Search for the SM Higgs at LEP

F. Cerutti CERN and LNF-INFN

- Introduction: SM Higgs production and decay
- The experimental method:

  discriminating variables and test statistics
- Combined results from the 4 LEP experiments
- Latest updates from the experiments:

  ALEPH final publication
- Conclusions

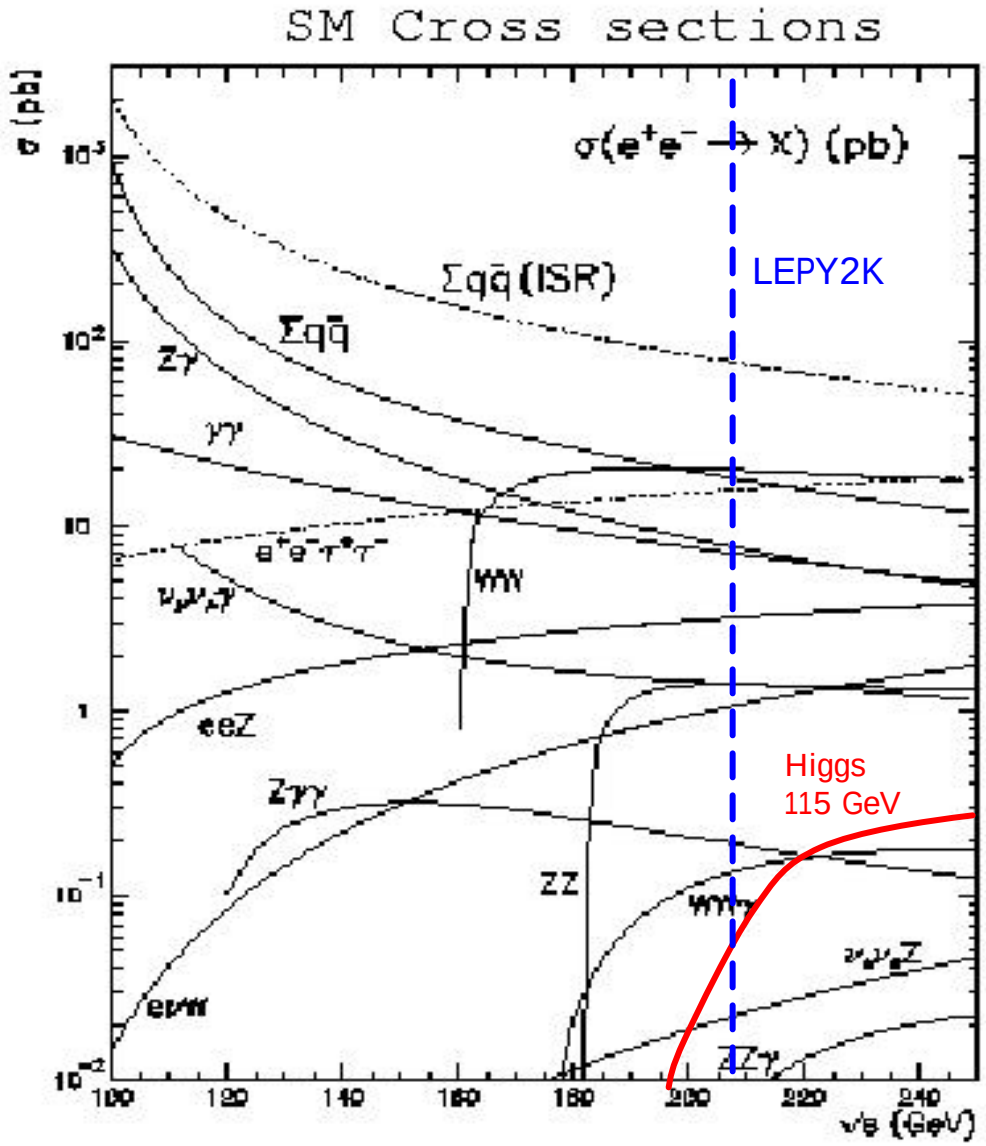
H production dominated by ZH

threshold behavior at $E_{LEP}=M_H+M_Z$

For M_H=115 GeV @ E_{LEP}~207 GeV

σ~60 fb

~30 H events expected in LEP 2000 sample



rejection factors needed < 10^3

(at hadron colliders ~10^6)

Higgs decay

- A 115 GeV Higgs decays into:
  - bb = BR~74% $\tau\tau$ =BR~7%
  - gg,cc =BR~11% W*W*=BR~7% Z*Z*=BR<1%

4 channels searched for

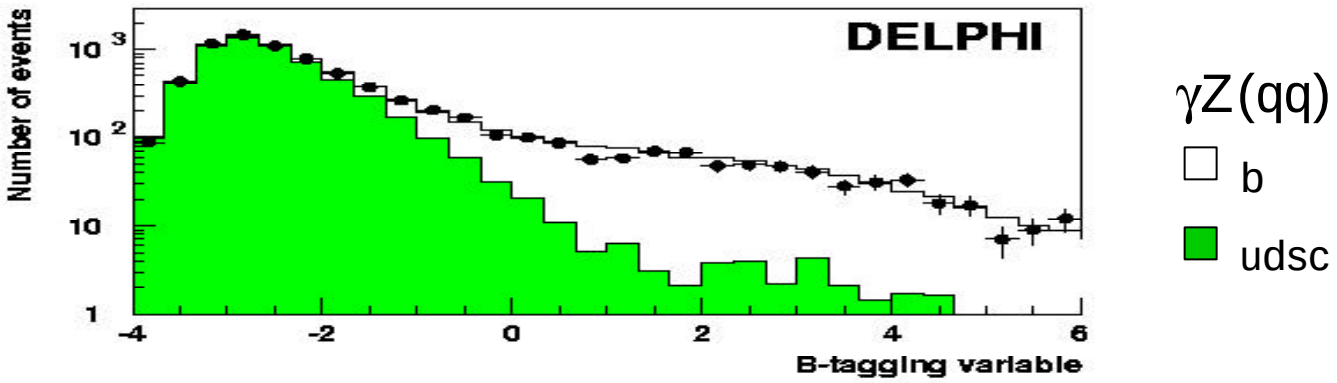
$H \to bb$, $Z \to qq$ 4-jet BR~54%	$H \to bb$, $Z \to \nu\nu$ Missing energy BR~15%
$H \to bb$, $Z \to ll$ Leptonic BR~5%	$H \to bb$ ($\tau\tau$) , $Z \to \tau\tau$ (qq) tau-tau BR~8%

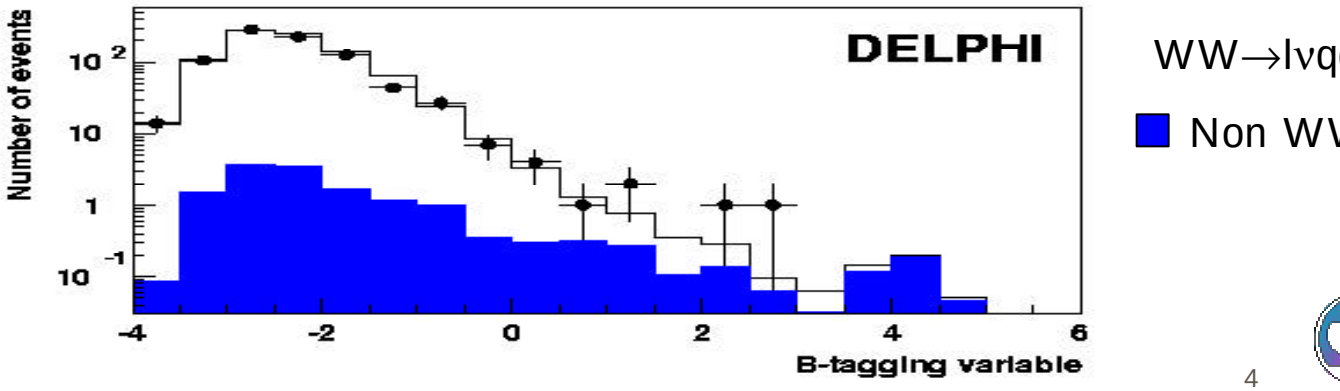
- 4-jet b-tag- Event shapes (jet-jet angles, H prod-angle, thrust .....)
  - background: ZZ $\to$bbqq, qq(g)bb, WW (cscs)
- Missing energy b-tag - missing energy, acoplanarity, ..
  - background: ZZ$\to$bb$\nu\nu$, ($\gamma\gamma$)bb
- Leptonic/tau-tau b-tag - lepton ID or τ-ID
  - background: ZZ$\to$bb*ll* *or* ZZ $\to$bb$\tau\tau$
- For all channels: reconstructed Higgs mass M_h^{reco}

Discriminating variables

- Reconstructed mass: typical mass resolutions
  - Precise knowledge of $(E_{LEP}, \vec{P}_{LEP})$ and M_Z used to improve mass resolution (Ex. 4-jet channel 5C fit)
  - Leptonic ~2 GeV 4-jet~2.5 GeV
  - tau-tau ~3 GeV Missing energy ~3.5 GeV

  * Close to threshold mass shape is NOT Gaussian: long tails at small m_h
- b-tag: impact parameter, secondary vertex, jet mass, hig- P_t lepton combined with NN or Likelihood techniques

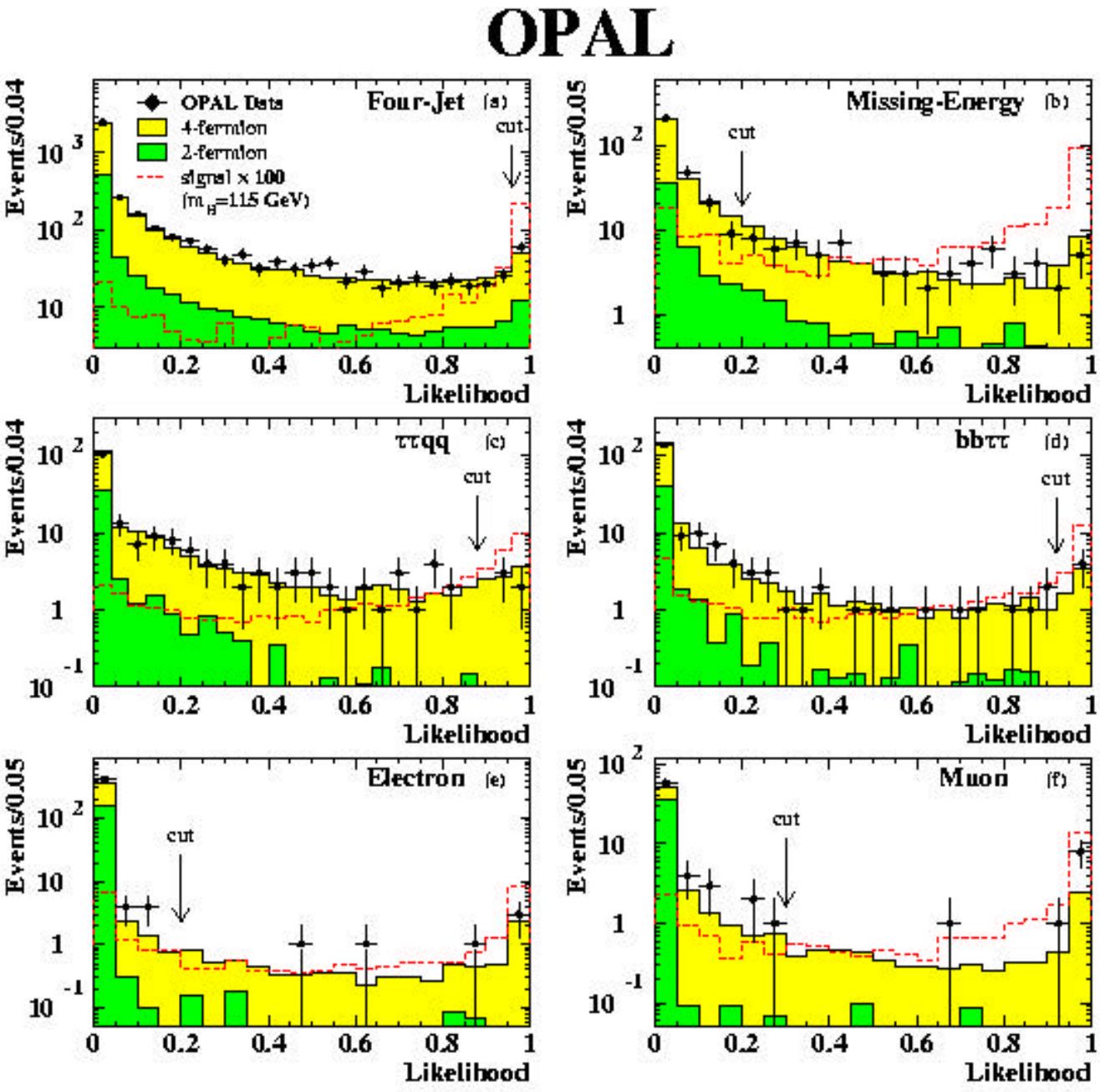




Discriminating variables

- Other event shape variables combined with b-tag to form the 2nd *discriminating-variable*

