Higgs and New*er* Particle Searches at LEP (and some future prospects)

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and

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- Standard Model *sketch*

  $\longrightarrow$Especially the SM Higgs boson

- Colliders ...
- SM Higgs search
- Beyond the Standard Model
- Conclusions

Standard Model of Electroweak Interactions

Fermions

S = 1/2

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$$

u_R c_R t_R

d_R s_R b_R

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

e_R μ_R τ_R

Bosons

S = 0

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$H^0_{SM}$$

"Missing Link"

S = 1

$$\{ W_1 \; W_2 \; W_3 \}$$

$$B$$

⇓ ~~EW~~

$$\{ W^{+/-} \; Z^0 \; \gamma \}$$

Papers by and about Higgs

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this behavior is a gauge-invariant version of a model used by Goldstone[2] himself: Two real[4] scalar fields φ_1, φ_2 and a real vector field A_μ interact through the Lagrangian density

$$L = -\tfrac{1}{2}(\nabla\varphi_1)^2 - \tfrac{1}{2}(\nabla\varphi_2)^2 - V(\varphi_1^2+\varphi_2^2) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (1)$$

where

$$\nabla_\mu\varphi_1 = \partial_\mu\varphi_1 - eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2 = \partial_\mu\varphi_2 + eA_\mu\varphi_1,$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu.$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on φ_1 and φ_2 and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^2)=0$, $V''(\varphi_0^2)>0$; then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \quad (2a)$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \quad (2b)$$

$$\partial_\mu F^{\mu\nu} = e\varphi_0\{\partial^\nu(\Delta\varphi_1) - e\varphi_0 A^\nu\}. \quad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \quad (3)$$

into the form

$$\partial_\mu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2\varphi_0^2 B^\mu = 0. \quad (4)$$

Equation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e=0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.[6] The model of the most immediate interest is that in which the scalar fields form an octet under SU(3): Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $Y=0$, $I_3=0$ members of the octet.[7] There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe

SPIRES

FIND AUTHOR HIGGS,P

Result: 8 documents found (mostly reviews)

FIND TITLE HIGGS

Result: 5349 documents found (~200 in 2001)

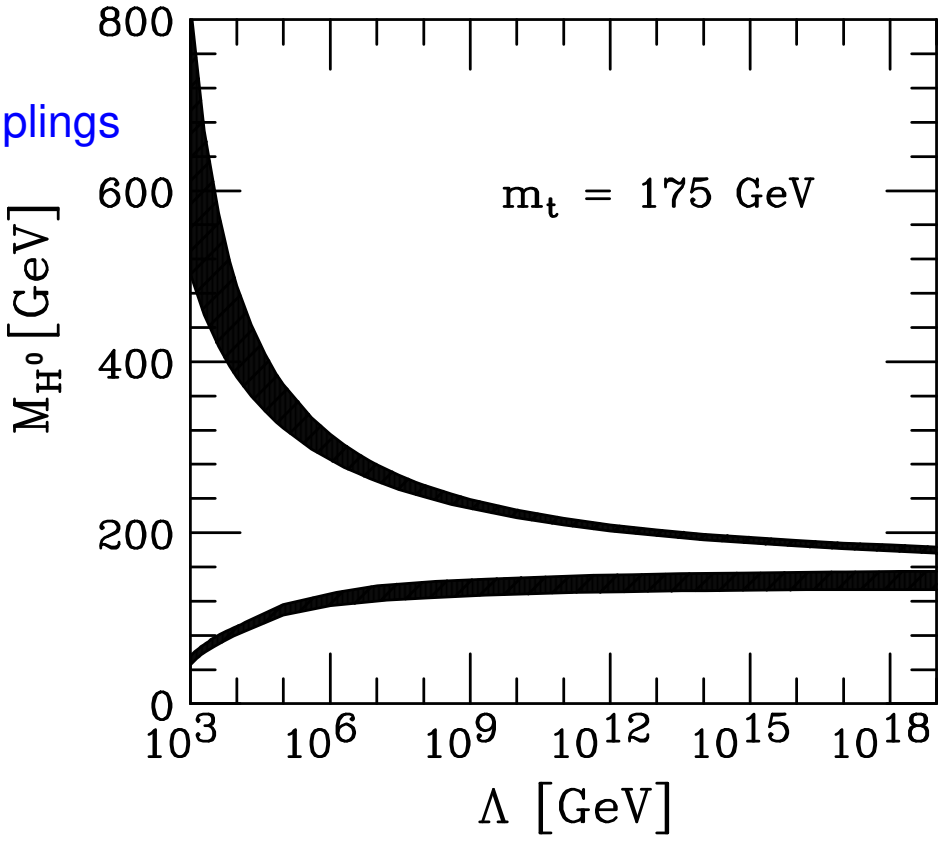
Theoretical Constraints on $M_{\mathrm{H^0}}$

- $M_{\mathrm{H^0}}$ Theoretically constrained

  Max: Perturbativity, divergent couplings

  Min: Vacuum Stability

- Depend on theory cutoff scale Λ



eg. If $\Lambda = M_{Pl} \approx 10^{19}$ GeV:

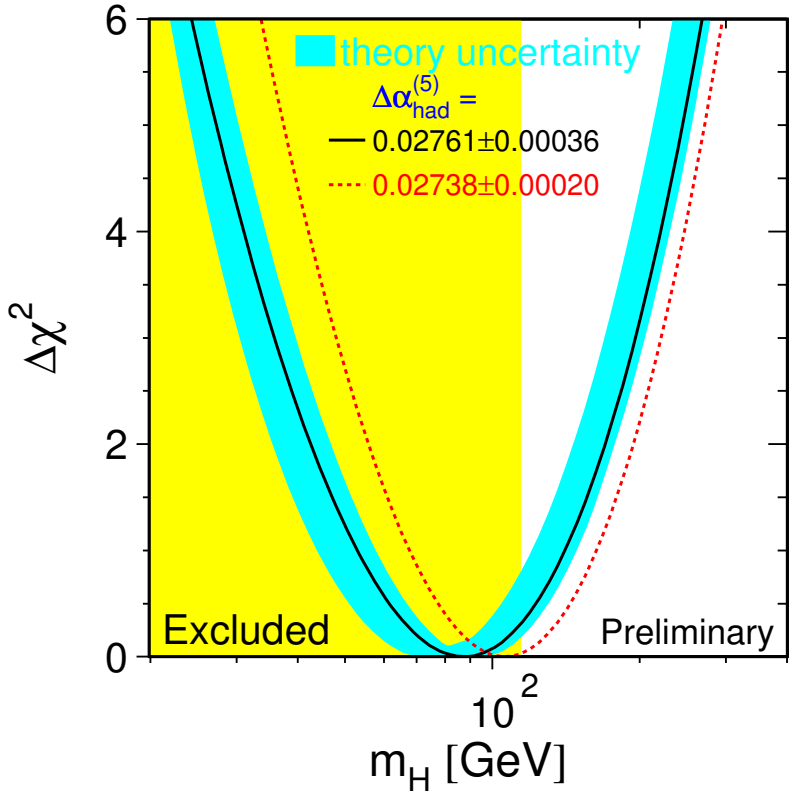
150 GeV $< M_{\mathrm{H^0}} <$ 170 GeV

eg. (Recall mSUSY: $M_{\mathrm{h}} <$ 130 GeV)

Experimental Constraints on M_{H^0}

- H^0 enters into loops
- Global fits to precision EW data

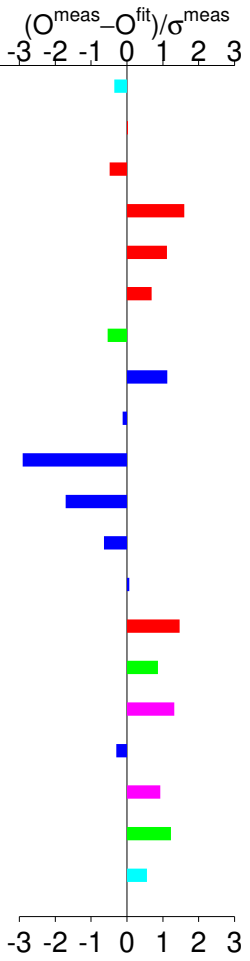
  M_{H^0} only unconstrained parameter



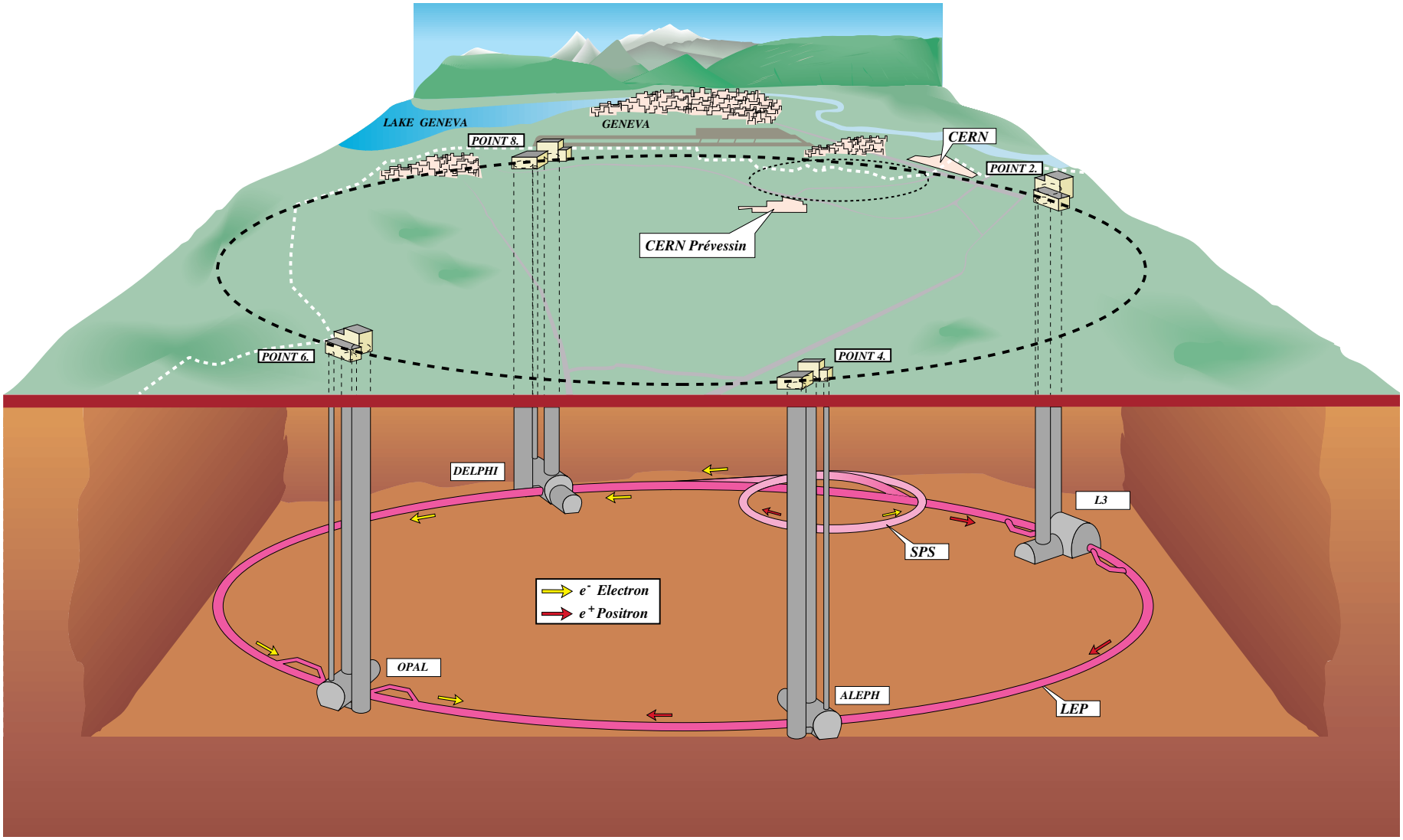
M_{H^0} <196 GeV (95% CL)

Summer 2001

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
σ^0_{had} [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A^{0,b}_{fb}$	0.0990 ± 0.0017	-2.90
$A^{0,c}_{fb}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
Q_W(Cs)	-72.50 ± 0.70	.56

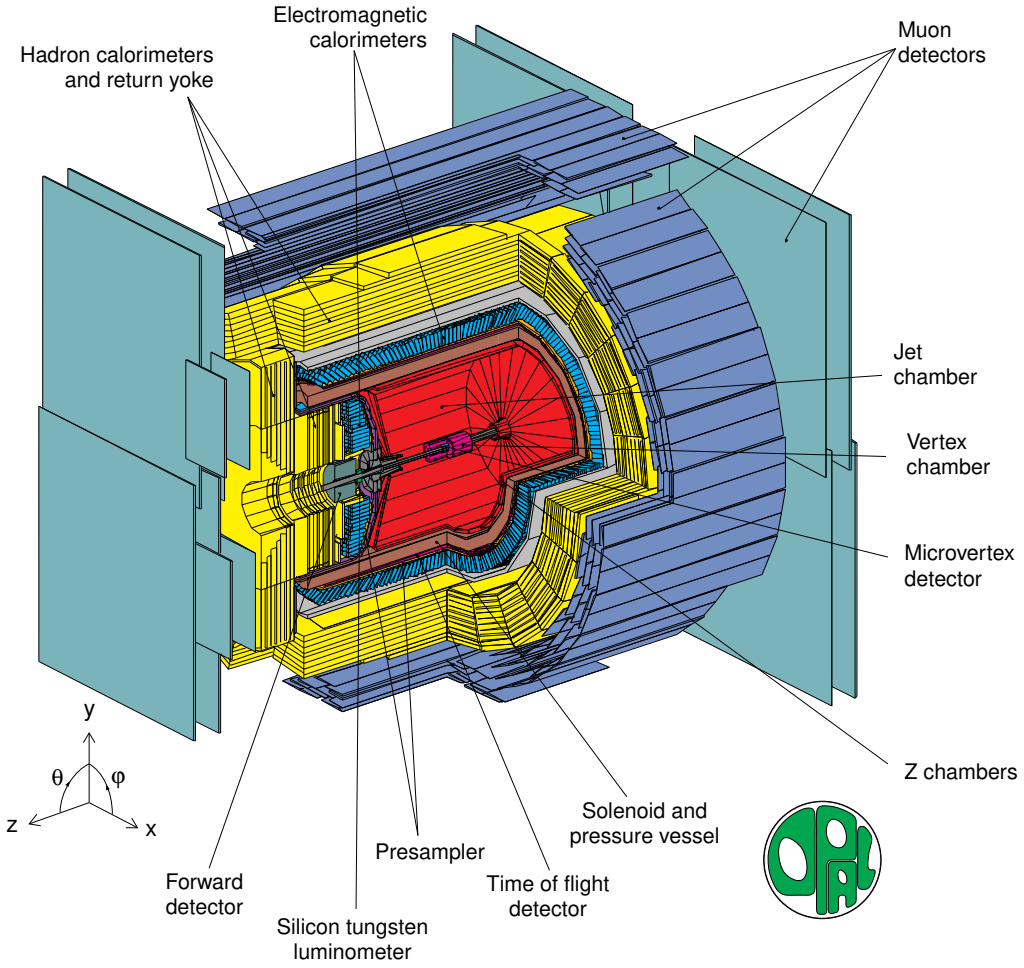


The LEP e^+e^- Collider



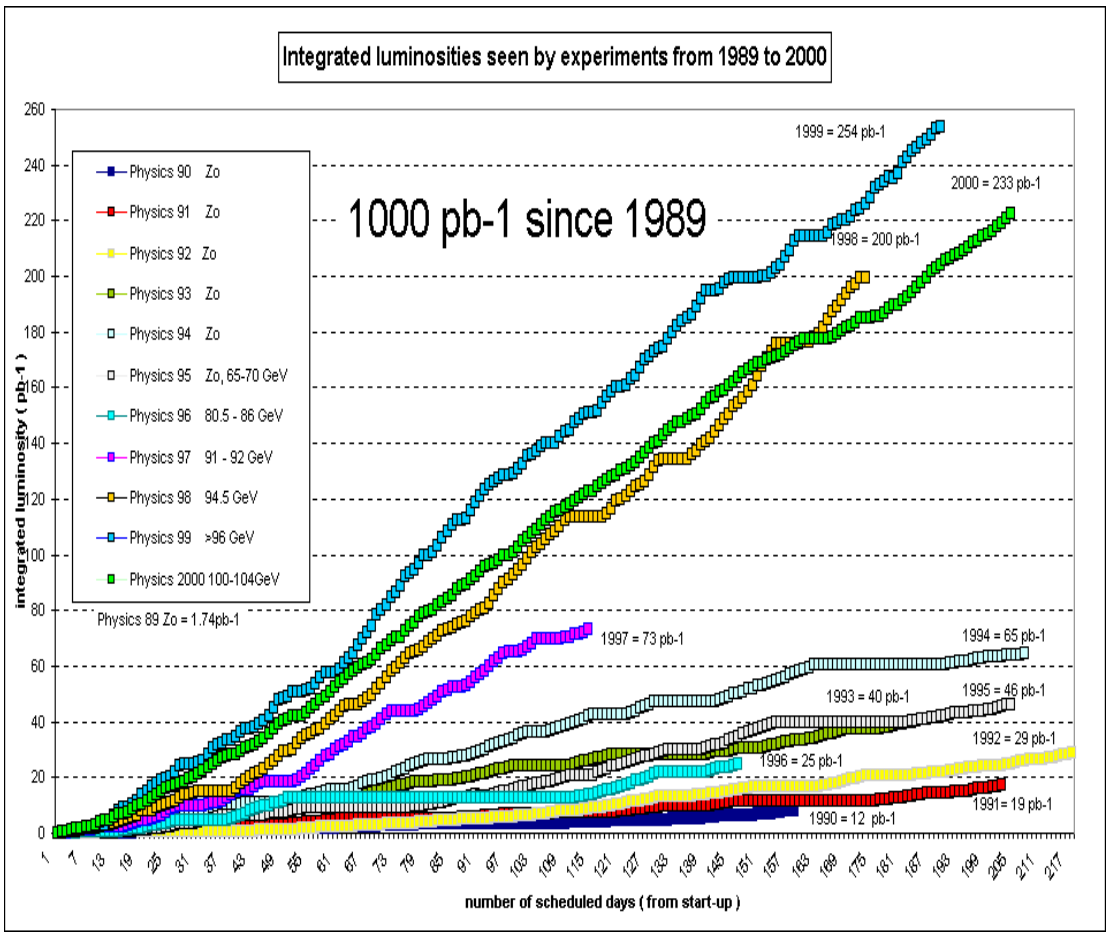
Typical LEP Detector

- Central drift chambers (x, y, z)
  - Magnet $\Rightarrow p$
- Si detector $\Rightarrow$ b-tag
- Hermetic Calorimetry
  - EM and Hadronic
  - $|\cos\theta| > 20$ mrad
- Muon chambers



