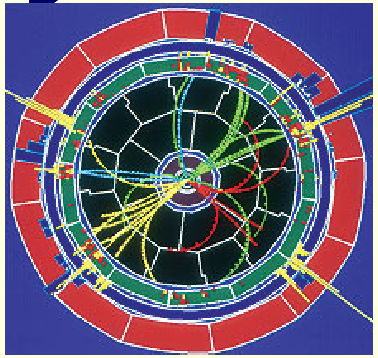
Search for neutral Higgs bosons decaying into four τ at LEP2



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Outline

- Introductory comments
- Motivations for a “new” Higgs search at LEP
- ALEPH data and Montecarlo
- Event Selections
- Interpretations and Results
- Conclusions

NEW RESULTS: FIRST TIME PUBLIC HERE @ La Thuile !!!!

- LEP stopped in 2000: after 10 years there are still some uncovered analyses

- Theoretical hints for a missed low mass Higgs in a region NOT accessible to the LHC program

- Hard to look at the archived data. It was an archaeological exercise

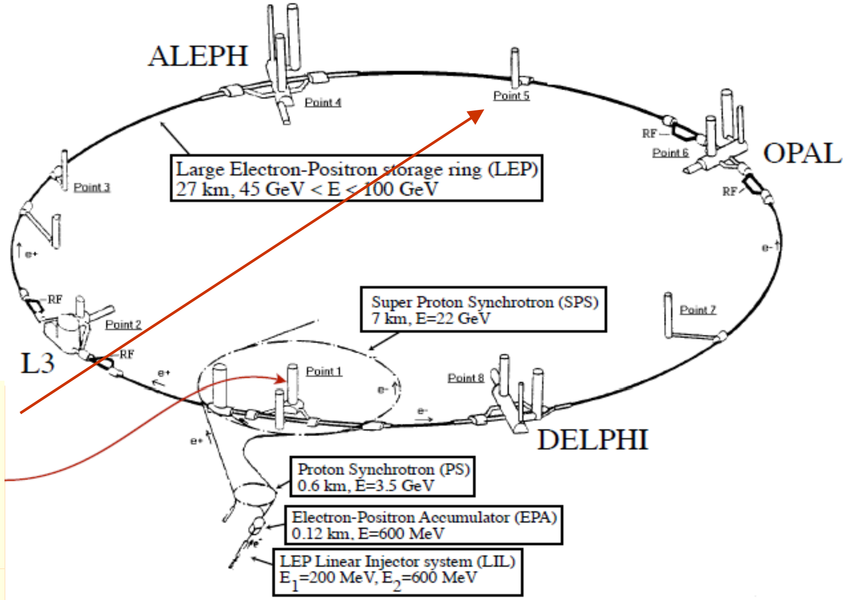
- Results are the subject of a recently submitted preprint (2 days ago!!!) by the ALEPH Collaboration:
  arXiv:1003.0705v1 (to be submitted to JHEP)

LEP

LEP operated from 1989-2000

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

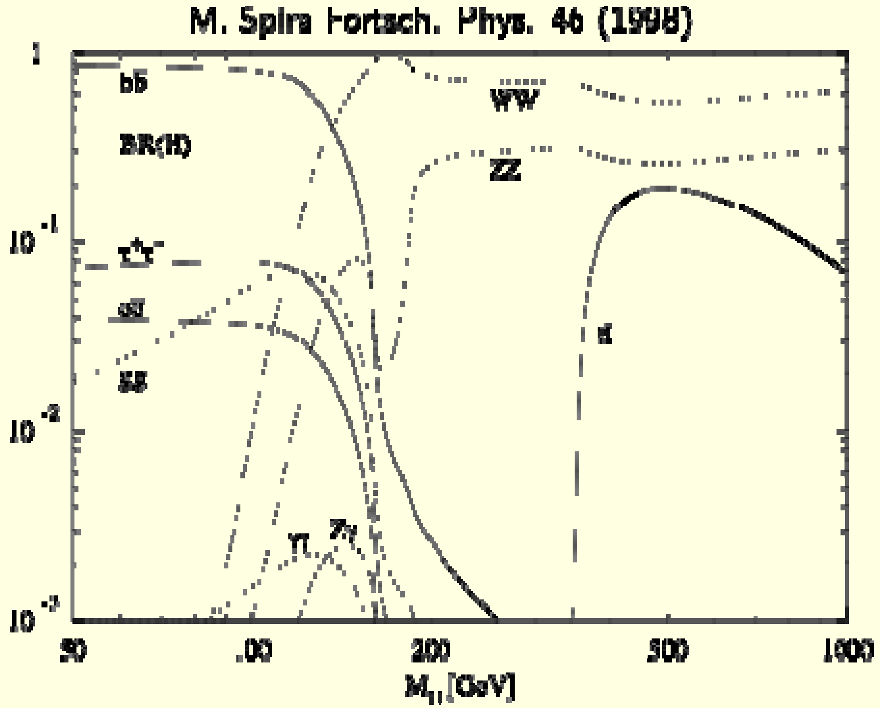
E_{CM} (GeV)	183	189	192	196	200	202	205	207
$\int \mathcal{L}\,dt$ (pb^{-1})	56.82	174.21	28.93	79.83	86.30	41.90	81.41	133.21

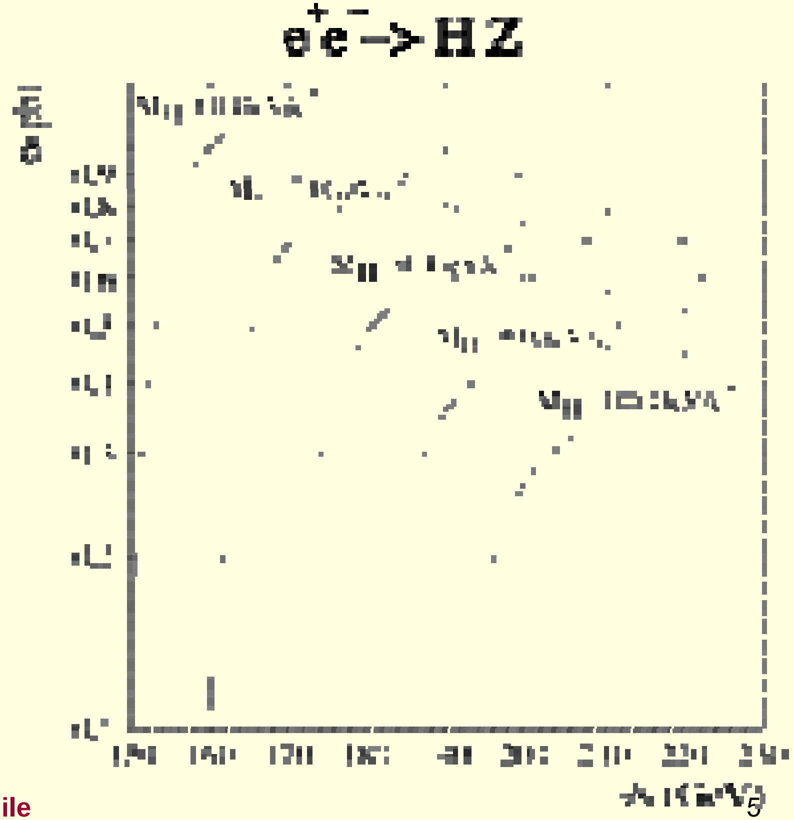


ATLAS and CMS cavern started the excavation directly above the LEP tunnel in the last days of running

Higgs production at LEP

- Higgs primarily produced higgsstrahlung process
  - kinematic upper bound for production ~115 GeV
  - in that mass range, standard model Higgs decays dominated by $H \to bb, \tau\tau$

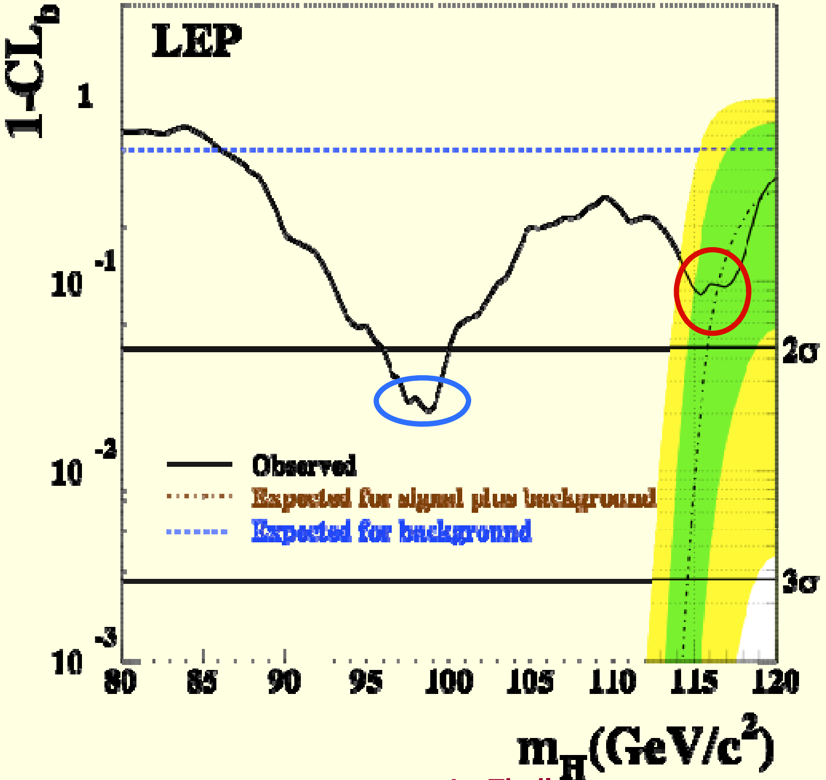

M. Spira Fortsch. Phys. 46 (1998)


$e^+e^- \to HZ$

Higgs Searches at LEP

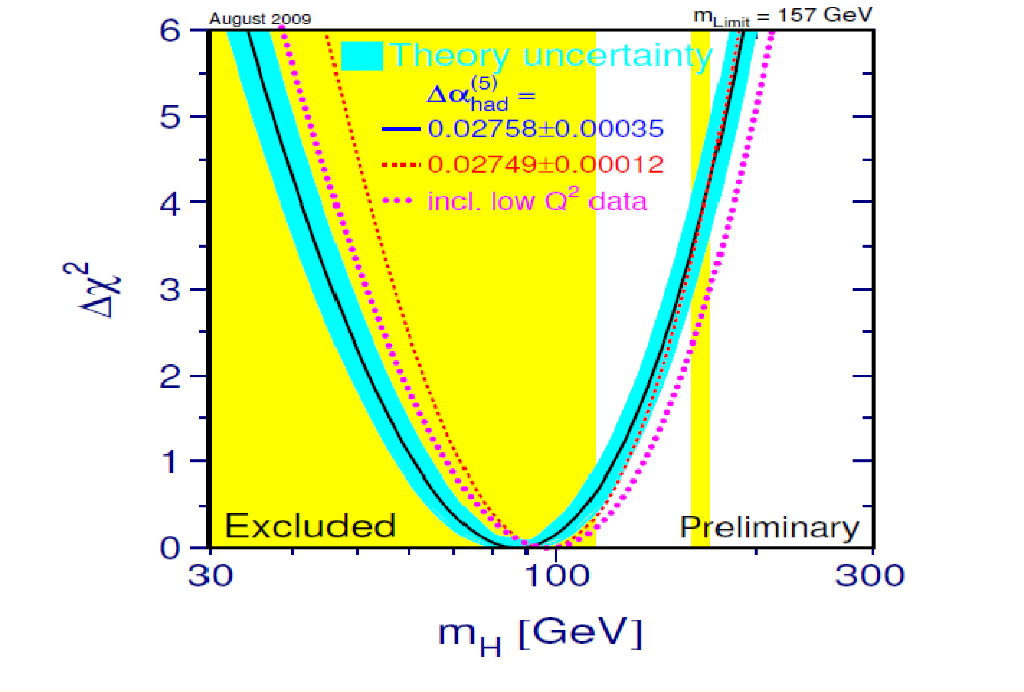
Searches dominated by H→bb, ττ

- Direct searches for Standard Model Higgs put a limit at $M_H > 114.4$ GeV
    - Decay independent limit (from Z recoil) at 82 GeV
    - Excesses observed at 98 and 115 GeV but < 3σ



Higgs Searches

- Electroweak fits prefer a Higgs lighter than 100 GeV



At 95% CL, $m_{h_{SM}} < 157\ \mathrm{GeV}$ and the $\Delta\chi^2$ minimum is near $85\ \mathrm{GeV}$ when all data are included.

Higgs Searches

- Electroweak fits prefer a Higgs lighter than 150 GeV
- No indication of new Physics below the TeV scale

- Introduce fine tuning problems for SM and MSSM

- LEP paradox:
    - Hard maintain naturalness if m_H<150 GeV and new Physics (SUSY) at the TeV scale

- This has motivated theories with extended Higgs sectors or next-to-minimal supersymmetric extension to the SM

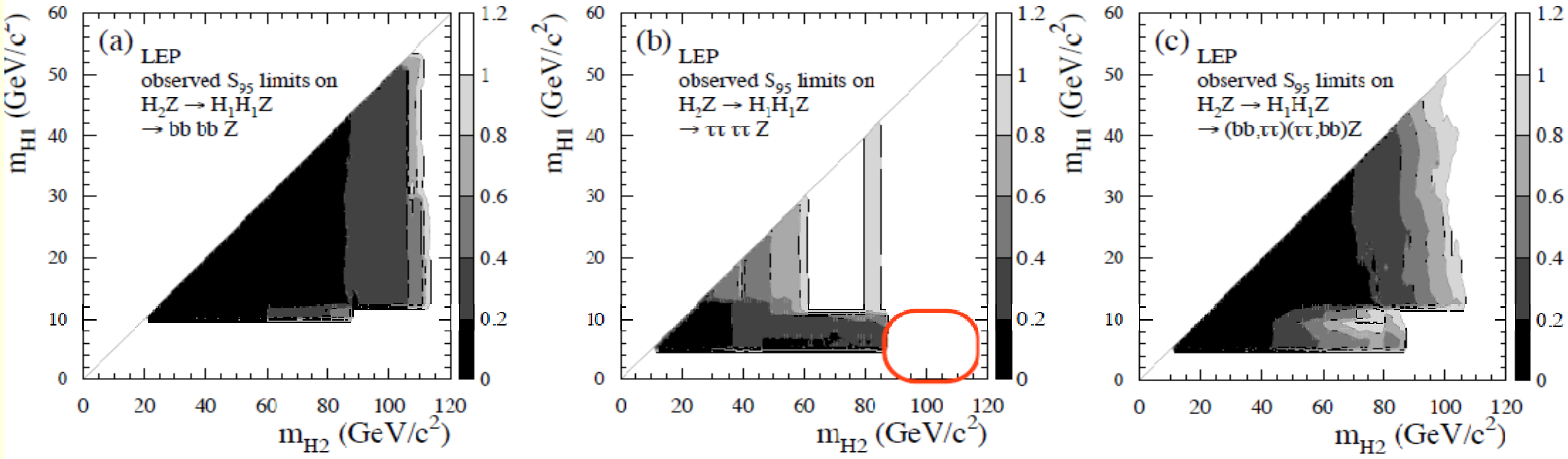
How could we have missed the Higgs at LEP?

