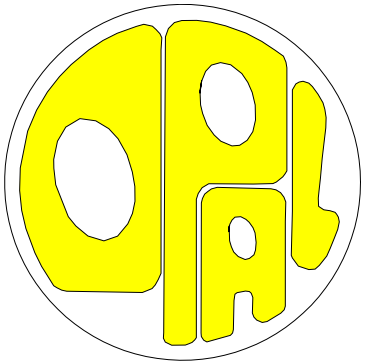
And Now The End Is Near: Physics Results from LEP2



Standard Model Measurements

Fermion pair production cross-sections and asymmetries

Gauge boson pair production cross-sections

Running of α_{em}

QCD and running of α_s

W mass

LEP combined electroweak results

Searches for Physics Beyond the Standard Model

Indirect Searches via precision Standard Model measurements

Direct searches for new particles

Supersymmetry (gravity-mediated, gauge mediated), excited fermions, contact interactions, large compact extra dimensions, leptoquarks, additional gauge bosons, anomalous gauge boson couplings

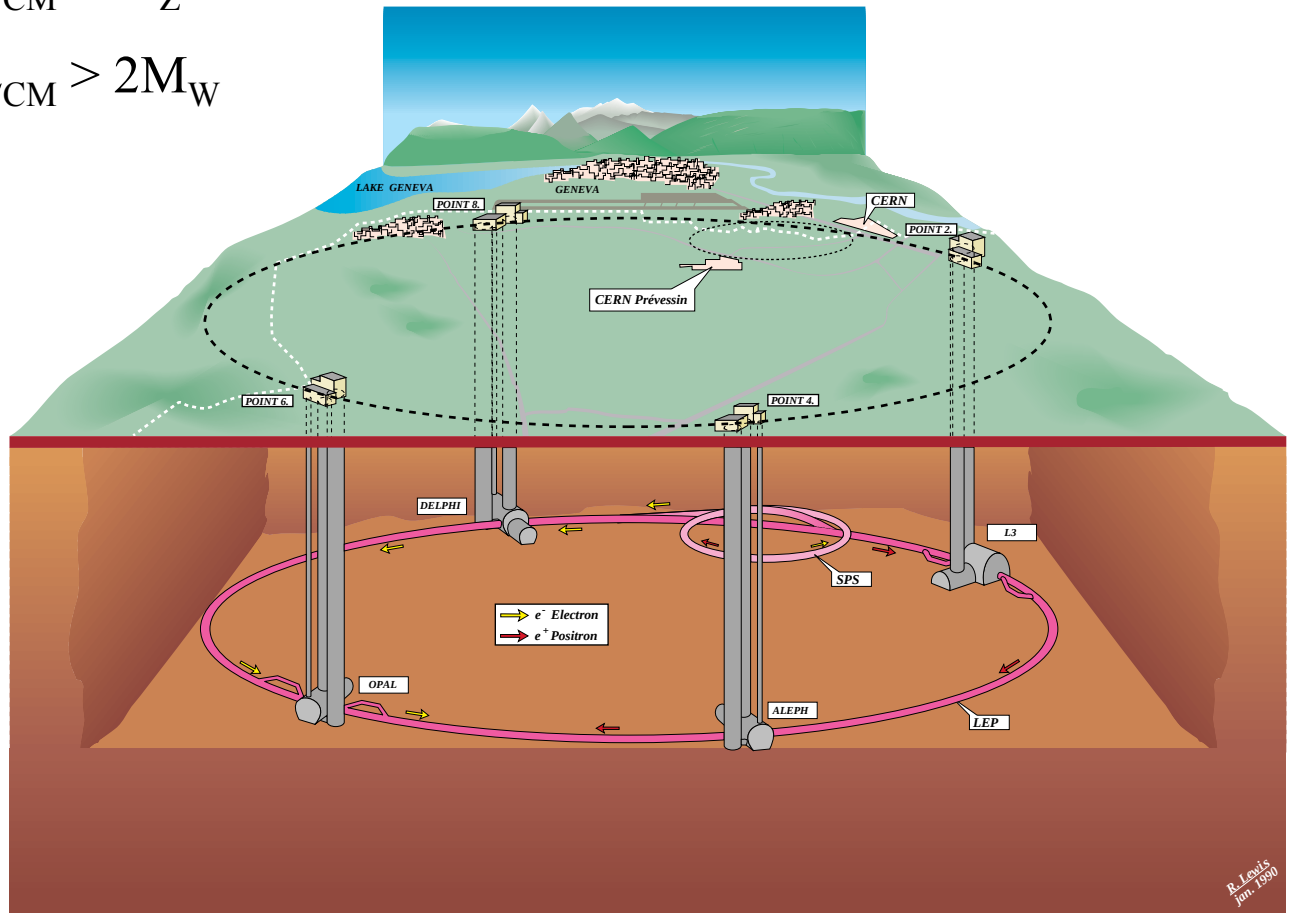
The Large Electron Positron Collider at CERN

Two phase experimental program:

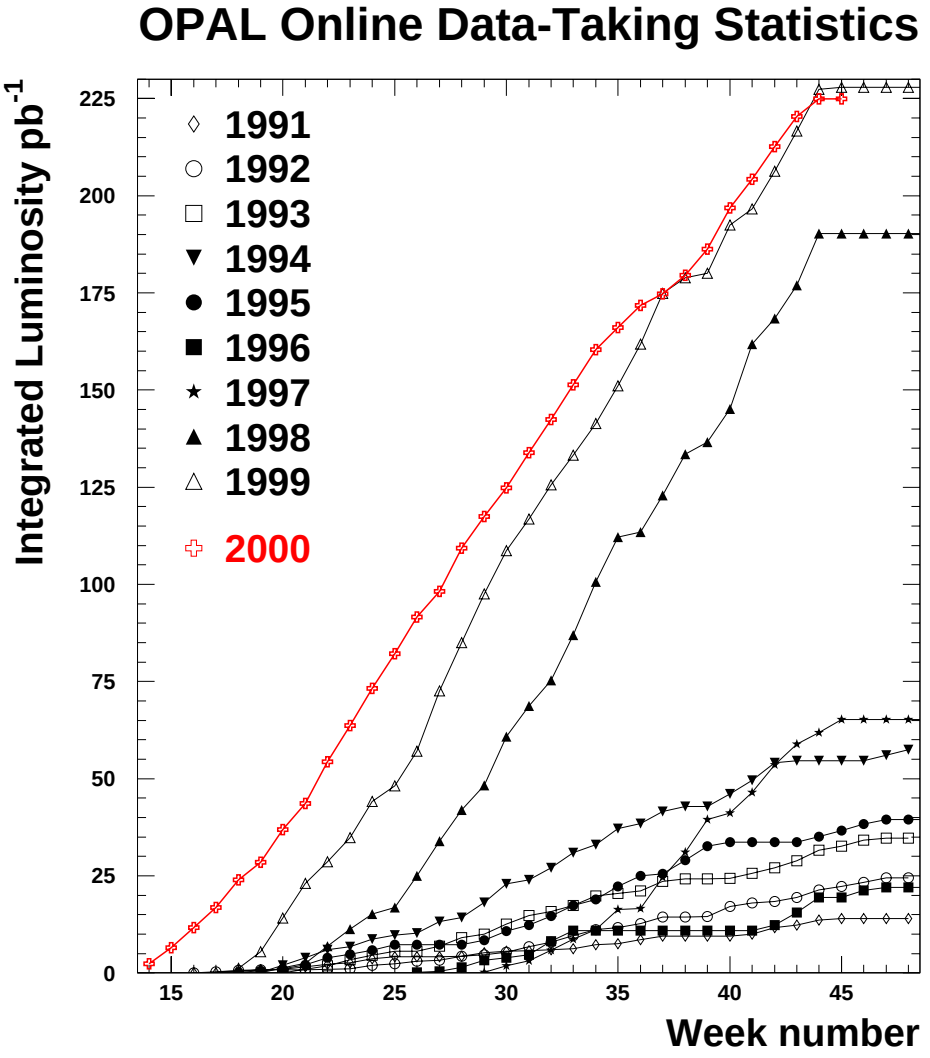
1989-1995 $E_{CM} \sim M_Z$

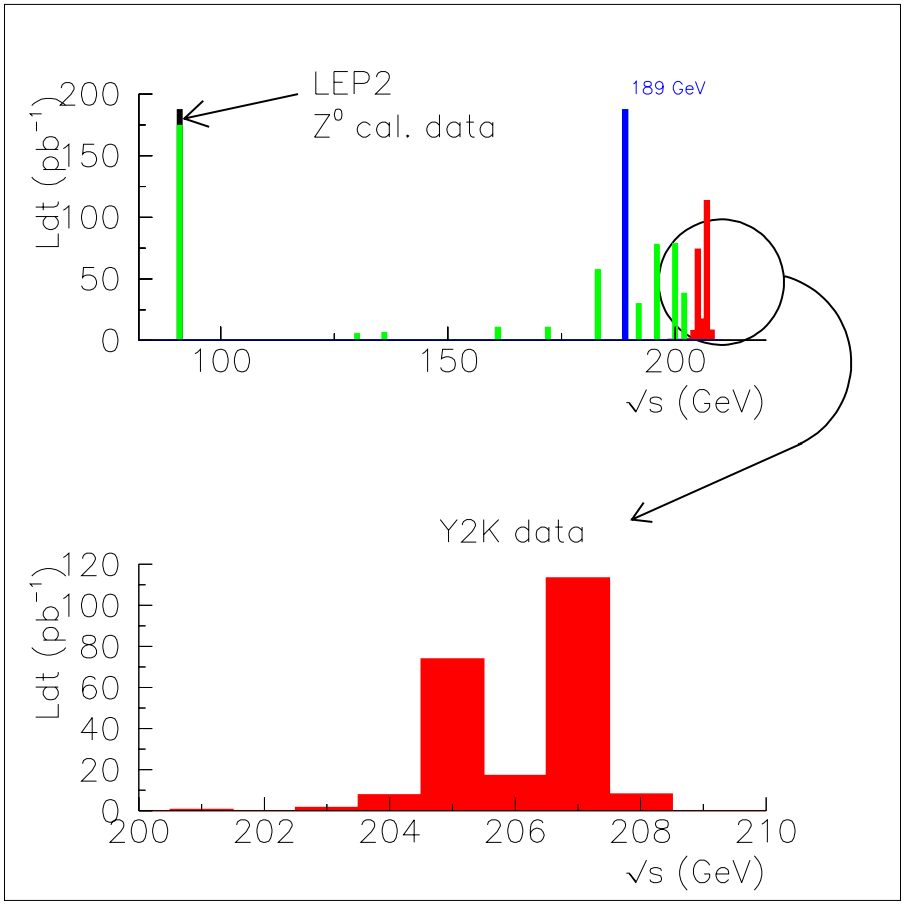
1996-2000 $E_{CM} > 2M_W$

Highest energy running in 2000 achieved $E_{CM} \sim 209$ GeV

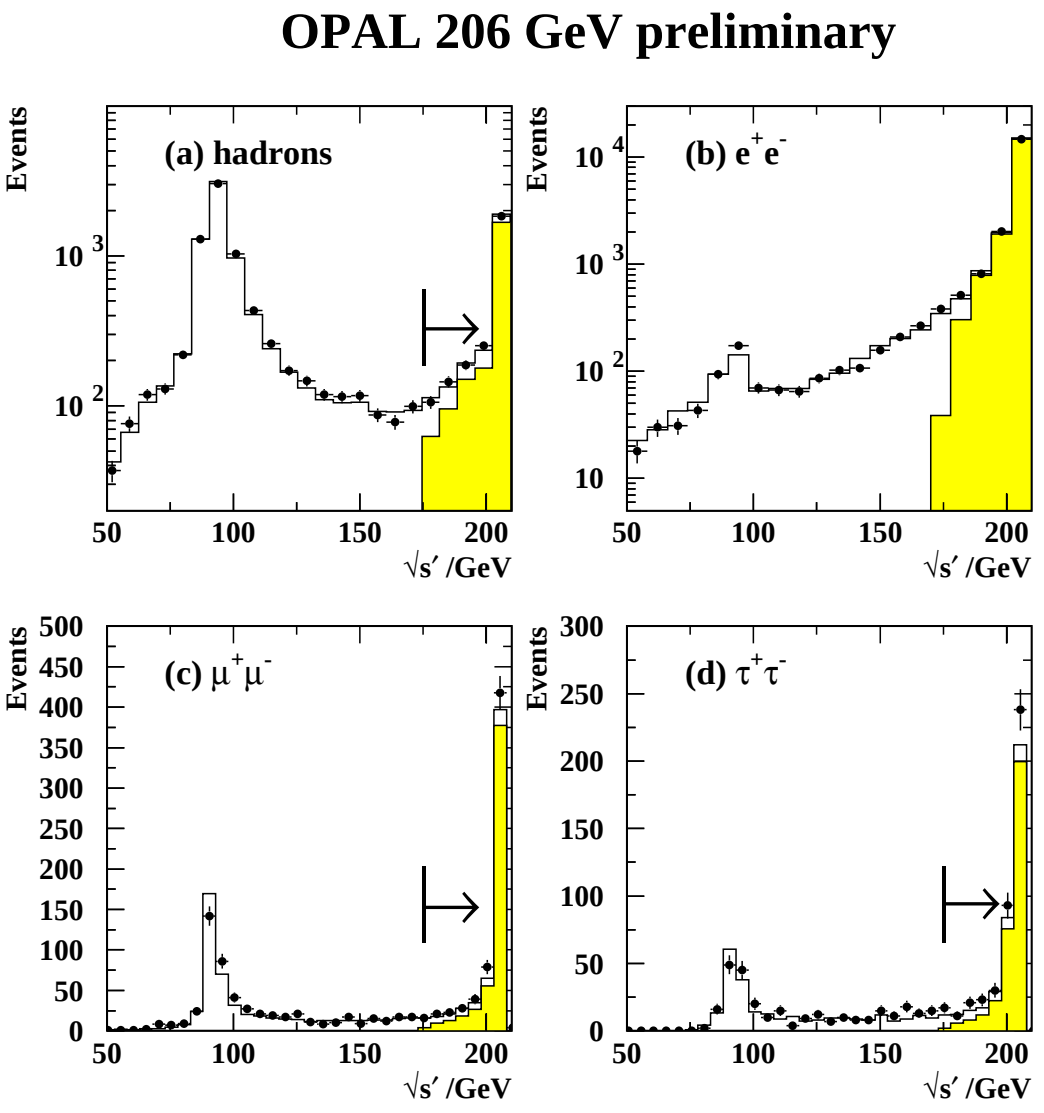


The OPAL Data Sample





Fermion Pair Production Cross-sections



$\sqrt{s'} \equiv$ Effective centre-of-mass energy in initial state (after ISR)

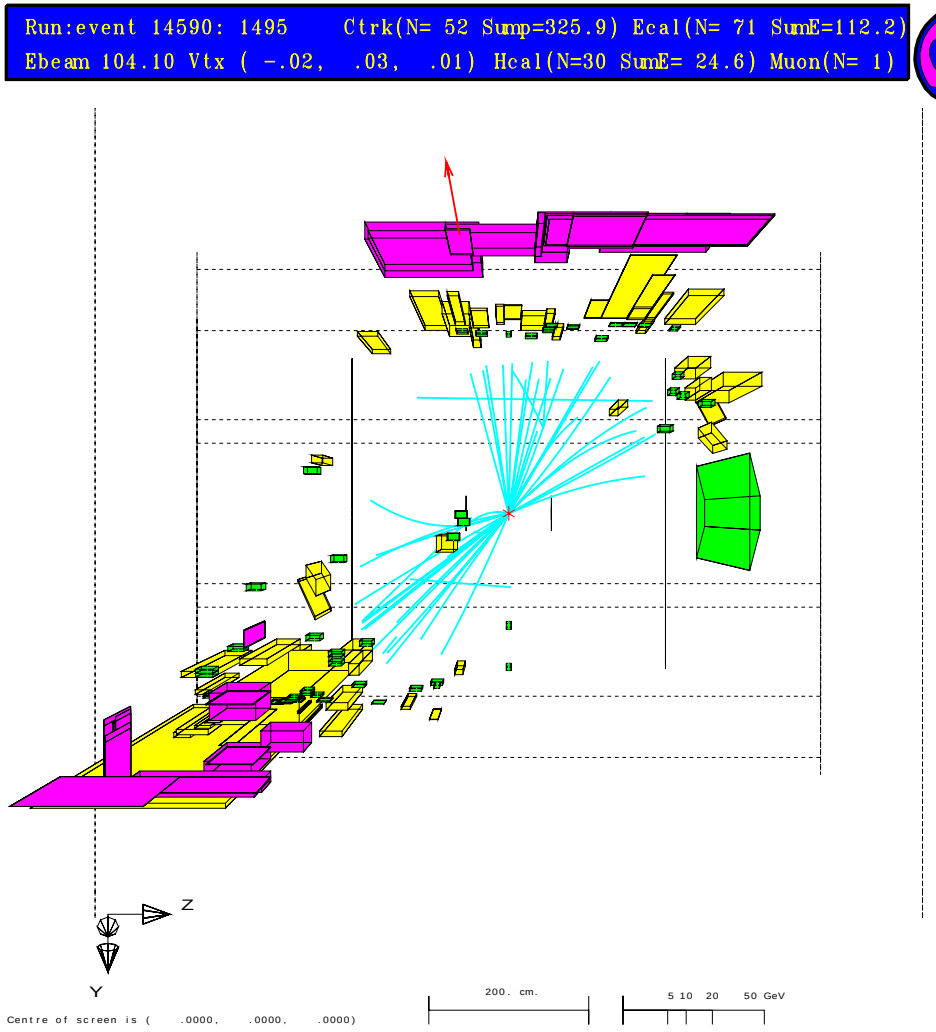
$s' > 0.01$

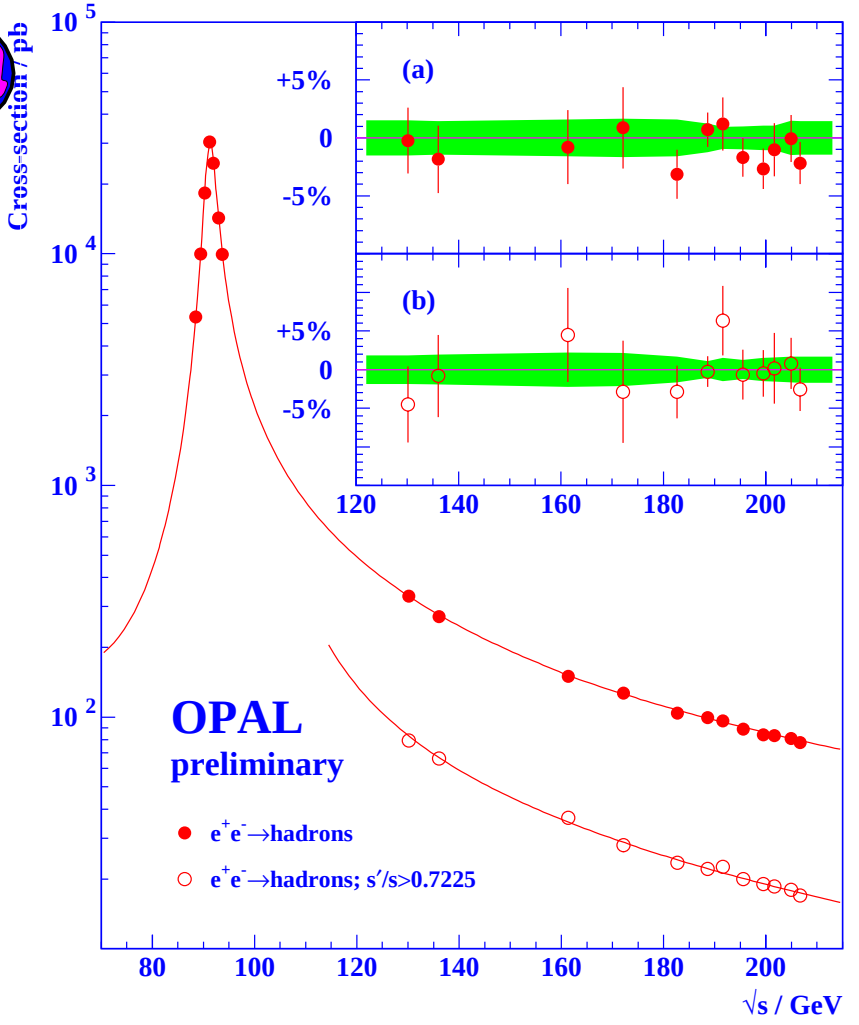
$s' > 0.7225$

non-radiative sample

Fermion Pair Production Cross-sections

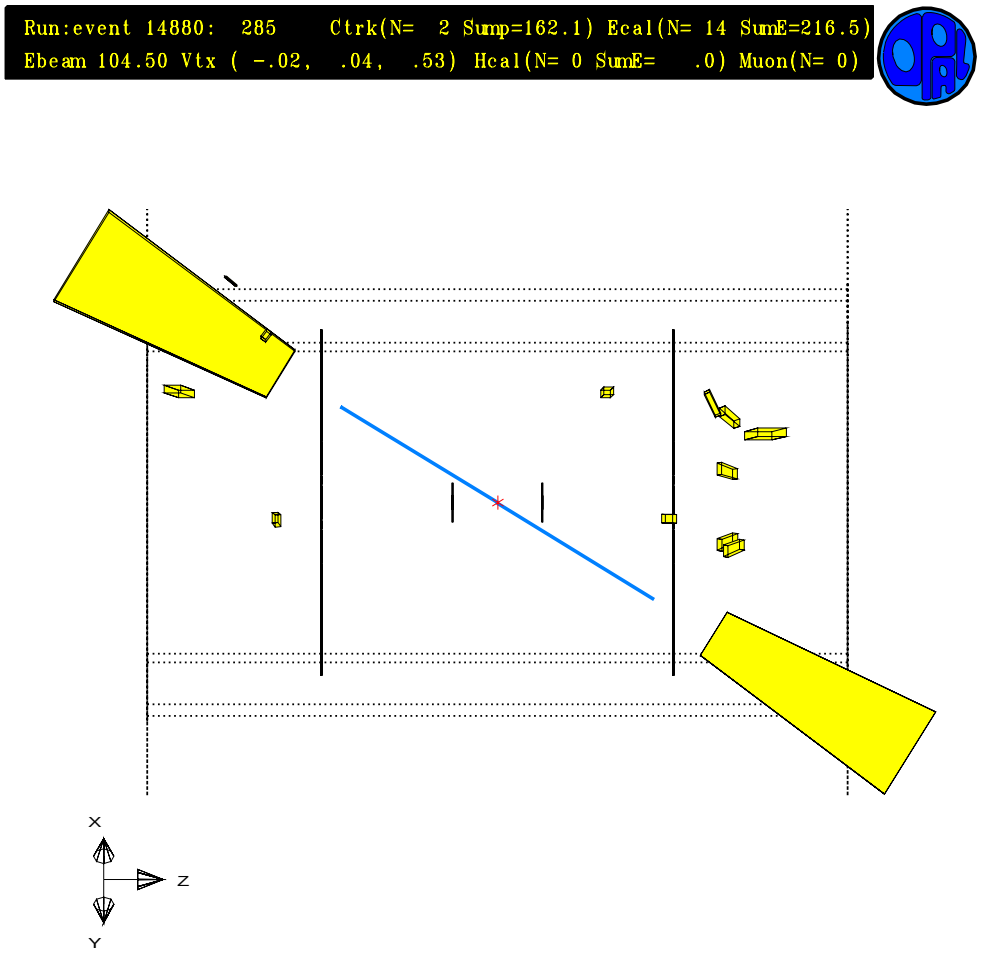
$e^+e^- \rightarrow$ **hadrons at 208 GeV**