LEP2 Data Sets

Stage	$\sqrt{s}$	Year	Luminosity
LEP 1	$\approx M_{Z^0}$	1989-1995	175 pb^{-1}
LEP 1.5	130-140 GeV	1995	5 pb^{-1}
LEP 2	161 GeV	1996	10 pb^{-1}
	172 GeV	1996	10 pb^{-1}
	183 GeV	1997	55 pb^{-1}
	189 GeV	1998	180 pb^{-1}
	192–202 GeV	1999	230 pb^{-1}
	200–209 GeV	2000	220 pb^{-1}

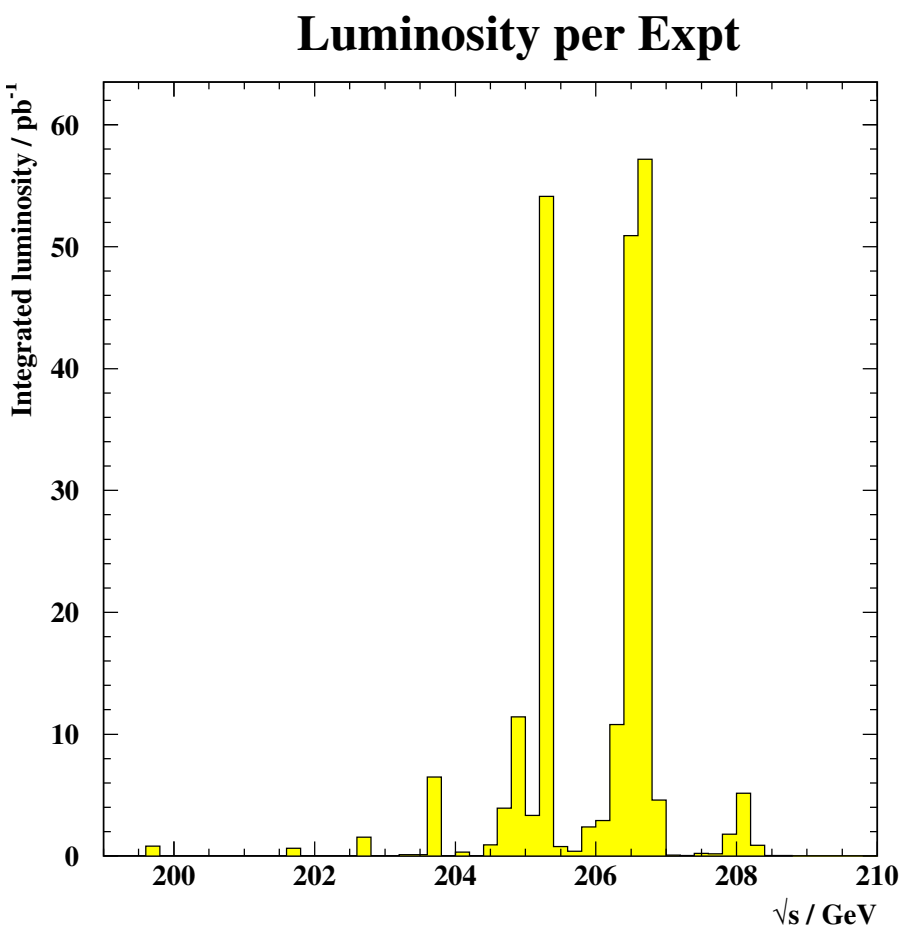


LEP's Final Year: Y2K

- New Emphasis

  Energy over **Luminosity**

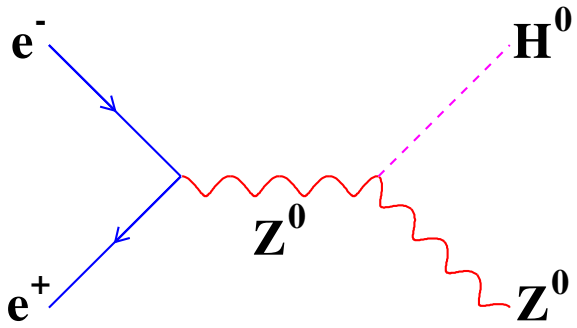
- Used *mini-ramps* to increase energy as beam current decreases



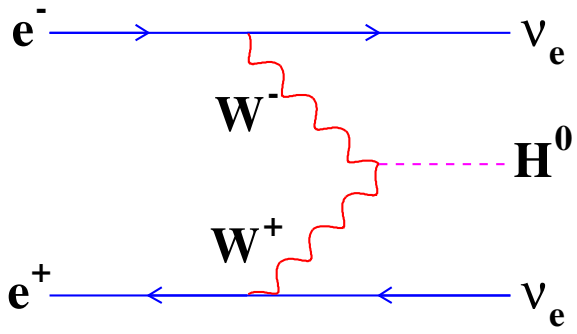
Standard Model Higgs Production

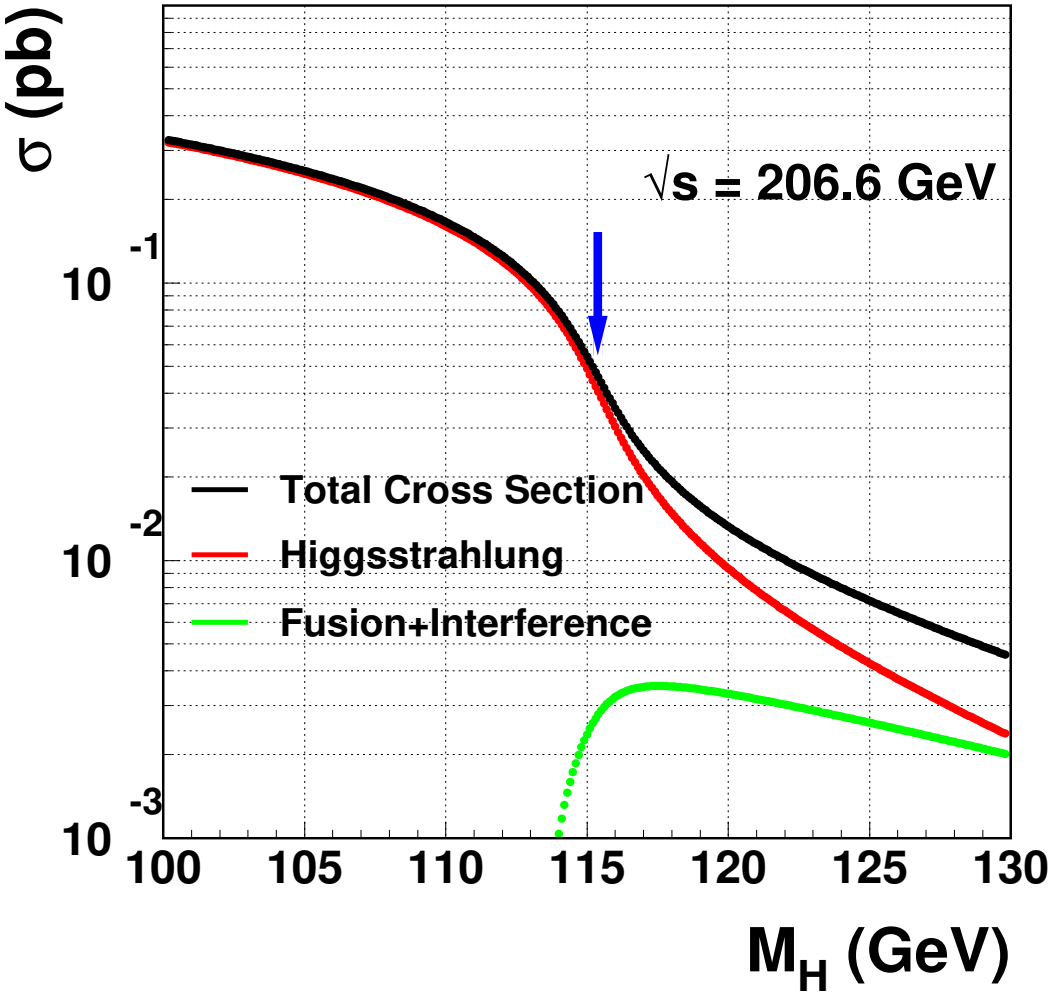
Production

"Higg-strahlung" $e^+e^- \rightarrow ZH^0$:



"Fusion" $e^+e^- \rightarrow \nu\bar{\nu}H^0$:

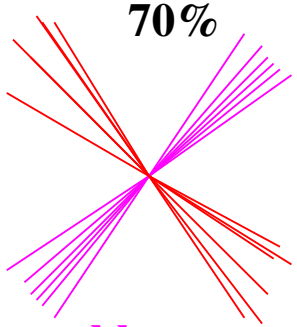




Standard Model Higgs Topologies

4 Jet

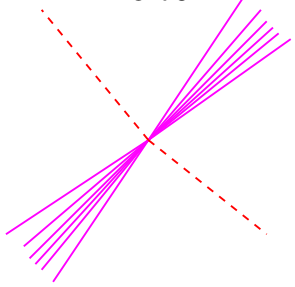
70%



bb qq

Missing Energy

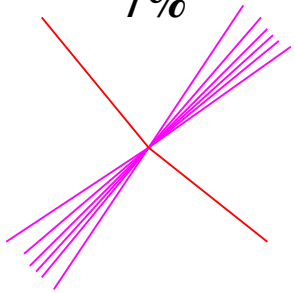
20%



bb νν

Lepton (e/μ)

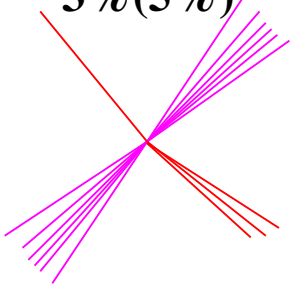
7%



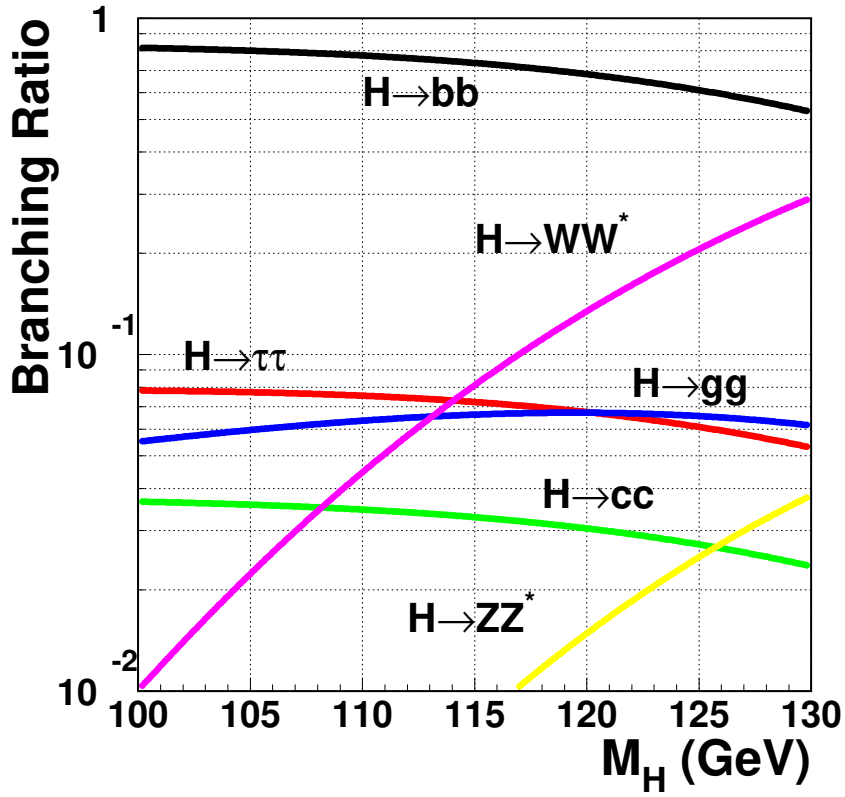
bb ll

Tau

3%(5%)

