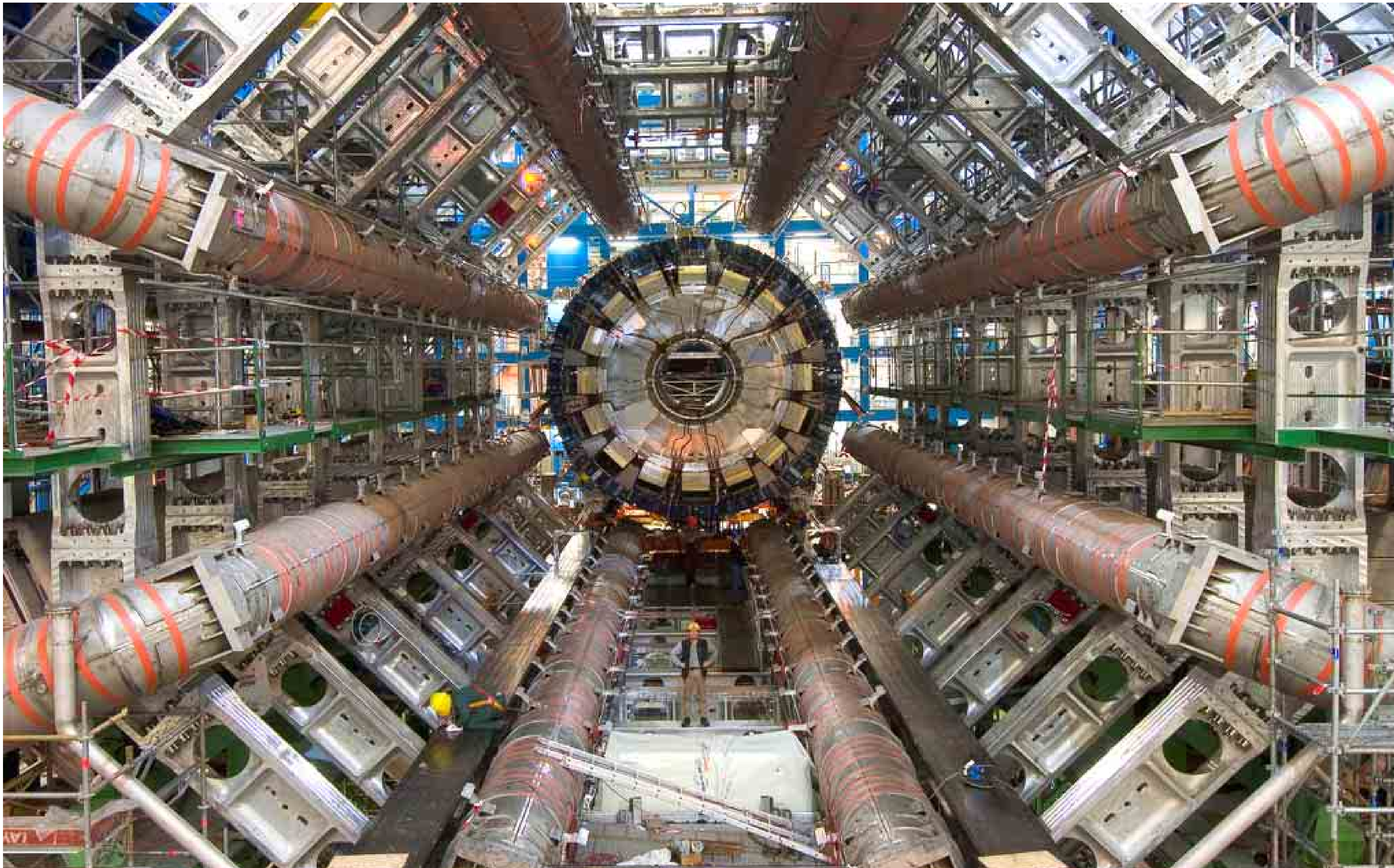
Higgs discovery prospects and statistics at the LHC (ATLAS)

Eilam Gross Weizmann institute of Science/ATLAS

ATLAS with a Perspective

A Legend Comes True



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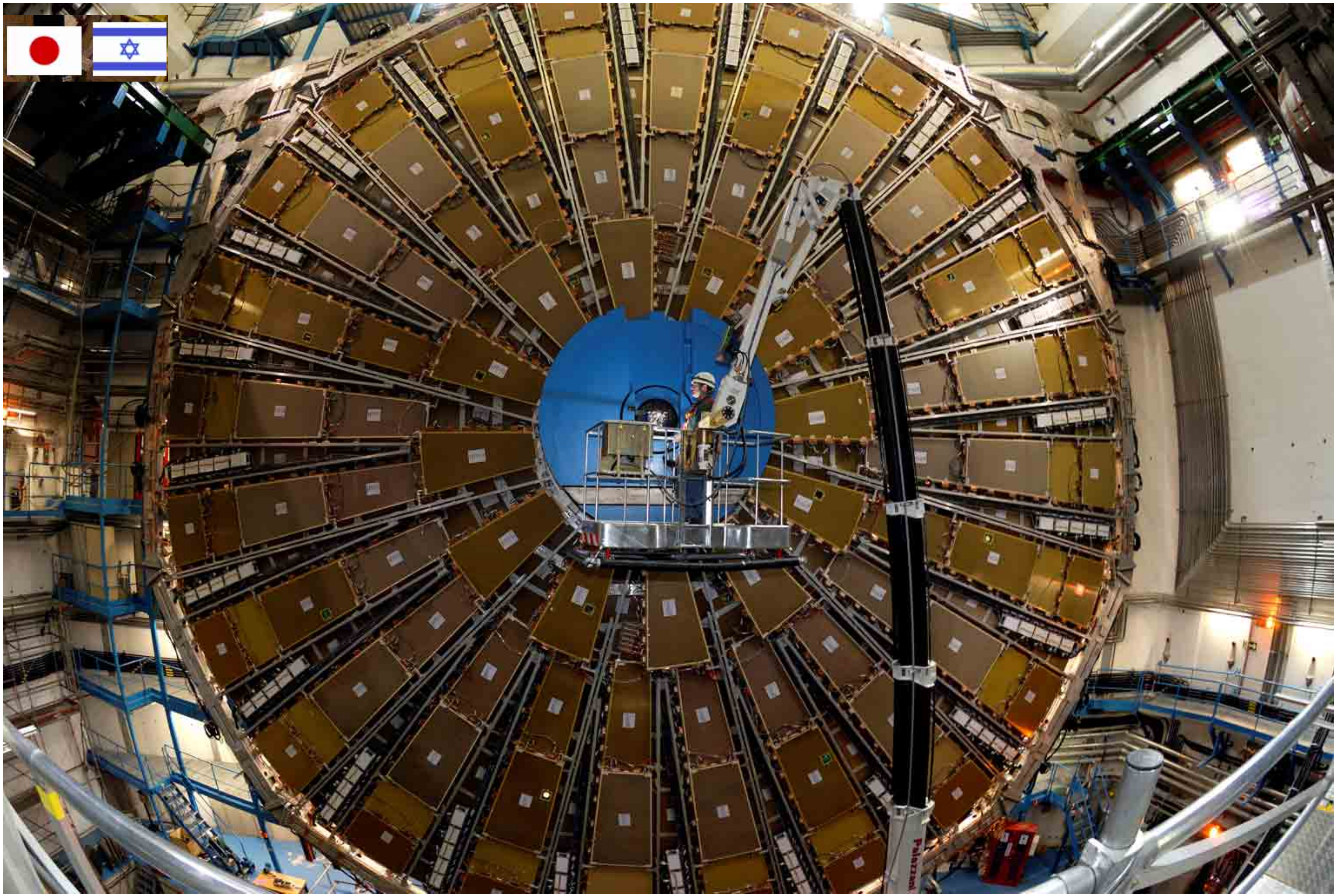
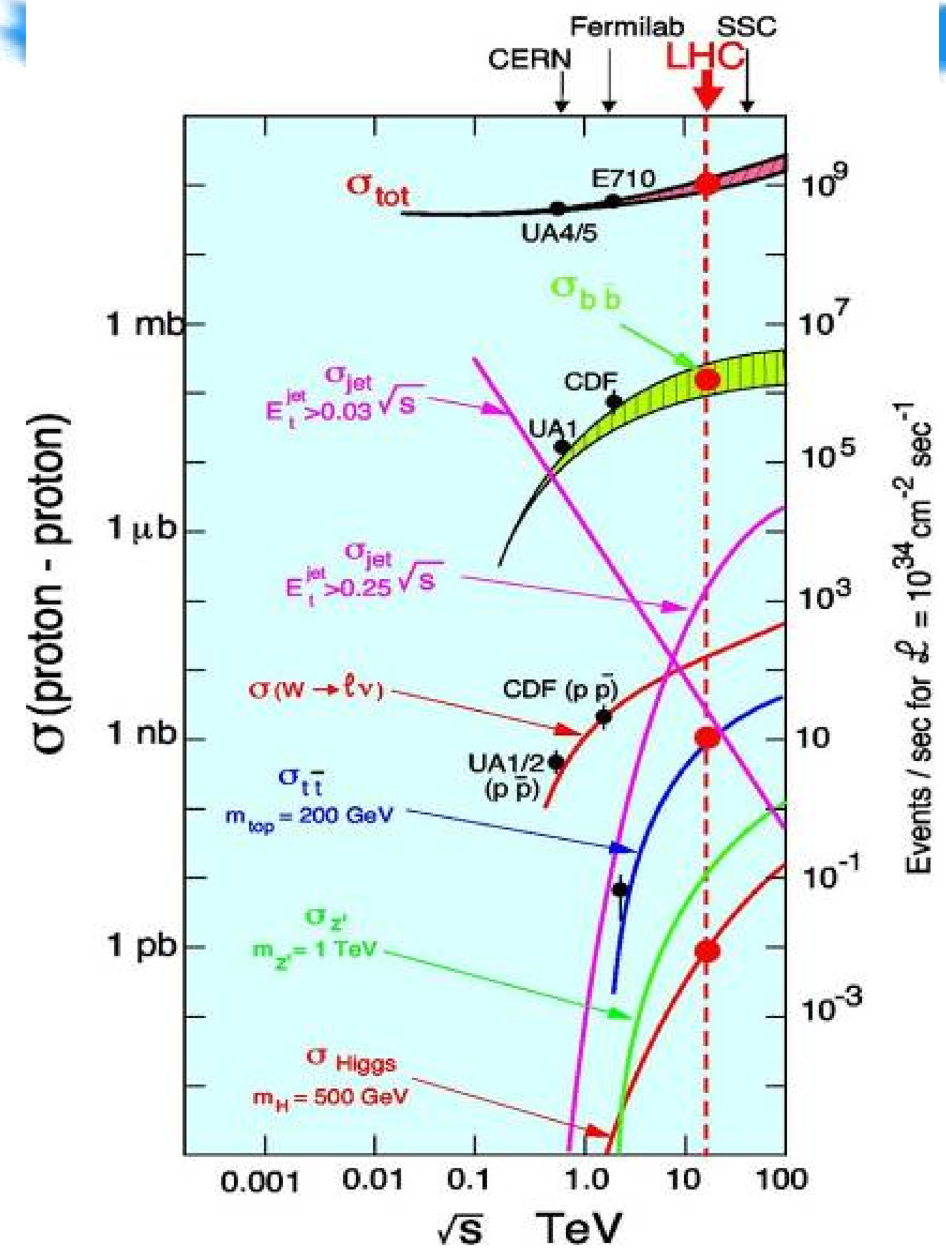
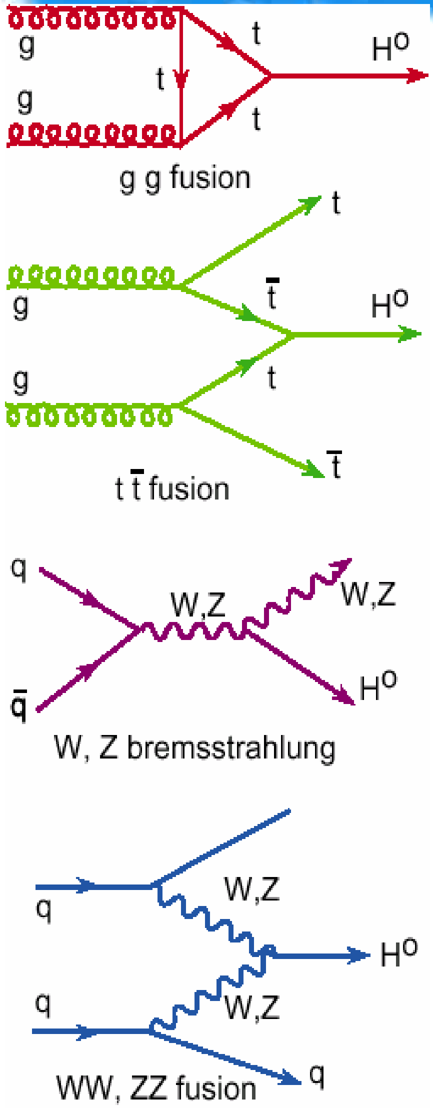


