good quality" tracks with $p_T > 2$ GeV in $\Delta R<0.2$

τ_{1P}

no nearby-track
(ϕ,η) from track at vertex

build E_T^{eflow}, use $\Delta R < 0.2$

build discrimination variables
use $\Delta R < 0.2$ as a "core",
$0.2 < \Delta R < 0.4$ for isolation only

τ_{1P} - single-prong candidates

τ_{3P}

2 nearby tracks
(ϕ,η) from bary centre of tracks
Σcharge = +-1

build E_T^{eflow}, use $\Delta R < 0.2$

build discrimination variables
use $\Delta R < 0.2$ as a "core",
$0.2 < \Delta R < 0.4$ for isolation only

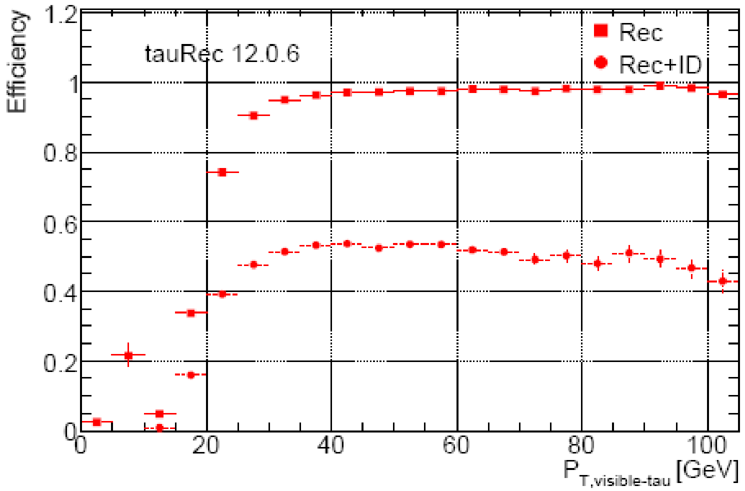
τ_{3P} - three-prong candidates

Tau Efficiency

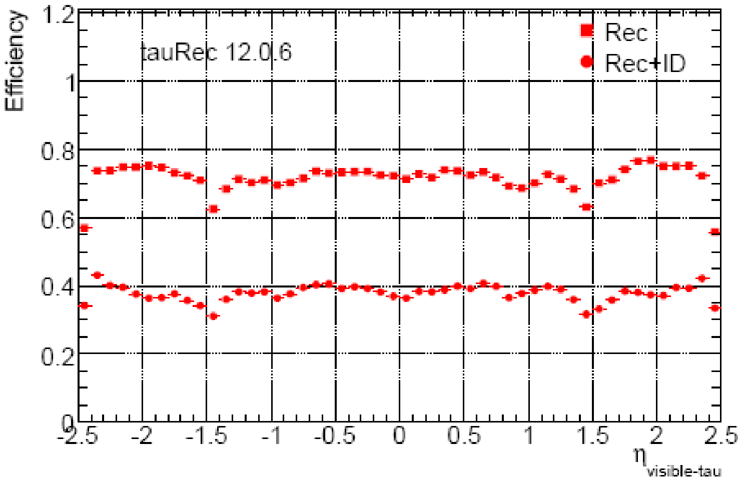
faking tau	**estimated** FR
electrons	~2%
muons	~0.5%
jets	~0.1%

FR depends on event activity and tau ID requirements, so this table just gives a rough order of magnitude estimate

(a)



(b)

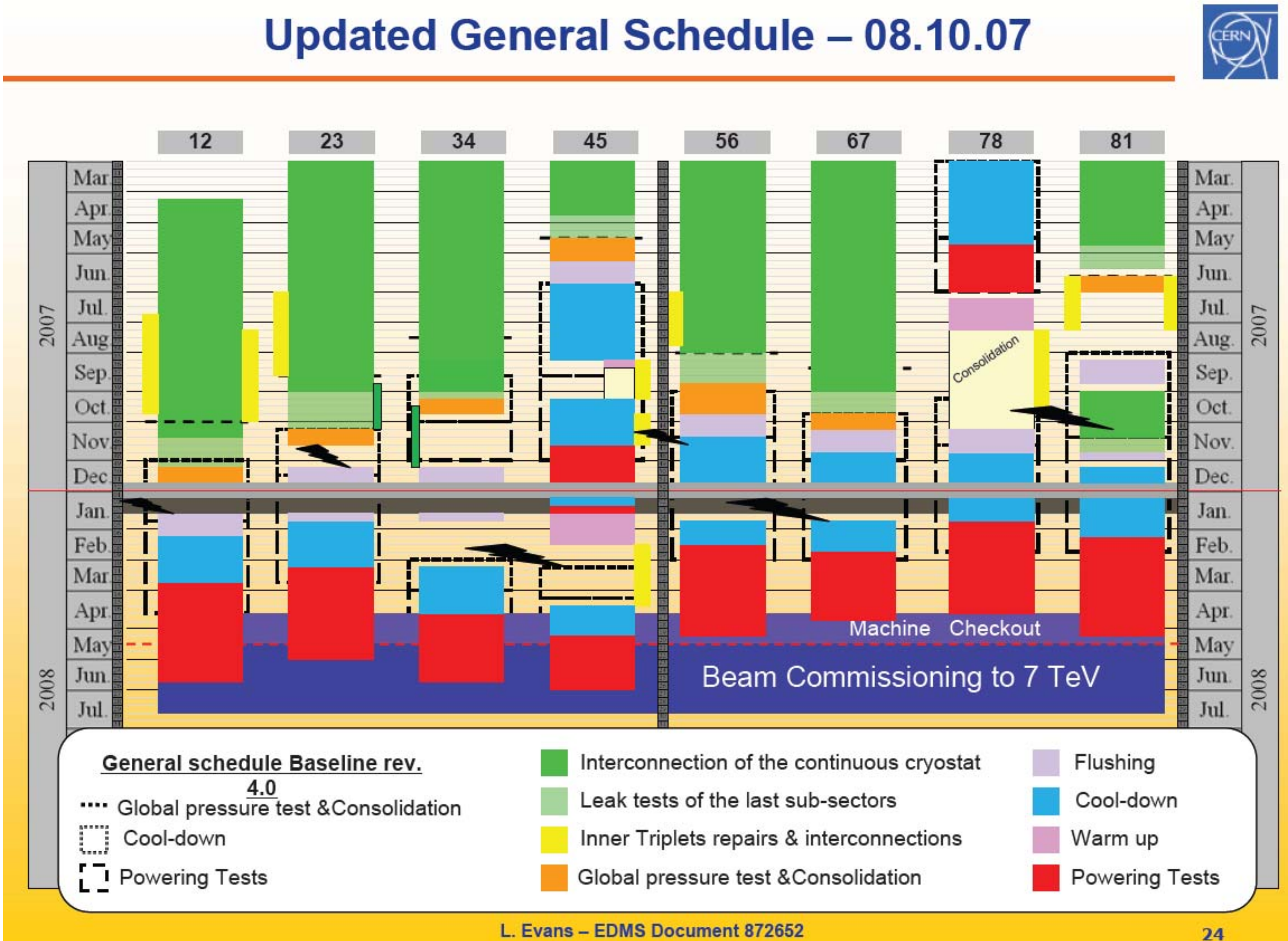


Efficiency of reconstruction and rec/id with *tauRec* as a function of (a) Pt and (b) η in Z sample.

