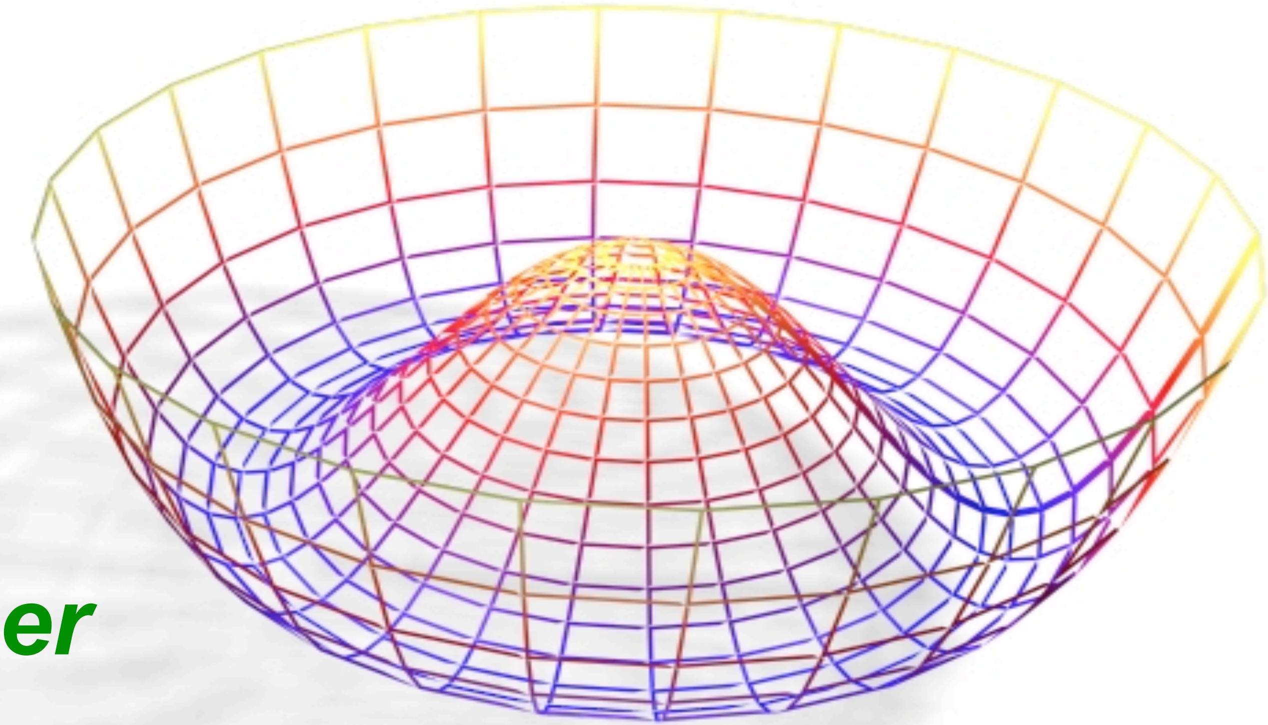
CENTER FOR
COSMOLOGY AND
PARTICLE PHYSICS

Searching for Exotic Higgs decays in Archived LEP Data



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Foreword / History / Acknowledgments

Thank you to the Galileo Galilei Institute for the invitation

- apologies for arriving late, the program looks very interesting and I wish I could have been here for all of it

I joined ALEPH in ‘99, during its last year of data taking, and was active in the LEP Higgs searches

- In ‘05, I worked together with Marcello Maggi and Bruce Knuteson in the context of an ALEPH data archival project and to try Bruce’s Quaero algorithm at LEP
- now possible to publish under ALEPH archival policy

I’d like to thank Neal Weiner, Spencer Chang, Tilman Plehn, and Bob McElrath in particular for pointing out this great opportunity.

- after a few failed attempts in the last few years to investigate these exotic scenarios, 3 things came together
  1. the LHC “incident”
  2. James Beacham, a graduate student at NYU was looking for a research project
  3. Itay Yavin came to NYU and offered help (including learning to use ROOT)

In addition Paolo Spagnolo @ INFN in Pisa was working on this independently.

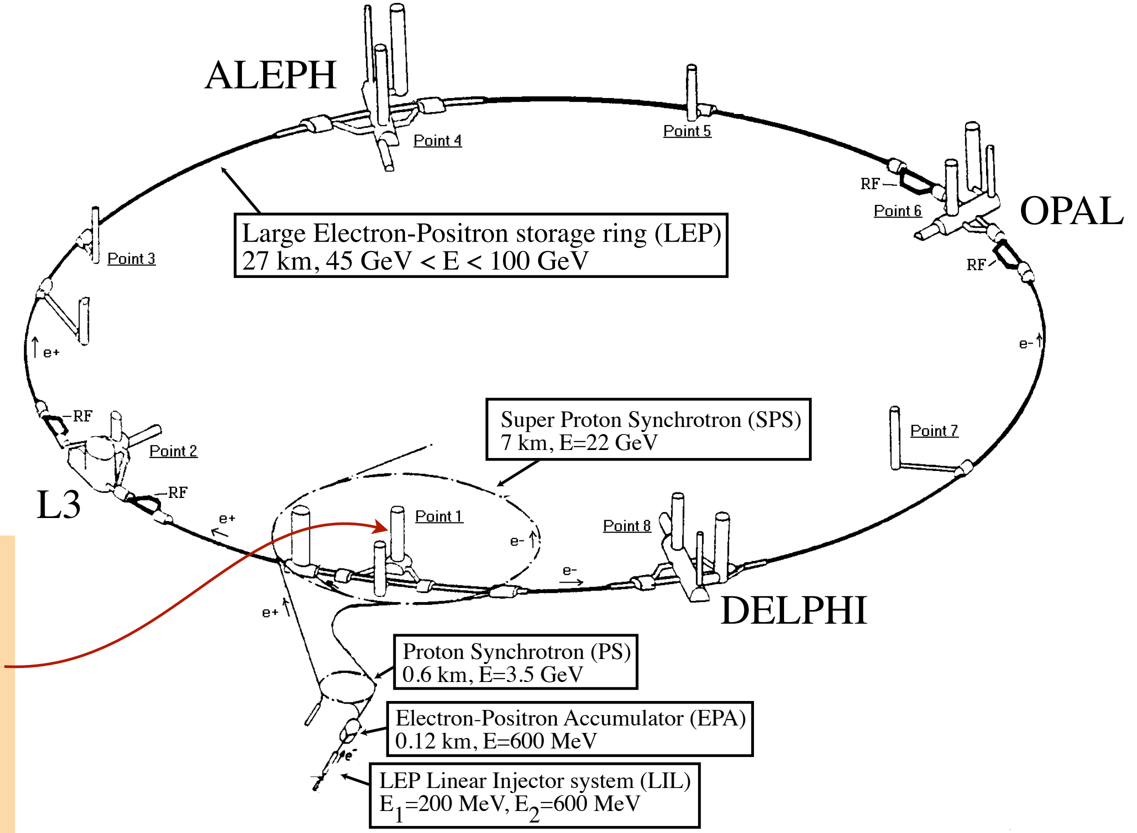
we are merging our analyses into what will likely be the last ALEPH paper

LEP

LEP operated from 1989-2000

- LEP1 running at the Z resonance (<1996)
- LEP2 running from $\sqrt{s} = 183 - 207\,\mathrm{GeV}$

E_{CM} (GeV)	183	189	192	196	200	202	205	207
$\int \mathcal{L}\,dt$ (pb^{-1})	56.82	174.21	28.93	79.83	86.30	41.90	81.41	133.21



I got to see the excavation of the ATLAS cavern directly above the LEP tunnel in the last days of running

Some results from LEP Higgs searches

Searches for the Standard Model Higgs put a limit at M_H>114.4 GeV

- searches dominated by $H \rightarrow bb, \tau\tau$
- decay independent limit (from Z recoil) at 82 GeV
- searches in the (CP conserving) MSSM also quite stringent
  - m_h, m_A < 93 for $0.5 < \tan\beta < 2.5$ in “m_h–max” scenario
- excesses seen at 97 and 115 GeV, but not consistent with SM or MSSM

Electroweak fits prefer a Higgs significantly lighter than this bound

- introduces fine tuning problems for Standard Model and MSSM
- LEP paradox:
  - no indication of new physics => scale of new physics >1TeV
  - hard maintain naturalness if m_H >114 and scale of new is physics is >1TeV

This has motivated theories with extended Higgs sectors or next-to-minimal supersymmetric extensions to the Standard Model

How could we have missed the Higgs?

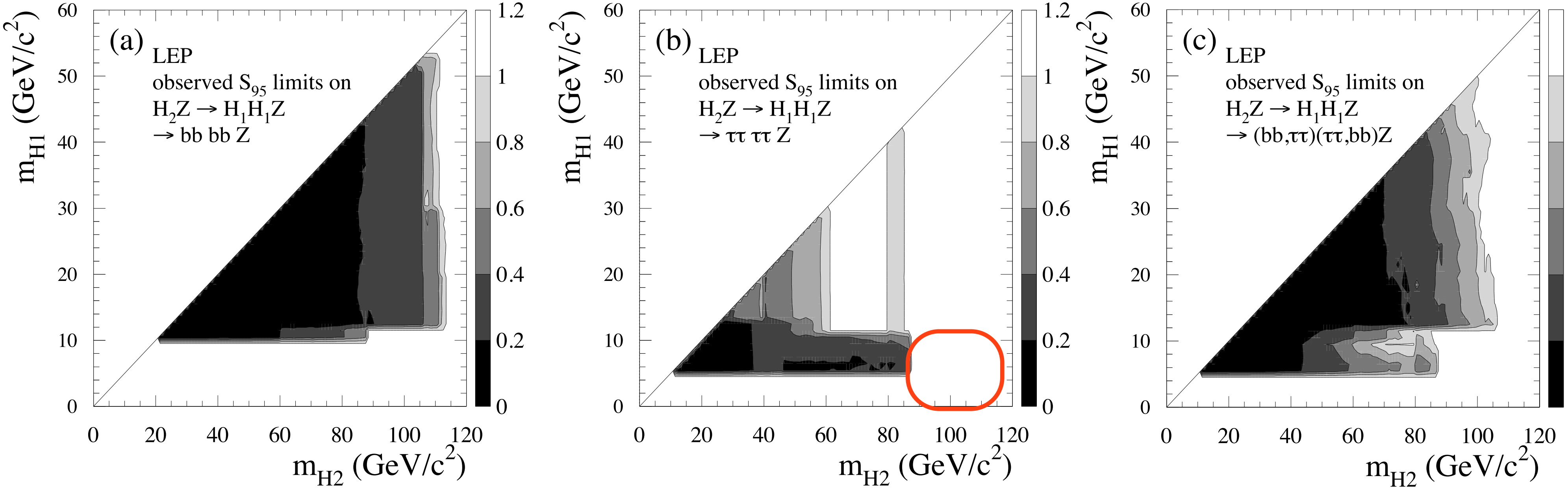
If the Higgs exists and is light, how could we have missed it at LEP?

- if the production cross-section were smaller than expected
  - this has direct implications on how the Higgs couples to the Z and it's role in EWSB
- or maybe it decayed into something exotic that the standard analysis missed
  - Is that difficult to achieve? No, the Hbb coupling is quite small. It doesn't take much for a new decay mode to dominate the bb mode.
- would the existing analyses have seen it?
  - that depends, in some cases the existing searches may still be quite efficient.

