Higgs and New Particle Searches at LEP

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and

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- Standard Model *sketch*

  $\longrightarrow$Especially the SM Higgs boson

- The LEP Collider
- 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

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

$$B$$

$\Downarrow$ ~~EW~~

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

Papers by and about Higgs

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BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
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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, 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 $2\varphi_0^2 V''(\varphi_0^2)^{1/2}$; 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

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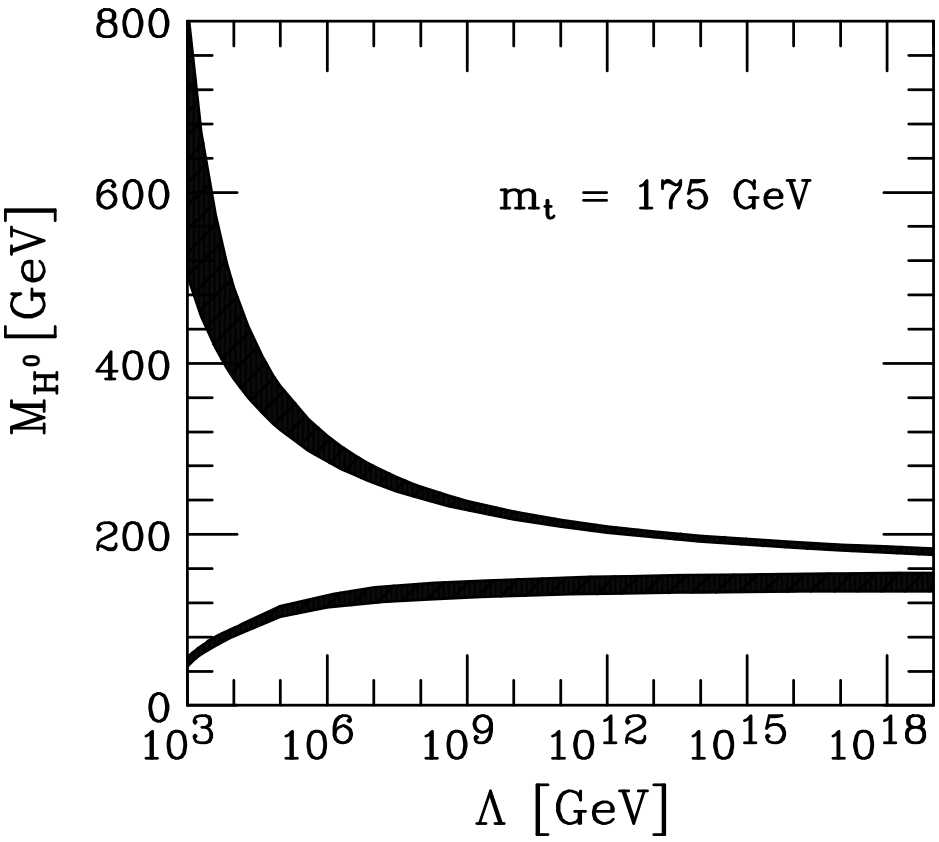
Theoretical Constraints on M_{H^0}

- M_{H^0} Theoretically constrained

  Max: Perturbativity

  Min: Vacuum Stability

- Depend on theory cutoff scale Λ



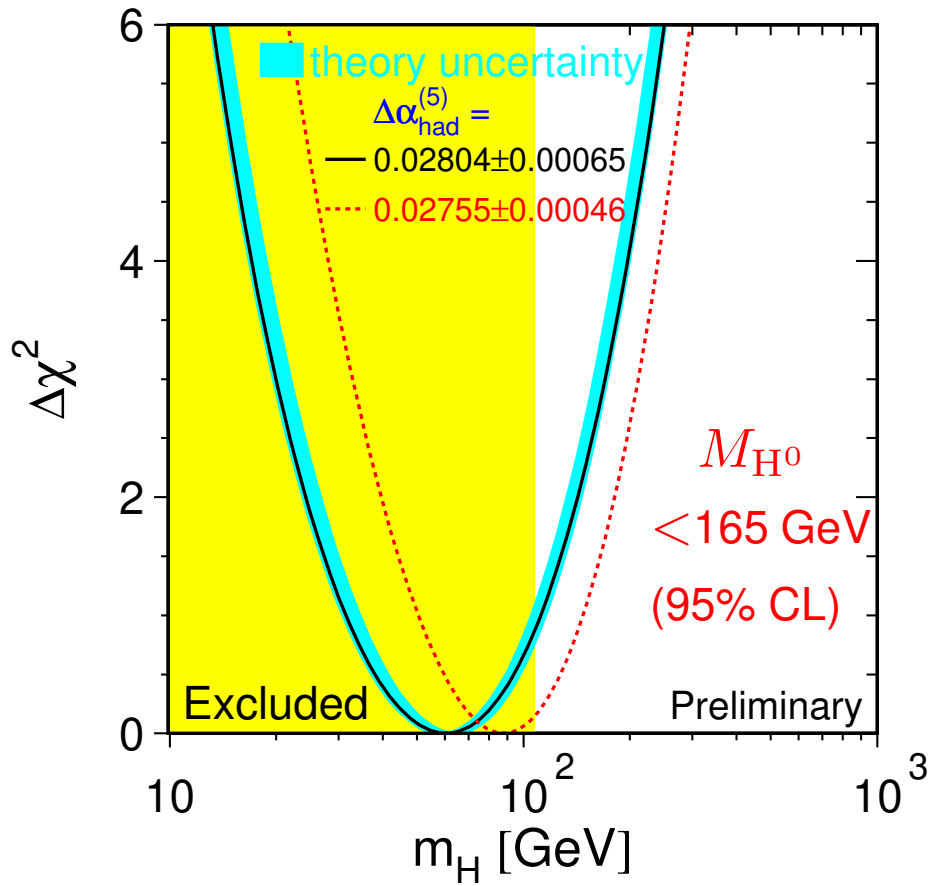
eg. If $\Lambda = M_{Pl} \approx 10^{19}$ GeV:

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

Experimental Constraints on M_{H^0}

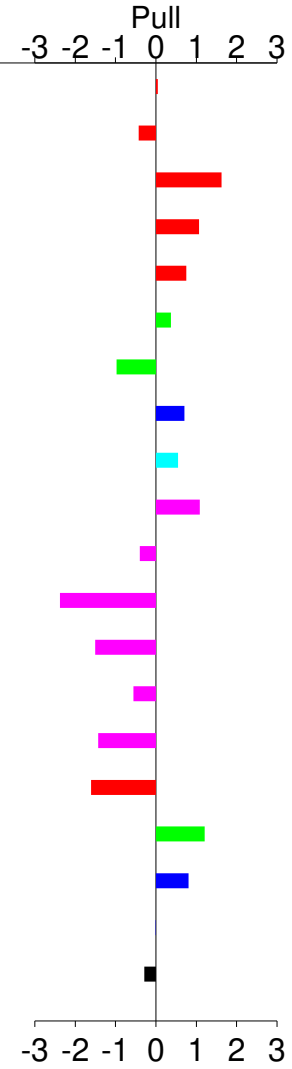
- H^0 enters into loops
- Global fits to precision EW data

  M_{H^0} only unconstrained parameter

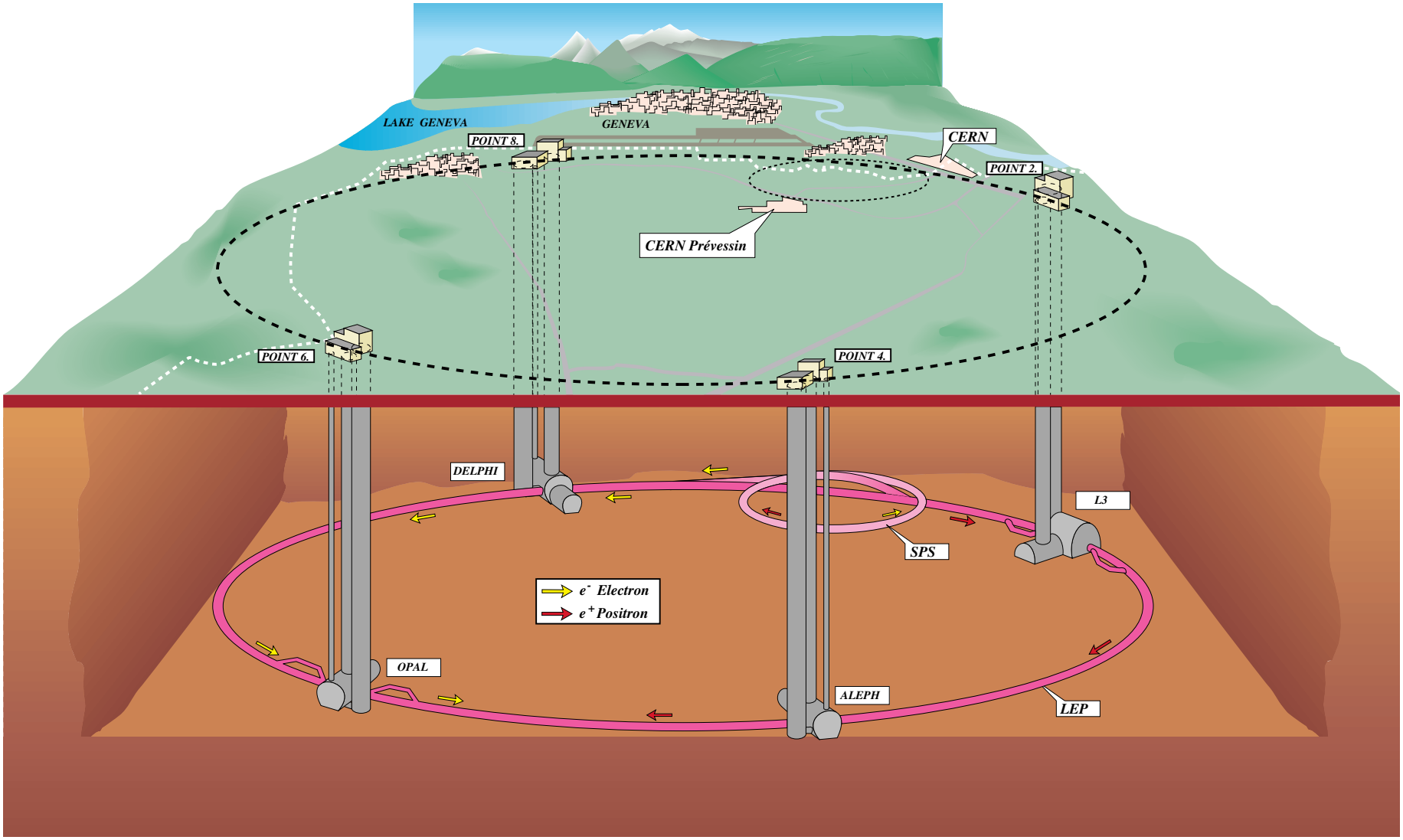


Osaka 2000

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.07
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.75
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.70
m_W [GeV]	80.427 ± 0.046	.55
R_b	0.21653 ± 0.00069	1.09
R_c	0.1709 ± 0.0034	-.40
$A^{0,b}_{fb}$	0.0990 ± 0.0020	-2.38
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.51
A_b	0.922 ± 0.023	-.55
A_c	0.631 ± 0.026	-1.43
$\sin^2\theta^{lept}_{eff}$	0.23098 ± 0.00026	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.81
m_t [GeV]	174.3 ± 5.1	-.01
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.29

