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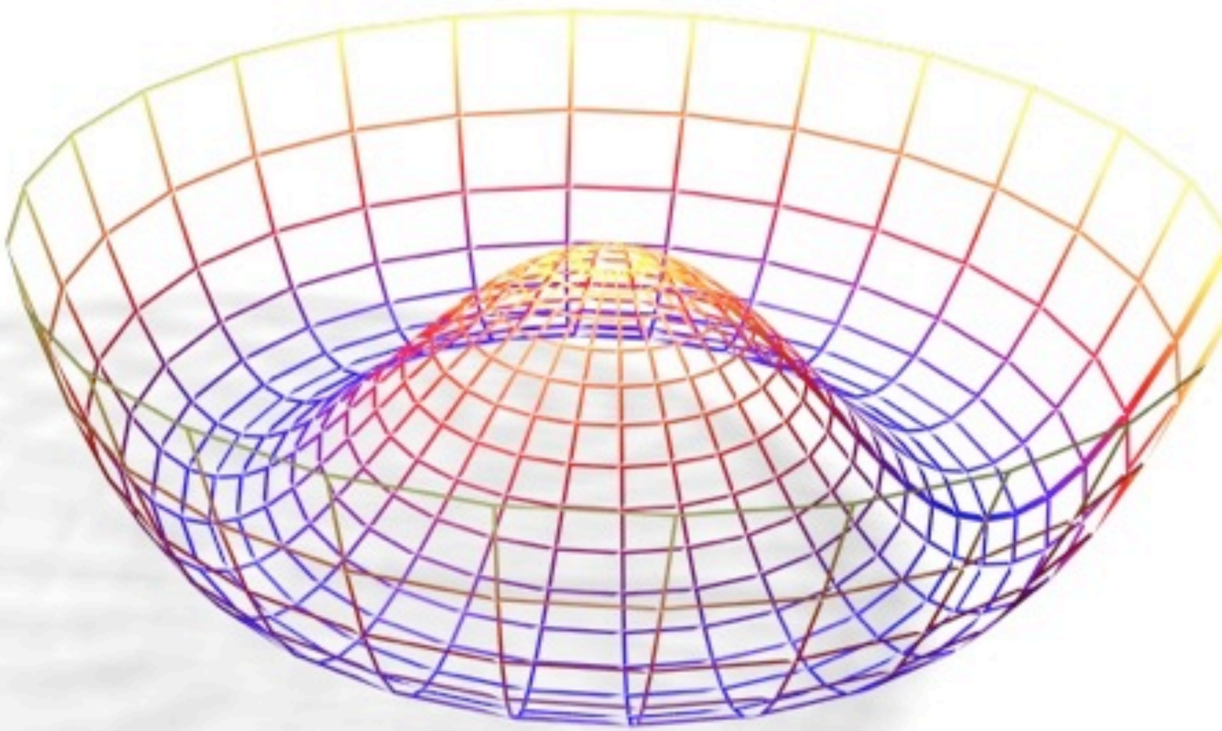
Searching for the Higgs in 10 year-old LEP data



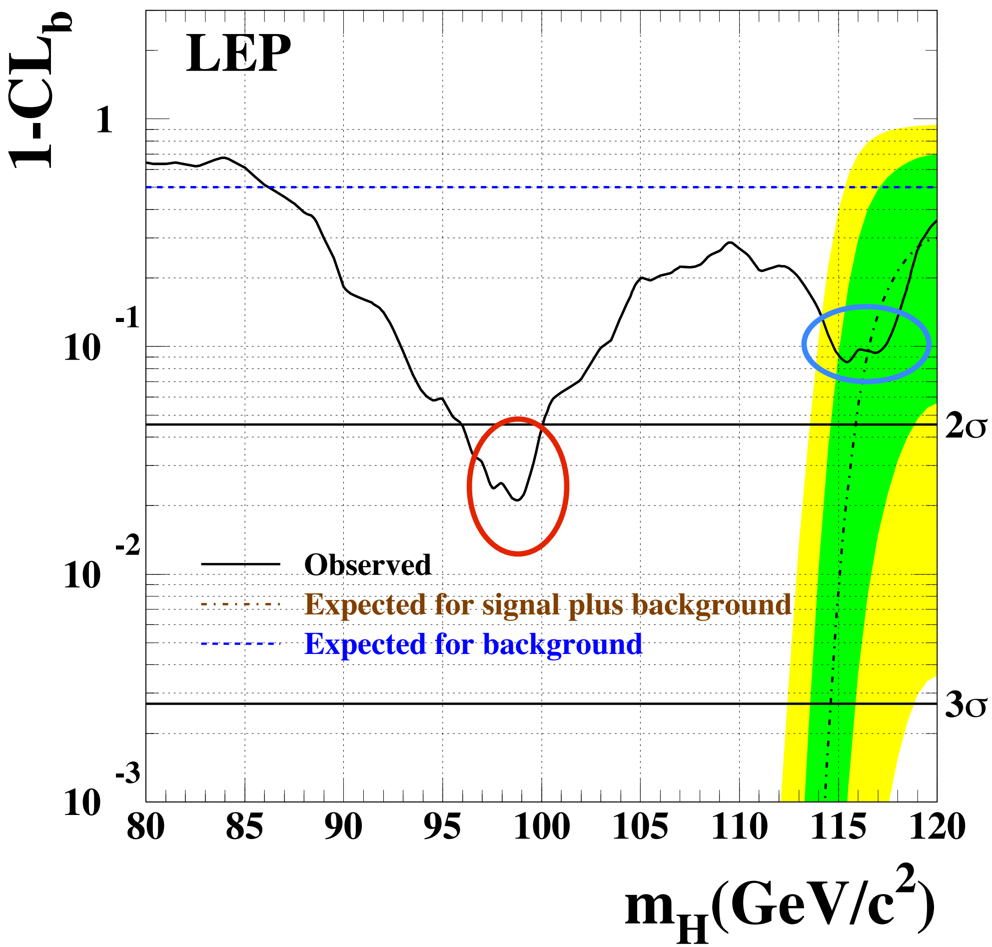
Kyle Cranmer,
New York University

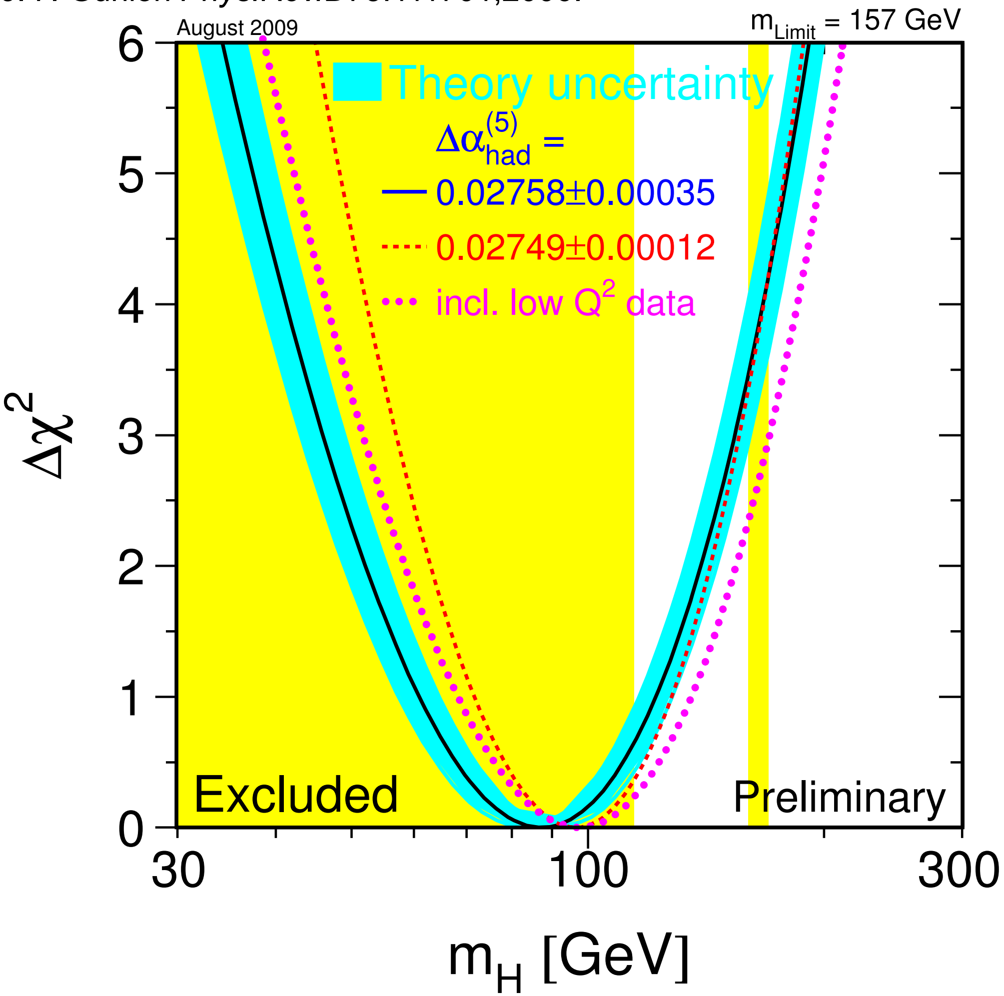
arXiv:1003.0705

The Higgs after LEP

In the years since LEP ended, the indirect constraints on the Higgs from EW precision measurements has provided some guidance and consternation

- fits prefer light Higgs mass, below the region excluded by direct searches
- In addition, some attention drawn to the excess around 98 GeV
  - eg. consistency with NMSSM: R. Dermisek and J. F. Gunion *Phys.Rev.*D73:111701,2006.





How could we have missed the Higgs?

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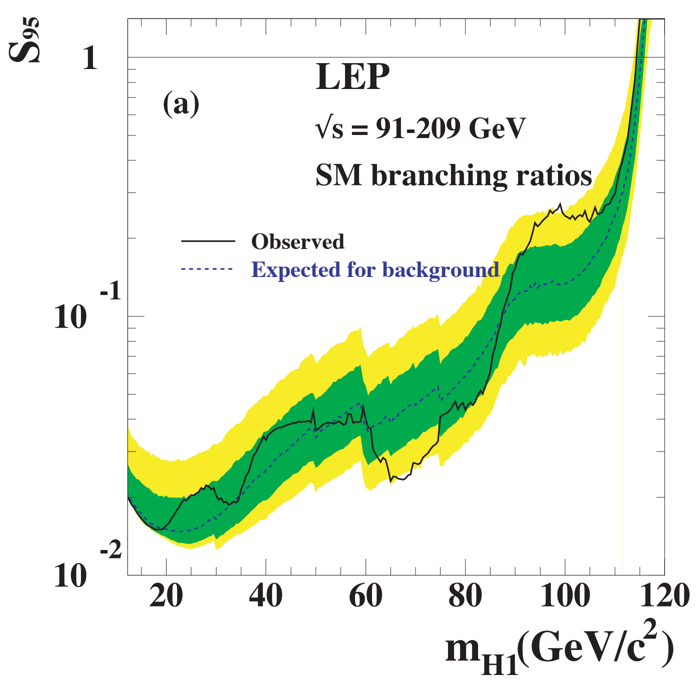
If the Higgs exists and is light, how could we have missed it at LEP?

- if the production cross-section were smaller than expected
  - this has direct implications on how the Higgs couples to the Z and its role in electroweak symmetry breaking
- or if it decayed into something exotic that the standard analysis missed
  - Is that difficult to achieve?



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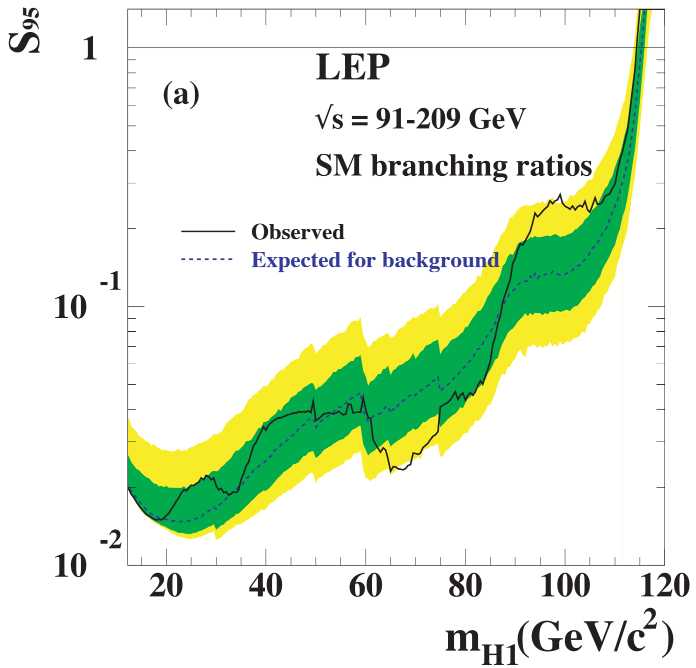

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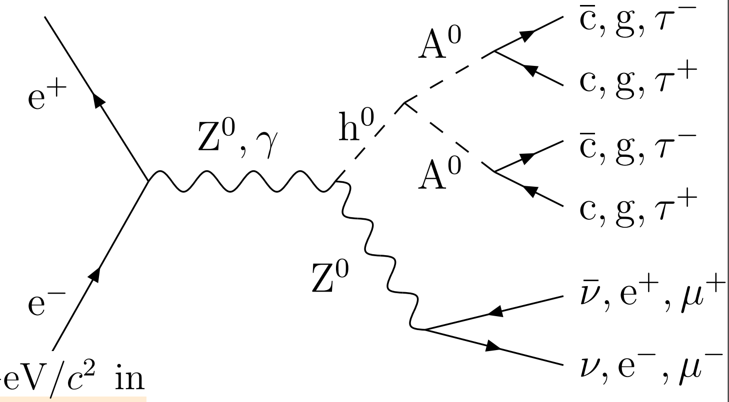
A prime example is next-to-minimal MSSM, where a is naturally light.

- allows for $h \to aa$, where a is pseudoscalar (mixture of A from MSSM)
- if $m_a < 2\, m_b$ evades $4b$ searches and expect $a \to \tau^+\tau^-$

OPAL low A-mass search (a parable)

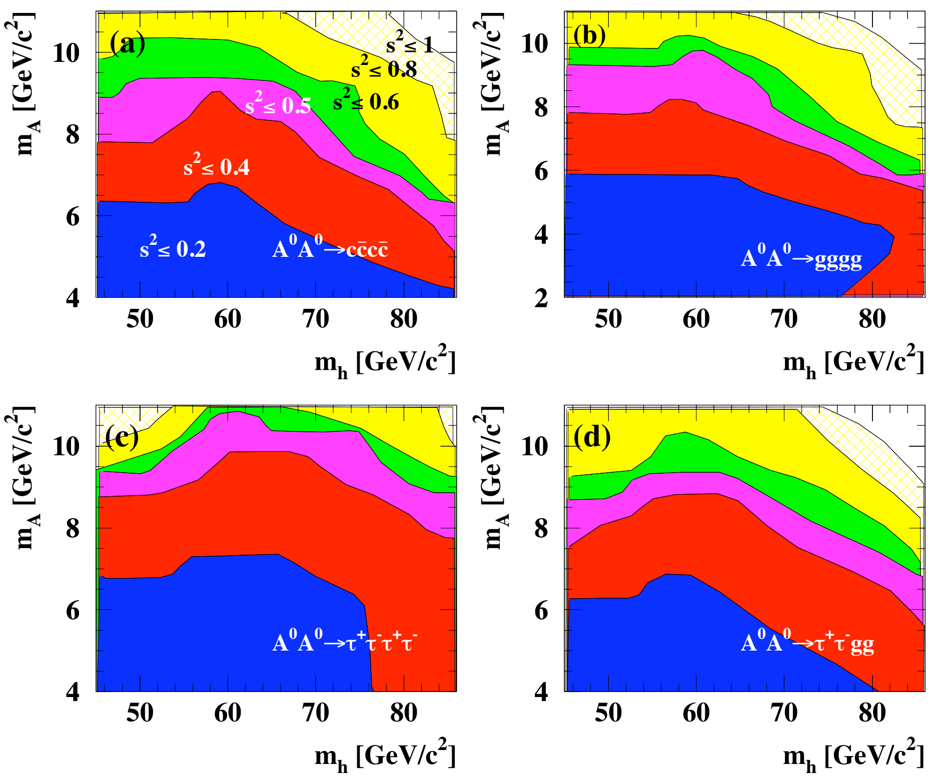
OPAL also carried out a searches in the region $2m_\tau < m_a < 2m_b$



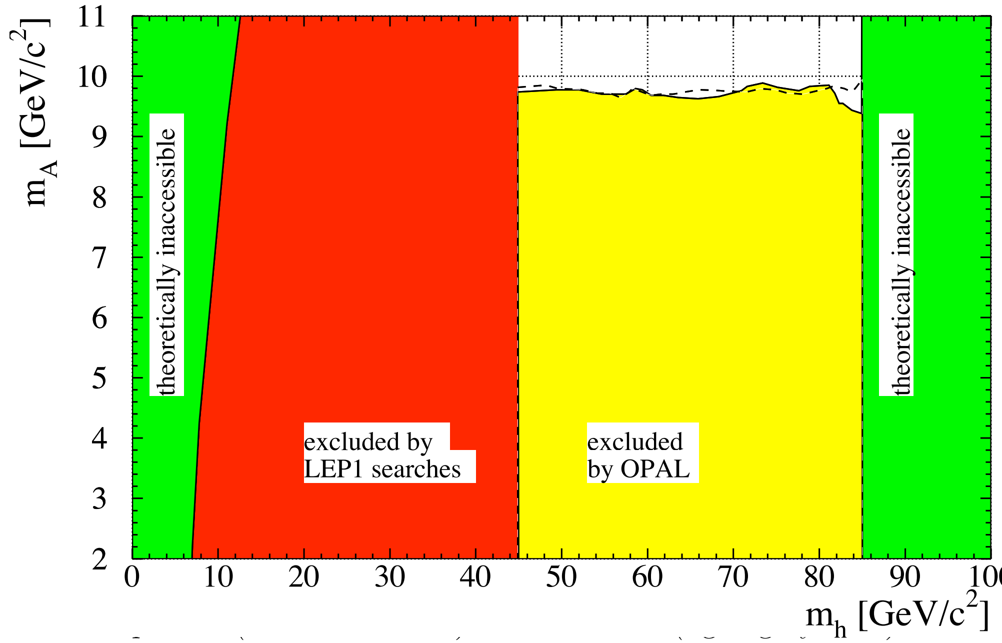
Search for a low mass CP-odd Higgs boson in e^+e^- collisions with the OPAL detector at LEP2

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



Eur. Phys. J. C27 (2003) 483–495, [hep-ex/0209068].



