Search for MSSM Higgs at LEP

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OUTLINE

- Introduction of MSSM
- Main Backgrounds
- L3 Analysis Procedure
- LEP Combined Results
- Conclusions

Introduction

- Minimal Supersymmetric Standard Model

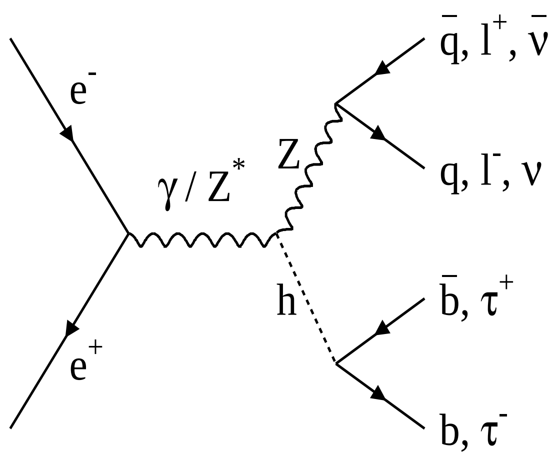
Two Higgs doublets $\Longrightarrow$ 5 Higgs bosons

$\rightarrow$ 3 neutral (h & H CP-even, A CP-odd),

$\rightarrow$ 2 charged Higgs.

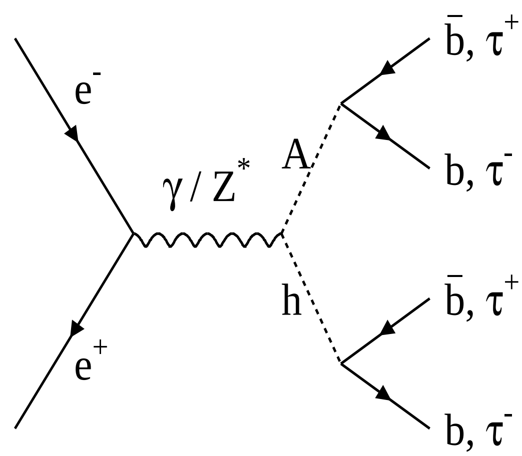
- Neutral Higgs - Two Complementary Processes

Higgsstrahlung



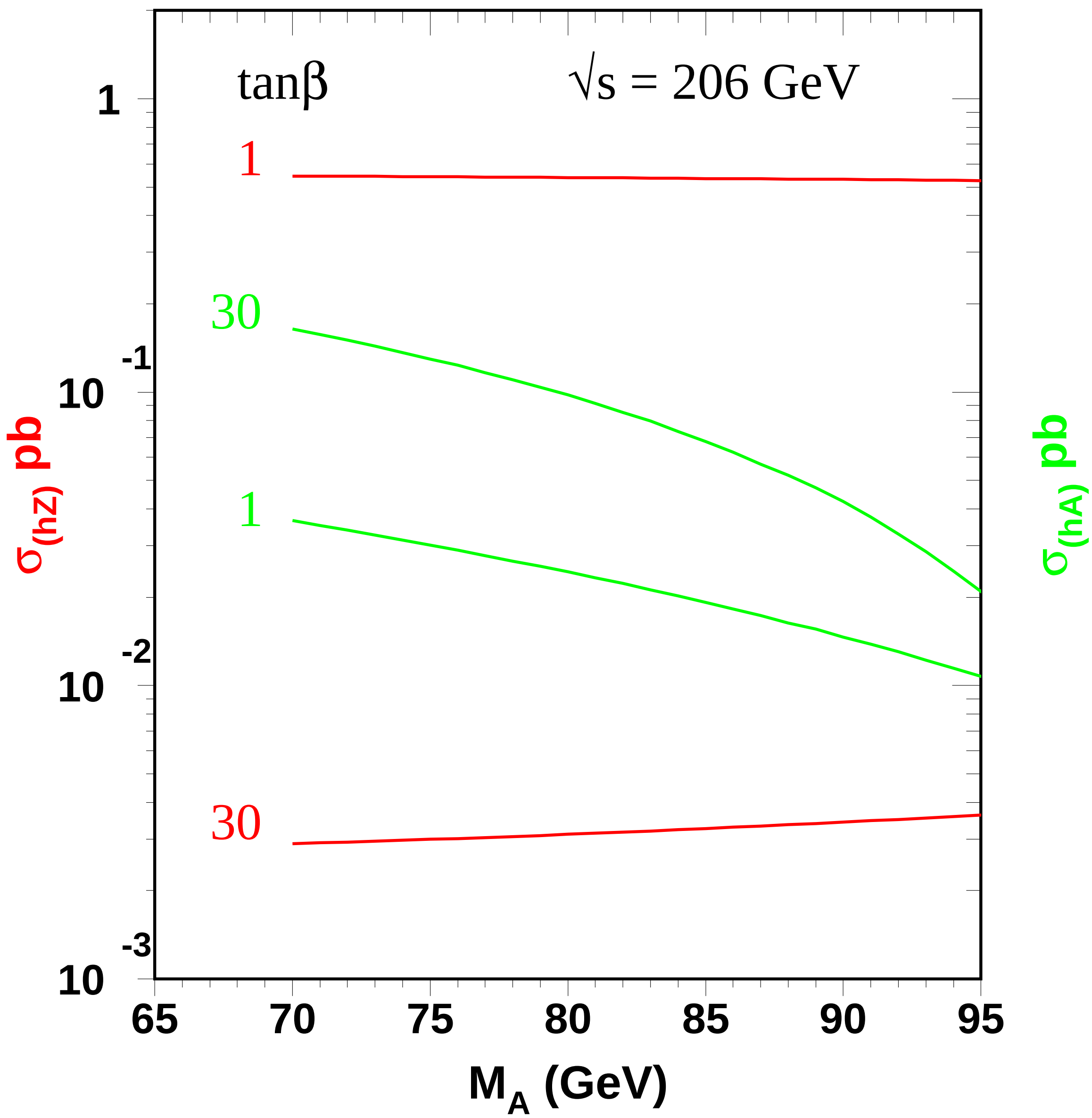
$$\sigma_{hZ} = \sin^2(\beta - \alpha)\sigma_{hZ}^{SM}$$

Pair Production



$$\sigma_{hA} = \cos^2(\beta - \alpha)\bar{\lambda}\sigma_{hZ}^{SM}$$

⟹ hZ production is dominant at low $tan\beta$



⟹ hA is dominant at large $tan\beta$.

Introduction

- **Parameters of the MSSM**

  1. Ratio of two Higgs vacuum expectation values: $\tan\beta$
  2. Mass of A boson: m_A
  3. Gaugino mass parameter: M_2
  4. Scalar fermion mass: m_0
  5. Higgsino mass parameter: μ
  6. Higgs-sfermion trilinear coupling: A

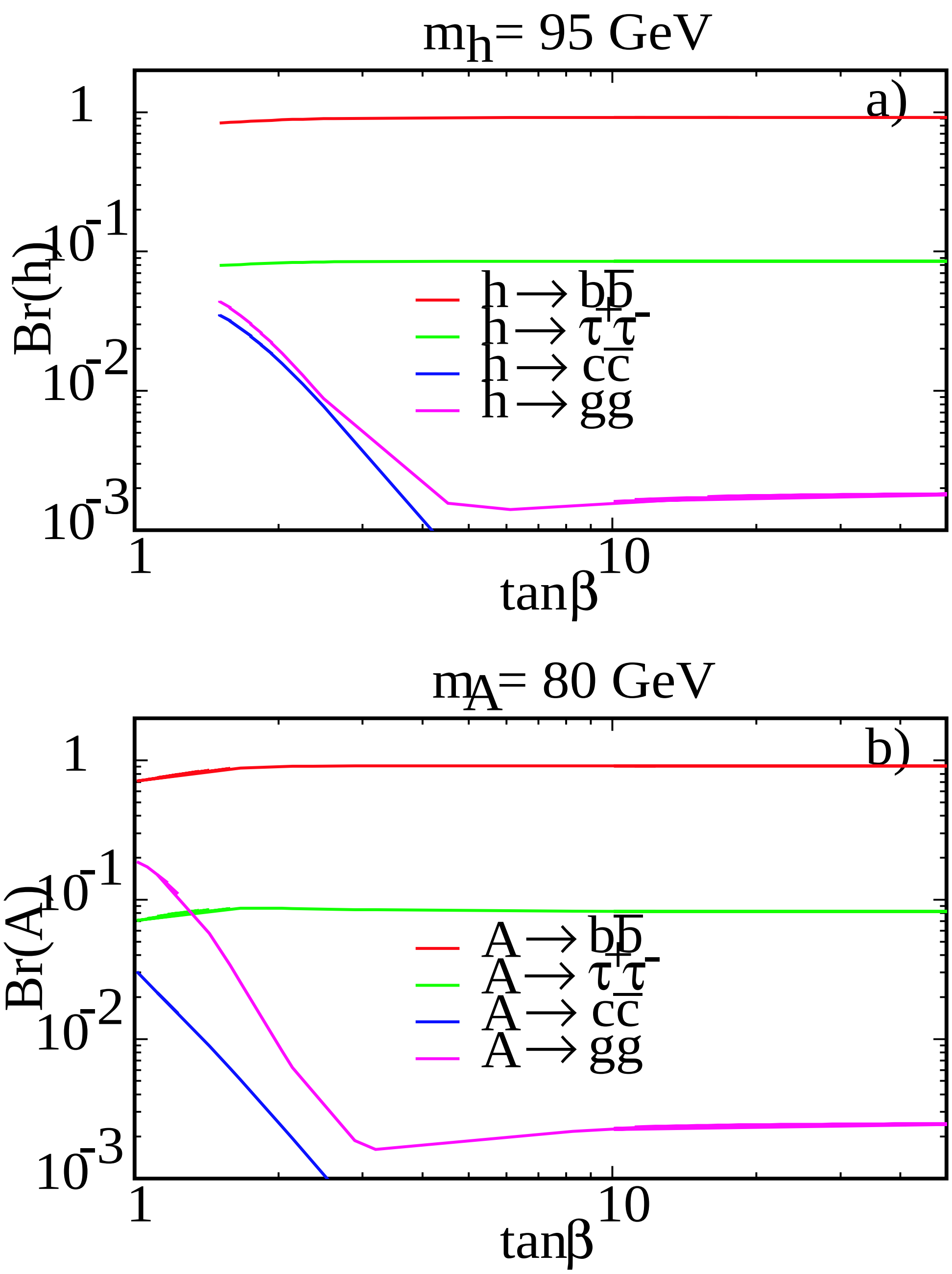
- **Three Benchmark Scenarios**

  $\rightarrow$ m_h Maximal
  $X_t = A - \mu\cot\beta = \sqrt{6}$ TeV

  $\rightarrow$ Minimal Mixing: No mixing in stop sector
  $X_t = A - \mu\cot\beta = 0$

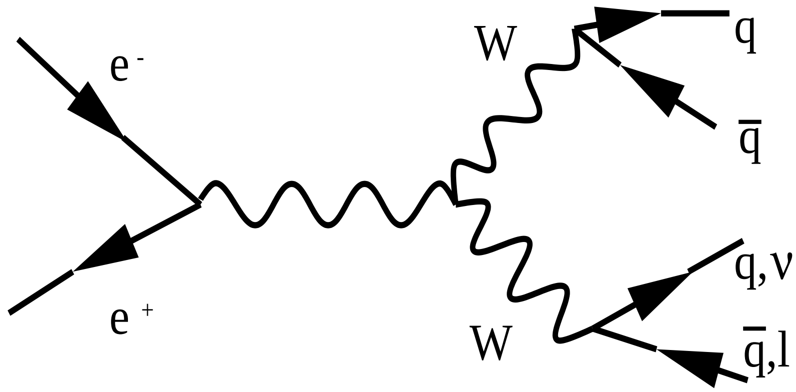
  $\rightarrow$ large μ

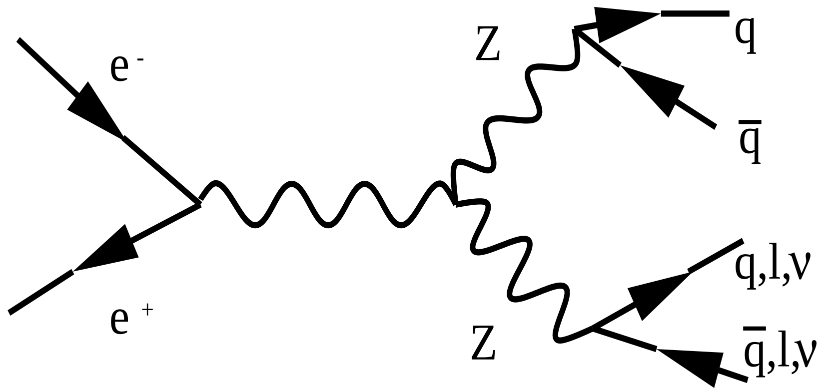
- Higgs decay into $b\bar{b}$ and $\tau^+\tau^-$ is dominant.

