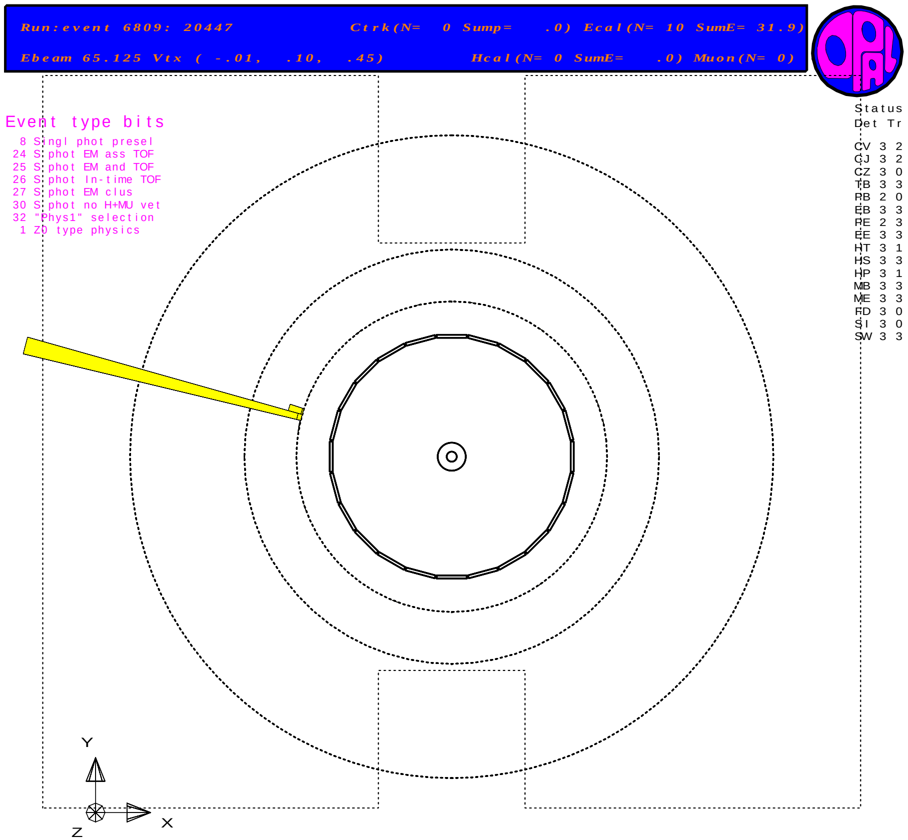
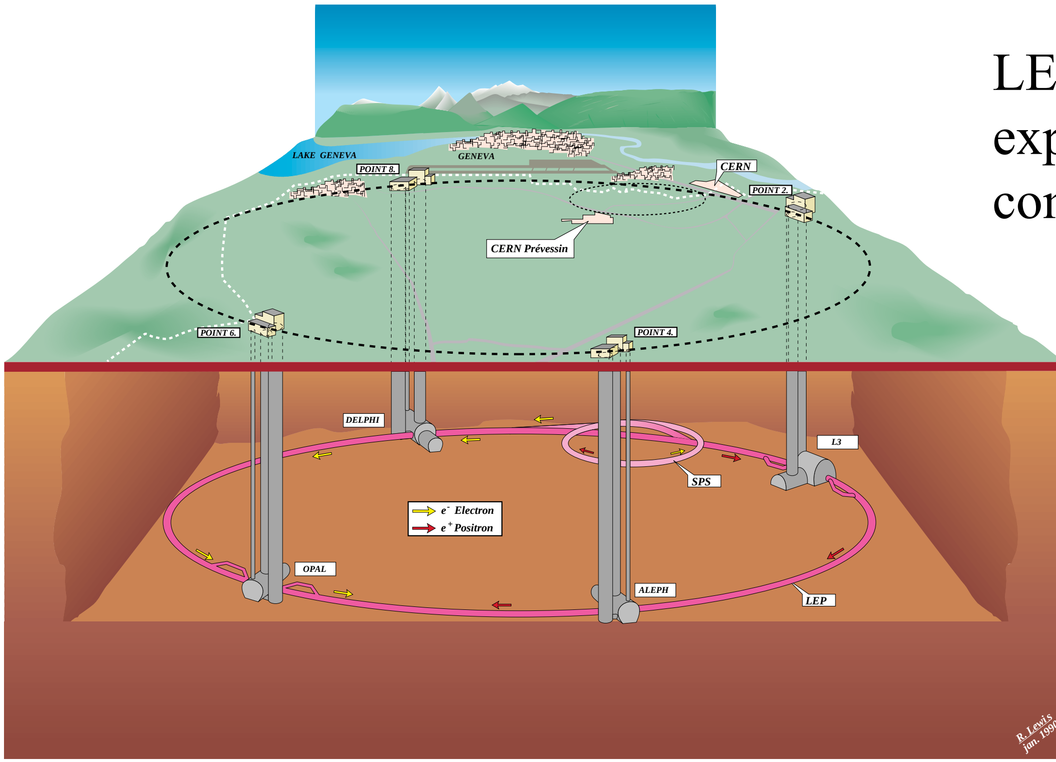
New Physics Searches with Photonic Final States at LEP2

- Introduction
- The Standard Model and Beyond
- OPAL Detector / Data Sample
- Photonic Final States
  - ➢ with missing energy
  - ➢ without missing energy
- New Physics Scenarios
  - ➢ Supersymmetry
  - ➢ Large Extra Dimensions
  - ➢ Other New Physics



The LEP e^+e^- Collider at CERN



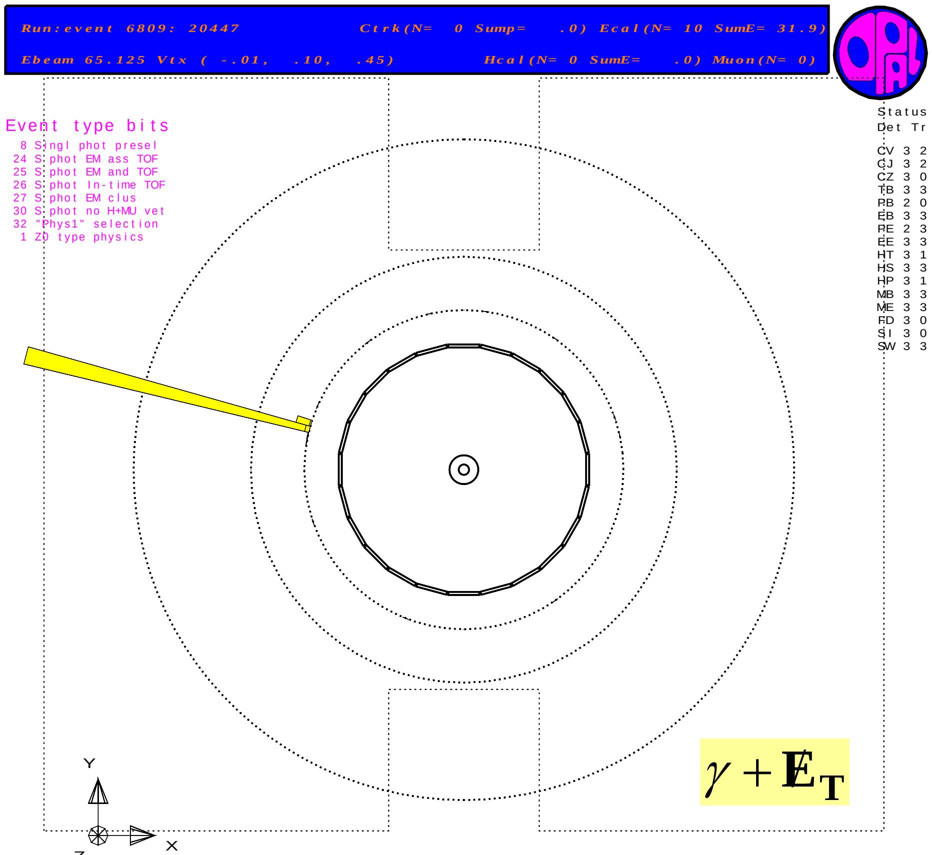
LEP running for two-phase experimental program now complete

Phase 1 – precision measurements of the Z^0 ($E_{CM} \sim M_Z$)

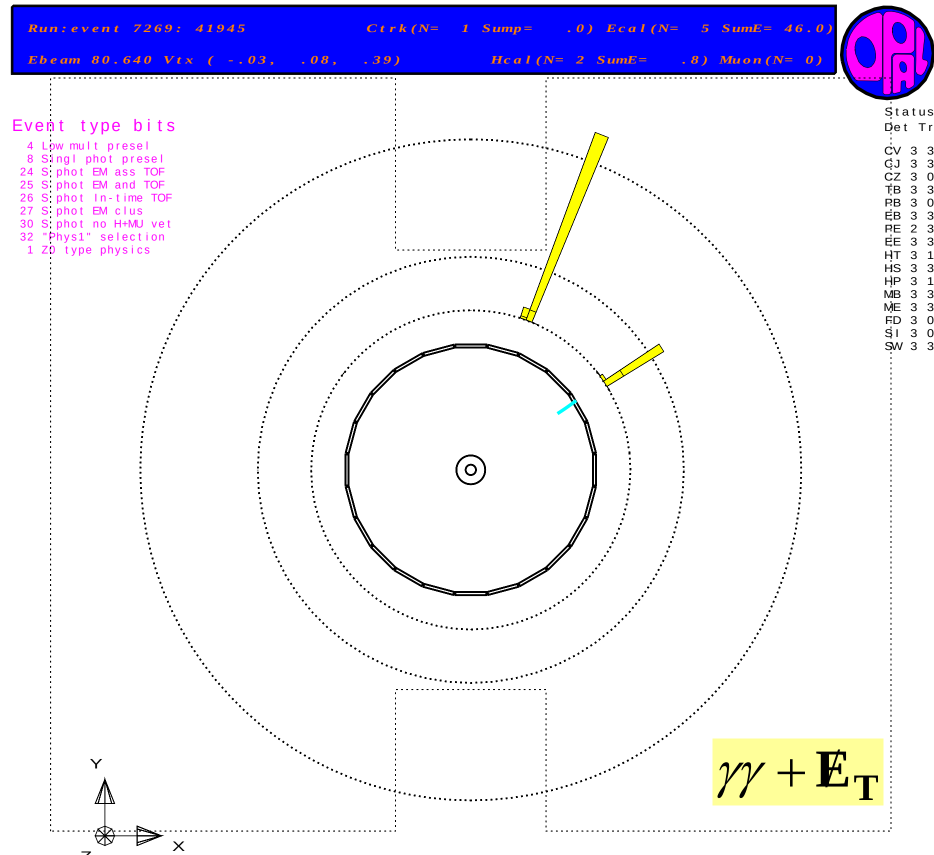
Phase 2 – precision measurements of the $W^\pm$ ($E_{CM} > 2M_W$)

Centre-of-mass energy in final year of operation reached 209 GeV

Photonic Events With Missing Energy



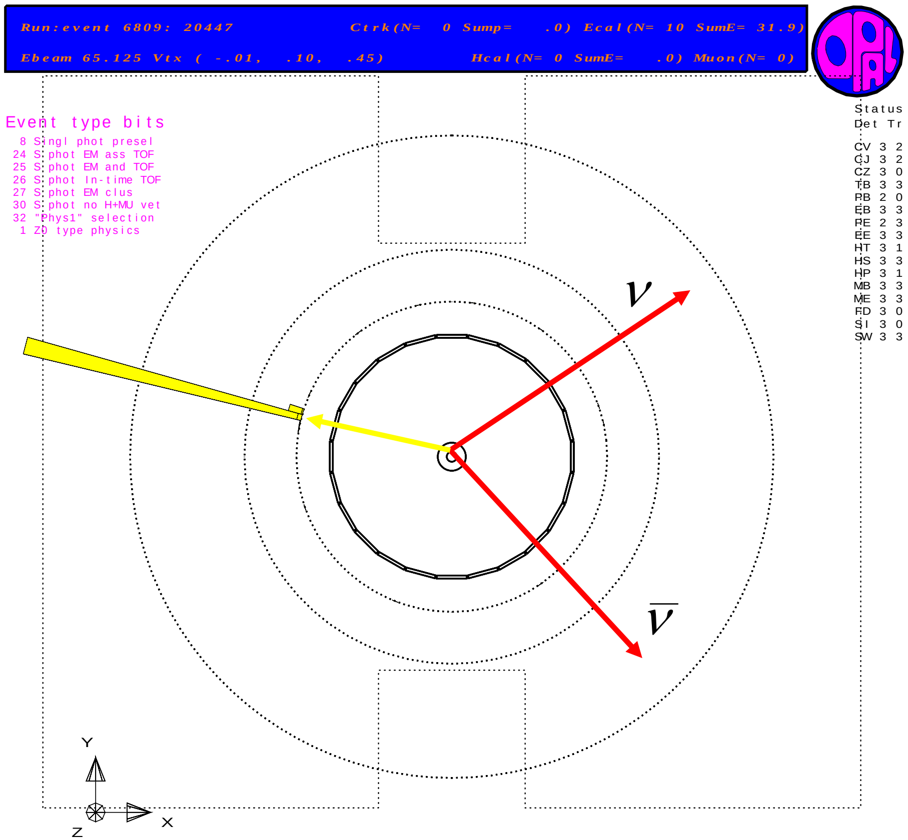
"single photon"



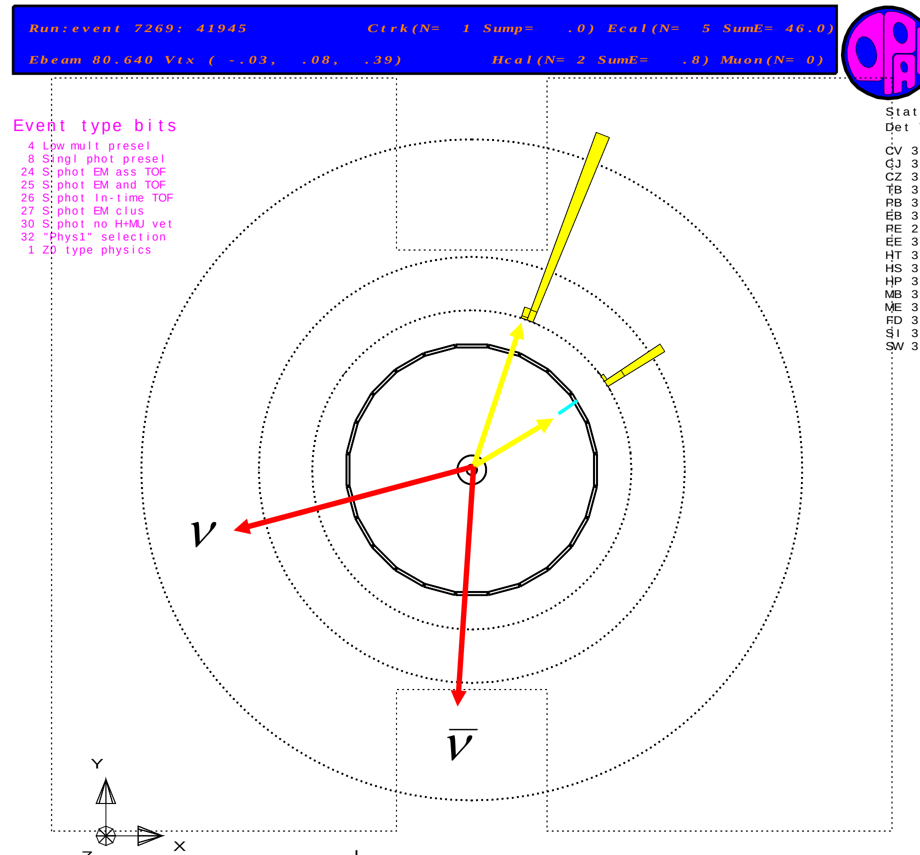
"acoplanar photons"

Track stub from photon conversion.
Retain efficiency for conversions to reduce modeling uncertainties

Photonic Events With Missing Energy

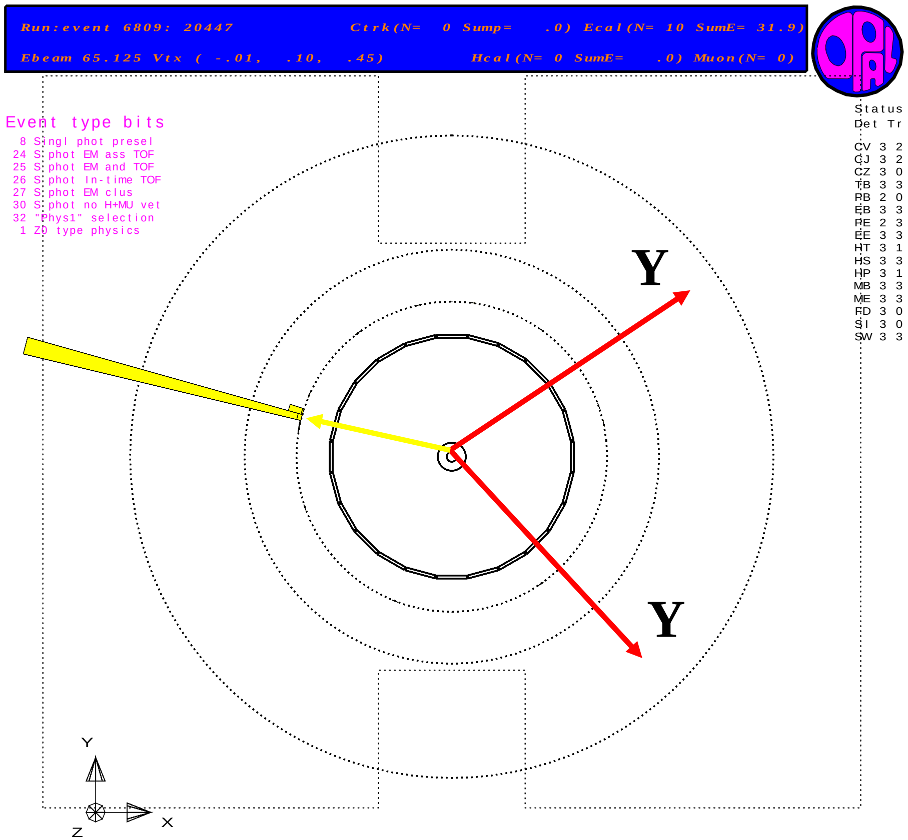


$$e^+e^- \rightarrow \nu\bar{\nu}\gamma$$

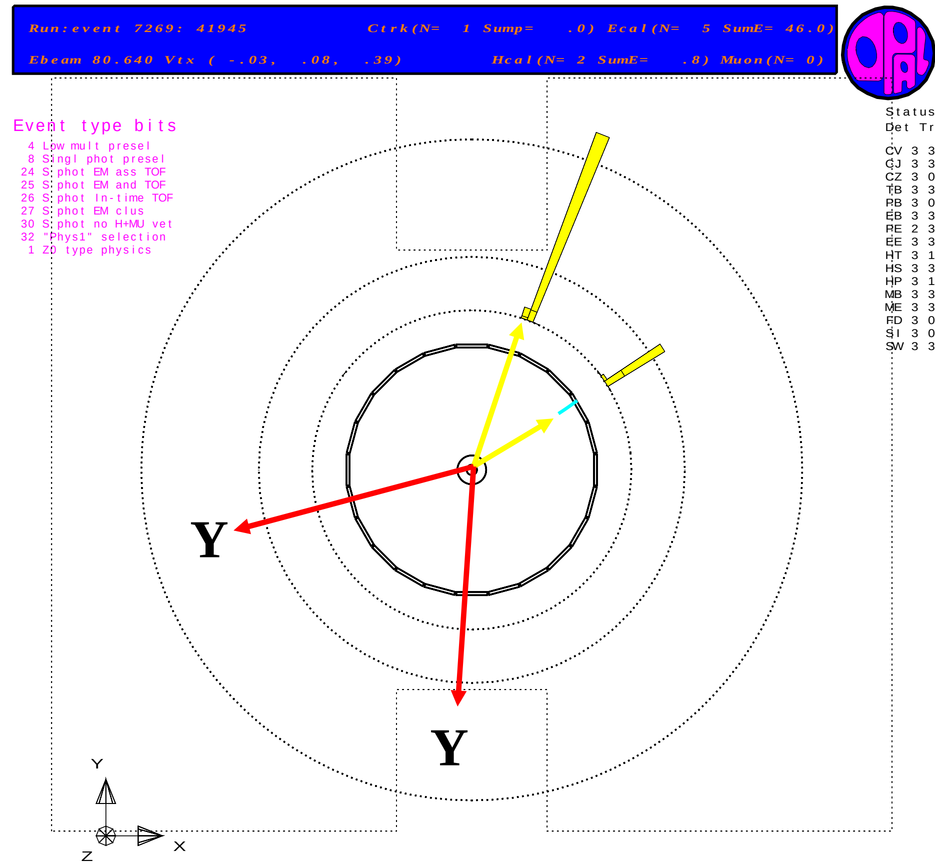


$$e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$$

Photonic Events With Missing Energy



$$e^+e^- \to XY,\ X \to Y\gamma$$



$$e^+e^- \to XX,\ X \to Y\gamma$$

Y invisible (neutral and weakly interacting)

The Standard Model of Particle Physics

$$\mathbf{SU}(3)_{\mathbf{C}} \times \mathbf{SU}(2)_{\mathbf{L}} \times \mathbf{U}(1)_{\mathbf{Y}}$$

matter particles

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

gauge bosons

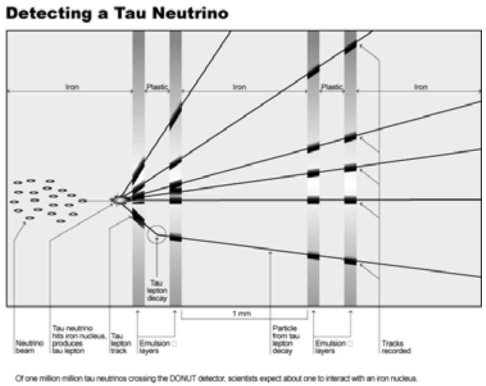
$$\gamma$$

$$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$$

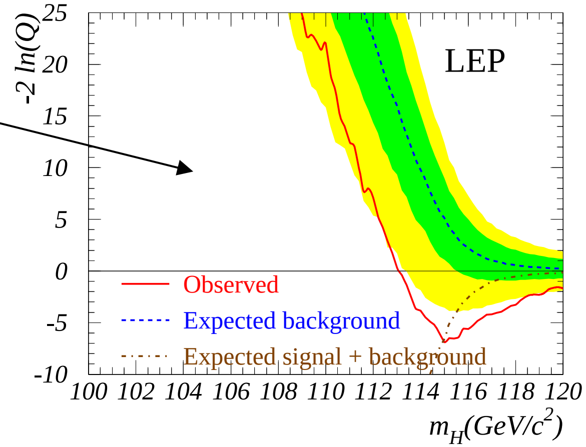
$$\mathbf{g}$$

Higgs $\mathbf{H}^0$

DONUT@FERMILAB



LEP combined



Standard Model (almost) complete in terms of particle content. But still unsatisfactory

And what about gravity ?

