New Particle Searches at LEP2

Brigitte Vachon

University of Victoria

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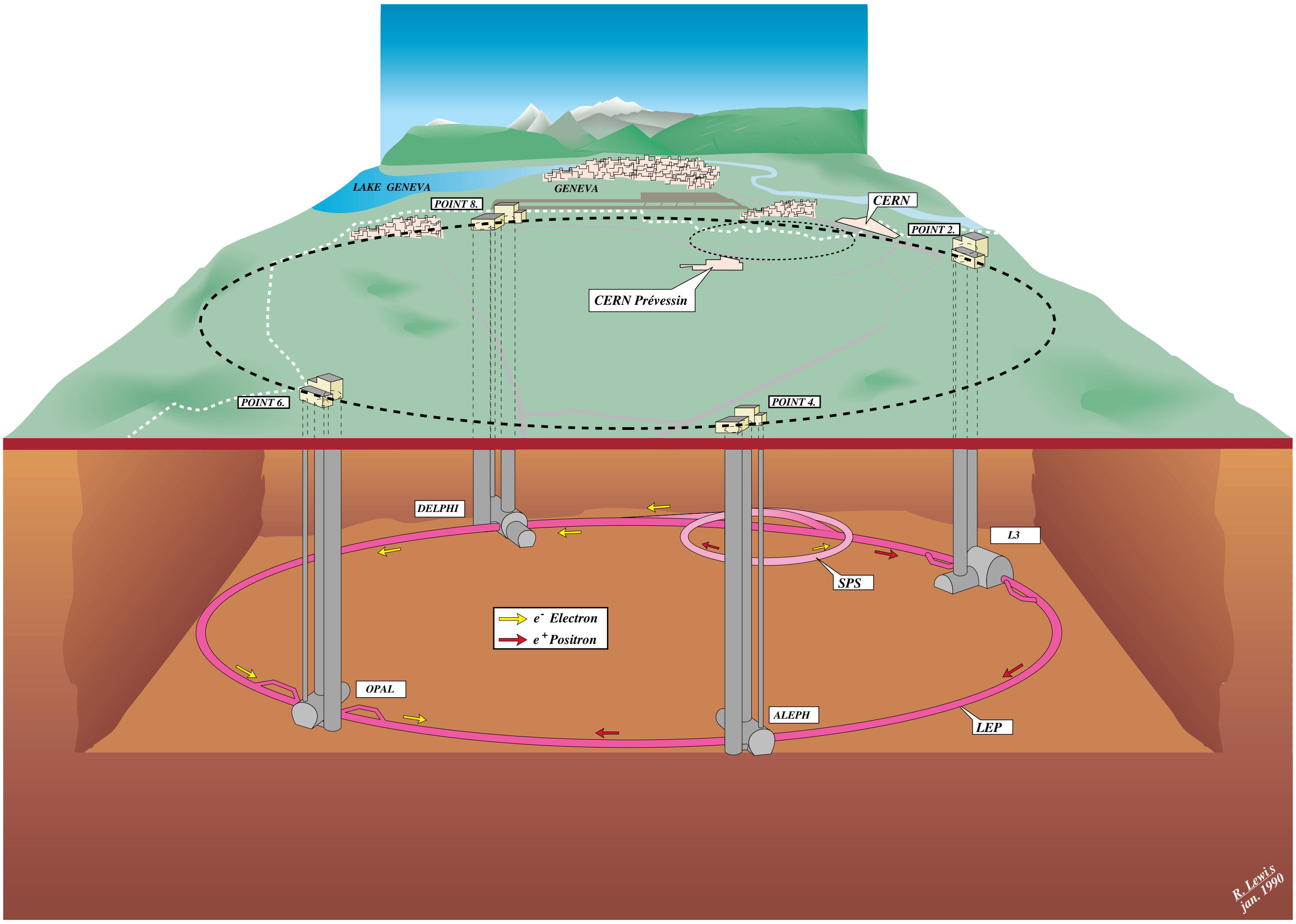
Outline

- The OPAL experiment at LEP
- What to search for?
- Direct Searches
  - Excited Leptons
  - FCNC in Single Top Production
  - SUSY (SUGRA, GMSB)
- Indirect Searches
  - Gravity in extra dimensions
- Summary

Large Electron Positron Collider



Stage	year	$\sqrt{s}$	$\mathcal{L}$ /expt.
LEP1	1990-1995	$\approx$ 91 GeV	175 pb^{-1}
LEP1.5	1995	130-140 GeV	5 pb^{-1}
LEP2	1996	161, 172 GeV	20 pb^{-1}
	1997	183 GeV	55 pb^{-1}
	1998	189 GeV	180 pb^{-1}
	1999	192, 196, 200, 202 GeV	200 pb^{-1}
	2000	200-209 GeV	180 pb^{-1}

More than 600 pb^{-1}/expt were recorded at high energy !

Omni-Purpose Apparatus at LEP

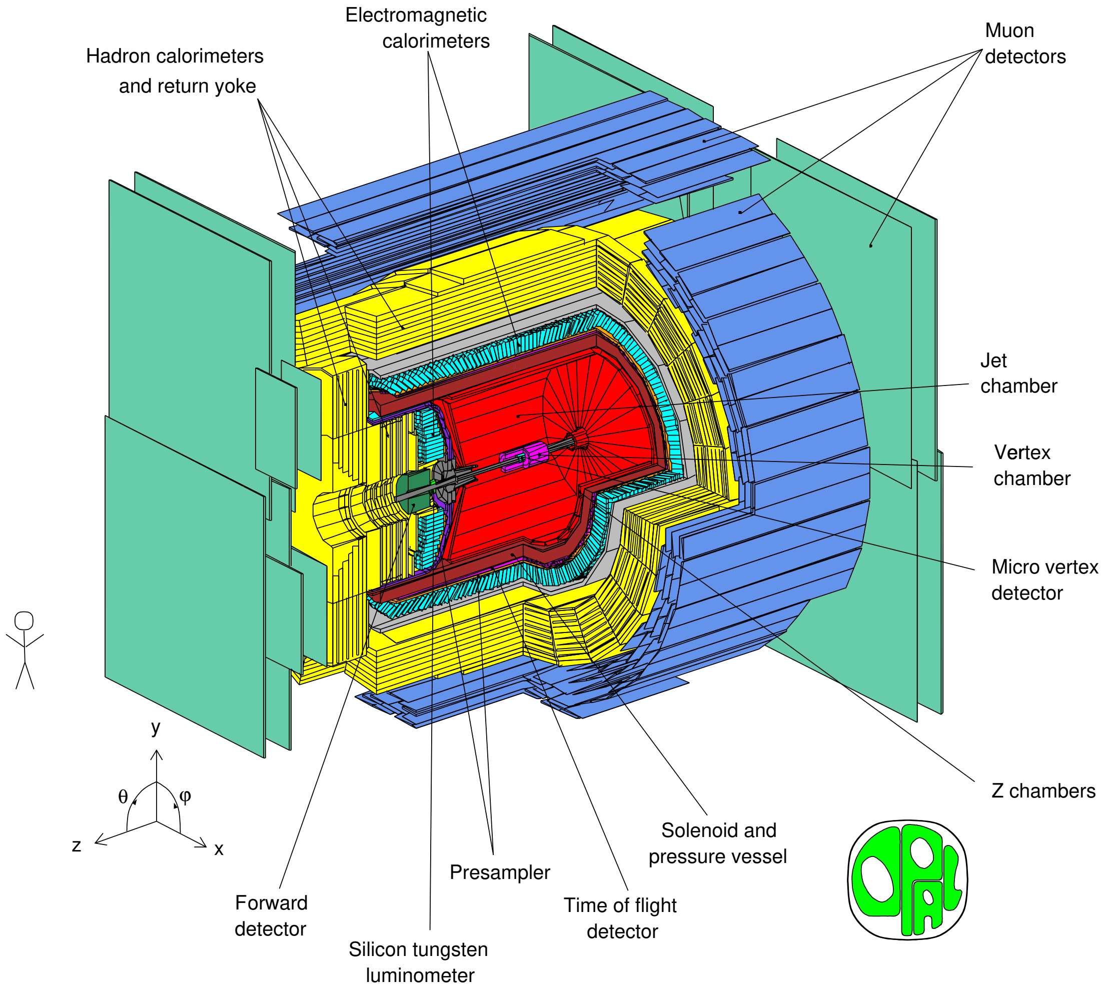
- 4π hermetic
- Tracking detectors

  x,y,z

  dE/dx

  p (magnetic field)
- Calorimeters

  EM and hadronic
- Muon detectors



What to search for? SM and beyond

$$\underbrace{W_1\ W_2\ W_3\ B}$$

$$\cancel{EW}$$

$$g\quad H^0\quad \overbrace{W^{\pm}\quad Z^0\quad \gamma}$$

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

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

Unification

(more symmetry within GUT)