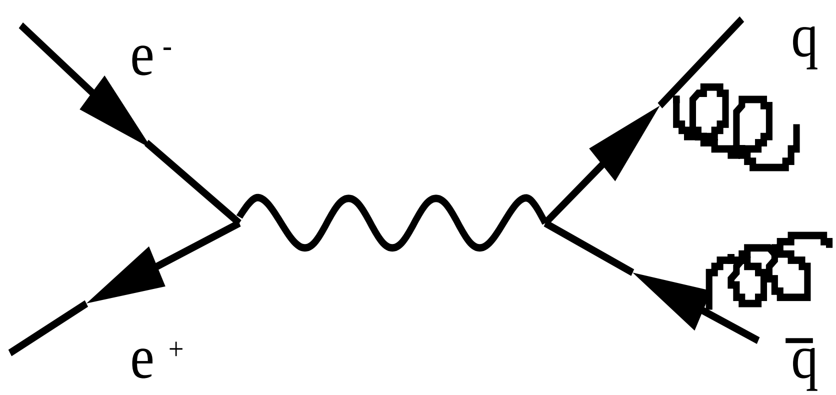


$\Longrightarrow$ focused on $hA \to b\bar{b}b\bar{b}$ and $hA \to b\bar{b}\tau^+\tau^-$.

Main Backgrounds

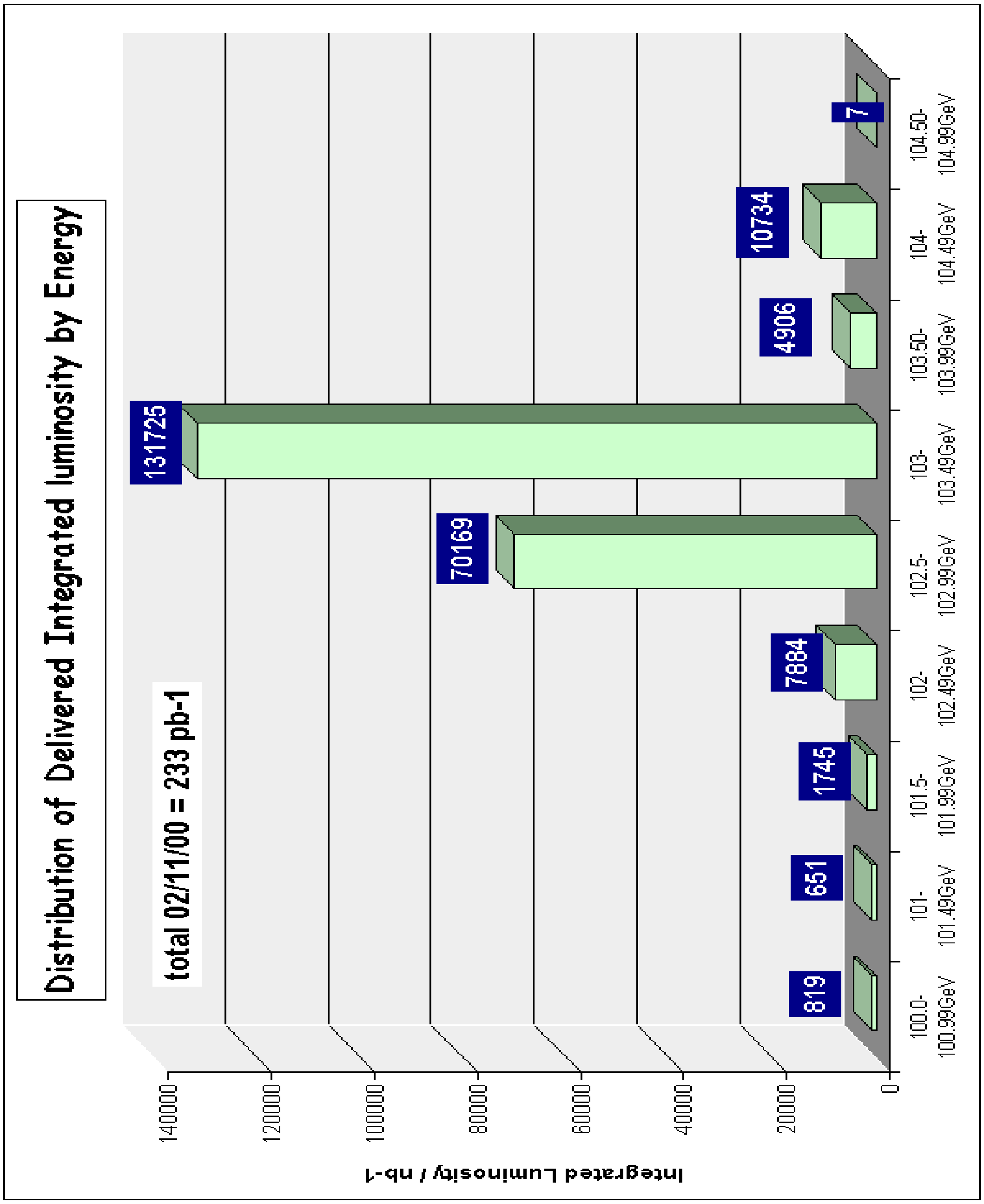






- Main backgrounds come from WW, ZZ, $q\bar{q}$, $e\nu qq$ and Zee etc.

Data Taking in Y2k



Analysis Procedure

- 4-jet channel: hA $\rightarrow b\bar{b}b\bar{b}$

Preselection

$\Downarrow$

Neural Network

$\Downarrow$

Final Discriminant

Step 1. **Preselection:** To reject low multiplicity backgrounds while keeping high signal efficiencies($\sim$ 90%).

Step 2. **Neural Network:** Discriminant distributions are combined in a neural network.

Step 3. **Final Discriminant:** Neural network outputs are used to construct final discriminant variable.

- Preselection Cuts

1. Number of tracks ≥ 20
2. Number of calorimetric clusters ≥ 35
3. Visible energy: $0.6 < E_{vis}/\sqrt{s} < 1.4$
4. Perpendicular imbalance energy $\leq 0.35 \bullet E_{vis}$
5. Lepton energy < 65 GeV
6. Longitudinal component of the missing momentum: $P^{L}_{miss}/(m_{vis} - m_{Z}) < 0.4$

- Event $\Rightarrow$ 4-jet using DURHAM algorithm
- Kinematic fit: 4-momentum conservation(4C) fit

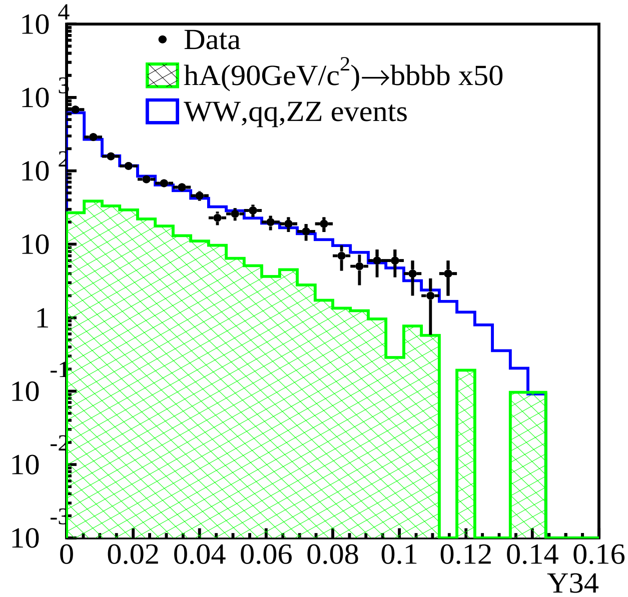
- Neural Network Inputs:

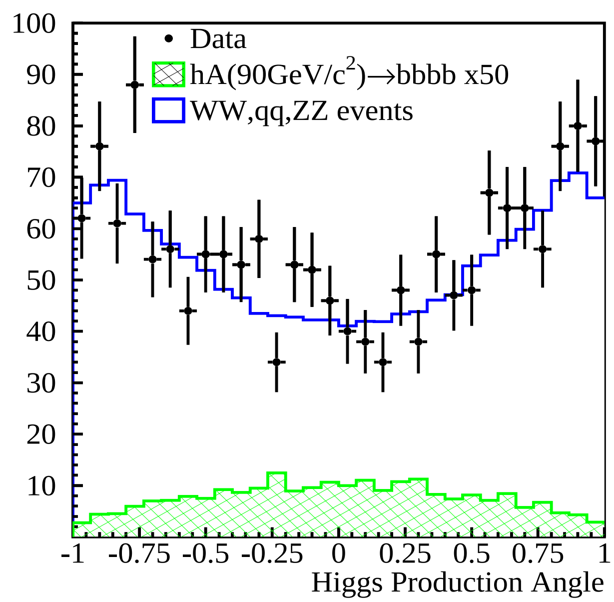
1. Event B_{tag}
2. Event Sphericity
3. Event Thrust
4. P^{L}_{miss}
5. Polar angle of Higgs boson: θ_{Higgs}
6. DURHAM jet resolution parameter: Y^{D}_{34}
7. mass χ^2

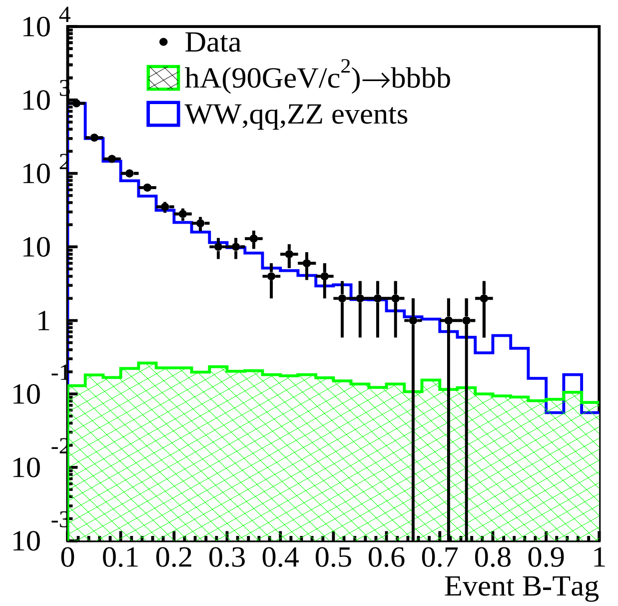
$$\chi^2(m_A, m_h) = \frac{(\Sigma_i - m_h - m_A)^2}{\sigma^2_\Sigma} + \frac{(\Delta_i - |m_h - m_A|)^2}{\sigma^2_\Delta}$$

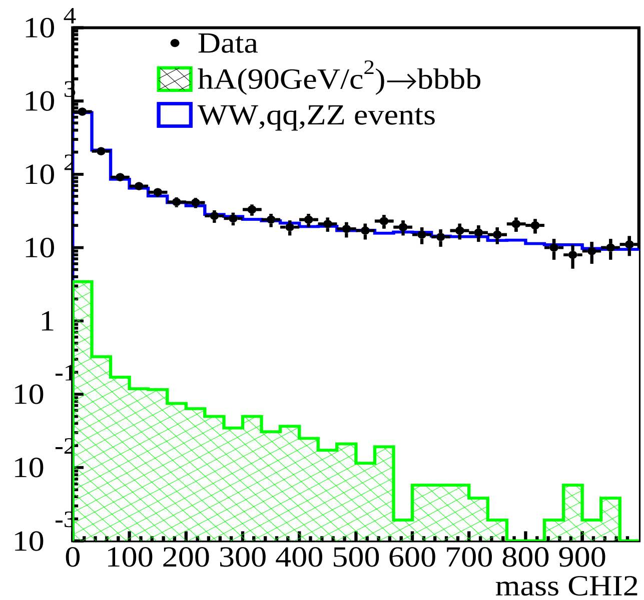
- Neural Network Outputs:

Three outputs, Y_{hA}, Y_{WW} and Y_{qq}


Data
hA(90GeV/c2)→bbbb x50
WW,qq,ZZ events
Y34


Data
hA(90GeV/c2)→bbbb x50
WW,qq,ZZ events
Higgs Production Angle

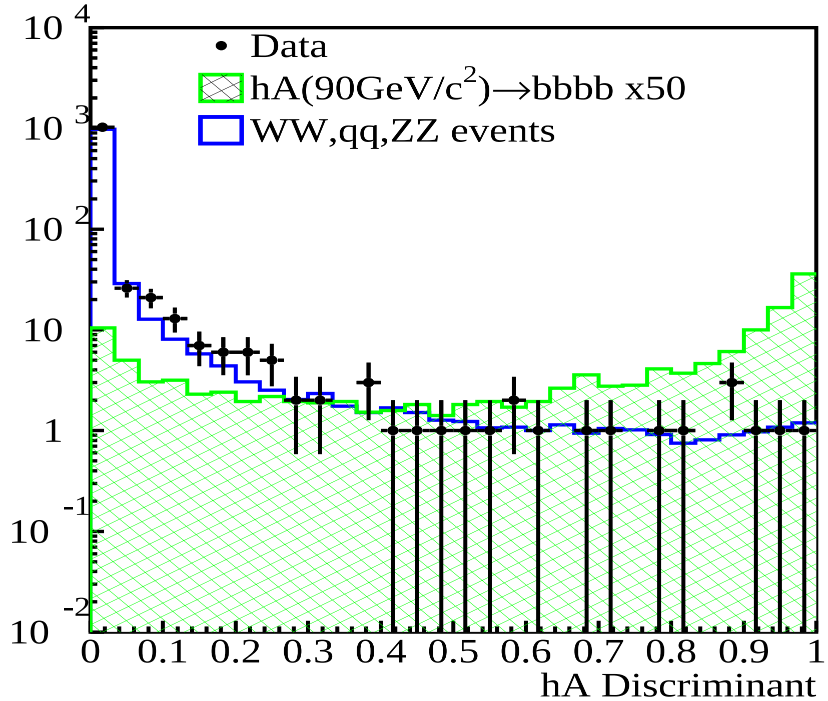

Data
hA(90GeV/c2)→bbbb
WW,qq,ZZ events
Event B-Tag

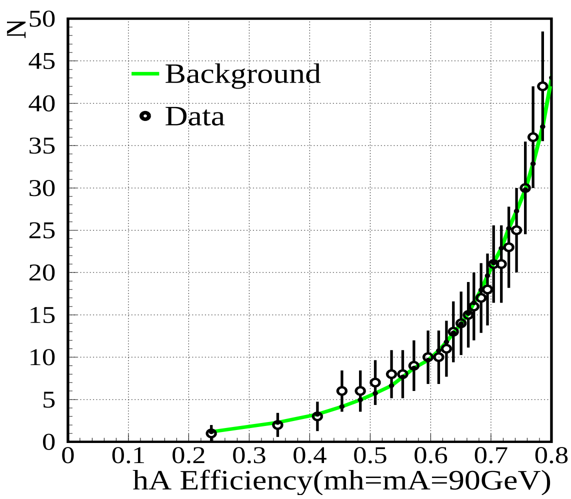

Data
hA(90GeV/c2)→bbbb
WW,qq,ZZ events
mass CHI2

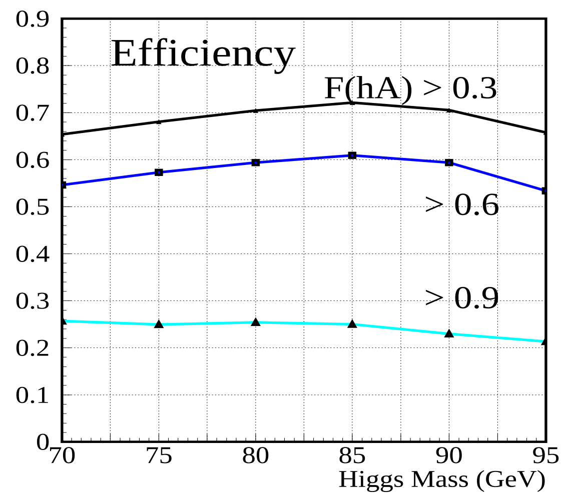
Final Discriminant of 4-jet Channel

- The Final Discriminant is defined as:

$$F_{hA} \equiv Y_{hA} \bullet (1 - Y_{WW}) \bullet (1 - Y_{q\bar{q}})$$

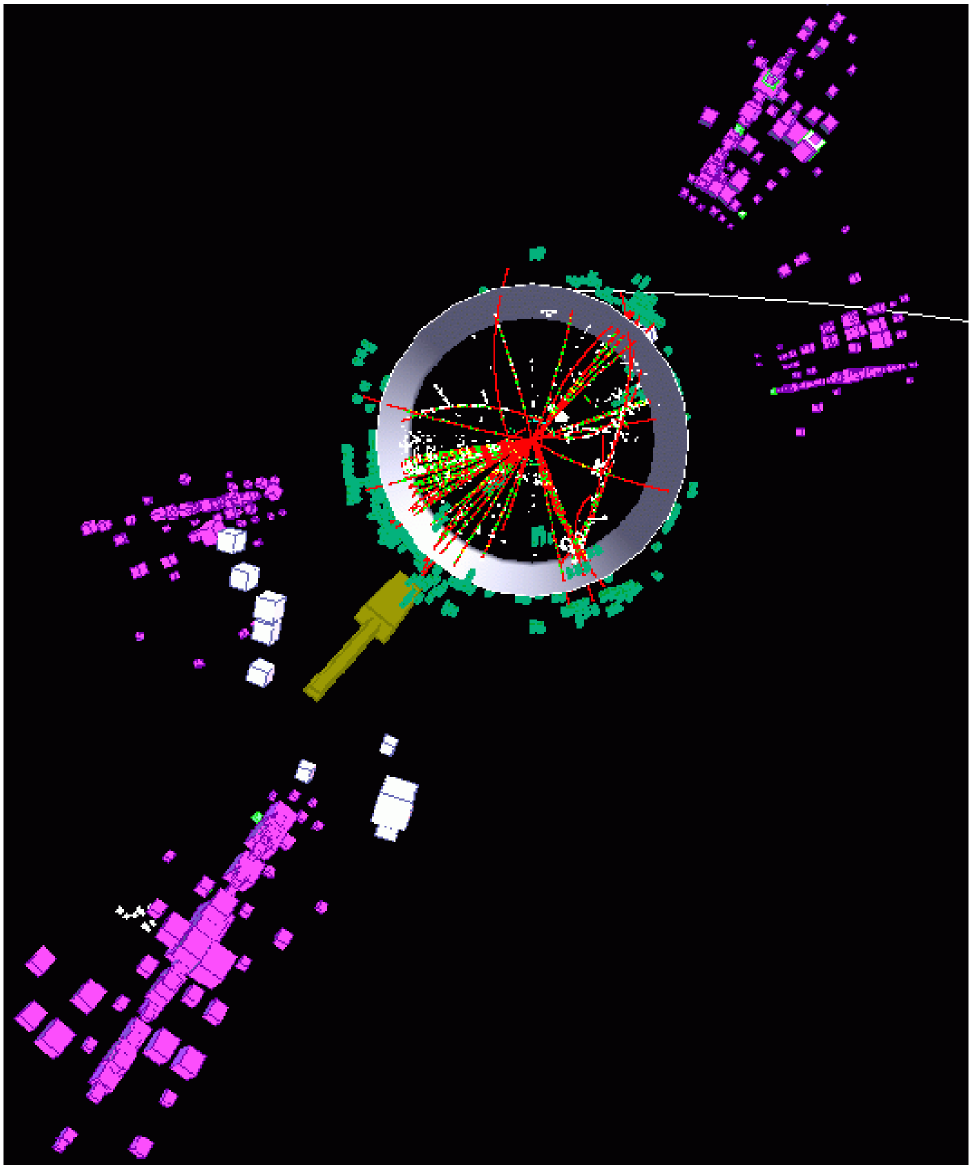






⇒ Data agree with MC backgrounds.
⇒ Efficiency is insensitive to Higgs Mass.

Candidate of hA $\rightarrow b\bar{b}b\bar{b}$



- High Discriminant = 0.98
- High B-tag = 0.6
- $m_h + m_A = 178.8$ GeV

Selection Results

	ALEPH	DELPHI	L3	OPAL
Inte. Lumi. (pb^{-1})	217	224	217	208
hA $\rightarrow bbbb$ $channel$				
Data	10	5	12	11
Total Background	5.5	6.5	7.8	10.3
4-fermion Bkgd.	4.1	4.4	5.6	6.9
$q\bar{q}$ Bkgd.	1.4	2.1	2.2	3.4
Efficiency	47%	47%	42%	48%
Expected Signal	3.5	3.6	3.2	3.4

- The signal efficiency and rate are shown for $m_h = m_A = 90\ GeV/c^2$, with $tan\beta \sim 20$.

Analysis Procedure

- Tau channel: hA $\rightarrow b\bar{b}\tau^+\tau^-$

Preselection

$\swarrow \quad \searrow$

Particle based | **Jet based selection**

$\searrow \quad \swarrow$

Final Discriminant

Step 1. **Preselection:** To reject low multiplicity backgrounds while keeping high signal efficiencies($\sim$ 80%).

Step 2. **Final Selection:** Two inclusive selections are performed. One based on tau identification(Particle based selection) and the other relying on event kinematics(Jet based selection).

Step 3. **Final Discriminant:** B-tag of jets, di-jet masses are used to construct final discriminant.

Analysis Procedure

- Preselection Cuts:

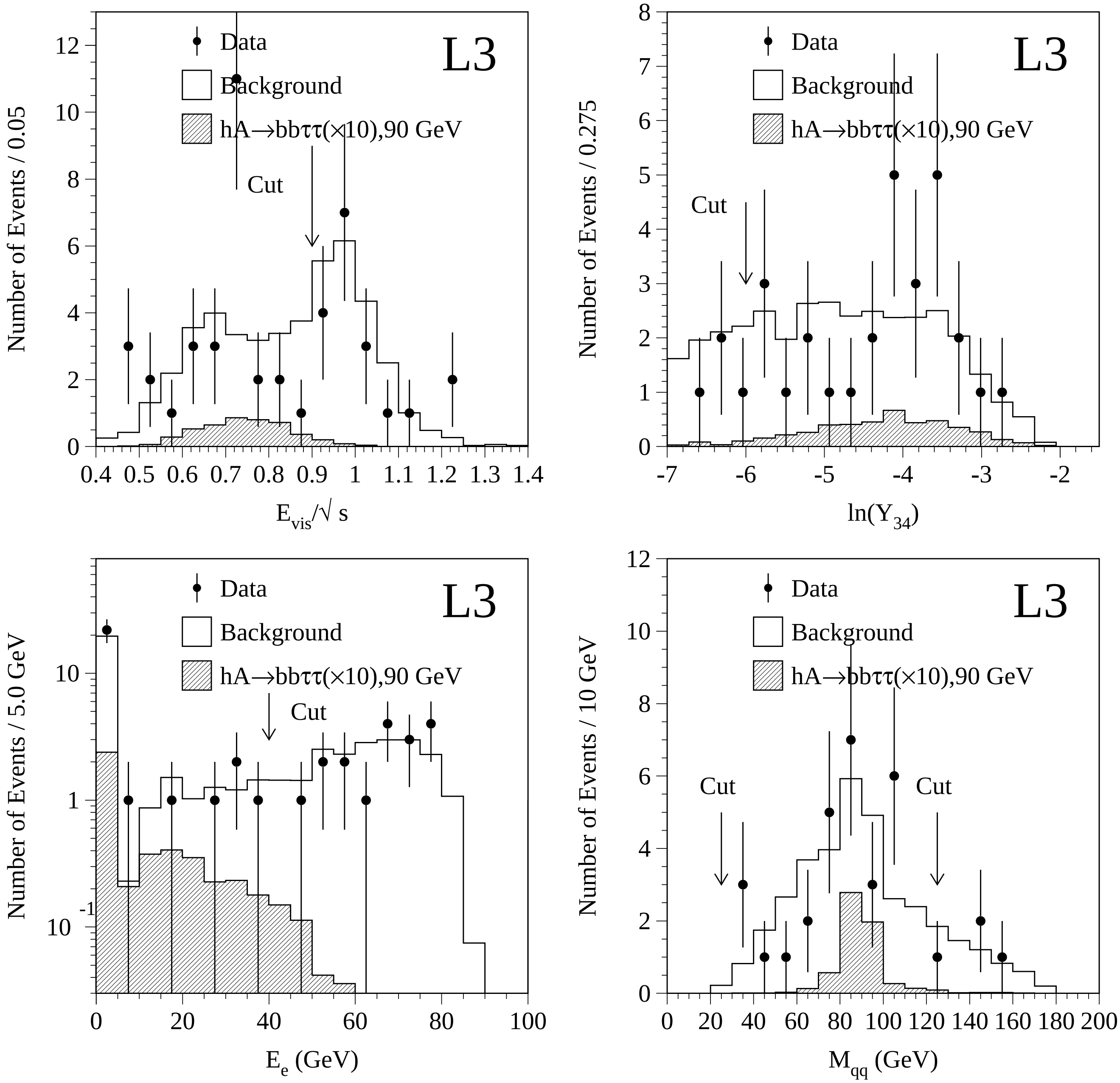
$N_{scnt} \geq 4$
$N_{gtrk} \geq 5$
$N_{src} \geq 15$
$E_{vis}/\sqrt{S} \geq 0.4$
$LOG(Y_{34}^{D}) \geq -7$
effective energy ≥ 100 GeV

- Final Selection Cuts:

particle-based	jet-based
$LOG(Y_{34}^{D}) \geq -6$	$LOG(Y_{34}^{D}) \geq -6$
$E_{\gamma,e,\mu} \leq 40$ GeV	$E_{\gamma,e,\mu} \leq 40$ GeV
$E_{vis}/\sqrt{S} \leq 0.95$	$E_{vis}/\sqrt{S} \leq 0.90$
$\theta_{qq}, \theta_{\tau\tau} \geq 70°$	$\theta_{qq}, \theta_{\tau\tau} \geq 70°$
$25 \leq M_{qq}, M_{\tau\tau} \leq 125$ GeV	$25 \leq M_{qq}, M_{\tau\tau} \leq 125$ GeV
no 3-3 prong decay	no 3-3 prong decay
$N_{\tau} \geq 2$	$\theta_{jj}^{min} \geq 25°$
	$\lvert cos\theta_{miss} \rvert \leq 0.9$