  (NN or Likelihood technique)



- Analysis strategy:

1) Loose pre-selection applied (reject $\gamma\gamma$ and γqq)

2) background-only or background+signal(M_H) hypothesis tested on data (N_{obs}) by means of a test statistics based on 2 *discriminating-variables*:

{M^{reco}_H , Event NN/L}

- Test statistics used likelihood ratio Q= L_{s+b}/L_b

$$Q(M_H) = e^{-s(M_H)} \prod_{j=1}^{n_{chan}} \prod_{i=1}^{N^j_{obs}} \frac{S(X_i, M_H)_j + B(X_i)_j}{B(X_i)_j}$$

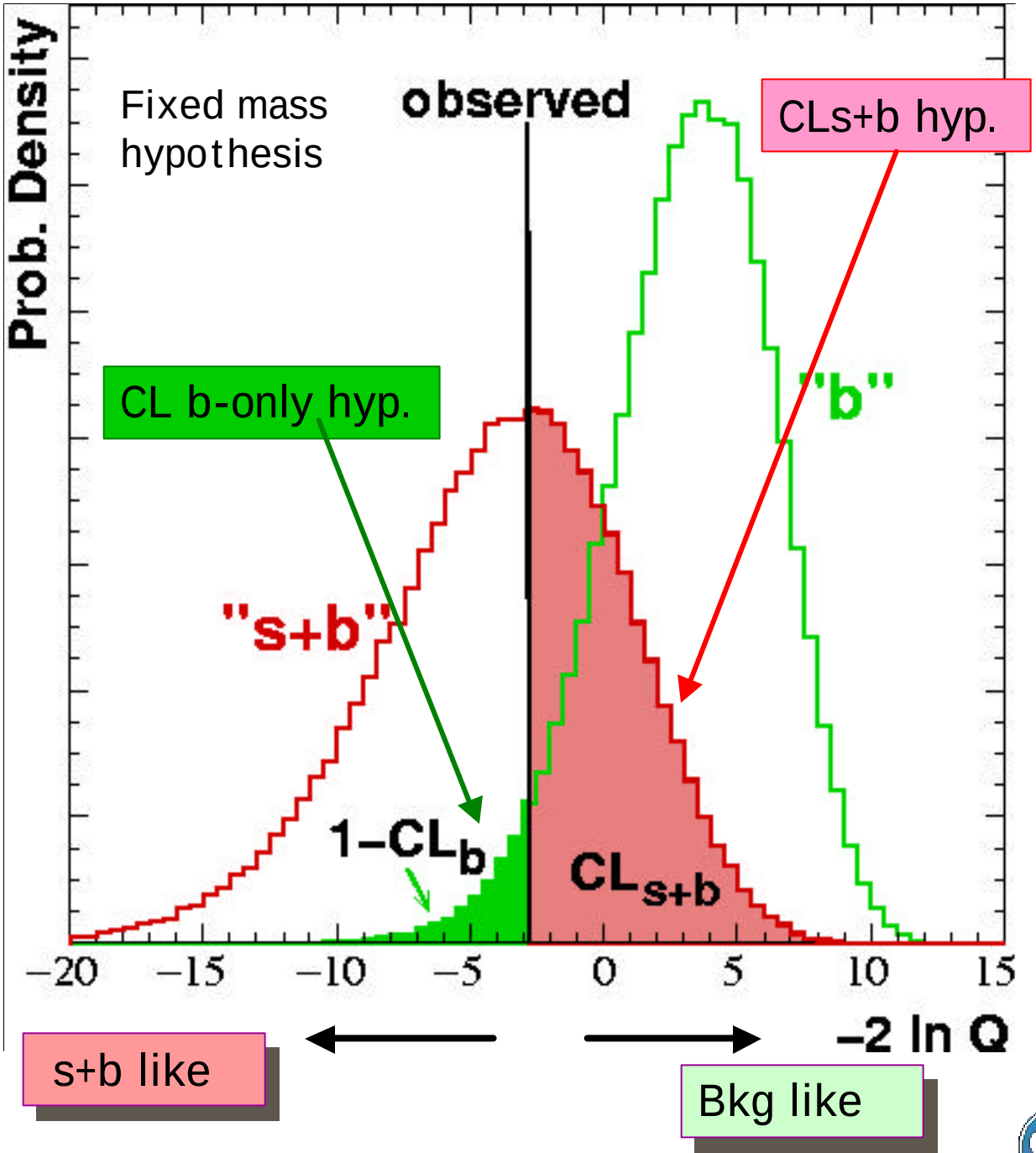
  - M_H = Tested Higgs mass hypothesis
  - X^i = 2 *discriminating variable*
  - S,B expected signal and bkg in cha=j bin=I

$$q = -2\ln(Q) = 2s - 2\sum_{j=1}^{n_{chan}} \sum_{i=1}^{N^J_{obs}} \log\left(1 + s_{i,j}/b_{i,j}\right)$$

- Gives optimal s+b vs b separation (no loss due to cuts)
- Gives ordering principle signal-like=small q
- Is additive event contributes $w_i=\log(1+s_i/b_i)$

The LR estimator

- Signal-like (bkg-like) outcome characterized by large (small) values of Q or by small (large) values of q



Combined LEP results

- LEP results from last LEPHIGGS wg combination:

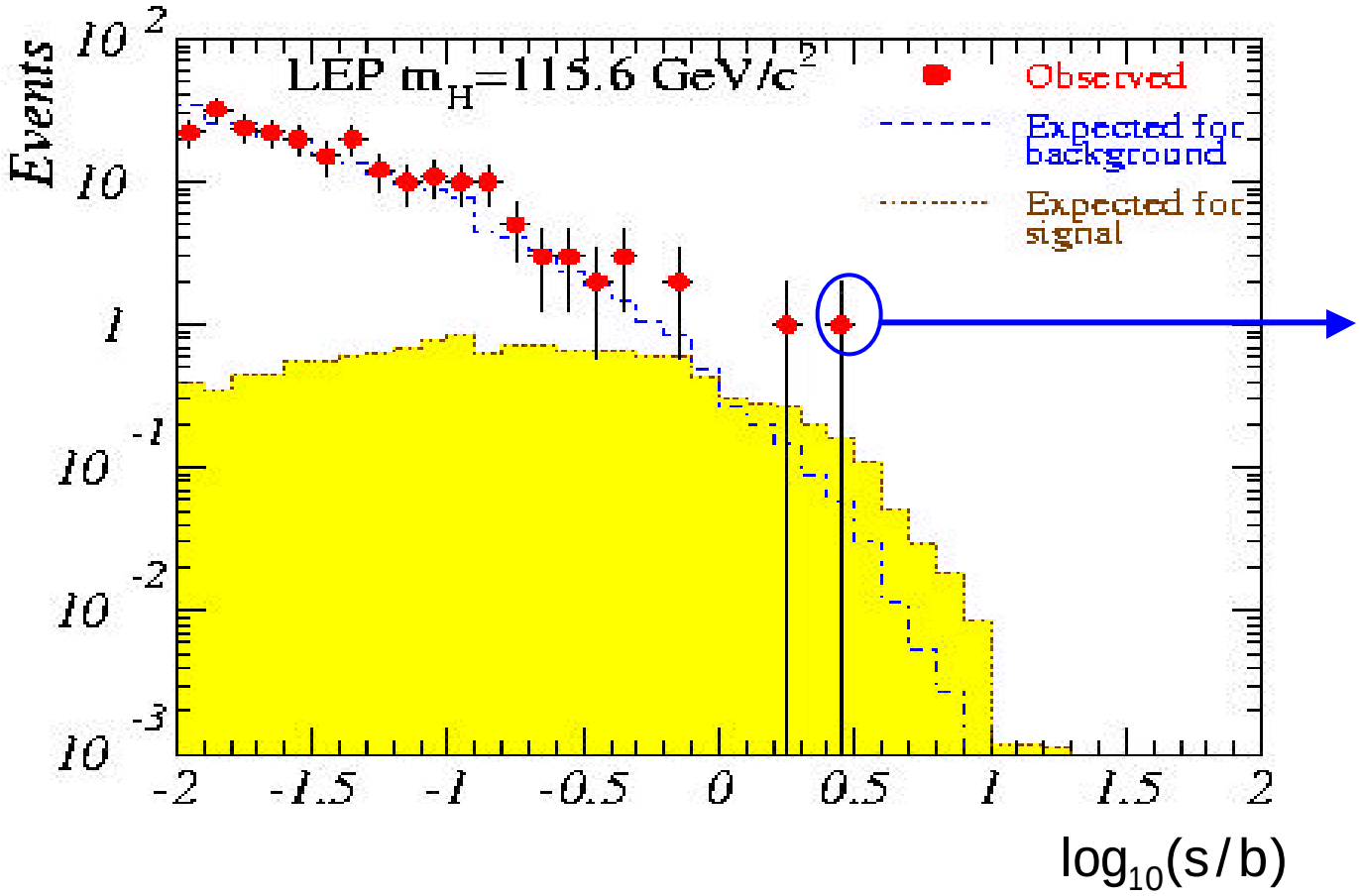
  CERN-EP/2001-055 July 2001

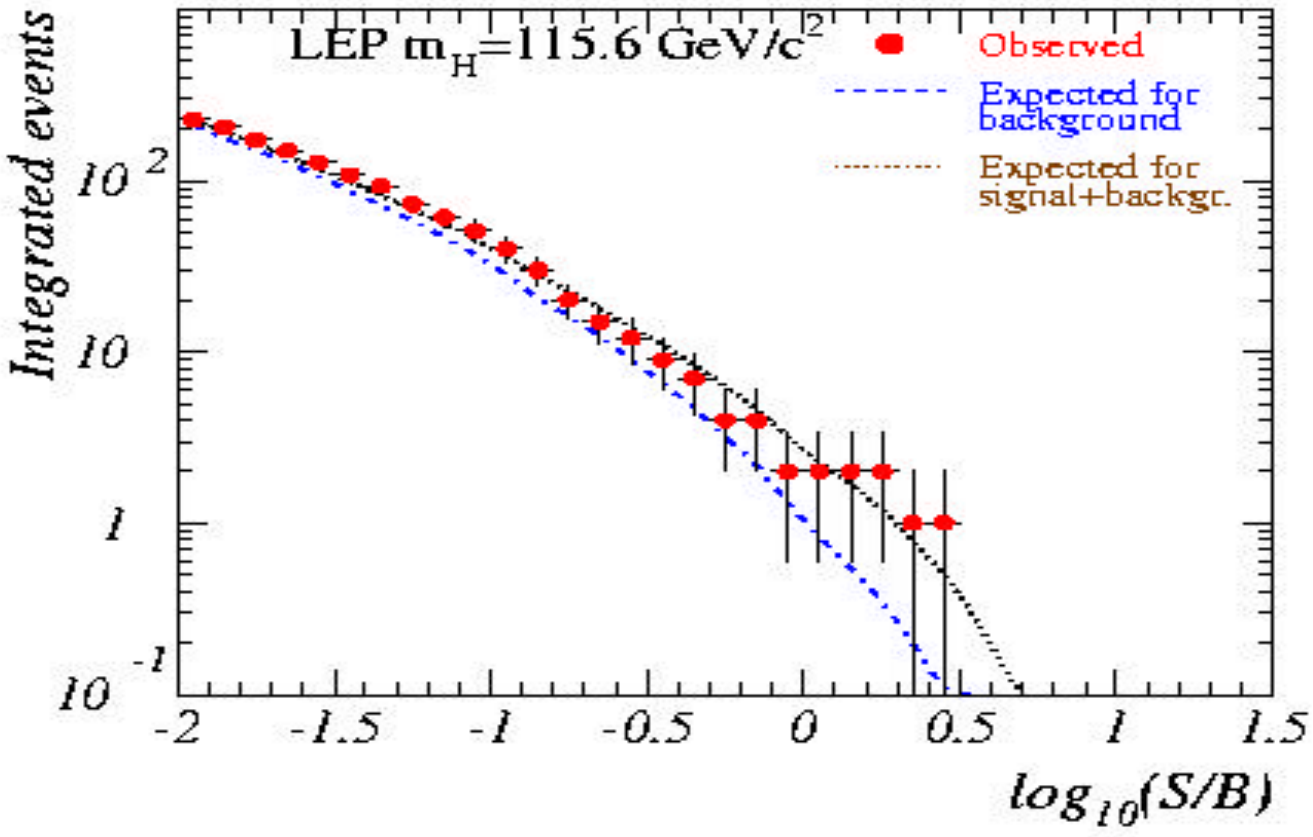
- Based on the following publications:
  - A: Phys.Lett. B485 2000 Preliminary
  - D: Phys.Lett. B499 2001 Preliminary
  - L: Phys.Lett. B517 2001 Final
  - 0: Phys.Lett. B499 2001 Preliminary
- ALEPH has published final results:

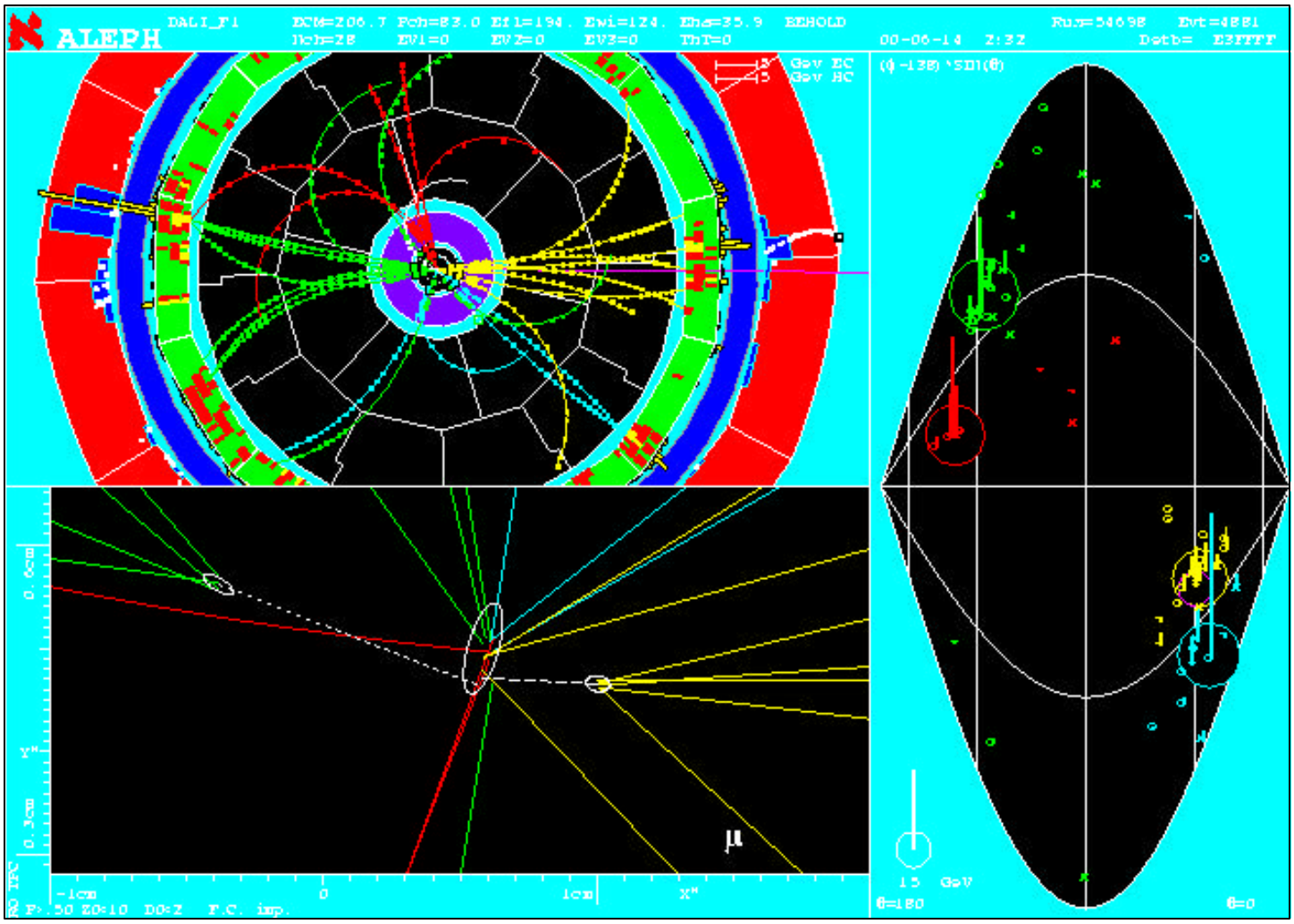
  more information in the final part of the talk

	Integrated L pb^{-1}				
E_{cm} GeV	A	D	L	O	LEP
Full ≥189	629	610	627	599	2565
≥206 1RF margin	130	142	139	130	542

The LEP results







2 b cand.

HZ hyp. m_H=114 GeV±3 GeV

NN = 0.996 s/b(M_H=115)=4.7

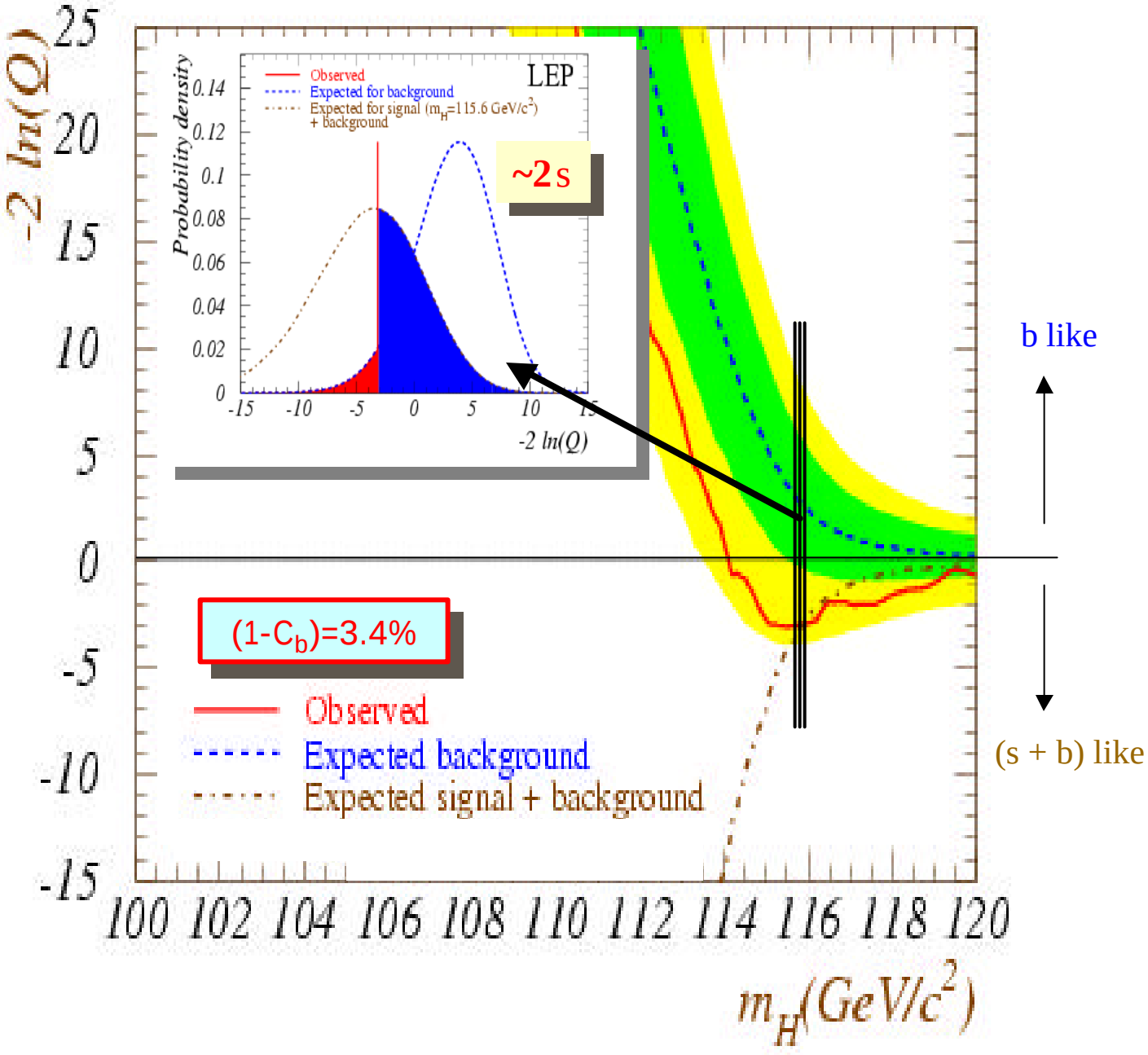
jet	b-tag:
Z	
1	0.14
2	0.01
H	
3	0.99
4	0.99

5C fit P(χ^2)=53%
m_H=112.4GeV
m_Z=93.3GeV

ZZ hyp. 6C fit
m_Z=102 GeV
m_Z=91.7GeV

The LEP results

- Minimum of LR @ Higgs mass 115.6 GeV
- In agreement with what expected for SM Higgs



Most significant candidates

Candidates with $s/b \geq 0.3$ at M_H=115 GeV

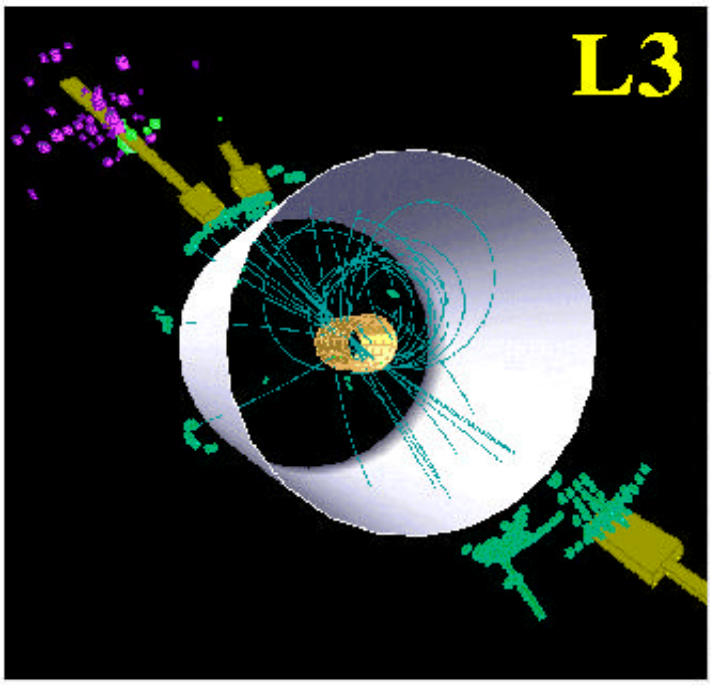
Exper.	Chan.	m^{rec}_H	s/b M_H=115
A	4-jet	114.3	4.7
A	4-jet	112.9	2.3
A	4-jet	110.0	0.9
L	Miss-En	115.0	0.5
O	4-jet	110.7	0.5
D	4-jet	114.3	0.5
A	Lepton	118.1	0.5
A	Tau-tau	115.4	0.4
A	4-jet	114.5	0.4
O	4-jet	112.6	0.4
L	4-jet	108.3	0.3
D	4-jet	97.2	0.3

