Search for SUSY, Extra Dimensions and Exotics at LEP

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on behalf of

the LEP collaborations

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Outline

- SUSY
  - RPC, RPV
  - SUGRA, GMSB, AMSB
- Extra Dimensions (ADD framework)
  - Indirect constraints, direct searches
- Exotica
  - FCNC (single top), exited leptons, leptoquarks, technicolor

Concentrate on final results and preliminary LEP combinations

Data sample

- ~2.8 fb^{-1} (~700 pb^{-1} per experiment) at 130-210 GeV

No discovery $\rightarrow$ all limits at 95% CL

- 'Almost' model independent upper bounds on cross-section times branching ratios
- Limits on particle masses or parameters of a given model

Solutions to the Hierarchy Problem

- SUSY: additional symmetry between fermions and bosons
  - Associates a SUSY partner to each SM particle:
    - R- and L-handed sleptons, squarks; gauginos, higgsinos
    - Minimal SUSY (MSSM): 2 Higgs doublets (H_u, H_d)
  - SUSY breaking (Unbroken SUSY: mass degenerate particles)
    - Define two distinct sectors with no renormalizable, tree level interactions between them:
      - hidden (particles neutral w.r.t. SM gauge groups)
      - visible (SM particles and SUSY partners)
    - Break SUSY in the hidden sector and transmit the breaking to the visible sector in some way:
      - Gravity mediation: SUGRA
      - Gauge mediation: GMSB
      - Anomaly mediation: AMSB
- Technicolor: no elementary Higgs
- Extra dimensions: only one fundamental scale

General SUSY

Parameters in the superpotential:

- coupling of Higgs fields in the superpotential: μ
- R-parity violating couplings: λ_{ijk}, λ'_{ijk}, λ''_{ijk}, μ'

R-parity: Multiplicative quantum #: +1/-1 for SM/SUSY particles

- Conserved - RPC SUSY

  Production in pairs, cascade decays to stable LSP
- Violated - RPV SUSY

  Many new possibilities including single production, direct decays to SM particles, unstable LSP

Soft SUSY breaking parameters

- Gaugino mass terms: $m_{1/2}^{g}$ (g=1,2,3)
- Scalar mass terms: m_0^{s} (s=scalar fields, neglecting mixing between generations)
- Trilinear couplings of scalars: A^{u}_{ij}, A^{d}_{ij}, A^{e}_{ij} (i,j=1,2,3)
- Bilinear coupling of Higgs fields: B_0

MSUGRA

Parameters at the GUT scale motivated by supergravity:

- Coupling of Higgs fields: μ
- Soft SUSY breaking parameters
  - Common gaugino mass: $m_{1/2}$
  - Common scalar mass: m_0
  - Common scalar trilinear couplings of scalars: A_0
  - Bilinear coupling of Higgs fields: B_0 ➢ $\tan\beta$

Gaugino masses at the EW scale:

- $M_1 = 5/3\ g'^2/g^2\ M_2 \sim \frac{1}{2}\ M_2$
- $M_3 = g_s^2/g^2\ M_2$

Mass Eigenstates

Mixing of weakly interacting gauginos and higgsinos due to non-zero Higgs vev's:

- 2 charginos (M_2, μ, $\tan\beta$)
- 4 neutralinos (M_1, M_2, μ, $\tan\beta$)

Mixing of L and R scalar fermions (μ, A_f, $\tan\beta$)

- $\tilde{f}_1 = \tilde{f}_L \cos\vartheta_{\tilde{f}} + \tilde{f}_R \sin\vartheta_{\tilde{f}}$
- important for 3rd generation (prop. to fermion mass)
- sfermion mass (m_0, $m_{½}$ or M_2, $\tan\beta$)

Sleptons (RPC)

$\tilde{\ell}^+\tilde{\ell}^- \rightarrow \ell^+\tilde{\chi}_1^0\ell^-\tilde{\chi}_1^0$

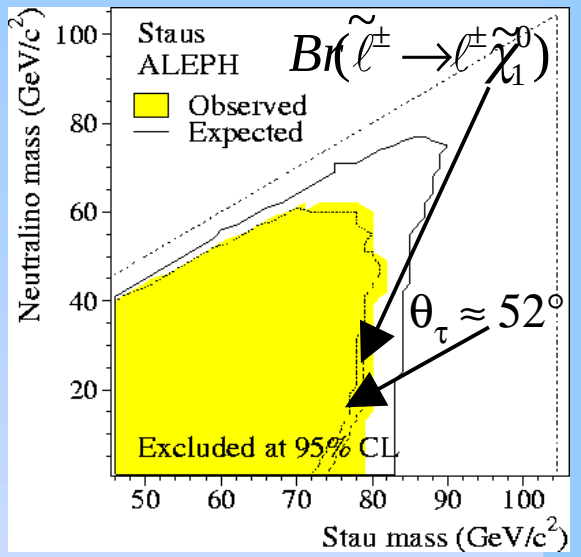
s-channel via γ or Z: LL/RR prod.

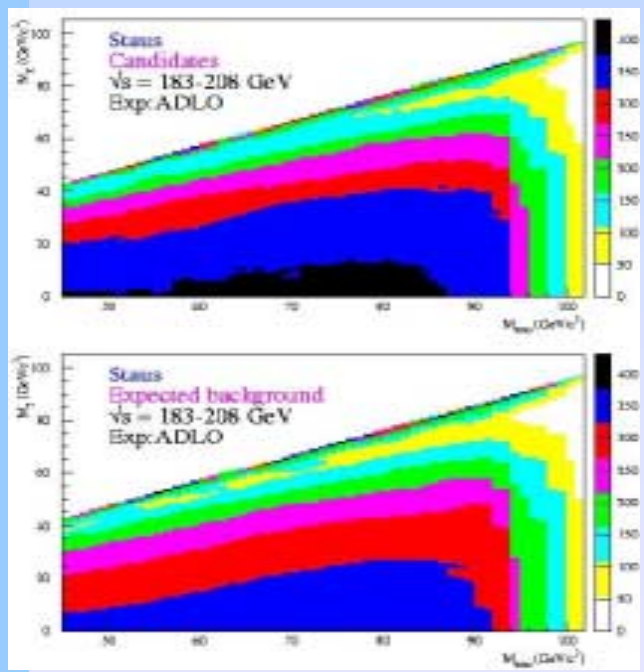
For selectron also t-channel via χ^0: LR prod.

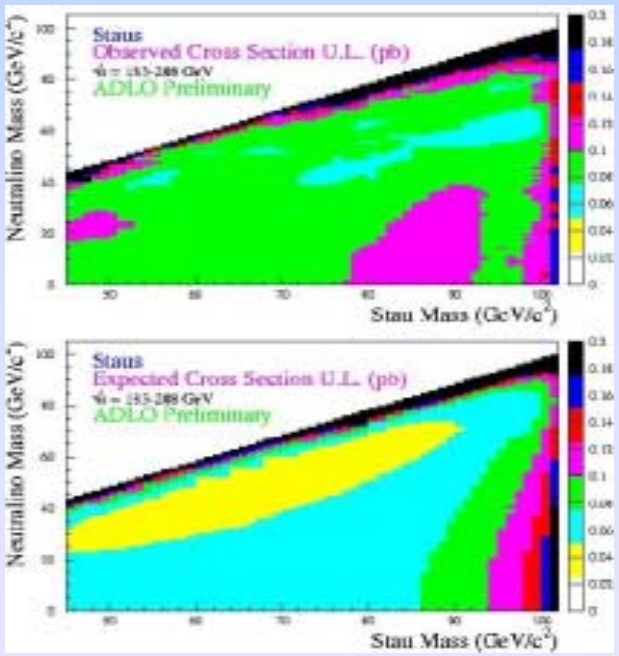
(M_2, μ, tanβ)

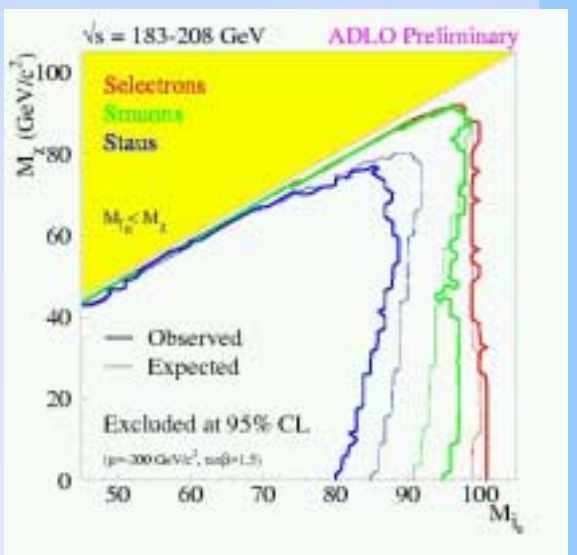
Limits for right-handed sleptons (smaller cross-section)

Mixing may be sizable for staus (A_τ, μ, tanβ)









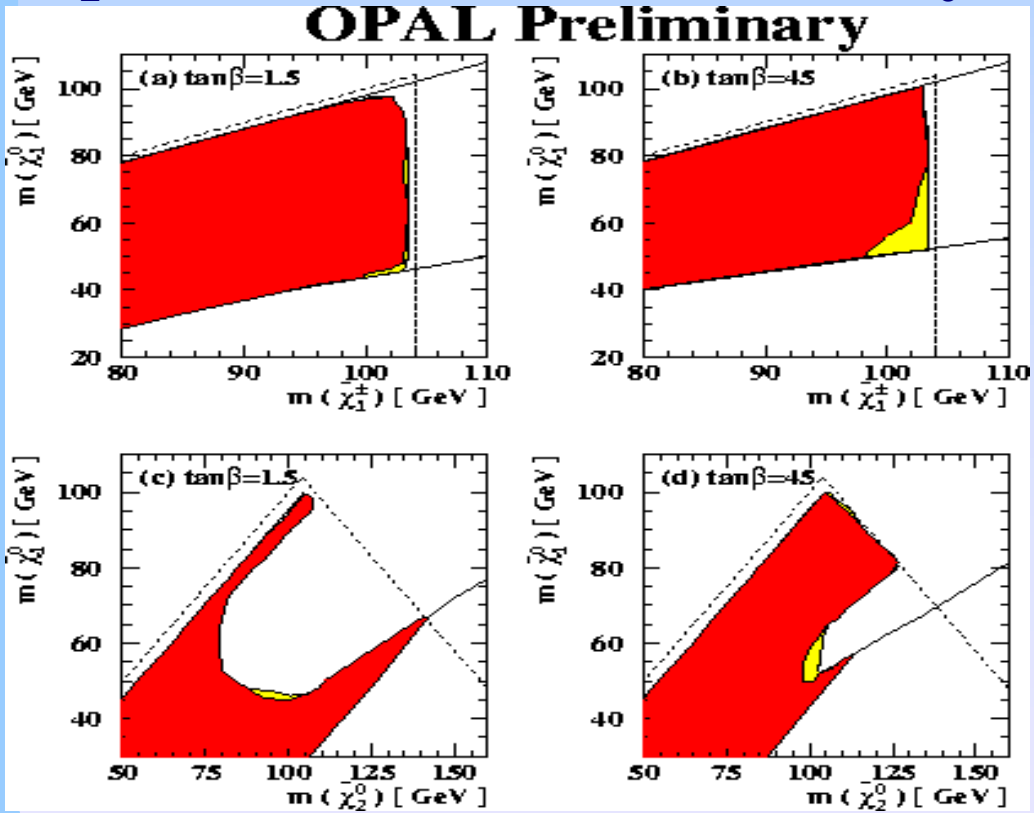
Chargino and Neutralino Searches

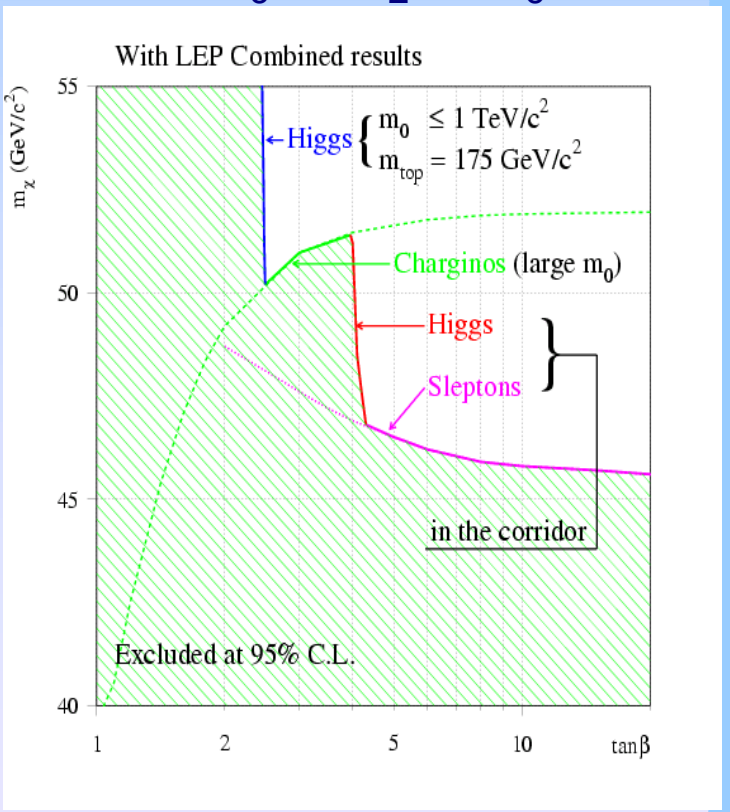
$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^{(*)+} \tilde{\chi}_1^0 W^{(*)-}$$

$$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 Z^{(*)0}$$

Low and high multiplicity final states depending on the W/Z decay
Special ISR analysis for small Δm