Beyond the Standard Model

Hierarchy problem (2 fundamental energy scales) $\mathbf{M}_{\mathbf{EW}} / \mathbf{M}_{\mathbf{planck}} \approx 10^{-17}$

Naturalness problem radiative corrections to Higgs mass squared $\propto \Lambda^2$ where Λ is the energy scale to which the theory remains valid → fine tuning problem with Higgs mass: can be resolved by

New physics at the TeV scale $\Lambda \approx 1$ **TeV**

OR

A symmetry protecting the Higgs mass against large radiative corrections

(Supersymmetry)

Supersymmetry

Each SM boson (fermion) has a fermionic (bosonic) supersymmetric partner with IDENTICAL MASS and COUPLINGS

leptons | **sleptons**

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \leftrightarrow \begin{pmatrix} \tilde{e} \\ \tilde{\nu}_e \end{pmatrix} \begin{pmatrix} \tilde{\mu} \\ \tilde{\nu}_\mu \end{pmatrix} \begin{pmatrix} \tilde{\tau} \\ \tilde{\nu}_\tau \end{pmatrix}$$

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

quarks | **squarks**

spin – ½ | **spin – 0**

$W^\pm$	$\tilde{W}^\pm$	
Z^0	$\tilde{Z}^0$	**gauginos**
γ	$\tilde{\gamma}$	
h^0	$\tilde{h}^0$	
H^0	$\tilde{H}^0$	**higgsinos**
A^0	$\tilde{A}^0$	
$H^\pm$	$\tilde{H}^\pm$	
g	$\tilde{g}$	**gluinos**

This defines the particle content of the Minimal Supersymmetric Standard Model or MSSM

Mass eigenstates are mixtures of gauginos and higgsinos

2 Charginos $\tilde{\chi}^{\pm}_{i=1,2}$

4 Neutralinos $\tilde{\chi}^{0}_{j=1,4}$

Supersymmetry is a Broken Symmetry

Unbroken supersymmetry implies $M_{SUSY} = M_{SM}$

We do not see supersymmetric matter made of snucleons and selectrons

⇒ Supersymmetry is a <u>Broken Symmetry</u>

M_{SUSY} can be large

R-Parity Is a quantum number which distinguishes SM and SUSY particles

Most SUSY models assume <u>R-Parity conservation:</u> this has two immediate consequences

- supersymmetric particles must be produced in pairs
- there must be a Lightest Supersymmetric Particle or LSP ⇒ Missing-energy signature

Supersymmetry may

- Solve the naturalness problem (if $M_{SUSY} < 1$ TeV) (also gauge coupling unification)
- Provide a mechanism for dynamical EW symmetry breaking
- Provide a viable CDM (WIMP) candidate
- Be needed for unification with gravity

SUSY Phenomenology

The MSSM has > 100 free parameters in addition to those of the SM

Predictive models typically require some assumptions about how SUSY is broken and about parameter unification at high energies (5 parameter CMSSM)

Phenomenology depends on the mass hierarchies of the SUSY particles

Most importantly - what is the LSP ?

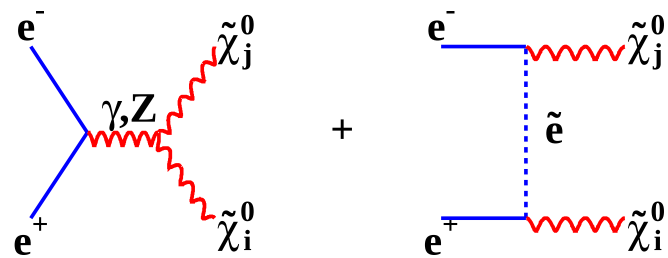
Currently there are two phenomenologically very different classes of models

- Models with a massive LSP (usually the lightest neutralino $\tilde{\chi}_1^0$)
- Models with a light gravitino ($\tilde{\mathbf{G}}$) LSP (the phenomenology is then dictated by the identity of the Next-to-Lightest Supersymmetric particle (NLSP)

The light gravitino scenario occurs in a number of classses of models including those with gauge-mediated supersymmetry breaking (GMSB)or no-scale supergravity

The Neutralino LSP Scenario

Photonic events with missing energy can arise from neutralino pair production



i, j = 1,4

Decays of the $\tilde{\chi}_i^0$ depend on the mass hierarchies and neutralino composition

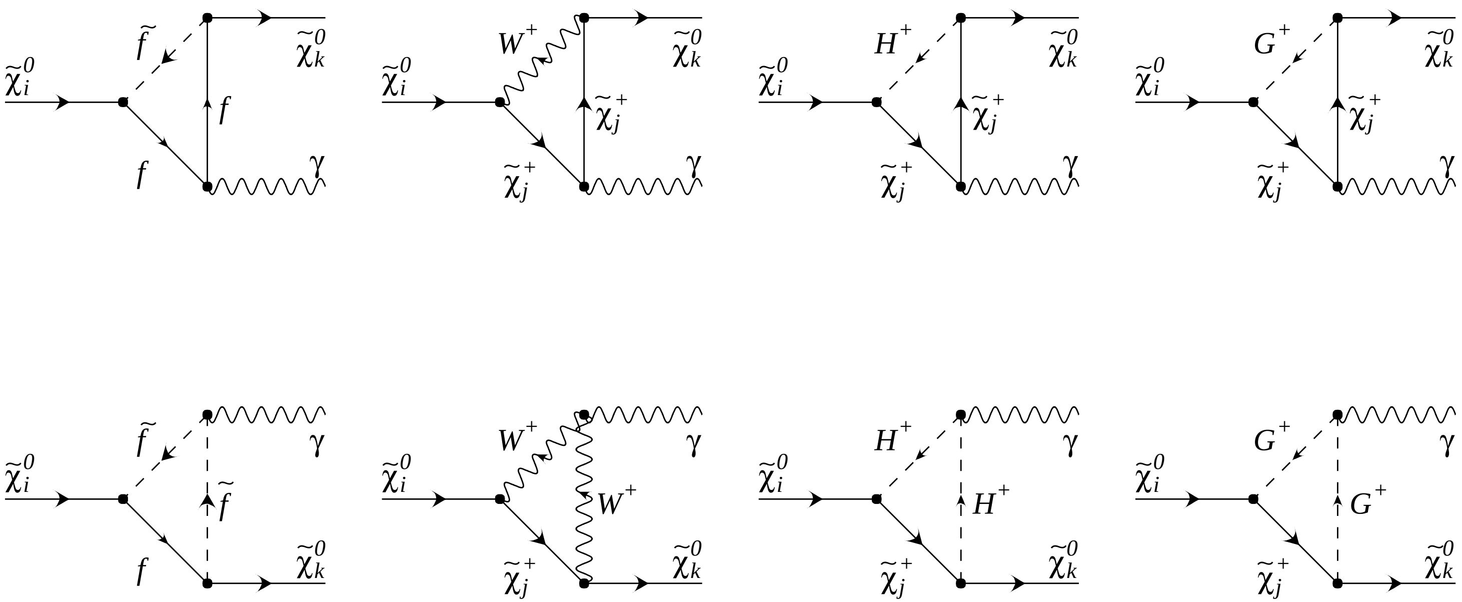
In much of the CMSSM parameter space $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \mathbf{Z}^*$

BUT

There are regions of parameter space for which $\mathbf{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma)$ is large or dominant

process	signature	
$\mathbf{e^+e^-} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$	**invisible**	**ISR gives** $\gamma + \not{E}_\mathbf{T}$ **signature**
$\mathbf{e^+e^-} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0$	$\gamma + \not{E}_\mathbf{T}$	
$\mathbf{e^+e^-} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$	$\gamma\gamma + \not{E}_\mathbf{T}$	
$\mathbf{e^+e^-} \rightarrow \tilde{\chi}_3^0 \tilde{\chi}_1^0$	$\gamma(\gamma) + \not{E}_\mathbf{T}$	**if** $\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 \gamma \; (\tilde{\chi}_2^0 \gamma)$

Dominant Radiative Neutralino Decay



$$\tilde{\chi}_{\mathbf{i}}^0 \rightarrow \tilde{\chi}_{\mathbf{k}}^0 \gamma$$

Two classes of enhancement of radiative branching fraction

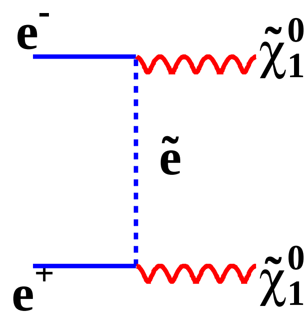
- kinematic: $\mathbf{M}(\tilde{\chi}_2^0) - \mathbf{M}(\tilde{\chi}_1^0)$ small
- dynamical: neutralino composition prevents tree level decays

The Light Gravitino LSP Scenario

Phenomenology dictated by the identity of the NLSP

This is frequently the lightest neutralino $\tilde{\chi}_1^0$ (always for no-scale supergravity models)

Production dominantly t-channel
because $\tilde{\chi}_1^0$ dominantly $\tilde{\mathbf{B}}$



$$\mathbf{e}^+\mathbf{e}^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$$
$$\tilde{\chi}_1^0 \rightarrow \tilde{\mathbf{G}}\gamma$$
$$\Rightarrow \quad \gamma\gamma + \not{\mathbf{E}}_\mathbf{T} \quad \textbf{signature}$$

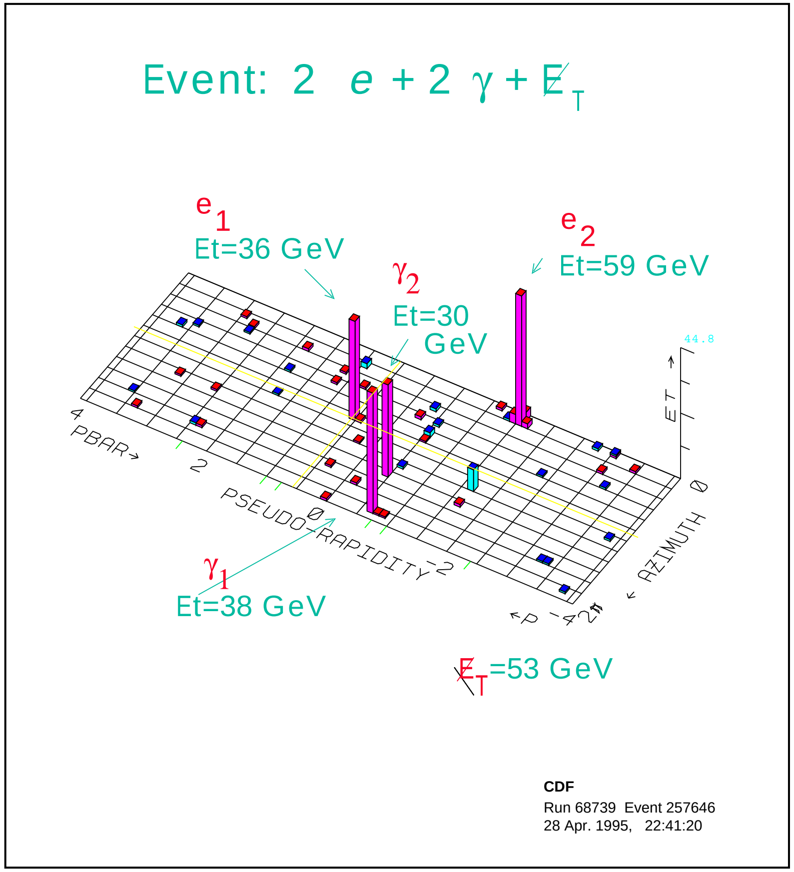
This has been called the premiere channel for the discovery of supersymmetry at LEP

Caveat: in models with a light $\tilde{\mathbf{G}}$ the lifetime of the NLSP is essentially arbitrary

NLSP decay length ~ μ**m – km**

Is this Supersymmetry ?

SM probability quoted as $10^{-5} - 10^{-6}$



Event can be interpreted as $\mathbf{p\bar{p}} \rightarrow \tilde{\mathbf{e}}^{+}\tilde{\mathbf{e}}^{-}$ in both the neutralino and gravitino LSP scenarios

$$\tilde{\mathbf{e}}\tilde{\mathbf{e}} \rightarrow \mathbf{ee}\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma\gamma$$

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

In light gravitino scenario observation implies prompt decay

Large Compact Extra Dimensions

- Hierarchy problem: $\mathbf{M}_{\mathbf{EW}} / \mathbf{M}_{\mathbf{planck}} \approx 10^{-17}$
- Postulate M_{planck} effective energy scale, not fundamental
- Assume n compact spatial dimensions of (compactified) radius R

Arkani-Hamed, Dimopoulos and Dvali

$$\mathbf{V}(\mathbf{r}) = \frac{\mathbf{m}_1\mathbf{m}_2}{\mathbf{M}_{\mathbf{D}}^{2+\mathbf{n}}} \bullet \frac{1}{\mathbf{r}^{\mathbf{n}+1}} \quad \text{(r << R)}$$

$$\mathbf{V}(\mathbf{r}) = \left\{ \frac{\mathbf{m}_1\mathbf{m}_2}{\mathbf{M}_{\mathbf{D}}^{\mathbf{n}+2}} \bullet \frac{1}{\mathbf{R}^{\mathbf{n}}} \right\} \frac{1}{\mathbf{r}} \quad \text{(r >> R)}$$

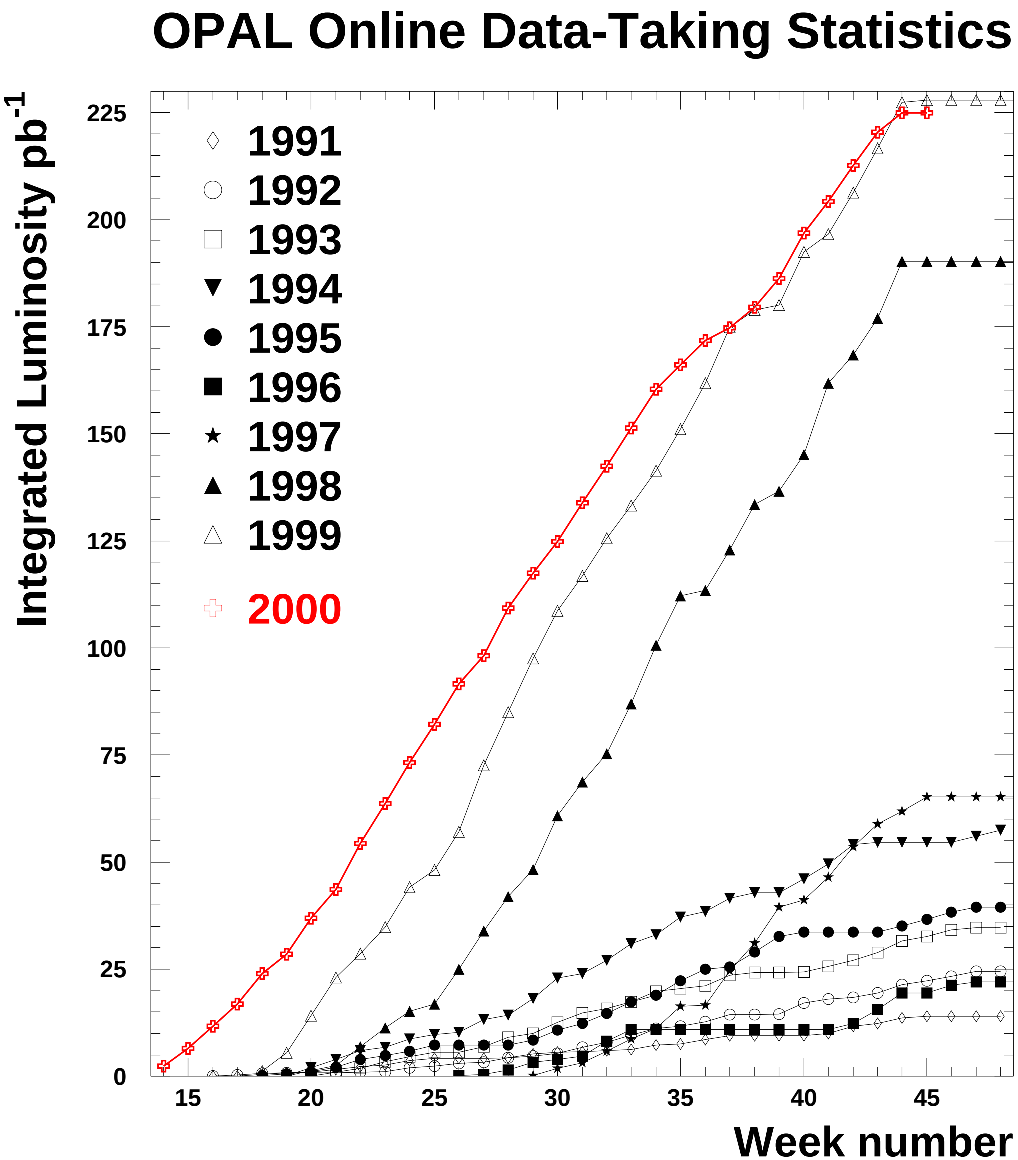
- Effective 4-dimensional M_{planck} then given by $\mathbf{M}_{\mathbf{planck}}^2 = \mathbf{M}_{\mathbf{D}}^{\mathbf{n}+2}\mathbf{R}^{\mathbf{n}}$
- Requiring $M_D \sim M_{EW}$ → $R \sim 10^{(30/n)-17}$ cm

- n=1 → $R \sim 10^{13}$cm - excluded by $1/r^2$ tests of gravity
- n=2 → R ~0.1-1mm - limited to very high M_D by SN1987 data