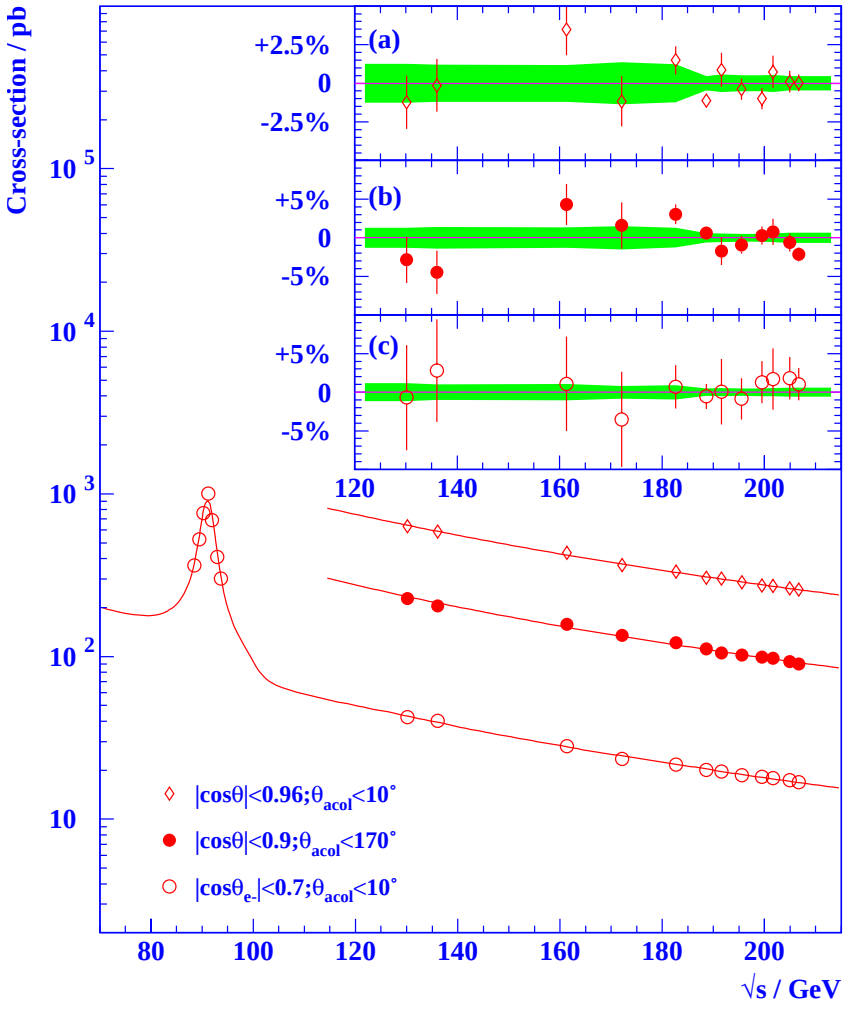


Fermion Pair Production Cross-sections

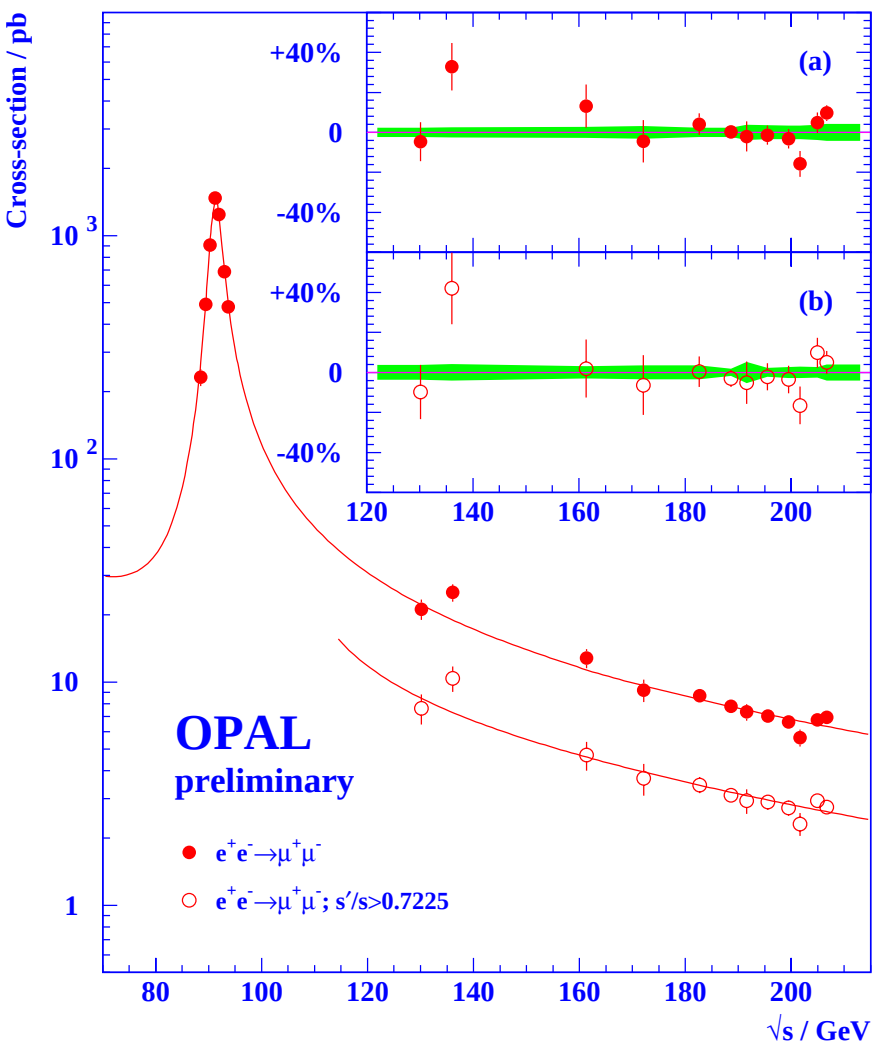
Bhabha event at 209 GeV !

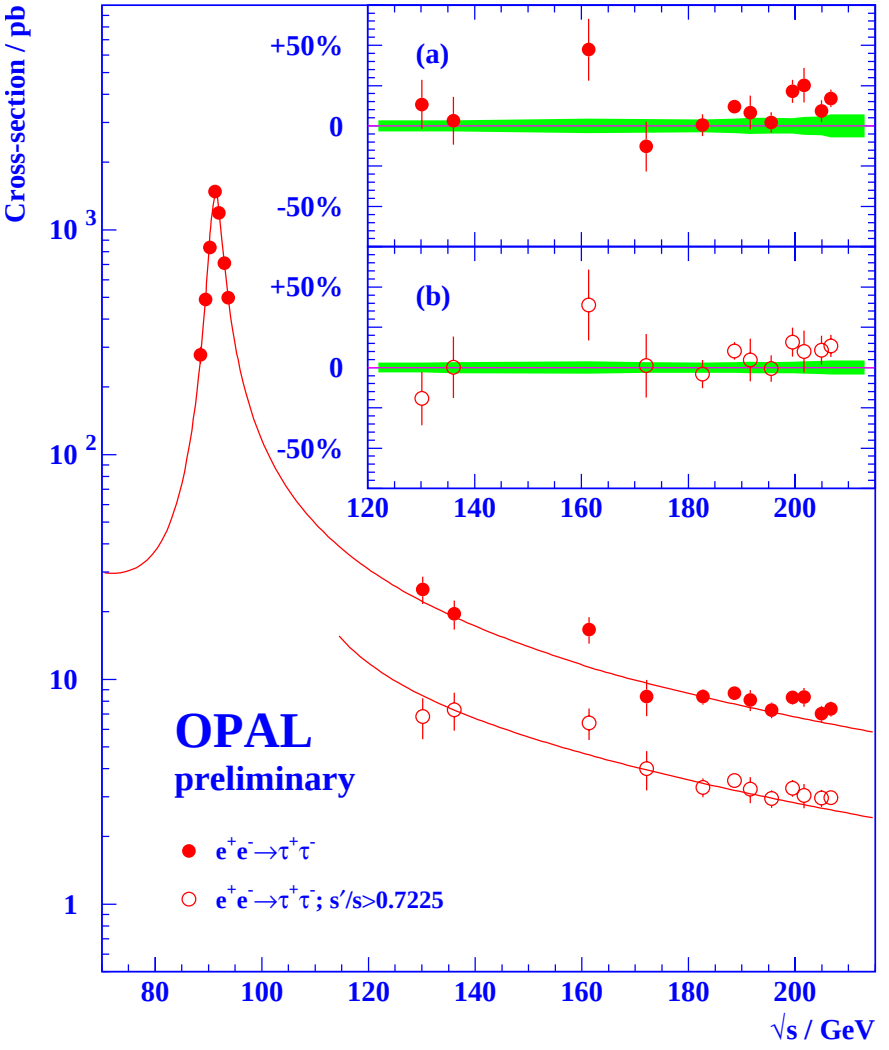


OPAL preliminary $e^+e^- \to e^+e^-$



Fermion Pair Production Cross-sections





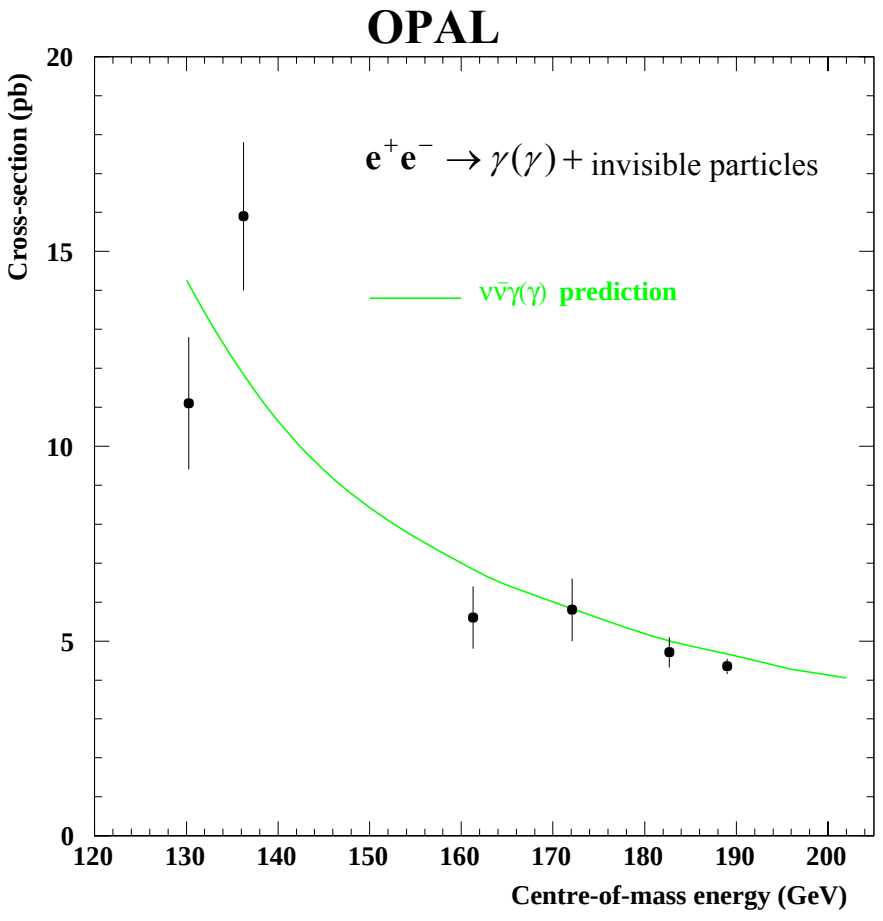
Small excess at highest energies ~ 2.5σ

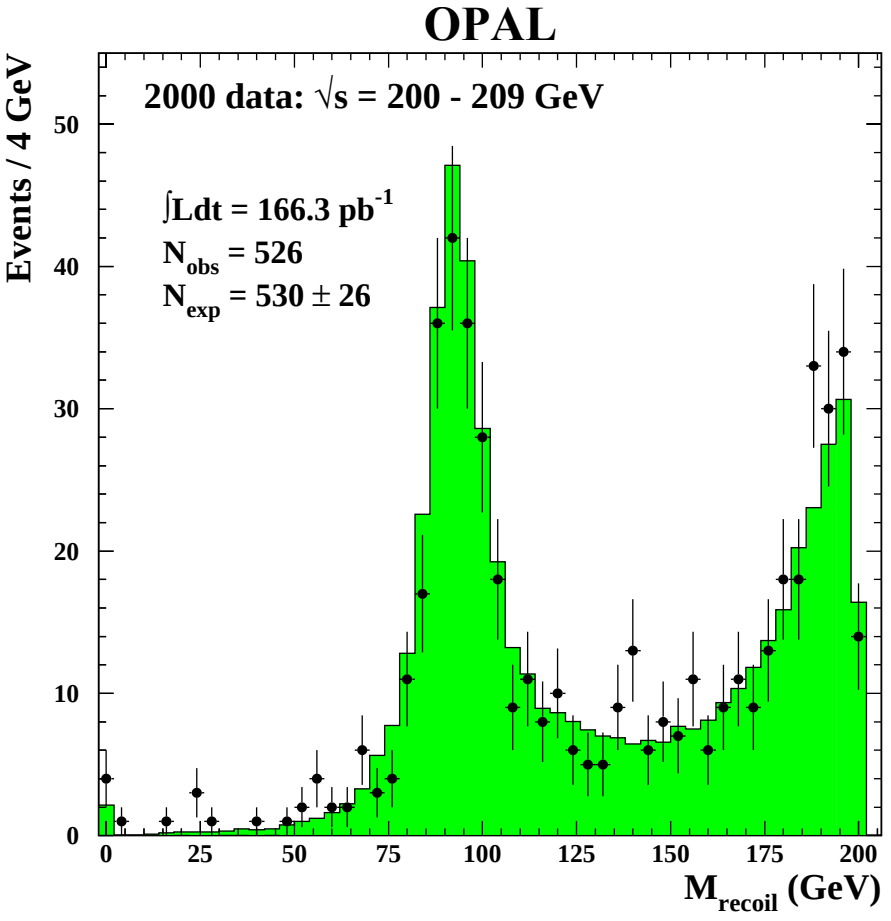
Fermion Pair Production: Neutrinos !

Invisible final states can be investigated via ISR (neutrino counting at LEP1)

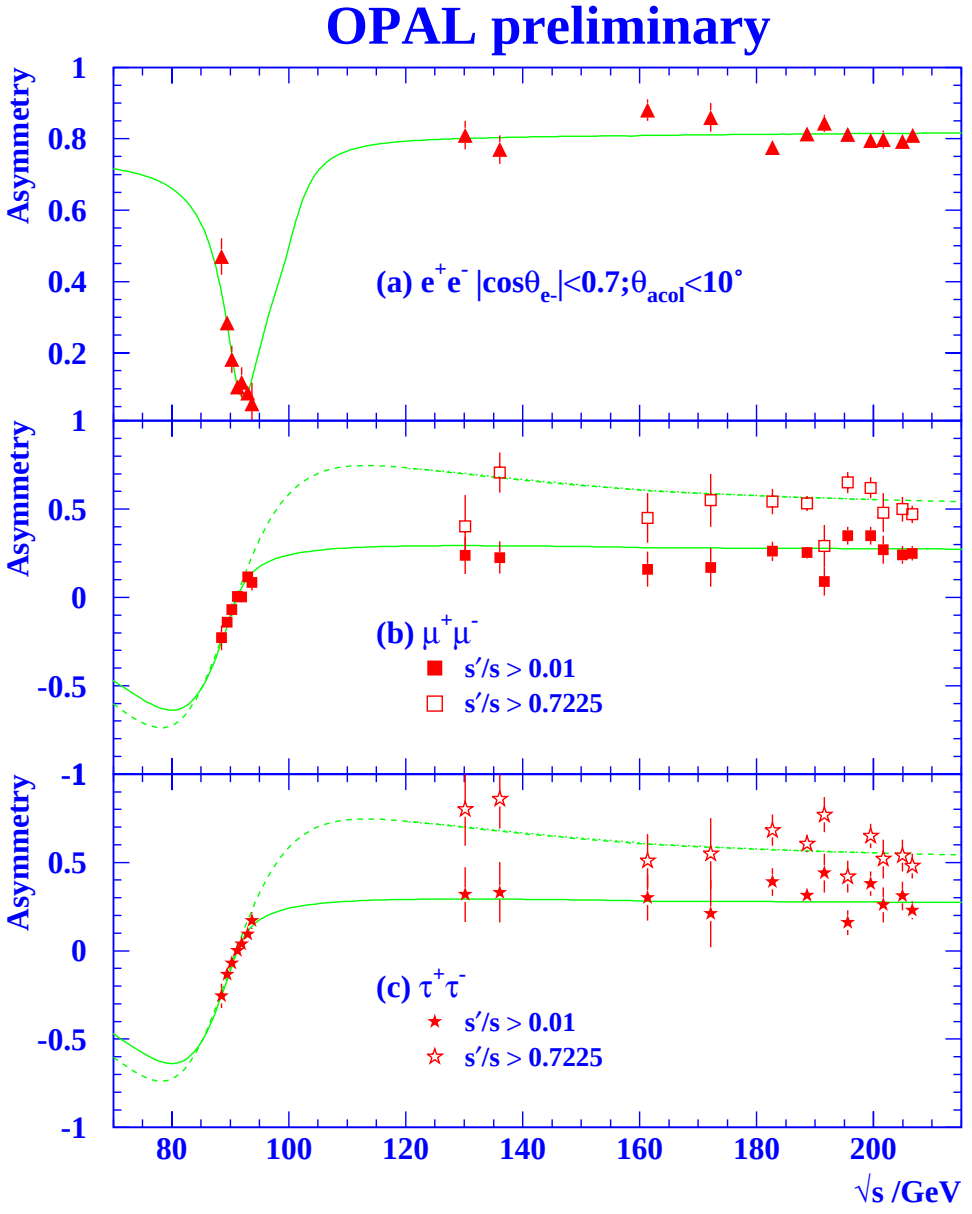
Agreement with SM good for energies up to 189 GeV