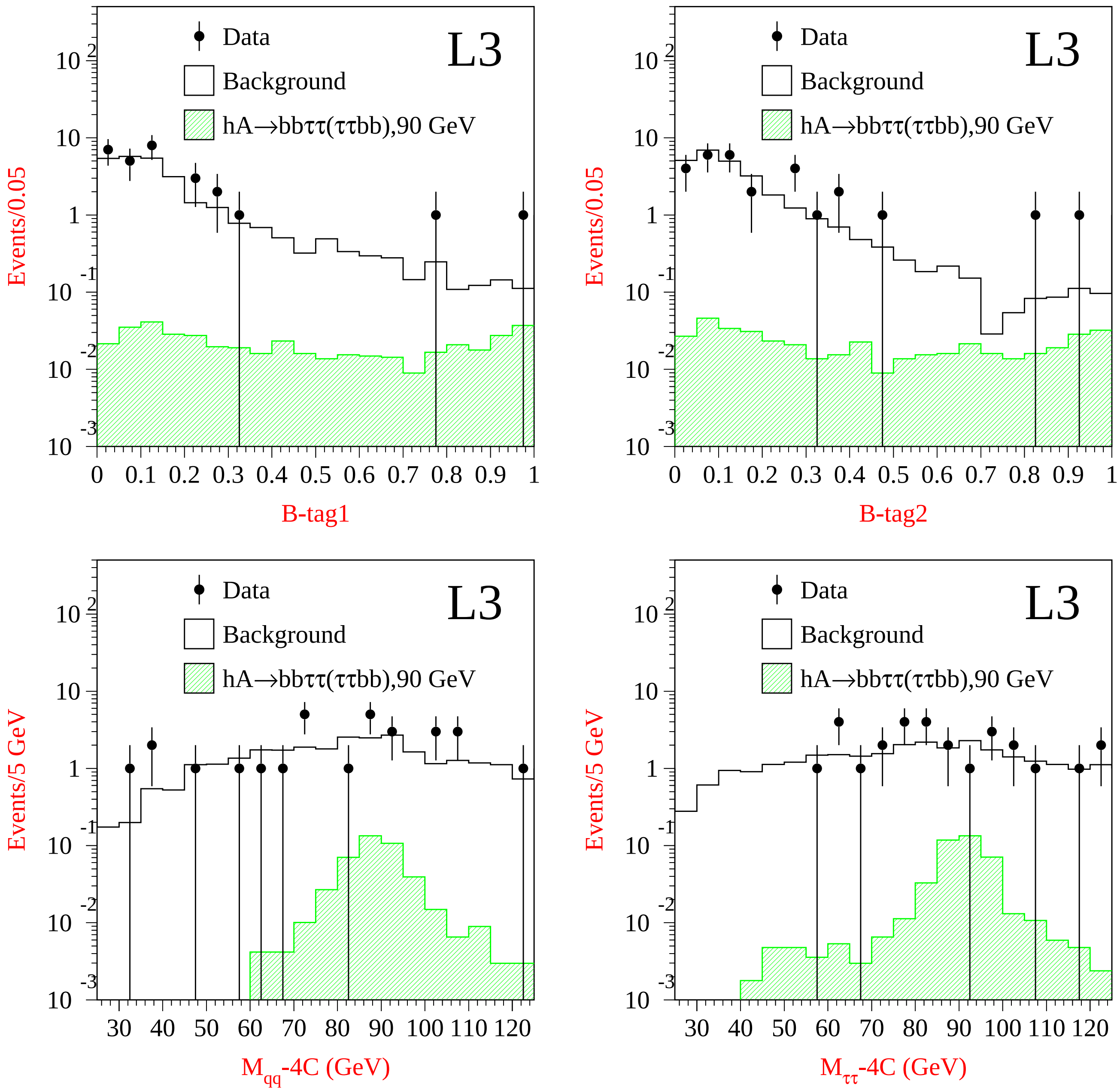
Selection Cuts

• N-1 plots of Tau channel



Discriminant Variables of Tau Channel

- Distributions used to construct final discriminant.



Final Discriminant Calculation

⇒ Compute the probability density function f_j^i,

j means event class(hA, WW, ZZ, qq etc.),
i denotes certain variables(b-tag, 2-jet mass etc.).

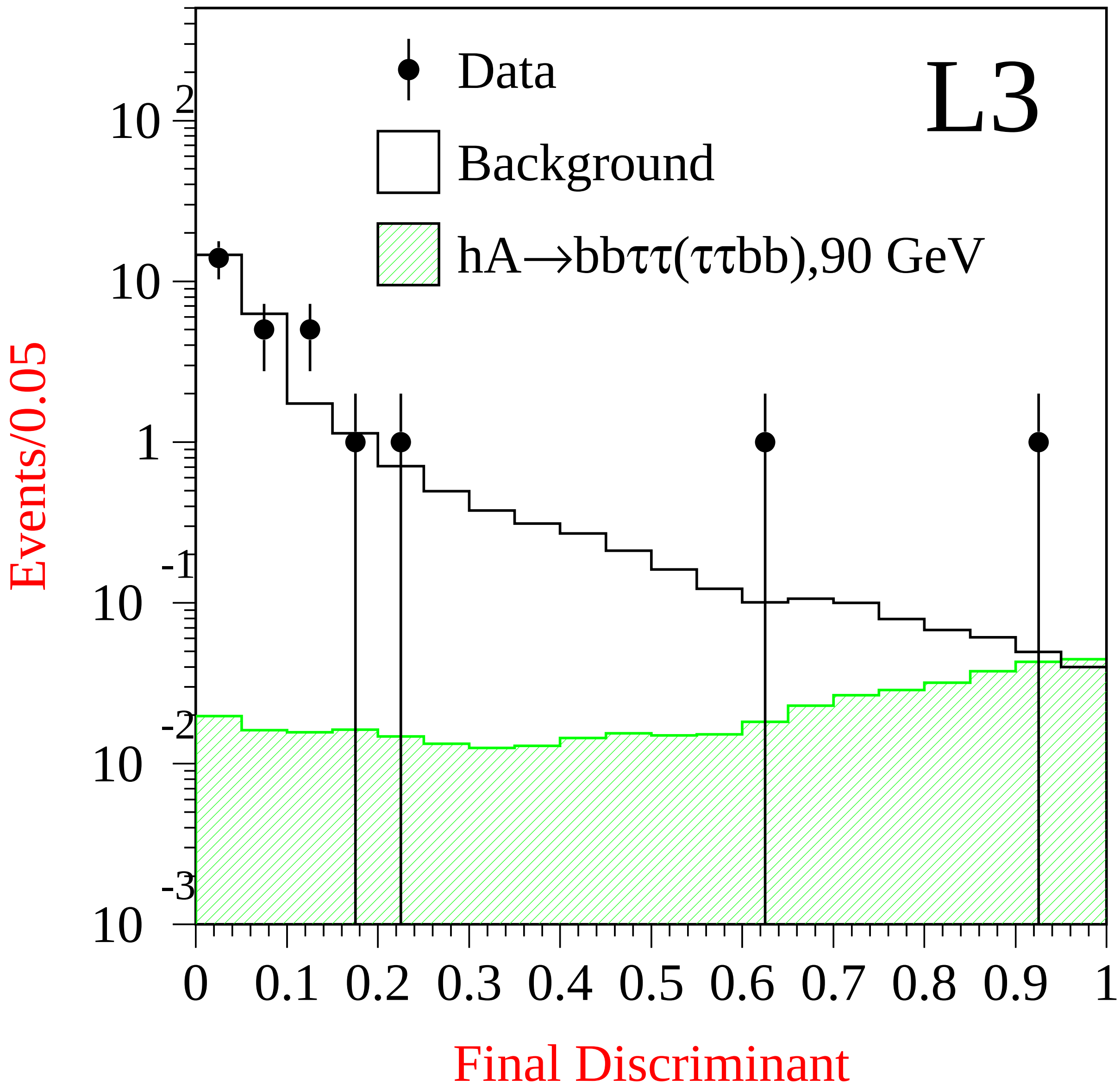
⇒ Derive figure of merit for event class j based only on variable i is defined as:

$$P_j^i = \frac{f_j^i}{\sum_k f_k^i} \tag{1}$$

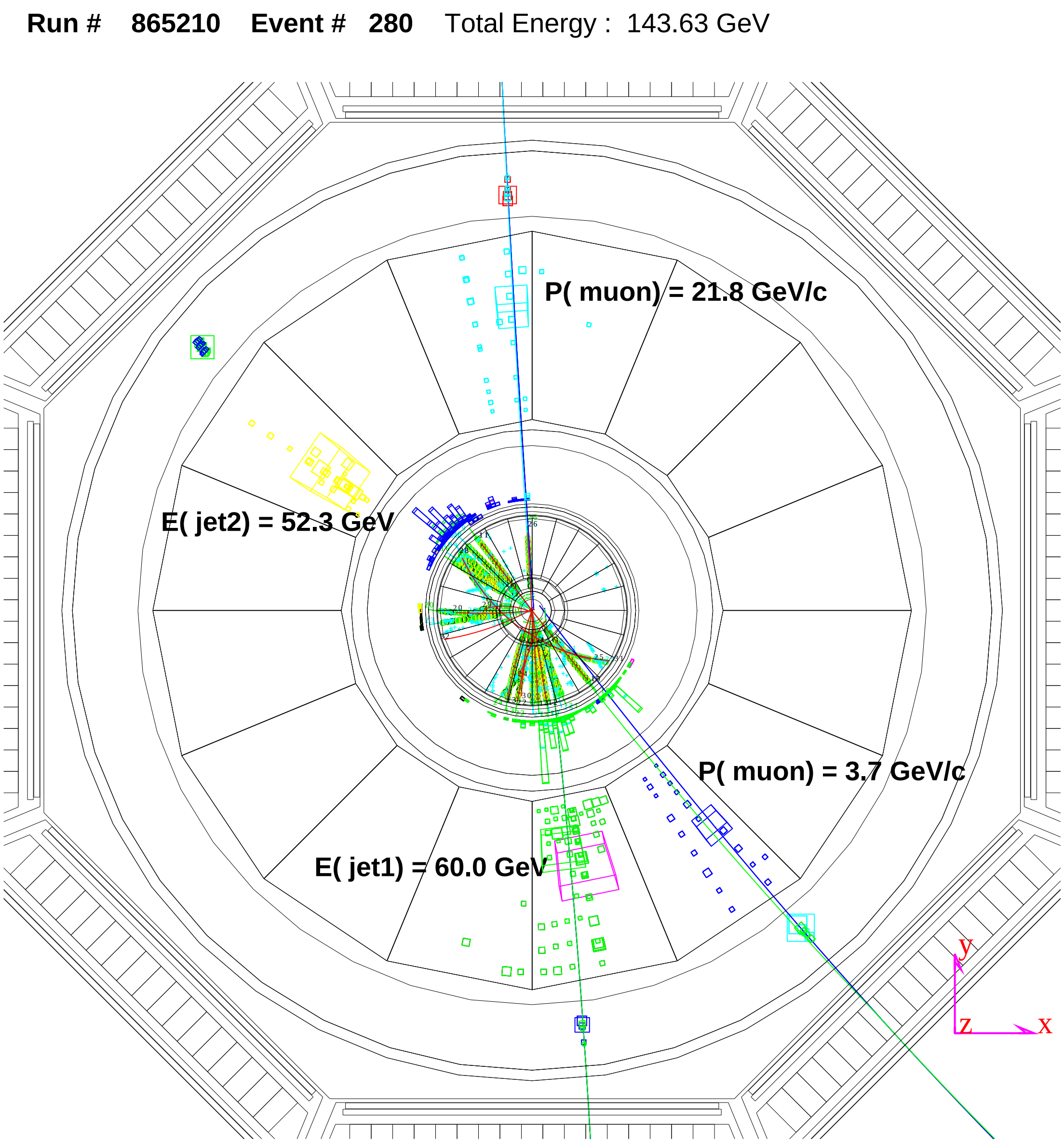
⇒ Compute final event discriminant based on all variables and assume hA event class:

$$F_{hA} = \frac{\prod_i P_{hA}^i}{\sum_k \prod_i P_k^i} \tag{2}$$

Final Discriminant of Tau Channel



Candidate of hA $\rightarrow b\bar{b}\tau^+\tau^-$



- F_{hA} = 0.91, B_{tag1} = 0.965, B_{tag2} = 0.359, M_{jj} = 90.68 GeV, $M_{\tau\tau}$ = 98.28 GeV.

