Results from the OPAL Experiment

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On behalf of the OPAL Collaboration

LEP Fest, 10th October 2000

- Introductory Remarks

  Luminosity .. Y2K Data

- Physics Results

  PRELIMINARY LEP2, including $\sqrt{s} > 202$ GeV

  – Standard Model cross-sections and couplings

  – Indirect limits on new physics

  – Search for SM and MSSM Higgs

  – Searches for new particles

- Where do we go from here?

Apologies .. Consult our Web site

30 minutes is too short to give adequate recognition to the intensive work over the past few weeks (months) (years) ..

Please consult our public web site

'The OPAL experiment at LEP'
http://opal.web.cern.ch/Opal/PPwelcome.html

where you will find all OPAL physics results and, in particular, 3 Collective Physics Notes prepared for this LEP Fest

- Measurement of Standard Model Processes in e+e- Collisions at $\sqrt{s} > 202$ GeV
- Updated Results of Higgs Boson Searches in e+e- Collisions at the Highest LEP Energies
- New Particle Searches in e+e- Collisions at $\sqrt{s}$ = 200-209 GeV

Special People .. Many Thanks

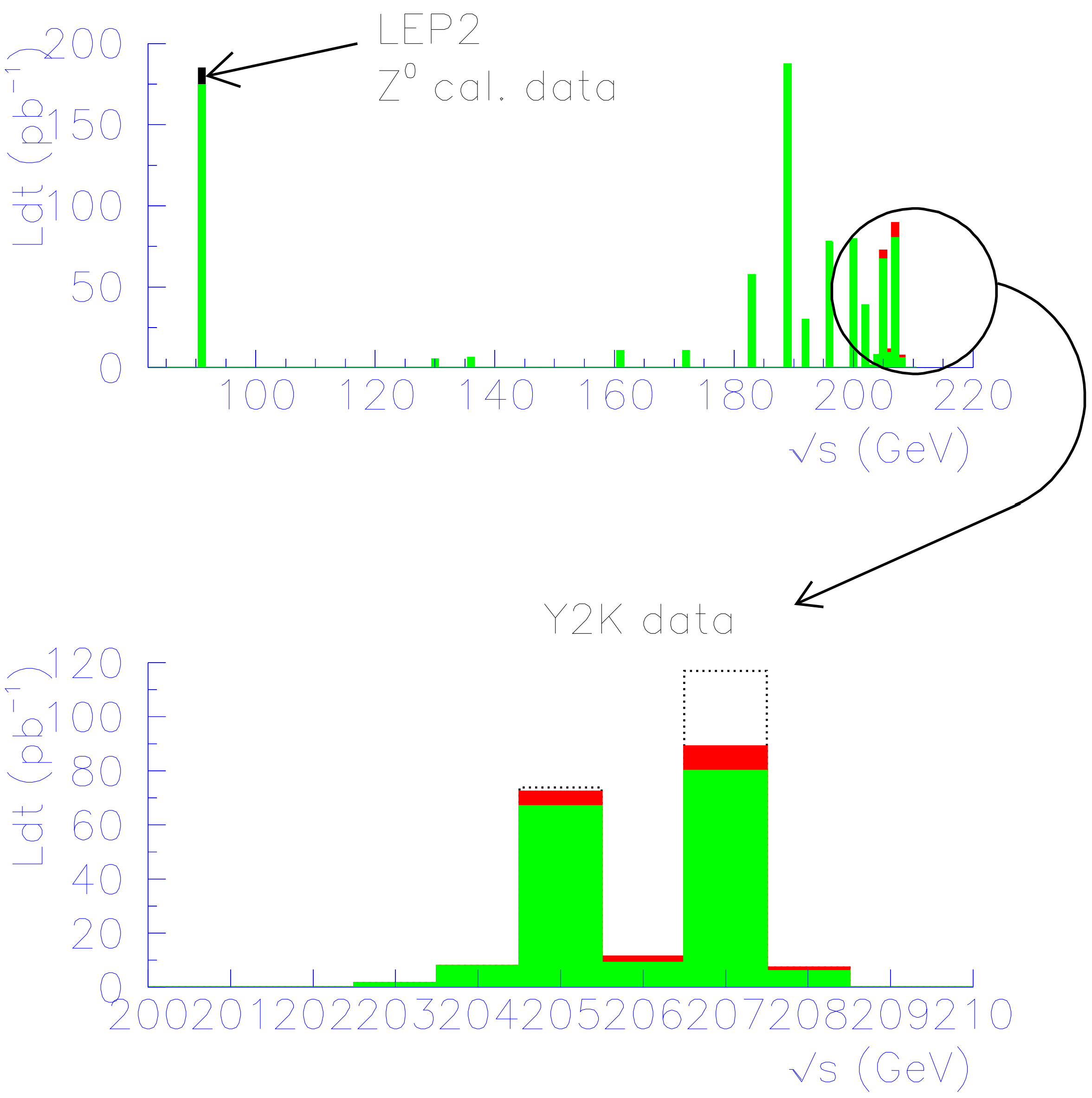
- OPAL Spokesmen
  - Aldo Michelini, early beginnings - 1993
    Design, construction, installation, exploitation LEP1
  - Rolf Heuer, 1994 - mid 1998
    LEP1 to LEP2 transition, precision physics
  - Dave Plane, mid 1998 - present
    LEP2 highest energies/luminosities
- OPAL Secretary
  - Mette Stuwe, early beginnings - present