LHC

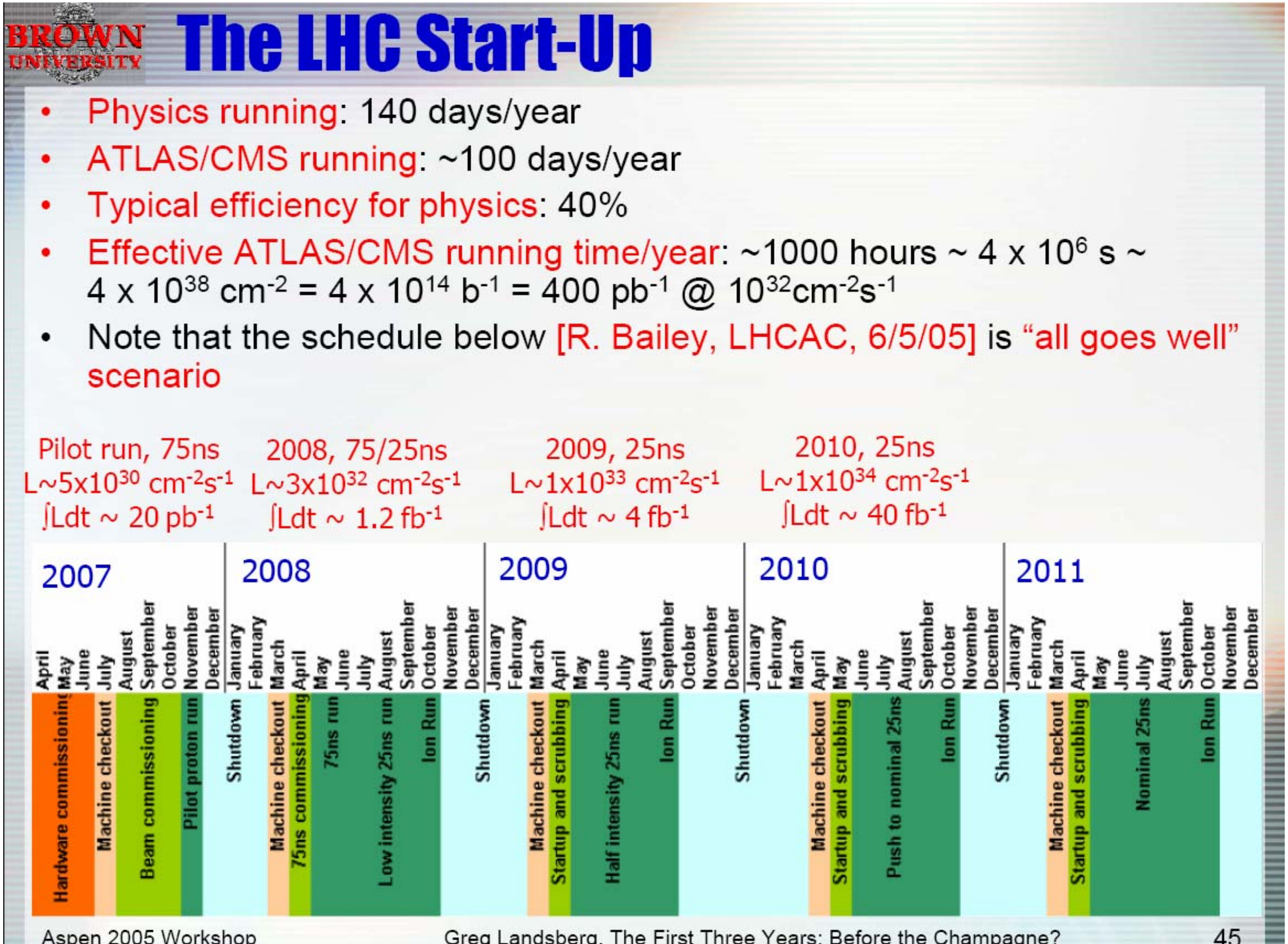
LHC Status

LHC Schedule as presented by Lyn Evans at the October ATLAS Week:



LHC Start-Up

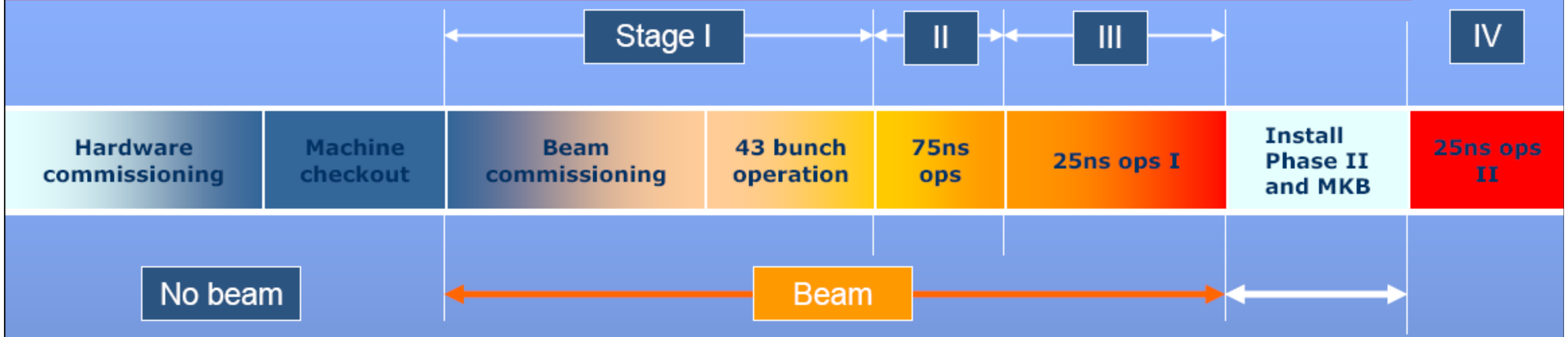
Slide from G. Landsberg presented at Aspen 2005:



LHC Start-up

From Lyn Evans June 14, 2007 MAC Presentation:

Staged commissioning plan for protons (R. Bailey)



I. Pilot physics run

- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Expected performance ~10^{31} cm^{-2} s^{-1} at ~1 event/crossing
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

II. 75ns operation

- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Expected performance ~10^{32} cm^{-2} s^{-1} at ~1 event/crossing
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

III. 25ns operation I

- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

IV. 25ns operation II

- Push towards nominal performance

L. Evans – EDMS document no. 849946 52

LHC Start-up

From Lyn Evans June 14, 2007 MAC Presentation:

General schedule

- Engineering run originally foreseen at end 2007 now precluded by delays in installation and equipment commissioning.
- 450 GeV operation now part of normal setting up procedure for beam commissioning to high-energy
- General schedule being reassessed, accounting for inner triplet repairs and their impact on sector commissioning
  - All technical systems commissioned to 7 TeV operation, and machine closed April 2008
  - Beam commissioning starts May 2008
  - First collisions at 14 TeV c.m. July 2008
  - Pilot run pushed to 156 bunches for reaching 10^{32} $cm^{-2}.s^{-1}$ by end 2008
- No provision in success-oriented schedule for major mishaps, e.g. additional warm-up/cooldown of sector

