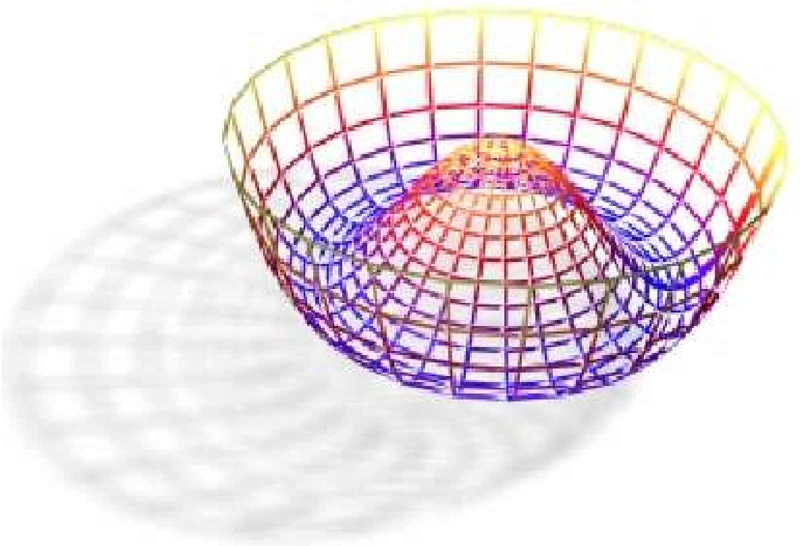
Higgs Searches at the LHC: Challenges, Prospects, and Developments

Kyle Cranmer
Brookhaven National Laboratory

March 14, 2006
University of Pennsylvania Seminar

Outline
- Introduction to SM and MSSM Higgs Sector
- Overview of progress in recent years
- LHC discovery and measurement potential
- Timeline for the Near Future and Distant Future



The *Standard Model* of particle physics is a particular Quantum Field Theory that represents our best understanding of particles and their interactions.

The standard model is very predictive and has survived numerous precise tests over the years.

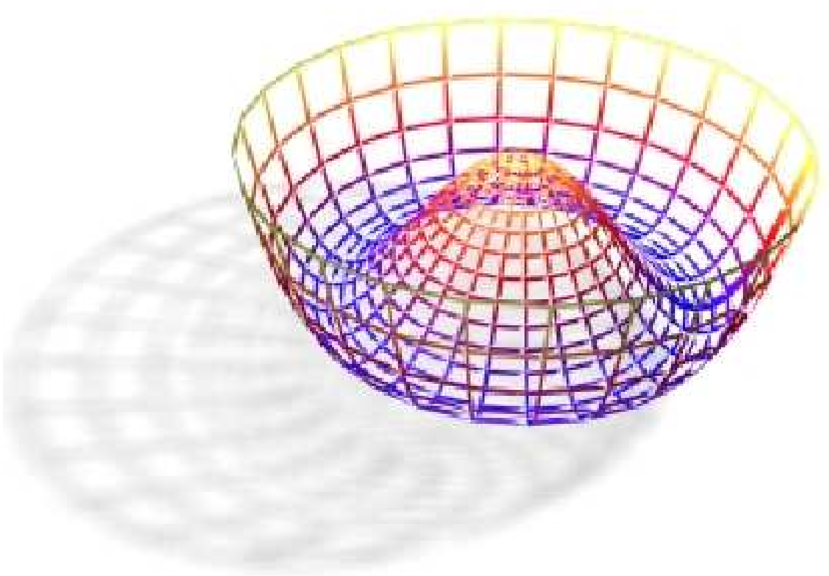
The only particle of the standard model that we have not observed is the Higgs boson.

Despite its success, we have reason to believe that it is not the whole story: we expect that there will be some deviation from the standard model near the TeV energy scale.

Physics beyond the standard model includes: SuperSymmetry (SUSY), extra space-time dimensions, new high-mass resonances, etc.

The Large Hadron Collider (LHC) at CERN and the two large multi-purpose detectors (ATLAS and CMS) have been built specifically to find the standard model Higgs boson (if it exists) and explore the theoretical landscape of beyond the standard model.

The Higgs mechanism provides a gauge invariant theory of Electroweak interactions with massive $W^{\pm}$ and Z bosons



$$\mathcal{L}_{\mathsf{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

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

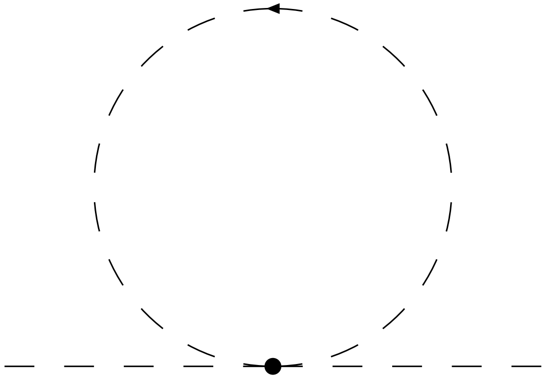
Spontaneous Symmetry Breaking
$\Rightarrow$ Goldstone Bosons
$\Rightarrow$ longitudinal states of $W^{\pm}$ and Z

Theory predicts:

- $g_{HWW} \propto m_W$
- $g_{Hff} \propto m_f$
- $g_{HHH} \propto m_H^2/m_w$
- $g_{HHHH} \propto m_H^2/m_W^2$

The Higgs Mass is unknown in the S.M., but expected to be $\lesssim$ 1 TeV

While the standard model Higgs gives us massive $W^{\pm}$ and Z bosons, it also introduces quadratic divergences in the Higgs' self energy.



One solution is to introduce Supersymmetry, which provides a fermion $\leftrightarrow$ boson symmetry, new loops, and ± 1 factors that cancel the divergences exactly

Because we have not observed SUSY partners, SUSY must be broken in nature

MSSM parametrizes soft SUSY-breaking terms with 105 parameters

mSUGRA, mAMSB, mGMSB, etc. are specific, well-motivated theories with fewer parameters and restricted phenomenology

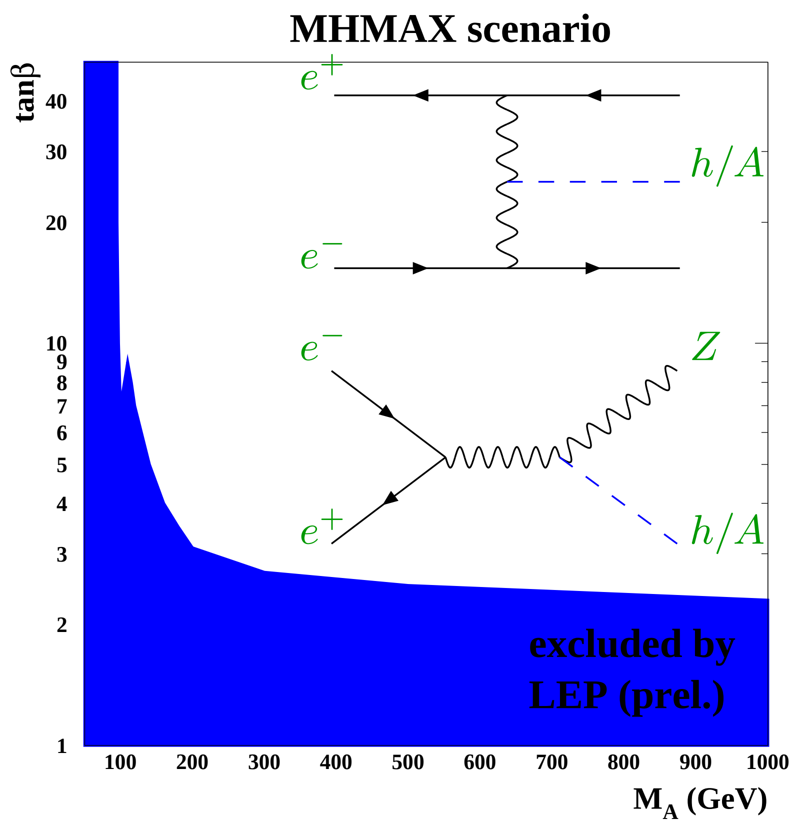
The MSSM requires two Higgs doublets, which give rise to 5 physically observable Higgs bosons: h, H, A, and $H^{\pm}$.

Unlike the SM, there is a theoretical limit on the mass of the lightest Higgs $M_h < 135$ GeV

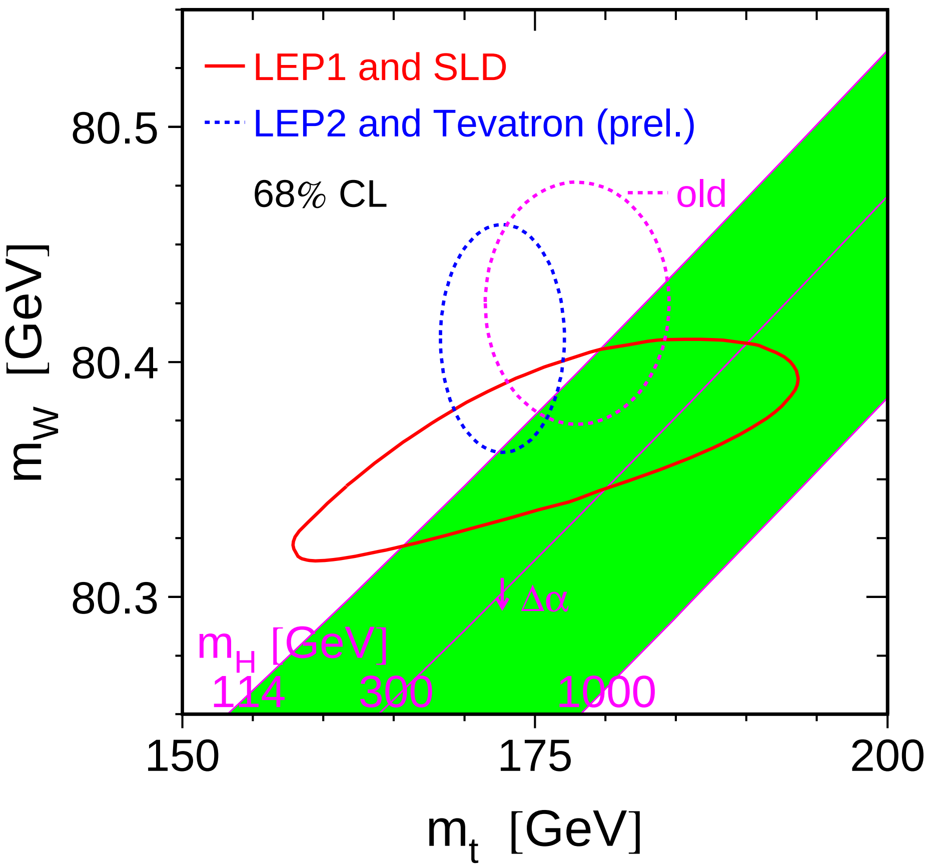
The MSSM Higgs sector is usually parametrized by M_A and $\tan\beta = v_1/v_2$

The h and H bosons are standard-model-like with couplings modified by functions like $\cos(\beta-\alpha)$ and $\cos(\alpha)/\cos(\beta)$.

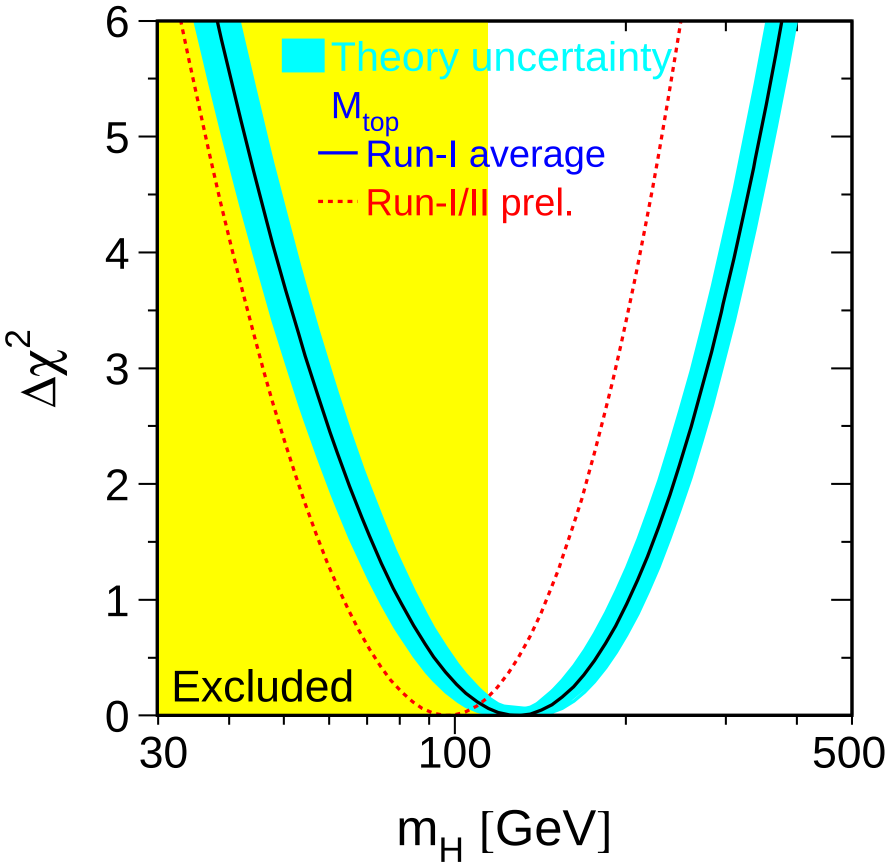
Thus, most standard model Higgs searches can be reinterpreted in the MSSM Higgs sector (using tools like `FeynHiggs`)



Electroweak precision measurements are indirectly sensitive to the Higgs mass through radiative corrections that go like $\propto \log(m_H)$

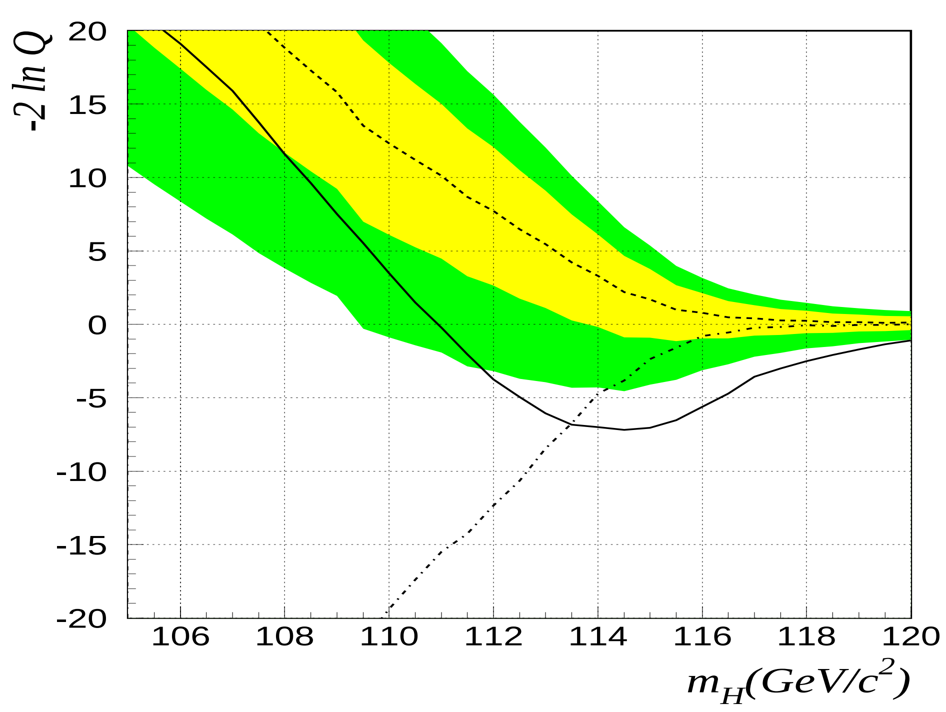


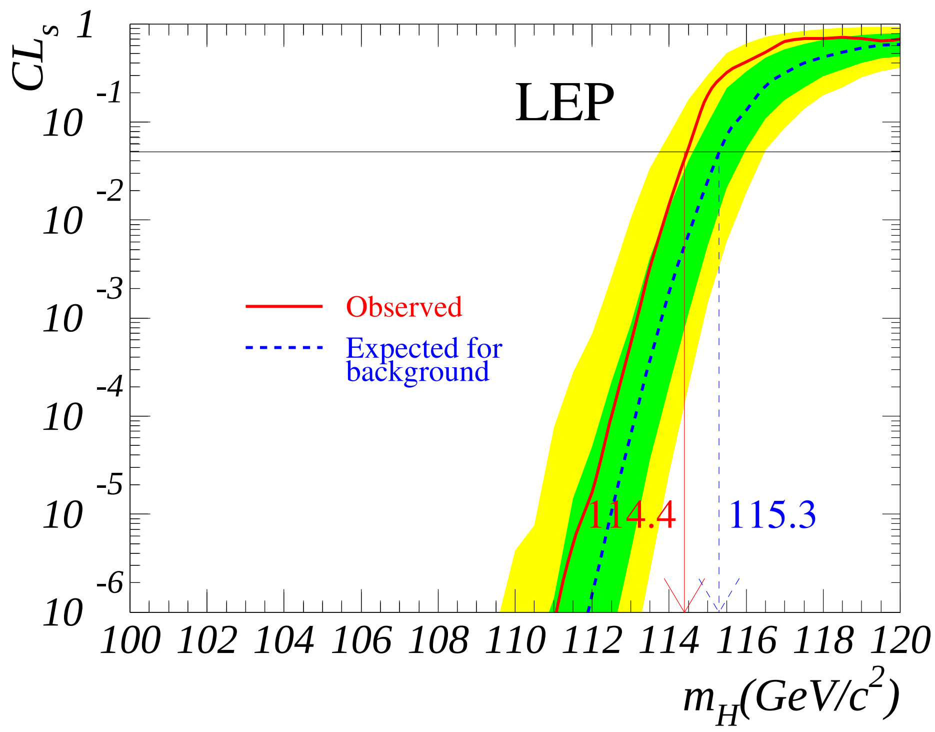
Revised top mass measurements from Tevatron prefer a lighter Higgs



LEP Electroweak Fits limit $m_H < 186$ GeV at 95% Confidence

Results from direct searches for the Higgs at LEP:

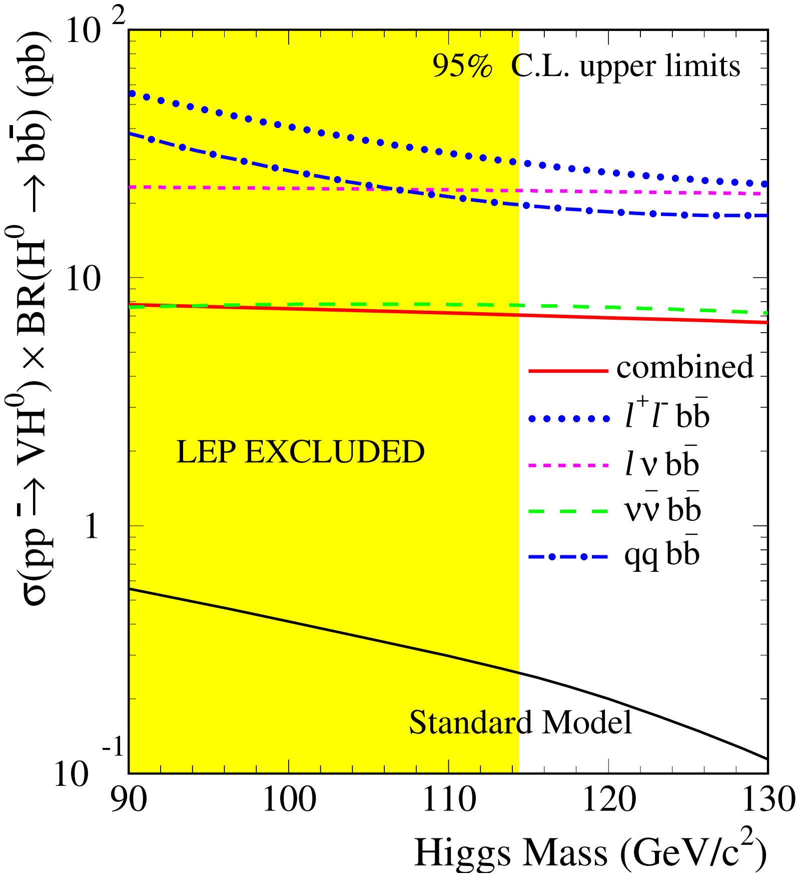


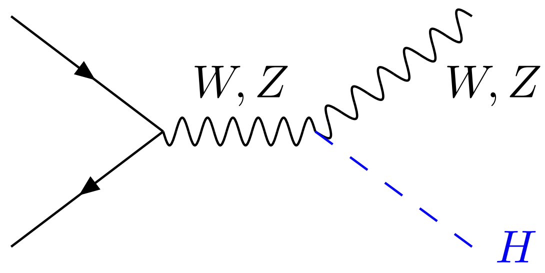


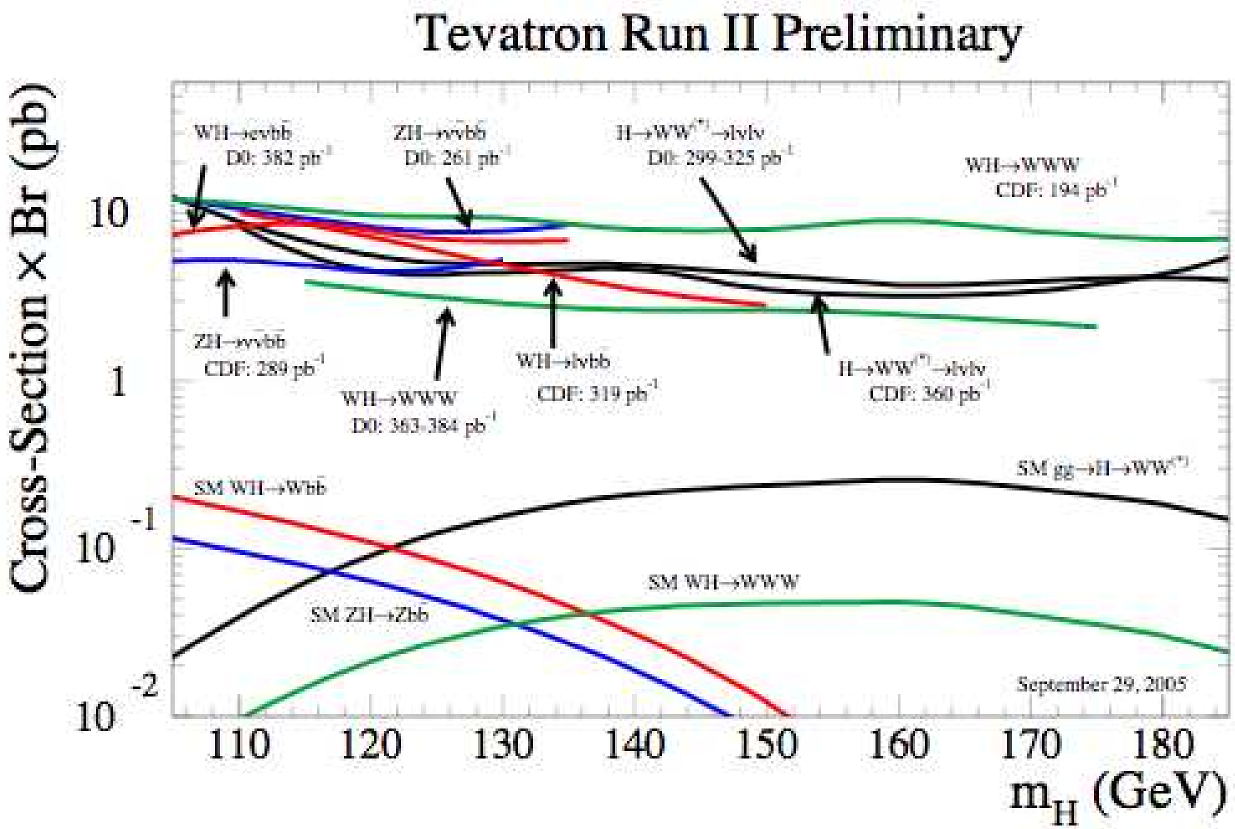
ALEPH observed an excess of events in $e^+e^- \rightarrow 4$jet channel, but no discovery

LEP direct search limit places $M_H > 114.4$ GeV at 95% Confidence

The low mass region is very exciting and very challenging for the LHC!







CDF RunI 106 pb^{-1}
(PRL, hep-ex/0503039)

A factor of >25 from S.M.