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

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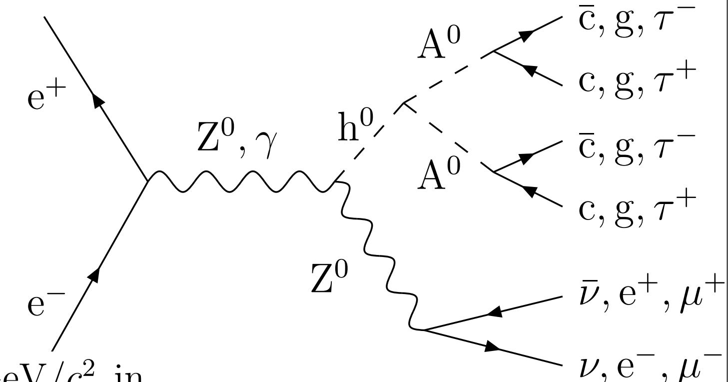

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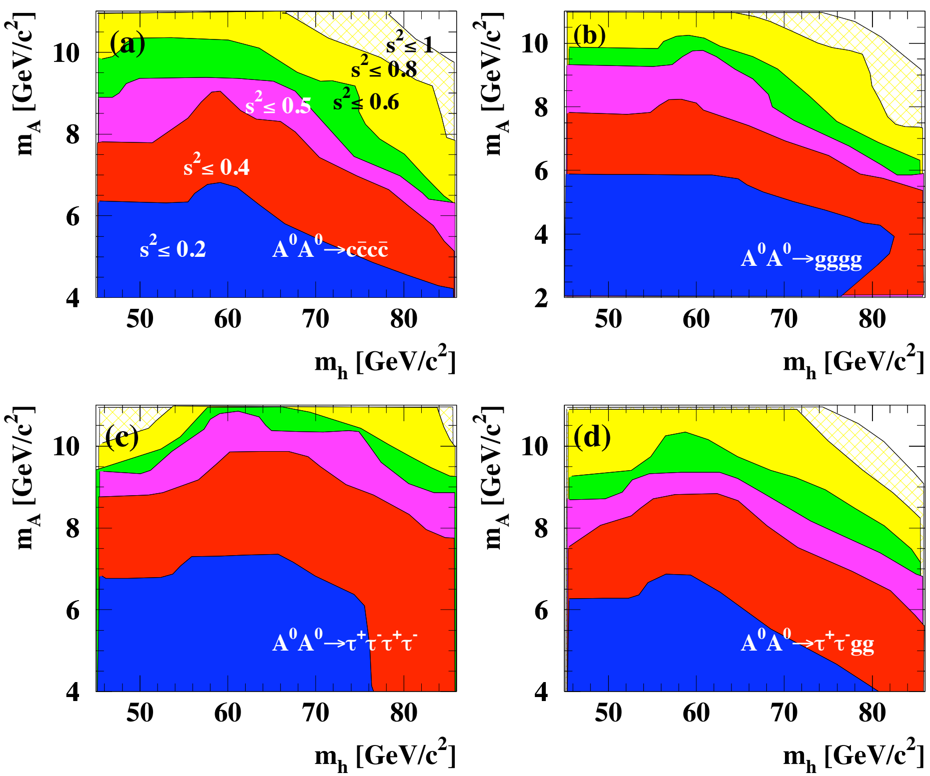
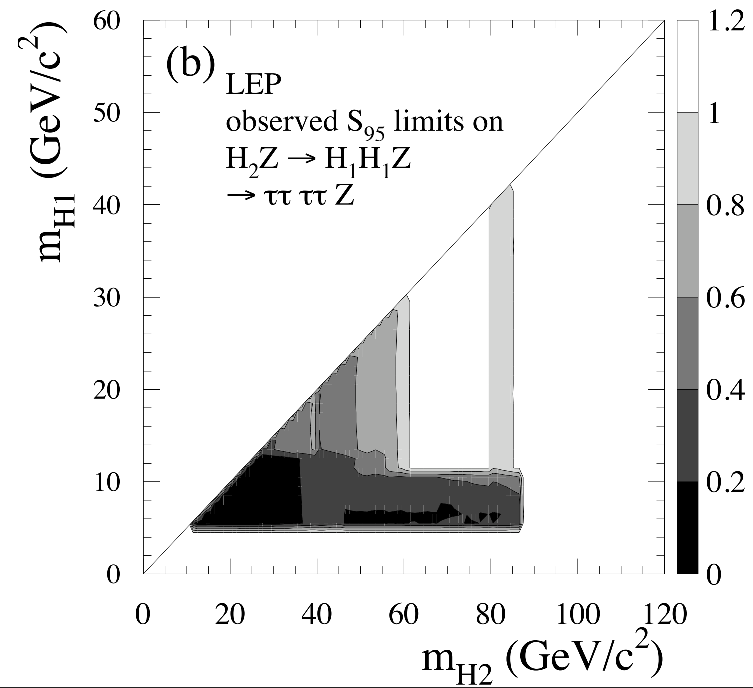


Eur.Phys.J.C47:547-587,2006



Going back to LEP data

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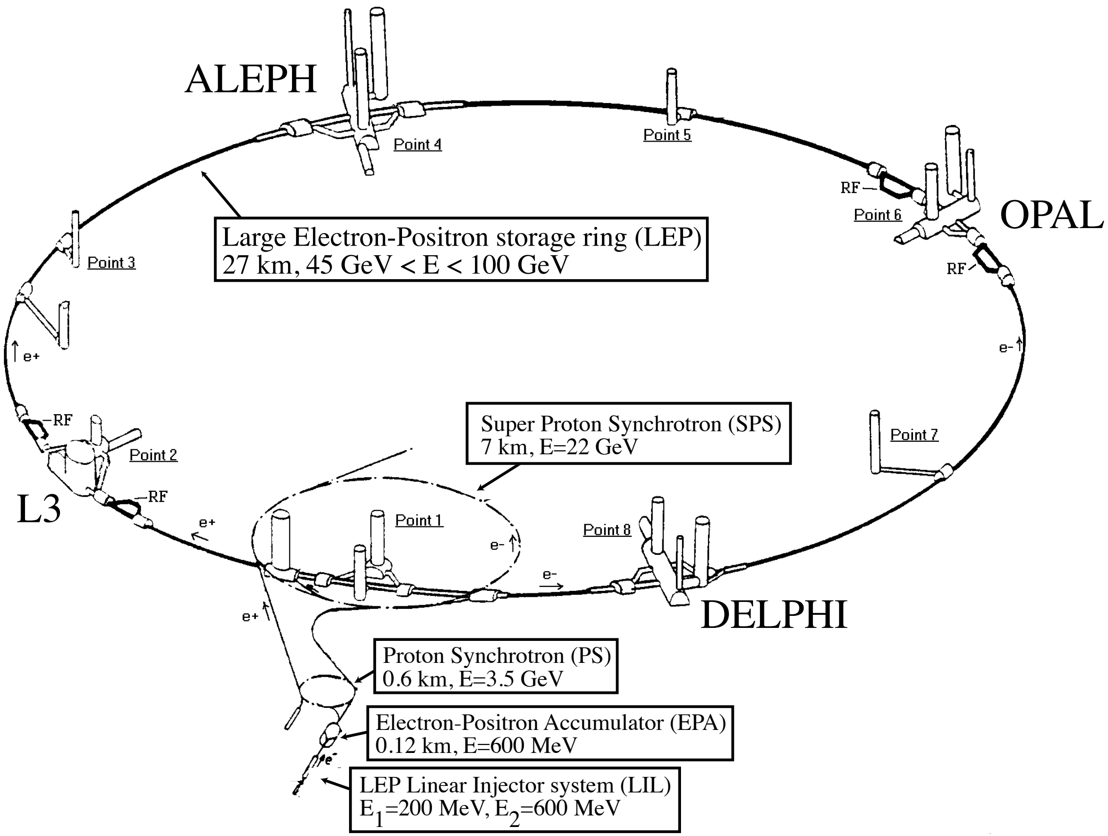
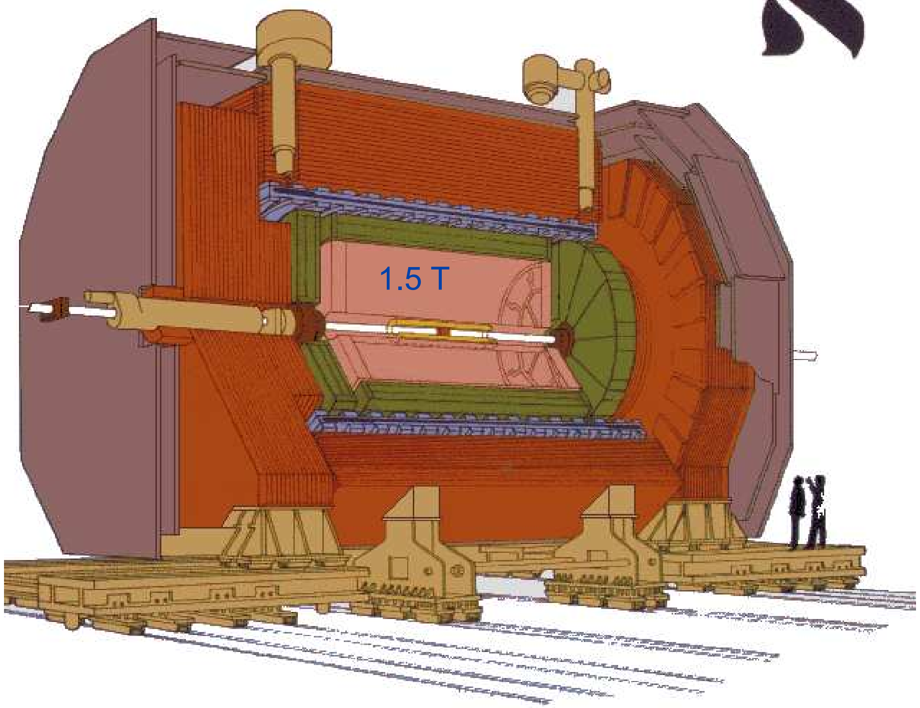
After several years of requests, we went back ALEPH's LEP2 data

- this was not totally unrelated to the LHC incident
- a bit of archeology to get access to data & analysis framework running

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

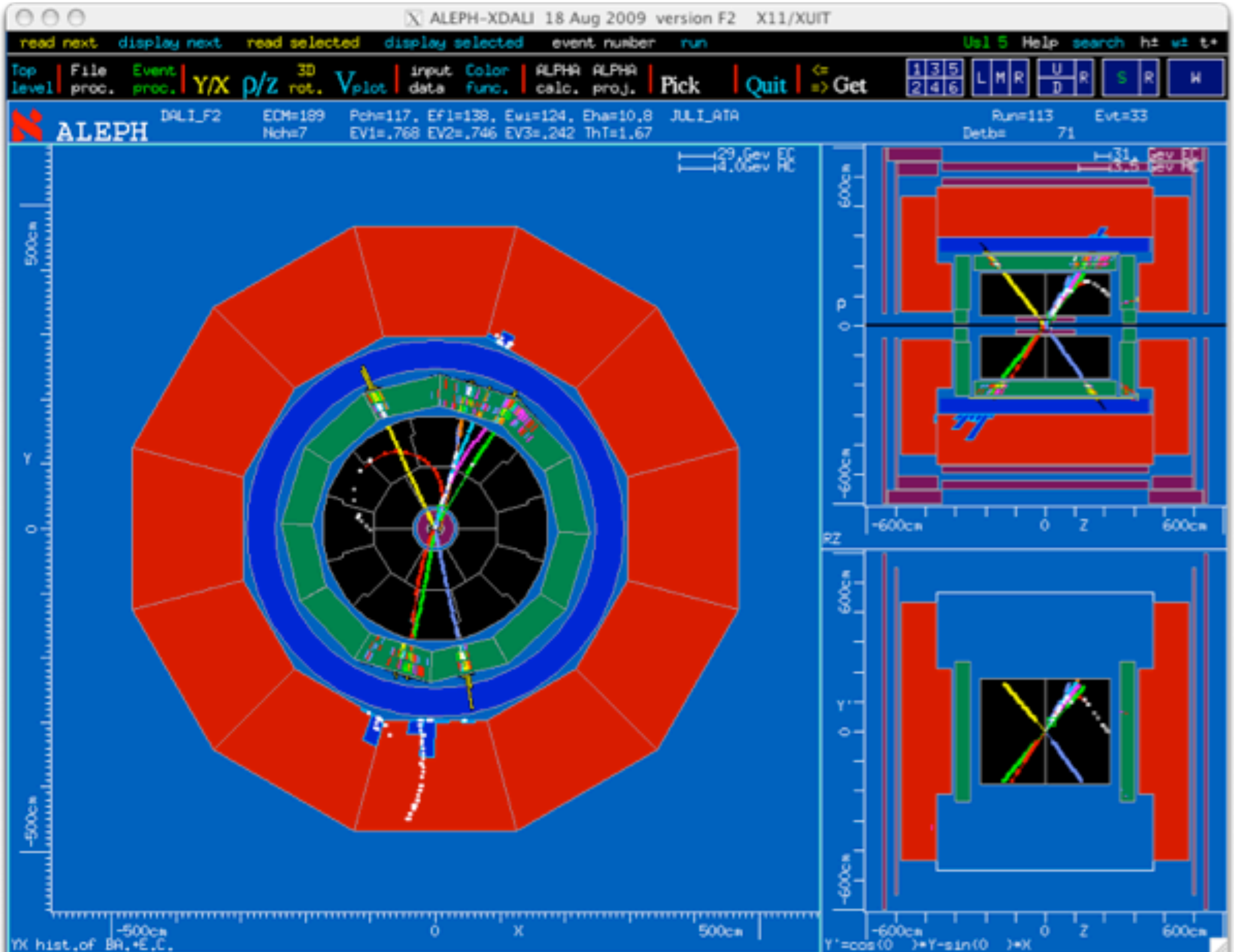
= 683 pb^{-1}





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 from tau decays)



Reconstructing $a \to \tau^+\tau^-$

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The h is produced nearly at rest, thus the $h \to aa$ are nearly back-to-back

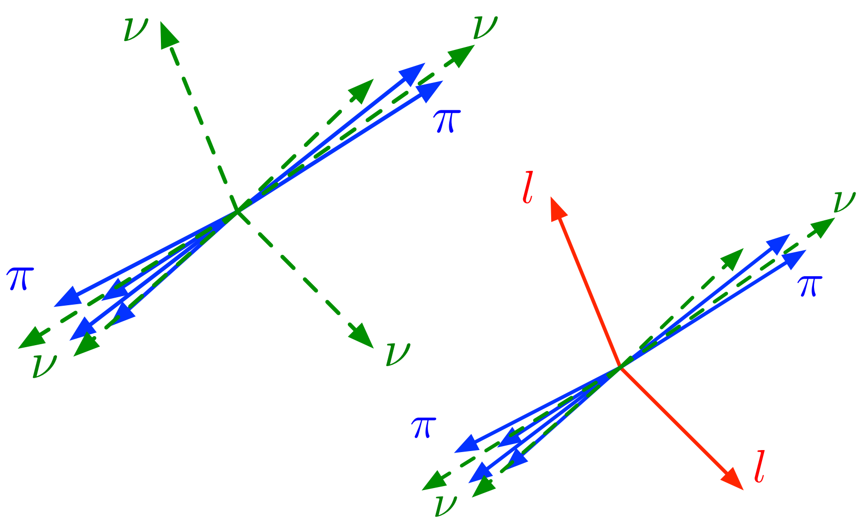
On each side, $a \to \tau^+\tau^-$ leads to a well collimated jet from the decay products of **two** taus with mass $< m_a$, which were clustered with JADE algorithm (requiring m<15 GeV)