L. Evans – EDMS document no. 849946

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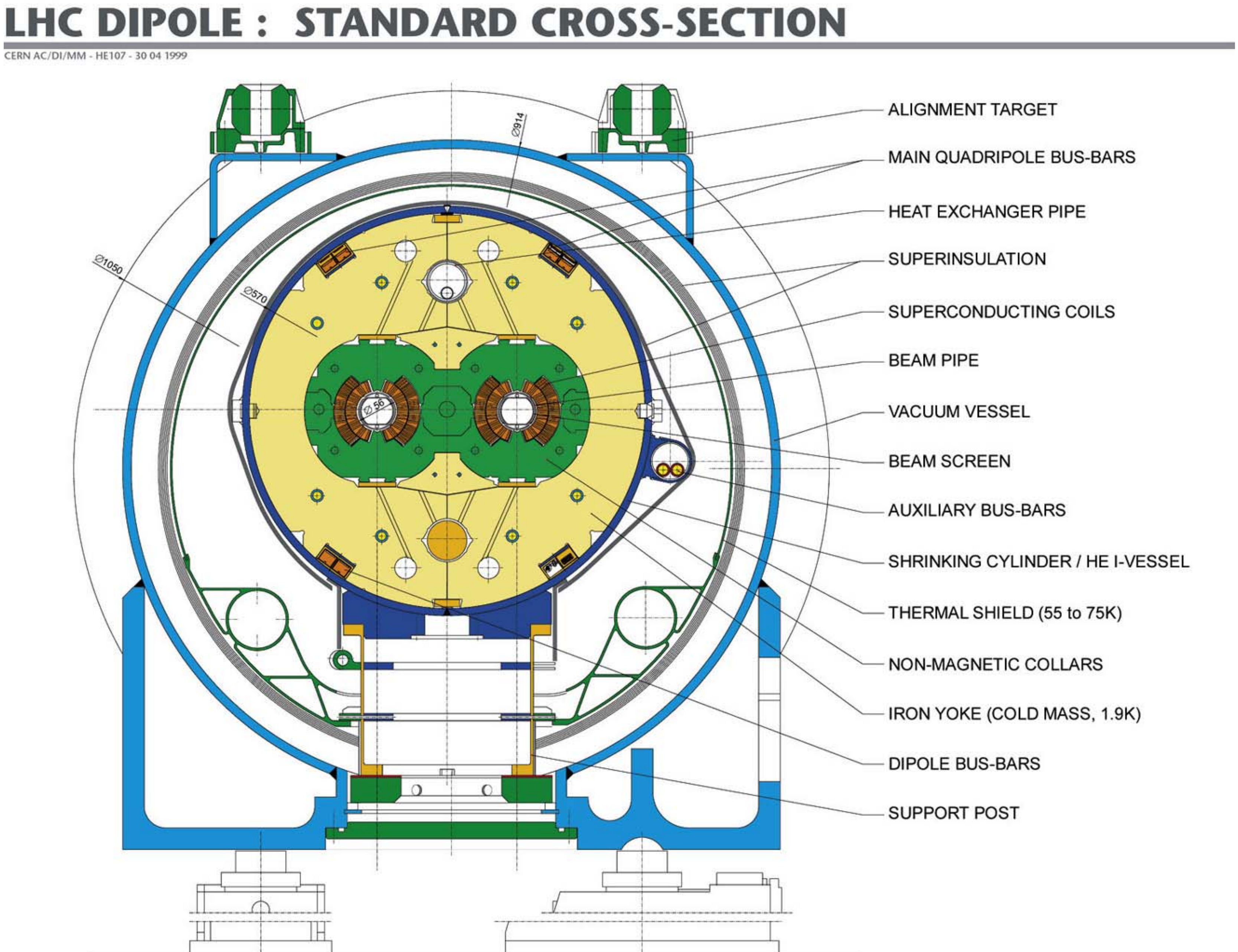
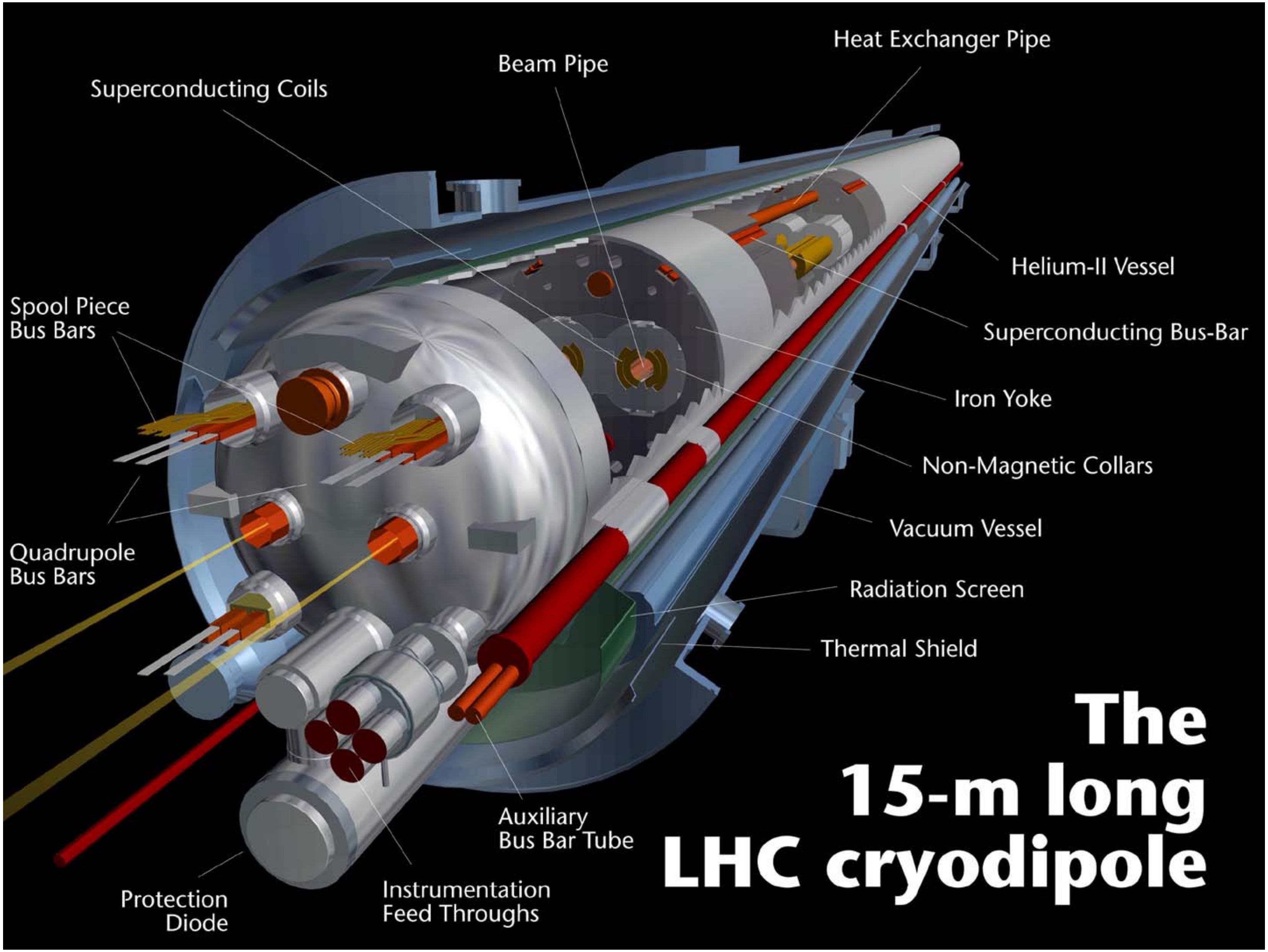
LHC Dipole


LHC DIPOLE : STANDARD CROSS-SECTION
CERN AC/DI/MM - HE107 - 30 04 1999
ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST
∅914
∅1050
∅570
∅ 56