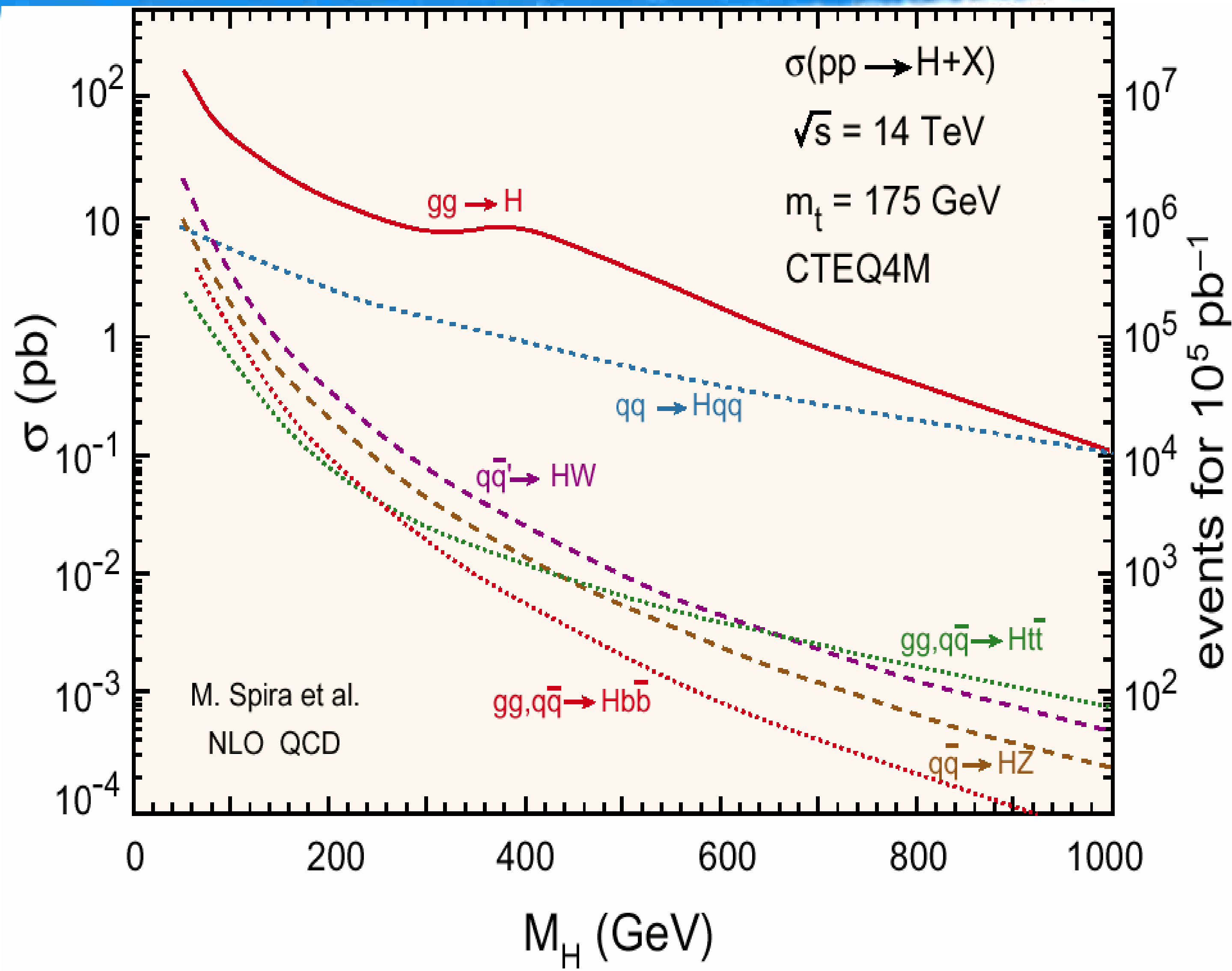
The Technical Challenge



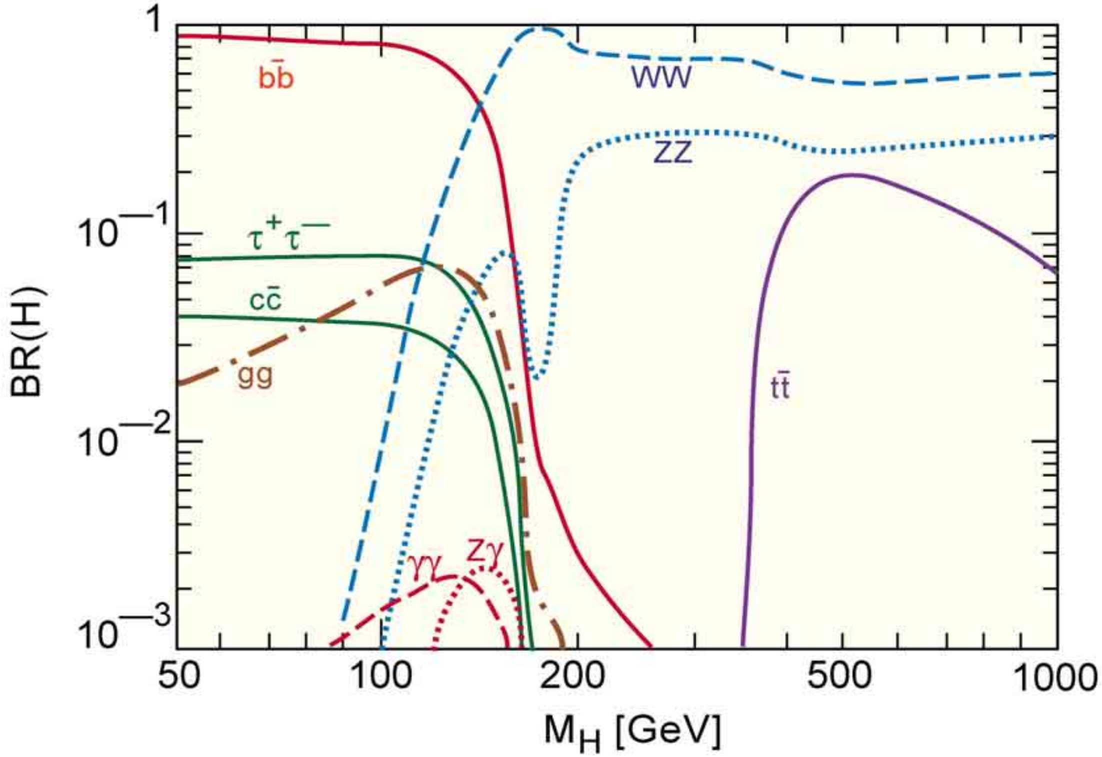
- ~10^9 proton-proton collisions/sec
- ~$1/10^{11}$ collisions produce a Higgs Boson
- One can only accommodate ~200 collisions/sec
- Rejection rate> 99.9995%
- How do you make sure not to loose a Higgs Boson?
- Make sure we “push the button” (trigger) only when interesting things happen
- This is a tremendous technical challenge! Which require state of the art fast systems.
- **σ_{tot} ~ 100 mb, σ_b ~ 1 mb, σ_{jet} > 1 nb, σ_H> 1~pb**
  The small S/B requires control samples to understand the background

Higgs Production @ LHC





σ * BR – The Analysis Challenge



- The Higgs decay to bb is still dominant up to ~150 GeV, the Weak Bosons then enter the game
- However, H→4 leptons has a clear signature as well as H→γγ with BRs of O(10^{-3}). This is a challenge in analysis which makes the need for measuring background from data mandatory!
- The decay to ττ, though only a few % is still very appealing for the medium – light SM Higgs
- For MSSM Higgs bb and ττ are dominant

LHC - Brief Status

As reported by Sergio Bertolucci, LP07

- Engineering run originally foreseen at end 2007 now precluded by delays in installation and equipment commissioning.

- Beam commissioning starts May 2008

- First collisions at 14 TeV c.m. July 2008

- First month devoted to collecting millions of minimum bias events and di-jets events for first alignment, calibrations and performance studies of the detector (@ 10^{29})

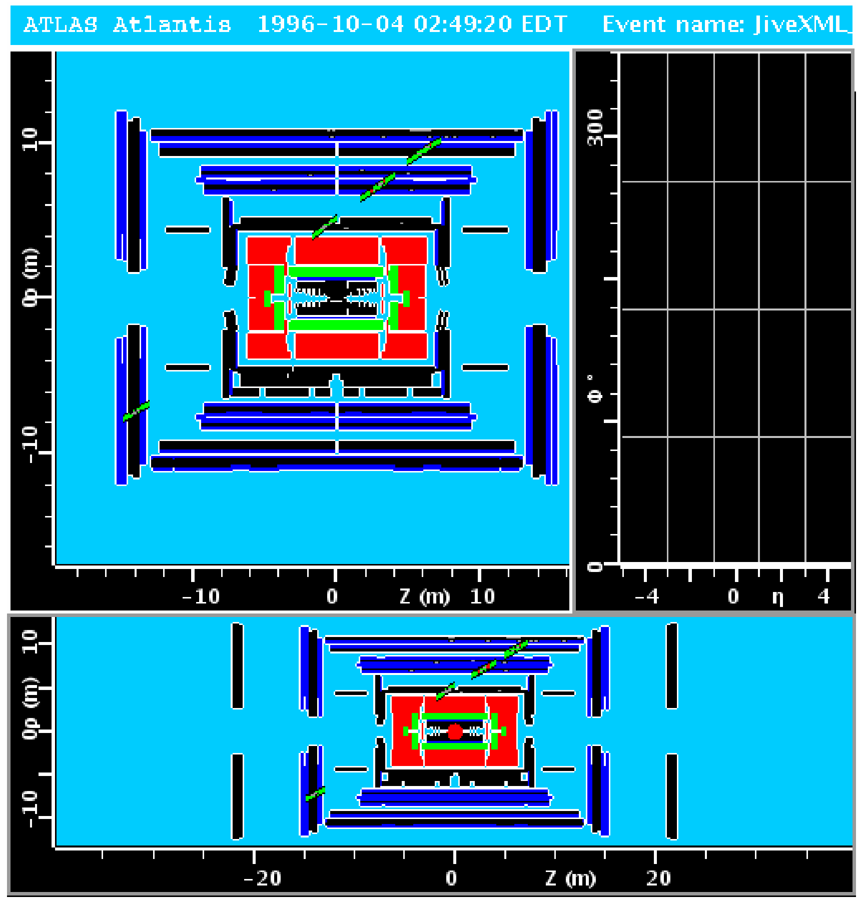
LHC - Brief Status

As reported by Sergio Bertolucci, LP07

- Pilot run pushed to reach 10^{32} cm^{-2} s^{-1} by end 2008
- This is equivalent to O(100 pb^{-1})/experiment
- Use Z→ee,μμ to calibrate, align and understand the trackers, the EM CAL, and the Muon system.
- Use W→jj to calibrate jets and study b-tag performance (tt→blν bjj)
- "Rediscover" SM Physics at √s=14 TeV, this is your new background
- After all, the LHC is designed to go beyond the known SM Physics, first and foremost to discover the Higgs Boson.

Cosmic Ray Tests

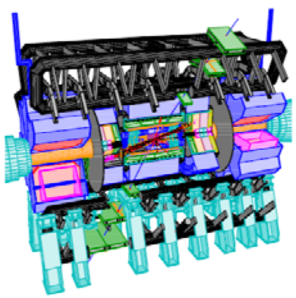
Tracks in the **Muon chambers** and in the Transition-Radiation Tracker **TRT**



The References

ATLAS

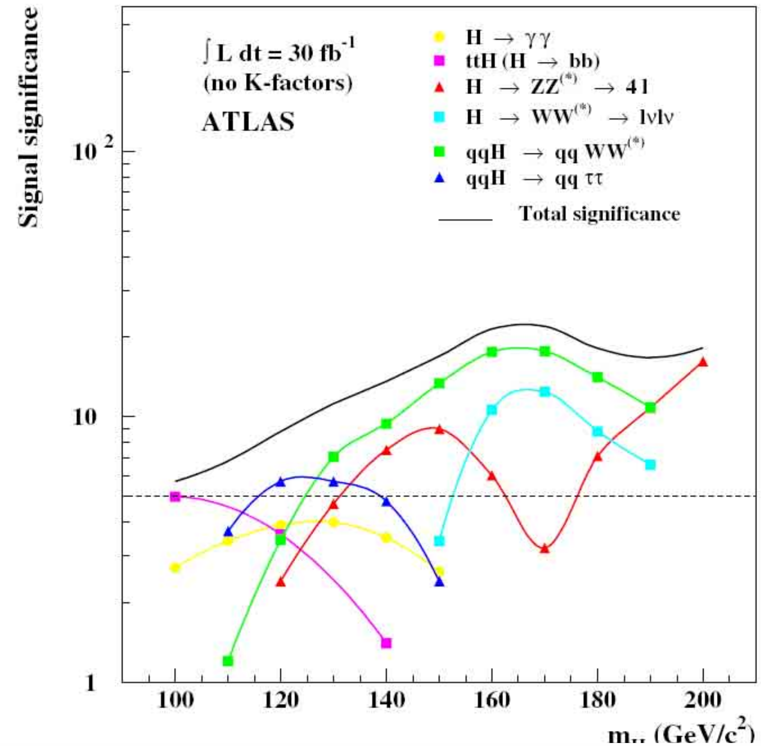
ATLAS DETECTOR AND PHYSICS PERFORMANCE



Technical Design Report

Issue: 1
Revision: 0
Reference: ATLAS TDR 14, CERN/LHCC 99-14
Created: 25 May 1999

Volume I



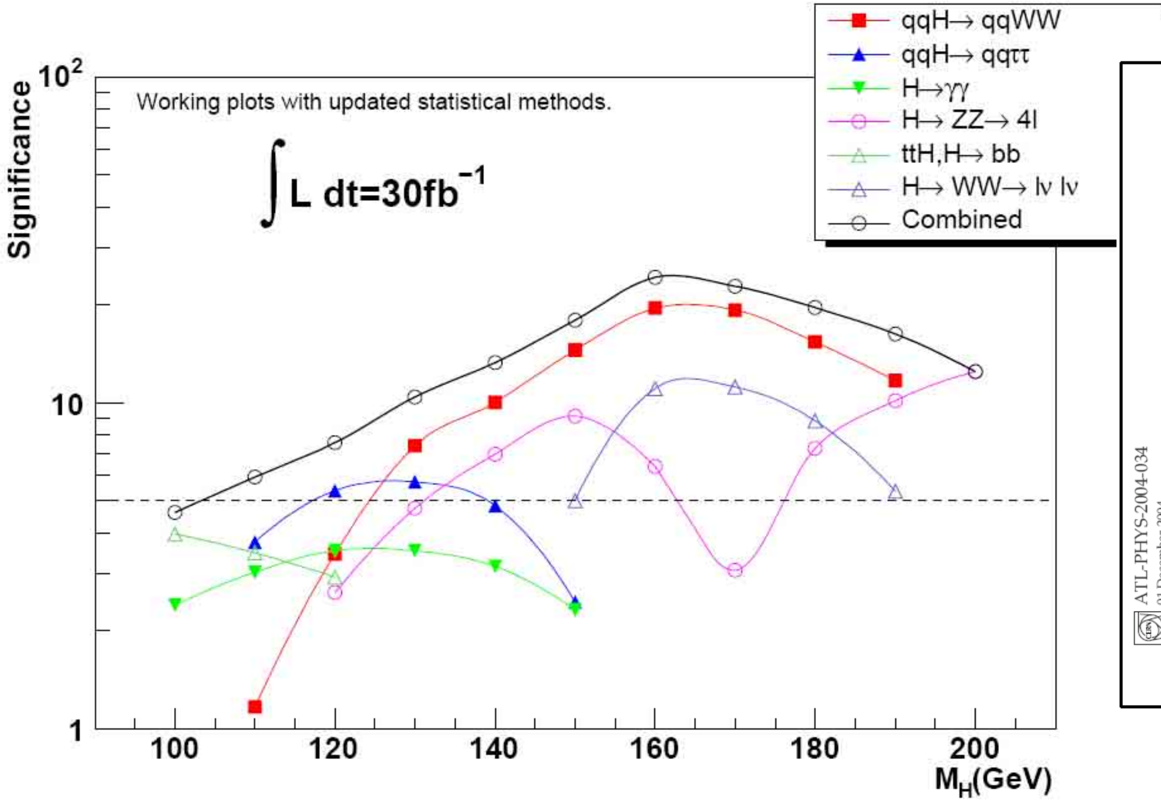
Eur Phys J C **32**, s02, s19–s54 (2003)
DOI: 10.1140/epjcd/s2003-01-010-8