LEP Higgs limits in H1, H2 plane

Search for Neutral MSSM Higgs Bosons at LEP

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP Working Group for Higgs Boson Searches[1]



(factor x SM cross section that corresponds to 95% exclusion)

Here we see that Higgs bosons produced via Higgsstrahlung decaying to 4b are highly constrained

- 4τ are less constrained with a notable hole for $m_h > 85$ & $2m_\tau < m_a < 10\,\mathrm{GeV}$

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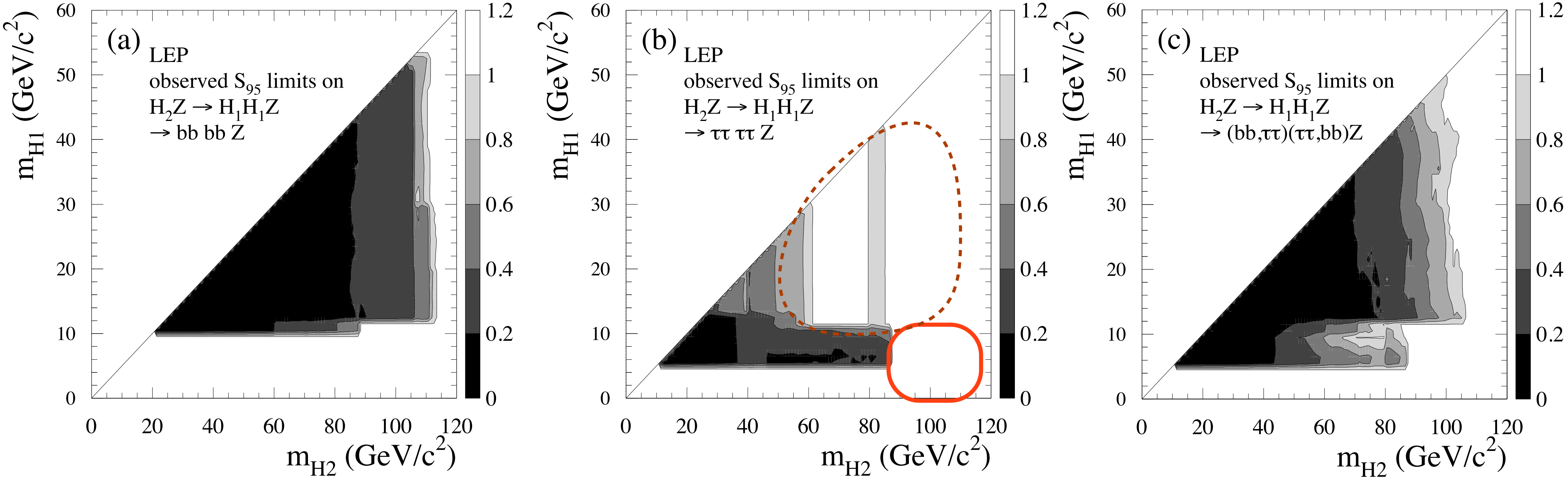

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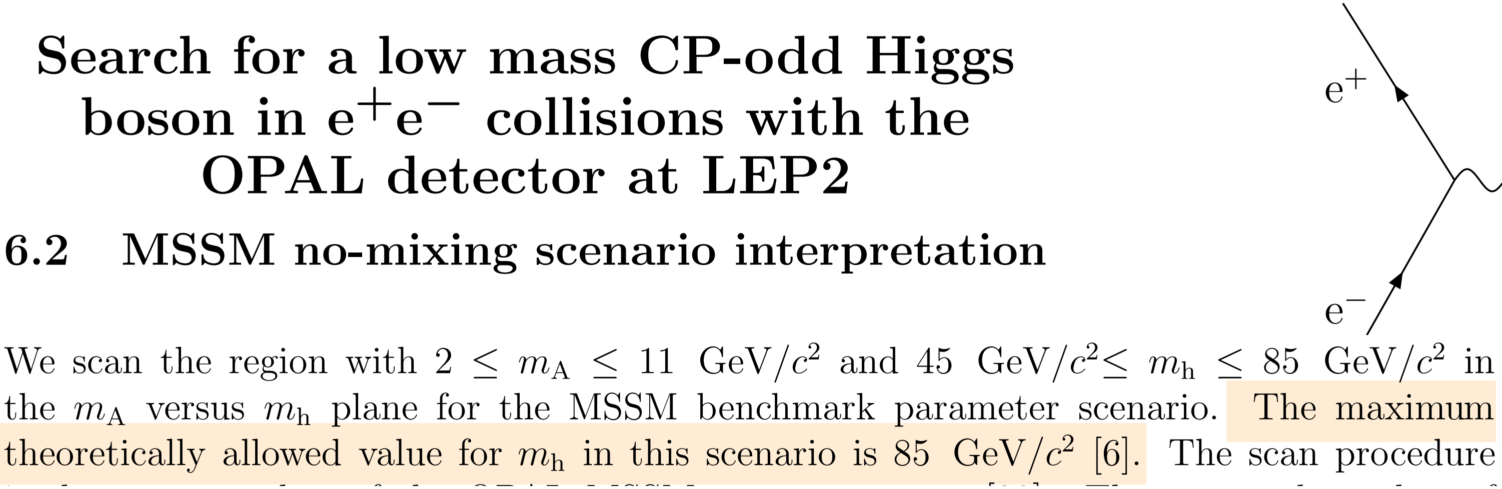
OPAL low A-mass search (a parable)

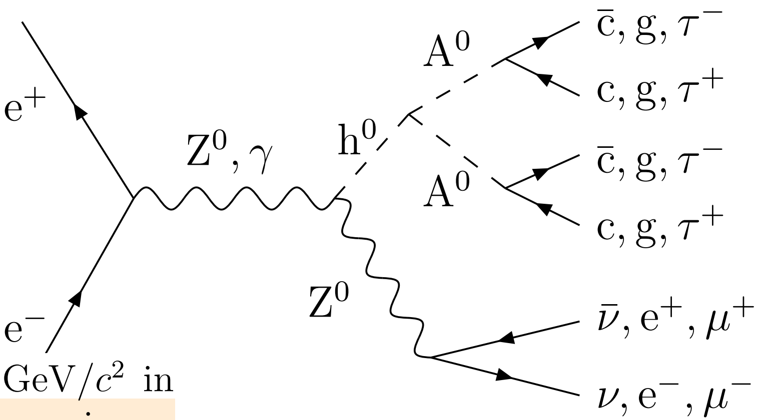
OPAL also carried out a searches in the region $2m_\tau < m_a < 10\,\mathrm{GeV}$

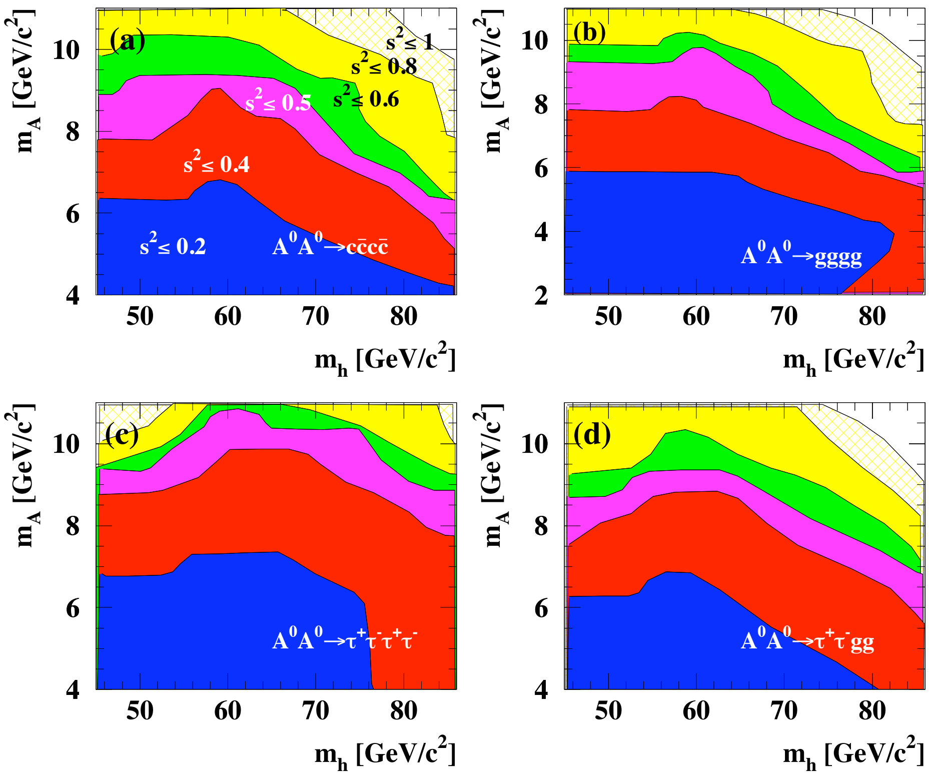


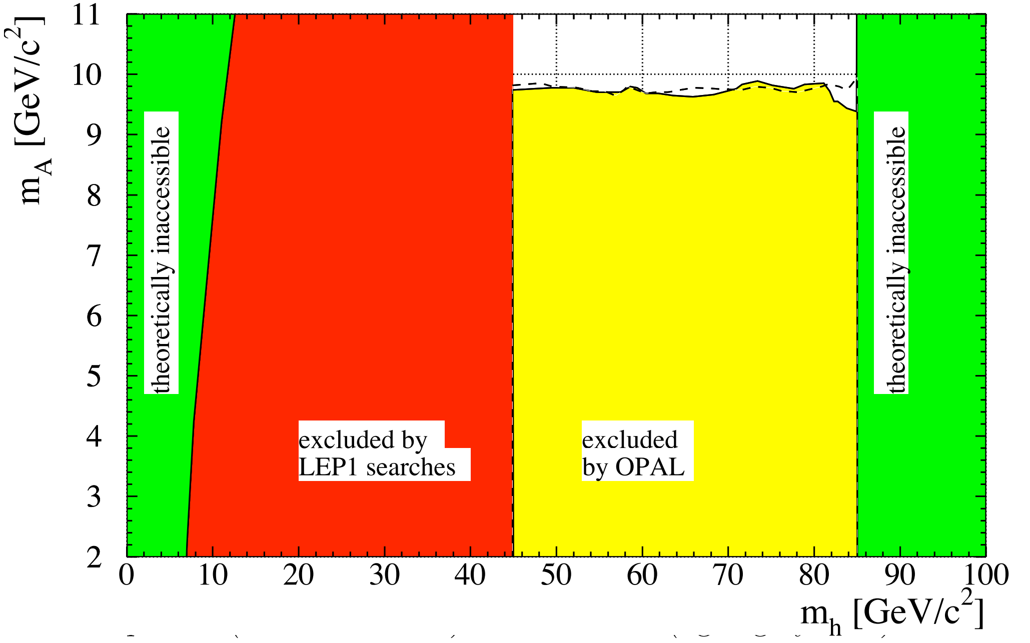
Search for a low mass CP-odd Higgs boson in e^+e^- collisions with the OPAL detector at LEP2

6.2 MSSM no-mixing scenario interpretation

We scan the region with $2 \leq m_A \leq 11$ GeV/c^2 and 45 GeV/$c^2 \leq m_h \leq 85$ GeV/c^2 in the m_A versus m_h plane for the MSSM benchmark parameter scenario. The maximum theoretically allowed value for m_h in this scenario is 85 GeV/c^2 [6]. The scan procedure







95% CL in the m_A versus m_h plane for the MSSM no-mixing benchmark

Other motivations for a light a

The searches above were done with a 2 higgs doublet model in mind

- the same search is also sensitive to a wide range of theories with extended Higgs sectors
  - probably the most useful prototype is the next-to-minimal SSM, in which the MSSM is extended with an additional singlet superfield $\hat{S}$
    - the scalar part naturally acquires a vev. and can provide a dynamical explanation for the size of the μ term.
    - this gives rise to a (mostly singlet) CP-odd scalar boson a
    - approximate accidental symmetries (à la Peccei-Quinn or when trilinear couplings vanish) can give a mechanism to make the a light
  - in addition, Hooper and Tait have considered similar scenarios in the context of the PAMELA excess

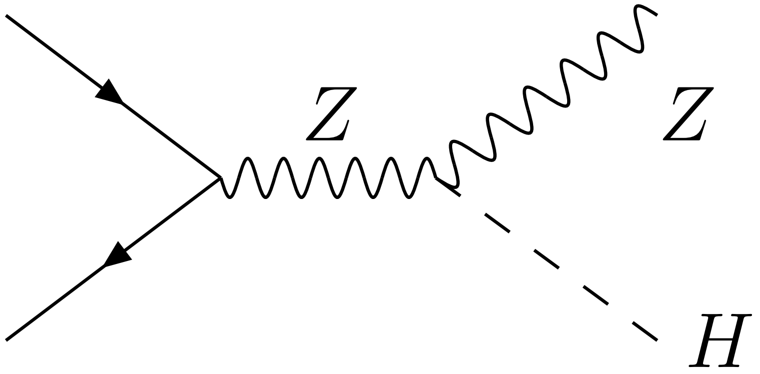
Here we are taking a very model independent attitude, and just look for all the uncovered $h \to aa \to X$ scenarios that are not already ruled out and which are kinematically feasible

- in particular, we are also interested in looking for mixed decays that may not be expected if the a is a pseudo-scalar.