Gravity in extra dimensions

SUSY $\left\{ \begin{array}{l} \text{Gravity mediated SUSY breaking (SUGRA)} \\ \text{Gauge Mediated SUSY Breaking (GMSB)} \end{array} \right.$

Extend SM

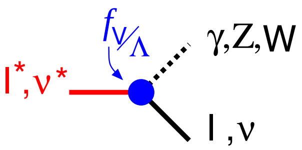
(substructure, new forces,...)

Compositeness $\begin{pmatrix}\nu_l^*\\ l^*\end{pmatrix}$

Excited Leptons

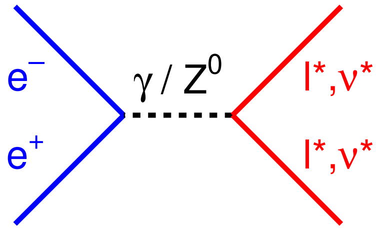
Substructure at an energy scale Λ $\Longrightarrow$ Excited leptons ℓ^*,ν^*

Decay promptly $\begin{cases} \ell^* \rightarrow \ell\gamma, \nu W, \ell Z \\ \nu^* \rightarrow \nu\gamma, \ell W, \nu Z \end{cases}$



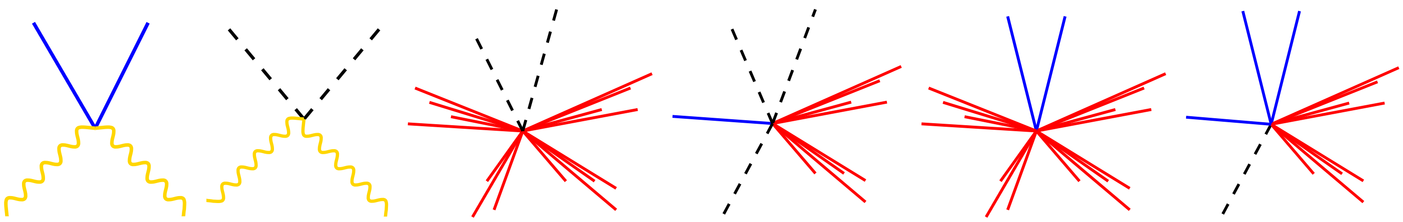
$\left.\begin{array}{l} f_\gamma \\ f_Z \\ f_W \end{array}\right\} \Longrightarrow f, f'$ Control strength of weak/EM couplings

Pair production of Excited Leptons



Discovery up to $\mathrm{M}_* \sim \sqrt{\mathrm{s}}/2$

Topologies

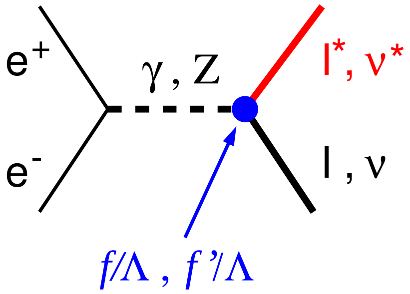


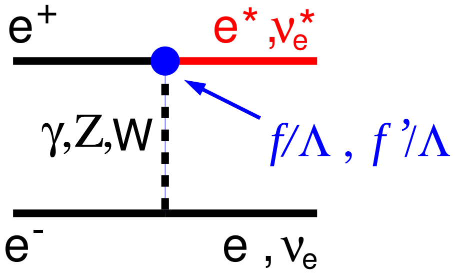
95% CL Mass Limits (GeV)

	$\mathbf{e^*}$	$\boldsymbol{\mu^*}$	$\boldsymbol{\tau^*}$	$\boldsymbol{\nu_e^*}$	$\boldsymbol{\nu_\mu^*}$	$\boldsymbol{\nu_\tau^*}$
$f = f'$	102.9	102.9	102.8	99.5	99.5	91.9
$f = -f'$	91.3	91.3	91.3	94.3	94.3	94.3

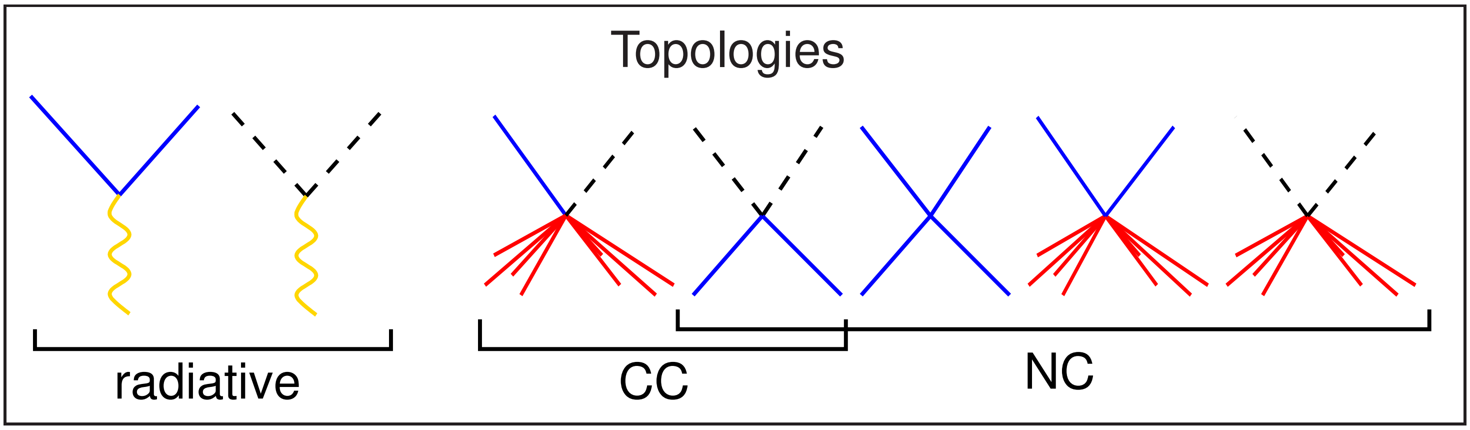
$\sqrt{s}$ = 209 GeV ($\approx 170\ \mathrm{pb}^{-1}$), $\sqrt{s}$ = 202 GeV, $\sqrt{s}$ = 189 GeV