- 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 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?
  - it depends: in some existing searches may still be sensitive
  - but there is no easy and accurate way to determine the efficiency of existing analyses to alternative models

LEP limits for $H_2Z \rightarrow H_1 H_1$ in the H_1 H_2 plane (for issance H1 = pseudoscalar a)

Search for Neutral MSSM Higgs Bosons at LEP

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

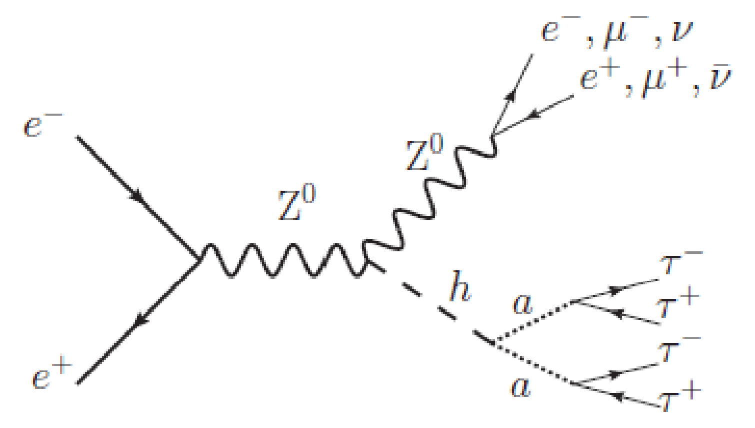


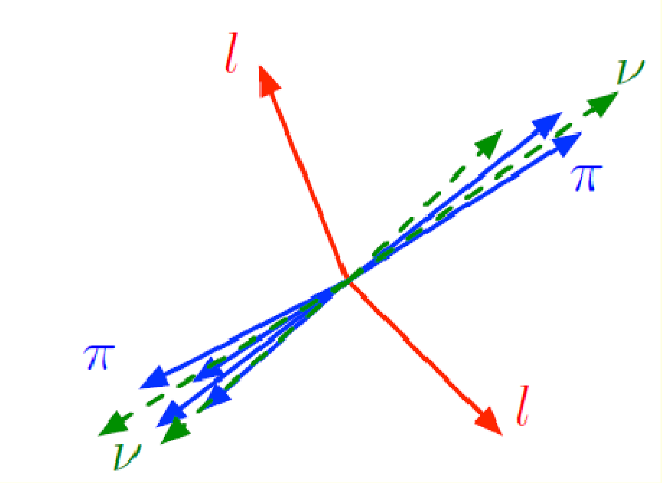
(factor x SM cross section that corresponds to 95% exclusion)

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

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

Higgs reconstruction in 4 taus



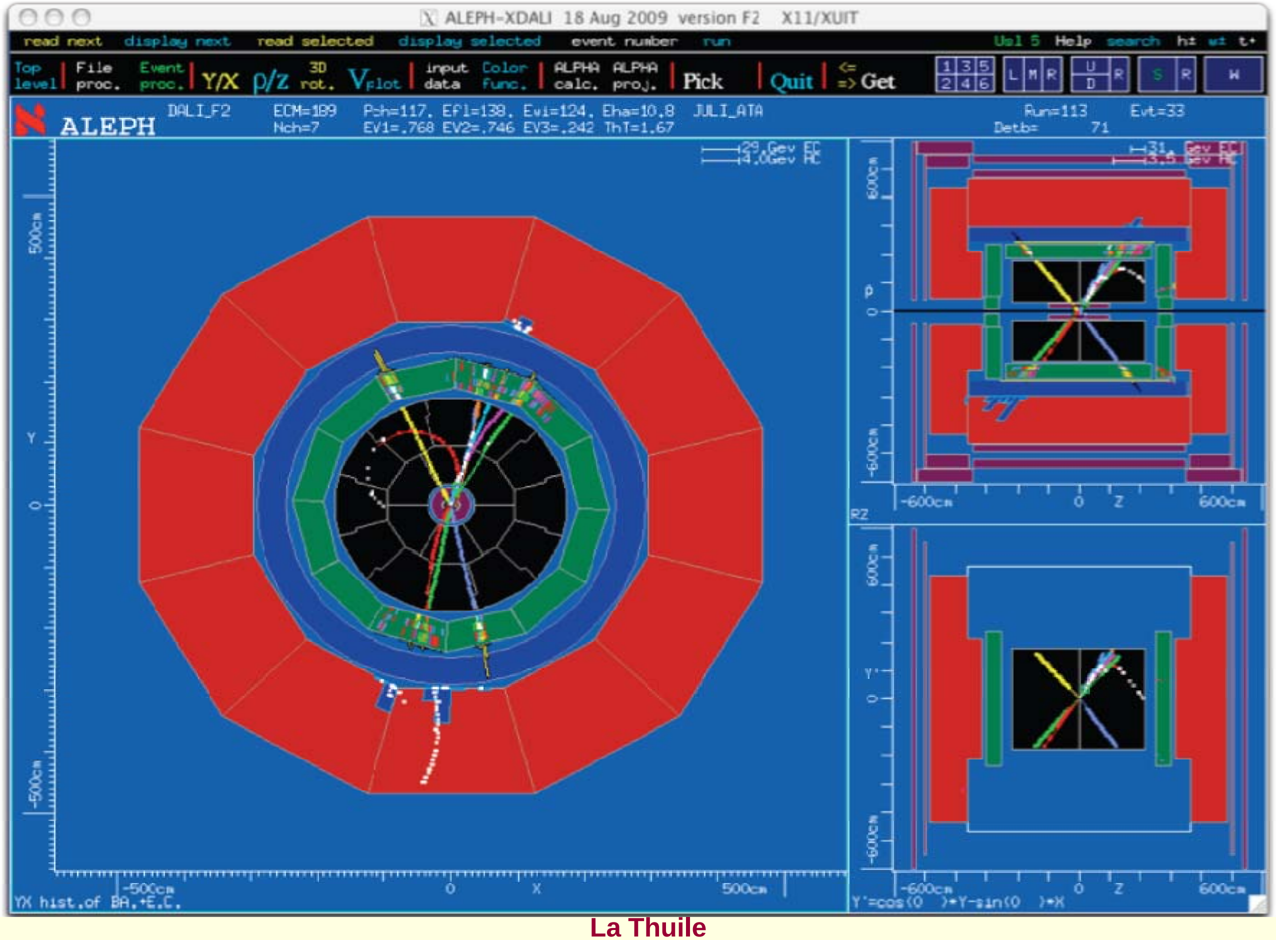


- $e^+e^- \rightarrow HZ \rightarrow aa\,\ell\ell \rightarrow \tau\tau\tau\tau\,\ell\ell$
- At LEP the centre-of-mass energy is known
- M_H as recoil to Z: clean topology
- 4-vector constraint for neutrinos

ALEPH

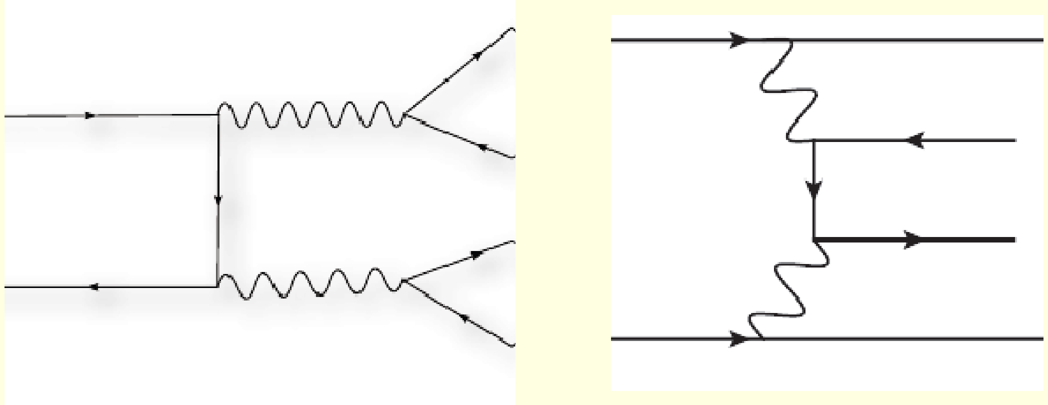
Simulated event $e^+e^- \to ZH \to 2e4\tau$

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)



Monte Carlo simulation

- More than 10 years of running in a very clean environment and tuning MC to data
- Very good description of SM processes in the ALEPH MC
- 2 important background processes for this search:
  - 4 fermions
  - $\gamma\gamma$



Monte Carlo simulation

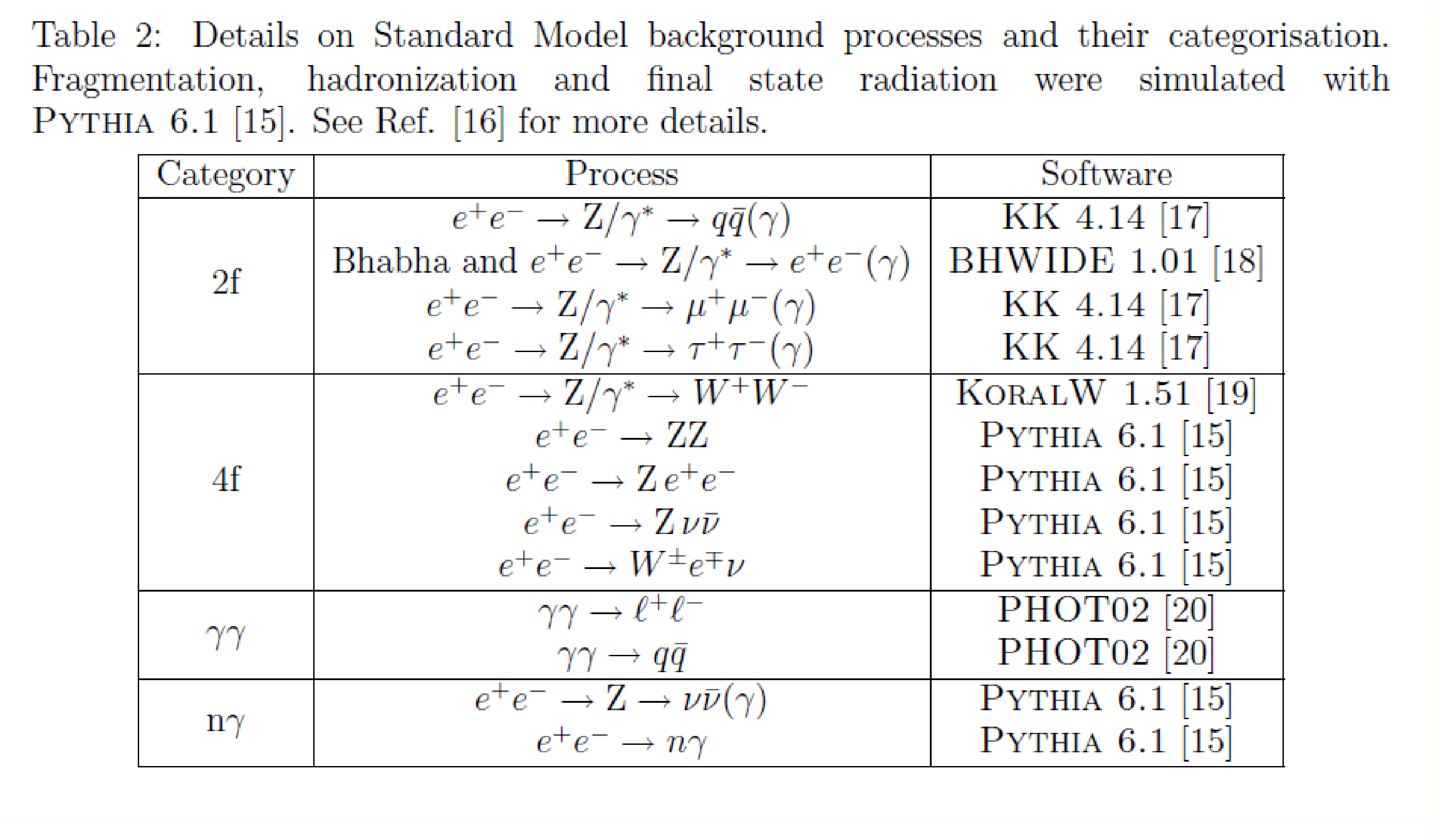


Table 2: Details on Standard Model background processes and their categorisation. Fragmentation, hadronization and final state radiation were simulated with PYTHIA 6.1 [15]. See Ref. [16] for more details.