LHC Dipole II



ATLAS

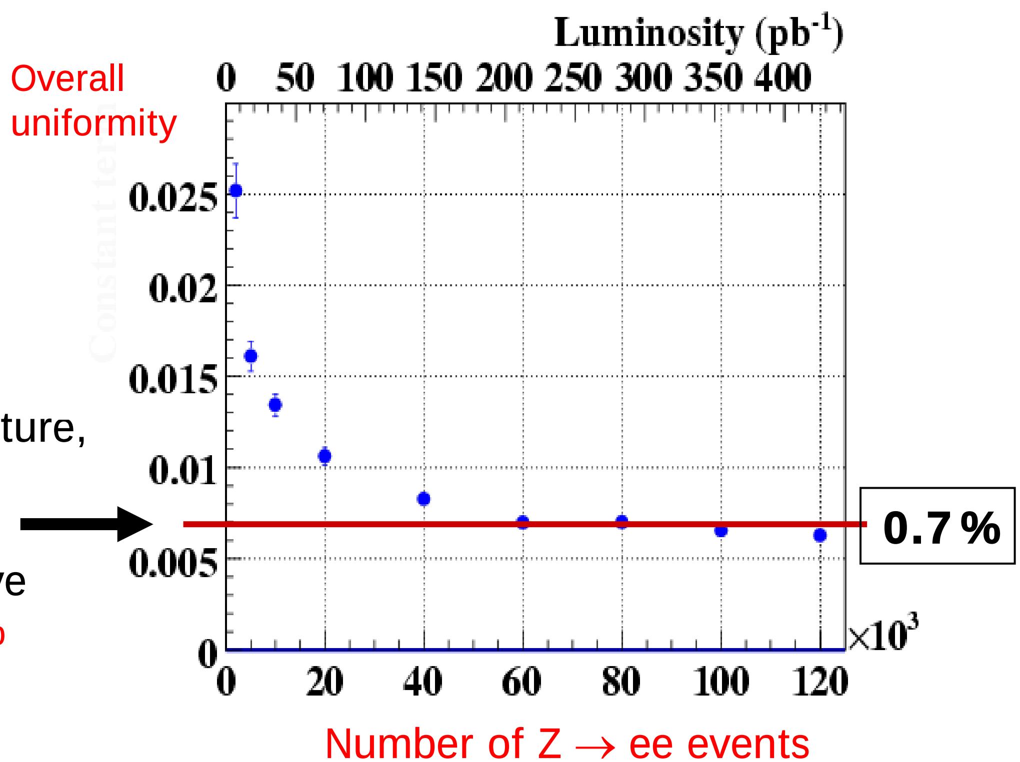
Expected calorimeter performance at day 0

	Expected performance day-0	Physics samples for improvement
ECAL uniformity	1-2% (~0.5% locally)	Isolated electrons, $Z \rightarrow ee$
e/γ E-scale	~ 2 %	$Z \rightarrow ee$
HCAL uniformity	~ 3 %	Single pions, QCD jets
Jet E-scale	< 10%	γ/Z + 1j, $W \rightarrow jj$ in tt events

ECAL calibration:

use Z-mass constraint to correct residual long-range non-uniformities (module-to-module variations, temperature, effect of upstream material, etc.)

~ 10^5 $Z \rightarrow ee$ events enough to achieve the goal response uniformity of ~ 0.7%



Slide from M. Nessi

Pixel Tracker Module

Each Pixel Module has

- **16 Front-End ICs**
  - **2880 channels / IC**
  - **18 columns x 160 rows**
  - **Bump bonds to sensor**
- **One Module Controller Chip**
  - **Collects data from the 16 FE chips**
  - **Translates commands into chip signals**

Total Number of Modules

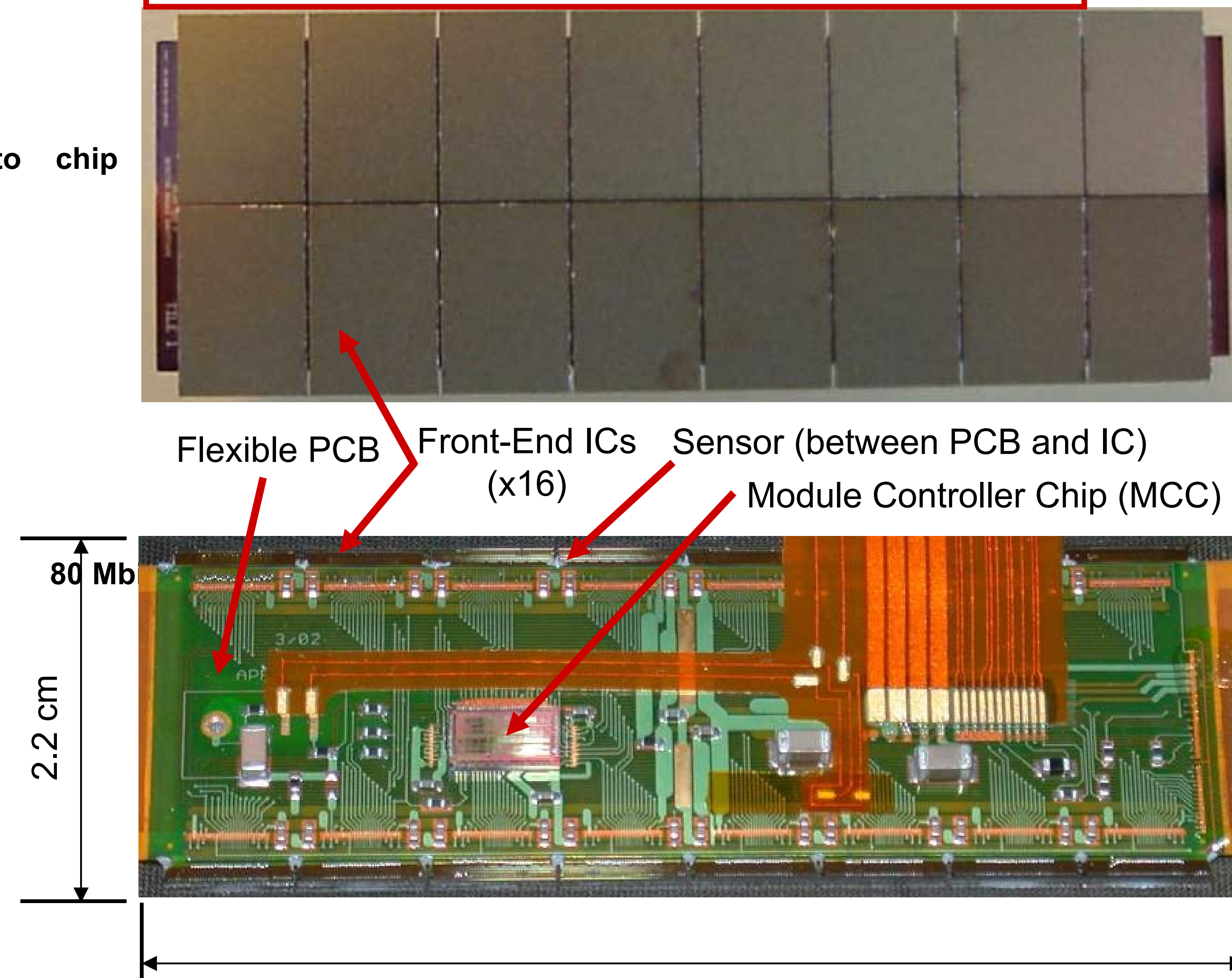
- **1456 (Barrels)**
- **144 x 2 (End-caps)**

Read-out Rate:

- **B-Layer 160 Mbit/s**
- **Layer-1 and Endcaps 80 Mb**
- **Layer-2 40 Mbit/s**

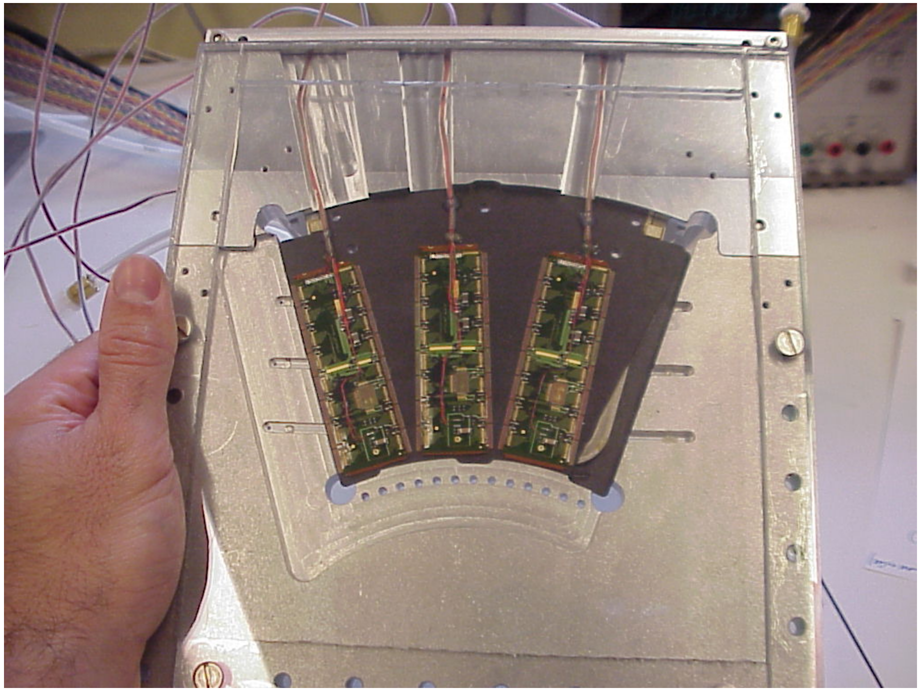
There are over 80 million channels in the ATLAS Pixel Tracker

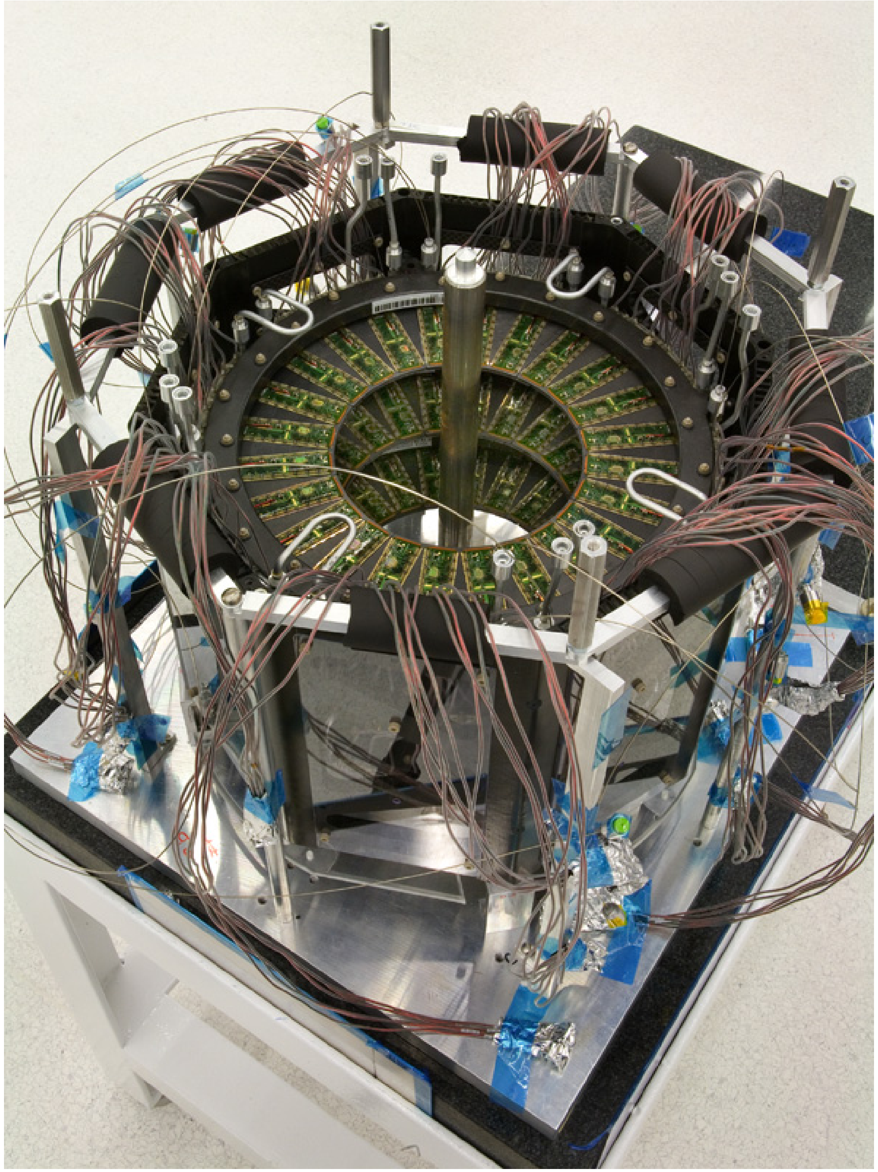
ATLAS Pixel Module (46080 channels) Pixel Size: 50 x 400 μm



The Pixel Endcap

Sector and Disks





Semiconductor Tracker Module

Each side of an SCT Module has

- Two silicon sensors
  - Manufactured by Hamamatsu
  - 768 instrumented strips at an 80 µm pitch
- An array of six binary readout chips
  - ABCD3TA ASICs
  - Discriminator
  - Pipeline
  - Data Compression Logic
  - Read-out Buffer

Total number of modules:

- 2112 (Barrels)
- 988 x 2 (End-caps)