MSSM scan:
M_2 (0:2 TeV), $|\mu|$ (-0.5, 0.5 TeV), m_0 (0: 0.5 TeV), A_0 ($\pm M_2$, $\pm m_0$, 0)

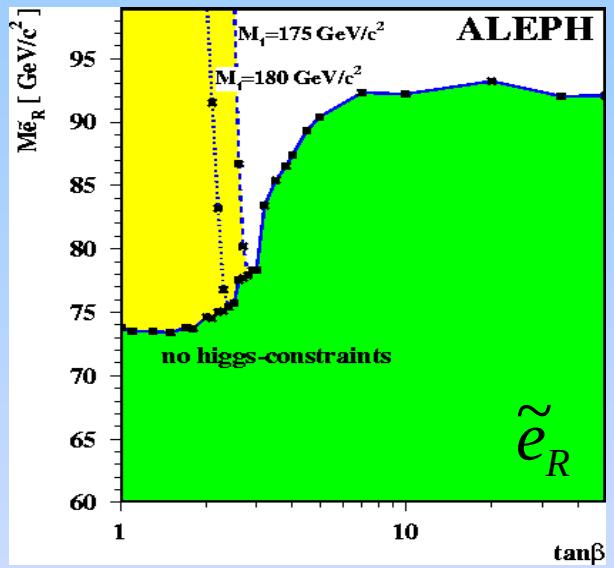


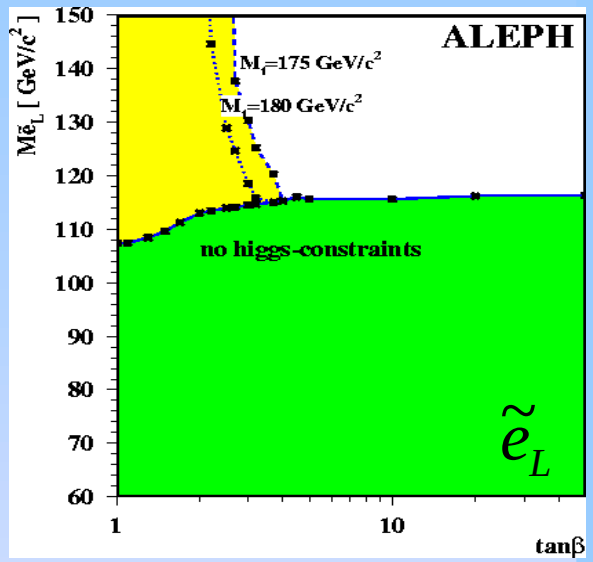


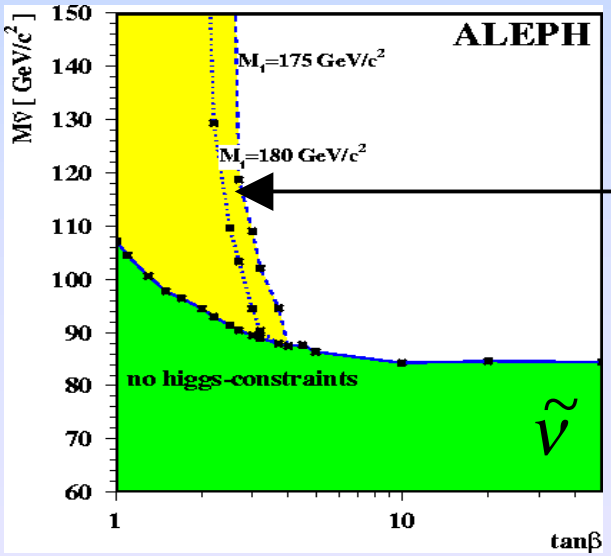
Absolute Mass Limits: Selectron, Sneutrino

- Neutralino LSP
- Gaugino and sfermion mass unification at GUT scale
- no sfermion mixing
  - 73 / 107 / 84 GeV
- Higgs limit m_t=175 GeV
  - 77 / 115 / 84 GeV

  m_t=180 GeV
  - 75 / 115 / 84 GeV
- **MSUGRA (A_0=0)**
  - **96 / 113 / 80 GeV**



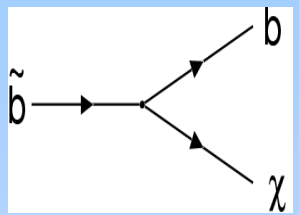


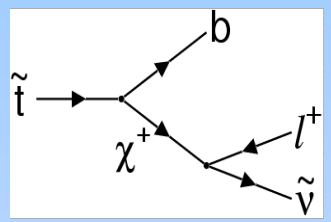


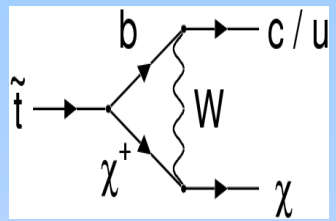
m_h limit → $m_{1/2}$ limit
for fixed m_0 and tanβ
m_A and (A_τ - μ cotβ)
chosen to maximize m_h
for given m_0, $m_{1/2}$, tanβ
$m_{1/2}$ limit weakens with m_0
→ take m_0=100 GeV

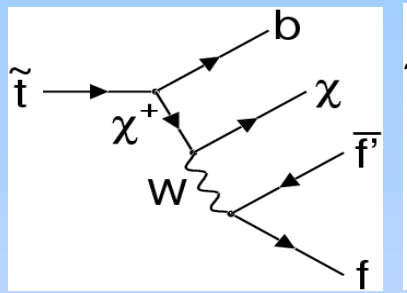
Squarks (RPC)

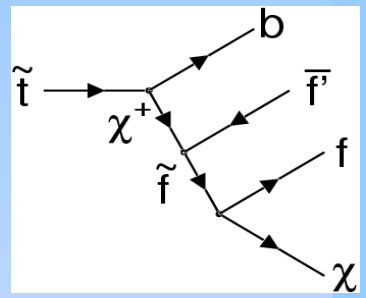
- Neutralino or sneutrino LSP



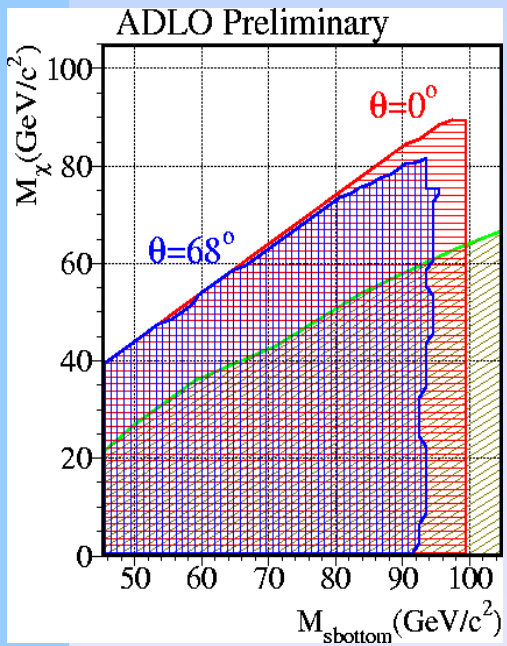


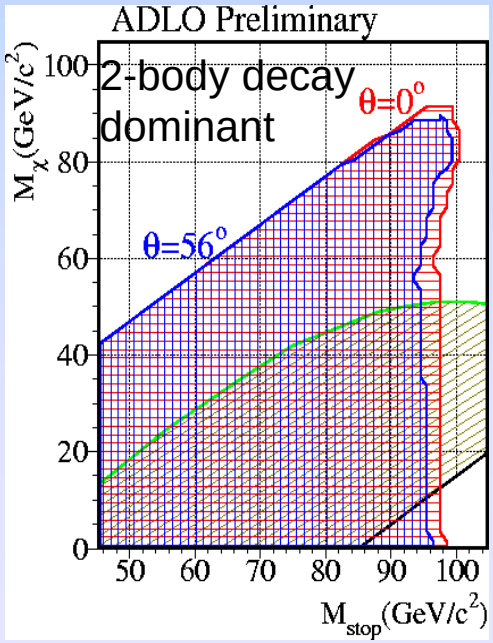


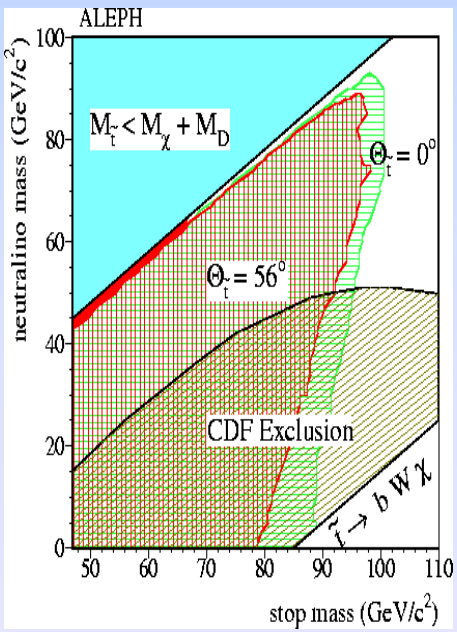


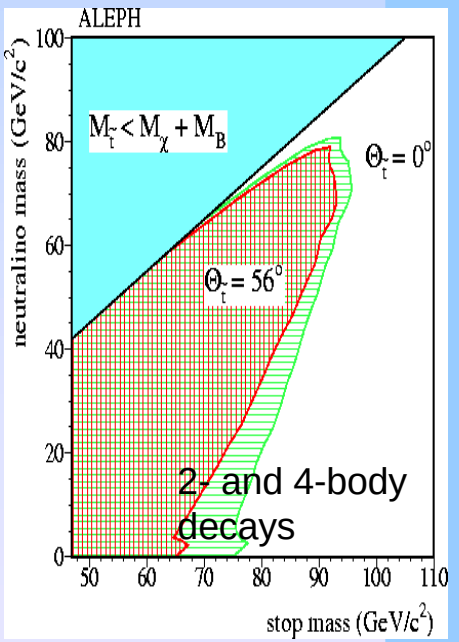


- New: 4-body stop decays
  can be enhanced if charginos, sleptons are light









RPV SUSY

- $W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$

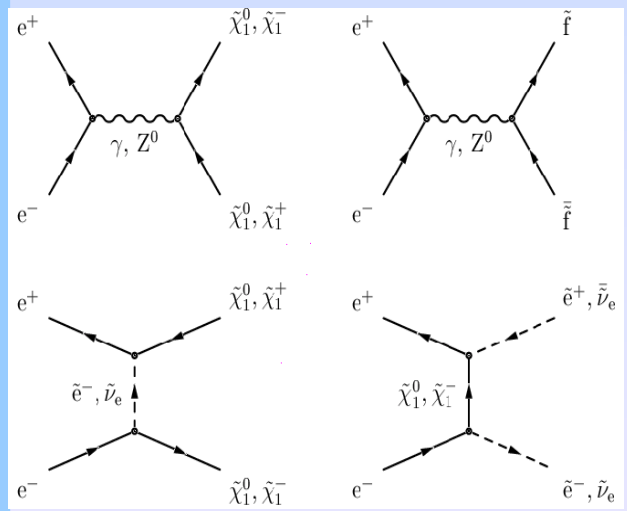
  L-violation B-violation

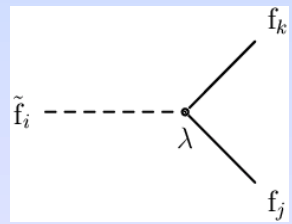
- Strong limits on products of Yukawa couplings from precision data (e.g. p-decay)