Models with large compact extra dimensions

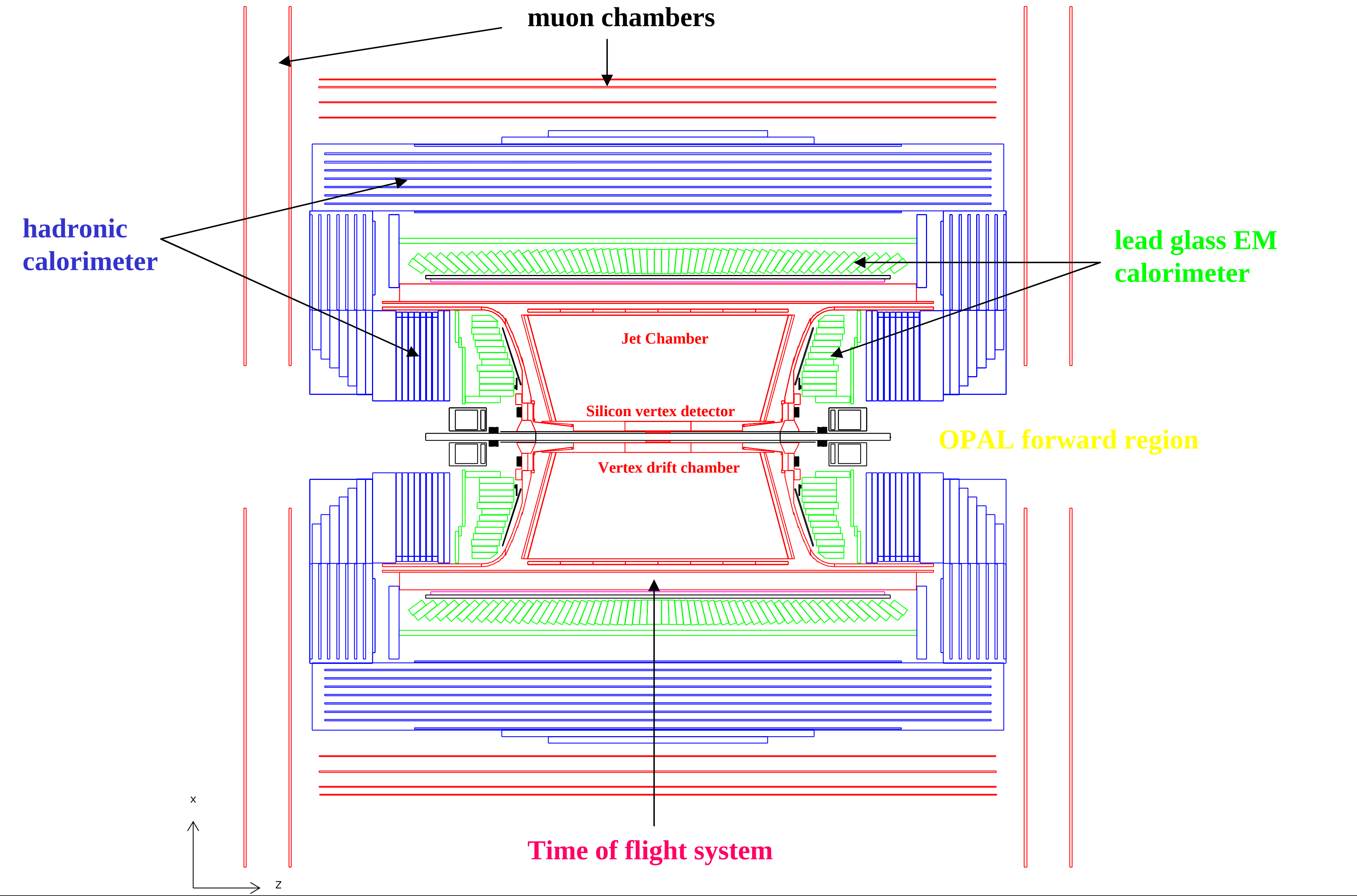
- Massless gravitons in 4+n dimensions → tower of massive KK states in 4D
  - Coupling to each state ~ $1/M_{planck}$
  - but high multiplicity of such states: sum over states ~ M_{planck}/M_D
  - Cross-section therefores goes as ~ $1/M_D$ rather than $1/M_{planck}$
- Model of Arkani-Hamed, Dimopoulos and Dvali (ADD)
  - Only gravitons propagate freely in the extra dimensions or "bulk"
  - SM particles confined to 3-brane
  - Only this model has been specifically addressed by the LEP collaborations
- Experimental signatures:
  - Direct production of gravitons → missing energy signature
  - Virtual gravitons exchange → modified cross-sections, precision observables

OPAL Data Sample

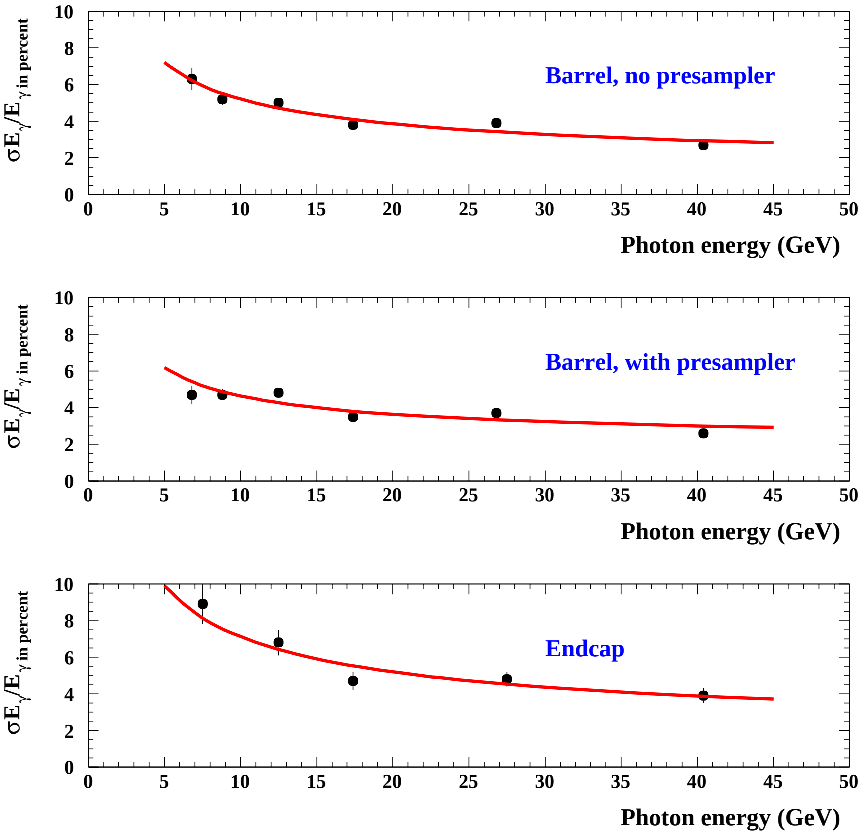


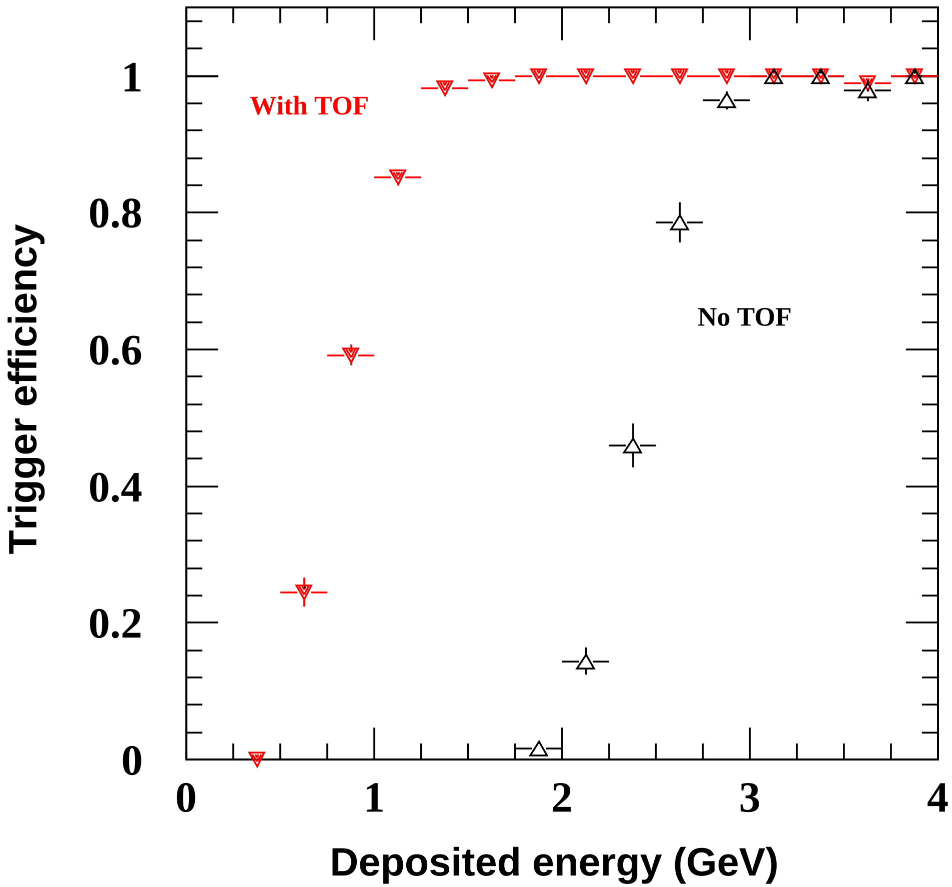
Year	$\sqrt{s}$ (GeV)	$\int$ Ldt (pb^{-1})
1998	189	187.2
1999	192 – 202	224.0
2000	200 – 209	220.7

The OPAL Detector



OPAL ECAL Performance





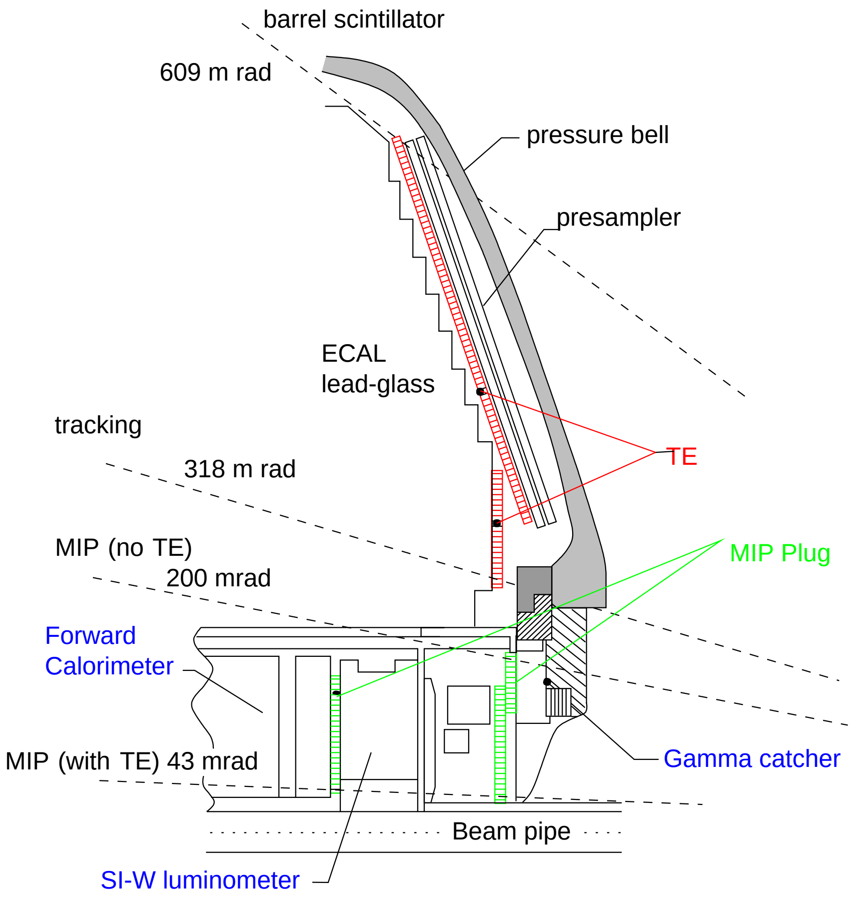
Typical resolutions:

$\sigma_E \sim$ 3-5%

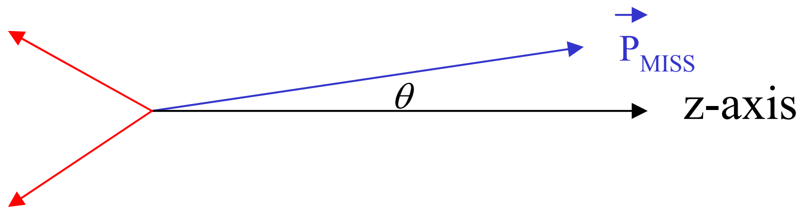
σ_θ, $\sigma_\varphi \sim$ 3-4 mrad

Trigger fully efficient for single photon events with energy deposits of 1.5 GeV if there is an associated TOF hit

The OPAL Forward Detector Region



Calorimetric coverage down to 24 mrad in polar angle



Maximum p_T that can be carried away by a beam energy particle is $0.024E_{beam}$

Missing-energy selections require $\sum_i \vec{\mathbf{p}}_{\mathbf{T}}(\gamma_{\mathbf{i}})/\mathbf{E}_{\mathbf{beam}} > 0.05$

Scintillating Tile Endcap Detector

TE provides timing hermiticity

MIP Plug provides far forward veto coverage for minimum ionizing particles

Forward calorimeters and MIP plug used for forward vetos

Kinematic Acceptance for Photons + Missing E_T Selections

Definitions $x \equiv E/E_{beam}$ $x_T \equiv E_T/E_{beam}$

$\gamma(\gamma) + \not{E}_T$ (single photon)

- at least 1 photon with $x_T > 0.05$ and $15^o < \theta < 165^o$

$\gamma\gamma(\gamma) + \not{E}_T$ (acoplanar photons)

- at least 2 photons with $x > 0.05$ and $15^o < \theta < 165^o$

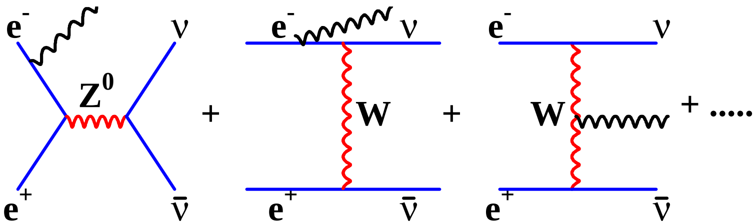
- one photon with $E > 1.75$ GeV and $|\cos\theta| < 0.8$ and a second photon with $E > 1.75$ GeV and $15^o < \theta < 165^o$

Each selection allows for one (and only one) additional photon ($E > 300$ MeV) provided the event is still consistent with the presence of missing E_T

(this reduces sensitivity to modelling of higher-order corrections)

SM Contributions to Photonic Events with Missing Energy

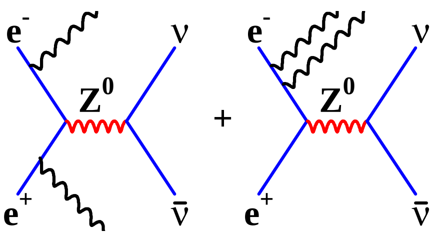
Radiative neutrino pair production $\quad \mathbf{e^+e^-} \rightarrow \nu\bar{\nu} + \mathbf{n}\gamma$



Single photon + missing energy

➡ direct measurement of $\Gamma_{\mathbf{Z}}^{\mathbf{invisible}}$ at LEP1

(count number of light neutrinos)

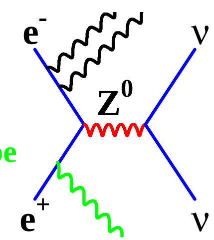


+ W - exchange etc ....

Two photons + missing energy (acoplanar photons)

Radiative return events should have missing mass near M_Z (tails are mostly from W-exchange contribution)

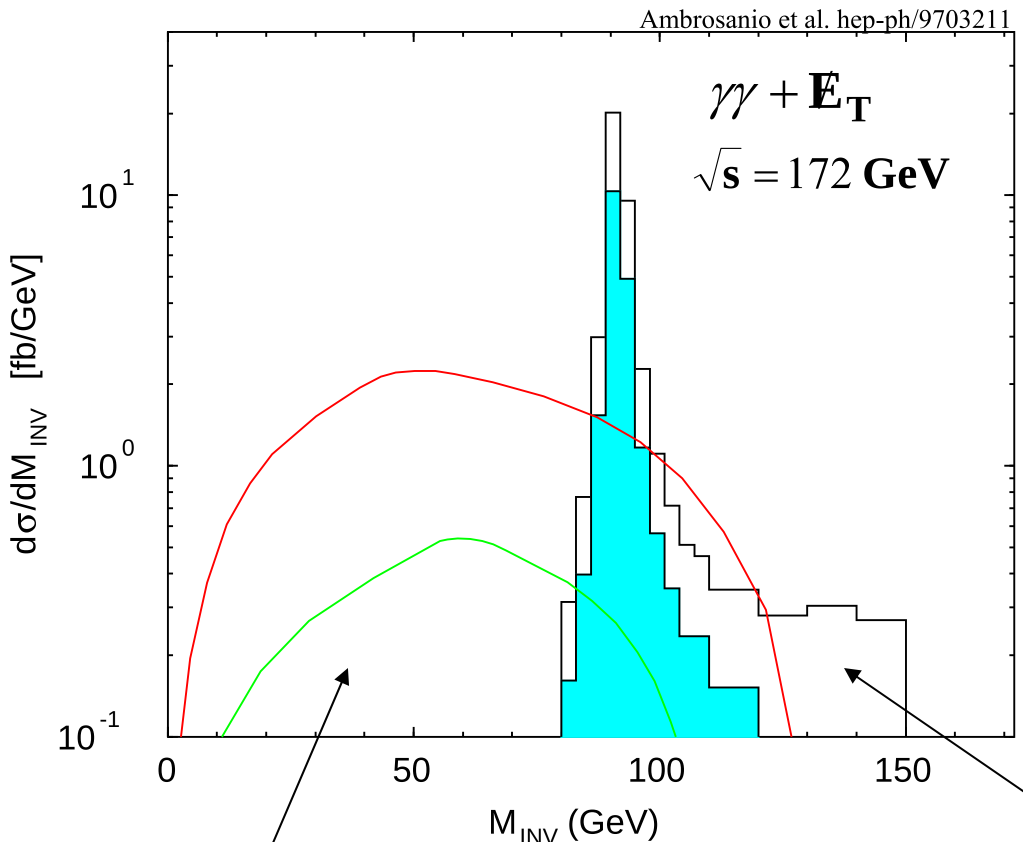
γ lost along beampipe



Higher-order corrections can shift cross-section from the Z peak into the high mass tail (Monte Carlo generators must treat these cases)

(Use KORALZ, NUNUGPV98)

Recoil-Mass Distributions



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

$\mathbf{M}(\tilde{\chi}_1^0) = 75$ **GeV**

$\mathbf{M}(\tilde{\chi}_1^0) = 82$ **GeV**

$e^+e^- \to \nu\bar{\nu}\gamma\gamma$

$e^+e^- \to \nu\bar{\nu}\gamma\gamma$
$(\mathbf{E}_\gamma > 18$ **GeV**$)$

Region favoured by light gravitino models

Mostly high-energy photons

Region favoured by neutralino LSP models

$$\mathbf{M}_{\mathbf{rec}} > 2\mathbf{M}(\tilde{\chi}_1^0)$$

Can get low-energy photons ….