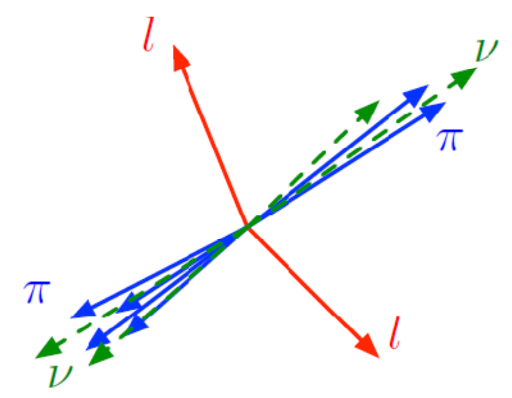
Category	Process	Software
2f	$e^+e^- \to Z/\gamma^* \to q\bar{q}(\gamma)$	KK 4.14 [17]
	Bhabha and $e^+e^- \to Z/\gamma^* \to e^+e^-(\gamma)$	BHWIDE 1.01 [18]
	$e^+e^- \to Z/\gamma^* \to \mu^+\mu^-(\gamma)$	KK 4.14 [17]
	$e^+e^- \to Z/\gamma^* \to \tau^+\tau^-(\gamma)$	KK 4.14 [17]
4f	$e^+e^- \to Z/\gamma^* \to W^+W^-$	KORALW 1.51 [19]
	$e^+e^- \to ZZ$	PYTHIA 6.1 [15]
	$e^+e^- \to Z\,e^+e^-$	PYTHIA 6.1 [15]
	$e^+e^- \to Z\,\nu\bar{\nu}$	PYTHIA 6.1 [15]
	$e^+e^- \to W^\pm e^\mp \nu$	PYTHIA 6.1 [15]
$\gamma\gamma$	$\gamma\gamma \to \ell^+\ell^-$	PHOT02 [20]
	$\gamma\gamma \to q\bar{q}$	PHOT02 [20]
nγ	$e^+e^- \to Z \to \nu\bar{\nu}(\gamma)$	PYTHIA 6.1 [15]
	$e^+e^- \to n\gamma$	PYTHIA 6.1 [15]

Events selection

- $Z \rightarrow \ell\ell = \mu^+\mu^-, e^+e^-, \nu\nu$
- $H \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$
  - Two back-to-back jets of $a \rightarrow \tau^+\tau^-$ collimated due to the low a mass

    $$2m_\tau < m_a \lesssim 2m_b$$

  - Jet reco by Jade algorithm clustering with M_{jet}<15 GeV



  - τ selection with track multiplicity (one prong – three prong):
    - Each jet with 2, 4 or 6 tracks (72%, 25%,3%)

$H \rightarrow 4\tau$ and $Z \rightarrow \mu^+\mu^-, e^+e^-$

LOOSE

- Two muons /electrons identified with opposite charge
- $|\cos\theta_{j1}| < 0.9$, $|\cos\theta_{j2}| < 0.9$ for a proper containment of the jet in the tracking volume
- $\cos\theta_{jl} < 0.95$ for a good lepton isolation
- Missing Energy > 20 GeV
- Additional photons from f.s.r. added

FINAL

- $80 < M_Z < 102$ GeV/c^2
- $\cos\theta_{j1j2} < 0$ jets back to back
- $N_{track} = 2$ or 4 for each jet

$H \rightarrow 4\tau$ and $Z \rightarrow \nu\nu$

LOOSE

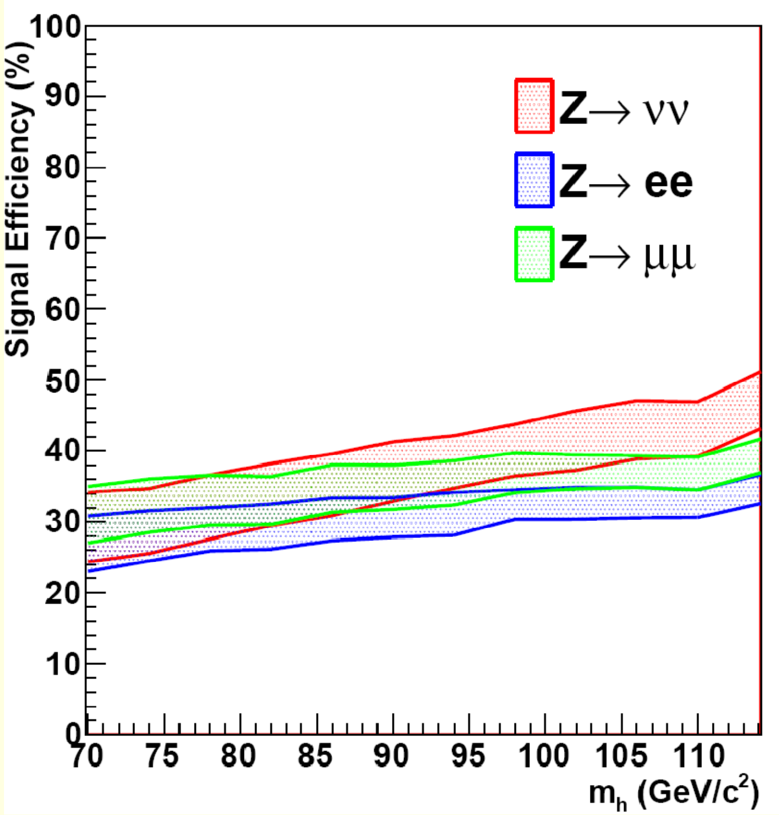
- $E_{vis} > 0.05\ E_{cm}$ reject the $\gamma\gamma$ background
- $|\cos\theta_{miss}| < 0.9$ missing momentum .. .. ..
- $m_{j1j2} > 10$ GeV/c^2 dijet invariant mass
- $|\cos\theta_{j1}| < 0.85$, $|\cos\theta_{j2}| < 0.85$
- $\cos\theta_{j1j2} < 0$ jets back to back
- $E_{j1} > 25$ GeV highest energy jet

FINAL

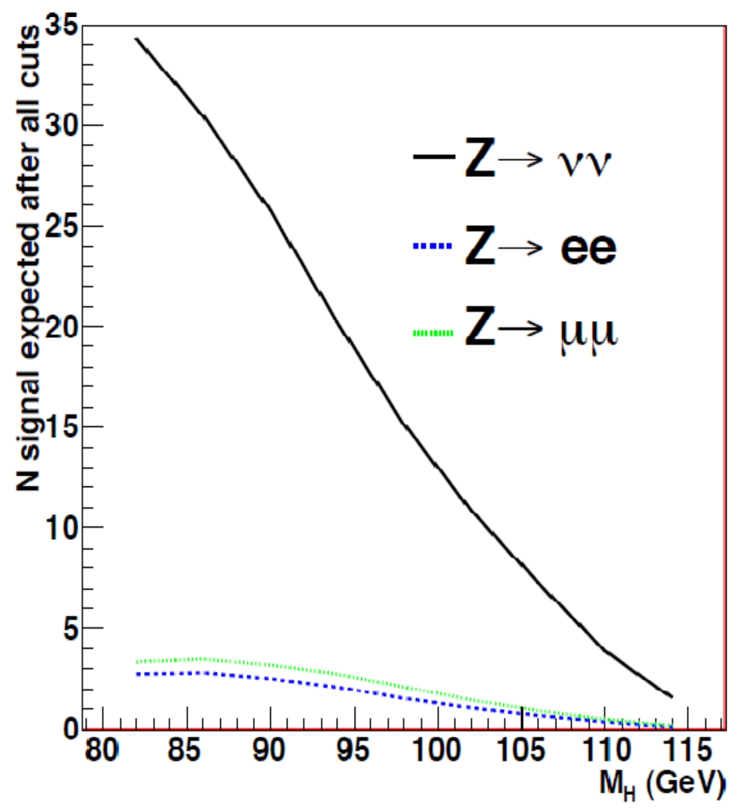
- $E_{j1} + E_{j2} + \text{miss}(E) > E_{cm} - 5$ GeV rejected events with events with energy deposits in the forward regions of the detector
- Miss(E)>60 GeV and miss(m)>90 GeV/c^2 Consistency with $Z \rightarrow \nu\nu$
- Ntrack = 2 or 4 for each jet

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

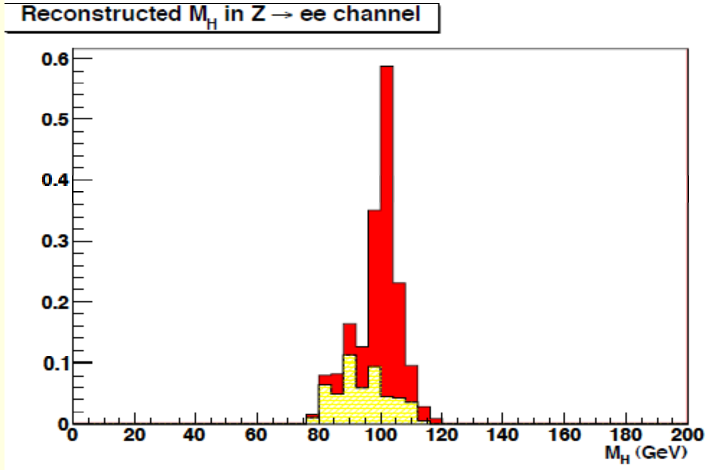


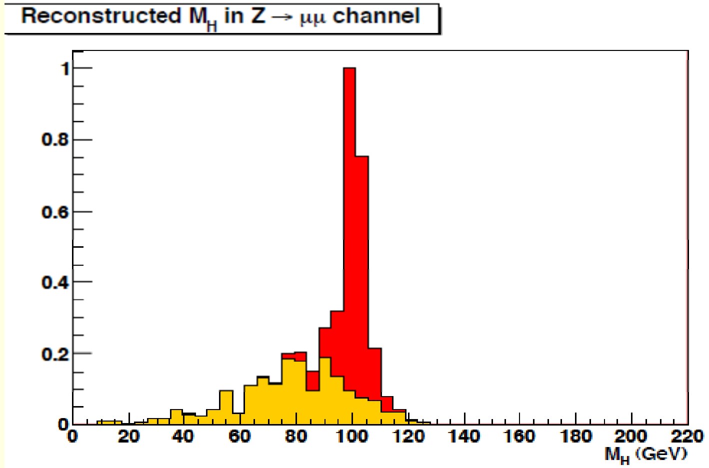
The upper (lower) portion of the efficiency band corresponds to m_a = 4 (10) GeV/c^2

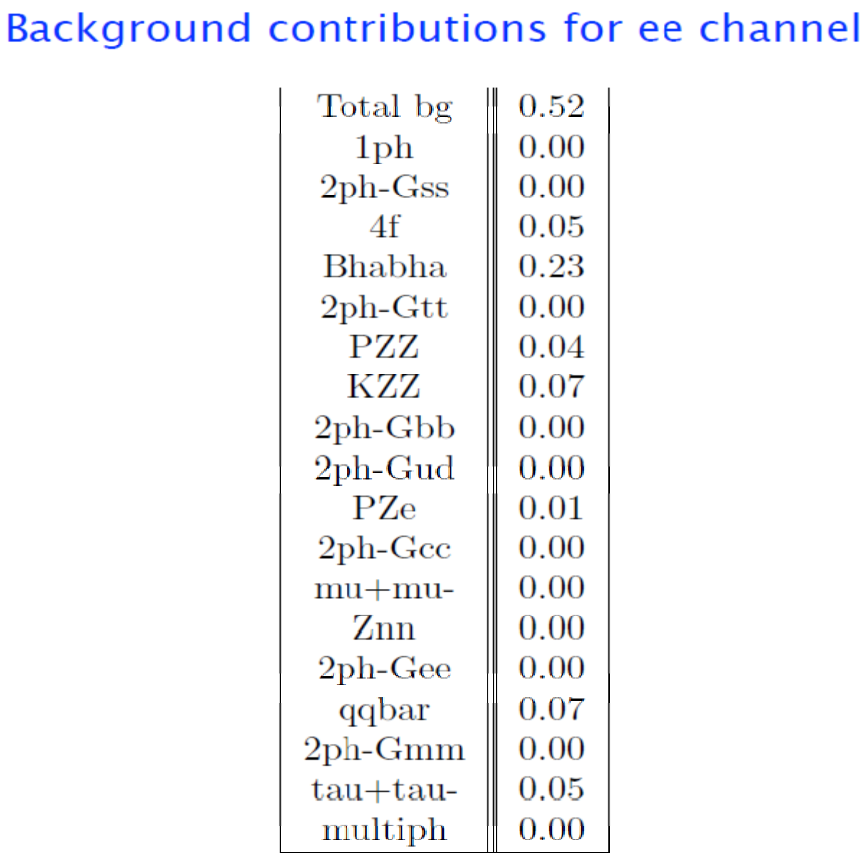


(m_a = 10 GeV/c^2)