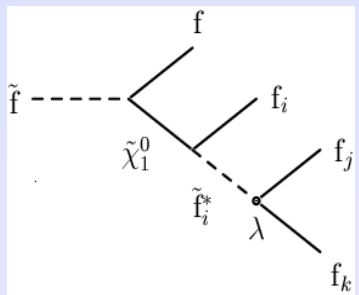
Usual assumptions on couplings:

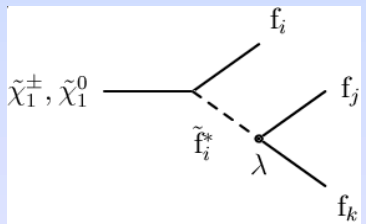
- only one is non-vanishing
- $<10^{-5}$ (if SUSY particle decays in detector)

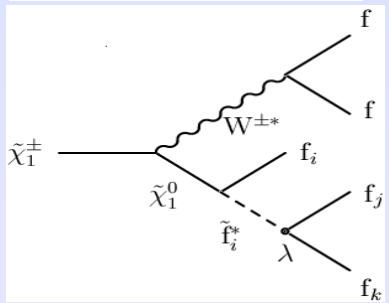
RPC pair-production followed by RPV direct or cascade decay









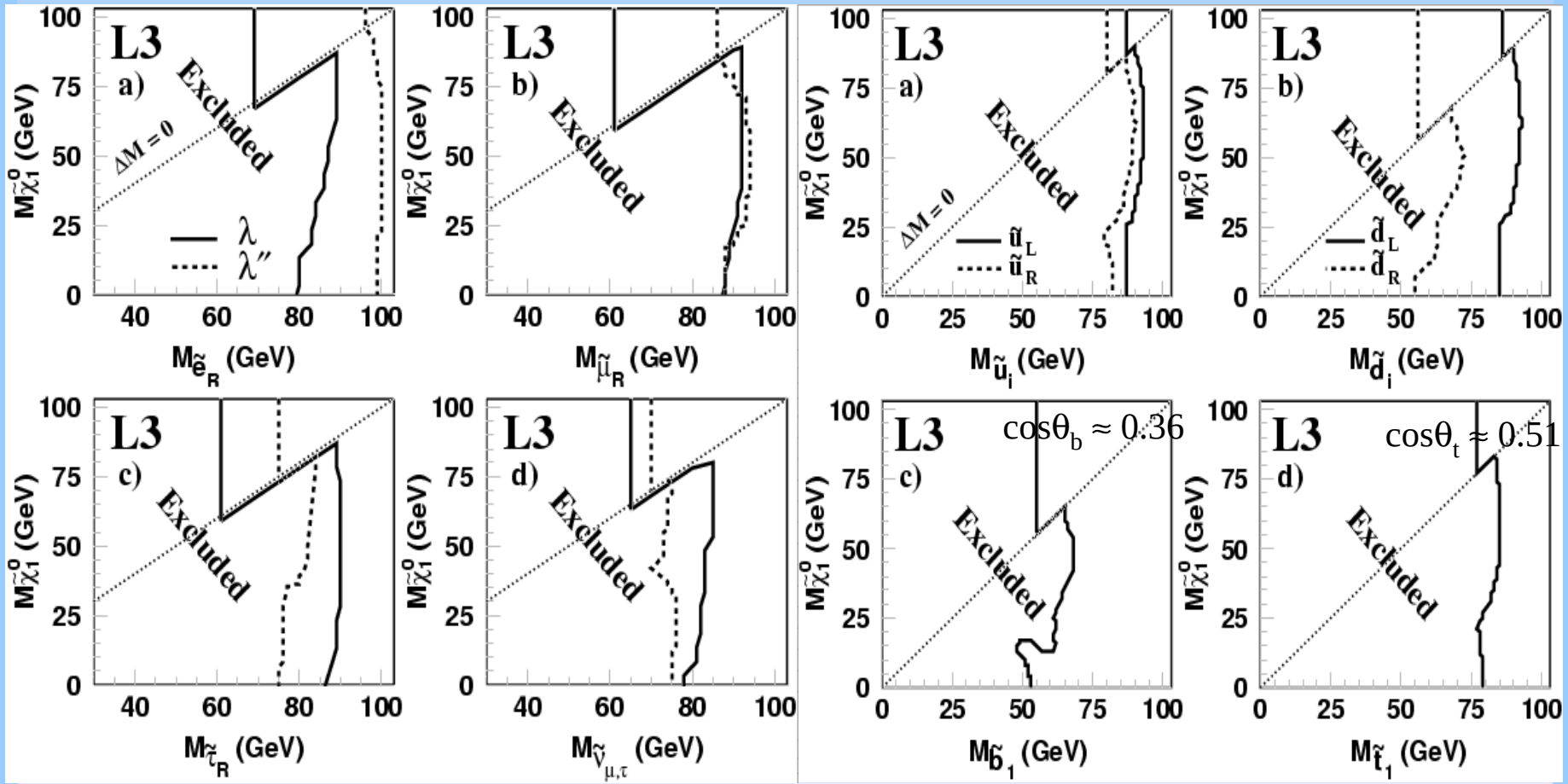


Final states:
2 l + E_{miss}
to 10 jets

Sfermions (RPV)

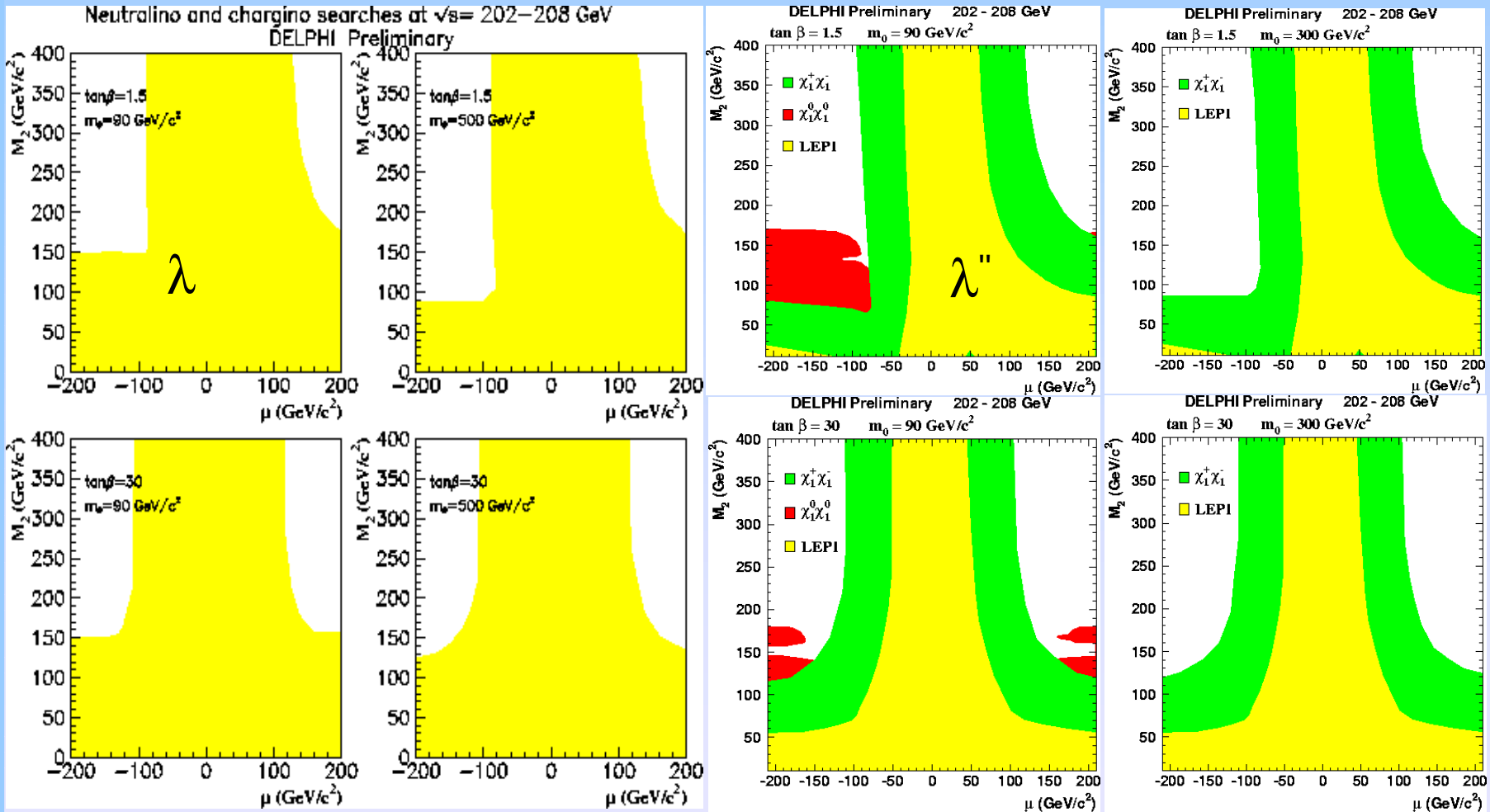
- Mixing for 3rd generation squarks
- MSSM scan

  m_0 (0 : 0.5 TeV), M_2 (0 : 1TeV), μ (-0.5 : 0.5 TeV), tanβ (0.7 : 40)



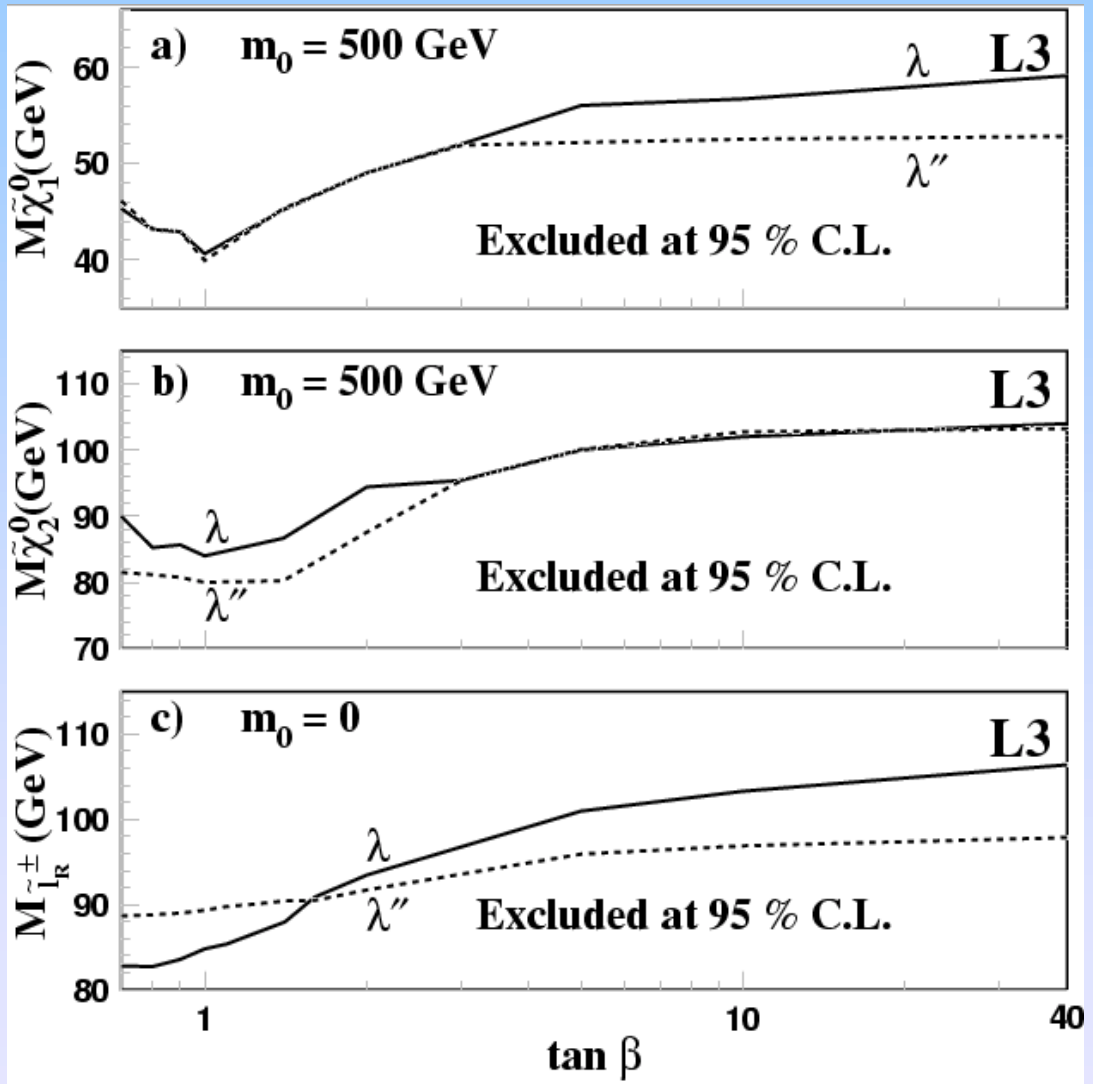
Charginos and Neutralinos (RPV)