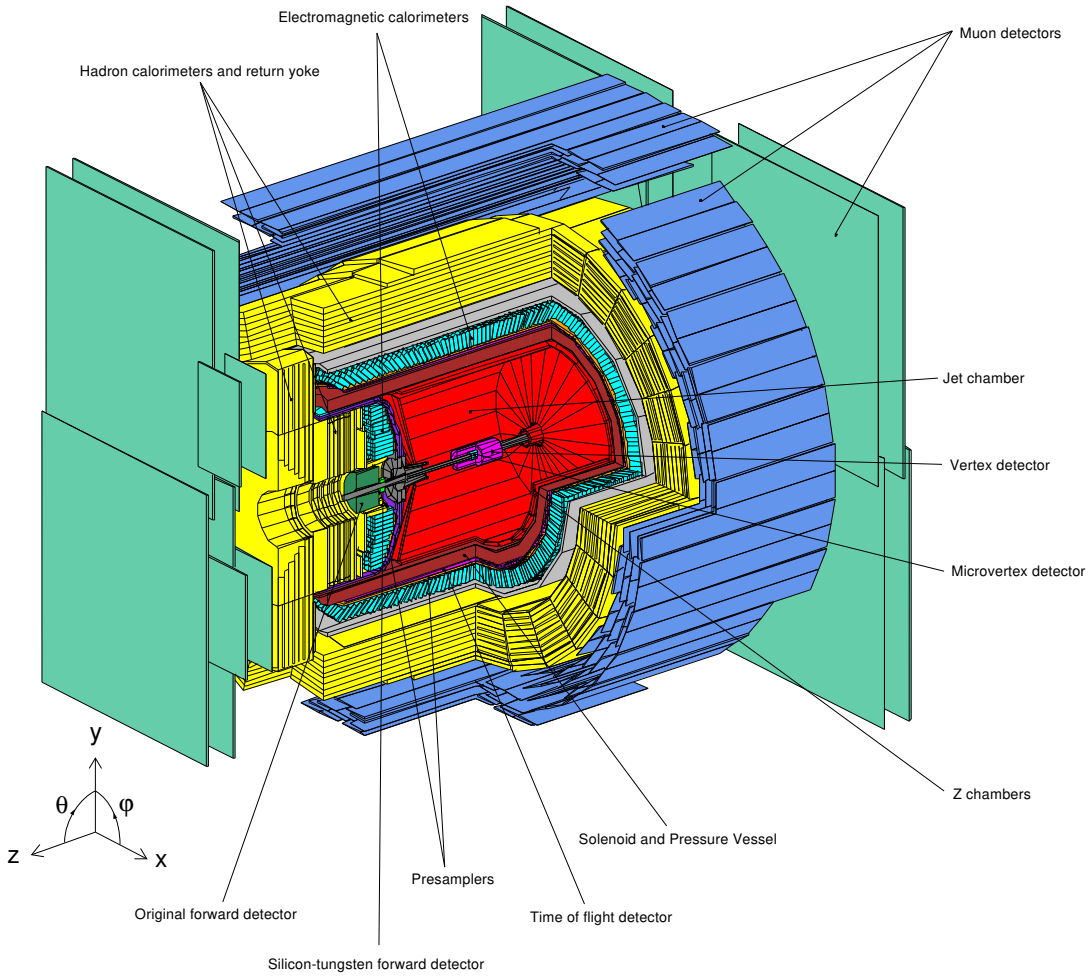


The LEP e^+e^- Collider



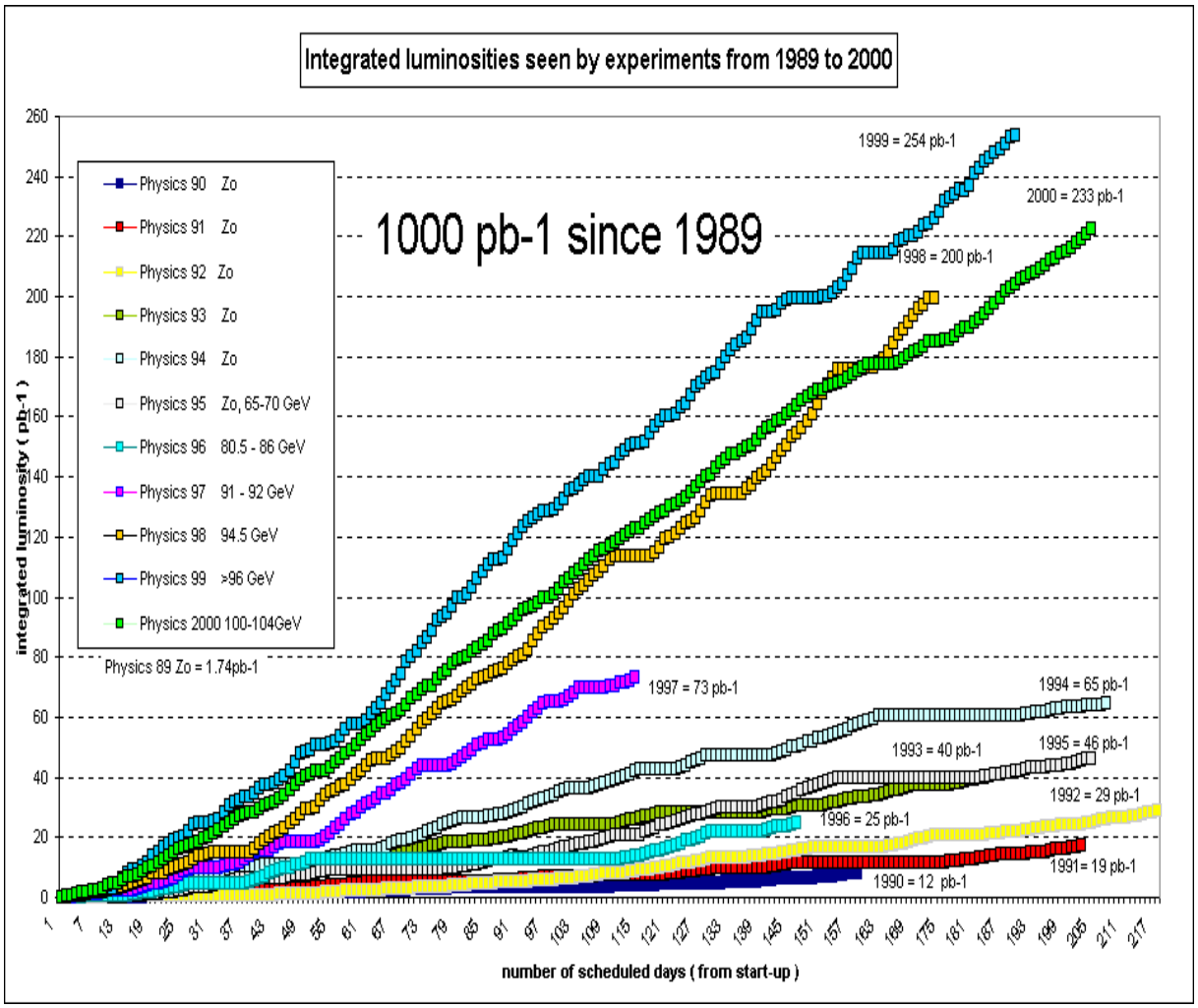
Typical LEP Detector

- 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}

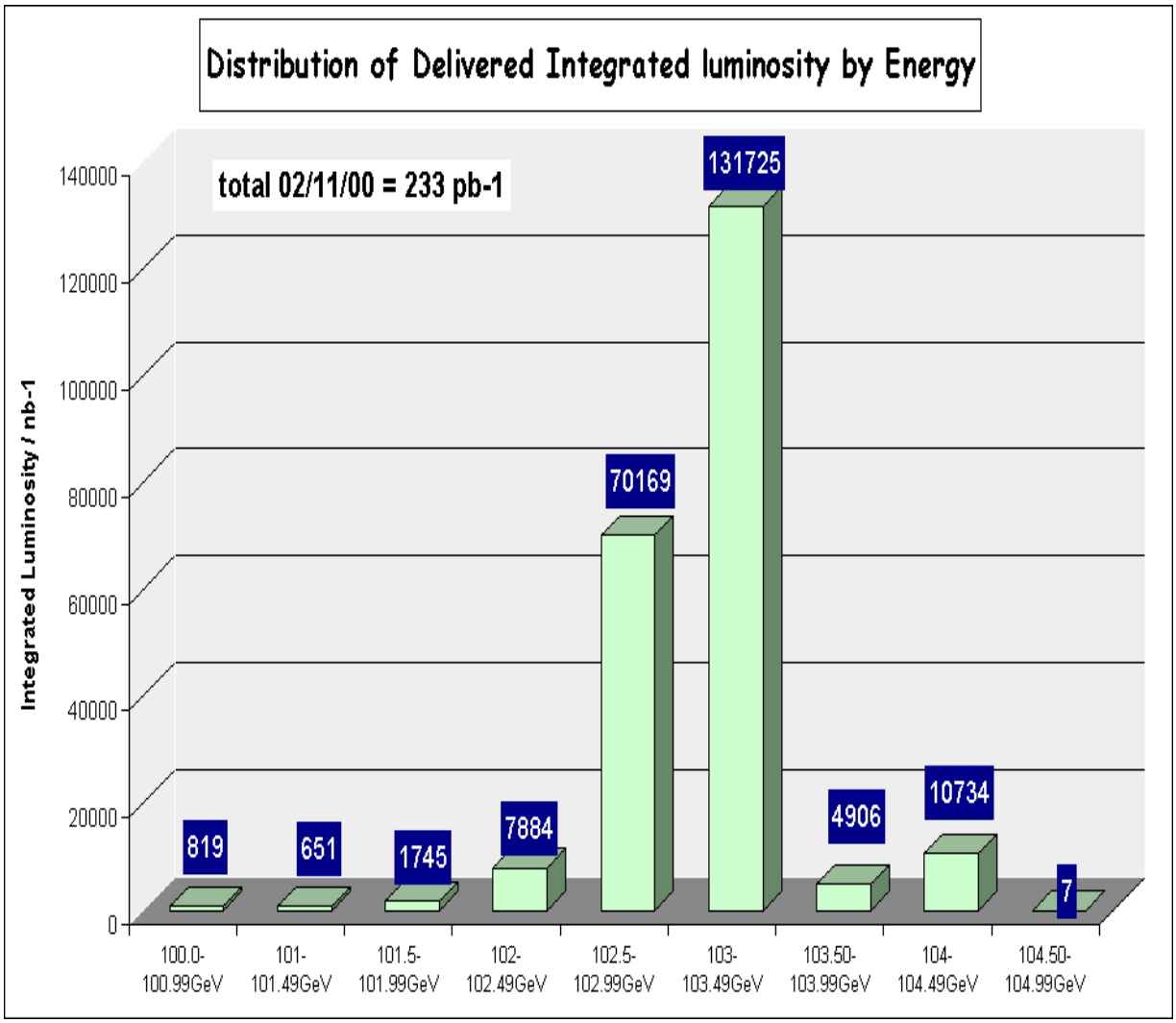


LEP's Final Year: Y2K

- New Emphasis

  Energy over **Luminosity**

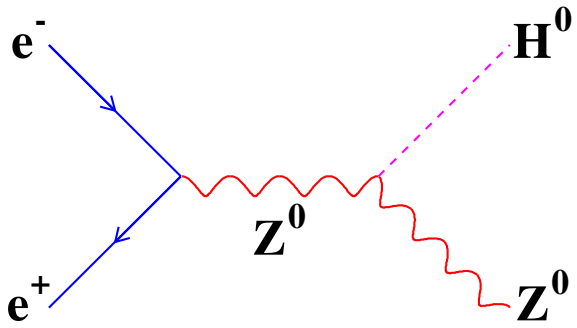
- Used *mini-ramps* to increase energy as beam current decreases



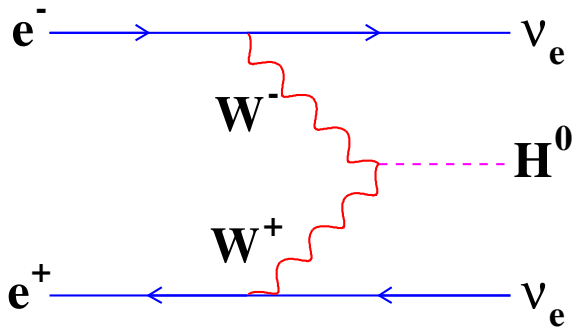
Standard Model Higgs Production

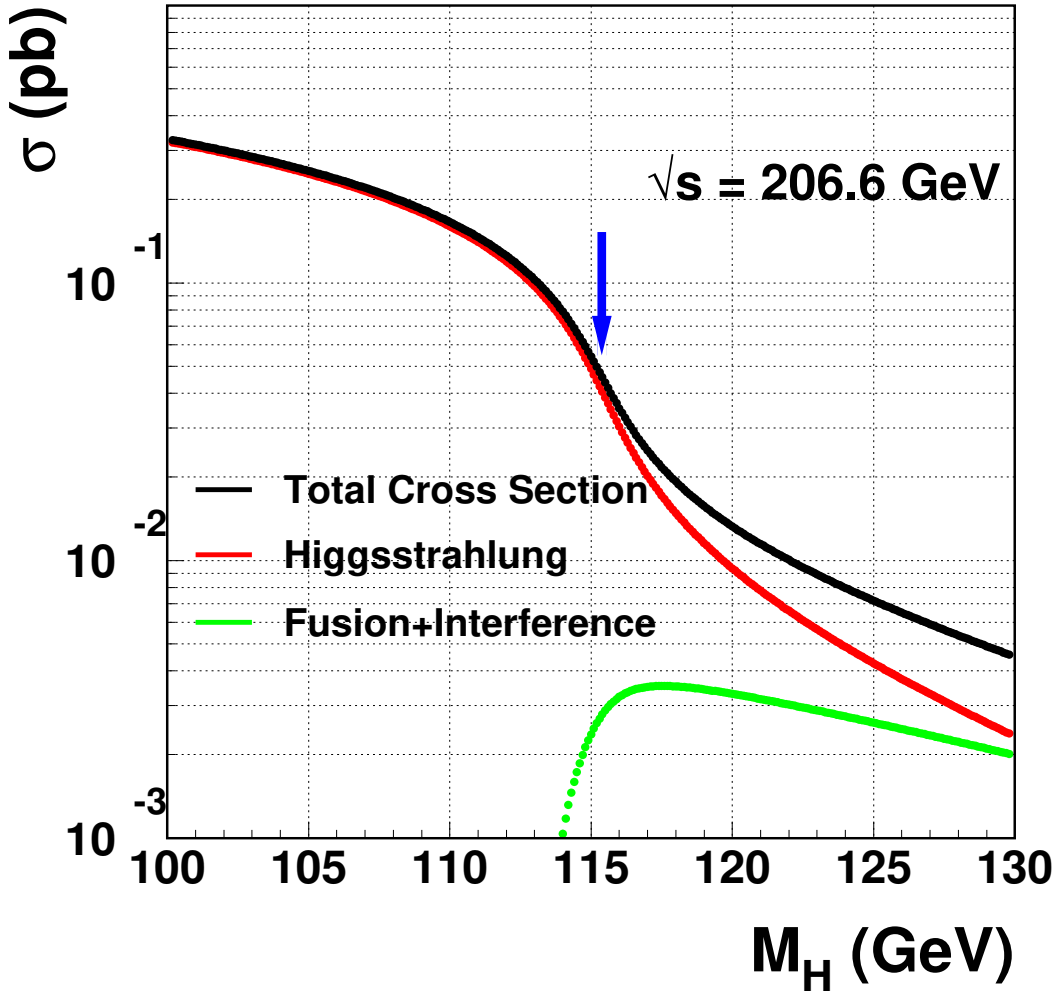
Production

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



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

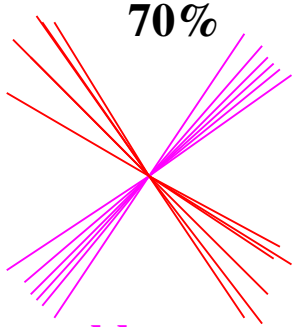




Standard Model Higgs Topologies

4 Jet

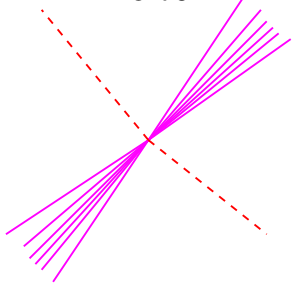
70%



bb qq

Missing Energy

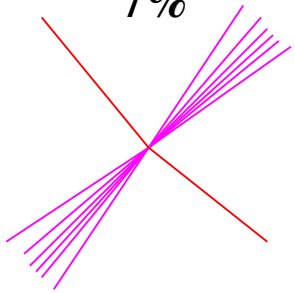
20%



bb νν

Lepton (e/μ)

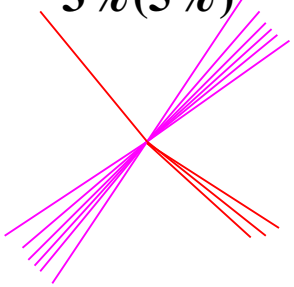
7%



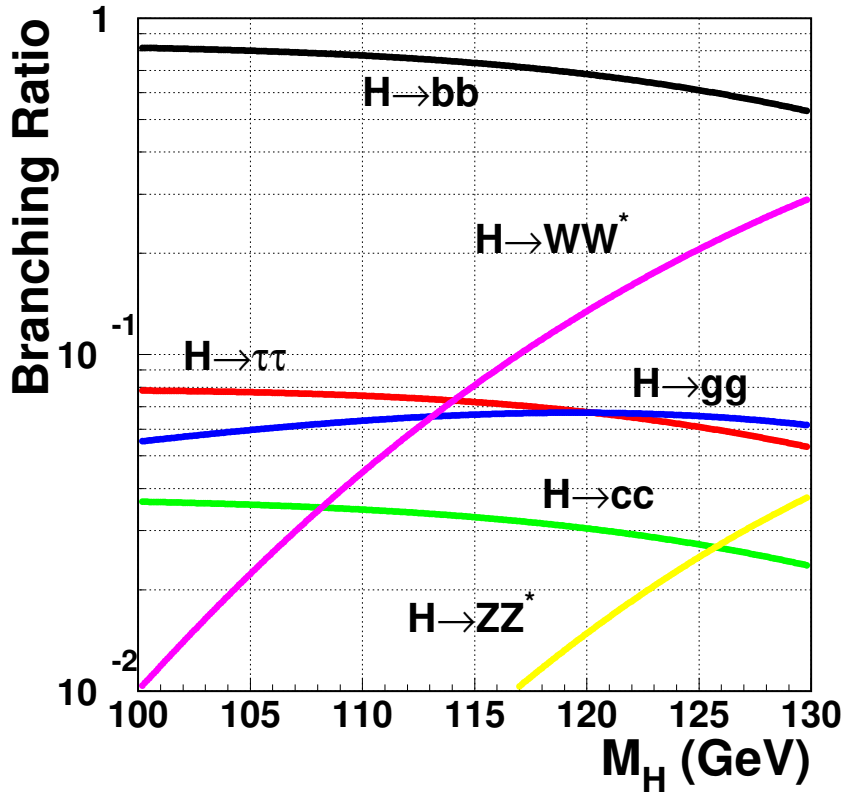
bb ll

Tau

3%(5%)