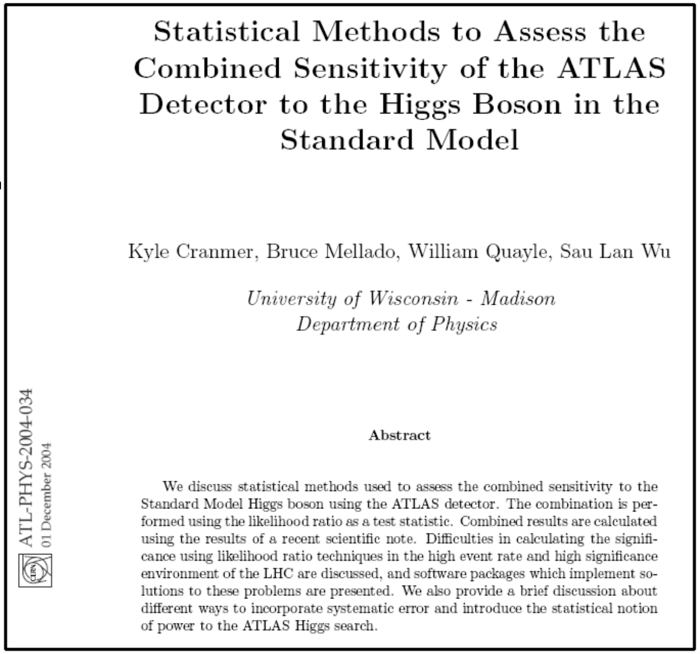
EPJ C direct
electronic only

Prospects for the search for a standard model Higgs boson in ATLAS using vector boson fusion

S. Asai[8], G. Azuelos[5], C. Buttar[7], V. Cavasinni[6], D. Costanzo[6,*], K. Cranmer[9], R. Harper[7], K. Jakobs[4], J. Kanzaki[3], M. Klute[1], R. Mazini[5], B. Mellado[9], W. Quayle[9], E. Richter-Wąs[2], T. Takemoto[3], I. Vivarelli[6], Sau Lan Wu[9]

The References





Statistical Methods to Assess the Combined Sensitivity of the ATLAS Detector to the Higgs Boson in the Standard Model

Kyle Cranmer, Bruce Mellado, William Quayle, Sau Lan Wu

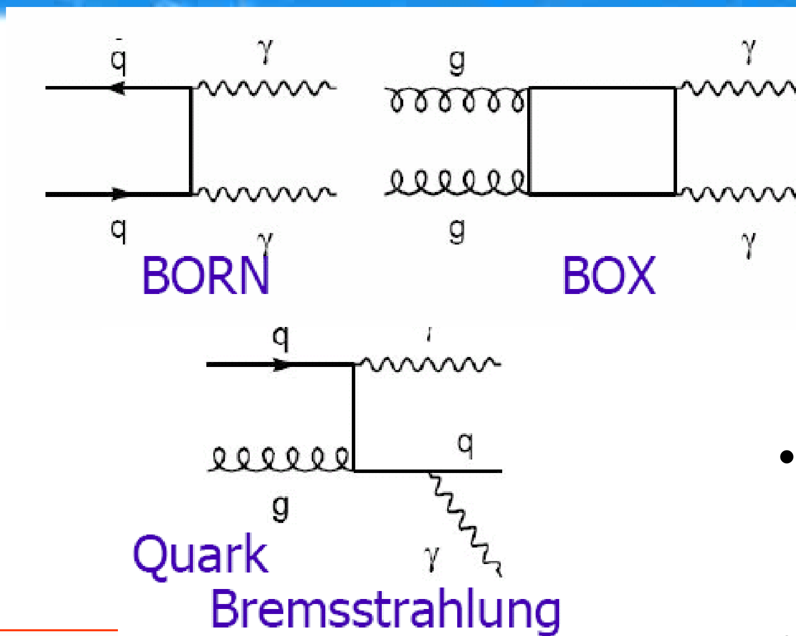
University of Wisconsin - Madison
Department of Physics

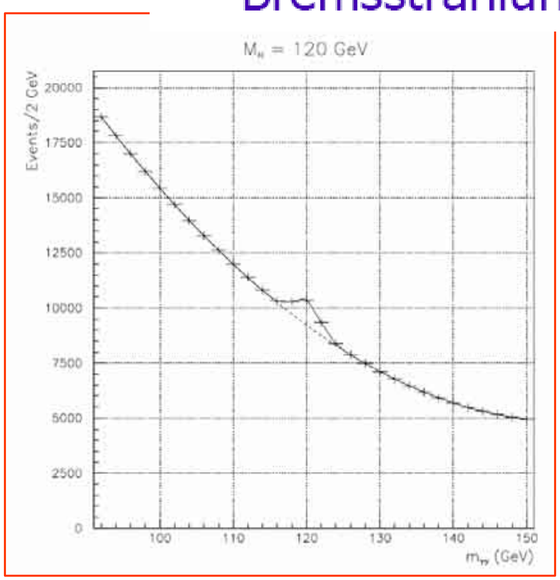
ATL-PHYS-2004-034
01 December 2004

Abstract

We discuss statistical methods used to assess the combined sensitivity to the Standard Model Higgs boson using the ATLAS detector. The combination is performed using the likelihood ratio as a test statistic. Combined results are calculated using the results of a recent scientific note. Difficulties in calculating the significance using likelihood ratio techniques in the high event rate and high significance environment of the LHC are discussed, and software packages which implement solutions to these problems are presented. We also provide a brief discussion about different ways to incorporate systematic error and introduce the statistical notion of power to the ATLAS Higgs search.

$m_H \sim 120$ GeV



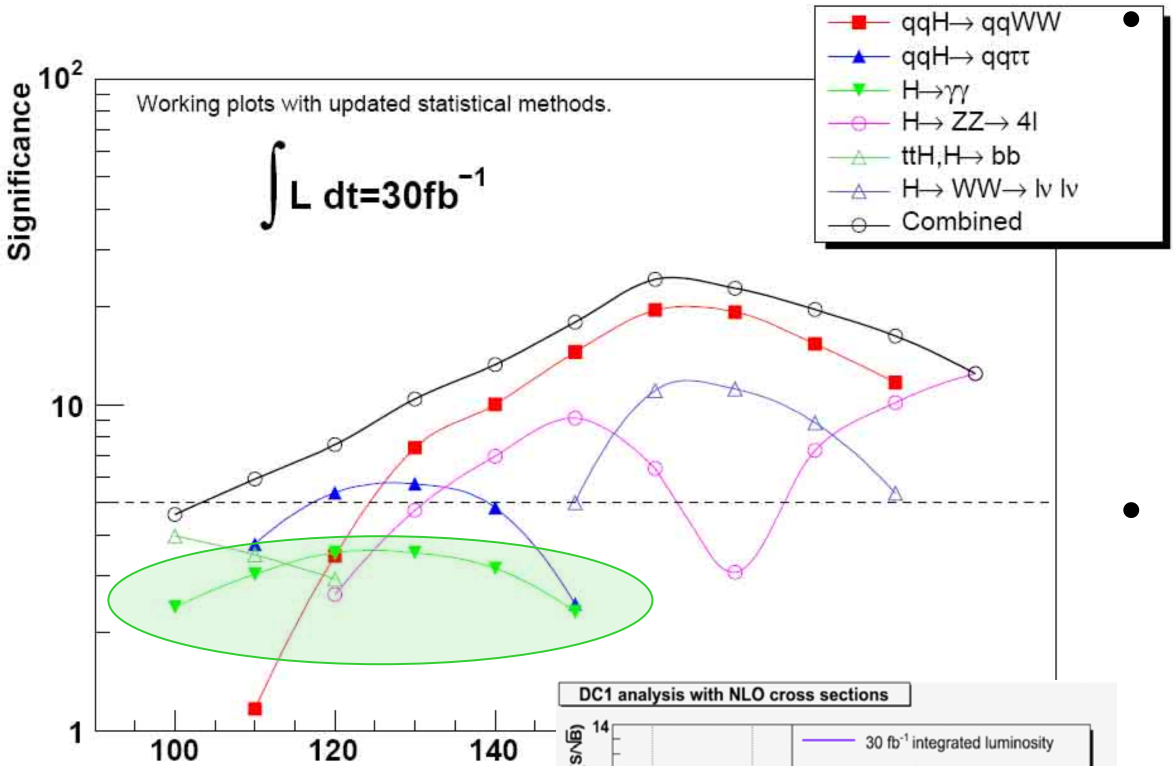


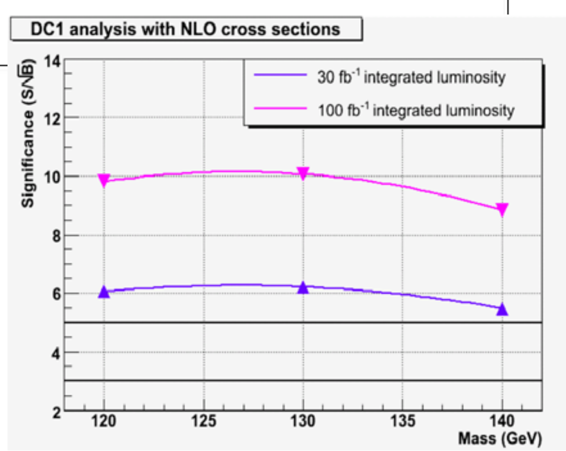
H→γγ, classical bump hunting
BR ~$2{\cdot}10^{-3}$

Irreducible background (now at NLO compared with TEVATRON)

- S/B~1:20. requires control of the background
- Normalization via side bands
- For best mass need good measurements of photon angles & energy
- Need to reject fake photons and photons from pions.

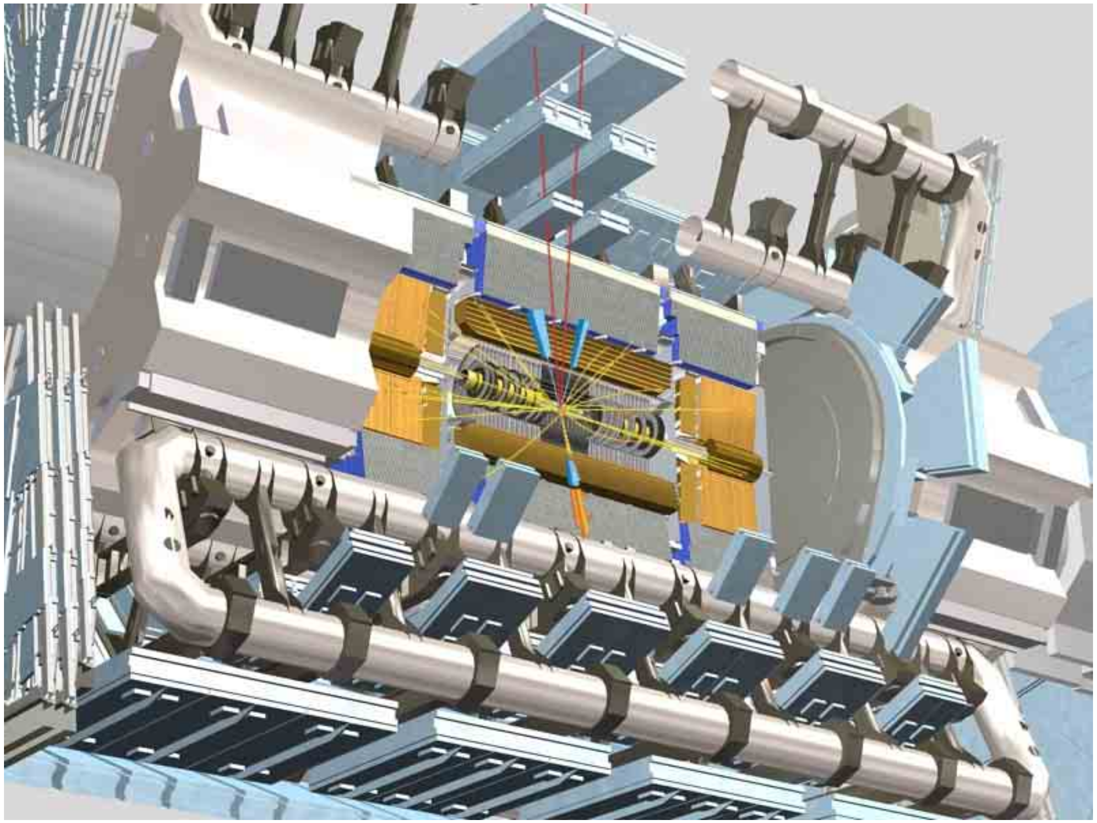
m_H~120 GeV



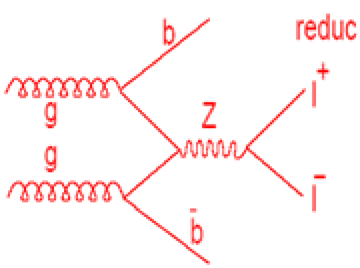


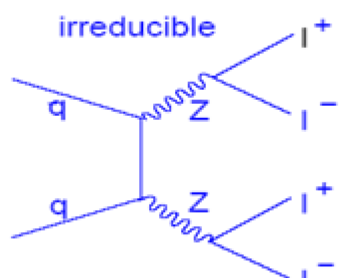
- Sensitivity can be increased by inclusive searches separating to
  - H+0j
  - H+1j
  - H+2j (dominated by VBF, qq→qqH)
- Resolution on mass ~1.6 GeV (@ m_H=120)
- Excellent prospects, especially for L>10fb^{-1}

The Golden Channel H→ZZ*→4 leptons

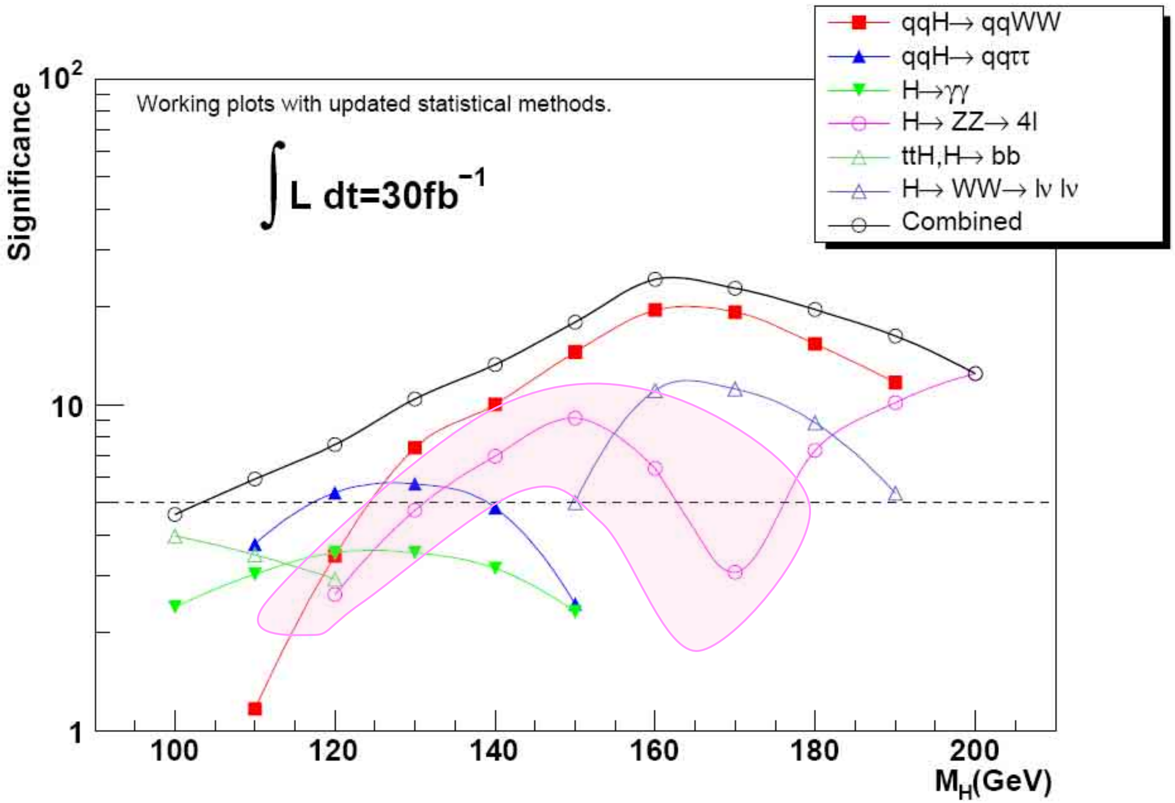


- Very low BR of H→ZZ* for low-medium m_H
- Yet, very clean and therefore appealing especially H→ZZ*→4μ
- Resulting reconstructed mass resolution ~1% (1.6-2.0 GeV)
- Reducible backgrounds (reject through lepton isolation, IP cuts):
  - Zbb→4leptons
  - tt→4leptons
- ZZ*/γ*→4 leptons irreducible background dominant after selection