$\Rightarrow e^+e^- \rightarrow hA,\ h \rightarrow b\bar{b},$
$A \rightarrow \tau^+\tau^-(\tau^\pm \rightarrow \mu^\pm\nu\bar{\nu})$

Selection Results

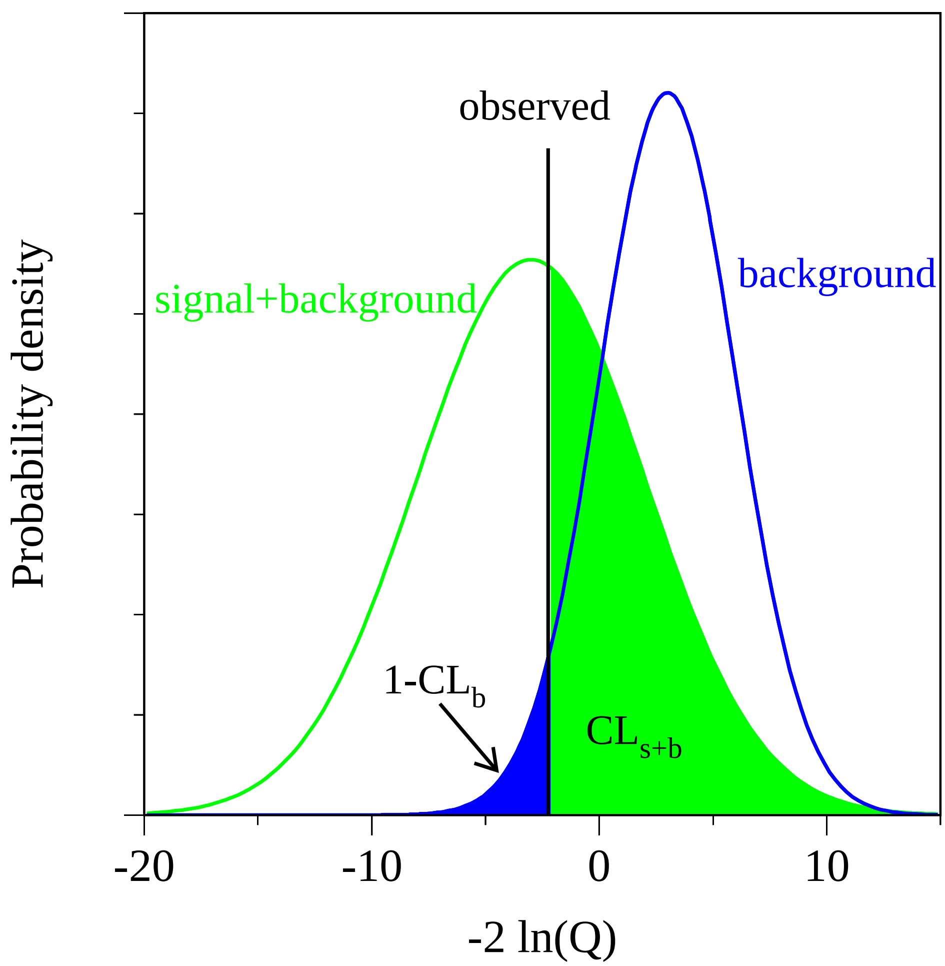
	ALEPH	DELPHI	L3	OPAL
Inte. Lumi. (pb^{-1})	217	224	217	205
hA $\rightarrow b\bar{b}\tau^+\tau^-$ $channel$				
Data	3	5	2	5
Total Background	3.0	6.0	3.2	4.5
4-fermion Bkgd.	2.8	5.6	2.9	4.1
$q\bar{q}$ Bkgd.	0.2	0.4	0.3	0.4
Efficiency	41%	25%	33%	43%
Expected Signal	0.6	0.4	0.4	0.6

- The signal efficiency and rate are shown for $m_h = m_A = 90\ GeV/c^2$, with $tan\beta \sim 20$.

- Likelihood Ratio test-statistic:

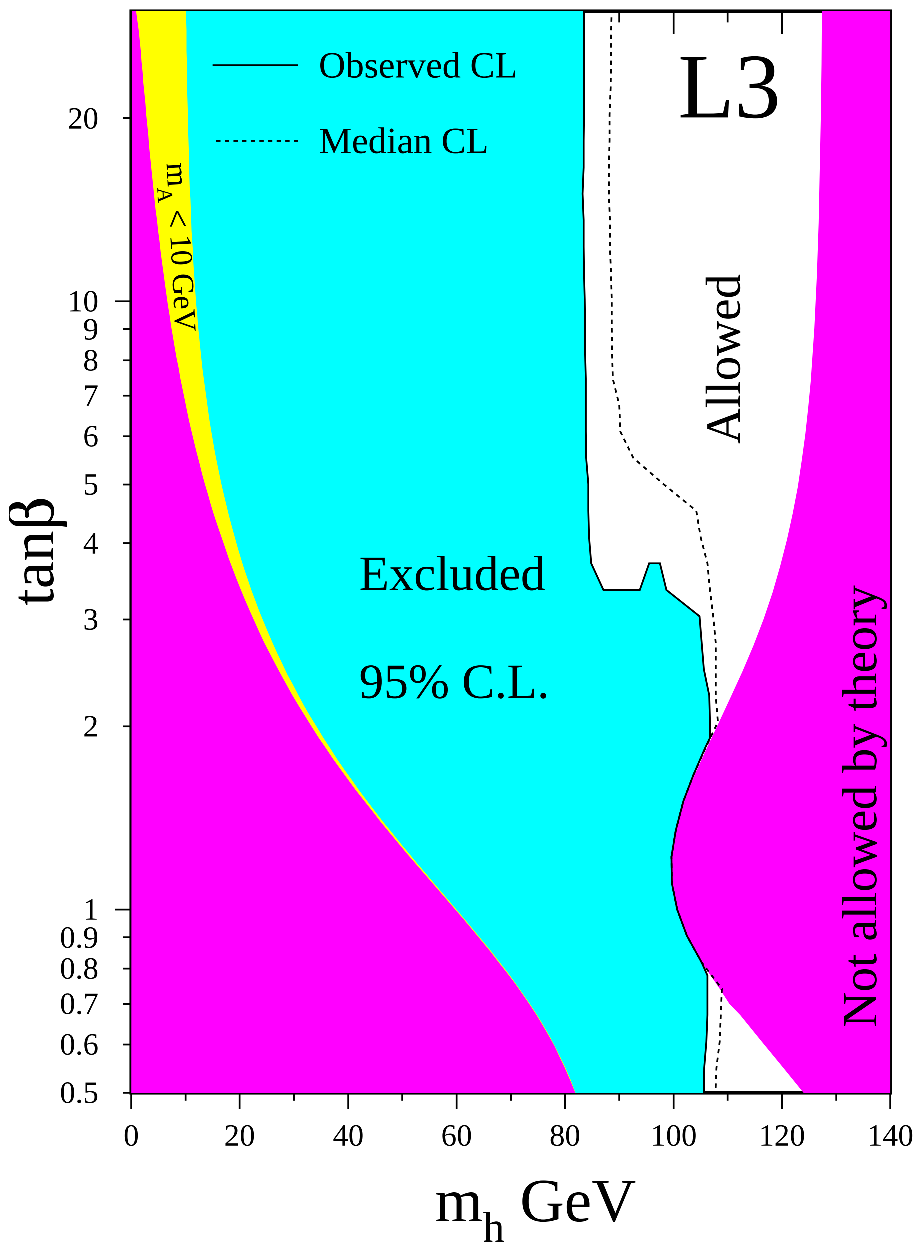
$$Q = \frac{L(s+b)}{L(b)}$$

- Monte Carlo experiments are based on Poisson statistics.



$\Rightarrow$

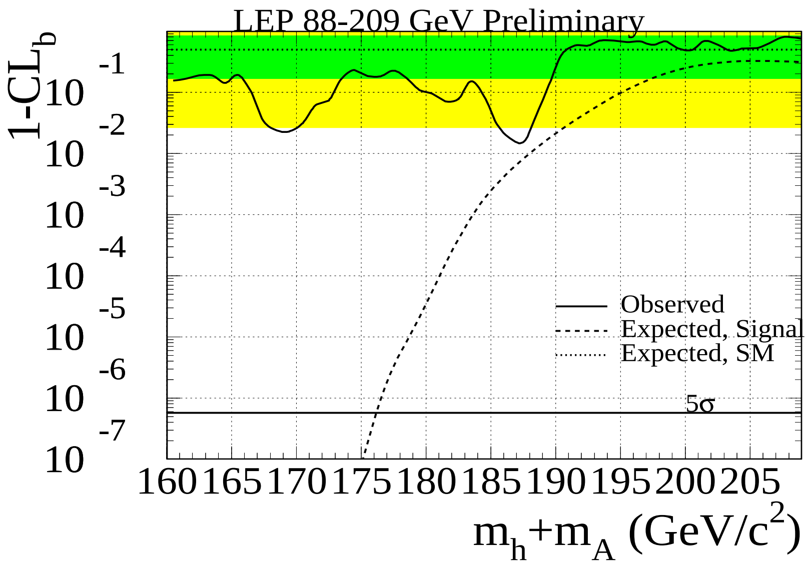
$$CL_s \equiv \frac{CL_{s+b}}{CL_b}$$

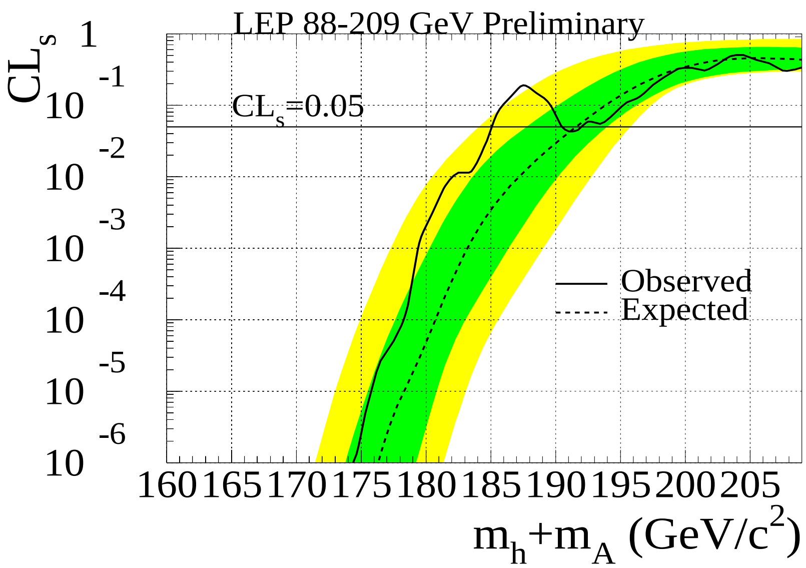


- m_h Maximal Scenario

$\Rightarrow m_h$: obs / exp = 83.7 / 88.1 GeV

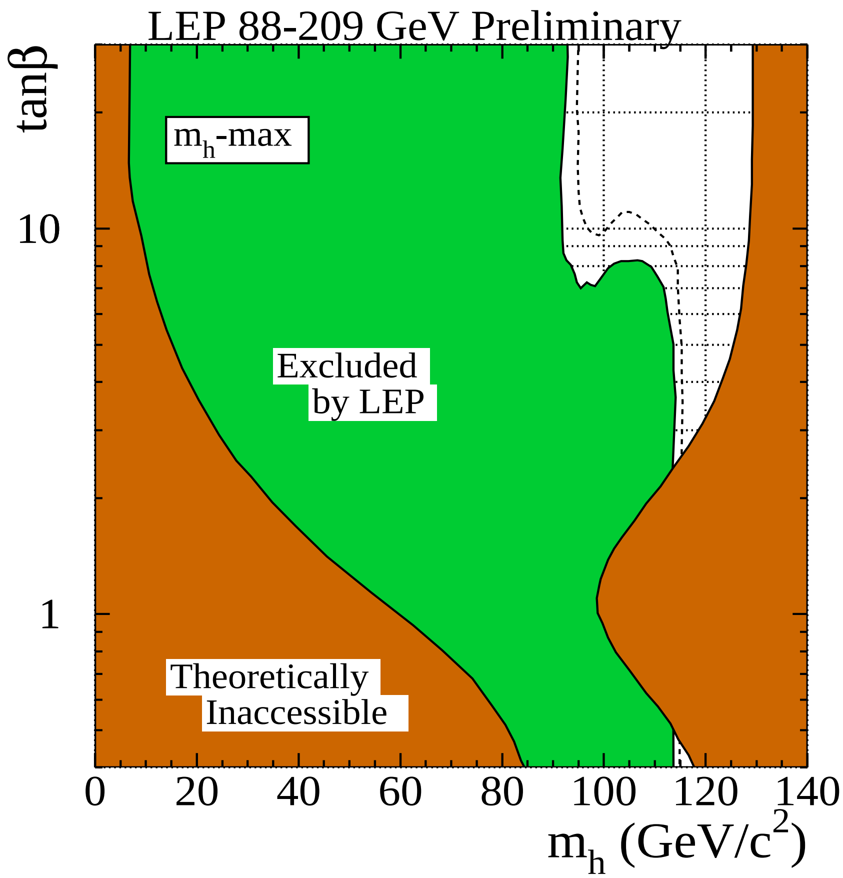
$\Rightarrow m_A$: obs / exp = 83.9 / 88.3 GeV