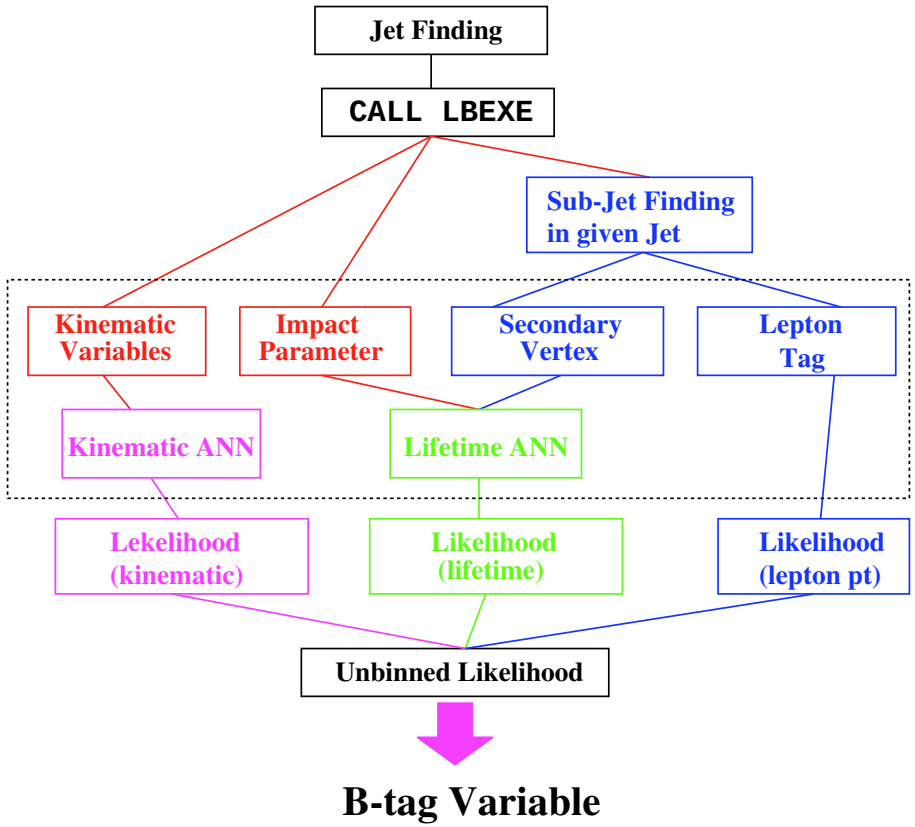


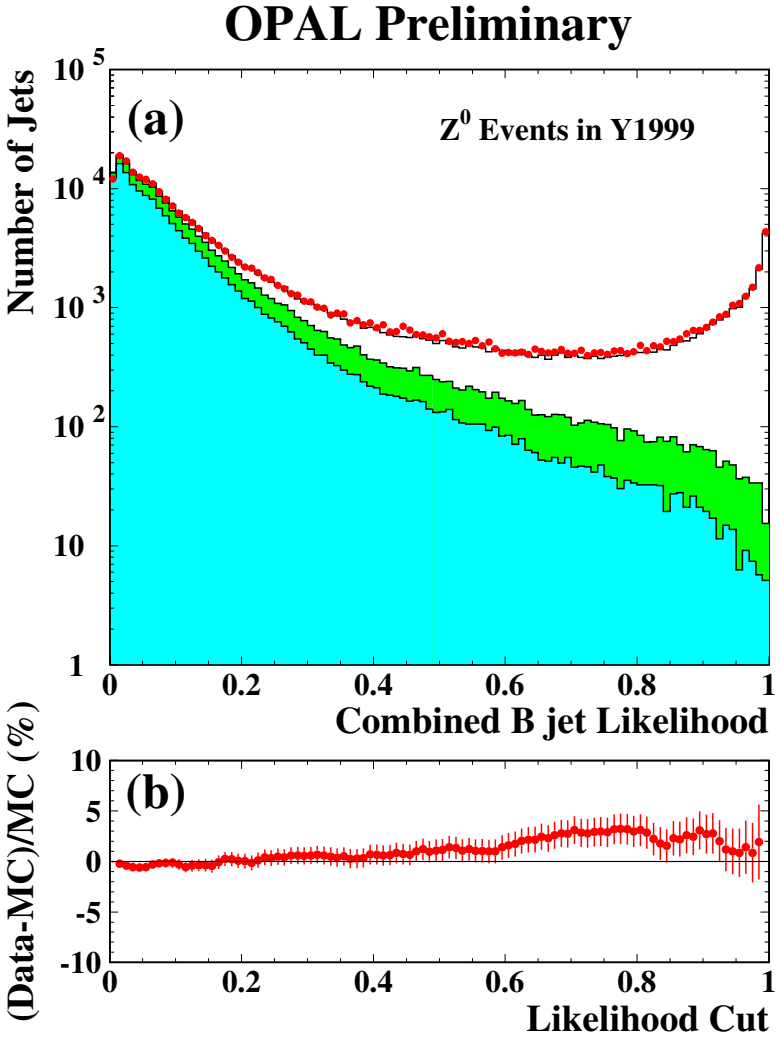
bbττ or ττqq



- Key to analysis: b-tagging -

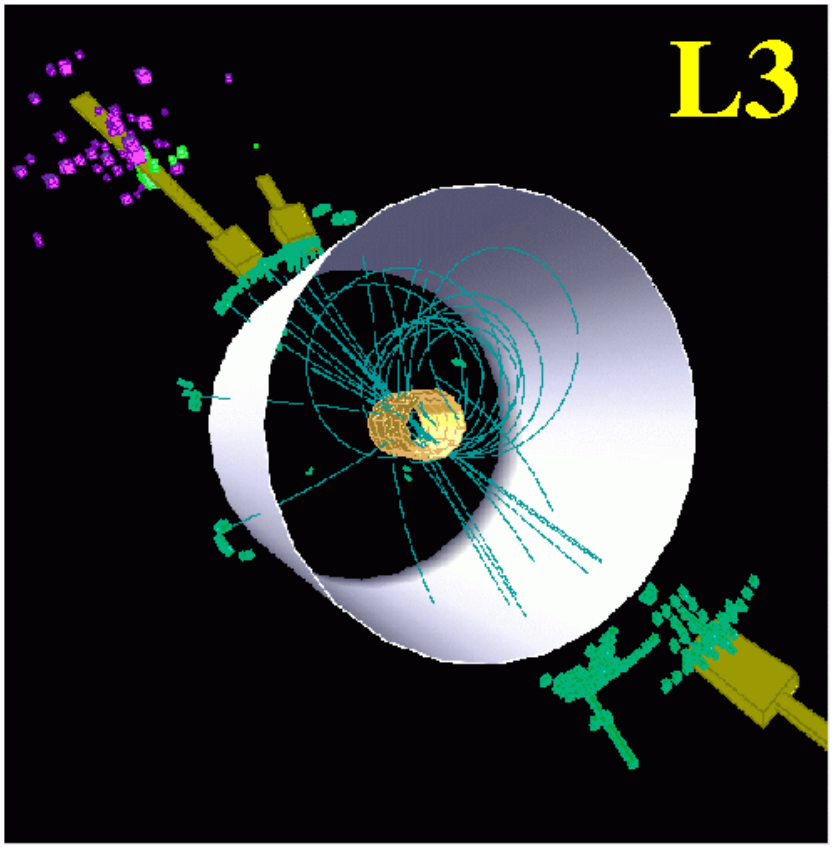
Example: higgs b-Tagging in OPAL





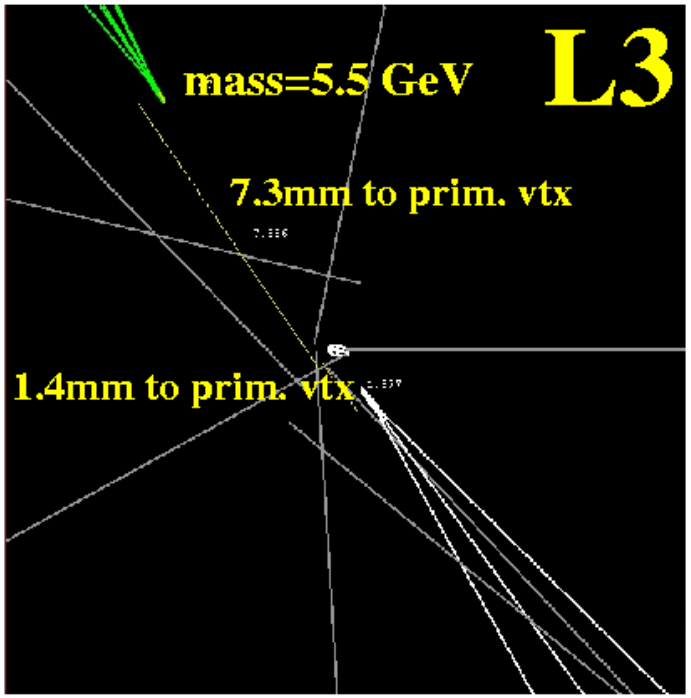
L3: Higgs Candidate

most significant Hνν candidate

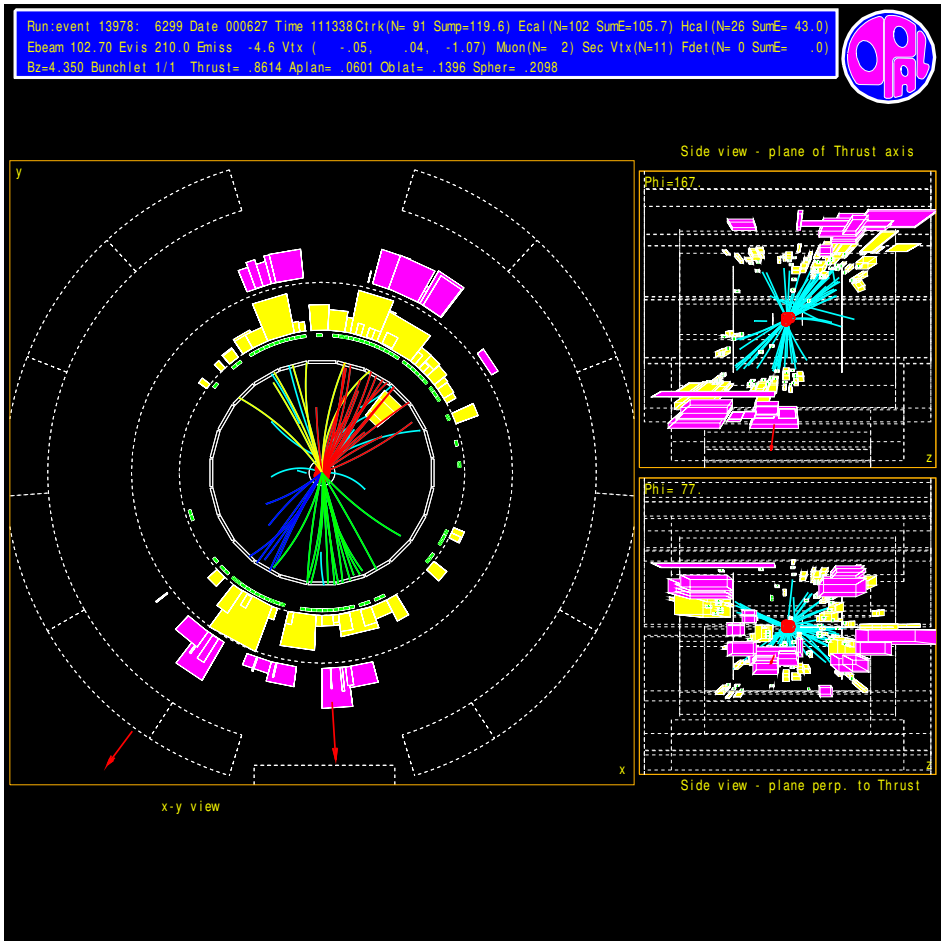


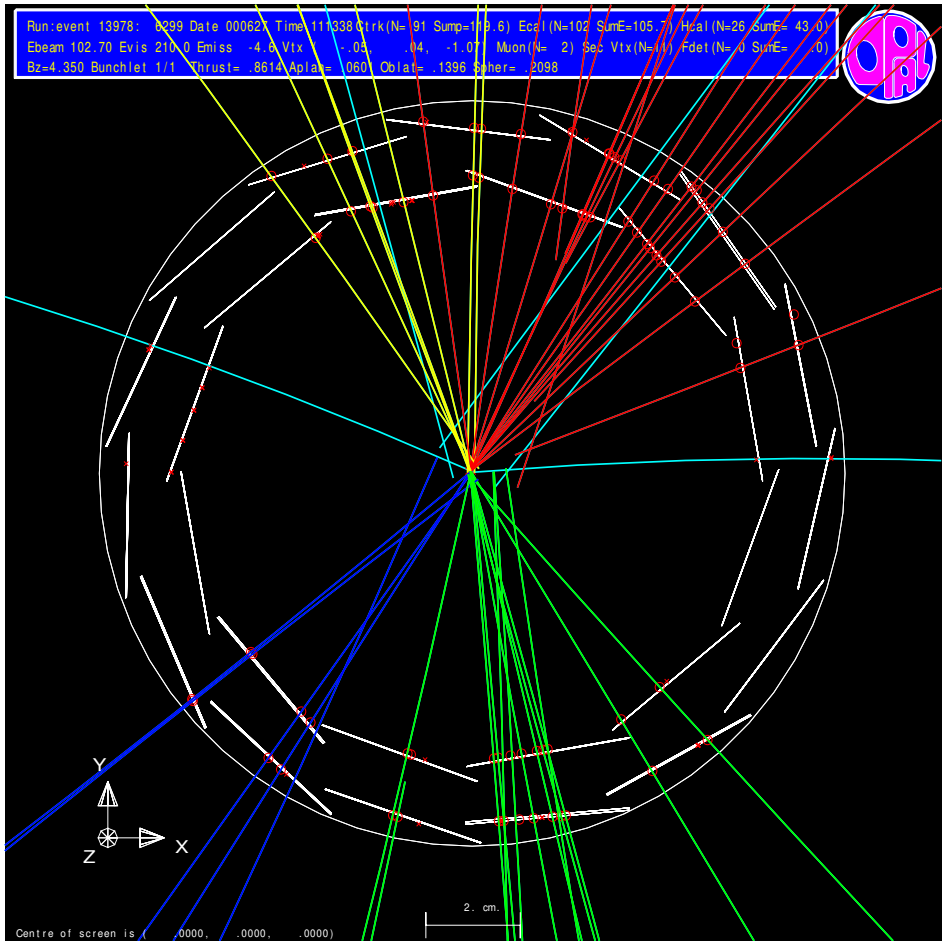
measured H mass=114.4 GeV
H mass resolution ~3 GeV

Secondary vtx's view



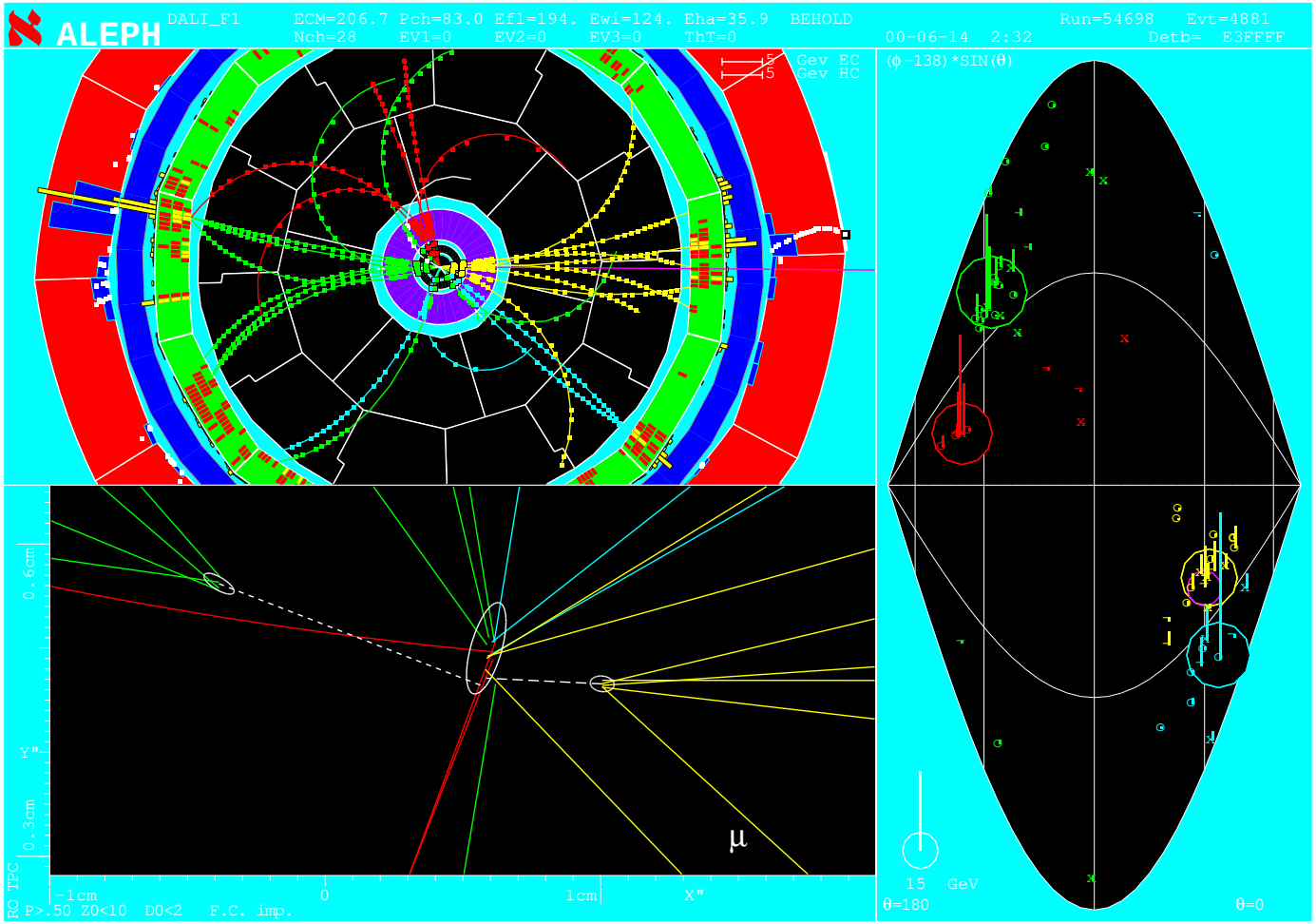
OPAL: Higgs Candidate





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

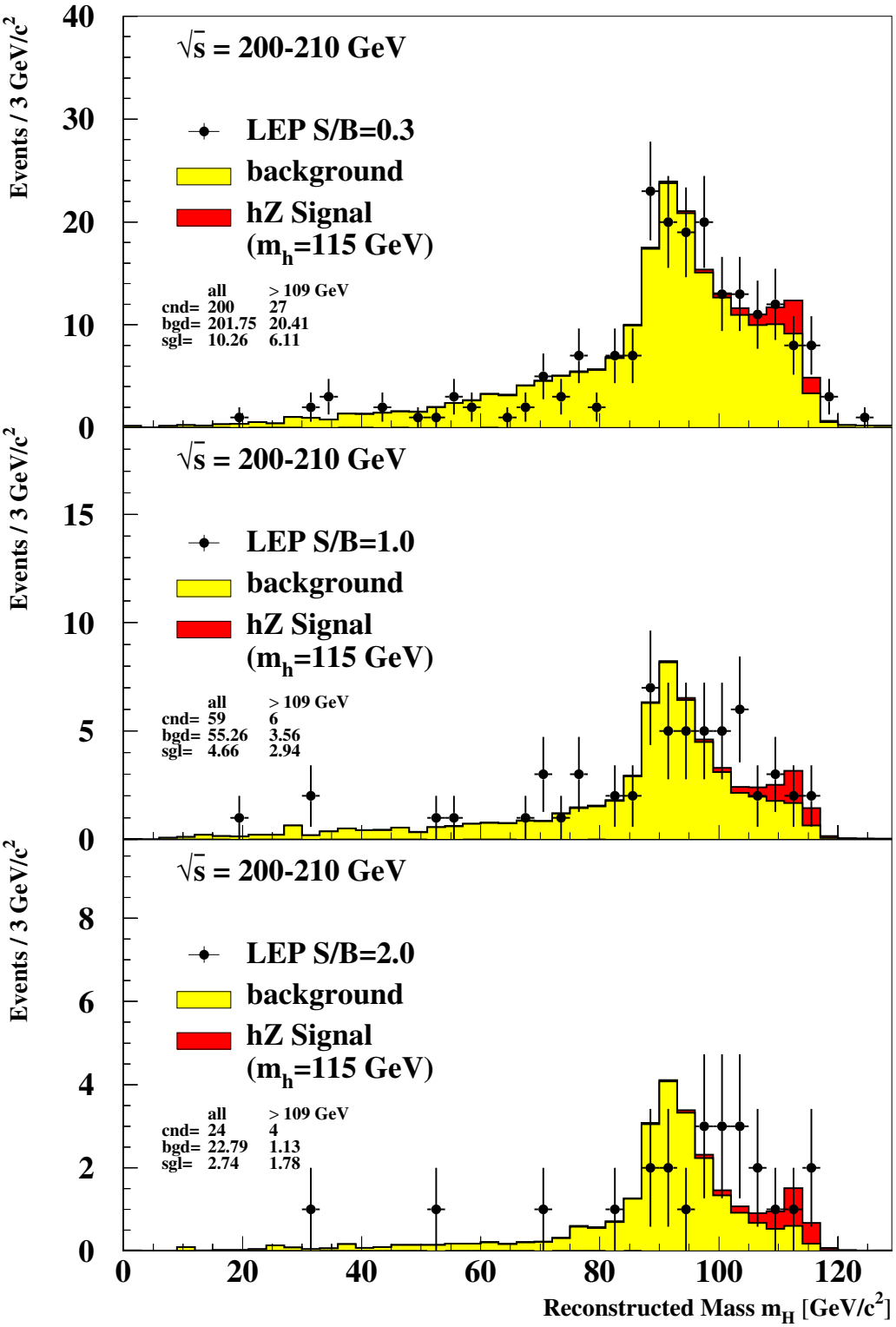
ALEPH: Higgs Candidate



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



$\Rightarrow$ $M_{\mathrm{H}^0}^{\mathrm{rec}}$ not the whole story

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:

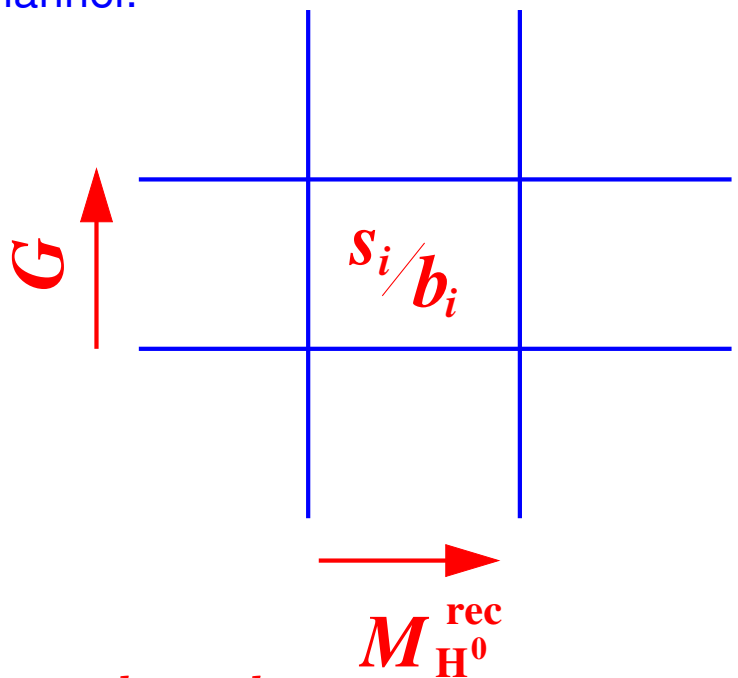
$M_{\rm H^0}^{\rm rec}$: Reconstructed Higgs Mass

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:

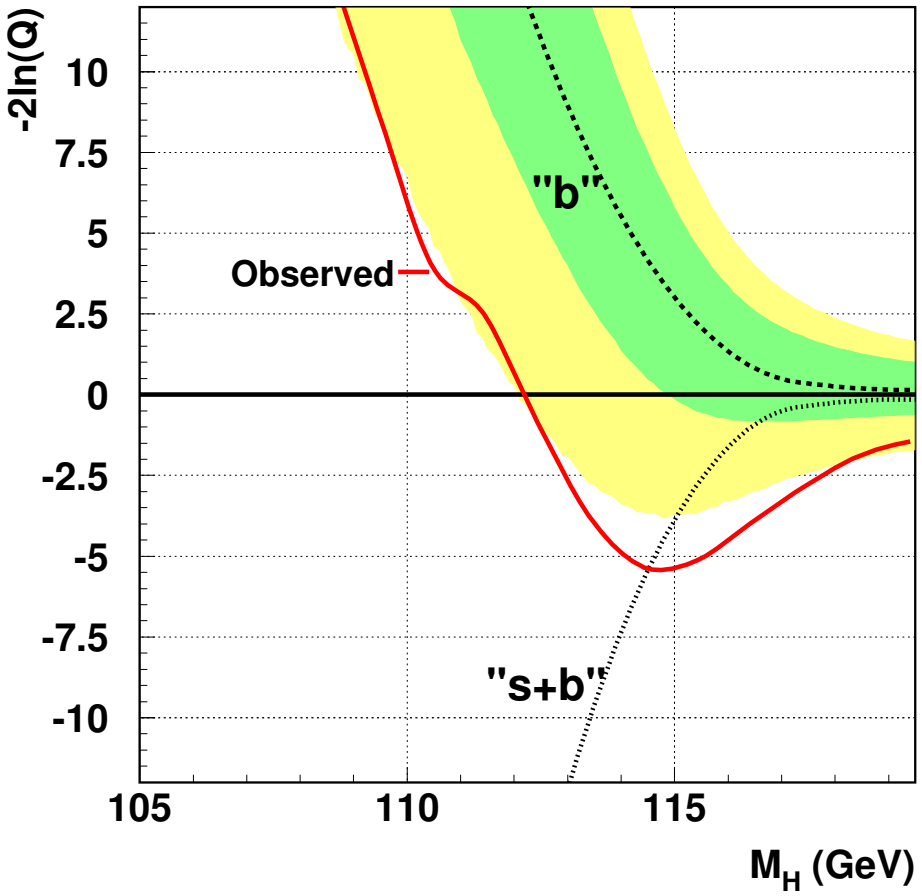
Set of all events $\Rightarrow$ "$s+b$" or "b"?

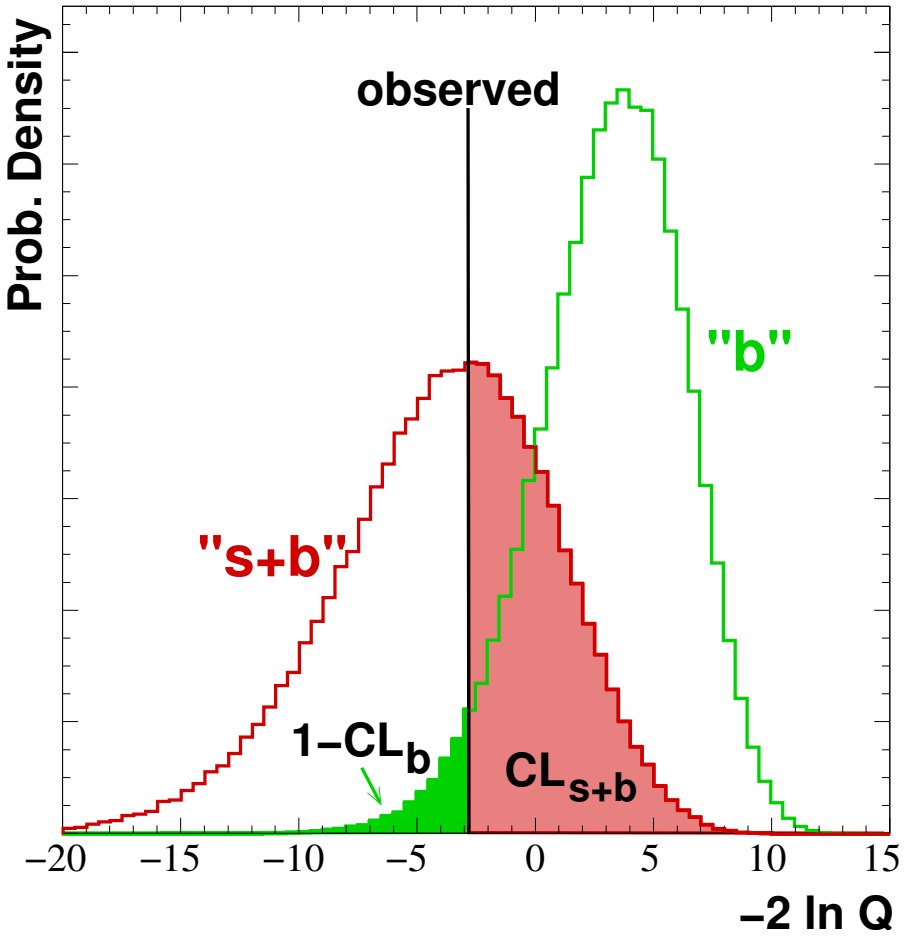
Use *Likelihood Ratio*:

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

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

Statistics cont.

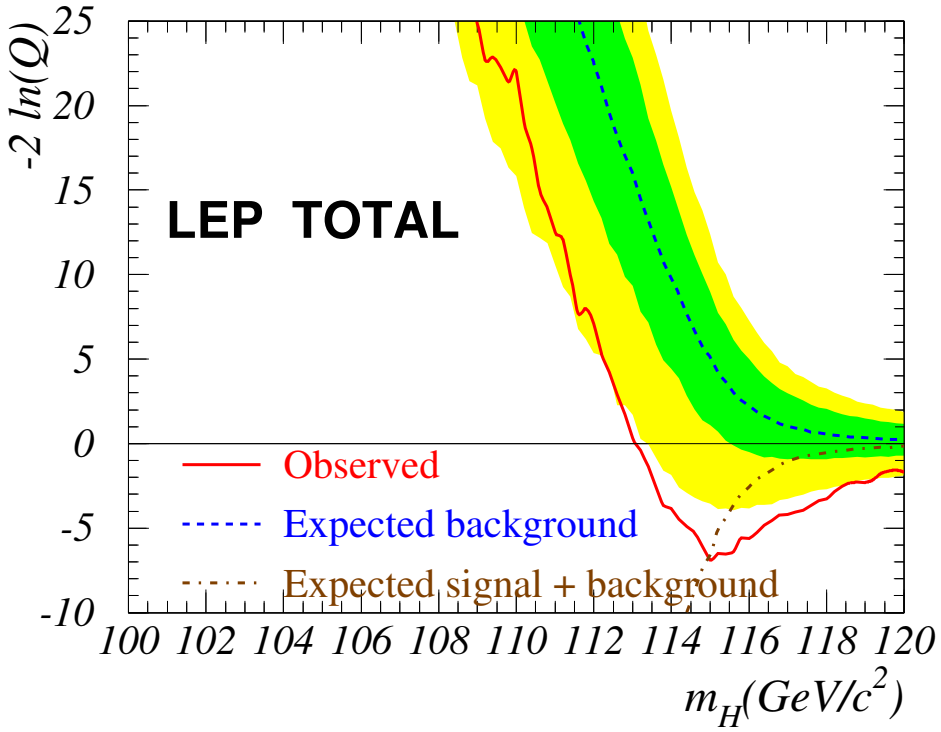


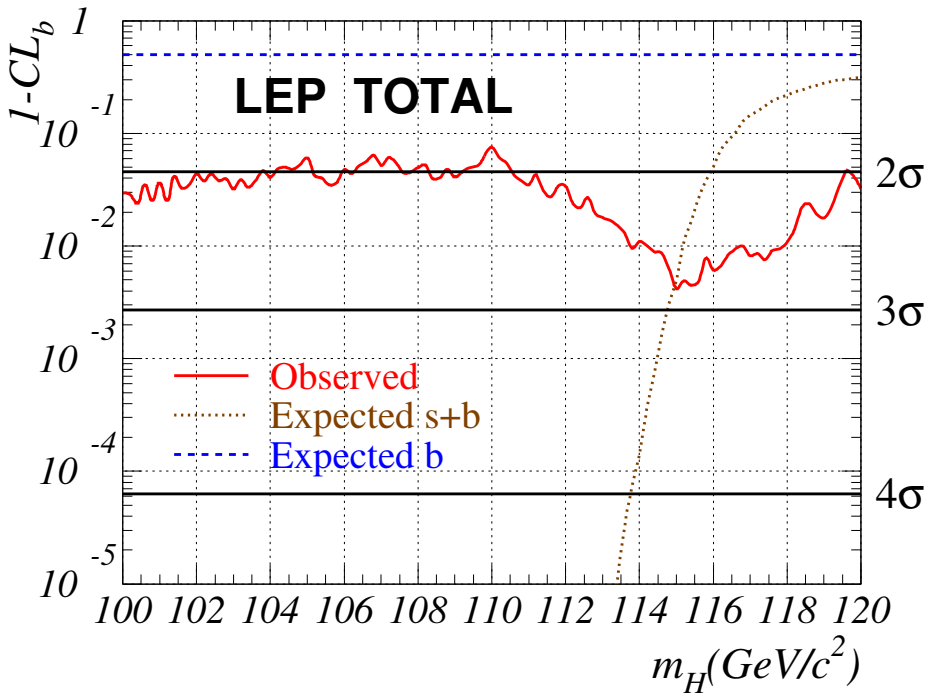


$1 - \mathrm{CL_b} = 1 - \mathrm{Prob}(\text{“}b\text{”})$

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

LEP Results

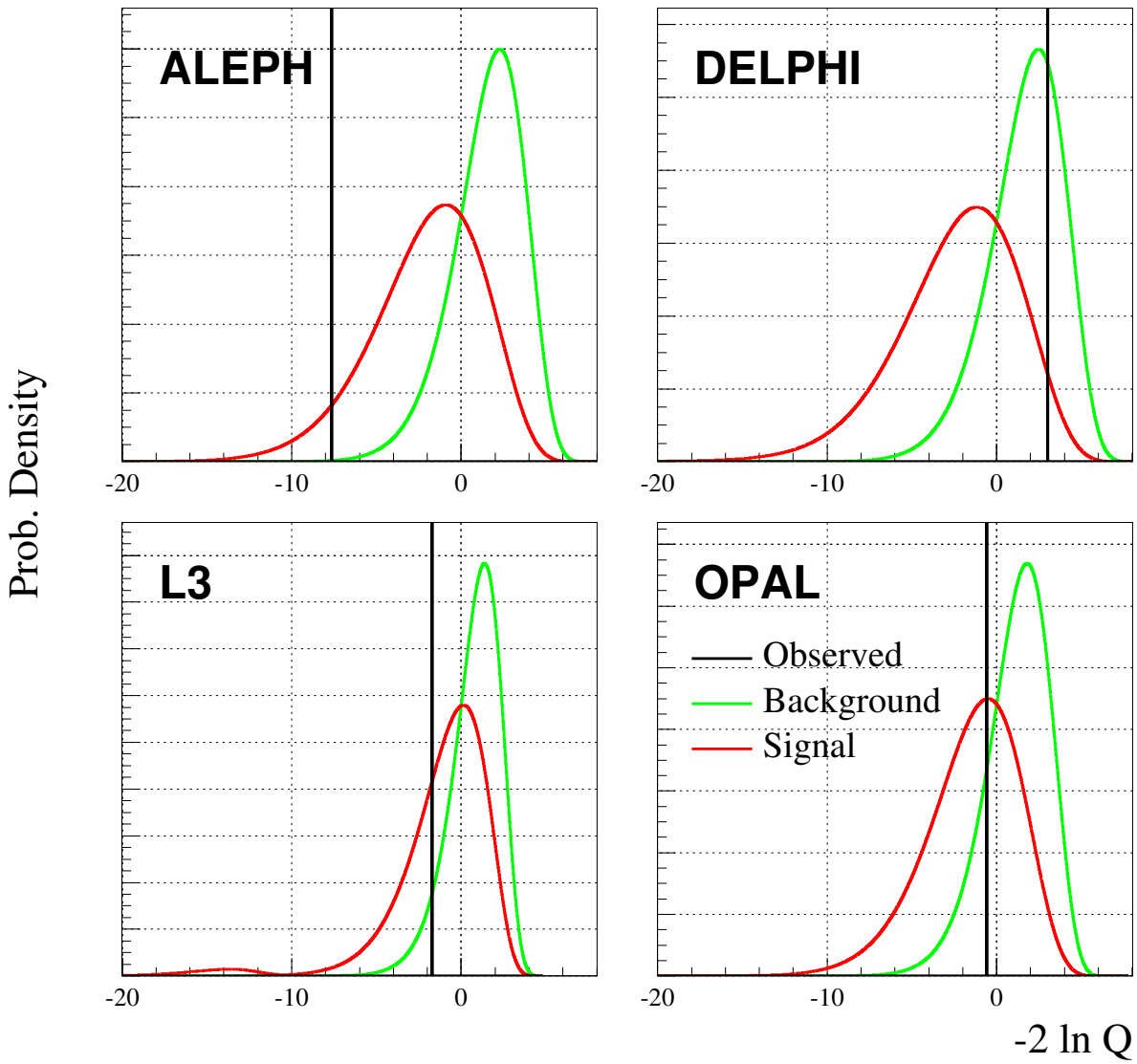




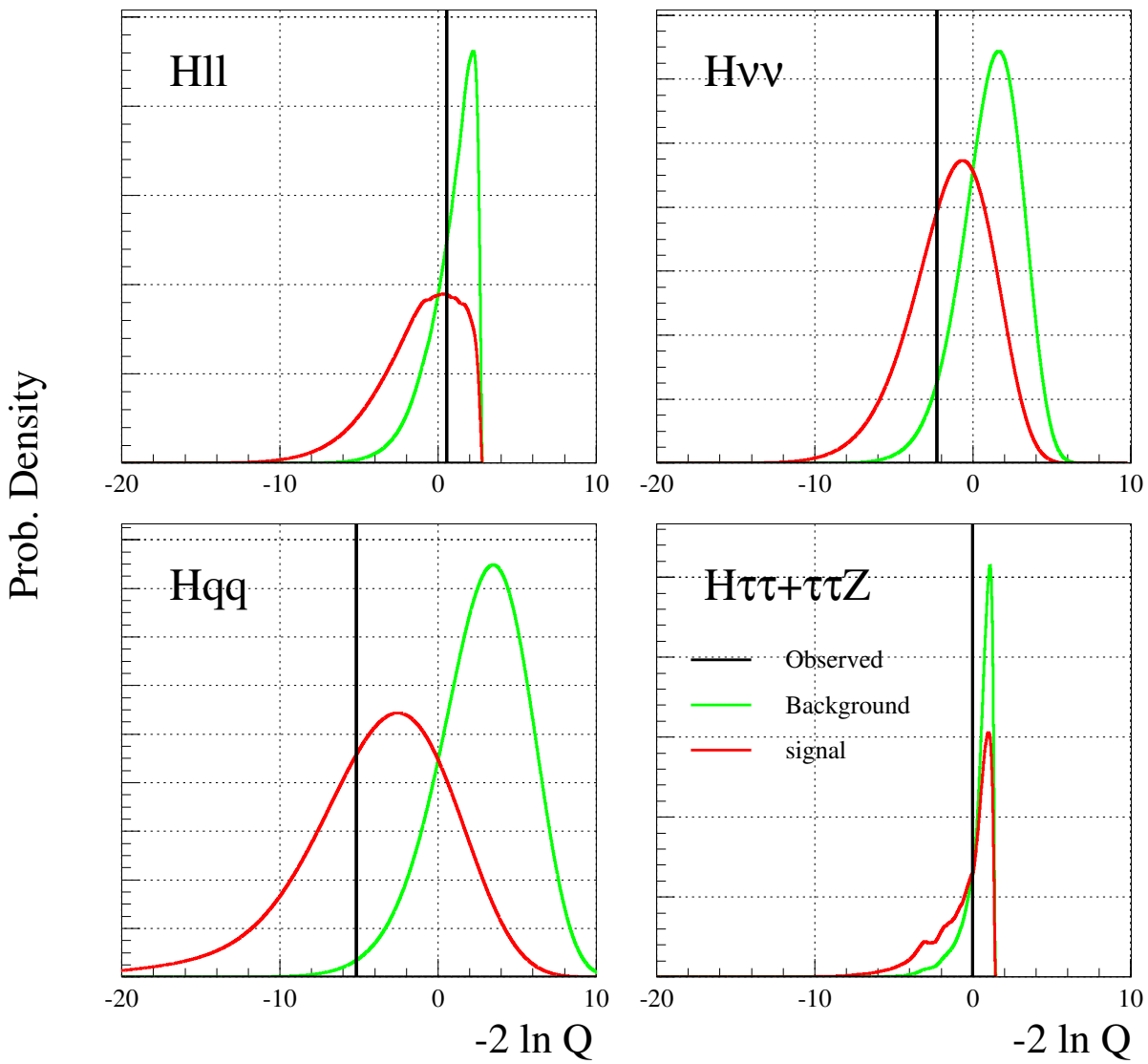
$M_{\mathrm{H^0}} = 115.0^{+1.3}_{-0.9}$ GeV