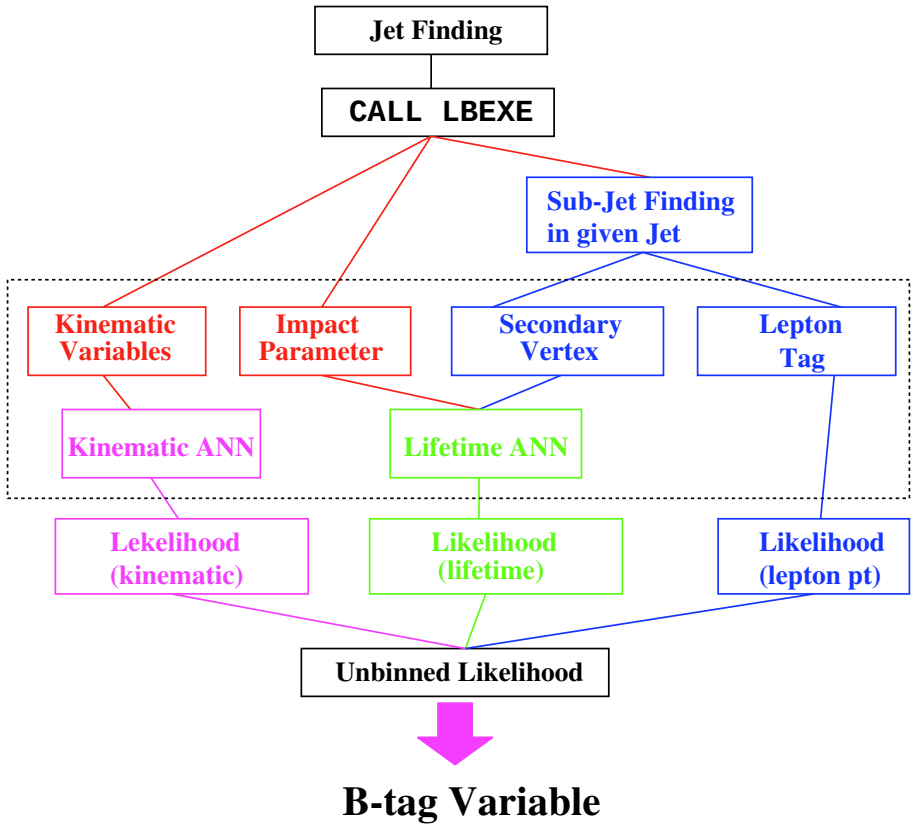


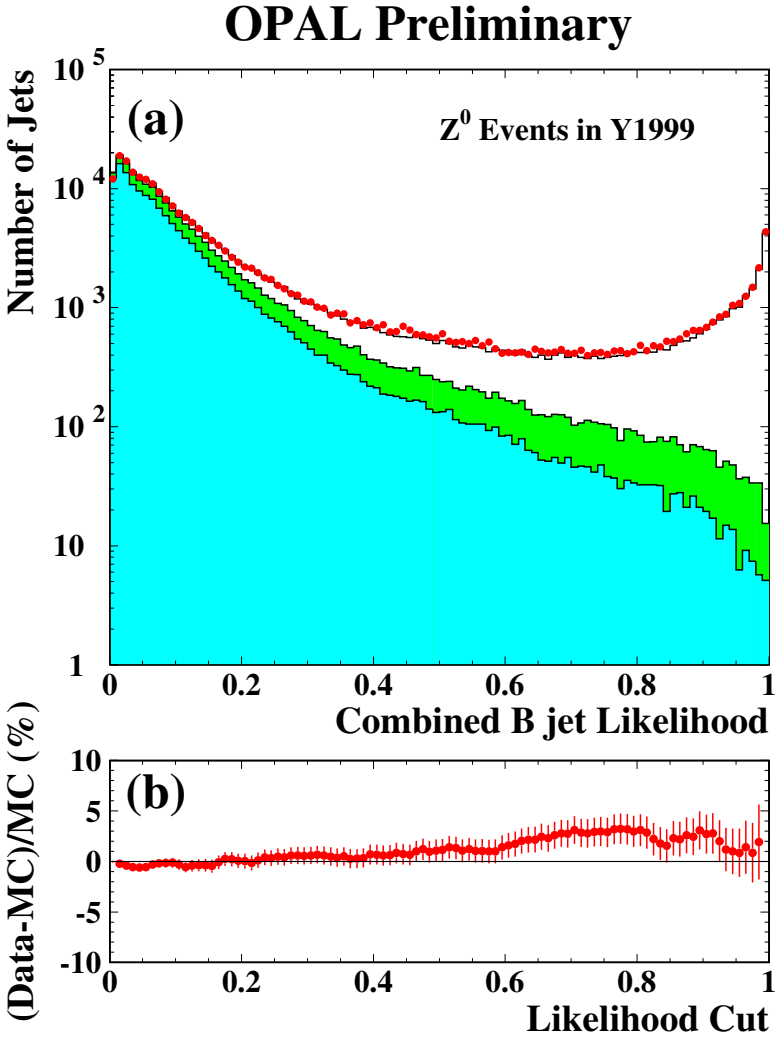
bbττ or ττqq



- Key to analysis: b-tagging -

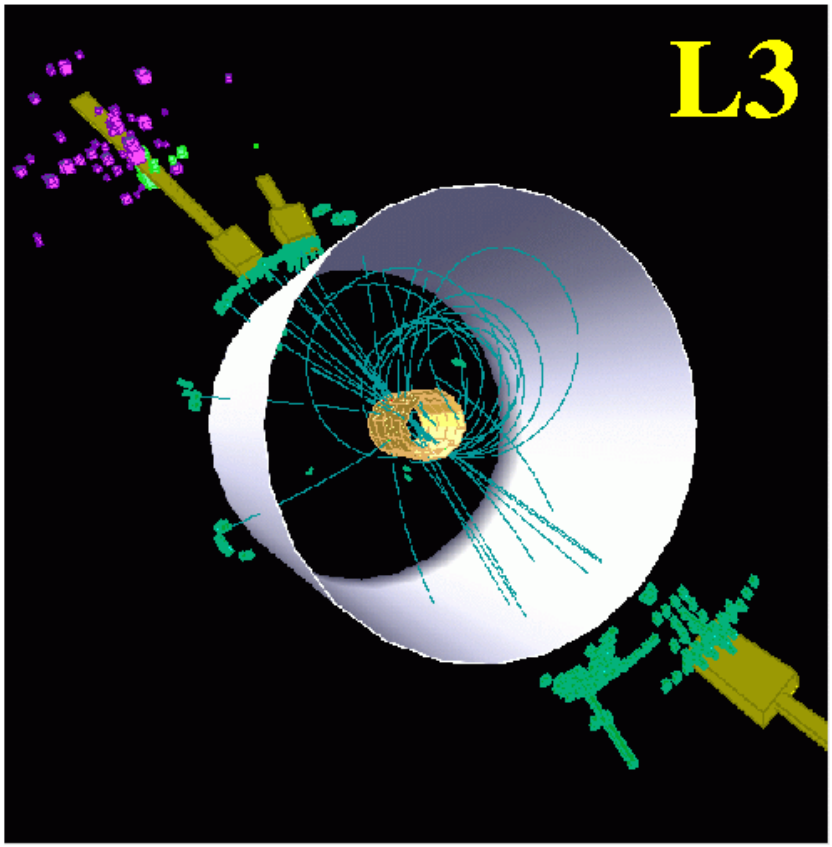
Example: higgs b-Tagging in OPAL





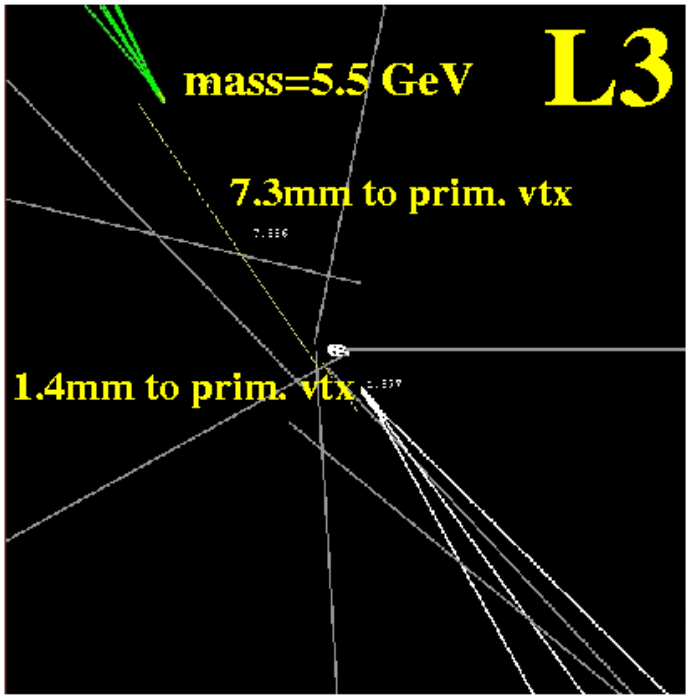
L3: Higgs Candidate

most significant Hνν candidate

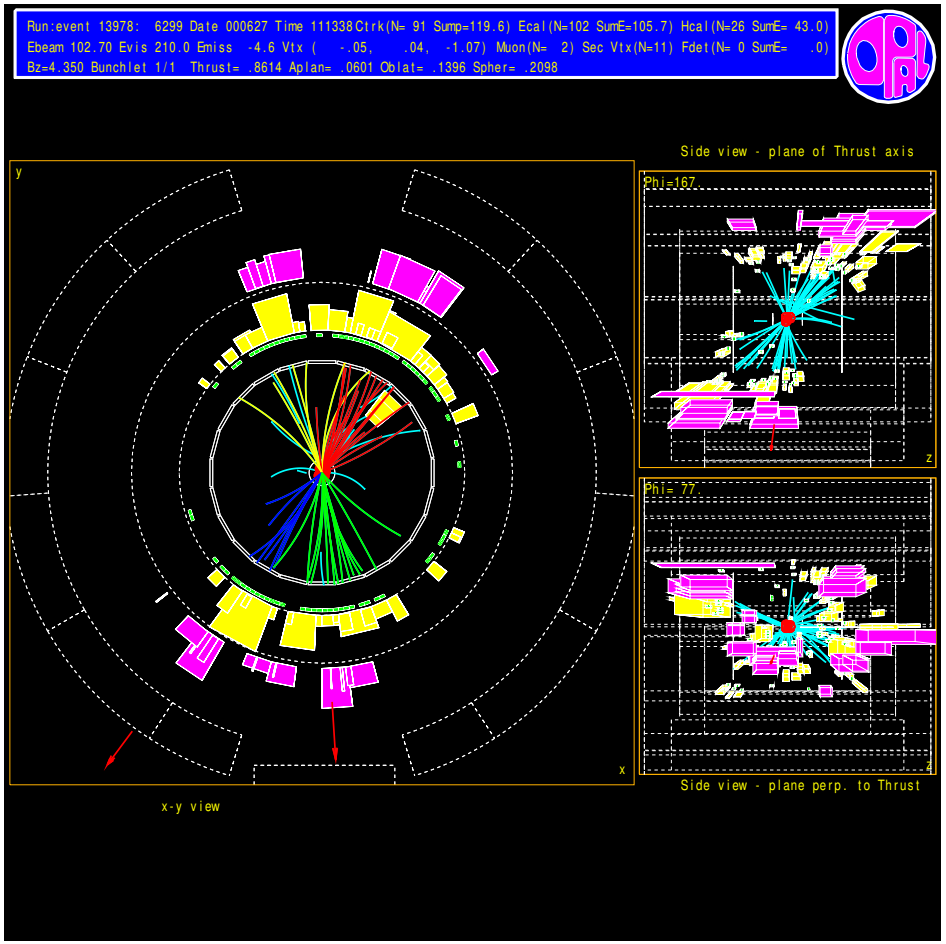


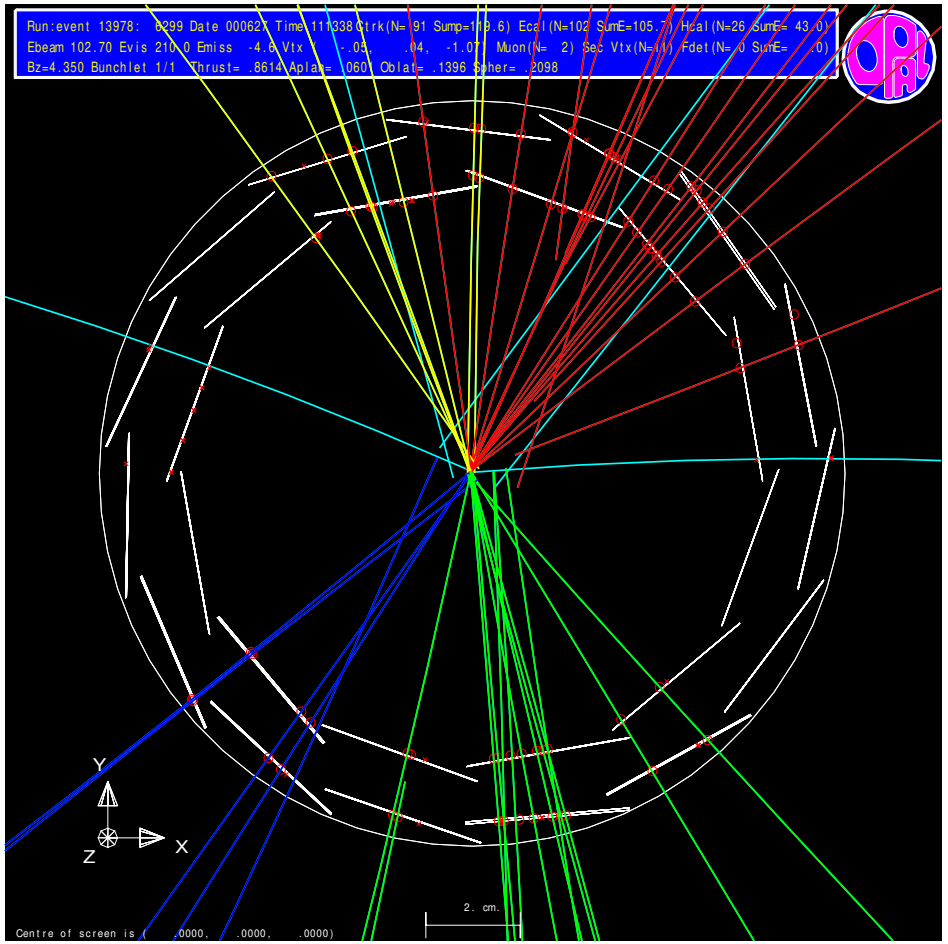
measured H mass=114.4 GeV
H mass resolution ~3 GeV

Secondary vtx's view



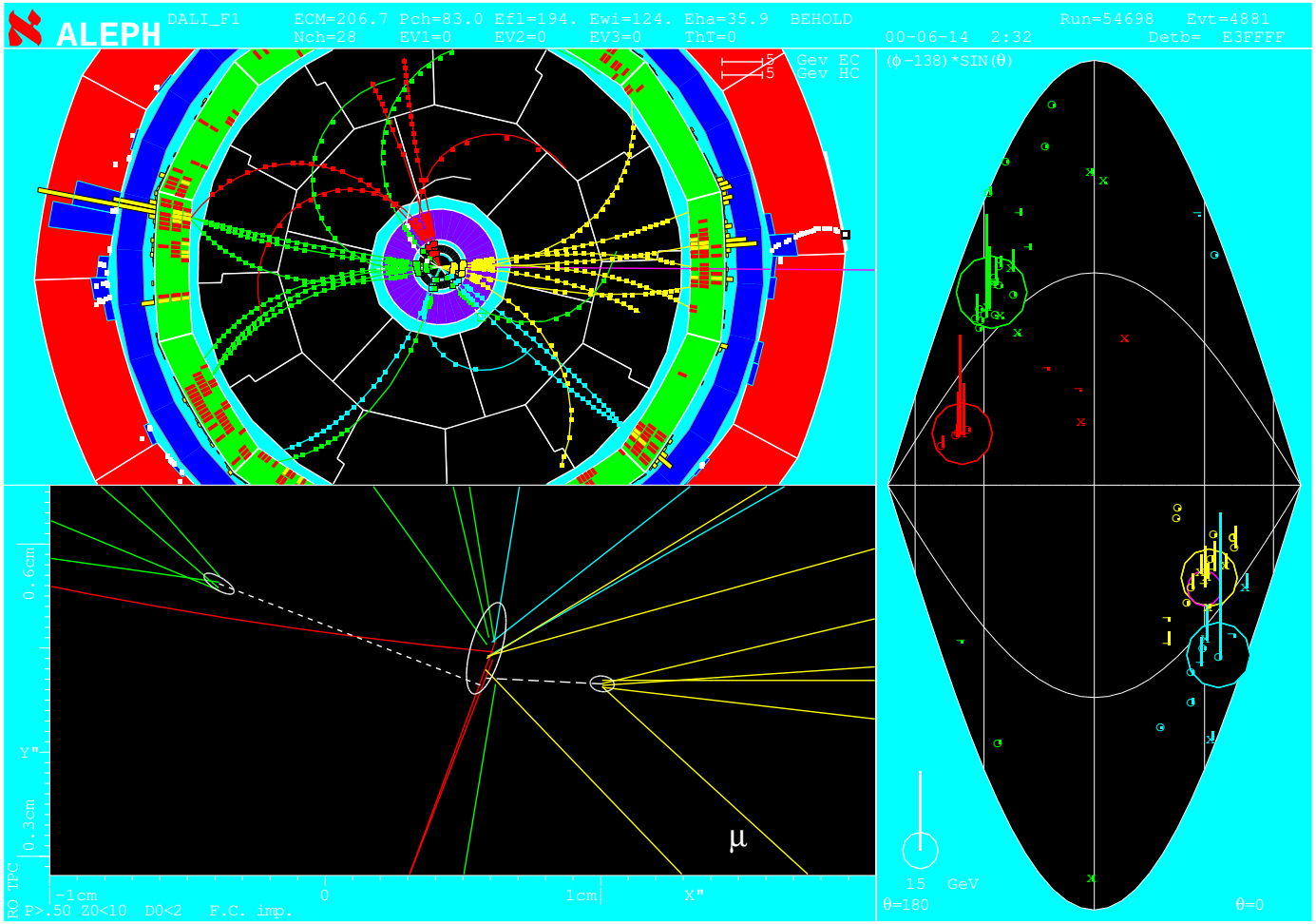
OPAL: Higgs Candidate





Candidate $e^+e^- \to H^0Z^0 \to b\bar{b}q\bar{q}$ $\quad M^{rec}_{H^0} = 113 \pm 3$ GeV

ALEPH: Higgs Candidate

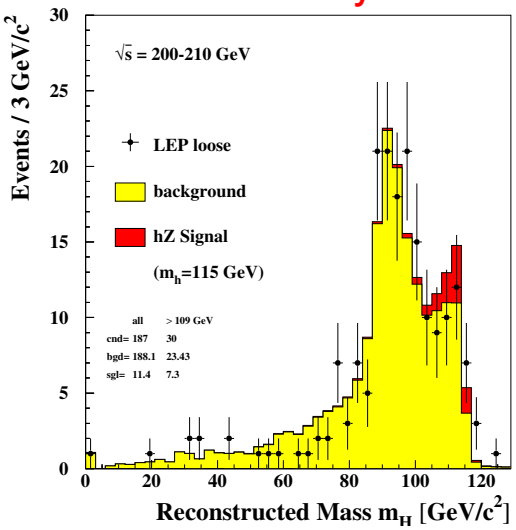


Candidate $e^+e^- \rightarrow H^0Z^0 \rightarrow b\bar{b}q\bar{q}$ $\quad M^{rec}_{H^0} = 114 \pm 3$ GeV

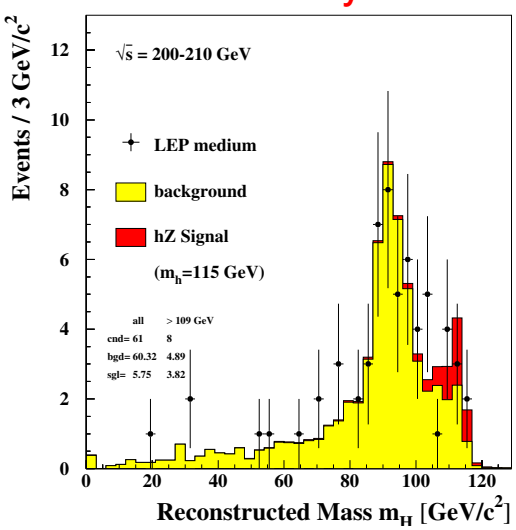
Reconstructed higgs mass spectra

$M_{\mathrm{H}^0}^{\mathrm{rec}}$ with increasingly tighter cuts

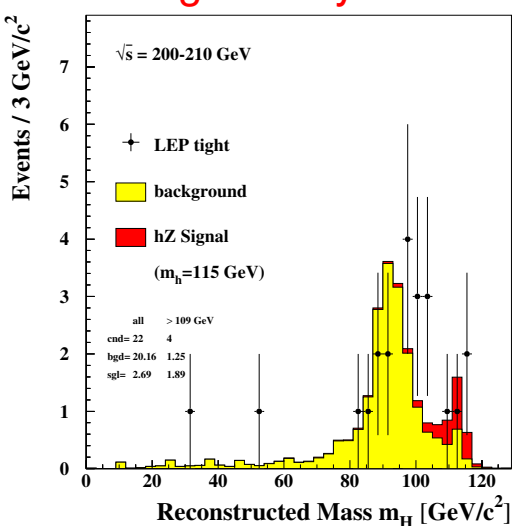
Low Purity



Med Purity



High Purity



Optimal sensitivity $\Rightarrow$ use $M_{\mathrm{H}^0}^{\mathrm{rec}}$ and "Event Purity" together

Statistical Channel Combination

- 4 decay modes
- 4 detectors
- Many $E_{\rm CM}$

  $\mathcal{O}(100)$ "channels" with different sensitivities

For each event in each channel define:

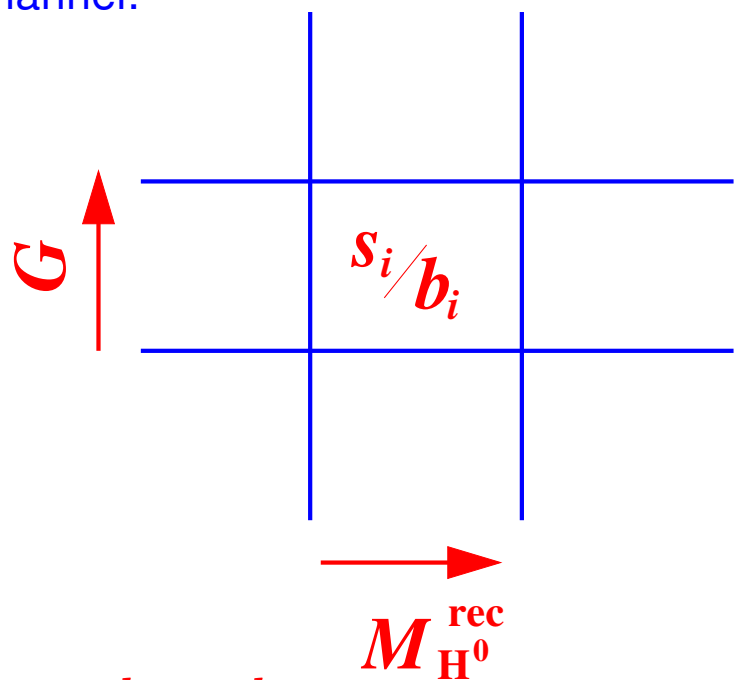
$M_{\rm H^0}^{\rm rec}$: Reconstructed Higgs Mass

G : Global Discrimination variable (b-tag, kinematics ...)