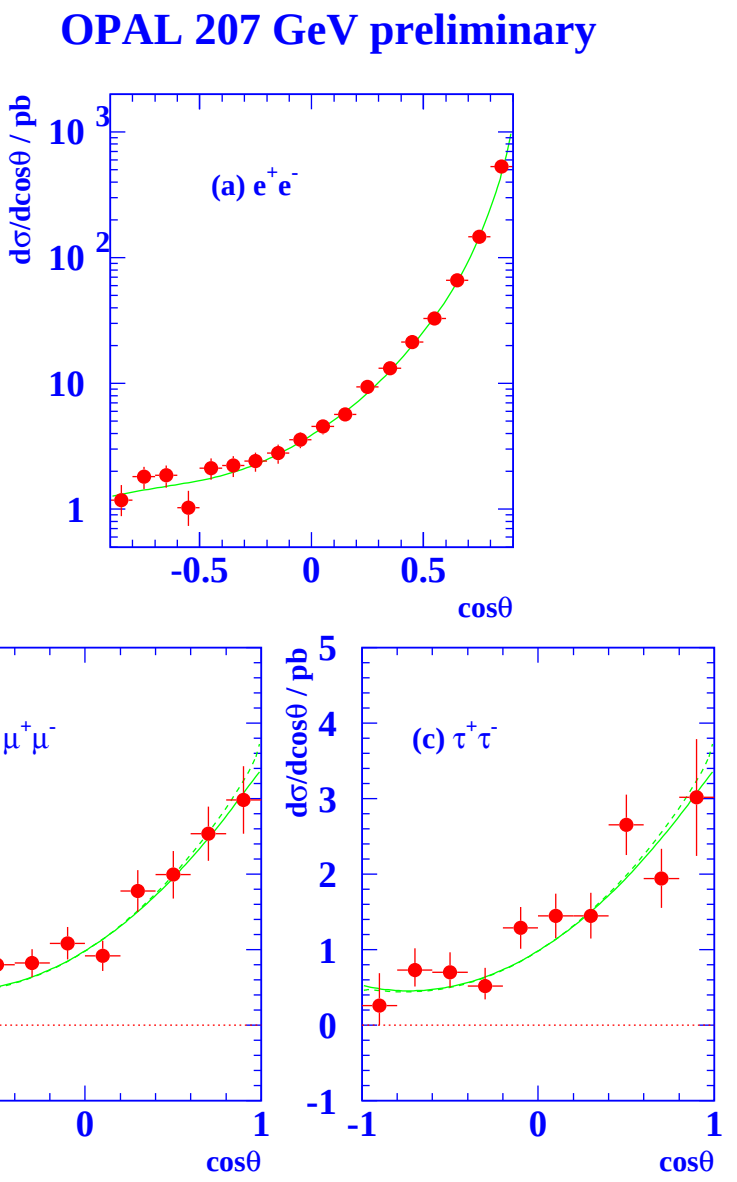
And no evidence for anything new in the 2000 data



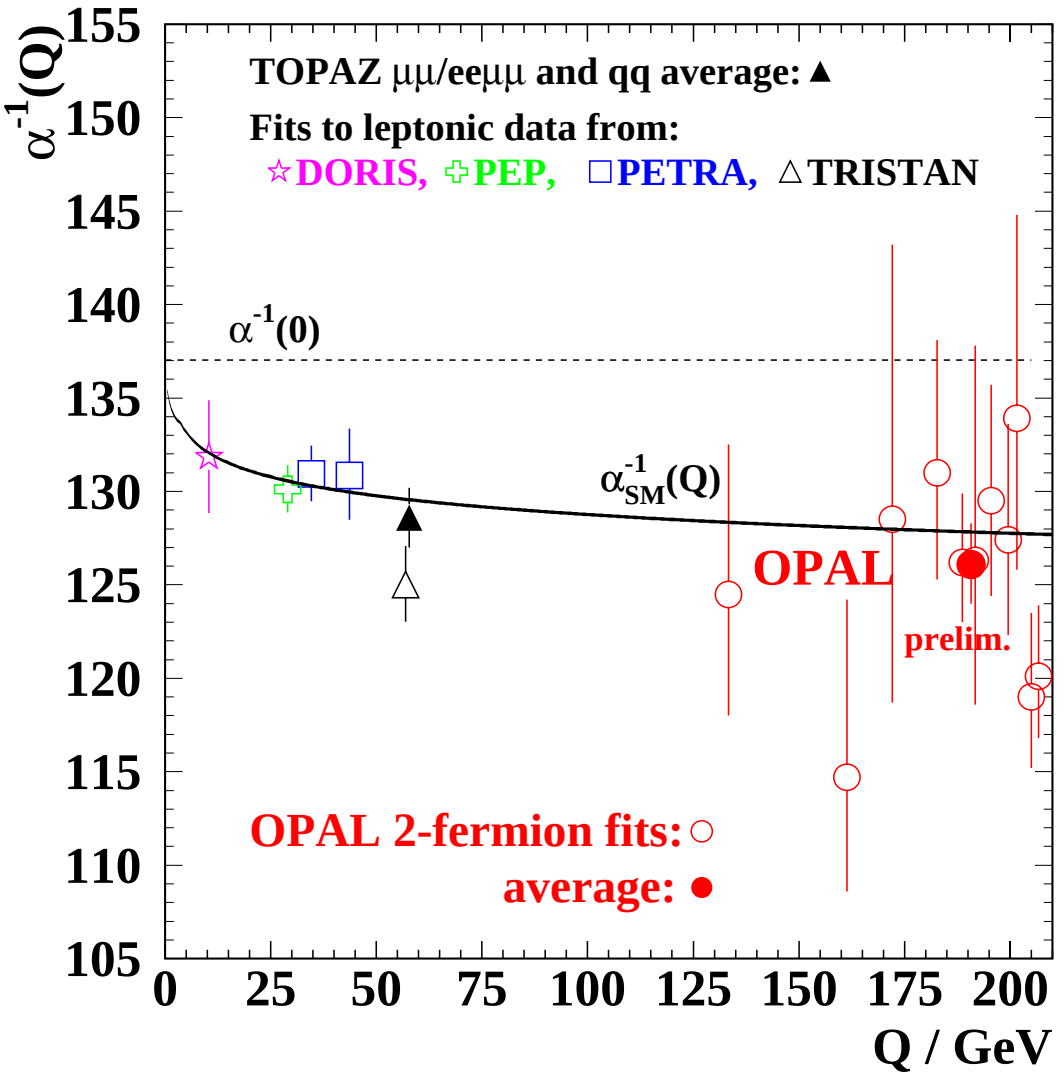


Lepton Pair A_{FB} and differential cross-sections



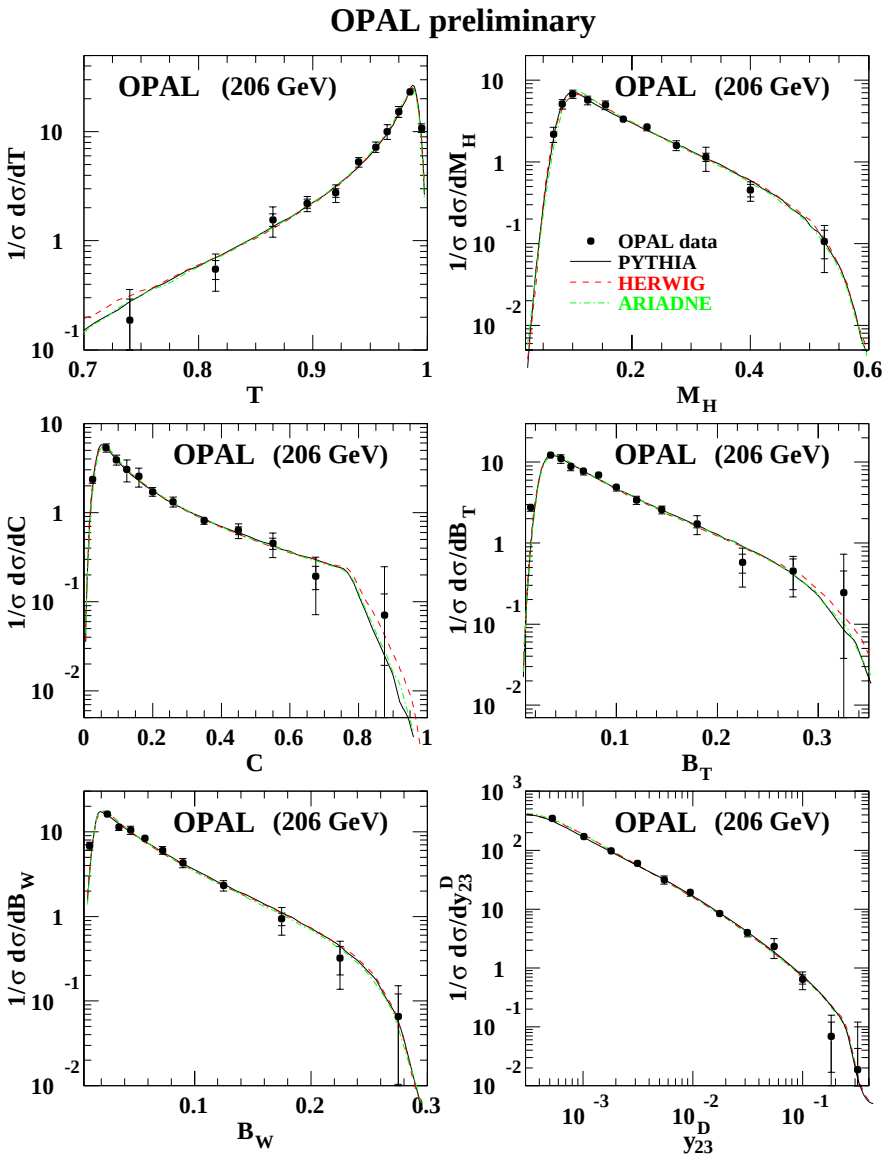


Running of Electromagnetic Coupling Constant



Charged lepton total non-radiative cross-sections and forward backwards asymmetries at each energy used for fit to α_{em}

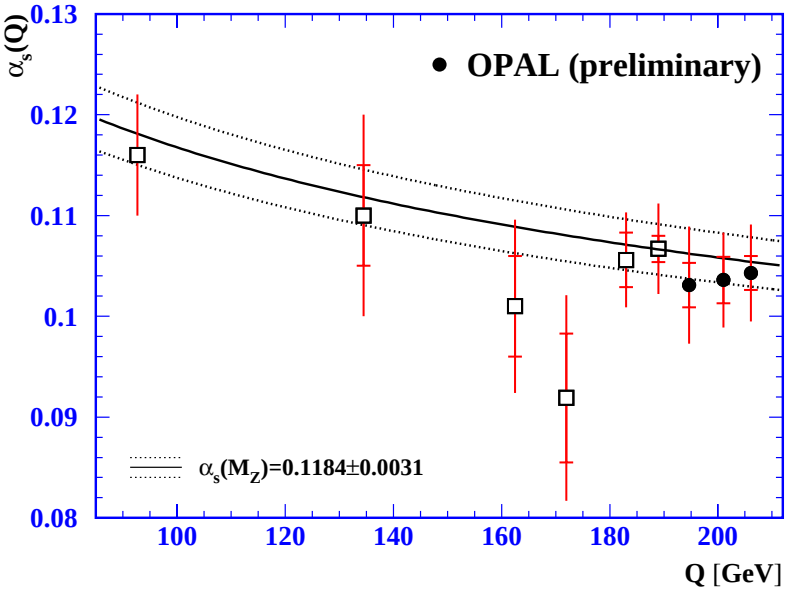
QCD Analyses



Select non-radiative $e^+e^- \to q\bar{q}$ events

$\sqrt{s}$ (GeV)	**204.9**	**206.6**
$\int L$ (pb^{-1})	82.3	137.3
Selected	1183	1802
Expected	1175	1919

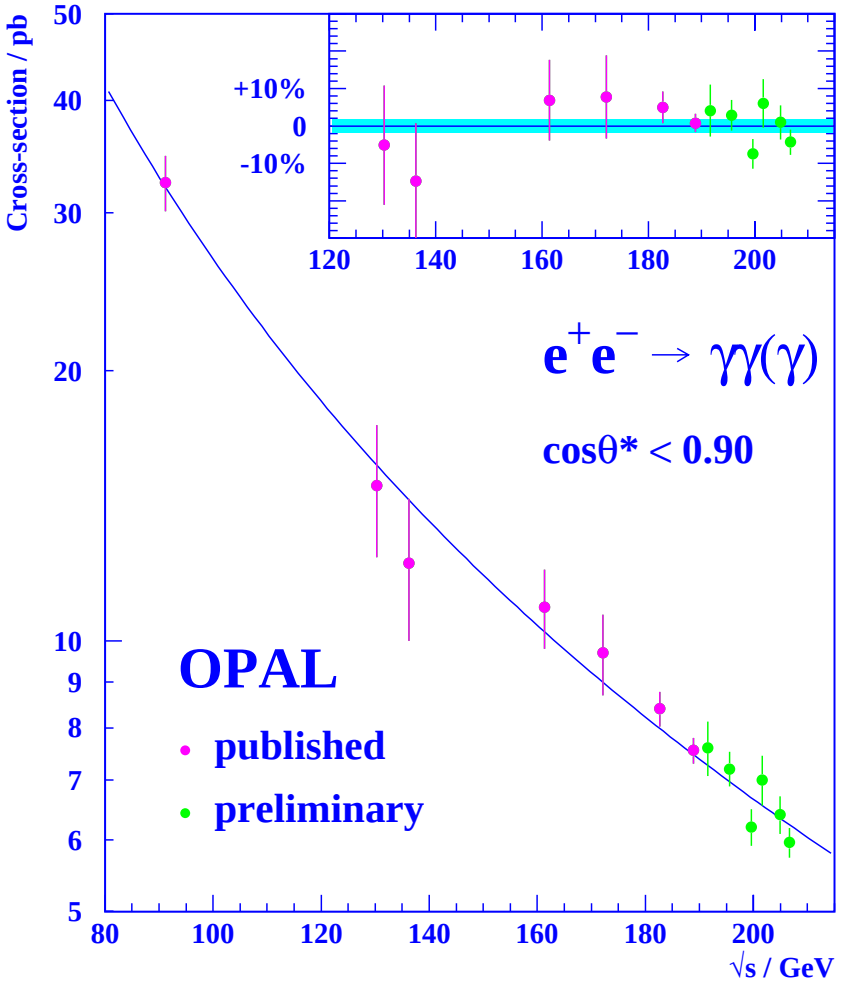
OPAL measurements of $\alpha_s(Q)$

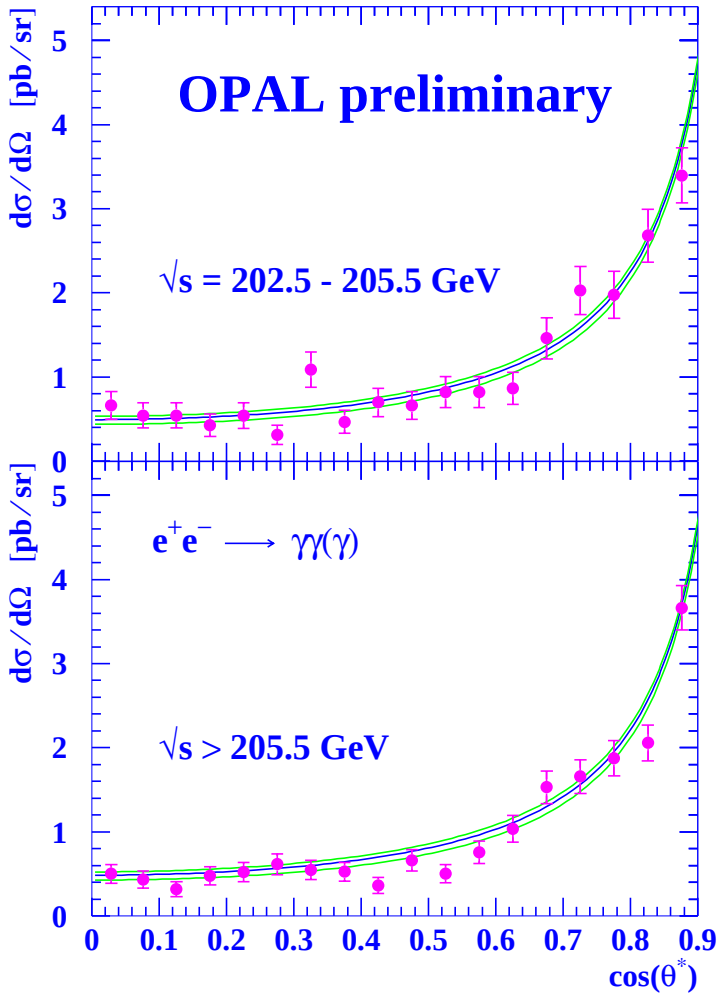


Gauge Boson Pair Production: Photons

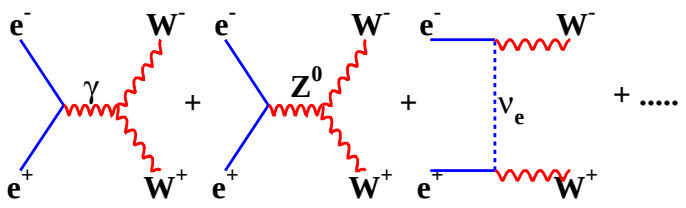
$e^+e^- \to \gamma\gamma(\gamma)$ has negligible electroweak contributions at LEP2 energies