- Most significant Candidates in 4-jet channel

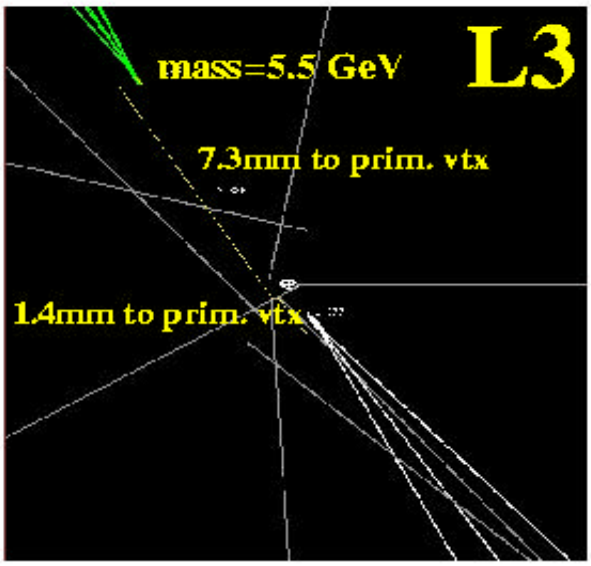
L3 candidates

most significant Hνν candidate

s(115.6)/b=0.5



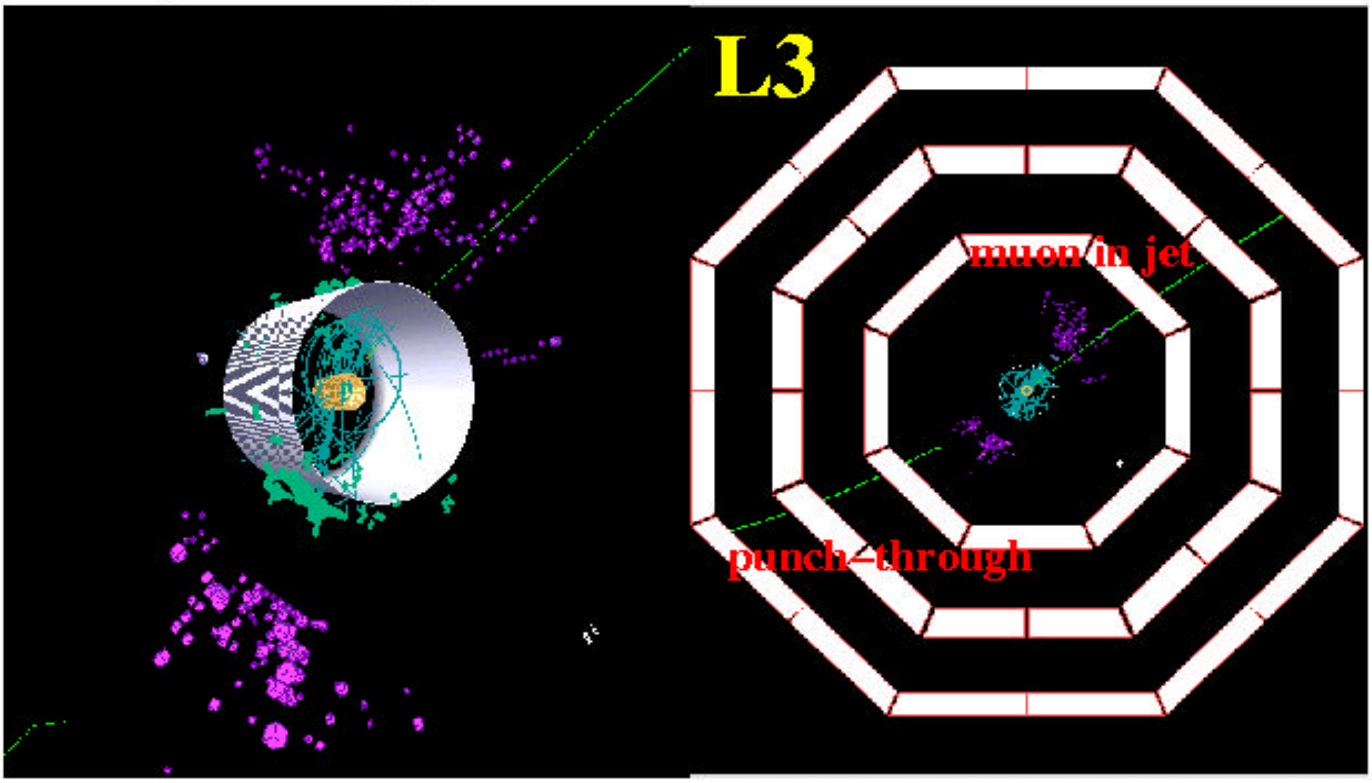
Secondary vtx's view



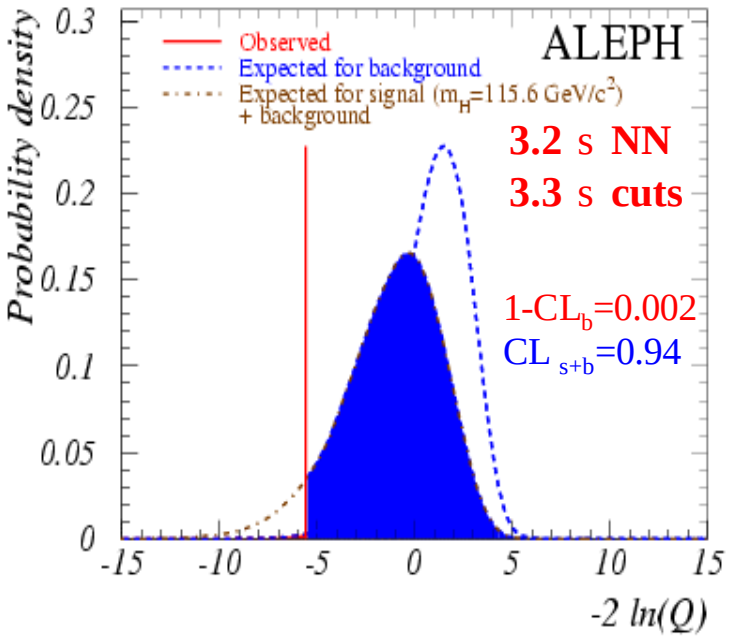
measured H mass=114.4 GeV

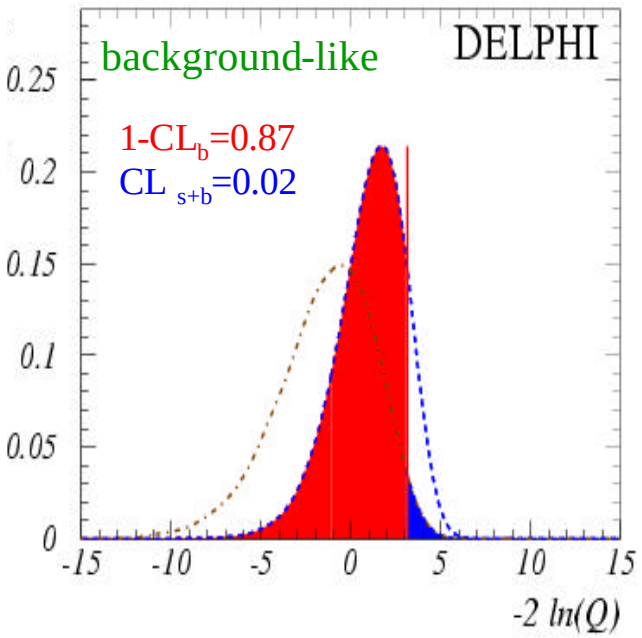
H mass resolution ~3 GeV

most significant Hqq candidate

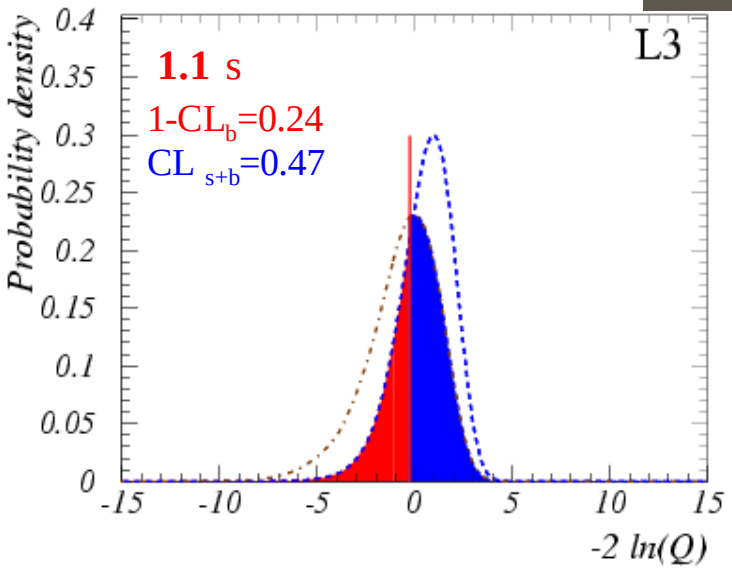


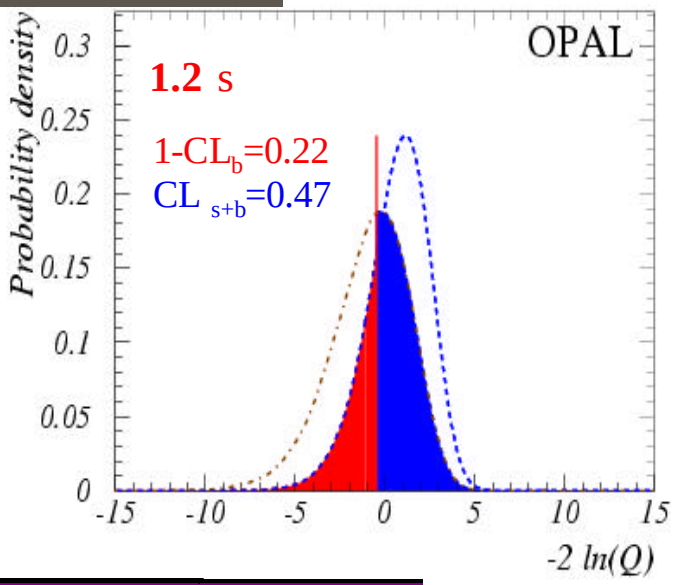
measured Higgs mass=114.6 GeV mass resolution~4 GeV





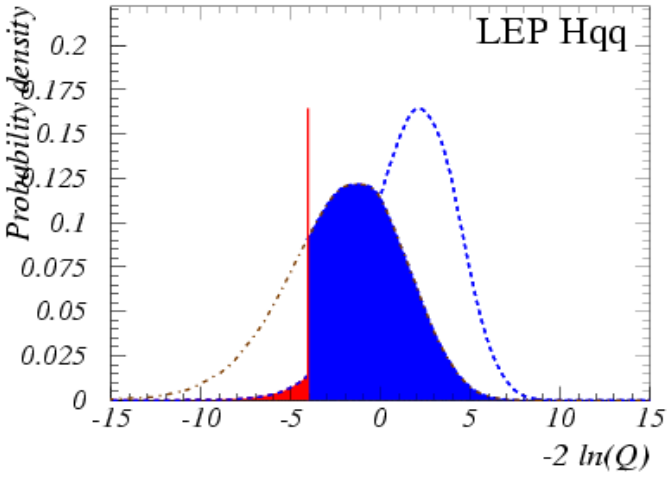
M_H=115.6 GeV

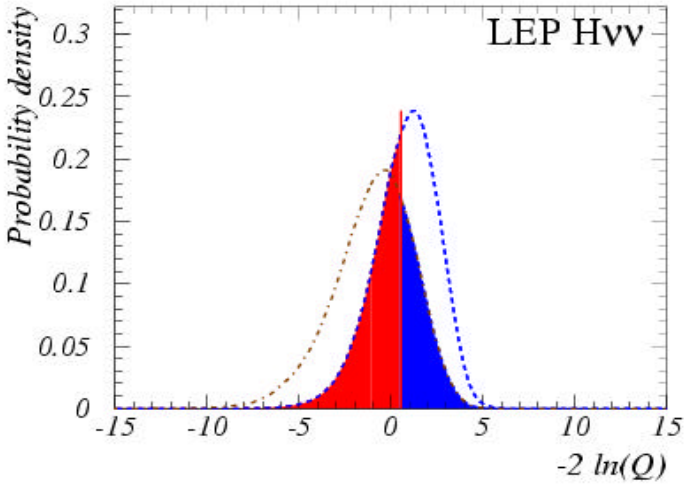


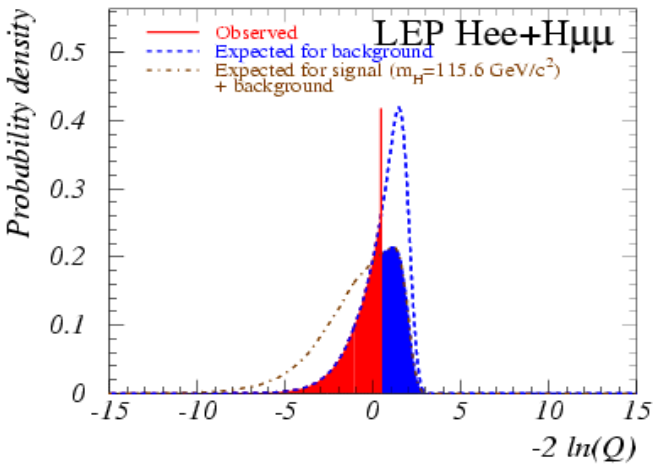


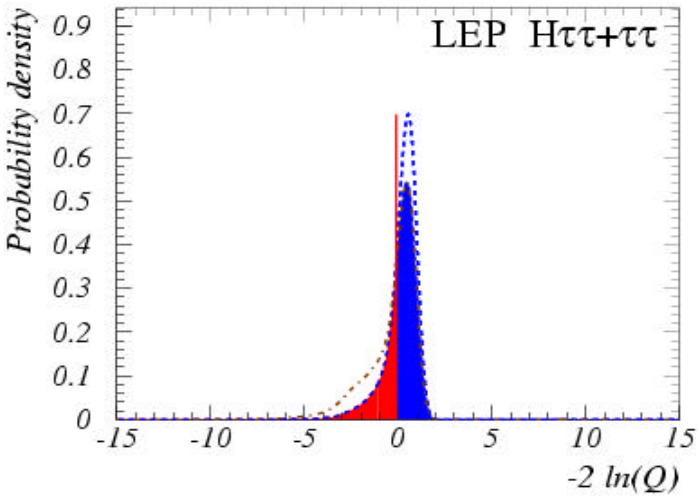
	1 - CL_b	CL_{s+b}
A	0.002	0.94
D	0.87	0.02
L	0.24	0.47
O	0.22	0.47
LEP	0.034	0.44