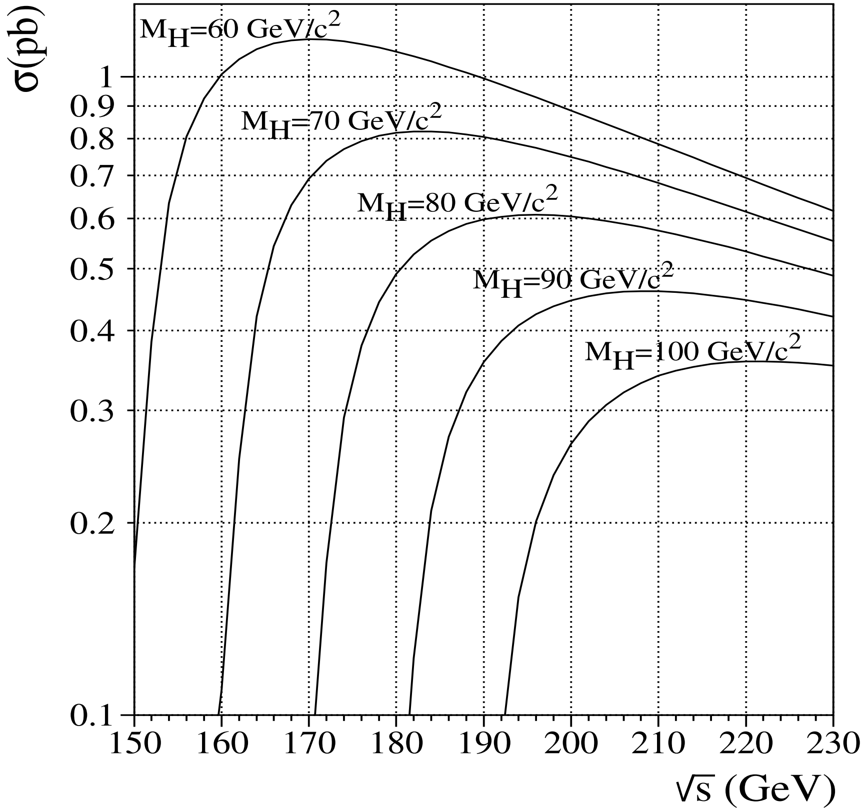
Planned searches

We're mainly interested in looking for **standard production** and **exotic decays**, thus expect to present result as 90/95% confidence limit on:

$$\xi^2 = \frac{\sigma\, \mathrm{BR}(h \to aa)\, \mathrm{BR}(a \to XX)\, \mathrm{BR}(a \to YY)\, (2 - \delta_{XY})}{\sigma_{SM}}$$



$e^+e^- \to$ H Z



particularly for:

$$e^+e^- \to Zh \to Z + 4\tau$$

focus today

$$e^+e^- \to Zh \to Z + 2\mu 2\tau$$
$$e^+e^- \to Zh \to Z + 4\mu$$

some progress

$$e^+e^- \to Zh \to Z + (\mu\mu/\tau\tau) q\bar{q}$$
$$e^+e^- \to Zh \to Z + (\mu\mu/\tau\tau) gg$$

$$e^+e^- \to ah \to 6\mu$$
$$e^+e^- \to ah \to 6\tau$$

suggested here at GGI

(need to check on limits for electron modes)

$H \to aa \to 2\mu 2\tau$ at the Tevatron

FERMILAB-PUB-09-257-E

Search for NMSSM Higgs bosons in the $h\to aa\to\mu\mu\ \mu\mu$, $\mu\mu\ \tau\tau$ channels using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

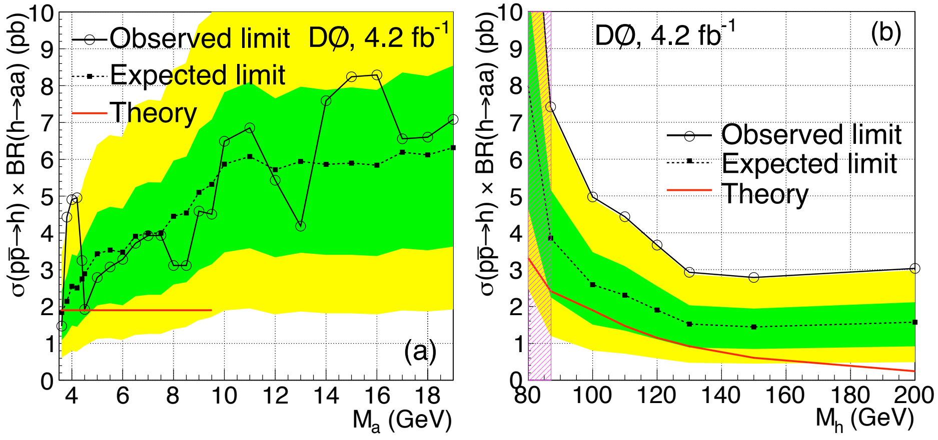


FIG. 3: The expected and observed limits and ±1 s.d. and ±2 s.d. expected limit bands for $\sigma(p\bar{p}\to h+X)\times\text{BR}(h\to aa)$, for (a) M_h=100 GeV and (b) M_a=4 GeV. The signal for BR$(h\to aa)$=1 is shown by the solid line. The region M_h<86 GeV is excluded by LEP.

M_a (GeV)	$\sigma\times$BR [exp] obs (fb)
0.2143	[10.0] 10.0
0.3	[9.5] 9.5
0.5	[7.3] 7.3
1	[6.1] 6.1
3	[5.6] 5.6

Sample	$\sigma\times 2\times$BR
Data	
M_a=3.6 GeV	[23.8] 19.1 fb
M_a=4 GeV	[23.9] 45.9 fb
M_a=7 GeV	[25.0] 24.6 fb
M_a=10 GeV	[24.7] 27.3 fb
M_a=19 GeV	[30.0] 33.7 fb

Andy Haas and company collaborated with Wacker and Lisanti to look for these signatures at the Tevatron

Discovering the Higgs with Low Mass Muon Pairs

Mariangela Lisanti and Jay G. Wacker[1]

[1] *SLAC, Stanford University, Menlo Park, CA 94025*
Physics Department, Stanford University, Stanford, CA 94305

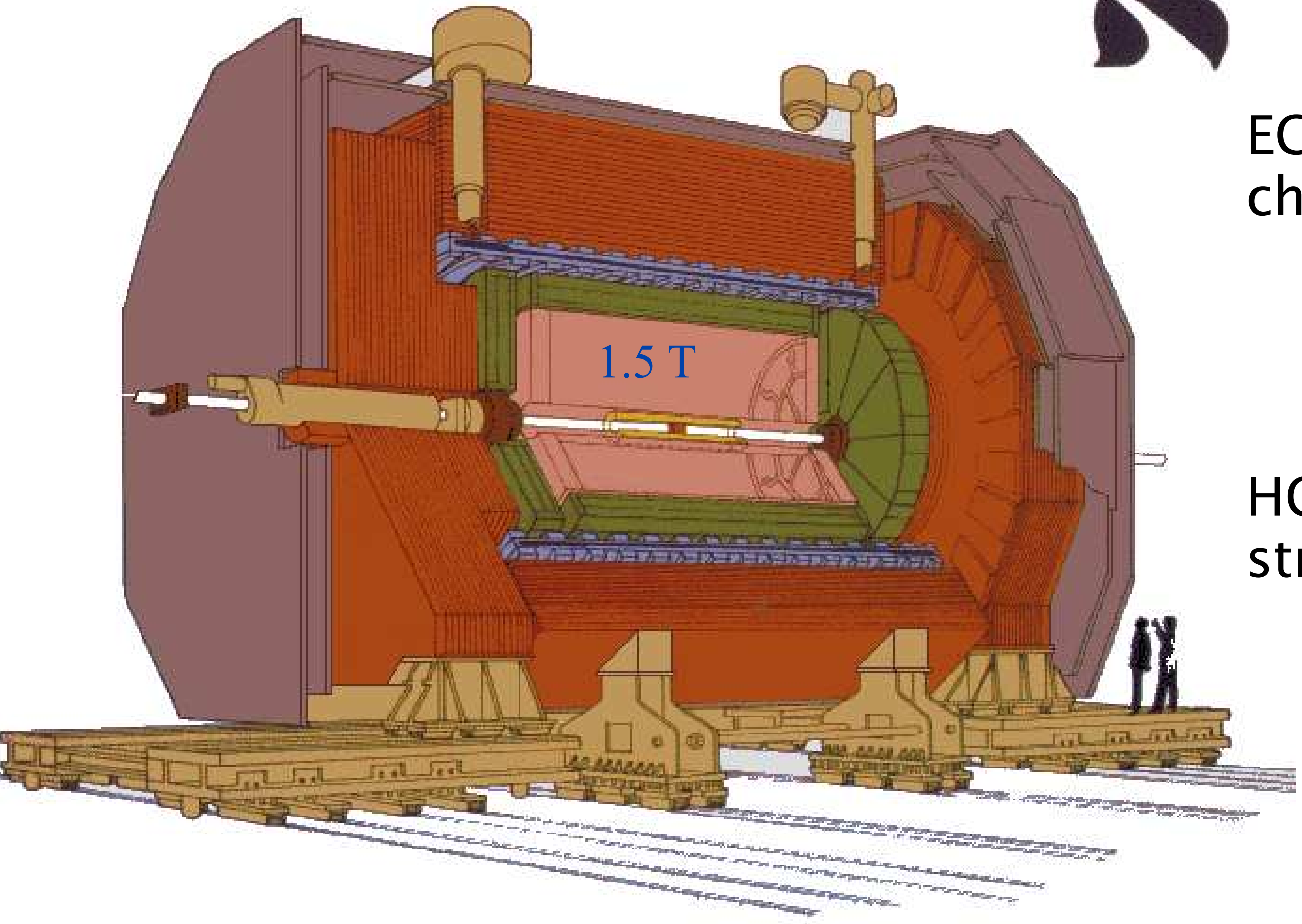
(Dated: March 8, 2009)

These searches are probing ~1% of the expected production cross-section.

- there are not enough signal events at LEP to compete

However, the 4τ signature is significantly more difficult at hadron colliders than at

The ALEPH detector



Tracking: silicon + large time projection chamber (~31 hits)

$$\frac{\Delta 1/p_T}{1/p_T} = (6\cdot 10^{-4} \oplus 5\cdot 10^{-3}/p_T)$$

ECAL: lead + proportional wire chambers, 22X_0

$$\frac{\Delta E}{E} = 0.18/\sqrt{E}$$

HCAL: 23 layers of iron yolk + streamer tubes

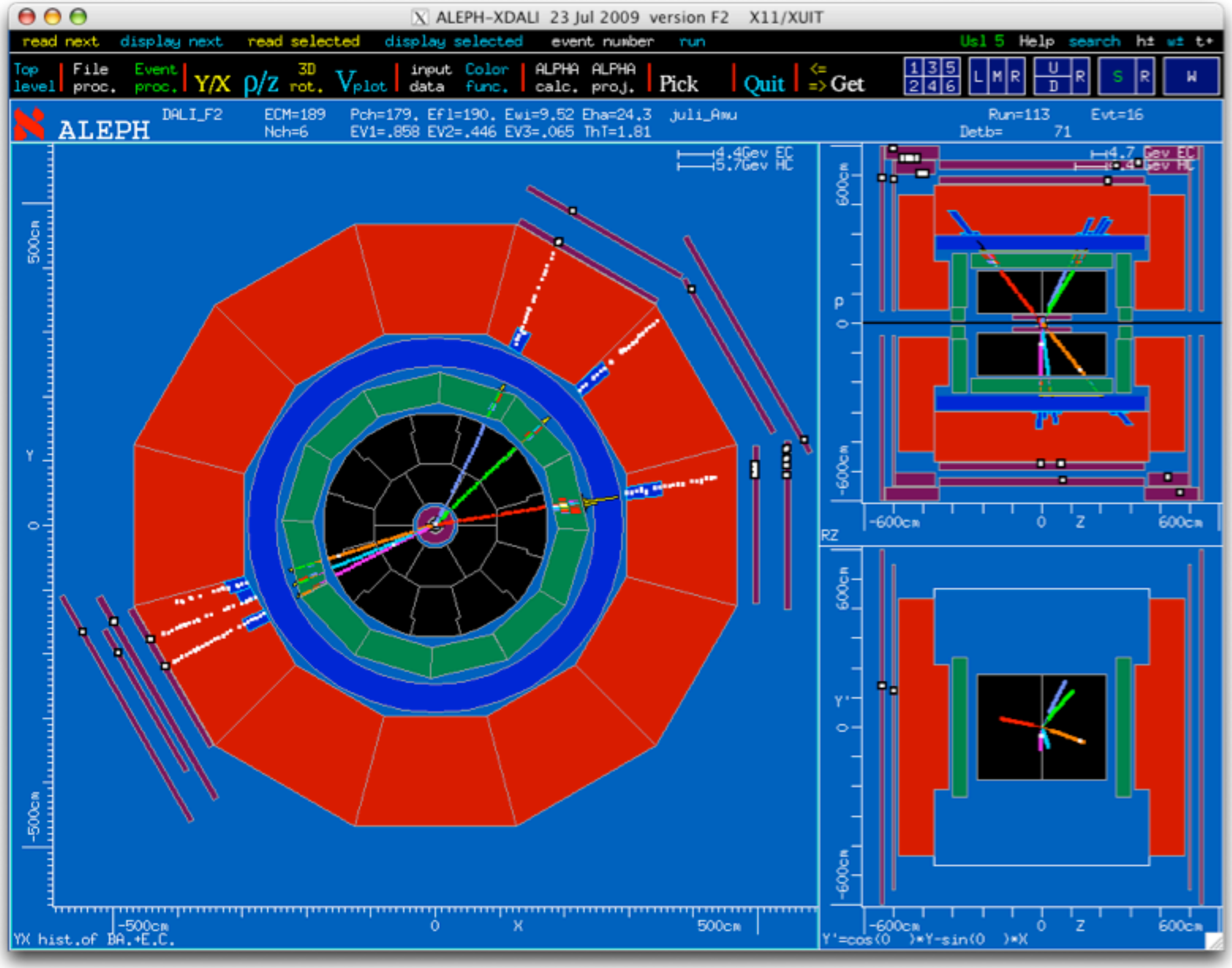
$$\frac{\Delta E}{E} = 0.85/\sqrt{E}$$

muons identified via HCAL +2 muon chambers

Detector simulation based on Geant 3, analysis based on 10 year old fortran framework