Differential cross-section extremely well predicted by SM





$W^{\pm}$ Boson Pair Production Cross-section



Cross-section measurement uses reconstruction in all final states

$q\bar{q}q\bar{q}$

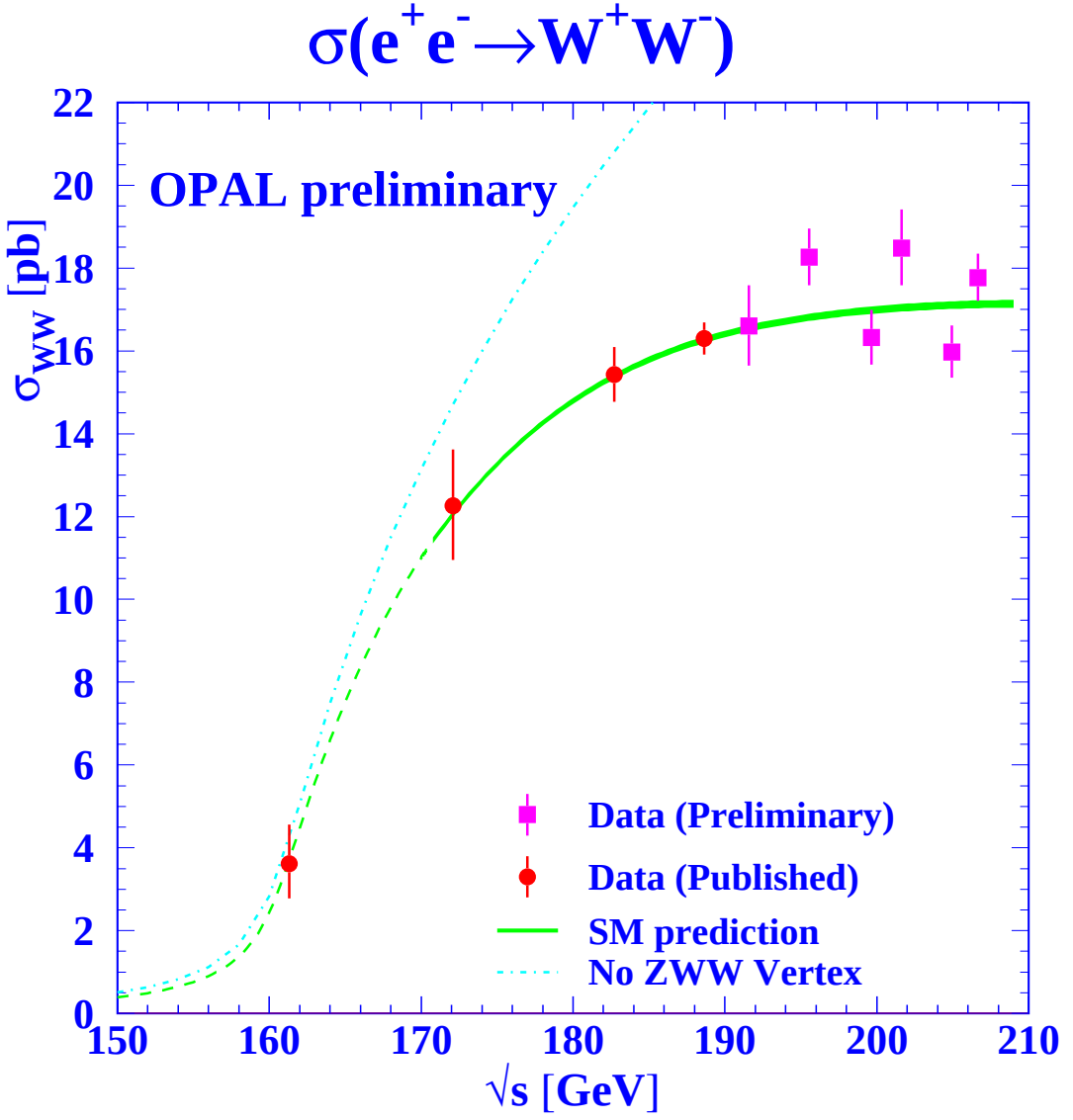
$q\bar{q}\ell\nu$

$\ell\nu\ell\nu$

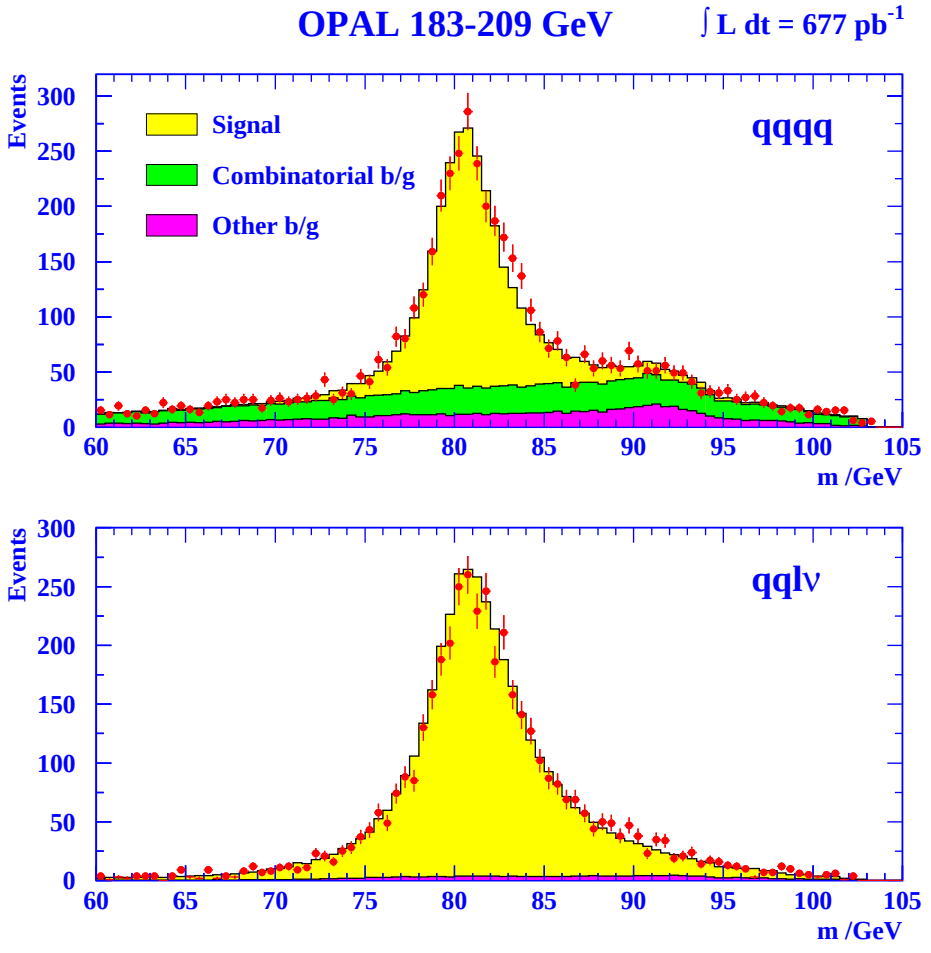
Assuming SM branching fractions for the W decays

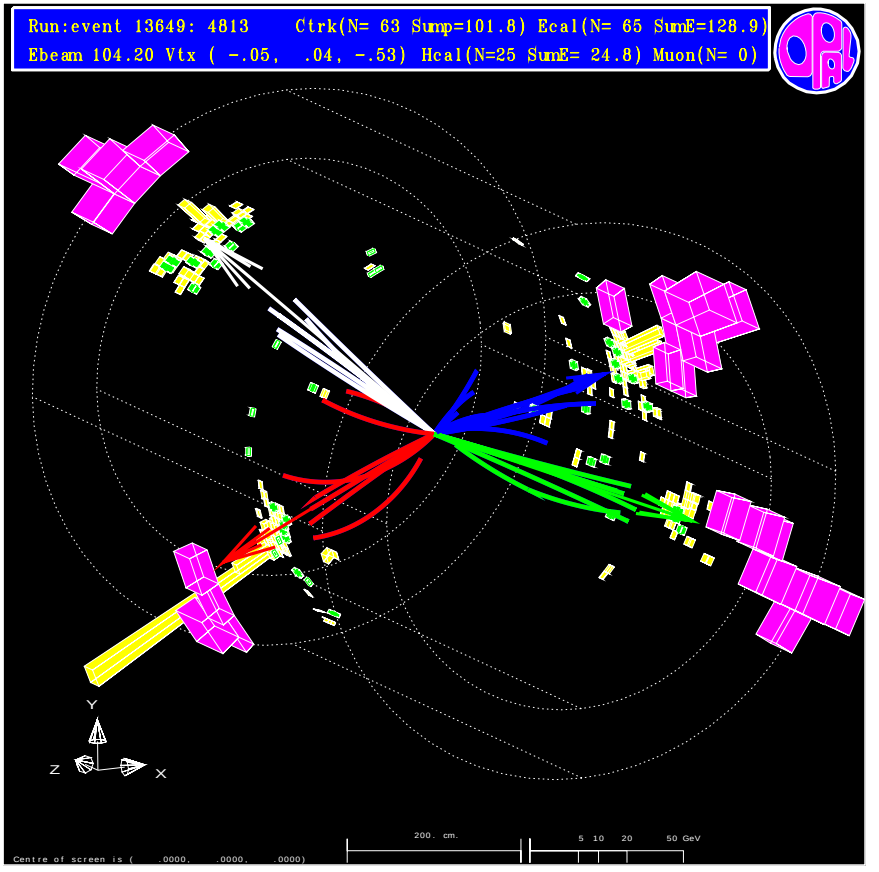
$\sigma(161\ \text{GeV})$ sensitive to M_W

$$M_W = 80.40 \pm {}^{0.46}_{0.43}\ \text{GeV}$$



$W^{\pm}$ Boson Mass Measurement





M_W from 480 pb^{-1} 172-202 GeV

$M_W = 80.510 \pm 0.067 \pm 0.031$ GeV (qqll)

$M_W = 80.408 \pm 0.066 \pm 0.100$ GeV (qqqq)

$M_W = 80.486 \pm 0.053 \pm 0.039$ GeV (combined direct)

LEP combined (direct +threshold)

$$\mathbf{M_W = 80.427 \pm 0.046\ GeV}$$

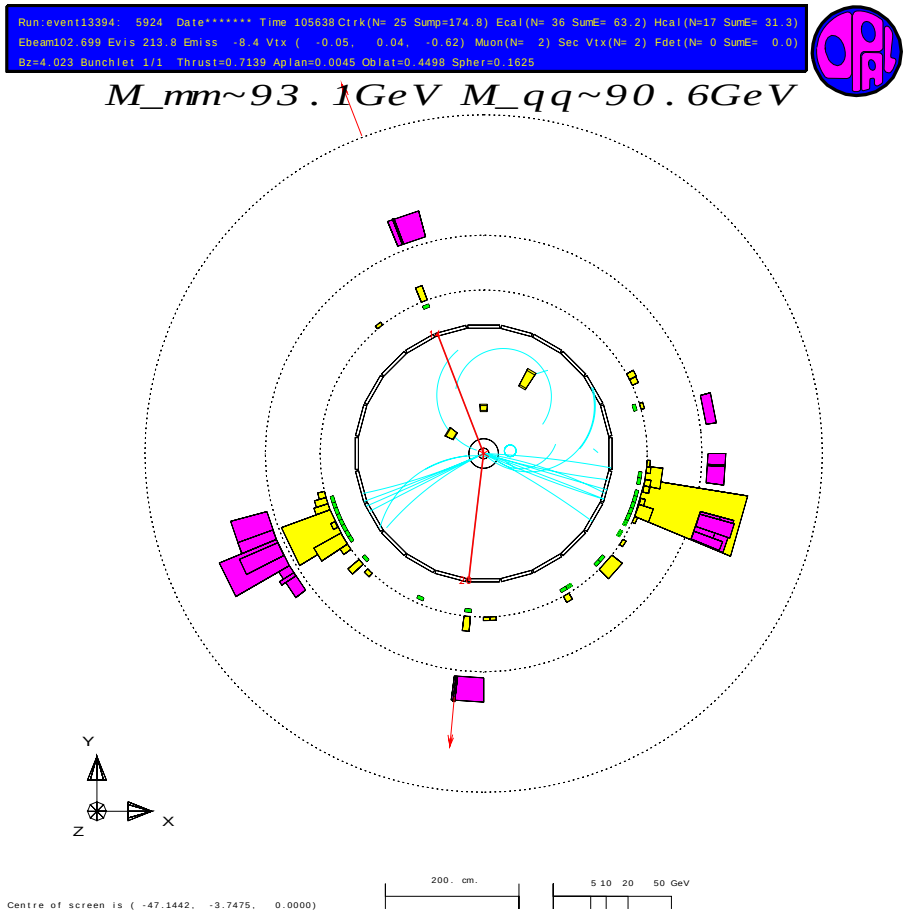
ZZ Production Cross-section

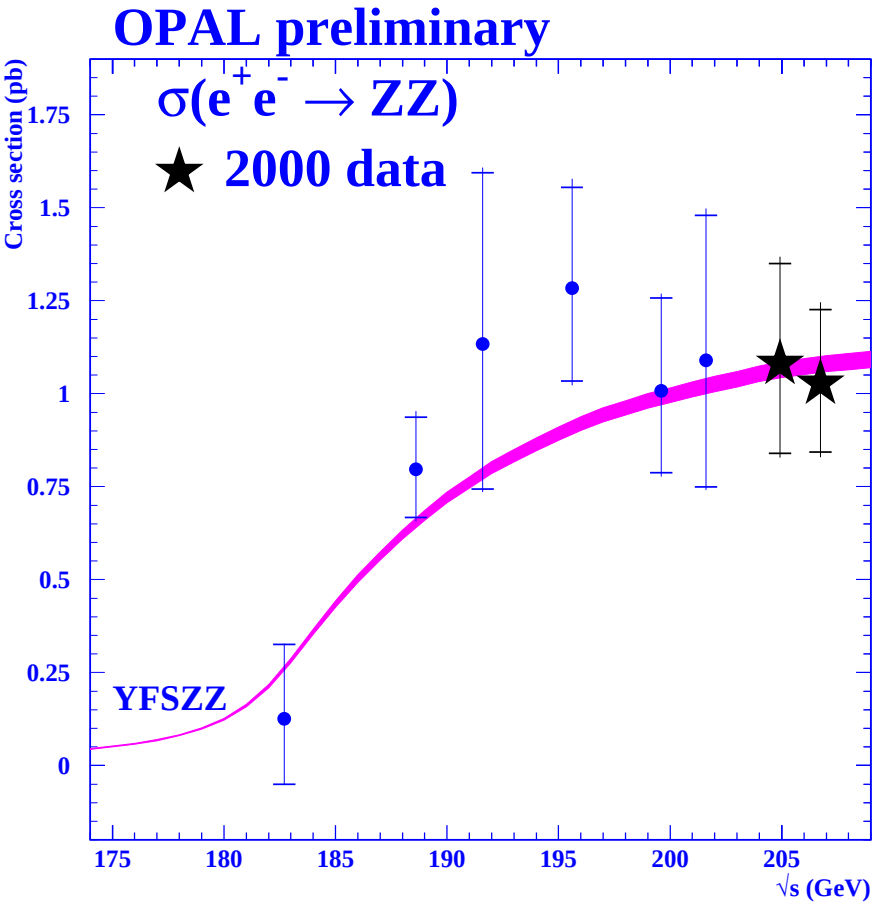
Reconstruct decay channels: qqqq, qqll, qqνν, llνν, llll

Cross-sections assume SM Z decays fractions

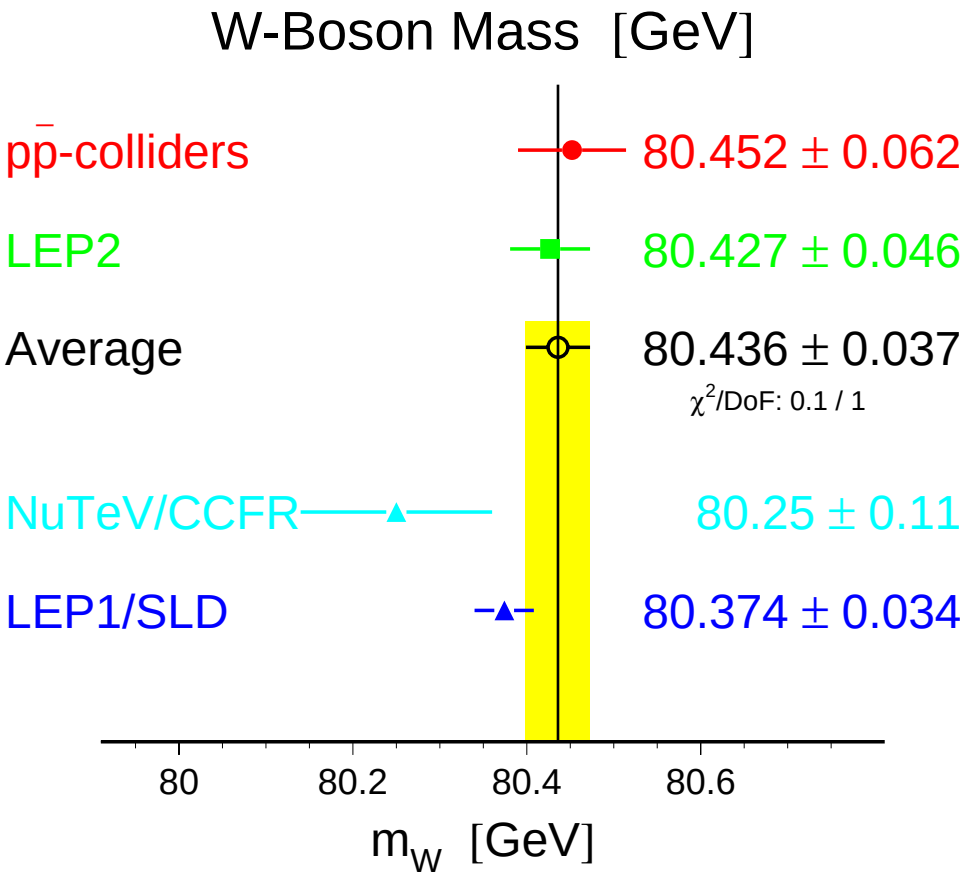
At $\sqrt{s}$ = 205 GeV select 77 events
expected SM bkgd = 37 events

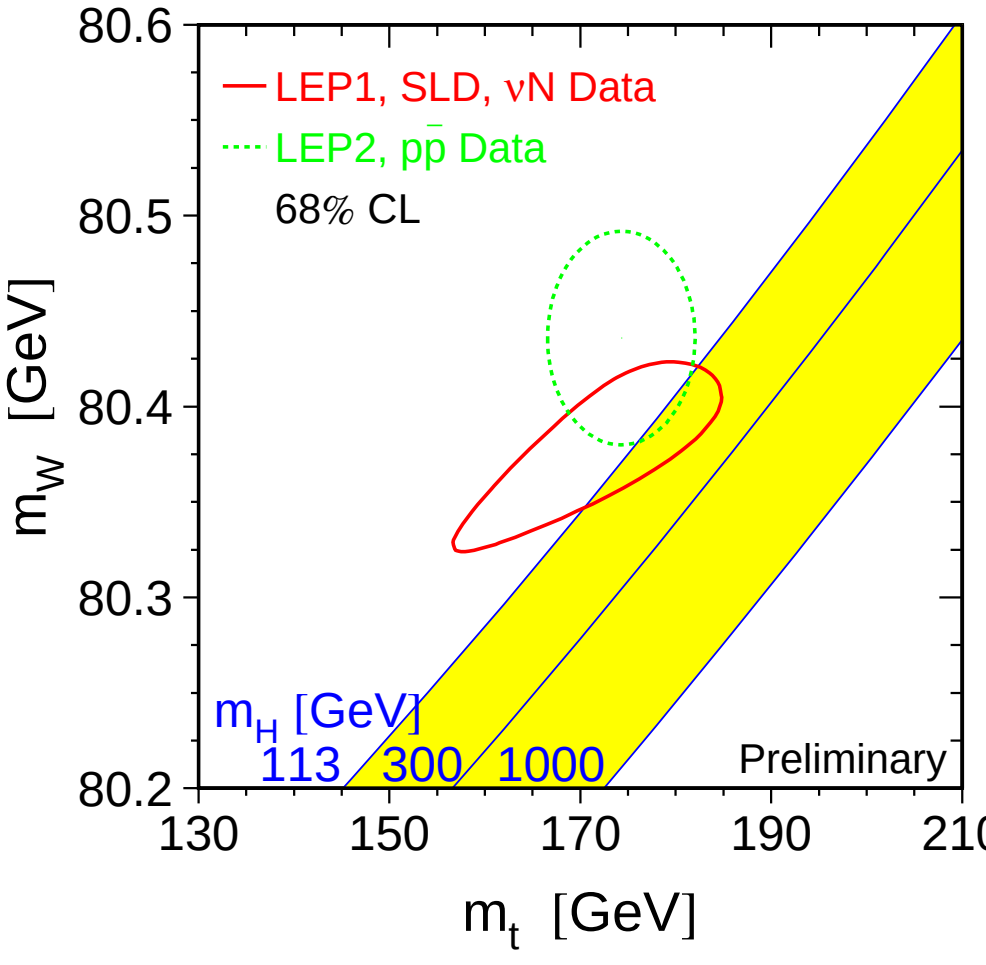
At $\sqrt{s}$ = 207 GeV select 85 events
expected SM bkgd = 45 events





LEP Electroweak Combined Results





Search for Single Top Production

$m_t = 174.3 \pm 5.1$ GeV (Tevatron)

$\mathbf{e^+e^- \rightarrow \bar{t}c,\ \bar{t} \rightarrow bW^*}$

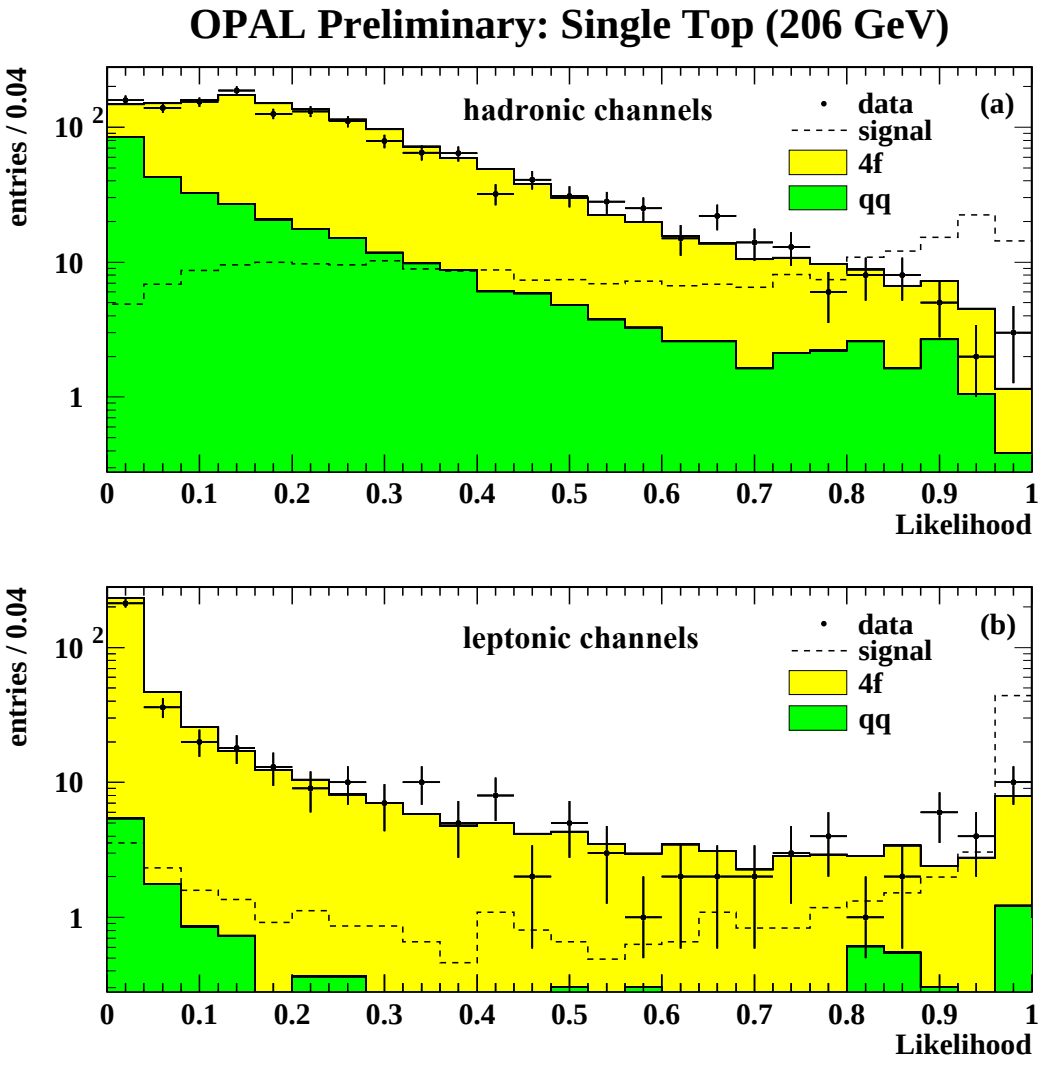
Kinematically accessible at LEP2 energies: proceeds via loop diagram