M_H=115.6 GeV





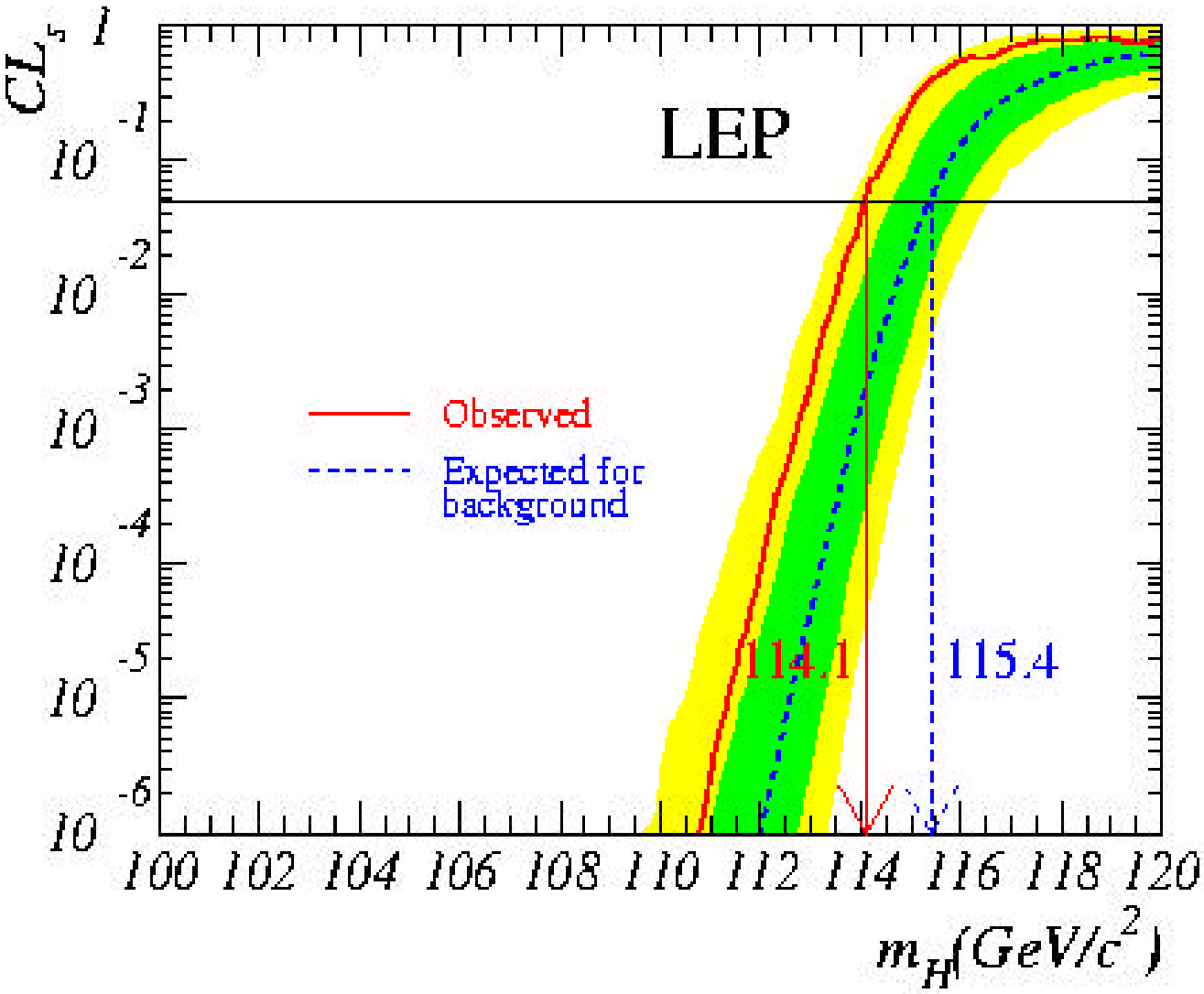




	4-jet	Miss-En	All but 4-jet
$(1-CL_b)$	0.016	0.40	0.34
CL_{s+b}	0.74	0.26	0.19

Exclusion limits

- Lower limit on M_H can be derived



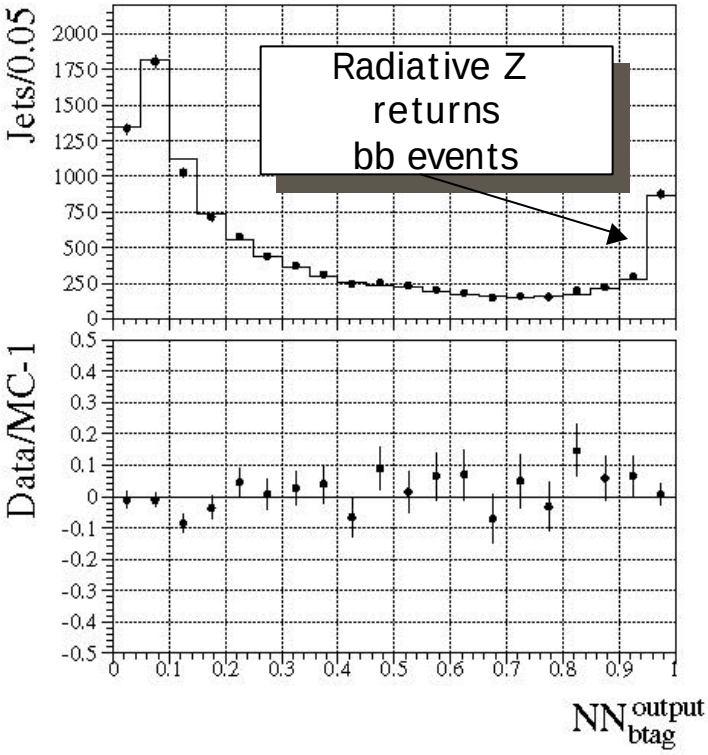
M_H > 114.1 GeV @ 95%CL

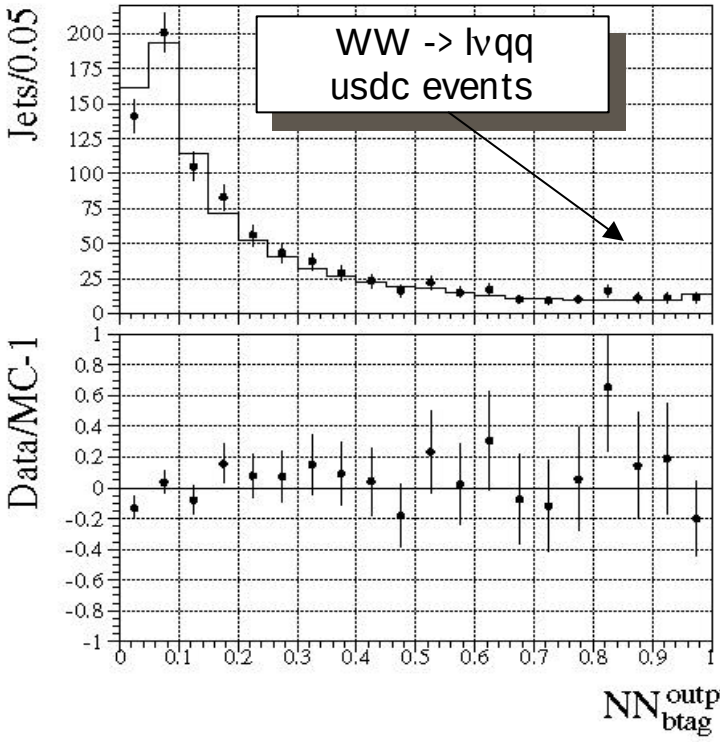
Systematic checks: btag

btag calibrated with Zpeak data

MC *IPs smeared* until ε_{udsc} and ε_b agree with Data

agreement cross-checked with HE data





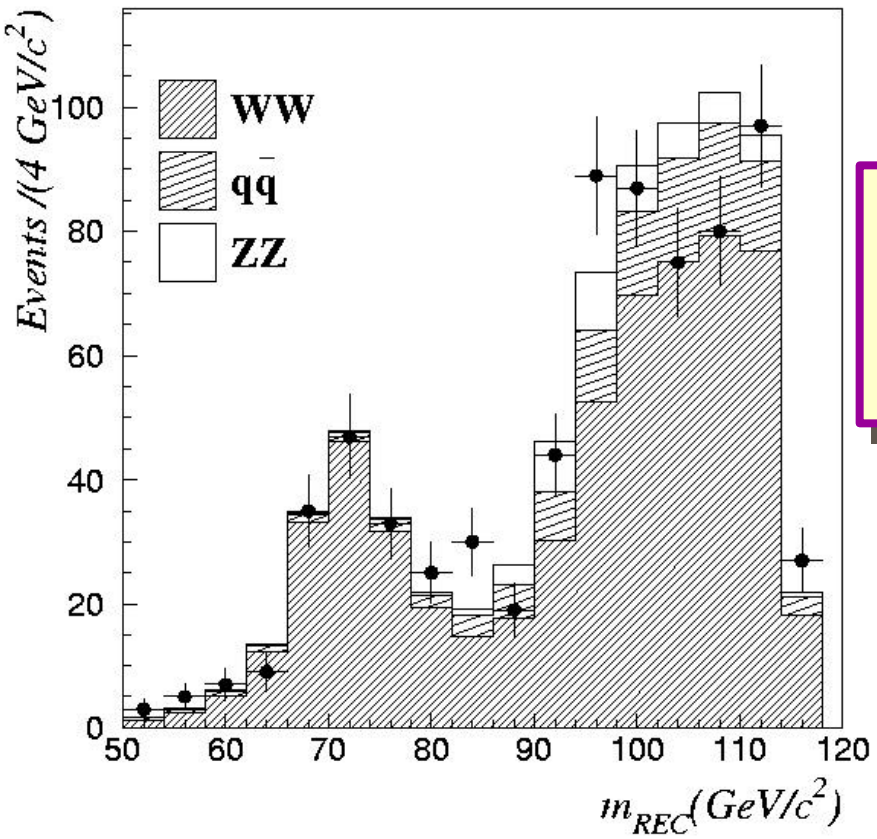
Effect on expected bkg

$M_H > 109$ GeV

ZZ=4 % qq=4% WW=10%

Tot=5%

Reconstructed mass bias ?