Exclusion on μ - M_2 plane for fixed m_0 and tanβ



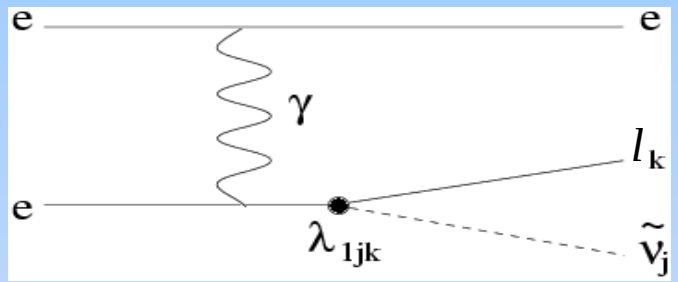
Absolute Mass Limits

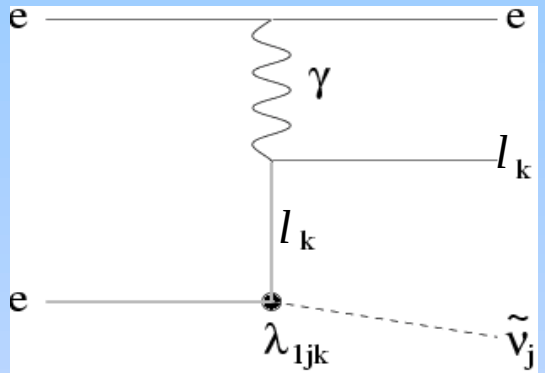
- Gaugino and scalar mass unification at GUT scale
- MSSM scan
- Z lineshape constraint
- m_0 value corresponds to worst case
- Chargino limit close to kinematic limit



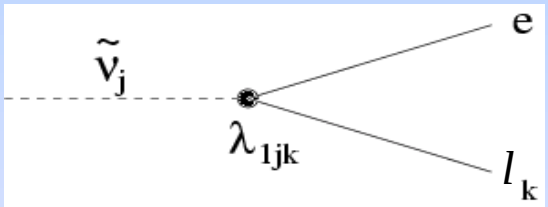
Single Sneutrino Production in RPV SUSY

- Production



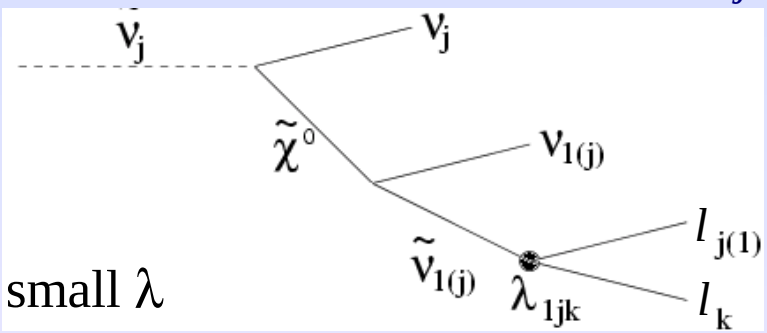


- Direct decay: *(e)* l_k *e* l_k

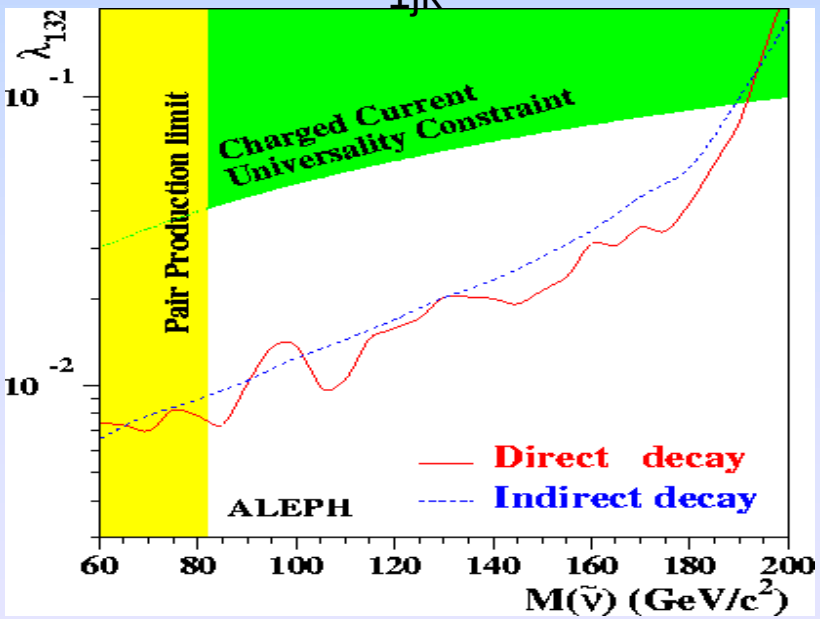


large λ
small Δm

- Indirect decay: *(e)* l_k *ν ν* l_j l_k



Limits on λ_{1jk} couplings

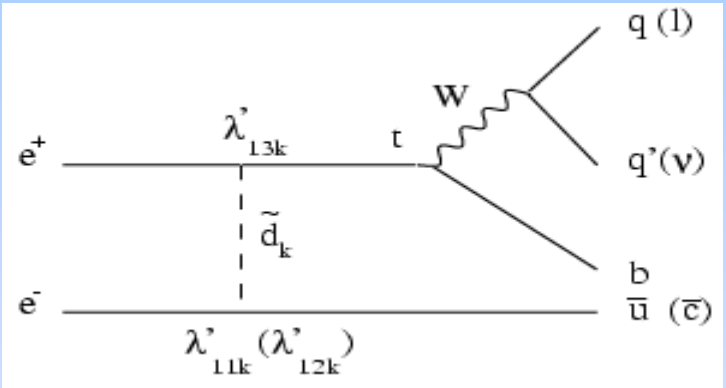


Single Top Production in RPV SUSY

t-channel light squark exchange

Limit on cross-section

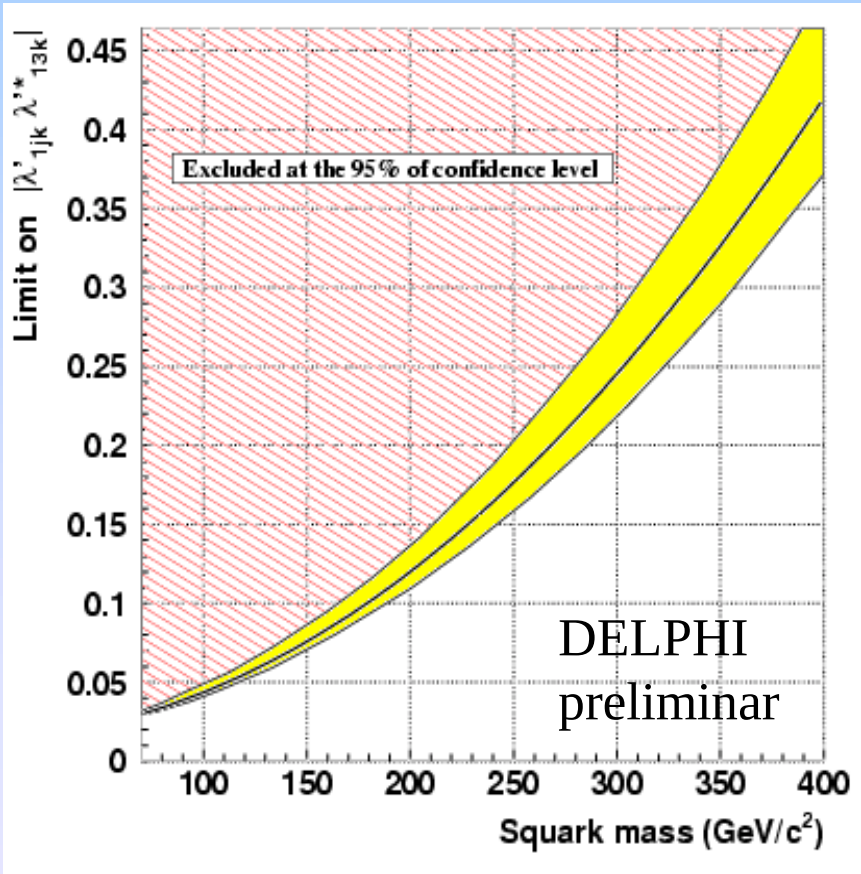
$\sigma(e^+e^- \to t\bar{c} + \bar{t}c) < 0.11\text{pb}$ at $\sqrt{s} = 206$ GeV



$$\sigma = \left|\lambda'_{1jk}\lambda'^{*}_{13k}\right|^2 f(\sqrt{s}, m_{\tilde{d}_k})$$

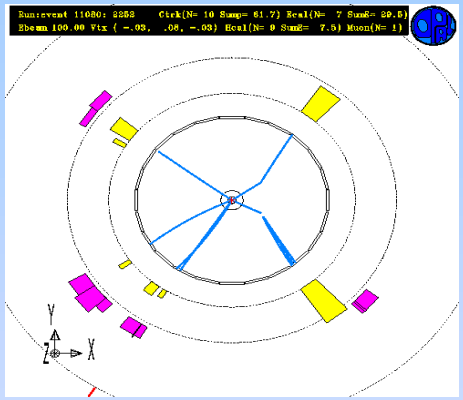
$$\left|\lambda'_{1jk}\lambda'^{*}_{13k}\right| < 0.43 \text{ for } m_{\tilde{d}_k} = 100 \text{ GeV}$$
with $j,k = 1,2$

Note: stronger LEP1 limit from $B \to X \nu \bar{\nu}$



GMSB

- Gravitino LSP: weakly interacting, mass typically < 1 GeV
  Neutralino or slepton NLSP: lifetime depends on F
- Parameters
  - $F^{1/2}$ - intrinsic SUSY breaking scale
  - Λ - overall mass scale of SUSY particles
  - M_{mess} - mass of messenger particles
  - N_5 - # of messenger particle sets
  - tanβ and sign(μ) - Higgs vev and mixing parameter

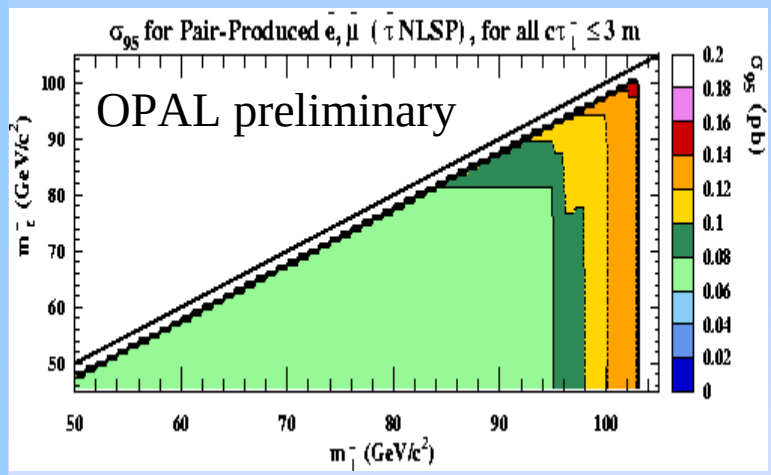


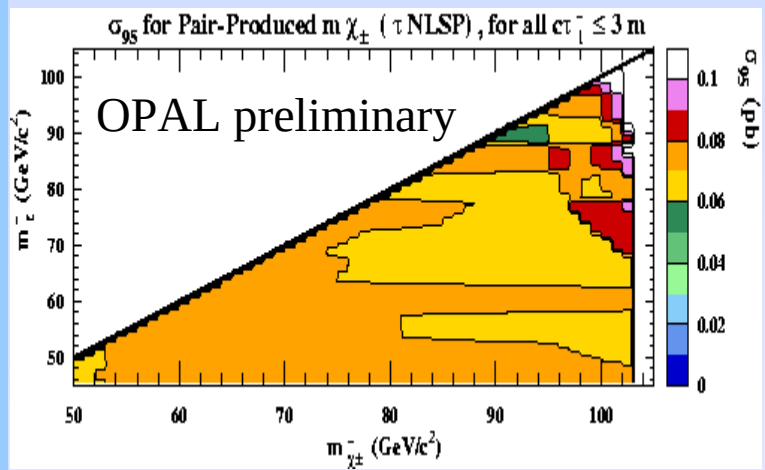
- Signatures depend on lifetime (γs, *l*s, kinks, large impact parameters, heavy stable charged particles)
  - Neutralino NLSP $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}\gamma\tilde{G}$
  - Slepton NLSP $\tilde{\ell}\tilde{\ell} \rightarrow \ell\tilde{G}\ell\tilde{G}$
  - Slepton NLSP with light neutralino $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \ell\tilde{\ell}\ell\tilde{\ell} \rightarrow \ell\ell\tilde{G}\ell\ell\tilde{G}$
  - Stau NLSP with light sleptons $\tilde{\ell}\tilde{\ell} \rightarrow \ell\tilde{\tau}_1\ell\tilde{\tau}_1 \rightarrow \ell\tau\tilde{G}\ell\tau\tilde{G}$
  - Stau NLSP with light chargino $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \nu_\tau\tilde{\tau}_1\nu_\tau\tilde{\tau}_1 \rightarrow \nu_\tau\tau\tilde{G}\nu_\tau\tau\tilde{G}$