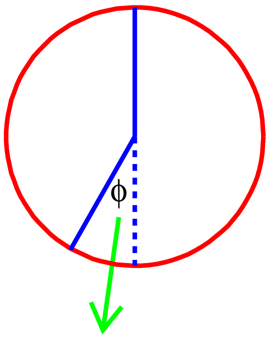
Depends on $\mathbf{M}(\tilde{\chi}_2^0) - \mathbf{M}(\tilde{\chi}_1^0)$

Sources of Reducible Physics Background

Three main classes of other backgrounds to photons missing energy selections:

- Real photonic events i.e. $\mathbf{e^+e^-} \rightarrow \gamma\gamma(\gamma)$

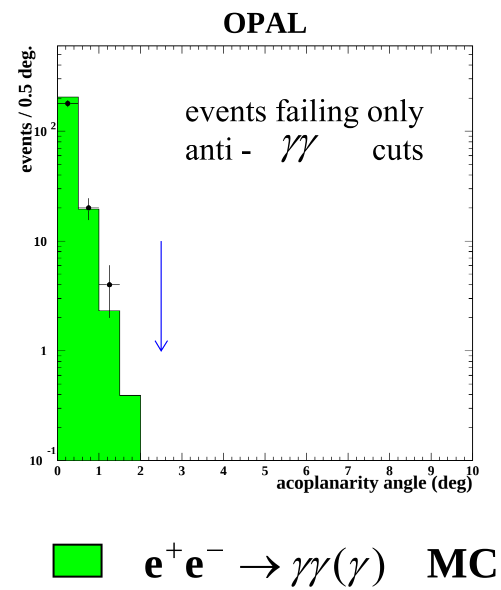
  can be suppressed with kinematic cuts (acoplanarity, total energy, planarity for $\gamma\gamma\gamma$ events)



- Bhabha Events

$\mathbf{e^+e^-} \rightarrow \mathbf{e^+e^-}$ (electons in acceptance i.e. mis-id'd as photons) rejected with kinematic cuts (as above) and vetos against prompt charged tracks (using raw hit information from the three innermost tracking detectors)

Charged track vetoes are designed to retain acceptance to photon conversions



Reducible SM Backgrounds Continued

Radiative Bhabha events

$$\mathbf{e^+e^-} \rightarrow (\mathbf{e^+e^-})\gamma(\gamma)$$

- electrons within kinematic acceptance: suppressed by charged track vetos
- electrons within detector acceptance: suppressed by forward vetos
- electrons outside of detector acceptance: suppressed by visible p_T cuts

Radiative lepton pair production

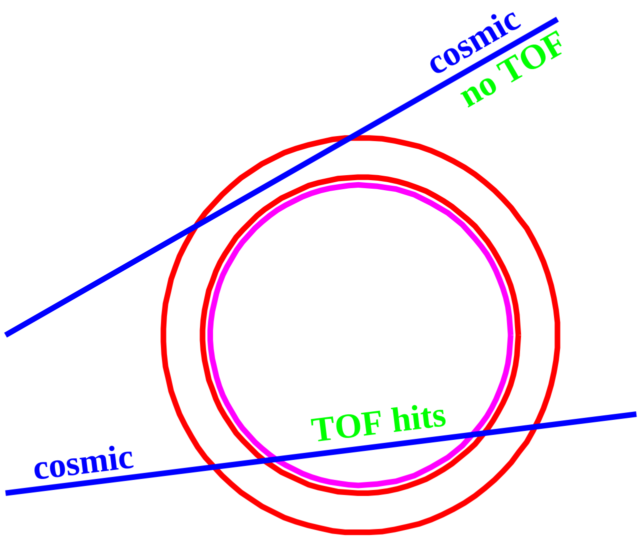
$$\mathbf{e^+e^-} \rightarrow \mu^+\mu^-\gamma(\gamma)$$

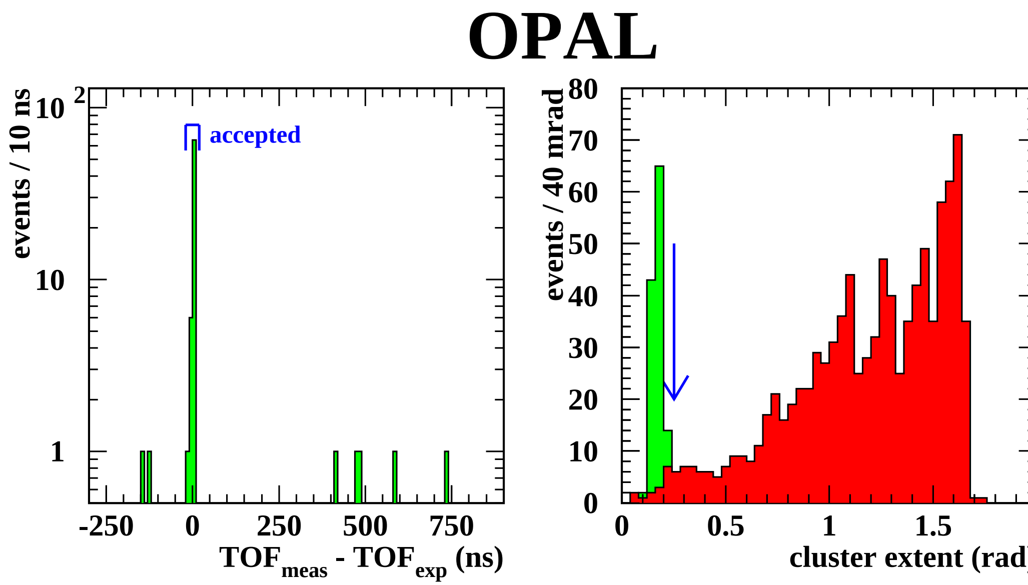
$$\mathbf{e^+e^-} \rightarrow \tau^+\tau^-\gamma(\gamma)$$

- charged particles within kinematic acceptance: suppressed by charged track vetos
- charged particles within detector acceptance: suppressed by forward vetos (MIP Plug)
- charged particles outside of detector acceptance: suppressed by visible p_T cuts

Cosmic Background

Cosmic-ray events can leave energy deposits in the electromagnetic calorimeter with and without timing information from TOF or TE (below for barrel region of detector)





Suppress comic ray contributinons using:

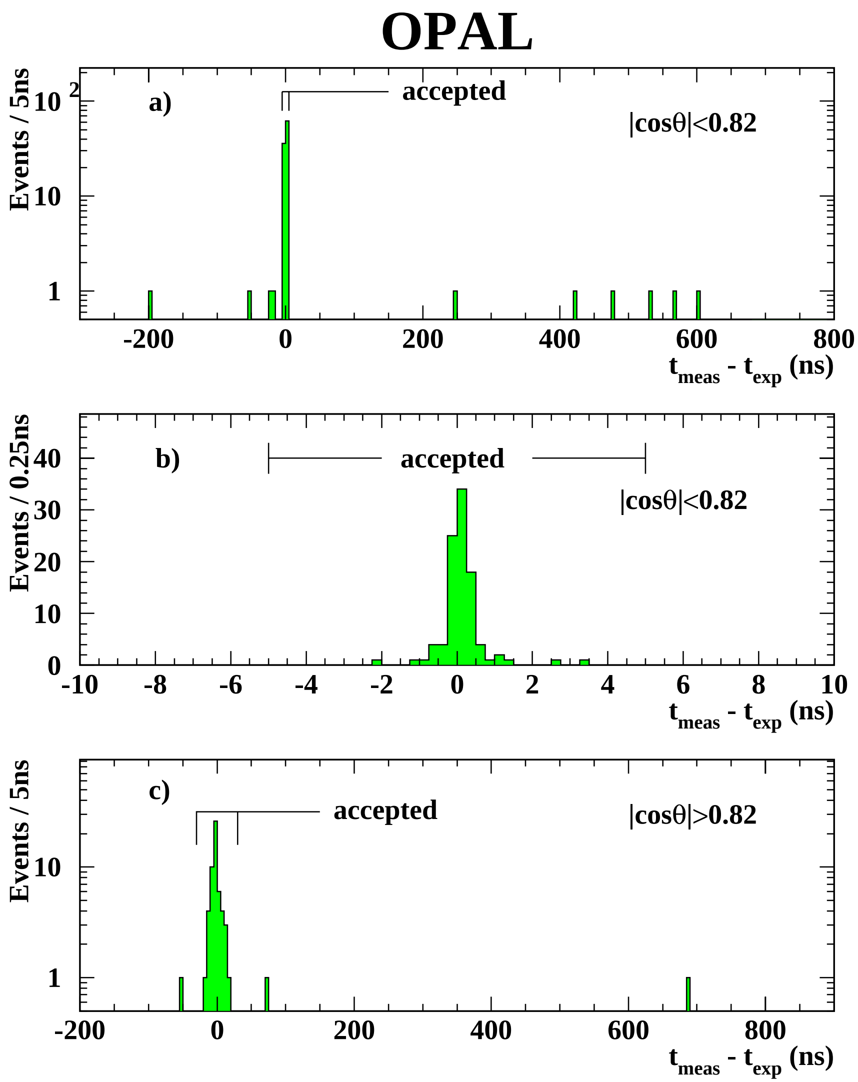
- Timing information (where present)
- HCAL energy deposits
- cluster extent in φ and ϑ
- muon chambers

OPAL data – selected or failing only the timing cut

OPAL data events failing only anti - $e^+e^- \to \gamma\gamma$ cuts

OPAL data events failing TOF timing or TOF timing and HCAL cuts

Timing Resolutions (TB and TE)

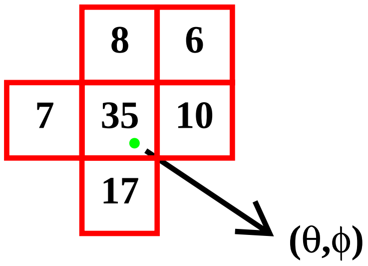


TOF system |cosθ| < 0.82

TE detector system |cosθ| > 0.82

Shower Shape Fit

Fit energy distribution amongst cluster blocks to an idealized shower profile for a photon originating at the interaction point with (θ,φ) as free parameters

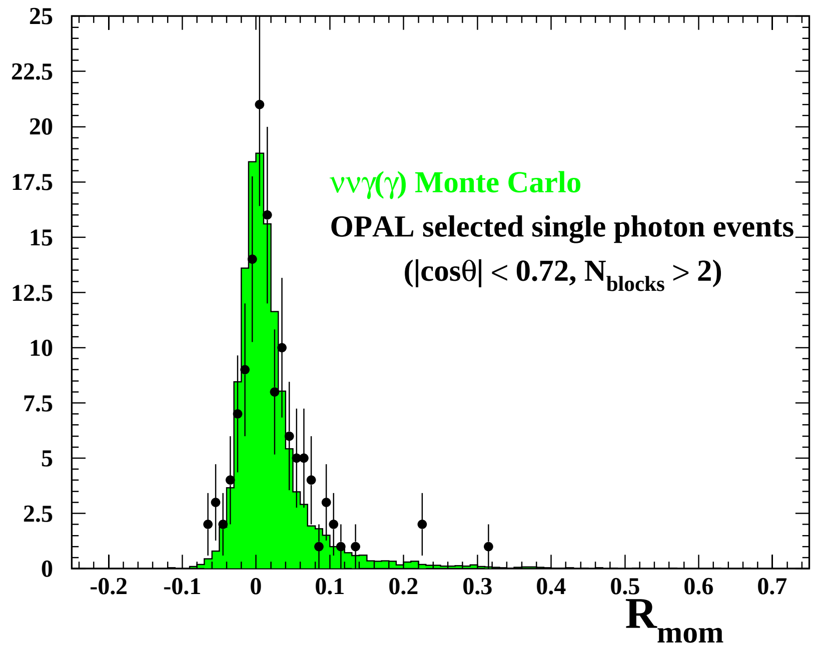


for best-fit (θ,φ) get a fit

$$\chi^2 = \sum_{\mathbf{i}} \frac{\mathbf{E}^{\mathbf{i}}_{\mathbf{meas}} - \mathbf{E}^{\mathbf{i}}_{\mathrm{exp}}}{\sigma^2_{\mathbf{i,meas}}}$$

And a shower width estimator R_{mom} given by

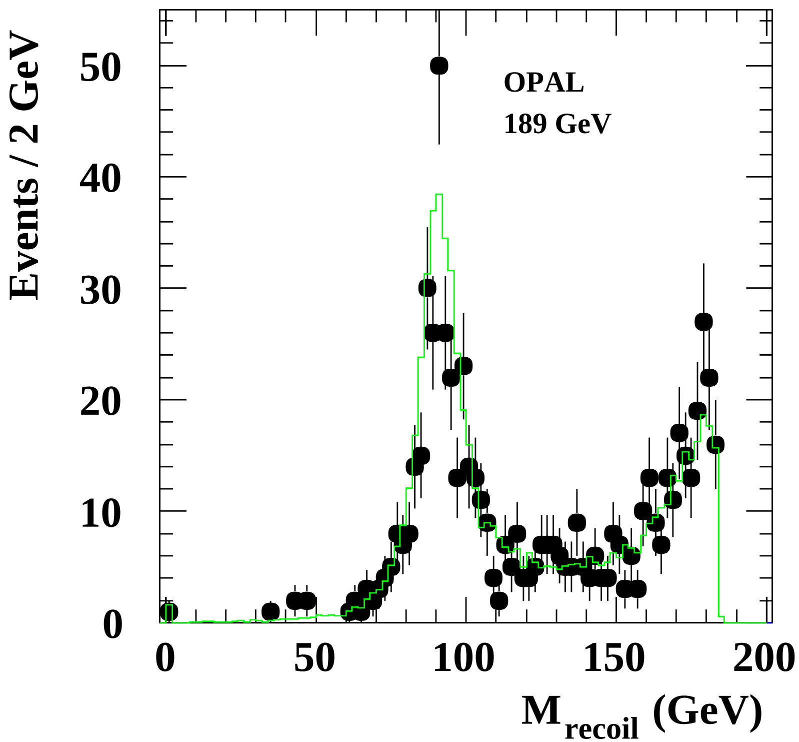
$$\mathbf{R}_{\mathbf{mom}} = \frac{\sum_{\mathbf{i}} \mathbf{r}_{\mathbf{i}} (\mathbf{E}^{\mathbf{i}}_{\mathbf{meas}} - \mathbf{E}^{\mathbf{i}}_{\mathrm{exp}})}{\sum_{\mathbf{i}} \mathbf{E}^{\mathbf{i}}_{\mathbf{meas}}} = \langle \mathbf{r} \rangle_{\mathbf{meas}} - \langle \mathbf{r} \rangle_{\mathrm{exp}}$$

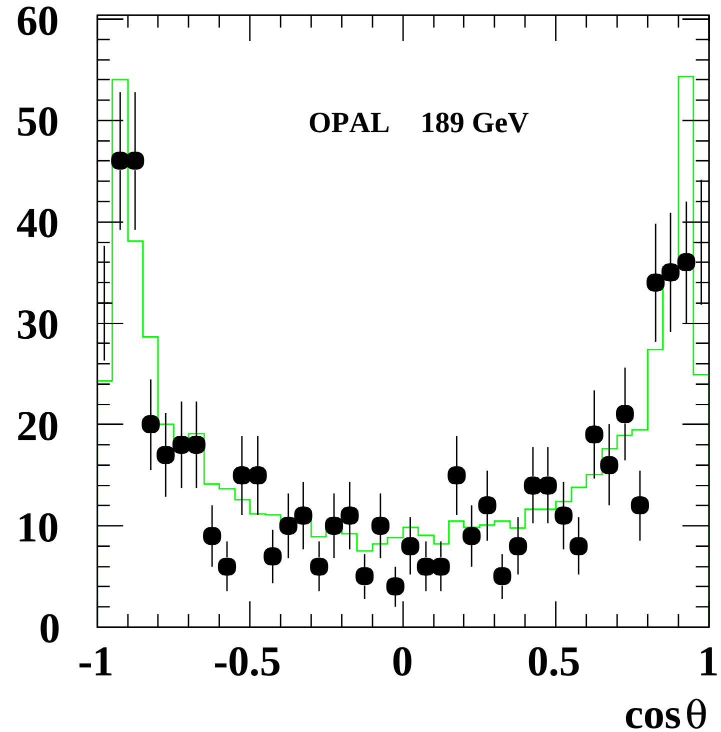


Where r_i is the radial distance (in X_o) from the shower origin

No hint for $\tilde{\chi}^0_1 \tilde{\mathbf{G}}$ with lifetime

Results of Single Photon + Missing Energy Selection





643 events selected

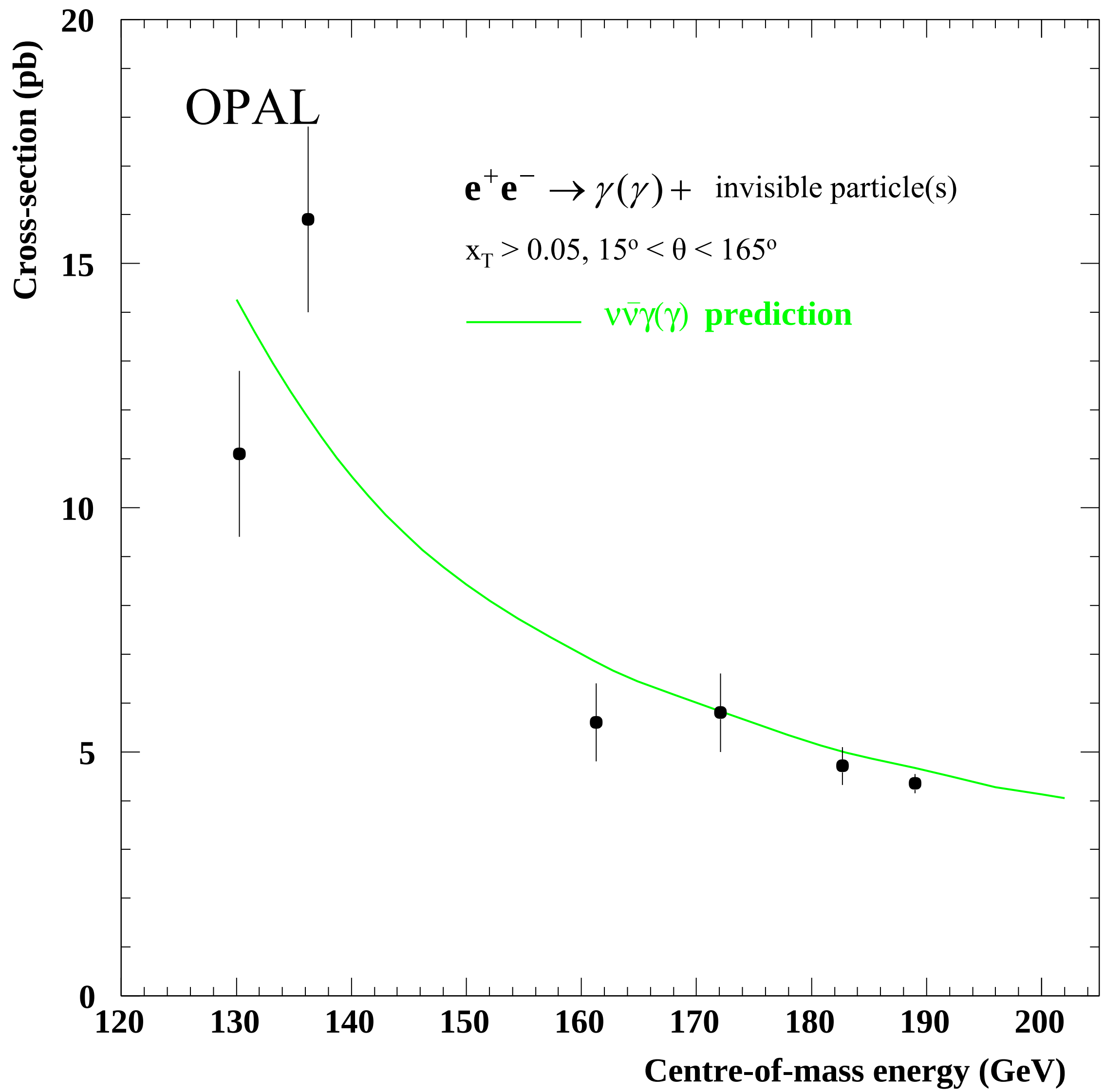
679 ± 5 ± 14 events expected from the SM process $\mathbf{e}^+\mathbf{e}^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$