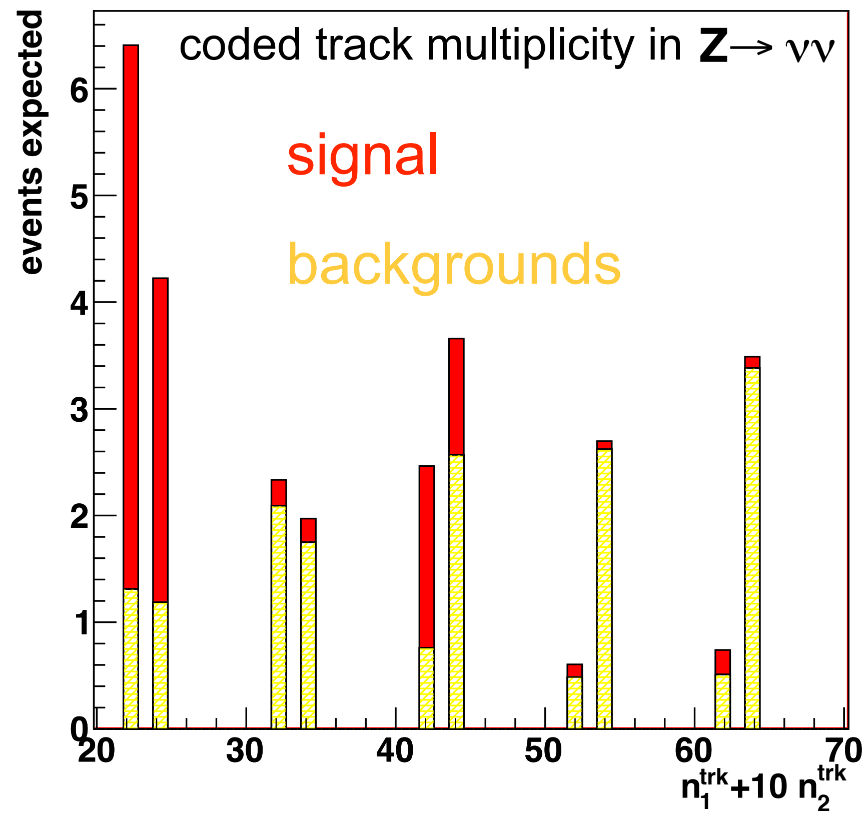
Standard tau algorithms will not be efficient for highly collinear $a \to \tau^+\tau^-$

- but the jet has a characteristic multiplicity corresponding to 1-prong and 3-prong branching ratios of the taus
  - expect 2, 4, or 6 tracks in each jet
  - conversions lead to some spillage
  - require jets to be well-contained so tracking efficiency is stable and high

Only use track multiplicity as di-tau jet discriminator (ie. leptonic & hadronic decays)

- in the end, only use jets with 2 or 4 tracks





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

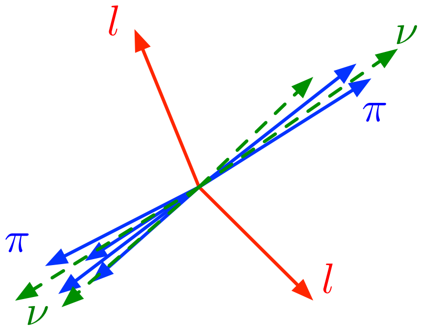
These channels are significantly cleaner due to the clear Z peak, but the signal rate is very low and signal efficiency is precious

- use standard ALEPH lepton ID
  - include isolated photon as part of Z-system when invariant mass is brought closer to the world average (more severe for electron channel)
  - electron channel suffers from Bhabha background: 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 a -> jets, but it is not efficient for the tau channel, so we dropped it.
- we make no attempt to reconstruct individual taus, we only use presence of two low-mass jets and then use track multiplicity as a descriminant

Loose selection (used as last chance to compare data & MC):

- 2 oppositely charged, isolated leptons, 2 jets, with $|\cos\theta_j| < 0.9$ $|\cos\theta_{jl}^{min}| < 0.95$

Final selection: $\not{E} > 20$ GeV $\cos\theta_{jj} < -0.5$ $80 < M_{\ell^+\ell^-(\gamma)} < 102$ $n_{1,2}^{trk} = 2$ or 4



@ loose selection	data	background
Z > e+ e-	299	332
Z > μ+ μ−	83	75

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

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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 $Z \to ll$

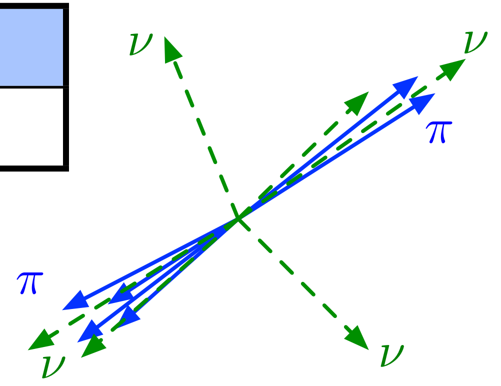
Loose selection requires:

- exactly 2 jets with at least 2 tracks and

$n_1^{trk} = 2 \text{ or } 4 \quad E_{j_1} > 25 \text{ GeV} \quad \not{E} > 30 \text{ GeV} \quad \not{m} > 20 \text{ GeV}/c^2, \ |\cos\theta_j| < 0.85 \quad m_{jj} > 10 \text{ GeV}$

- to reject "2 photon" and beam background events $E_{vis} > 5\%\, E_{CM} \quad \cos\theta_{\text{miss}} < 0.9$

@ loose selection	data	background
Z > νν	206	200



Final selection also required:

- less than 5 GeV in within 30° of beam axis; $n_{1,2}^{trk} = 2 \text{ or } 4$
- consistency with $Z \to \nu\bar{\nu}$: $\not{E} > 60 \text{ GeV and } \not{m} > 90 \text{ GeV}/c^2.$
- and small aplanarity (<0.05) consistent with 2 back-to-back highly collimated jets
  - signal has higher aplanarity for high m_a and low m_h: cut chosen to maintain efficiency

Expected yield and efficiency

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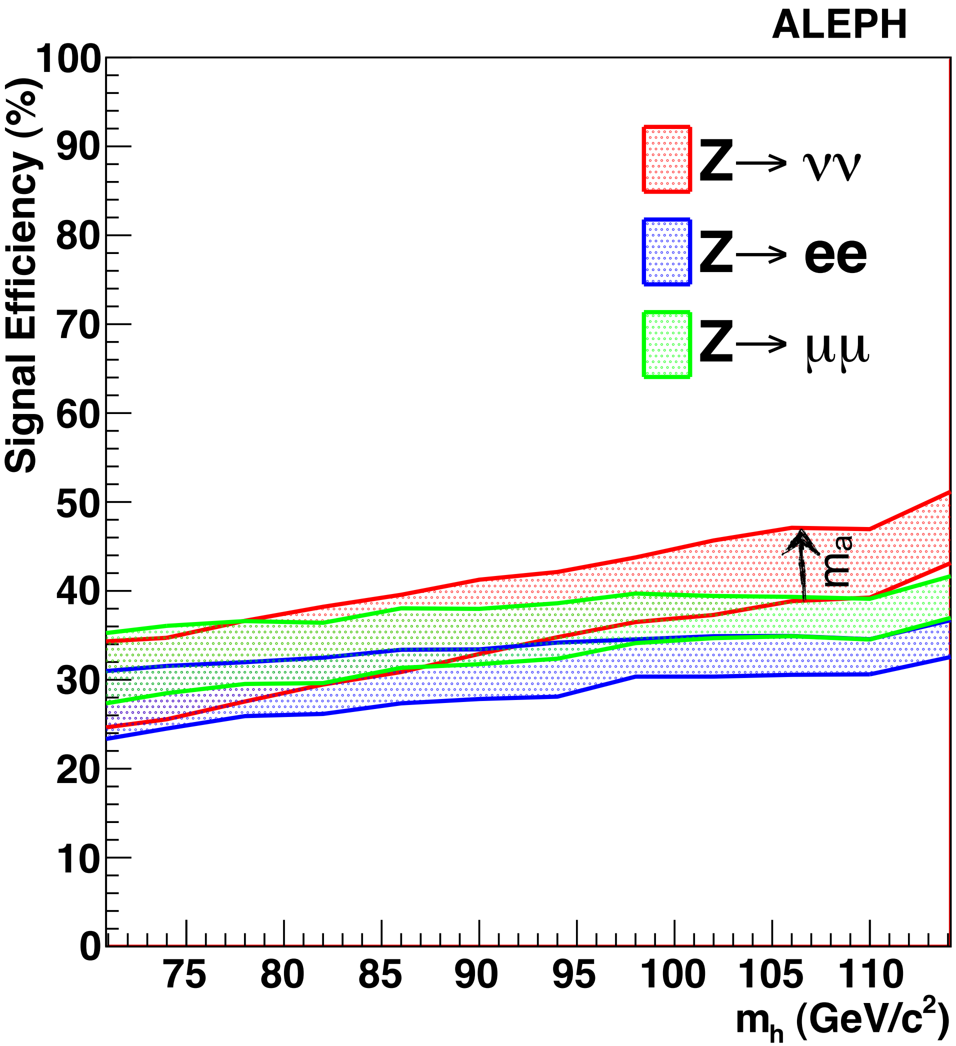
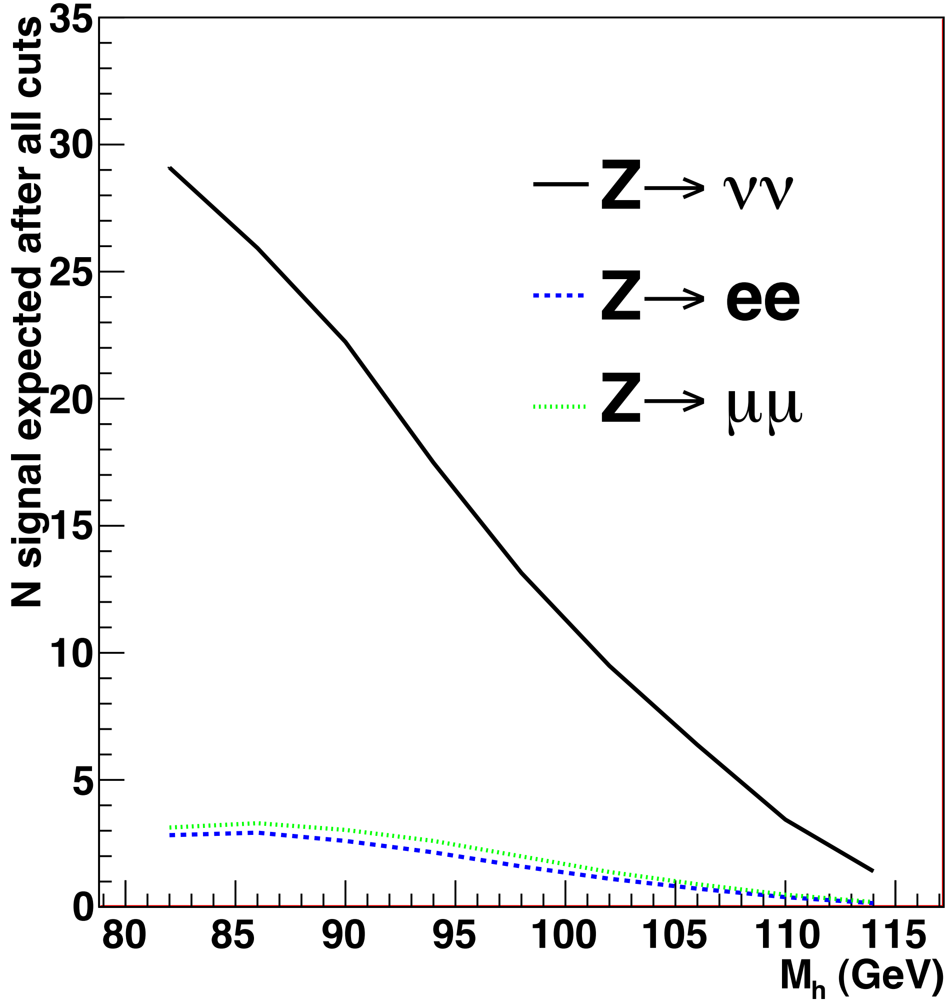
Our signal efficiency is pretty good, but very few events in lepton channels

- but we also have < 0.1 expected background in $Z \to ll$ channels
- expect 6 background events in $Z \to \nu\bar{\nu}$ channel

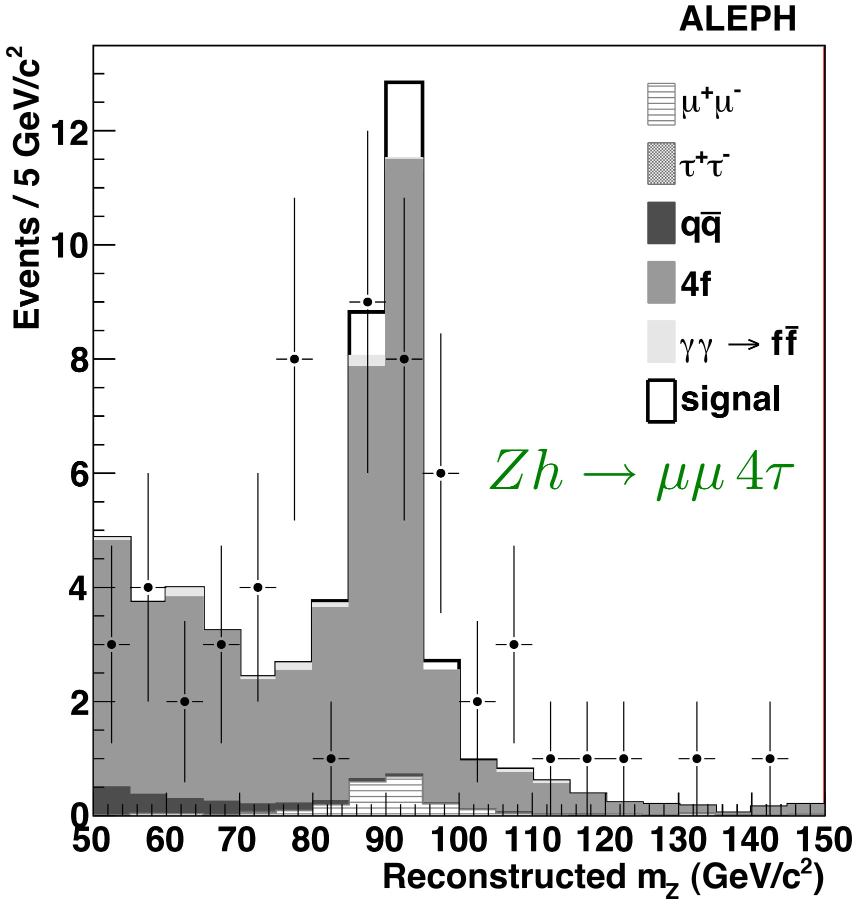


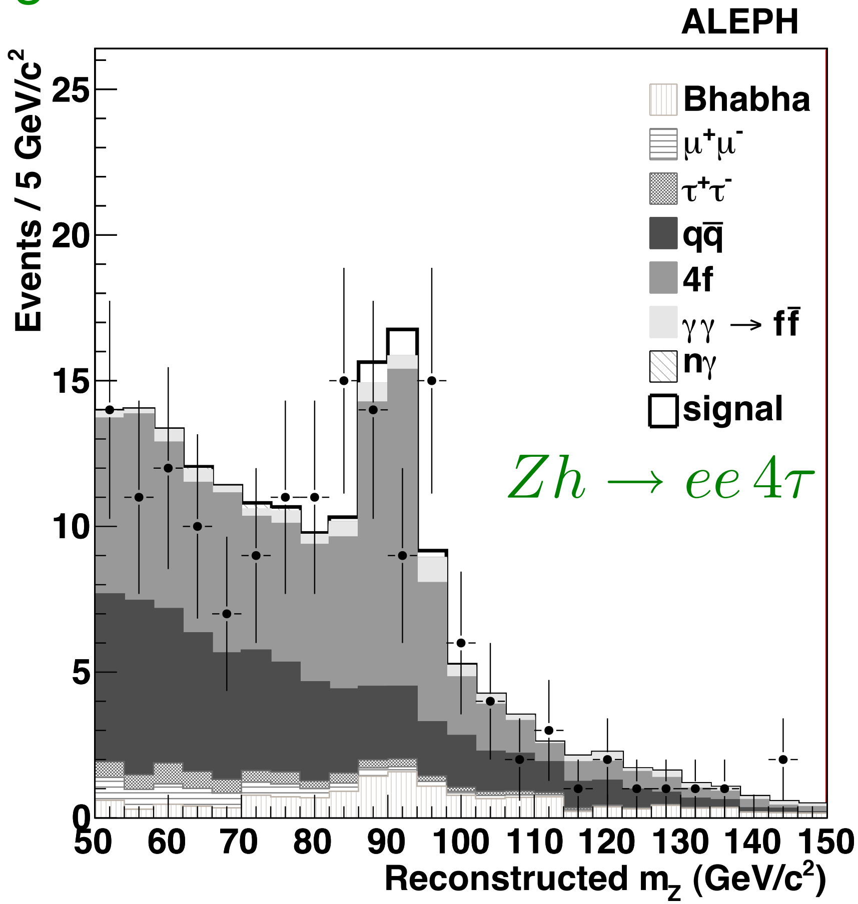


Results at loose selection

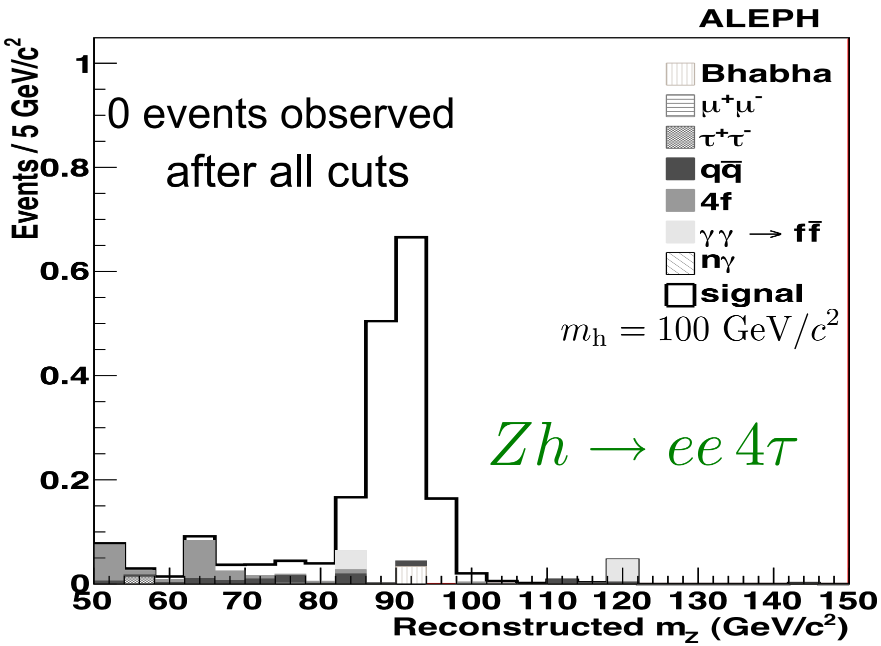
Backing up to the loose selection, we see good agreement between data and MC