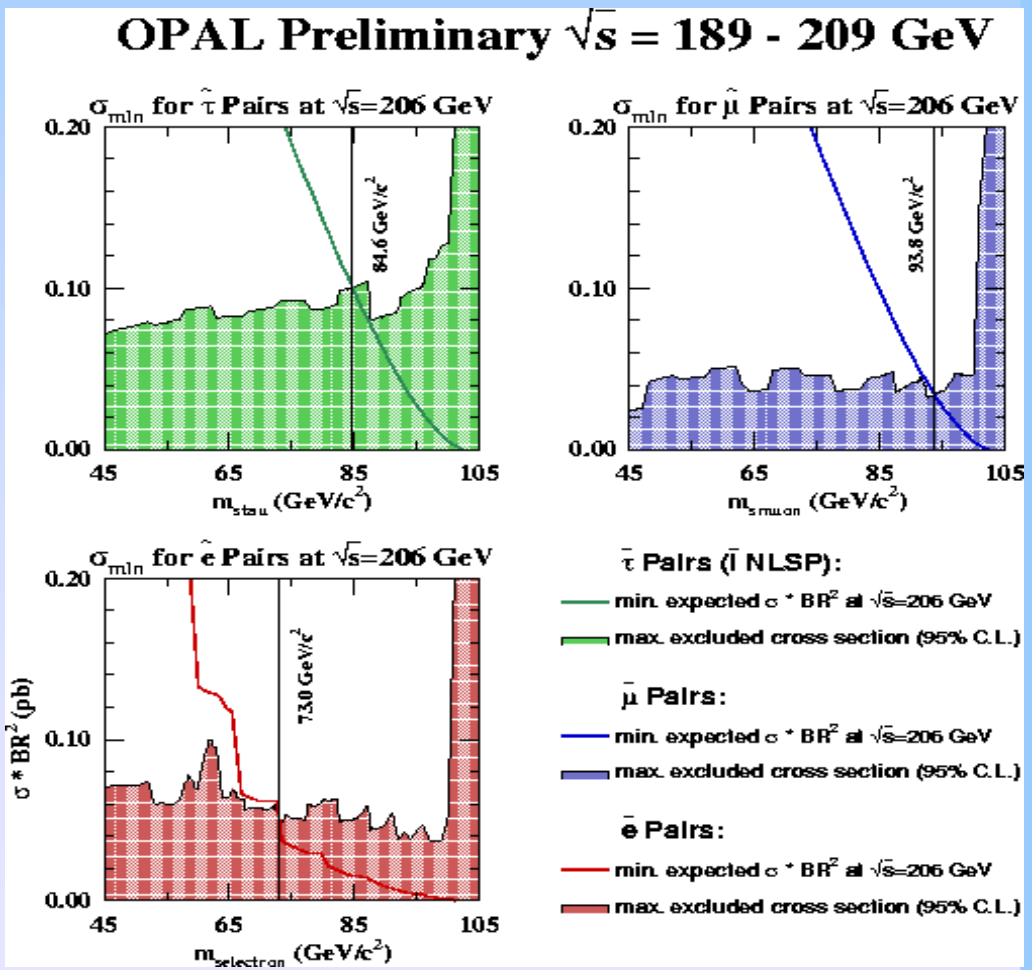
Cross-section and Mass Limits

GMSB scan

M_{mess} (1.01Λ :10^6 TeV), Λ (5:200 TeV), tanβ (2:50), N_5 (1:4), sign(μ) (+:-)







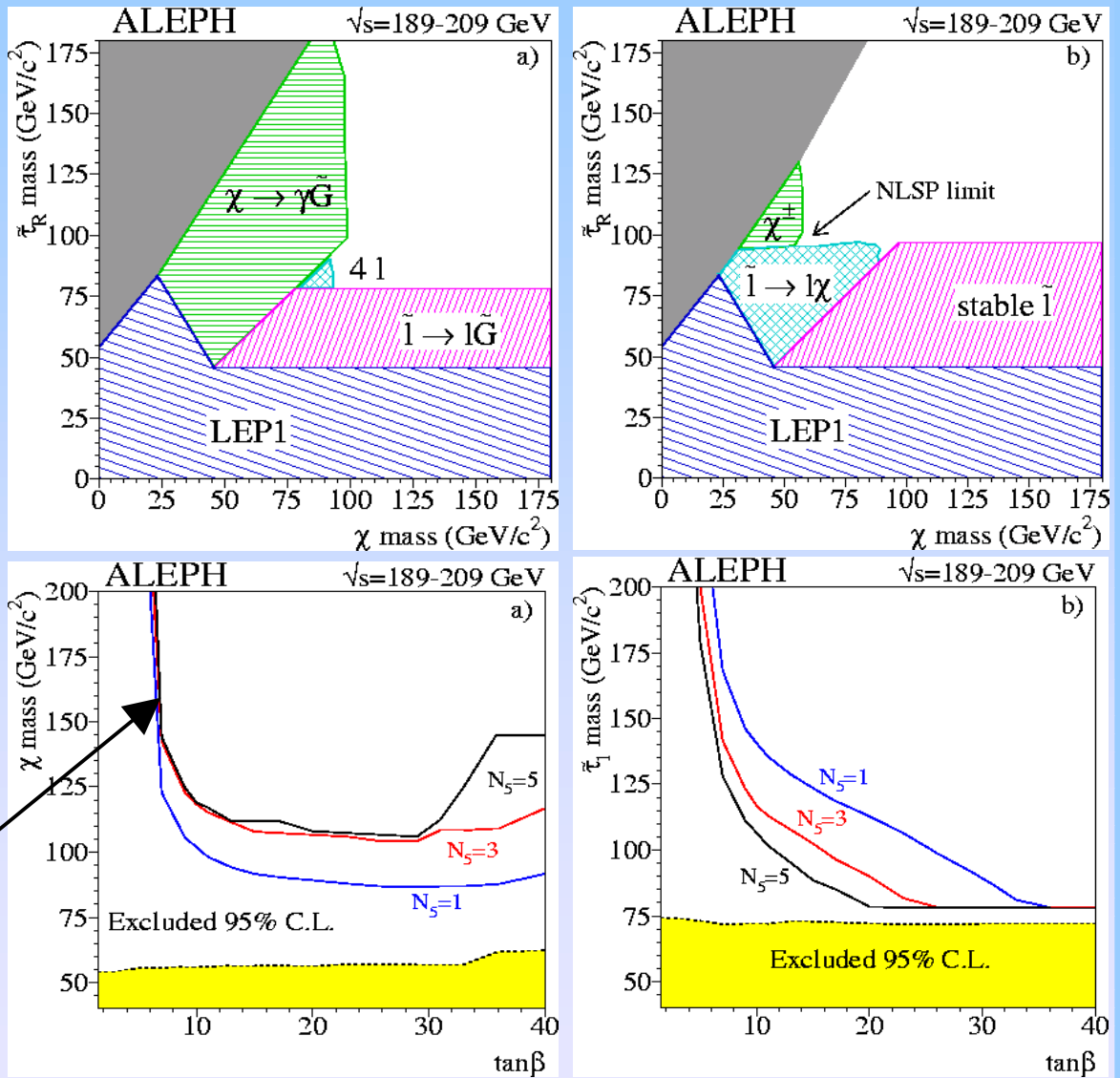
NLSP Mass Limits

GSMB scan:

- M_{mess} (10 : 10^9 TeV)
- m_G (0.1 : 10^5 eV)
- Λ (1 TeV : min($F^{1/2}$, M_{mess}))
- tanβ (1.5 : 40)
- N_5 (1:5)
- sign(μ) (+:-)

Included also

- LEP1 results
- SUGRA chargino, slepton search
- Neutral Higgs search



Limit on Mass Scale

At M_{mess}

$m_{scalar}^2 \sim N_5 \Lambda^2$

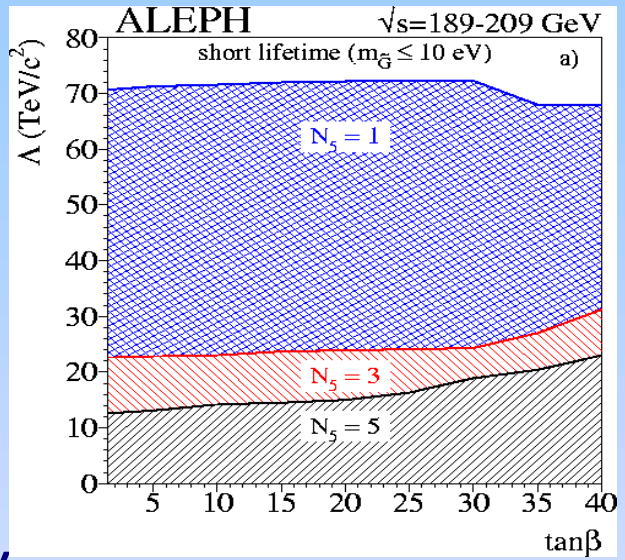
$m_{gaugino} \sim N_5 \Lambda$

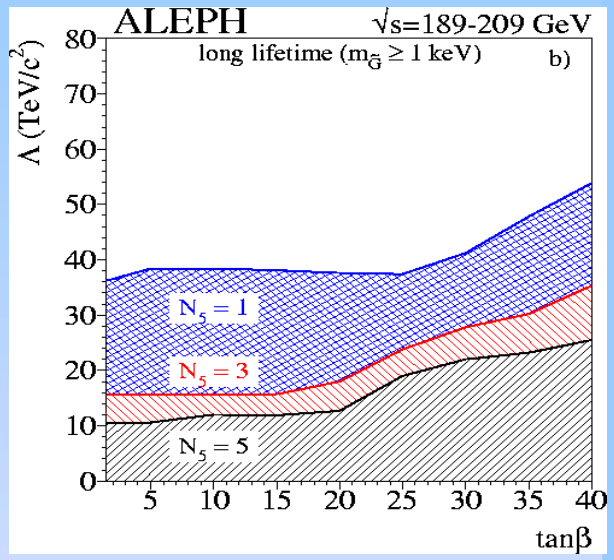
NLSP mass limit

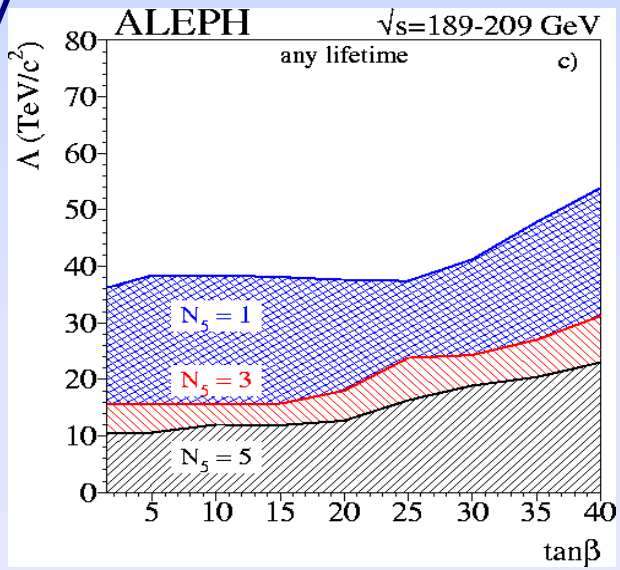
$\rightarrow$ limit on Λ for given N_5

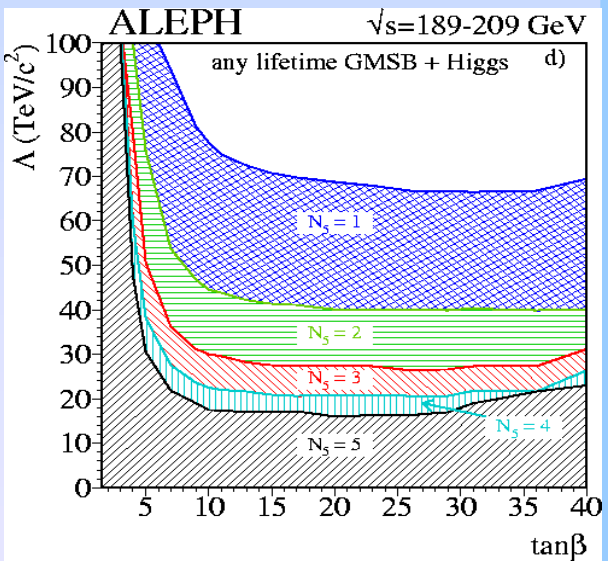
Abs. Limit ~ 10 TeV

for N_5=5, tanβ=1.5, M_{mess}=10^9 TeV, large m_G (stable NLSP)