9.2 ± 1.6 background events expected from other sources

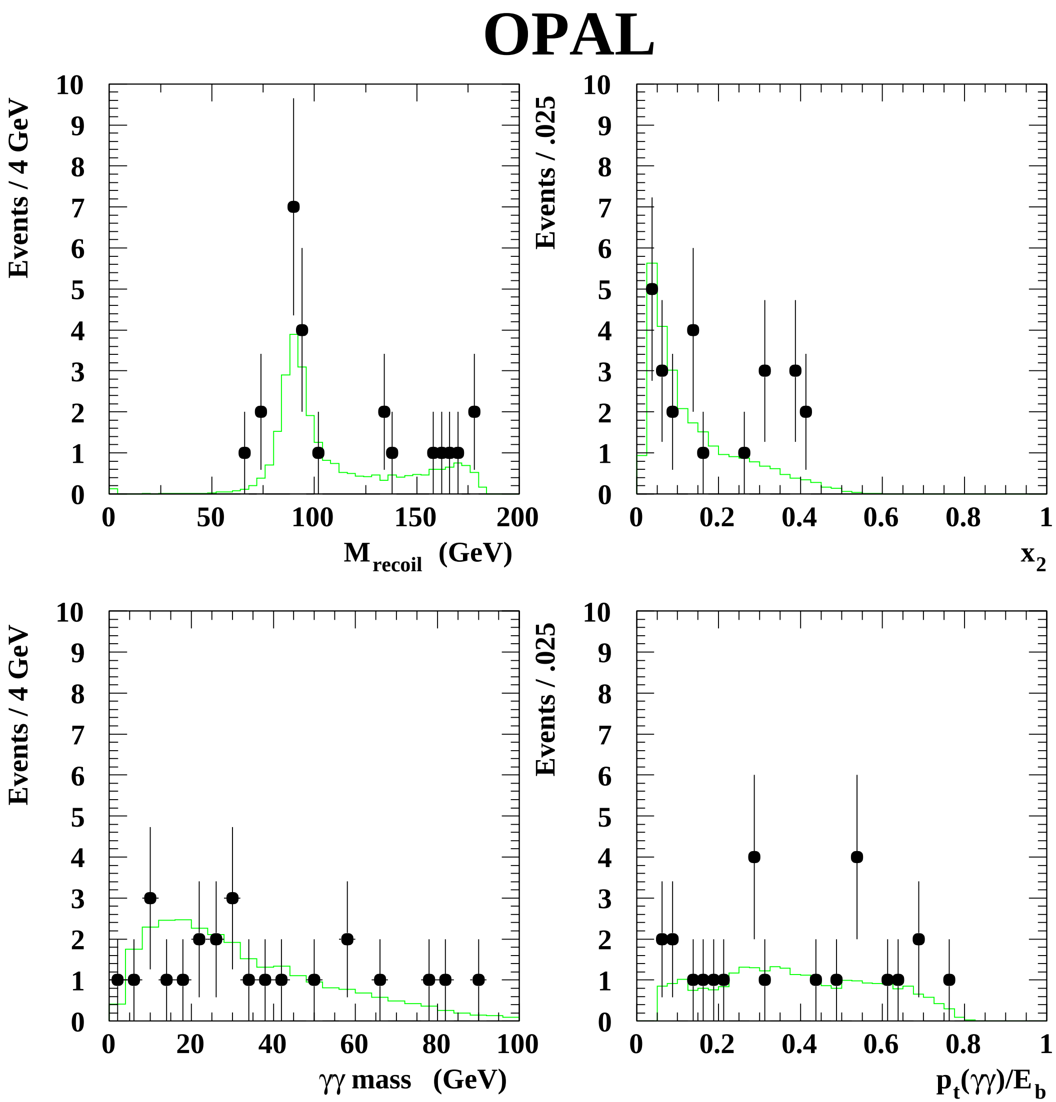
36 events with an additional γ with E_γ > 300 MeV (compared to a SM expectation of 33.6 ± 1.5

Selection efficiency 82.1 ± 1.7 %

Single Photon + Missing Energy Cross-Section



Results of Acoplanar Photons Selection



24 events selected

26.9 ± 1.2 expected from $e^+e^- \to \nu\bar{\nu}\gamma\gamma$

1 three photon event selected
(vs 1.20 ± 0.08 expected)

0.11 ± 0.04 background events expected

Selection efficiency 66.4 ± 2.9 %

Limits on Contributions from New Physics

Sensitivity to low energy photons needed for massive LSP scenario

Large geometric acceptance keeps high efficiency reduces model dependence associated with the assumption of angular distributions for new physics contributions

In absence of an excess, use results of single (acoplanar) photons selections to derive general (~model independent) limits on cross-section of contributions from the process

$$\mathbf{e^+e^- \to XY\ (XX),\quad X \to Y}\gamma$$

Assuming isotropic production and decay angular distributions

$\tilde{\chi}_1^0$	**LSP scenario**	$\mathbf{X} = \tilde{\chi}_2^0$	$\mathbf{Y} = \tilde{\chi}_1^0$
$\tilde{\mathbf{G}}$	**LSP scenario**	$\mathbf{X} = \tilde{\chi}_1^0$	$\mathbf{Y} = \tilde{\mathbf{G}}$

Quote limits separately for the two cases ($M_Y > 0$, $M_Y \sim 0$)

Kinematic Consistency Requirements

Limits set separately at each point (M_X , M_Y) plane

Reconstruction efficiencies for signal events are taken from fully simulated Monte Carlo events at grid points in the (M_X , M_Y) plane and then parametrized.

Restrict to (M_X , M_Y) points with $\mathbf{M_X + M_Y > M_Z}$ $(\gamma + \not{E}_T)$

$\mathbf{M_X > M_Z}/2$ $(\gamma\gamma + \not{E}_T)$

(radiative return to Z followed by Z decay to XY or XX has different kinematics than those assumed for the signal process)

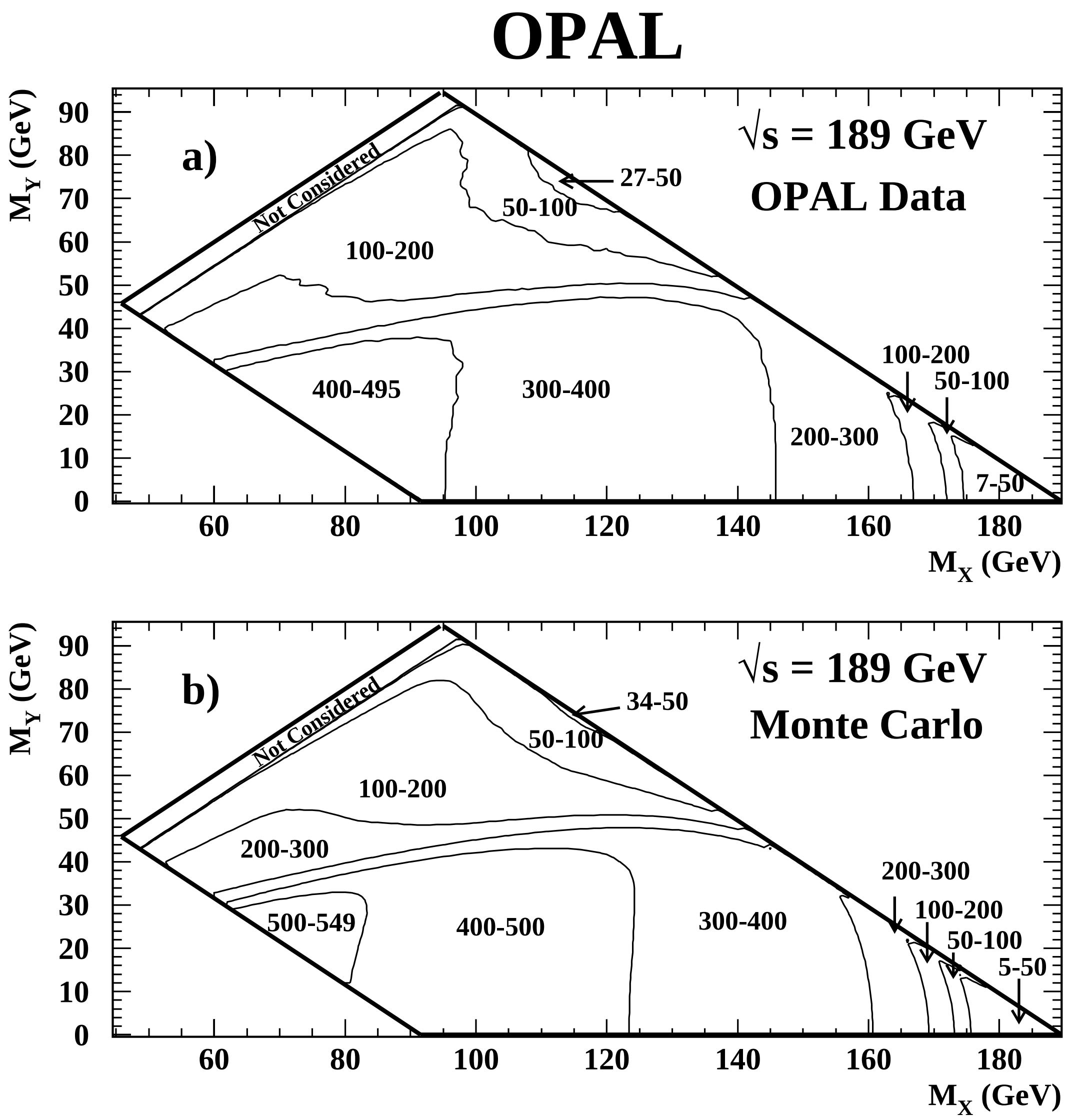
Restrict to mass differences above $M_X - M_Y > 5$ GeV (efficiency drops)

At each (M_X , M_Y) point require candidate events to be kinematically consistent

with $\mathbf{e^+e^- \rightarrow XY\ (XX)}$, $\mathbf{X \rightarrow Y}\gamma$ production and decay process

e.g. $E(\gamma_1)$, $E(\gamma_2)$ in the region allowed by two-body kinematics + resolution

Selection of Single Photon Events in (M_X, M_Y)

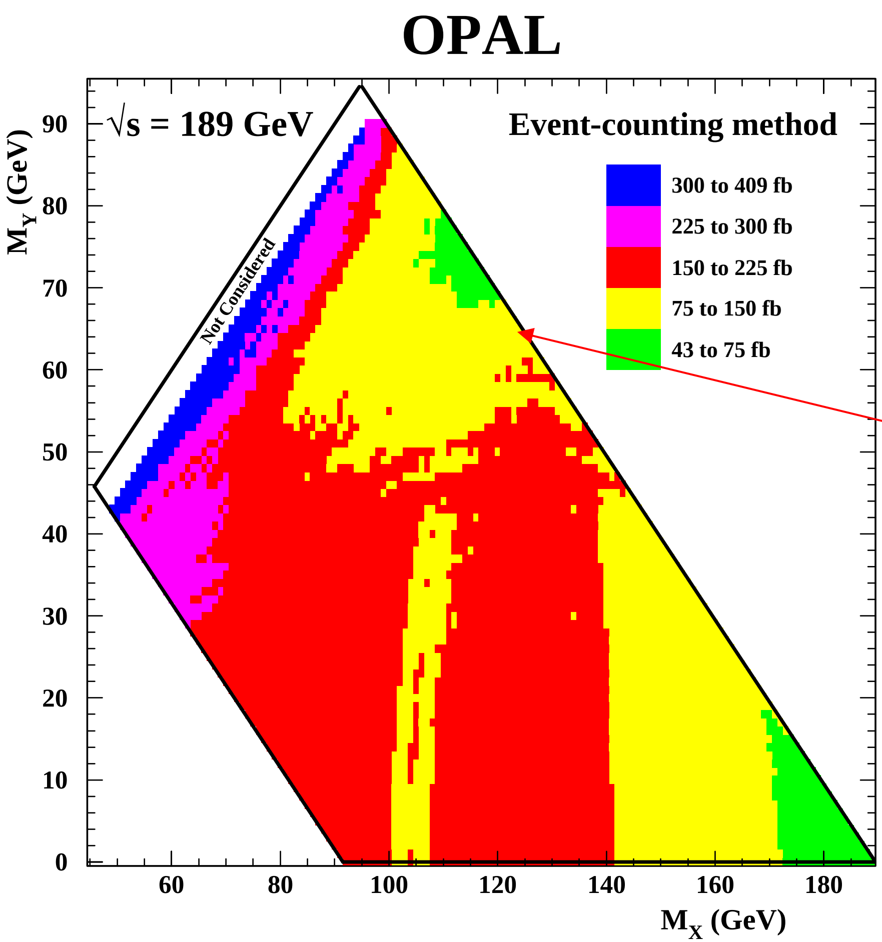


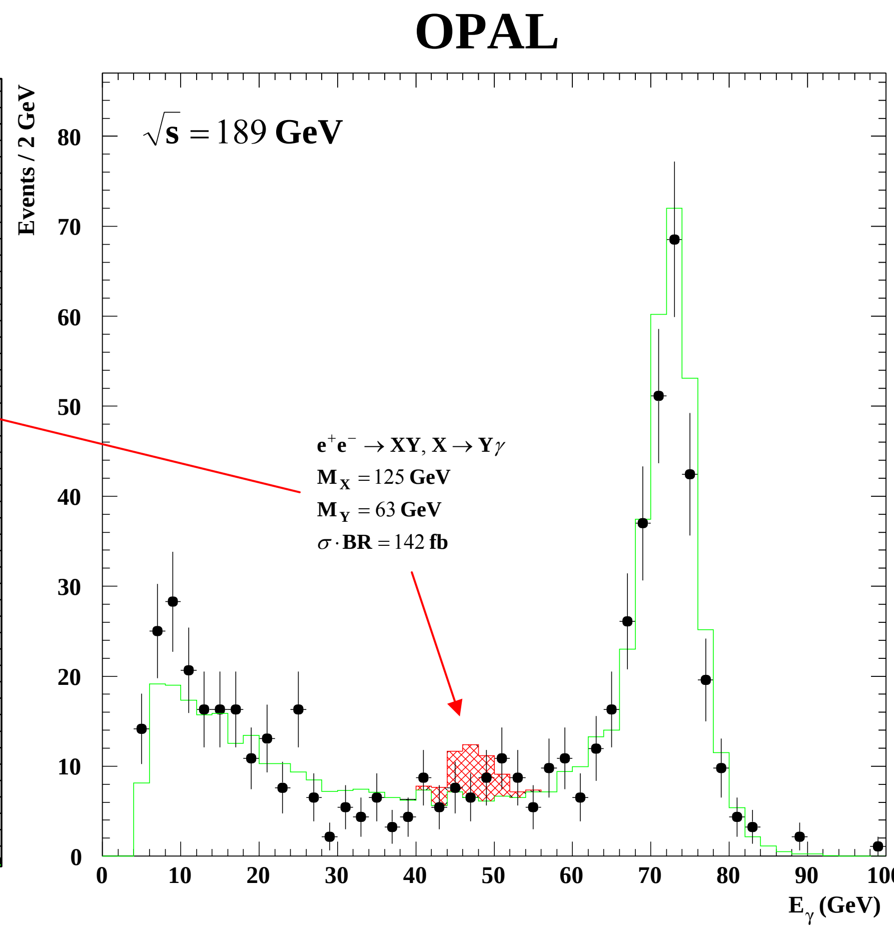
$$e^+e^- \rightarrow XY, \quad X \rightarrow Y\gamma$$

For new-physics searches events in regions of the detector with poor energy resolution are rejected

Limits are based on 552 events selected vs 601 ± 14 expected from SM

General Limits from Single Photon Analysis

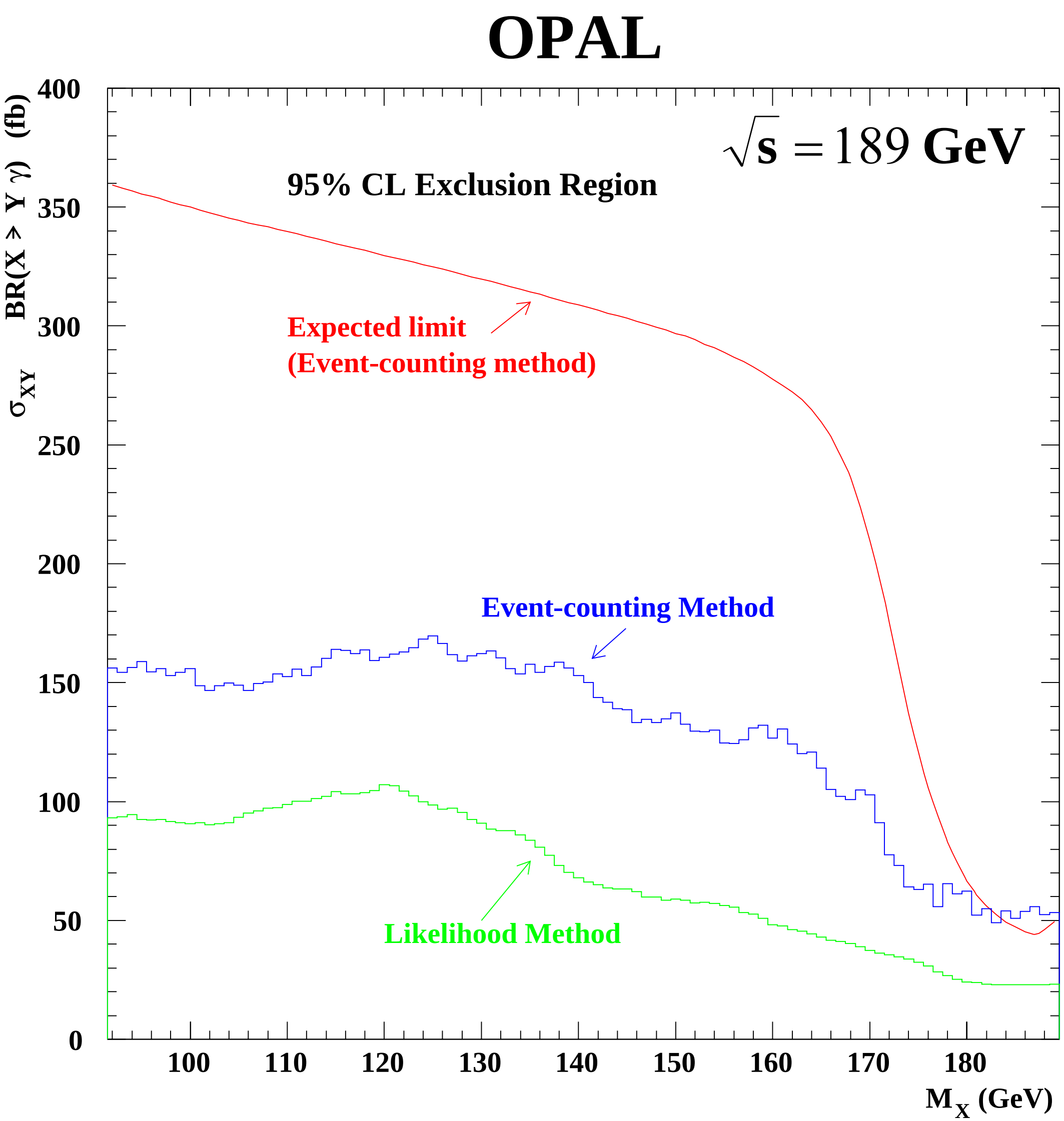




Limits are on $\sigma(\mathbf{e^+e^-} \to \mathbf{XY}) \times \mathbf{BR}(\mathbf{X} \to \mathbf{Y}\gamma)$ (at 95% confidence level)

(for instance $\mathbf{e^+e^-} \to \tilde{\chi}_2^0 \tilde{\chi}_1^0,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$)

Single Photon Limits for the Case $M_Y \sim 0$



Limits are on

$$\sigma(\mathbf{e}^+\mathbf{e}^- \to \mathbf{XY}) \times \mathbf{BR}(\mathbf{X} \to \mathbf{Y}\gamma)$$

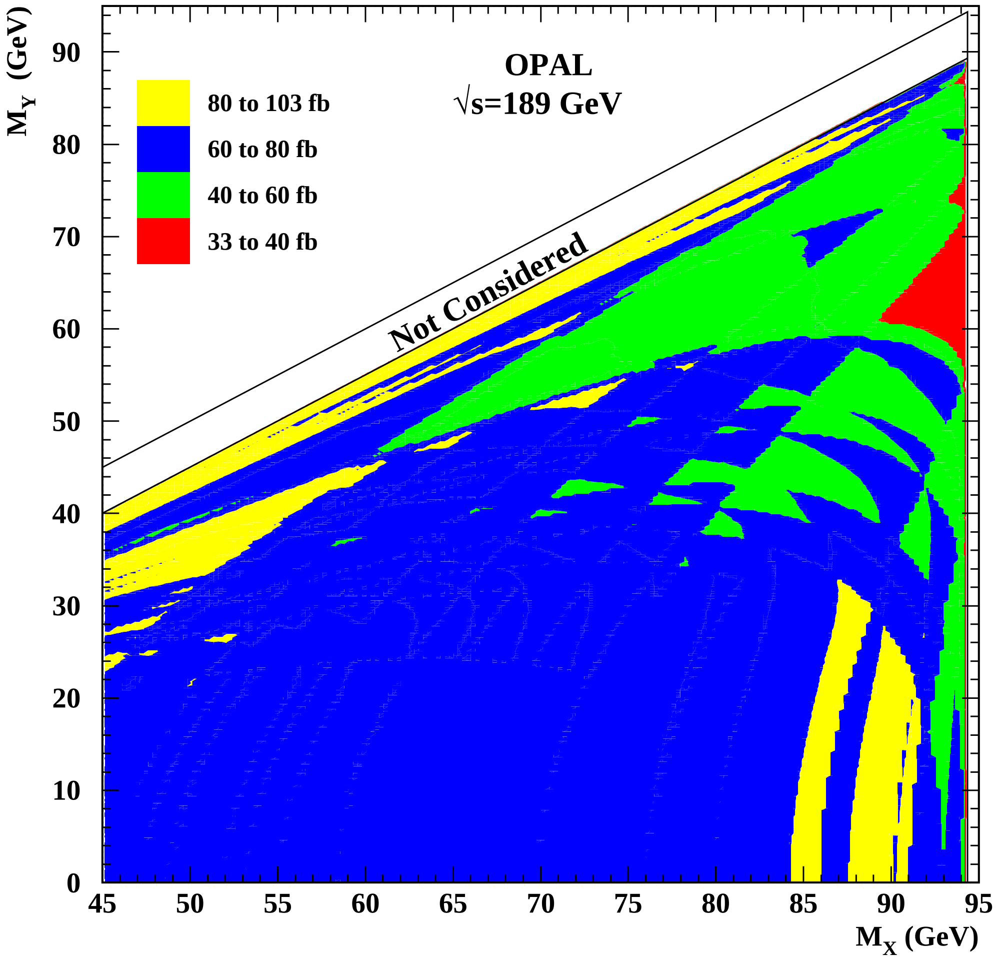
(at 95% confidence level) for the case of massless Y

e.g. $\mathbf{e}^+\mathbf{e}^- \to \tilde{\chi}_1^0 \tilde{\mathbf{G}},\ \tilde{\chi}_1^0 \to \tilde{\mathbf{G}}\gamma$