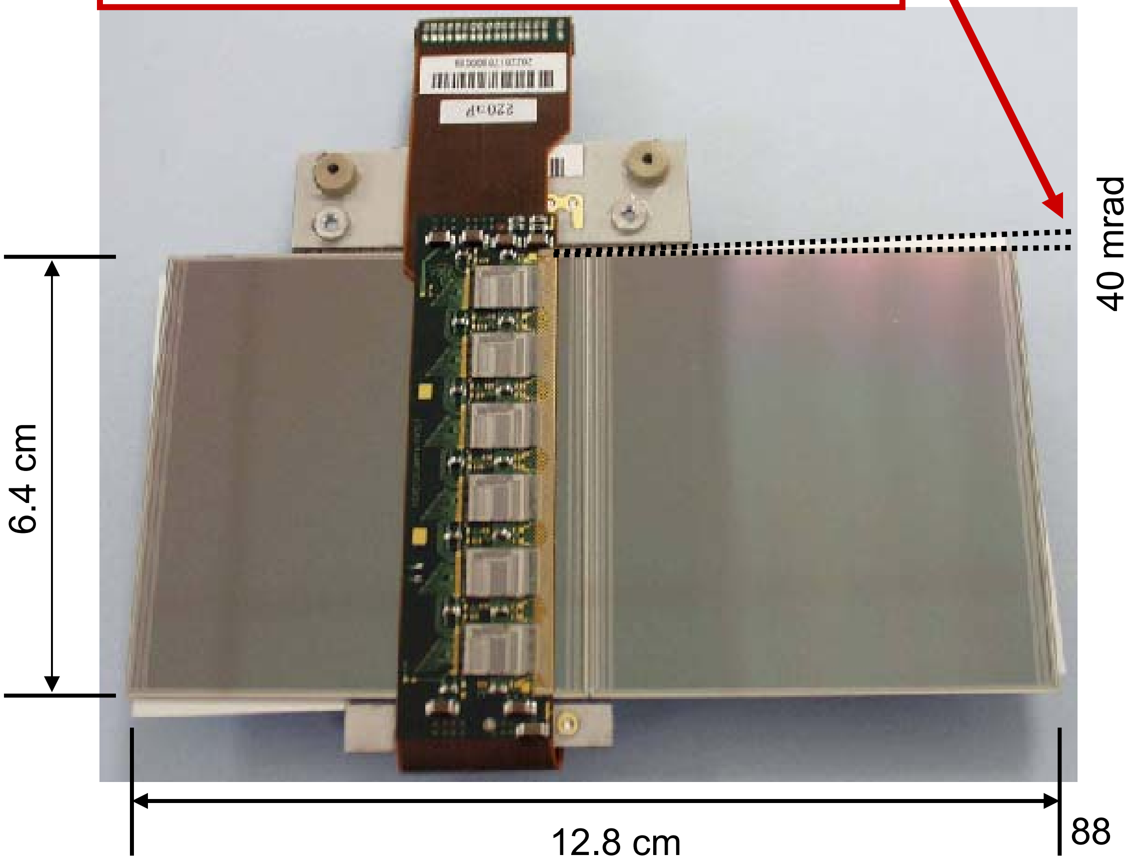
Read-out Rate:

- Barrels and End-caps 40 Mbit/s

There are over 6.2 million channels in the ATLAS Semiconductor Tracker

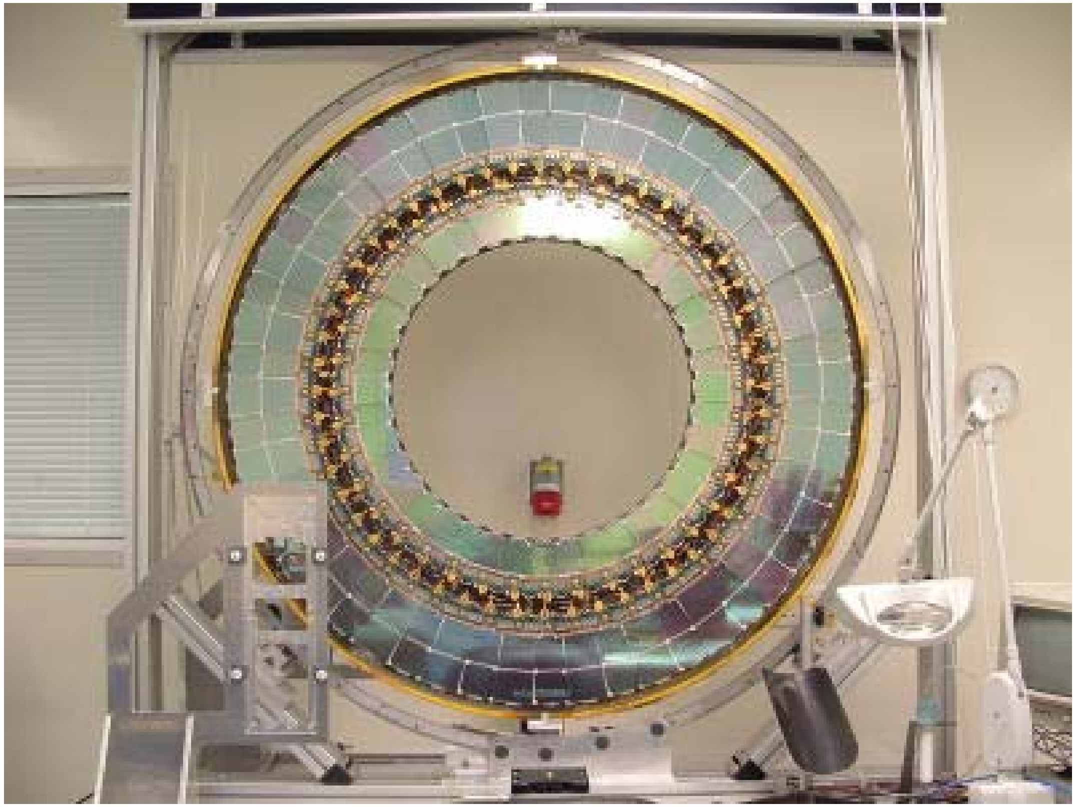
40 milliradian stereo angle between sides provides resolution in the axial direction

ATLAS SCT Module (1536 channels) Pitch: 80 µm



The SCT Endcap

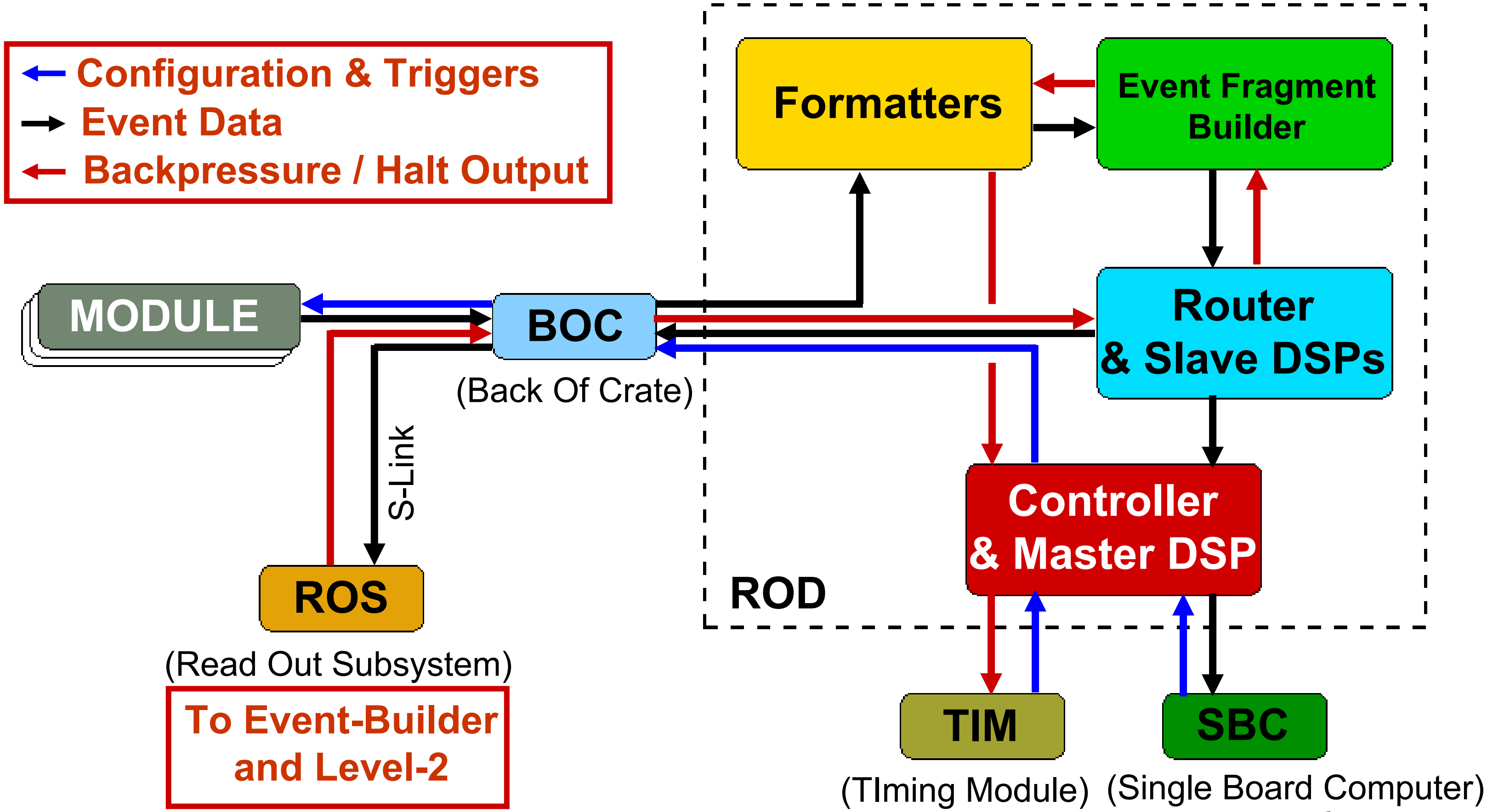
Module and Disk



The Silicon Read-Out Driver (ROD)