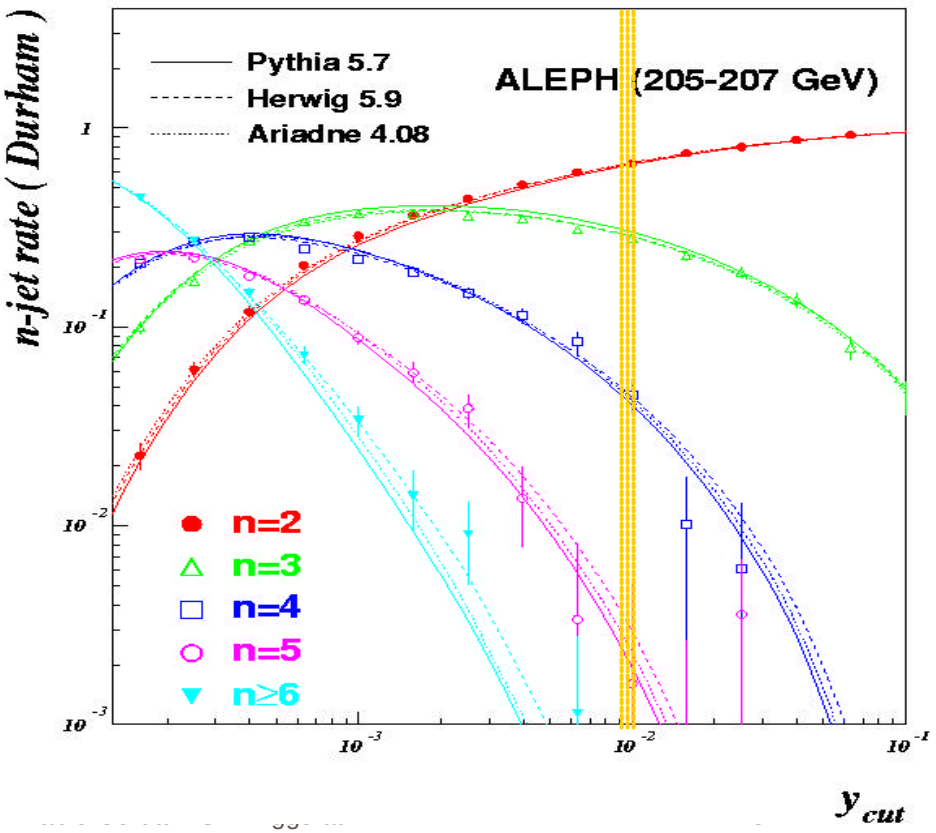


4-jet mass

b-tag NN<0.9

agreement DT-MC

qq(g) background *PRELIM, Stat.Err*



N-jet rate vs Y_{cut}

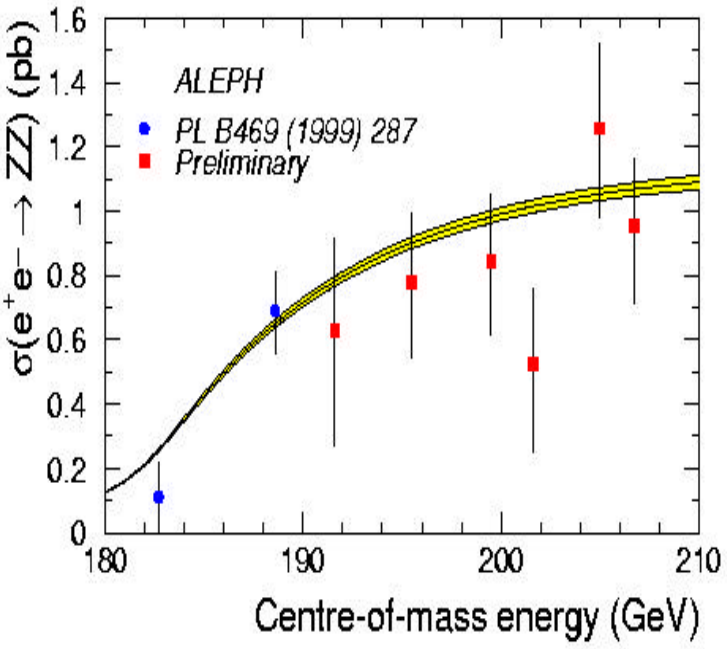
Good agreement

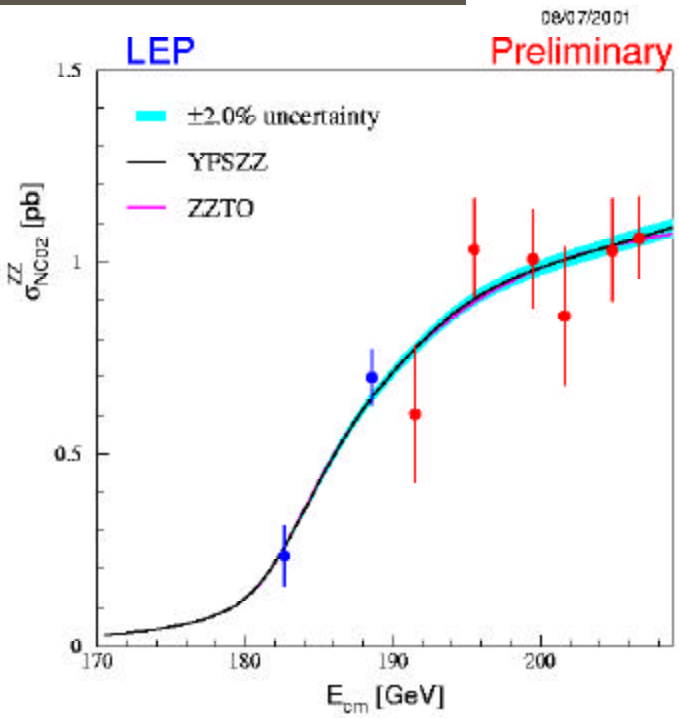
4-jet rate for

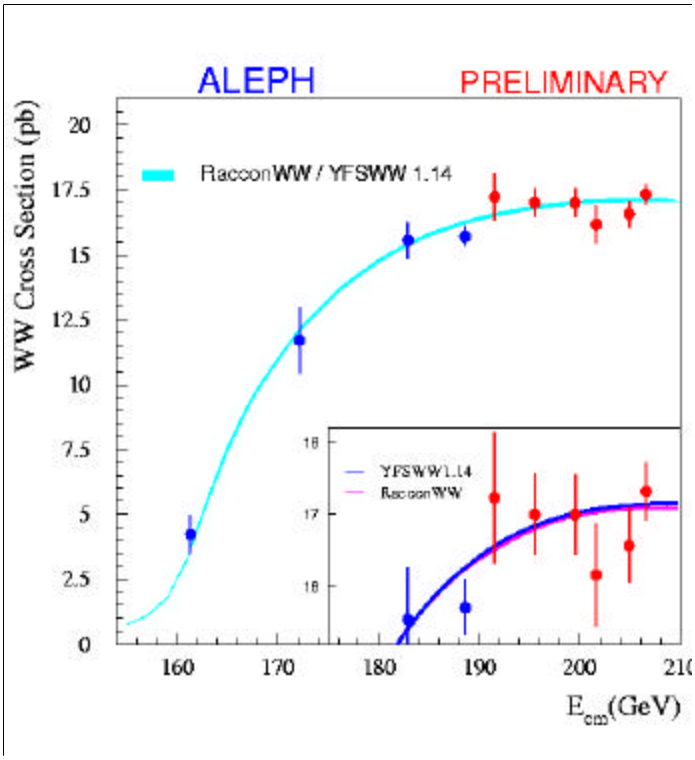
y_{cut}~0.01

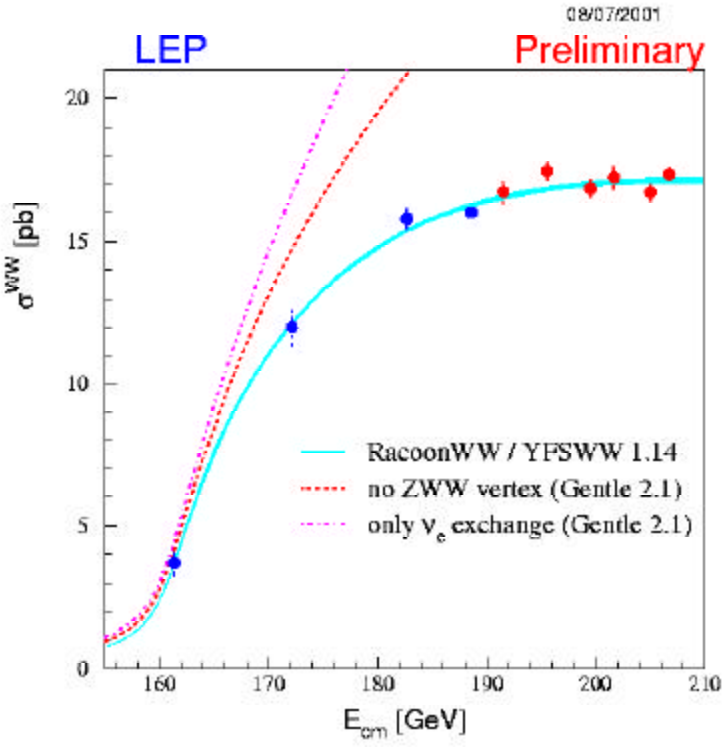
ZZ and WW backgrounds

cross-sections measured









Bkg. systematic studies

- Systematic on b studied by 4 LEP experiments
  $\delta bkg < 10\%$
- Systematic effects included in C_b and C_s with convolution technique
- ALEPH final publication:
  preliminary sys. estimate ($<0.2\sigma$) confirmed
  (detailed in the following)
- "2σ effect" is robust against systematic effects

Latest updates

- Aleph has published final results:

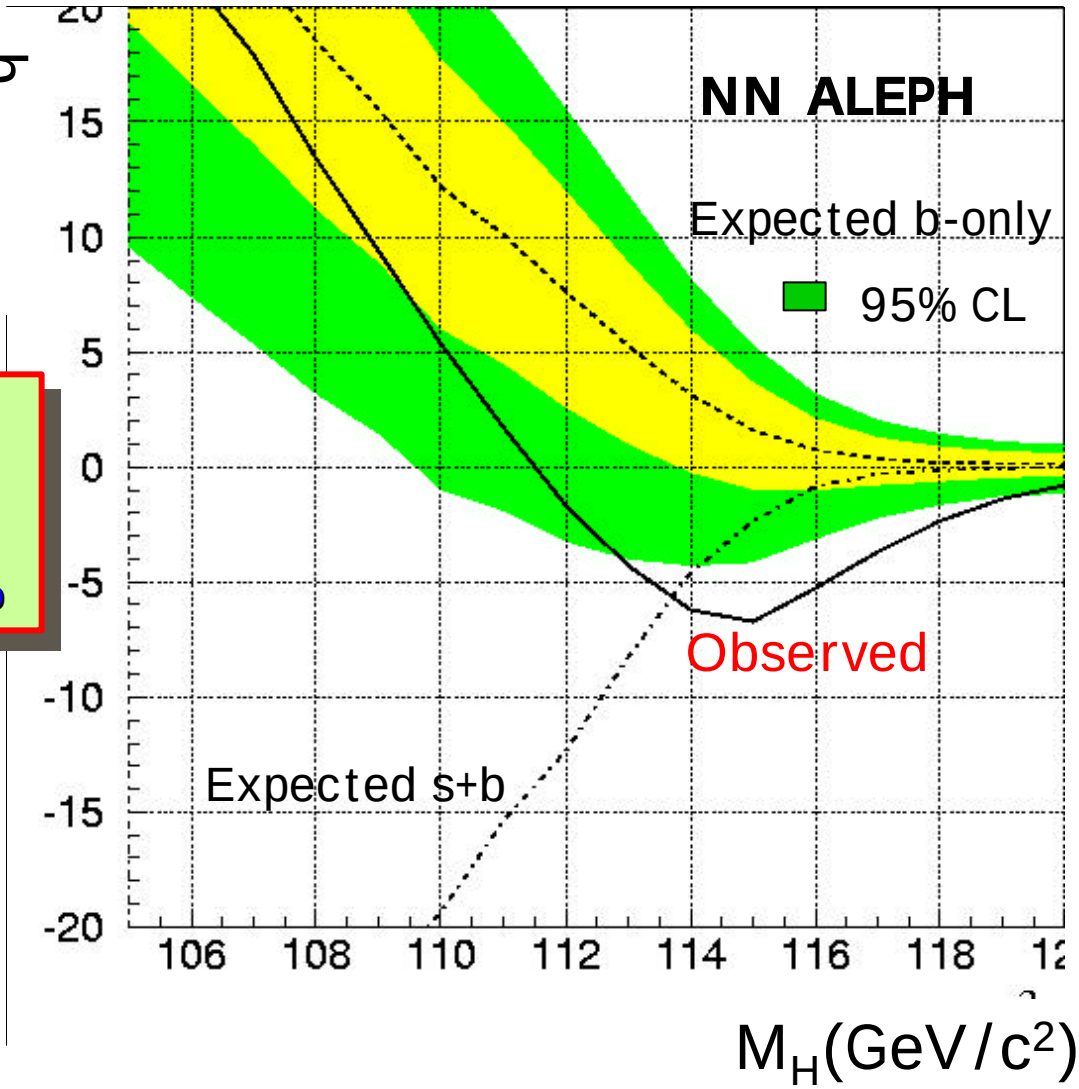
Physics Letters B 526 (2002) 191

  - Analyses unchanged (4-jet frozen in 1999)
  - Full reprocessing of the data (+1 pb^{-1})
  - Final estimate of systematics
  - Treatment of beam related background

CL b-only:

$1-C_b$=0.24%

it was 0.15%



Latest updates

Change in significance wrt previous publication

Update	NN signif. #s	CUT signif. #s
Previous publication	**2.96***	**3.06**
Final processing	-0.14	+0.21
Additional MC stat	-0.14	-0.36
Beam background rejection	+0.14	+0.13
Final result	**2.82**	**3.04**

*Definition of #σ is different between A and LEP (one-sided vs double-sided Gaussian integral)

Impact on significance

Systematic source	CUT stream	NN Stream
MC stat	±0.12σ	±0.08σ
B-tag	±0.06σ	±0.08σ
Gluon splitting	±0.04σ	±0.04σ
Jet resolution	±0.07σ	±0.07σ
Discriminating Variables	±0.04σ	±0.06σ
α_s (4-jet rate)	±0.04σ	±0.06σ

- If added in quadrature <0.2σ
- Systematics included in C_b and C_s with Gaussian convolution technique

3s effect confirmed in final publication for both streams

Robust against bkg systematics

Conclusions: 1

The LEP era ended with an intriguing result:

- Interesting Higgs candidates found:
  mainly A - 4-jet channel
- LR minimum observed @ M_H=115.6 C_{s+b} = 44%
- Compatibility with backg-only hypot. 3.4% (~2σ)
- Final LEP combination:Summer Conferences (A,O, D)
- Since A results unchanged
  combined significance @ 115.6 GeV shouldn't change
- s+b or b-only hypothesis ?