Expectation for m_h=100 GeV



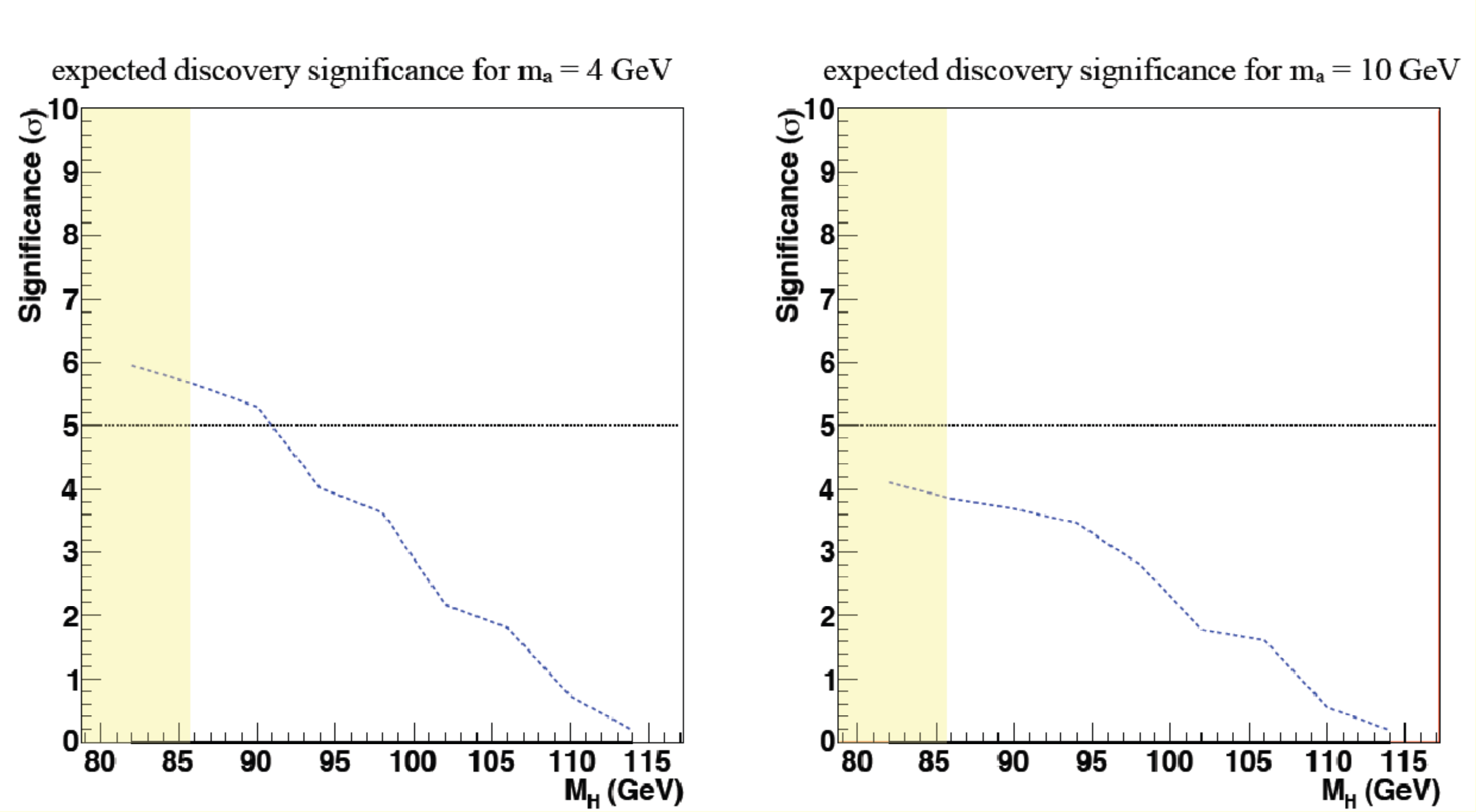




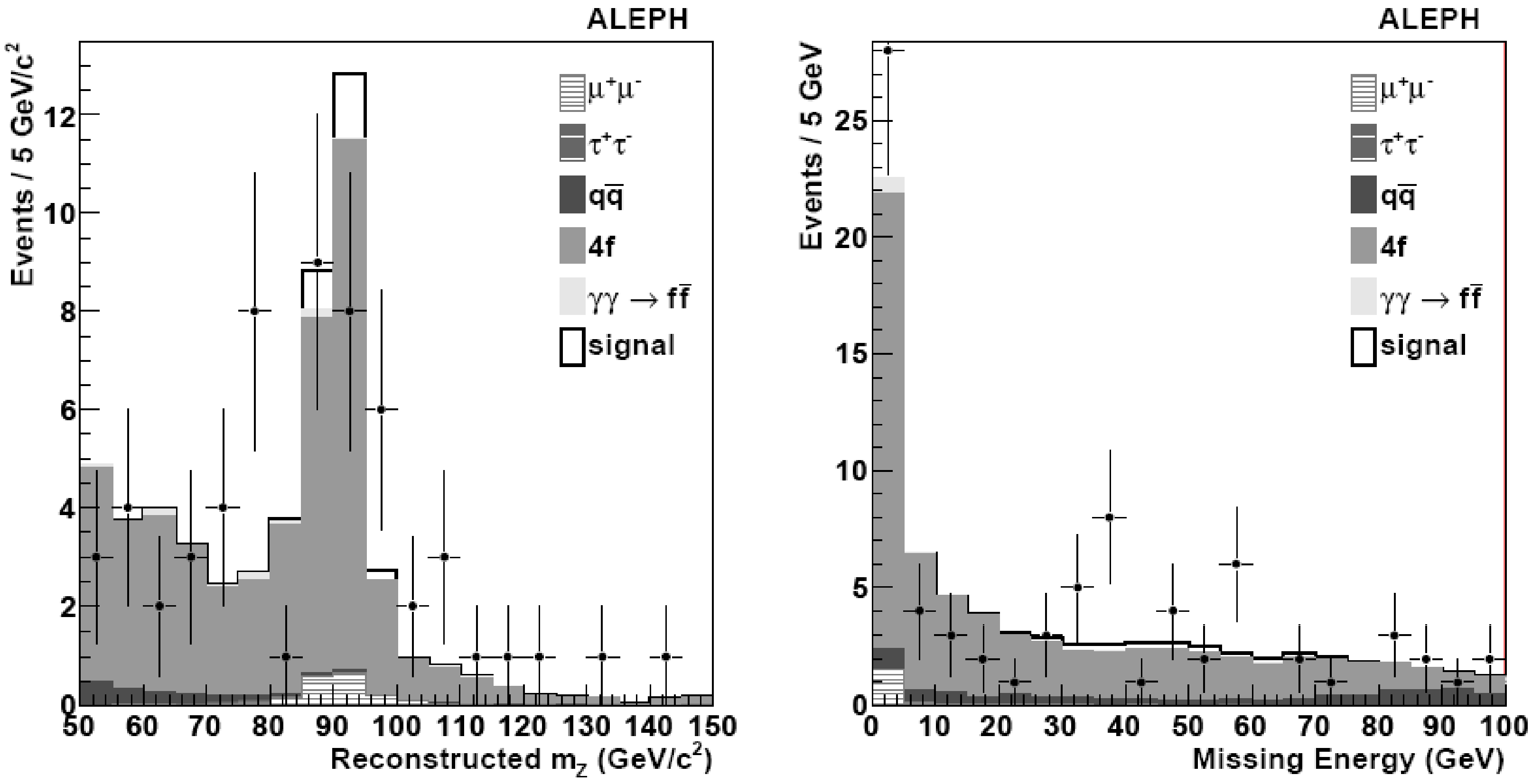
Background contributions for ee channel

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

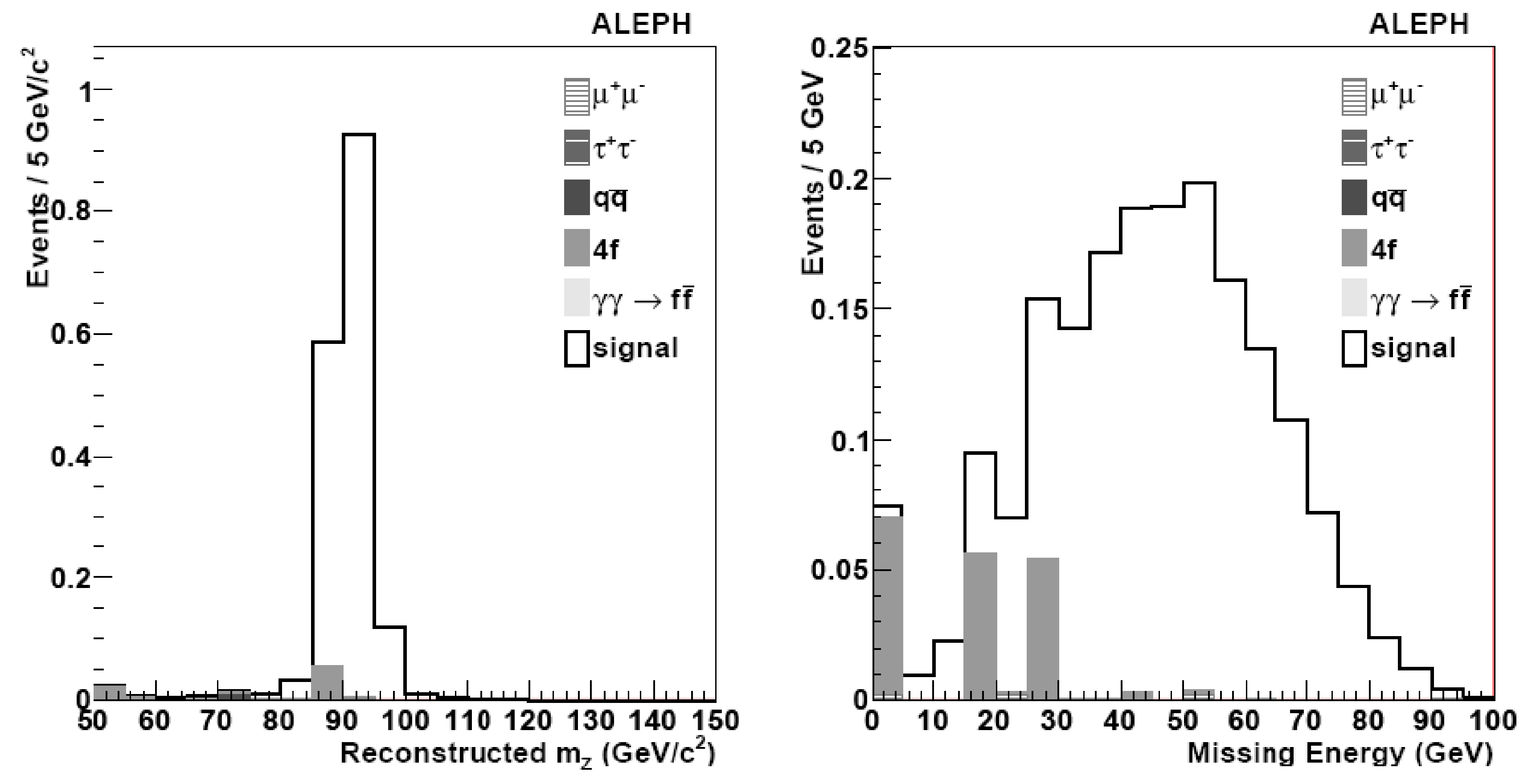
Discovery potential: 5σ sensitivity in an un-excluded region



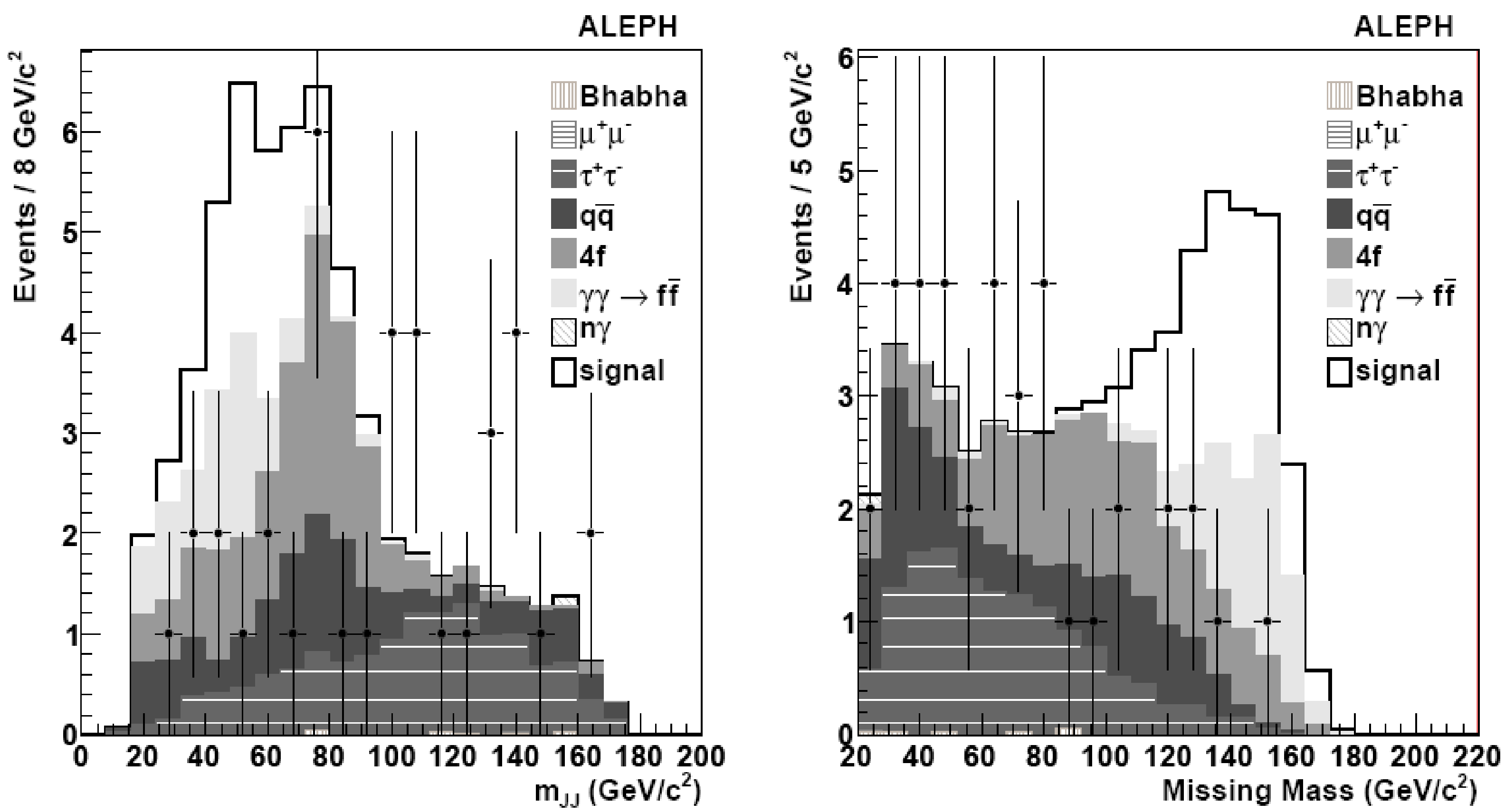
Loose selection: $H \rightarrow 4\tau$, $Z \rightarrow \mu^+\mu^-$



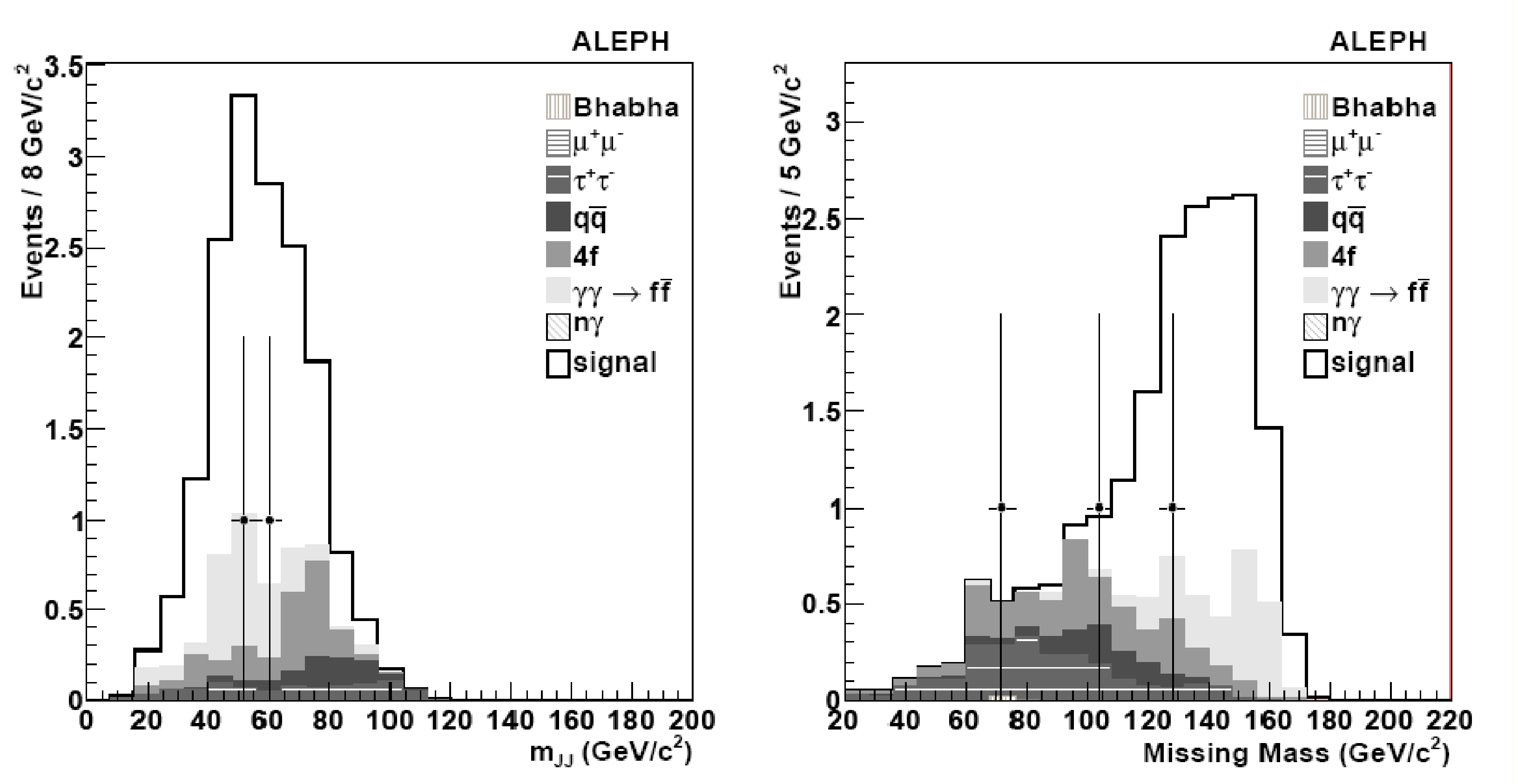
Final selection: $H \rightarrow 4\tau$, $Z \rightarrow \mu^+\mu^-$