Primary purpose: Module configuration, Trigger propagation, Data formatting

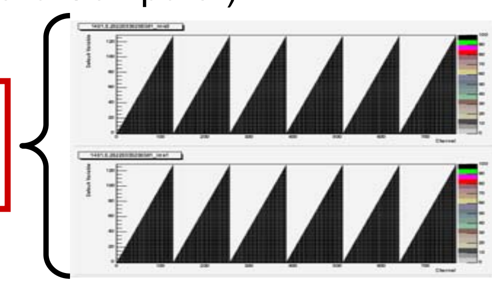
- A hybrid of FPGAs and DSPs



Secondary purpose: Calibrations / Monitoring

- FPGAs for time-critical functions (Event Data Path)
- DSPs for configuration, ROD control, calibrations and monitoring

Calibration Histograms



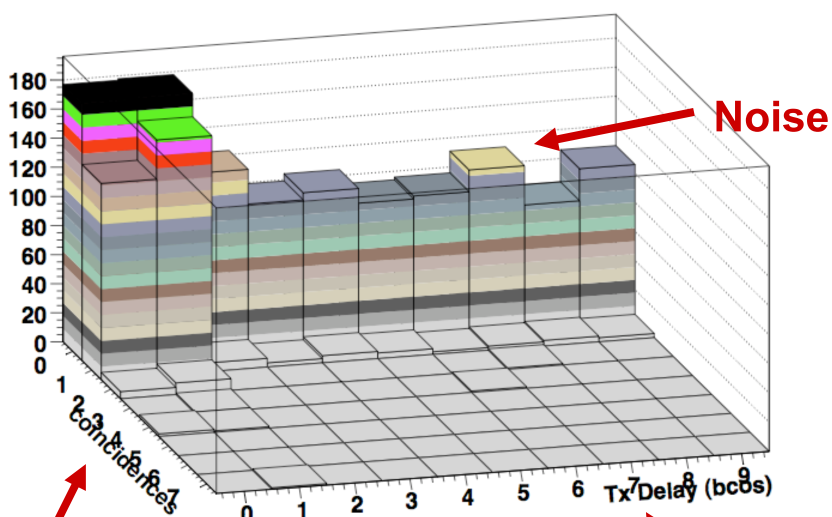
Cosmics Data-Taking

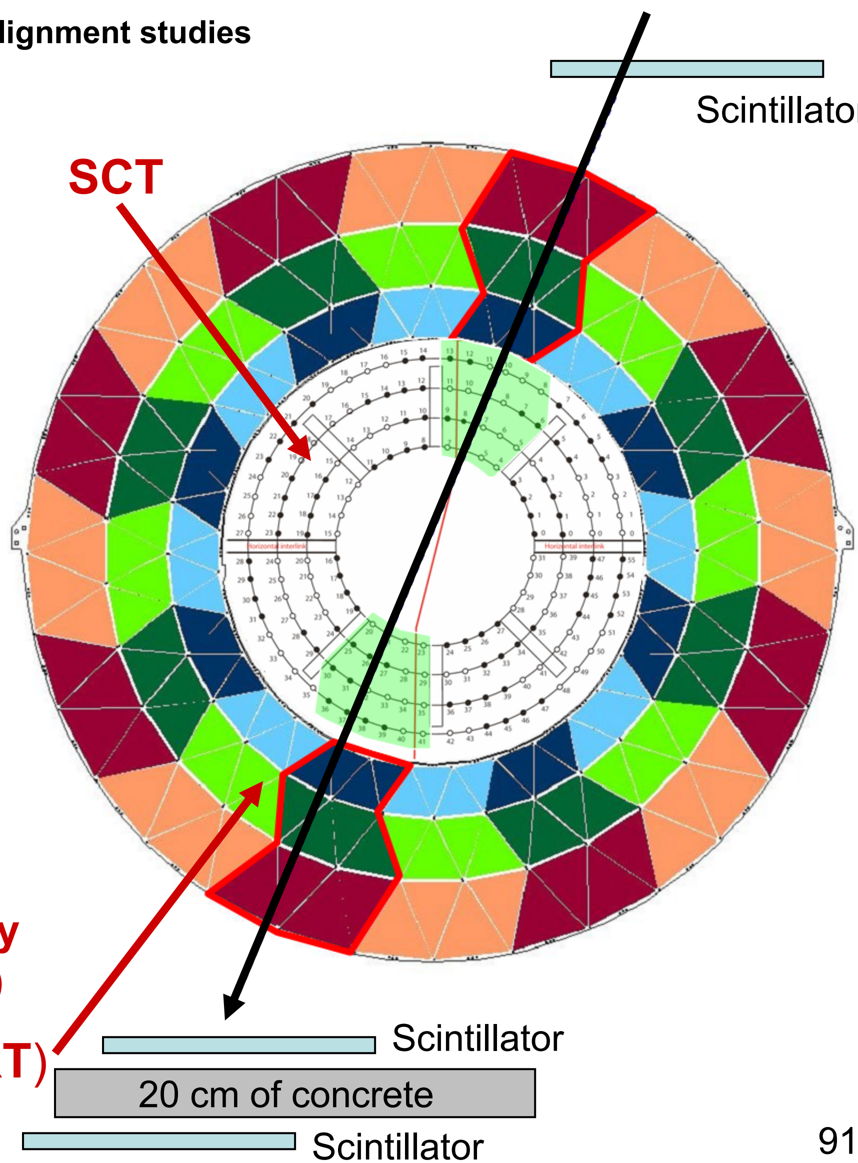
A total of 504 SCT Modules into 12 RODs were used during the combined cosmics data-taking run

TRT/SCT combined run in May 2006

- **ROD performed well; successfully collected more than 400k events**
- **Useful DAQ/Detector shake-down, data for efficiency and alignment studies**

On-ROD Histogramming used for timing in the SCT during cosmics running (i.e., delay the signal by the correct amount)