The Golden Channel



H→4 leptons

Sensitivity best for ~160 GeV and heavier Higgs Boson

A Lesson in Systematic

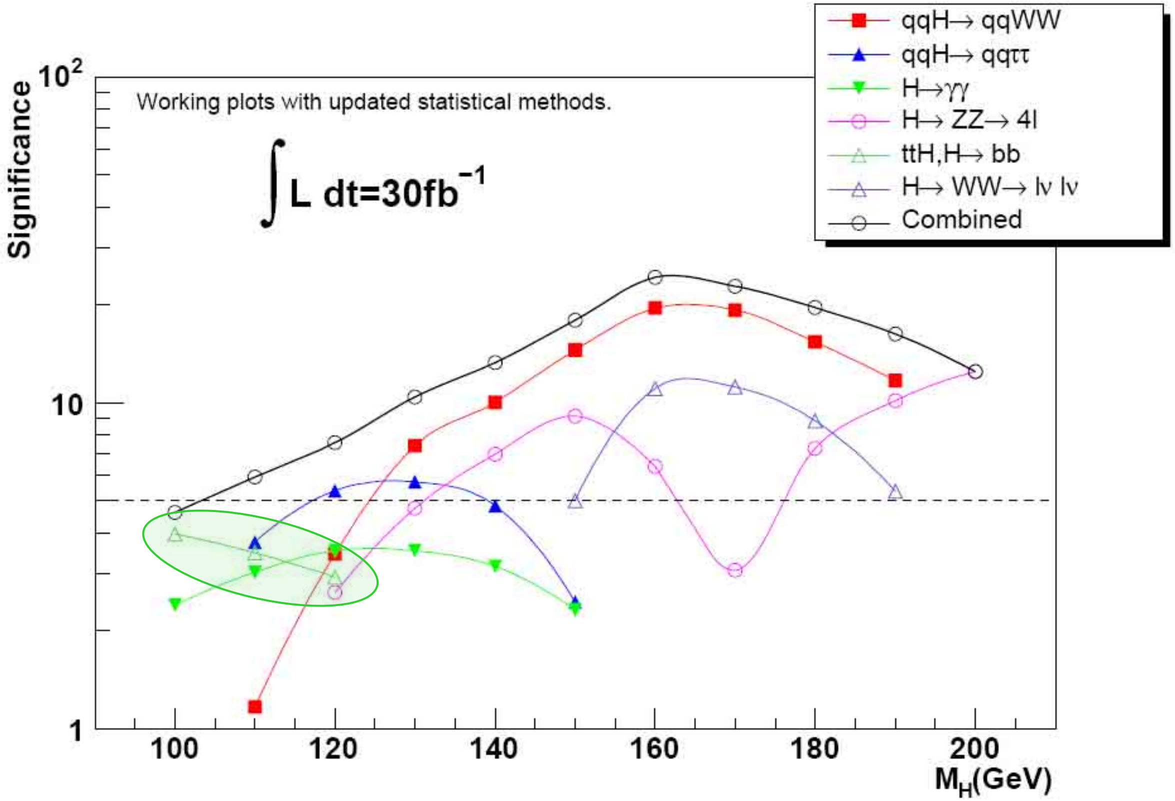
- In absence of systematics significance can be approximated to be $\frac{s}{\sqrt{b}}$
- However if there is systematics, say, Δb the significance is reduced to $\frac{s}{\sqrt{b(1+\Delta^2 \cdot b)}} \rightarrow \frac{s}{\Delta \cdot b}$
- For 5σ one needs

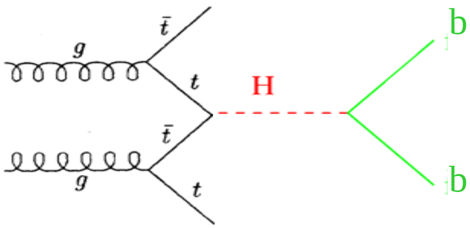
$$\frac{s}{b} > 5\Delta$$

- For 10% systematics this implies

$$\frac{s}{b} > 0.5$$

A Lesson in Systematics, ttH



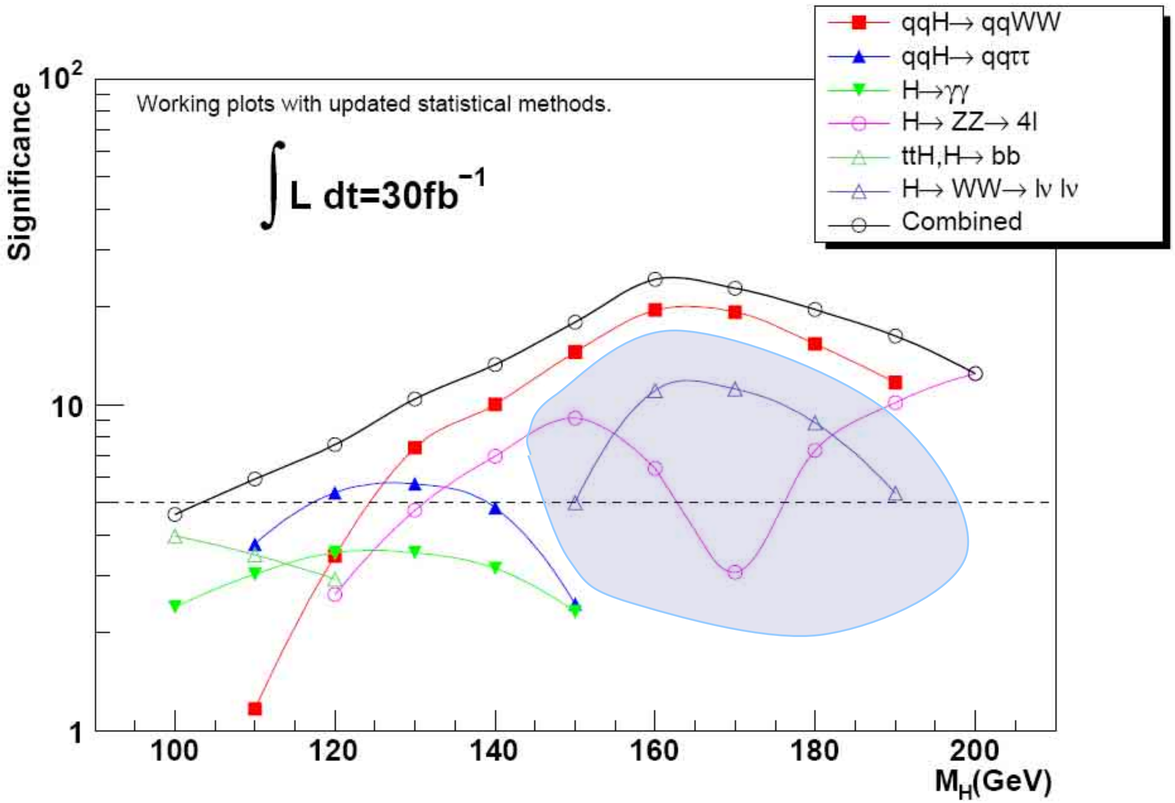


ttH, H→bb

A multi-jets final state

Looked promising until fast simulation was replaced by full simulation and systematics killed it

m_H~160, Gauge Bosons Playground



H→WW→lνlν
with l-l spin correlation

Dominant for $m_H \sim 2m_W$

Signature of 2 isolated leptons + missing E_T

No mass peak, use transverse mass
need to understand missing E_T

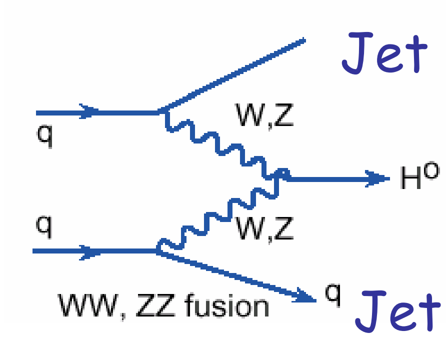
$$m_T = \sqrt{2\ P_T{}^{\ell\ell} \not{E}_T\ (1 - \cos\Delta\varphi)}$$

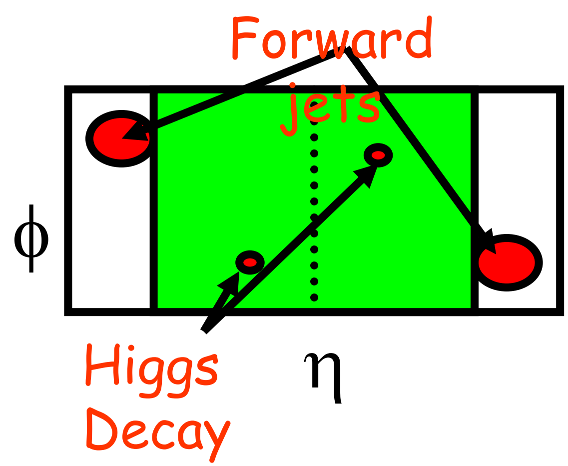
Main background from Wt(b) and tt, rejected via jet veto, yet systematics is still >10%

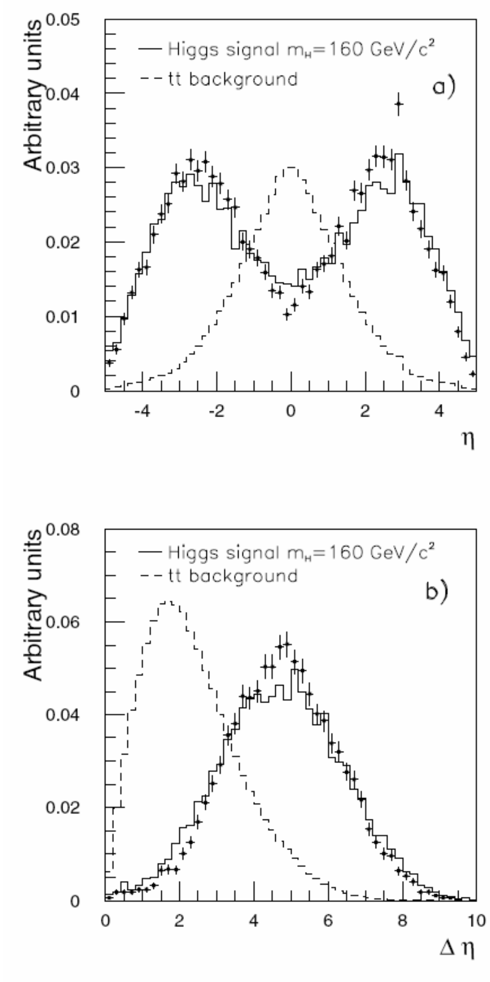
The Breakthrough: VBF

Han, Valencia, Willenbrock (1992);
Figy, Oleari, Zeppenfeld (2003,2004)

- qqH, H→WW,ττ
- Signature:
  - central jet veto (only signal decay products in the central region)
  - two high p_T jets with large $\Delta\eta$ separation
- Success of channel relies on understanding of the Missing Energy







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Han, Valencia, Willenbrock (1992);
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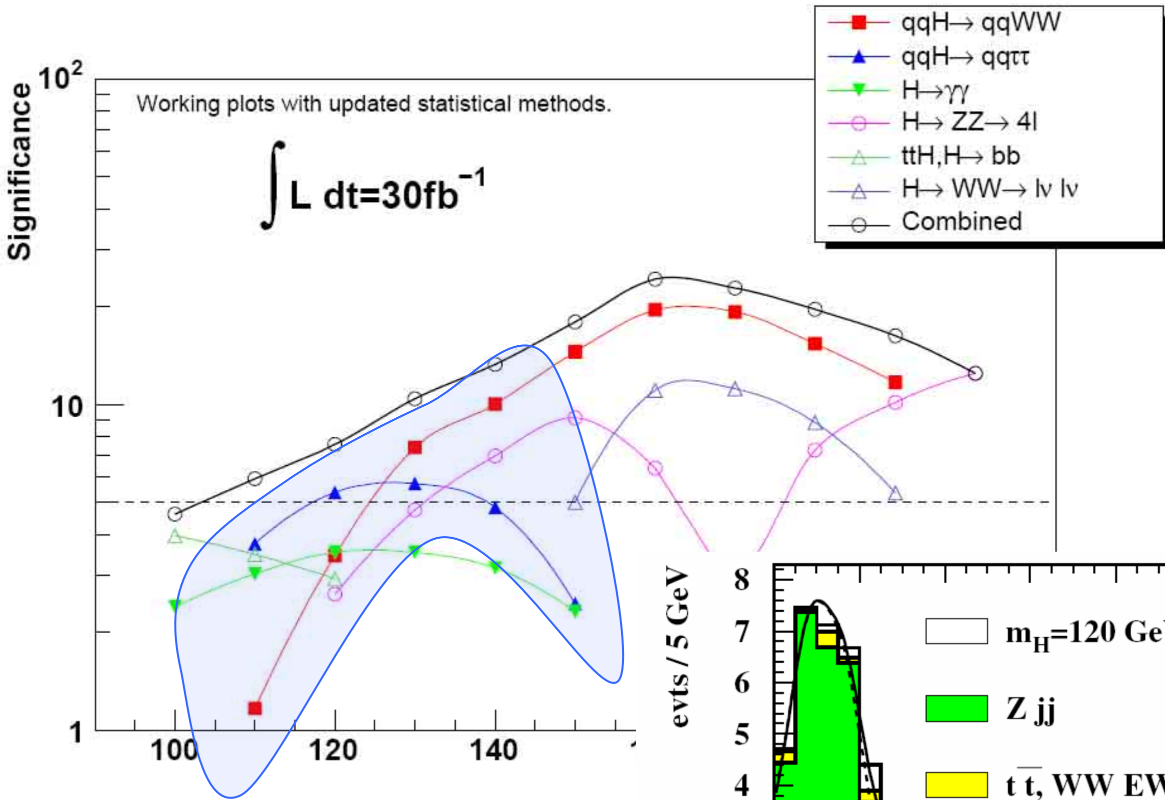
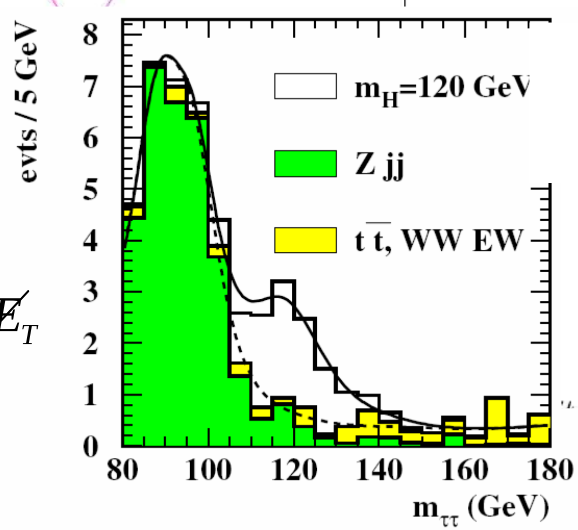