CDF & D∅ closing in on Standard Model with RunII

Improvements Underway

Identified potential to approach SM cross section exclusions

Tools common to CDF analyses

Analysis-specific improvements

Improvement	WH→lνbb	ZH→ννbb
Mass resolution	1.7	1.7
Continuous b-tag (NN)	1.5	1.5
Forward b-tag	1.1	1.1
Forward leptons	1.3	1.0
Track-only leptons	1.4	1.0
NN Selection	1.75	1.75
WH signal in ZH	1.0	2.7
CDF+DØ combination	2.0	2.0

And don't forget factor of 10 more data!

Challenge to develop and apply improvements to Higgs searches

J. Nielsen

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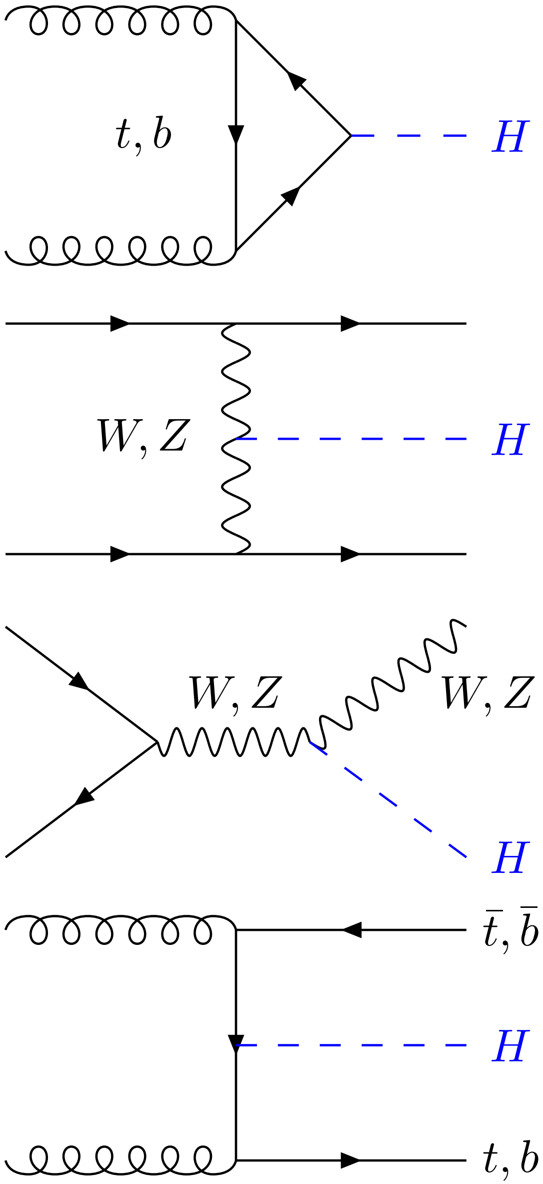
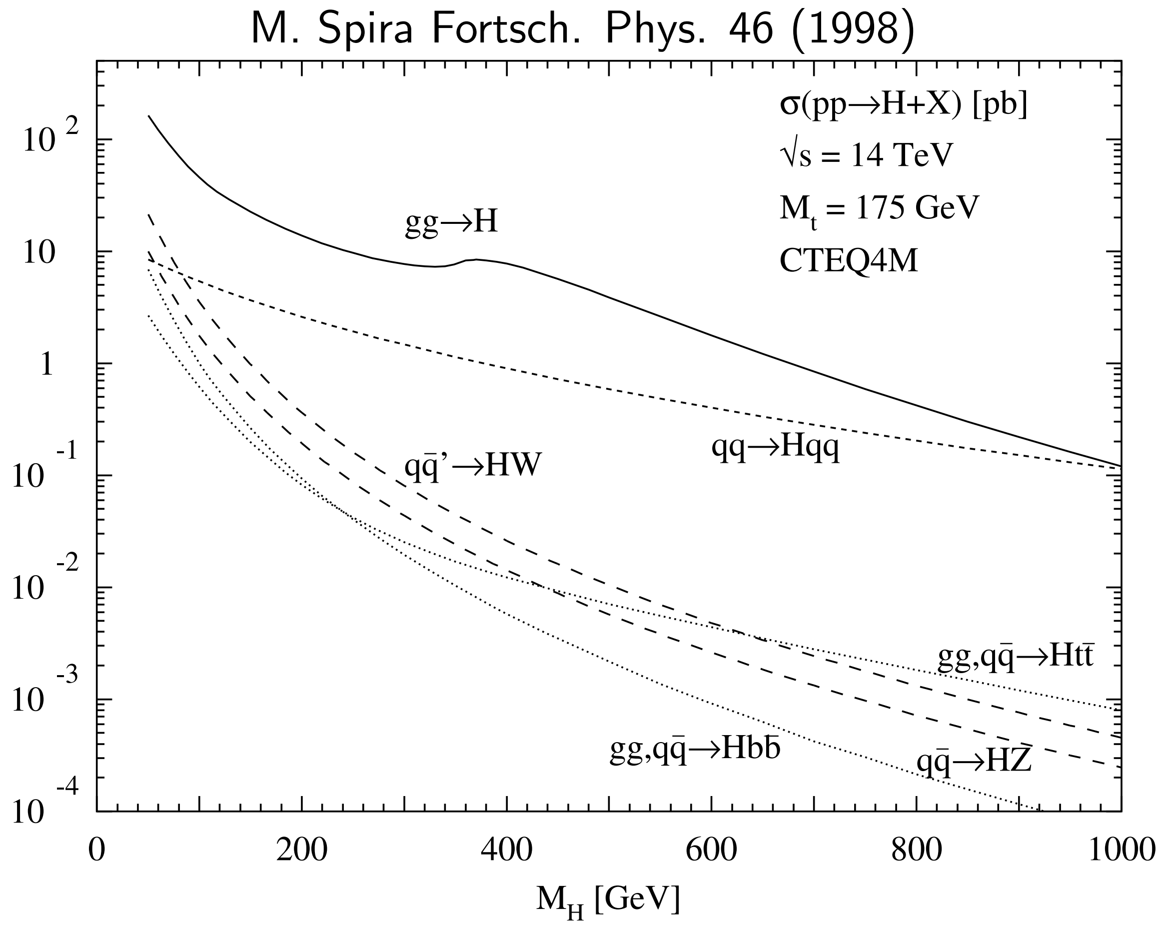
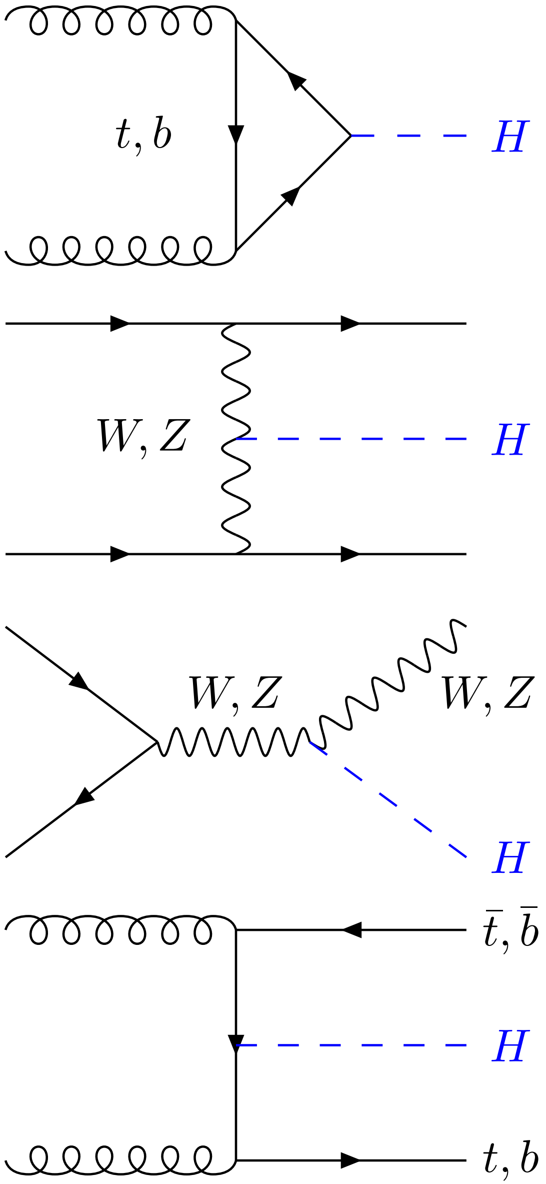
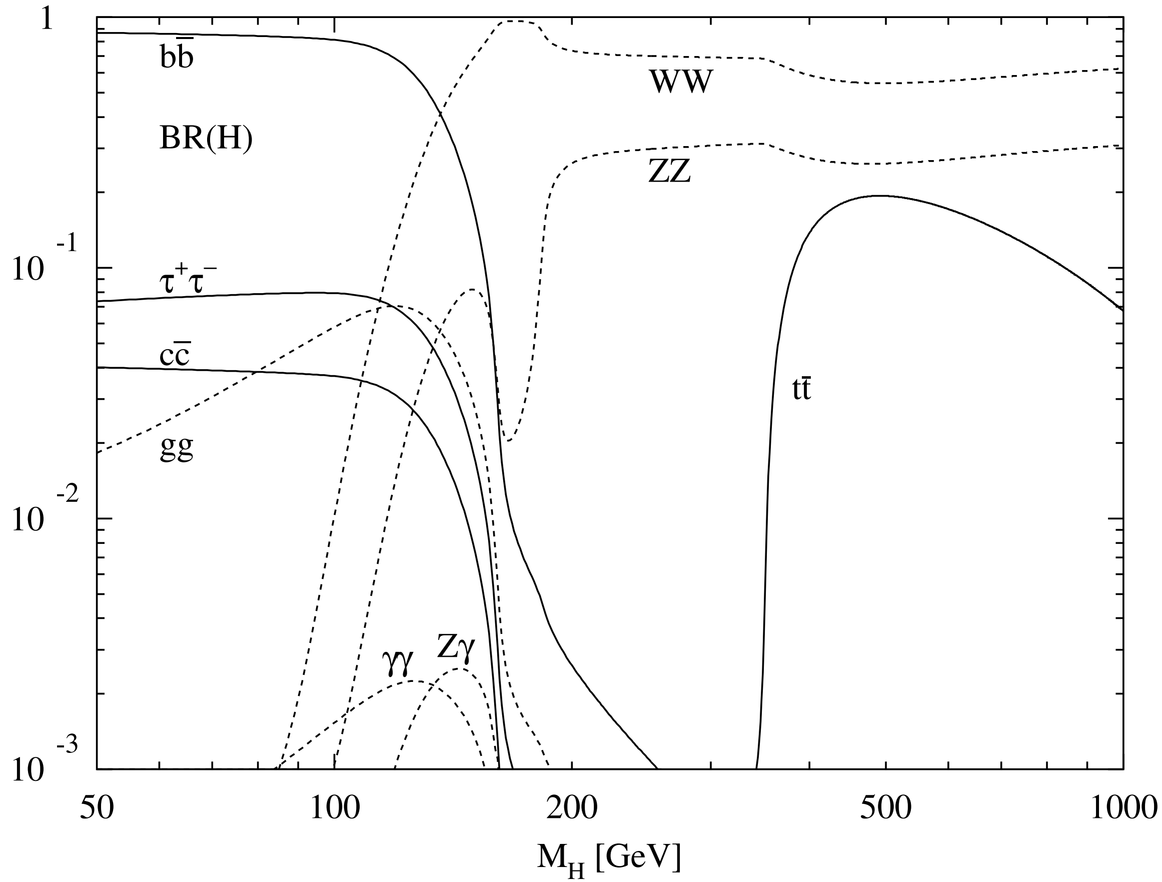




- Gluon-Gluon Fusion dominant production process.
- Vector Boson Fusion (Hqq) $\approx 20\%$ of gg at 120 GeV
- Associated production with W, Z and heavy quarks have small rate, but can provide trigger independent of H decay

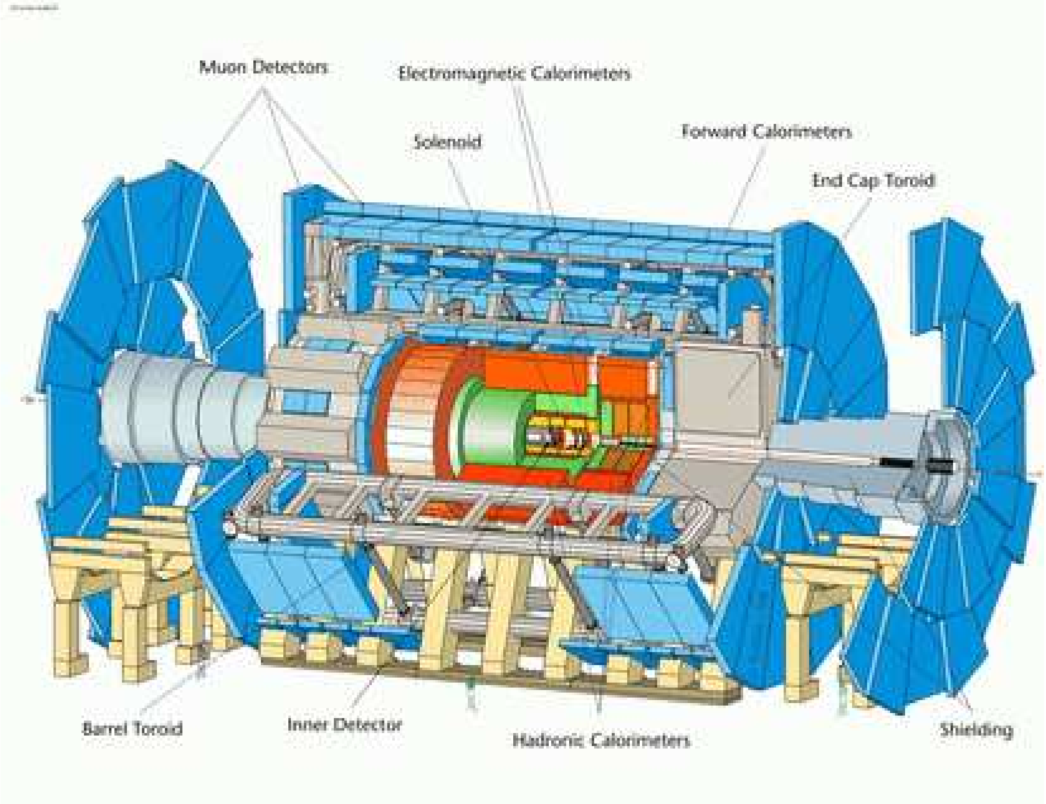


M. Spira Fortsch. Phys. 46 (1998)



- For $m_H < 2m_W$ Higgs mainly decays to fermions
- Couplings $\propto m_f$, so look for $H \rightarrow bb, \tau\tau$
- $BR(H \rightarrow b\bar{b})$ dominant at low mass, but need trigger
- $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ gold-plated channels

The ATLAS Detector



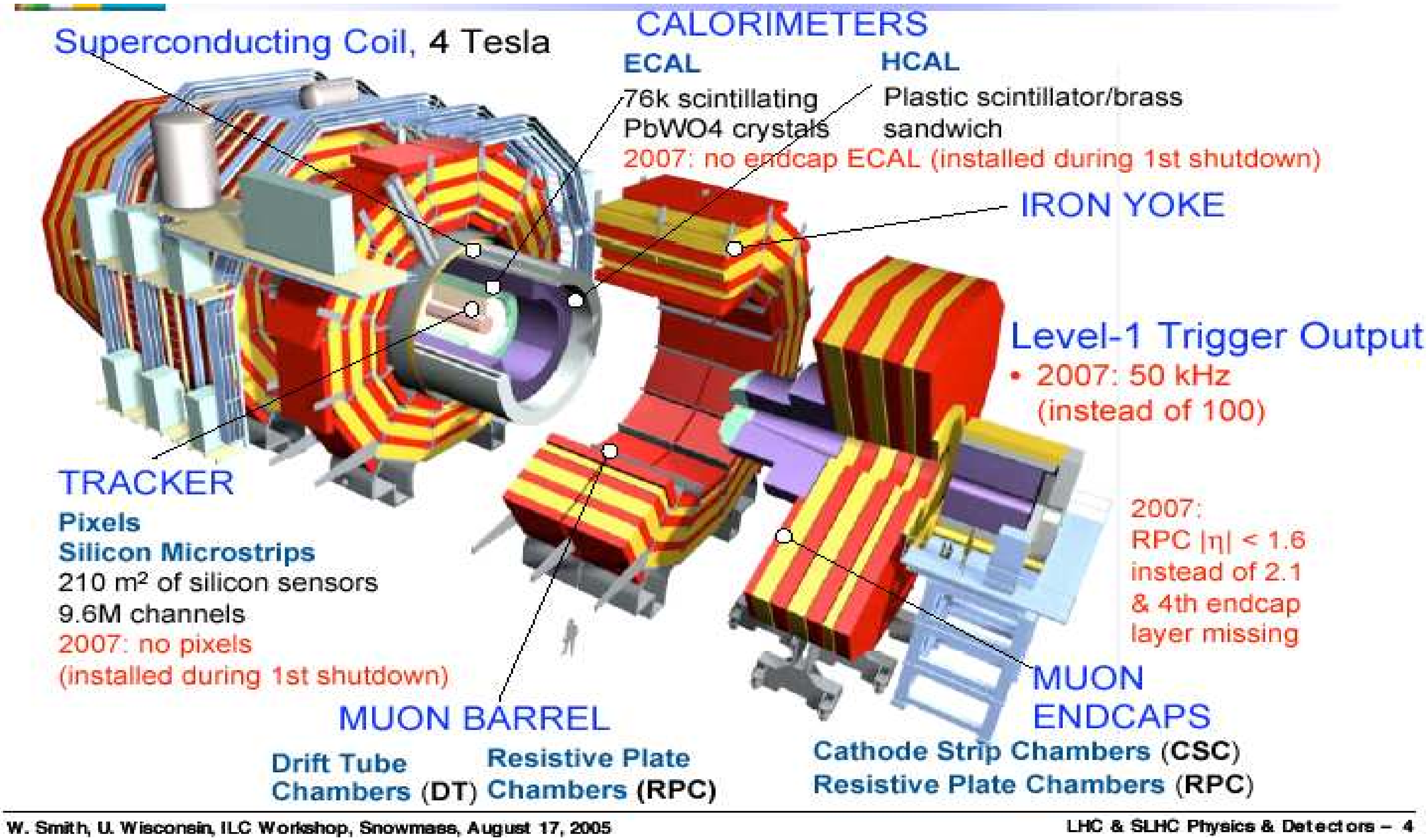
- Length $\approx$ 40 m
- Radius $\approx$ 10 m
- Weight $\approx$ 7000 tons
- # Readout Channels $\approx 10^8$

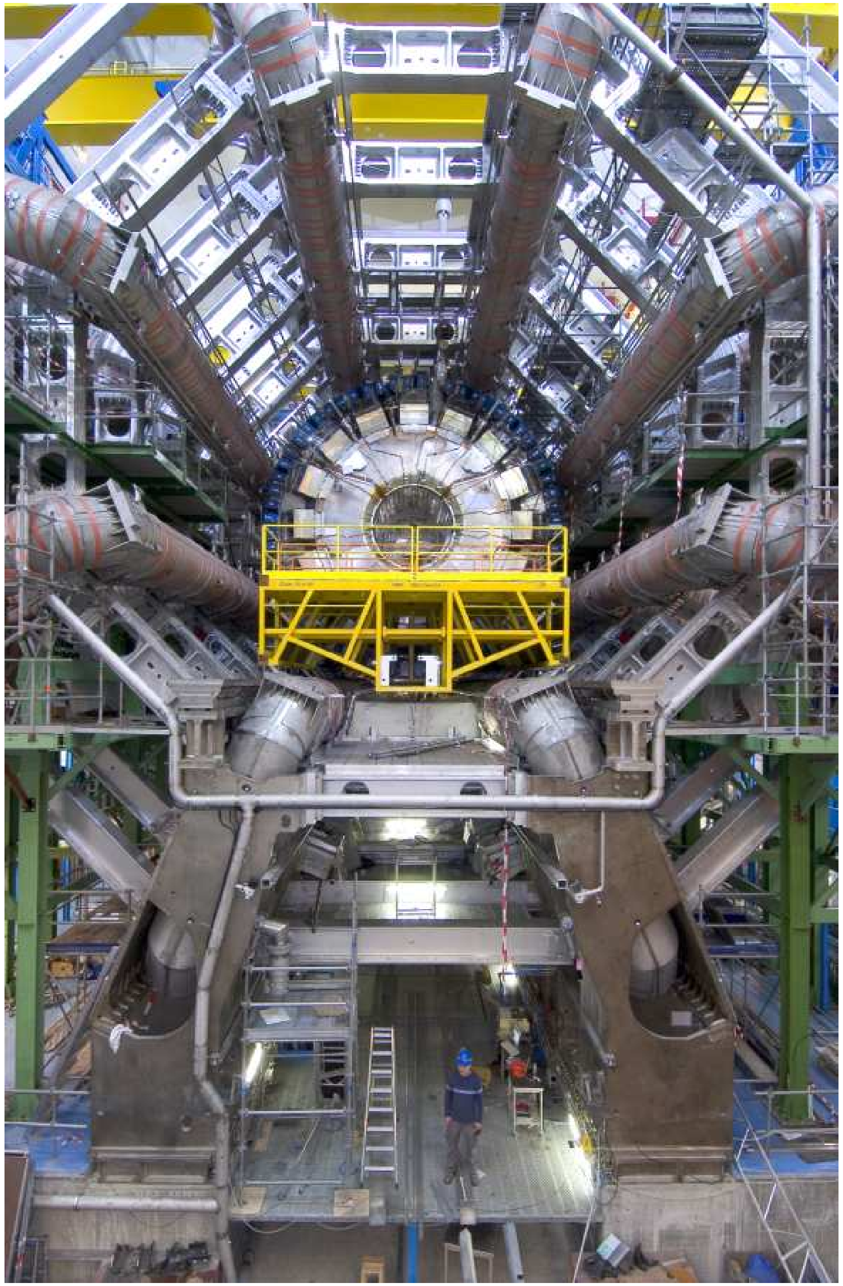
Sub-detector Highlights

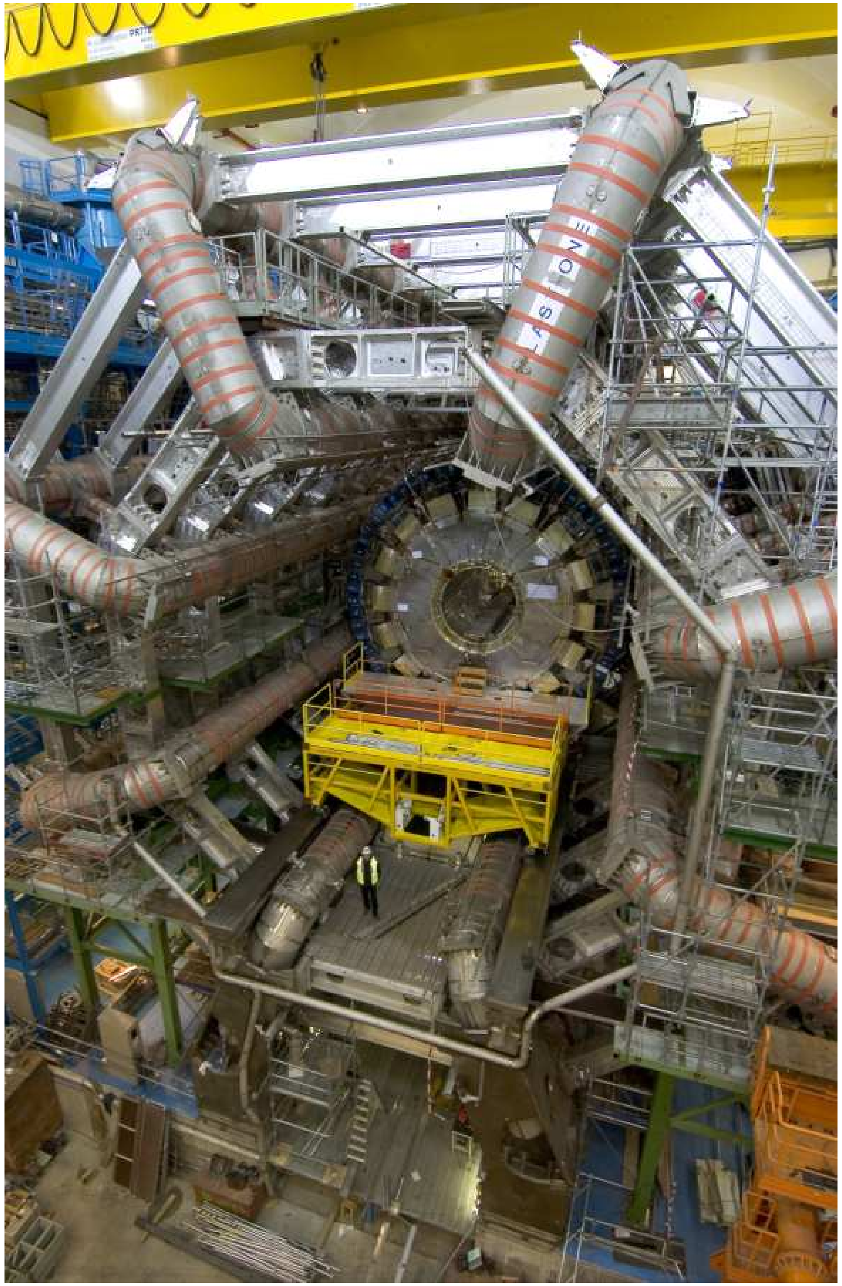
- Tracker: Si pixels + strips + Transition Radiation Tracker (TRT), B=2T
  $\sigma/p_T \approx 5 \cdot 10^{-4} p_T \oplus 0.01$
- EM Calorimeter: Pb - liquid Ar
  $\sigma/E \approx 10\%/\sqrt{E}$
- Hadronic Calorimeter:
  Fe-scint + Cu-liquid Ar (10λ)
  $\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$
- Muon Detectors:
  $\sigma/p_T \approx 10\%$ at 1 TeV
- Non-compensating calorimeter:
  $e/h \sim 1.3$

The ATLAS detector is a multipurpose detector...
flexible enough for the surprises which may lie ahead!