Loose selection H→ 4τ , Z → νν



Final selection $H \rightarrow 4\tau$, $Z \rightarrow \nu\nu$



Selected events: No Excess observed

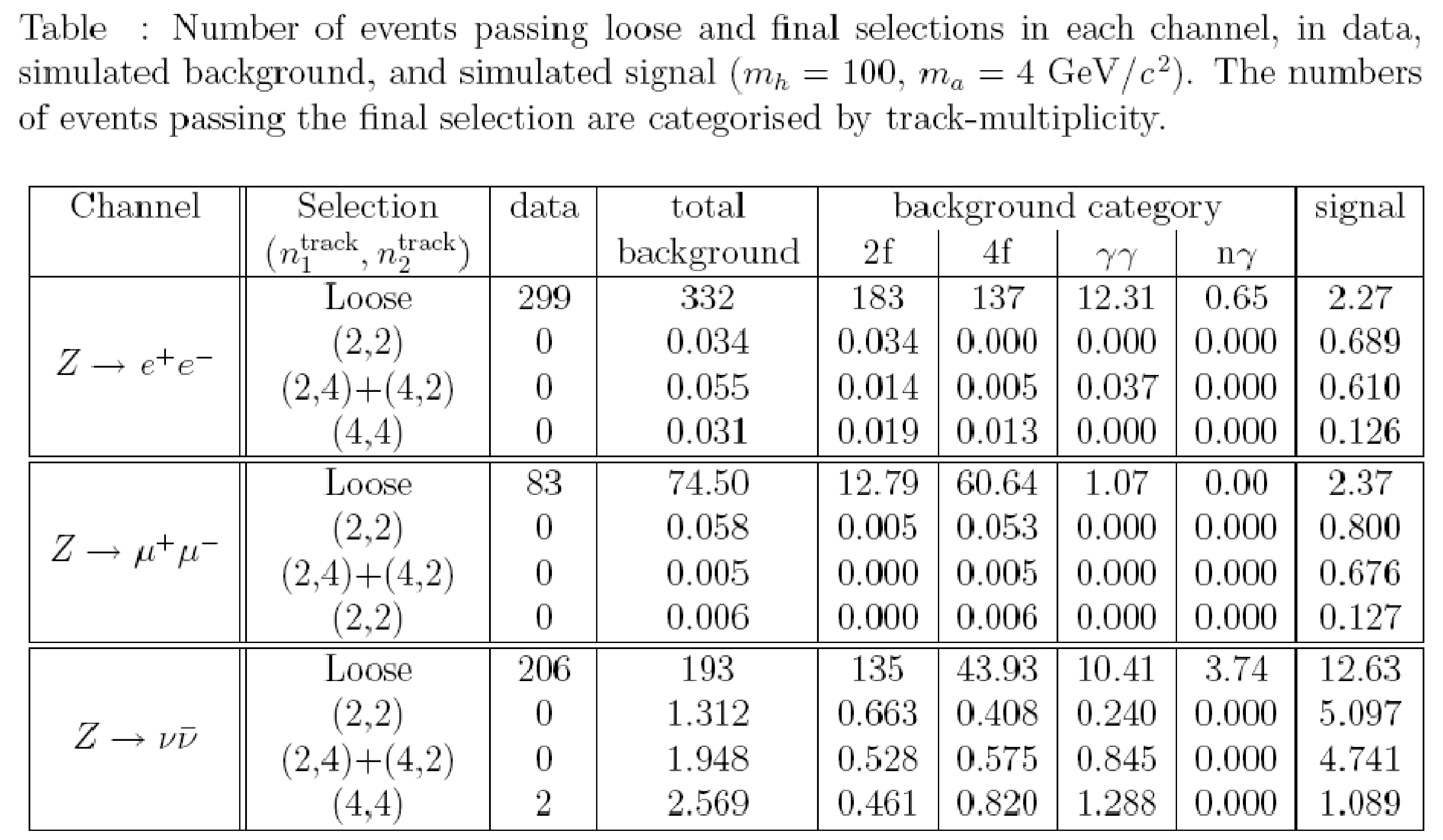
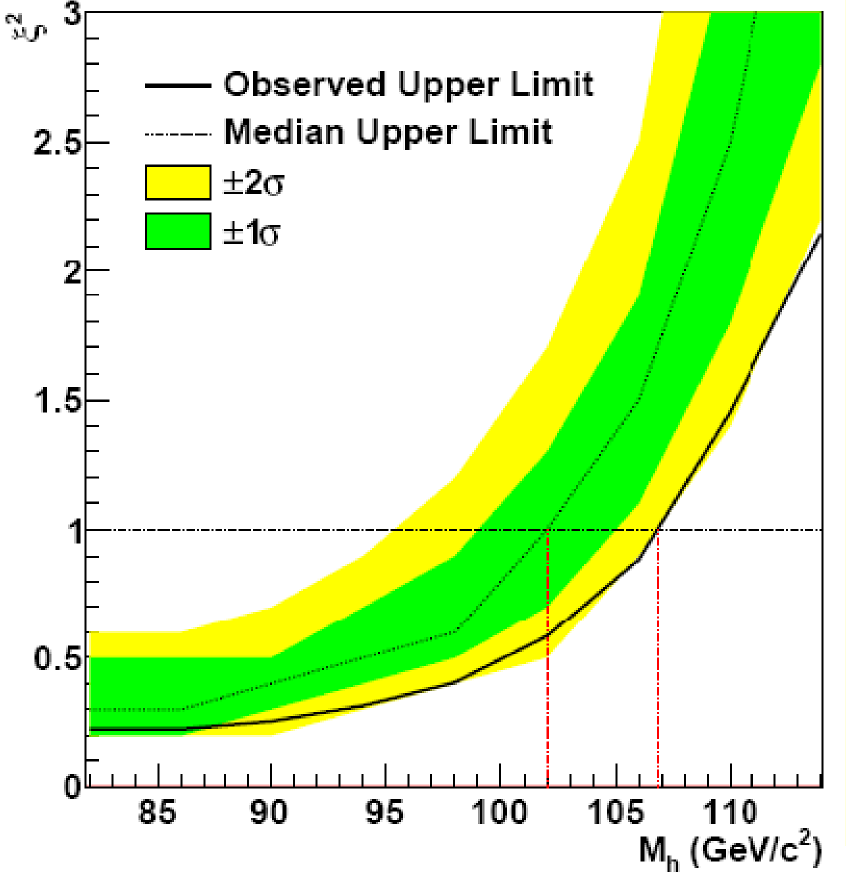


Table : Number of events passing loose and final selections in each channel, in data, simulated background, and simulated signal ($m_h = 100$, $m_a = 4$ GeV$/c^2$). The numbers of events passing the final selection are categorised by track-multiplicity.

Channel	Selection $(n_1^{\text{track}}, n_2^{\text{track}})$	data	total background	background category 2f	4f	$\gamma\gamma$	nγ	signal
$Z \rightarrow e^+e^-$	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
$Z \rightarrow \mu^+\mu^-$	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
$Z \rightarrow \nu\bar{\nu}$	Loose	206	193	135	43.93	10.41	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

Results: Limit on

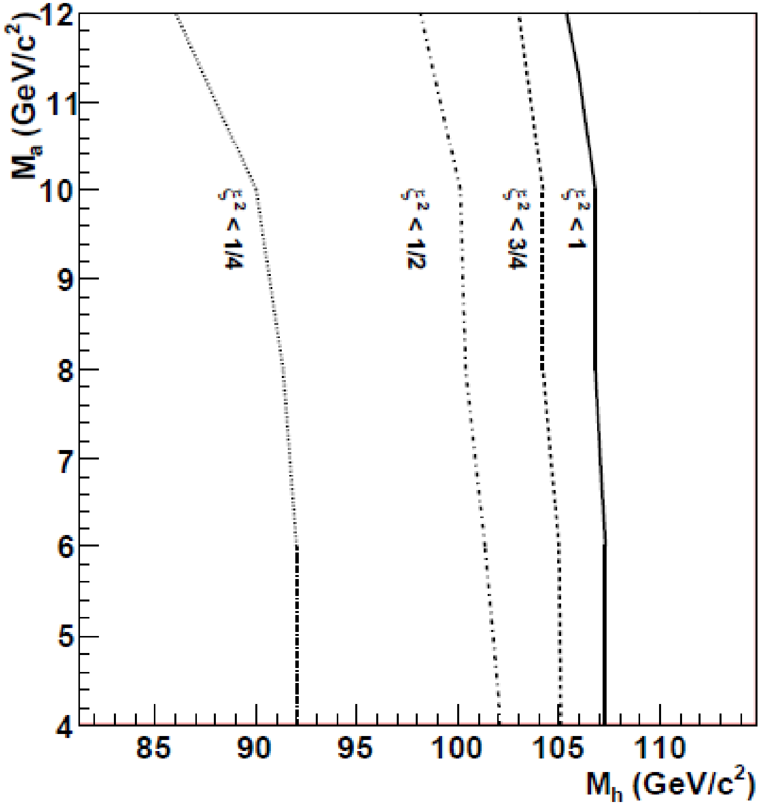
$$\xi^2 = \frac{\sigma\,\mathrm{BR}(h\to aa)\,\mathrm{BR}(a\to\tau\tau)^2}{\sigma_{SM}}$$



Observed and expected 95% confidence level limit on $\xi^2 = \frac{\sigma(e^+e^-\to Zh)}{\sigma_{SM}(e^+e^-\to Zh)} \times B(h\to aa)\times B(a\to\tau^+\tau^-)^2$ as a function of the Higgs boson mass for $m_a = 10\ \mathrm{GeV}/c^2$.

2d Limits on

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



Contour of observed 95% confidence level limit on ξ^2 in the $m_a - m_h$ plane.

Conclusions

- A search for the Higgs boson produced via higgsstrahlung at LEP2 energies has been performed, where h $\rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$ and

  Z $\rightarrow \ell\ell = \mu^+\mu^-$, e^+e^- , $\nu\nu$

- No evidence for an excess of events above background was observed

  limit on the combined production cross section times branching ratio, $\sigma(e^+e^- \rightarrow Zh)\times B(h \rightarrow aa)\times B(a \rightarrow \tau^+\tau^-)^2$ is presented.

- For $m_h < 107$ GeV/c^2 and $4 < m_a < 12$ GeV/c2 the quantity $\xi^2 < 1$ is excluded at 95% CL

- This analysis covers a region of parameter space previously left unexplored: namely $86 < m_h < 107$ GeV/c^2 and $4 < m_a < 12$ GeV/c^2, which further constrains models with non-standard Higgs decays, such as the NMSSM

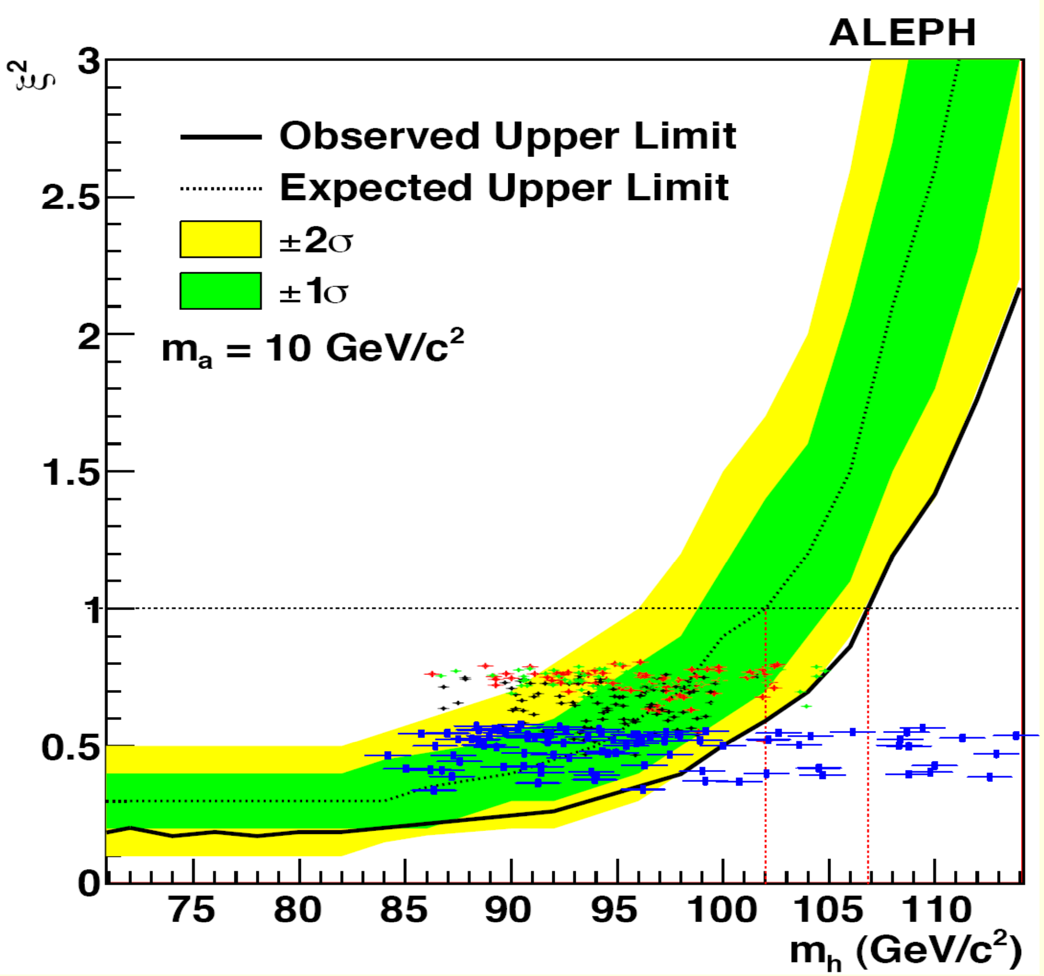
Acknowledgments

- Thanks to Neal Weiner and Riccardo Barbieri who triggered this work
- Thanks to Kyle, Itay and James from NYU who did most of the job
- Thanks to the old ALEPH Collaboration,

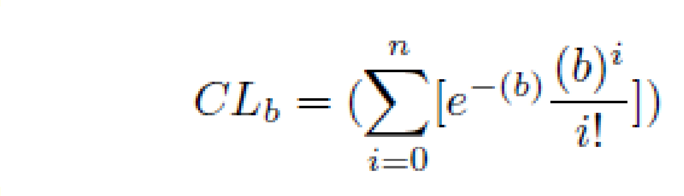
  especially the editorial board, for help, suggestions and review of the paper

Back-up slides…..