Simulated signal event $e^+e^- \to ZH \to 6\mu$

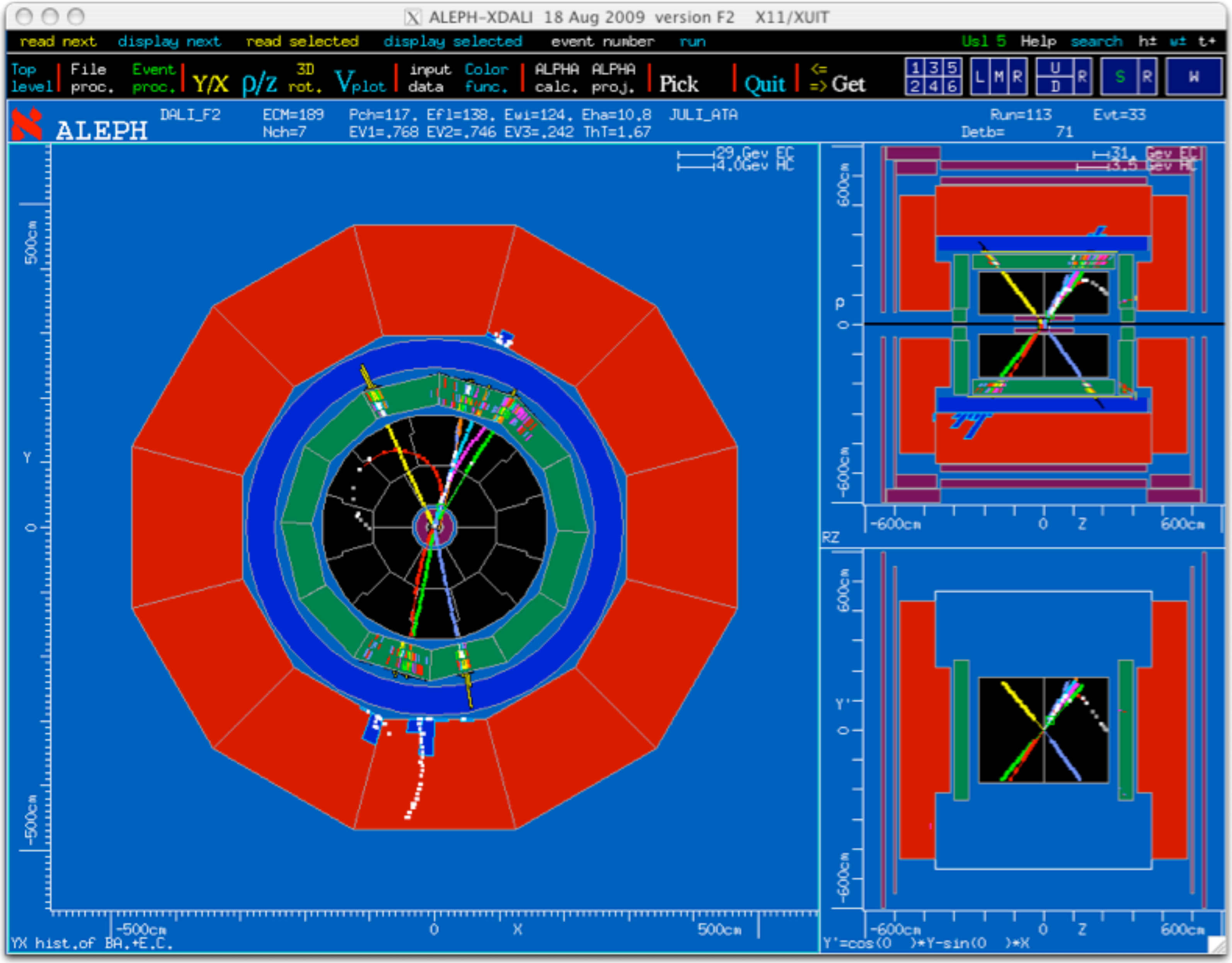
Signal's generated with HZHA03 (using generic 2HDM) and run through full GEANT3 simulation, ALEPH reconstruction, and analysis chain (it's so clean! I love e^+e^-)



```
DALI_F2   ECM=189   Pch=179. Efl=190. Ewi=9.52 Eha=24.3   juli_Amu            Run=113      Evt=16
          Nch=6     EV1=.858 EV2=.446 EV3=.065 ThT=1.81                        Detb=       71
```

Simulated signal event $e^+e^- \to ZH \to 2e4\tau$

2 back-to-back electrons clearly distinguished from 2 back-to-back jets.
not much else in the event (about 50 GeV of missing energy)



A Tevatron event, for comparison

Clearly the hadron colliders are more challenging

- lots of tracks, lots of hadronic energy deposits

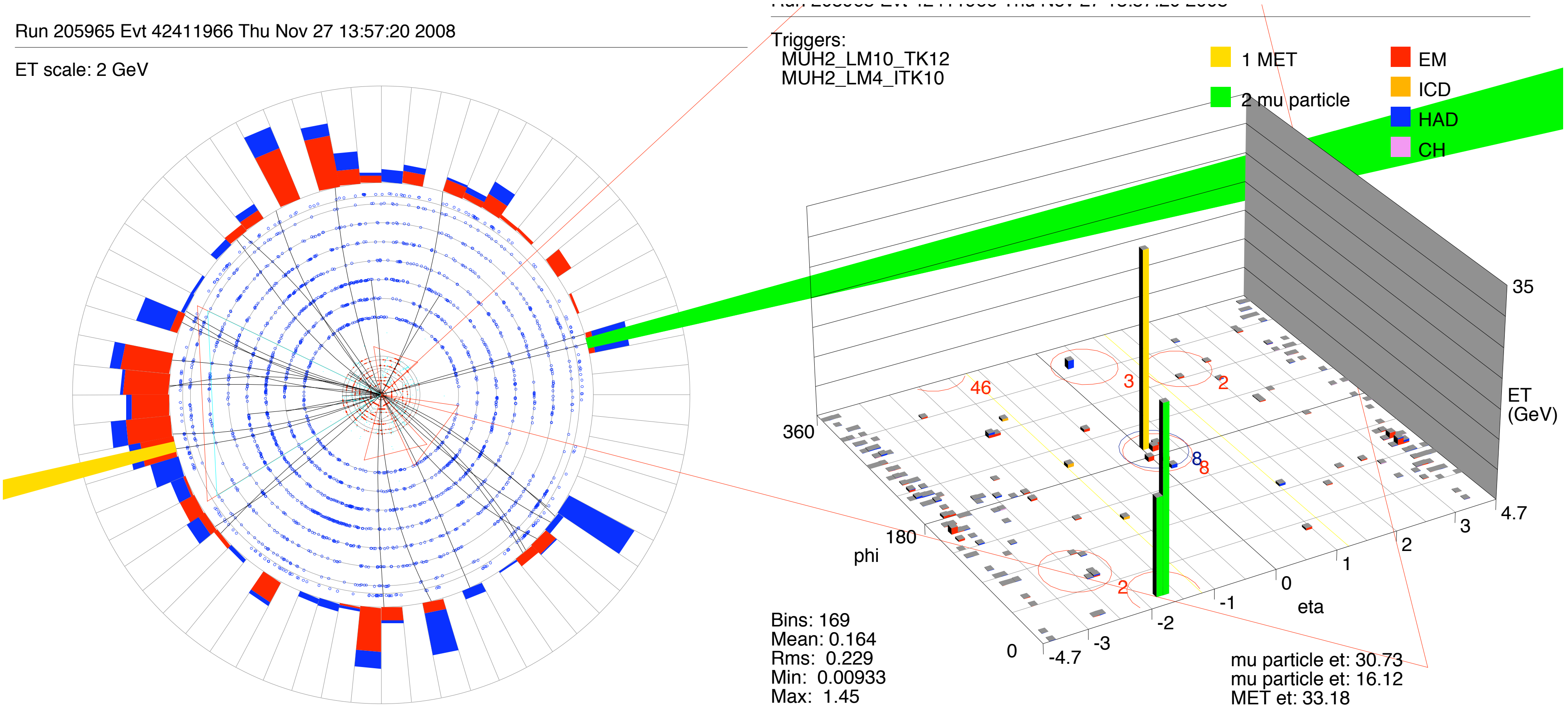
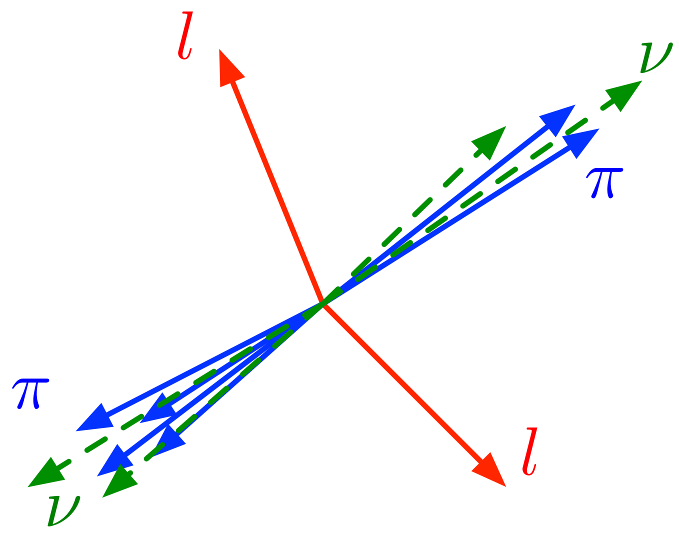


FIG. 6: Views of an event in data passing all the final “$\not\!\!E_T$” selections for the $2\mu 2\tau$ channel.

Higgs Mass reconstruction in $2l4\tau$ events

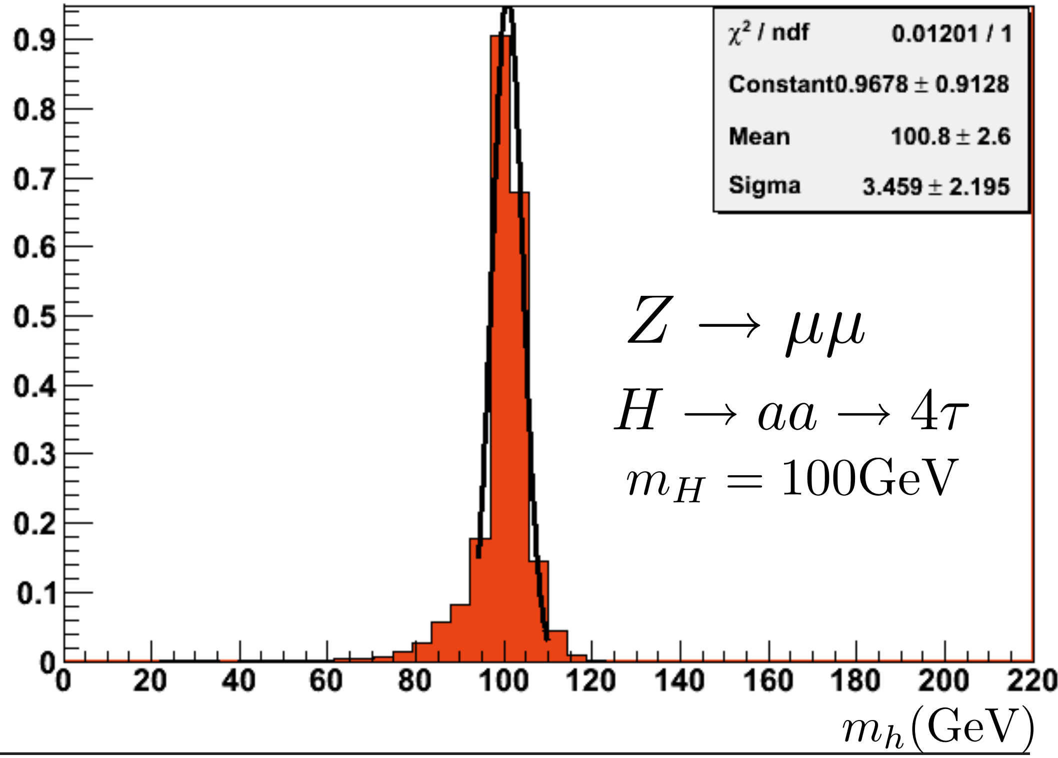
Even without resorting to the collinear approximation used for $H \rightarrow \tau\tau$ at the LHC, it is possible to reconstruct the Higgs mass

- because it's e^+e^- have the full 4-vector for the neutrino system



In the $Z \rightarrow \nu\nu$ channel, we do not have enough constraints to reconstruct the Higgs

- though several variables are sensitive to m_h



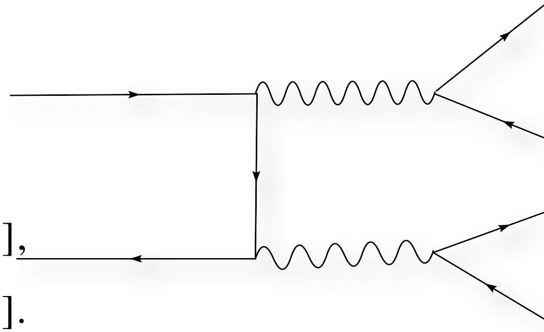
Monte Carlo Simulation

After decades of running in a very clean environment, and tuning Monte Carlo to data the description of standard model processes in ALEPH is excellent.

q$\bar{\text{q}}$	The process $e^+e^- \rightarrow Z/\gamma^* \rightarrow q\bar{q}(\gamma)$ is modeled using `KK` 4.14 [67], with initial state radiation from `KK` and final state radiation from PYTHIA.
e^+e^-	Bhabha scattering and $e^+e^- \rightarrow Z/\gamma^* \rightarrow e^+e^-(\gamma)$ is modeled using `BHWIDE` 1.01 [68].
$\mu^+\mu^-$	Pair production of muons, $e^+e^- \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-(\gamma)$, is calculated using `KK` 4.14 [67], including initial and final state radiative corrections and their interference.
$\tau^+\tau^-$	Pair production of taus, $e^+e^- \rightarrow Z/\gamma^* \rightarrow \tau^+\tau^-(\gamma)$, is calculated using `KK` 4.14 [67], including initial and final state radiative corrections and their interference.
1ph	Single photon production, $e^+e^- \rightarrow Z/\gamma^* \rightarrow \nu\bar{\nu}(\gamma)$, is included in the background estimate.
Nph	Multiphoton production, $e^+e^- \rightarrow n\gamma$, with $n \geq 2$, is included in the background estimate.