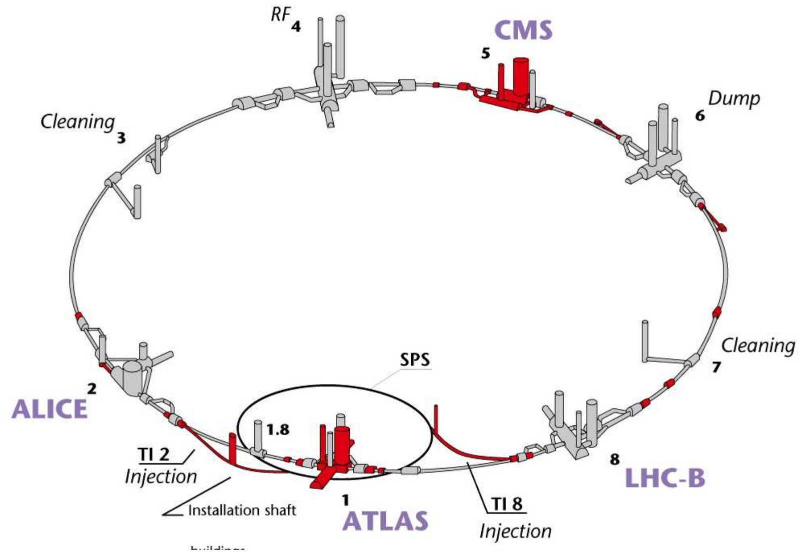
The CMS Detector



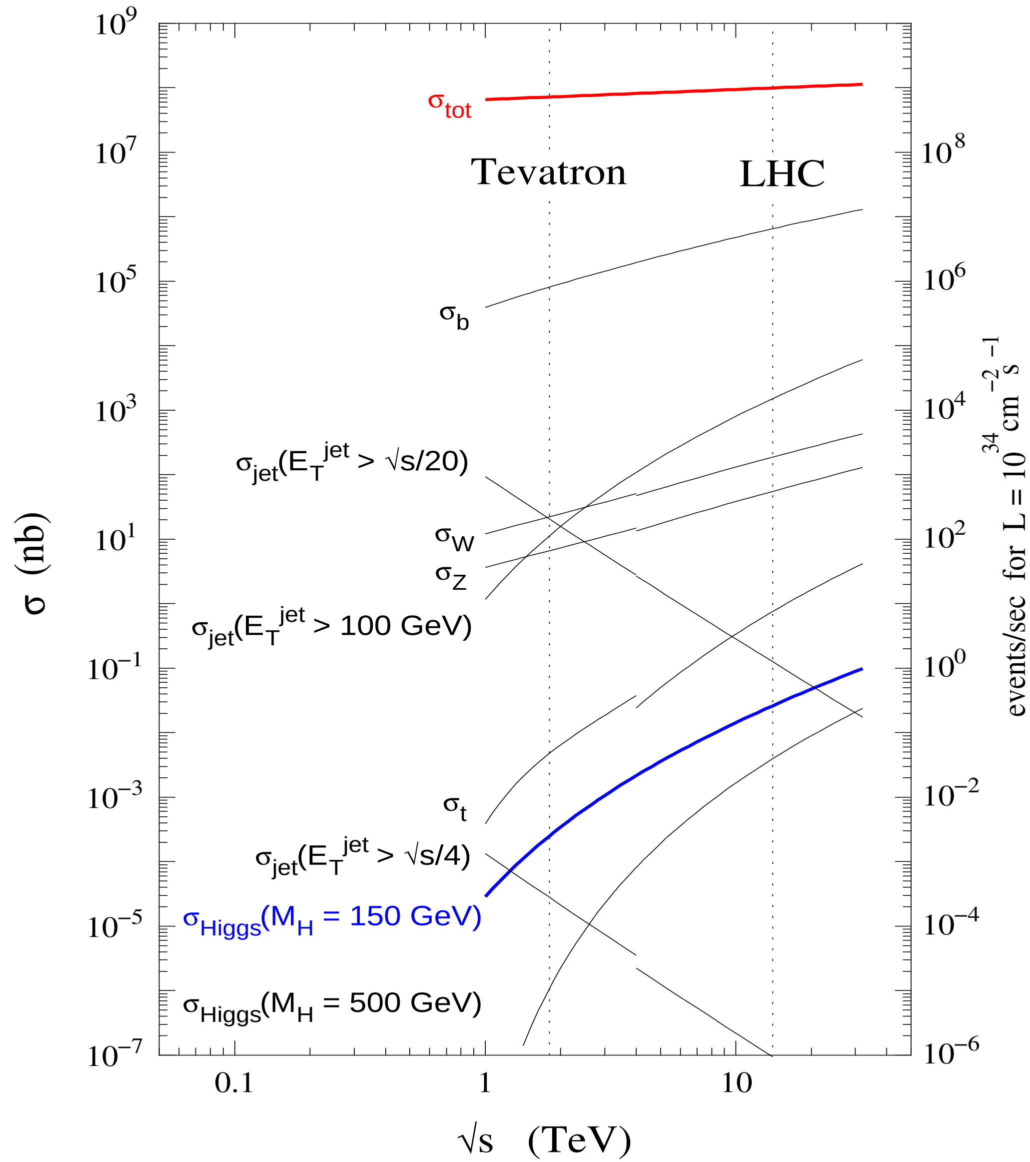




The LHC



- 26 km in circumference
- p-p @ $\sqrt{s} = 14$ TeV
- Instantaneous Luminosity $\approx 10^{33} - 10^{34}$ cm^{-2}s^{-1}
- "pile-up" : 2-20 inelastic collisions per bunch crossing
- 40 MHz bunch crossings

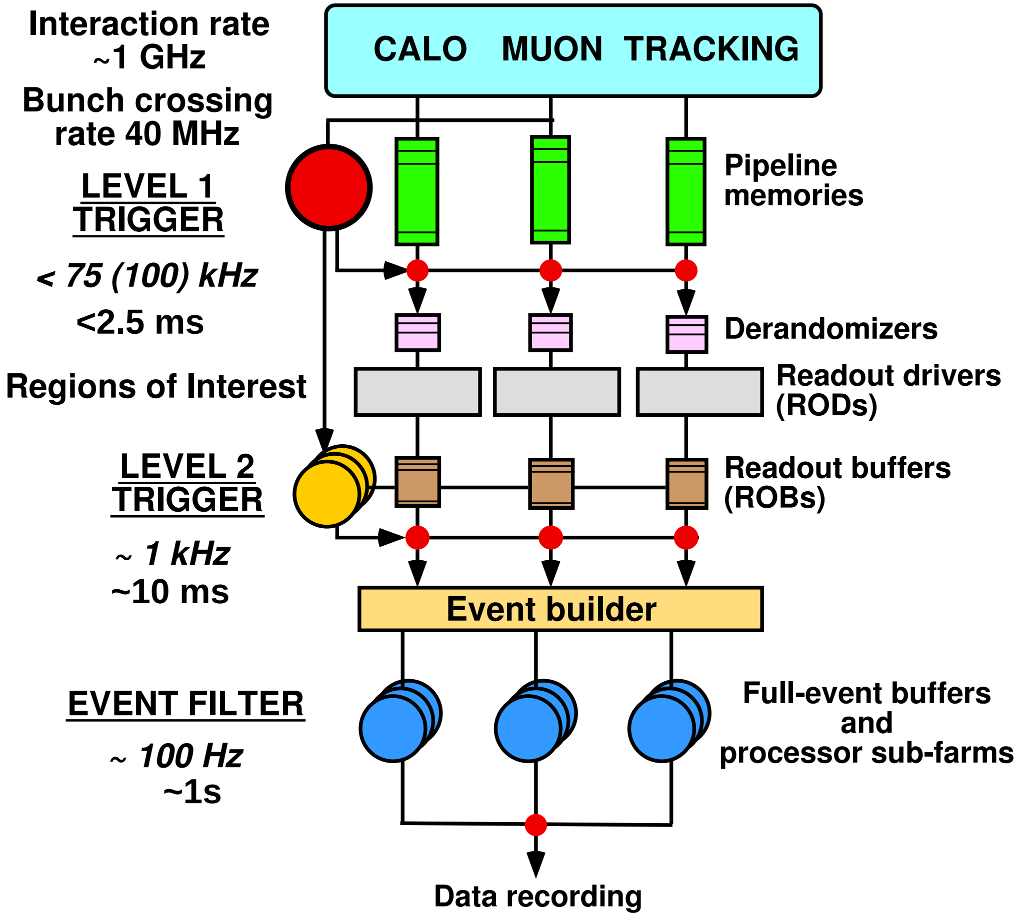


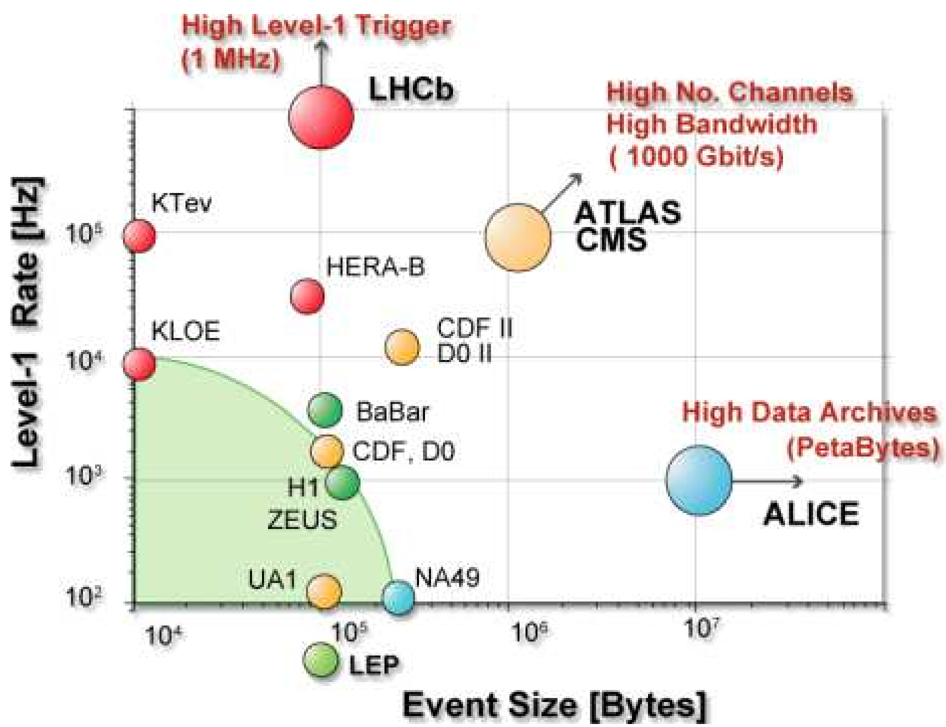
The ATLAS trigger is based on a 3-level design

Level 1 is in hardware, Level 2 & Event Filter are called "High-Level Trigger" implemented in software.

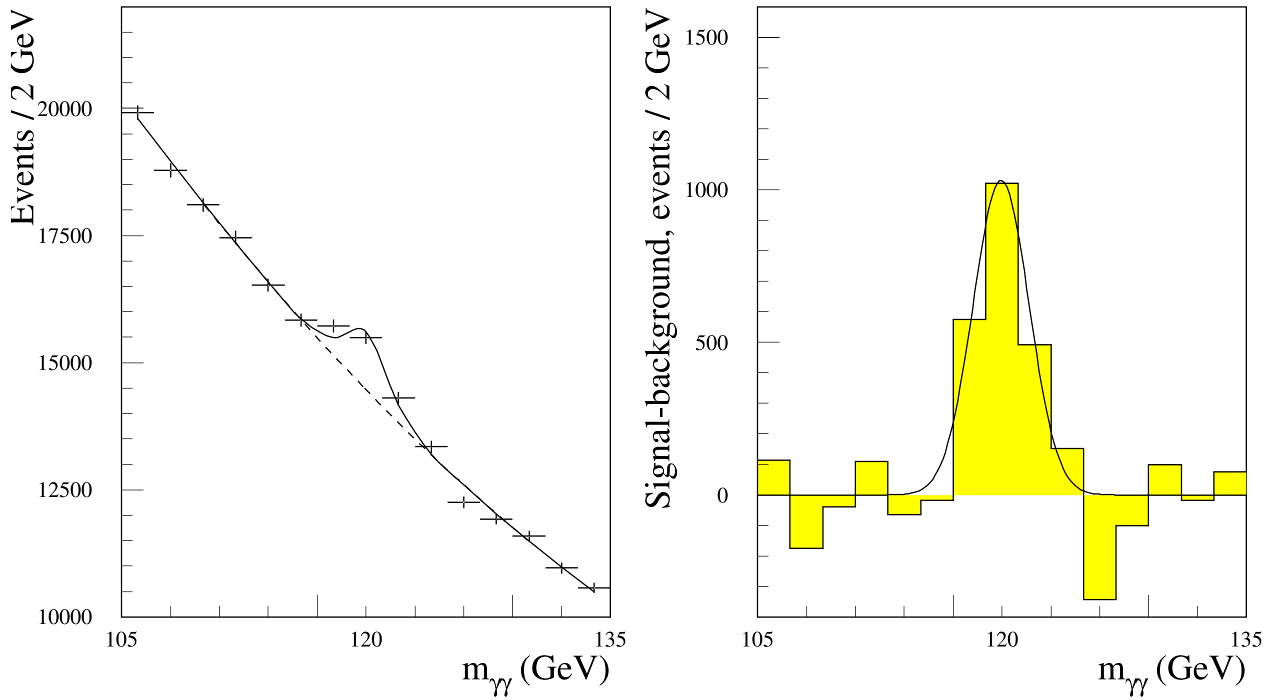
Level 2 constrained to "Regions of Interest", Event Filter has access to entire event

Output rate ~ 200 Hz. Event Size $\sim$ 2MB



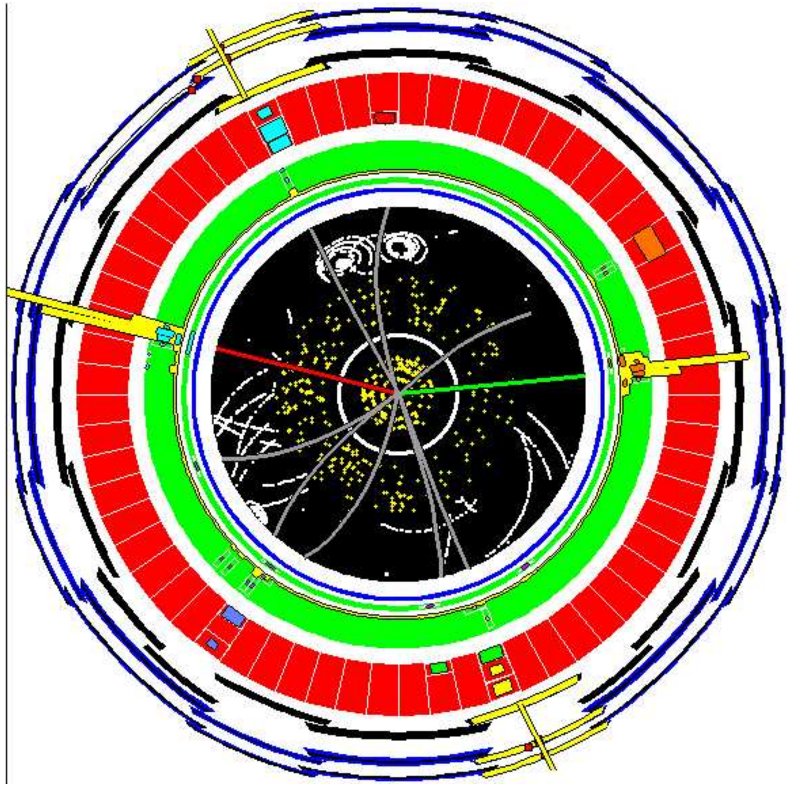


The Analyses



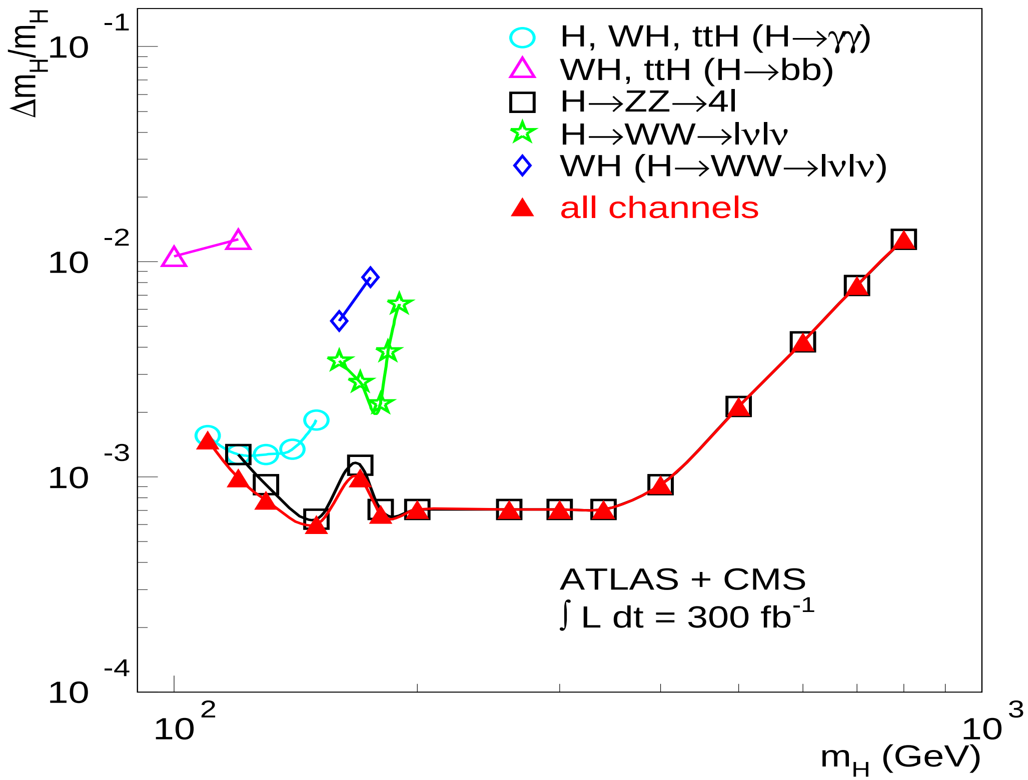
- Excellent EM Calorimetry needed for $\Delta M_H / M_H \approx 1\%$
- Excellent γ/jet separation needed
- Convincing signal with sideband subtraction
- Often associated with a hard jet (or 2 *à la* VBF), which can be used to improve S/B & reduce sensitivity to systematics

Considered the "golden channel"



Event Display for $H \rightarrow ZZ \rightarrow 2e2\mu$

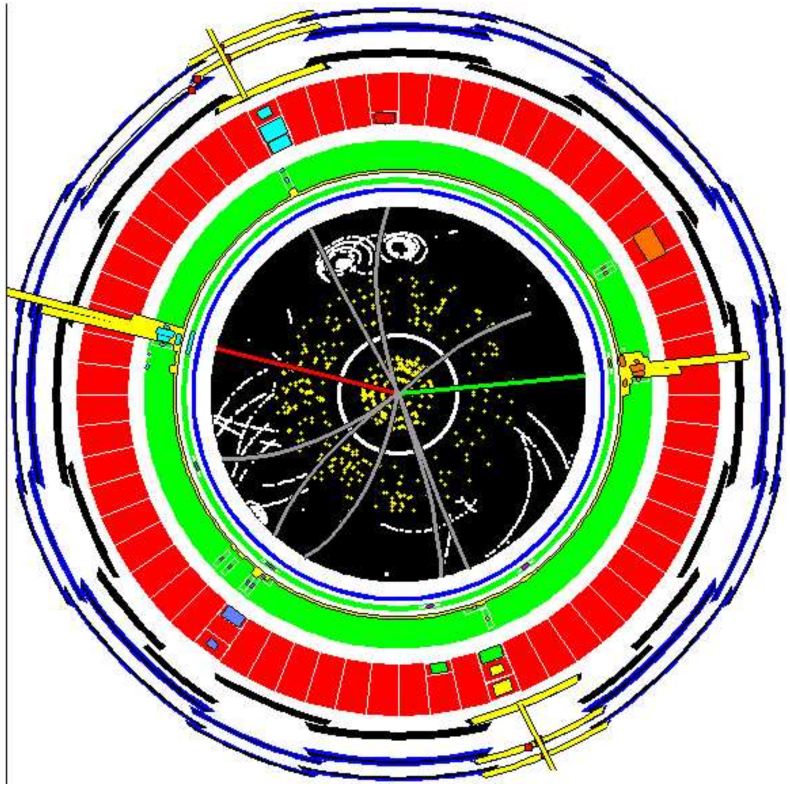
- Powerful if $m_H > 130$ GeV
- Recent analyses use MC@NLO for Signal & Background
- Provides precise mass determination



Considered the "golden channel"

- Powerful if $m_H > 130$ GeV

- Provides spin and CP measurement



Event Display for $H \to ZZ \to 2e2\mu$

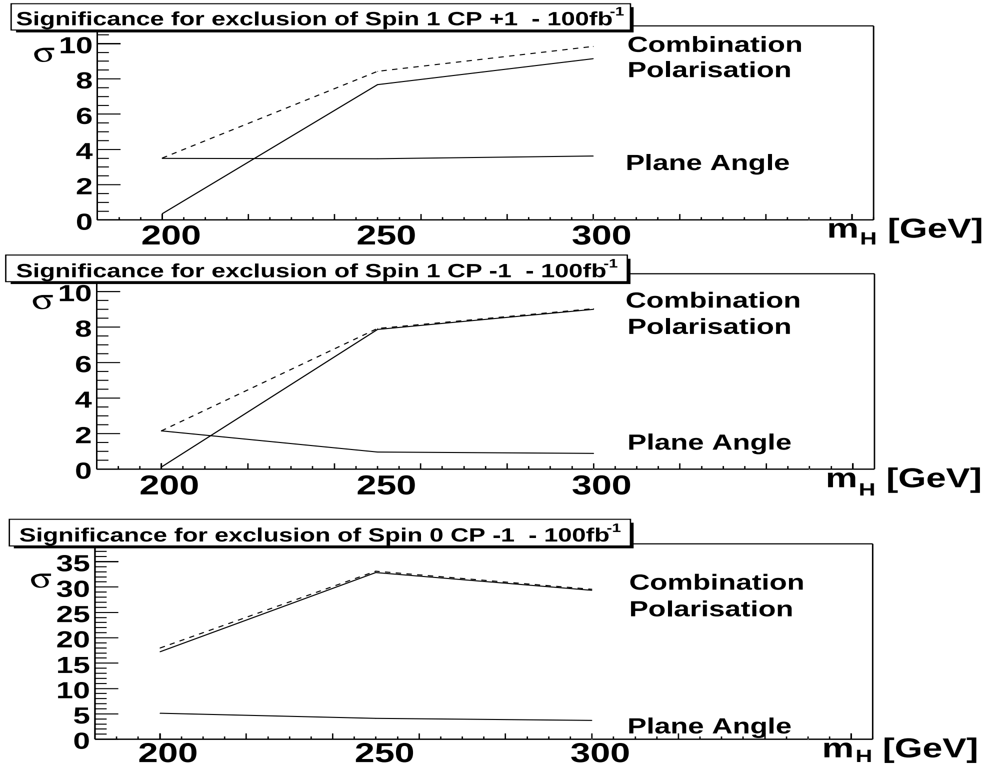


Figure 9: The overall significance for the exclusion of the non standard spin and CP-eigenvalue. The significance from the polar angle measurement and the decay-plane-correlation are plotted separately.