Single production of Excited Leptons





Discovery up to
$M_* \sim \sqrt{s}$

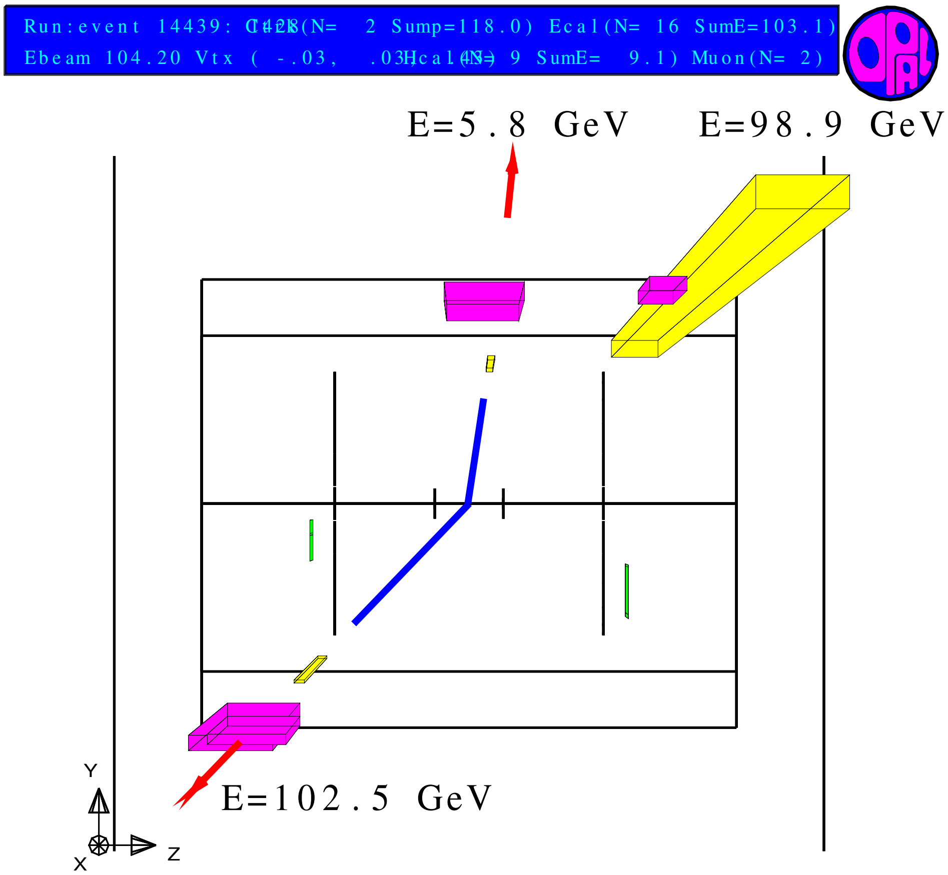


Candidate Event

$\mu^*\mu \rightarrow \mu\mu\gamma$

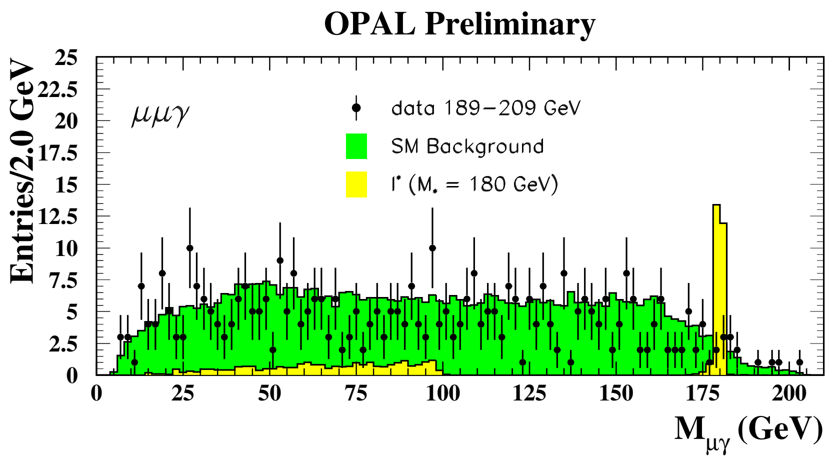
$\sqrt{s} = 208.4$ GeV

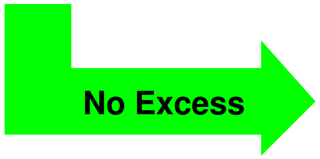
$M_{\mu^*} = 201.3$ GeV

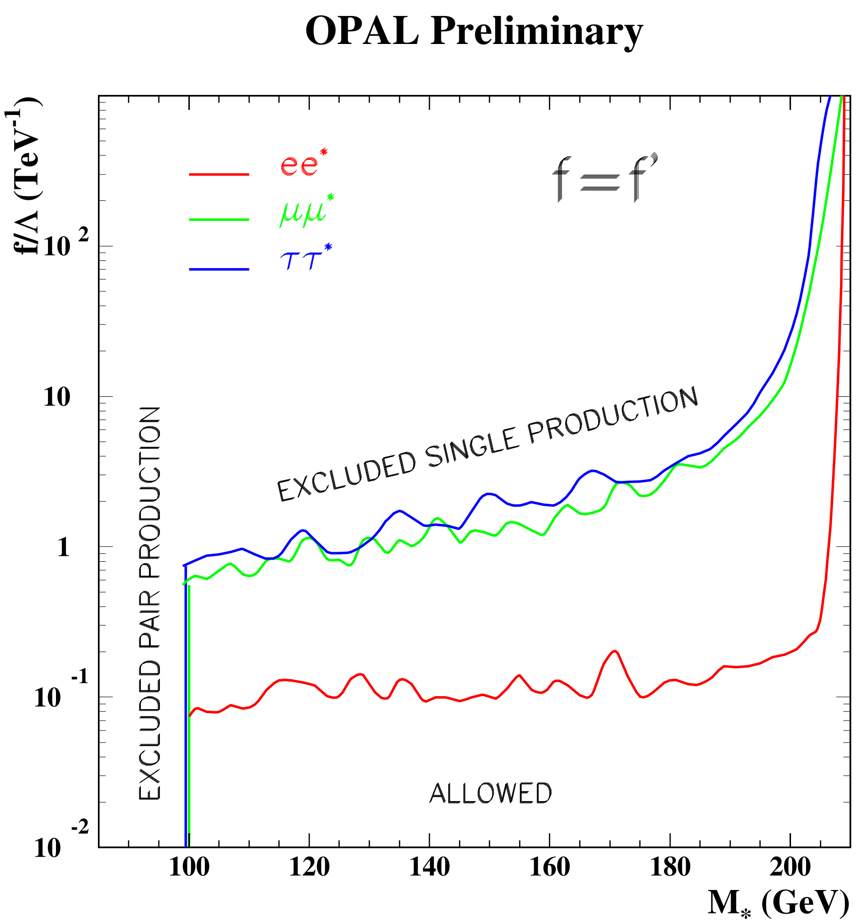


Single Production of Excited Leptons - continued

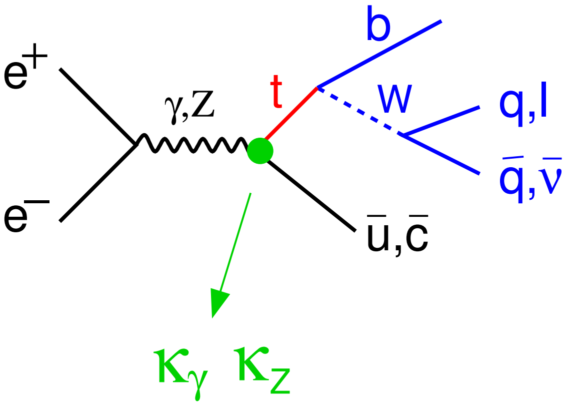
Look for peak in mass distribution



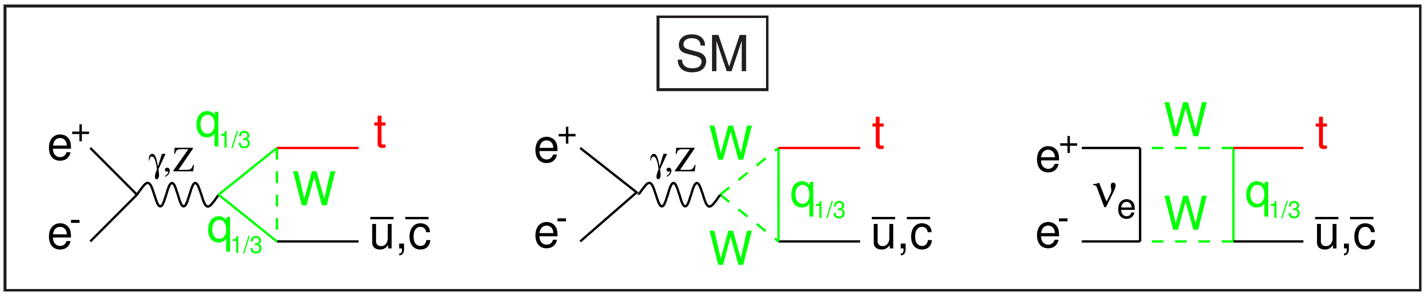


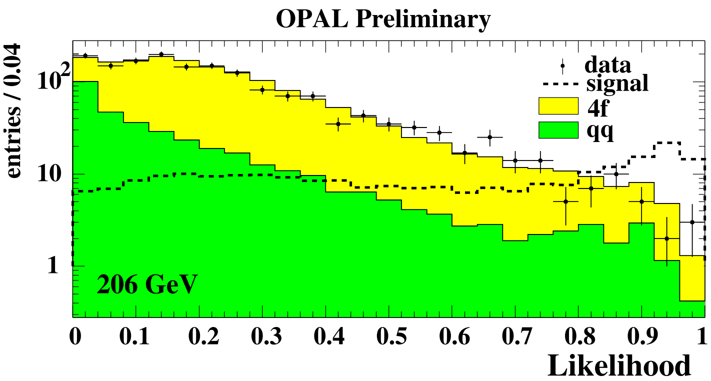


Search for FCNC in Single Top quark production

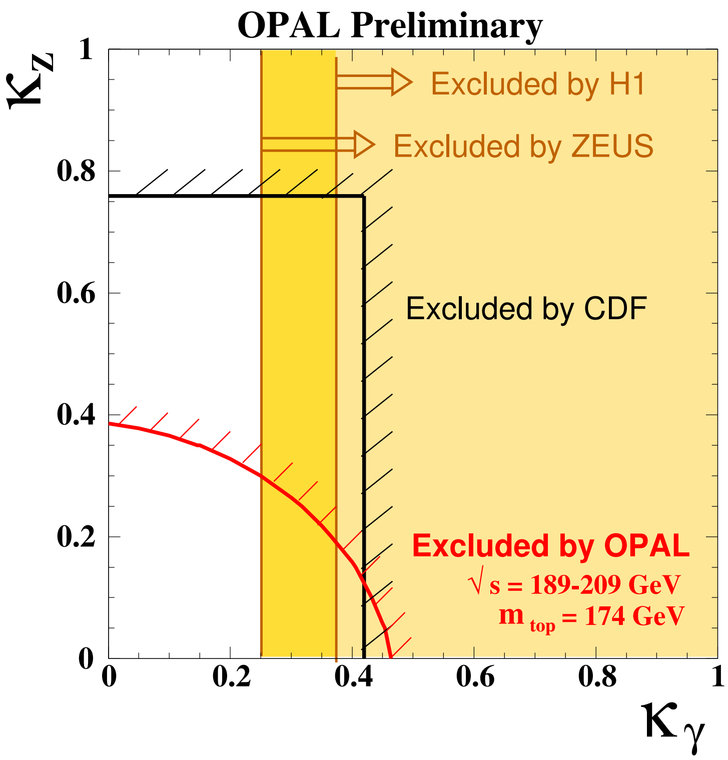


- In SM no tree-level FCNC
- $\sigma_{\rm SM} \sim 10^{-9}$ pb
- Kinematically allowed at LEP2 but not enough luminosity
- New Physics could enhance single top production (Z',SUSY)





No signal observed
Calculate limits ⟹



SUperSYmmetry

fermion $\Longleftrightarrow$ boson

More than 100 new parameters
Need to constrain model...

Minimal Supersymmetric SM

1	1/2	0
γ, Z^0	$\left.\begin{array}{c}\tilde{\gamma}\\ \tilde{Z}^0\\ \tilde{h}, \tilde{H}\end{array}\right\}\tilde{\chi}^0_j$	h^0, H^0, A^0
$W^\pm$	$\left.\begin{array}{c}\tilde{H}^\pm\\ \tilde{W}^\pm\end{array}\right\}\tilde{\chi}^\pm_i$	$H^\pm$
g	$\tilde{g}$	
	$\ell^\pm_{L,R}$	$\left.\tilde{\ell}^\pm_{L,R}\right\}\tilde{\ell}^\pm_{1,2}$
	ν_L	$\tilde{\nu}_L$
	$q_{L,R}$	$\left.\tilde{q}_{L,R}\right\}\tilde{q}_{1,2}$