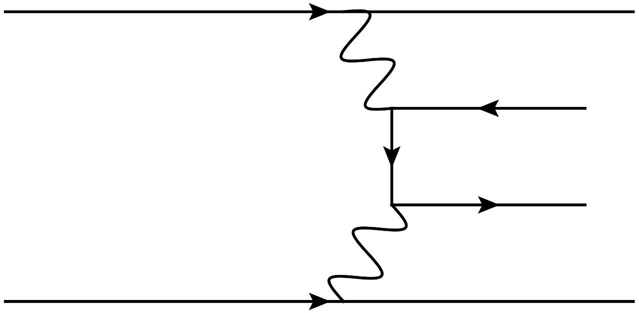
Monte Carlo

Two particularly important processes for these searches are 4 fermion and 2 photon processes

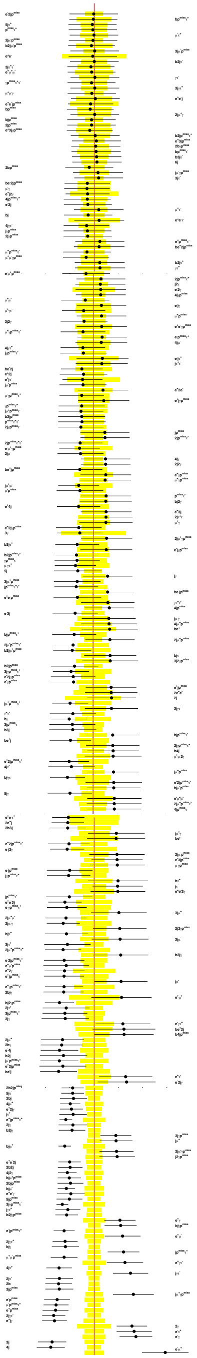


4f Four fermion events compatible with WW final states are generated using `KoralW` 1.51 [69], with quarks fragmented into parton showers and hadronized using either `PYTHIA` 6.1 [38]. Events with final states incompatible with WW production but compatible with ZZ production are generated with `KoralZ`

2ph Two-photon interaction processes, $\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}X$, are generated with the `PHOT02` generator [70]. When X is a pair of leptons, a QED calculation is used with preselection cuts to preferentially generate events that mimic WW production. When X is a multi-hadronic state, a modified version of `PYTHIA` is used to generate events with the incident beam electron and positron scattered at $\theta < 12^\circ$ and $168^\circ < \theta$, respectively. Events in which the beam electron or positron is scattered through an angle of more than 12° are generated using `HERWIG` 6.2 [39].

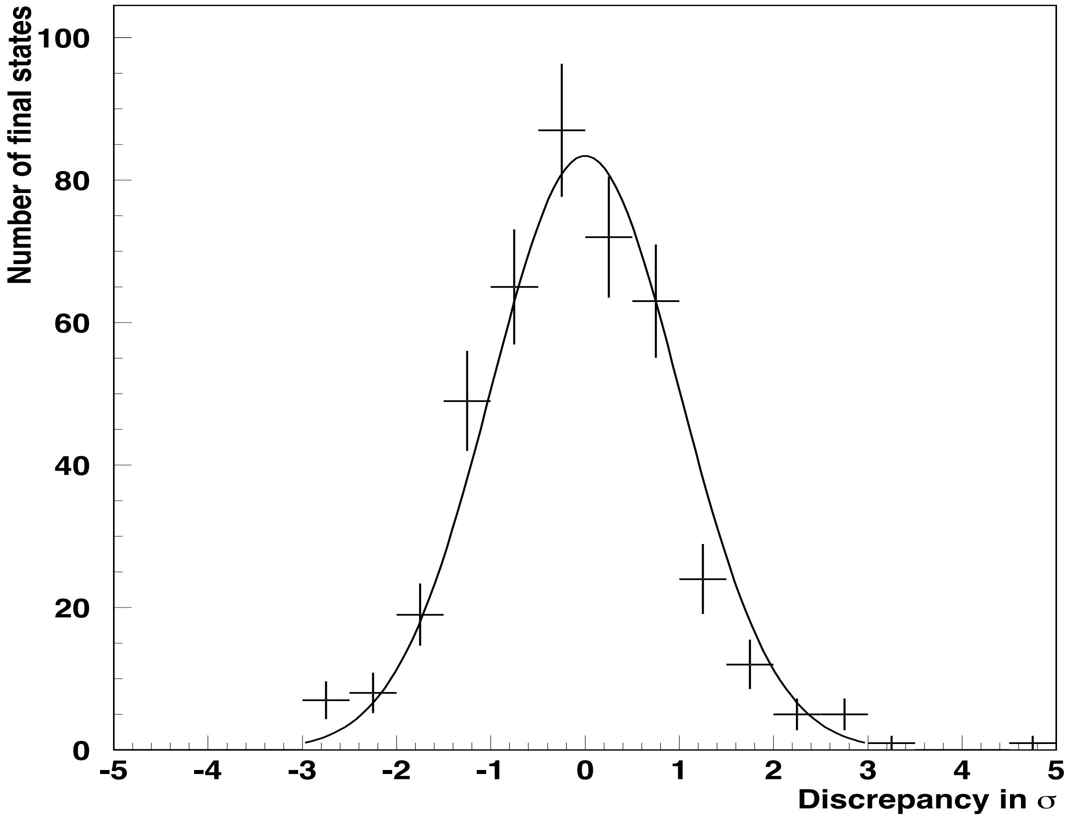


A side note



In 2005, I worked together with Bruce Knuteson to try his Quaero algorithm on ALEPH's LEP2 data

- we used these same Monte Carlo samples and compared predictions to several hundred final states.
- That analysis did NOT use full simulation of ALEPH detector, but still saw excellent agreement with SM.



Blind analysis

Because the LEP data is old and it is not possible to confirm anything with "next year's data", we had to be quite careful

- remember, we're shooting for a discovery!
- no one would believe a signal if we adjusted our cuts looking at data
  - Also, we don't want to spoil the other analyses that we might be interested in: $a \longrightarrow \mathrm{jets}, \mu, ..$

But we do need to verify that our Monte Carlo is describing the data well.

- So we did a blind blind analysis and defined 5 control samples

1. exclude m_{ll} around M_Z, that kills our signal, but otherwise similar
2. Select events if #tracks<2 for each jet (kills $\tau\tau, \mu\mu, q\bar{q}, gg$)
3. in $Z \rightarrow ll$ exclude events with $M(j_1, j_2, \mathrm{invisible}) > 60\mathrm{GeV}$
4. in $Z \rightarrow \nu\nu$ exclude events with missing mass > 80 GeV
5. exclude events with #track>6 in both jets (to remove taus) AND if di-jet mass > 60 (to avoid seeing $h \rightarrow aa \rightarrow q\bar{q}, gg$ if it exists)

Blind analysis

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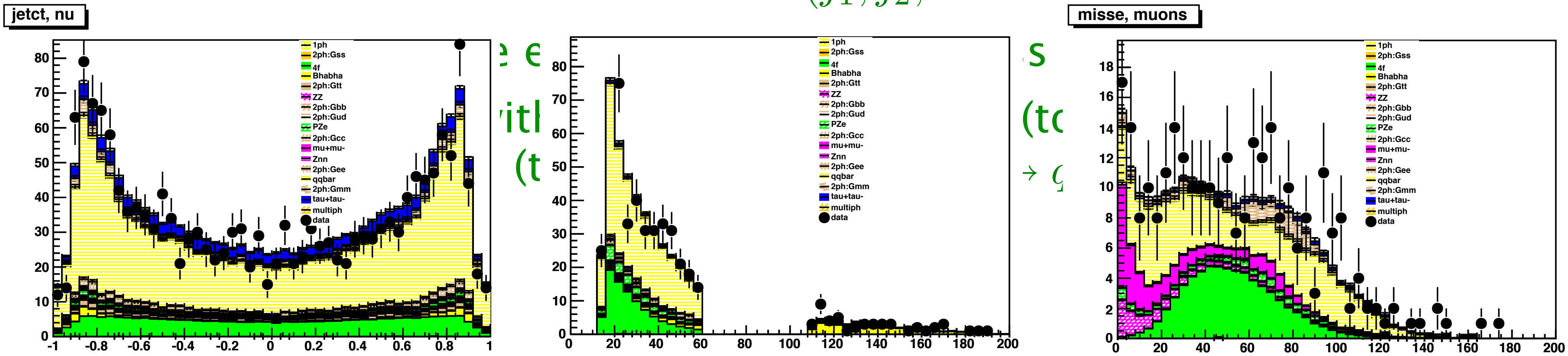


Choice of jet algorithms

At LEP, the dominant jet algorithms were DURHAM and JADE.

- both are iterative recombination type algorithms: merge if $m_{ij}^2/E_{tot}^2 < y_{cut}$
  - y_{cut} is an adjustable parameter and E_{tot} was often chosen to be the visible energy in the event
  - Often (as in the case of the OPAL analysis), events were “forced into N jets”, eg. the algorithm scanned y_{cut} until the event had exactly N jets.
    - Then that value of y_{cut} would be used as a discriminating variable together with the jet’s mass.
- DURHAM defines m_{ij}^2 in a way that is more robust to soft radiation, which is good if you are interested in bona fide hadronic showers.
  - But we are looking for a purely electroweak decay, so the straight invariant mass combination of JADE is more natural.
  - Furthermore, we know that we are interested in $m_a < 10\,\mathrm{GeV}$ which leads to an obvious choice for y_{cut} if we use a fixed E_{tot}.

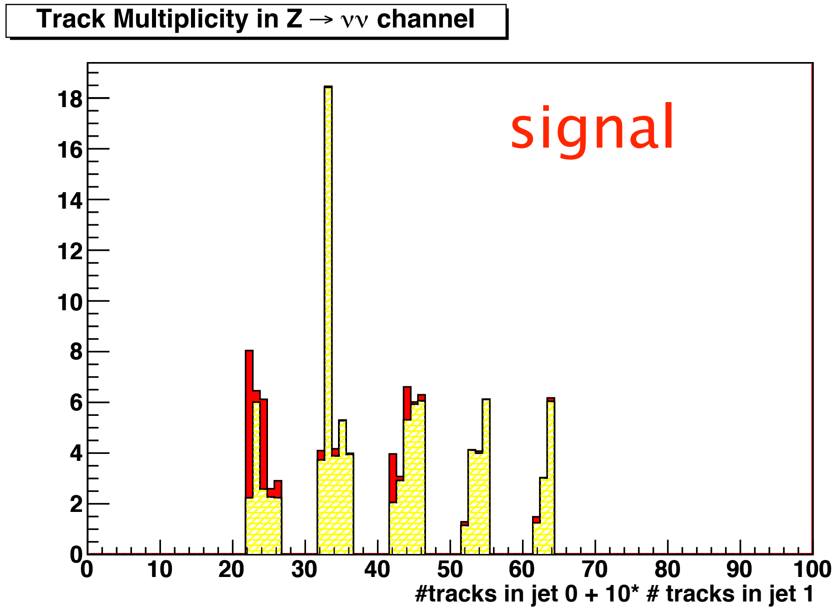
By choosing this approach our s/b was significantly higher than forcing to two jets with DURHAM and cutting on the jet mass