The OPAL Collaboration .. past/present

- CANADA
  Alberta, Carleton, CRPP/NRC, Montreal, UBC, Victoria
- FRANCE
  Saclay
- GERMANY
  Aachen, Bonn, Freiburg, Hamburg/DESY, Heidelberg, LMU-Munich, MPI-Munich
- HUNGARY
  Budapest, Debrecen
- ISRAEL
  Technion, Tel Aviv, Weizmann
- ITALY
  Bologna
- JAPAN
  ICEPP-Tokyo/Kobe
- CERN
- UK
  Birmingham, Brunel, Cambridge, Manchester, QMW, RAL, UCL/Birkbeck
- USA
  Chicago, Duke, Indiana, Maryland, Oregon, Riverside, Yale

OPAL Luminosity Summary

- Special thanks to the LEP Division and all the technical staff associated with the LEP program. Each year, 1989-2000, has been great!

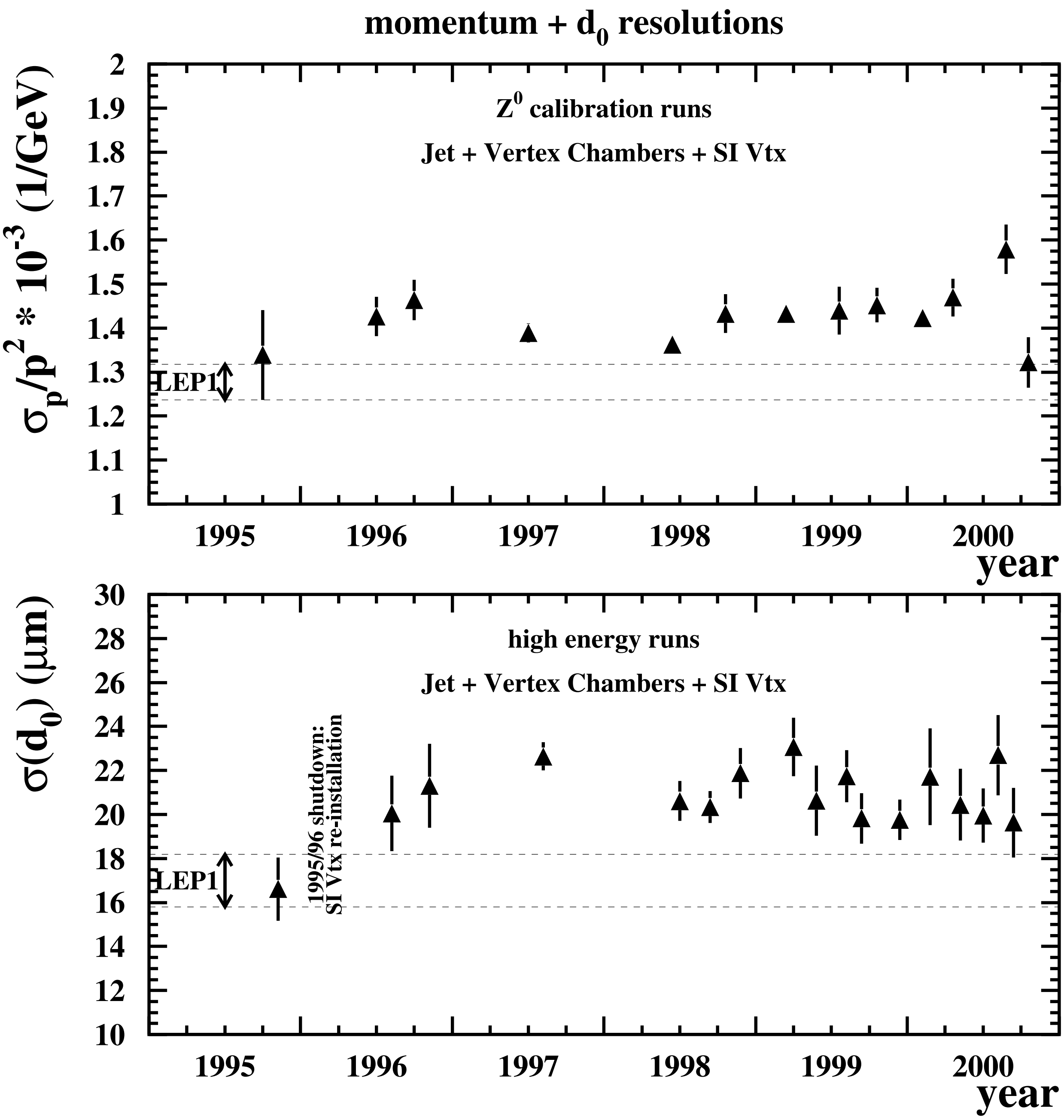


Today: Total luminosity recorded in Y2K almost 200 pb^{-1}