Extra Dimensions

- Explain the hierarchy between the EW and Planck scales through geometrical considerations
- Original model from Arkani-Hamed - Dimopoulos - Dvali (1998)
- Vast number of new models since
- LEP results mostly in the ADD framework:
  n extra compact dimensions of size R
  Planck scale in 4+n dimension $M_D \sim m_{EW}$
  SM particles propagate in 4D, gravity in 4+n D
  4D Planck scale: $M_{planck}^2 \sim R^n M_d^{n+2}$
- KK graviton couples to momentum tensor:
  contribute to most SM processes
- KK graviton propagates in the bulk:
  energy, momentum not conserved in 4D
- Spin-2 KK graviton may have momentum component in the bulk:
  may appear as spin-0, 1 or 2 in 4D

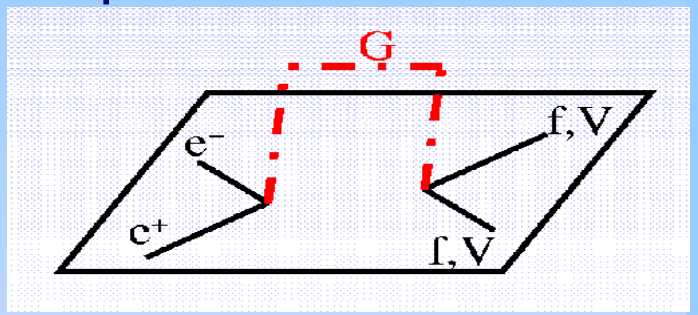
Indirect Limits on ADD Extra Dimensions

- Contribution to fermion and boson pair-production:

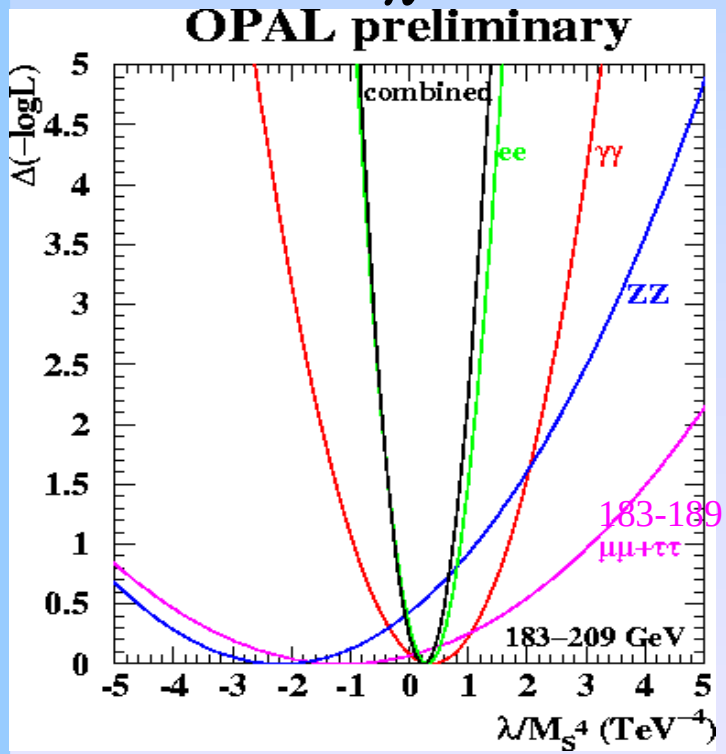
$$e^+e^- \to \ell^+\ell^-, q\bar{q}, \gamma\gamma, Z^0Z^0, W^+W^-$$

- $$\sigma = \sigma_{SM} + \alpha_G \sigma_{\text{intf}} + \alpha_G^2 \sigma_{grav}$$

with $\alpha_G = \frac{2\lambda}{\pi} M_S^{-4}$ (notation of J. Hewett)



Contribution of 1 KK state ~ $1/M_{plack}^2$
summed over all KK states ~ $1/M_D^2$

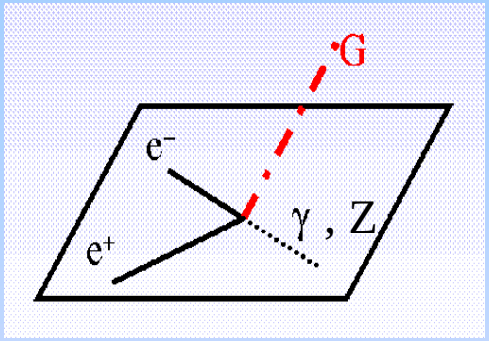


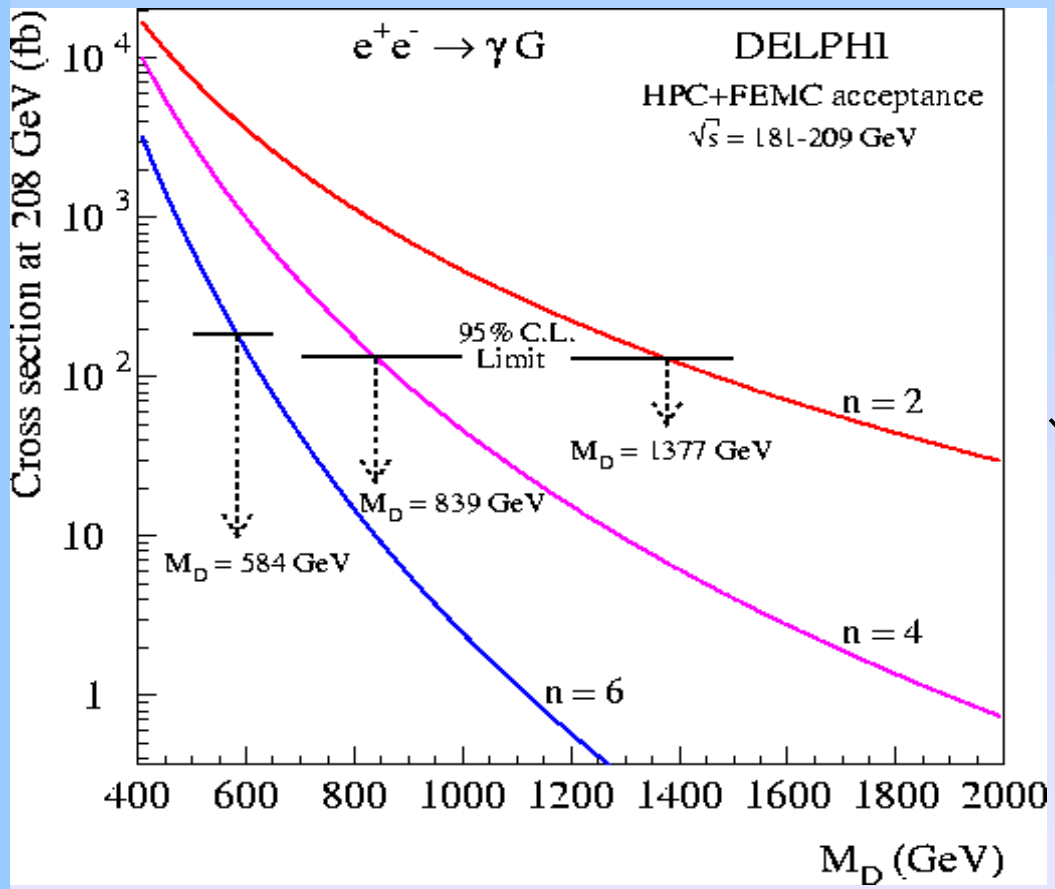
Best limits from e^+e^- measurements:
$M_S > 1.18 / 1.17$ TeV for $\lambda = +1 / -1$
only small improvement expected from LEP combination

LEP combined $\gamma\gamma$ result:
$M_S > 0.97 / 0.94$ TeV for $\lambda = +1 / -1$
(individual experiments: 0.83 -0.92 TeV)

Direct Search for EDs

- Sensitive directly to M_D and not to UV cut-off M_S
- $\gamma + E_{miss}$ or $Z + E_{miss}$ search



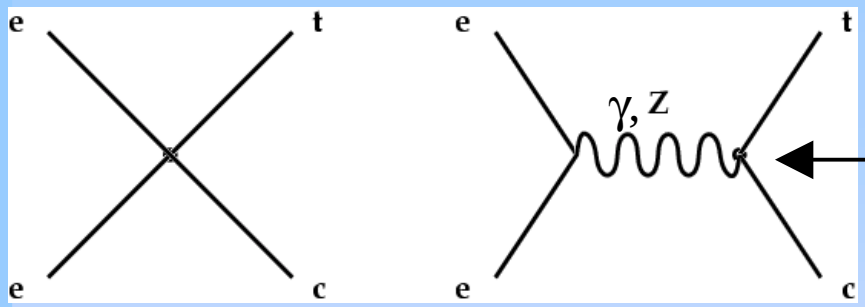


Limit on the size of EDs

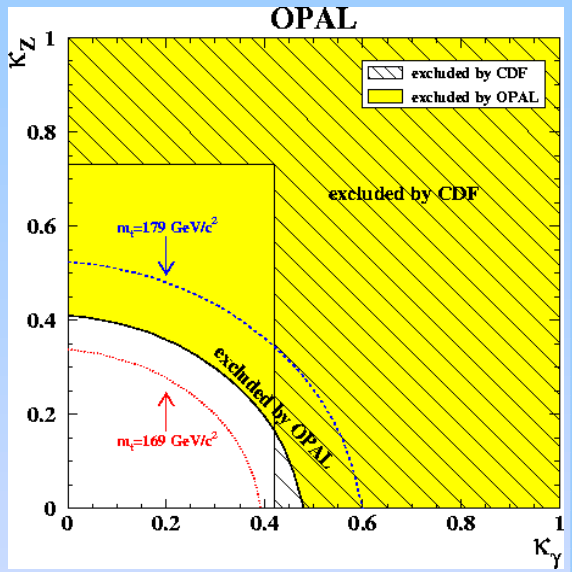
n=2	R<0.25 mm
n=4	R<13 pm
n=6	R<54 fm

Single Top Production

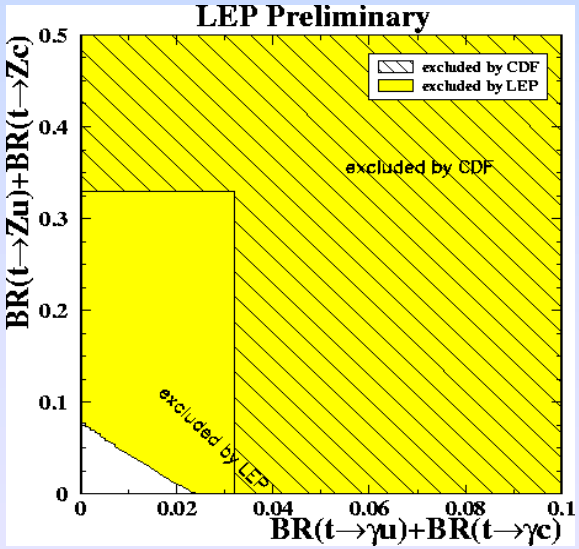
Via 4f contact interactions or FCNC

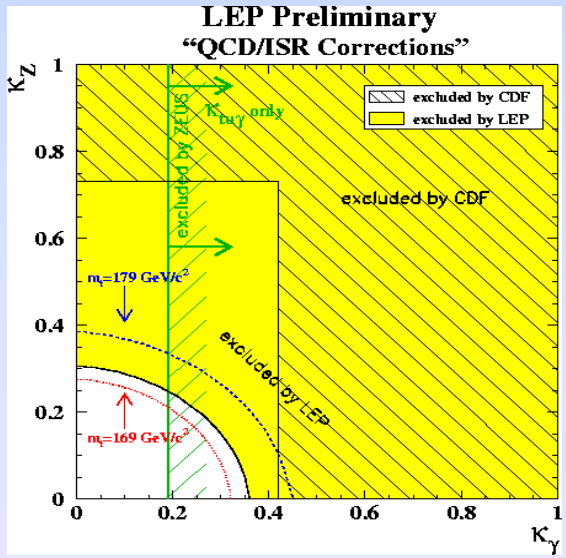


Anomalous couplings: κ_γ, κ_Z



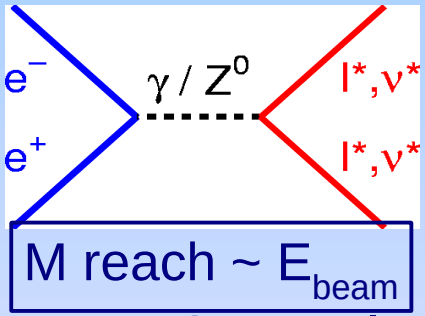
- $t \rightarrow bW$ decay
- Final states: bclν, bcqq'
- Special care for fragmentation modelling
- 4f cont. int. limits for various model assumptions: O(1 TeV)