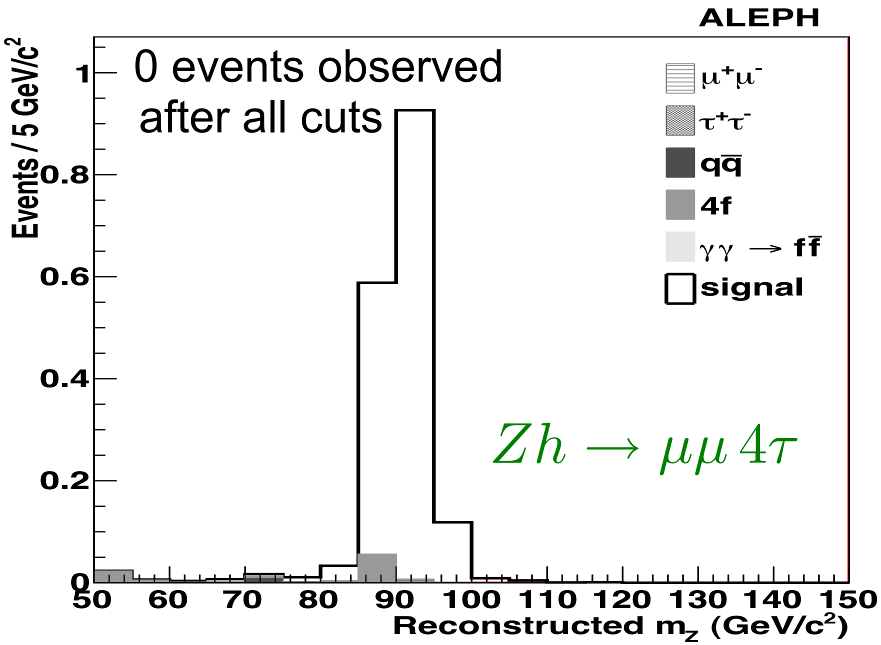
- Estimate systematics from tracking, jet energy scale, energy deposits in forward region (beam halo), etc.
  - 5% uncertainty on signal efficiency; 10% for background in lepton channels; 30% for neutrino channel
  - data/MC consistent well within this range... statistical errors dominate

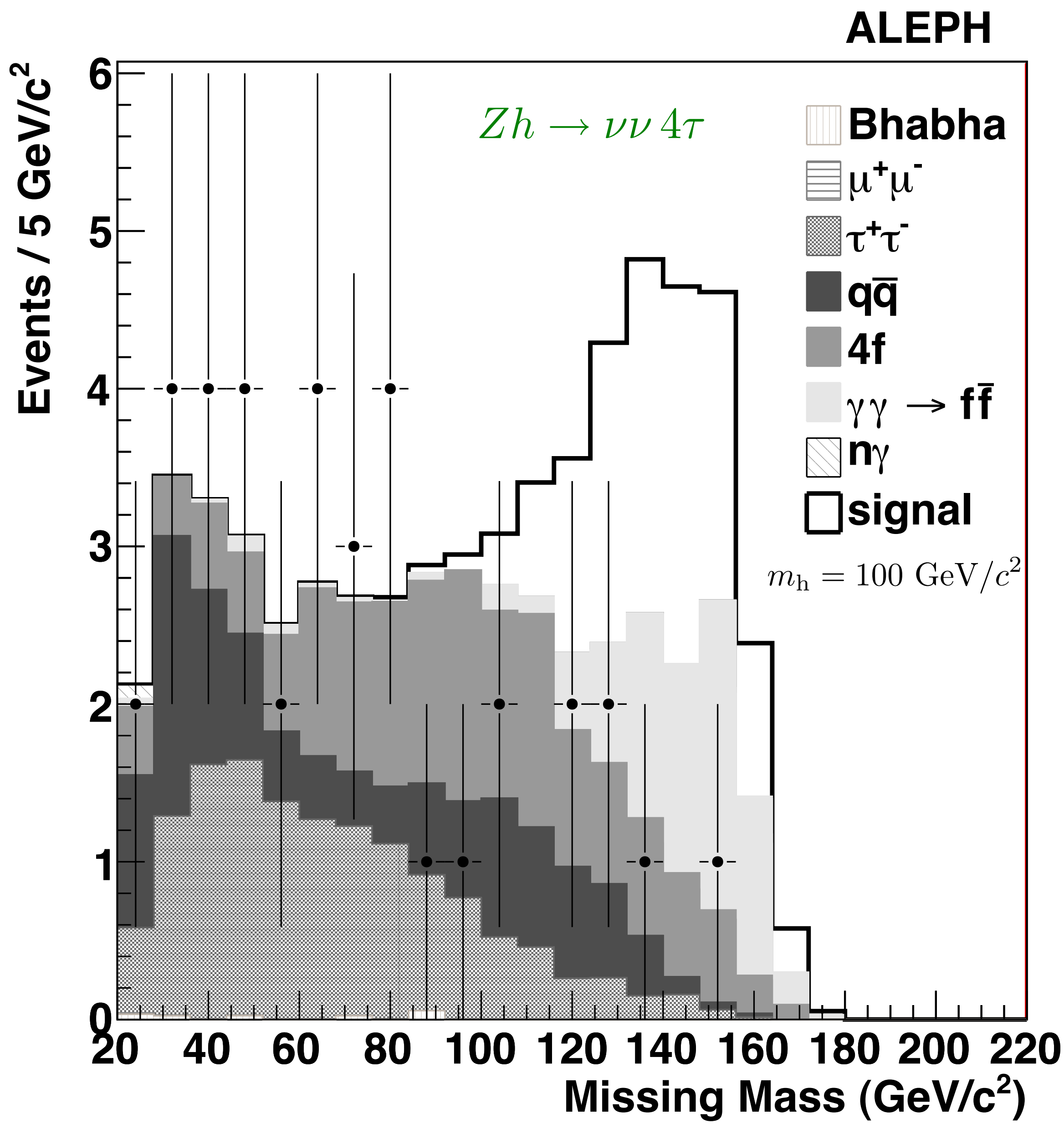




What did we see?







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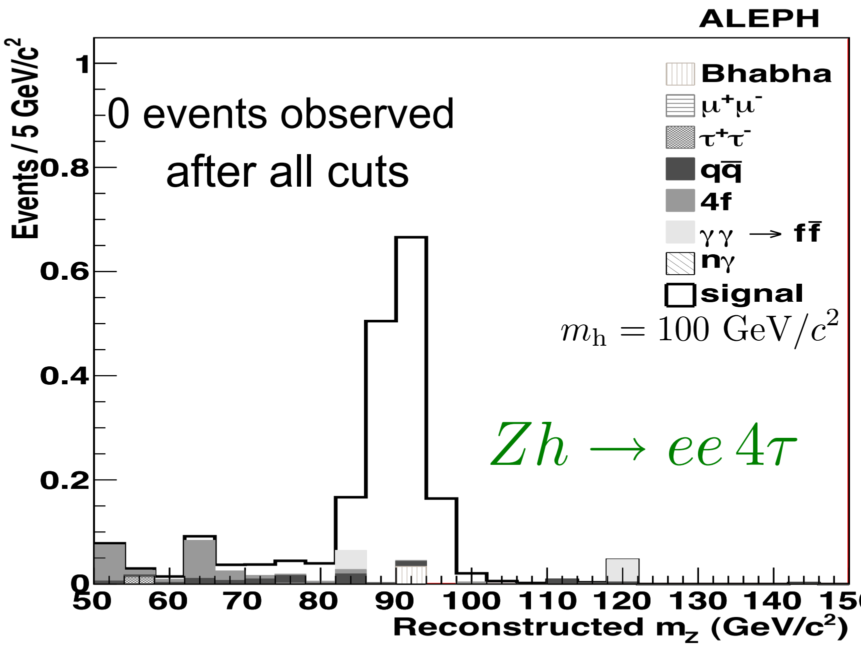

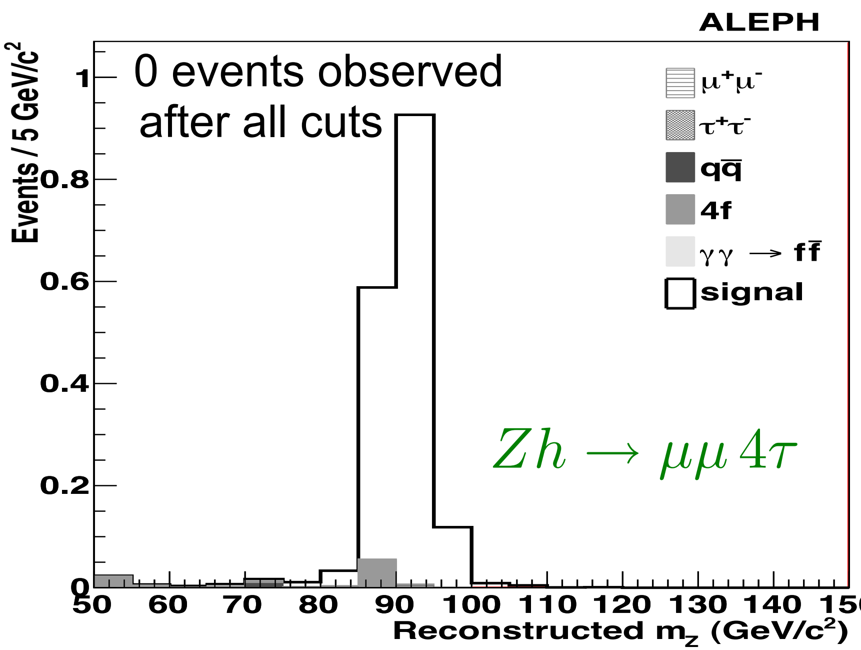

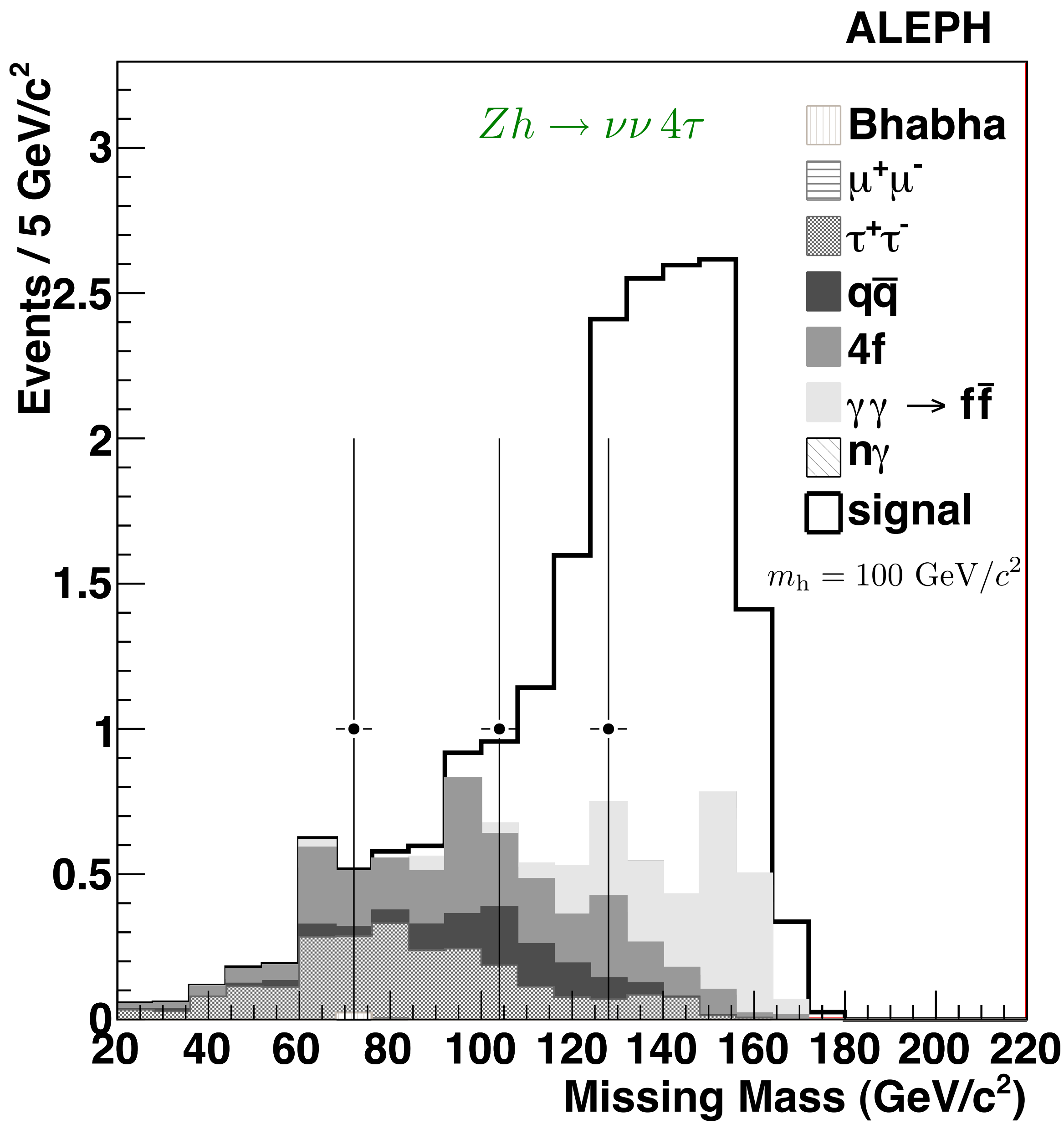

New limits

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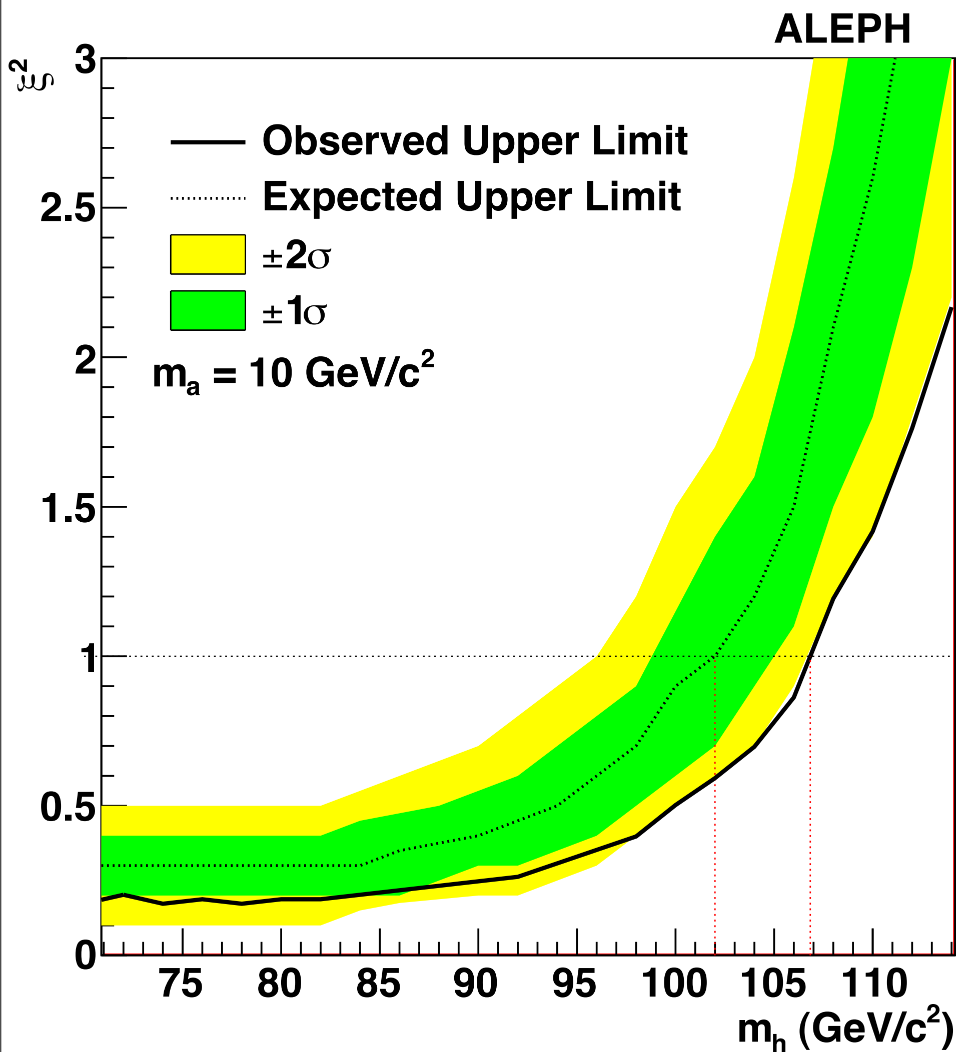
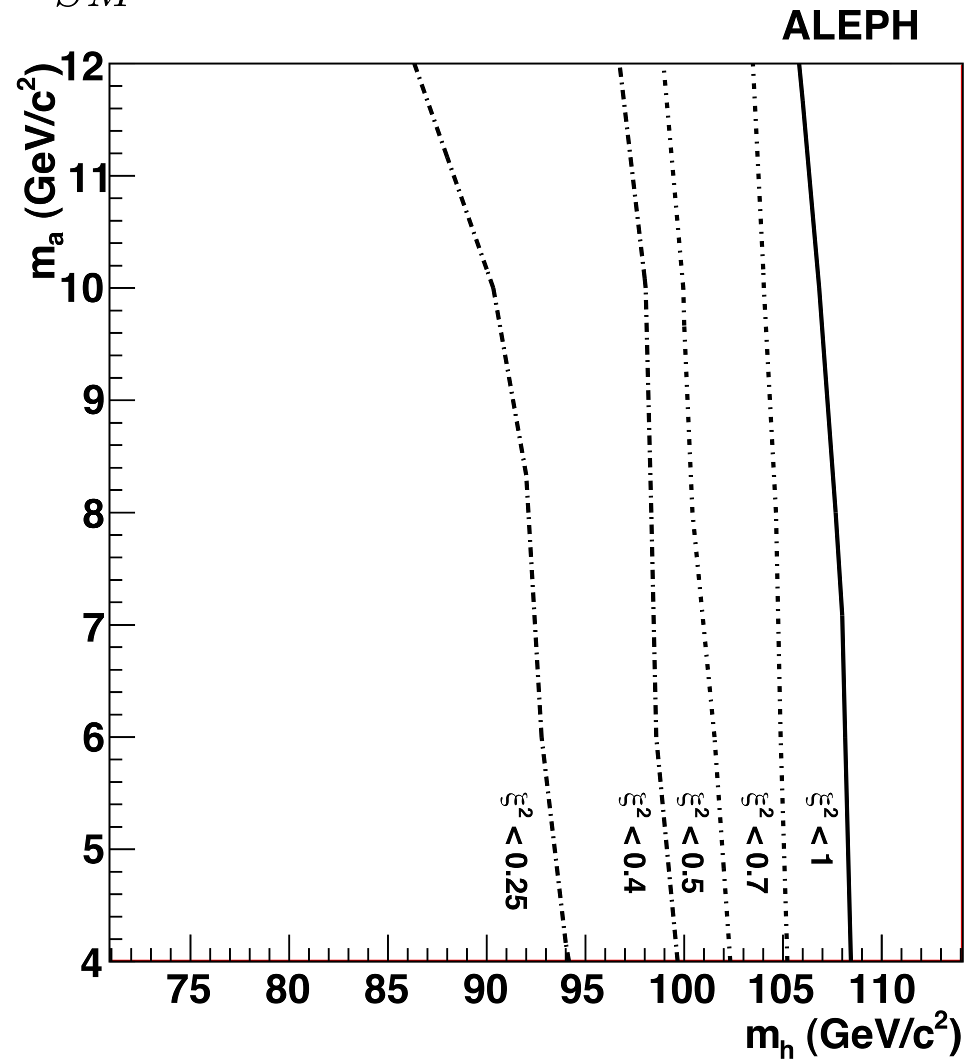
Limits based on event counts in 3 track multiplicity bins X 3 Z decay channels