- Additionally we have track multiplicity in jets as a handle

Thumbnail of $Zh \to \nu\nu\, 4\tau$

This channel drives the analysis because of the larger Z branching ratio

- it is also the most difficult, because you don’t have a clean $Z \to ll$
- initially ask for exactly 2 jets with at least 2 tracks with $m_{jj} > 10\text{GeV}$
- to reject “2 photon” and beam bkg events $\cos\theta_{miss} < 0.97$, $E_{vis} > 5\%\, E_{CM}$
- require large missing energy, missing mass, that the jets aren’t too forward, and remove events with very low aplanarity (unobserved initial state radiation in a 2->2 process with subsequent photon conversions or brehmsstrahlung)
- Finally, we have the track multiplicity distribution, which is very powerful at discriminating signal from background



After these cuts expect about 11 events from background

mainly 2ph and 4f

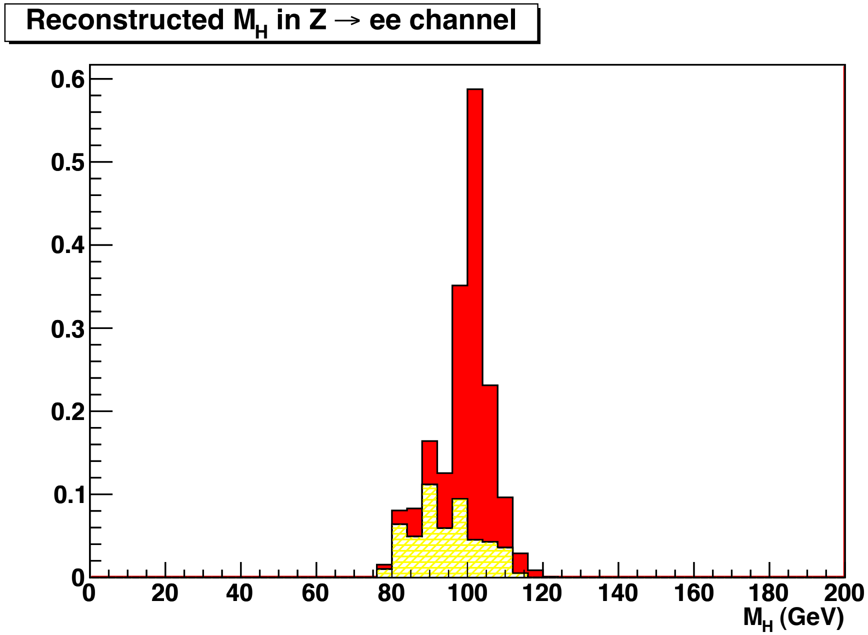
Total bg	11.01
1ph	0.13
2ph-Gss	0.49
4f	0.76
Bhabha	0.00
2ph-Gtt	0.24
ZZ	0.34
2ph-Gbb	0.06
2ph-Gud	4.32
PZe	0.10
2ph-Gcc	1.30
mu+mu-	0.00
Znn	0.01
2ph-Gee	0.00
qqbar	1.80
2ph-Gmm	0.00
tau+tau-	1.45
multiph	0.00

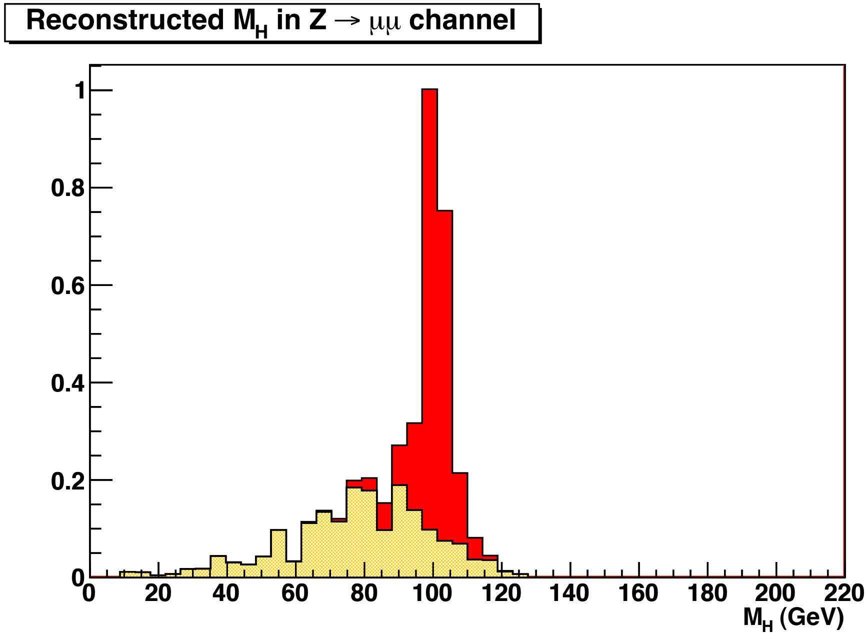
Thumbnail of $Zh \rightarrow ee\,4\tau$ & $Zh \rightarrow \mu\mu\,4\tau$

These channels are significantly cleaner due to the clear Z peak, but the signal rate is very low and signal efficiency is precious

- use standard ALEPH lepton ID
  - worked hard to improve Z mass reconstruction by adding appropriate photons to Z (more severe for electron channel)
  - electron channel suffers from Bhabha background, where we have 2 good electrons which produce brehmsstrahlung photons that convert to give 2 track “jets”
  - note, in OPAL analysis, the had a requirement on E_{vis}. Makes sense for jet channels, but it is not efficient for the tau channel, so we dropped it.
- again, we make no attempt to reconstruct taus, we just remove leptons and photons from the event, and run our JADE jet algorithm on remainder
  - again we use track multiplicity to focus the analysis on taus
  - we can also use the reconstructed Higgs mass to cut down on background

Expectations for a 100 GeV Higgs


Reconstructed M_H in $Z \to ee$ channel


Reconstructed M_H in $Z \to \mu\mu$ channel

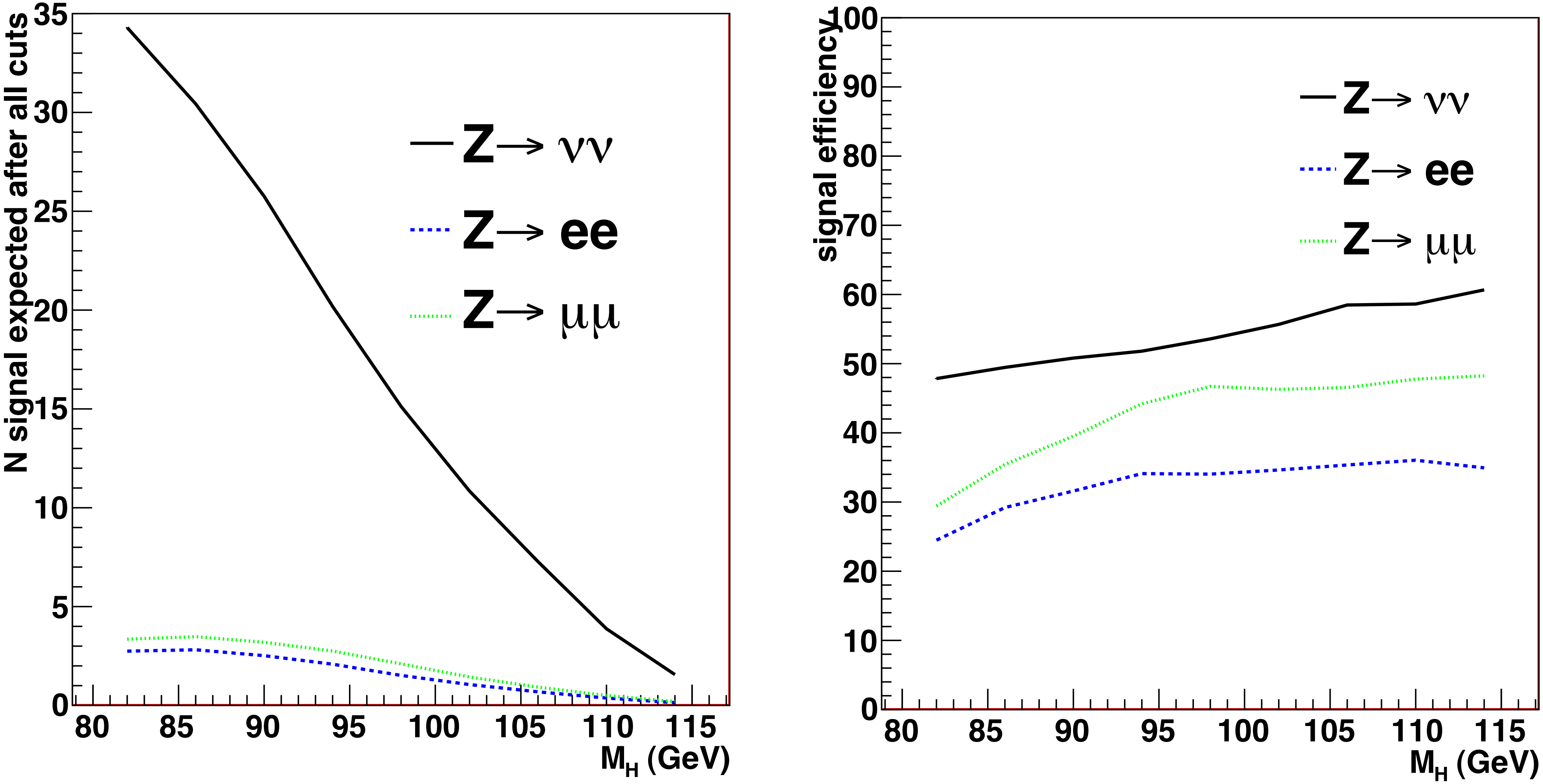
Background contributions for ee channel

Total bg	0.52
1ph	0.00
2ph-Gss	0.00
4f	0.05
Bhabha	0.23
2ph-Gtt	0.00
PZZ	0.04
KZZ	0.07
2ph-Gbb	0.00
2ph-Gud	0.00
PZe	0.01
2ph-Gcc	0.00
mu+mu-	0.00
Znn	0.00
2ph-Gee	0.00
qqbar	0.07
2ph-Gmm	0.00
tau+tau-	0.05
multiph	0.00

Expected yield and efficiency for $m_a = 4$ GeV

Our signal efficiency is pretty good, but clearly we have very few events in lepton channels