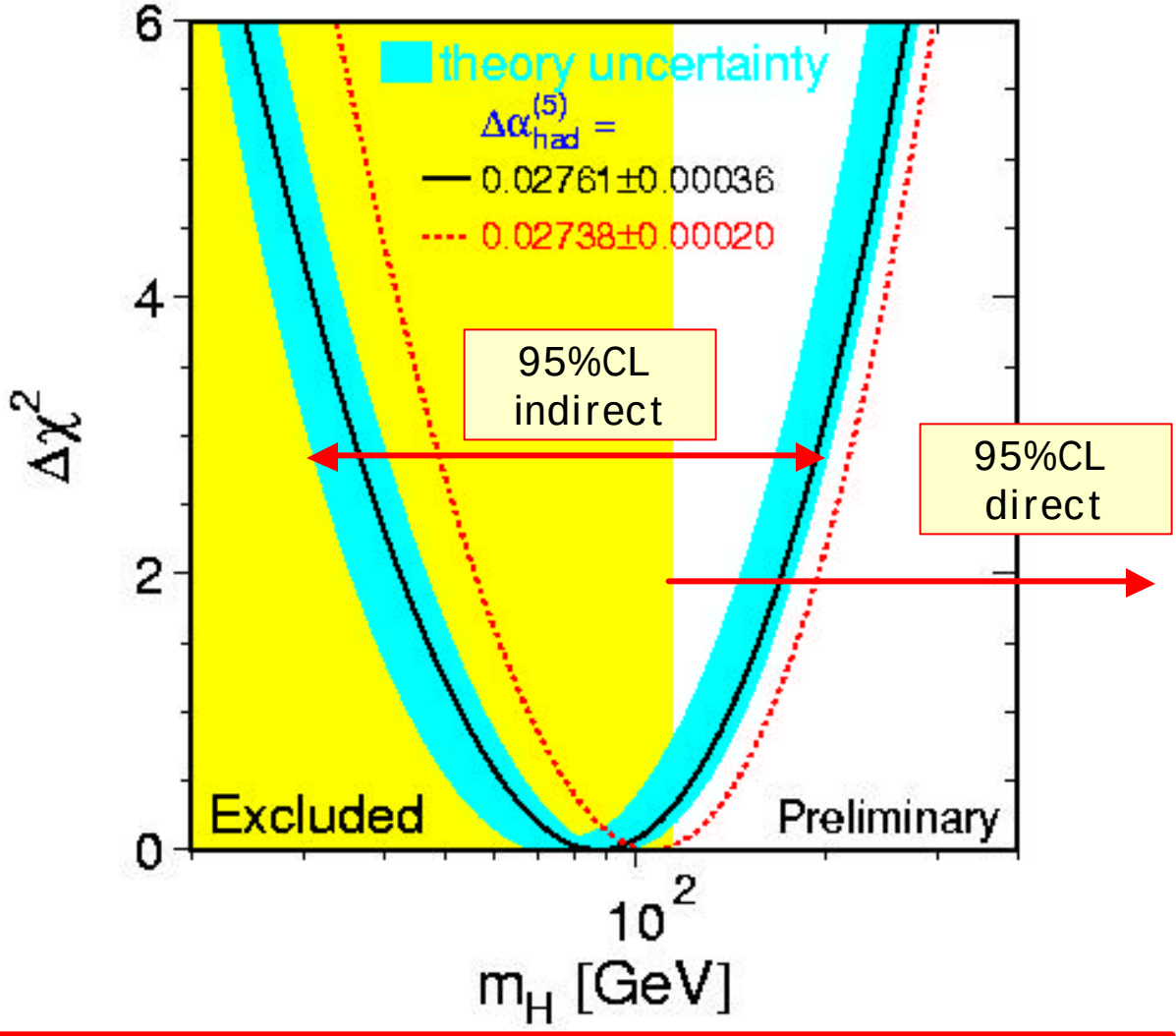
future experiment will clarify the nature of the effect:

Tevatron , LHC

Be patient … La Thuile 200? …… (?=8)

Conclusions: 2

- LEP* impact on Higgs boson very relevant
  - Before LEP $0 < M_H < \sim 1$ TeV



After LEP

114 GeV(direct)$< M_H <$196 GeV (EW fit) @95% CL

*data from CDF, D0, SLD and NuTEV included in EW indirect limit

Caveat: bad χ^2/ndf of the EW fit not taken into account

Acknowledgment

Many thanks to all the members of the

LEPHIGGS working group

Why significance went down ?

- A: correlation between *discriminating-variables*
- L:
  - New 4-jet and re-optimization of missing-energy
  - Best candidate (Hνν): s/b=1.6 (Nov.) → 0.7 (now)
- All : Additional 10-16 pb^{-1} (only 1 new signif. Cand. O)

MH=115 GeV

$m_H \approx 115$ GeV	LEPC 3 / 11 / 2000 (P.Igo-Kemenes talk)	Now →	Reference
ALEPH	3.4 σ	3.0 σ	Phys. Lett. B495 (2000)
DELPHI	$1\text{-}CL_b=0.68$	$1\text{-}CL_b=0.77$	Phys. Lett. B499 (2001)
L3	1.8 σ	1.0 σ	Submitted to Phys.Lett.
OPAL	1.3 σ	1.3 σ	Phys. Lett. B499 (2001)
Combined	2.9 σ	2.1 σ	CERN/EP-2001-055

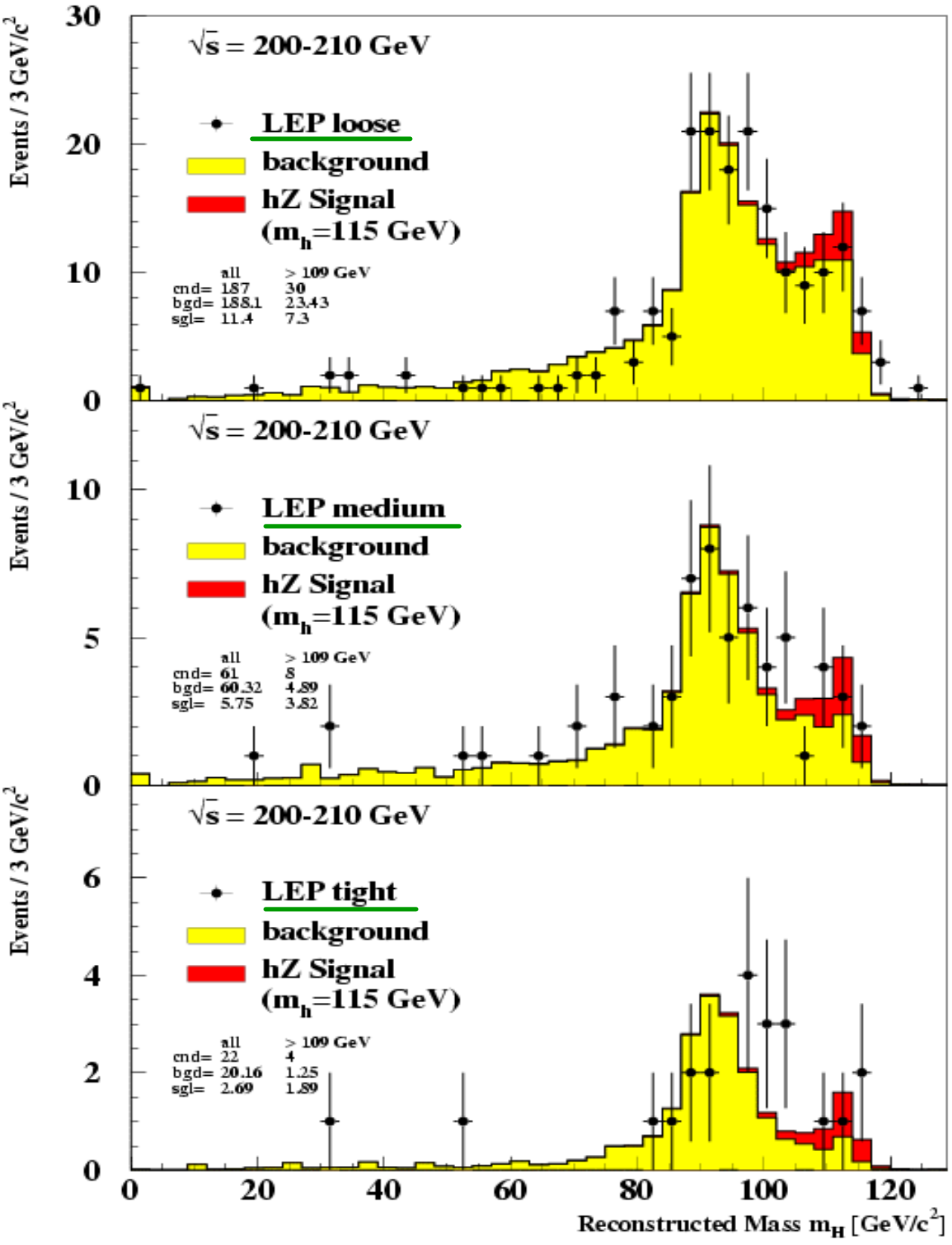
In addition :

- Data reprocessed with refined calibration
- Many systematics studied in detail (e.g. detector performance, bkg's, threshold behavior)

*Note : all experiments have published but only L3 is final

The LEP results

Mass spectra do not show all the info (e.g. b-tag,topology)



	$1-CL_b$	CL_{s+b}
A	0.002	0.94
D	0.87	0.02
L	0.24	0.47
O	0.22	0.47
LEP	0.034	0.44
DLO	0.49	0.07
ALO	0.0037	0.83

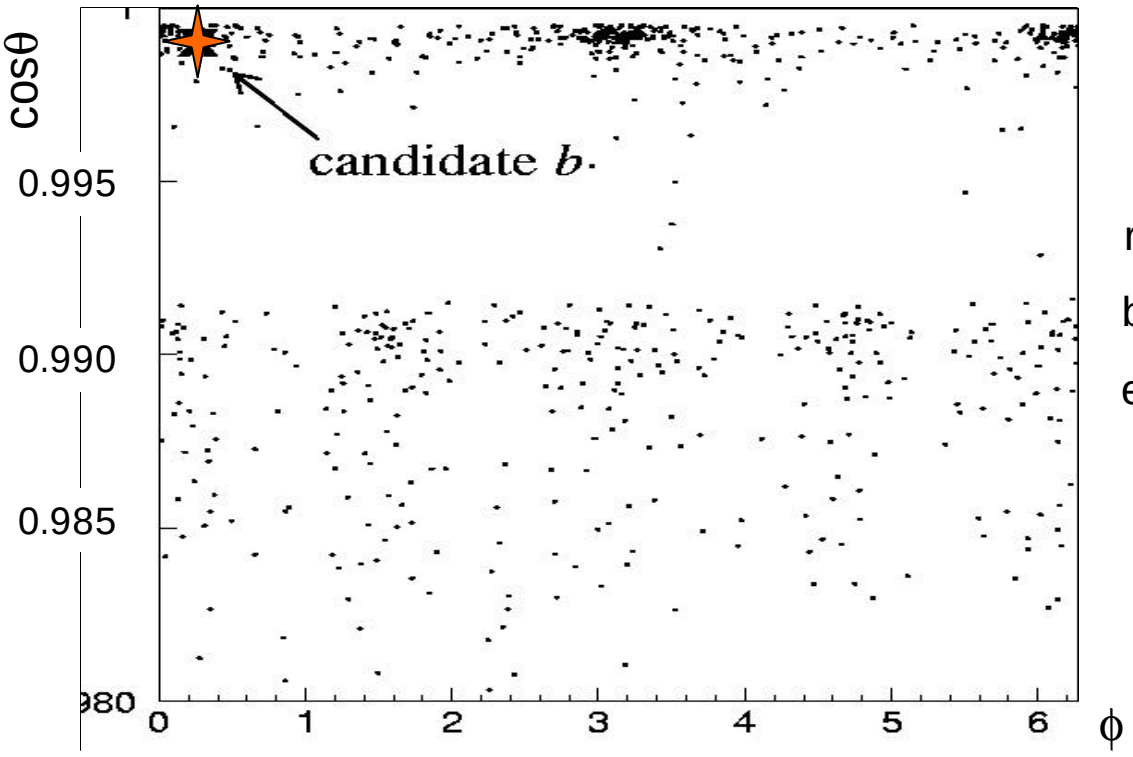
Latest updates

Final processing

- Final Processing (and +1 pb^{-1}) 1 additional candidate selected by CUT:
  - M_H^{reco}=111.8 GeV - H jets btag 0.97 0.87
  - Z jets btag 0.09 0.28 - Weight at 115 GeV=0.25
- Increase CUT significance at 115 GeV by ~0.2σ
- 3 most significant NN candidates unaffected

Beam background rejection

- 2nd most significant 4-jet cand. 22 GeV isolated low-θ deposit: beam-related bkg warning not simulated in MC !