$\sigma(SM) \sim 10^{-9}$ pb

Some SM extensions can enhance this production cross-section

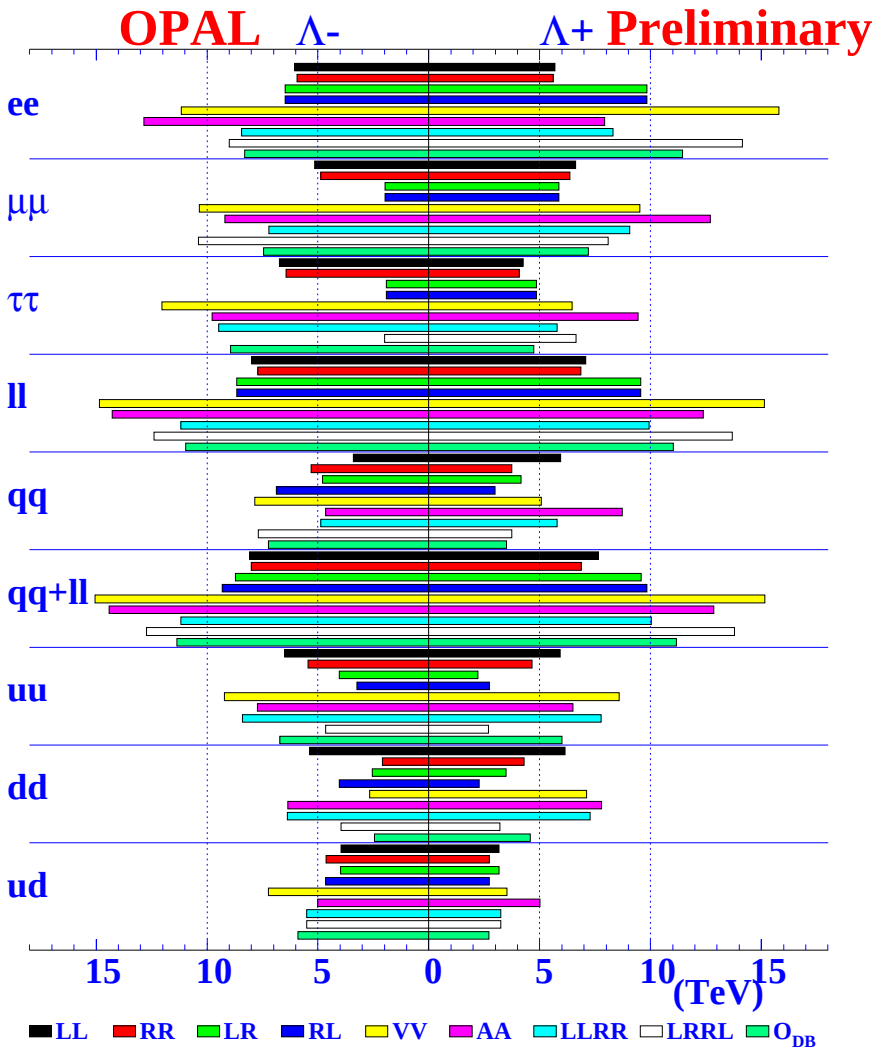
30 events selected

29.4 events expected from SM



Signal distributions for $\sigma = 3$ pb

Four Fermion Contact Interactions



from fermion pair-production differential cross-sections measurements

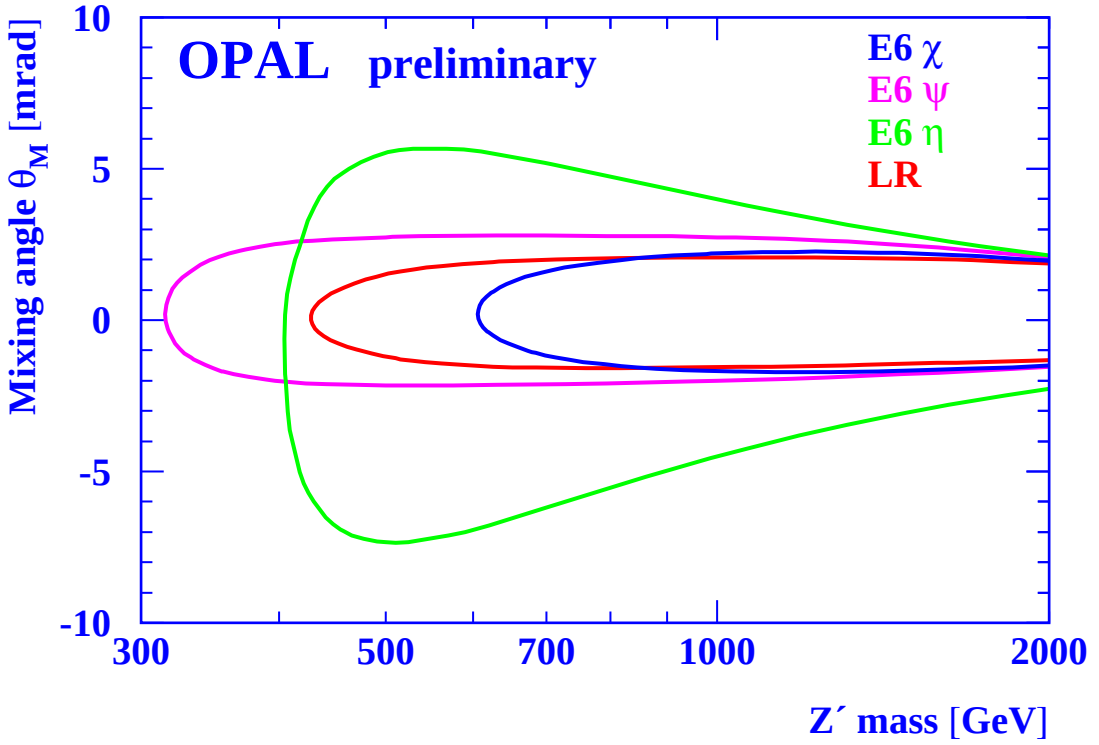
$$L^{\text{contact}} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{i,j=L,R} \eta_{ij} [\bar{c}_i \gamma^\mu c_i][\bar{f}_j \gamma_\mu f_j]$$

Limits on Additional Neutral Gauge Bosons

Z' predicted in various extensions to the Standard Model

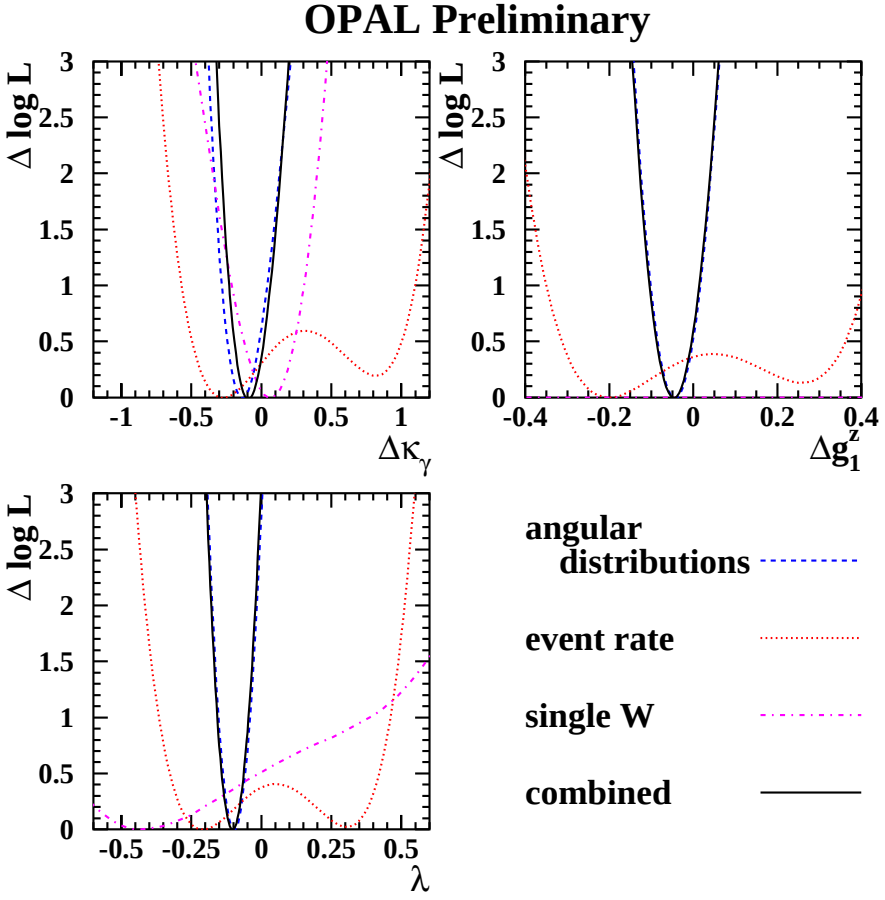
Limits depend on mass of additional state and mixing with Z^0

Possible Z' exchange in fermion pair production modifies observed cross-sections and asymmetries



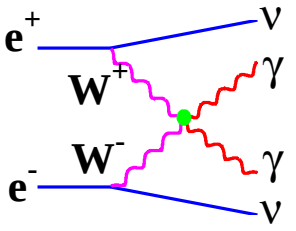
Searches for Anomalous Triple Gauge Couplings

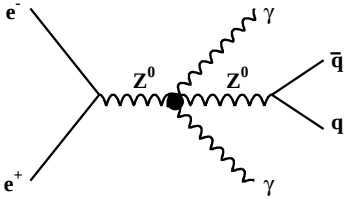
Charged current TGCs (from W- pair and single-W production)



Limits also on:

QGC's WWγγ, ZZγγ (ννγγ, qqγγ)

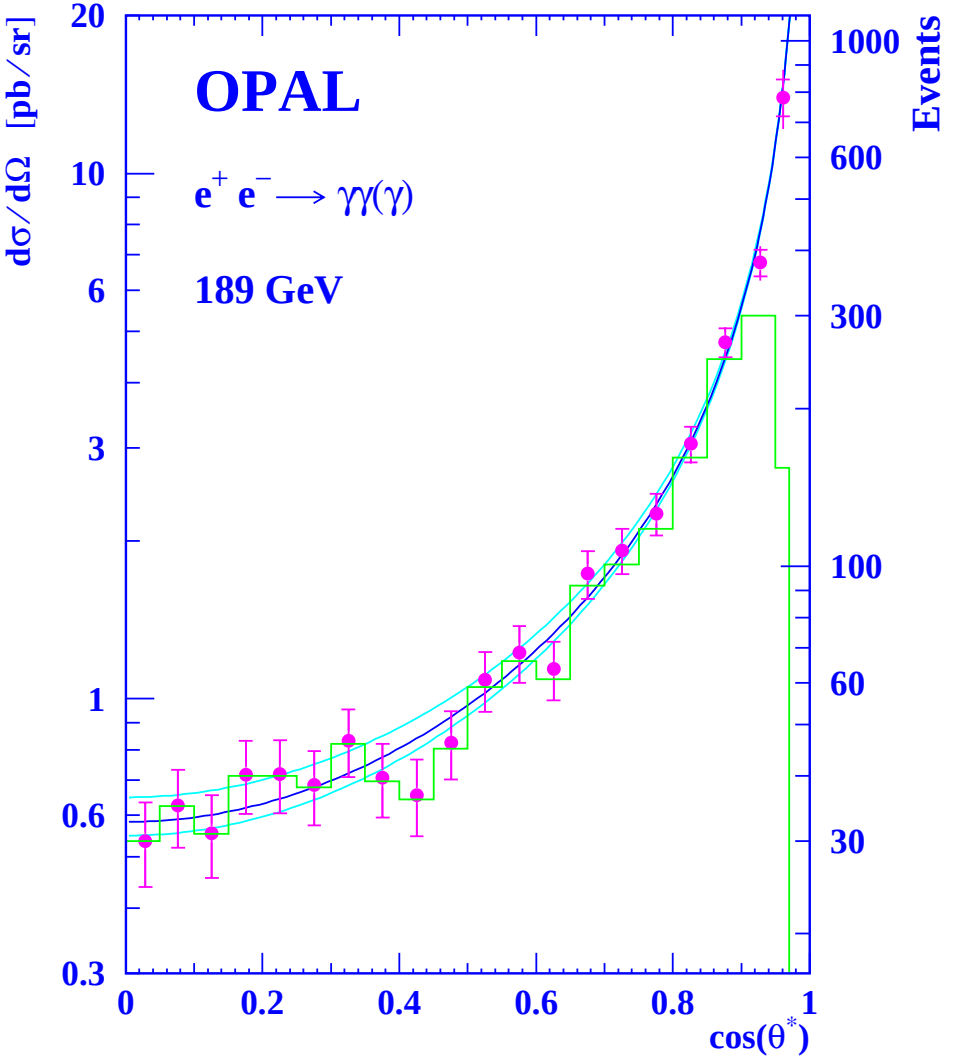




Neutral Current TGCs (ννγ, qqγ)

All results consistent with Standard Model expectations

Limits on Deviations from QED from Photonic Final States



1740 event selected

1776 events expected from SM

Fit for deviations from QED

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

Most current limits (2000 data)

$\Lambda_+ > 344$ **GeV**

$\Lambda_- > 325$ **GeV**

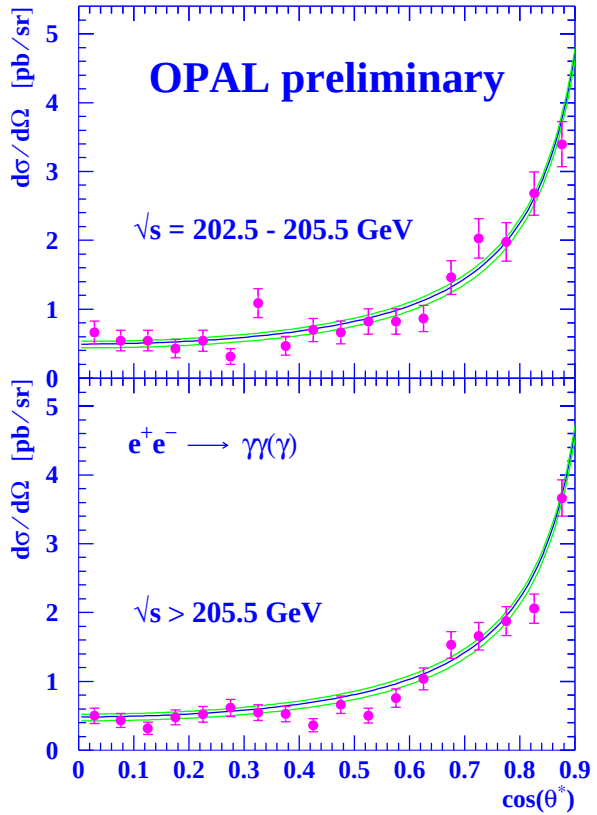
Limit on mass of excited electron (contributes via t-channel exchange)

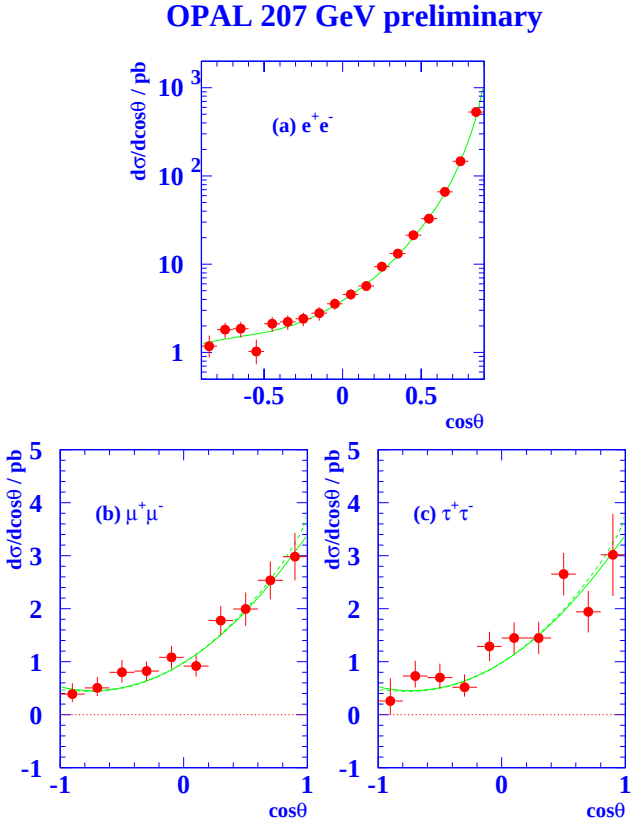
$M_{e^*} > 354$ **GeV**

Indirect Searches for Large Compact Extra Dimensions

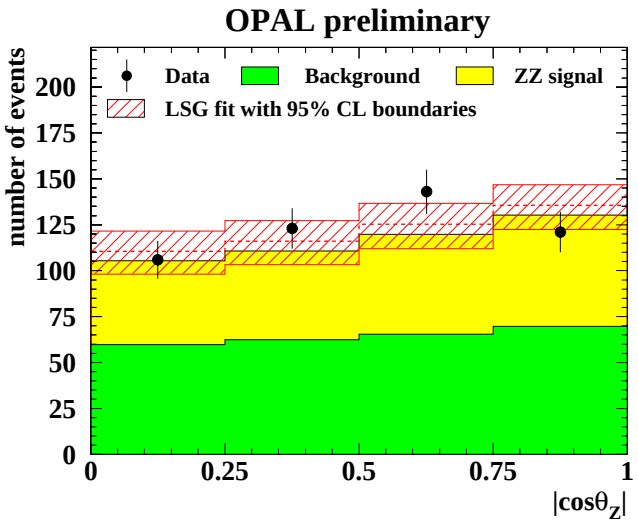
$$\left(\frac{d\sigma}{d\Omega}\right)_{LSG} = \left(\frac{d\sigma}{d\Omega}\right)_{SM} \pm \mathbf{A}(\cos\theta)\frac{|\lambda|}{M_S^4} + \mathbf{B}(\cos\theta)\left[\frac{|\lambda|}{M_S^4}\right]^2$$

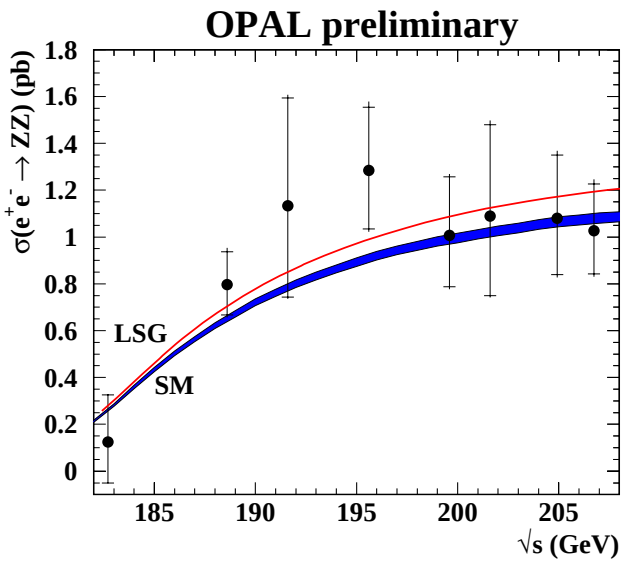
Limits set on $M_S(\lambda = \pm 1)$ (different signs of interference)