$$\tau\tau \rightarrow e\mu + \not{E}_T$$

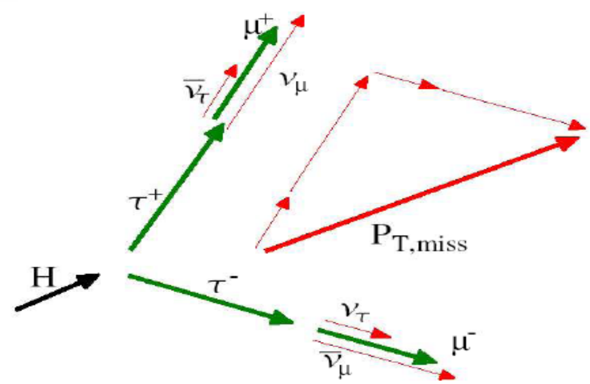
$$30 \;\; fb^{-1}$$



qqH, H→WW,ττ

The ττ decay mode extends the sensitivity to lower Higgs masses where there is a BR(H→ττ)

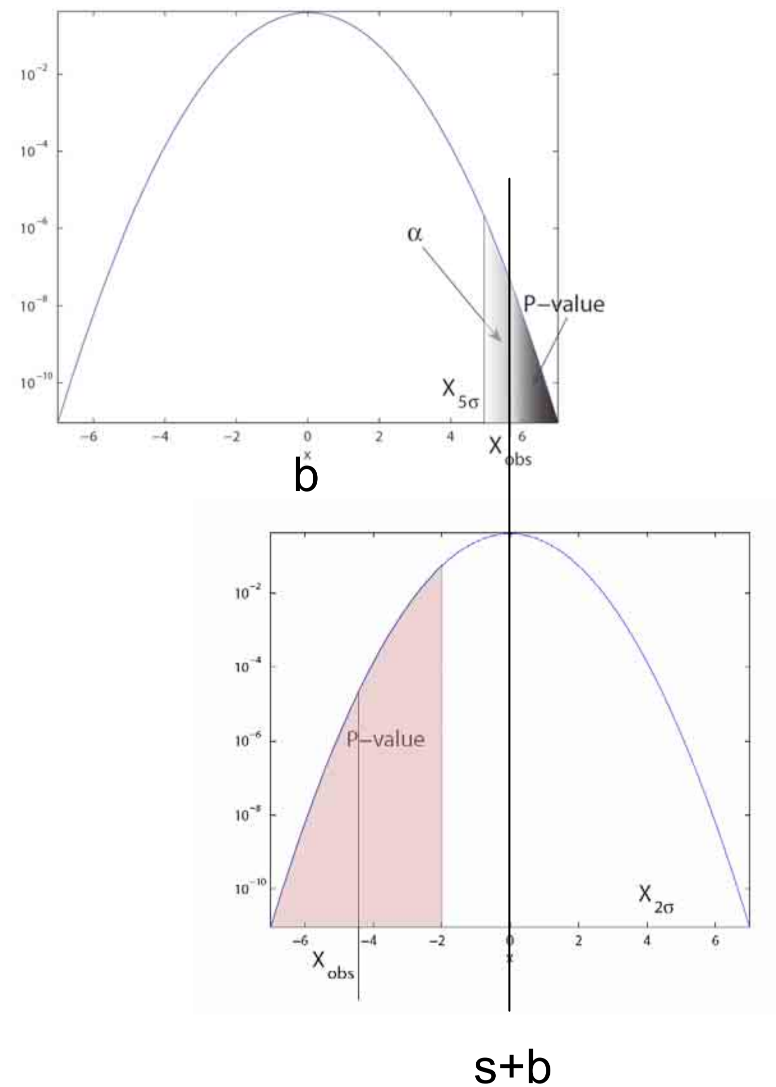
Mass can be reconstructed for ττ using the collinear approximation



Towards Combination of Channels

- Discovery:
  If the probability of the background to give an observation as or more incompatible than the observed one (p-value=1-CL_b) is less than ~$2.8 \cdot 10^{-7}$
  we claim a 5σ discovery

- Exclusion:
  If the probability of the would be s+b to fluctuate down and give an observation as or less compatible with s+b, is less than ~5% we claim an exclusion at the 95% C.L.



The LEP CL_b+C&H Method

- The C&H is a hybrid (Bayesian nature) Integrate on all possible values of unknown true b

$$n_{\exp ected} = \mu s + b$$

$$prob(n_{obs}, b_{obs} \mid \mu) = \int P(n_{obs} \mid \mu s + b)\pi(b)db$$

- $\pi(b)$ is the prior of b, e.g.

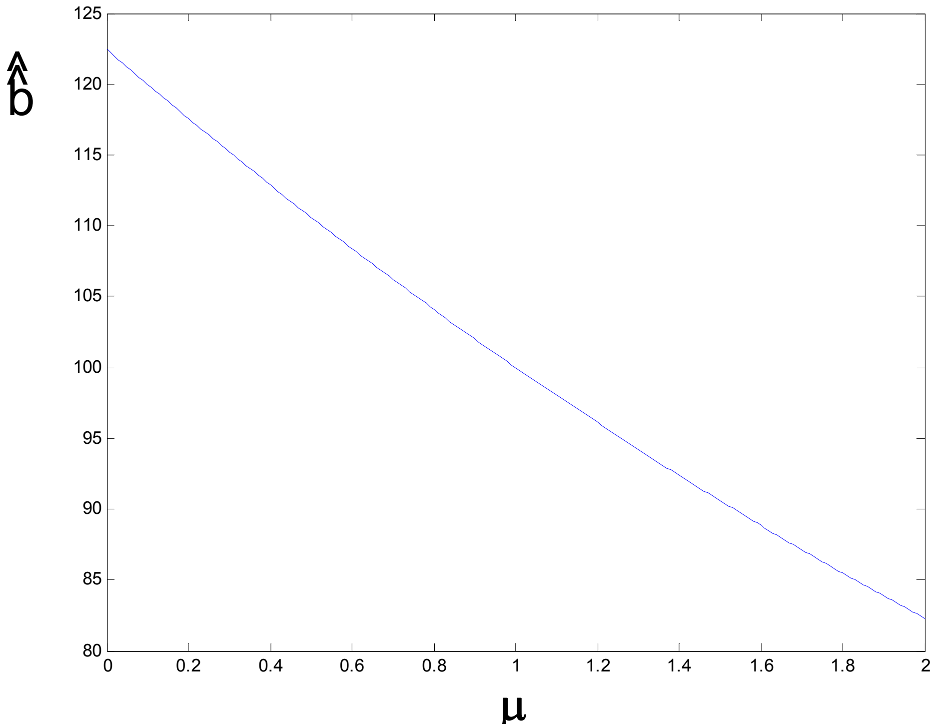
$$\pi(b) \sim G(b_{obs} \mid b, \sigma_b)$$

Profiling the Likelihood

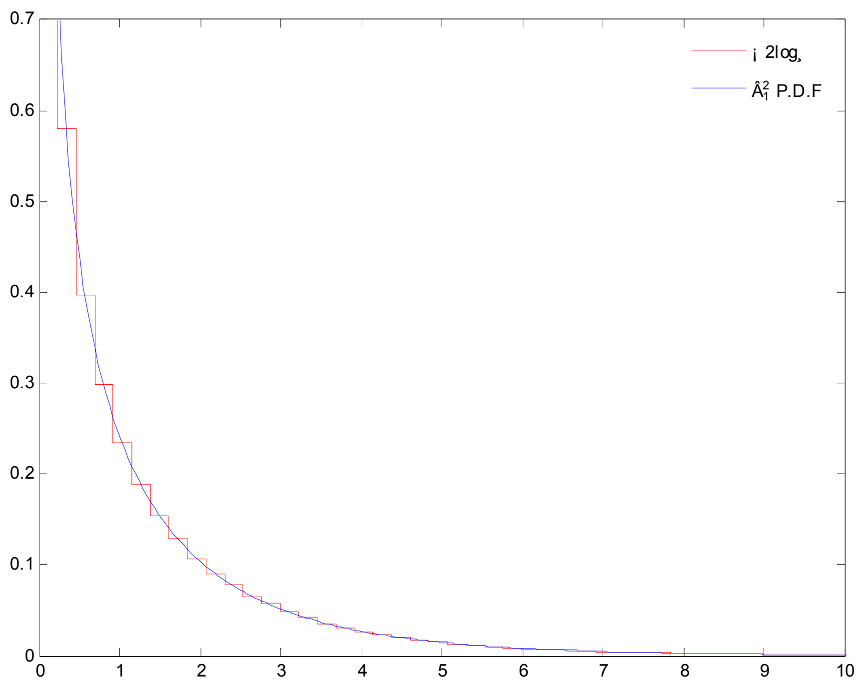
- Profile Likelihood: $$\lambda(\mu) = \frac{L(\mu s, \hat{\hat{b}}(\mu s))}{L(\hat{\mu} s, \hat{b})}$$

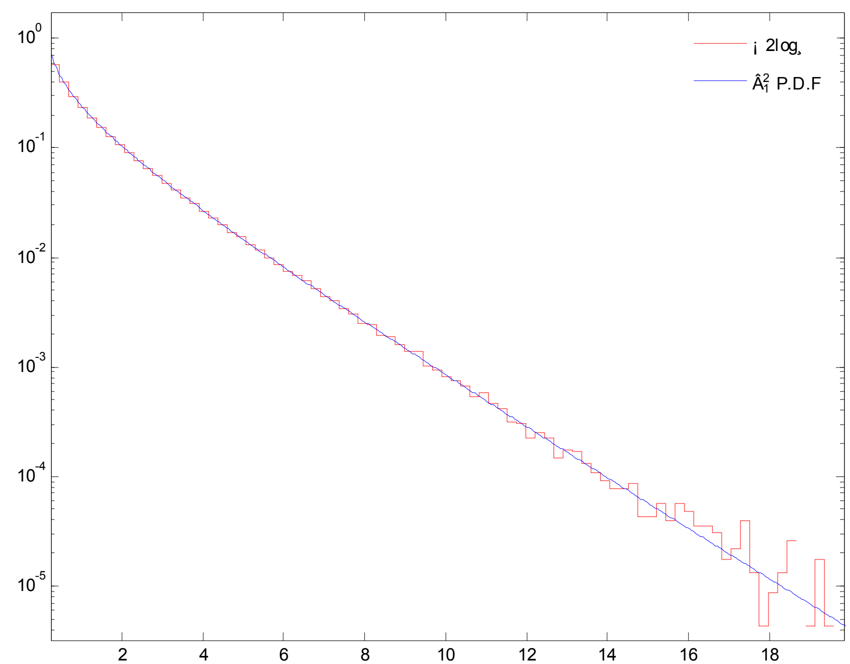
  Where $\hat{s}, \hat{b}$ are MLE

$\hat{\hat{b}}(s)$ is the MLE of b given μ



- $\lambda(\mu) = \dfrac{L(\mu s, \hat{\hat{b}}(\mu s))}{L(\hat{\mu} s, \hat{b})}$ distributes as a χ^2 with 1 d.o.f
- This ensures simplicity, coverage, speed





The Profile Likelihood for Significance Calculation

$$\lambda(\mu) = \frac{L(\mu s, \hat{\hat{b}}(\mu s))}{L(\hat{\mu} s, \hat{b})}$$

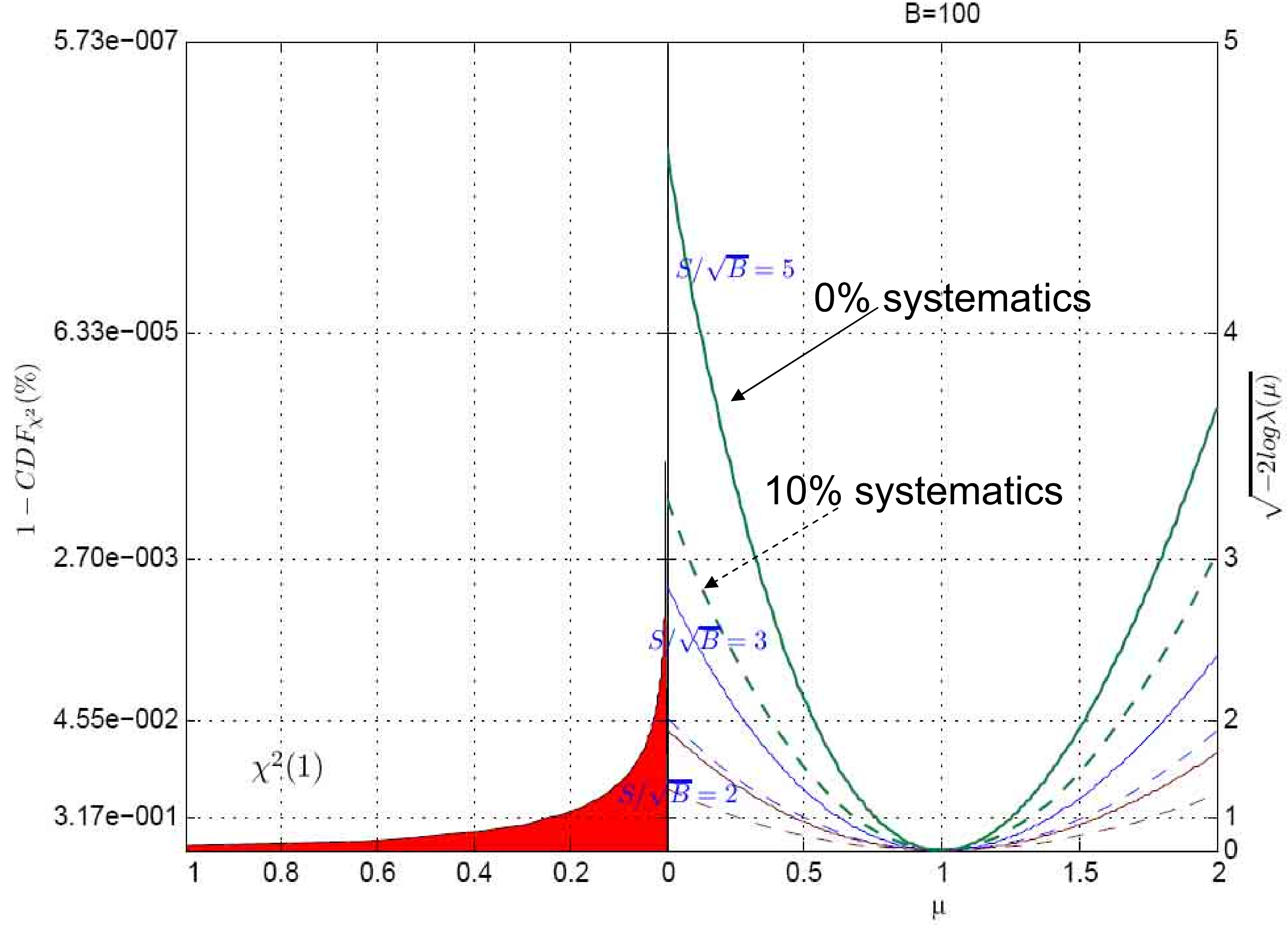
$$-2\log\lambda(\hat{\mu} \pm N\sigma_{\hat{\mu}}) = N^2$$