Additional Channels:

- ATLAS & CMS included VBF $H \to WW$ and VBF $H \to \tau\tau$ channels
- Corresponding updates to SUSY scans & coupling measurements
- Many new channels under investigation: $ttH(H \to WW, \tau\tau)$; $ZH(H \to \gamma\gamma)$; etc. !

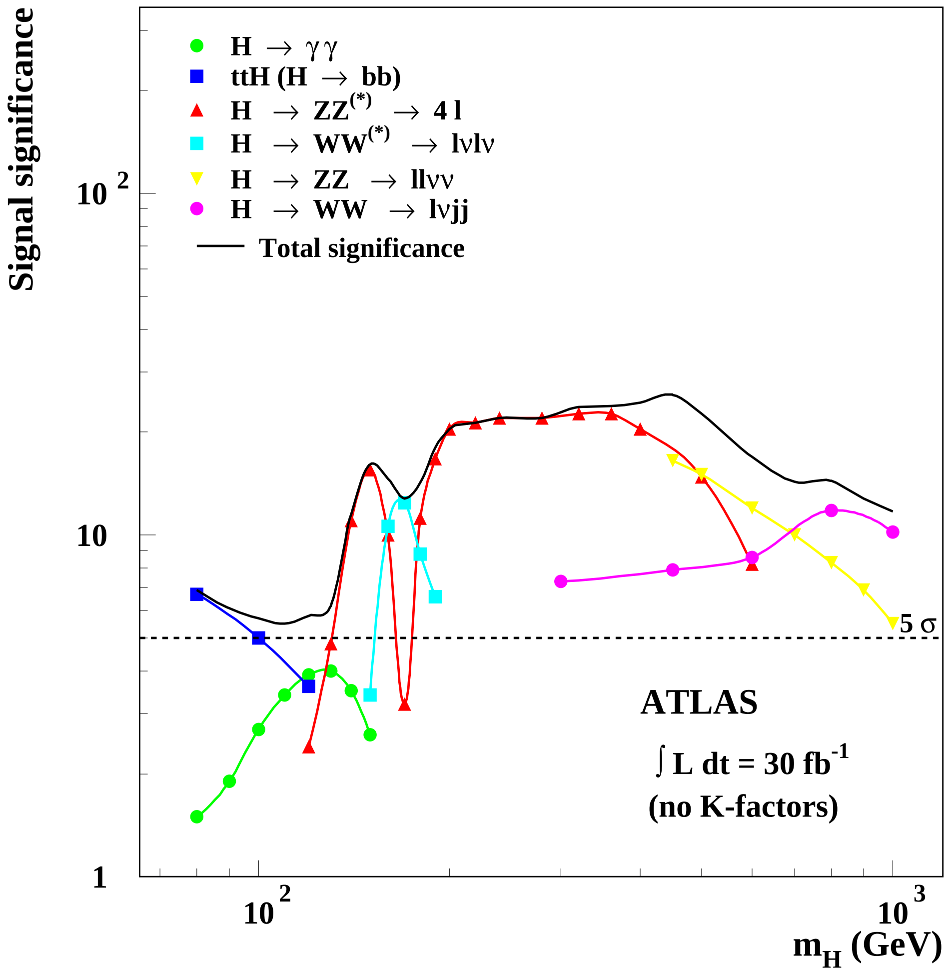
Improved Monte Carlo:

- NLO & NNLO x-sec. generators (MCFM, PHOX,etc.) and event generators (MC@NLO)
- Higher-order tree-level generators (MadEvent, Alpgen, etc.)
- Matrix Element - Parton Shower matching (CKKW, MLM, Sherpa, etc...)
- New Underlying Event & Min-Bias tunings (Pythia, Jimmy)

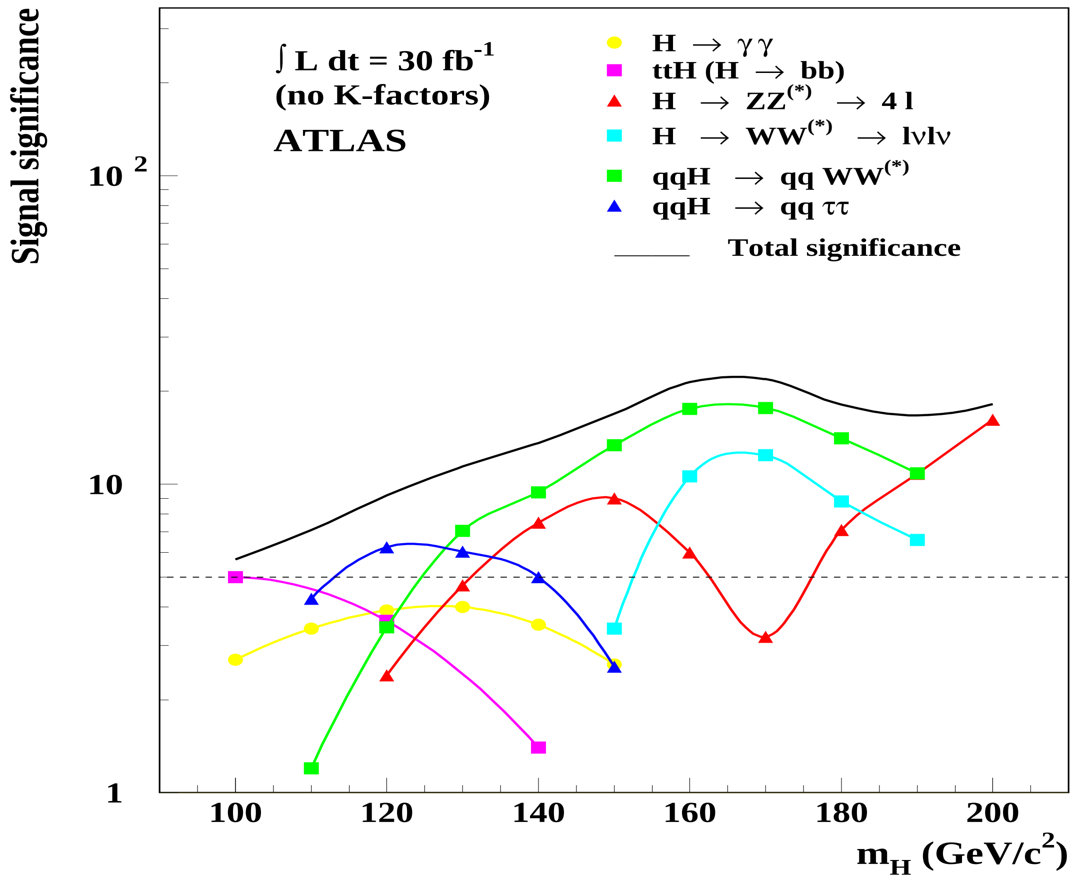
Improved Realism in Simulation:

- Most channels studied with Geant3 or Geant4 and use real reconstruction algorithms
- Studies with Pile-up, underlying event, electronic noise, cavern background, etc.
- Determine background control samples from data, estimation of systematics, etc.

Higgs Discovery Potential 1999 → 2003



Higgs Potential in ATLAS TDR (1999)

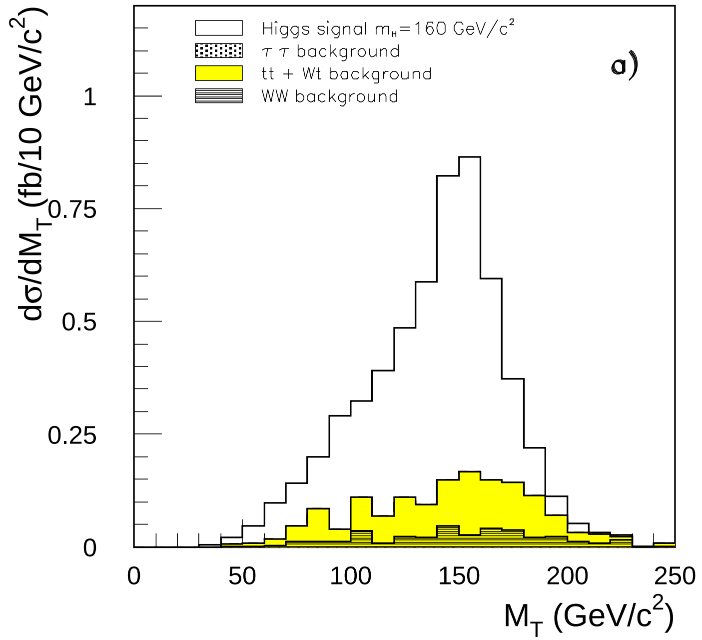


Addition of Vector Boson Fusion Channels at Low mass SN-ATLAS-2003-024

Both ATLAS and CMS cover entire SM Higgs mass range early in LHC running

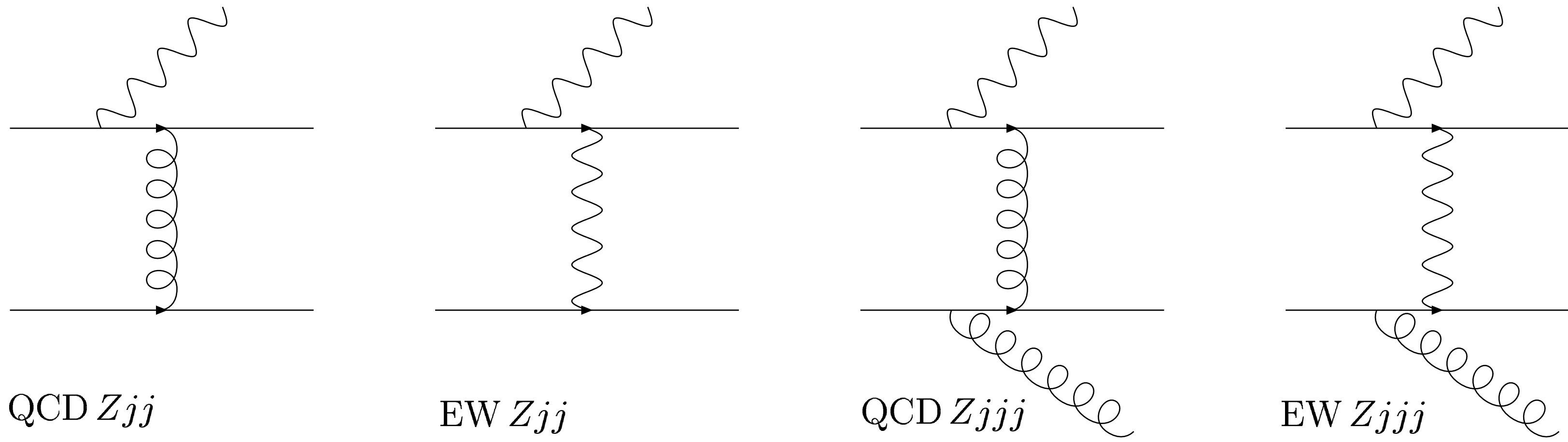
VBF $H \to WW \to ll\nu\nu$: Scientific Note Results

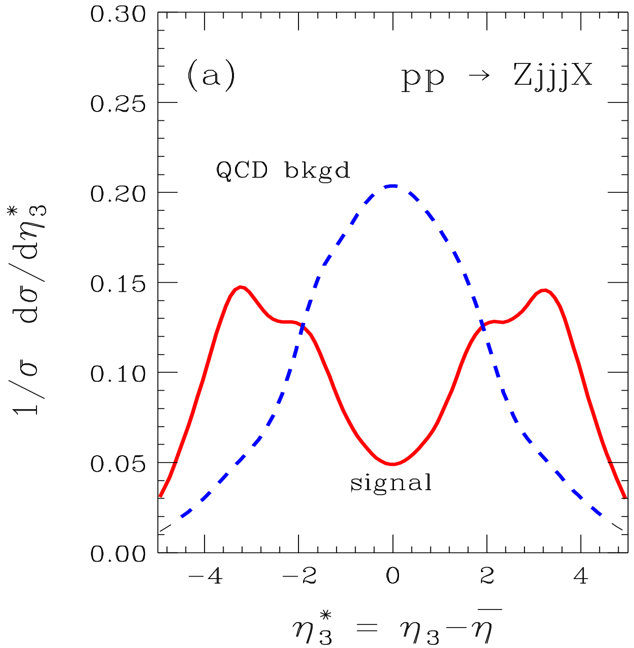
	signal (fb)		background (fb)					
	VV	gg	$t\bar{t}$ + Wt	$WW+jets$ EW	$WW+jets$ QCD	$\gamma^*/Z+jets$ EW	$\gamma^*/Z+jets$ QCD	total
Lepton acceptance	5.20	17.30	8456	17.1	617.2	7.09	4980	14077
+ Forward Tagging	1.85	0.27	82.6	10.7	1.83	2.10	45.2	142.4
+ Lepton angular cuts	1.36	0.18	13.5	0.89	0.27	0.81	7.47	22.9
+ τ rejection	1.27	0.18	12.9	0.83	0.27	0.15	1.64	15.8
+ Jet mass	0.88	0.08	6.39	0.43	0.08	0.11	0.83	7.84
+ P_T^{tot}	0.68	0.05	1.40	0.32	0.04	0.10	0.46	2.32
+ Jet veto	0.59	0.05	0.61	0.28	0.04	0.10	0.32	1.35
+ $m_T(\ell\ell\nu)$-cut	0.52	0.05	0.58	0.27	0.03	0.02	0.05	0.95
$H \to WW^{(*)} \to e\mu + X$	0.52	0.05	0.58	0.27	0.03	0.02	0.05	0.95
$H \to WW^{(*)} \to ee/\mu\mu + X$	0.50	0.04	0.58	0.30	0.03	0.03	0.39	1.33



- Based on work of Rainwater, Zeppenfeld in 1999-2000 (hep-ph/9906218)
- Used fast simulation (90% lepton efficiency) & LO $t\bar{t}$ M.C.
- Can't reconstruct m_H, only "transverse mass" m_T
- Dominated by irreducible $t\bar{t}$+jets and WW+jets background
- Possible discovery channel for $M_H > 125$ GeV with 30 fb^{-1}

To evaluate VBF channels, need Zjj, $WWjj$, & $t\bar{t}j$ matrix element for high-p_T forward jets



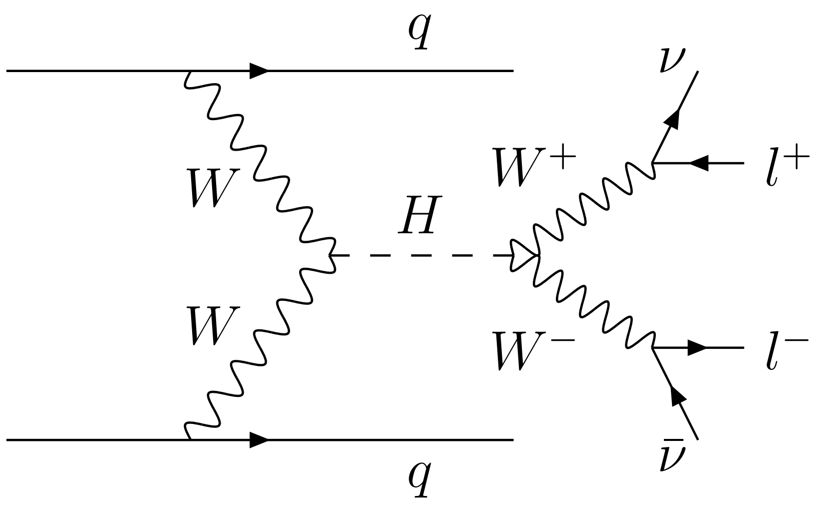


Parton-Shower severely under-estimates high-p_T tail.

For ATLAS scientific note, we worked with Zeppenfeld to interface background Matrix Element code to Showering & Hadronization generators like PYTHIA and HERWIG (MadCUP)

Now we mainly rely on general purpose tools like MadEvent, Alpgen, & Sherpa

Complex final state of VBF $H \to WW \to llE_T^{miss}$ well-suited for multivariate methods



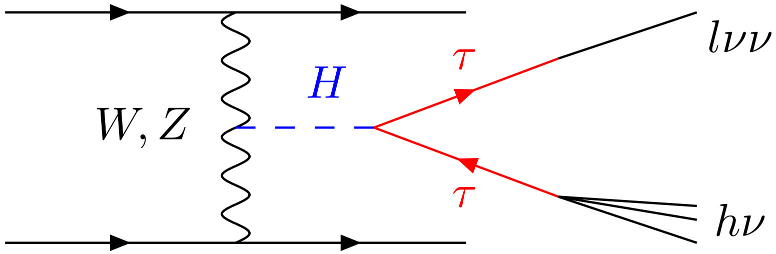
Used 7 variables:
$\Delta\eta_{ll}$, $\Delta\phi_{ll}$, M_{ll}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, M_{jj}, M_T

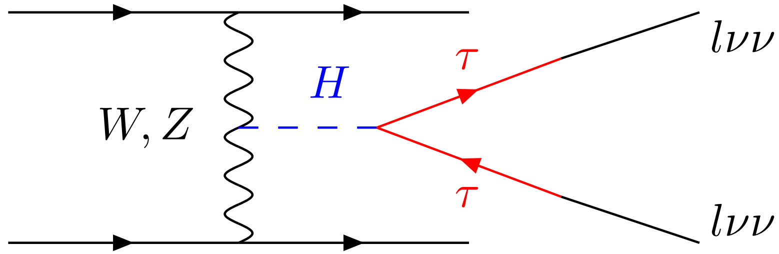
Compared Neural Networks, Genetic Programming, and Support Vector Regression

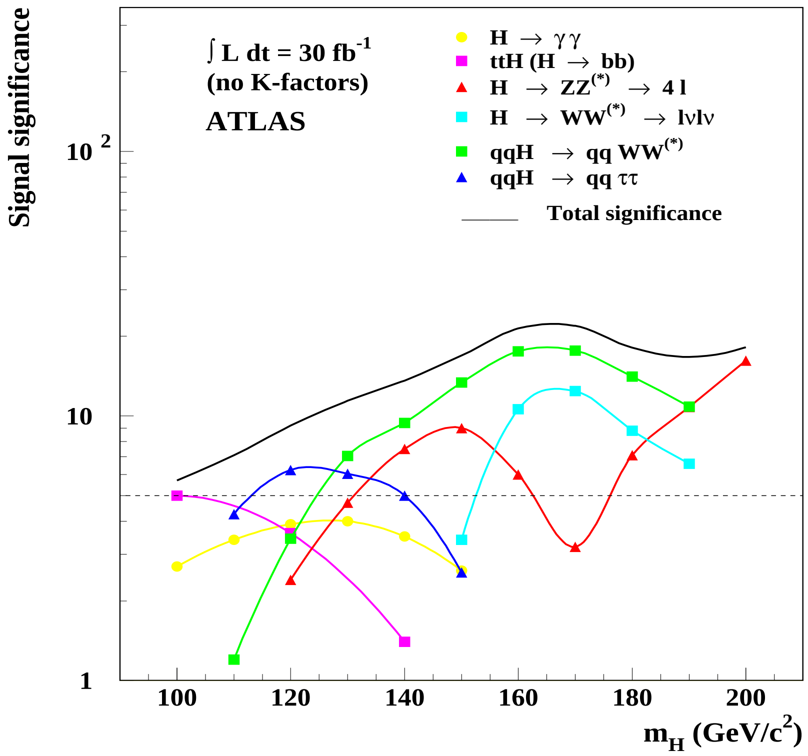
	Ref. Cuts	low-m_H Cuts	NN	GP	SVR
120 ee	0.87	1.25	1.72	1.66	1.44
120 $e\mu$	2.30	2.97	3.92	3.60	3.33
120 $\mu\mu$	1.16	1.71	2.28	2.26	2.08
Combined	2.97	3.91	4.98	4.57	4.26
130 $e\mu$	4.94	6.14	7.55	7.22	6.59

Table 1: Expected significance in sigma after 30 fb^{-1} for two cut analyses and three multivariate analyses for different Higgs masses and final state topologies.

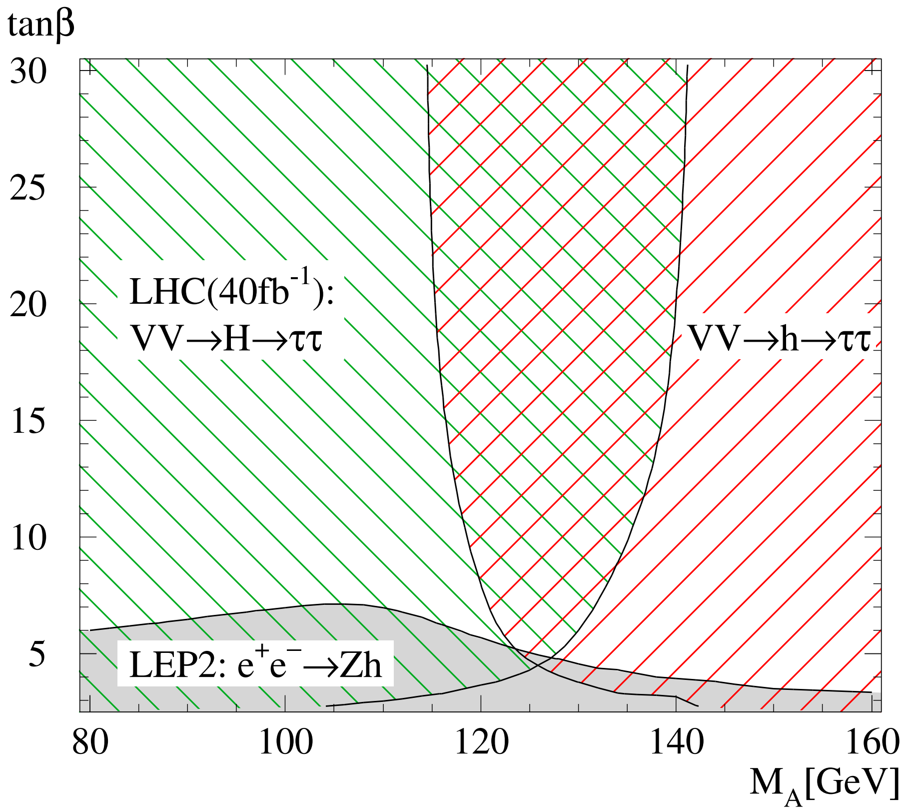
The VBF $H \to \tau\tau$ channel and Why It's Important







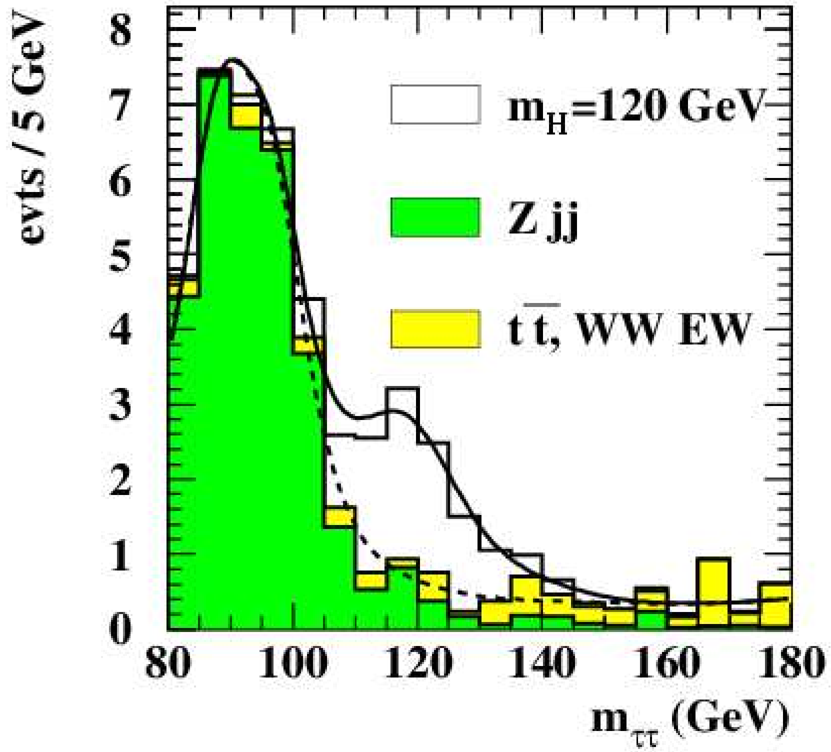
Standard Model (Atlas Scientific Note)



Plehn, et. al hep-ph/9911385

Most powerful channel near LEP limit and very important for MSSM.