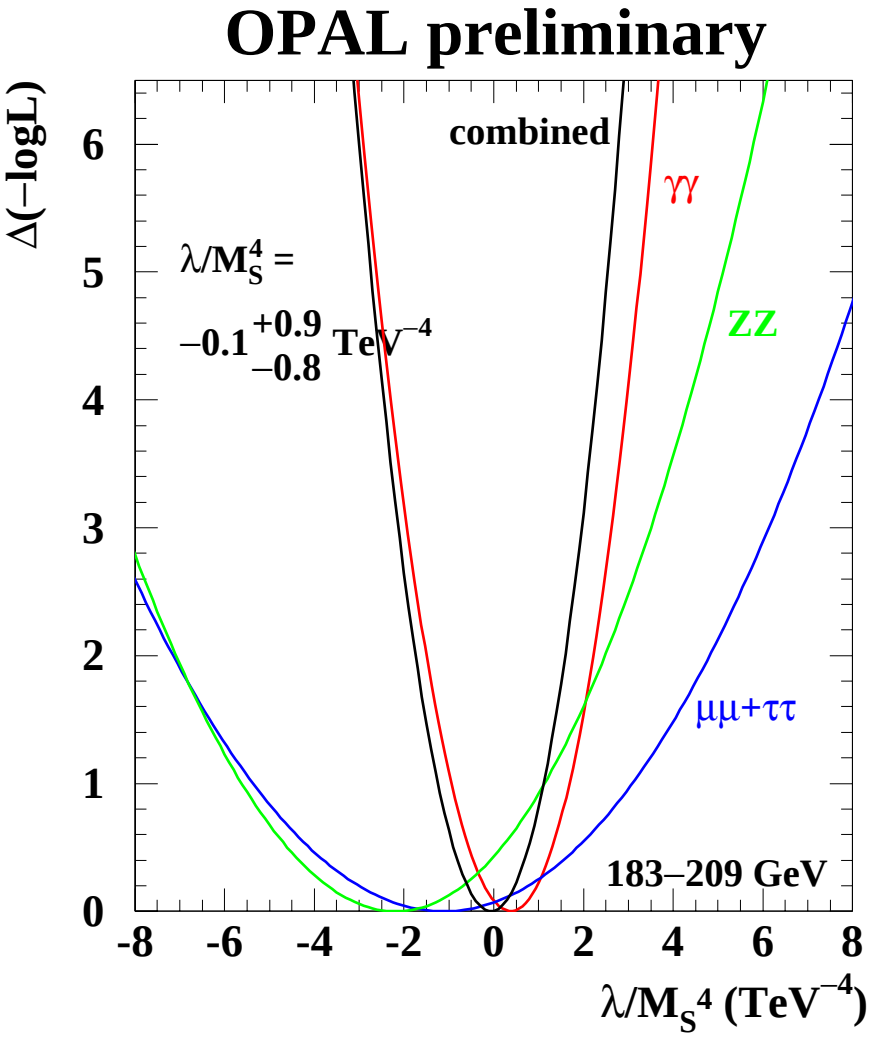




Indirect Searches for Large Compact Extra Dimensions



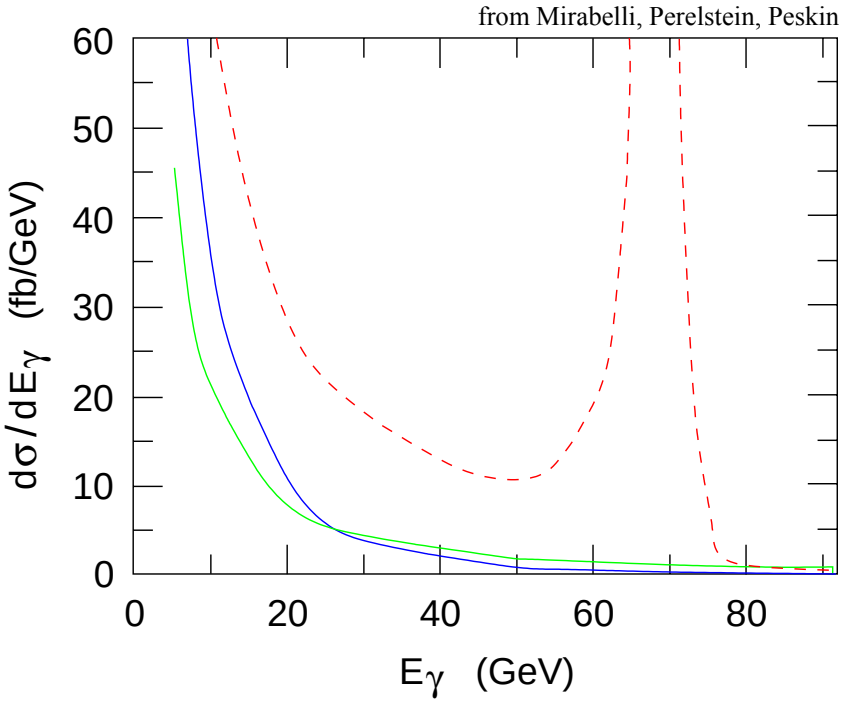


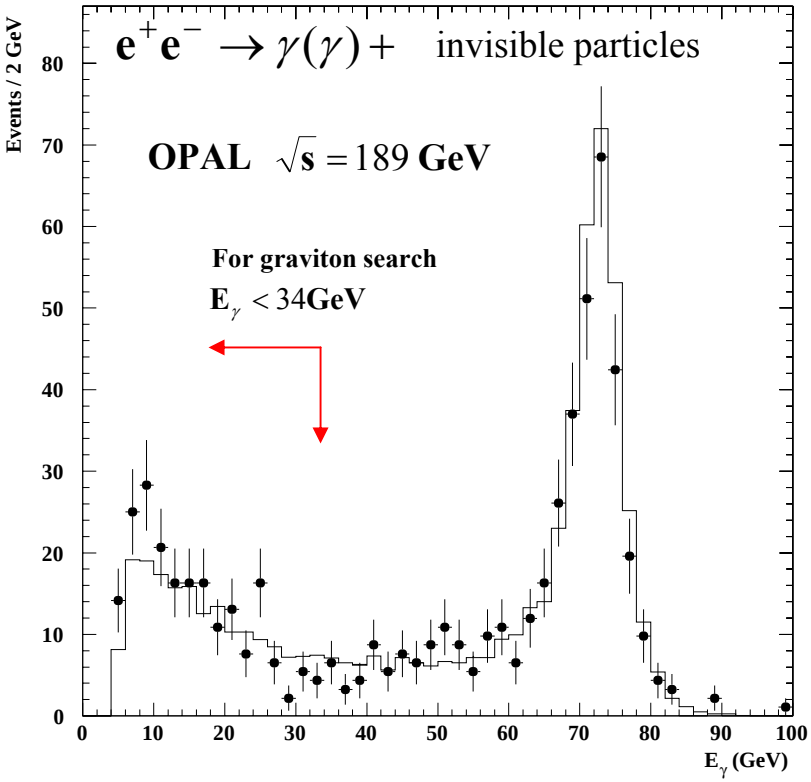


M_s > 0.90/0.83 TeV @ 95% CL for λ = +/-1

Direct Searches for Large Compact Extra Dimensions

$e^+e^- \to G_{KK}\gamma \to \gamma + \not{E}_T$ final state





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

Supersymmetric Particle Searches

R-parity conservation: SUSY particles must be produced in pairs
There must be some lightest SUSY particle (LSP)
⇨ missing energy signature

MSSM: 105 free parameters in addition to those of the SM

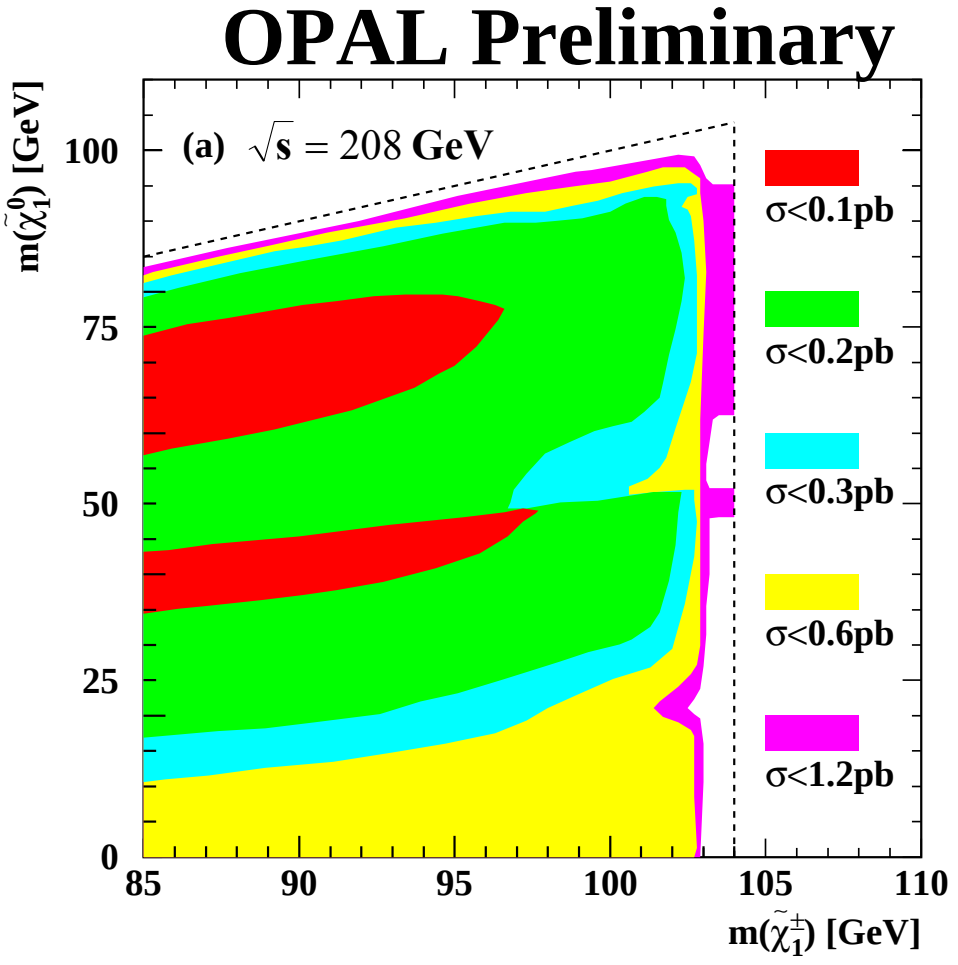
CMSSM (mSUGRA)

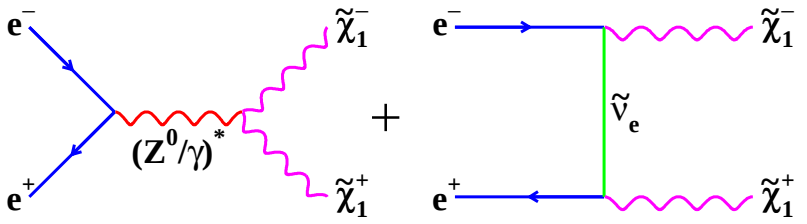
- gravity-mediated SUSY breaking
- LSP (usually) the lightest neutralino
- 5 parameter model: m_o, $m_{1/2}$, tanβ, μ, A
- phenomenology dictated by identity of LSP

Gauge-mediated SUSY

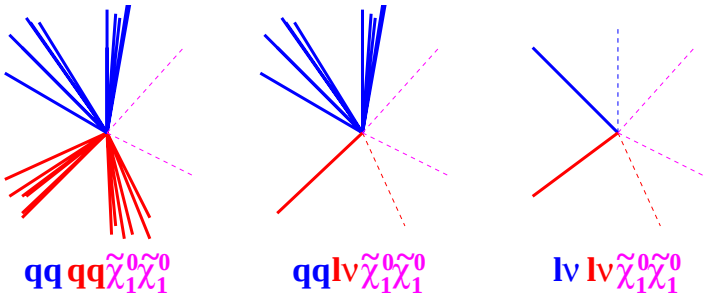
- SUSY breaking mediated by SM gauge interactions
- LSP is a very light gravitino
- 6 parameter version
- phenomenology dictated by identity of NLSP
- NLSP either the lightest neutralino or the lightest slepton
- NLSP lifetime is arbitrary – can be long lived

CMSSM: Chargino Production Limits



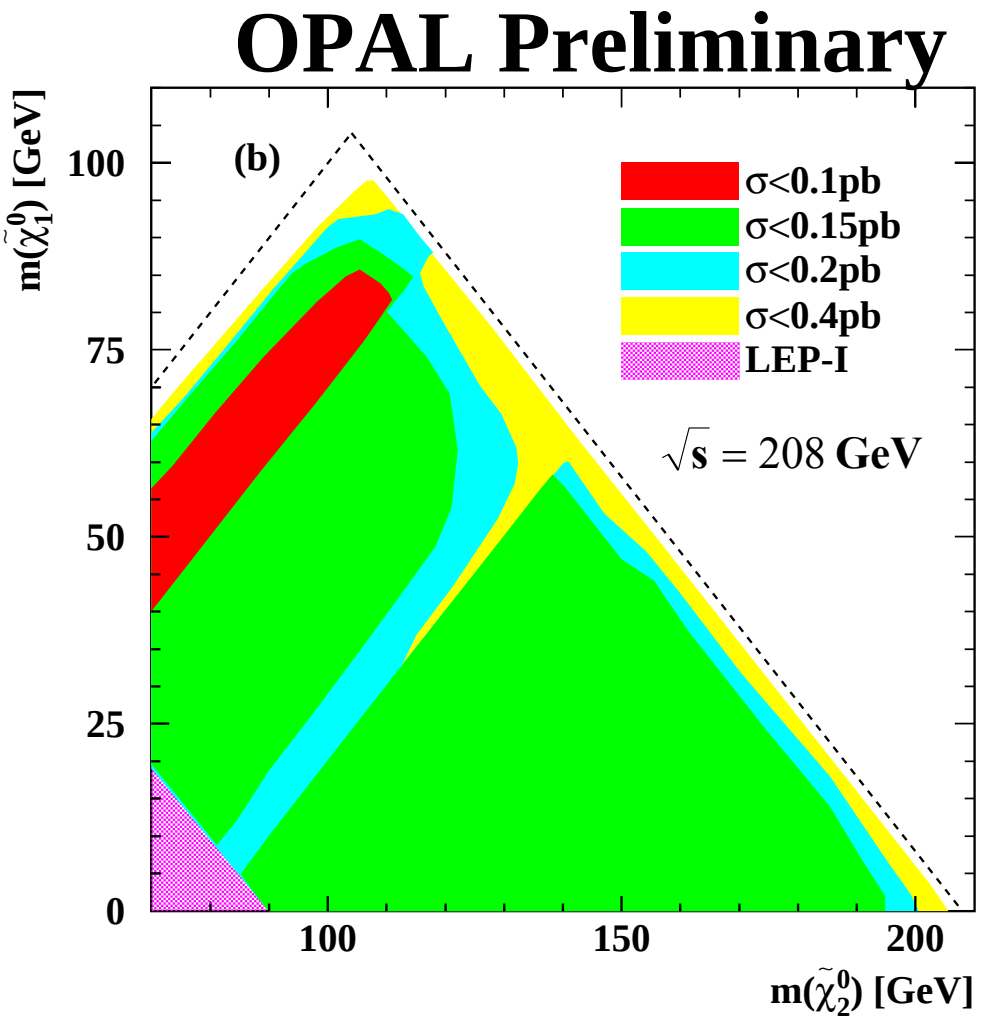


Chargino decays $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \mathbf{W}^{(*)}$



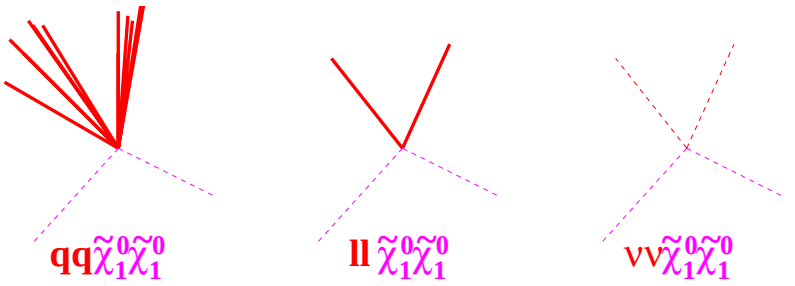
95% CL upper limits are on $\sigma(\mathbf{e}^+\mathbf{e}^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-) \times \mathbf{BR}^2(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \mathbf{W}^{(*)})$
for each mass pairing in the plane

CMSSM: Neutralino Production Limits



$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to$ **invisible final state**

$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^{(*)}$

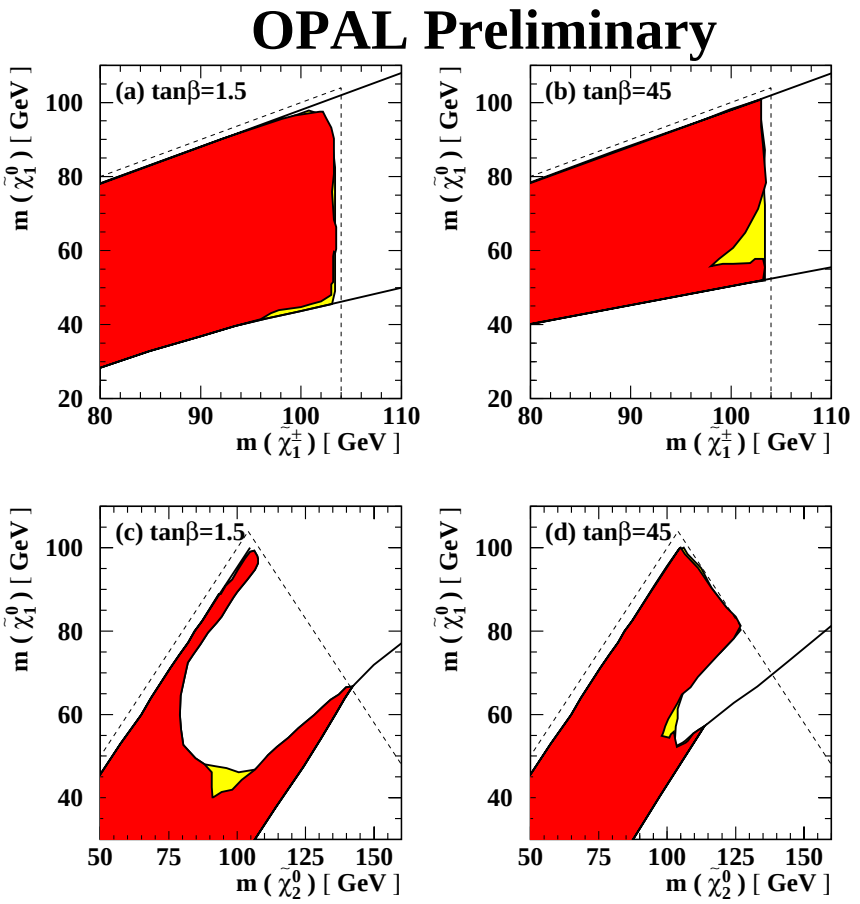


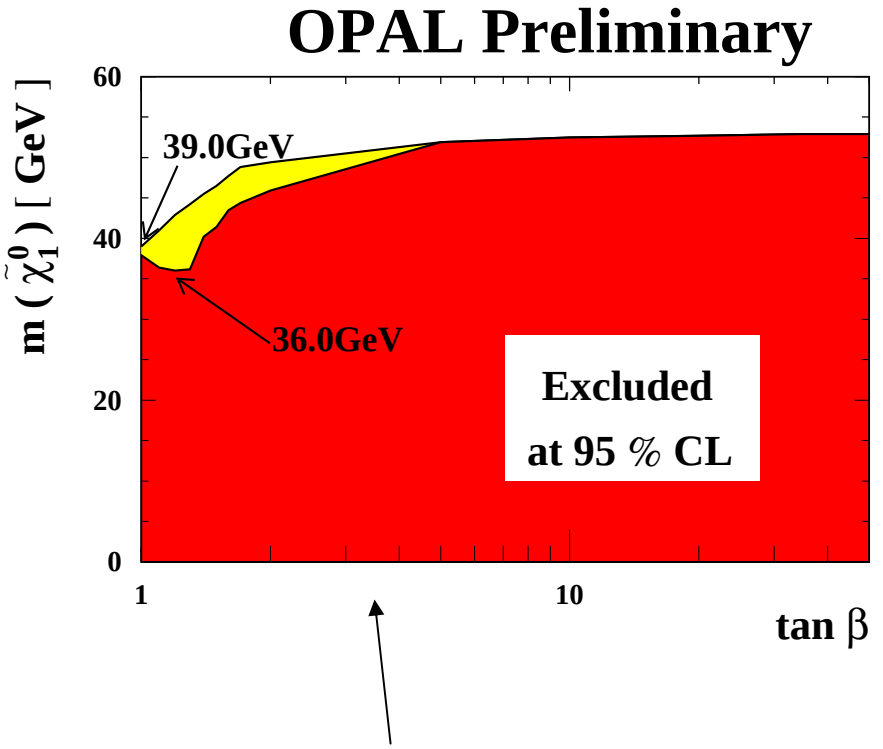
95% CL upper limits are on

$\sigma(e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0) \times BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^{(*)})$