$1 - \mathrm{CL_b} = 2.9\sigma$

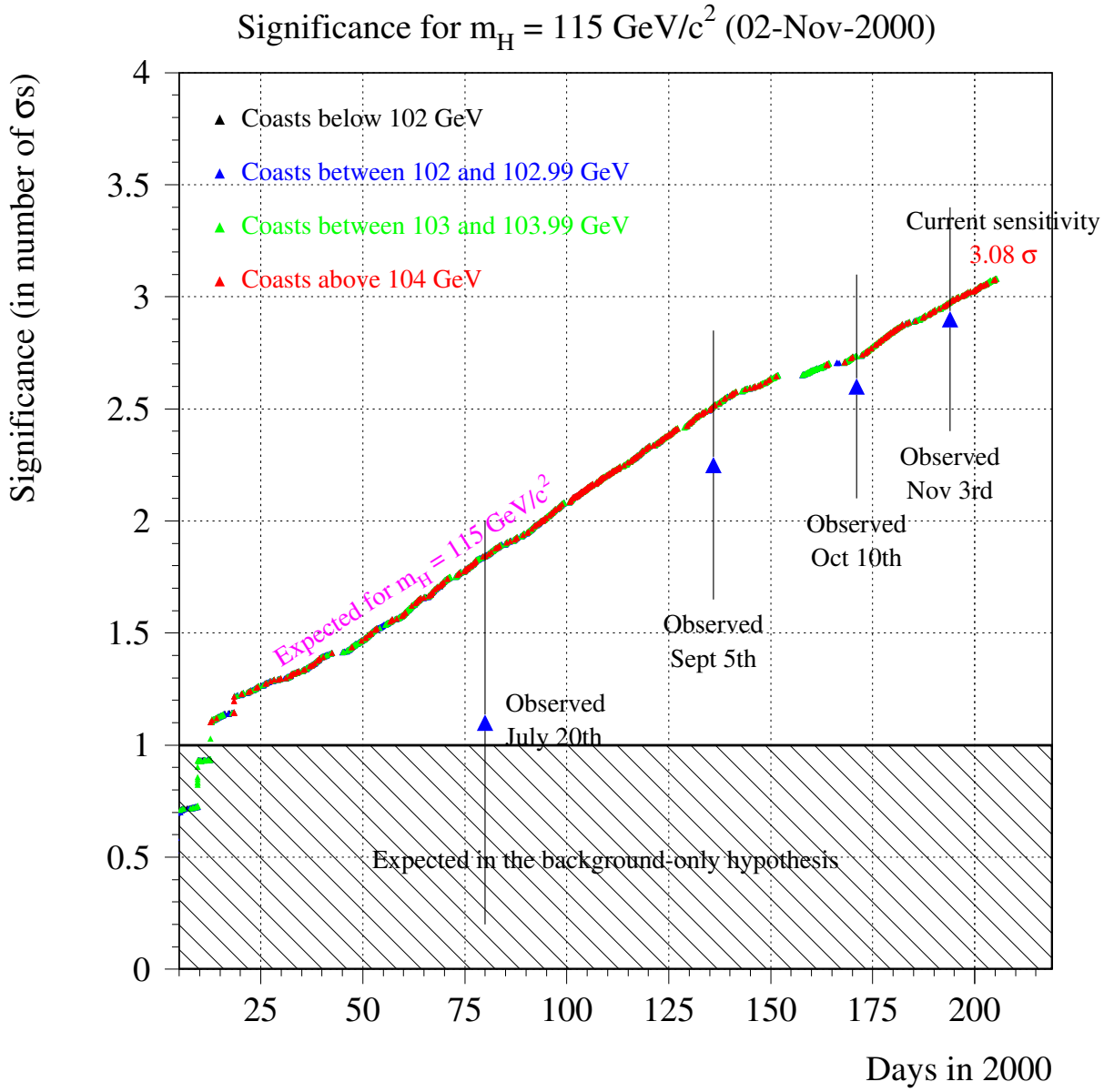
M_{H^0} = 115 GeV: ADLO?



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



Evolution with Luminosity



- With another 200 pb^{-1} with $E_{\rm cm} = 208$ GeV in 2001

  $\Rightarrow$ Expected 5σ

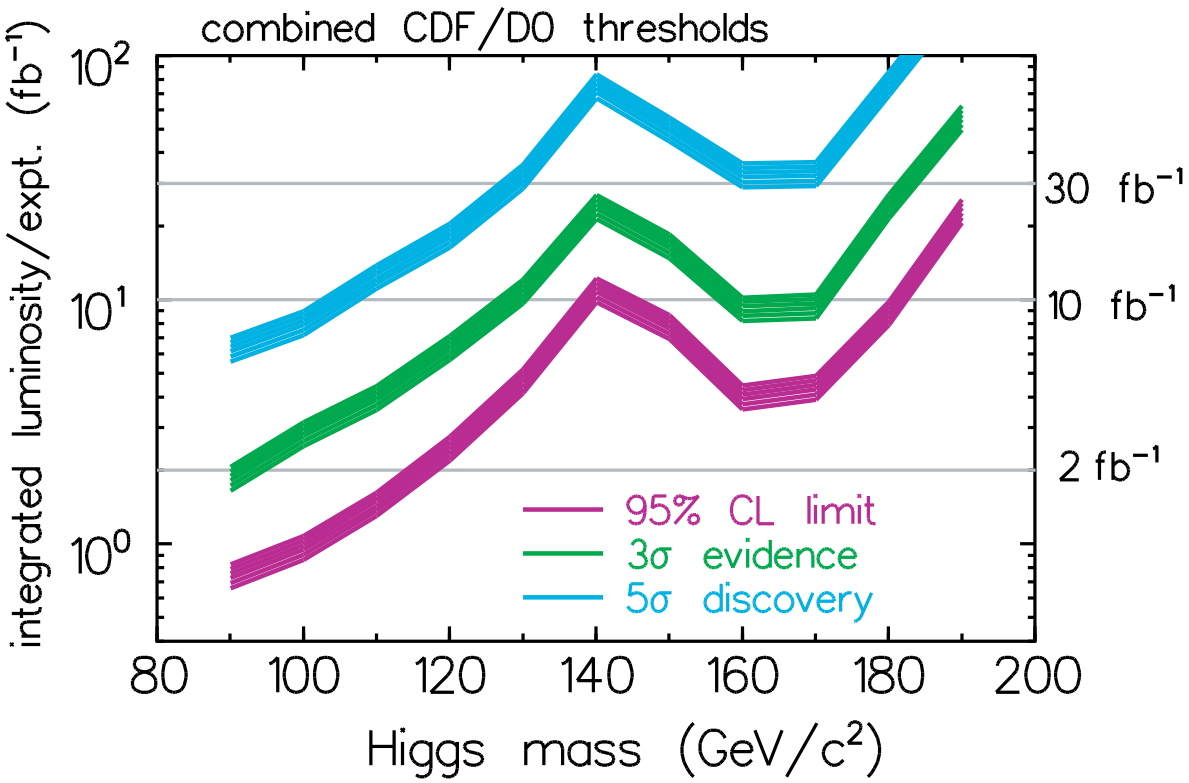
- But LEP is being **dismantled**

  (to install the LHC in the same tunnel)

- When will we know?

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

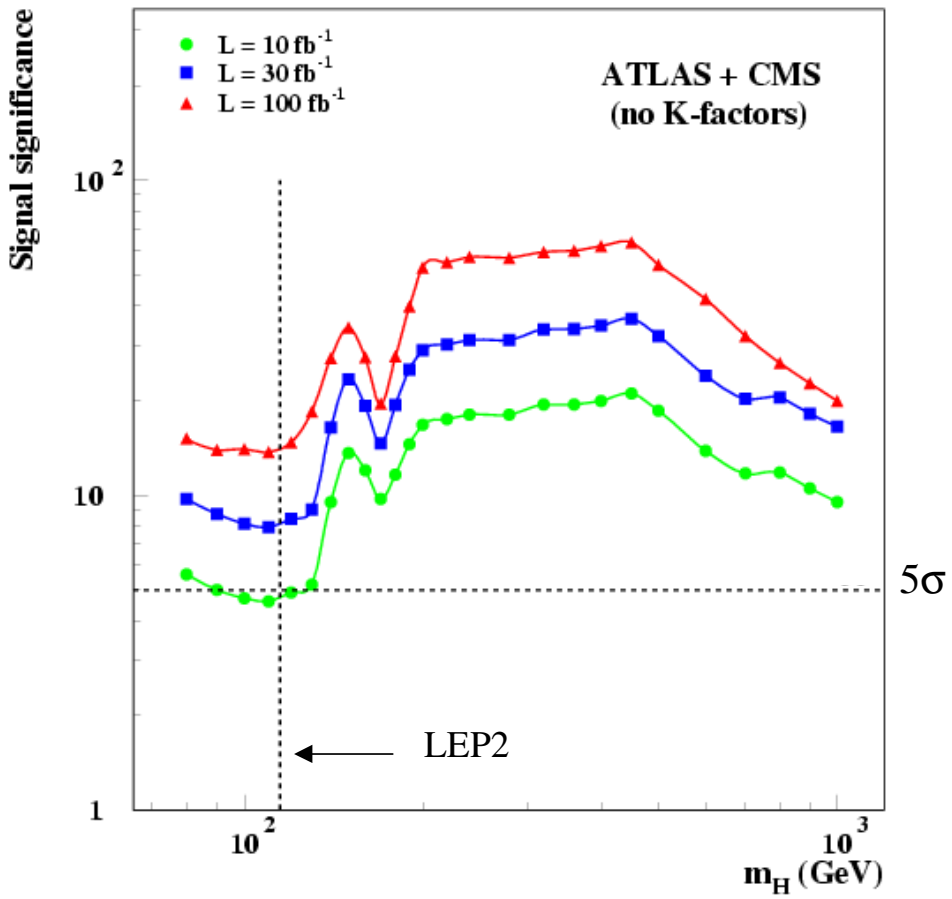
Tevatron Plans:

- 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

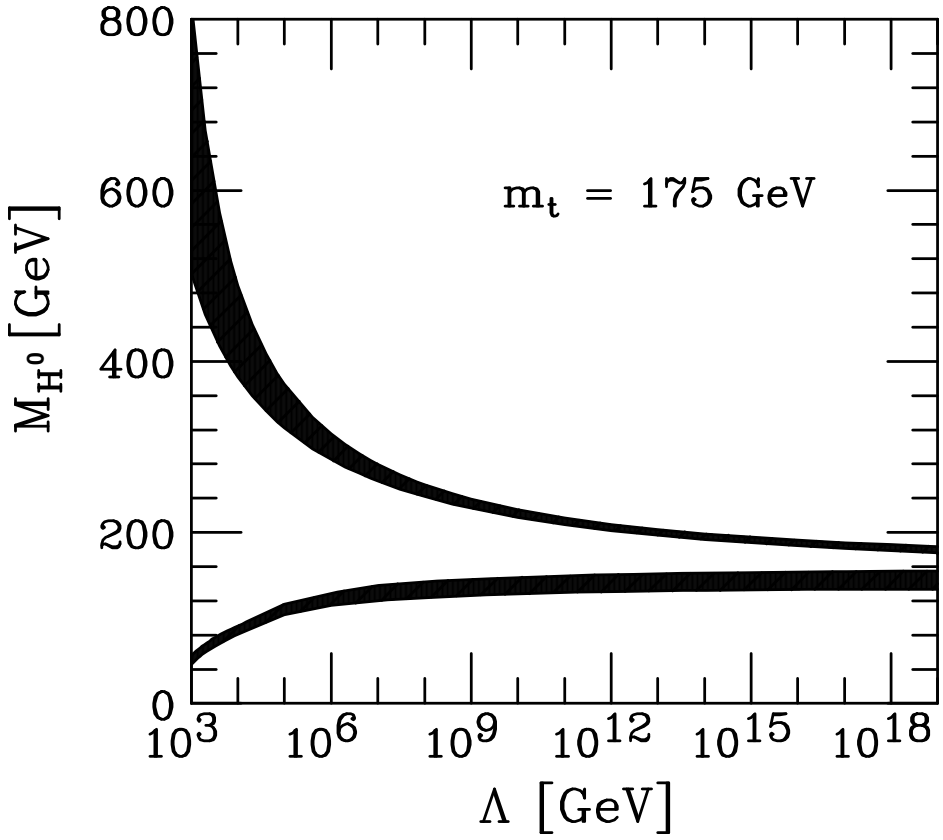
Will see it near beginning of program

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

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

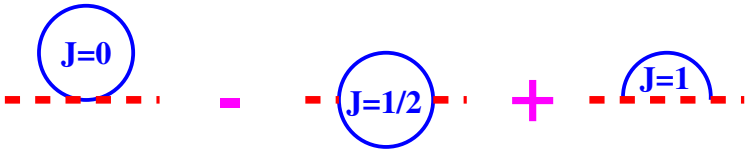
$\Lambda < 10^6$ GeV

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



Fine tuning problem:

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



Roadmap Beyond the Standard Model

$\{ W_1\ W_2\ W_3 \}$ $\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$

B

EW

$\begin{pmatrix} \upsilon_e \\ e \end{pmatrix}$ $\begin{pmatrix} \upsilon_\mu \\ \mu \end{pmatrix}$ $\begin{pmatrix} \upsilon_\tau \\ \tau \end{pmatrix}$

MORE?

$\begin{pmatrix} t' \\ b' \end{pmatrix}$ $\begin{pmatrix} \upsilon_L \\ L \end{pmatrix}$

composite?

$\begin{pmatrix} q^*_{2/3} \\ q^*_{1/3} \end{pmatrix}$ $\begin{pmatrix} \upsilon^*_l \\ l^* \end{pmatrix}$

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

Hierarchy Problem

~~SUSY~~ Minimal ⇒ MSSM FCNC ⇒ SUGRA { STRINGY, $\tilde{\chi}^0$ CDM

GMSB { AVOID GRAVITY FCNC, ...