cMSSM

M_2	SU(2) gaugino mass (EW scale)
m_0	Common scalar mass (GUT scale)
A_0	Common trilinear coupling (GUT scale)
$\tan\beta$	ratio of v.e.v. of Higgs doublets (v_2/v_1)
μ	Higgs mixing parameter
M_A	Pseudo scalar Higgs mass

To suppress FCNC

$\Downarrow$

R-parity $\begin{cases} +1 & \text{particles} \\ -1 & \text{sparticles} \end{cases}$

$\Downarrow$

- Sparticles produced in pair
- Lightest Supersymmetric Particle is stable ($\Rightarrow$ Missing Energy)

SUSY Breaking scenario

No sparticles yet

$\Downarrow$

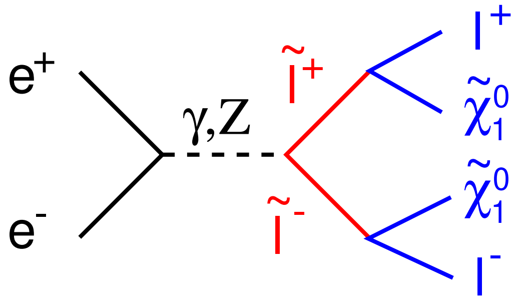
SUSY must be a broken symmetry!

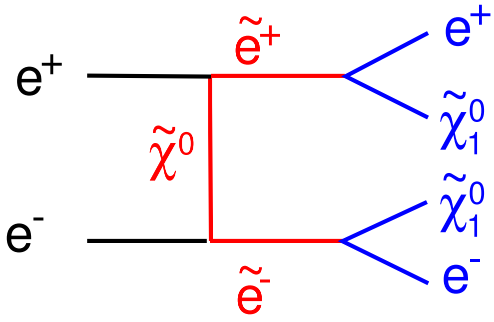
SUGRA		GMSB
	Hidden ~~SUSY~~	
	$\Downarrow$	
Gravity	Messenger	Gauge interactions
	$\Downarrow$	
	Visible	LSP: $\tilde{\mathrm{G}}$
LSP: $\tilde{\chi}_1^0$	$\mathrm{e}, \mu, \tau \ldots$	NLSP: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$
	$\tilde{\mathrm{e}}, \tilde{\mu}, \tilde{\tau}, \ldots$	$\tilde{\ell}_R^{\pm} \rightarrow \ell^{\pm} \tilde{G}$

SUGRA:
- Missing $\mathrm{E_t}$

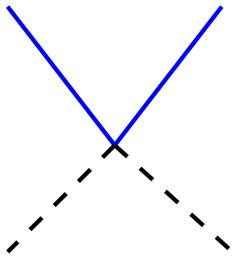
GMSB:
- Missing $\mathrm{E_t}$
- Energetic γ or $\ell^{\pm}$

Sleptons - $\tilde{\ell}$



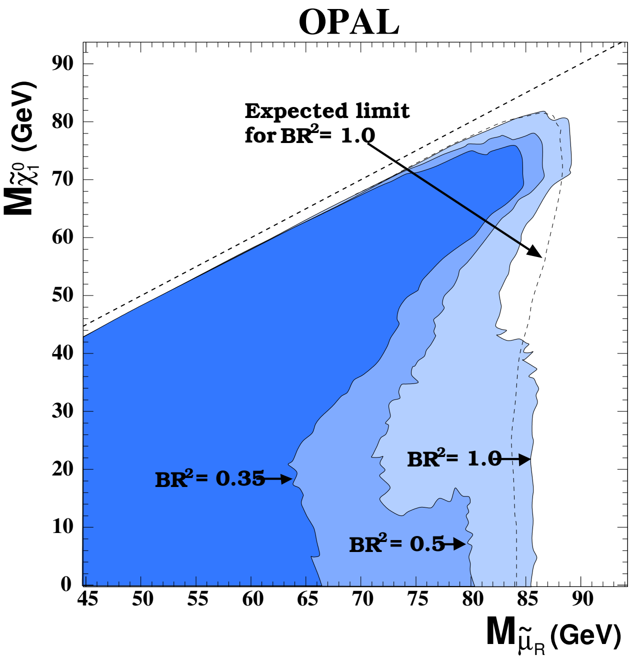


t-channel contribution depends on SUSY parameters



- Acoplanar lepton pair
- $\not\!\!E_t$

95% CL exclusion region



Mass limits

Assuming 100% BR($\tilde{\ell}_R \rightarrow \ell\tilde{\chi}^0_1$)