OPAL data taking efficiency in Y2K = 92%

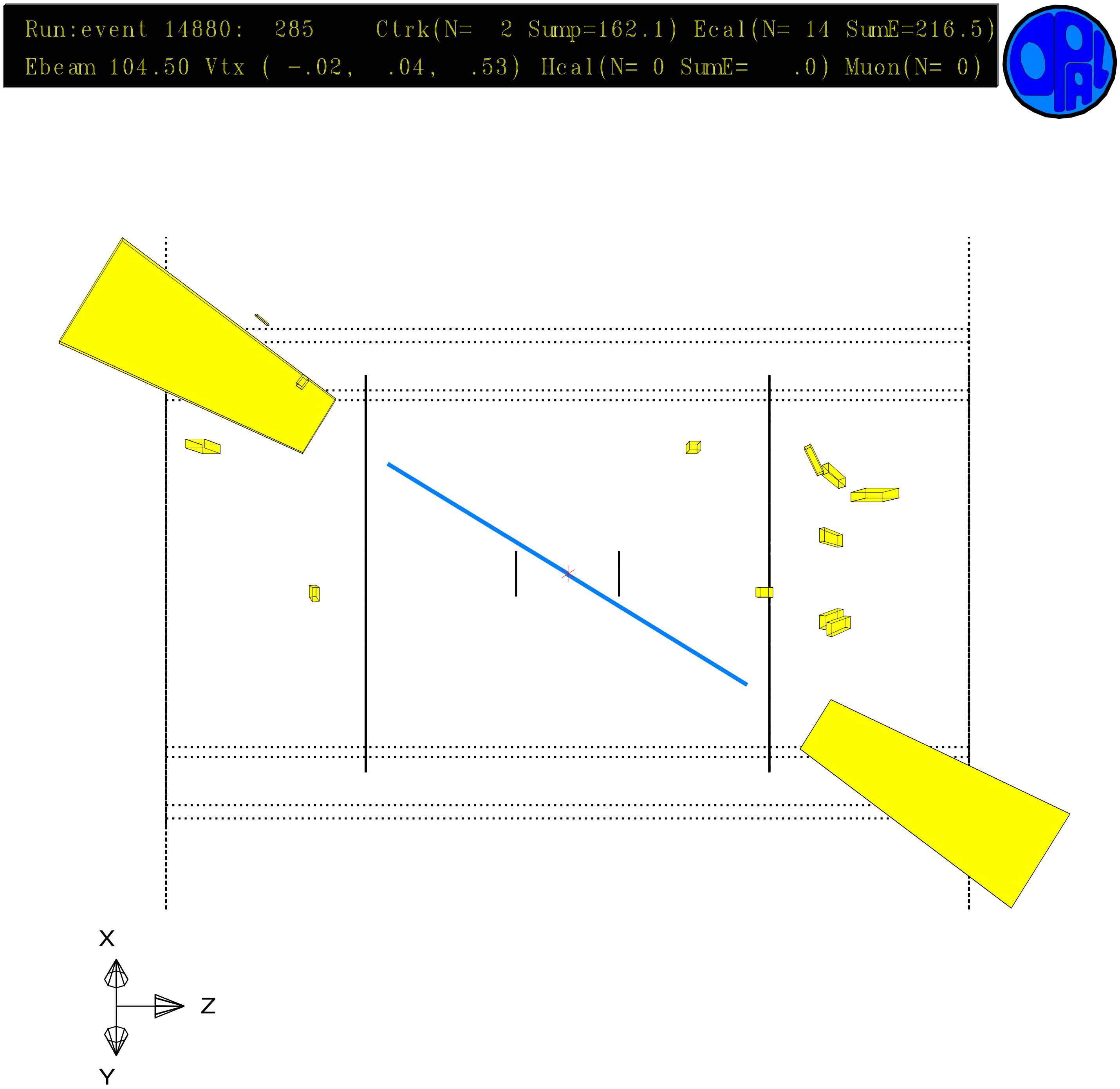
OPAL Data Quality

- Calibration procedures for OPAL have maintained steady and robust resolutions throughout the LEP2 period



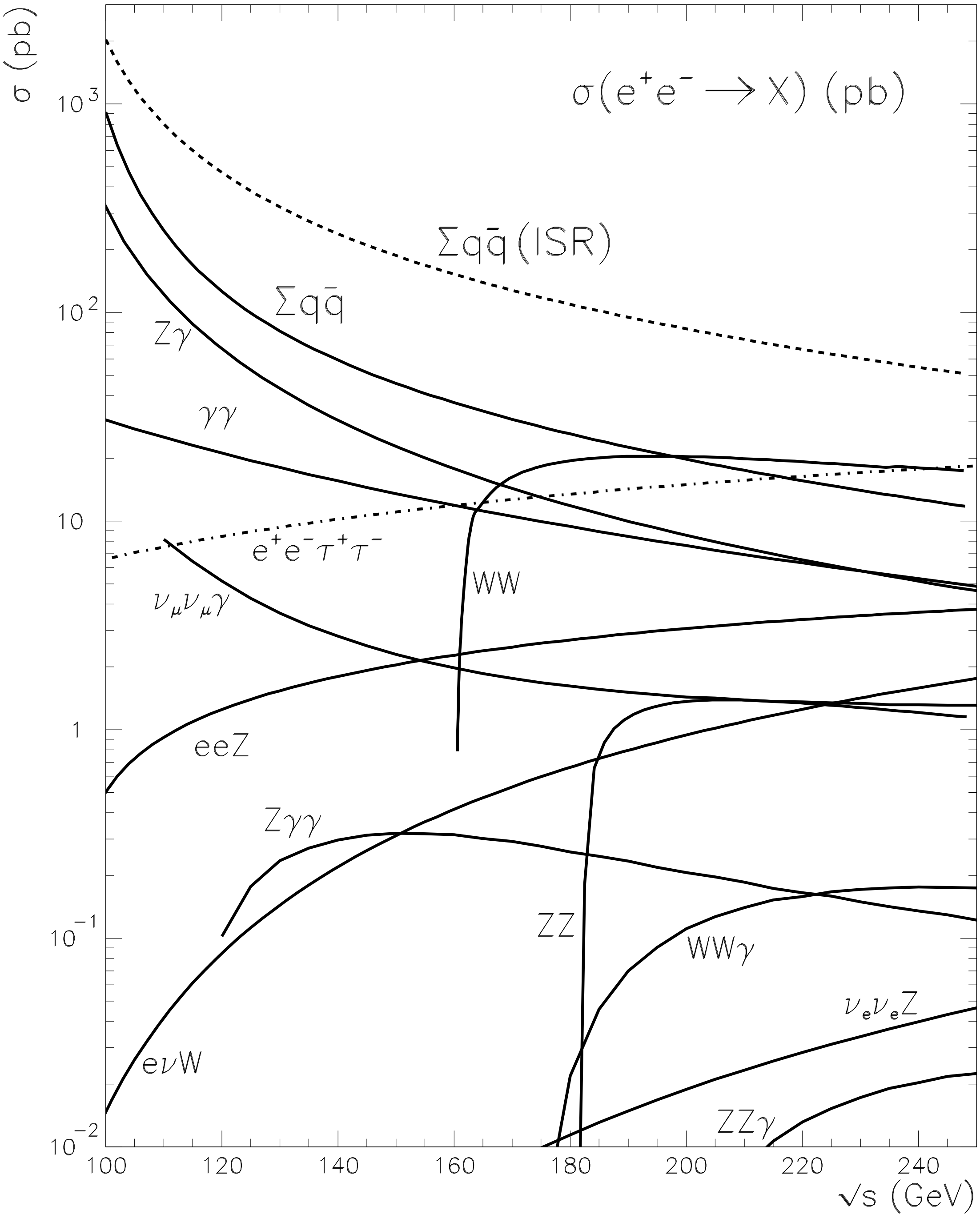
A Bhabha event at 209 GeV

- 10 August 2000, LEP sets energy record at 209 GeV
- Run lasted less than 2 minutes. Pity! 80 nb^{-1}