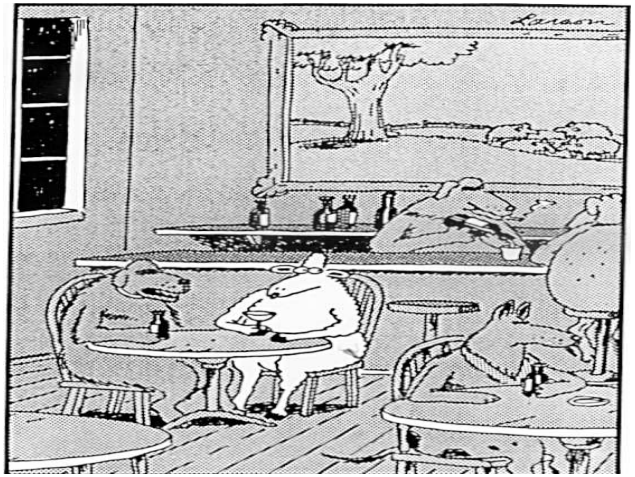
SUSY ⇒ $\tilde{W}^{+/-}\ \tilde{Z}^0\ \tilde{\gamma}$ $\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}$ $\begin{pmatrix} \tilde{c} \\ \tilde{s} \end{pmatrix}$ $\begin{pmatrix} \tilde{t} \\ \tilde{b} \end{pmatrix}$

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
	$\tilde{\ell}^{\pm}_{\mathrm{L,R}}$ } $\tilde{\ell}^{\pm}_{1,2}$	$\ell^{\pm}_{\mathrm{L,R}}$	
	$\tilde{\nu}_{\mathrm{L}}$	ν_{L}	
	$\tilde{\mathrm{q}}_{\mathrm{L,R}}$ }$\tilde{q}_{1,2}$	$\mathrm{q}_{\mathrm{L,R}}$	
		$\tilde{g}$	g
		$\tilde{\gamma}$	γ
	$\mathrm{h}^0, \mathrm{H}^0, \mathrm{A}^0$	$\tilde{\mathrm{h}}, \tilde{\mathrm{H}}$ } $\tilde{\chi}^0_{\mathrm{j}}$	
		$\tilde{\mathrm{Z}}^0$	Z^0
	$\mathrm{H}^{\pm}$	$\tilde{\mathrm{H}}^{\pm}$ } $\tilde{\chi}^{\pm}_{\mathrm{i}}$	
		$\tilde{\mathrm{W}}^{\pm}$	$\mathrm{W}^{\pm}$

"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}, μ	Higgs(ino) mass/mixing parameters
A_U, A_D, A_L,	Trilinear sfermion/higgs coupling matrices

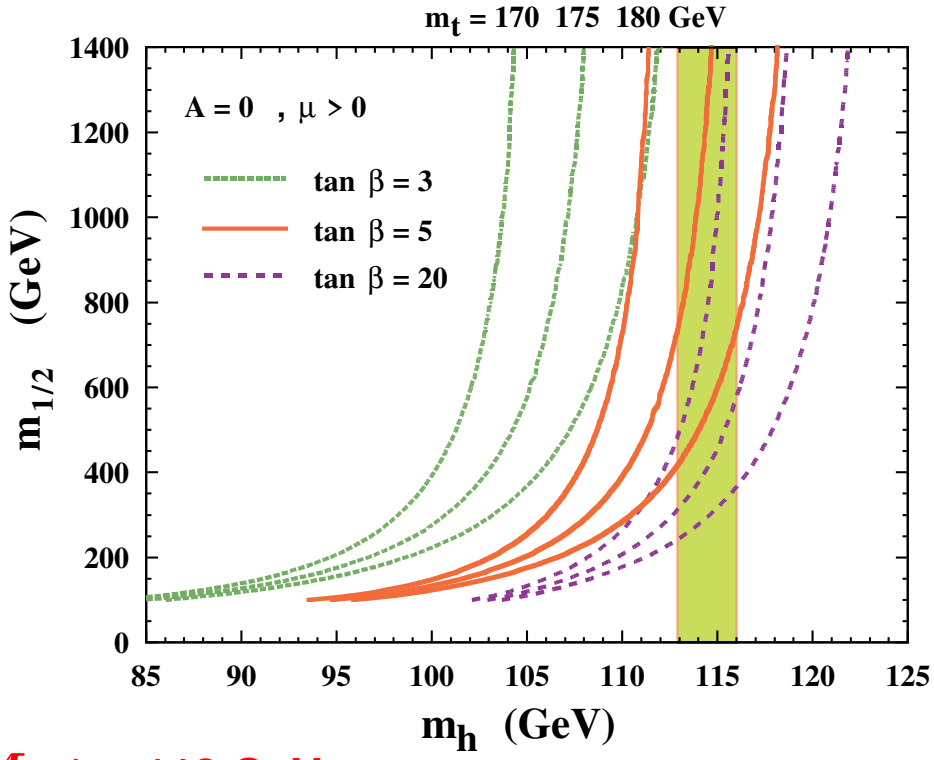
105 new parameters, unsuppressed FCNC, ...

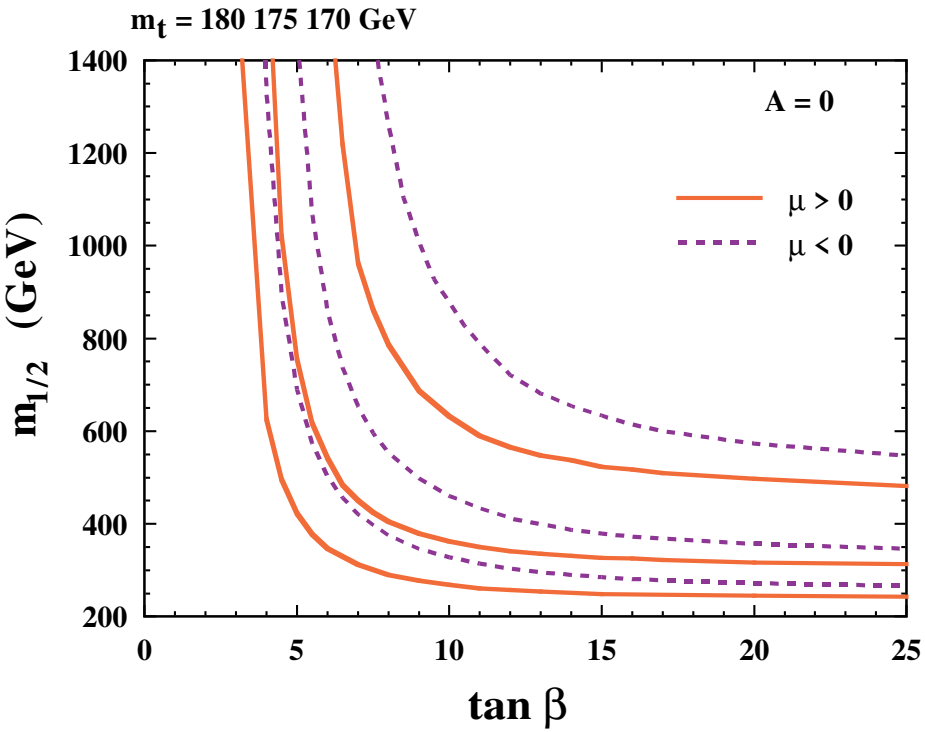
(SUGRA) Constrain it $\Rightarrow$ CMSSM

M_2	EW-scale $SU(2)$ Gaugino Mass
	(or $m_{1/2}$ = Unified GUT Scale Mass)
m_0	Common GUT-scale (Plank!) scalar mass
	(EW-scale masses from RGE's)
$\tan\beta$	v_2/v_1, Ratio of vev's of two higgs doublets
A_0	Common trilinear coupling
μ	Higgs mixing parameter
m_{A^0}	Pseudo Scalar Higgs Mass

6'ish new parameters, FCNC *etc.* controllable

Allowed mSUGRA parameters for $M_{\mathrm{h}} = 115$ GeV





$M_{\mathrm{h}} > 113$ GeV $\Rightarrow$

- $M_{\tilde{\chi}^{\pm}} > 240$ GeV
- $M_{\tilde{g}} > 600$ GeV
- $M_{\tilde{\mathrm{q}}} > 700$ GeV

Out of Tevatron Reach

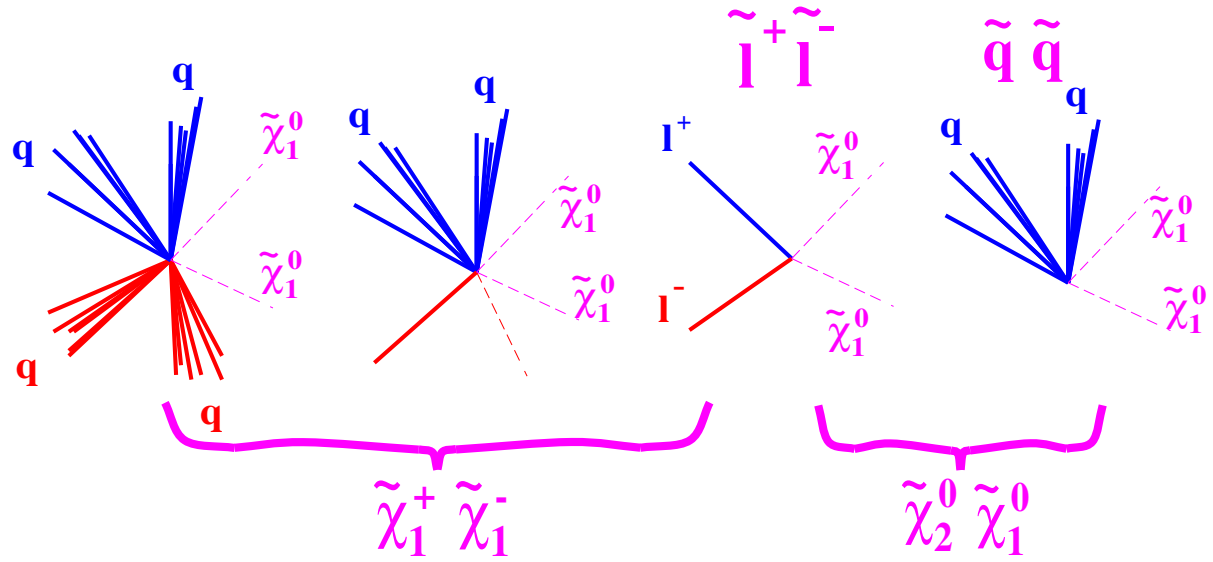
$\Rightarrow$ **LHC**

Current constraints: **LEP**

Parameters $\leftrightarrow$ Search Channels

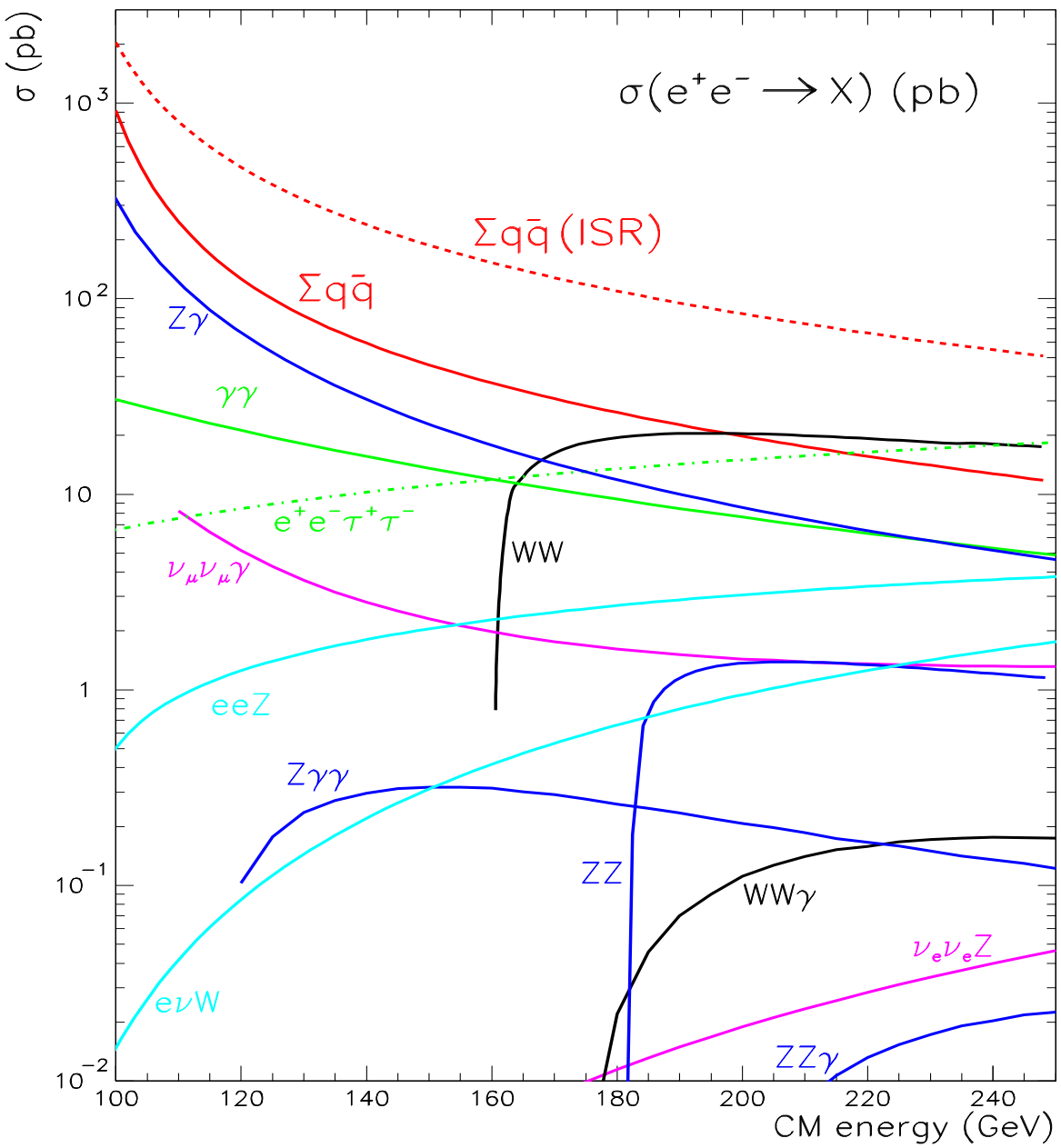
$\mu << M_2$ Higgsino Region no $\tilde{\nu}$ coupling	$\mu >> M_2$ Gaugino Region		
	Large $m_0, m_{\tilde{f}}$	Small $m_0, m_{\tilde{f}}$	
			Large $\tilde{q}$ Mix
$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$		$\tilde{\ell}^+\tilde{\ell}^-$	$\tilde{t}\tilde{t}, \tilde{b}\tilde{b}$

Primary Search Topologies



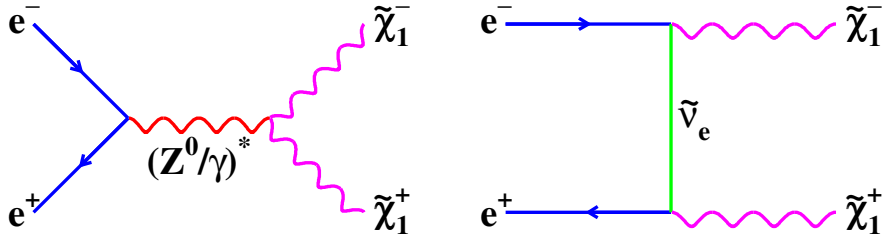
- Select events with significant missing energy
- Categorize using
  - hadronic jets
  - charged leptons
  - Event Visible Energy, jet/lepton energies
- Depend Strongly on $\Delta M = M_{\mathrm{SUSY}} - M_{\mathrm{LSP}}$

Background from the SM



- 4-Fermion, especially $\mathrm{W^+W^-}$
  - $\sigma \sim 20$ pb
  - Large visible energy (large ΔM region)
- $\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}\gamma^{(*)}\gamma^{(*)} \rightarrow \mathrm{e^+e^-ff}$
  - σ *enormous* (say $\sim$ 100-10000 pb)
  - Small visible energy (small ΔM region)

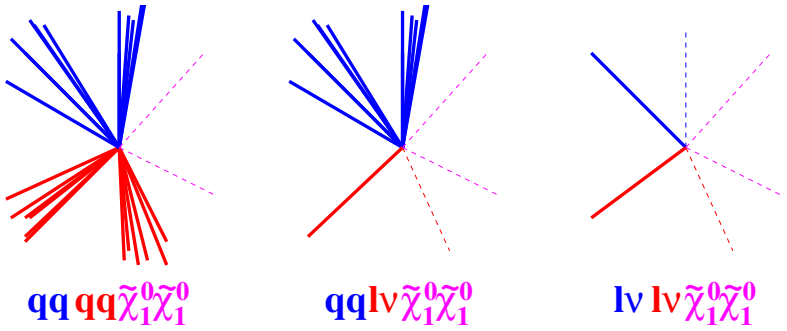
Charginos



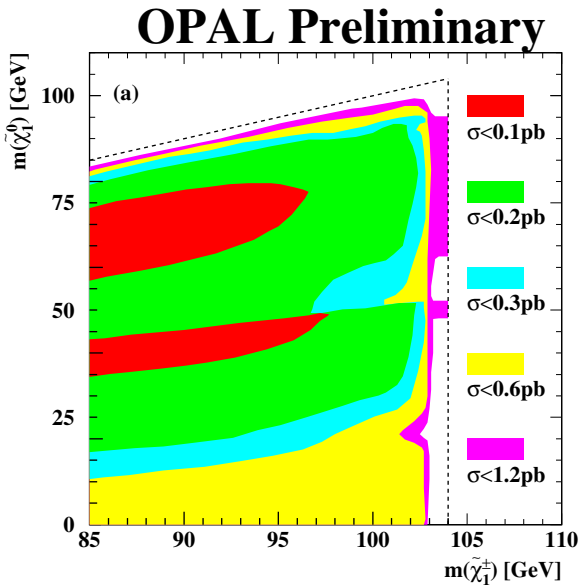
- $\sigma > 4$ pb unless $\tilde{\nu}_e$ is light.
- Chargino decay via W (most of MSSM)

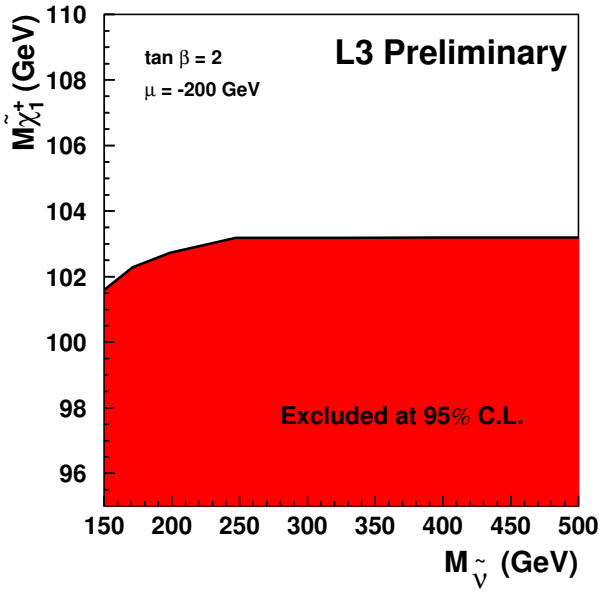
$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (\mathrm{W}^+ \tilde{\chi}_1^0)(\mathrm{W}^- \tilde{\chi}_1^0)$$