$M_{\tilde{\mu}_R} > 82.3$ GeV $\Delta M > 3$ GeV

$M_{\tilde{\tau}_R} > 81.0$ GeV $\Delta M > 8$ GeV

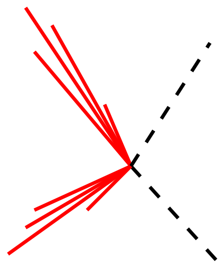
$M_{\tilde{e}_R} > 87.1$ GeV $\Delta M > 5$ GeV
$\mu < -100$ GeV
$\tan\beta = 1.5$

Scalar top - $\tilde{t}$

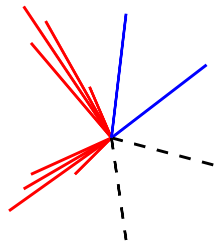
light $\tilde{t}_1$ $\left\{ \begin{array}{l} \bullet \text{ SUSY radiative corrections} \\ \bullet \text{ large mixing} \rightarrow m_t \end{array} \right.$

$$\tilde{t}_1 = \cos\theta_{\tilde{t}}\tilde{t}_L + \sin\theta_{\tilde{t}}\tilde{t}_R$$

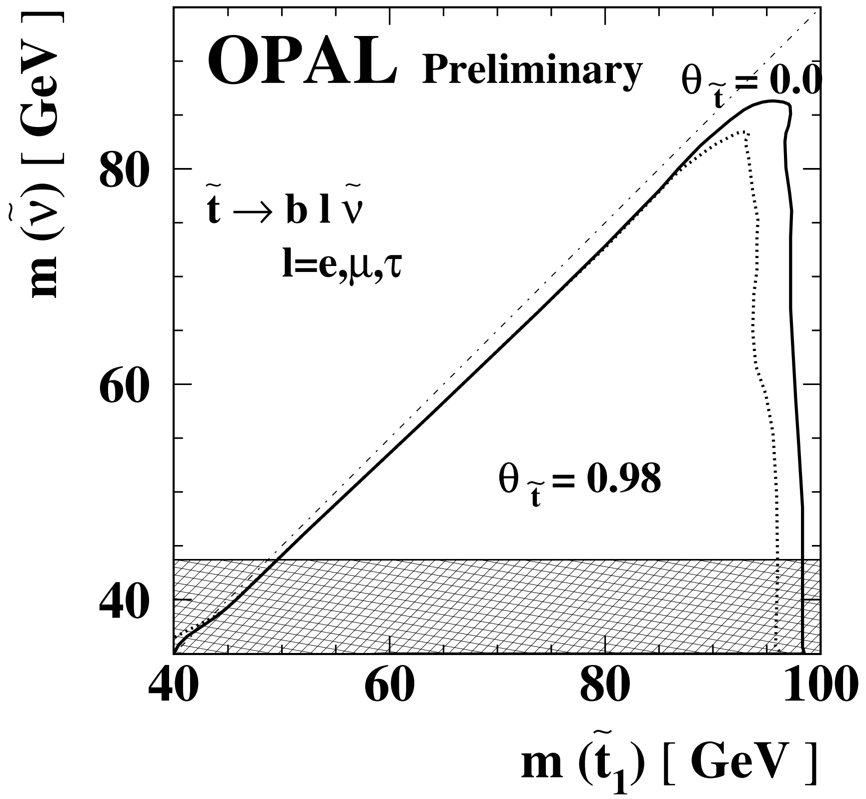
$\tilde{t}_1\tilde{t}_1 \rightarrow (c\tilde{\chi}^0_1)(c\tilde{\chi}^0_1)$



$\tilde{t}_1\tilde{t}_1 \rightarrow (b\tilde{\nu}\ell)(b\tilde{\nu}\ell)$



95% CL excluded region

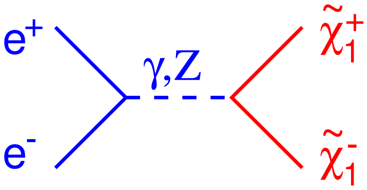


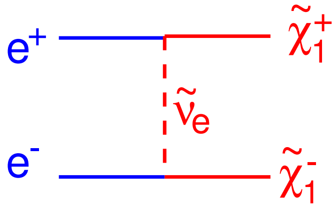
Mass limits

$\tilde{t}_1 \rightarrow b\tilde{\nu}\ell$
$M_{\tilde{t}_1} > 92.7$ GeV
$\Delta M \geq 10$ GeV
$\theta_{\tilde{t}}$=0.98

$\tilde{t}_1 \rightarrow c\tilde{\chi}^0_1$
$M_{\tilde{t}_1} > 95.7$ GeV
$\Delta M \geq 10$ GeV
$\theta_{\tilde{t}}$=0.98

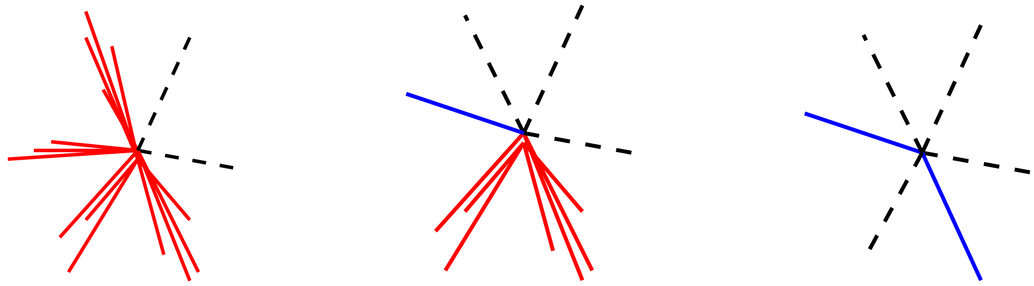
Charginos - $\tilde{\chi}_1^{\pm}$





$\sigma \gtrsim 4$ pb
depends on $m_{\tilde{\nu}_e}$

Most of MSSM parameter space $\boxed{\tilde{\chi}_1^+\tilde{\chi}_1^+ \to (W^+\tilde{\chi}_1^0)(W^-\tilde{\chi}_1^0)}$

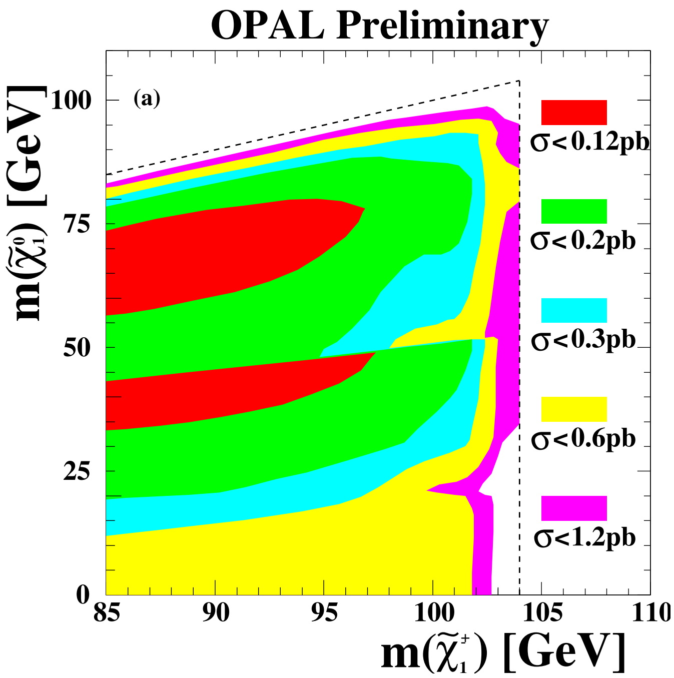


qqqq $\tilde{\chi}_1^0\tilde{\chi}_1^0$ (47%)