In each bin i of each channel:

- Sig: $s_i(M_{\rm H^0}^{\rm true})$
- Bkg.: b_i
- Evt.: N_i

Each event $\Rightarrow s_i/b_i$



Hypothesis test:

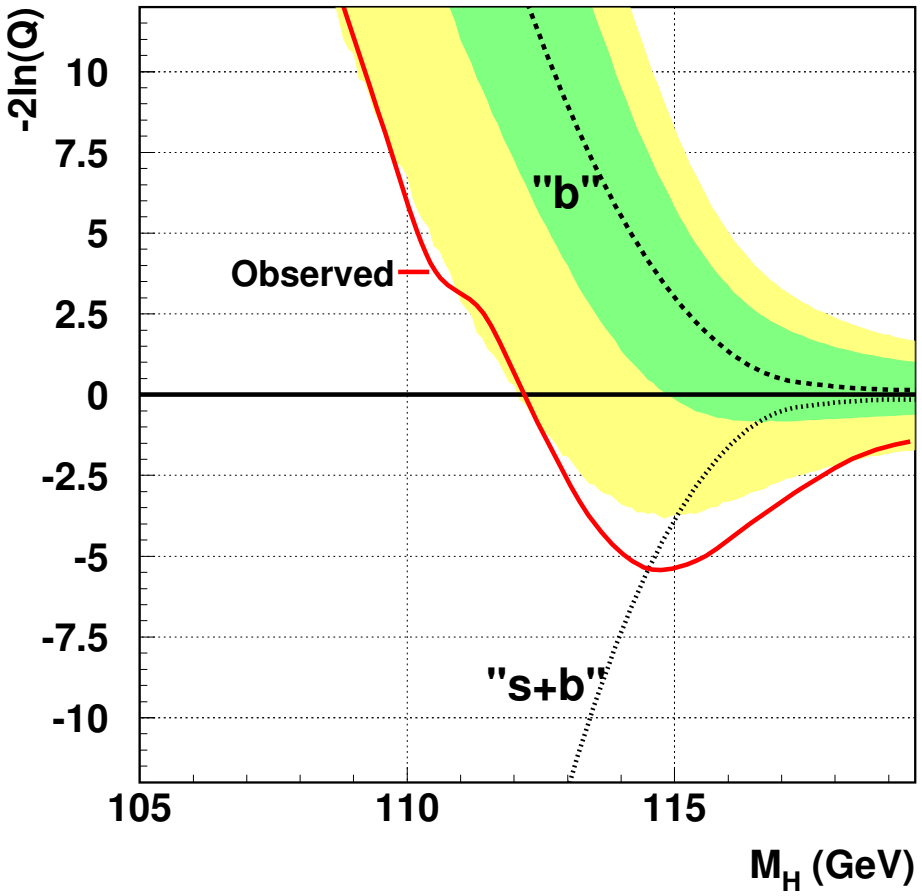
Set of all events $\Rightarrow$ "$s+b$" or "b"?

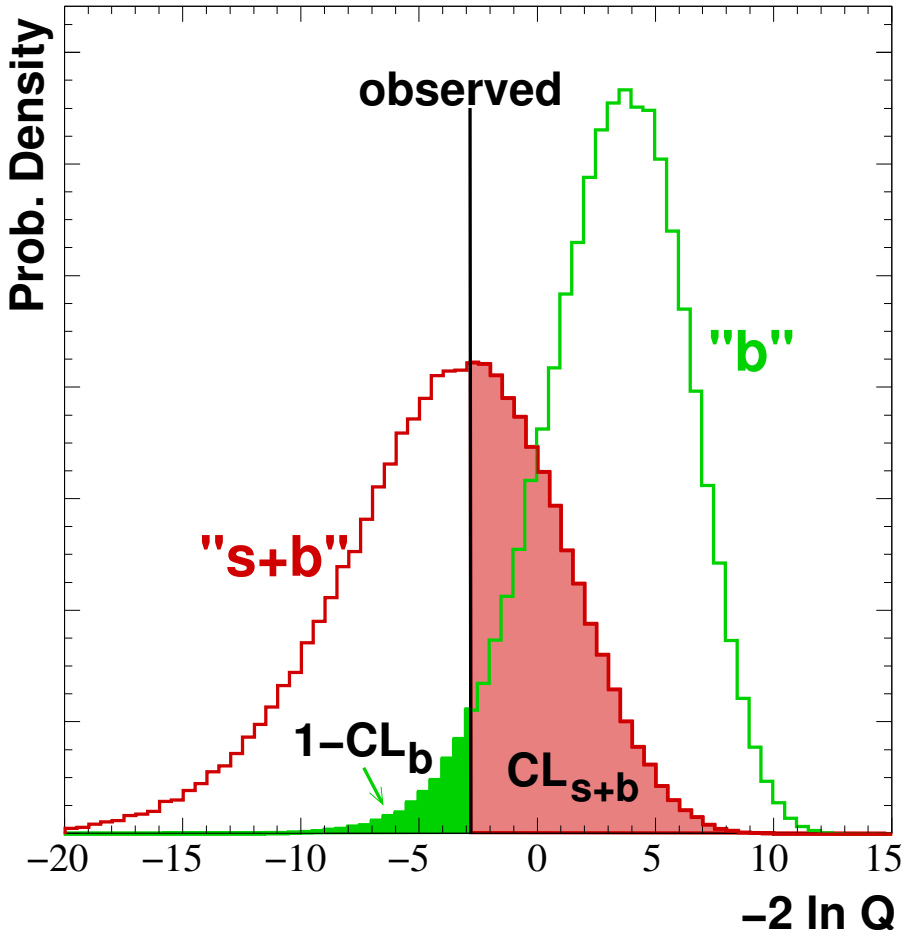
Use *Likelihood Ratio*:

$$Q(M_{\rm H^0}^{\rm true}) = \mathcal{L}(s+b)/\mathcal{L}(b)$$

$$-ln\, Q(M_{\rm H^0}^{\rm true}) = \sum_i s_i - \sum_i N_i[1 + s_i(M_{\rm H^0}^{\rm true})/b_i]$$

Statistics cont.: example results

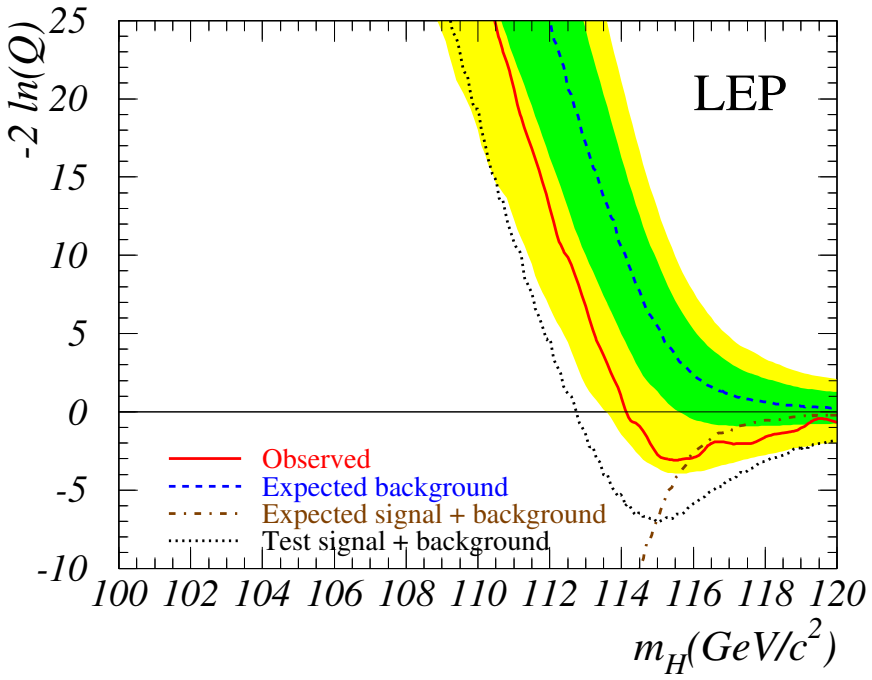


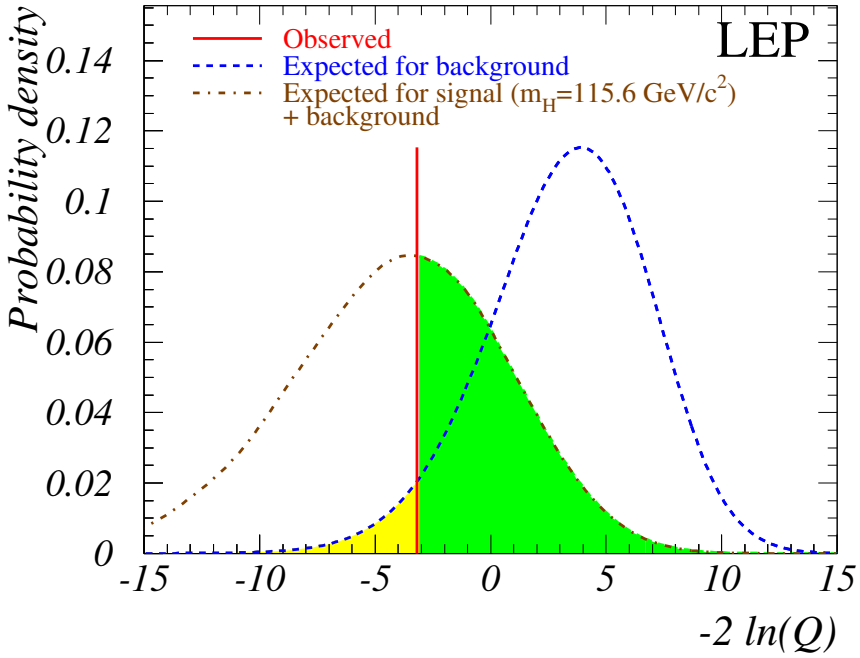


$1 - \mathrm{CL_b} = 1 - \mathrm{Prob}(\text{“}b\text{”})$

$\mathrm{CL_{s+b}} = \mathrm{Prob}(\text{“}s + b\text{”})$

LEP Results: reported at EPS2001

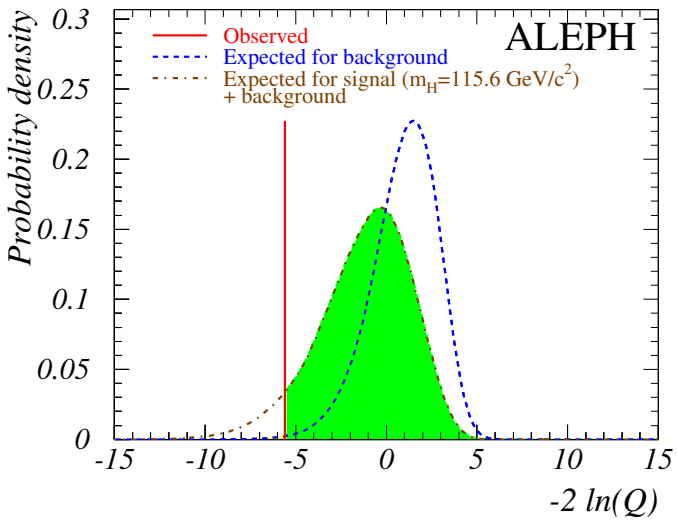


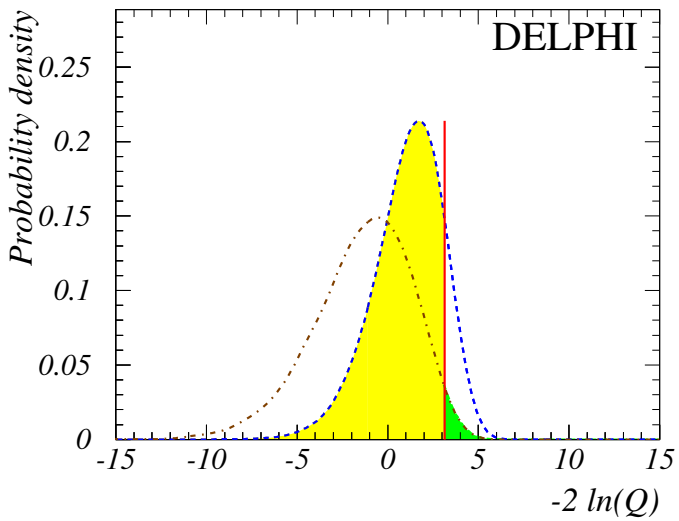


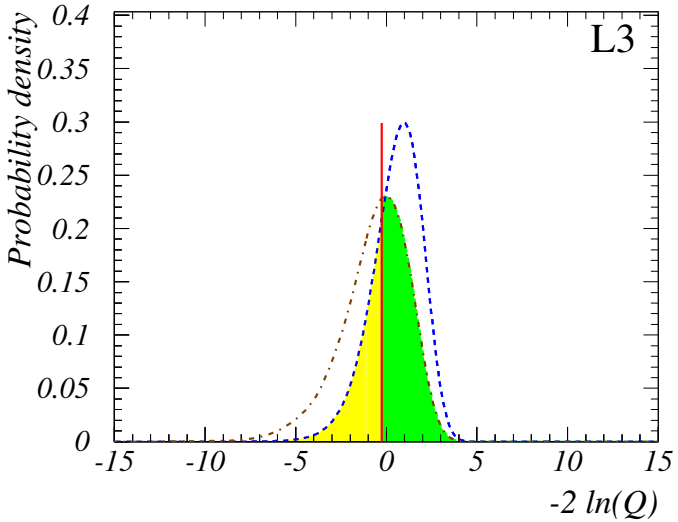
Best $M_{\mathrm{H^0}} = 115.6$ GeV

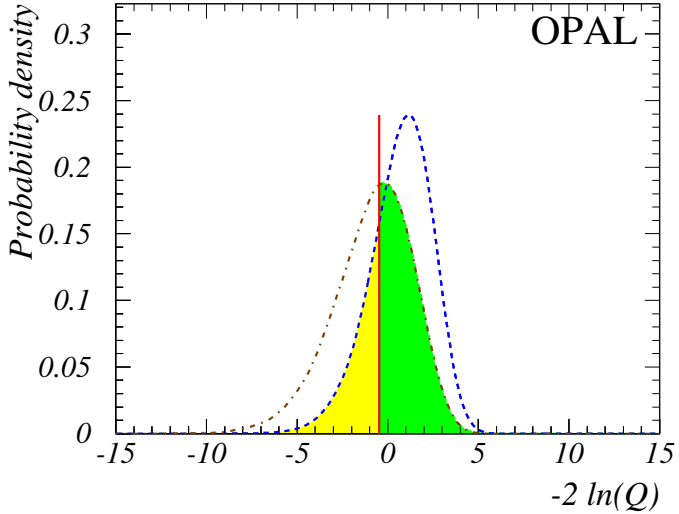
$1 - \mathrm{CL_b} = 3.4\%$

$M_{H^0} = 115$ GeV: ADLO?

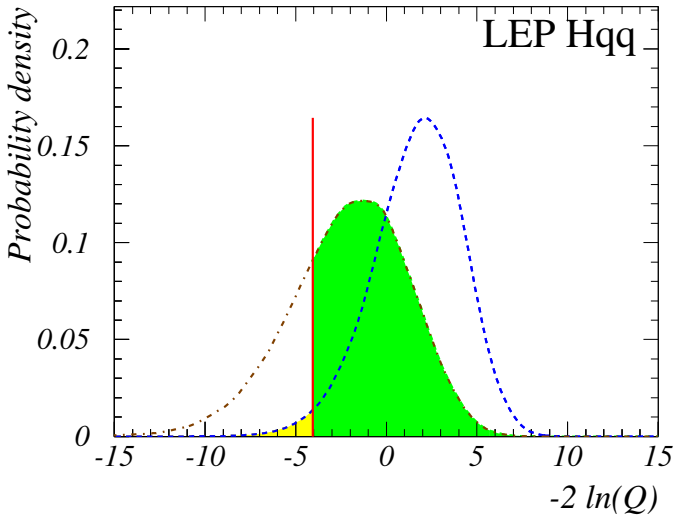


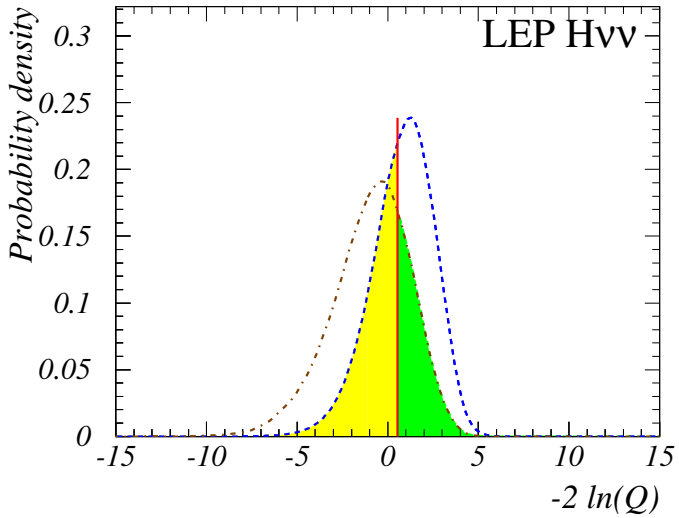


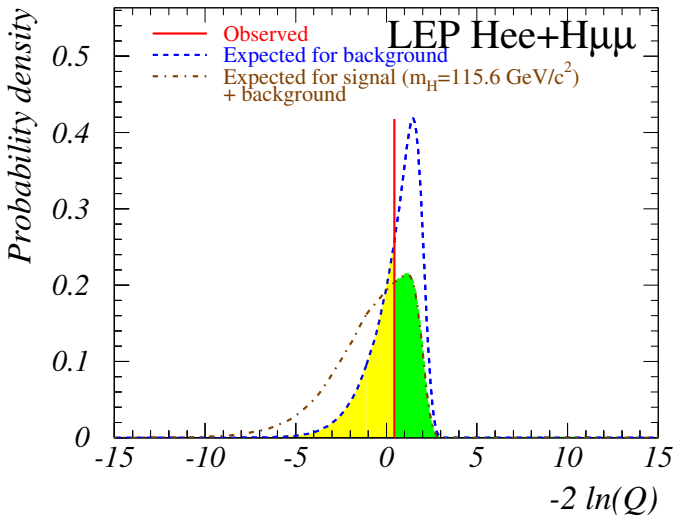


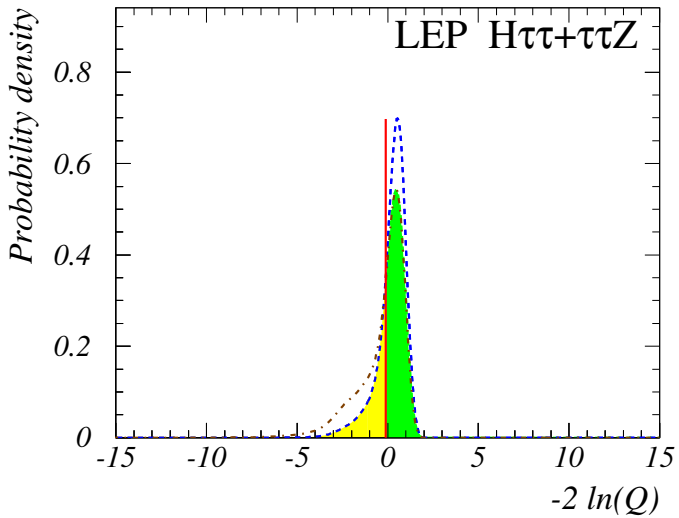


M_{H^0} = 115 GeV: Decay Modes?