- m_h maximal scenario, $tan\beta >$20

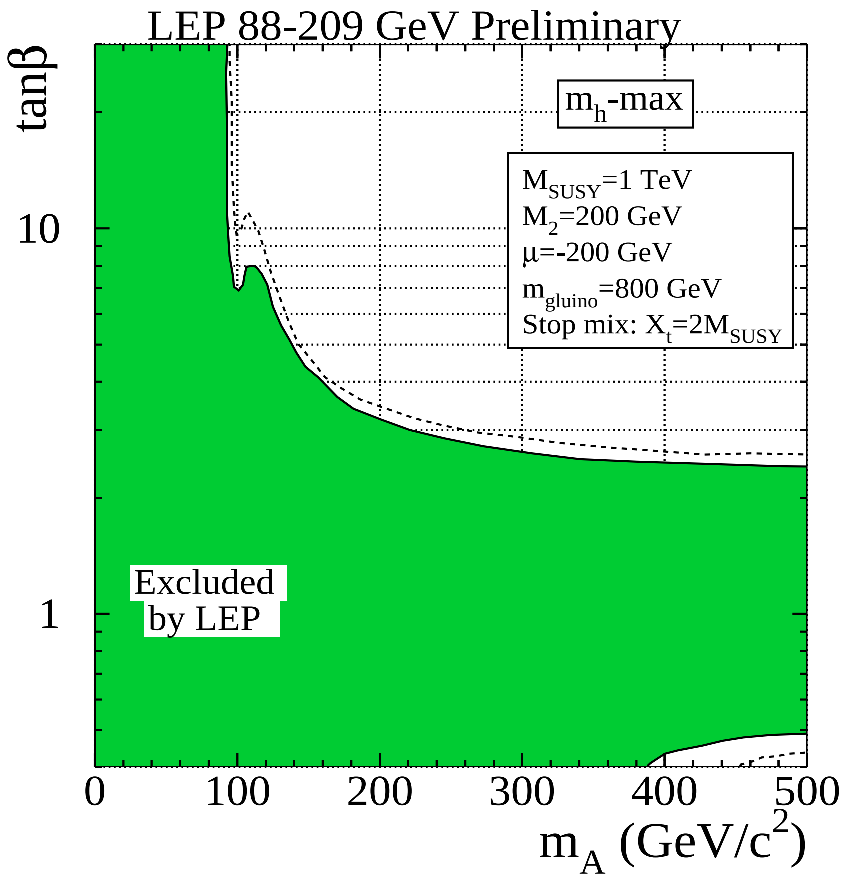
LEP Combined Results



m_h (GeV)	ALEPH	DELPHI	L3	OPAL
obs. limit	89.6	89.8	83.7	79.3
med. limit	91.7	89.0	88.1	85.1

⇒ LEP Combined Results: 91.0 / 94.6 GeV.

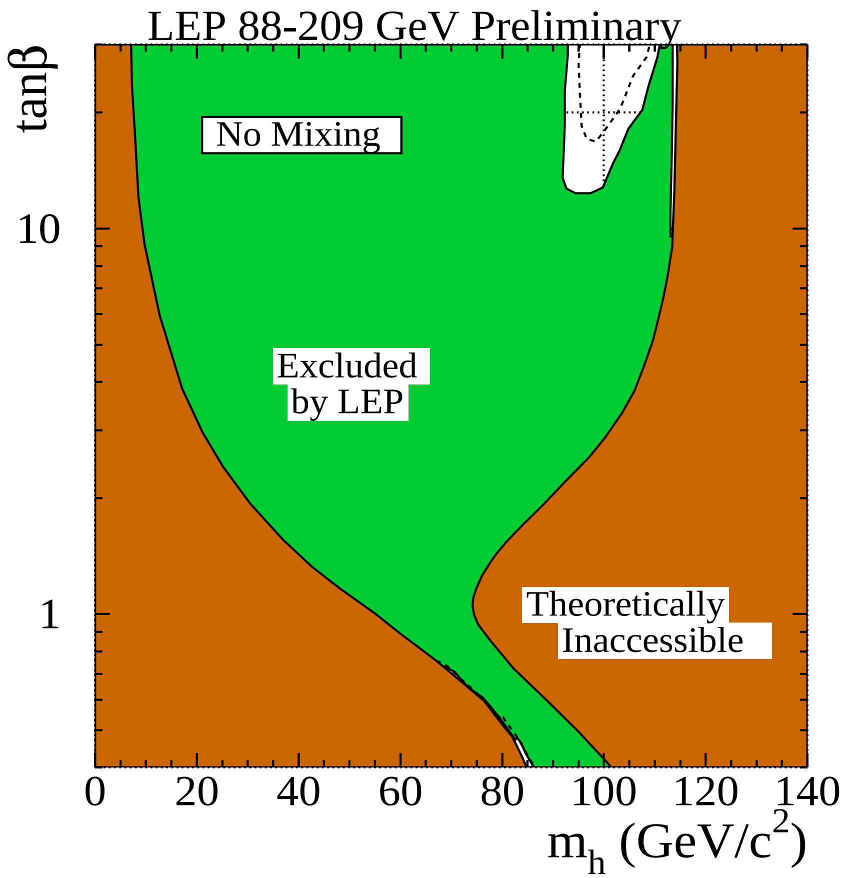
LEP Combined Results



m_A (GeV)	ALEPH	DELPHI	L3	OPAL
obs. limit	90.0	90.8	83.9	80.6
med. limit	92.1	90.0	88.3	86.9

⇒ LEP Combined Results: 91.9 / 95.0 GeV.