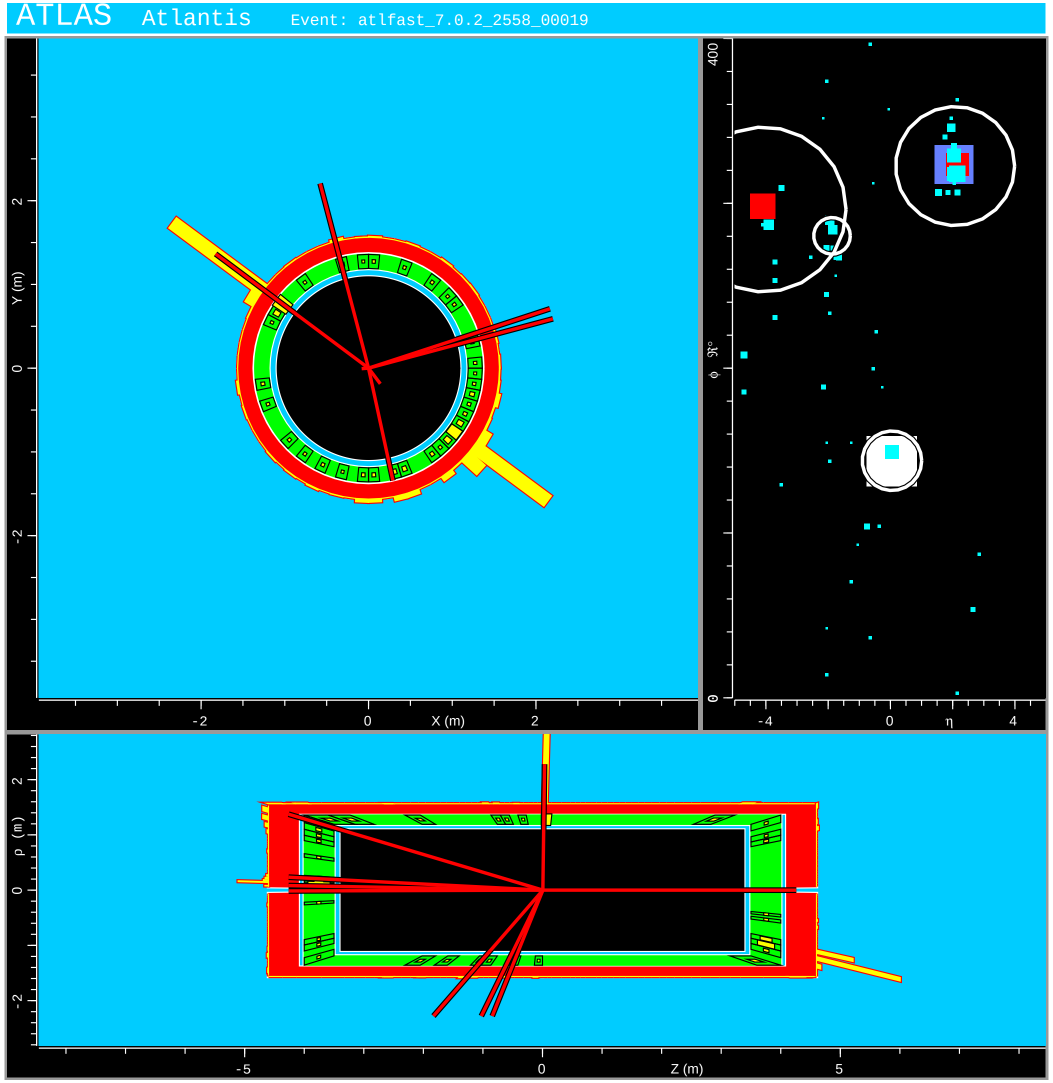
	signal (fb)		background (fb)					
	VV	gg	$t\bar{t}+jets$	$WW+jets$		$\gamma^*/Z\ +jets$		Total
				EW	QCD	EW	QCD	
Lepton acceptance	5.55		2014.	18.2	669.8	11.6	2150.	4864.
+ Forward Tagging	1.31		42.0	9.50	0.38	2.20	27.5	81.6
+ P_T^{miss}	0.85		29.2	7.38	0.21	1.21	12.4	50.4
+ Jet mass	0.76		20.9	7.36	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



- Based on work of Rainwater, Zeppenfeld, Hagiwara, Plehn in 1999-2000
- Used fast simulation: 90% lepton efficiency, parametrized τ-id, etc.
- Possible discovery channel for $M_H =$ 115-140 GeV with 30 fb^{-1}
- Dominated by irreducible $Z \to \tau\tau$ background
- Published in: Eur. Phys. J., C 32 (2004) 19-54 & SN-ATLAS-2003-024

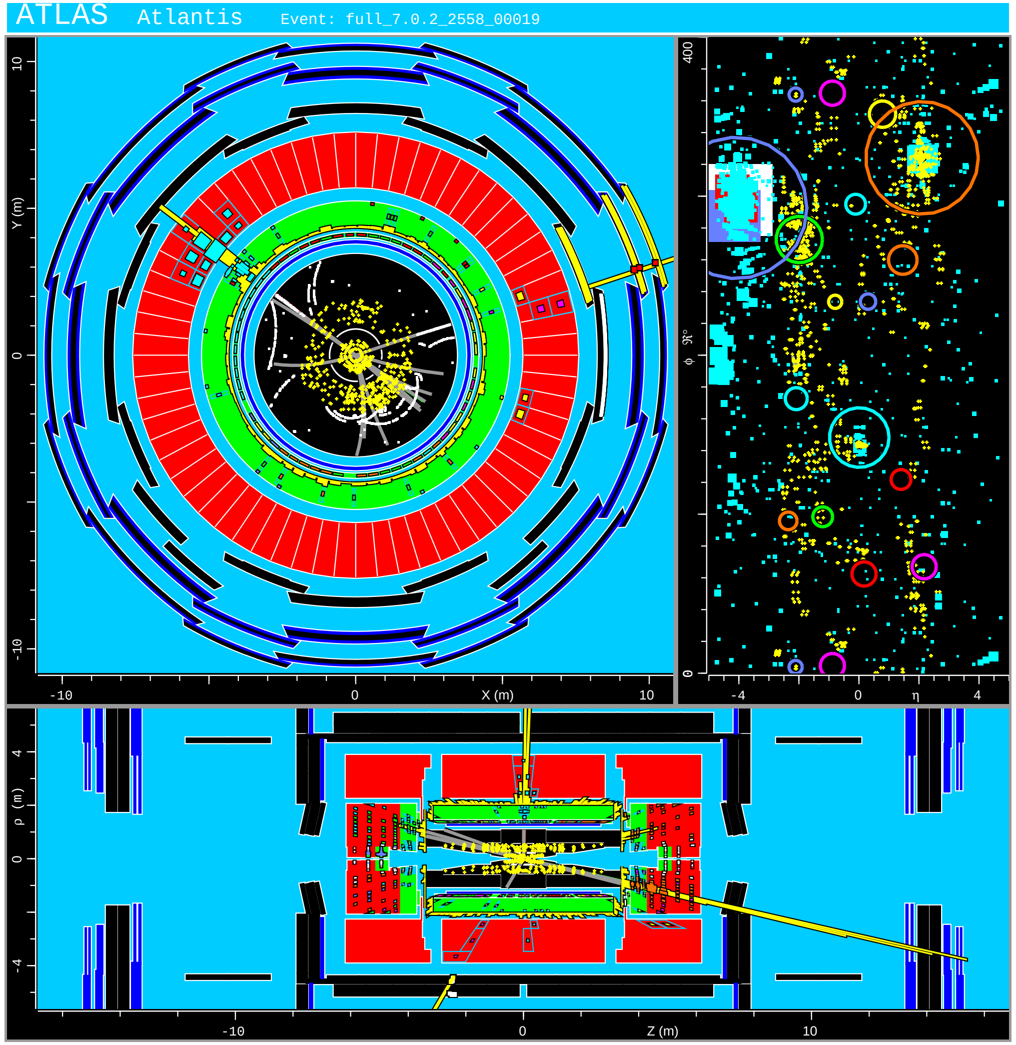
Simulating The ATLAS Detector

ATLFAST

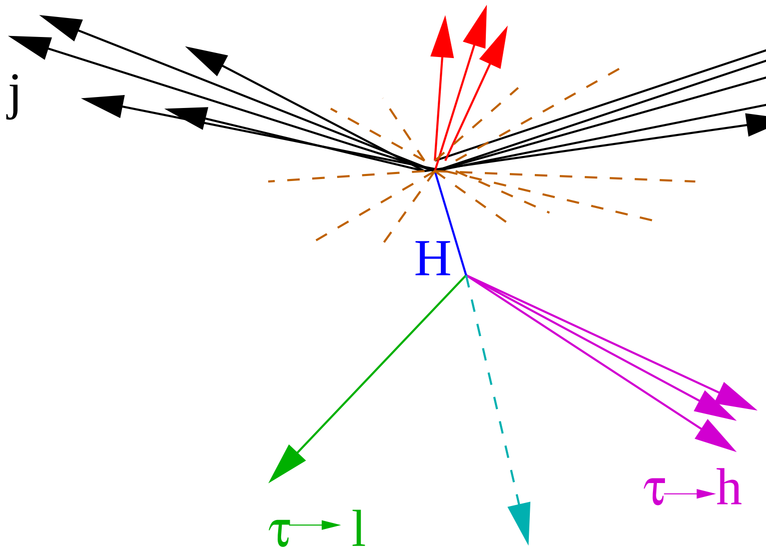


Parametrized Resolutions &
Particle Identification Efficiency

GEANT

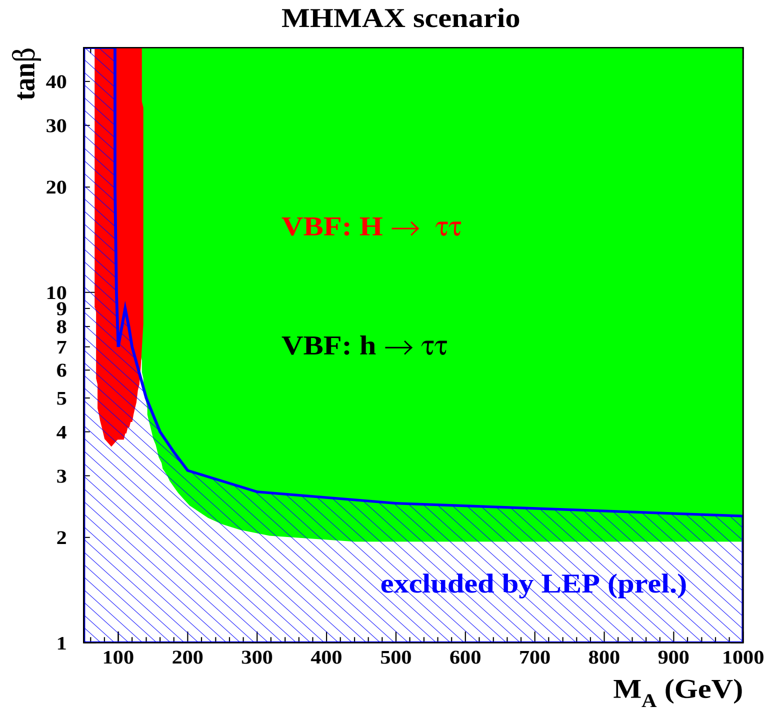


Detailed Showering Model,
Simulation of Detector Electronics



There is still on-going work with the full simulation, but fast simulation results seem to be generally robust

Complementarity of $h \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ allows this channel to cover most of the MSSM Higgs plane.



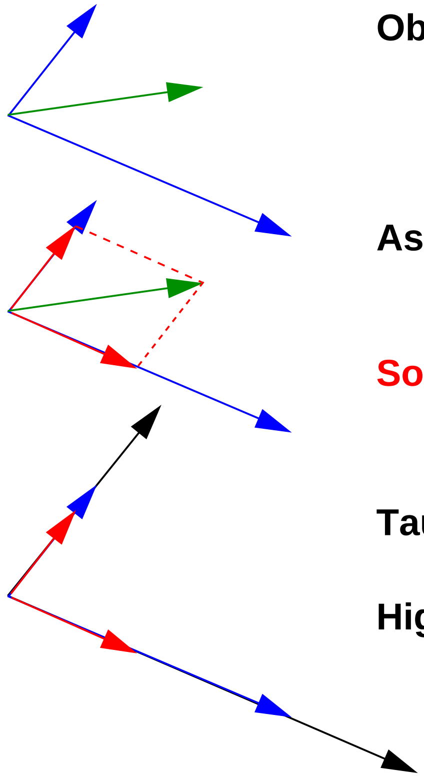
MissingET is the dominant experimental issue

Unexpected complications from finely segmented calorimeter and noise suppression

Several GeV of bias in MissingET if one simply cuts all cells with $E < 2\sigma_{noise}$

Translates into bias on $m_{\tau\tau}$

Mass Reconstruction:



Observe

missing transverse momentum

and visible Tau−decay products

Assume Tau decay products

collinear with original Tau

Solve 2 linear equations

for the neutrinos

Taus can be reconstructed

Higgs can be reconstructed

$$x_{\tau h} = \frac{h_x l_y - h_y l_x}{h_x l_y + \not{p}_x l_y - h_y l_x - \not{p}_y l_x}$$

$$x_{\tau l} = \frac{h_x l_y - h_y l_x}{h_x l_y - \not{p}_x h_y - h_y l_x + \not{p}_y h_x}$$

Some Comments:

After jet cuts, $M_{\tau\tau}$ is the only discrimination we use between $Z \to \tau\tau$ and $H \to \tau\tau$

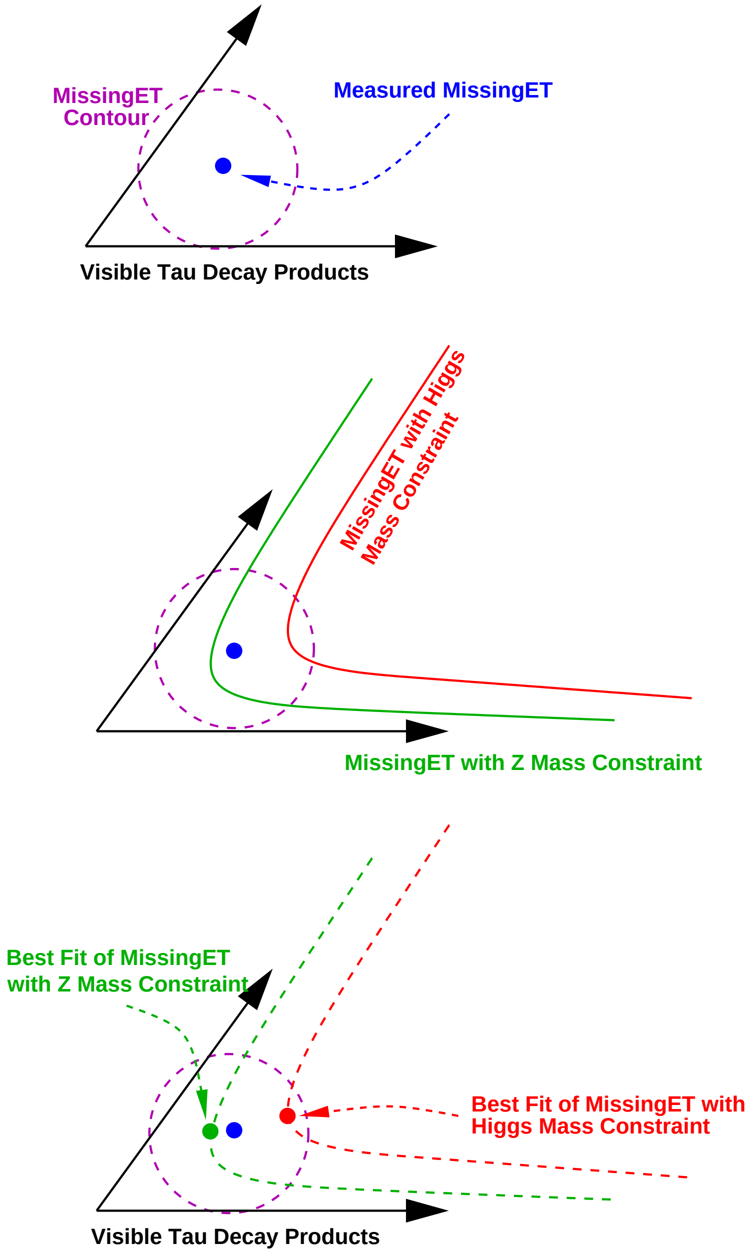
Collinear approximation doesn't take into account MissingET resolution

Define x_τ: fraction of τ's momentum in visible decay product

$$M_{\tau\tau} = \sqrt{2(E_h + E_{\nu h})(E_l + E_{\nu l})(1 - \cos\theta_{\tau\tau})}$$

is equivalent to $M_{\tau\tau} = \frac{M_{ll}}{\sqrt{x_{\tau l} x_{\tau h}}}$

only when $0 < x_\tau < 1$



We Observe MissingET and **visible τ decay products**. From $\sum |E_T|$ we know 1σ MissingET contour

Assuming ν's collinear with τ's the MissingET can be

- Constrained to Hypothesized Higgs Mass
- Constrained to Z Mass
- $x_{\tau l} = \left(M_{ll}^2 / M_0^2\right) / x_{\tau h}$

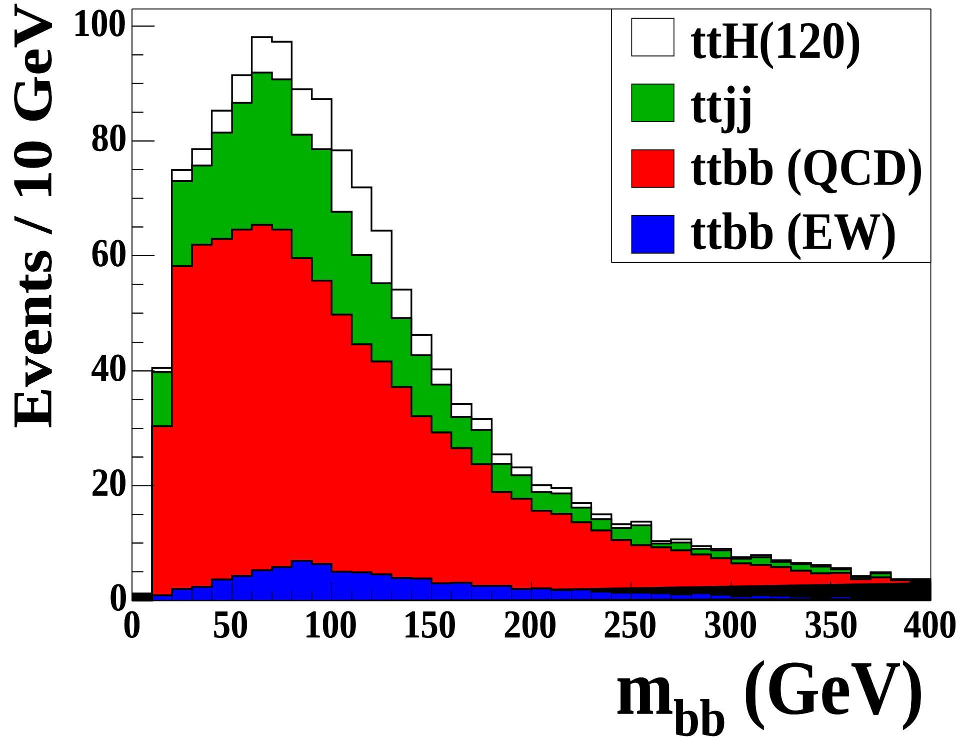
Kinematic fits can be used to find hypothetical MissingET most consistent with observed MissingET and mass constraint. Each has it's own χ^2

Finally, $\Delta\chi^2$ quantifies if event is more consistent with $H \to \tau\tau$ or $Z \to \tau\tau$

Leads to a low- and high-purity sample. Preliminary results very promising.

Progress on Systematics

J. Cammin & M. Schumacher, ATL-PHYS-2003-024 (nice thesis by J. Cammin)



Combinatorial background is challenging with 4b-jets and $\geq$ 6 jets total

Signal efficiency goes like ϵ_b^4

Signal & bkgnd. have similar shape

Estimating $ttjj$ and $ttbb$ background from data difficult, large systematics

It's not clear if this channel will ever reach 5σ

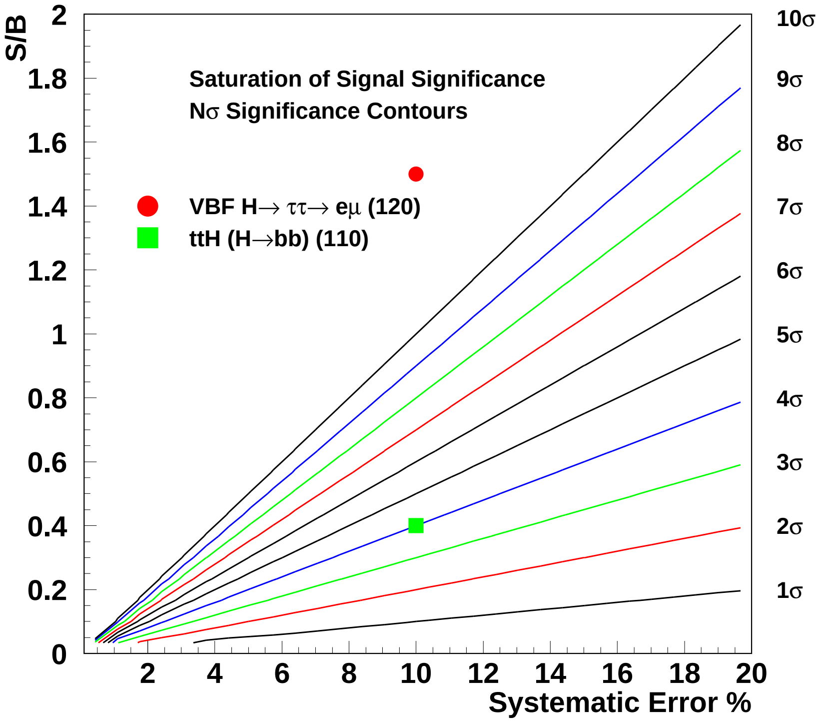
- This is (was) one of the few powerful channels near the LEP limit
- Do ATLAS and CMS results agree?