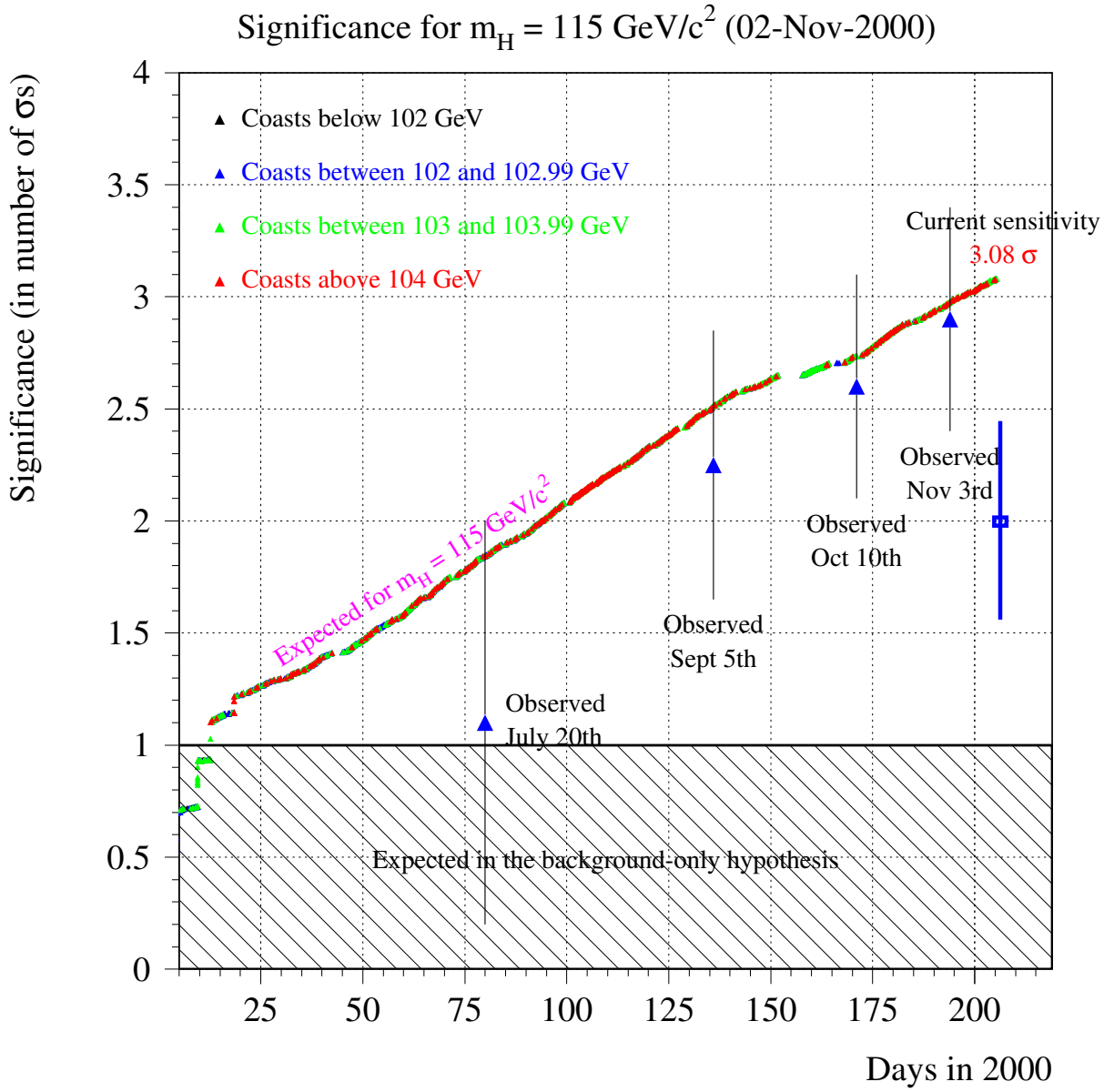








Evolution with Luminosity



- Prob(Nov 3) = 0.4%
- Prob(Now) = 3.4%

⇒ Significance dropped ∼ 8× little new data

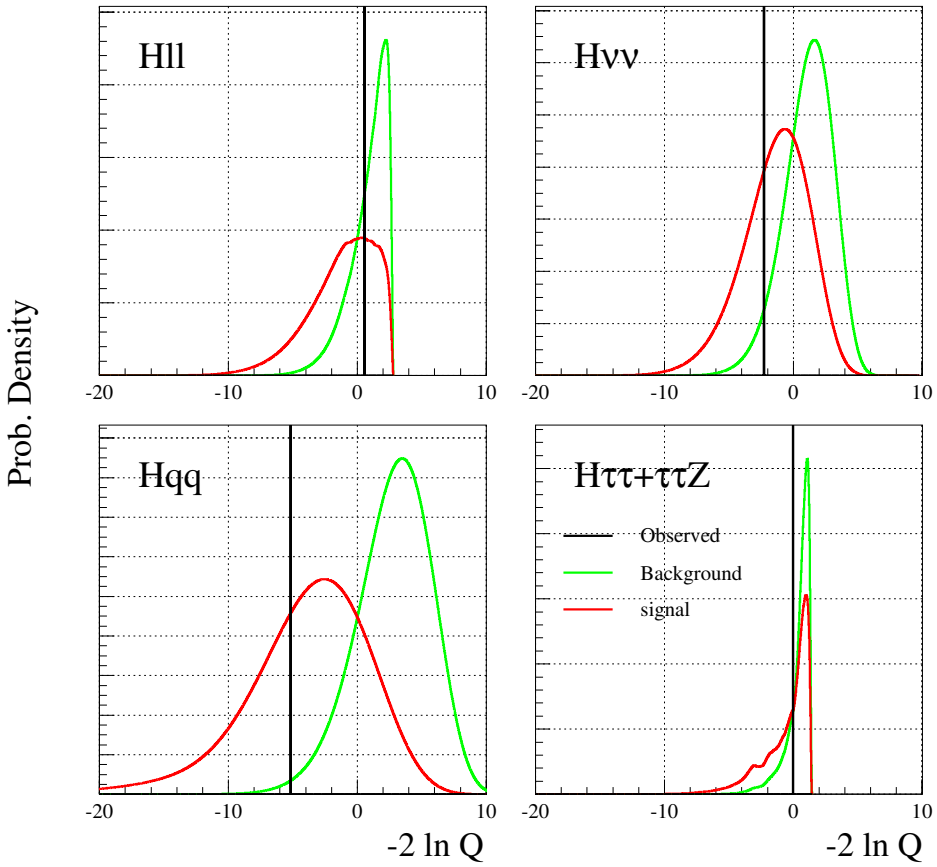
What Happened?

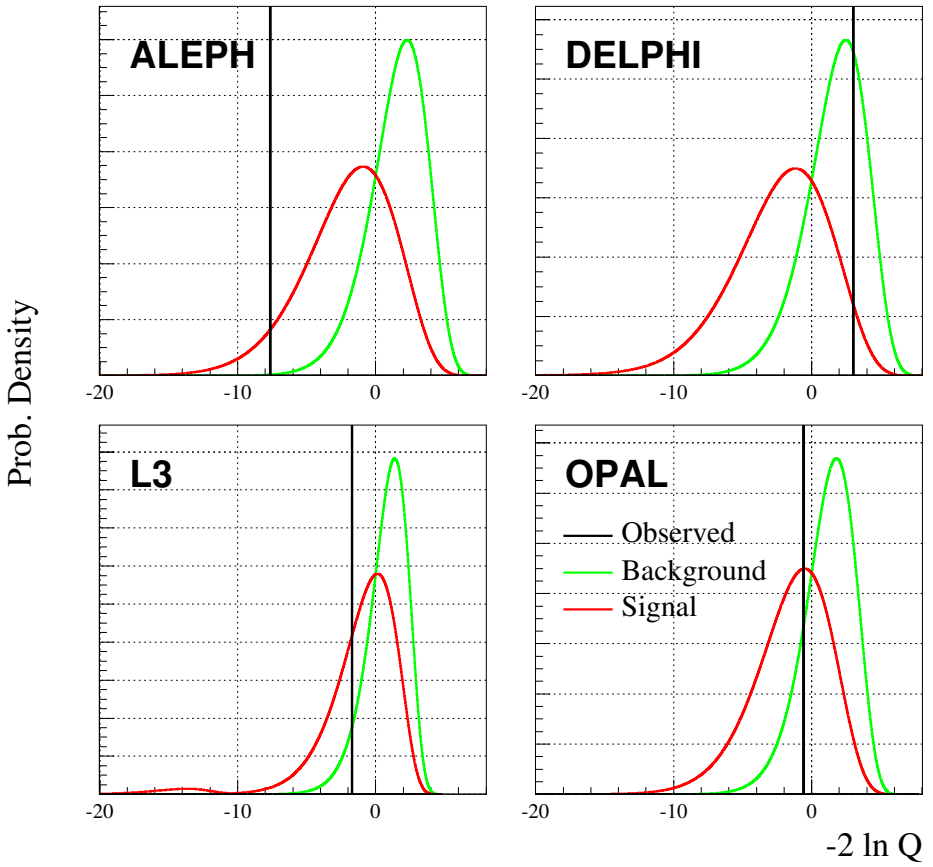
Date	ALEPH	DELPHI	L3	OPAL	LEP
LEPC Sept 5, 2000	0.00016	0.67	0.84	0.47	0.025
LEPC Nov 3, 2000	0.00065	0.68	0.068	0.19	0.0042
Summer, 2001	0.0026	0.77	0.32	0.20	0.034

- ALEPH and L3 lost about 4-5$\times$ significance
- Various reasons:
  - Data reprocessing (very small effect)
  - Cross-checks $\Rightarrow$ bug fixes
  - Full treatment of $\sqrt{s}$ distribution in Y2K
- Also lost "two-experiments" and "two-channels"

Note: All experiments have published, but only L3 "final"
(Expect ALEPH, DELPHI, OPAL final results soon)

November 3rd results ...

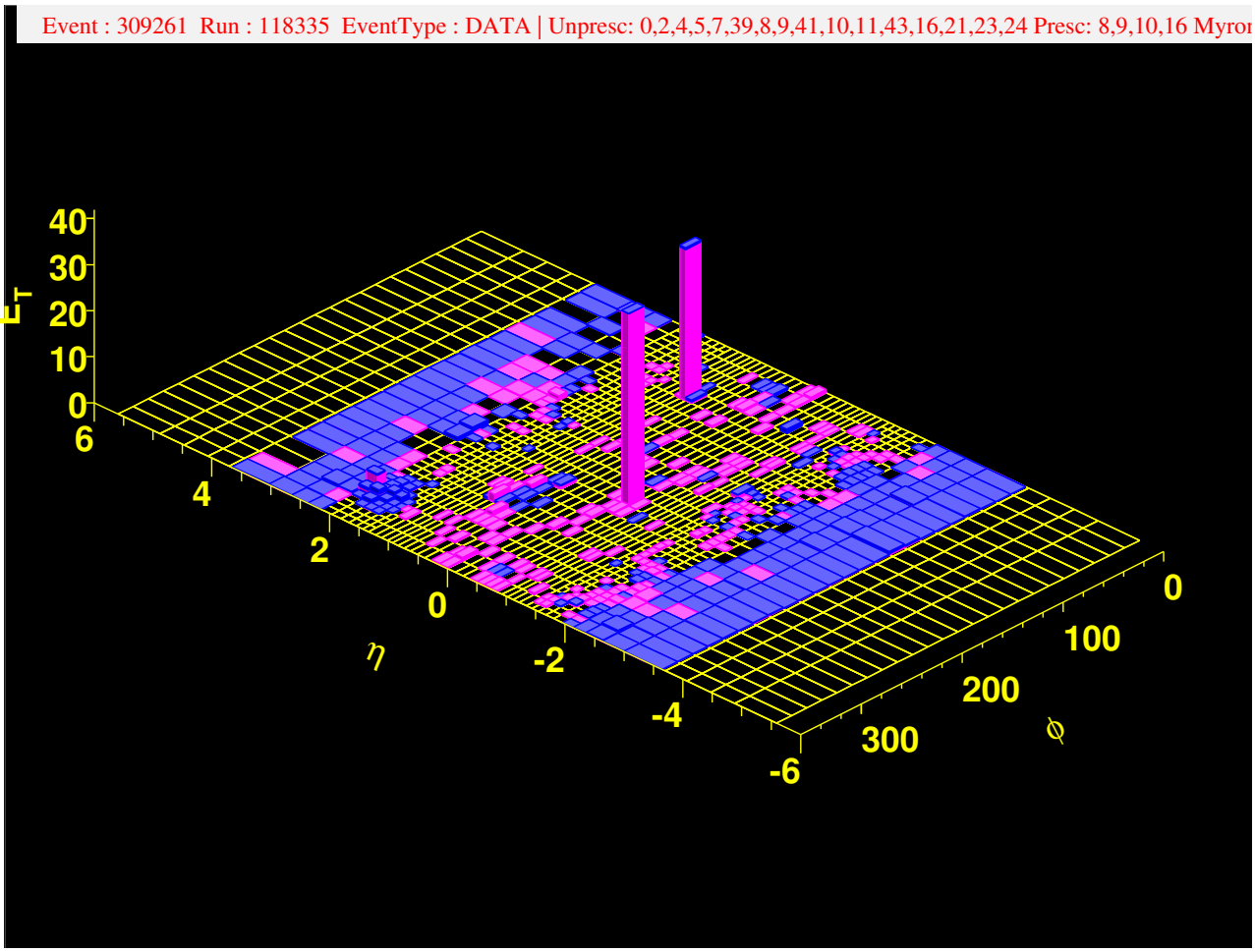




What's Next? ... Tevatron II

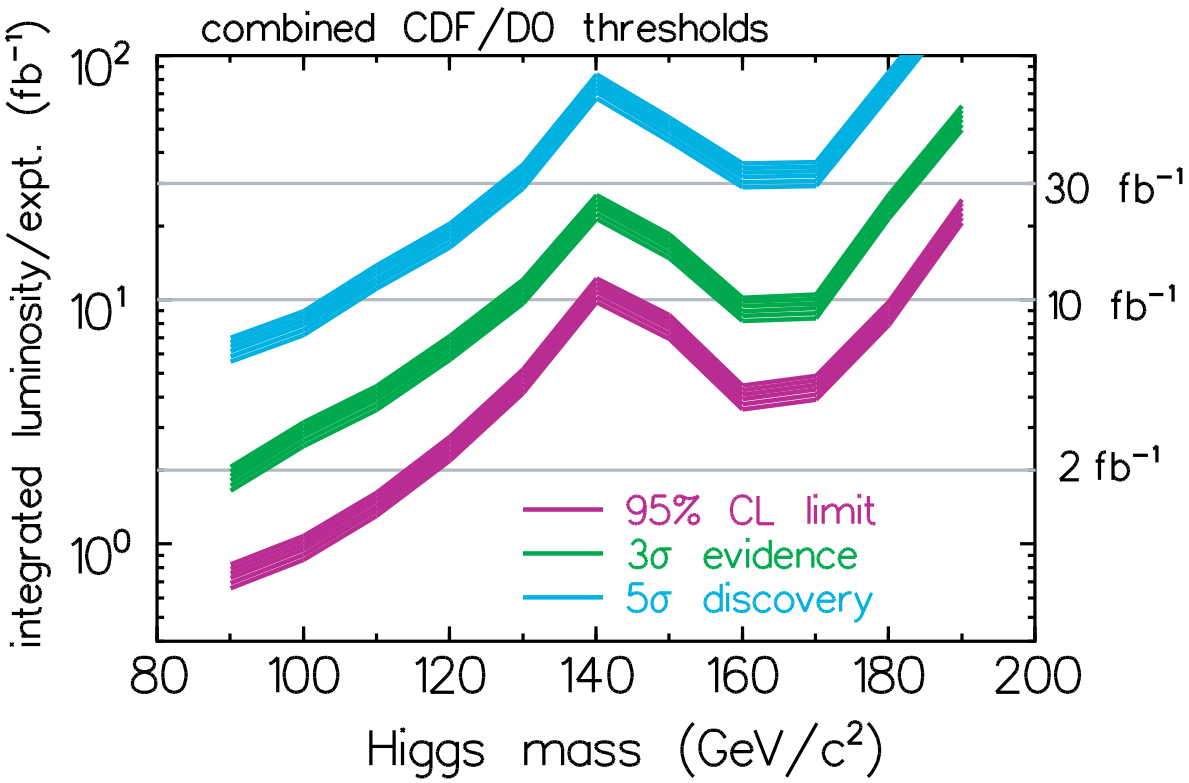
- Fermilab $\mathrm{p\bar{p}}$ Collider, $E_{\mathrm{CM}} = 2$ TeV
- Running now until early October, $\sim$15 pb^{-1} "debugging" data
- Shutdown $\sim$1 month, then take $\sim$200 pb^{-1} by next summer
- CDF mostly working, D0 slightly behind

CDF: Run II 1^{st} $\mathrm{Z}^0 \rightarrow \mathrm{e}^+\mathrm{e}^-$



Tevatron Prospects

- Fermilab $p\bar{p}$ Collider, $E_{CM} = 2$ TeV



5 σ discovery of 115 GeV Higgs:

Need $>$ 15 fb^{-1}

Larger Higgs Masses: more difficult

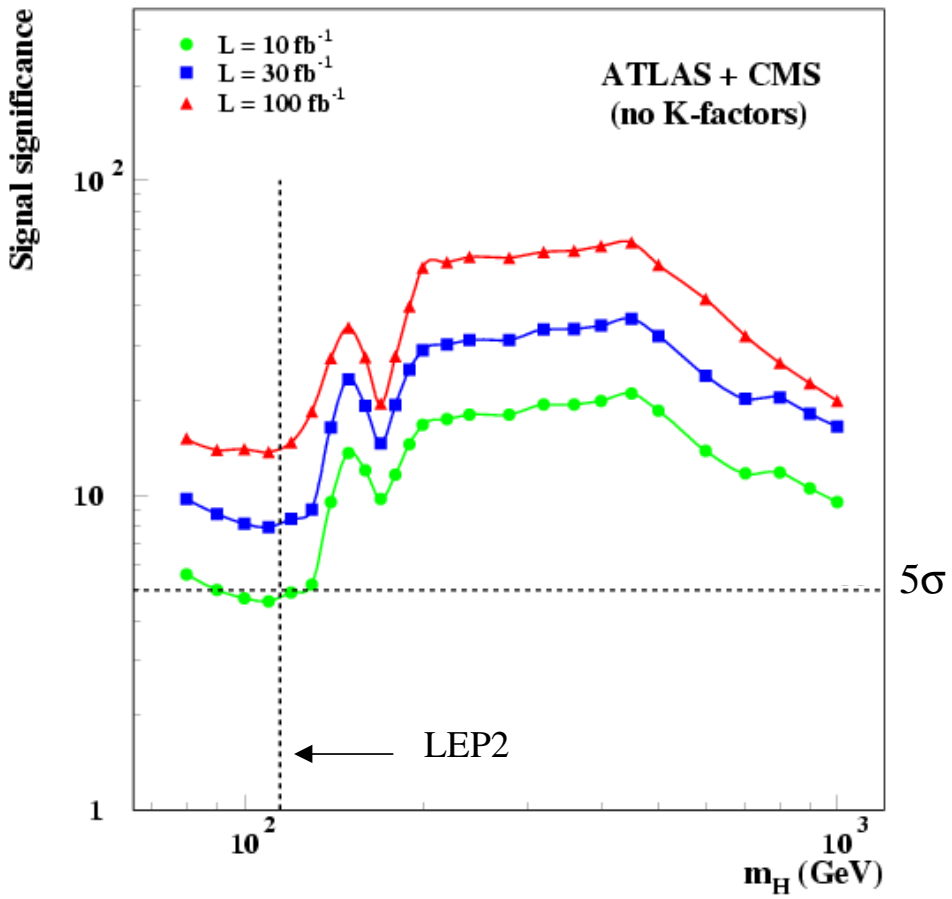
Tevatron Plans:

- Run II: 2 fb^{-1} by 2003
- Proposal: $>$ 15 fb^{-1} by 2007

May see it at the end of the program

LHC Prospects

- pp Collider, $E_{\mathrm{CM}} = 14$ TeV



5 σ discovery of 115 GeV Higgs:

Need 10 fb^{-1}

Larger Higgs Masses: **much easier!**

LHC Plans:

- 2006: 2 fb^{-1}
- 2007: 10 fb^{-1}
- Later: much more

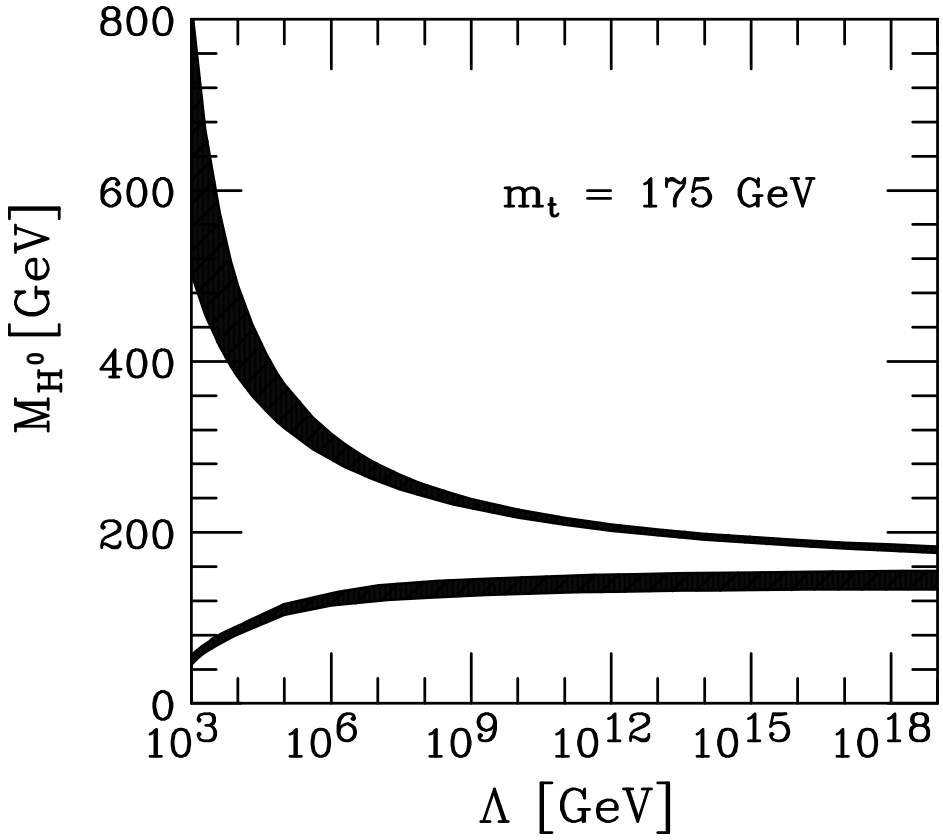
Will see it near beginning of program

$M_{H^0} = 115$ GeV: so what?

$M_{H^0} = 115$ GeV $\Rightarrow$

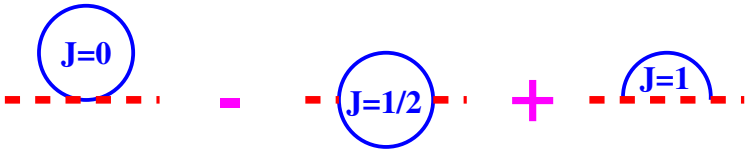
$\Lambda < 10^6$ GeV

SUSY? ($M_{h^0} < 130$ GeV)



Fine tuning problem:

$\delta m_{H^0_{SM}} =$



Roadmap Beyond the Standard Model

$\{ W_1\ W_2\ W_3\ B \}$ $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$ $\begin{pmatrix} \upsilon_e \\ e \end{pmatrix} \begin{pmatrix} \upsilon_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \upsilon_\tau \\ \tau \end{pmatrix}$

MORE? $\begin{pmatrix} t' \\ b' \end{pmatrix} \begin{pmatrix} \upsilon_L \\ L \end{pmatrix}$ composite? $\begin{pmatrix} q^*_{2/3} \\ q^*_{1/3} \end{pmatrix} \begin{pmatrix} \upsilon^*_l \\ l^* \end{pmatrix}$

EW

H^0_{SM} $\{ W^{+/-}\ Z^0\ \gamma \}$

Hierarchy Problem

~~SUSY~~ $\Rightarrow$ MSSM (Minimal; FCNC)

SUGRA { STRINGY, $\tilde{\chi}^0$ CDM

GMSB { AVOID GRAVITY FCNC, ...

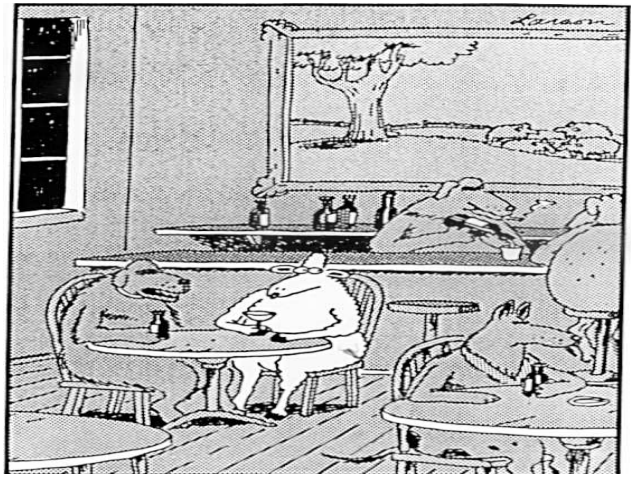
SUSY $\Rightarrow$ $\tilde{W}^{+/-}\ \tilde{Z}^0\ \tilde{\gamma}$ $\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix} \begin{pmatrix} \tilde{c} \\ \tilde{s} \end{pmatrix} \begin{pmatrix} \tilde{t} \\ \tilde{b} \end{pmatrix}$

2HDM $\tilde{h}^0\ \tilde{H}^0\ \tilde{H}^{+/-}$ $\begin{pmatrix} \tilde{\upsilon}_e \\ \tilde{e} \end{pmatrix} \begin{pmatrix} \tilde{\upsilon}_\mu \\ \tilde{\mu} \end{pmatrix} \begin{pmatrix} \tilde{\upsilon}_\tau \\ \tilde{\tau} \end{pmatrix}$

$h^0 H^0 A^0 H^{+/-}$

TECHNICOLOUR

GRAVITY IN EXTRA DIMENSIONS



Confession time, Mona: I've lead you astray.

SUSY MODELS: guide the eye ...

Spin	0	1/2	1
	$\tilde{\ell}^{\pm}_{L,R}$ } $\tilde{\ell}^{\pm}_{1,2}$	$\ell^{\pm}_{L,R}$	
	$\tilde{\nu}_L$	ν_L	
	$\tilde{q}_{L,R}$ } $\tilde{q}_{1,2}$	$q_{L,R}$	
		$\tilde{g}$	g
		$\tilde{\gamma}$	γ
	h^0, H^0, A^0	$\tilde{h}, \tilde{H}$ } $\tilde{\chi}^0_j$	
		$\tilde{Z}^0$	Z^0
	$H^{\pm}$	$\tilde{H}^{\pm}$	
		$\tilde{W}^{\pm}$ } $\tilde{\chi}^{\pm}_i$	$W^{\pm}$

"Minimal" Field content: MSSM

M_1, M_2, M_3	$U(1), SU(2), SU(3)$ Gaugino Masses
$m_{\tilde{f}}$	sfermion masses
$v, \tan\beta, m_{A^0}, \mu$	Higgs(ino) mass/mixing parameters
$A_U, A_D, A_L,$	Trilinear sfermion/higgs coupling matrices

105 new parameters, unsupressed FCNC, ...

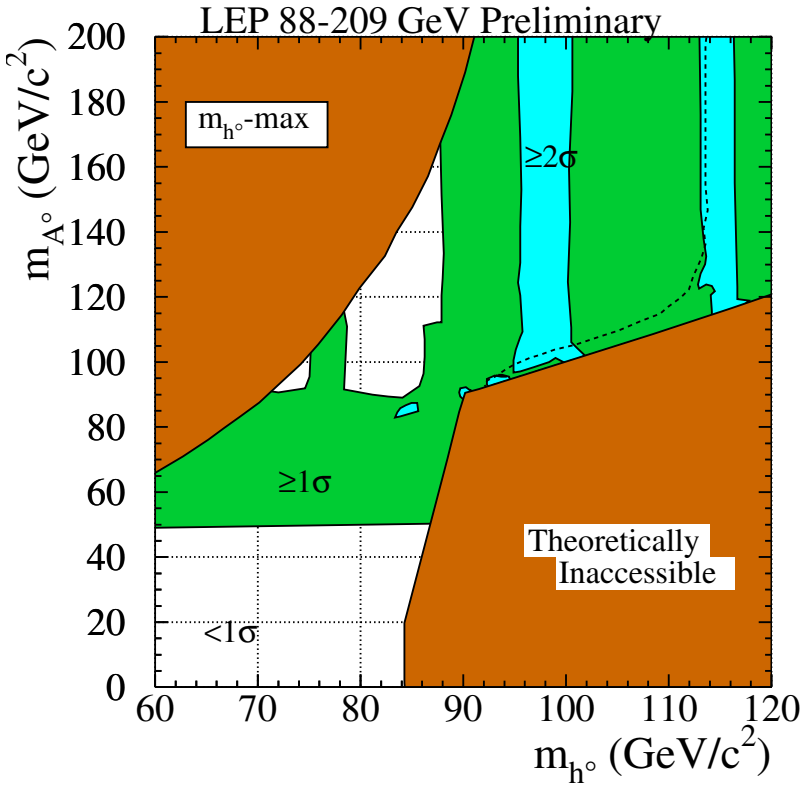
Impose a SUSY breaking mechanism:

Gravity mediated	SUGRA *etc.*	FCNC?
Gauge Mediated	GMSB	CDM Candidate?
Anomaly Mediated	AMSB	...

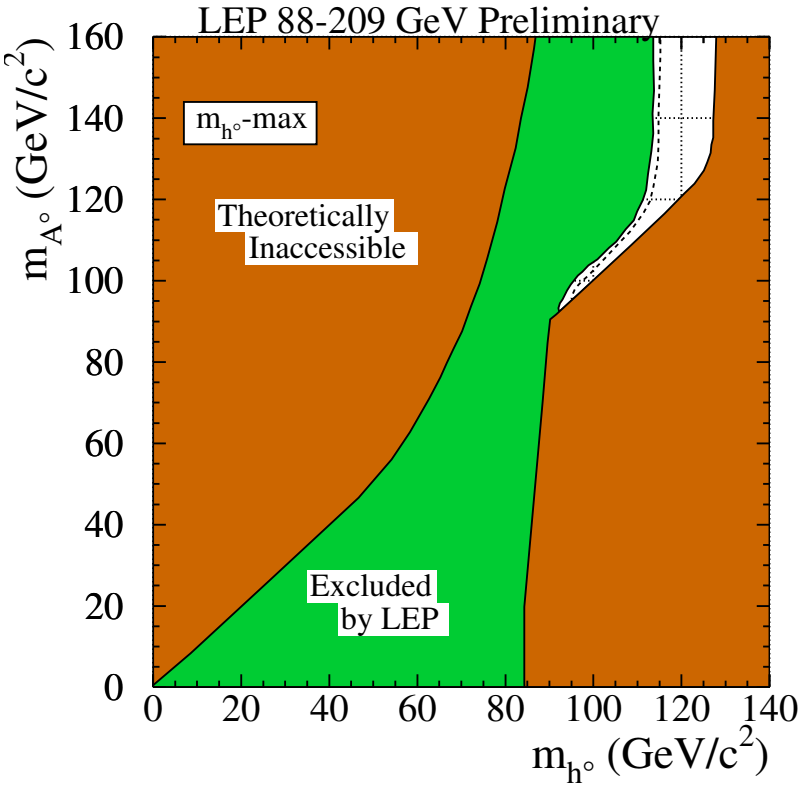
In any model: there should still be a light higgs

LEP MSSM Higgs Exclusions (conservative scenario)

Data Significance



Exclusion Region



LHC MSSM higgs prospects

- LHC will discover ∼ any higgs
- Even if SUSY is true

  May still only see a SM-like higgs

  (“death scenario”)

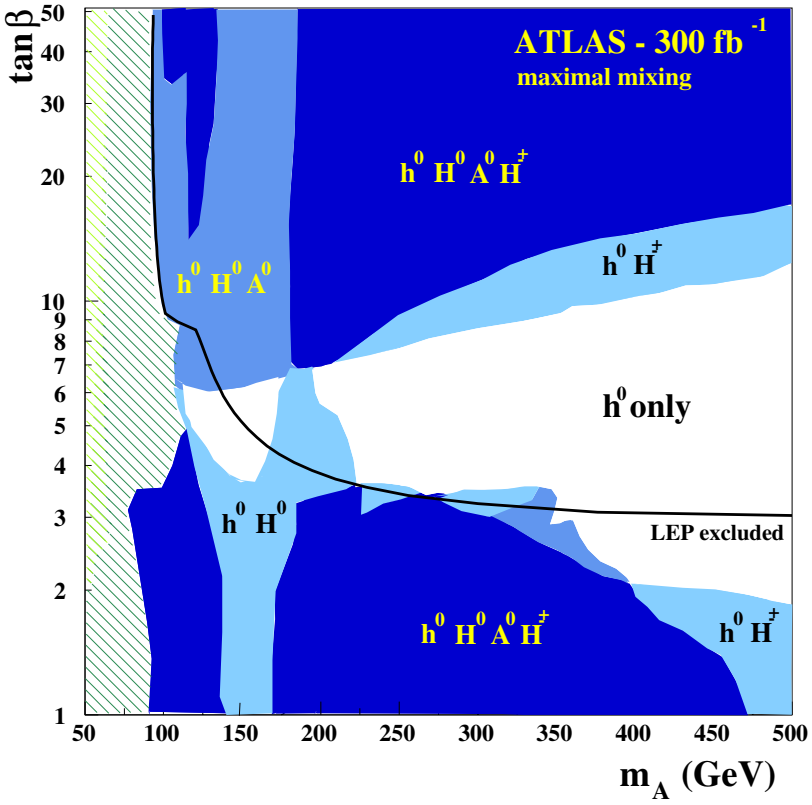
Need:

- Precision measurements

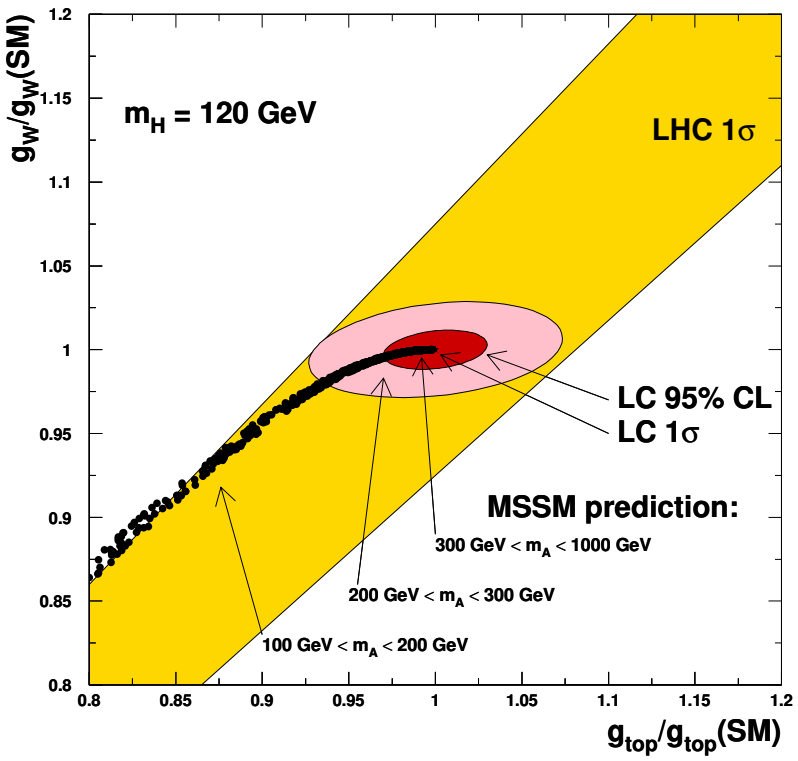
  ... of higgs

  (... of rest)

- Direct SUSY searches
- Direct searches for everything else



Precision Higgs physics: TESLA?