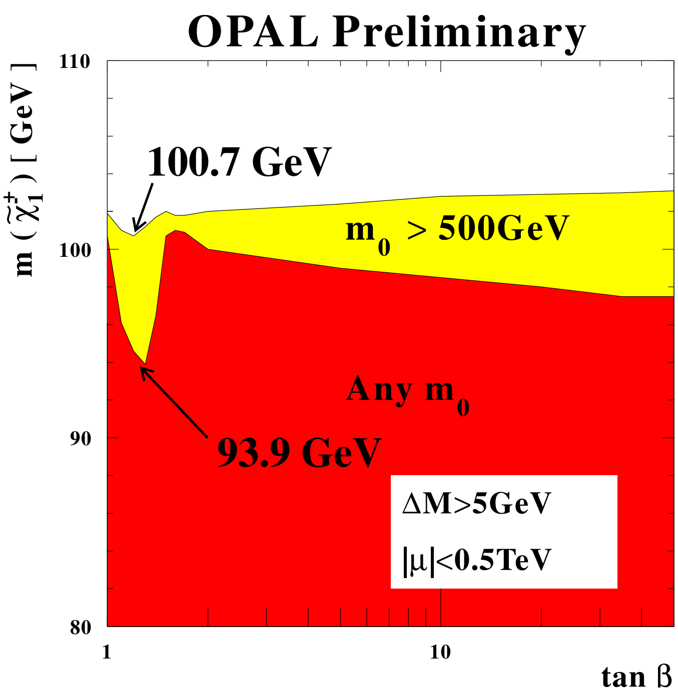
qq$\ell\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$ (43%)

$\ell\nu\ell\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$ (10%)

Cross-section limit



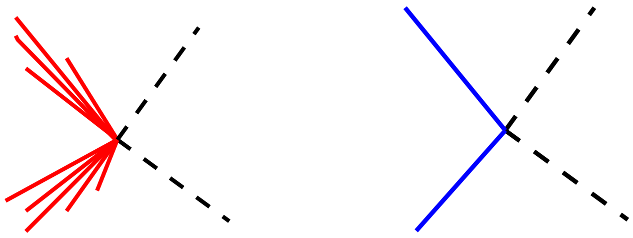
Mass limit



Neutralinos - $\tilde{\chi}_1^0, \tilde{\chi}_2^0$

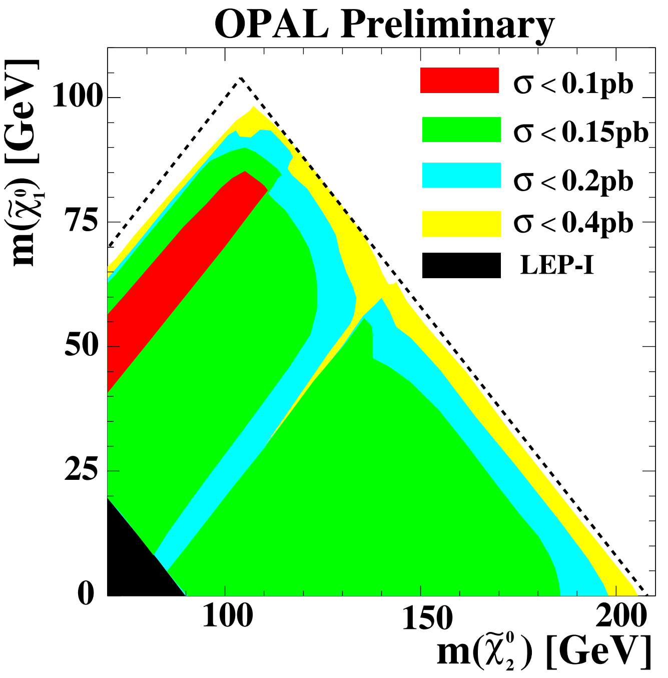
$e^+e^- \longrightarrow \tilde{\chi}_2^0 \; \tilde{\chi}_1^0$

$\quad\quad\quad\quad \hookrightarrow \tilde{\chi}_1^0 \nu\bar{\nu}$, $\tilde{\chi}_1^0 l^+ l^-$, $\tilde{\chi}_1^0 q\bar{q}$



$qq\tilde{\chi}_1^0\tilde{\chi}_1^0$ $\quad\quad$ $\ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$

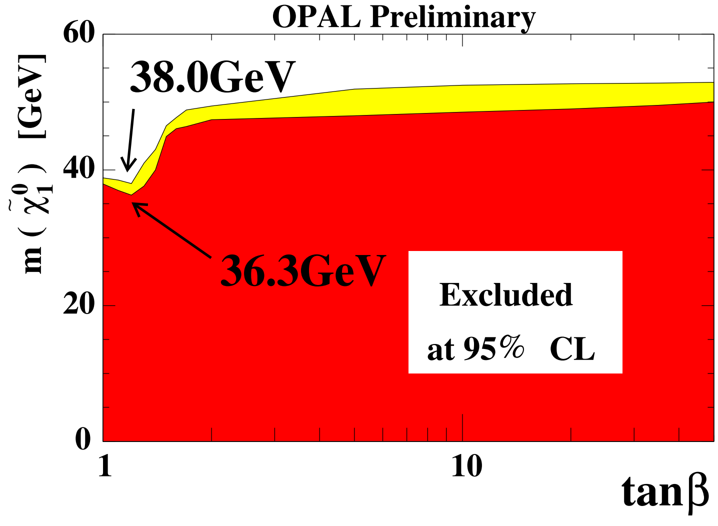
Cross-section limit



Mass limit

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

$m_{\tilde{\chi}_1^0} > 36.3$ GeV for all m_0



Gauge Mediated SUSY Breaking

$\tilde{G}$ is the LSP! $m_{\tilde{G}} < 1$ GeV

Two possible NLSP

$\tilde{\chi}_1^0$	$\tilde{\ell}_{\mathrm{R}}^{\pm}$
$\tilde{\chi}_1^0 \to \gamma \tilde{G}$	$\tilde{\ell}_{\mathrm{R}}^{\pm} \to \ell^{\pm} \tilde{G}$
photons + $\not{E}$	leptons + $\not{E}$

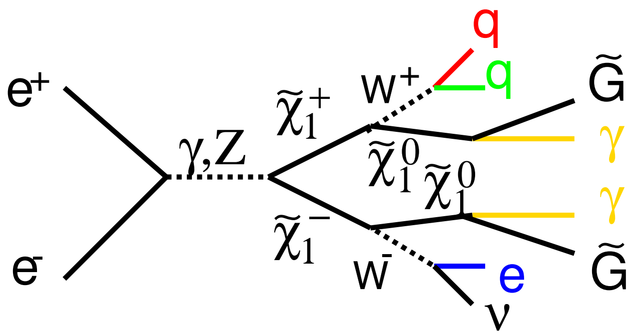
NLSP lifetime can be sizeable

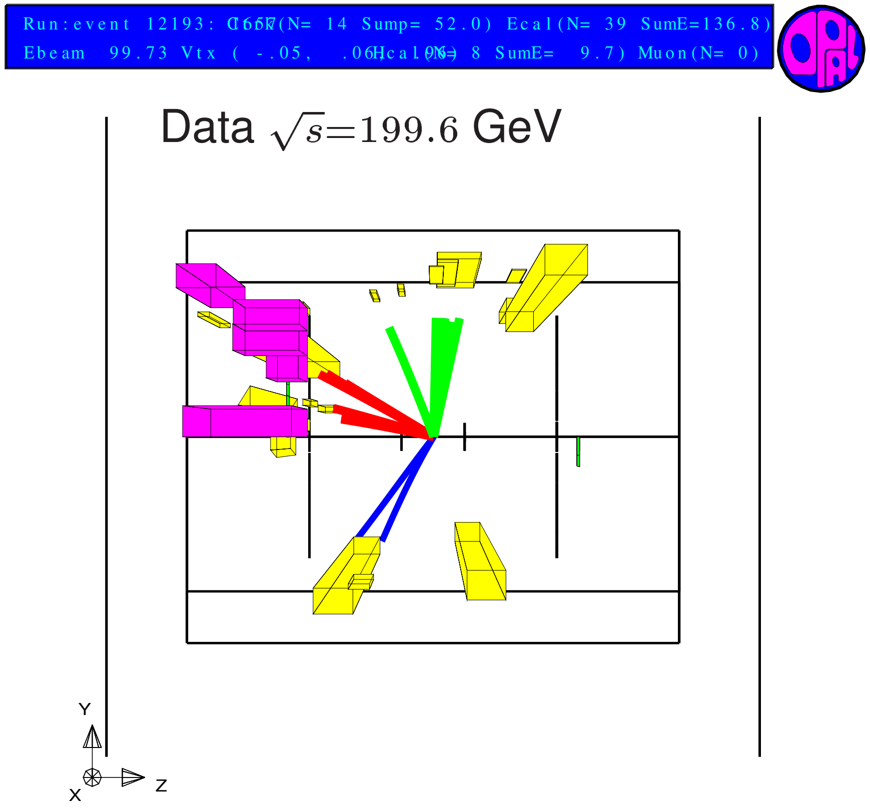
$1 \mu\mathrm{m} <$ decay length $< 10^{11}$ km