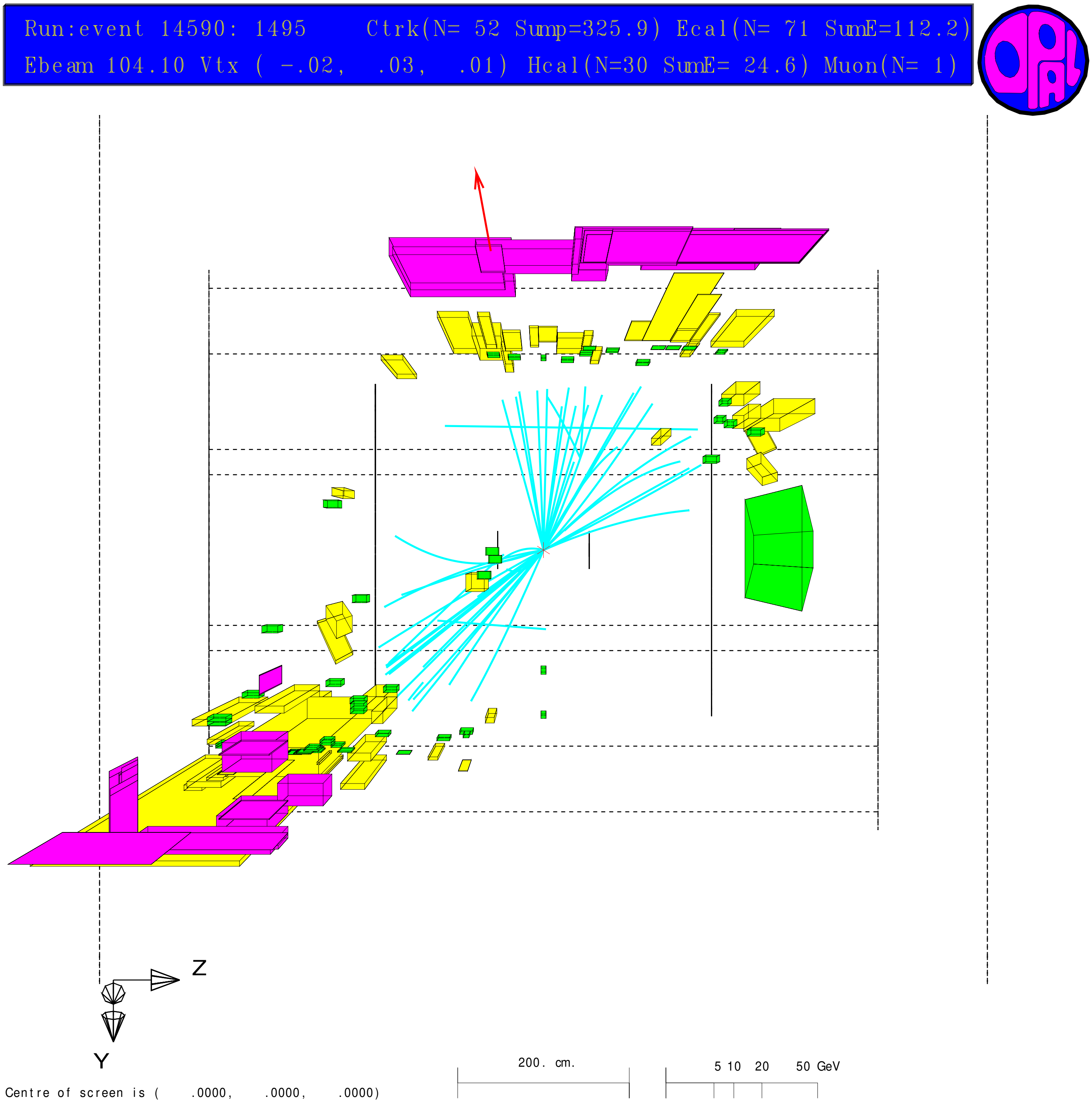
Standard Model Cross-sections

- from CERN Yellow Report, LEP2 Physics



A Multihadron event at 208 GeV

- One person’s signal is another person’s background!