- but we also have almost no background in lepton channels

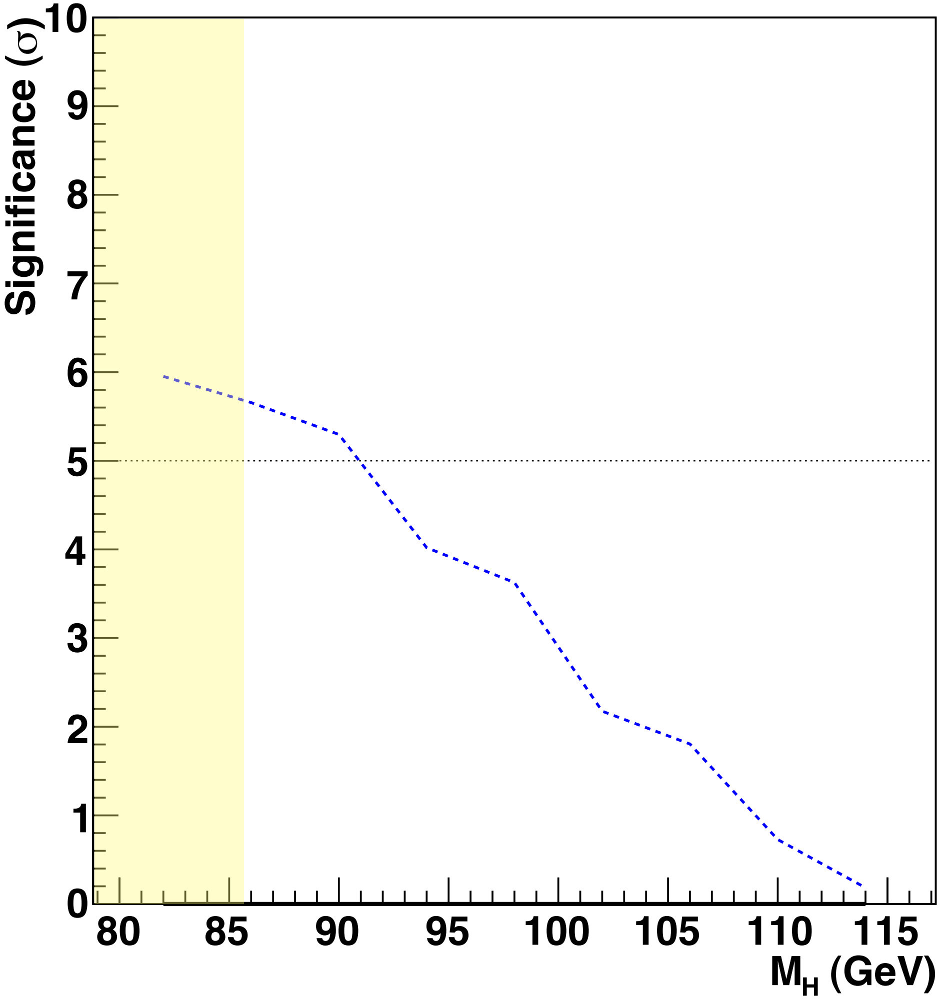


Expected significance @ m_a = 4, 10 GeV

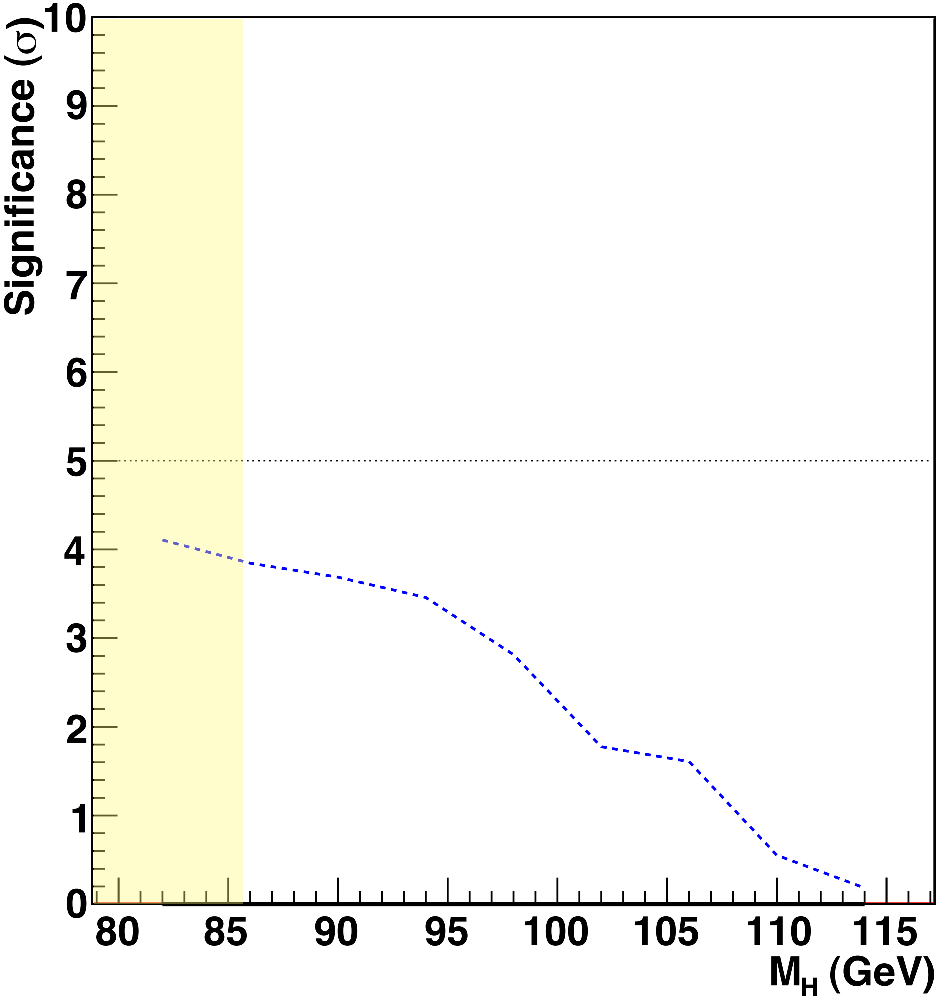
The final results are being considered as an ALEPH publication, so unfortunately I can’t show them to you, but here are the expected limits

- ALEPH has it’s 20th anniversary on Tuesday, results will be presented then, hopefully published soon after

expected discovery significance for $m_a = 4$ GeV



expected discovery significance for $m_a = 10$ GeV



“Unboxing” celebration

For what it’s worth: Our goal was not to just set a limit... certainly not a mediocre one. We saw we had discovery sensitivity early on, so we really went for a discovery.

- since the analysis was blind, we really didn’t know

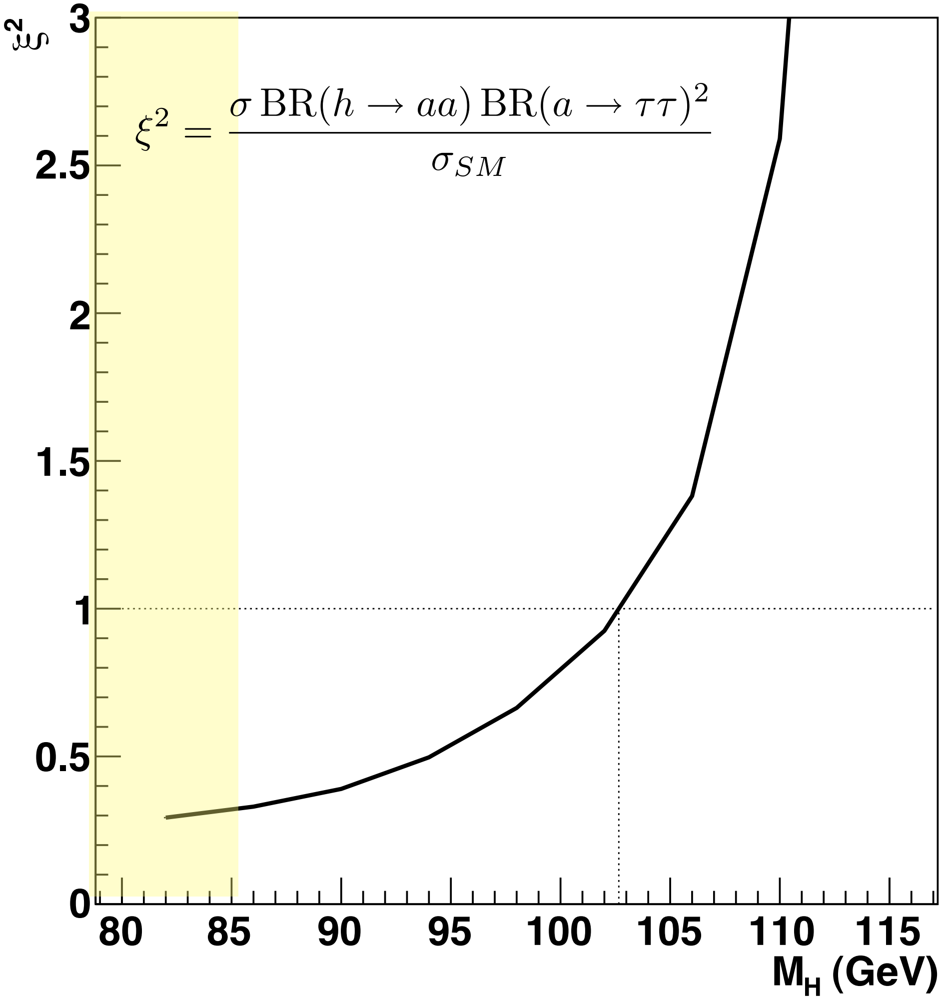
Champaign
(to be consumed regardless of result)

Expected limits @ m_a = 4,10 GeV

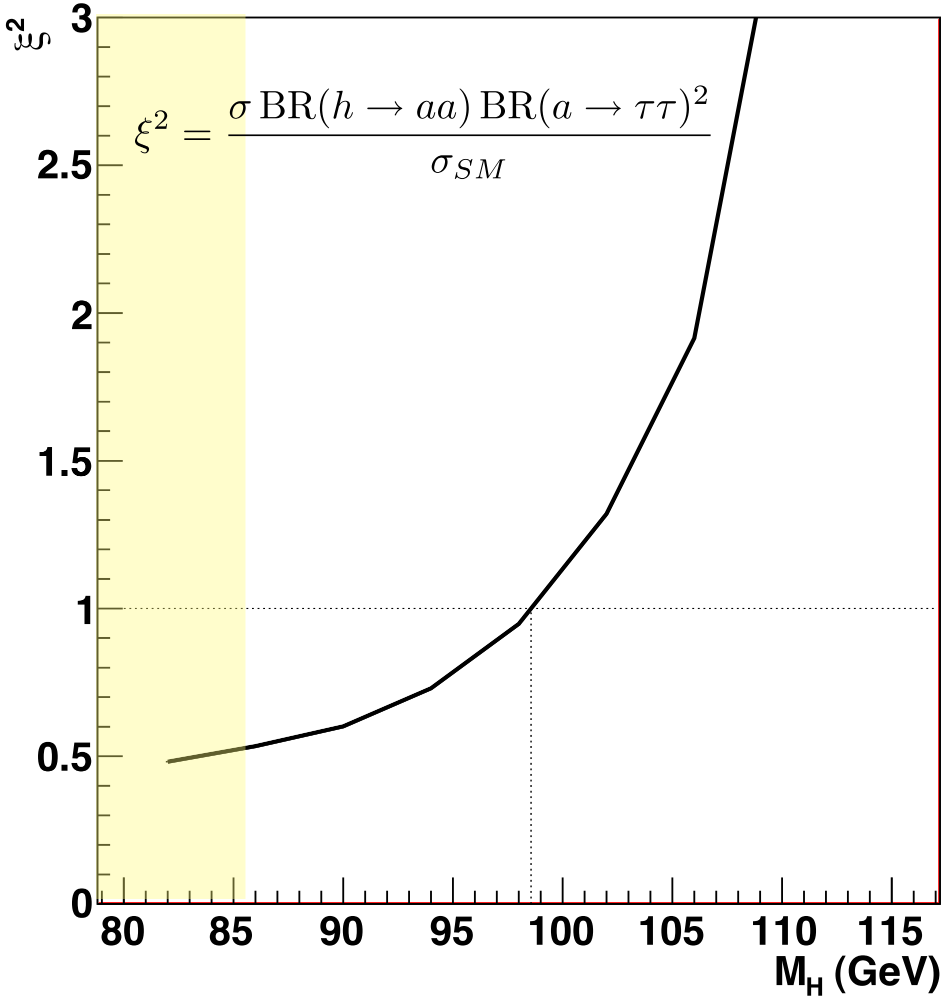
The final results are being considered as an ALEPH publication, so unfortunately I can't show them to you, but here are the expected limits

- ALEPH has it's 20th anniversary on Tuesday, results will be presented then, hopefully published soon after

expected limit for m_a = 4 GeV



expected limit for m_a = 10 GeV



Conclusions

After quite a bit of struggling, we have resurrected the ALEPH analysis engine (including the ability to produce Monte Carlo signal and simulate events in the ALEPH detector)

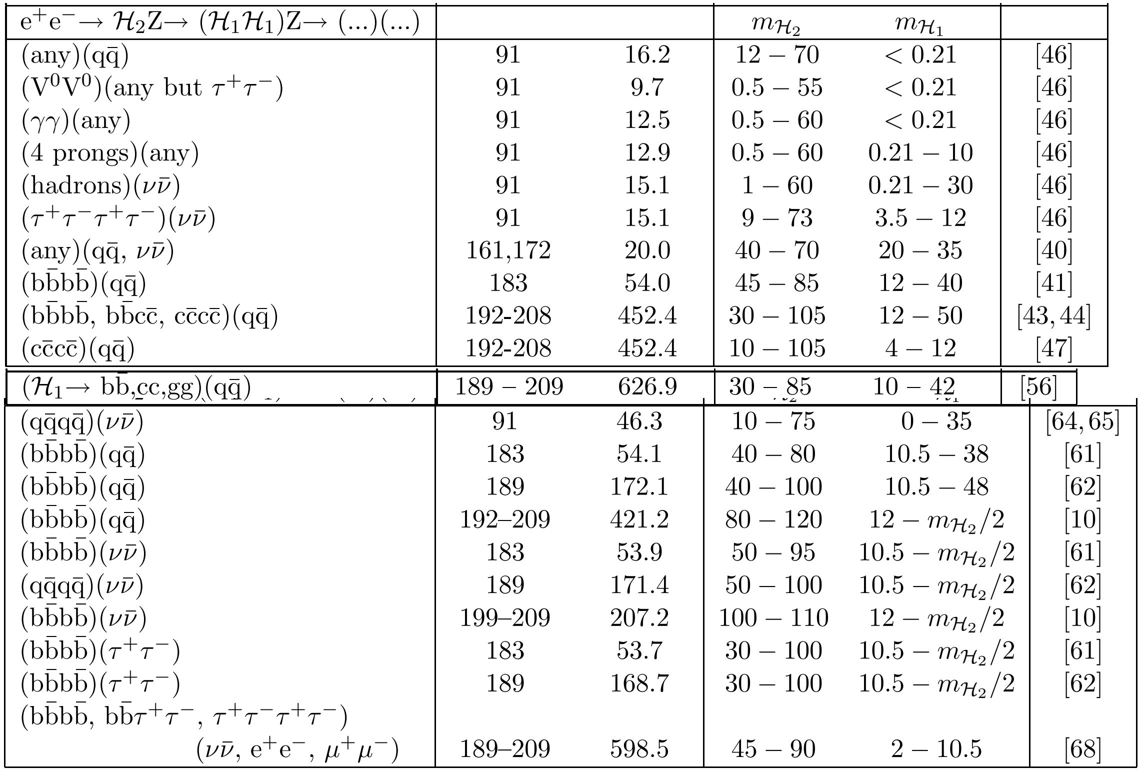
Our first analysis of $e^+e^- \rightarrow Zh \rightarrow (ee, \mu\mu, \nu\nu)\, 4\tau$ is essentially complete, and will extend the reach of the OPAL analysis

- we have sensitivity for a 5σ discovery up to ~90 GeV
- expected limits ($\xi^2 = 1$) are 99–103 GeV depending on m_a

We plan to continue to look at other exotic decays, and your input is welcome (though we have finite time)

- I'd like to thank Itay and James again for helping this project gain critical mass
- Hopefully there will be a new ALEPH paper soon!