- weak dependence on m_a and improved sensitivity over previous limits

$$\xi^2 = \frac{\sigma\,\mathrm{BR}(h \to aa)\,\mathrm{BR}(a \to \tau\tau)^2}{\sigma_{SM}}$$





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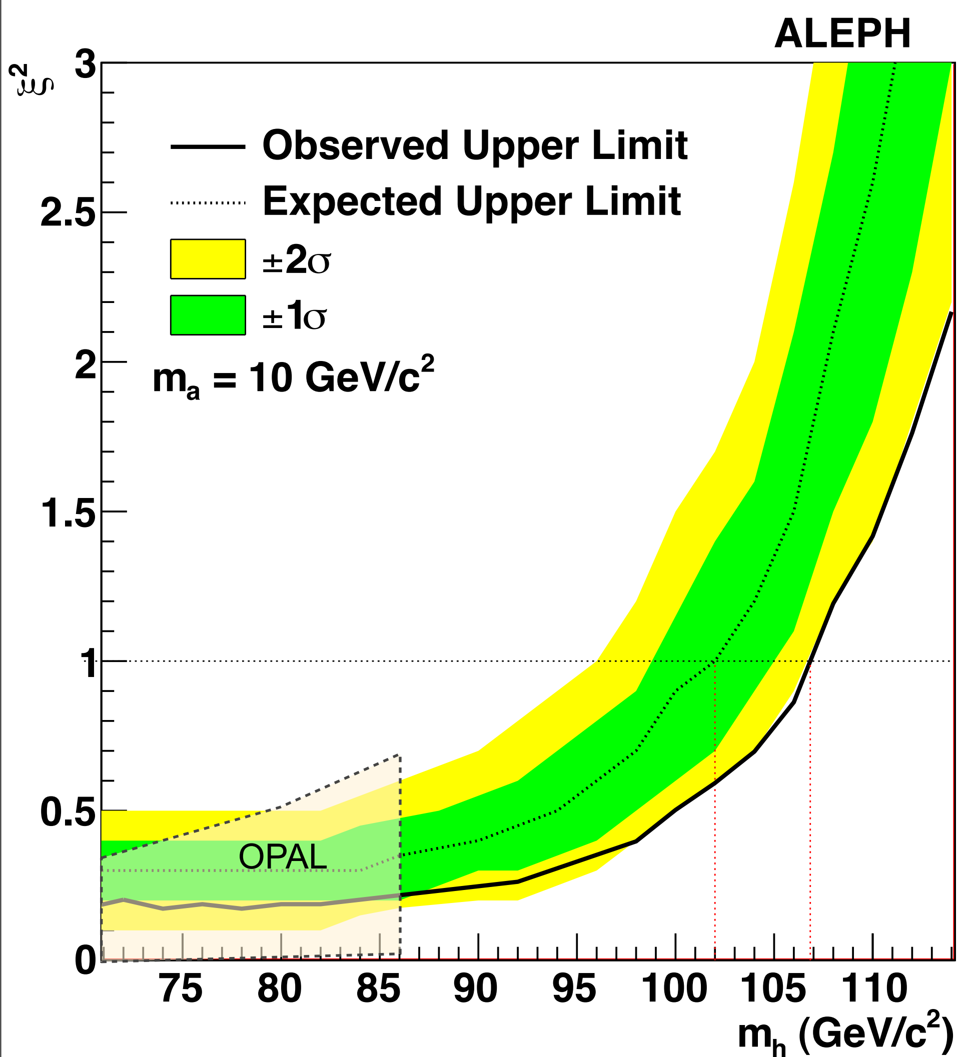

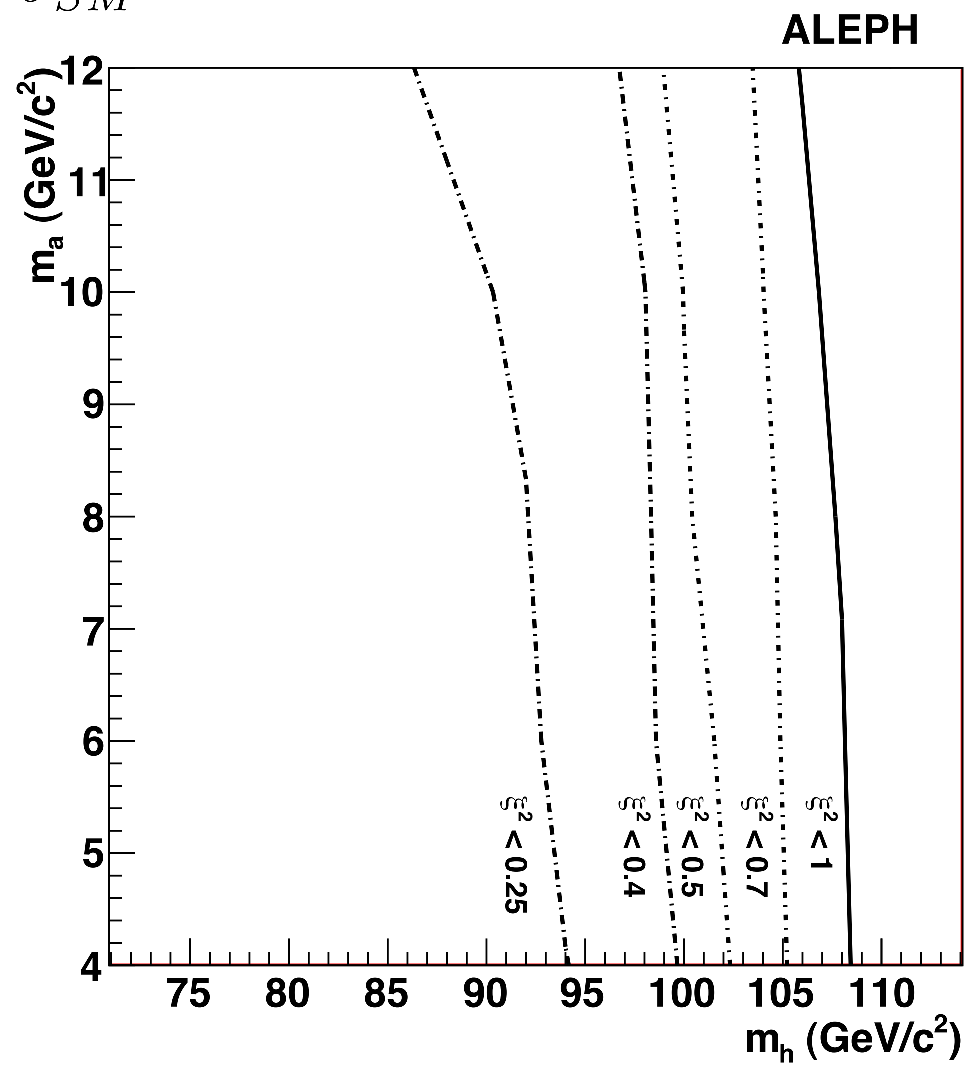

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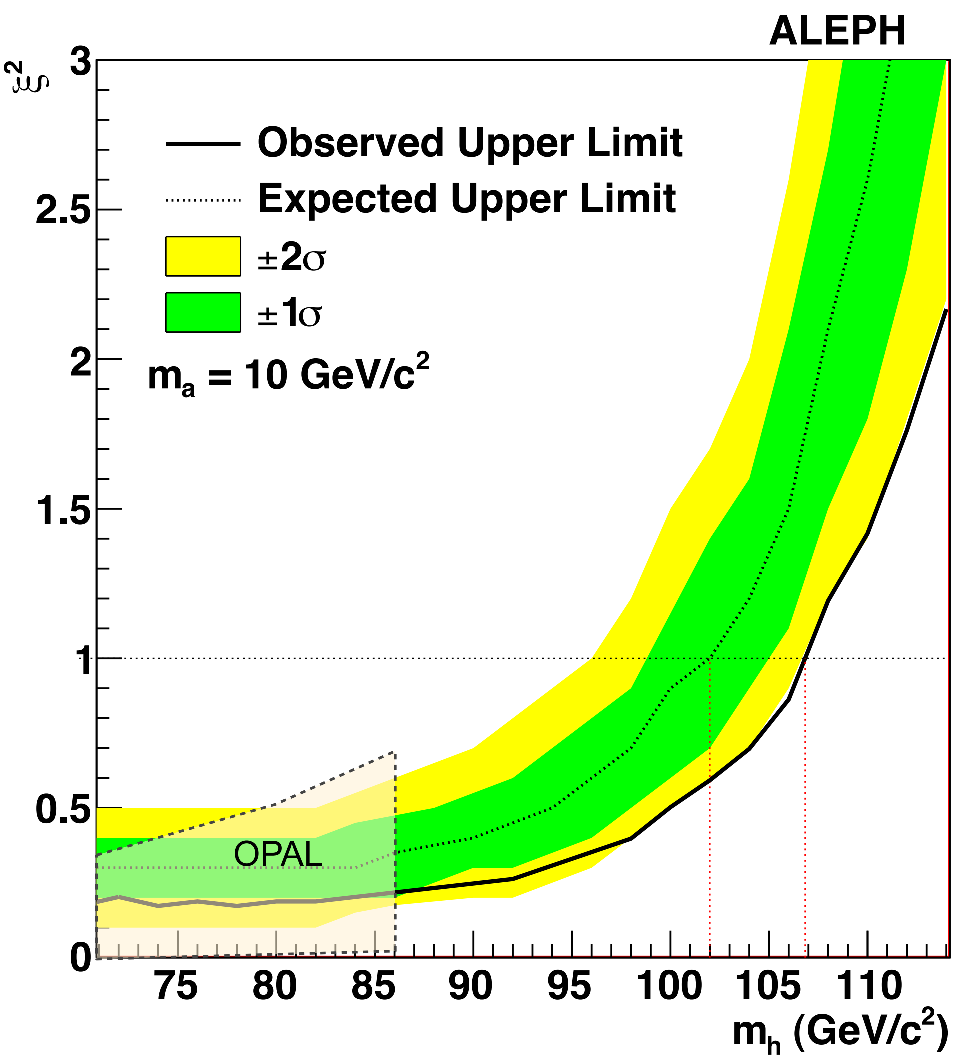