- Signature : $\mathrm{W}^+\mathrm{W}^-$ plus missing energy



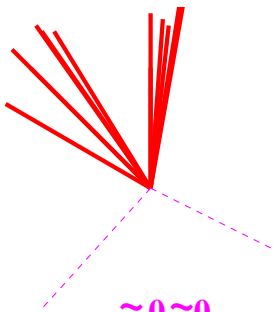
- Many selections $\Rightarrow$ Consistent with SM



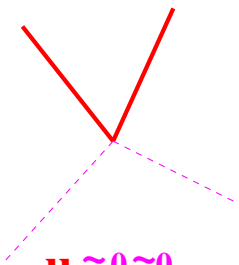


Neutralino Search

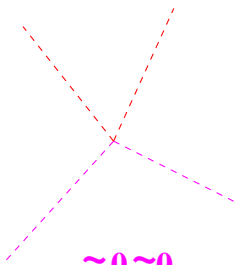
- Enough luminosity to search for neutralino production
- Observed as : $\tilde{\chi}_2^0\tilde{\chi}_1^0 \longrightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 Z^* \longrightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 f\bar{f}$



$q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$



$l^+l^-\tilde{\chi}_1^0\tilde{\chi}_1^0$

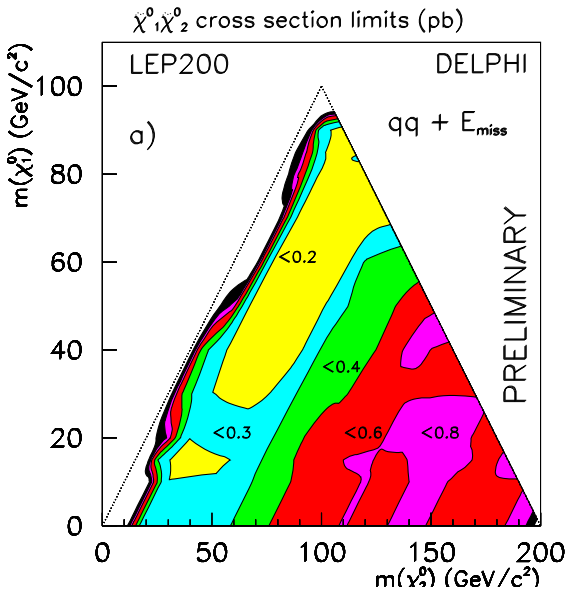


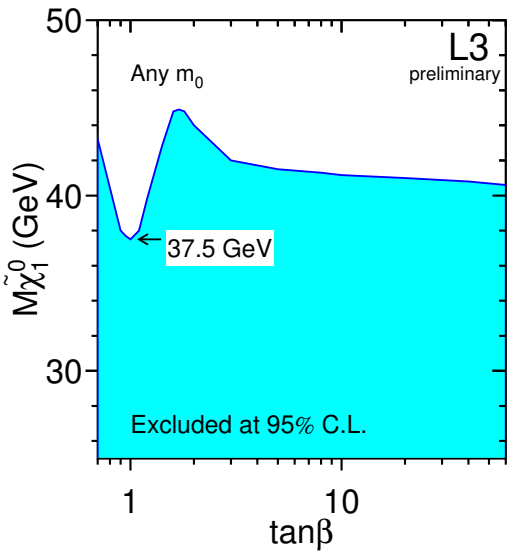
$\nu\bar{\nu}\tilde{\chi}_1^0\tilde{\chi}_1^0$

- Everything consistent with SM here too ...

LIMITS

Cross-section | Mass





What do mass limits really mean? $\Rightarrow$

MSSM Parameter Limits

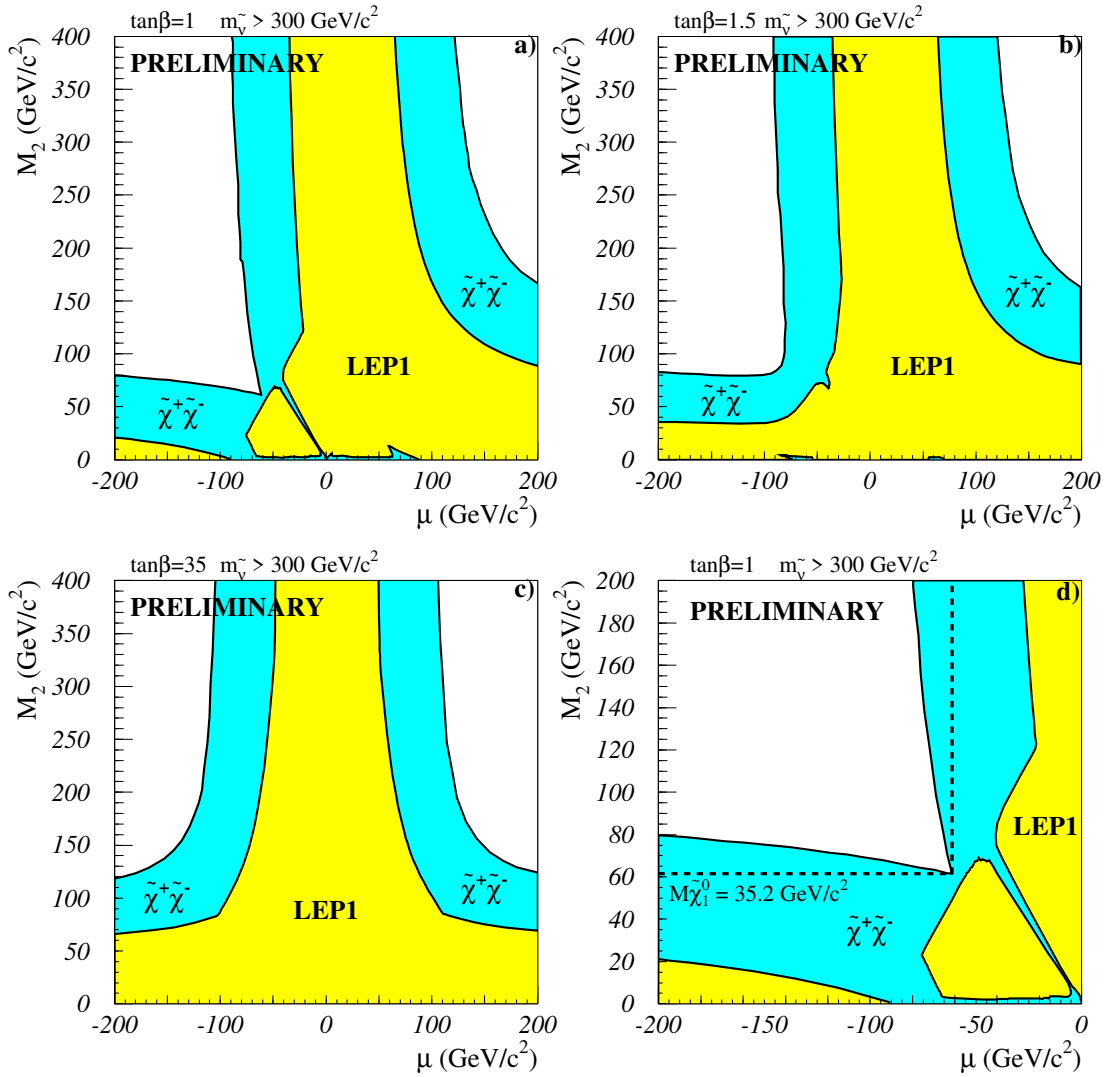
- Important parameters: $\tan\beta$, M_2, μ, m_0
- A_0 matters if including MSSM higgs

$\Rightarrow$ Plot M_2 *vs.* μ for different $\tan\beta$

– Show Large and "any" m_0 separately (heavy/light $\tilde{\nu}$)

"any" $\Rightarrow$ parameter scan over allowed ranges

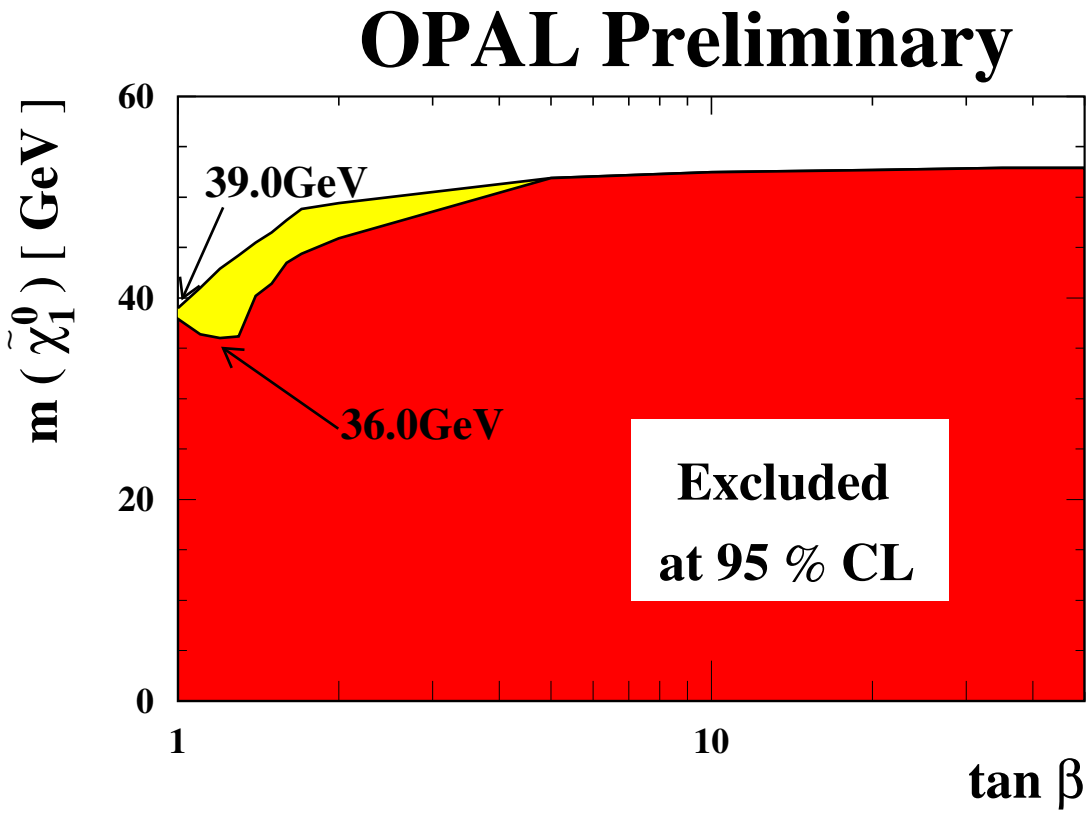
DELPHI MSSM limits at 202 GeV



M_χ Excluded: All $\{\tan\beta, M_2, \mu, m_0, A_0\} \Rightarrow M_\chi$ excluded

$\tilde{\chi}_1^0$ LSP Mass Limit

Combine $\tilde{\chi}^+\tilde{\chi}^-, \tilde{\chi}_2^0\tilde{\chi}_1^0, \tilde{\ell}^+\tilde{\ell}^-$



	LSP $\tilde{\chi}_1^0$ limit (GeV)	
	Large m_0	Any m_0
ALEPH	37.2	–
DELPHI	–	38.2
L3	–	39.4
OPAL	39.0	36.0

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

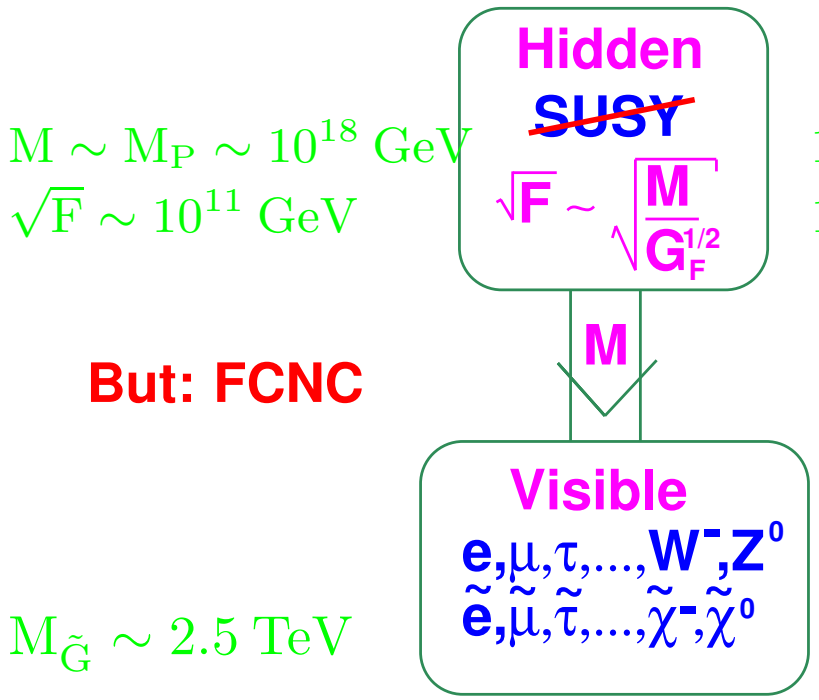
$M_{\tilde{G}} \sim 2.5$ TeV

Gauge

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

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

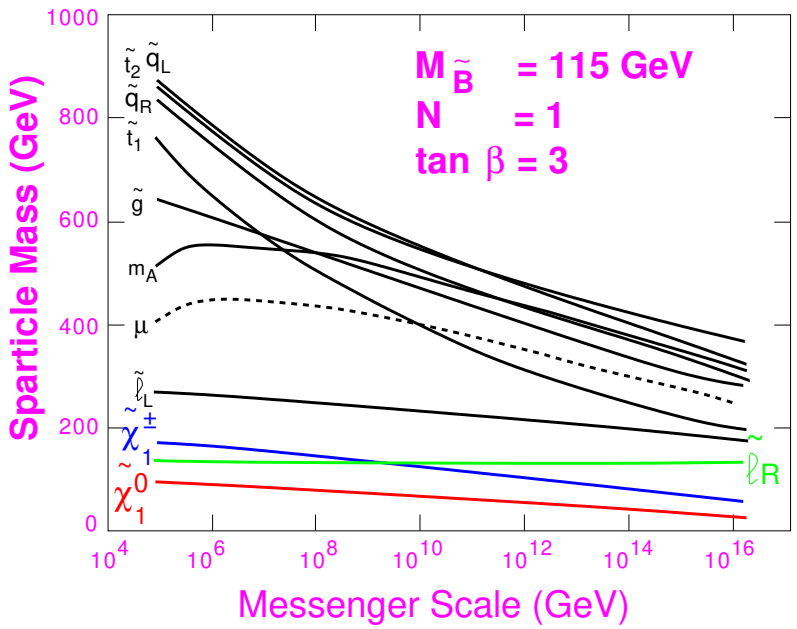
No FCNC



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

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

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



NLSP

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

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

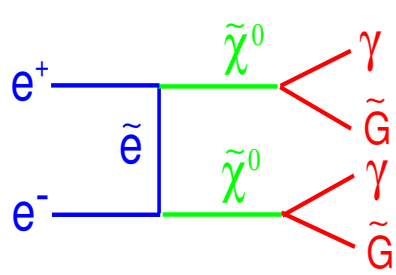
NLSP $c\tau =$

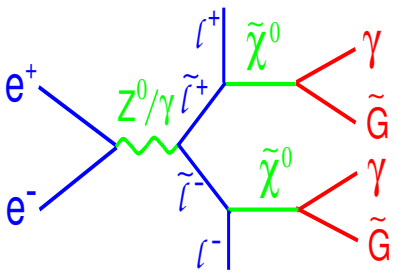
1 μm–10^{11} km

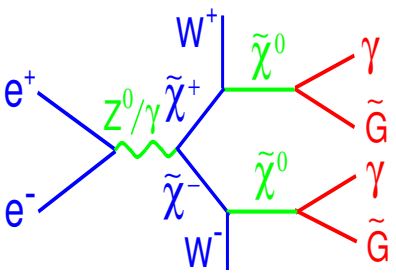
Minimal Model: $F,\ \Lambda,\ M,\ N,\ \tan\beta$ and $\mathrm{sign}(\mu)$

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

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

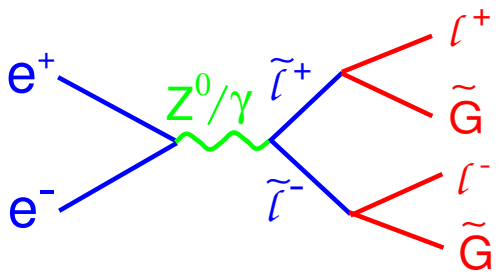


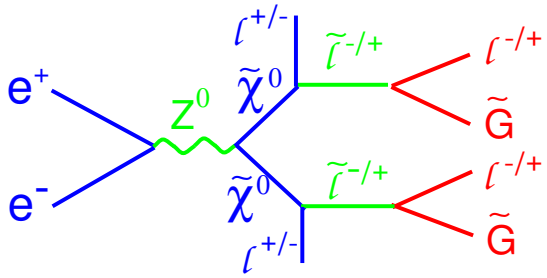




$c\tau \sim 0$:	$\gamma\gamma + \not{E}_T$	$\ell^+\ell^-\gamma\gamma + \not{E}_T$	$\gamma\gamma$ + jets/$\ell^\pm + \not{E}_T$
$0 < c\tau < \infty$:	$\gamma + \not{E}_T$	$\ell^+\ell^-\gamma + \not{E}_T$	γ + jets/$\ell^\pm + \not{E}_T$
$c\tau \sim \infty$:	$\not{E}_T$	$\ell^+\ell^- + \not{E}_T$	jets/$\ell^\pm + \not{E}_T$