For each mass pairing in the plane

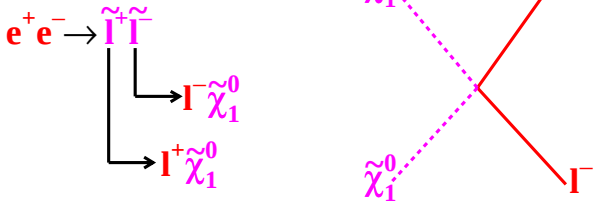
CMSSM: Mass Limits for Chargino/Neutralinos



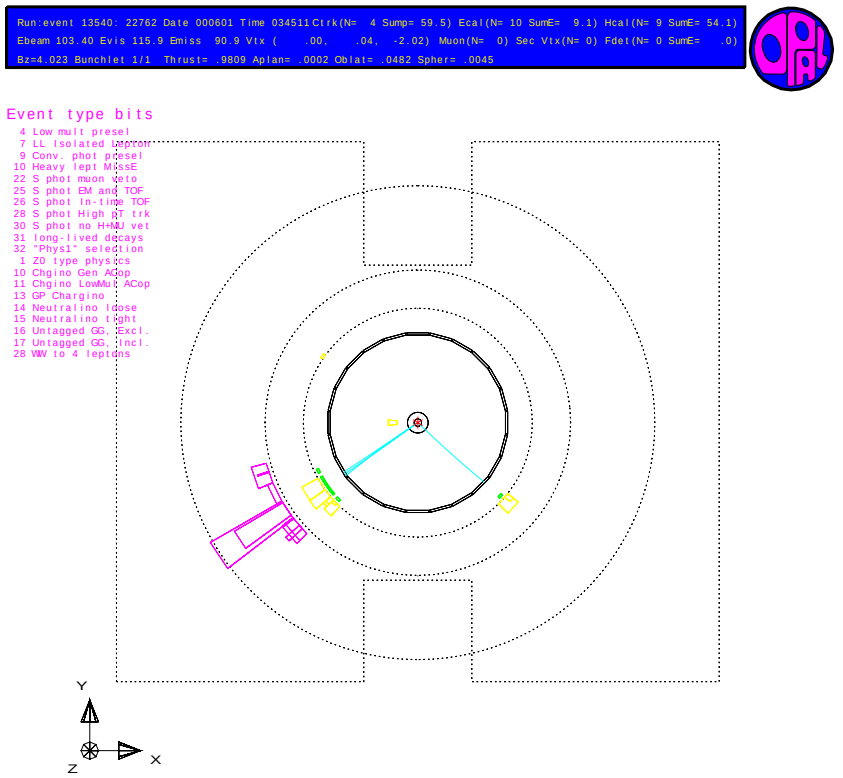


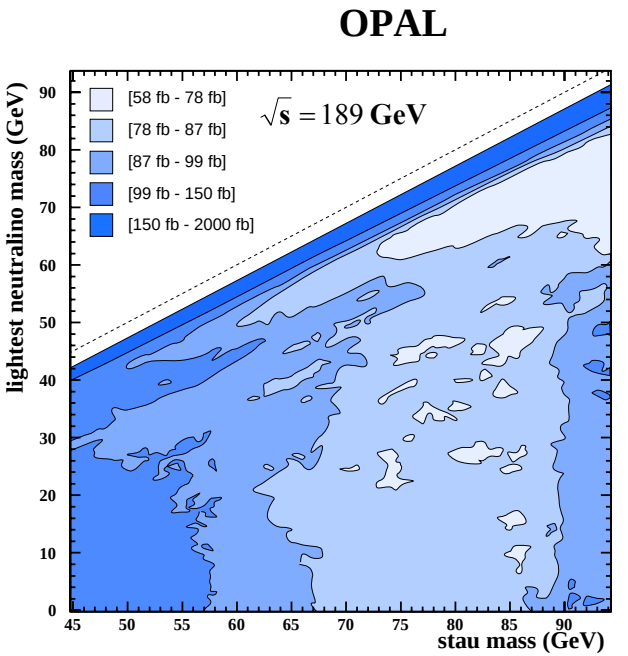
Absolute lower limit on the mass of the lightest neutralino (WIMP candidate for Cold Dark Matter)

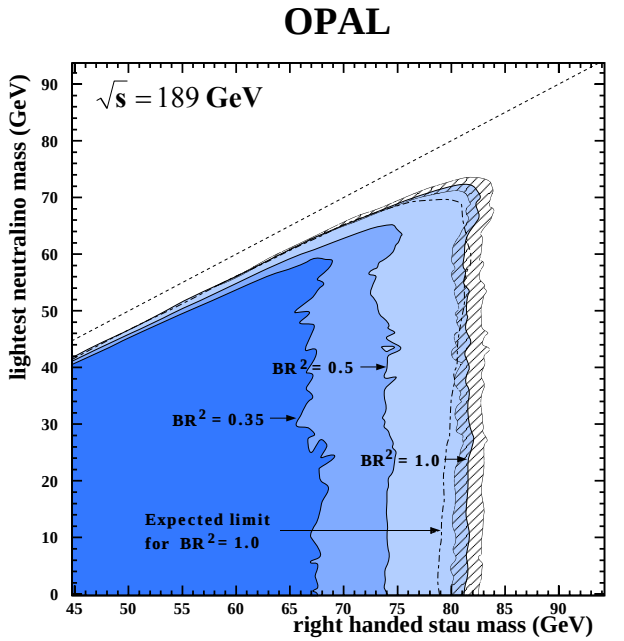
CMSSM: Slepton Searches



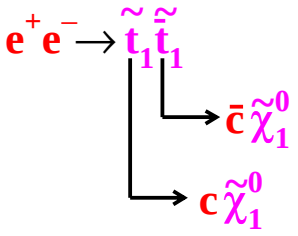
- Acoplanar leptons
- Missing E_T

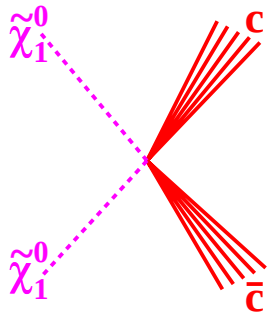






CMSSM: Squark Searches

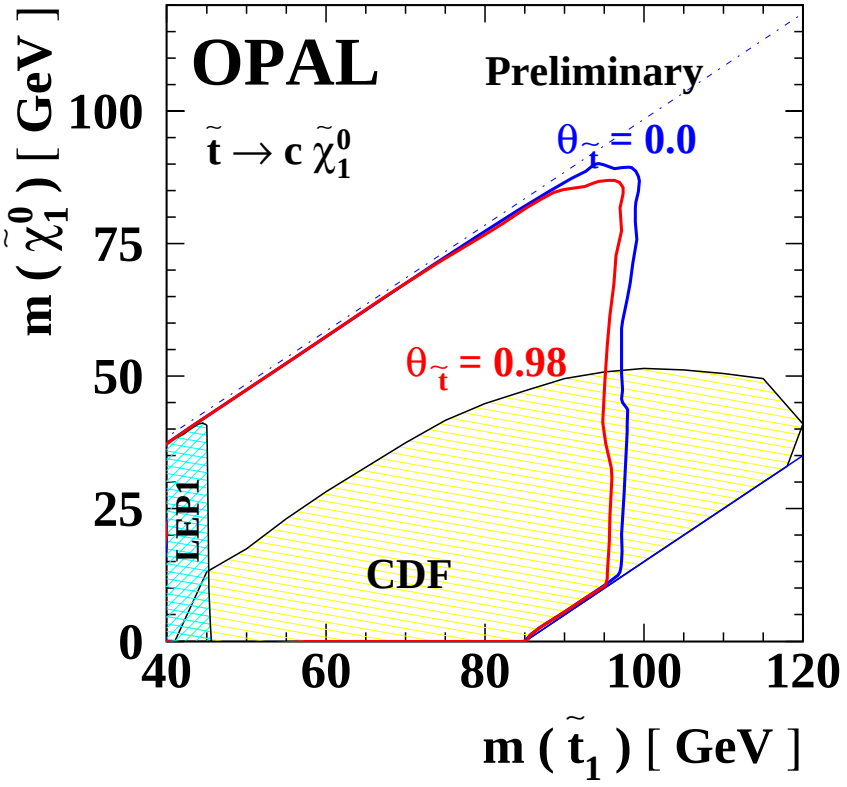


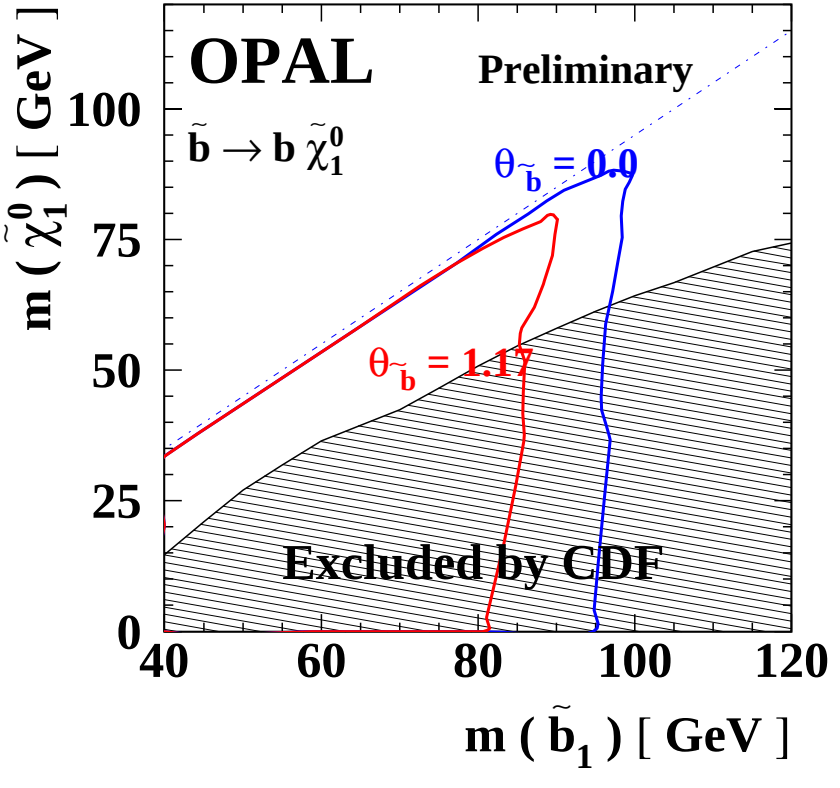


- Acoplanar Jets
- Missing E_T

Limits depend on squark mixing angles

Same topology can be used for sbottom search



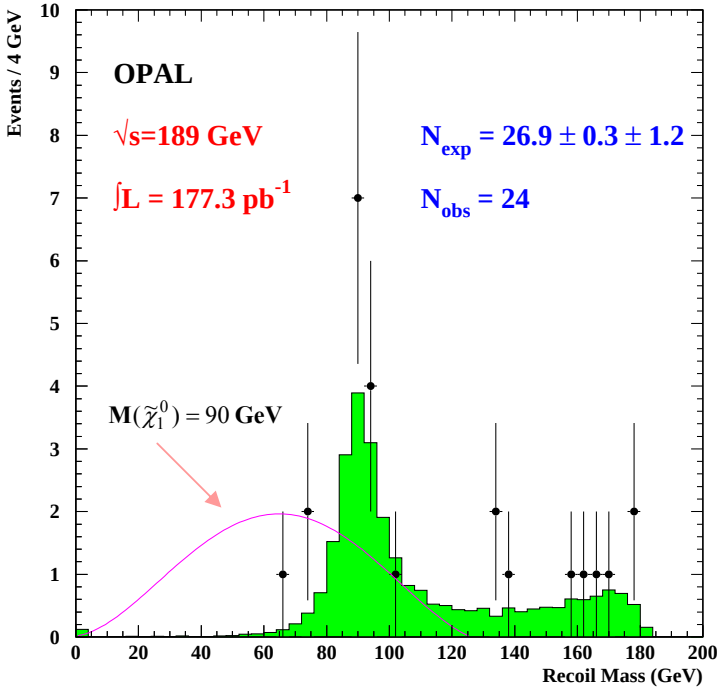


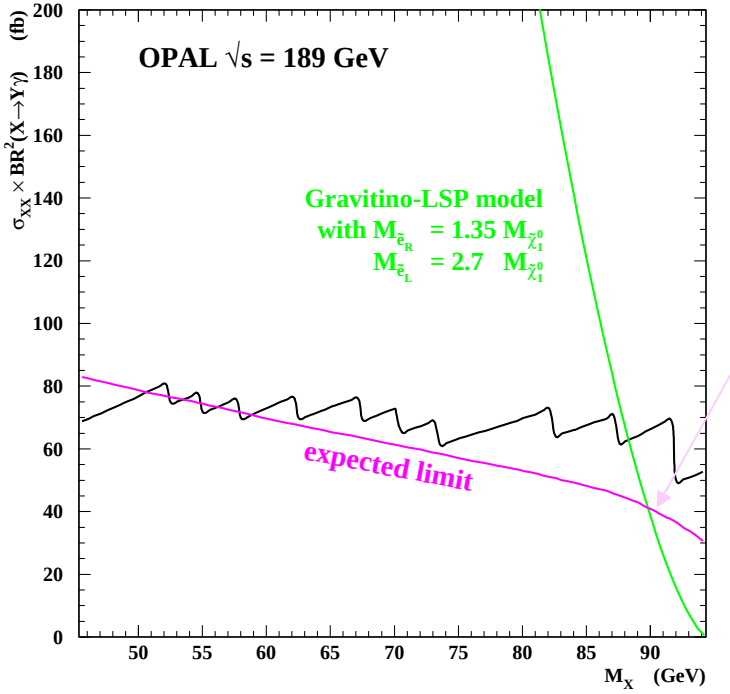
SUSY with a Light Gravitino: Neutralino NLSP Search

Variety of final states (similar to CMSSM signatures but with additional energetic photons from $\tilde{\chi}_1^0 \to \tilde{\mathbf{G}}\gamma$ decays at end of decay chain)

Some unusual signatures: $\mathbf{e^+e^-} \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to (\tilde{\mathbf{G}}\gamma)(\tilde{\mathbf{G}}\gamma) \to \gamma\gamma + \not{\mathbf{E}}_\mathbf{T}$ final state no longer invisible

SM background from $\mathbf{e^+e^-} \to \nu\bar{\nu}\gamma\gamma$



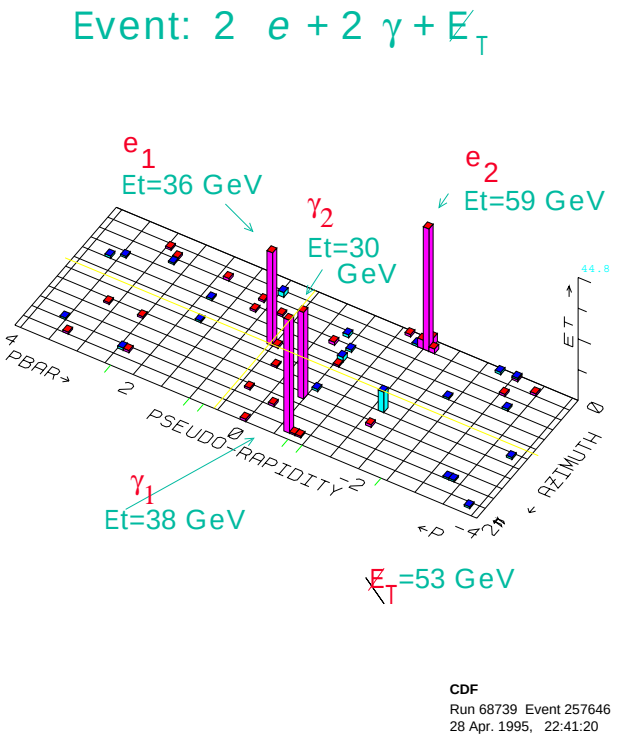


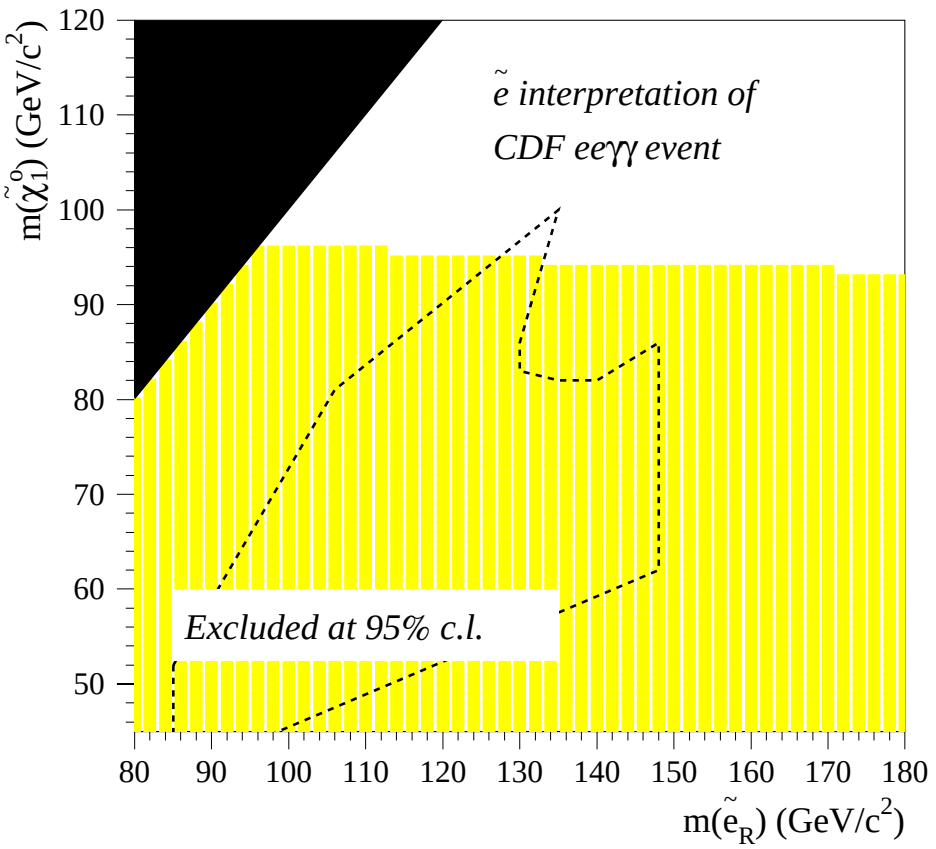
$\mathbf{M}(\tilde{\chi}_1^0) > 88.3$ **GeV** @95% **CL**

Gravitino LSP scenario occurs in various SUSY models (GMSB, no-scale supergravity)

The CDF $ee\gamma\gamma + \not{E}_T$ Event

Is this supersymmetry ?