Limits lower than expected limit due to overall deficit in number of selected events

General Limits From Acoplanar Photons Analysis

95% CL upper limits on $\sigma(\mathbf{e^+e^-} \to \mathbf{XX}) \times \mathbf{BR}^2(\mathbf{X} \to \mathbf{Y}\gamma)$ from acoplanar photons analysis



e.g. $\mathbf{e^+e^-} \to \tilde{\chi}_2^0\tilde{\chi}_2^0,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$

Numbers of events expected and selected agree well across entire (M_X, M_Y) plane

General limits from single-photon and acoplanar photon analyses are included in scan of CMSSM parameter space

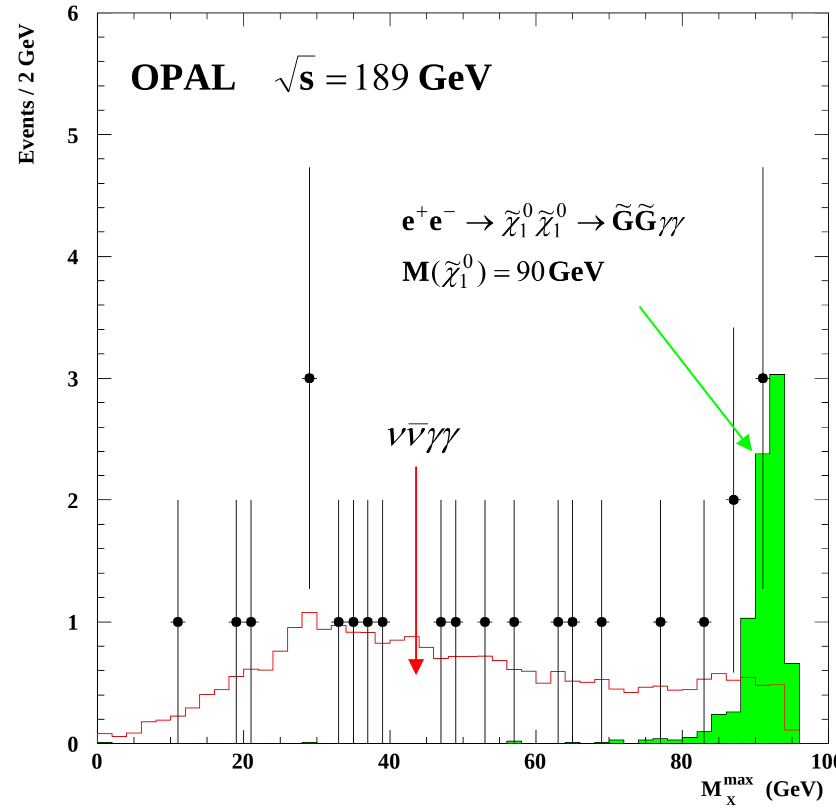
→ an absolute limit on the mass of the lightest neutralino

$\mathbf{M}(\tilde{\chi}_1^0) > 31.6\ \mathbf{GeV}$ (95% **CL**)

$\mathbf{M_X^{max}}$ Kinematic Consistency for Acoplanar Photons

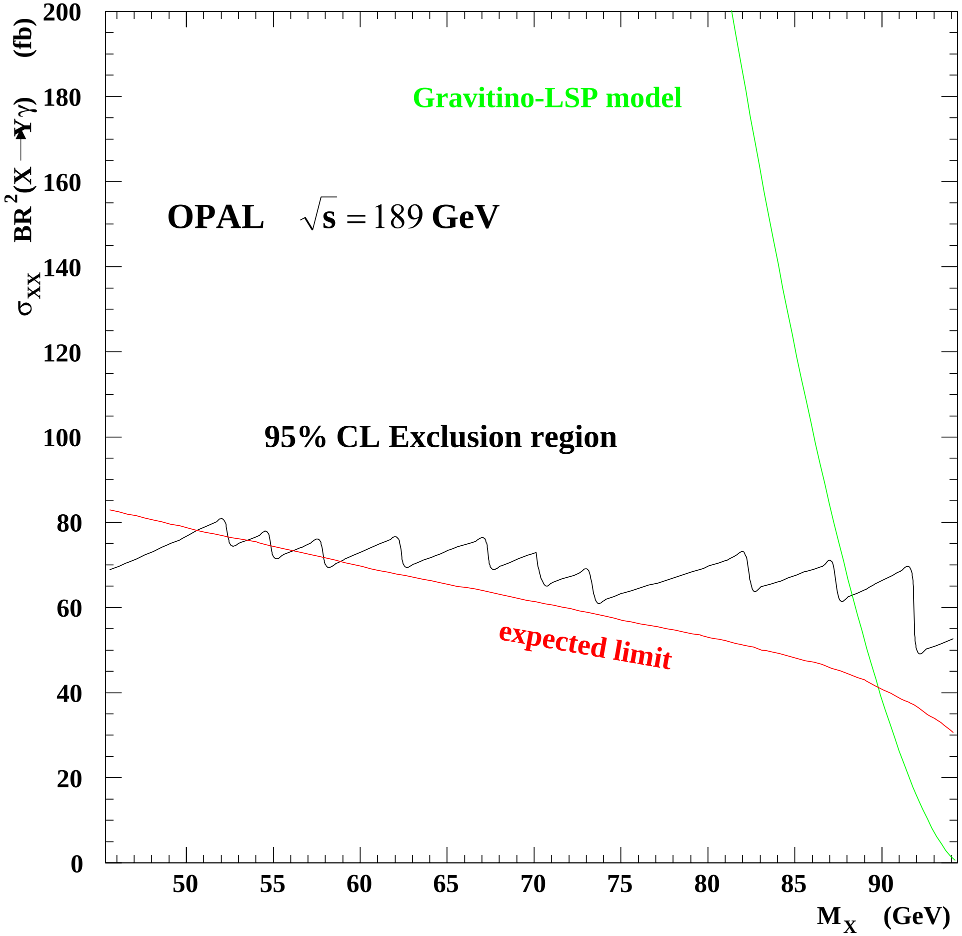
Calculate $\mathbf{M_X^{max}}$, the maximum mass for which each selected event is kinematically consistent with coming from the decay sequence $\mathbf{e^+e^- \to XX}$, $\mathbf{X \to Y\gamma}$ for massless Y (Uses full event kinematics instead of photon energies only)

M_X (GeV)	efficiency	efficiency with $\mathbf{M_X^{max} > M_X - 5\,GeV}$	N_{data}	$N_{\nu\bar{\nu}\gamma\gamma}$
94	72.2 ± 1.2 %	70.4 ± 1.2 %	3	1.34 ± 0.07
90	71.3 ± 1.2 %	67.5 ± 1.2 %	5	2.40 ± 0.09
80	72.3 ± 1.2 %	68.7 ± 1.2 %	7	4.81 ± 0.13
70	71.4 ± 1.2 %	69.2 ± 1.2 %	9	7.22 ± 0.15
60	74.0 ± 1.1 %	71.1 ± 1.2 %	11	10.05 ± 0.18
50	70.2 ± 1.2 %	67.7 ± 1.2 %	14	13.67 ± 0.20



Acoplanar Photons for Light Gravitino Scenario ($M_Y \sim 0$)

95% CL upper limit on $\sigma(\mathbf{e^+e^-} \to \mathbf{XX}) \times \mathbf{BR}^2(\mathbf{X} \to \mathbf{Y}\gamma)$ for $M_Y \sim 0$



e.g. $\mathbf{e^+e^-} \to \tilde{\chi}_1^0 \tilde{\chi}_1^0,\ \tilde{\chi}_1^0 \to \tilde{\mathbf{G}}\gamma$

Light gravitino model has

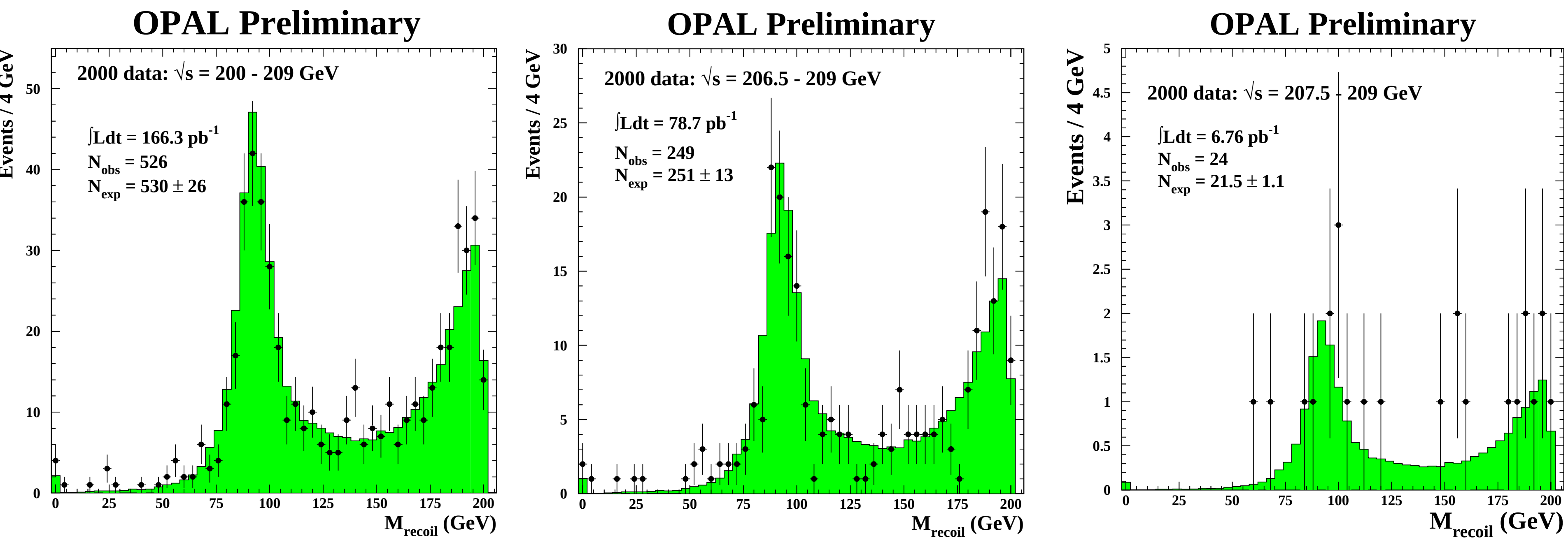
$\tilde{\chi}_1^0 \equiv \tilde{\mathbf{B}}$

$\mathbf{M}(\tilde{\mathbf{e}}_\mathbf{R}) = 1.35\,\mathbf{M}(\tilde{\chi}_1^0)$

$\mathbf{M}(\tilde{\mathbf{e}}_\mathbf{L}) = 2.7\ \ \mathbf{M}(\tilde{\chi}_1^0)$

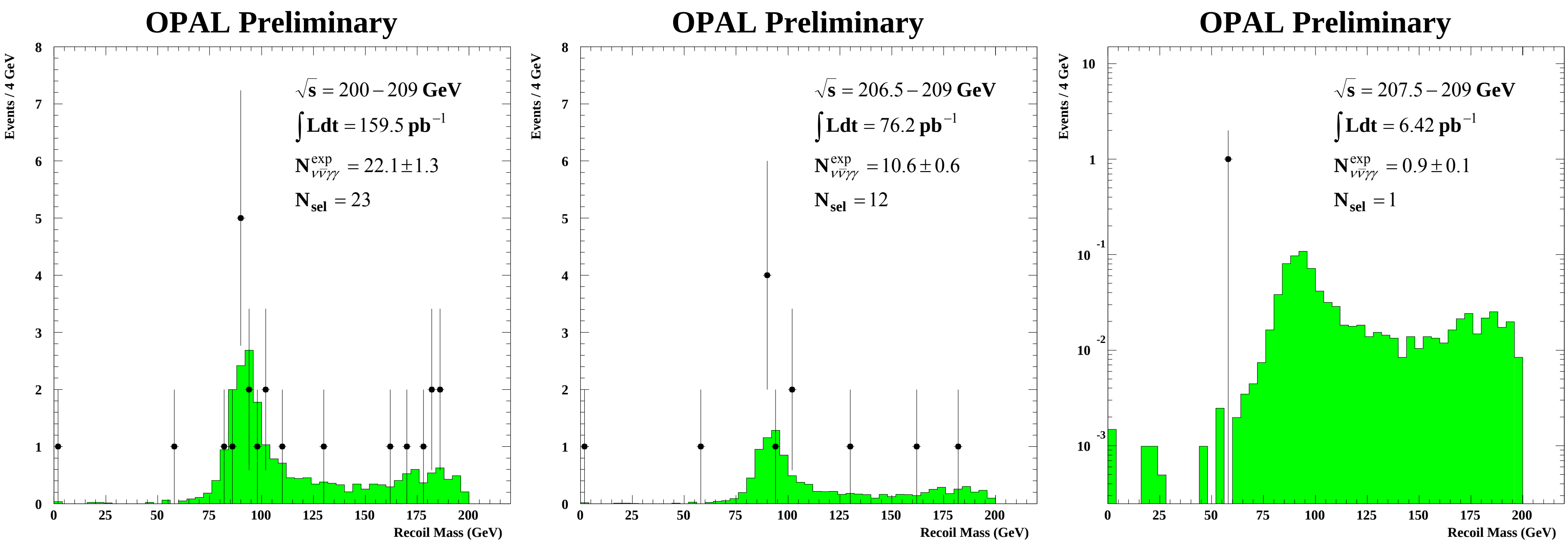
$\tilde{\chi}_1^0$ masses between 45 GeV and 88.3 GeV are excluded at 95% CL

Updated Results for Single-photon Selection



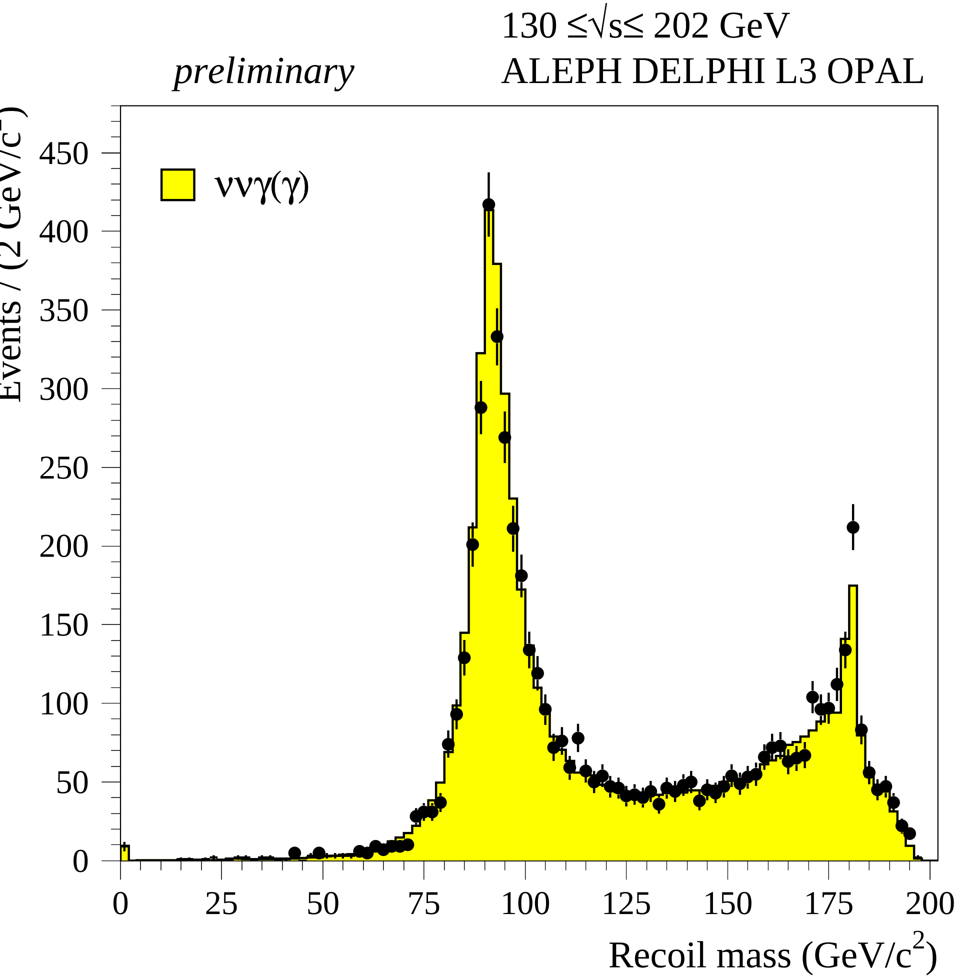
No evidence for non-Standard Model contributions to single photon plus missing energy final states in highest energy data samples from LEP

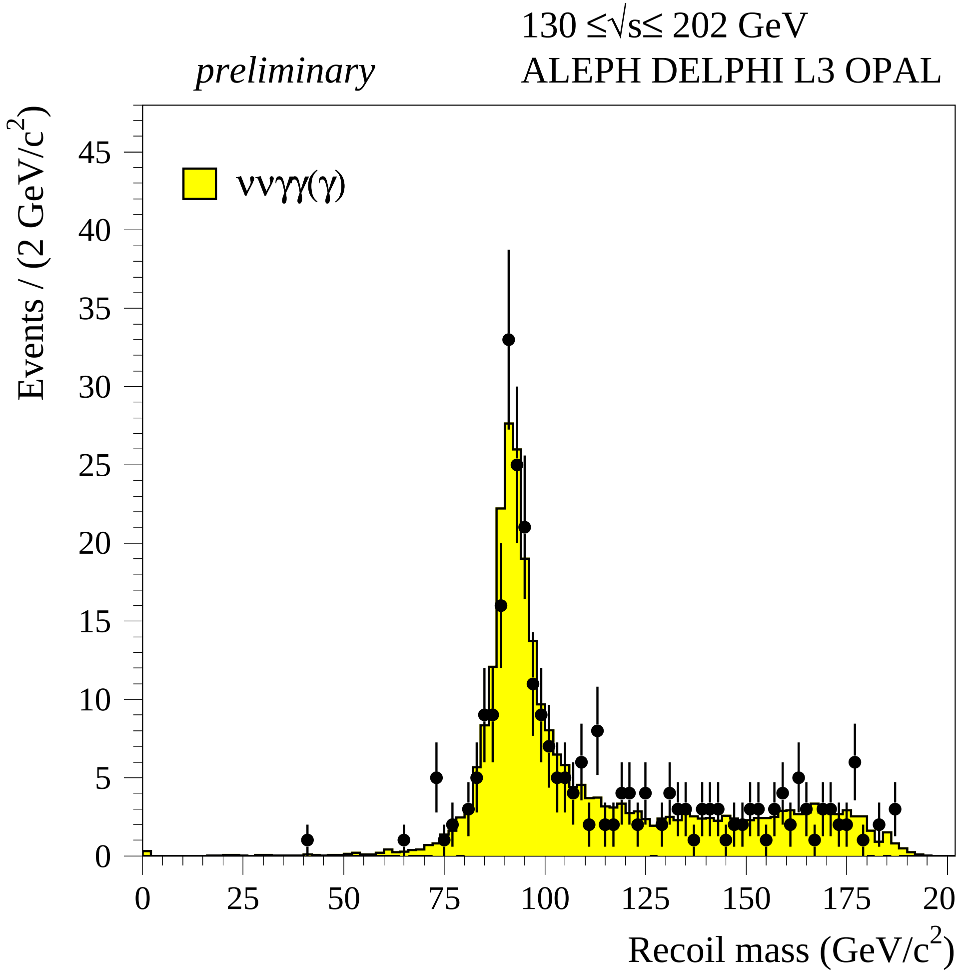
Updated Results for Acoplanar-photons Selection



No evidence for non-Standard Model contributions to acoplanar photons final states in highest energy data samples from LEP