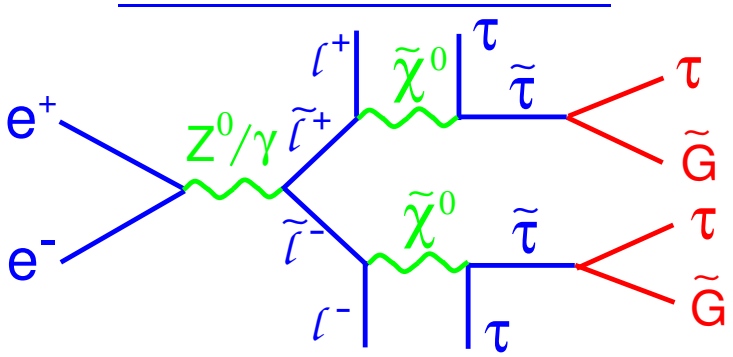
$\tilde{\ell}^\pm$ NLSP





$c\tau \sim 0$:	$\ell^+\ell^- + \not{E}_T$	$4 \times \ell^\pm + \not{E}_T$
$0 < c\tau < \infty$:	$2 \times$ Kinked Tracks	$2 \times \ell^\pm + 2 \times$ Kinked Tracks
$c\tau \sim \infty$:	$2 \times$ Stable Charged	$2 \times \ell^\pm + 2 \times$ Stable Charged

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

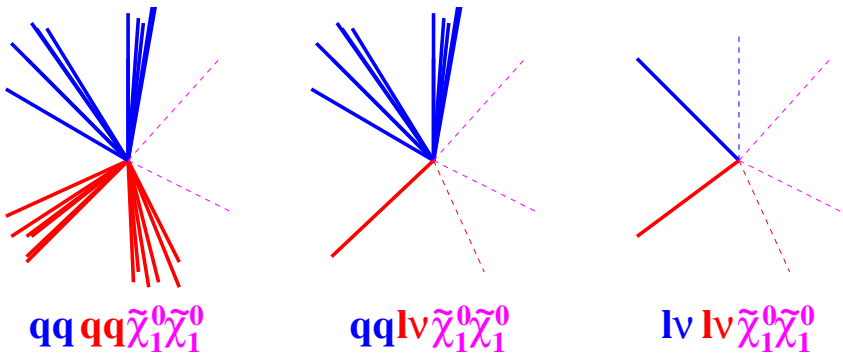


$c\tau \sim 0$:	$\tau^\pm\tau^\pm + (\ell^\pm\tau^\mp\ell^\pm\tau^\mp)$
$0 < c\tau < \infty$:	Kinked Tracks + $(\ell^\pm\tau^\mp\ell^\pm\tau^\mp)$
$c\tau \sim \infty$:	Stable Charged + $(\ell^\pm\tau^\mp\ell^\pm\tau^\mp)$

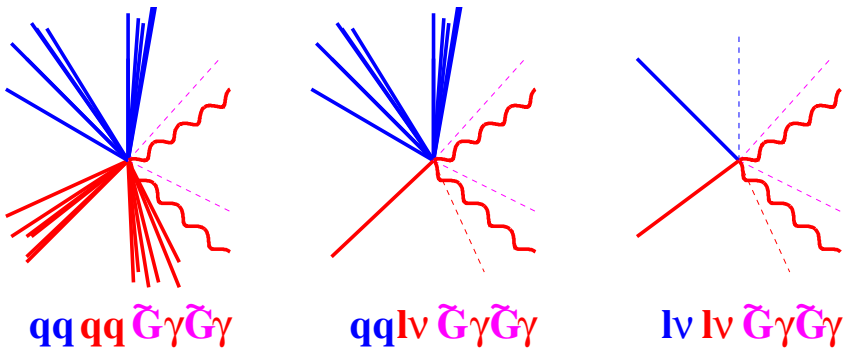
$\tilde{\chi}_1^+\tilde{\chi}_1^-$ with $\tilde{\chi}_1^0$ NLSP

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

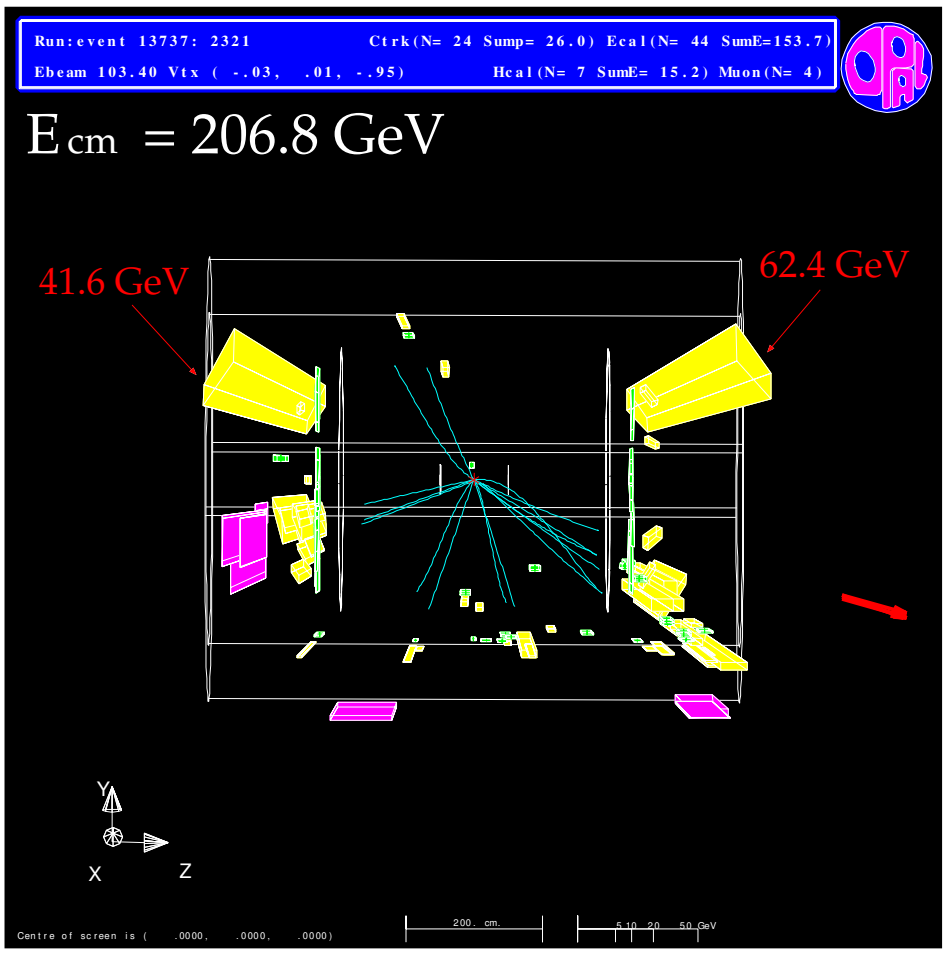
Model Interesting $\Rightarrow$

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	15.9 ± 0.8	19	2.7 ± 0.2	1
High Mult	24.4 ± 7.3	34	9.0 ± 2.8	14

- High Multiplicity Candidate



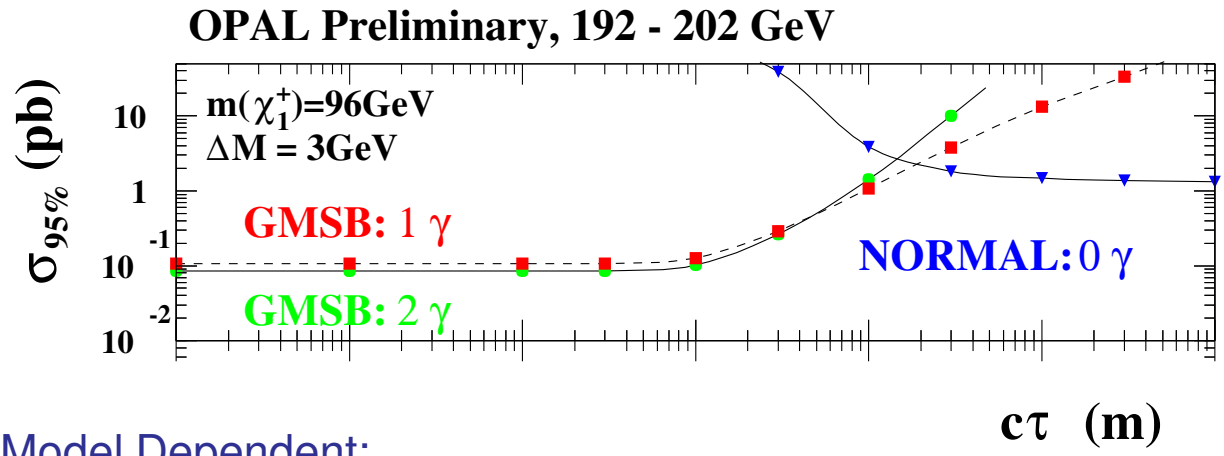
Consistent with :

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

GMSB Limits

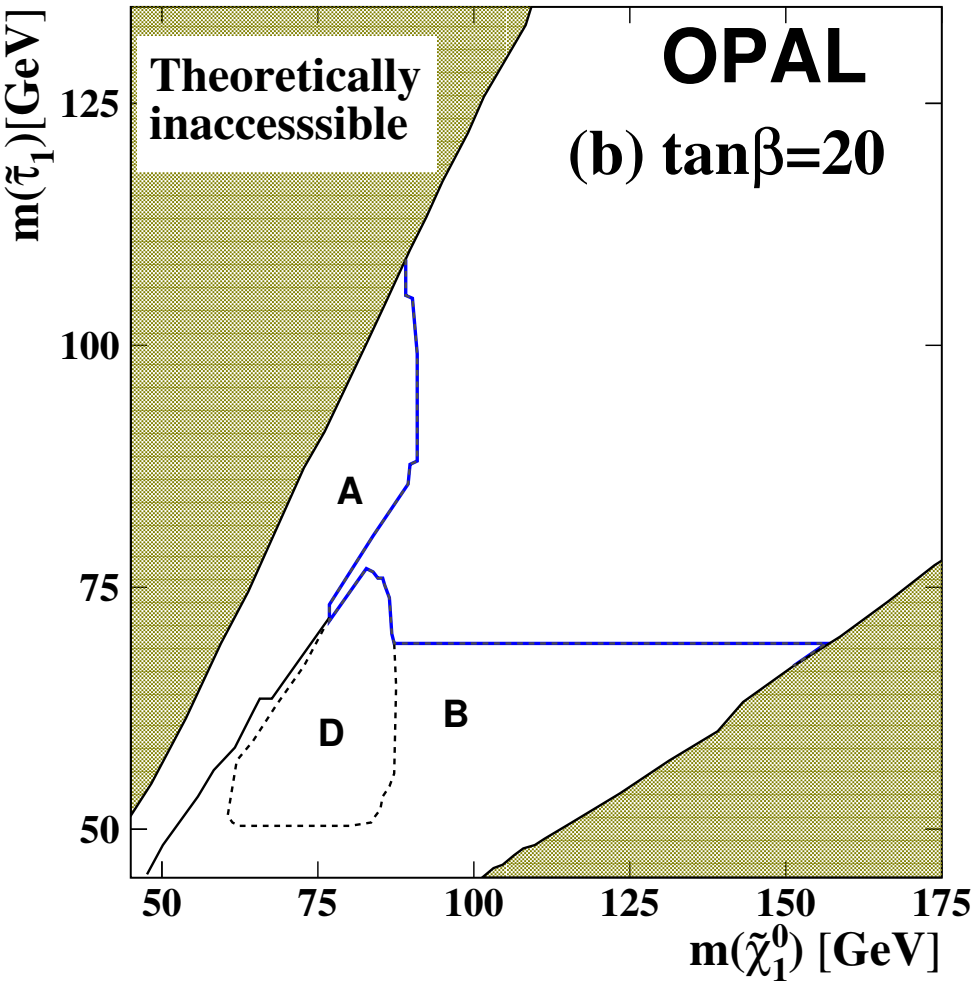
Model Independent:

- Production cross-section vs. NLSP lifetime



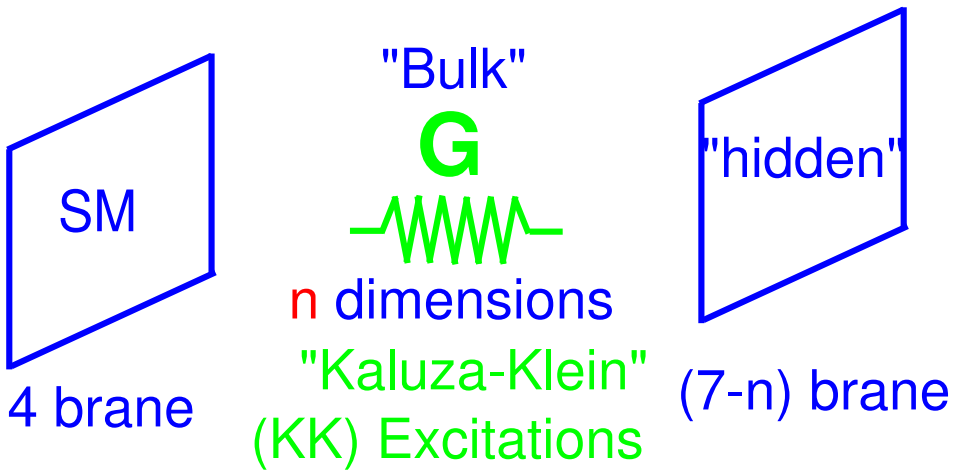
Model Dependent:

- Scan GMSB parameter space, exclude mass regions

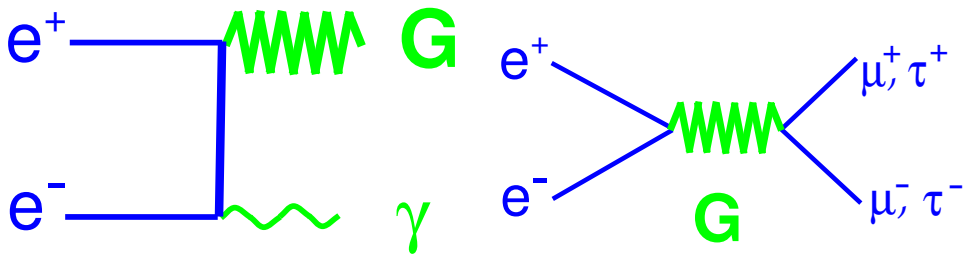


Gravity in Extra Dimensions

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

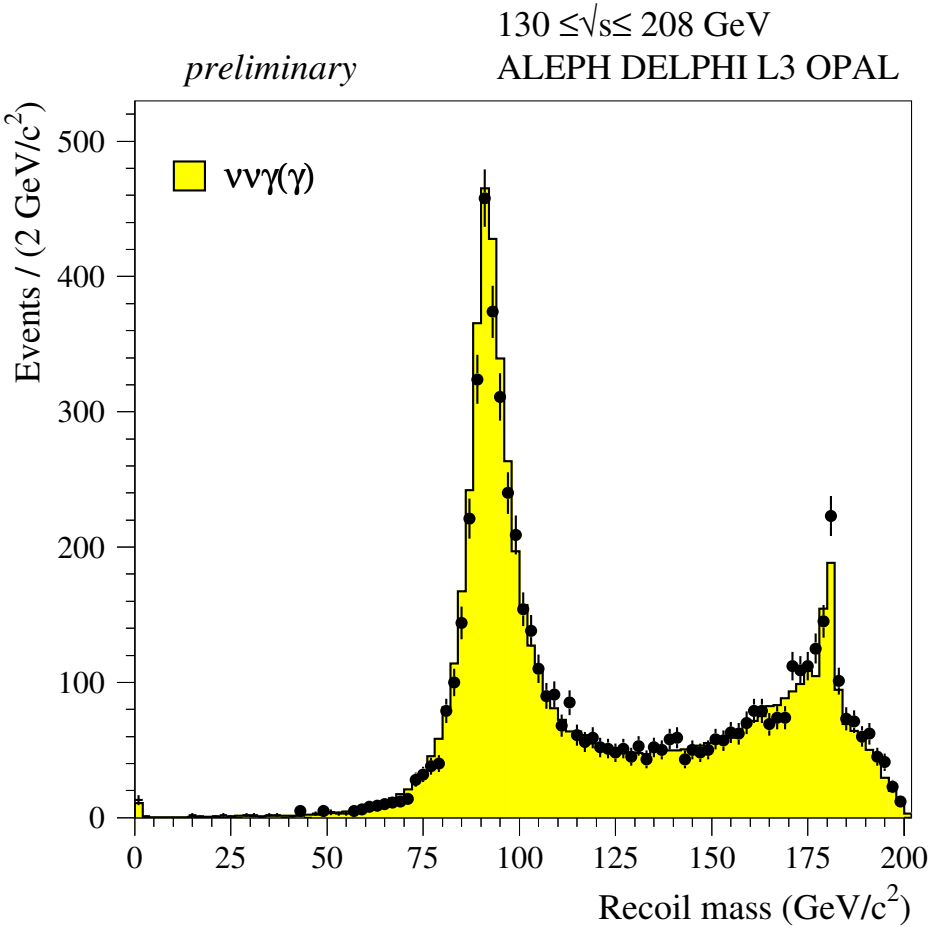
n : Number of large dim., $1 < R < 7$

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

Gravity in Extra Dim: Results

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

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



eg. OPAL 189 GeV

n	M_D Lower Limit (GeV) 95%C.L.
2	1086
3	862
4	710
5	605
6	528
7	470

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
- Excess in the Standard Model Higgs Search

  $\sim 3\,\sigma$
- Many other searches conducted

  No current significant excesses

  ... but data still to be analyzed!
- LEP is now **OFF**
- For 115 GeV higgs:

  Tevatron has some chance by $\sim$ 2007

  LHC will see it $\sim$ 2007

Discovery of particles beyond the Standard Model?

Large Hadron Collider $\sim$ 2006++