$$N = \sqrt{-2\log\lambda(\mu)}$$

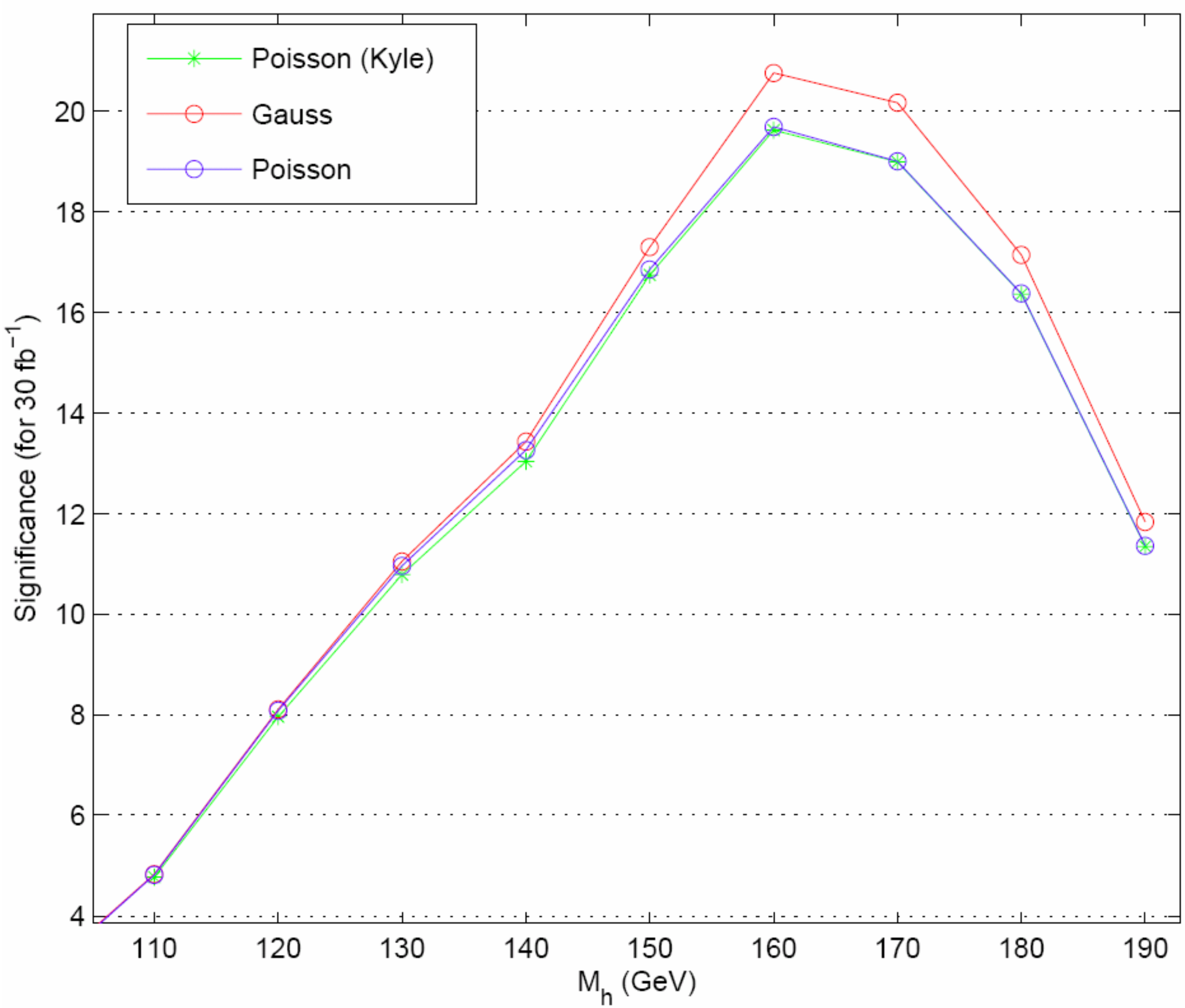
- In particular if we generate background only experiments, $\lambda(\mu=0)$ is distributed as χ^2 with 1 d.o.f
- Discovery has to do with a low probability of the background only experiment to fluctuate and give us a signal like result….
- To estimate a discovery sensitivity we simulate a data compatible with a signal (s+b) and evaluate for this data $\lambda(\mu=0)$. For this data, the MLE of μ is 1

With 10% Background Systematics

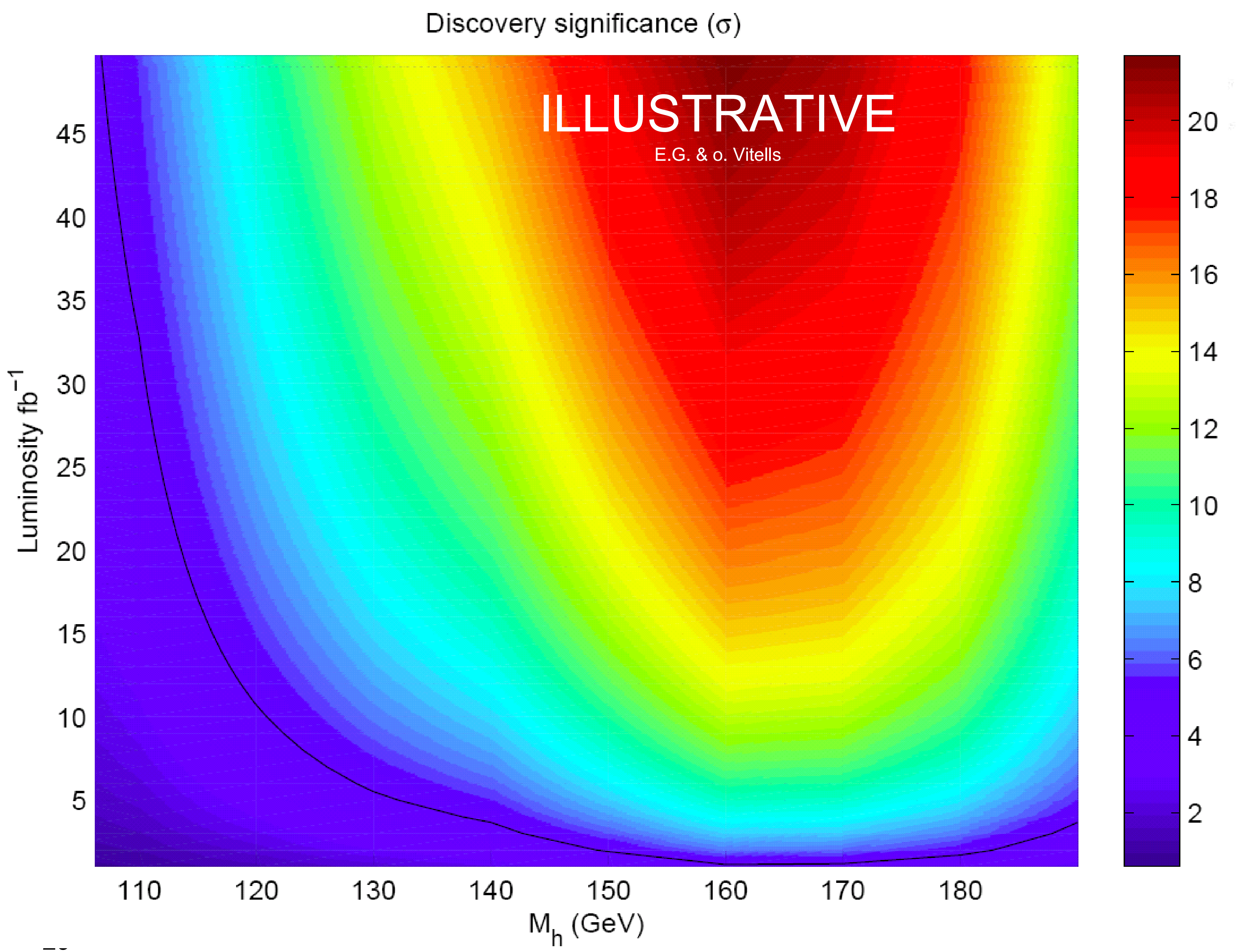
For b=100 with 10% systematics, significance for S/√B=5 drops to ~3.6



Results



Poisson (Kyle)
Gauss
Poisson
Significance (for 30 fb^{-1})
20
18
16
14
12
10
8
6
4
110
120
130
140
150
160
170
180
190
M_h (GeV)



Discovery significance (σ)
ILLUSTRATIVE
E.G. & o. Vitells
Luminosity fb^{-1}
45
40
35
30
25
20
15
10
5
110
120
130
140
150
160
170
180
M_h (GeV)
20
18
16
14
12
10
8
6
4
2

Exclusion with Profile Likelihood

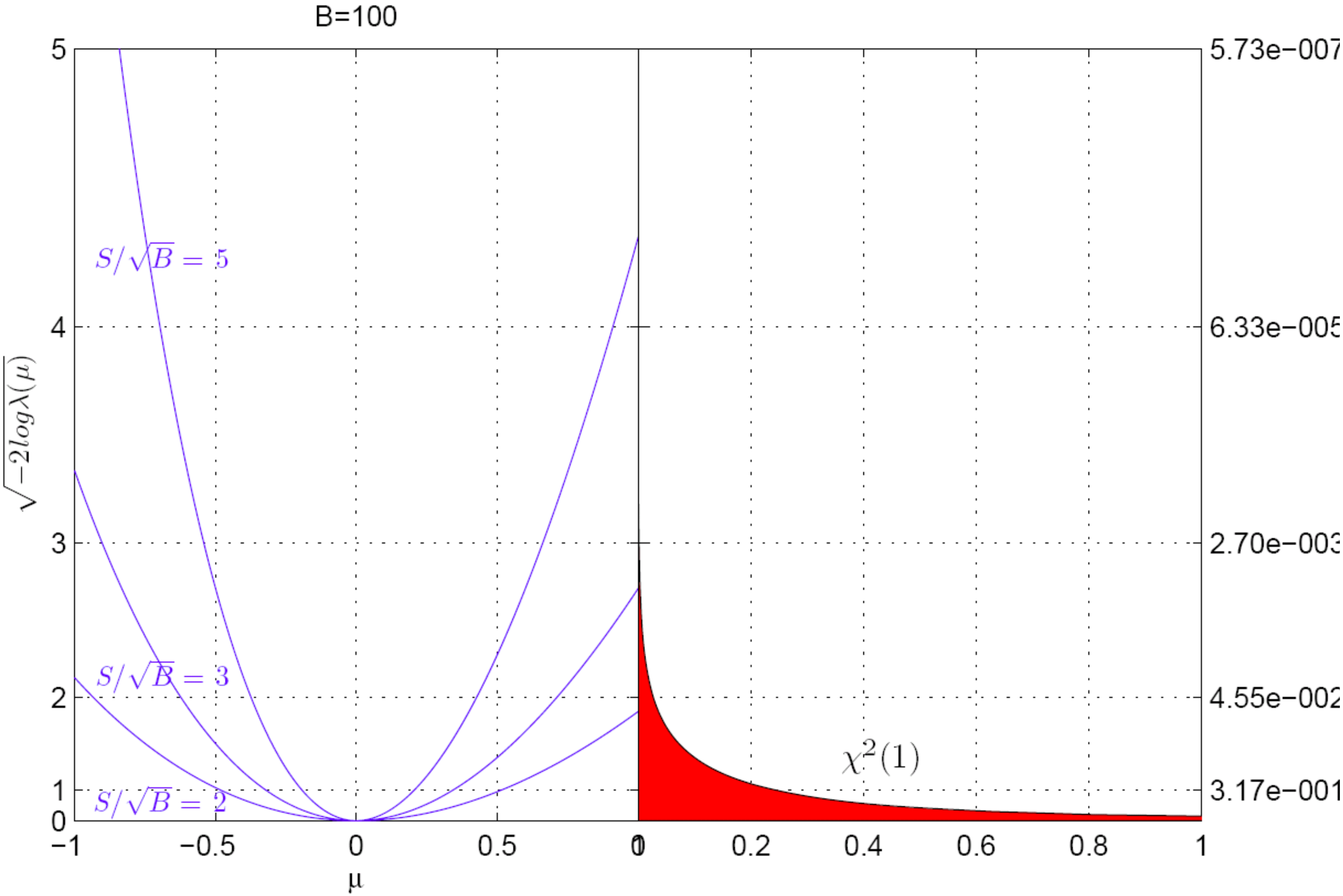
- Exclusion is related to the probability of the "would be" signal to fluctuate down to the background only region (i.e. the p-value of the s+b "observation")

- Here we suppose the data is the background only and the exclusion sensitivity is given by