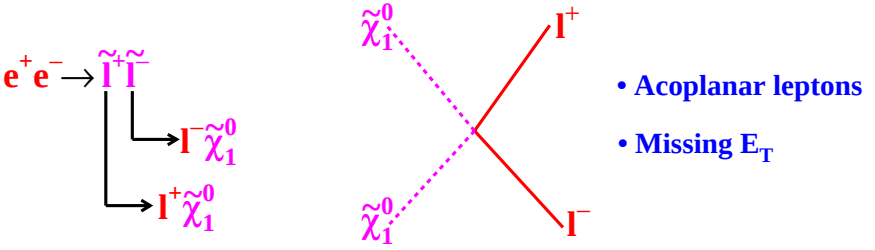


Can be interpreted as selectron pair production in light gravitino scenario

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

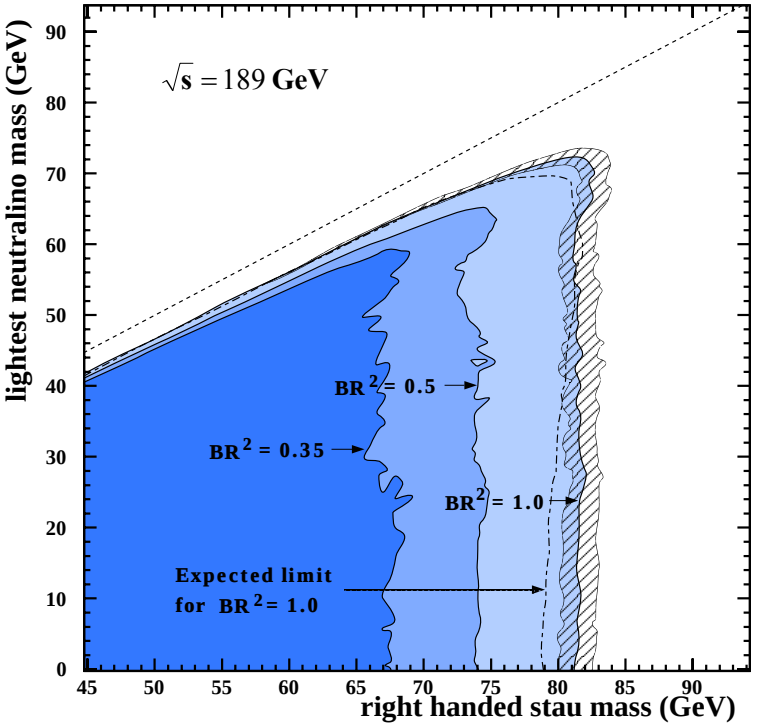
SUSY with a Light Gravitino: Slepton NLSP Searches

Signature as before in CMSSM with gravitinos instead of neutralinos
i.e. $\tilde{l} \to \tilde{G} l$ instead of $\tilde{l} \to \tilde{\chi}_1^0 l$

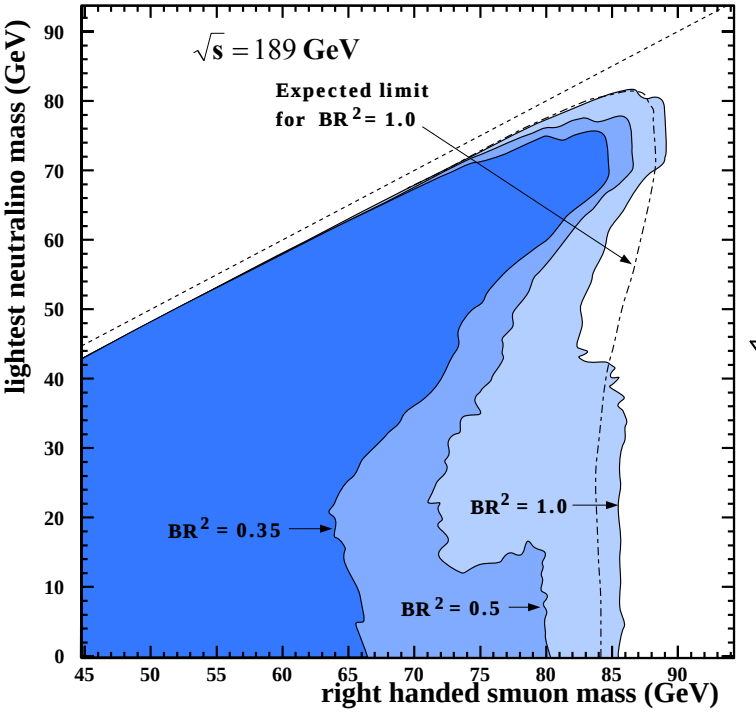


- Acoplanar leptons
- Missing E_T

OPAL



OPAL



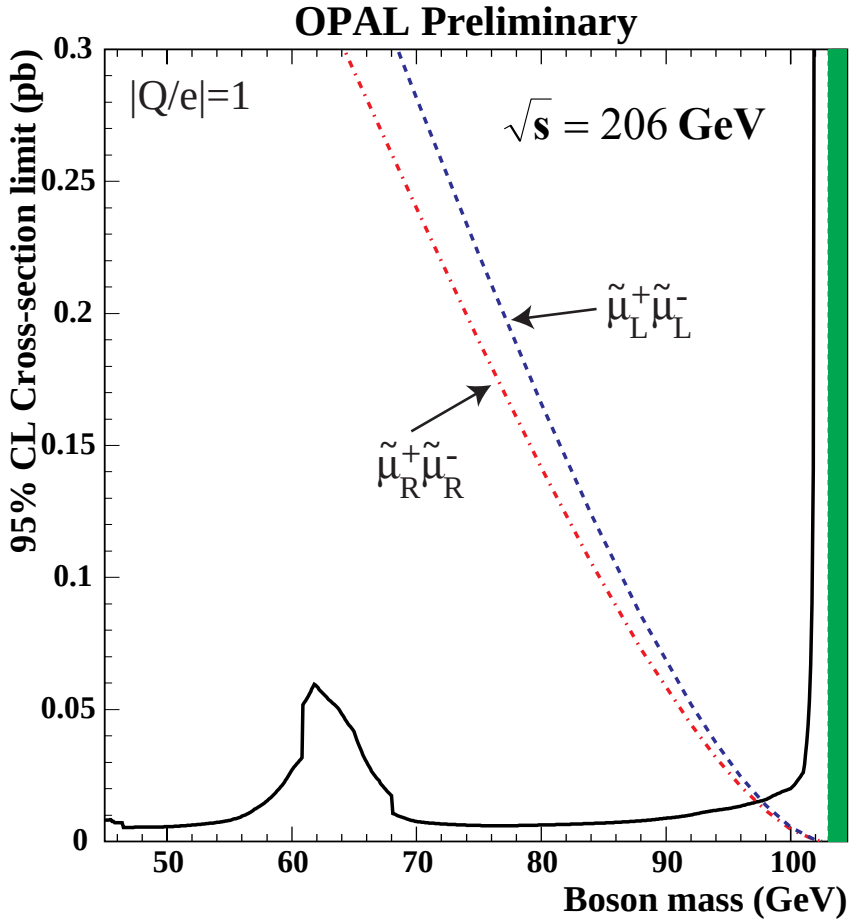
$M(\tilde{\mu}_R) > 85.4$ GeV
$M(\tilde{\tau}_R) > 81.1$ GeV
$M(\tilde{\tau}_R) > 80.0$ GeV

for any degree of stau mixing

Limits for $M_{LSP} = 0$ axis and BR=1.0 apply

Long Lived Heavy Charged Particles

Slepton NLSP with long lifetime ⇨ heavy "stable" charged particles (decays far outside the detector)



Get mass limits near the kinematic limit for $\tau > 1\mu s$

Limits as well for ("heavy stable")

$|Q/e| = 2/3$ spin-1/2 particles

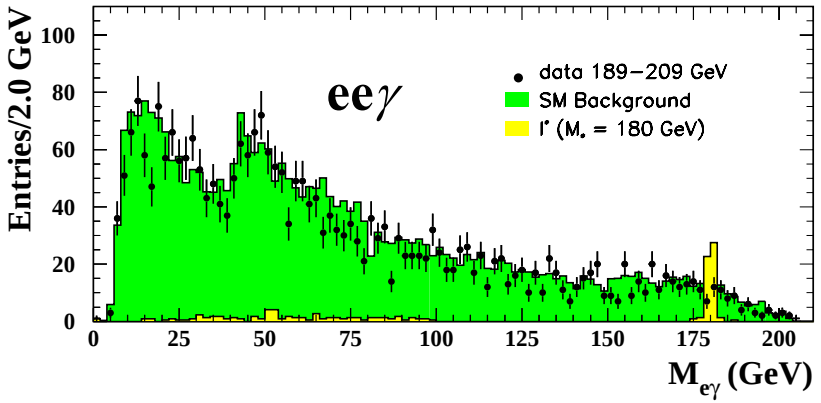
$|Q/e| = 1$ spin-1 particles

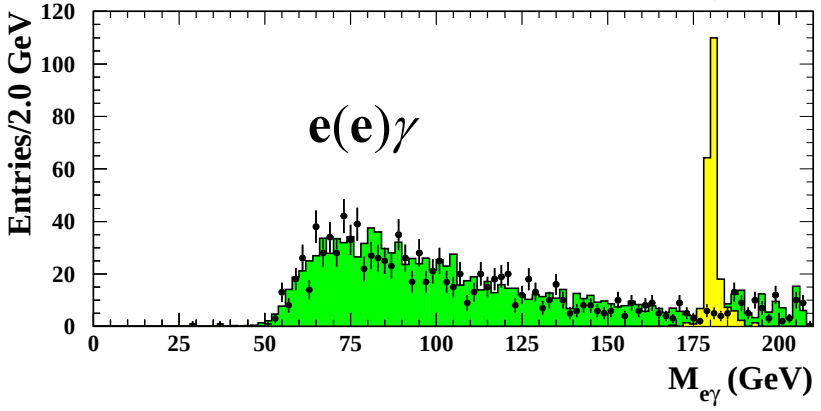
Cross-section predictions shown for model with GMSB

Search for Excited Leptons with Photonic Decays

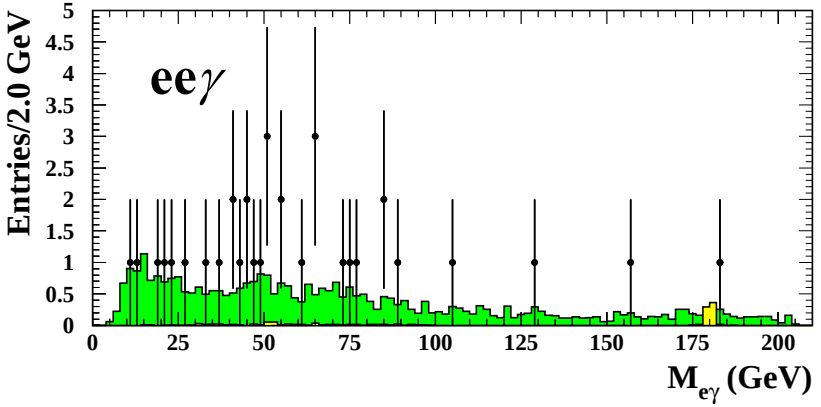
$e^+e^- \to \ell^*\ell^*, \ell\ell^*$ Mass reach best in single-production

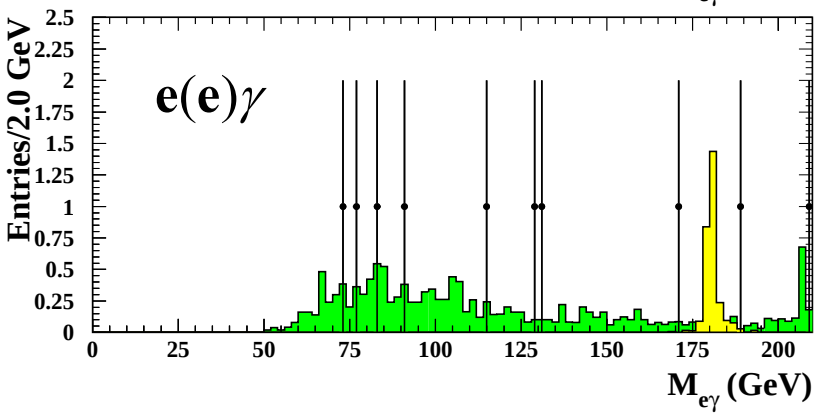
$\sqrt{s} = 189 - 209$ **GeV**





$\sqrt{s} = 207$ **GeV**

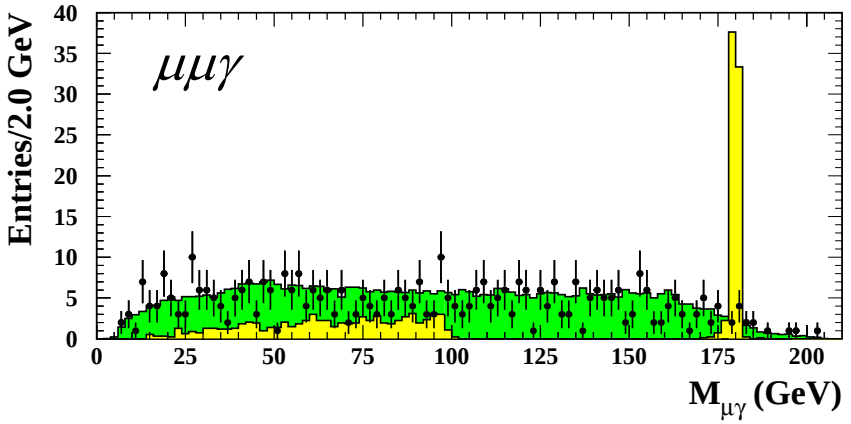


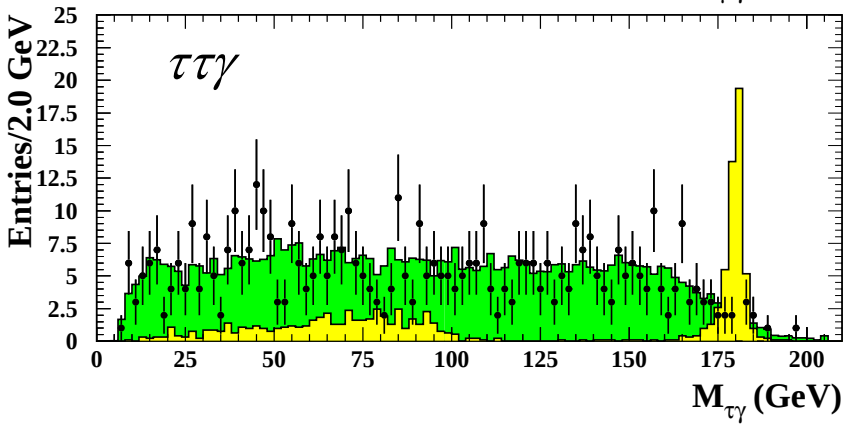


Signal distributions for $f/\Lambda = 0.5$

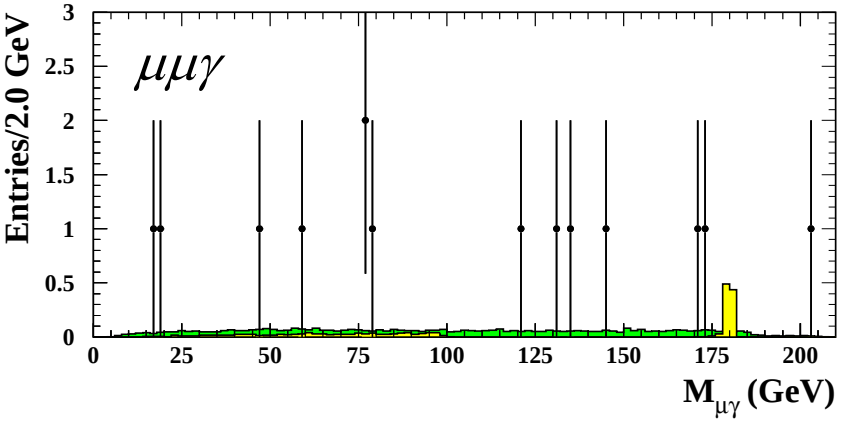
Search for Excited Leptons

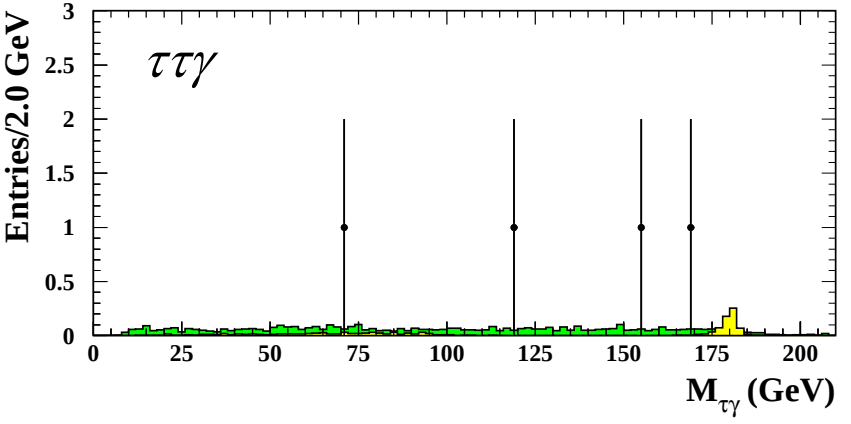
$\sqrt{s} = 189 - 209$ **GeV**



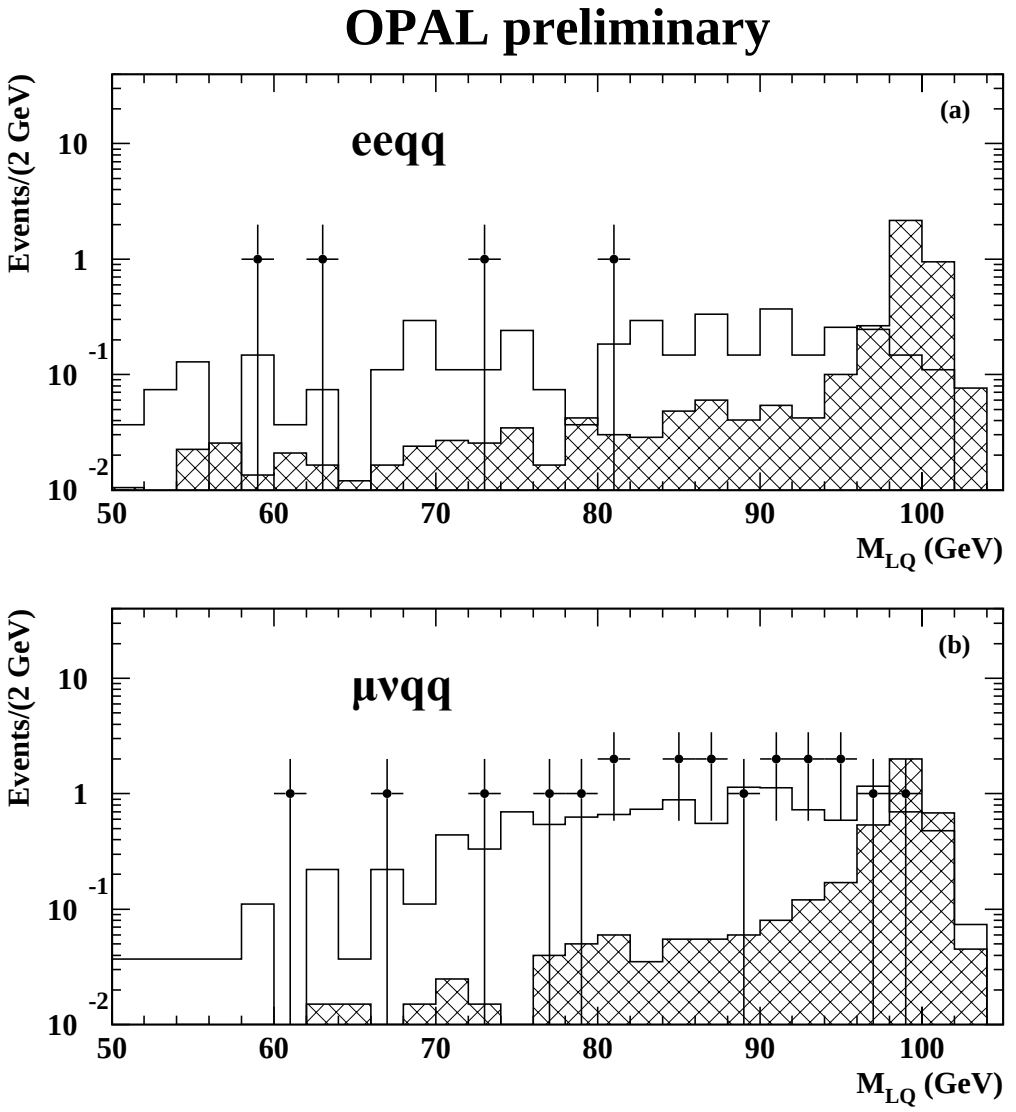


$\sqrt{s} = 207$ **GeV**





Leptoquark Pair Production



Leptoquark X

$$e^+e^- \to XX \to \ell q \ell' q'$$

Assume coupling to a single generation

eeqq	**eνqq**
$\mu\mu$qq	**$\mu\nu$qq**
$\tau\tau$qq	**$\tau\nu$qq**
$\nu\nu$qq	

Signal distributions for 99 GeV leptoquark

Summary

The decommisioning of LEP represents the end of an era

Both the LEP1 and LEP2 experimental programs have yielded valuable precision measurements of the SM as well as varied searches for whatever physics lies (just?) beyond it.

Electroweak combinations are already advanced

Searches combinations are in progress, but no real hints of anything new

The LHC is a hadron machine so a “discovery machine”

LEP’s real legacy is represented by the SM measurements at $\sqrt{\mathbf{s}} = \sim 90 - 209\ \mathbf{GeV}$