Limits vs Theory

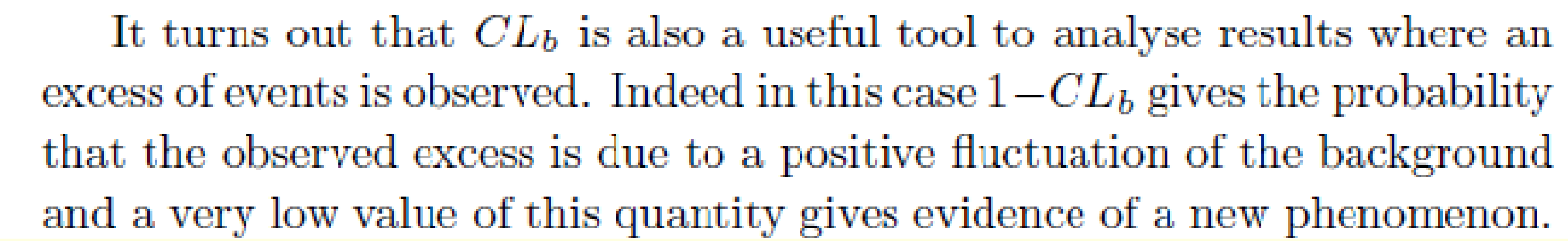


Setting Confidence Limits: CL_b



$$CL_b = (\sum_{i=0}^{n}[e^{-(b)}\frac{(b)^i}{i!}])$$

- CL_b is close to one in presence of big fluctuation of bkg (signal?)



It turns out that CL_b is also a useful tool to analyse results where an excess of events is observed. Indeed in this case $1-CL_b$ gives the probability that the observed excess is due to a positive fluctuation of the background and a very low value of this quantity gives evidence of a new phenomenon.

Setting Confidence Limits

$$CL_{s+b} = (\sum_{i=0}^{n}[e^{-(s+b)}\frac{(s+b)^i}{i!}])$$

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

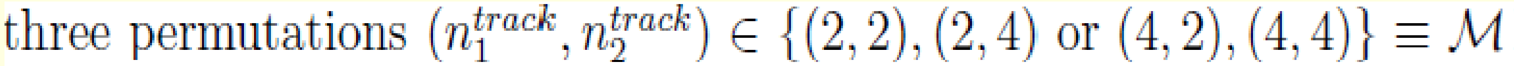
is used to set the exclusion limits. A signal hypothesis is therefore excluded at a certain confidence level CL when

$$1 - CL_s \leq CL.$$

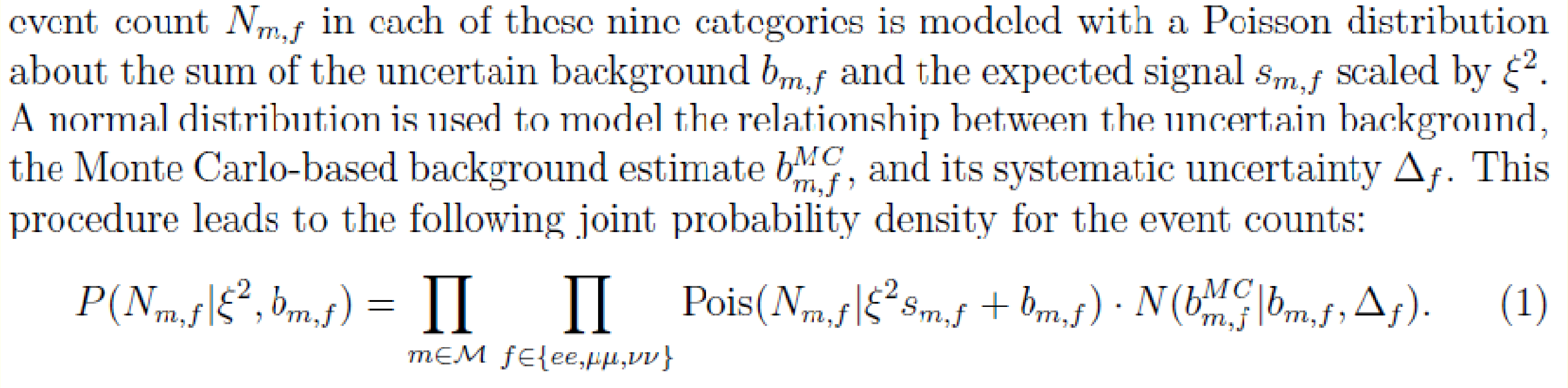
- CL$_s$ is close to one when we are not able anymore to distinguish signal from background = signal NOT excluded

Setting Confidence Limits

- Method: 3 final states f = $\mu^+\mu^-$, e^+e^- , $\nu\nu$



three permutations $(n_1^{track}, n_2^{track}) \in \{(2,2),(2,4) \text{ or } (4,2),(4,4)\} \equiv \mathcal{M}$



event count $N_{m,f}$ in each of these nine categories is modeled with a Poisson distribution about the sum of the uncertain background $b_{m,f}$ and the expected signal $s_{m,f}$ scaled by ξ^2. A normal distribution is used to model the relationship between the uncertain background, the Monte Carlo-based background estimate $b_{m,f}^{MC}$, and its systematic uncertainty Δ_f. This procedure leads to the following joint probability density for the event counts:

$$P(N_{m,f}|\xi^2, b_{m,f}) = \prod_{m\in\mathcal{M}} \prod_{f\in\{ee,\mu\mu,\nu\nu\}} \text{Pois}(N_{m,f}|\xi^2 s_{m,f} + b_{m,f}) \cdot N(b_{m,f}^{MC}|b_{m,f}, \Delta_f). \qquad (1)$$

Choice of Jet Algorithms

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

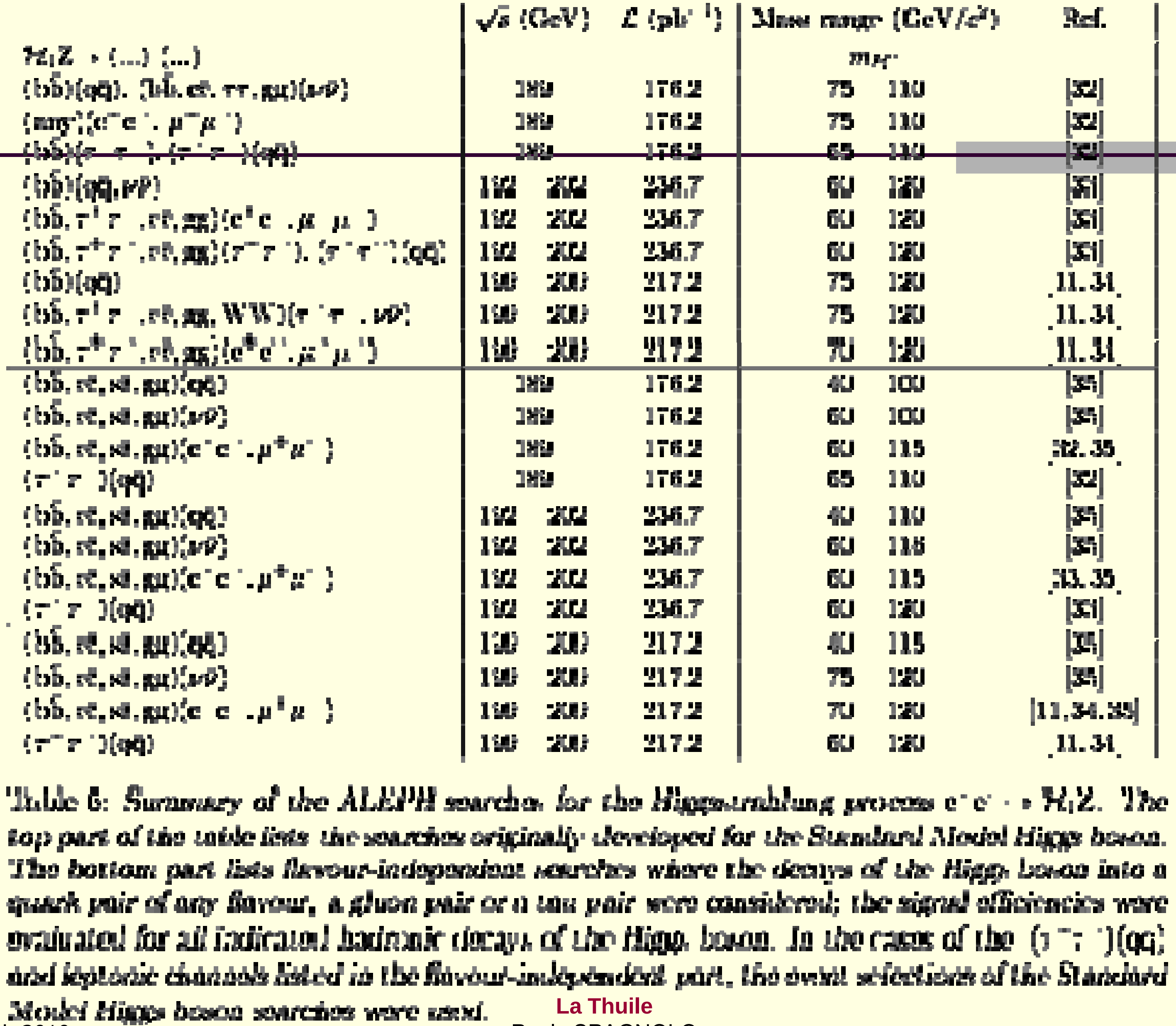
- both are iterative recombination type algorithms: merge if $m_{ij}^2/E_{tot}^2 < y_{cut}$
  - y_{cut} is an adjustable parameter and E_{tot} was often chosen to be the visible energy in the event

- 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

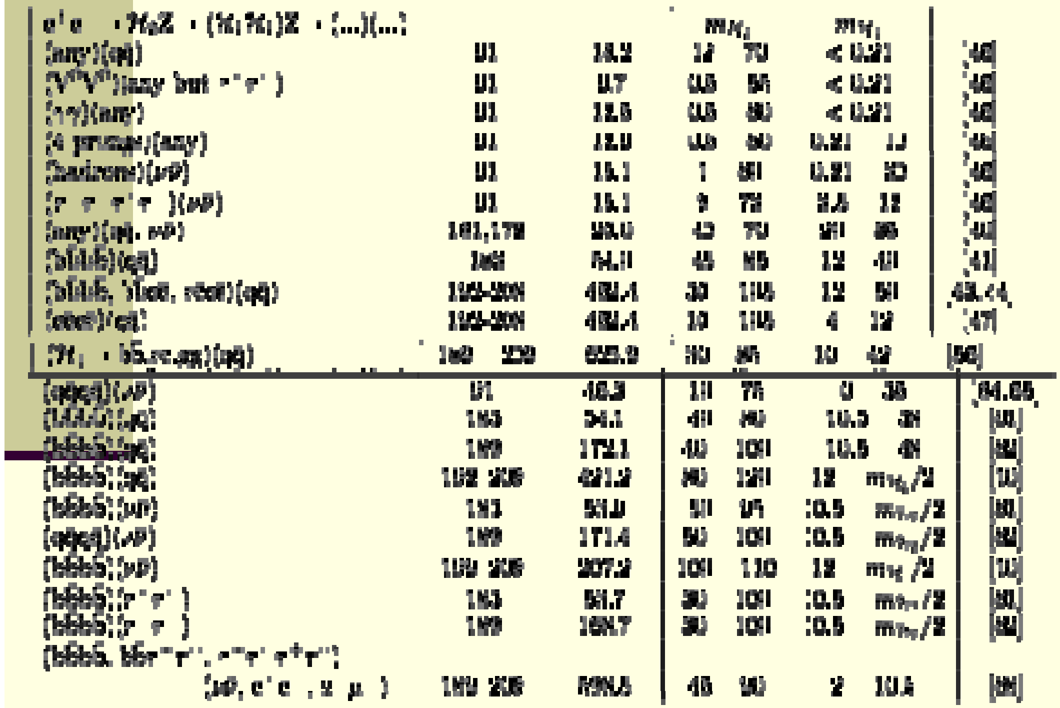
ALEPH Higgs Searches



	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	Mass range (GeV/c^2)	Ref.
$\mathcal{H}_1 Z \to (\ldots)(\ldots)$			$m_{\mathcal{H}_1}$	
$(b\bar{b})(q\bar{q})$, $(b\bar{b}, c\bar{c}, \tau\tau, gg)(\nu\bar{\nu})$	189	176.2	75 110	[32]
$(any)(e^+e^-, \mu^+\mu^-)$	189	176.2	75 110	[32]
$(b\bar{b})(\tau^+\tau^-)$, $(\tau^+\tau^-)(q\bar{q})$	189	176.2	65 110	[32]
$(b\bar{b})(q\bar{q}, \nu\bar{\nu})$	192 202	236.7	60 120	[31]
$(b\bar{b}, \tau^+\tau^-, c\bar{c}, gg)(e^+e^-, \mu^+\mu^-)$	192 202	236.7	60 120	[31]
$(b\bar{b}, \tau^+\tau^-, c\bar{c}, gg)(\tau^+\tau^-)$, $(\tau^+\tau^-)(q\bar{q})$	192 202	236.7	60 120	[31]
$(b\bar{b})(q\bar{q})$	199 209	217.2	75 120	[11, 31]
$(b\bar{b}, \tau^+\tau^-, c\bar{c}, gg, WW^*)(\tau^+\tau^-, \nu\bar{\nu})$	199 209	217.2	75 120	[11, 31]
$(b\bar{b}, \tau^+\tau^-, c\bar{c}, gg)(e^+e^-, \mu^+\mu^-)$	199 209	217.2	70 120	[11, 31]
$(b\bar{b}, c\bar{c}, s\bar{s}, gg)(q\bar{q})$	189	176.2	40 100	[35]
$(b\bar{b}, c\bar{c}, s\bar{s}, gg)(\nu\bar{\nu})$	189	176.2	60 100	[35]
$(b\bar{b}, c\bar{c}, s\bar{s}, gg)(e^+e^-, \mu^+\mu^-)$	189	176.2	60 115	[32, 35]
$(\tau^+\tau^-)(q\bar{q})$	189	176.2	65 110	[32]
$(b\bar{b}, c\bar{c}, s\bar{s}, gg)(q\bar{q})$	192 202	236.7	40 110	[35]
$(b\bar{b}, c\bar{c}, s\bar{s}, gg)(\nu\bar{\nu})$	192 202	236.7	60 115	[35]
$(b\bar{b}, c\bar{c}, s\bar{s}, gg)(e^+e^-, \mu^+\mu^-)$	192 202	236.7	60 115	[33, 35]
$(\tau^+\tau^-)(q\bar{q})$	192 202	236.7	60 120	[31]
$(b\bar{b}, c\bar{c}, s\bar{s}, gg)(q\bar{q})$	199 209	217.2	40 115	[35]
$(b\bar{b}, c\bar{c}, s\bar{s}, gg)(\nu\bar{\nu})$	199 209	217.2	75 120	[35]
$(b\bar{b}, c\bar{c}, s\bar{s}, gg)(e^+e^-, \mu^+\mu^-)$	199 209	217.2	70 120	[11, 34, 35]
$(\tau^+\tau^-)(q\bar{q})$	199 209	217.2	60 120	[11, 31]

Table 6: *Summary of the ALEPH searches for the Higgsstrahlung process $e^+e^- \to \mathcal{H}_1 Z$. The top part of the table lists the searches originally developed for the Standard Model Higgs boson. The bottom part lists flavour-independent searches where the decays of the Higgs boson into a quark pair of any flavour, a gluon pair or a tau pair were considered; the signal efficiencies were evaluated for all indicated hadronic decays of the Higgs boson. In the cases of the $(\tau^+\tau^-)(q\bar{q})$ and leptonic channels listed in the flavour-independent part, the event selections of the Standard Model Higgs boson searches were used.*

Summary of similar LEP searches



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[44] DELPHI Collaboration, J. Abdallah et al., Eur. Phys. J. C38 (2005) 409.