Many interesting and unique experimental topologies

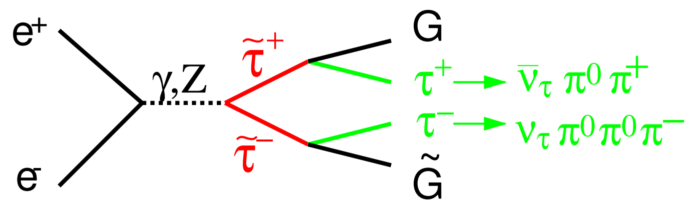
Interesting topologies in GMSB

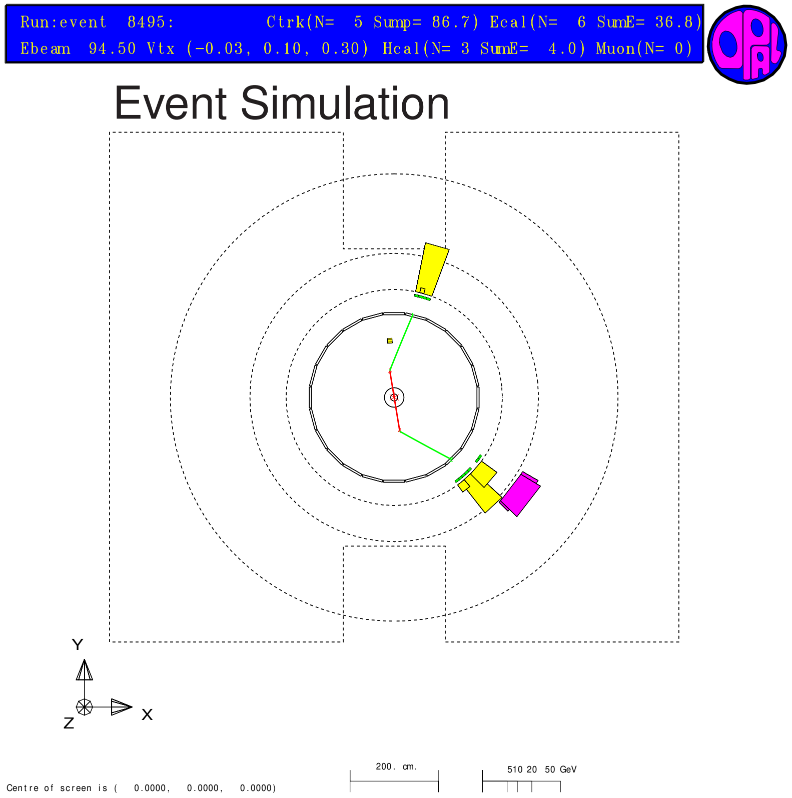
$\tilde{\chi}_1^0$ NLSP - prompt decay





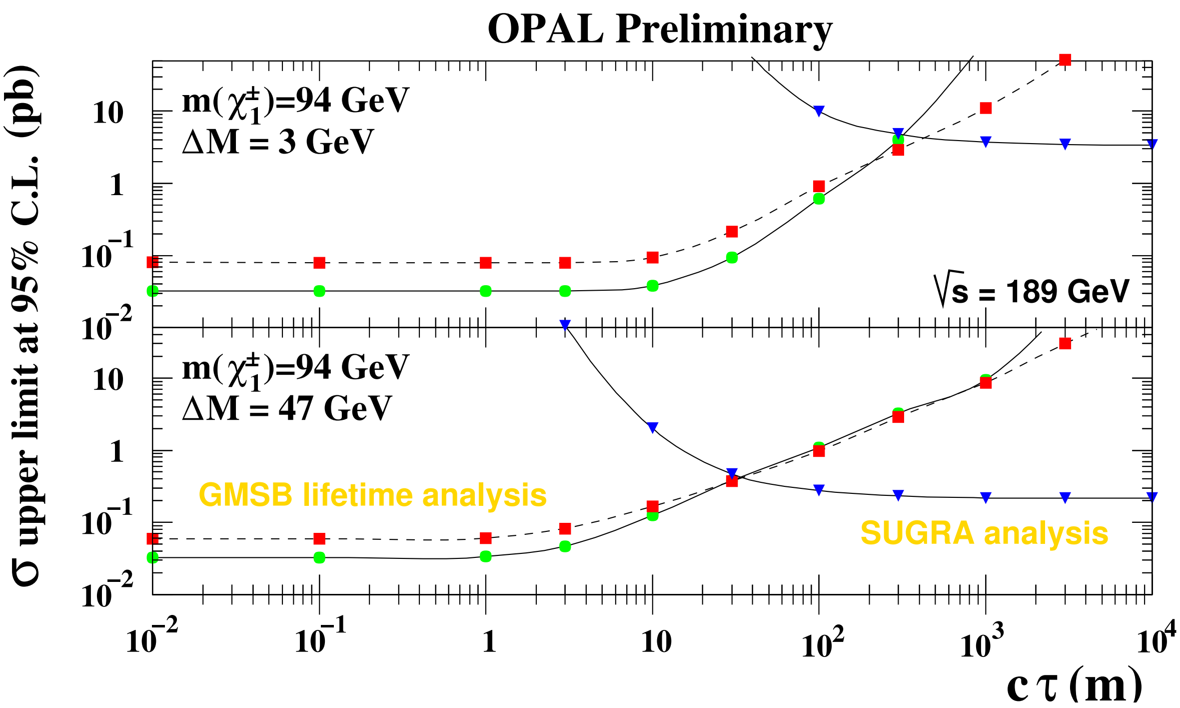
$\tilde{\ell}^\pm$ NLSP - medium lifetime



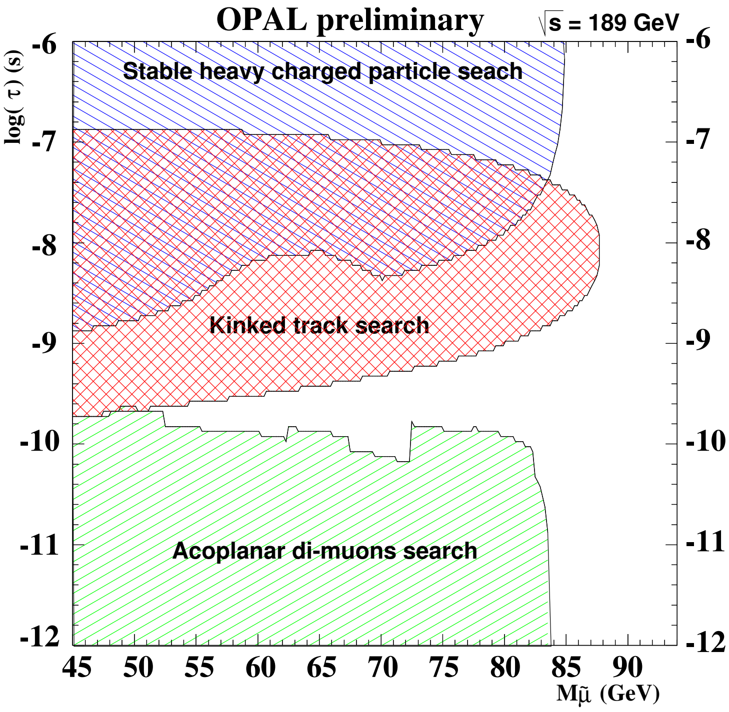


GMSB limits

Cross-section limits for $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ vs NLSP lifetime