	M_H (GeV)	$\delta(X)/X$ LHC $2 \times 300\,\mathrm{fb}^{-1}$	$\delta(X)/X$ LC $500\,\mathrm{fb}^{-1}$
M_H	120	9×10^{-4}	3×10^{-4}
M_H	160	10×10^{-4}	4×10^{-4}
Γ_{tot}	120-140	-	0.04 - 0.06
$g_{Hu\bar{u}}$	120-140	-	0.02 - 0.04
$g_{Hd\bar{d}}$	120-140	-	0.01 - 0.02
g_{HWW}	120-140	-	0.01 - 0.03
$\frac{g_{Hu\bar{u}}}{g_{Hd\bar{d}}}$	120-140	-	0.023-0.052
$\frac{g_{Hb\bar{b}}}{g_{HWW}}$	120-140	-	0.012-0.022
$\frac{g_{Ht\bar{t}}}{g_{HWW}}$	120	0.070	0.023
$\frac{g_{HZZ}}{g_{HWW}}$	160	0.050	0.022
$\mathcal{CP}$ test	120	-	0.03
λ_{HHH}	120	-	0.22

Gauge-Mediated SUSY Breaking

- SUSY breaking mechanism unknown:
- Assume mediation method:

Gravity

$M \sim M_P \sim 10^{18}$ GeV

$\sqrt{F} \sim 10^{11}$ GeV

But: FCNC

$M_{\tilde{G}} \sim 2.5$ TeV

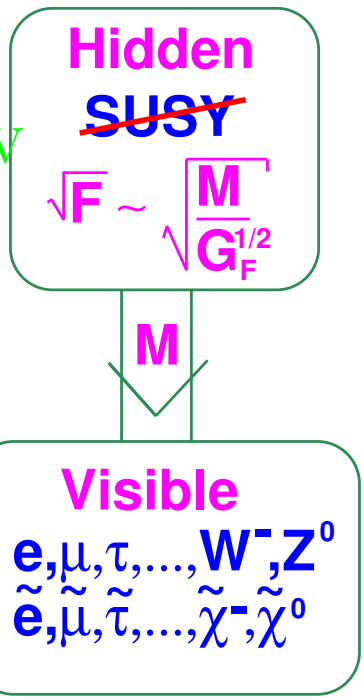
Gauge

$10^3 < M < 10^{15}$ GeV

$10^3 < \sqrt{F} < 10^{10}$ GeV

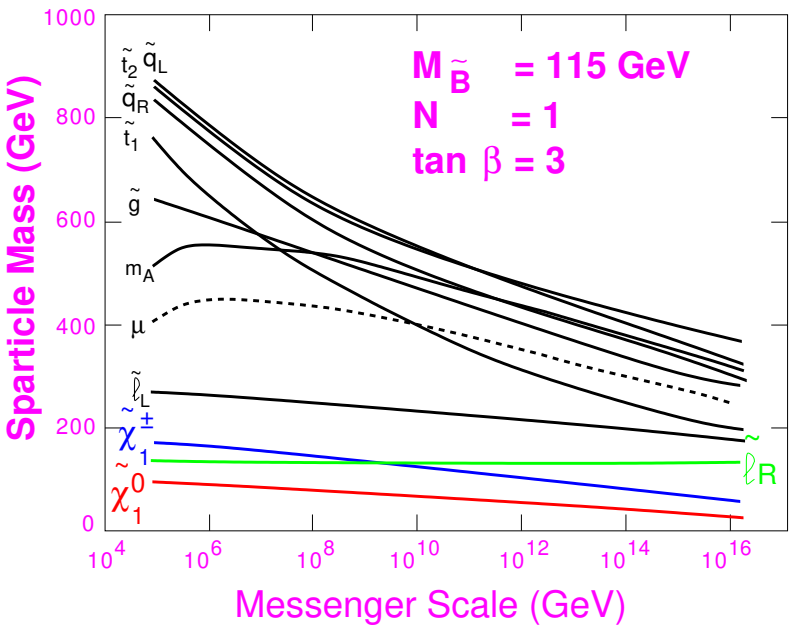
No FCNC

$M_{\tilde{G}} < 1$ GeV $\Rightarrow$ LSP



Spectrum: $\Lambda = k\frac{F}{M}$

Example GMSB mass spectra (Dimopoulos *et al.*, hep-ph/9609434):



NLSP

$\tilde{\chi}_1^0 \to \gamma\tilde{G}$

$\tilde{\ell}_R^{\pm} \to \ell^{\pm}\tilde{G}$

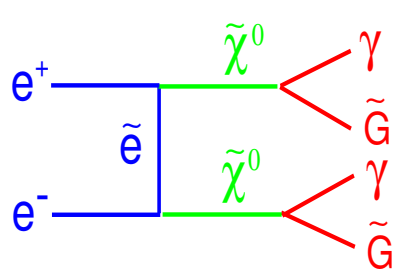
NLSP $c\tau =$

1 μm–10^{11} km

Minimal Model: $F,\ \Lambda,\ M,\ N,\ \tan\beta$ and $\mathrm{sign}(\mu)$

$\tilde{\chi}_i^+\tilde{\chi}_i^-$, $\tilde{\chi}_i^0\tilde{\chi}_j^0$, $\tilde{\ell}^+\tilde{\ell}^-$ ...

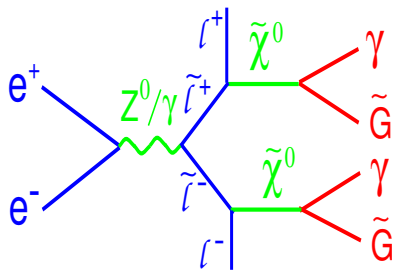
$\tilde{\chi}_1^0$ NLSP



$c\tau \sim 0$: $\gamma\gamma + \not{E}_T$

$0 < c\tau < \infty$: $\gamma + \not{E}_T$

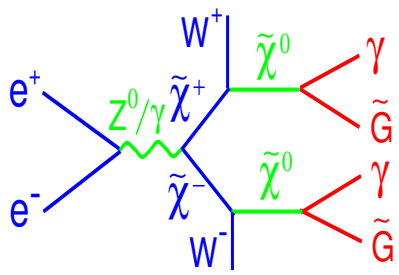
$c\tau \sim \infty$: $\not{E}_T$



$\ell^+\ell^-\gamma\gamma + \not{E}_T$

$\ell^+\ell^-\gamma + \not{E}_T$

$\ell^+\ell^- + \not{E}_T$

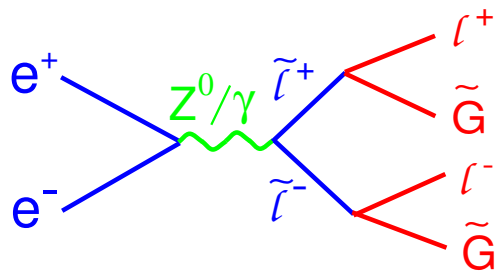


$\gamma\gamma + \text{jets}/\ell^\pm + \not{E}_T$

$\gamma + \text{jets}/\ell^\pm + \not{E}_T$

$\text{jets}/\ell^\pm + \not{E}_T$

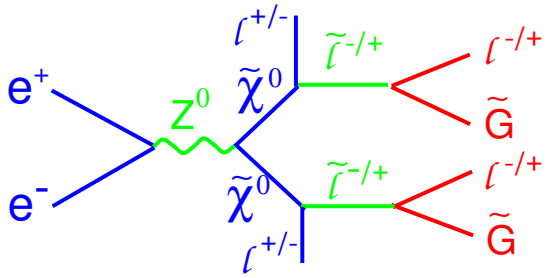
$\tilde{\ell}^\pm$ NLSP



$c\tau \sim 0$: $\ell^+\ell^- + \not{E}_T$

$0 < c\tau < \infty$: $2 \times$ Kinked Tracks

$c\tau \sim \infty$: $2 \times$ Stable Charged

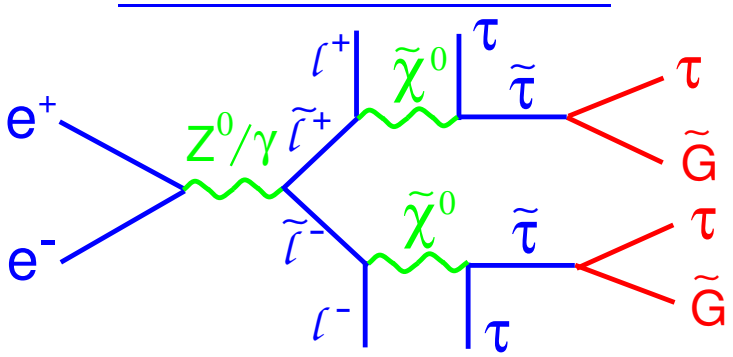


$4 \times \ell^\pm + \not{E}_T$

$2 \times \ell^\pm + 2 \times$ Kinked Tracks

$2 \times \ell^\pm + 2 \times$ Stable Charged

$\tilde{\tau}^\pm$ NLSP ($\tan\beta > 10$)



$c\tau \sim 0$: $\tau^\pm\tau^\pm + (\ell^\pm\tau^\mp\ell^\pm\tau^\mp)$

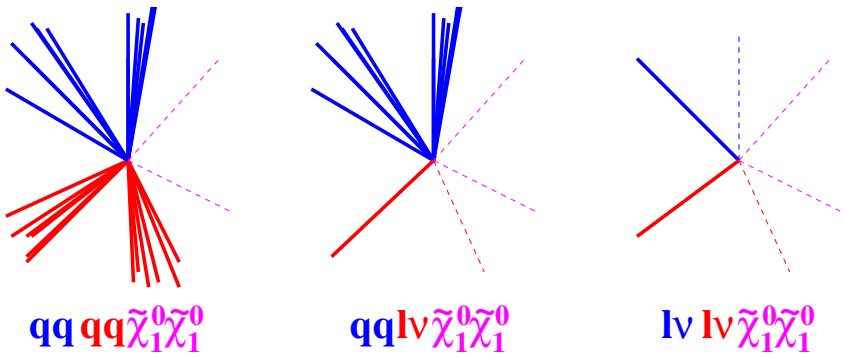
$0 < c\tau < \infty$: Kinked Tracks $+ (\ell^\pm\tau^\mp\ell^\pm\tau^\mp)$

$c\tau \sim \infty$: Stable Charged $+ (\ell^\pm\tau^\mp\ell^\pm\tau^\mp)$

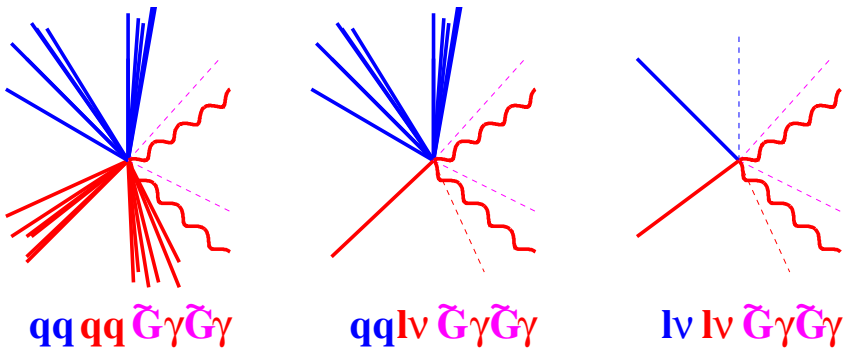
$\tilde{\chi}_1^+\tilde{\chi}_1^-$ with $\tilde{\chi}_1^0$ NLSP

Final state topology depends on the $\tilde{\chi}_1^0$ decay length ($c\tau$)

Long τ :



Short τ :



- Search topology: ≥ 1 photon + missing energy
- photon may be displaced from origin

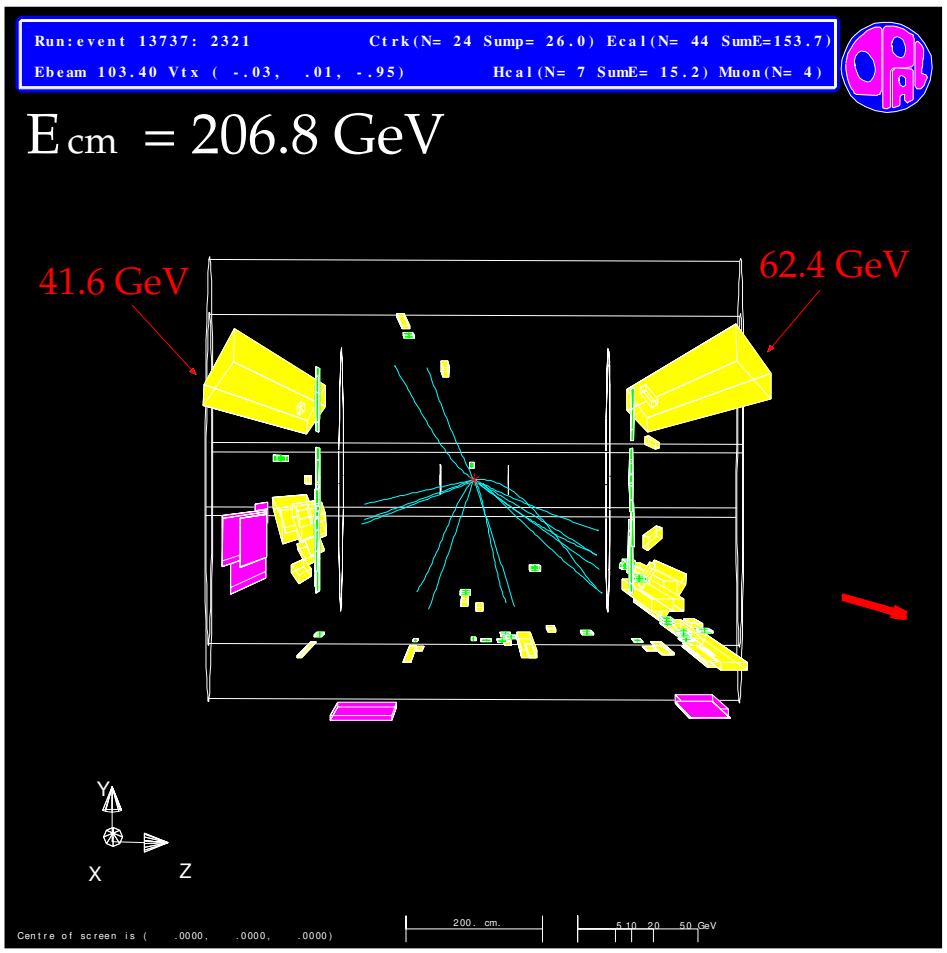
Model Interesting $\Rightarrow$

New Experimental Signatures

$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$ with $\tilde{\chi}_1^0$ NLSP

Channel	1 γ		2 γ	
OPAL'00	Bkg	Data	Bkg	Data
Low Mult	16.9 ± 0.9	19	2.9 ± 0.2	1
High Mult	26.0 ± 7.8	32	9.6 ± 3.0	14

- High Multiplicity Candidate



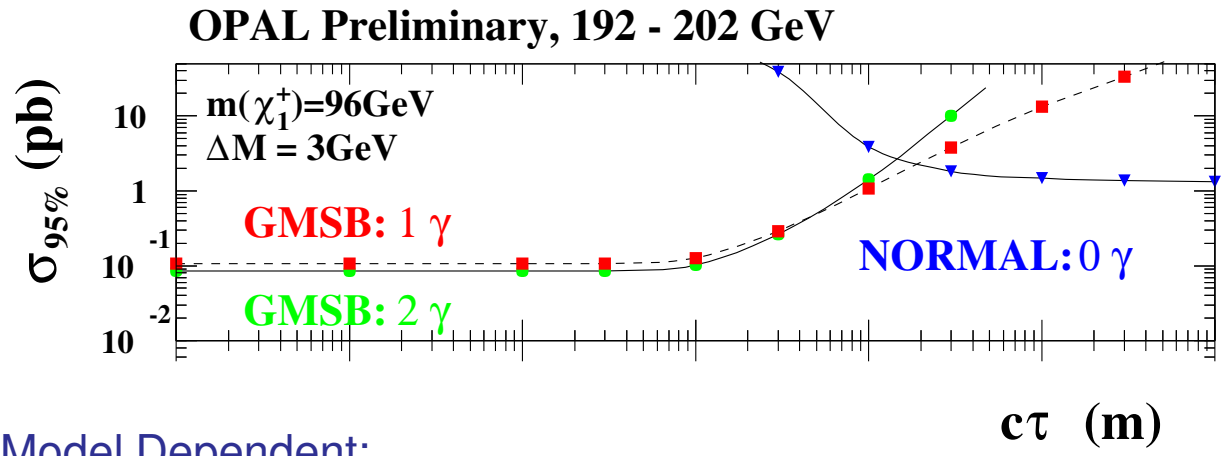
Consistent with :

$$\tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow q\bar{q}\gamma\gamma\tilde{G}\tilde{G}$$