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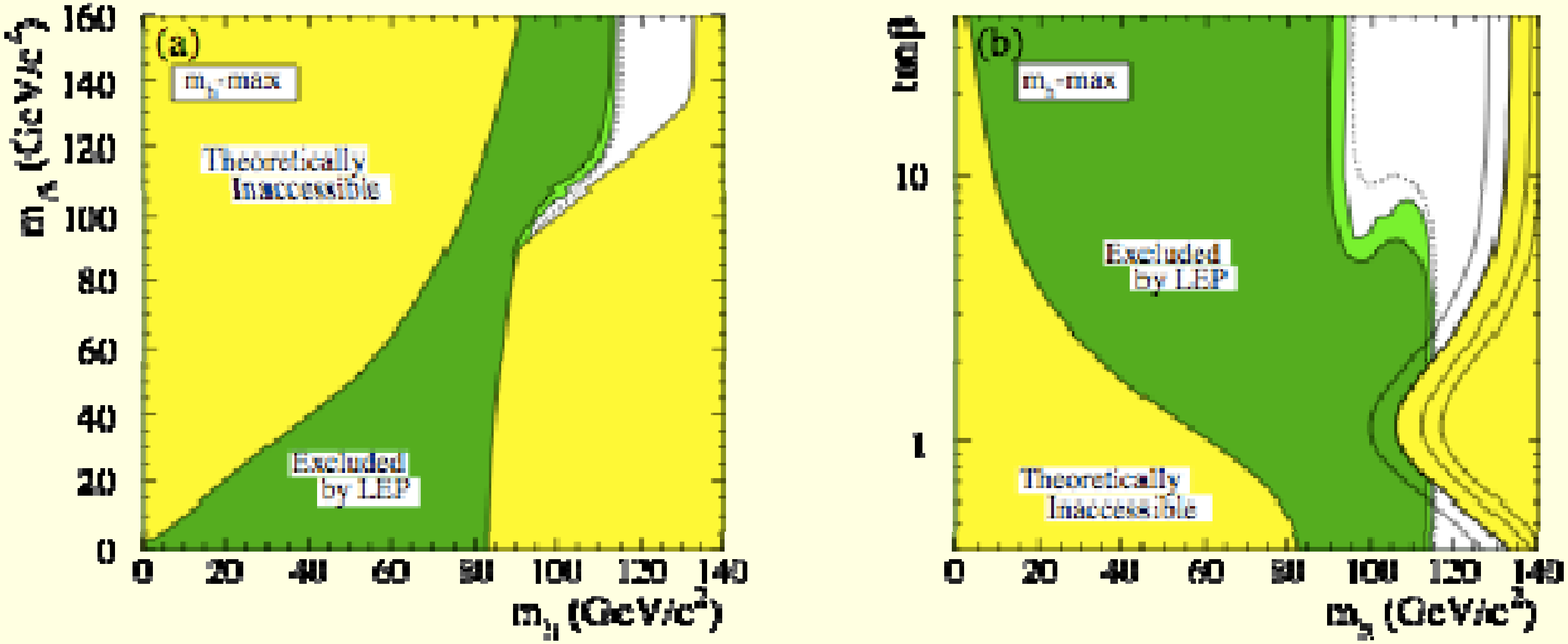
[57] OPAL Collaboration, G. Abbiendi et al., Eur. Phys. J. C40 (2005) 317.

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

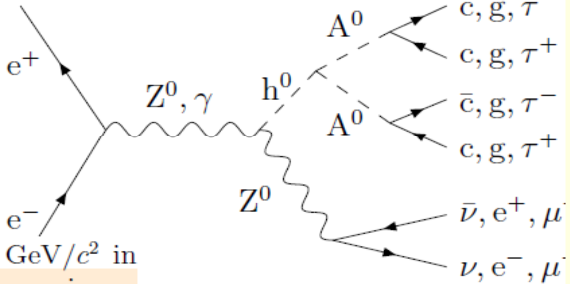
mh-ma limits


(a)
m_h-max
Theoretically Inaccessible
Excluded by LEP
m_A (GeV/c^2)
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
m_h (GeV/c^2)
(b)
m_h-max
Excluded by LEP
Theoretically Inaccessible
tanβ
10
1
0
20
40
60
80
100
120
140
m_h (GeV/c^2)

OPAL low mass searches

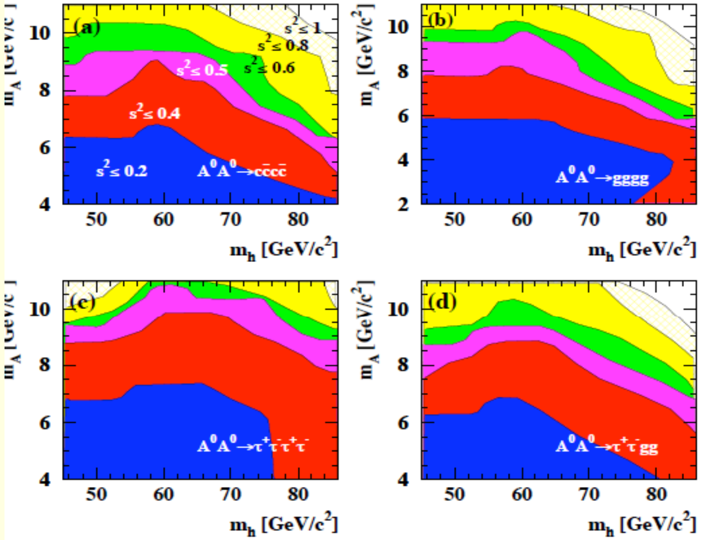
OPAL also carried out a searches in the region $2m_\tau < m_a < 10\,\mathrm{GeV}$

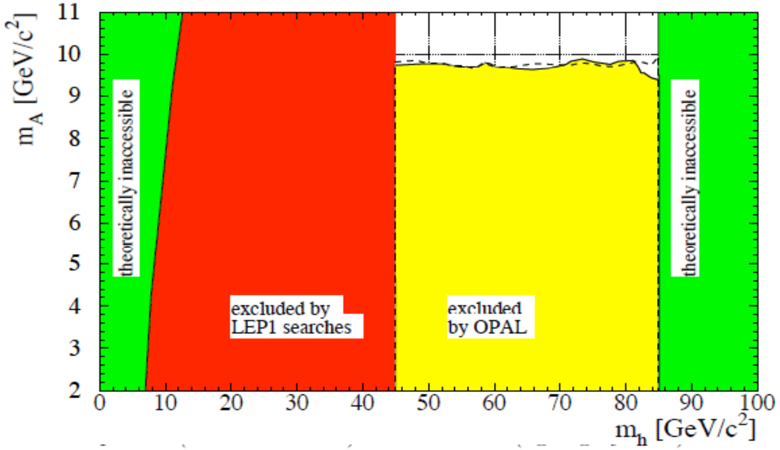
Search for a low mass CP-odd Higgs boson in e^+e^- collisions with the OPAL detector at LEP2



6.2 MSSM no-mixing scenario interpretation

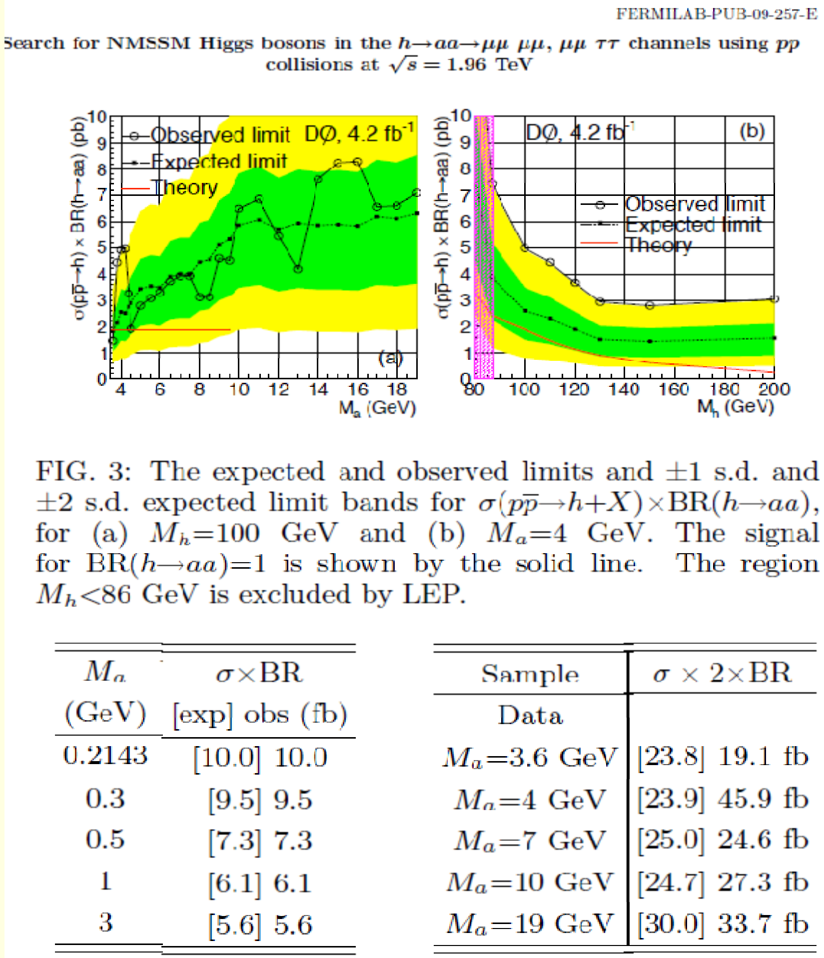
We scan the region with $2 \leq m_\mathrm{A} \leq 11$ GeV/c^2 and 45 GeV/$c^2 \leq m_\mathrm{h} \leq 85$ GeV/c^2 in the m_A versus m_h plane for the MSSM benchmark parameter scenario. The maximum theoretically allowed value for m_h in this scenario is 85 GeV/c^2 [6]. The scan procedure





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

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



FERMILAB-PUB-09-257-E

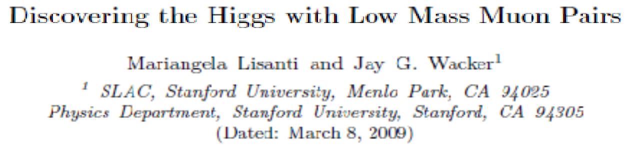
Search for NMSSM Higgs bosons in the $h \to aa \to \mu\mu\ \mu\mu$, $\mu\mu\ \tau\tau$ channels using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

FIG. 3: The expected and observed limits and ±1 s.d. and ±2 s.d. expected limit bands for $\sigma(p\bar{p} \to h+X) \times \mathrm{BR}(h \to aa)$, 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]

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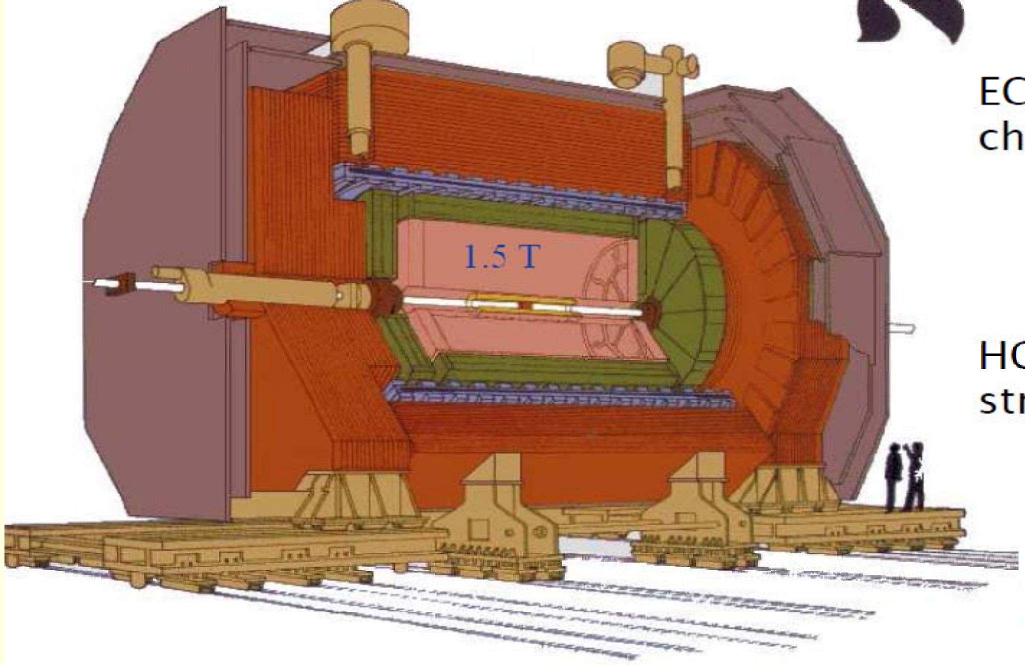
Physics Department, Stanford University, Stanford, CA 94305
(Dated: March 8, 2009)