Background determination from sidebands carries two sources of error:

- Class I: statistical error from sideband measurement

- Class II: systematic on extrapolation from sideband to signal-like area (shape systematic)

The shape systematic does not (necessarily) reduce with increased luminosity



Normal significance measure $s/\sqrt{b}$ is replaced by $s/\sqrt{b(1+b\Delta^2)}$

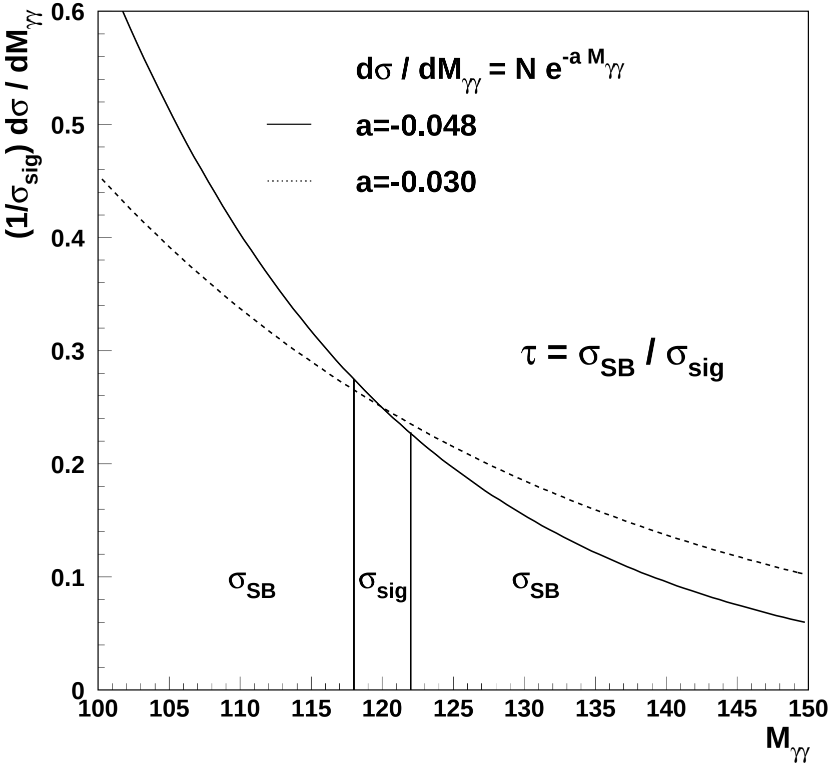
If s/b is fixed as we increase luminosity, the expected significance saturates:

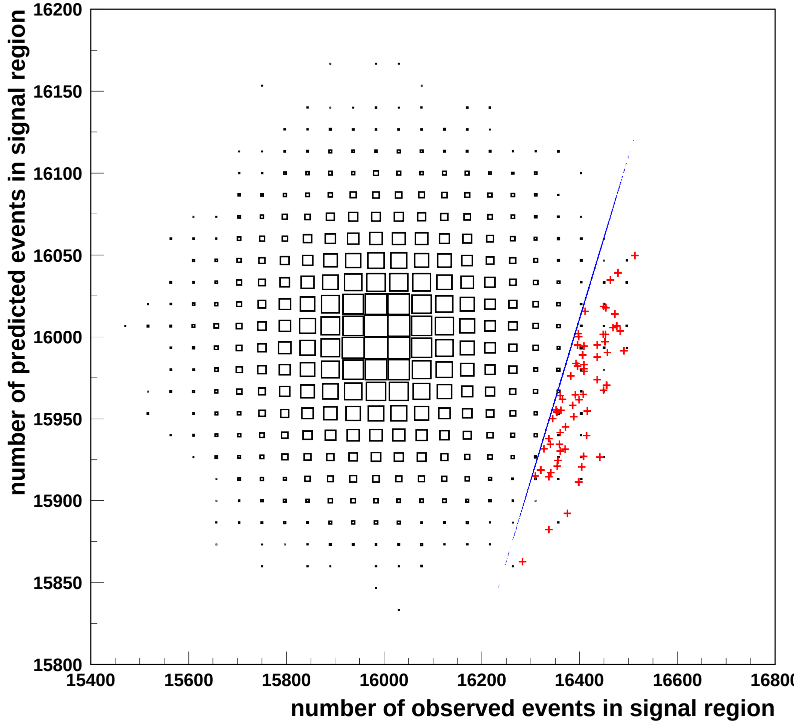
$$\sigma_\infty = \frac{s/b}{\Delta_{shape}}$$

With its low S/B and 10% shape systematic, $ttH(\to bb)$ can't get to 5σ even with $L \to \infty$

Systematic Error on background for $H \to \gamma\gamma$ usually considered negligible

S. Paganis & I Tested background prediction from side-band with ToyMC





Systematic Error is small, but not negligible:

$$N\sigma \approx \frac{s}{\sqrt{b + (\delta b)^2}} \to \frac{s}{\sqrt{b}\sqrt{1 + 1/\tau}}$$

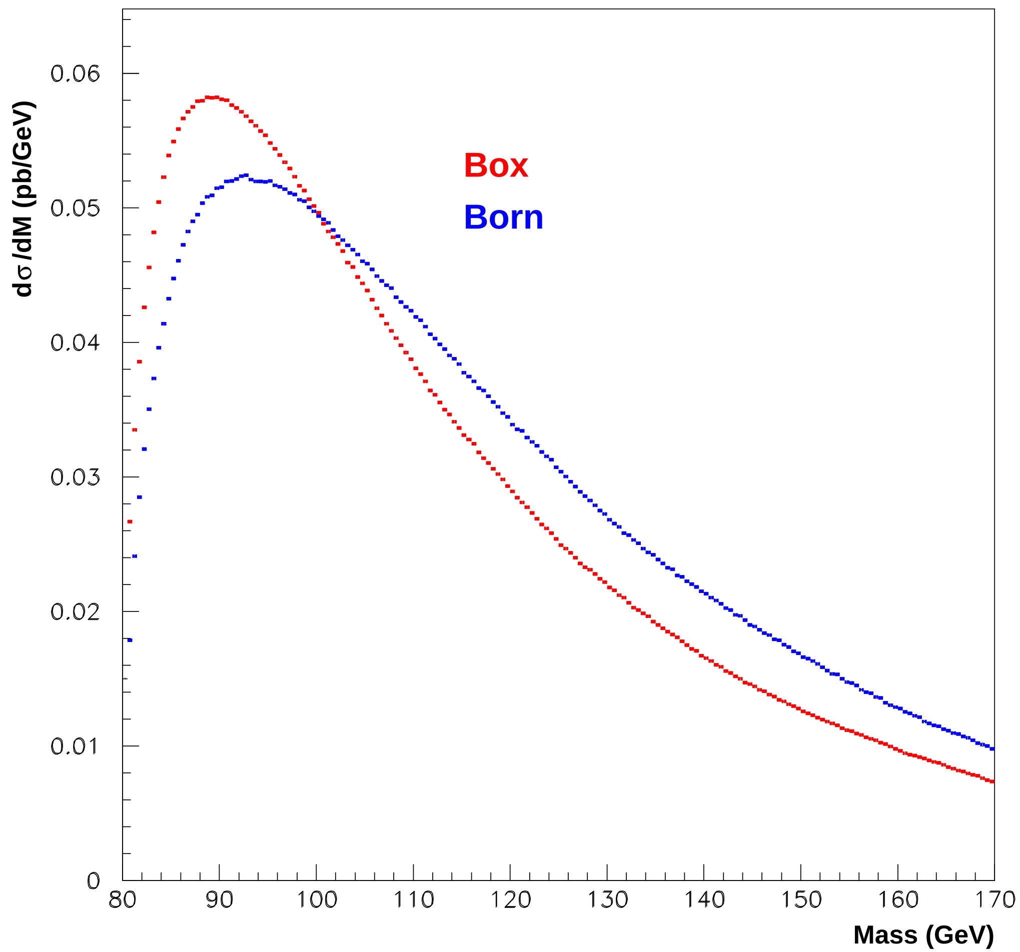
At PhyStat2003, Sinervo provided a classification of systematic errors.

The background uncertainty discussed on previous slide is another statistical error (Class I)

In the $H \to \gamma\gamma$ example, there is also uncertainty on the shape of the continuum $M_{\gamma\gamma}$ spectrum.

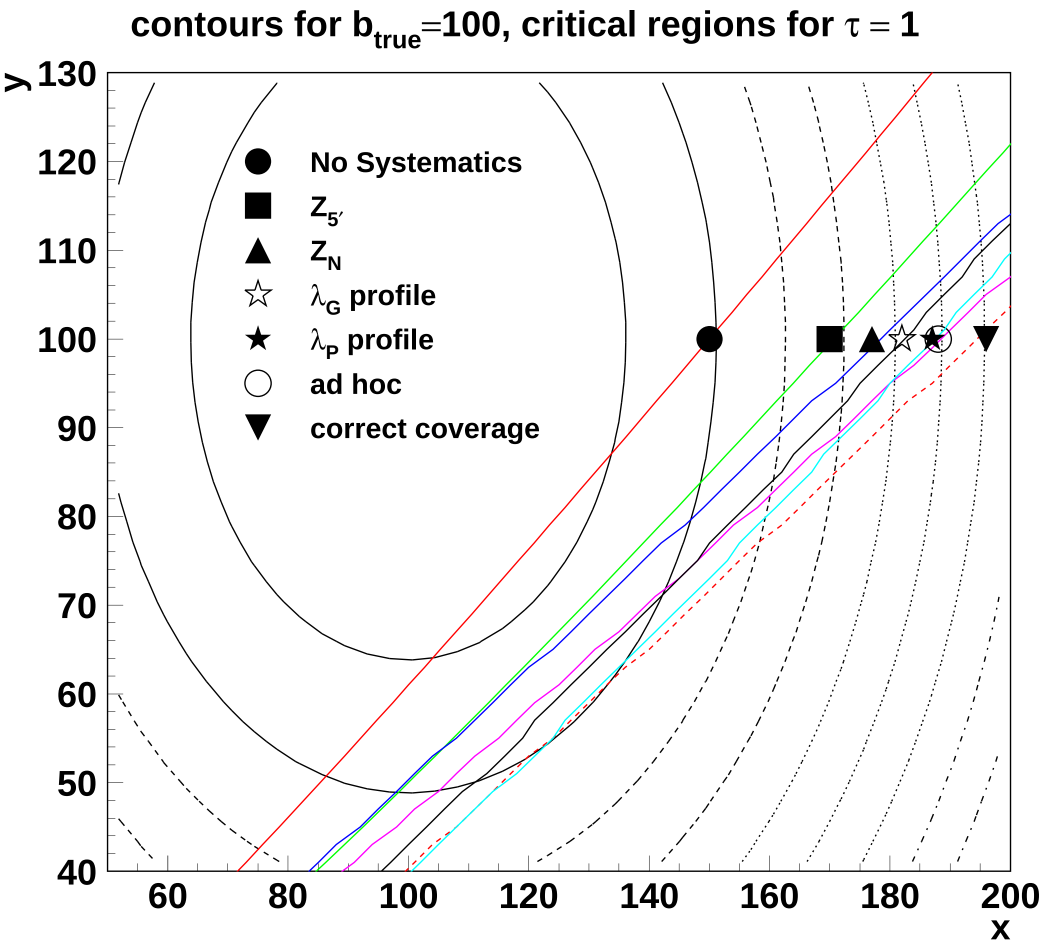
These shape uncertainties impact the background prediction from the sideband, and do not scale like statistical errors (Class II)

Class II systematics under investigation for $H \to \gamma\gamma$



Two plausible shapes for the continuum $M_{\gamma\gamma}$ spectrum.

At PhyStat2005, I compared the most common statistical methods to incorporate background uncertainty in significance calculation.



(ovals indicate contours of true pdf)

Simple example where:

- sideband is same size as signal-like region
- truth $=$ 100 background events

$x =$ events in signal like region

$y =$ sideband measurement $=$ background estimate

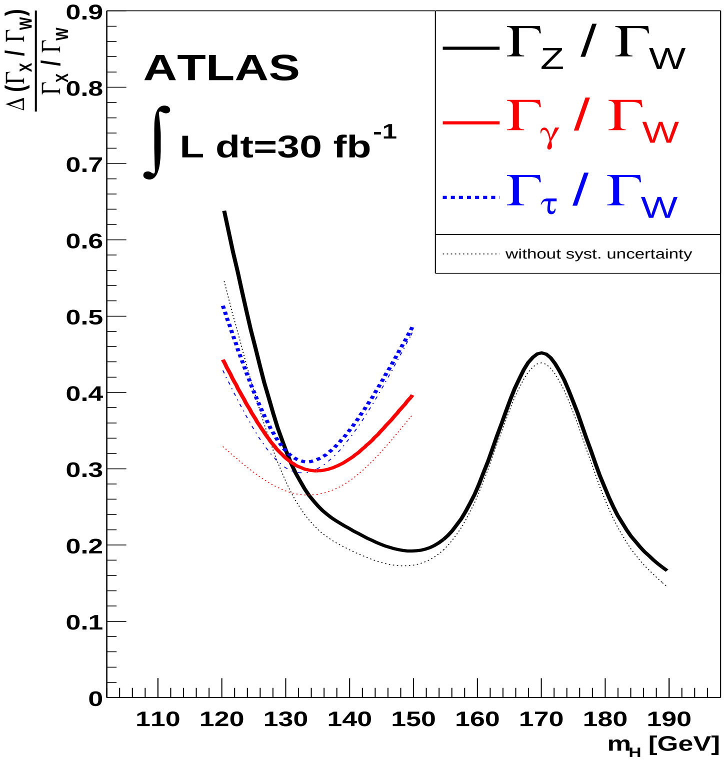
lines $=$ discovery criterion

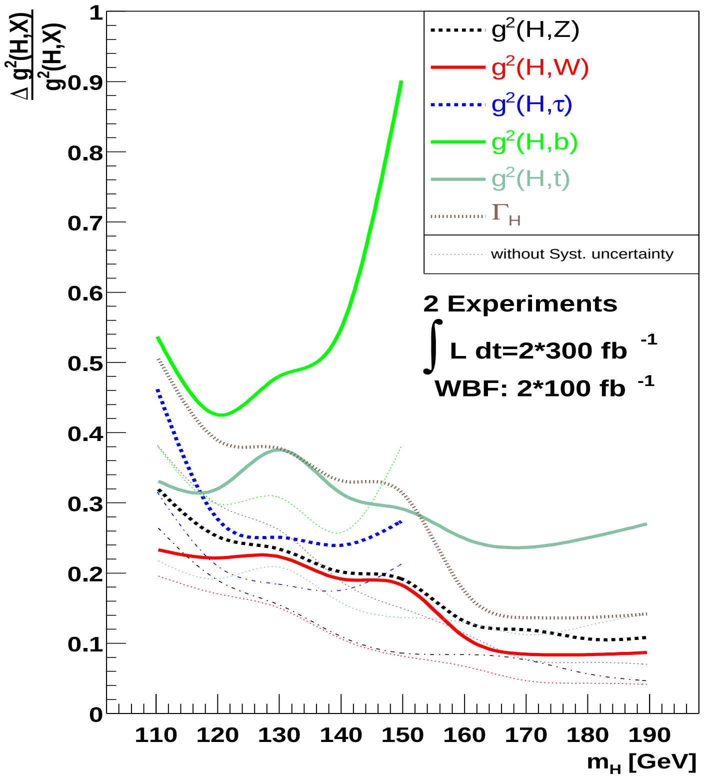
Clearly the background uncertainty needs to be incorporated

Large variation in discovery criterion ($\pm$15 events), and most give too many discoveries when signal is absent

Coupling Measurements

M. Dührssen, et. al. ATL-PHYS-2003-030 & Phys.Rev.D70:113009,2004 (hep-ph/0406323)





Assume CP-even, spin-0, only one Higgs

Ratios of partial widths
to within 20% with 30 fb^{-1}

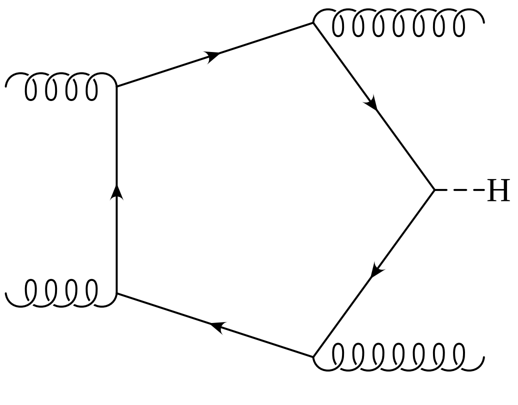
Weak assumptions:
$g(H,V) < 105\% g(H,V,SM)$
allow for unobserved decays & new loops

Absolute couplings measured
to within 10% with 2×300 fb^{-1}

Progress on Systematic Error

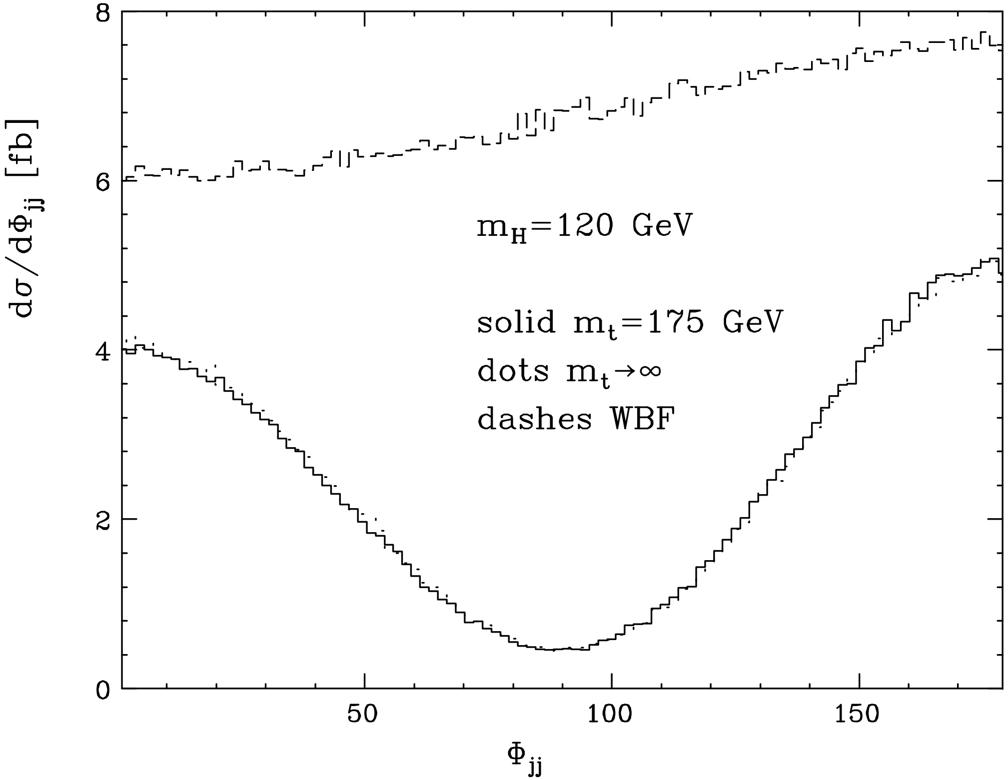
GF	20%
$t\bar{t}H$	15%
WH	7%
ZH	7%
WBF	4%
$gg \to Hgg$	100%

Table 2: Theoretical QCD and PDF uncertainties on the various Higgs boson production channels. The channel $gg \to Hgg$ was added to all WBF analyses at 10% of the WBF rate with an uncertainty of a factor 2.



(c)

V. Del Duca, C. Oleari, D. Zeppenfeld, et. al. hep-ph/0108030



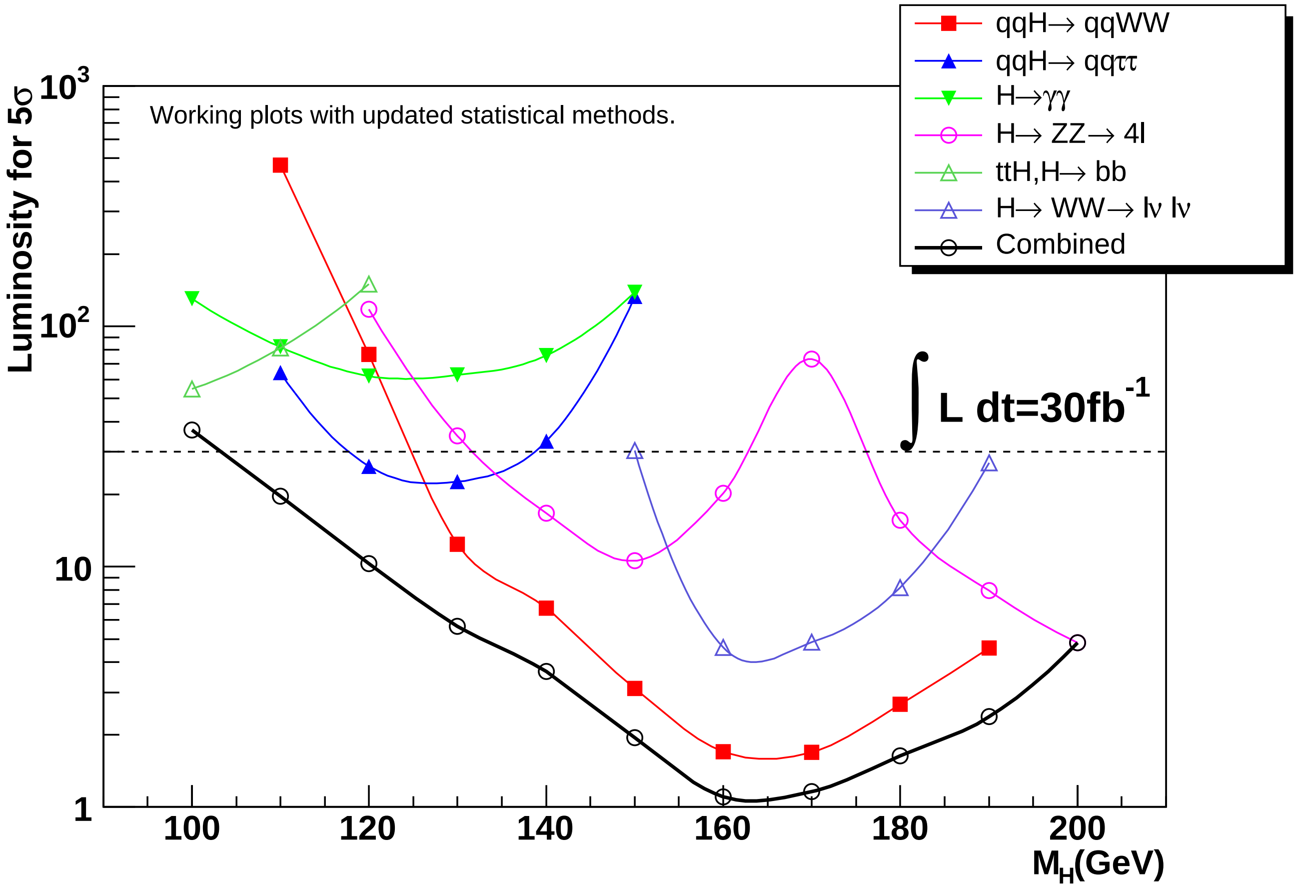
$\Delta\phi_{jj}$ can be used to fit relative contribution from $gg \to Hgg$

Should reduce systematic error considerably.

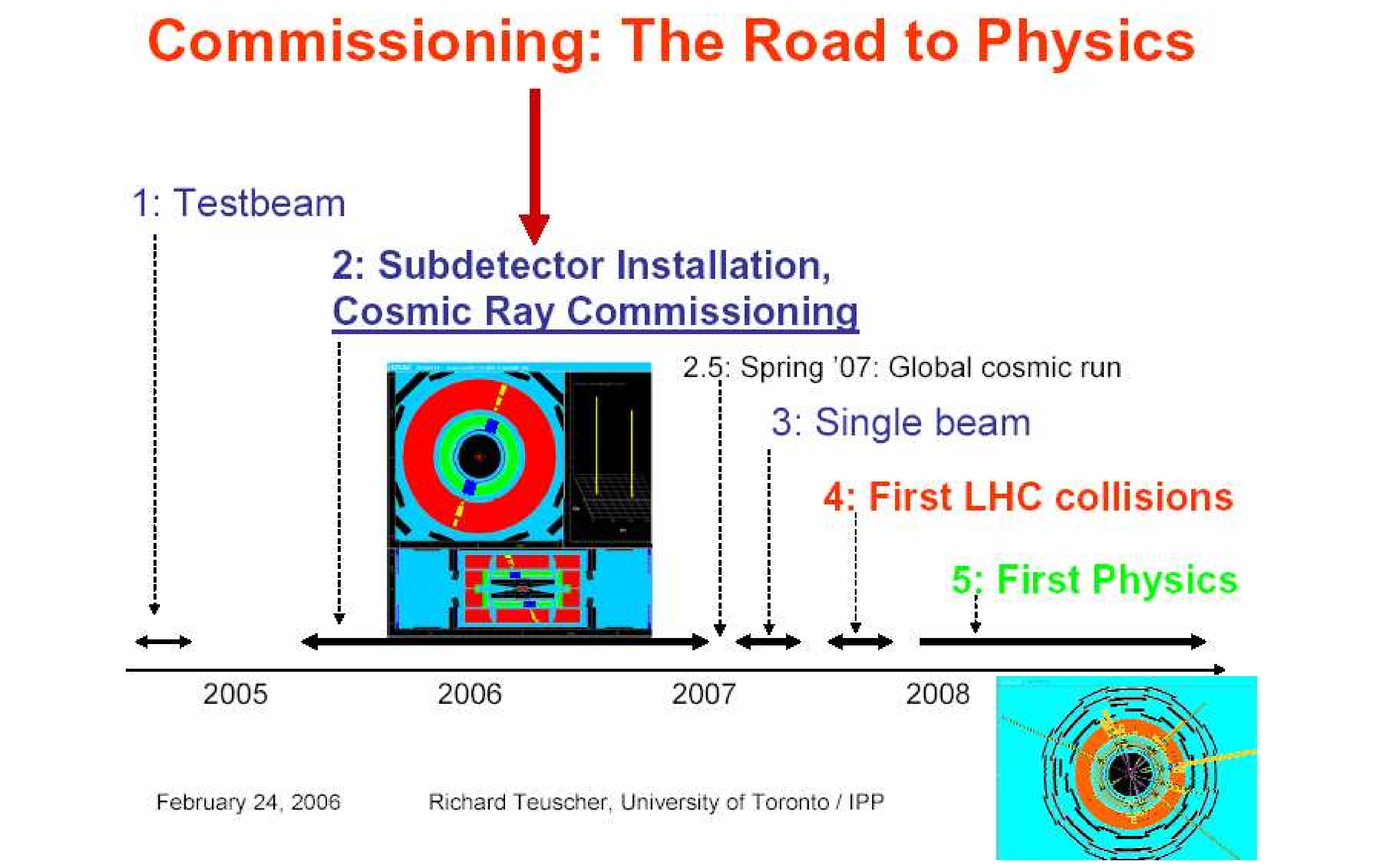
The Near Future:

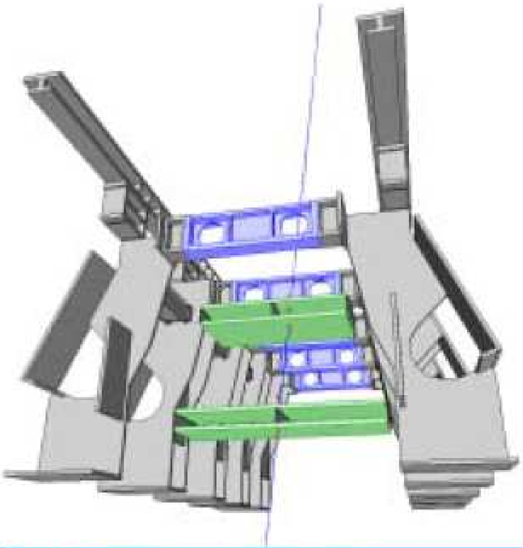
The Timeline for Startup

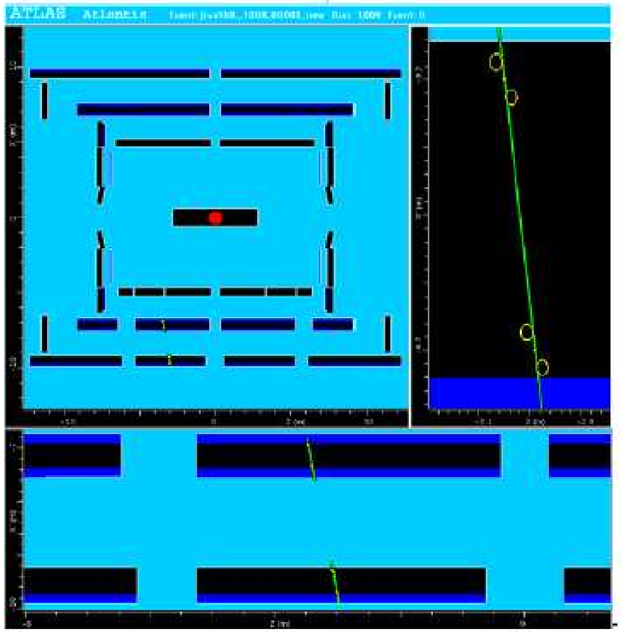
Even including our (naive?) estimates of systematics, the standard model Higgs can be discovered with 1-15 fb^{-1} of data



Of course, that's well understood data. How long will that take?