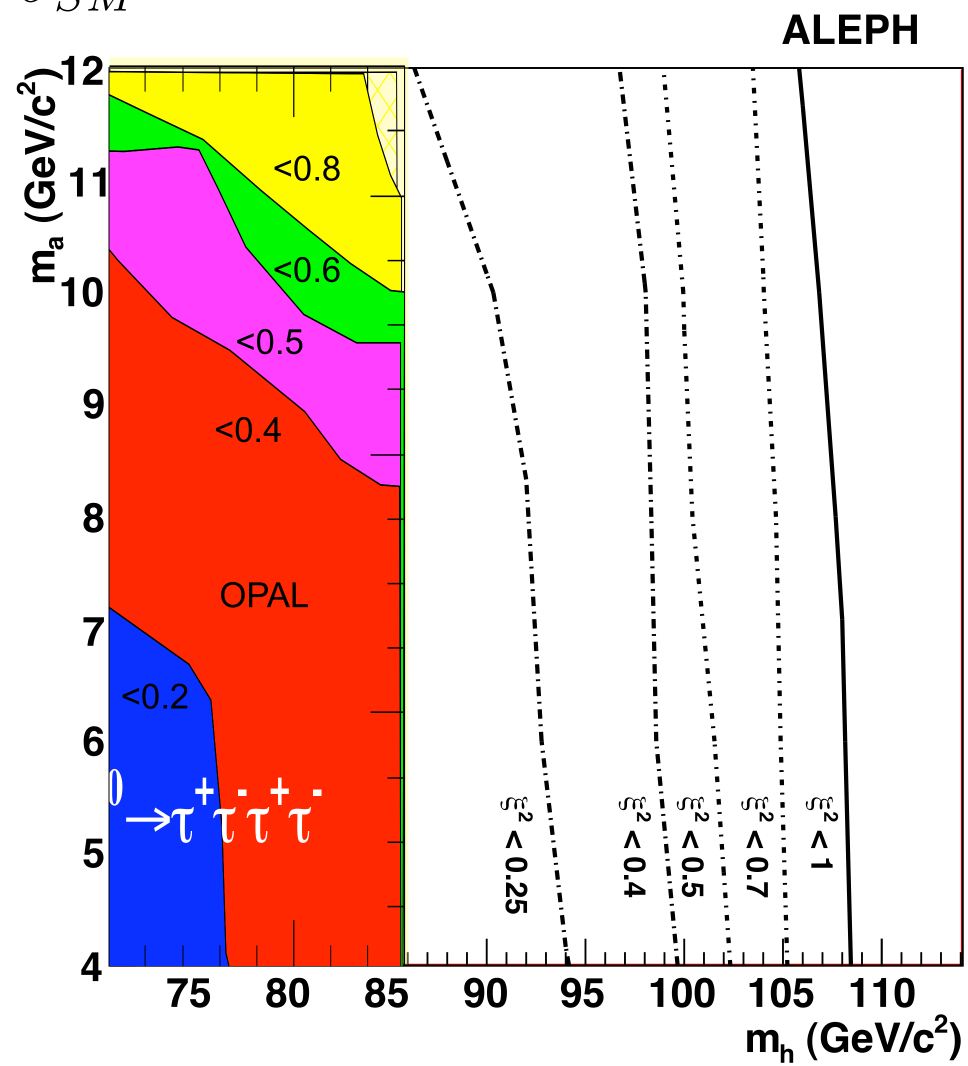

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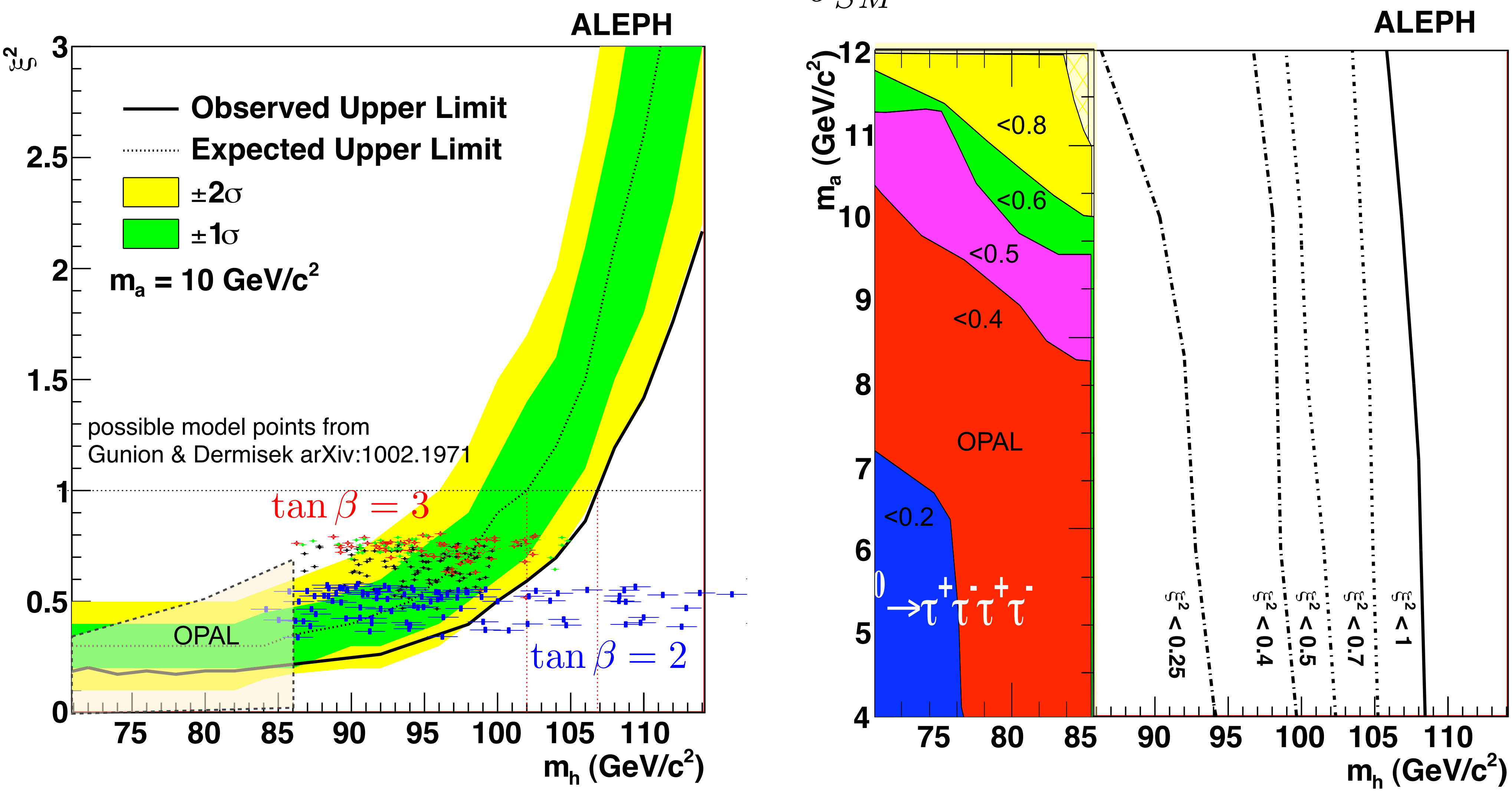


Conclusions

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

- allows us to close the few remaining holes in LEP Higgs searches

Our first analysis of $e^+e^- \to Zh \to (ee, \mu\mu, \nu\nu)\, 4\tau$ had discovery sensitivity, but we saw no excess. The new limits:

- extend and improve the limits from the OPAL analysis
- exclude most of the “ideal” NMSSM Higgs scenarios, except for those at low $\tan\beta \approx 2$, where there is a larger BR($a \to c\bar{c}, gg$)

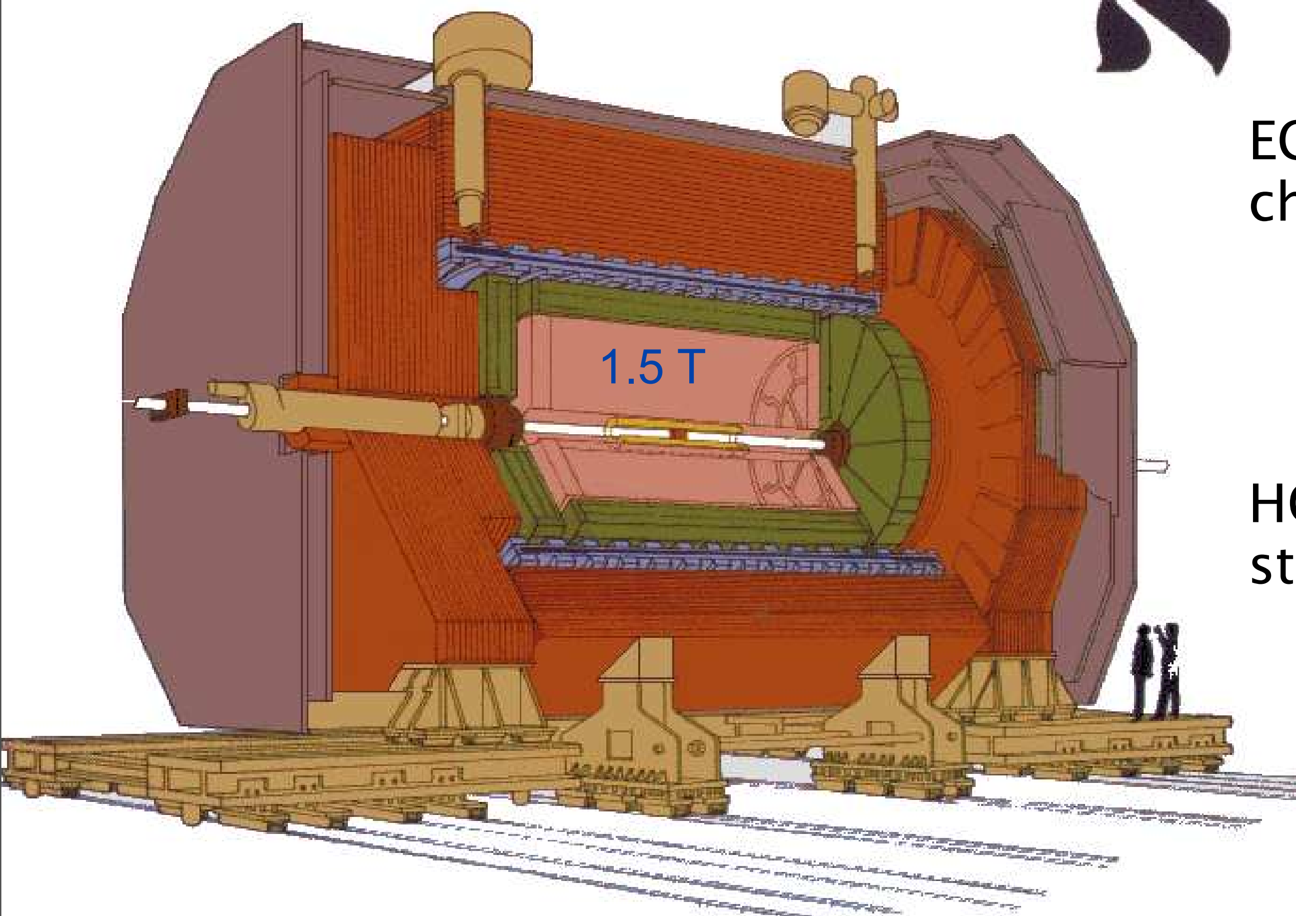
These new results published in arXiv:1003.0705 (submitted to JHEP)

- we may follow up with other analyses to close remaining holes

Many thanks to Itay Yavin, James Beacham, Neal Weiner, Riccardo Barbieri, and others that pushed this along

Backups

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

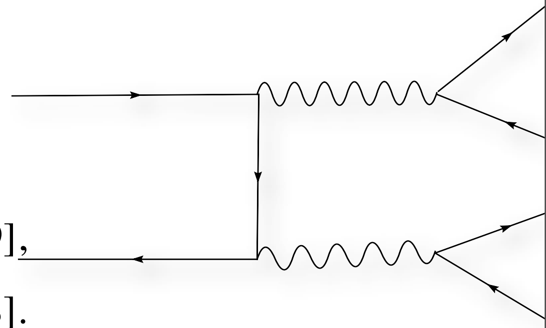
Numbers of events in different track multiplicity bins

- Table 3: Number of events passing loose and final selections in each channel, in data, simulated background, and simulated signal ($m_h = 100$, $m_a = 4$ GeV/c^2). The numbers of events passing the final selection are categorised by track multiplicity.

Channel	Selection $(n_1^{track}, n_2^{track})$	data	total background	background category 2f	4f	$\gamma\gamma$	nγ	signal
$Z \to e^+e^-$	Loose	299	332	183	137	12.31	0.65	2.27
	(2,2)	0	0.034	0.034	0.000	0.000	0.000	0.689
	(2,4)+(4,2)	0	0.055	0.014	0.005	0.037	0.000	0.610
	(4,4)	0	0.031	0.019	0.013	0.000	0.000	0.126
$Z \to \mu^+\mu^-$	Loose	83	74.50	12.79	60.64	1.07	0.00	2.37
	(2,2)	0	0.058	0.005	0.053	0.000	0.000	0.800
	(2,4)+(4,2)	0	0.005	0.000	0.005	0.000	0.000	0.676
	(2,2)	0	0.006	0.000	0.006	0.000	0.000	0.127
$Z \to \nu\bar{\nu}$	Loose	206	200	135	47.97	13.50	3.74	12.63
	(2,2)	0	1.312	0.663	0.408	0.240	0.000	5.097
	(2,4)+(4,2)	0	1.948	0.528	0.575	0.845	0.000	4.741
	(4,4)	2	2.569	0.461	0.820	1.288	0.000	1.089

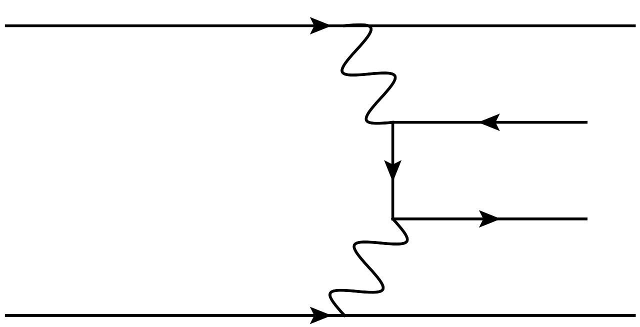
$$P(N_{m,f}|\xi^2, b_{m,f}) = \prod_{m\in\mathcal{M}} \prod_{f\in\{ee,\mu\mu,\nu\nu\}} \text{Pois}(N_{m,f}|\xi^2 s_{m,f} + b_{m,f}) \cdot N(b^{MC}_{m,f}|b_{m,f}, \Delta_f).$$

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].



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.

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

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 $m_a < 15\,\mathrm{GeV}$ 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

Higgs production at LEP

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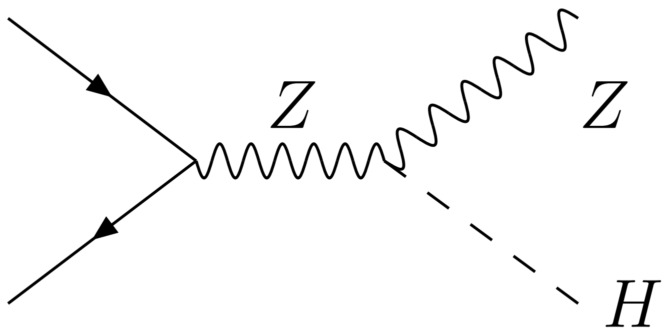
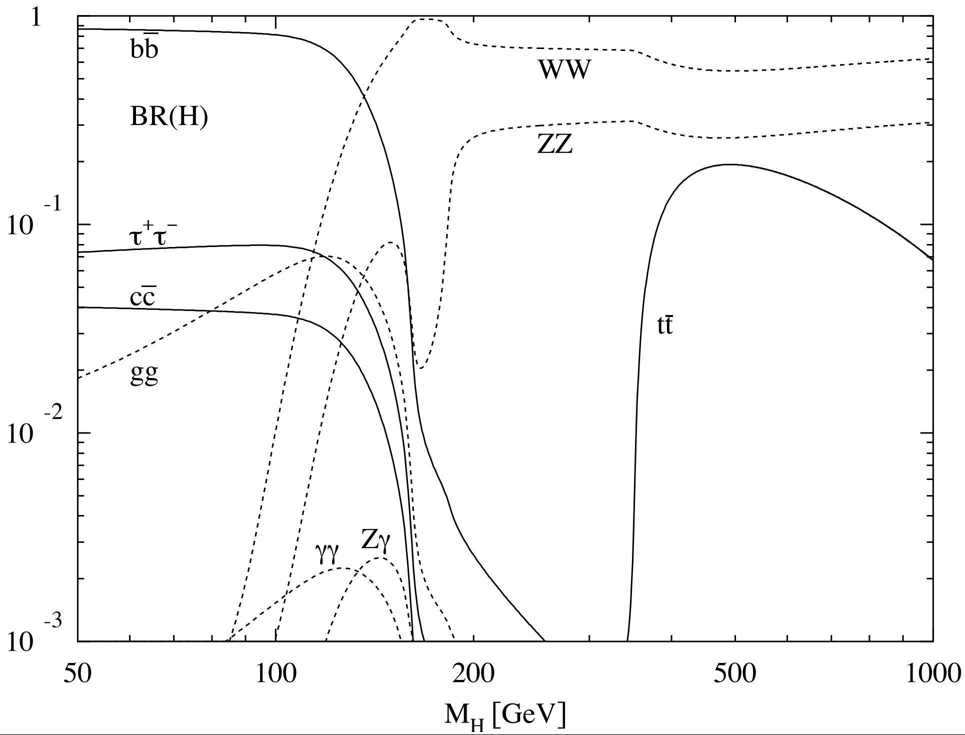
Higgs primarily produced via higgsstrahlung process

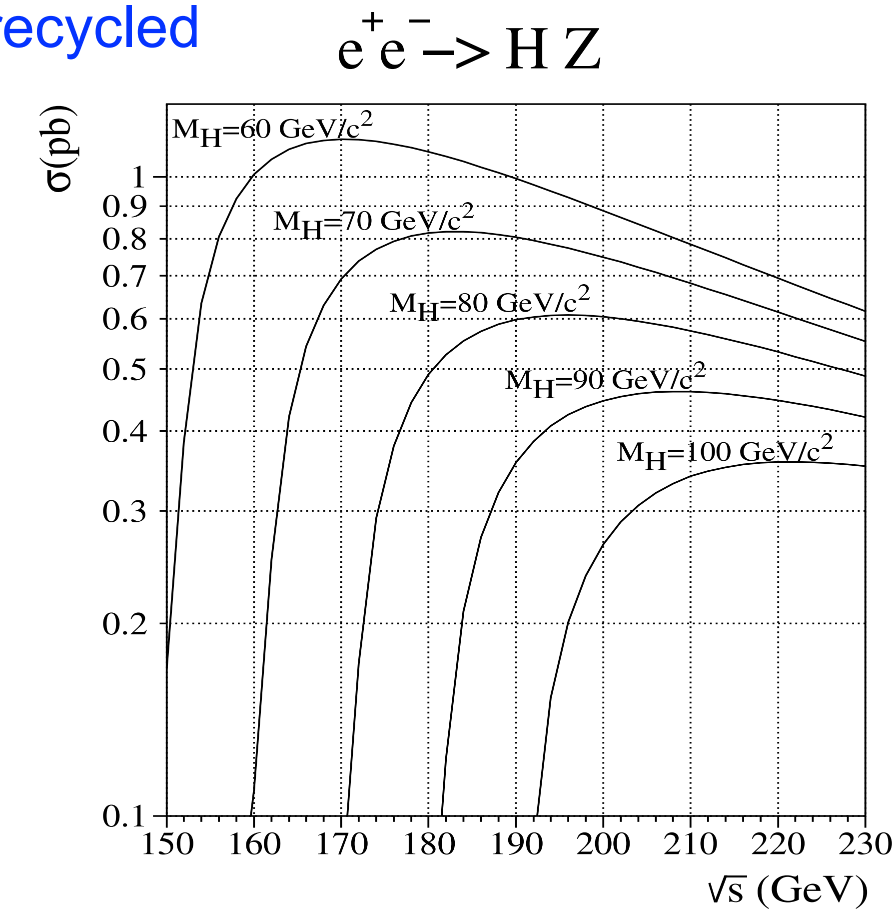
- kinematic threshold for production ~115 GeV
- in that mass range, standard model Higgs decays dominated by $H \to bb, \tau\tau$



Many (most) MSSM Higgs searches were recycled versions of SM searches

M. Spira Fortsch. Phys. 46 (1998)





Other motivations for a light a

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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 $\hat{S}$ [Gunion, et al]
    - 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