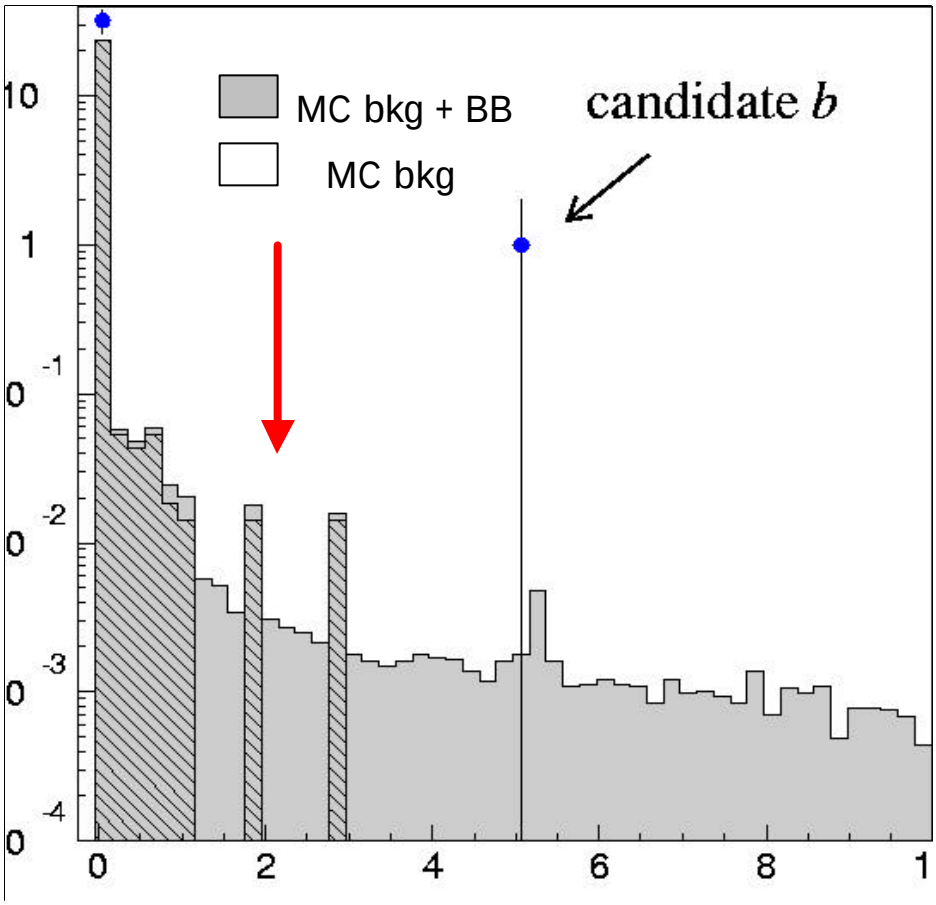


random beam-crossing events

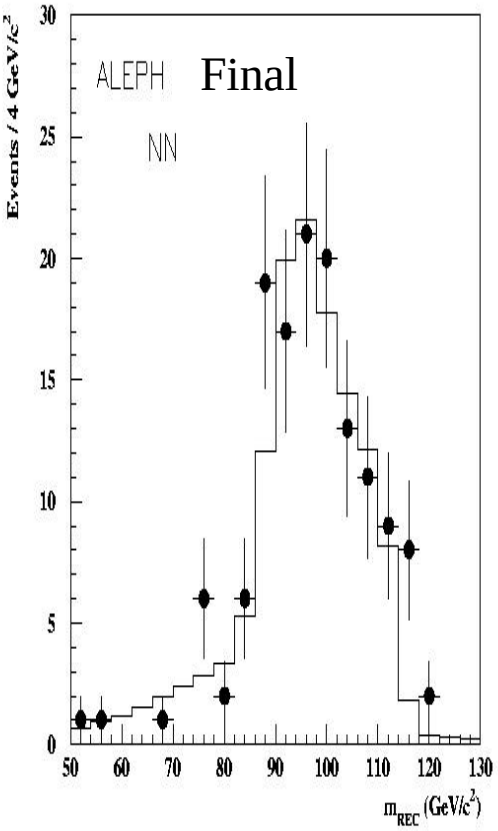
- Select isolated clusters E>3 GeV |cosθ|>0.98
- Kinematic fit of the event to 3 hyp..
  - Norm = Cluster part of event → standard 4-jet fit[χ^2(norm)]
  - ISR = Cluster ISR photon - fit rest of event to four-jets taking into account momentum imbalance caused hypothetical ISR photon [χ^2(ISR)]
  - BB = Cluster beam induced background - remove from event and fit rest of event to four-jets [χ^2(beam)]
- Build $R=\min\{\chi^2_{ISR},\chi^2_{Norm}\}/\chi^2_{BB}$

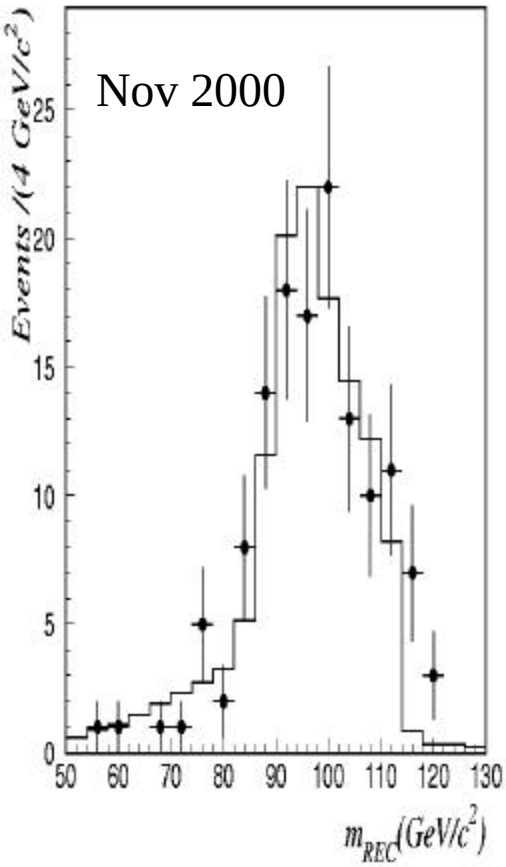
Latest updates

- If R>2 remove the cluster from the event (and recompute all the relevant quantities)
- Only one candidate (b) affected in the data:
  - M_H^{reco} 112.8 -> 114.4 GeV
  - NN 0.996 ->0.997
- NN and CUT significances increased by ~0.1 σ

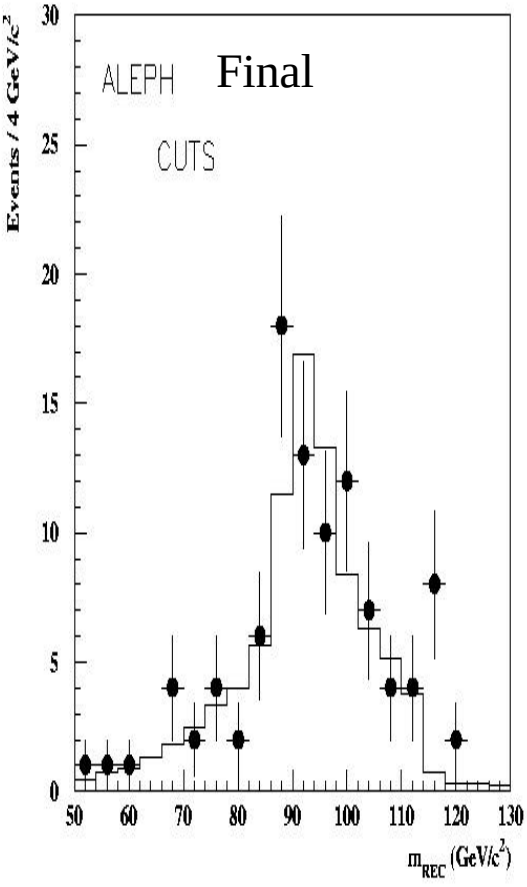


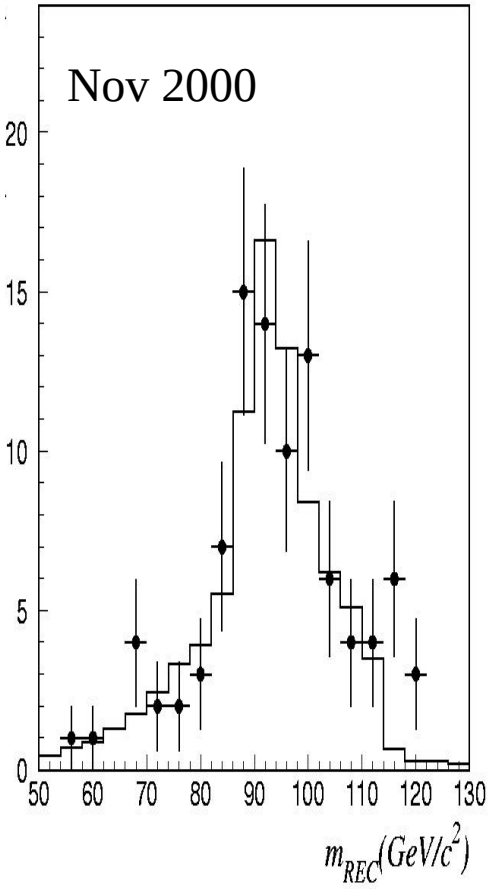
Reconstructed Higgs mass plot NN stream



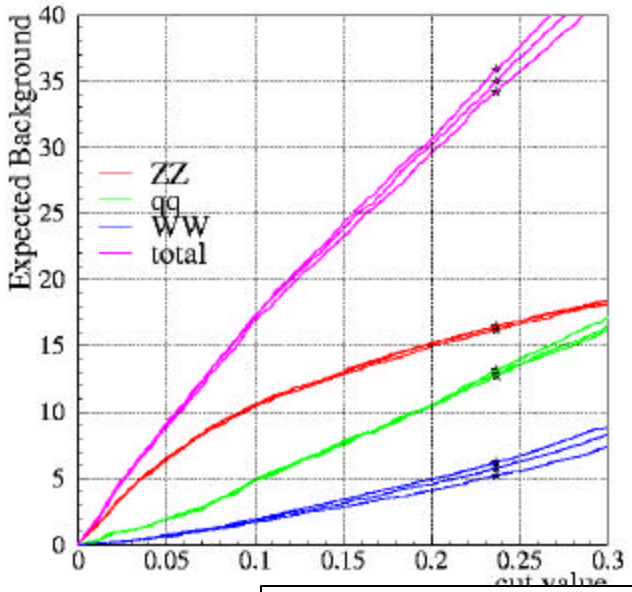


Reconstructed Higgs mass plot Cut stream

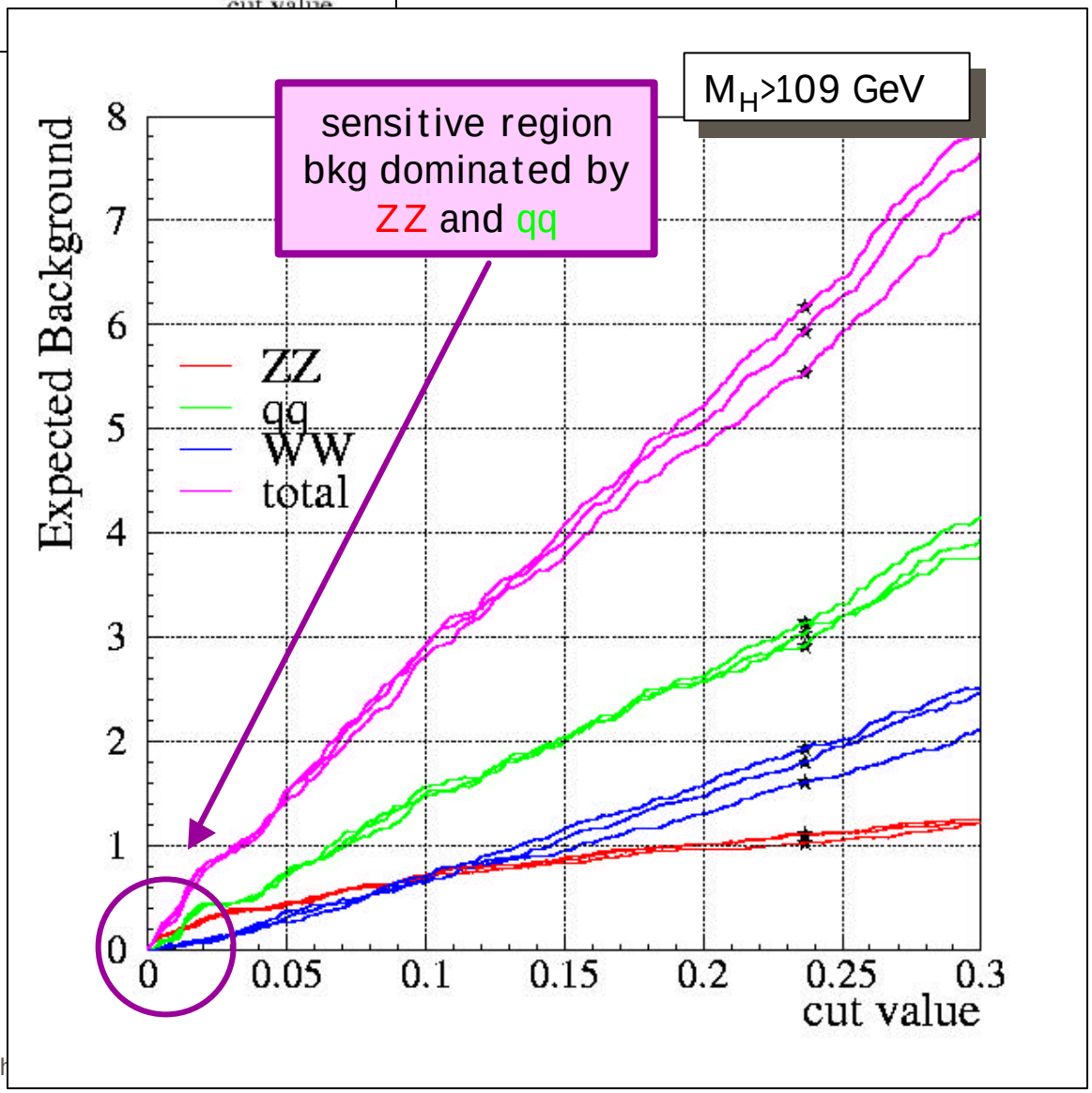




Background vs NN-output cut



All masses



Bkg. fluctuation or hint of a signal ?

The two hypothesis can be compared:

a) Statistical fluctuation: 3.4% (x~2=7% "look-where-else effect": 115.6 GeV arbitrary !)

b) Hint of a signal: 47%

- Internal Consistency DLO vs A: 7% (x~3~21% any of the 3 experiments could have a more significant "excess")
- With this statistics both hypotheses a) and b) are plausible: no scientific conclusion possible