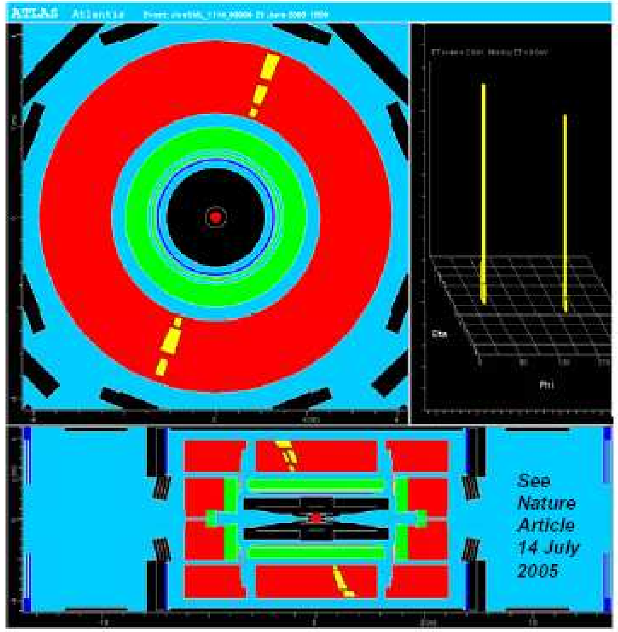

Commissioning: The Road to Physics
1: Testbeam
2: Subdetector Installation,
Cosmic Ray Commissioning
2.5: Spring '07: Global cosmic run
3: Single beam
4: First LHC collisions
5: First Physics
2005
2006
2007
2008
February 24, 2006
Richard Teuscher, University of Toronto / IPP



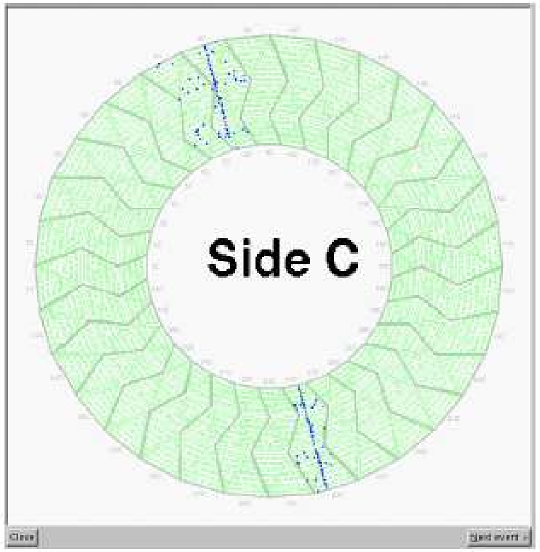


Muon chambers underground

TileCal:



Cosmic Ray Commissioning: First with Individual Subdetectors

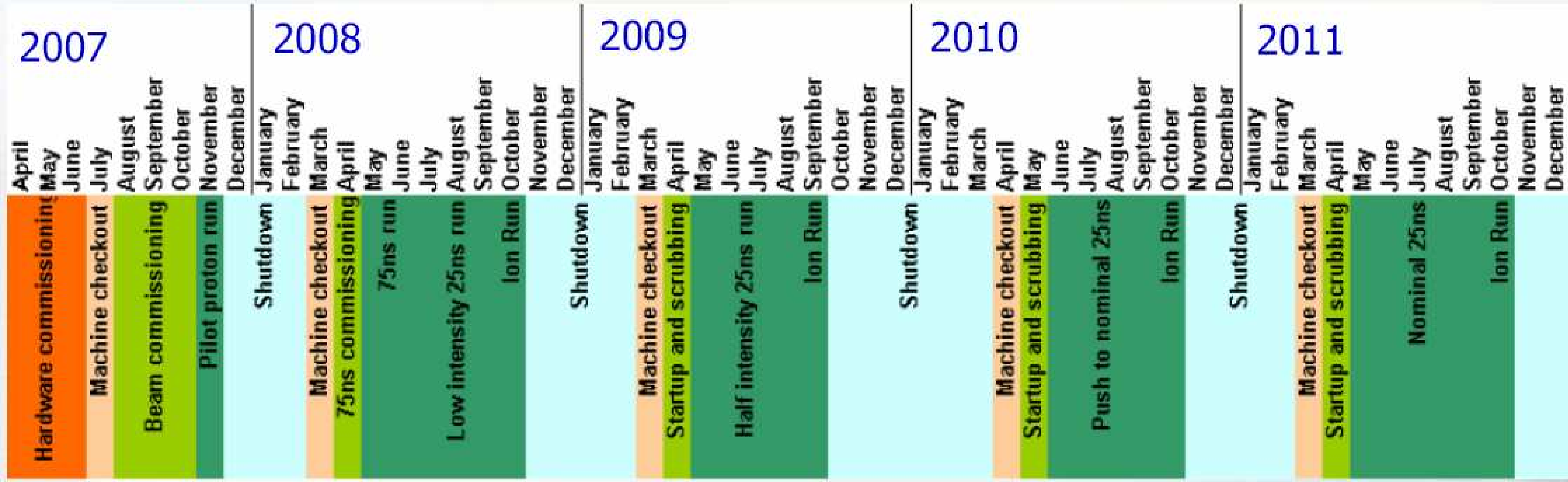


First muons in TRT on surface

Timeline for the LHC Commissioning

- Physics running: 140 days/year
- ATLAS/CMS running: ~100 days/year
- Typical efficiency for physics: 40%
- Effective ATLAS/CMS running time/year: ~1000 hours ~ 4×10^{6} s ~ 4×10^{38} cm^{-2} = 4×10^{14} b^{-1} = 400 pb^{-1} @ 10^{32}cm^{-2}s^{-1}
- Note that the schedule below [R. Bailey, LHCAC, 6/5/05] is "all goes well" scenario

Pilot run, 75ns	2008, 75/25ns	2009, 25ns	2010, 25ns
L~5×10^{30} cm^{-2}s^{-1}	L~3×10^{32} cm^{-2}s^{-1}	L~1×10^{33} cm^{-2}s^{-1}	L~1×10^{34} cm^{-2}s^{-1}
∫Ldt ~ 20 pb^{-1}	∫Ldt ~ 1.2 fb^{-1}	∫Ldt ~ 4 fb^{-1}	∫Ldt ~ 40 fb^{-1}



Aspen 2005 Workshop Greg Landsberg, The First Three Years: Before the Champagne? 45

The Distant Future:

An LHC Upgrade

Will Do

Discovery of SM Higgs:

- ◇ SM Higgs could be discovered over full mass range with 30 fb^{-1}
- ◇ Several Channels Available, VBF a big improvement

Measurements of Higgs Parameters:

- ◇ Masses 0.1 - 1%
- ◇ Ratios of Widths 10-60%
- ◇ Couplings 15-50%

MSSM Higgs:

- ◇ Cover most of $M_A - \tan\beta$ plane in $\sim$ 1year
- ◇ Many prospects to distinguish SM from MSSM Higgs sectors (eg. charged Higgs)

Won't Do

At All:

- ◇ Measurements of Higgs Self-Coupling
- ◇ Observe/Discover $H \rightarrow \mu\mu$?

In Some Cases:

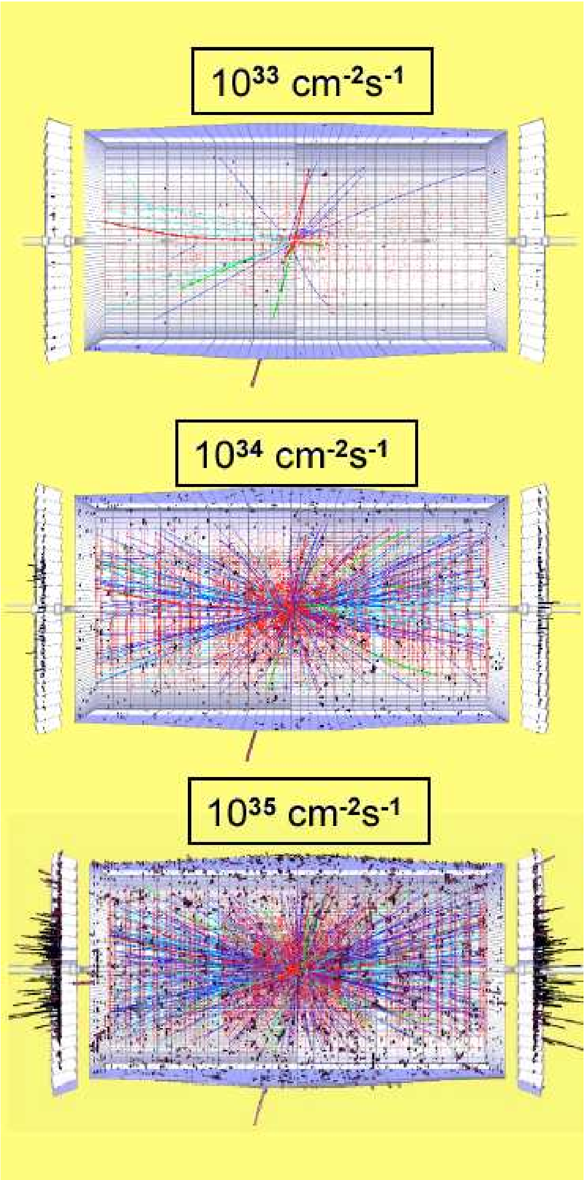
- ◇ Distinguish SM from MSSM Higgs Sector (small $\tan\beta$)

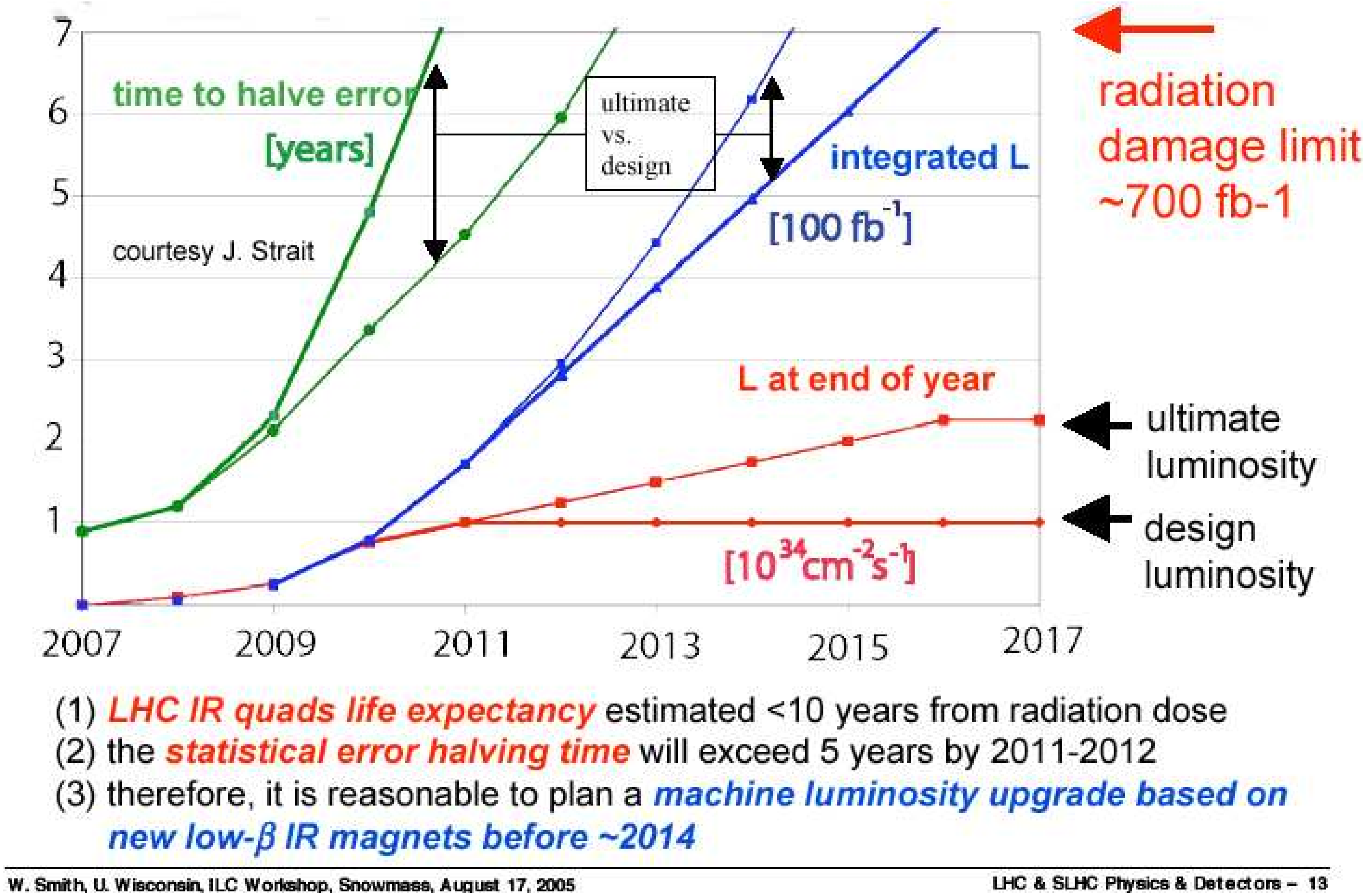
As Well as SLHC:

- ◇ Coupling Measurements
- ◇ Rare Decays $H \rightarrow \mu\mu$

Super-LHC

$H \rightarrow ZZ \rightarrow ee\mu\mu$

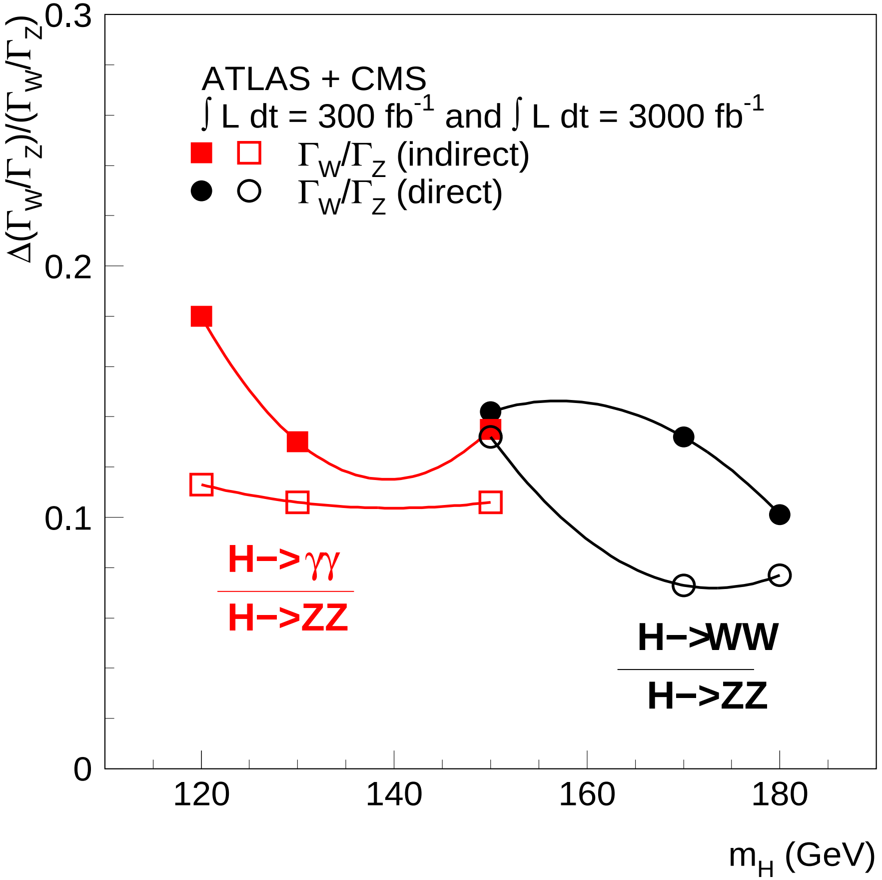


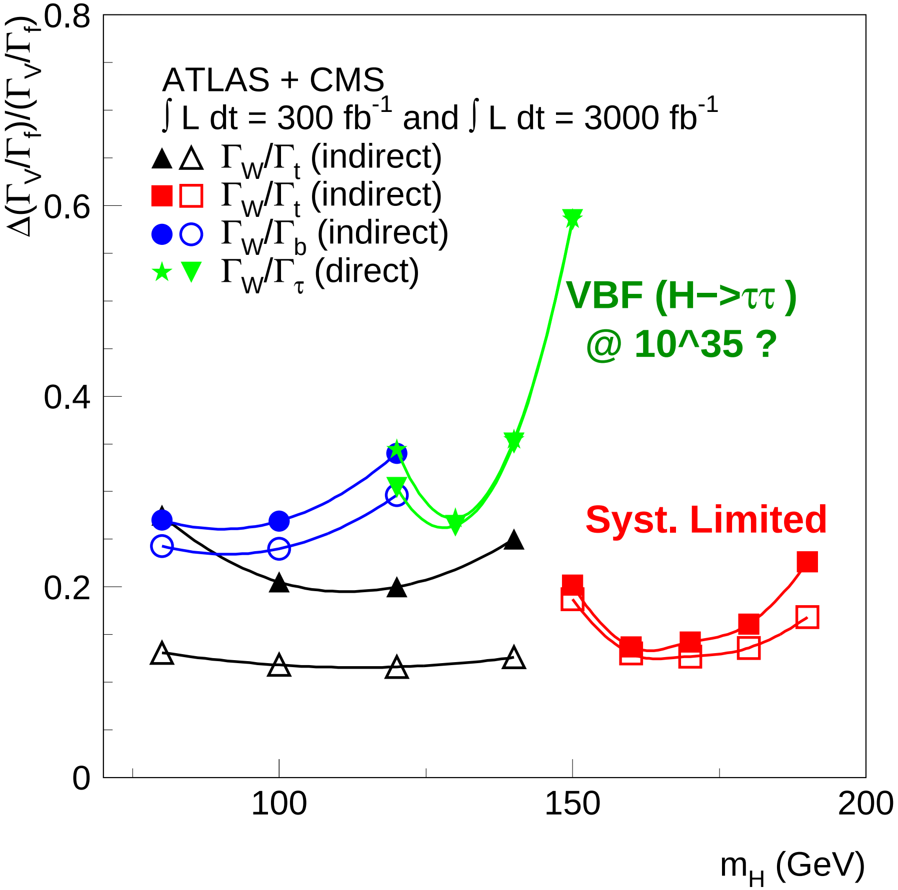


See Wesley Smith's talk:

http://cmsdoc.cern.ch/cms/TRIDAS/tr/0508/Smith_ILC_SLHC_Aug05.pdf

Results from main SLHC publication: hep-ph/0204087





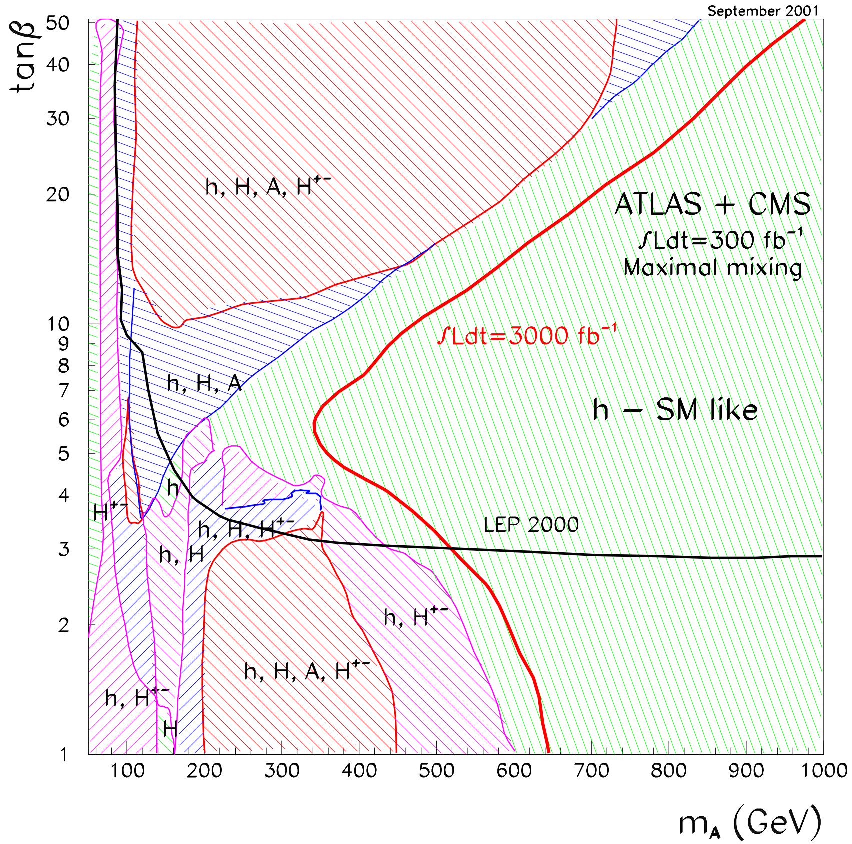
SLHC will significantly improve coupling measurements.

By the end of the LHC, we should understand forward jets and central jet veto much better!

Many new channels since this study, should be revisited.

Use of $H/A \to$ SUSY particles is model dependent.

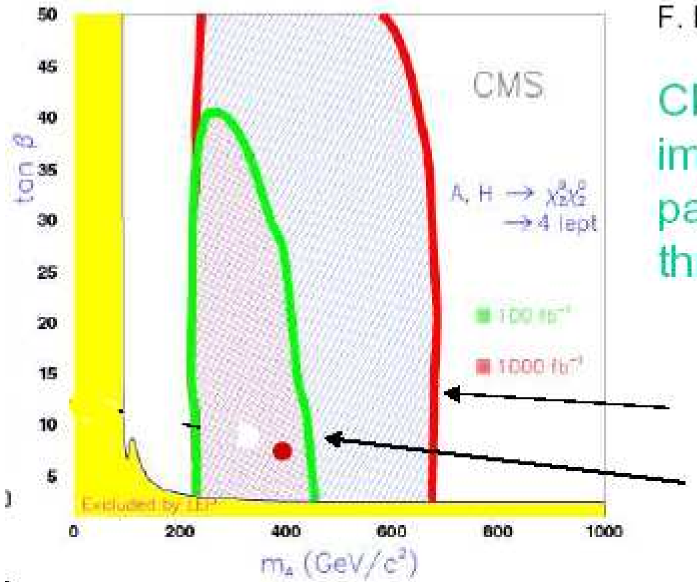
$H/A \to \chi_2^0\chi_2^0 \to 4l$ contributes in the region where only h is seen decaying to SM particles



↑ SLHC extends discovery potential for Heavy Higgs.