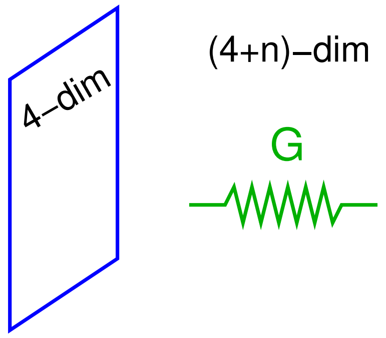


95% CL Exclusion region for $\tilde{\mu}$



Low Scale Gravity in Extra Dimensions

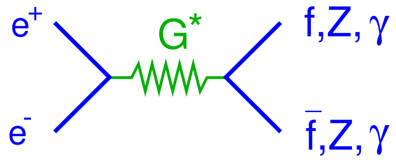
Theory of quantum gravity
in extra dimensions



Solve hierarchy problem $(\mathrm{M_{EW}} \ll \mathrm{M_{Pl}})$

$\Downarrow$

Choose Planck Mass in D-dimensions $\mathrm{M_D} \sim \mathrm{M_{EW}}$



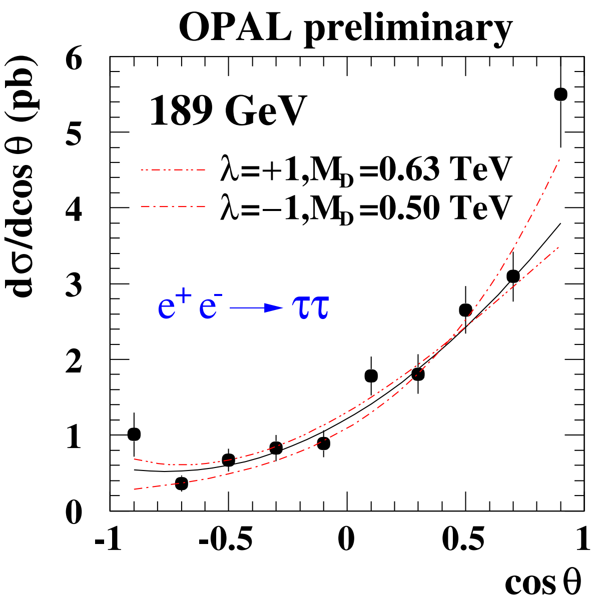
$$\frac{d\sigma}{d\Omega} = f\left(\frac{\lambda}{\mathrm{M_D^4}}\right)$$

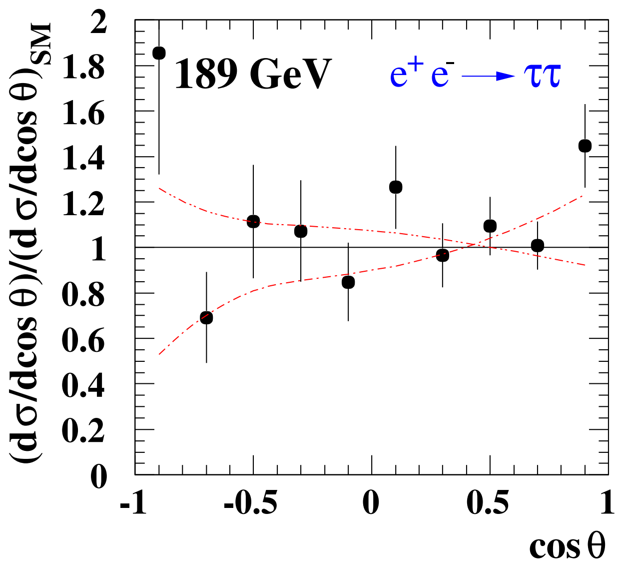
- λ depends on theory
- λ weakly depends on n
- λ is dimensionless
- sign(λ) undetermined

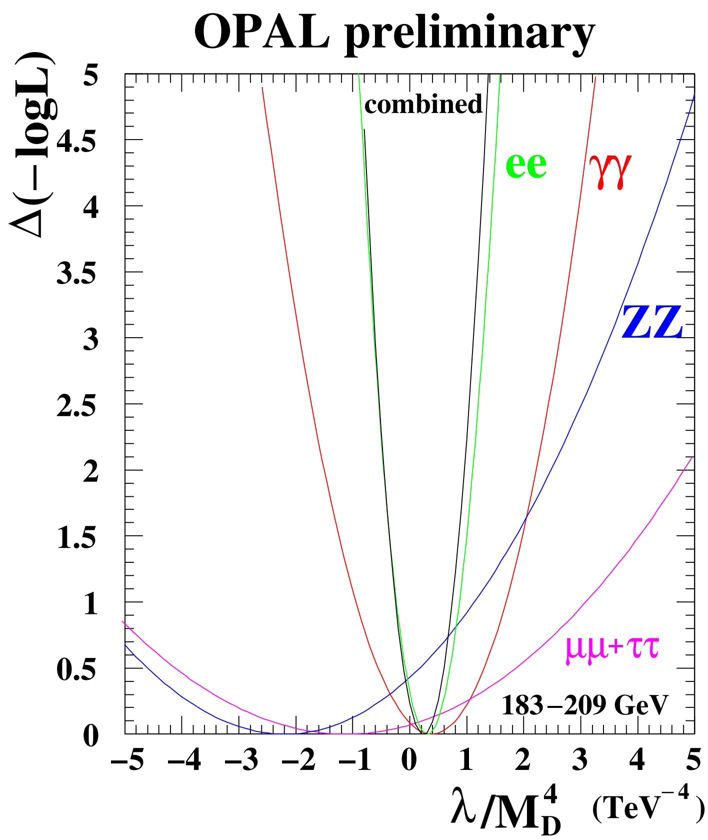
Low Scale Gravity in Extra Dimensions - continued

Fit differential and total cross-section of

$$e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \gamma\gamma, Z^0Z^0, W^+W^-$$







$$\sqrt{s} = 183 - 209 \text{ GeV}$$

$$\boxed{\begin{array}{ll} \lambda = +1 & \mathrm{M_D} > 1.03 \text{ TeV} \\ \lambda = -1 & \mathrm{M_D} > 1.17 \text{ TeV} \end{array}}$$

Using convention from T.G.Rizzo

Summary

- Lots of search topologies!
- Work towards OPAL/LEP final results
- For more info: http://opal.web.cern.ch/Opal/PPwelcome.html

No excess observed in preliminary results but...

The SPDG is an international collaboration that reviews Sparticle Physics and related areas of Astrophysics, and compiles/analyzes data on particle properties. SPDG products are distributed to 130,000 physicists, teachers, and other interested people. **The Review of Sparticle Physics** is the most cited publication in particle physics during the last twenty years. Plots of SPDG statistics are available.

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Review of Sparticle Physics | Charts, Educational materials, Sparticle Adventure | Information and Databases
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The Review of Sparticle Physics

C. Caso *et al*, The European Physical Journal **C103** (2018) 1 (2018 Authors)

- 2019 **2019 Web update of Reviews, Tables, Plots** **New November 2, 2019**
- 2019 **2019 Web update of Sparticle Listings** **New July 6, 2019**

- 2018 **2018 Summary Tables and Conservation Laws**
- **2018 Reviews, Tables, Plots (incl. Intro. Text)** **Superseded by 2019 Web Version**
- **2018 Sparticle Listings (published version)** **Superseded by 2019 Web Version**

- **Errata** (last changed January 18, 2020)
- Archived WWW editions: 2017 2016 2015
- Descriptions of the Summary Tables, Reviews, Listings, etc.
- **Ordering information** and list of products
- **2018 Authors** and **Directory of Sparticle Data Group Authors, Associates, and Advisors**
- Computer-readable files -- masses, widths, cross-sections, etc., including Palm Pilot XXII files.
- Encoder tools (for SPDG collaborators)