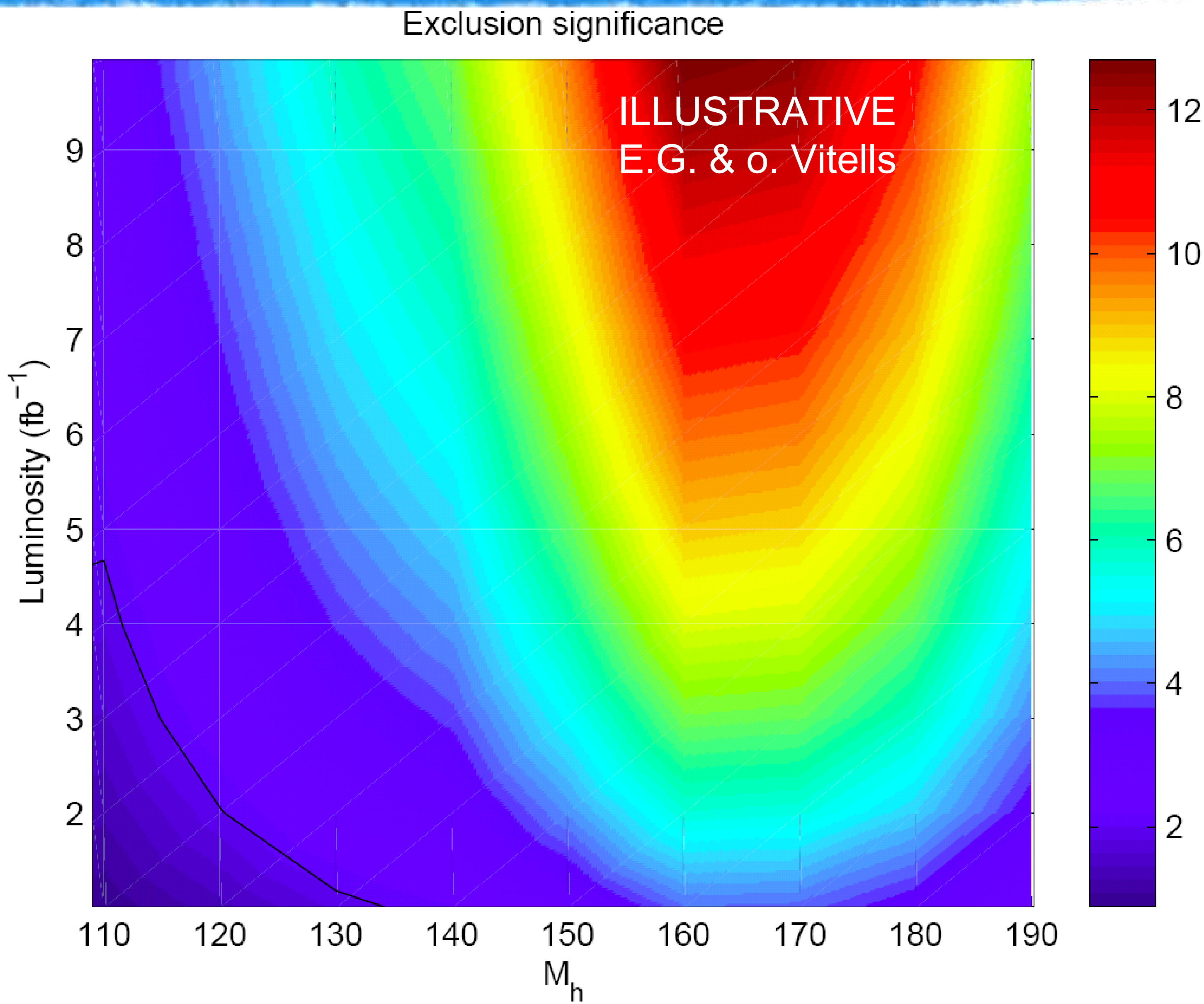
$$N = \sqrt{-2\lambda(\mu = 1)}$$

- Exclusion at the 95% C.L. means N=2

Exclusion – Moderate B (ΔB=0)



ATLAS Exclusion Sensitivity



Cases for ILC

- OK, so LHC discovered a Higgs Boson, now what?

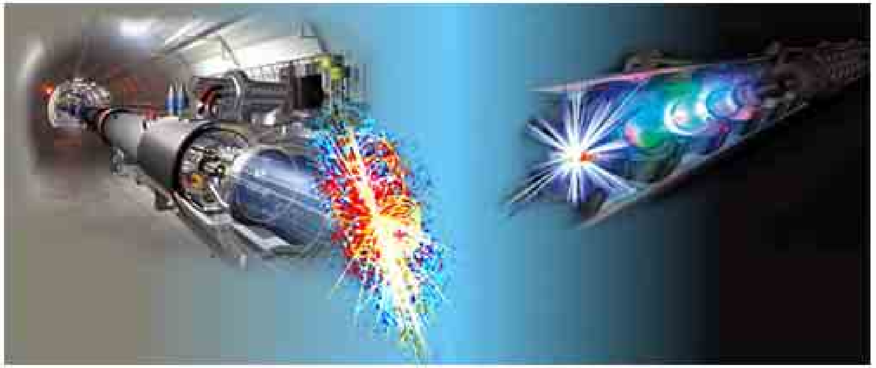
- What happens if we observe one Higgs and nothing more'?
  - Is it a SM Higgs Boson?
  - What is its width?
  - What is its spin?
  - What are its couplings?

- Even though some properties can be probed with the LHC, if the LHC is a Higgs hunter, the ILC would be a Higgs Probe…..

From LHC to ILC

The LHC Early Phase for the ILC

April 12 - 14, 2007



The LHC will produce its first physics data at 14 TeV in 2008 and has the promise of making groundbreaking discoveries with the first few femtobarns of data. This will certainly have profound implications for the complete high energy physics program. It is now time to examine the scenarios that may occur in the early phase of the LHC operation and investigate their impact for ILC physics.

A workshop on the LHC early phase and its impact on the ILC will be held at Fermilab, April 12-14, 2007. The purpose of this workshop is to bring together the LHC and ILC experimental and theoretical community with interest in collider physics to assess the prospects for LHC/ILC interplay based on early LHC data with an integrated luminosity of about 10 fb-1.

The workshop will combine plenary and working sessions, with the idea of initiating specific projects in these areas. We expect this activity will ramp up into a series of workshops throughout 2007 and 2008.

From LHC to ILC

LHC ILC Interplay

Interplay and Synergy

K. Desch, LCWS 07
Also workshop for the LHC early phase for the ILC, Fermilab, 07

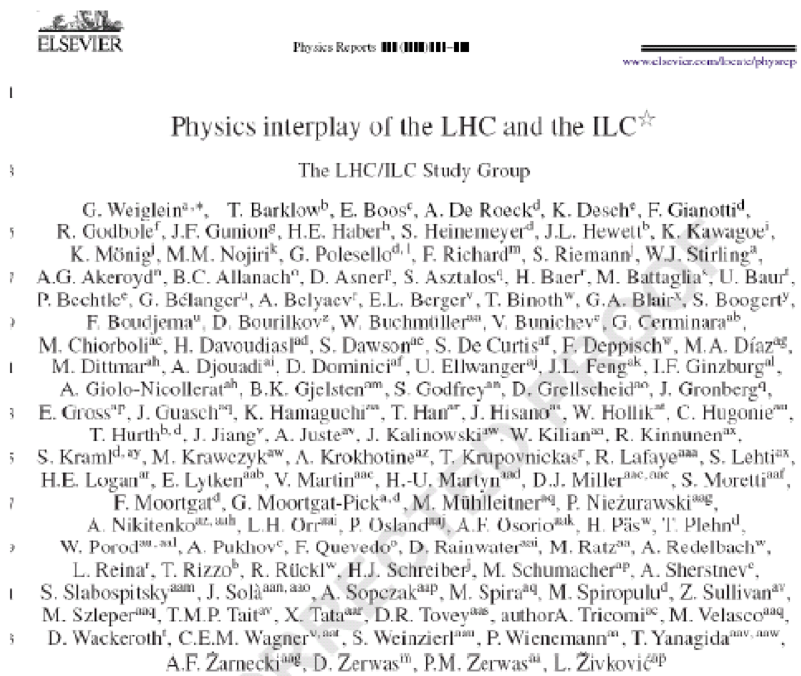
HC + LC > HC

HC ⊕ LC > HC + LC

HC ⊗ LC > HC ⊕ LC

LCWS Korea 2002

→ LHC/ILC Study group
Phys. Rept. 426 (2006) 47



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Physics interplay of the LHC and the ILC☆

The LHC/ILC Study Group

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Conclusion 2002-2006:

Terascale physics needs both LHC and ILC

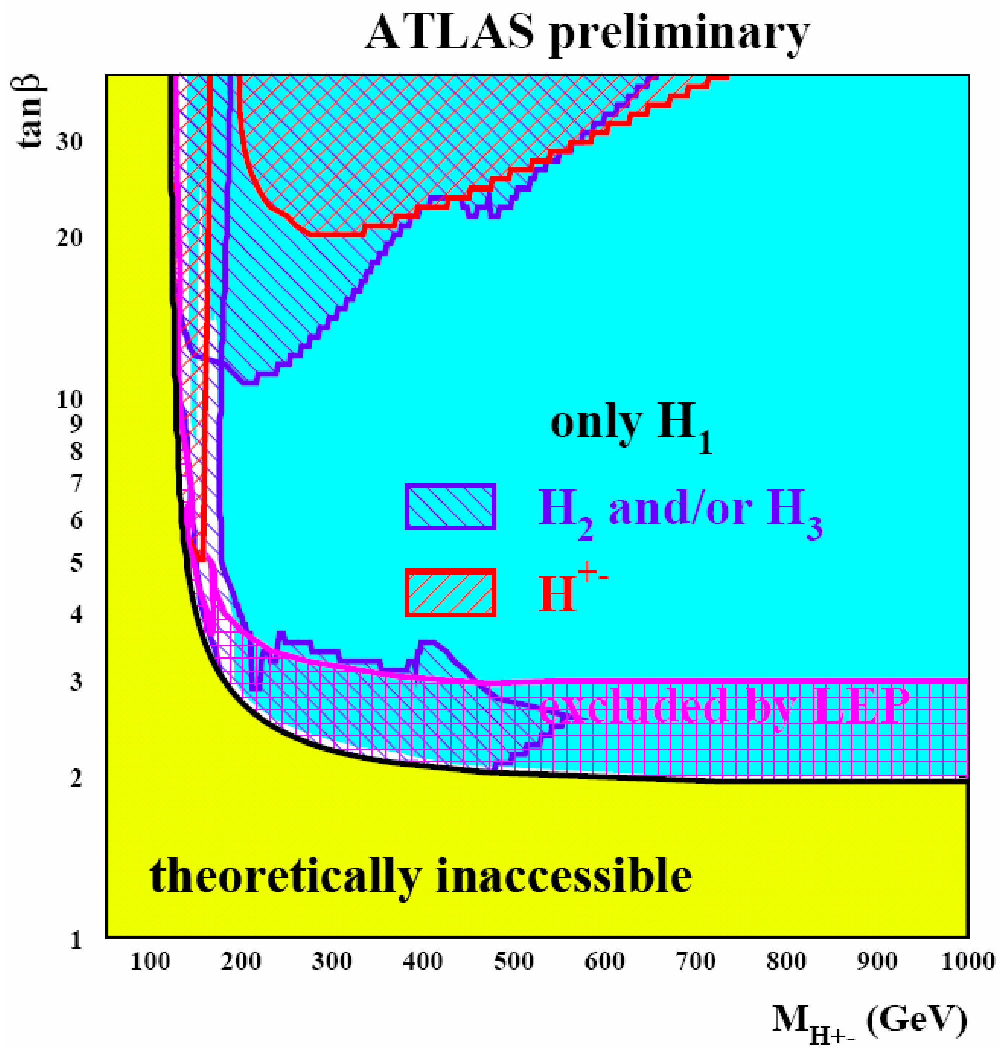
Many examples for

- joint interpretation (added value from ILC)
- joint analyses (feedback from ILC to LHC)

The Case of Observing One Scalar

- Even if the Higgs is supersymmetric there is a large region in the parameters space where the LHC can observe only one of the Higgs Bosons

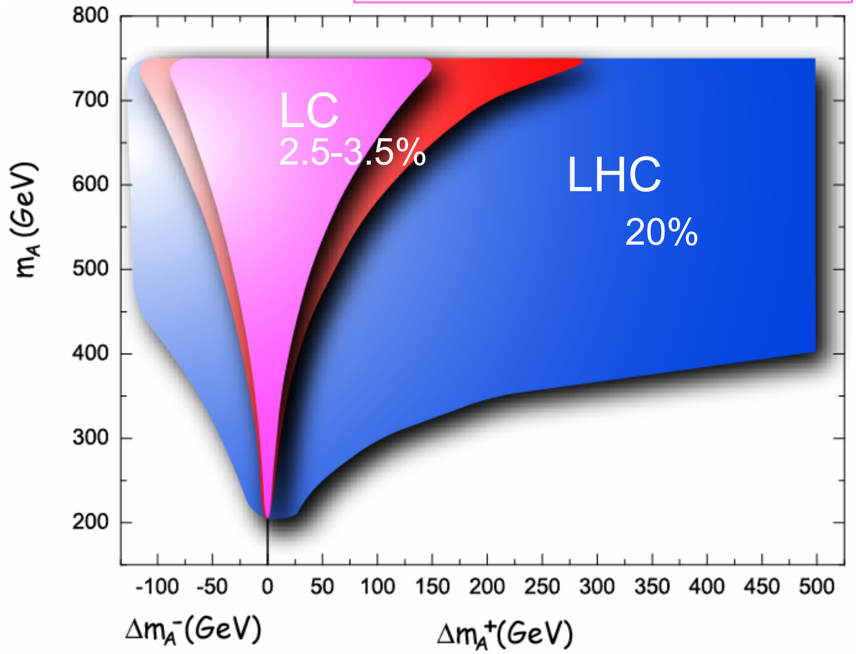
- An accurate measurements of the couplings & BRs of the observed Higgs can reveal its nature



Some Things ILC Does Better

- Here m_h=120

$$R = \frac{BR(H \to bb)/BR(H \to WW)}{[BR(H \to bb)/BR(H \to WW)]_{SM}}$$

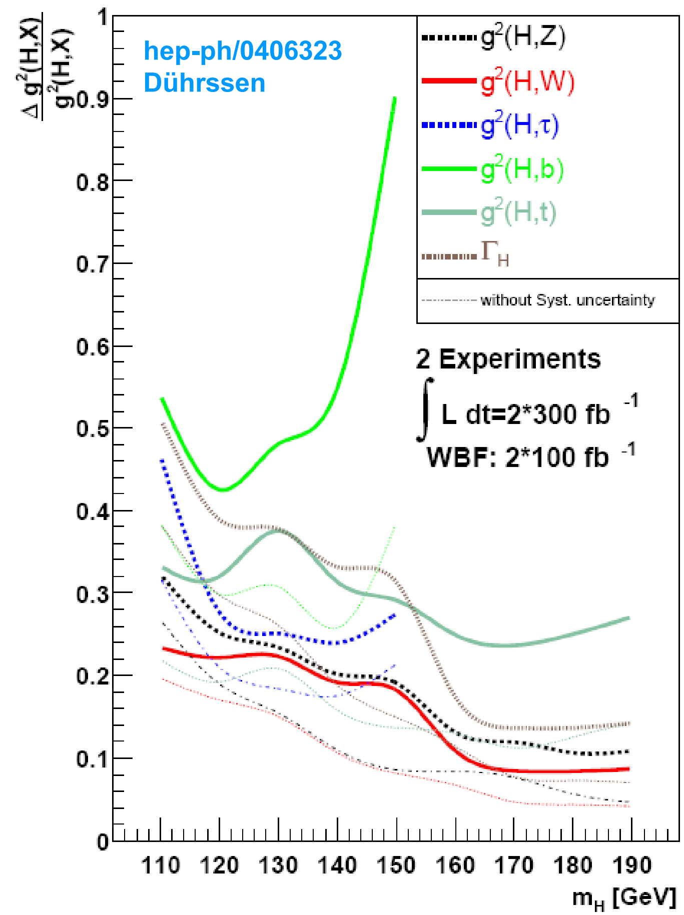


Δm_A = 30% for m_A = 800 GeV also in parameter regions where LHC is blind

LHC/LC interplay in the MSSM Higgs sector
Georg Weiglein and Sven Heinemeyer ,Lidia Zivkovic ,E.G. ,Klaus Desch
JHEP09(2004) (September 2004) 062 **2004** *.J. High Energy Phys*