These searches are probing ~ 10 times 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

The ALEPH detector: a piece of history



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

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

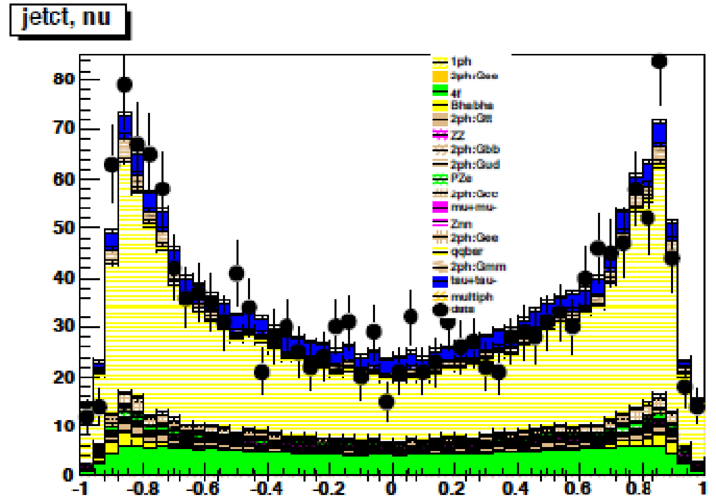
- remember, we're shooting for a discovery!
- no one would believe a signal if we adjusted our cuts looking at data
  - Also, we don't want to spoil the other analyses that we might be interested in: $a \longrightarrow \text{jets}, \mu, ..$

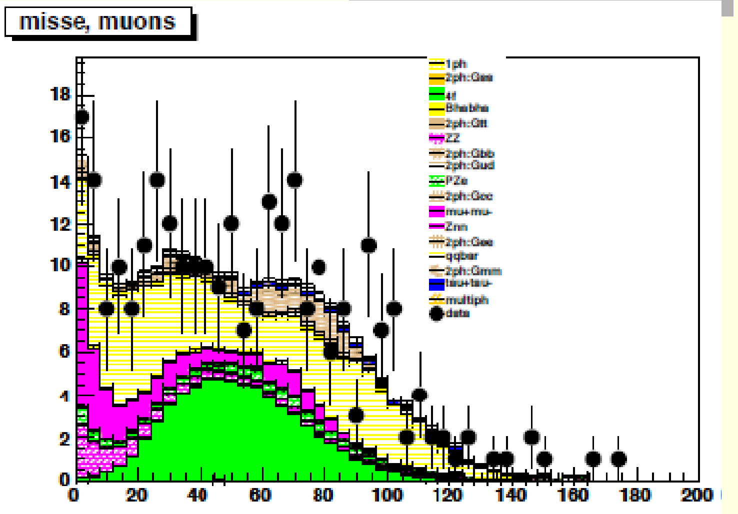
But we do need to verify that our Monte Carlo is describing the data well.

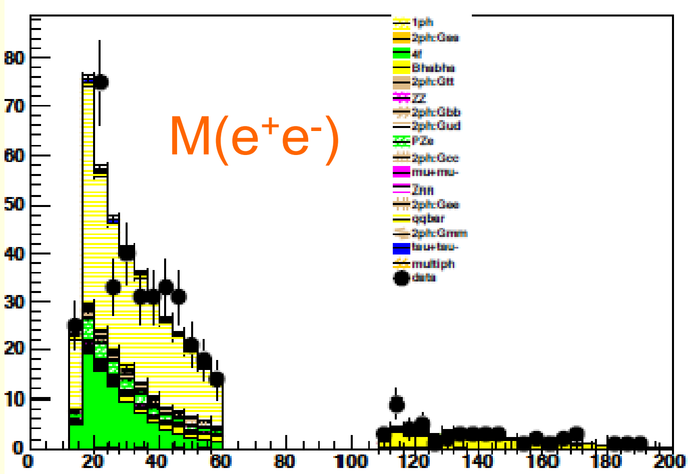
- So we did a blind blind analysis and defined 5 control samples

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 $M(j_1, j_2, \text{invisible}) > 60\text{GeV}$
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: control samples





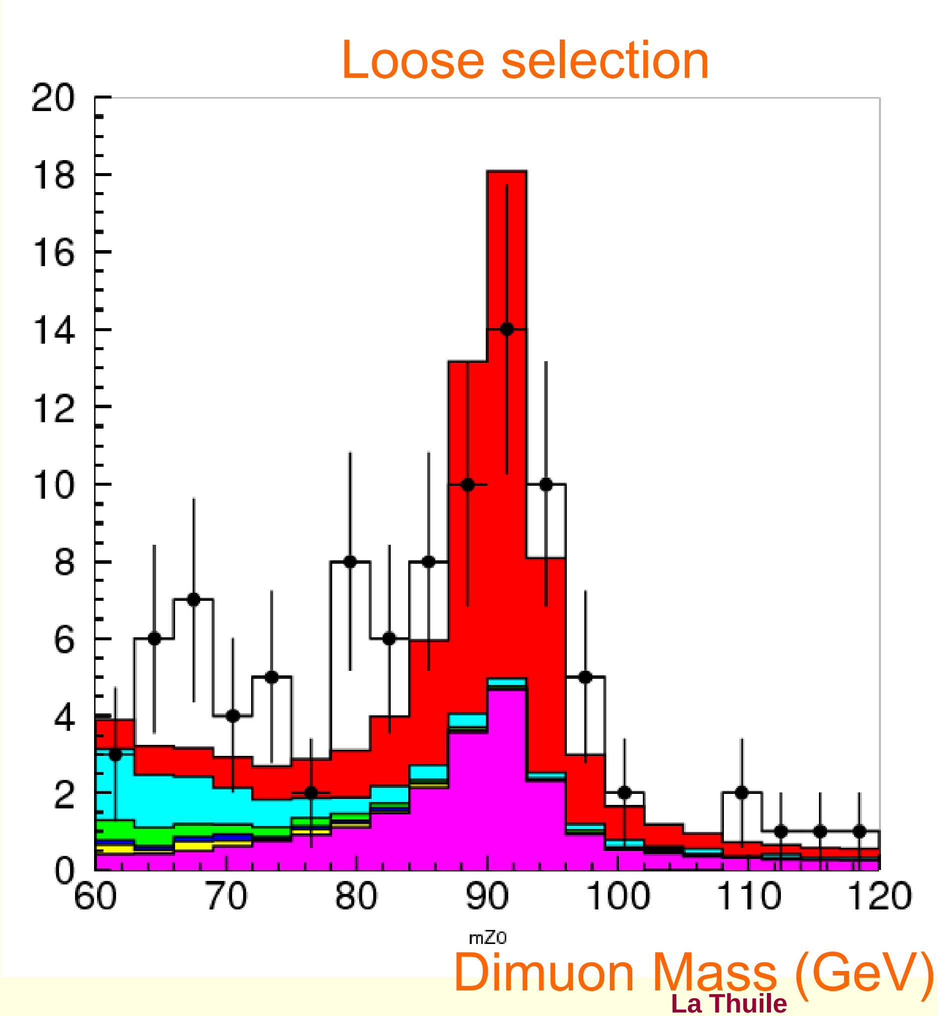


Systematics

- Given the low numbers of selected events, the final measurements are statistically limited
- Z $\rightarrow \mu^+\mu^-$, e^+e^-
  - total systematic uncertainties (from lepton Id) are 0.6%, 2.6% and 7.5% for the signal, ZZ, and Zee backgrounds.
  - Overall 10% background uncertainty for the other channels
- Z $\rightarrow \nu\nu$
  - Efficiency error was 5% for the signal and 10% for ZZ, and it is between 30% and 100% for the other background processes.
  - Overall 30% background uncertainty for the other channels

- With Loose cuts data and MC agree within these errors

M(μμ): *Data vs Montecarlo*



□ Data

🟥 MC ZZ

🟦 MC WW

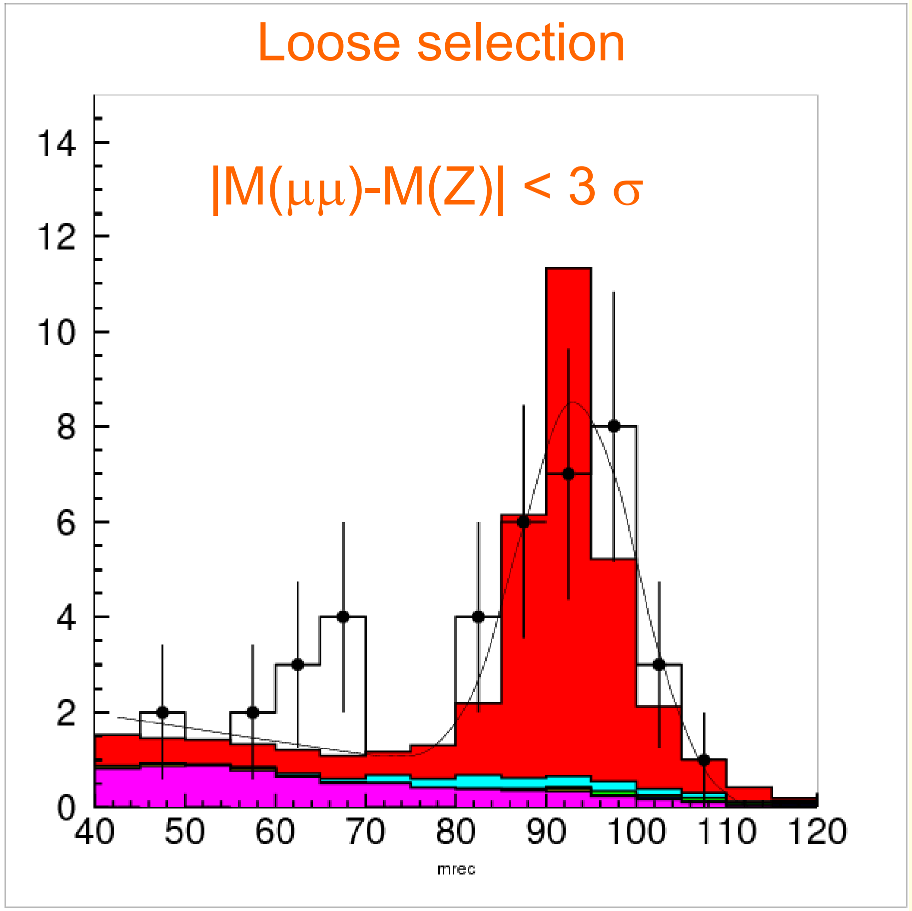
🟪 MC μμ

🟩 MC qq

🟨 MC γγ

🟦 MC ττ

Recoil Mass: *Data vs Montecarlo*



Recoil Mass(GeV)

□ Data

🟥 MC ZZ

🟦 MC WW

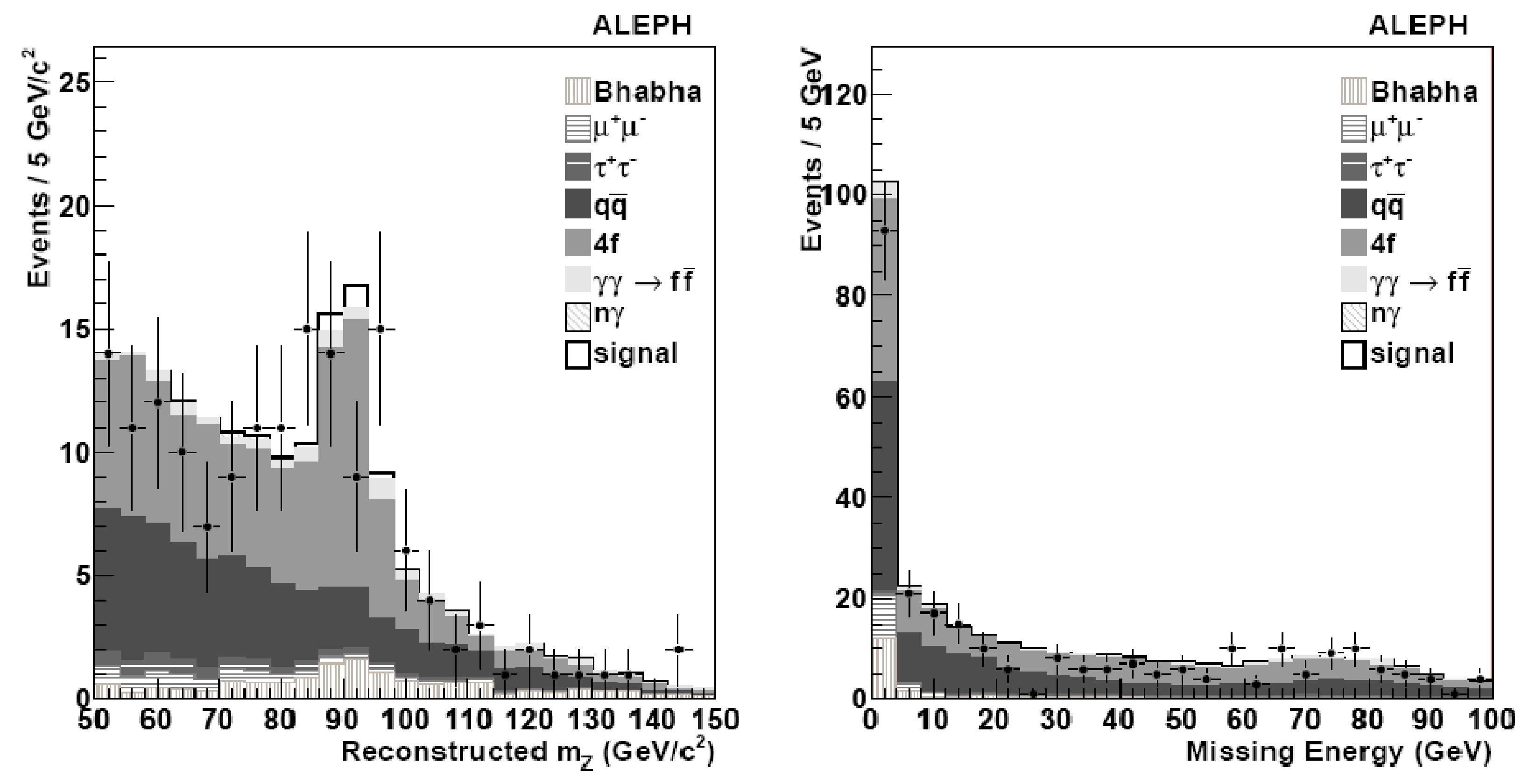
🟪 MC $\mu\mu$

🟩 MC qq

🟨 MC $\gamma\gamma$

🟦 MC $\tau\tau$

Loose selection: $H \rightarrow 4\tau$, $Z \rightarrow e^+e^-$



Final selection: H → 4τ , Z → e^+e^-