GMSB Limits

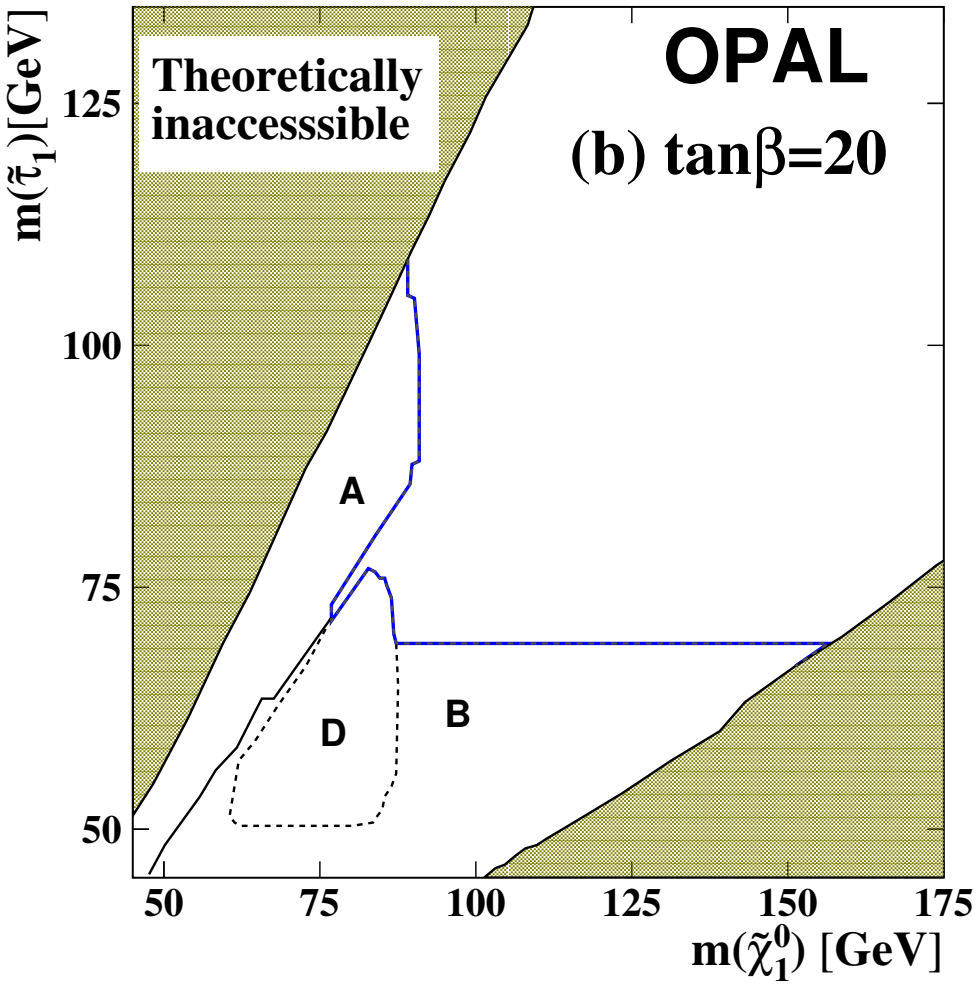
Model Independent:

- Production cross-section vs. NLSP lifetime



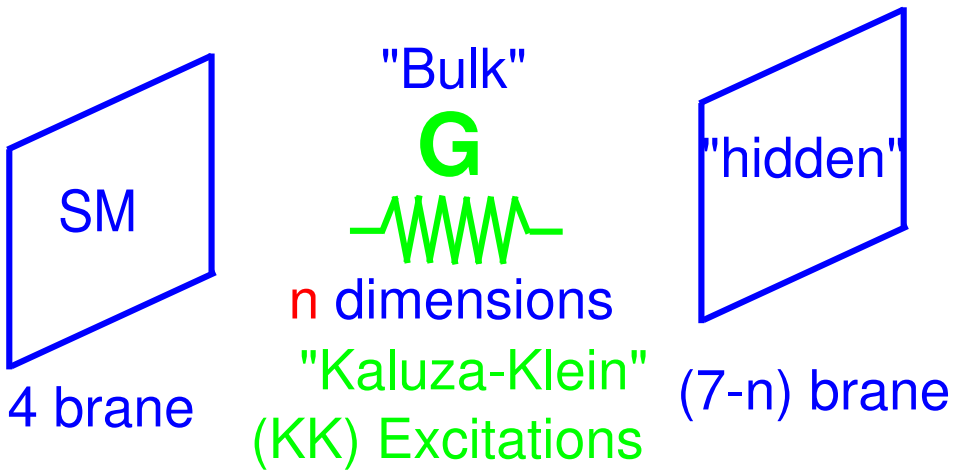
Model Dependent:

- Scan GMSB parameter space, exclude mass regions

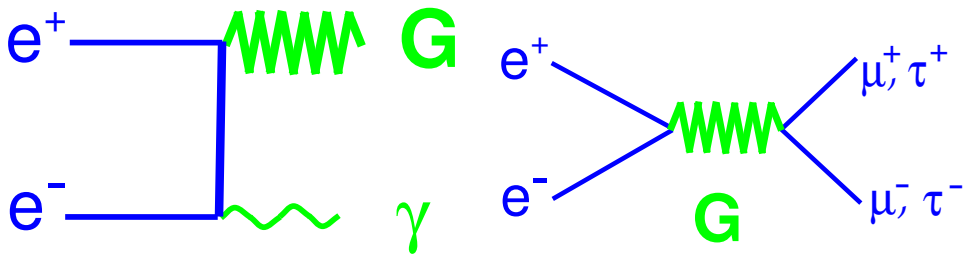


Gravity in Extra Dimensions

Overall Picture



Can affect Measurable Phenomena



WHY??

- Gravity "diluted"
  $\Rightarrow$ "$M_{\rm planck}$"$= M_D = M_{\rm EW}$
- No hierarchy problem

$$M_{Pl}^2 = R^n \times {M_D}^{n+2}$$

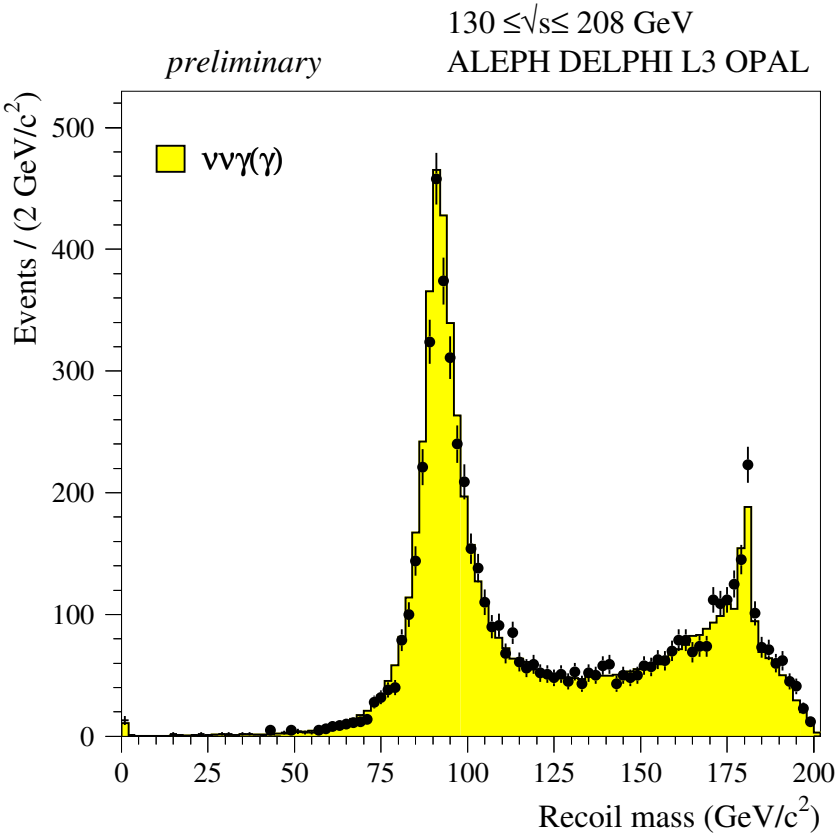
R : Extra dim. Compactification Radius

n : Number of large dim., $1 < R < 7$

n	R	Possible?
1	10^{13} cm	Excluded
2	1 mm	Not excluded!!
7	1 fm	Not excluded

Gravity XDim: Direct $e^+e^- \rightarrow G\gamma$

$$\frac{d^2\sigma}{dE_\gamma d\cos\theta} \propto \frac{1}{{M_D}^2}\left(\frac{\sqrt{s}}{M_D}\right)^n$$



Lower bounds on M_D
95% C.L. (TeV)

n	ALEPH (189-209)	L3 (189)	DELPHI (181-209)	OPAL (189)
2	1.28	1.02	1.38	1.09
3	0.97	0.81	–	0.86
4	0.78	0.67	0.84	0.71
5	0.66	0.58	–	0.61
6	0.57	0.51	0.58	0.53
7	–	0.45	–	0.47

Gravity XDim: Indirect $e^+e^- \rightarrow G^* \rightarrow f\bar{f}, VV$

$$\frac{d\sigma}{d\Omega} = f(\frac{\lambda}{{M_S}^4})$$

λ depends on model

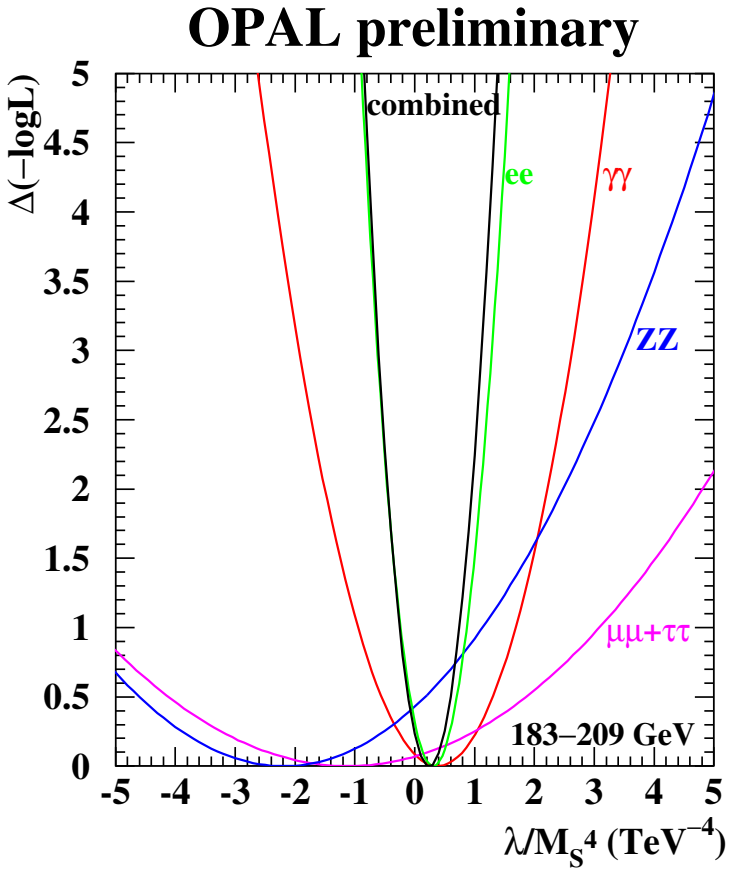
M_S UV cut-off $\sim M_D$

$e^+e^- \rightarrow e^+e^-$:

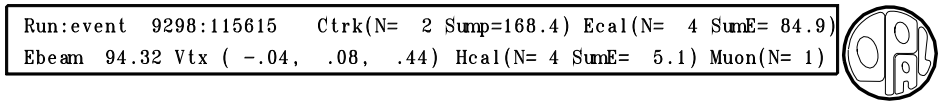
	M_S 95%C.L. (TeV)	
	$\lambda = -1$	$\lambda = +1$
L3	0.98	1.06
OPAL	1.00	1.15

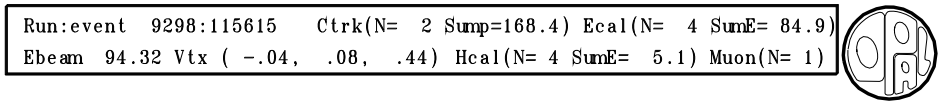
$e^+e^- \rightarrow \gamma\gamma$:

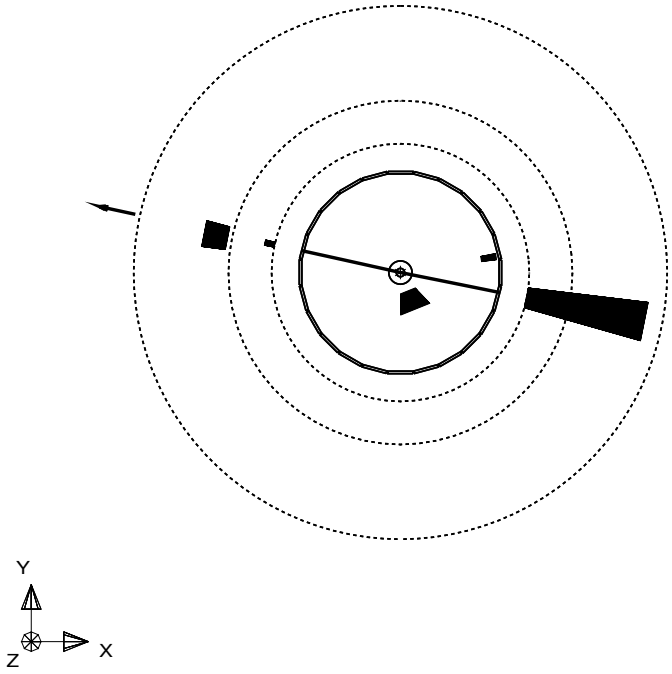
	M_S 95%C.L. (TeV)	
	$\lambda = -1$	$\lambda = +1$
DELPHI	0.70	0.77
L3	0.99	0.84
OPAL	0.89	0.83

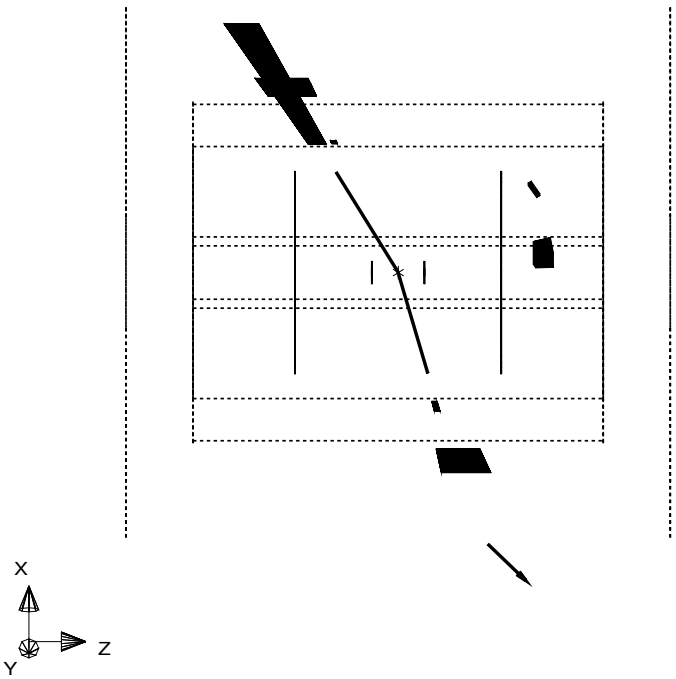


Topological searches: *eg.* Lepton Flavour Violation









1 $e^+e^- \rightarrow e\mu$ Candidate with 0.019 expected

More significant excess than LEP higgs!

Partial Search Channel List

$e^+e^- \to hZ$	$h \to b\bar{b}$	$b\bar{b}q\bar{q}$, $b\bar{b}\nu\bar{\nu}$, $b\bar{b}\ell^+\ell^-$
	$h \to \gamma\gamma$	$(q\bar{q}, \ell^+\ell^-, \nu\bar{\nu})+\gamma\gamma$
	$h \to \tilde{\chi}^0\tilde{\chi}^0$	$q\bar{q}$, $\ell^+\ell^- + \not{E}$
$e^+e^- \to hA$	$h, A \to b\bar{b}, \tau\tau$	$b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$
	$h \to AA$	$b\bar{b}b\bar{b}b\bar{b}$
$e^+e^- \to H^+H^-$	$H^+ \to q\bar{q}, \tau\nu$	$q\bar{q}q\bar{q}$, $q\bar{q}\tau\nu$, $\tau\nu\tau\nu$
$e^+e^- \to \tilde{\chi}^+\tilde{\chi}^-$	$\tilde{\chi}^- \to W^*\tilde{\chi}^0$	jets $(+\ell^\pm)$, $\ell^+\ell^- + \not{E}$
	(In)Direct RPV	jets, $\ell^\pm$, ν
	$(\tilde{\chi}^0 \to \gamma\tilde{G})$	jets, $\ell^+\ell^-$, $\gamma\gamma + \not{E}$
$e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_1$	$\tilde{\chi}^0_2 \to Z^0\tilde{\chi}^0_1$	2 jets $+ \not{E}$
	$\tilde{\chi}^0_2 \to \gamma\tilde{\chi}^0_1$	$\gamma + \not{E}$
$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$	$\tilde{\chi}^0_1 \to \gamma G$	$\gamma\gamma + \not{E}$
	$\tilde{\chi}^0_1$ Lifetime	non-pointing γ
	RPV Decays	jets, $\ell^\pm$, ν
$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$	$\tilde{\ell}^- \to \ell^-\tilde{\chi}^0_1$	$\ell^+\ell^- + \not{E}$
	$(\tilde{\chi}^0 \to \gamma\tilde{G})$	$\ell^+\ell^-\gamma\gamma + \not{E}$
	(In)Direct RPV	2,4,6$\times\ell^\pm + \not{E}$
	$\tilde{\ell}^\pm$ Lifetime	Kinked Tracks
		Stable, Charged
$e^+e^- \to \tilde{\nu}\tilde{\nu}$	(In)Direct RPV	$\ell^+\ell^-\ell^+\ell^-$
		jets $+ \not{E}$
$e^+e^- \to \tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}^0_1$	2 jets $+ \not{E}$
	$\tilde{t}_1 \to b\ell^+\tilde{\nu}$	2 jets $+ \ell^+\ell^- + \not{E}$
	(In)Direct RPV	$\ell^+q\ell^-q$
$e^+e^- \to N\bar{N}$	$N \to \ell W$	jets $+\ell^\pm$
$e^+e^- \to L^+L^-$	$L^+ \to \nu W$	jets, $\ell^\pm + \not{E}$
$e^+e^- \to \ell^{*+}\ell^{(*)-}$	$\ell^{*+} \to \ell^+\gamma$	$\ell^+\ell^-\gamma(\gamma)$
$e^+e^- \to \nu^*\bar{\nu}^*$	$\nu^* \to \nu\gamma$	$\gamma(\gamma) + \not{E}$
$e^+e^- \to \ell^*\ell, \nu^*\nu$	$\ell^* \to \ell Z$	jets, $\ell^\pm$, ν

Conclusions

- LEP ran spectacularly $\sqrt{s} \sim$ 200–209 GeV in 2000
- Small in the Standard Model Higgs Search at 115 GeV
  $\sim 2\,\sigma$
- Many other searches conducted
  No current significant excesses
  ... but data still to be analyzed!
- LEP is **OFF**
- For a light Higgs:
  Tevatron has some chance by $\sim$ 2007
  LHC will see it $\sim$ 2007
- Heavier higgs:
  LHC

Discovery of particles beyond the Standard Model?

Large Hadron Collider $\sim$ 2006++

Measurements of their properties??

$\sim$ LHC 2008+ / TESLA (2012??)