LEP Combined Results



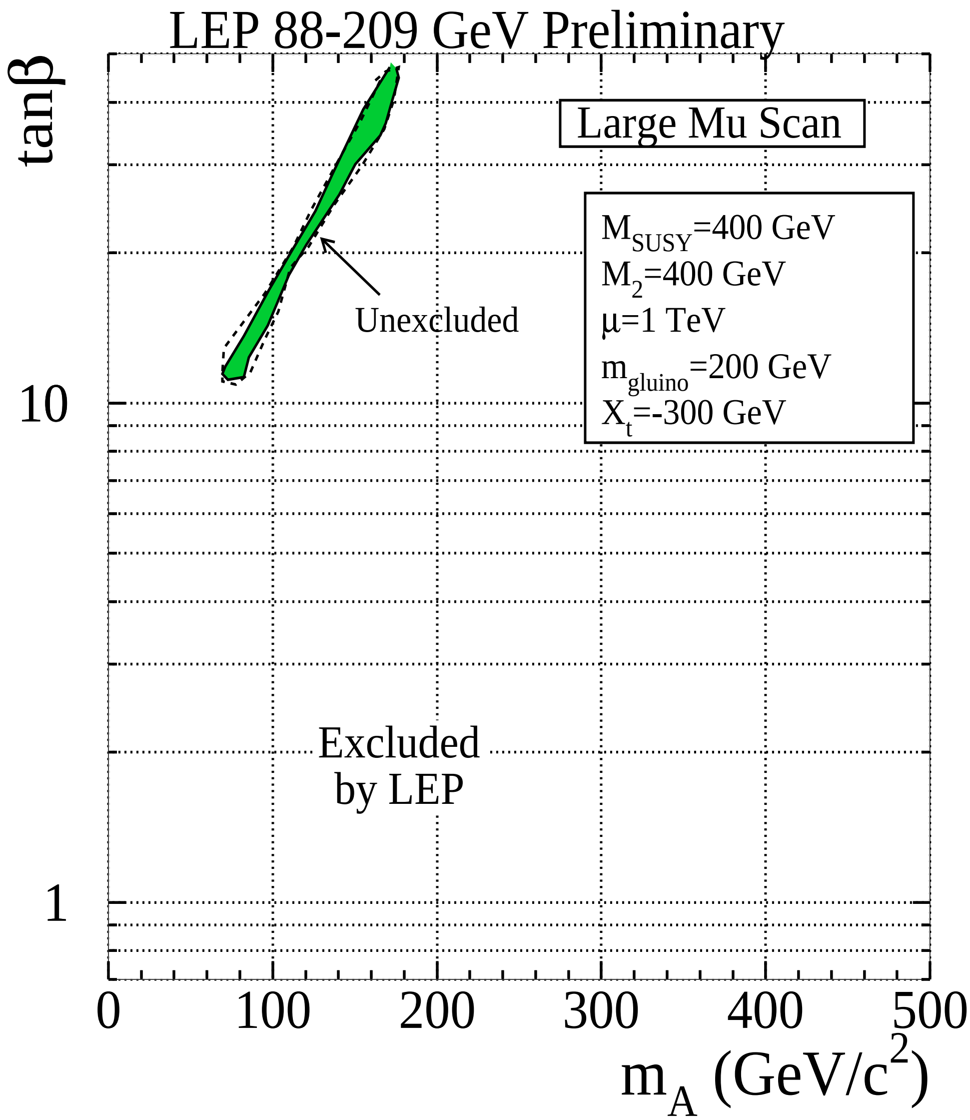
- No Mixing Scenario

⇒ $m_h > 91.5$ / 95.0 GeV, for $tan\beta > 1.2$

⇒ $m_A > 92.2$ / 95.3 GeV, for $tan\beta > 1.2$

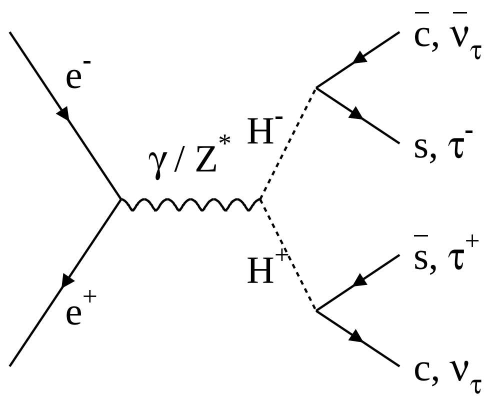
⇒ $0.8 < tan\beta < 9.6$ is excluded

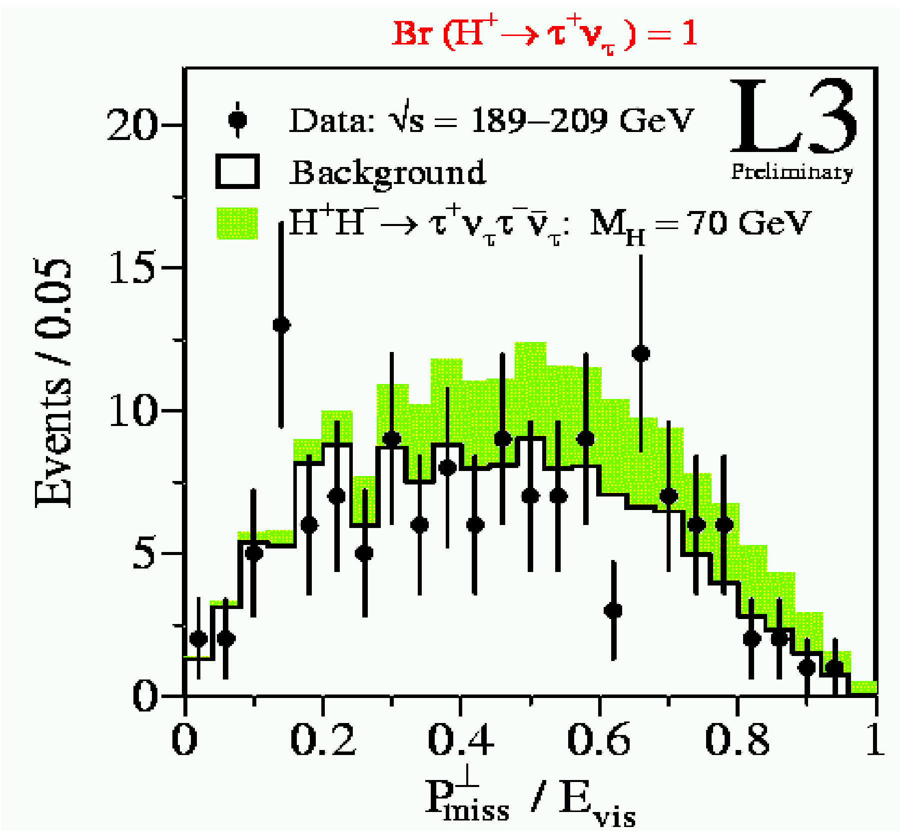
- Large μ Scenario



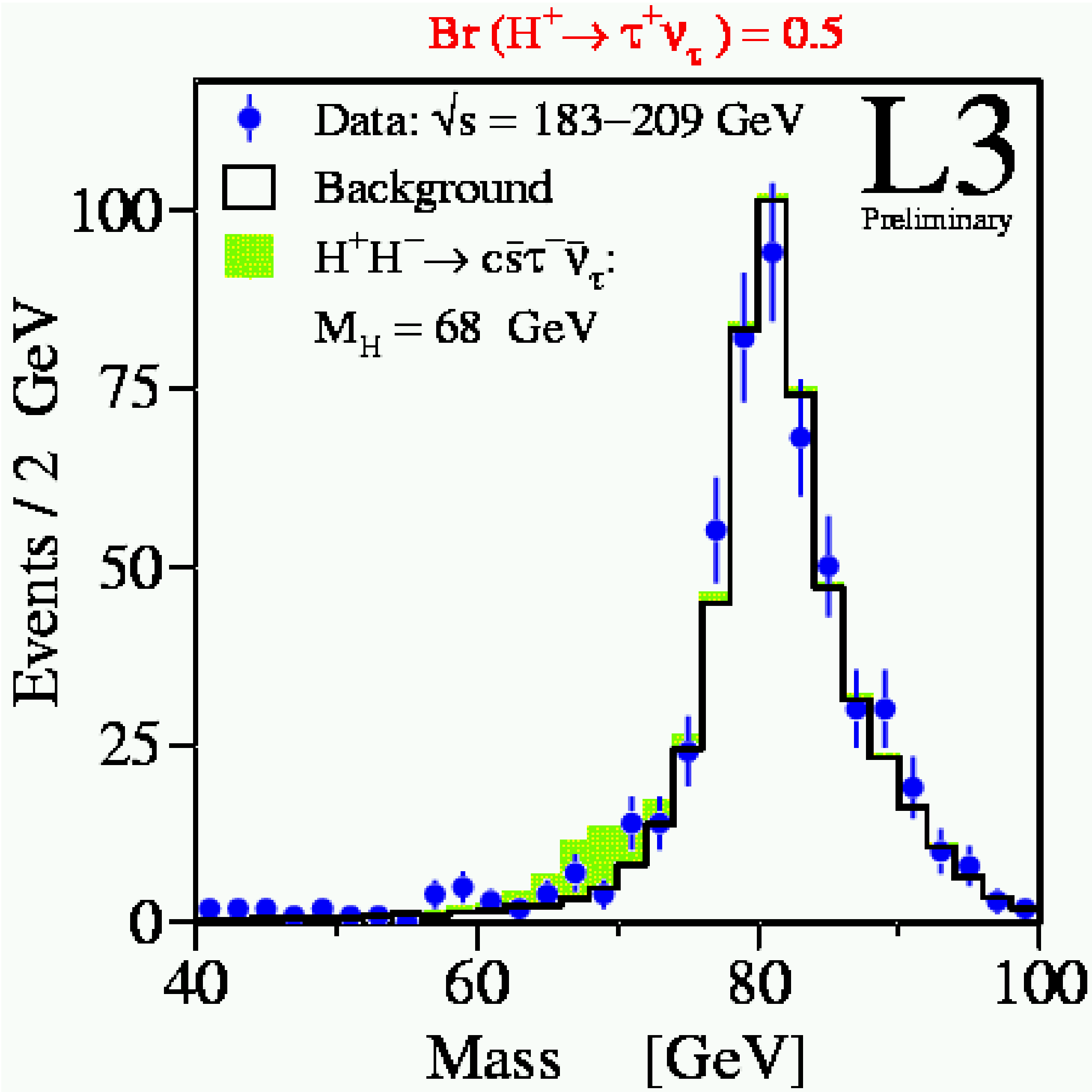
- h^0 decays into $c\bar{c}, gg, W^+W^-$ etc.

- Three final states: hadronic, semi-leptonic and leptonic decays.



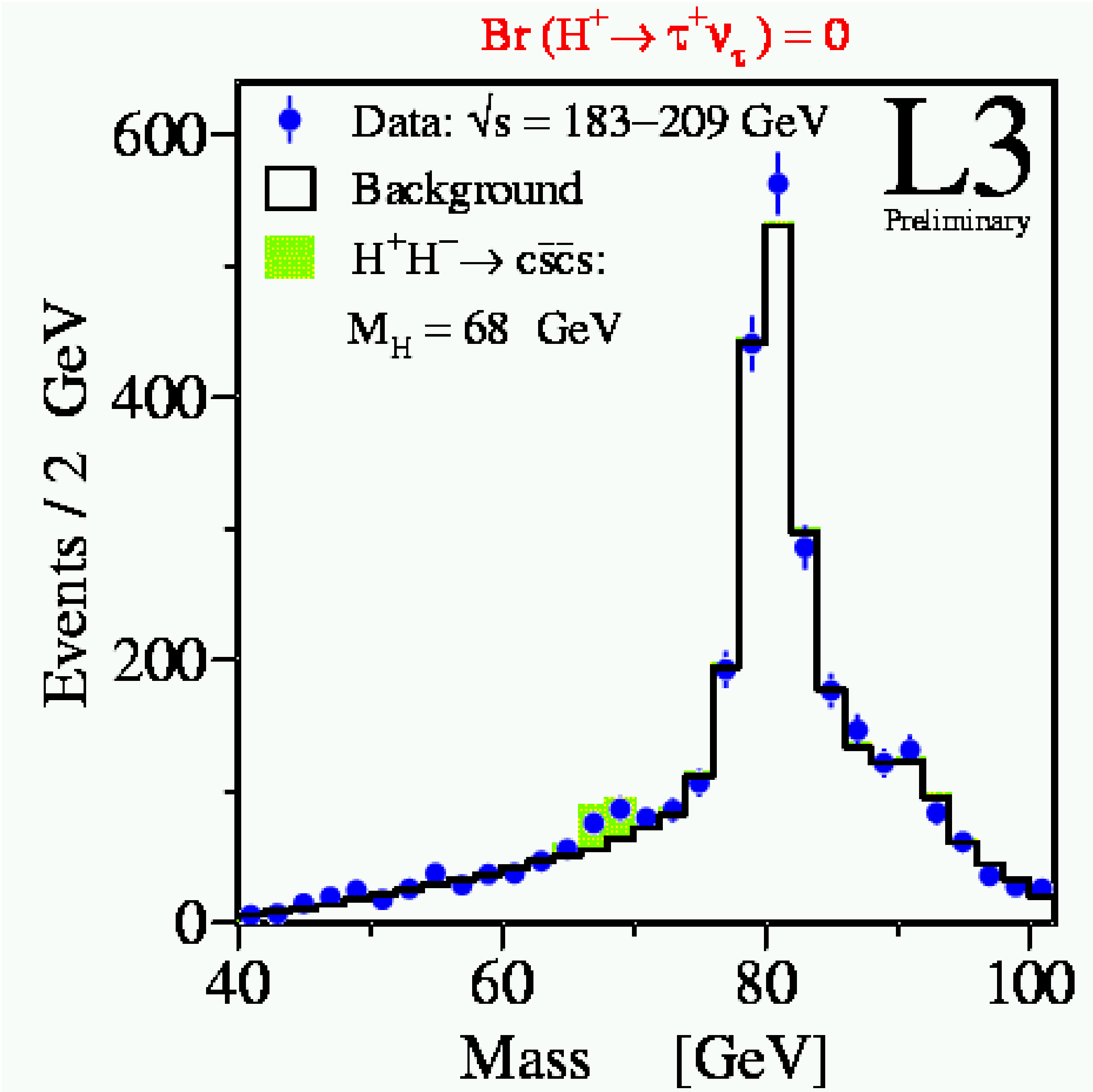


Charged Higgs Search



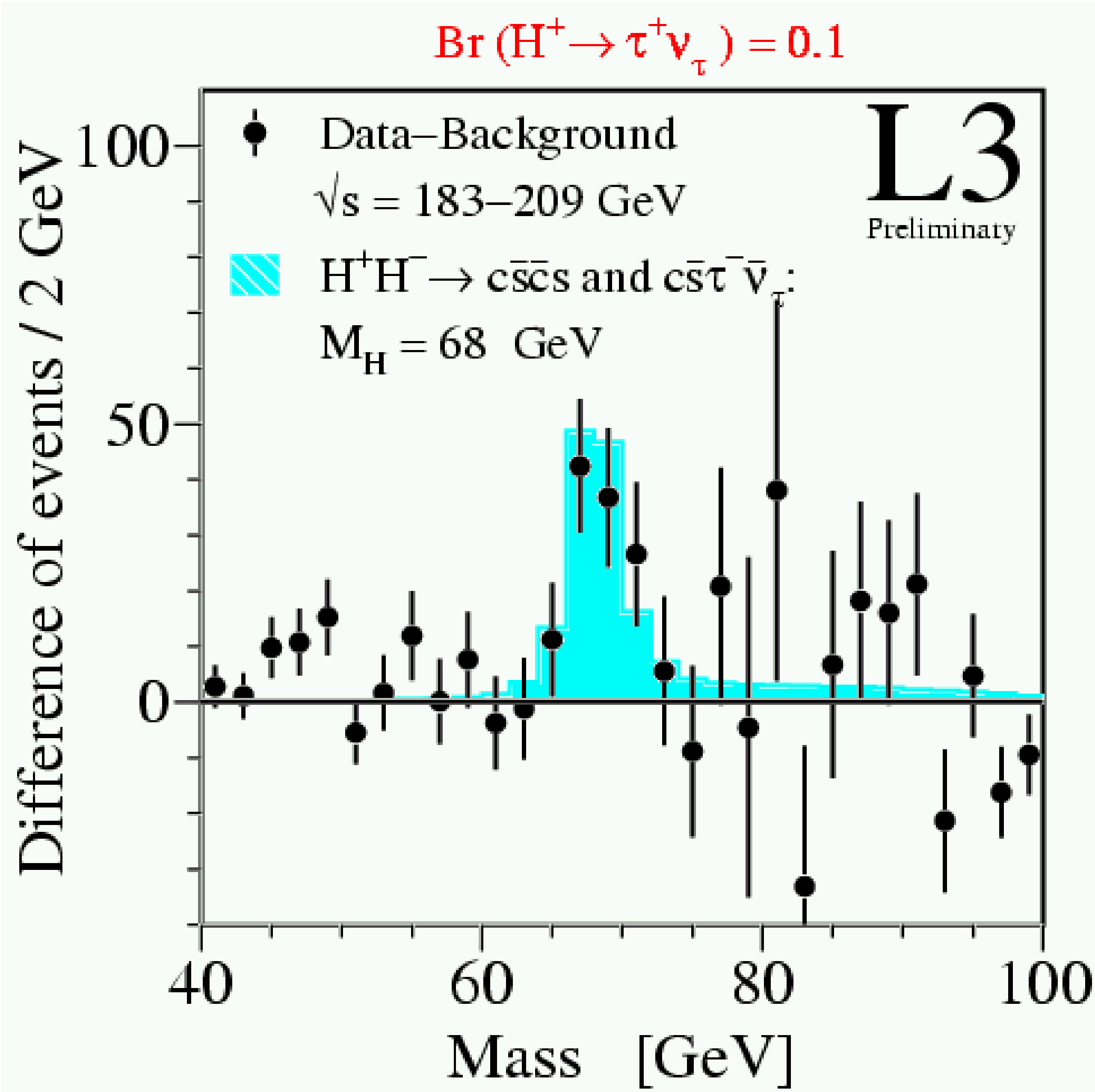
- $H^{\pm}$ semi-leptonic decays.

Charged Higgs Search



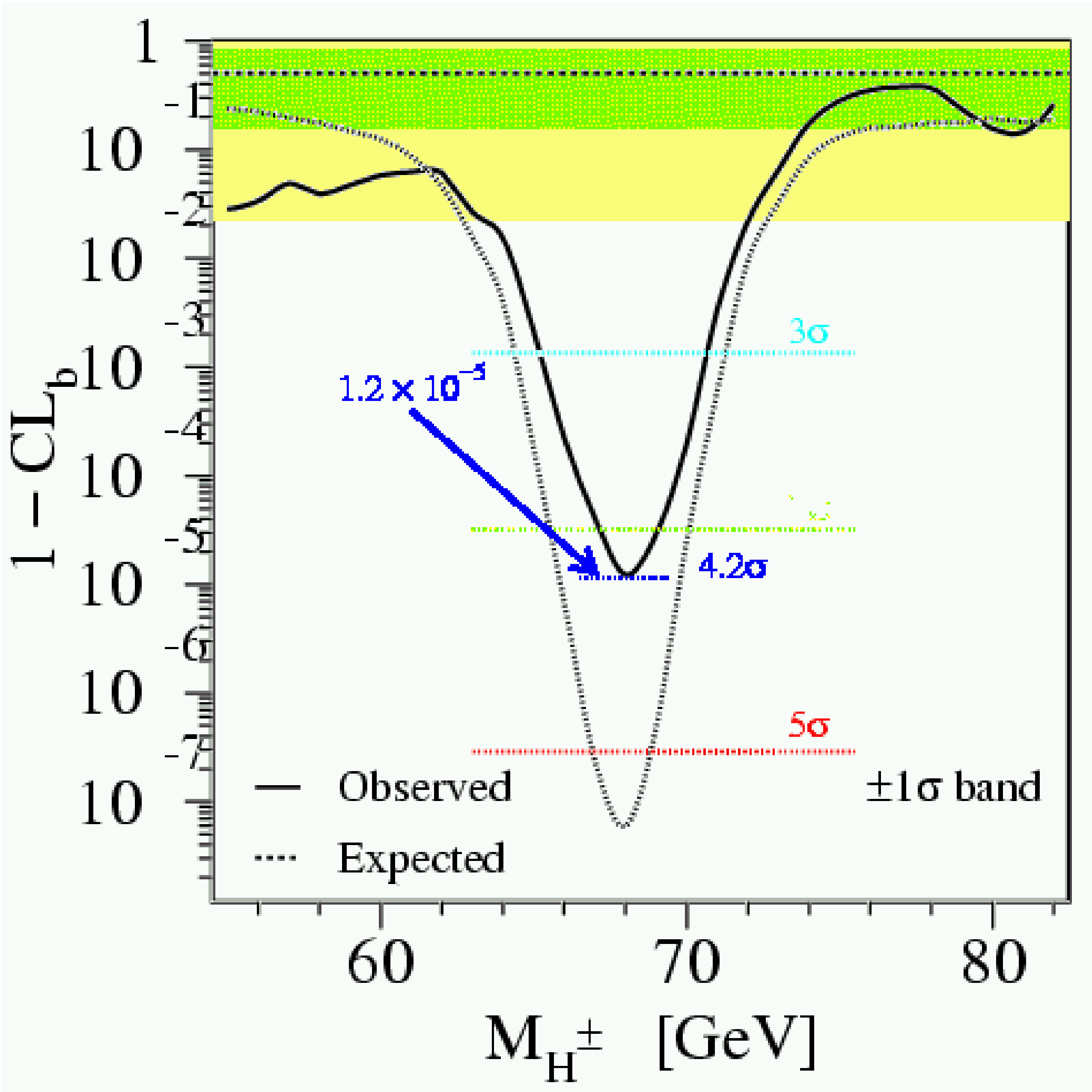
- $H^{\pm}$ hadronic decays.