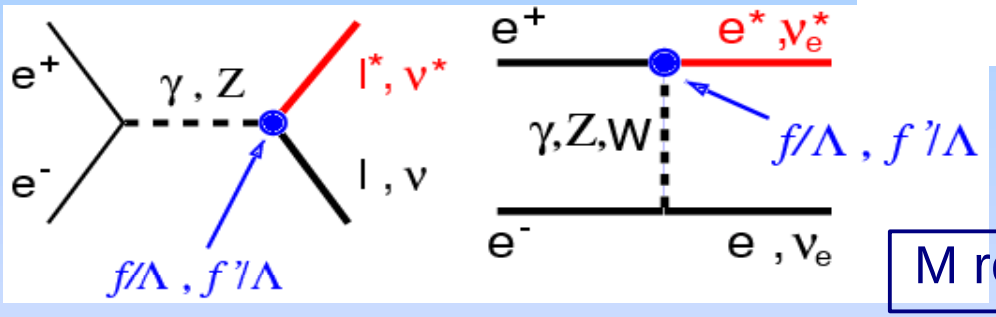


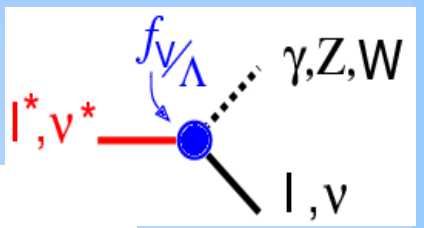


Exited Leptons

- Models with substructure sector at scale Λ predict l*, ν* with couplings fg, f'g' to EW gauge fields W_μ, B
- Production at LEP

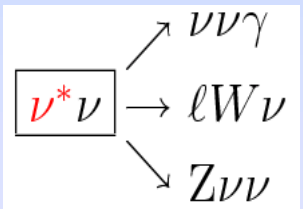


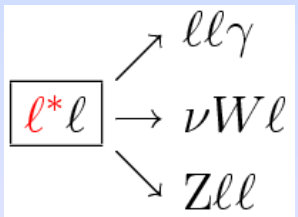


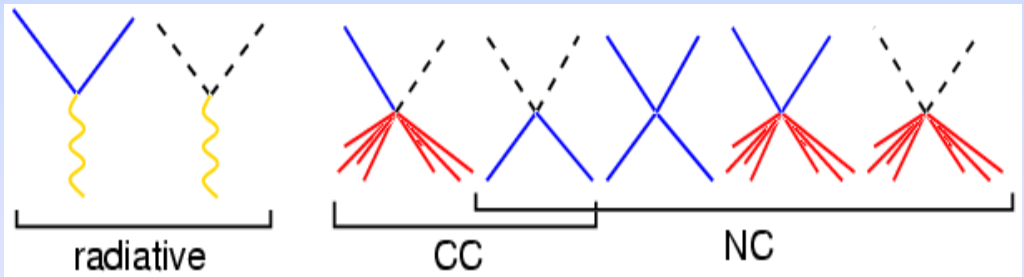


M reach ~ E_{cm}

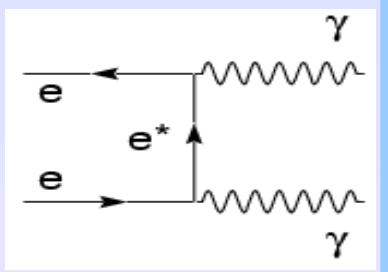
- Search topologies







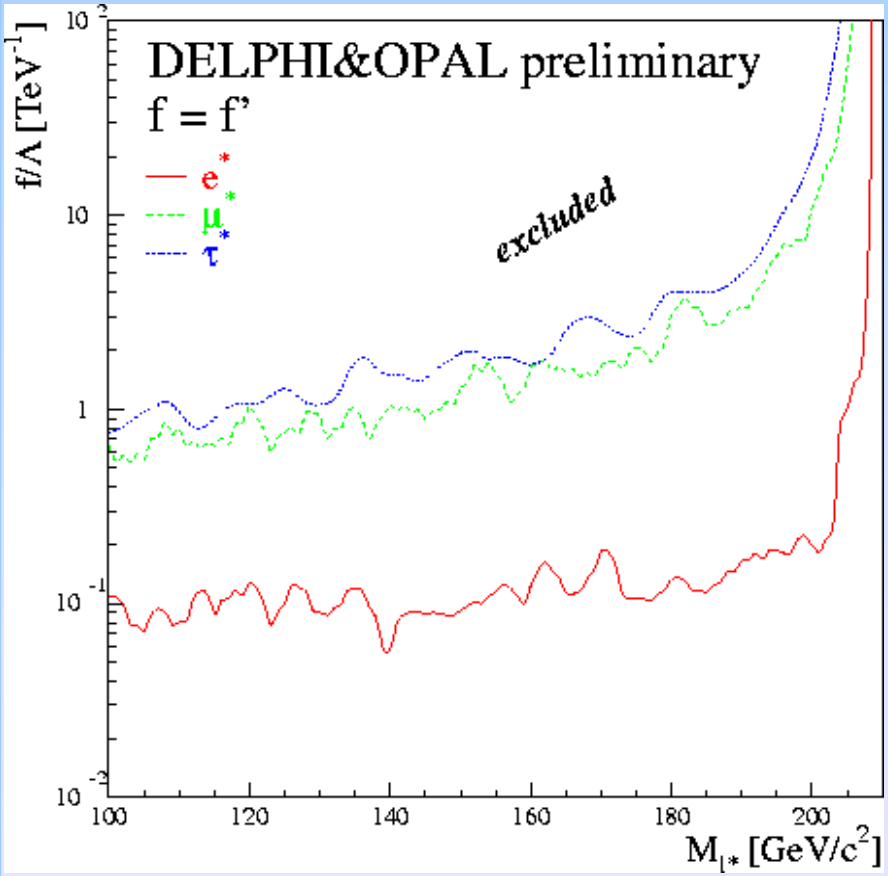
- For e* with f ≠ -f' search with M reach > E_{cm} by measuring $e^+e^- \rightarrow \gamma\gamma(\gamma)$

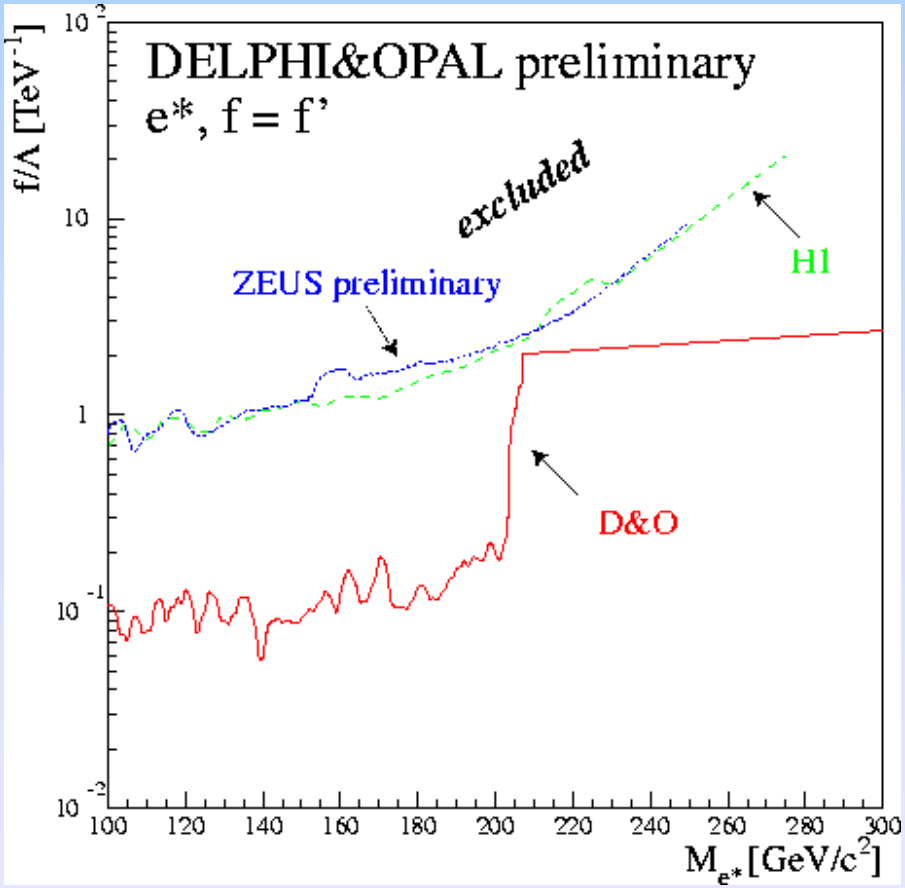


Exited Lepton Limits

Direct searches for charged exited leptons

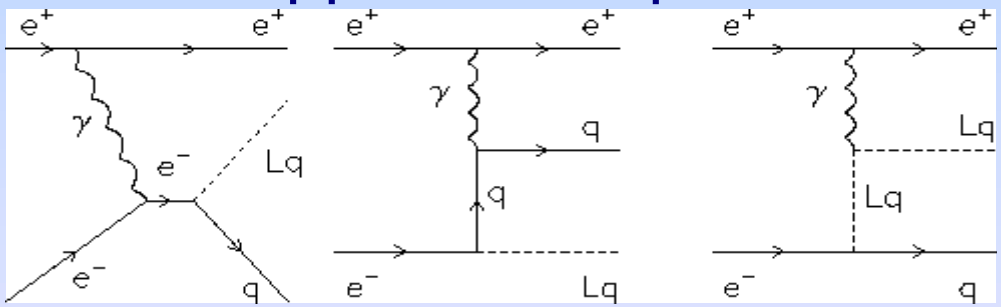
Direct searches and indirect limits from $\gamma\gamma(\gamma)$ for exited electrons

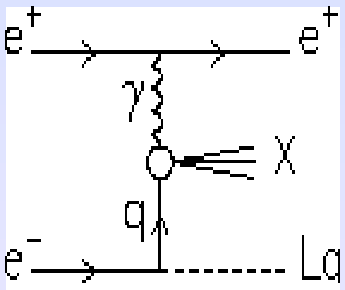


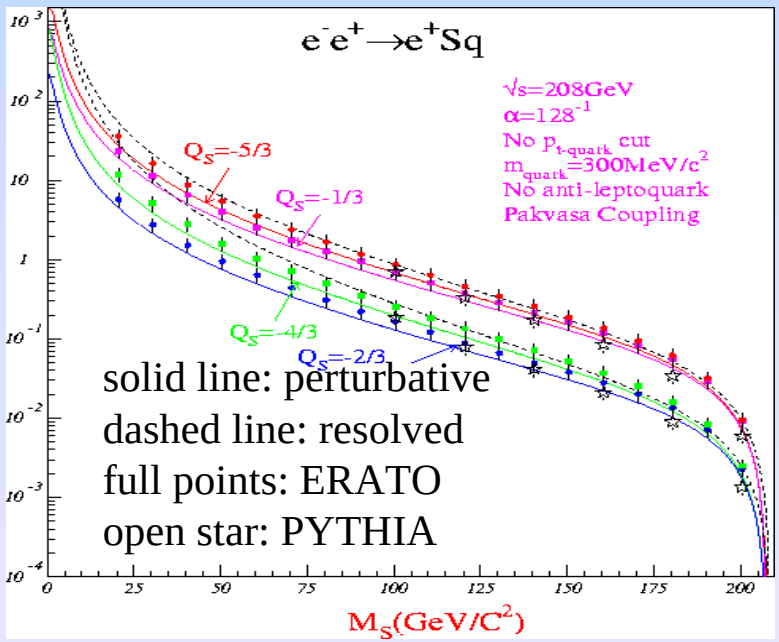


Leptoquarks

- Coloured, spin=0 or 1 particles
- BRW model: L & B conservation
- Couplings within one generation of fermions only
- Chiral couplings (respect lepton universality)
  $\rightarrow$ branching ratios to lq and νq restricted
- Two approaches: perturbative vs. resolved photon