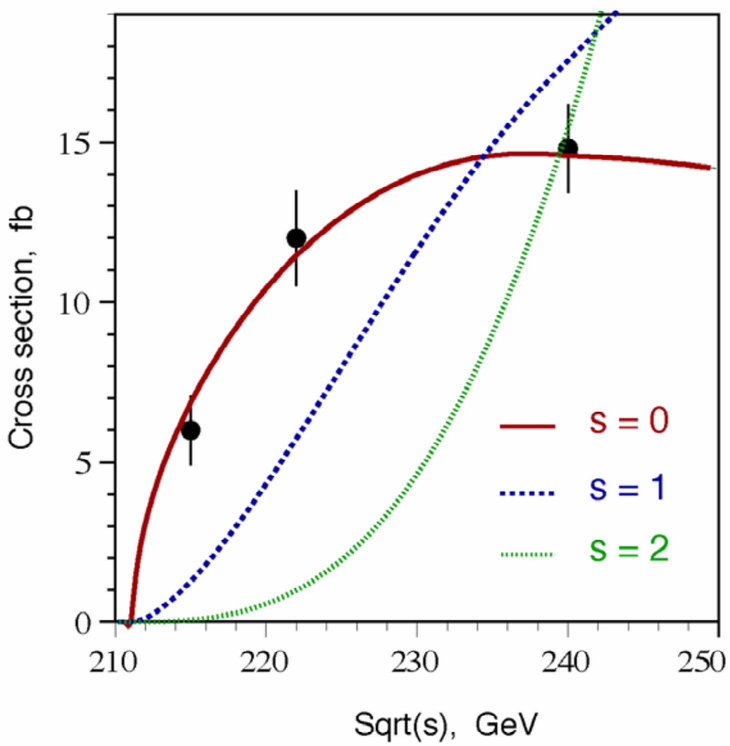


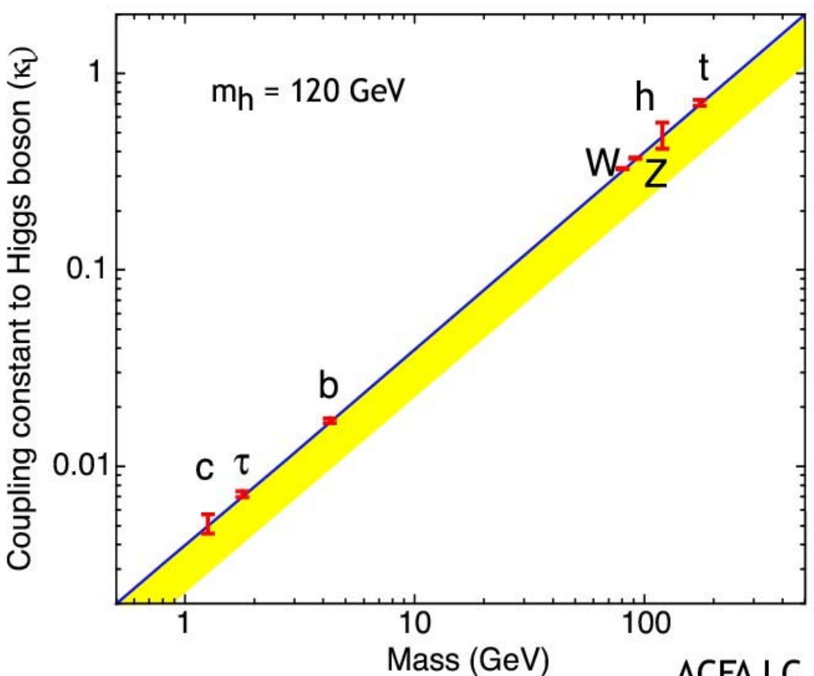


ILC

ILC

Measuring Higgs Properties…





ACFA LC study

Misc.

Significance

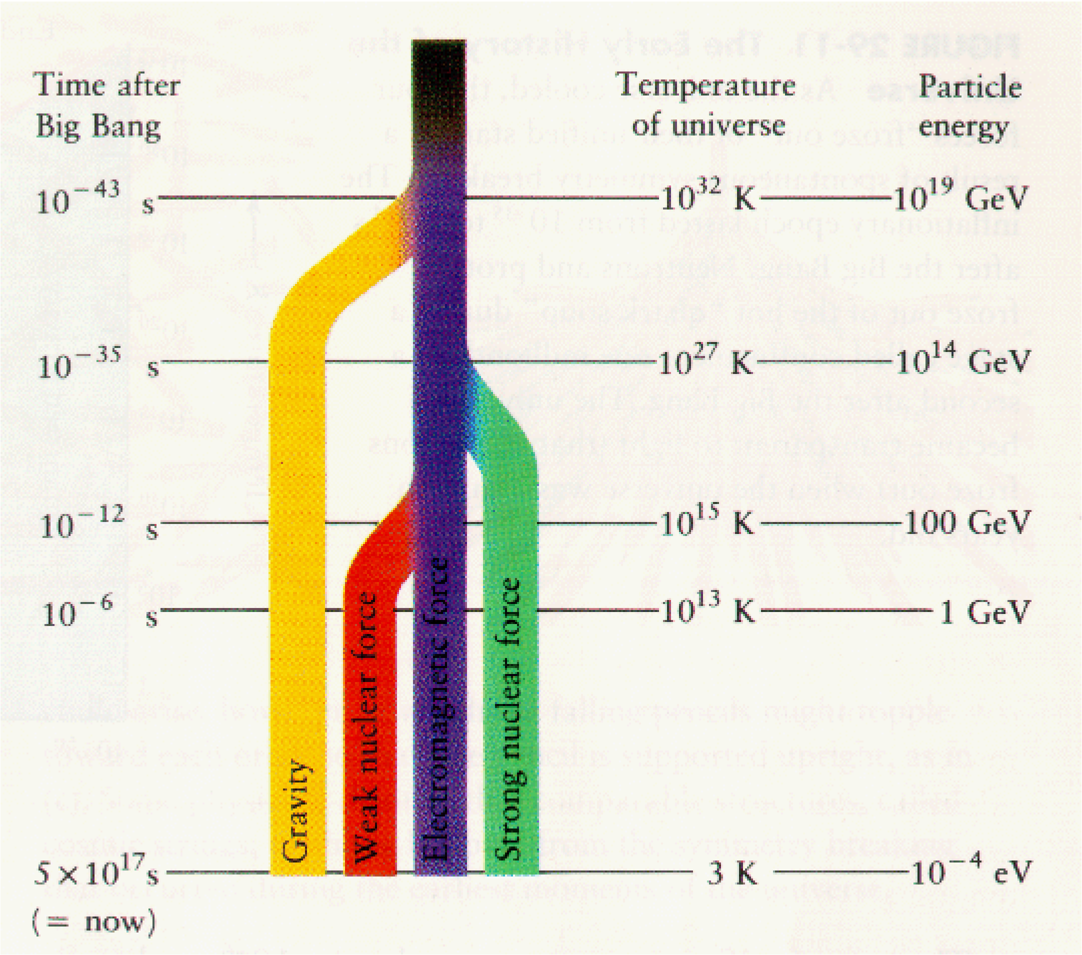
How it is determined for a counting experiment:

- **We observe N_0 events in an experiment**
- **Estimated background rate, N_b, is used as the mean of a Poisson distribution of observed events**
- **The p-value for our observation of N_0 events is then:**

$$\alpha = \sum_{n=N_0}^{\infty} \frac{\exp(-N_b)(N_b)^n}{n!}$$

- **The 5σ standard as a sort of rule of thumb to define the sensitivity necessary for a discovery.**
- **This corresponds to a p-value of ~5.0 x 10^{-7}**

The First Higgs observed at the LHC


Time after
Big Bang
Temperature
of universe
Particle
energy
10^{-43} s
10^{32} K
10^{19} GeV
10^{-35} s
10^{27} K
10^{14} GeV
10^{-12} s
10^{15} K
100 GeV
10^{-6} s
10^{13} K
1 GeV
5×10^{17} s
(= now)
3 K
10^{-4} eV
Gravity
Weak nuclear force
Electromagnetic force
Strong nuclear force