Excess of Events at 68 GeV



- 10% of $H^{\pm}$ decay into τ.

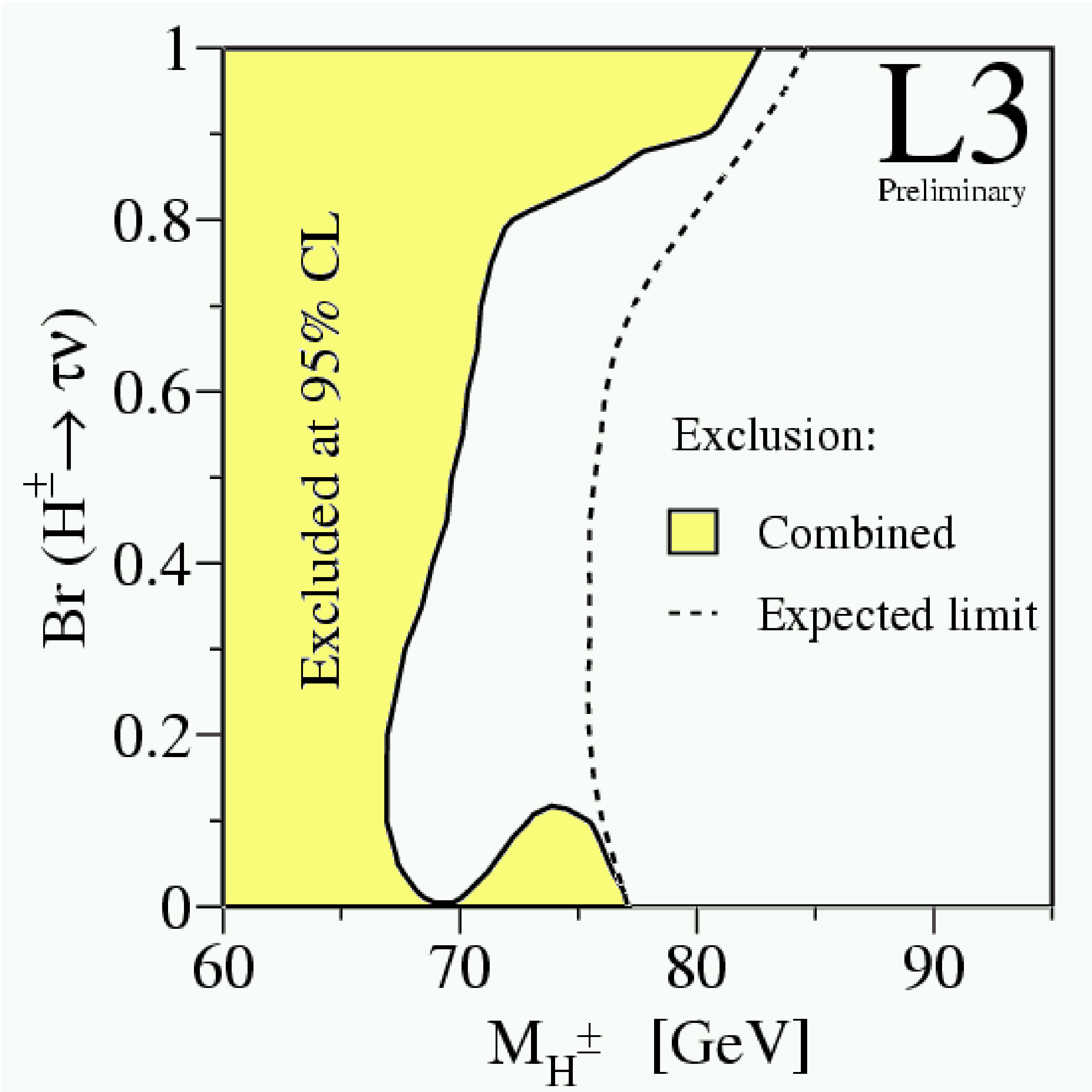
⇒ Apparent excess at 68 GeV



$\Rightarrow$ 4.2 σ excess at 68 GeV from L3.

But ......

Exclusion Limits of Charged Higgs

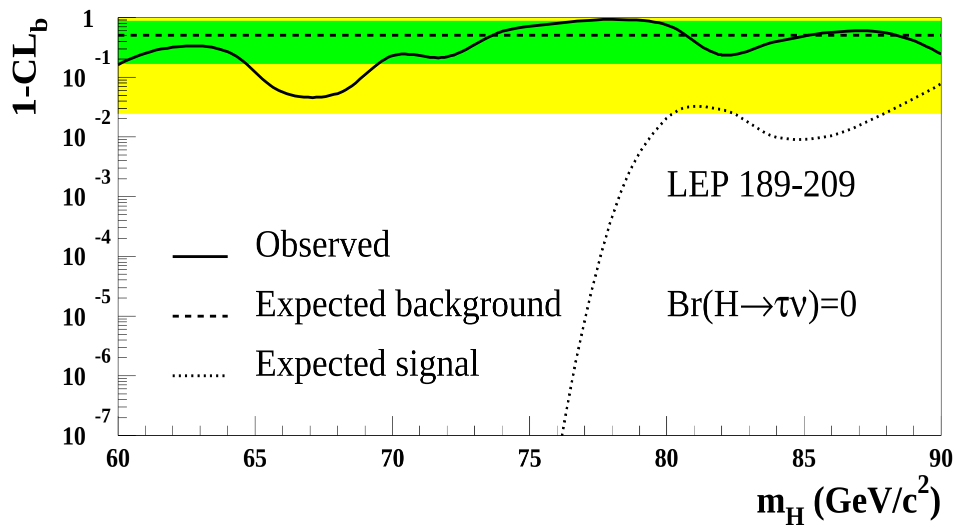


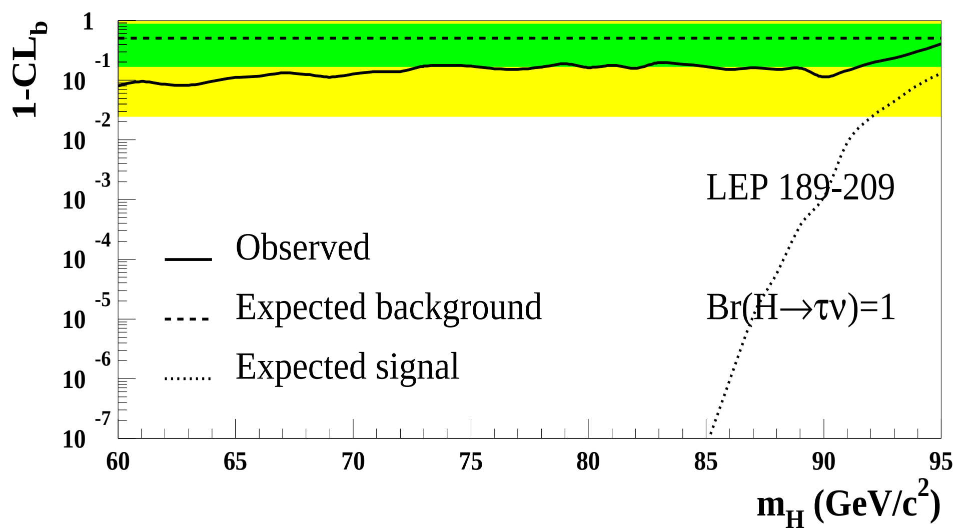
$\Rightarrow$ Br($H^{\pm} \rightarrow \tau\nu$ = 0.0), $M_{H^{\pm}} > 77.2$ (77.1) GeV.

$\Rightarrow$ Br($H^{\pm} \rightarrow \tau\nu$ = 0.1), $M_{H^{\pm}} > 66.9$ (76.0) GeV.

$\Rightarrow$ Br($H^{\pm} \rightarrow \tau\nu$ = 0.5), $M_{H^{\pm}} > 69.7$ (75.7) GeV.

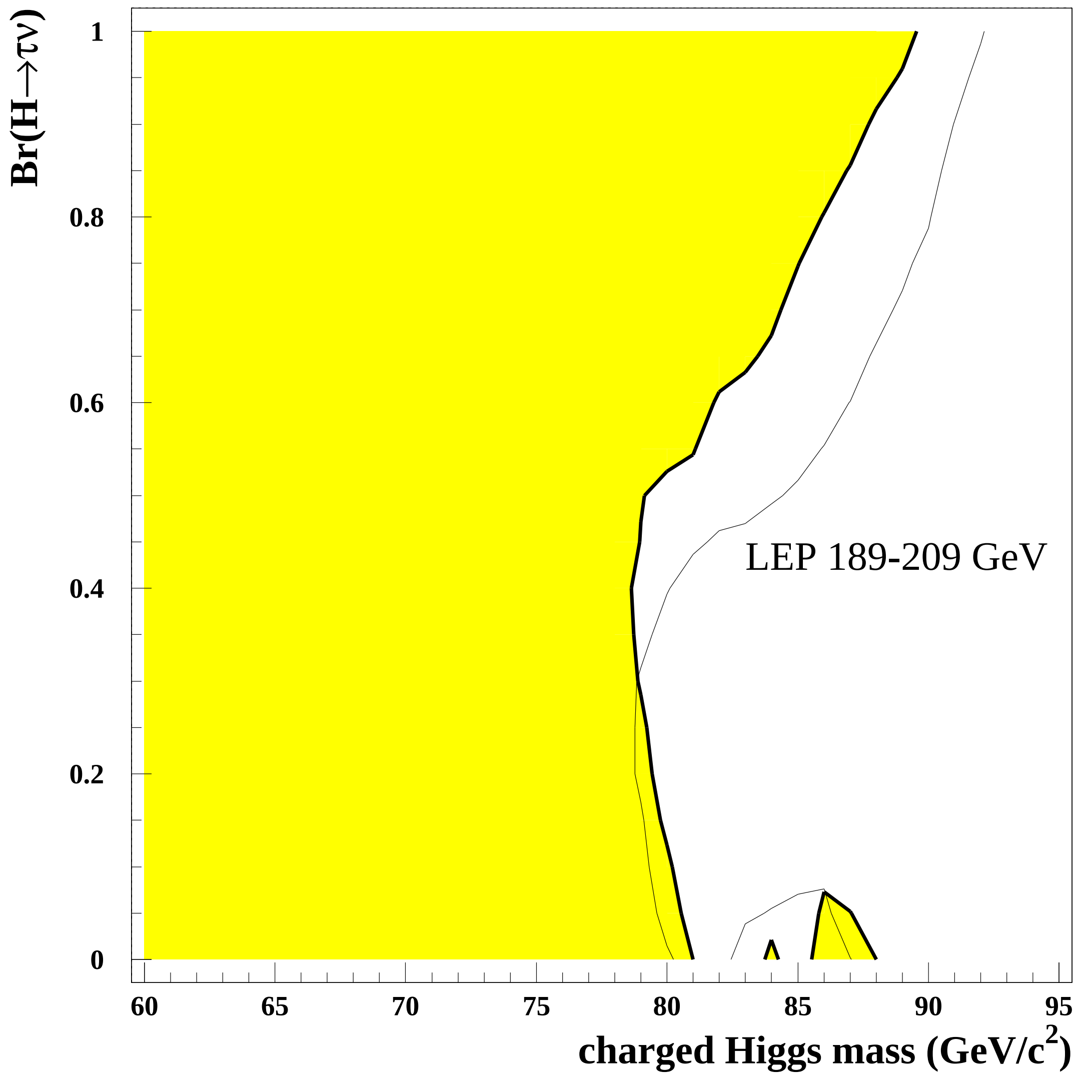
$\Rightarrow$ Br($H^{\pm} \rightarrow \tau\nu$ = 1.0), $M_{H^{\pm}} > 82.7$ (84.6) GeV.





⇒ LEP Combined Data agree well with SM back-grounds

LEP Combined Results



$\Rightarrow M_{H^\pm} > 78.6$ GeV at 95% C.L..

• More than 200 pb^{-1} data were collected per experiment in the Year 2000. In total $\sim$ 700 pb^{-1} were collected above Z^0 pole by each experiment.

$\Rightarrow$ No significant evidence of MSSM neutral and charged Higgs are observed up to $\sqrt{s} = 209$ GeV .

$\Rightarrow$ Neutral Higgs limits with 95% C.L.

$m_h > 91.0$ **GeV,** $m_A > 91.9$ **GeV**

$\tan\beta$ **is excluded from 0.5 to 2.4**

$\Rightarrow$ Charged Higgs limits with 95% C.L.

$m_{H^\pm} > 78.6$ **GeV**