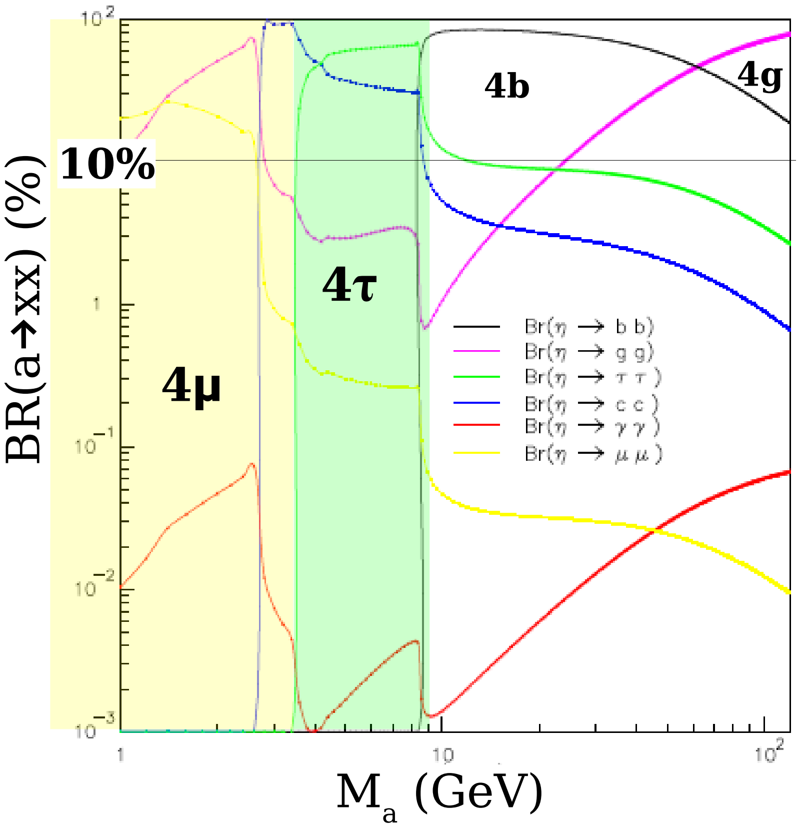
Here we are taking a model independent attitude, and just look for a signal like $h \to aa \to 2\tau\, 2\tau$ where the a is light, without interpreting it in the context of any particular model

- eg. place limit on:

$$\xi^2 = \frac{\sigma\, \mathrm{BR}(h \to aa)\, \mathrm{BR}(a \to \tau\tau)^2}{\sigma_{SM}}$$

NMSSM BR(a->X)

low tan beta have reduced BR(a->tau tau)



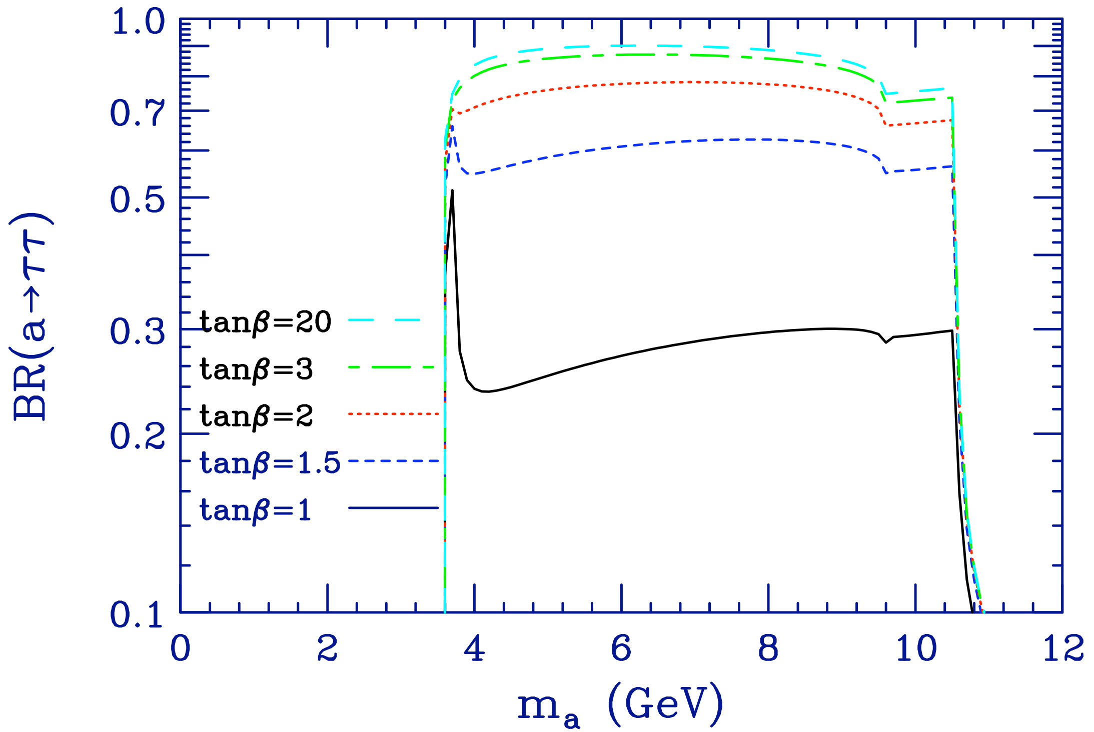


Figure 7: $B(a \to \tau^+\tau^-)$ for various $\tan\beta$ values.

Status of NMSSM after this result

Dermisek and Gunion consider status of NMSSM after this result

New constraints on a light CP-odd Higgs boson and related NMSSM Ideal Higgs Scenarios.

Radovan Dermisek

Department of Physics, Indiana University, Bloomington, IN 47405

John F. Gunion

Department of Physics, University of California, Davis, CA 95616, USA
and
Theory Group, CERN, CH-1211, Geneva 23, Switzerland

Abstract: Recent BaBar limits on $BR(\Upsilon(3S) \to \gamma a \to \gamma\tau^+\tau^-)$ and $BR(\Upsilon(3S) \to \gamma a \to \gamma\mu^+\mu^-)$ provide increased constraints on the $ab\bar{b}$ coupling of a CP-odd Higgs boson, a, with $m_a < M_{\Upsilon(3S)}$. We extract these limits from the BaBar data and compare to the limits previously obtained using other data sets, especially the CLEO-III $BR(\Upsilon(1S) \to \gamma \to \tau^+\tau^-)$ limits. Comparisons are made to predictions in the context of "ideal"-Higgs NMSSM scenarios, in which the lightest CP-even Higgs boson, h_1, can have mass below 105 GeV (as preferred by precision electroweak data) and yet can escape old LEP limits by virtue of decays to a pair of the lightest CP-odd Higgs bosons, $h_1 \to a_1 a_1$, with $m_{a_1} < 2m_B$. Most such scenarios with $m_{a_1} < 2m_\tau$ are eliminated, but the bulk of the $m_{a_1} > 7.5$ GeV scenarios, which are theoretically the most favored, survive. We also outline the impact of preliminary ALEPH LEP results in the $e^+e^- \to Z + 4\tau$ channel. For $\tan\beta \geq 3$, only NMSSM ideal Higgs scenarios with $m_{h_1} \sim 105$ GeV (the upper limit of "ideal") and m_{a_1} close to $2m_B$ satisfy the preliminary ALEPH limits. For $\tan\beta \lesssim 2$, the ALEPH results pick out the most theoretically preferred NMSSM scenarios which are those with m_{a_1} close to $2m_B$ and $m_{h_1} \sim 90$ GeV $-$ 100 GeV.

Keywords: Higgs, NMSSM, BaBar, ALEPH.

This analysis may be sensitive to other physics processes we have not considered.

Expected significance

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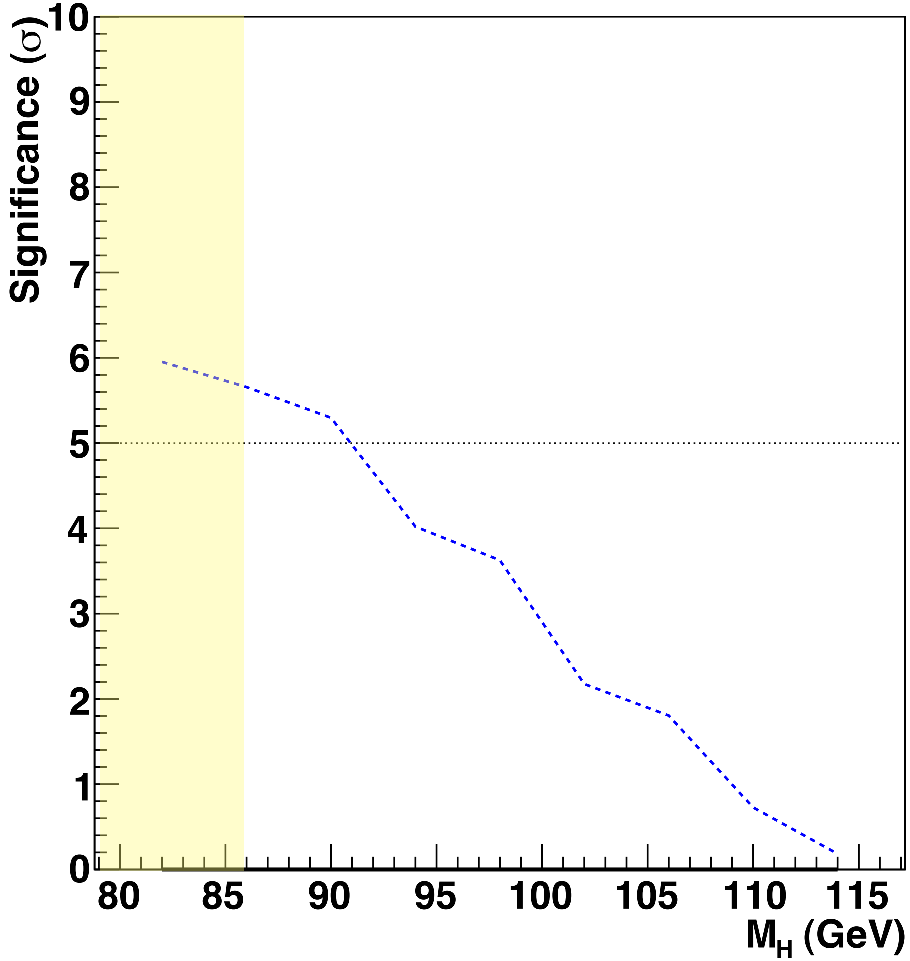
For what it's worth: Our goal was not to just set a limit... certainly not a mediocre one. We saw we had discovery sensitivity early on, so we really went for a discovery.

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

expected discovery significance for m_a = 4 GeV



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: $a \to \mathrm{jets}, \mu, ..$

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 $Z \to ll$ exclude events with $M(j_1, j_2, \mathrm{invisible}) > 60\mathrm{GeV}$
  4. in $Z \to \nu\nu$ 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 $h \to aa \to q\bar{q}, gg$ if it exists)

Blind analysis

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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

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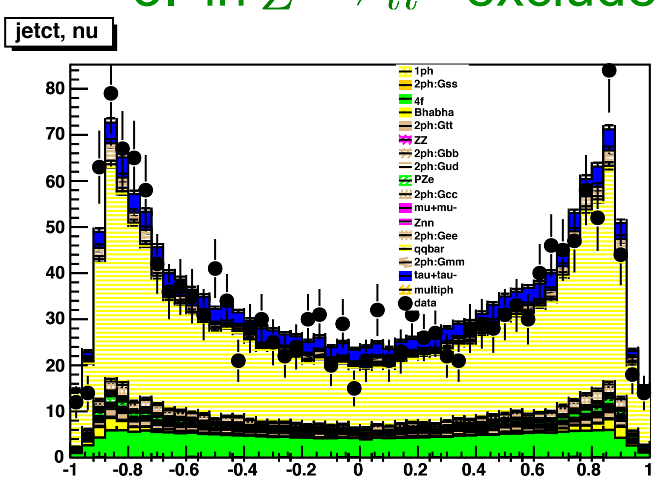

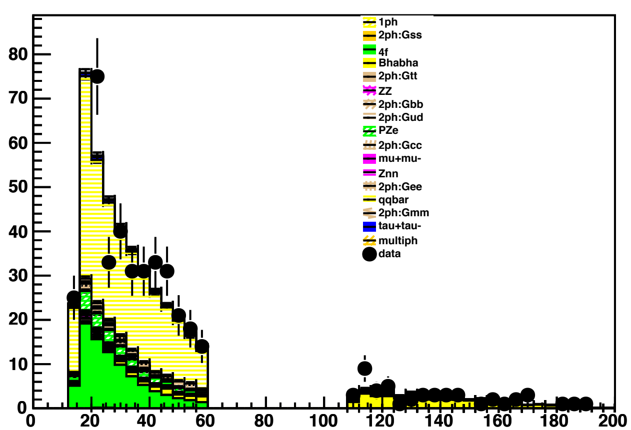

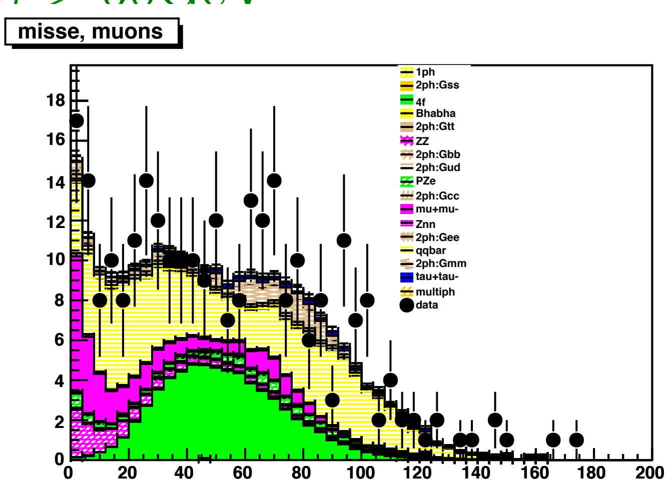

“Unboxing” celebration

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Particle Physics

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)

Thanks, Neal!

Oct. 9, 2009

Some results from LEP Higgs searches

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

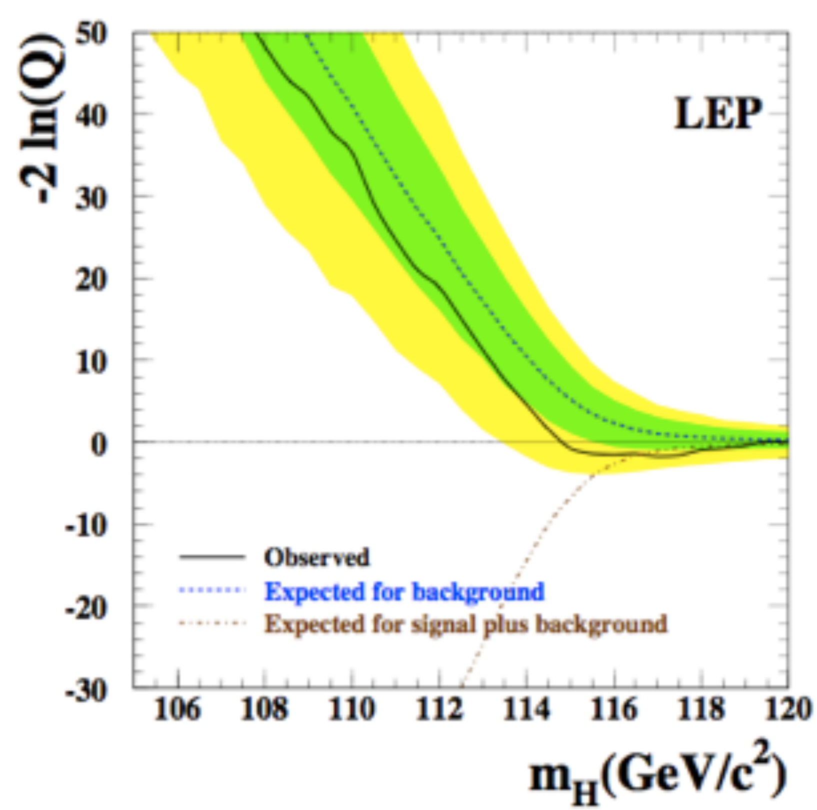
- SM searches dominated by $H \to bb, \tau\tau$

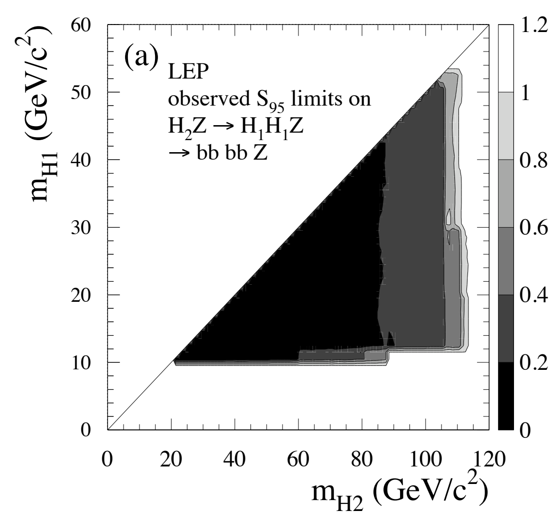
Searches for neutral Higgs bosons in the MSSM also quite stringent

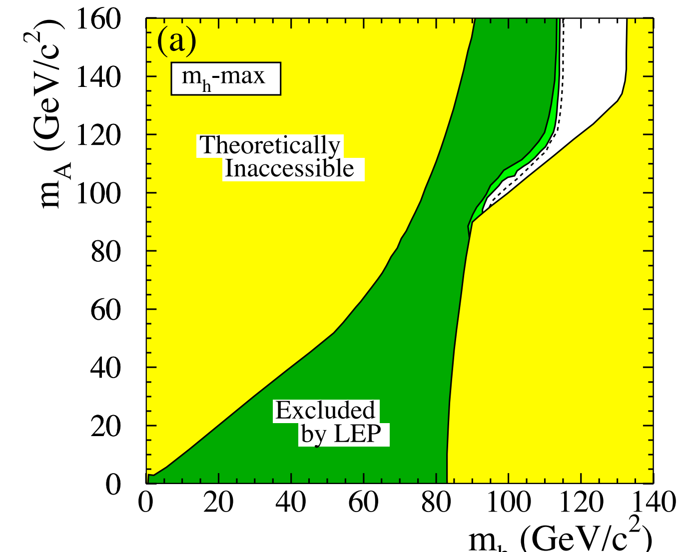
- m_h, m_A < 93 for $0.5 < \tan\beta < 2.5$ in "m_h-max" scenario

Decay independent based on Z recoil place a lower limit at 82 GeV

- other decay topologies, flavor independent analyses, etc. were considered.