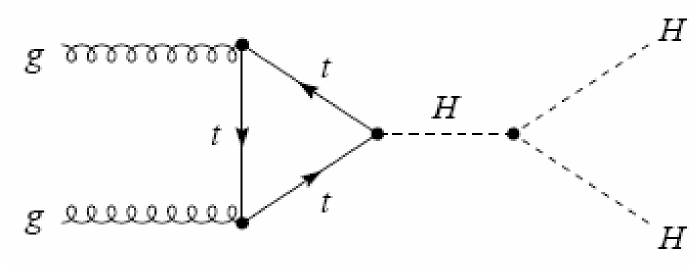
Moriond QCD 2006 - Helenka Przysiezniak

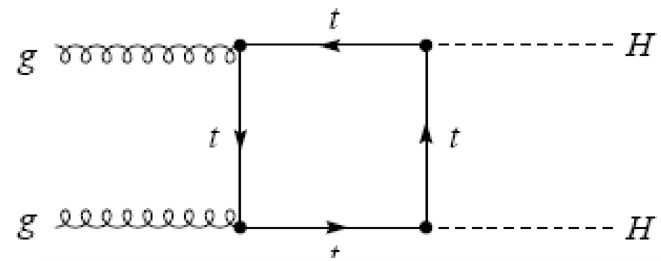
- LHC: for 300 fb^{-1} and 110<mH<190 GeV
  - $\Delta g^2/g^2$ ~ 10%-45% (except for b)
  - $\Delta\Gamma_H/\Gamma_H$ ~ 10%-50%

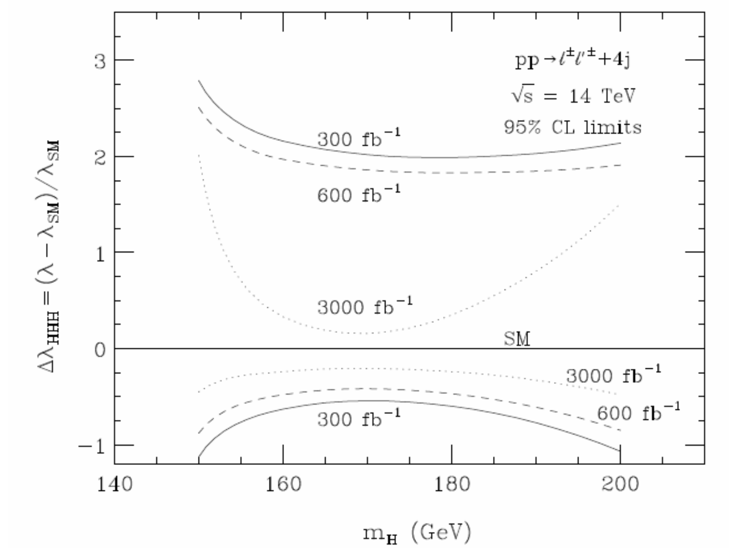


The Ultimate Goal: Probing the SSB Sector

- Derive 95%CL bounds from χ^2 fit to m_{vis} shape
- SM assumed to be valid except for self coupling.
- Assume m_H precisely known, and BR($H \to WW$) known to 10% or better.
- **$gg \to HH \to$ $(W^+W^-)(W^+W^-) \to (jj\ell^\pm\nu)\ (jj\ell'^\pm\nu)\ (\ell = e,\mu)$** for m_H>150 GeV/c2.
- The self coupling λ is determined to -60-300% within 1σ for **$150<m_H<200$ GeV**
- This will have to wait for a future collider



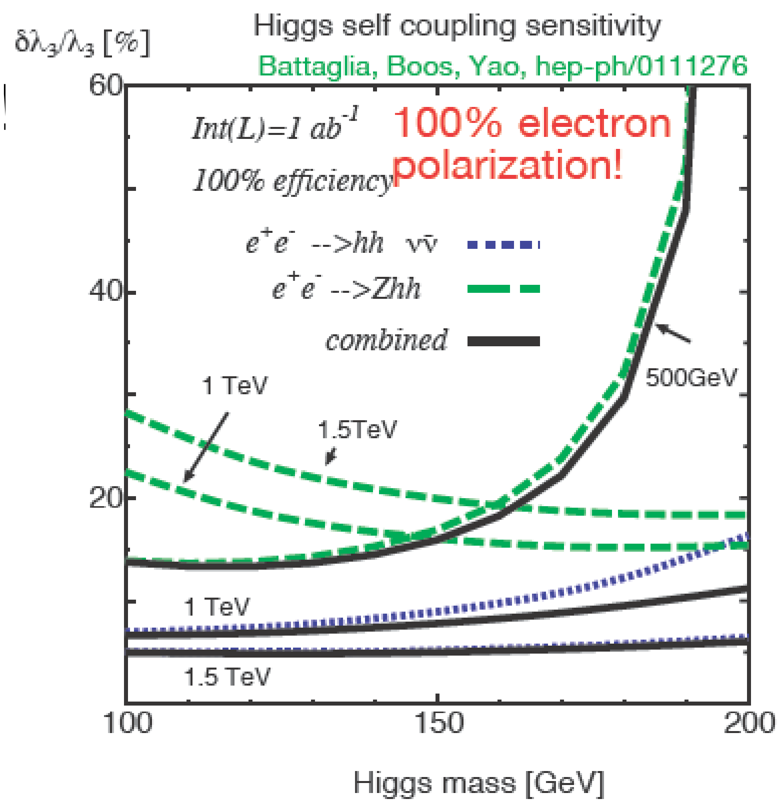




The Ultimate Goal: Probing the SSB Sector

K. Desch, LCWS 07
Also workshop for the LHC early
phase for the ILC, Fermilab, 07

- Self Higgs coupling is not a piece if cake for a LC as well!
- Needs >1 TeV with a polarized electron beam and 1 ab^{-1} to probe it to the level of ~10%
- This by itself might justify a LC (If we observe a scalar)

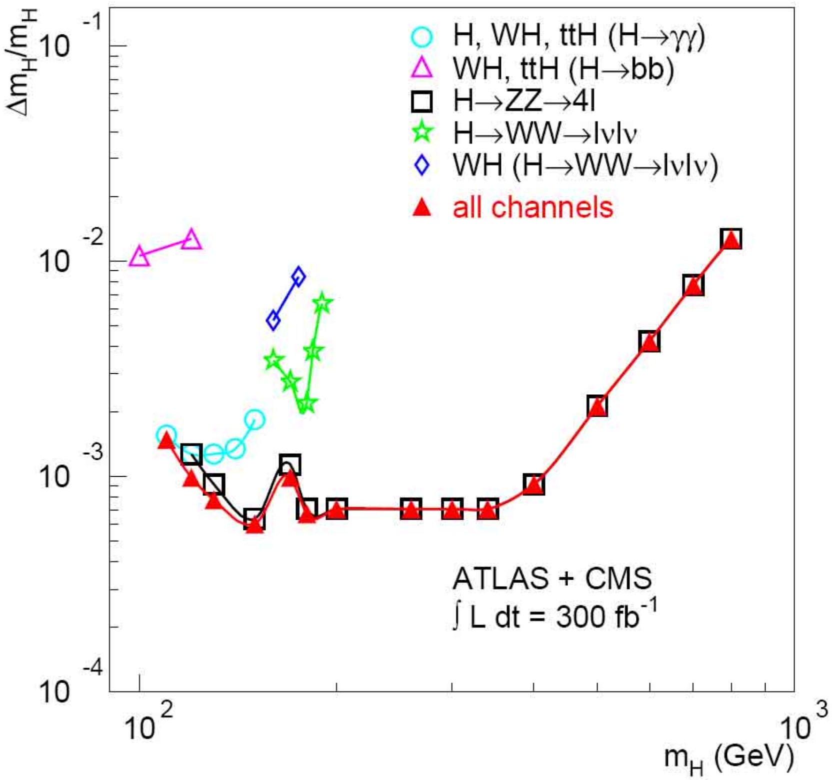


Some Things LHC Can Also Do

Moriond QCD 2006 - Helenka Przysiezniak

- Combining CMS and ATLAS with high luminosity (yet accessible within a few years) with channels like $H \to \gamma\gamma$, $H \to ZZ(^*) \to 4\ell$, WBF $H \to \tau\tau \to \ell$+hadr an accuracy of 0.1% might be achieved for the mass with m_H~120-400 GeV, that is not so different from LC

- This is under the condition that the systematics on the energy scale is below the 0.1% for photons/electrons and below 1% for jets….



PDG 20xx?

E.G. Higgs&SUSY Orsay 2001

Conclusion: PDG 2012? ?

SUMMARY TABLES OF PARTICLE PROPERTIES
Extracted from the Particle listings of the
Review of Particle Physics
Published in Eur. Jour. Phys **C3**, 1 (2012)
Available at http://www.eilamgross.com

GAUGE AND HIGGS BOSONS

H

$J^{PC}=0^{++}$ [a]
Charge = 0
Mass m=120.0±0.040 GeV [b]
Full Width Γ =3.6±0.2 MeV[a]

H DECAY MODES[b]	Fraction
bb	(67.8 ±1.6) %
cc	(3.08 ± 0.25)%
ττ	(6.8 ±0.35)%
gg	(7.04 ± 0.38)%
γγ	(0.21 ±0.0 5)%
WW	(13.3 ± 6.6)%

Or alternatively and much more interesting:

GAUGE AND HIGGS BOSONS

h

h DECAY MODES[c]	Fraction
bb/WW	11.06 ±0.25
$R=(bb/WW)_{meas/SM}$	1.32

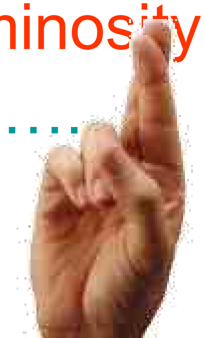
A

Mass m=400.0 ± 25 GeV [d]

[a] LC, [b] LC/LHC, [c] LC-A Global Fit, [d] LC indirectly

Conclusions

- LHC is a discovery machine
- LHC is scheduled to deliver data starting end of 2008
- The optimist expects to see a hint of a Higgs Boson by the end of 2009
- The pessimist will wait another year
- SUSY might come earlier
- The ILC is a probing machine
- The ILC can measure some properties of the new particles discovered, yet hard to measure, by the LHC
- ILC can tell a SM scalar from a SUSY scalar
- ILC with high CM and high luminosity can probe SSB
- ILC seems to wait for the LHC….



Backup

Luminosity – Technology Pushed to the Limit

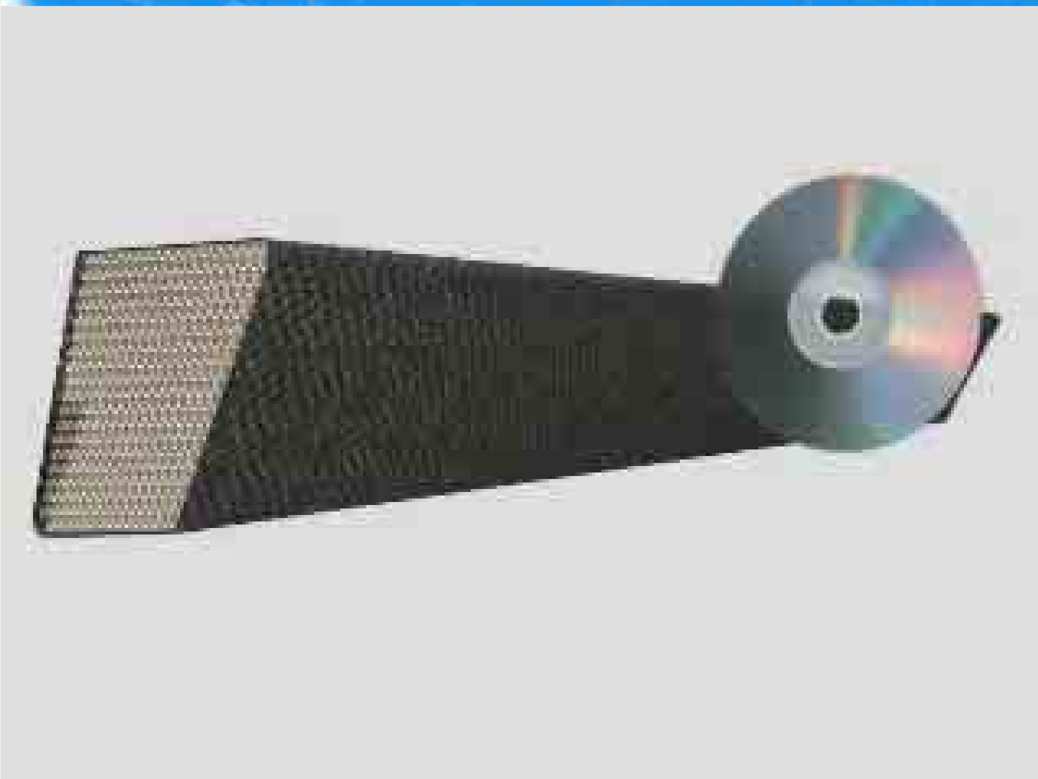
$$L \sim \frac{N_p^2 f_{rev} N_{bunches}}{\sigma_x \sigma_y}$$

- Beam parameters at LHC
  - $N_p \cong 10^{11}$; $\sigma \cong 15$ μm; $f = 11$ kHz; $N_{bunches} = 2808$
  - $L \sim 10^{34}$ cm^{-2} s^{-1} = 10nb^{-1}s^{-1}= 10^{7}mb^{-1}s^{-1},
    N=L·σ →
    Access to rare (low cross section) processes

How Does It Happen in ATLAS

- Inner detector
  - Pixel and strip silicon detectors at small radii
  - Straw-tube "transition-radiation tracker" (TRT) at larger radii
- EM calorimeter
  - Lead – liquid-argon sampling calorimeter
- Hadronic calorimeter
  - Iron – plastic scintillator calorimeter in barrel
  - Copper – liquid-argon calorimeter in endcap
- Muon spectrometer
  - Drift tubes for precise tracking
  - RPC and TGC detectors for triggering

Telling an Electron from a Pion - TRT



- Charged particles ionize the gas filled in tiny tubes (4 mm diameter) with straw like anodes which collect the electrons.
- There are over 300,000 1.5m straws in the end cap and over 50000 0.5 m straws in the barrel region

- Electrons, in addition, interact with the plastic coating of the tubes emitting X-rays which help to distinguish electrons from Pions.