↓ SLHC can extend discovery potential for $H/A \to \chi_2^0\chi_2^0 \to 4l$

example:
MSSM parameters: M_2 = 120 GeV, M_1 = 60 GeV, μ = -500 GeV, m(sleptons) = 250 GeV, m(squarks, gluinos) = 1 TeV

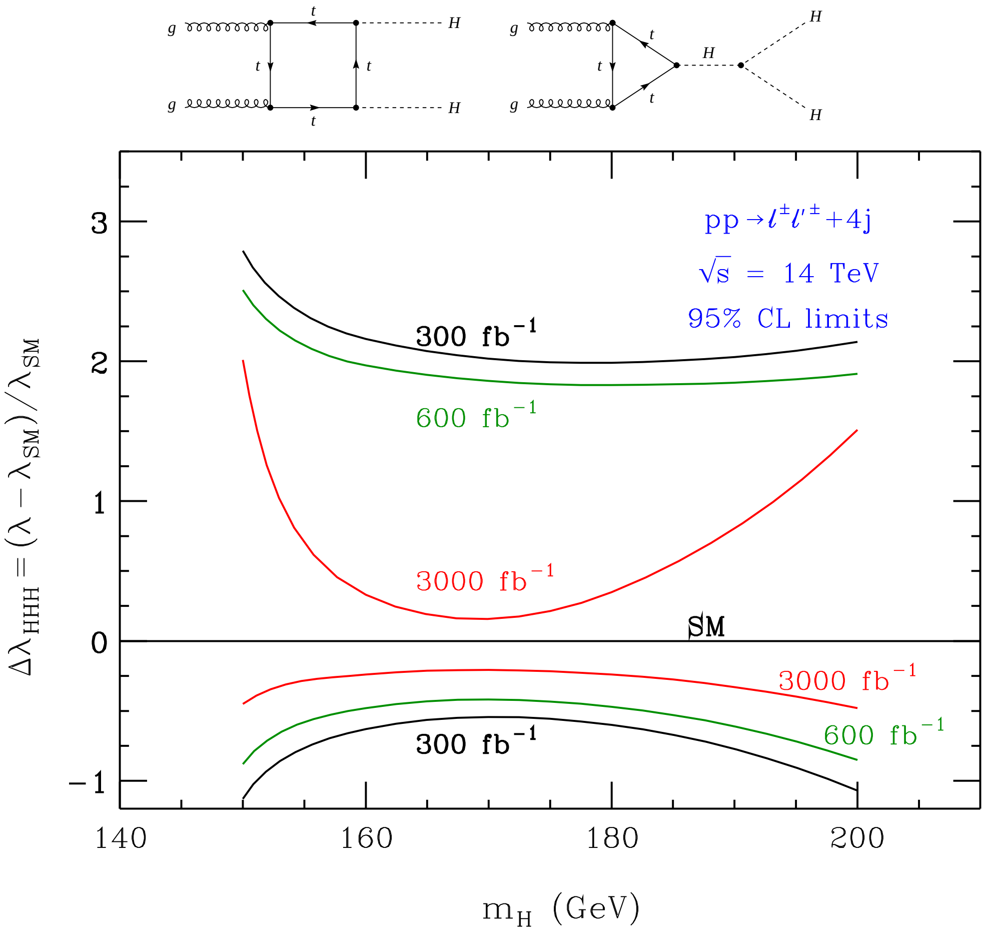


F. Moortgat

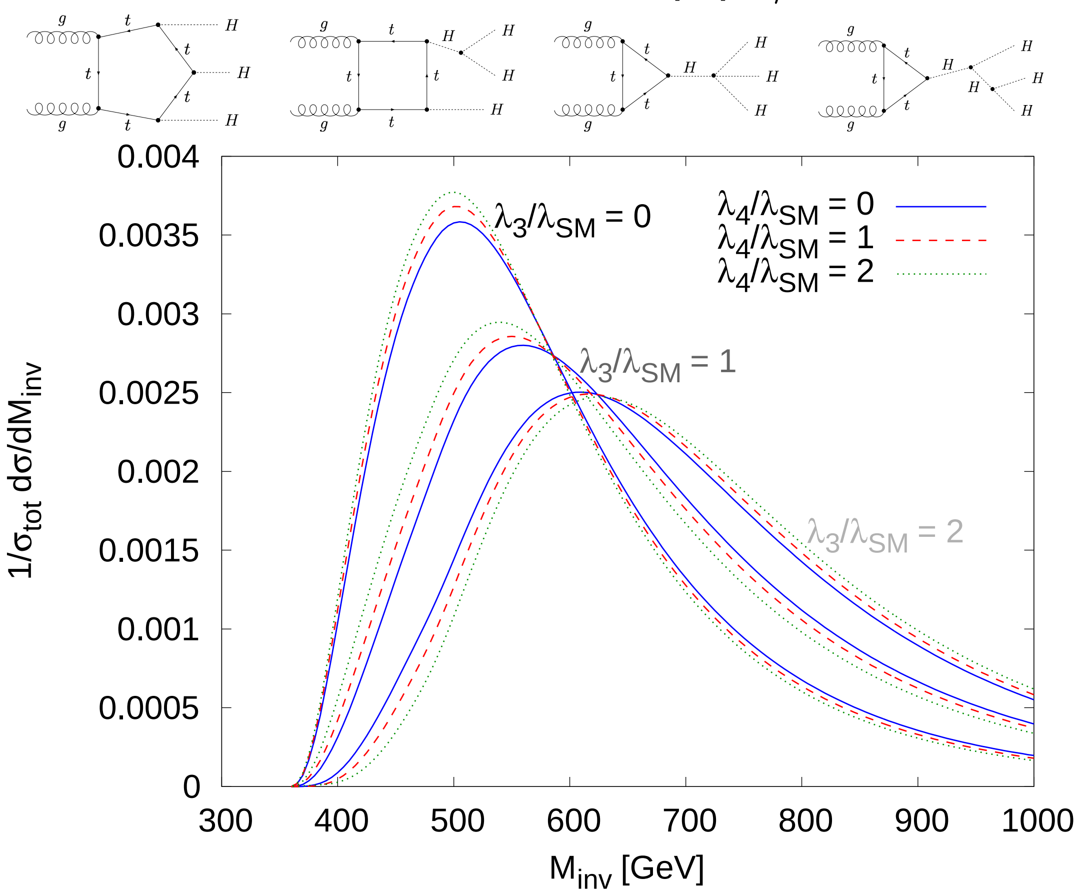
CMS, very preliminary
important as complements parameter space explorable through SM decay modes!

Higgs Self Coupling

hep-ph/0211224



Plehn & Rauch @ MPI hep-ph/0507321



Parton-level:

- $\lambda_{HHH} = 0$ can be excluded at 95% CL
- λ_{HHH} determined at 20-30%

ATLAS and CMS studies still preliminary

Interference between diagrams important

Variation in trilinear self-coupling dominates

No hope of measuring quartic self-coupling at SLHC or VLHC

Summary

If the standard model Higgs is there, we should discover it relatively early at the LHC

Several channels are available: opportunity to measure Higgs couplings to 15-50%

Recent effort is a mix of theoretical developments, improved realism in detector simulation, and more sophisticated analysis techniques

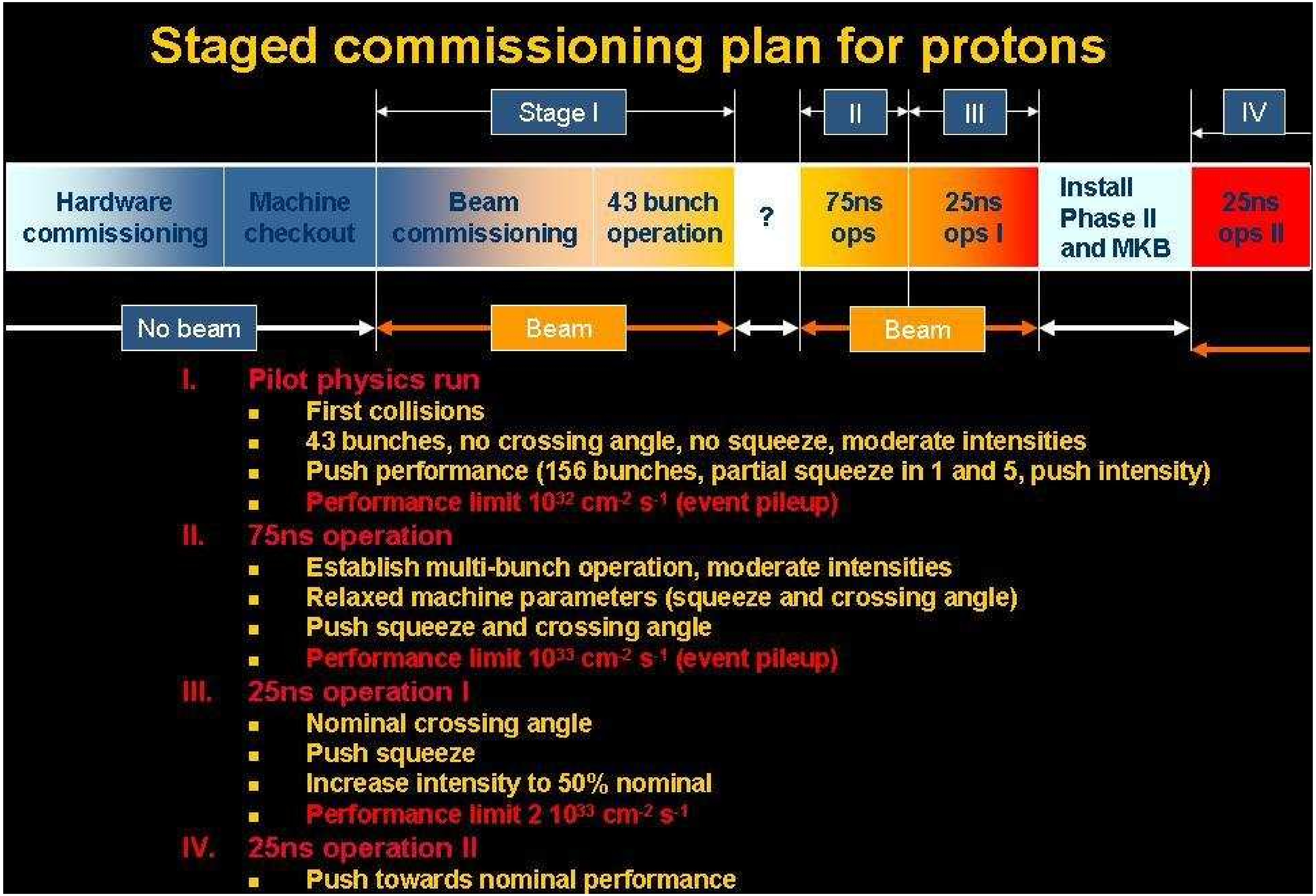
Most of the SUSY Higgs plane is covered by the LHC under most well-motivated scenarios.

LHC will not observe Higgs self-coupling. Many measurements and discovery reach are statistics-limited. $\Rightarrow$ motivation for a luminosity upgrade: "SuperLHC"

We have lots to do before turn-on!

Backup

LHC Commissioning (L. Evans Feb. 06)



LHC Commissioning (L. Evans Feb. 06)

Stage I physics run

$$L = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

$$Eventrate\ /\ Cross = \frac{L\sigma_{TOT}}{k_b f}$$

- Start as simple as possible
- Change 1 parameter (k_b N $\beta^*_{1,5}$) at a time
- All values for
  - nominal emittance
  - 7TeV
  - 10m β^* in point 2 (luminosity looks fine)

Protons/beam $\lesssim 10^{13}$ (LEP beam currents)

Stored energy/beam $\lesssim$ 10MJ (SPS fixed target beam)

Parameters			Beam levels		Rates in 1 and 5		Rates in 2	
k_b	N	β^* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
1	10^{10}	18	$1\ 10^{10}$	10^{-2}	10^{27}	<< 1	$1.8\ 10^{27}$	<< 1
43	10^{10}	18	$4.3\ 10^{11}$	0.5	$4.2\ 10^{28}$	<< 1	$7.7\ 10^{27}$	<< 1
43	$4\ 10^{10}$	18	$1.7\ 10^{12}$	2	$6.8\ 10^{29}$	<< 1	$1.2\ 10^{30}$	0.15
43	$4\ 10^{10}$	2	$1.7\ 10^{12}$	2	$6.1\ 10^{30}$	0.76	$1.2\ 10^{30}$	0.15
156	$4\ 10^{10}$	2	$6.2\ 10^{12}$	7	$2.2\ 10^{31}$	0.76	$4.4\ 10^{30}$	0.15
156	$9\ 10^{10}$	2	$1.4\ 10^{13}$	16	$1.1\ 10^{32}$	3.9	$2.2\ 10^{31}$	0.77

Stage II physics run

- Relaxed crossing angle (250 μrad)
- Start un-squeezed
- Then go to where we were in stage I
- All values for
  - nominal emittance
  - 7TeV
  - 10m β* in points 2 and 8

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

$$F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

$$Eventrate\ /\ Cross = \frac{L \sigma_{TOT}}{k_b f}$$

Protons/beam ≈ few 10^{13}

Stored energy/beam ≲ 100MJ

Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
936	$4\ 10^{10}$	18	$3.7\ 10^{13}$	42	$1.5\ 10^{31}$	<< 1	$2.6\ 10^{31}$	0.15
936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73	$2.6\ 10^{31}$	0.15
936	$4\ 10^{10}$	1	$3.7\ 10^{13}$	42	$2.5\ 10^{32}$	1.4	$2.6\ 10^{31}$	0.15
936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76

LHC Commissioning (L. Evans Feb. 06)

Stage III physics run

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

$$F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

$$Eventrate / Cross = \frac{L \sigma_{TOT}}{k_b f}$$

- Nominal crossing angle (285 μrad)
- Start un-squeezed
- Then go to where we were in stage II
- All values for
  - nominal emittance
  - 7TeV
  - 10m β* in points 2 and 8

Protons/beam ≈ 10^{14}

Stored energy/beam ≈ 100MJ

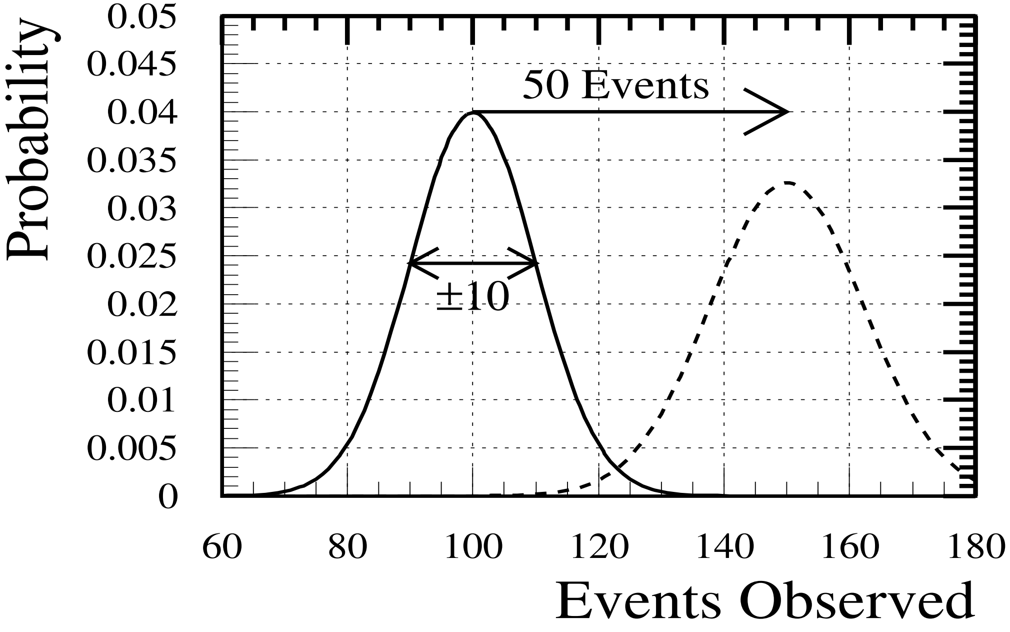
Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
2808	$4\ 10^{10}$	18	$1.1\ 10^{14}$	126	$4.4\ 10^{31}$	<< 1	$7.9\ 10^{31}$	0.15
2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72	$7.9\ 10^{31}$	0.15
2808	$5\ 10^{10}$	2	$1.4\ 10^{14}$	157	$5.9\ 10^{32}$	1.1	$1.2\ 10^{32}$	0.24
2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1	$1.2\ 10^{32}$	0.24
2808	$5\ 10^{10}$	0.55	$1.4\ 10^{14}$	157	$1.9\ 10^{33}$	3.6	$1.2\ 10^{32}$	0.24
Nominal			$3.2\ 10^{14}$	362	10^{34}	19	$6.5\ 10^{32}$	1.2

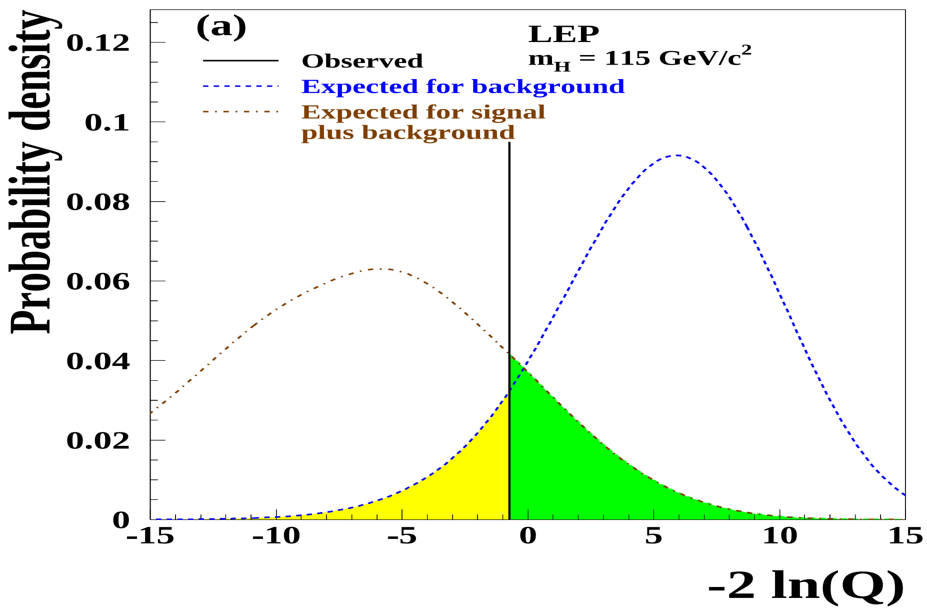
In addition to multivariate techniques , *the most powerful search* considers:

Likelihood of experiment $= \Pi$ likelihood of each event

This was done by LEP Higgs WG and follows from the Neyman-Pearson Lemma

Essentially, weight each event by $\log(1 + s/b)$

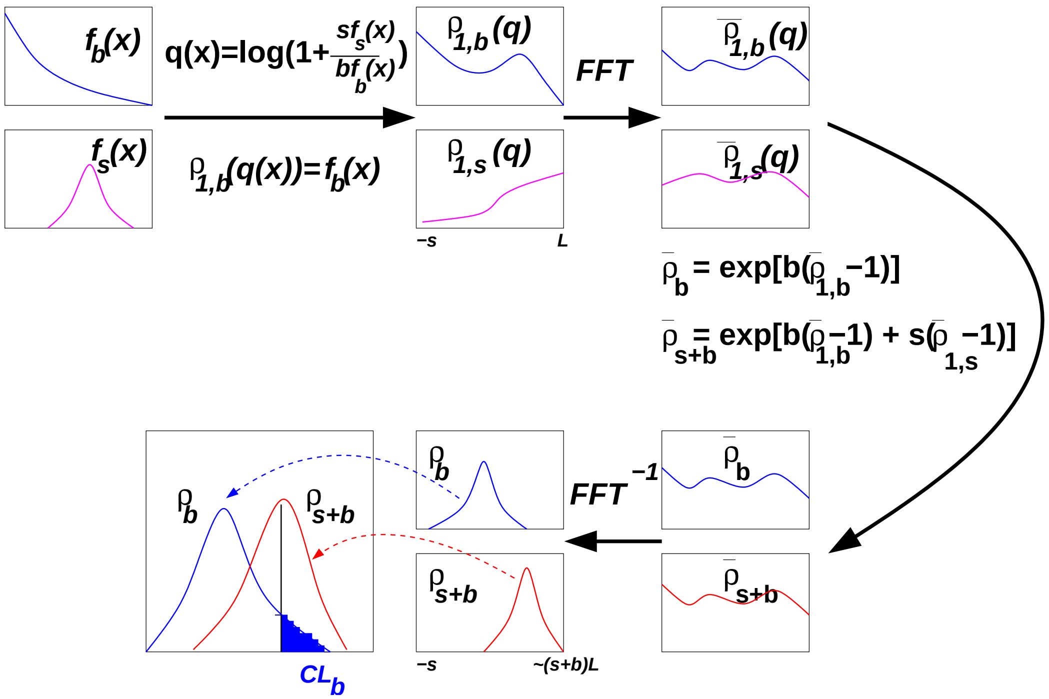




LEP Higgs Working group developed formalism to combine channels and take advantage of discriminating variables in the likelihood ratio.

$$Q = \frac{L(x|H_1)}{L(x|H_0)} = \frac{\prod_i^{N_{chan}} Pois(n_i|s_i+b_i) \prod_j^{n_i} \frac{s_i f_s(x_{ij}) + b_i f_b(x_{ij})}{s_i+b_i}}{\prod_i^{N_{chan}} Pois(n_i|b_i) \prod_j^{n_i} f_b(x_{ij})}$$

$$q = \ln Q = -s_{tot} \sum_i^{N_{chan}} \sum_j^{n_i} \ln\left(1 + \frac{s_i f_s(x_{ij})}{b_i f_b(x_{ij})}\right)$$

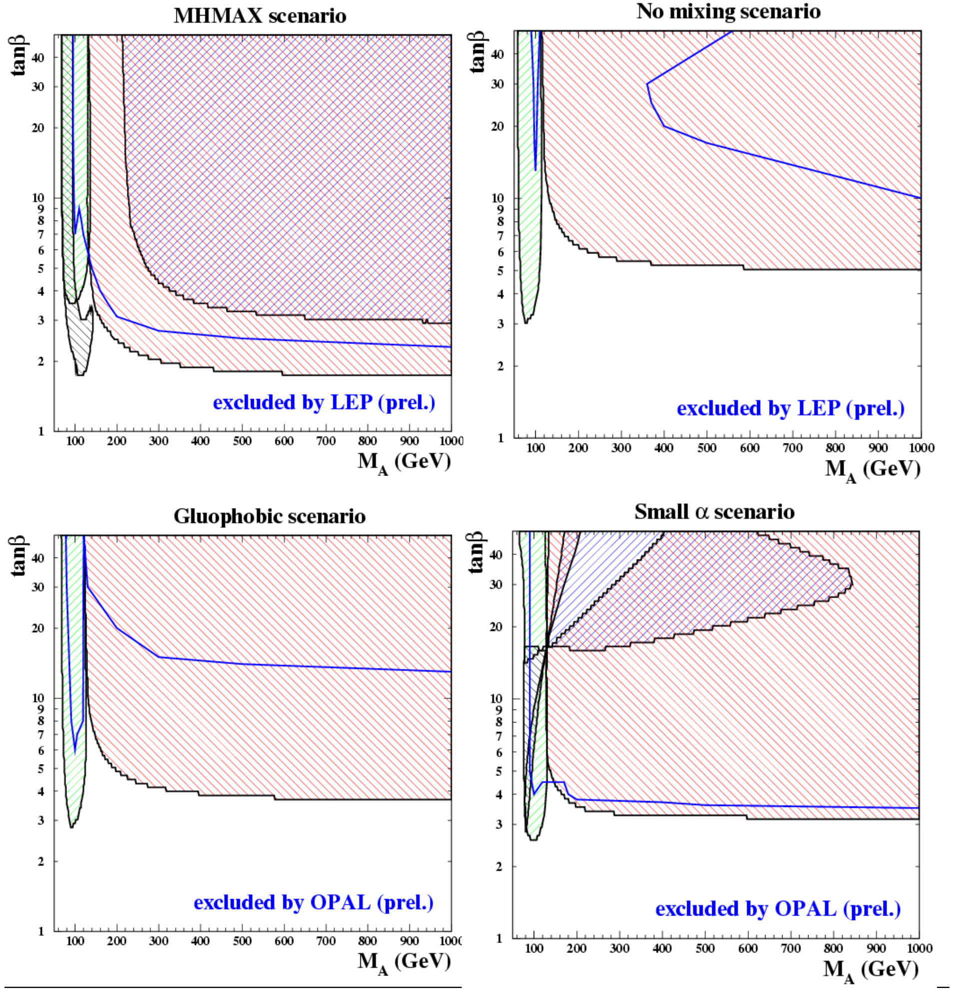


Hu and Nielsen's `CLFFT` used Fourier Transform and exponentiation trick to transform the log-likelihood ratio distribution for one event to the distribution for an experiment

Cousins-Highland was used for systematic error on background rate.

Getting this to work at the LHC is tricky numerically because we have channels with n_i from 10-10000 events (physics/0312050)

The MSSM plane with 30 fb^{-1}



Complementarity of VBF $h \to \tau\tau$ and $H \to \tau\tau$ covers almost all the plane not excluded by LEP

Also shown:

- VBF $h \to WW$
- VBF $H \to WW$

There are more recent ATLAS results from M. Schumacher (with systematic errors), but they are still preliminary.