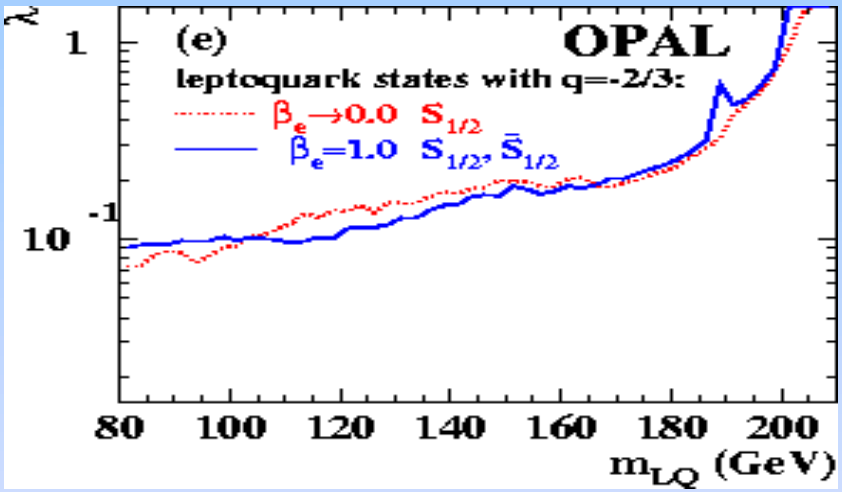


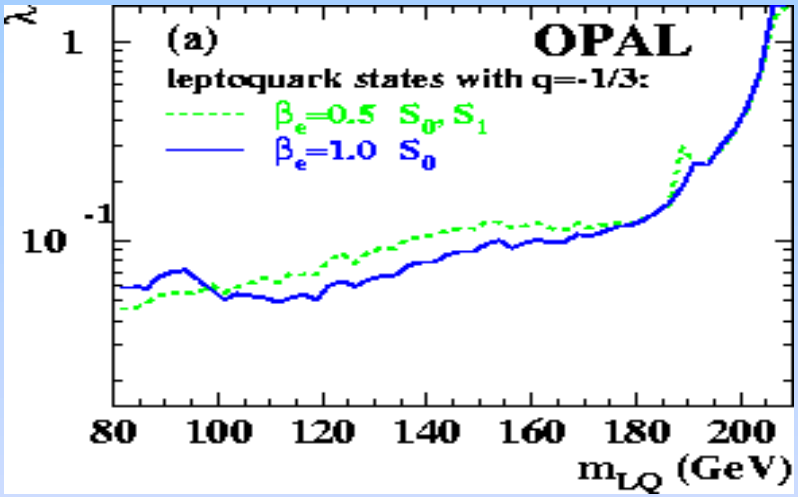


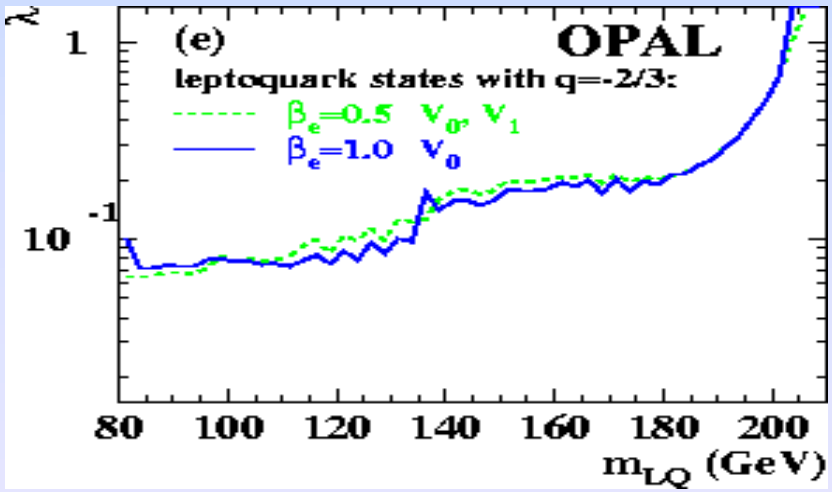


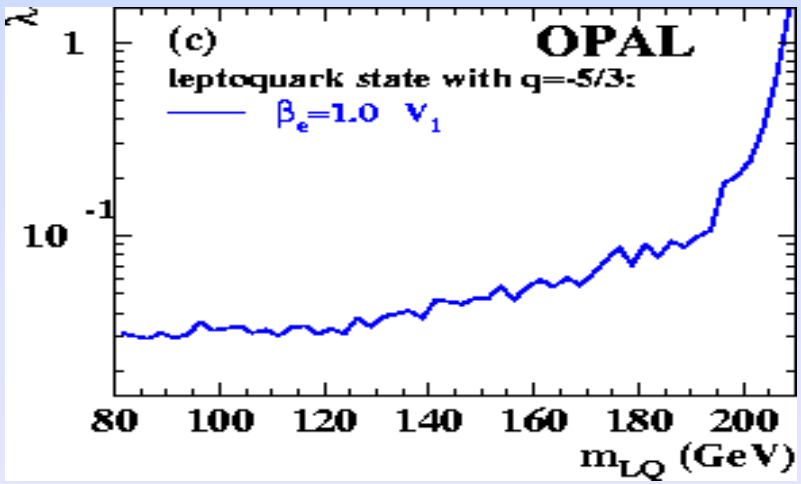
Limits on Leptoquarks

Worst and best limits on coupling









Technicolor

- EW symmetry breaking $\rightarrow$ observable scalar particle
- No elementary Higgs but a composite
- New QCD-like interaction
- Simple version of TC disagrees with experiments $\rightarrow$ more and more refined proposals
- LEP searches in the framework of Walking Extended TC (Straw Man Model)

$$\rho_T^0 / \omega_T^0 \rightarrow \pi_T^+ \pi_T^- \rightarrow b\bar{q}\bar{b}q, \quad b\bar{q}\tau\nu$$

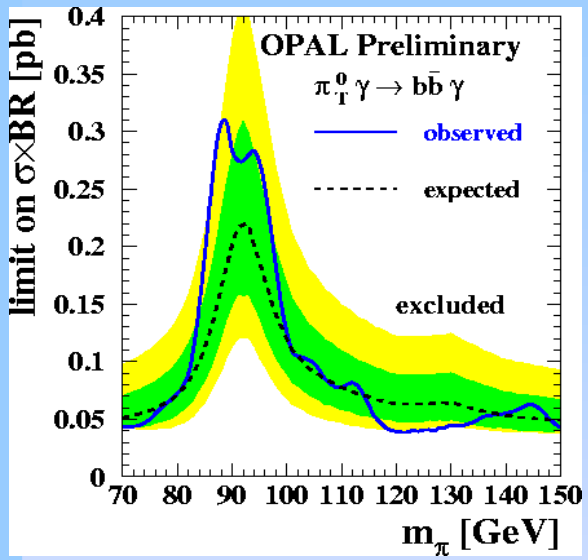
$$\rho_T^0 / \omega_T^0 \rightarrow \pi_T^0 \gamma \rightarrow b\bar{b}q\gamma$$

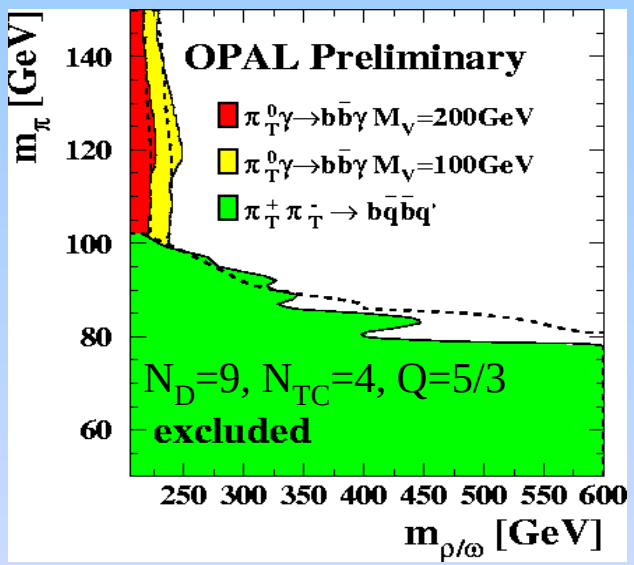
$$\rho_T^0 / \omega_T^0 \rightarrow \pi_T^+ W_L^- \rightarrow b\bar{q}\bar{q}q, \quad b\bar{q}\ell\nu$$

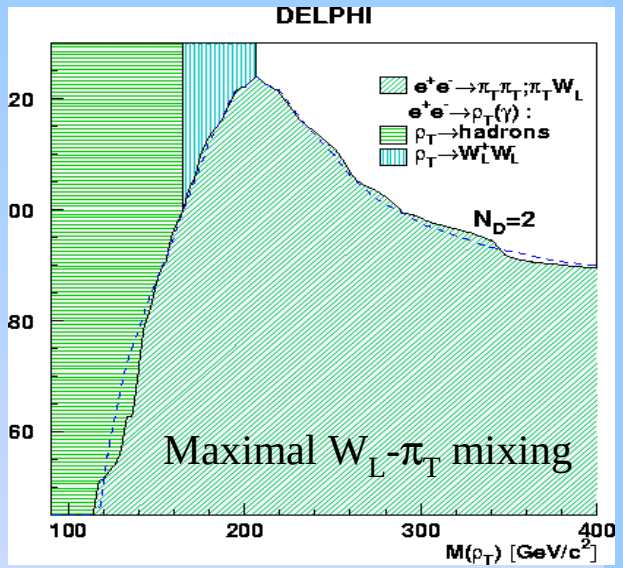
$$\rho_T^0 / \omega_T^0 \rightarrow W_L^+ W_L^-$$

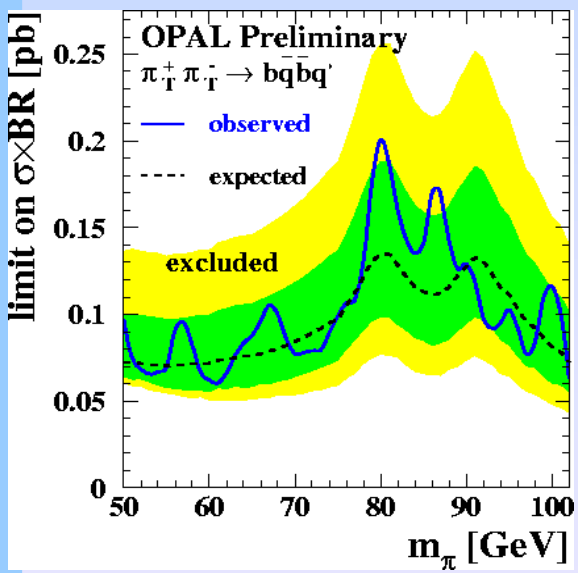
$$\rho_T^0 / \omega_T^0 \rightarrow q\bar{q}$$

Technicolor Limits









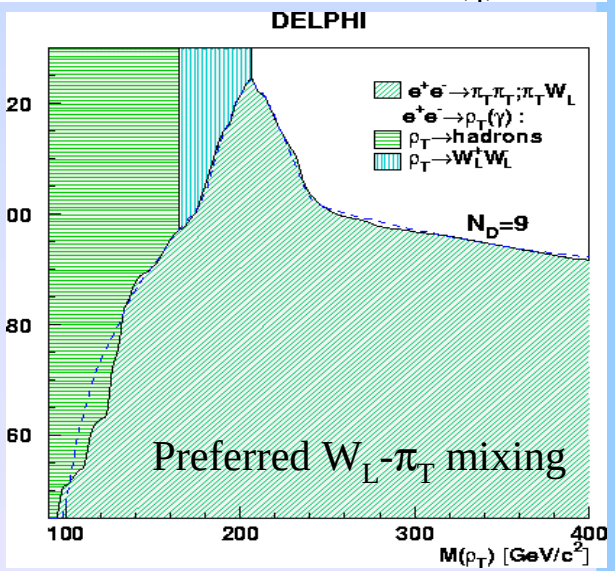
N_D: # of TC doublets

N_{TC}: # of TCs, SU(N_{TC})

$Q=Q_u+Q_d$: sum of techniquark el. charges

M_V: mass parameter

$1/M_V \sim A(\rho_T/\omega_T \to V\pi_T$



Summary

- Vast selection of models are tried and constrained at LEP
- First final results but many more to come
- LEP combinations of 'standard' BSM models on their way