LEP Higgs limits in H1, H2 plane

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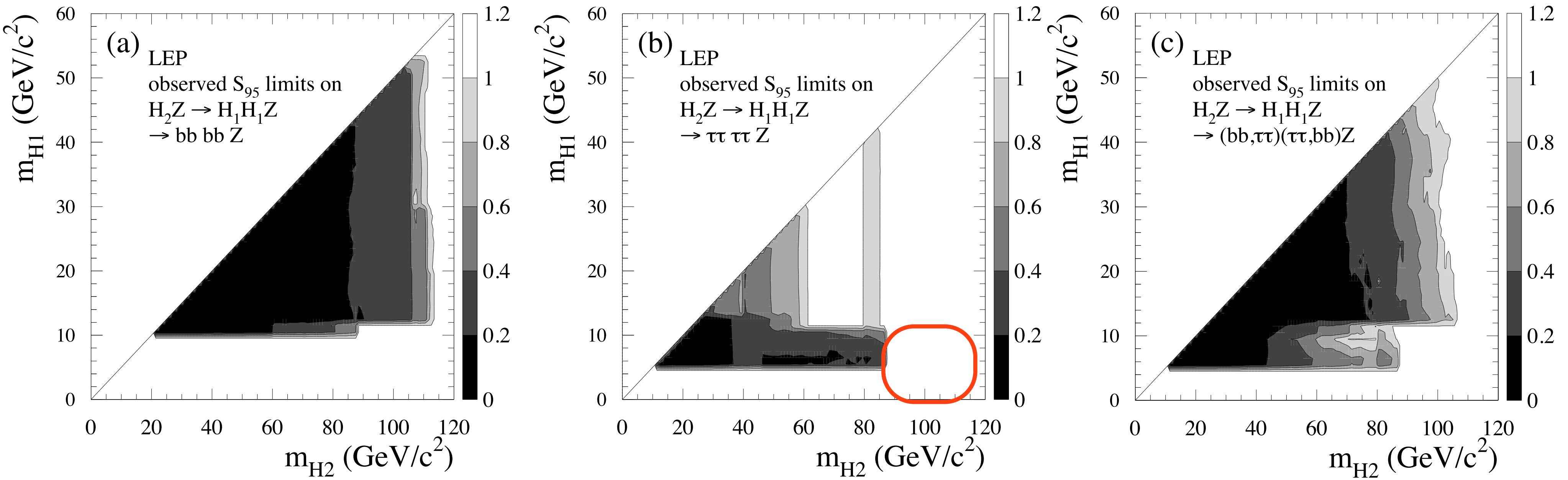
Search for Neutral MSSM Higgs Bosons at LEP

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 $m_h > 85$ GeV, $2m_\tau < m_a < 10$ GeV

Similar Searches at the LHC

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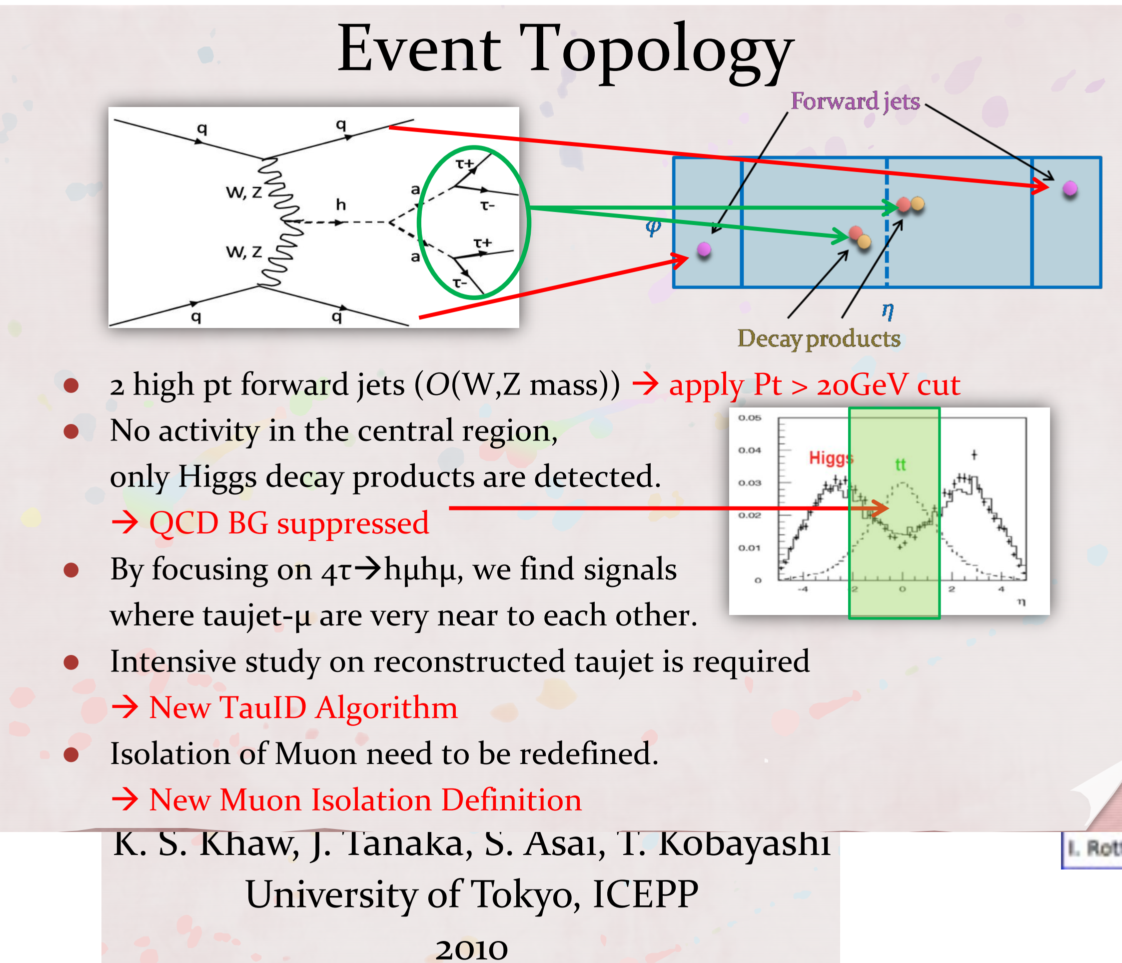
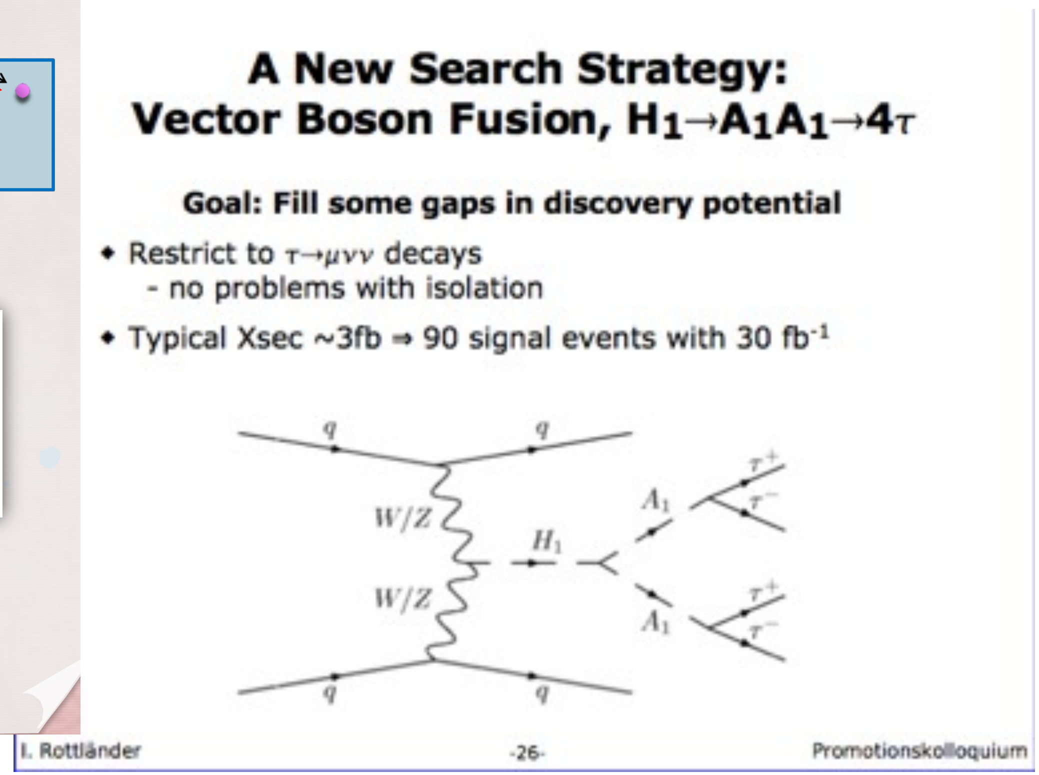
Searches for similar Higgs scenarios have been considered

- hadronic taus have significant QCD background, focus is on events with 2 or more muons (from tau decays)
- Lots of backgrounds; challenging search for the LHC





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

Phys. Rev. Lett.103:061801,2009

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

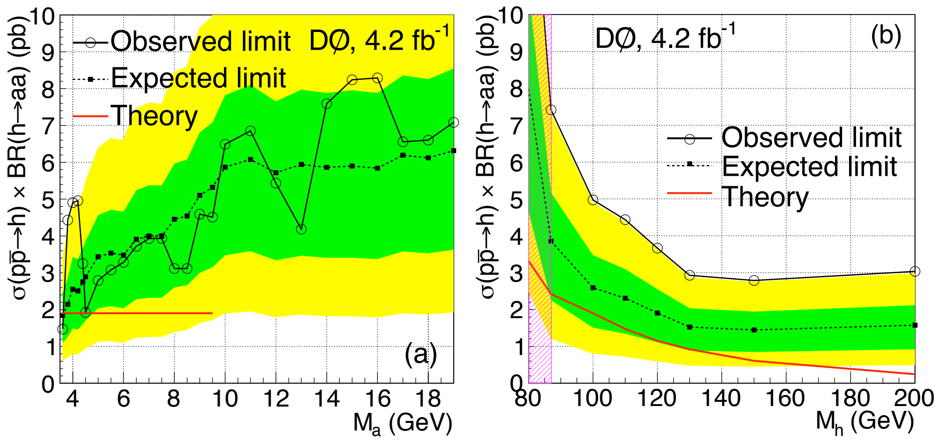


FIG. 3: The expected and observed limits and ±1 s.d. and ±2 s.d. expected limit bands for $\sigma(p\bar{p} \to h+X) \times \mathrm{BR}(h \to aa)$, for (a) M_h=100 GeV and (b) M_a=4 GeV. The signal for $\mathrm{BR}(h \to aa)$=1 is shown by the solid line. The region M_h<86 GeV is excluded by LEP.

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

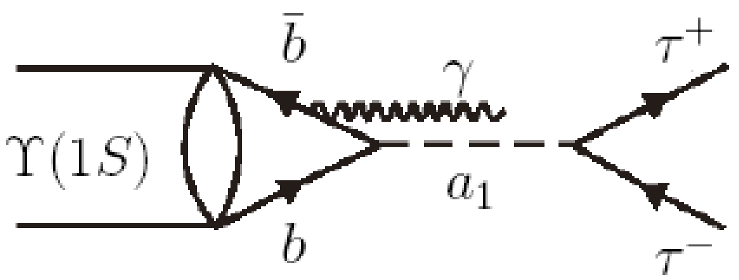
(Dated: March 8, 2009)

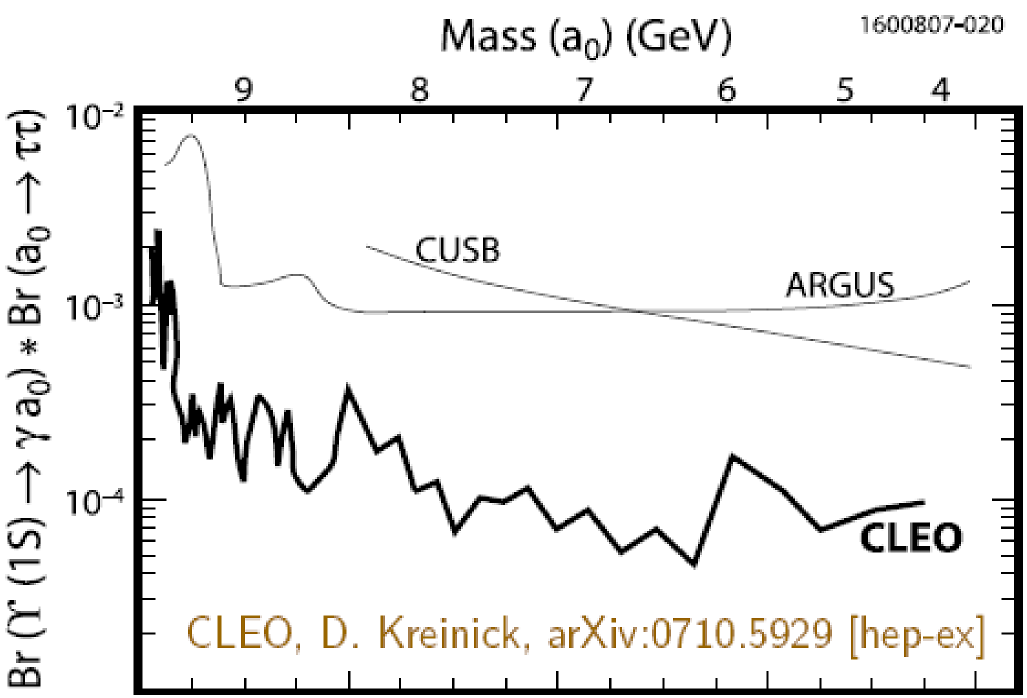
These searches are probing ~1% of the expected production cross-section.

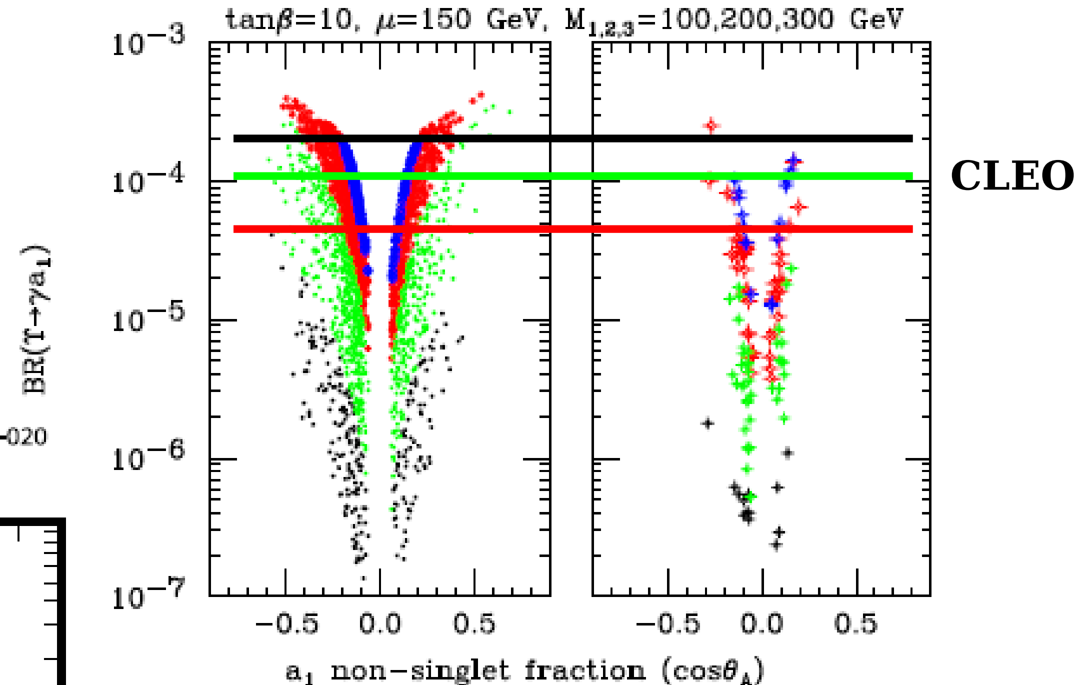
- there are not enough signal events at LEP to compete

However, the 4τ signature is significantly more difficult at hadron colliders than at LEP, due to QCD backgrounds.

Constraints from CLEO/BaBar







A_κ, A_λ, κ, λ scan $F < 15$ scan

$m_{a_1} < 2m_\tau$

$2m_\tau < m_{a_1} < 7.5\,GeV$

$7.5\,GeV < m_{a_1} < 8.8\,GeV$

$8.8\,GeV < m_{a_1} < 9.2\,GeV$

$$\mathcal{L}_{af\bar{f}} \equiv iC_{af\bar{f}} \frac{ig_2 m_f}{2m_W} \bar{f}\gamma_5 f a \,,$$

Summary of similar LEP searches

$e^+e^- \to \mathcal{H}_2 Z \to (\mathcal{H}_1\mathcal{H}_1)Z \to$ (...)(...)			$m_{\mathcal{H}_2}$	$m_{\mathcal{H}_1}$	
(any)($q\bar{q}$)	91	16.2	12 – 70	< 0.21	[46]
(V^0V^0)(any but $\tau^+\tau^-$)	91	9.7	0.5 – 55	< 0.21	[46]
($\gamma\gamma$)(any)	91	12.5	0.5 – 60	< 0.21	[46]
(4 prongs)(any)	91	12.9	0.5 – 60	0.21 – 10	[46]
(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]
(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]
($\mathcal{H}_1 \to$ bb,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.