Summary of similar LEP searches



$e^+e^- \rightarrow \mathcal{H}_2 Z \rightarrow (\mathcal{H}_1\mathcal{H}_1)Z \rightarrow (...)(...)$			$m_{\mathcal{H}_2}$	$m_{\mathcal{H}_1}$	
$(\text{any})(q\bar{q})$	91	16.2	$12-70$	< 0.21	[46]
$(V^0V^0)(\text{any but } \tau^+\tau^-)$	91	9.7	$0.5-55$	< 0.21	[46]
$(\gamma\gamma)(\text{any})$	91	12.5	$0.5-60$	< 0.21	[46]
(4 prongs)(any)	91	12.9	$0.5-60$	$0.21-10$	[46]
$(\text{hadrons})(\nu\bar{\nu})$	91	15.1	$1-60$	$0.21-30$	[46]
$(\tau^+\tau^-\tau^+\tau^-)(\nu\bar{\nu})$	91	15.1	$9-73$	$3.5-12$	[46]
$(\text{any})(q\bar{q}, \nu\bar{\nu})$	161,172	20.0	$40-70$	$20-35$	[40]
$(b\bar{b}b\bar{b})(q\bar{q})$	183	54.0	$45-85$	$12-40$	[41]
$(b\bar{b}b\bar{b},\ b\bar{b}c\bar{c},\ c\bar{c}c\bar{c})(q\bar{q})$	192-208	452.4	$30-105$	$12-50$	[43, 44]
$(c\bar{c}c\bar{c})(q\bar{q})$	192-208	452.4	$10-105$	$4-12$	[47]
$(\mathcal{H}_1 \rightarrow b\bar{b}, cc, gg)(q\bar{q})$	$189-209$	626.9	$30-85$	$10-42$	[56]
$(q\bar{q}q\bar{q})(\nu\bar{\nu})$	91	46.3	$10-75$	$0-35$	[64, 65]
$(b\bar{b}b\bar{b})(q\bar{q})$	183	54.1	$40-80$	$10.5-38$	[61]
$(b\bar{b}b\bar{b})(q\bar{q})$	189	172.1	$40-100$	$10.5-48$	[62]
$(b\bar{b}b\bar{b})(q\bar{q})$	192–209	421.2	$80-120$	$12-m_{\mathcal{H}_2}/2$	[10]
$(b\bar{b}b\bar{b})(\nu\bar{\nu})$	183	53.9	$50-95$	$10.5-m_{\mathcal{H}_2}/2$	[61]
$(q\bar{q}q\bar{q})(\nu\bar{\nu})$	189	171.4	$50-100$	$10.5-m_{\mathcal{H}_2}/2$	[62]
$(b\bar{b}b\bar{b})(\nu\bar{\nu})$	199–209	207.2	$100-110$	$12-m_{\mathcal{H}_2}/2$	[10]
$(b\bar{b}b\bar{b})(\tau^+\tau^-)$	183	53.7	$30-100$	$10.5-m_{\mathcal{H}_2}/2$	[61]
$(b\bar{b}b\bar{b})(\tau^+\tau^-)$	189	168.7	$30-100$	$10.5-m_{\mathcal{H}_2}/2$	[62]
$(b\bar{b}b\bar{b},\ b\bar{b}\tau^+\tau^-,\ \tau^+\tau^-\tau^+\tau^-)$ $(\nu\bar{\nu},\ e^+e^-,\ \mu^+\mu^-)$	189–209	598.5	$45-90$	$2-10.5$	[68]

[40] DELPHI Collaboration, P. Abreu et al., Eur. Phys. J. **C2** (1998) 1.

[41] DELPHI Collaboration, P. Abreu et al., Eur. Phys. J. **C10** (1999) 563.

[42] DELPHI Collaboration, P. Abreu et al., Eur. Phys. J. **C17** (2000) 187; [Addendum: Eur. Phys. J. **C17** (2000) 529].

[43] DELPHI Collaboration, J. Abdallah et al., Eur. Phys. J. **C32** (2004) 145.

[44] DELPHI Collaboration, J. Abdallah et al., Eur. Phys. J. **C23** (2002) 409.

[45] DELPHI Collaboration, J. Abdallah et al., Eur.Phys.J. **C44** (2005) 147.

[46] DELPHI 92-80 Dallas PHYS 191, *Neutral Higgs Bosons in a Two Doublet Model*, contribution to the 1992 ICHEP conference; quoted by G.Wormser, in proc. of the XXVI ICHEP conference (Dallas, August 1992), Vol. 2, pages 1309-14, ref. 4.

[47] DELPHI 2003-045-CONF-665, *DELPHI results on neutral Higgs bosons in MSSM benchmark scenarios*, contribution to the 2003 summer conferences.

[56] L3 Collaboration, P. Achard *et al.*, Phys. Lett. **B545** (2002) 30.

[60] OPAL Collaboration, K. Ackerstaff *et. al.*, Eur. Phys. J. **C5** (1998) 19.

[61] OPAL Collaboration, G. Abbiendi *et. al.*, Eur. Phys. J. **C7** (1999) 407.

[62] OPAL Collaboration, G. Abbiendi *et. al.*, Eur. Phys. J. **C12** (2000) 567.

[63] OPAL Collaboration, G.Abbiendi *et al.*, Eur. Phys. J. **C26** (2003) 479.

[64] OPAL Collaboration, G. Alexander *et. al.*, Z. Phys. **C73** (1997) 189.

[65] OPAL Collaboration, R. Akers *et. al.*, Z. Phys. **C64** (1994) 1.

[66] OPAL Collaboration, G. Abbiendi *et. al.*, Eur. Phys. J. **C18** (2001) 425.

[67] OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. **C40** (2005) 317.

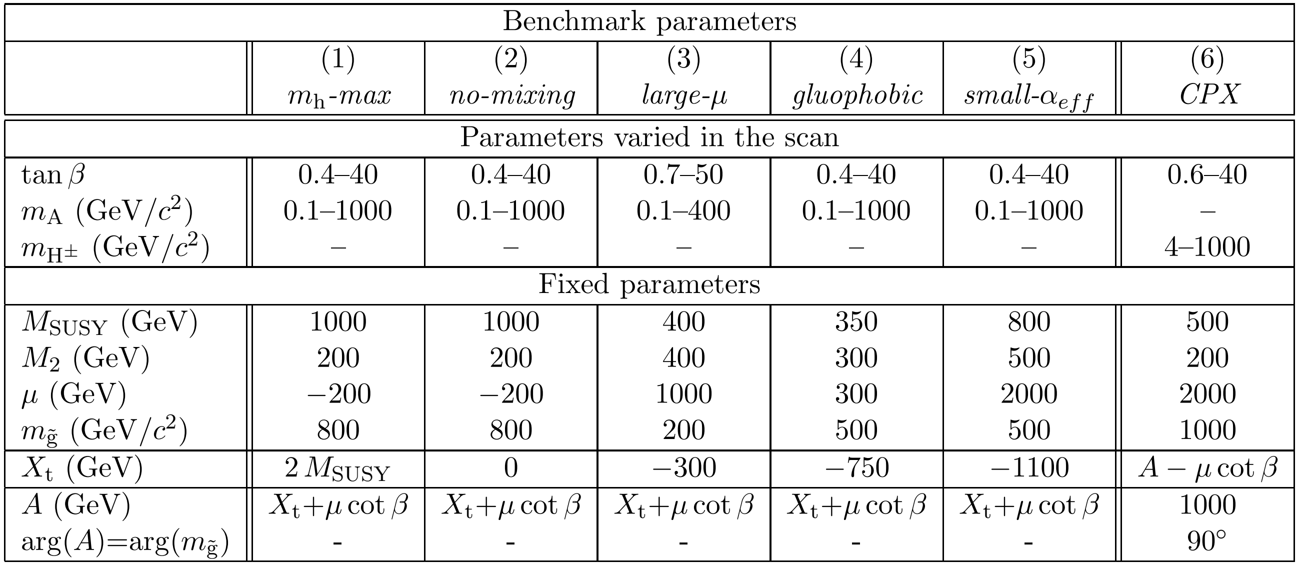
[68] OPAL Collaboration, G.Abbiendi *et al.*, Eur. Phys. J. **C27** (2003) 483.

$m_{\mathcal{H}_2}$(GeV/c^2)	$m_{\mathcal{H}_1}$(GeV/c^2)									
	10	15	20	25	30	35	40	45	50	55
20	0.020									
25	0.026									
30	0.037	0.046								
35	0.048	0.042								
40	0.053	0.056	0.051							
45	0.066	0.059	0.046							
50	0.087	0.058	0.048	0.049						
55	0.11	0.055	0.050	0.050						
60	0.29	0.103	0.094	0.094	0.053					
65	0.30	0.099	0.091	0.088	0.084					
70	0.25	0.098	0.097	0.095	0.083	0.059				
75	0.34	0.11	0.10	0.11	0.10	0.096				
80	0.39	0.13	0.14	0.14	0.13	0.12	0.13			
85	0.52	0.20	0.20	0.20	0.21	0.19	0.18			
90	≥ 1	0.23	0.23	0.23	0.27	0.26	0.24	0.28		
95	≥ 1	0.29	0.27	0.29	0.31	0.29	0.28	0.30		
100	≥ 1	0.30	0.29	0.31	0.30	0.27	0.28	0.29	0.29	
105	≥ 1	0.27	0.32	0.36	0.40	0.36	0.31	0.35	0.35	
110	≥ 1	0.44	0.54	0.55	0.96	0.97	≥ 1	≥ 1	0.89	≥ 1

Table 15: *The 95% CL upper bound, S_{95}, obtained for the normalised cross-section (see text) of the Higgsstrahlung cascade process* $e^+e^- \to (\mathcal{H}_2 \to \mathcal{H}_1\mathcal{H}_1)Z \to (b\bar{b}b\bar{b})Z$, *as a function of the Higgs boson masses* $m_{\mathcal{H}_1}$ *and* $m_{\mathcal{H}_2}$. *The numbers correspond to the contours shown in Figure 3 (a).*

	5	10	15	20	25	30	35	40	45
10	0.26								
15	0.033								
20	0.048	0.32							
25	0.070	0.076							
30	0.10	0.11	0.38						
35	0.18	0.19	0.51						
40	0.22	0.22	0.40	0.39					
45	0.30	0.31	0.49	0.49					
50	0.18	0.38	0.66	0.66	0.63				
55	0.18	0.37	0.68	0.69	0.68				
60	0.20	0.38	0.95	0.96	0.96	0.94			
65	0.20	0.38	≥ 1	≥ 1	≥ 1	≥ 1			
70	0.21	0.43	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1		
75	0.19	0.46	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1		
80	0.20	0.44	0.83	0.83	0.83	0.83	0.84	0.84	
85	0.25	0.56	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1	

Table 16: *The 95% CL upper bound, S_{95}, obtained for the normalised cross-section (see text) of the Higgsstrahlung cascade process* $e^+e^- \rightarrow (\mathcal{H}_2 \rightarrow \mathcal{H}_1\mathcal{H}_1)Z \rightarrow (\tau^+\tau^-\tau^+\tau^-)Z$*, as a function of the Higgs boson masses $m_{\mathcal{H}_1}$ and $m_{\mathcal{H}_2}$. The numbers correspond to the contours shown in Figure 3 (b).*



Benchmark parameters						
	(1) m_{h}-*max*	(2) *no-mixing*	(3) *large*-μ	(4) *gluophobic*	(5) *small*-α_{eff}	(6) *CPX*
Parameters varied in the scan						
$\tan\beta$	0.4–40	0.4–40	0.7–50	0.4–40	0.4–40	0.6–40
m_{A} (GeV/c^2)	0.1–1000	0.1–1000	0.1–400	0.1–1000	0.1–1000	–
$m_{\mathrm{H}^\pm}$ (GeV/c^2)	–	–	–	–	–	4–1000
Fixed parameters						
M_{SUSY} (GeV)	1000	1000	400	350	800	500
M_2 (GeV)	200	200	400	300	500	200
μ (GeV)	-200	-200	1000	300	2000	2000
$m_{\tilde{g}}$ (GeV/c^2)	800	800	200	500	500	1000
X_{t} (GeV)	$2\,M_{\mathrm{SUSY}}$	0	-300	-750	-1100	$A-\mu\cot\beta$
A (GeV)	$X_{\mathrm{t}}+\mu\cot\beta$	$X_{\mathrm{t}}+\mu\cot\beta$	$X_{\mathrm{t}}+\mu\cot\beta$	$X_{\mathrm{t}}+\mu\cot\beta$	$X_{\mathrm{t}}+\mu\cot\beta$	1000
arg(A)=arg($m_{\tilde{g}}$)	-	-	-	-	-	90°

mh-max results