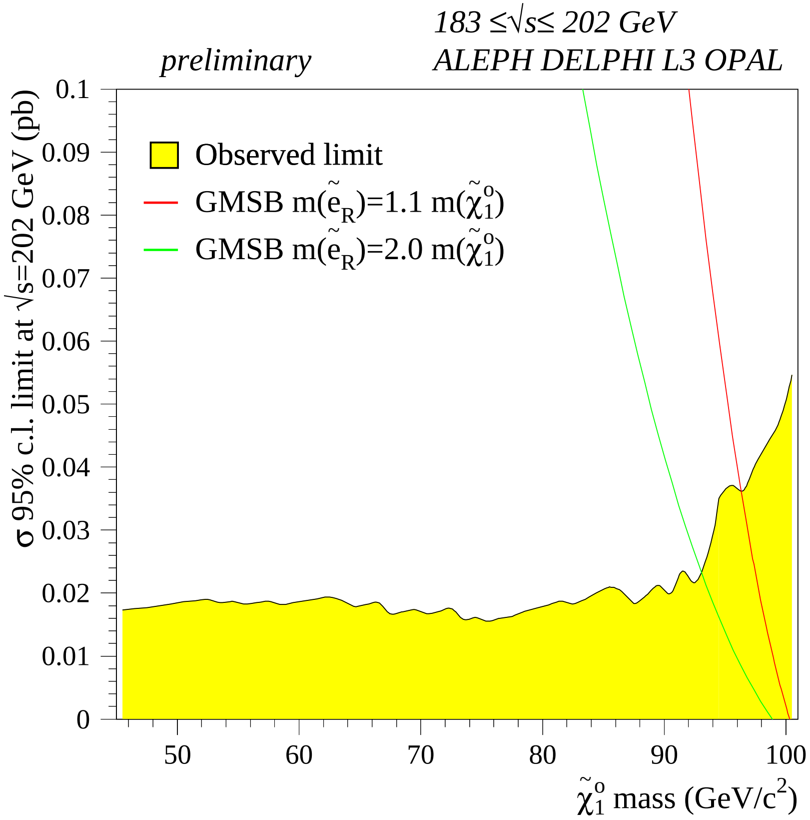
Recoil Mass Distributions from LEP SUSY WG

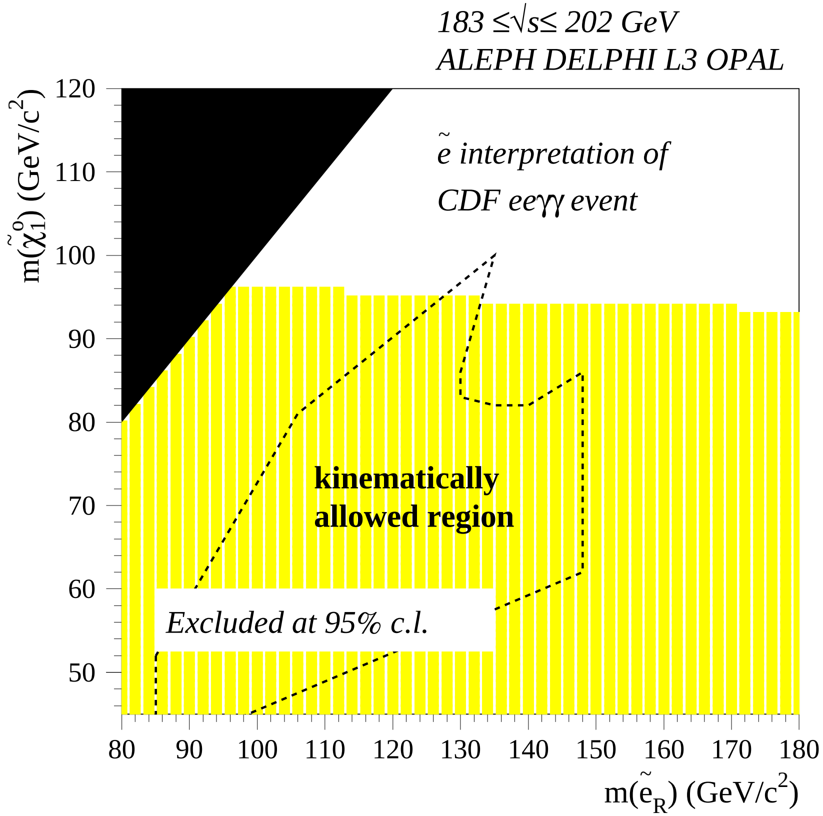




LEP SUSY Combined Limits on Light Gravitino Scenario

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

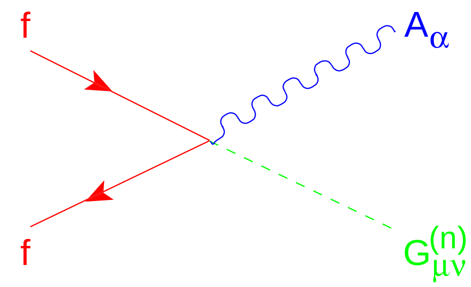




Searches for Large Compact Extra Dimensions

- Direct Searches $\mathbf{e^+e^- \rightarrow G_{KK}\gamma}$

  $\rightarrow \gamma + \not{E}_T$ final state



- Indirect Searches

Boson pair production

$$\mathbf{e^+e^- \rightarrow \gamma\gamma}$$

$$\mathbf{e^+e^- \rightarrow ZZ}$$

Fermion pair production

$$\mathbf{e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-}$$

Total / differential cross-sections, asymmetries etc modified by graviton exchange

Direct Searches: Graviton photon production

$\gamma + \not{E}_T$ final state: use results of single photon selection

$$\frac{d^2\sigma}{dx_\gamma d\cos\theta} = \frac{\alpha S_{n-1}}{64 M_D^2}\left(\frac{\sqrt{s}}{M_D}\right)^n f(x_\gamma, \cos\theta)$$

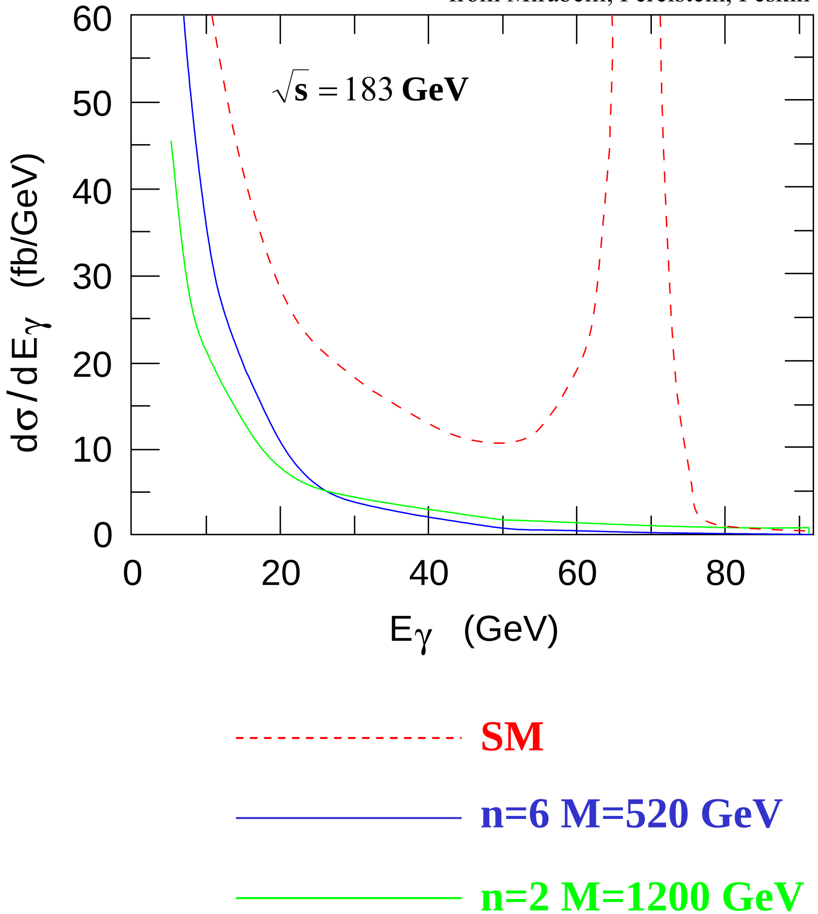
$$f(x_\gamma, \cos\theta) = \frac{2(1-x_\gamma)^{\frac{n}{2}-1}}{x_\gamma(1-\cos^2\theta)}\left[(2-x_\gamma)^2(1-x_\gamma+x_\gamma^2)\right.$$
$$\left. -3x_\gamma^2\cos^2\theta(1-x_\gamma) - x^4\cos^4\theta\right]$$

$$\sigma \propto s^{n/2} / M_D^{n+2}$$

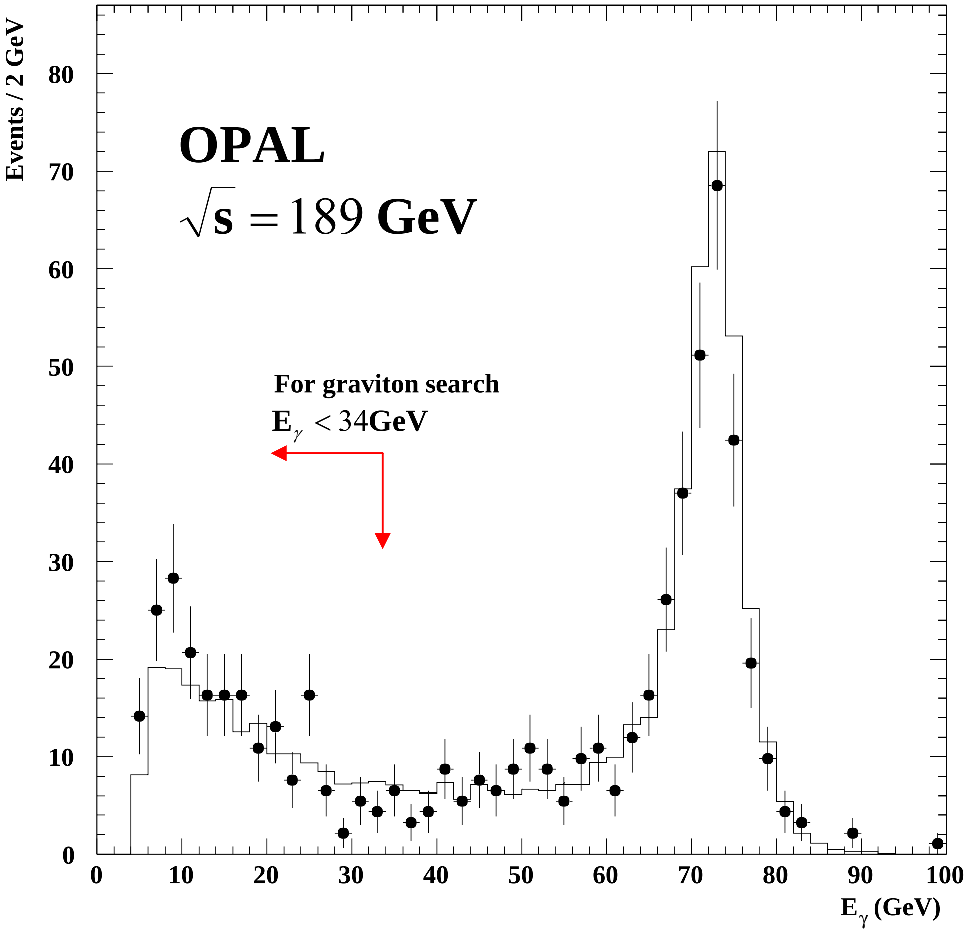
Cross-section rises as powers of $\sqrt{s}$

Cross-section rises at low E_γ

from Mirabelli, Perelstein, Peskin



OPAL Direct Search for $e^+e^- \to \gamma G_{KK}$



Cut on maximum photon energy chosen to minimize the limit expected in the absence of signal

n	2	3	4	5	6	7
σ^{95} (fb)	309	298	290	283	276	271
M_D^{95} (GeV)	1086	862	710	605	528	470

$\sigma^{95} \equiv$ Limit on cross-section within defined kinematic acceptance

$M_D^{95} \equiv$ Corresponding lower limit on 4+n dimensional Planck scale

208 candidates selected (196.0 ± 5.9 expected from $\nu\bar{\nu}\gamma$)

Photonic Events with No Missing Energy

$$\mathbf{e^+e^-} \rightarrow \gamma\gamma(\gamma) \qquad \left(\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega}\right)_{\mathbf{Born}} = \frac{\alpha^2}{\mathbf{s}}\frac{1+\cos^2\vartheta}{1-\cos^2\vartheta} \qquad (\beta\sim 1)$$

Negligible electroweak contributions at LEP energies

QED differential cross-section extremely well known – good place to look for contributions from non-standard processes

Event selection utilizes kinematic properties of QED events: acollinearity, planarity (three photon events), total energy deposit in ECAL

Background from events with primary charged tracks rejected using charged track vetos similar to those discussed earlier

Virtual Graviton Exchange Contributions to $e^+e^- \to \gamma\gamma$

Exchange of virtual KK gravitons modifies total and differential cross-sections

$$\left(\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega}\right)_{\mathbf{LSG}} = \left(\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega}\right)_{\mathbf{Born}} \pm \; 2\frac{\alpha \mathbf{s}}{\pi^3}\frac{|\lambda|}{\mathbf{M_S^4}}(1+\cos^2\theta) + \frac{\mathbf{s}^3}{16\pi^3}\left[\frac{|\lambda|}{\mathbf{M_S^4}}\right]^2(1-\cos^4\theta)$$

Interference term **Graviton exchange term**

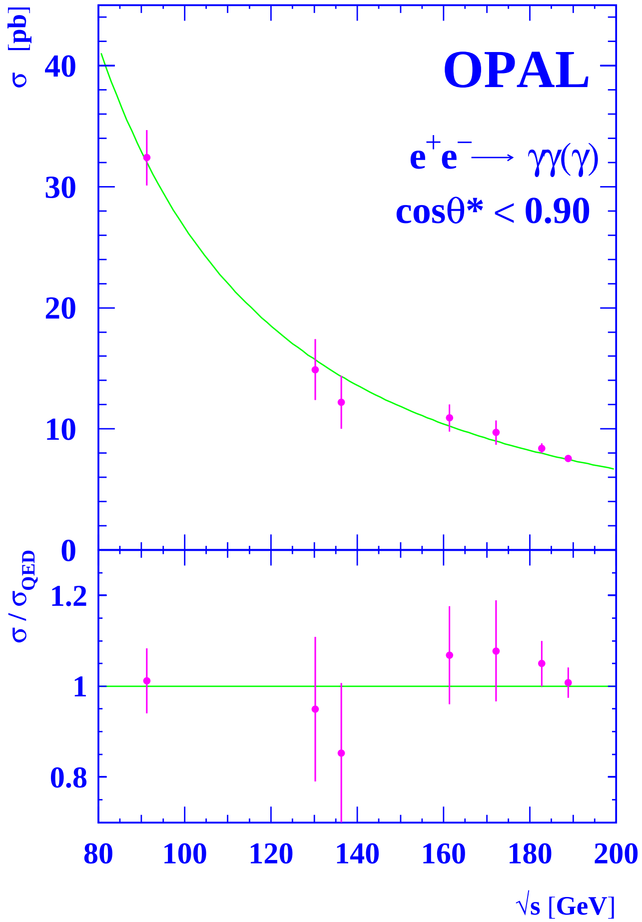
Limits set on $\mathbf{M_S}(\lambda = \pm 1)$ (different signs of interference)

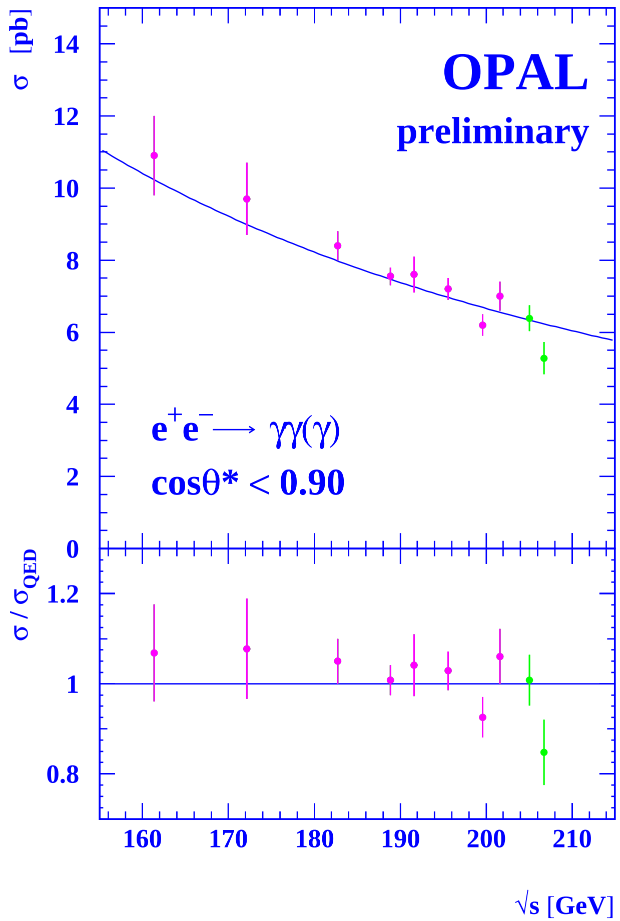
N.B. $\boxed{\dfrac{\mathbf{M_S}}{\mathbf{M_D}} \approx O(1)}$

λ parameterizes additional effects which depend on details of quantum gravitational theory. Contains (weak) dependence on number of extra dimensions

Photonic Events with No Missing Energy

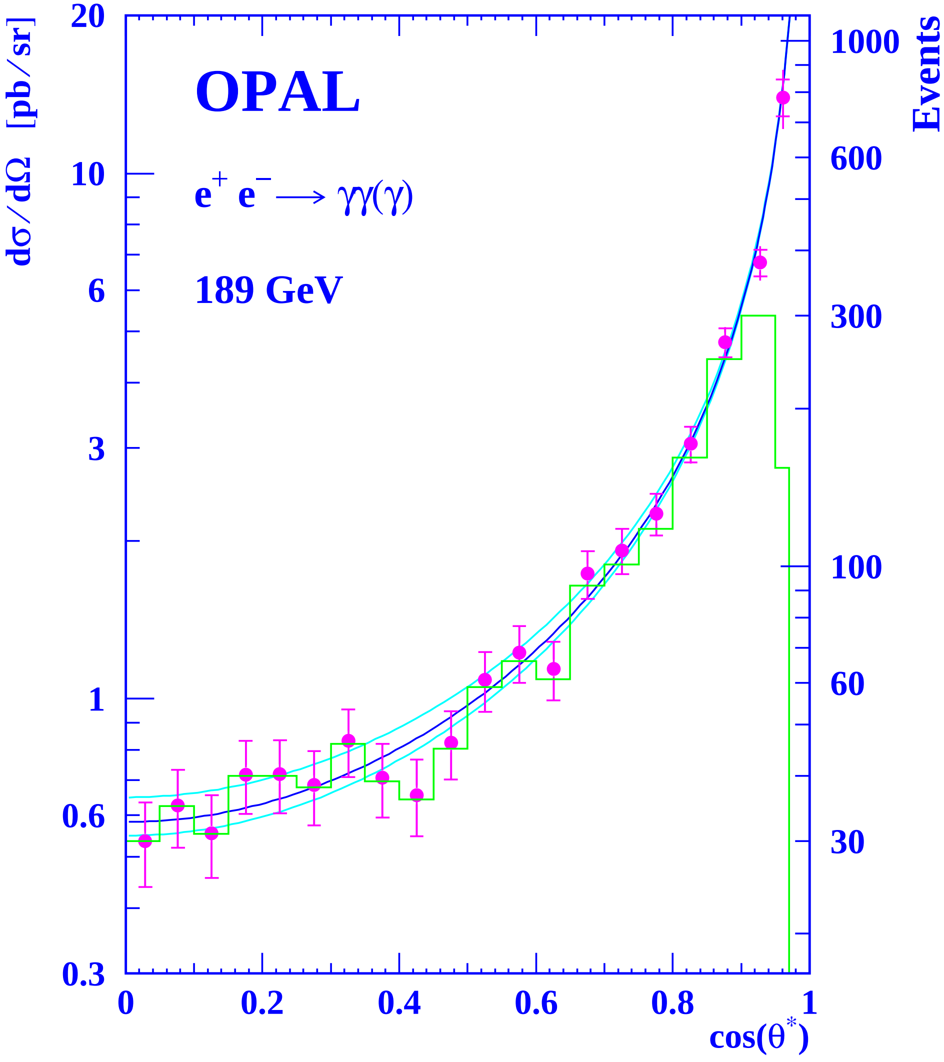
OPAL $\mathbf{e^+e^-} \rightarrow \gamma\gamma(\gamma)$ selections at $\sqrt{\mathbf{s}} \geq 189$ **GeV**





Measured cross-sections consistent with SM expectations: set limits on new physics contributions

Searches with Photonic Events with no Missing Energy



1740 event selected

1776 events expected from SM

Displayed fit is to function

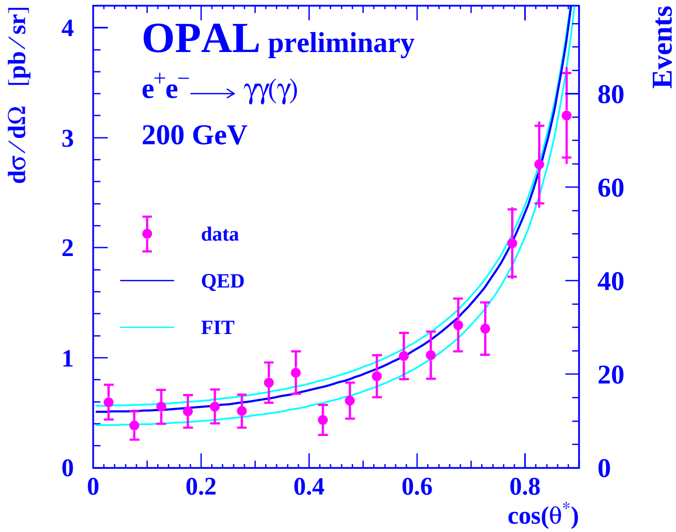
$$\left(\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega}\right)_{\Lambda_\pm} = \left(\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega}\right)_{\mathbf{Born}} \pm \frac{\mathbf{s}^2}{2\Lambda_\pm^4}(1+\cos^2\theta)$$

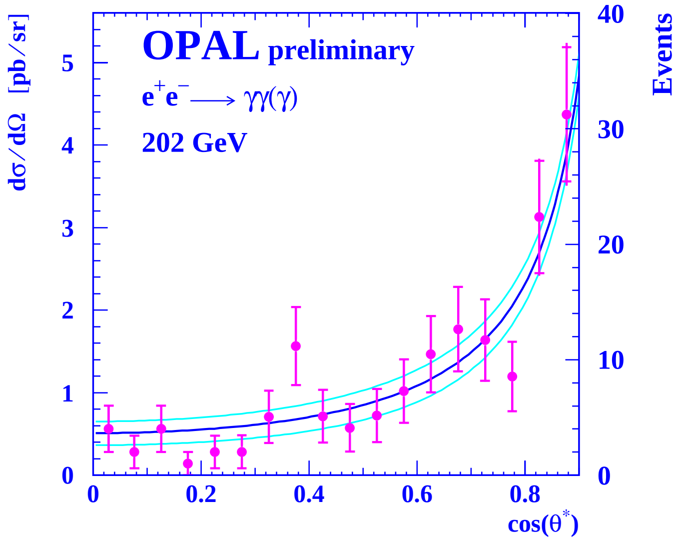
Fit also to $\left(\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega}\right)_{\mathbf{LSG}}$

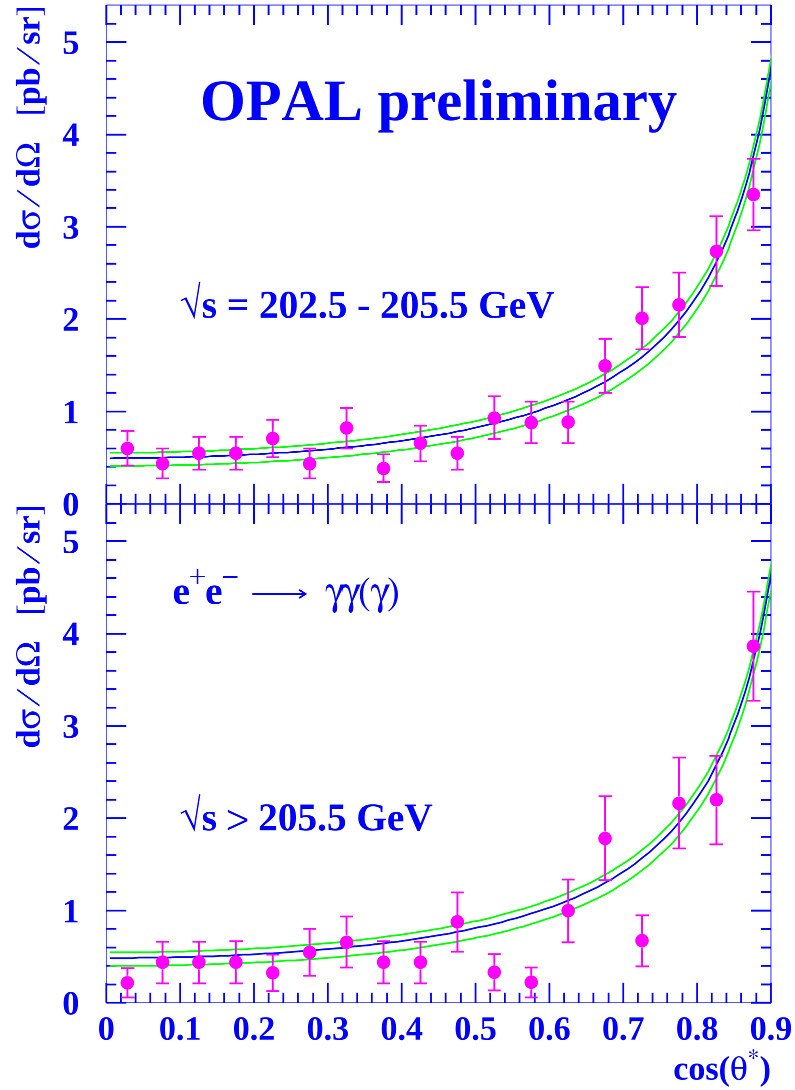
$\mathbf{M_S} > 714\ \mathbf{GeV} \quad (\lambda = +1)$

$\mathbf{M_S} > 785\ \mathbf{GeV} \quad (\lambda = -1)$

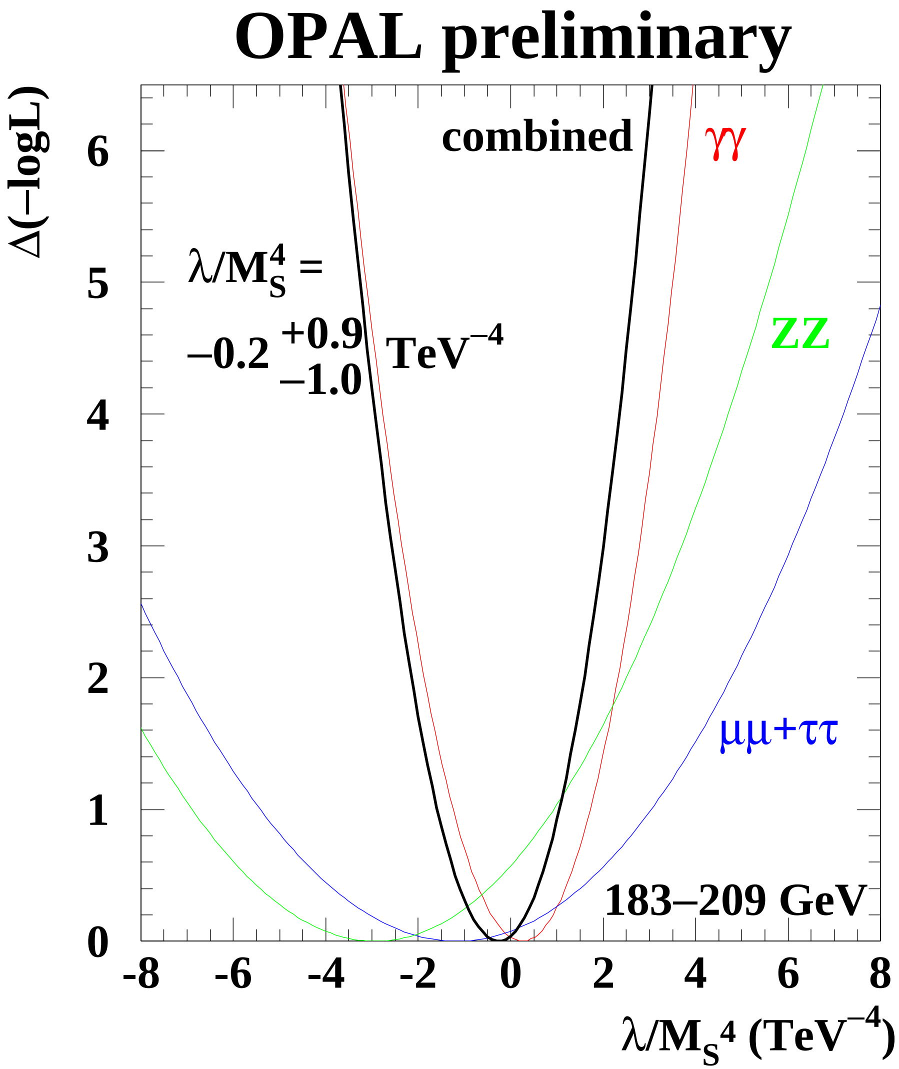
Updated Results for $e^+e^- \to \gamma\gamma(\gamma)$







OPAL Results on Indirect Searches for LSG



channel	Lower limit on M_S $\sqrt{s}$	$\lambda = 1$	$\lambda = -1$
$e^+e^- \to \mu^+\mu^-$	183 – 189	0.63	0.60
$e^+e^- \to \tau^+\tau^-$	183 – 189	0.50	0.63
$e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$	183 – 189	0.61	0.68
$e^+e^- \to \gamma\gamma$	183 – 209	0.85	0.82
$e^+e^- \to Z^0Z^0$	183 – 209	0.59	0.80
combined		0.83	0.90

Other Physics Results from Photonic Event Analyses

Photonic final states with missing energy

- Neutrino counting (as at LEP1)
- Excited neutrinos $\mathbf{e}^+\mathbf{e}^- \to \nu^*\nu^{(*)}, \nu^* \to \nu\gamma$ $\longrightarrow$ single (acoplanar) photon final state
  (Limits for $\mathbf{e}^+\mathbf{e}^- \to \mathbf{XY}\ (\mathbf{XX}),\quad \mathbf{X} \to \mathbf{Y}\gamma$ with $M_Y \sim 0$ apply)
- Search for trilinear neutral ($Z\gamma Z$, $Z\gamma\gamma$) gauge couplings (single photon final state)
- Search for anomalous quartic gauge boson couplings (acoplanar photons final state)
- gravitino pair production for superlight gravitino $\mathbf{e}^+\mathbf{e}^- \to \tilde{\mathbf{G}}\tilde{\mathbf{G}}\gamma$

Photonic final states without missing energy

- contact interactions ($\gamma\gamma e^+e^-$) or non-standard γe^+e^- couplings
- excited electrons (e^*) with $e^*e\gamma$ coupling (via t-channel contribution)
- Resonant contribution to $\mathbf{e}^+\mathbf{e}^- \to \gamma\gamma$ ($\mathbf{e}^+\mathbf{e}^- \to \mathbf{X}\gamma, \mathbf{X} \to \gamma\gamma$)

The Future

LEP now being decommissioned

Accelerator and associated experiments have had an excellent decade – many high precision tests of the SM, many searches for the physics that lies beyond it

BUT

Still no evidence for physics beyond the SM (and especially for Supersymmetry)

At the LHC (starting 2006/2007)

Cross-sections for SUSY particles are potentially very large at the LHC

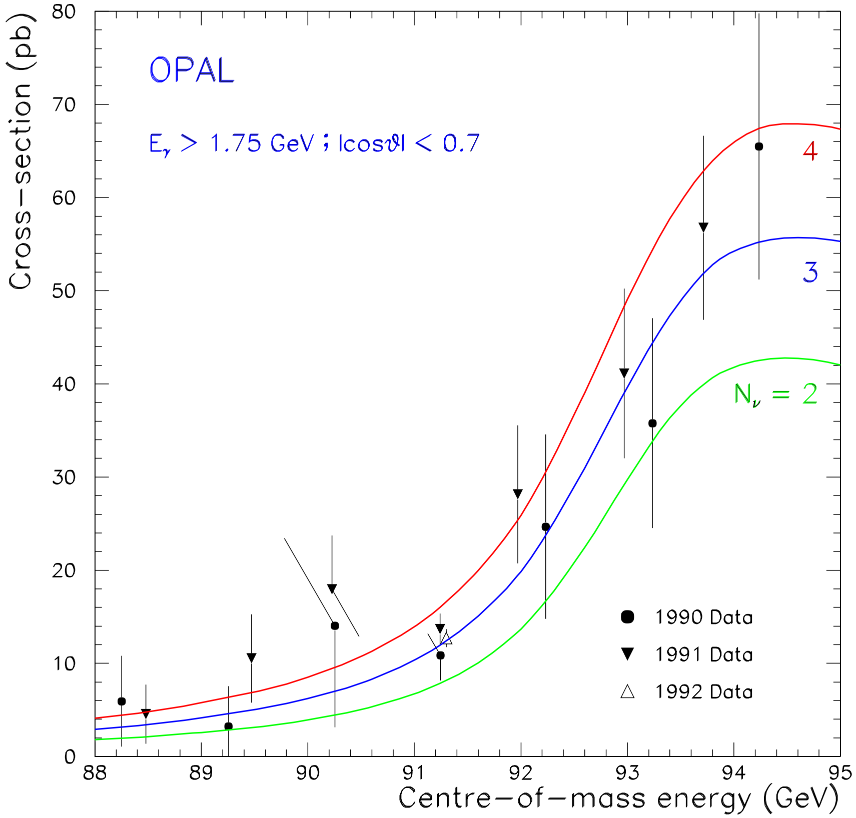
Typically can discover weak-scale SUSY with a single year of running at low luminosity (10^{33} cm^{-2}s^{-1})

Models with low-scale gravity predict some potentially spectacular signatures at the LHC.

These searches (SUSY and LSG) will remain interesting and current for some time

Neutrino Counting With Single Photon Events

LEP1 – direct measurement of Z^0 invisible linewidth



PDG 2000

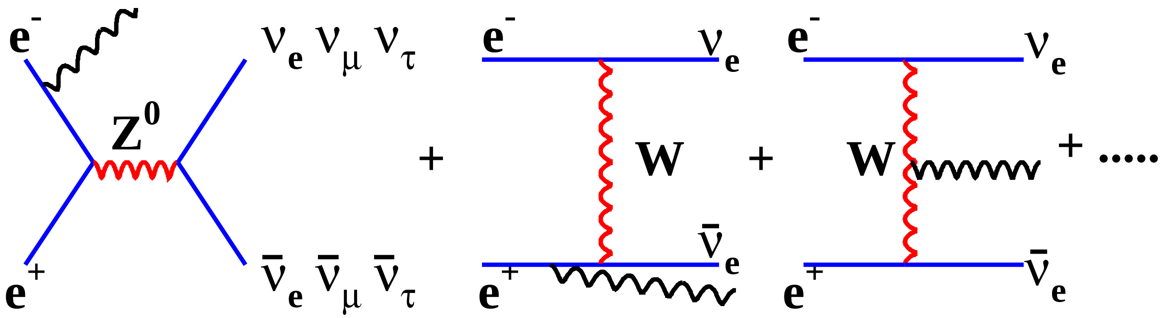
LEP combined result from $\nu\bar{\nu}\gamma$

➢ $N_\nu = 3.00 \pm 0.06$

LEP combined from direct and indirect measurements

➢ $N_\nu = 2.994 \pm 0.012$

Neutrino Counting With Single Photon Events

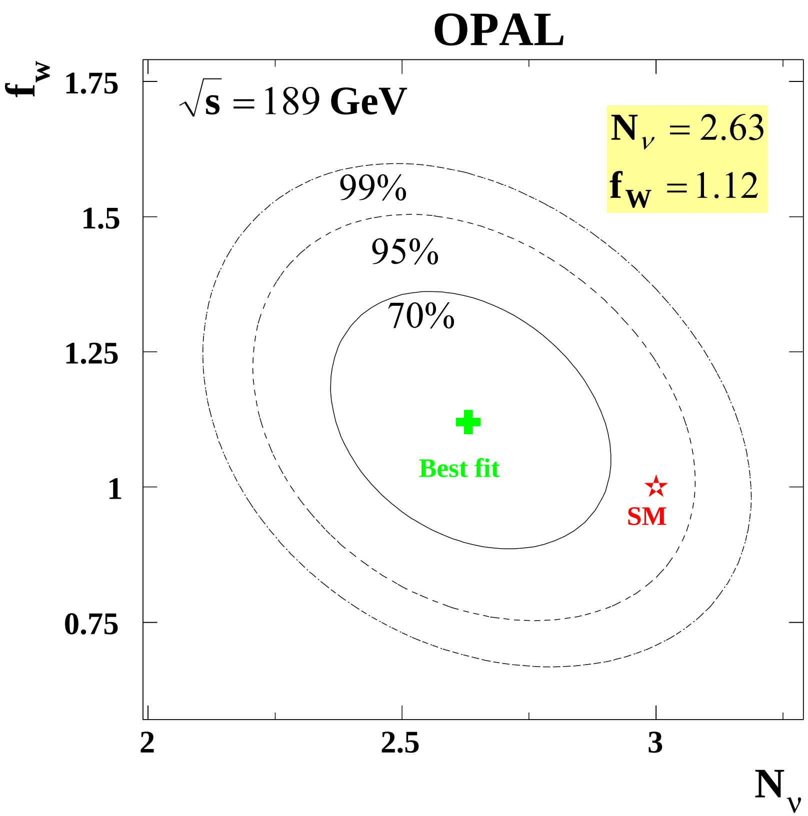


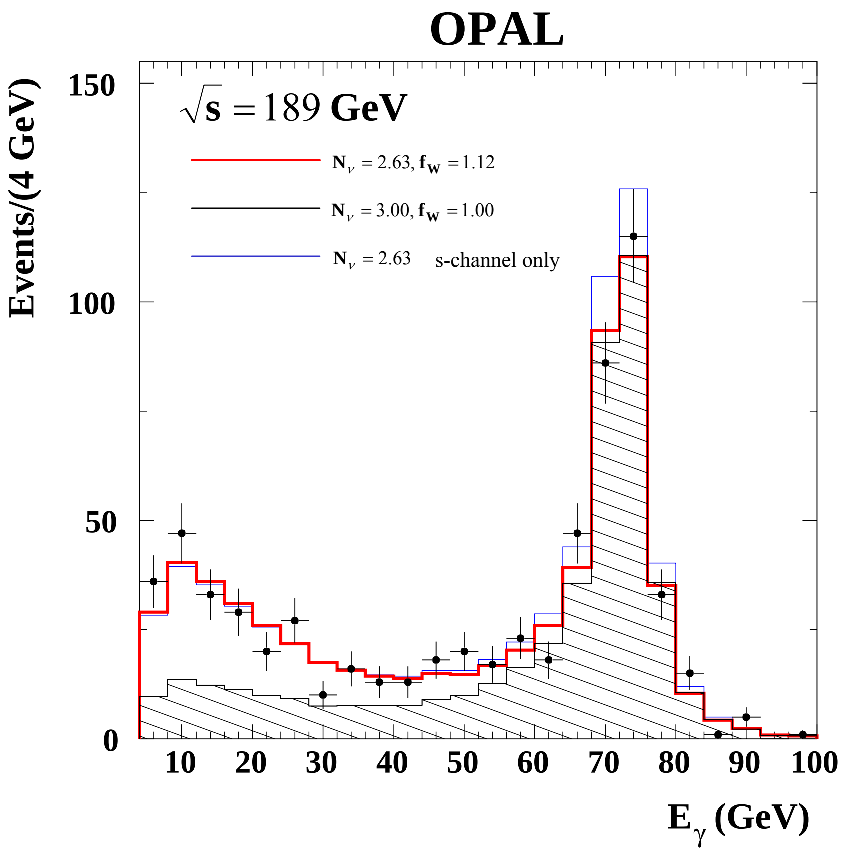
S-channel Z^0 production + W and W-Z interference

Parametrized in terms of

- N_ν number of light neutrinos in s-channel Z contribution (SM = 3)
- f_w scale factor for W and W-Z interference contributions (SM =1) (from Monte Carlo)

Neutrino Counting With Single Photon Events





$N_\nu = 2.63 \pm 0.15 \pm 0.11$ for $f_W = 1.00$ $N_\nu = 2.69 \pm 0.13 \pm 0.11$

$f_W = 1.12 \pm 0.13 \pm 0.12$ for $N_\nu = 3.00$ $f_W = 0.99 \pm 0.11 \pm 0.12$

Correlation coeff = -41%