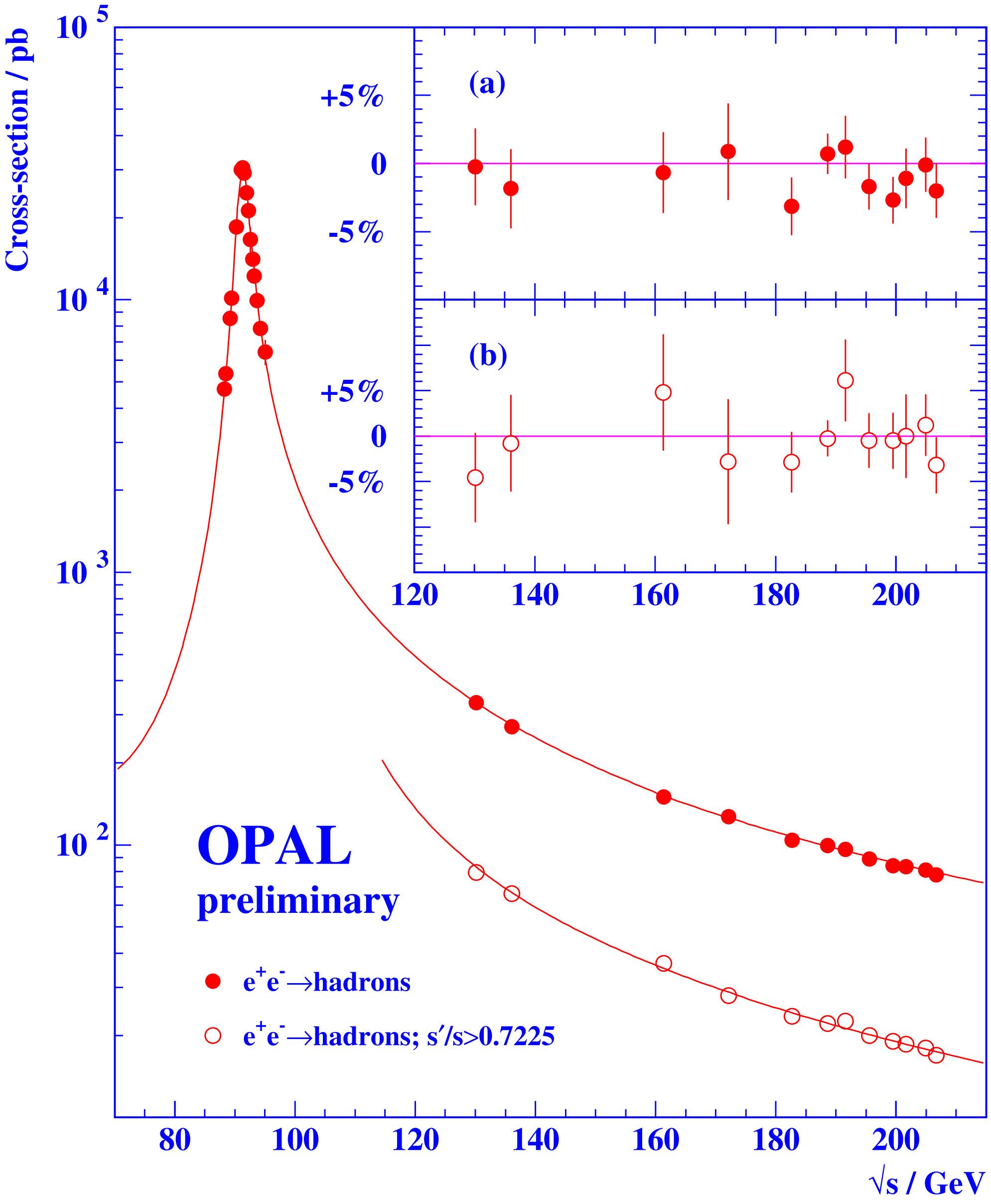


Cross-section for hadrons

- separate full-energy annihilation events from Z^0 radiative return

1478 non-radiative events at $\sqrt{s}$ = 205 GeV

1709 non-radiative events at $\sqrt{s}$ = 207 GeV



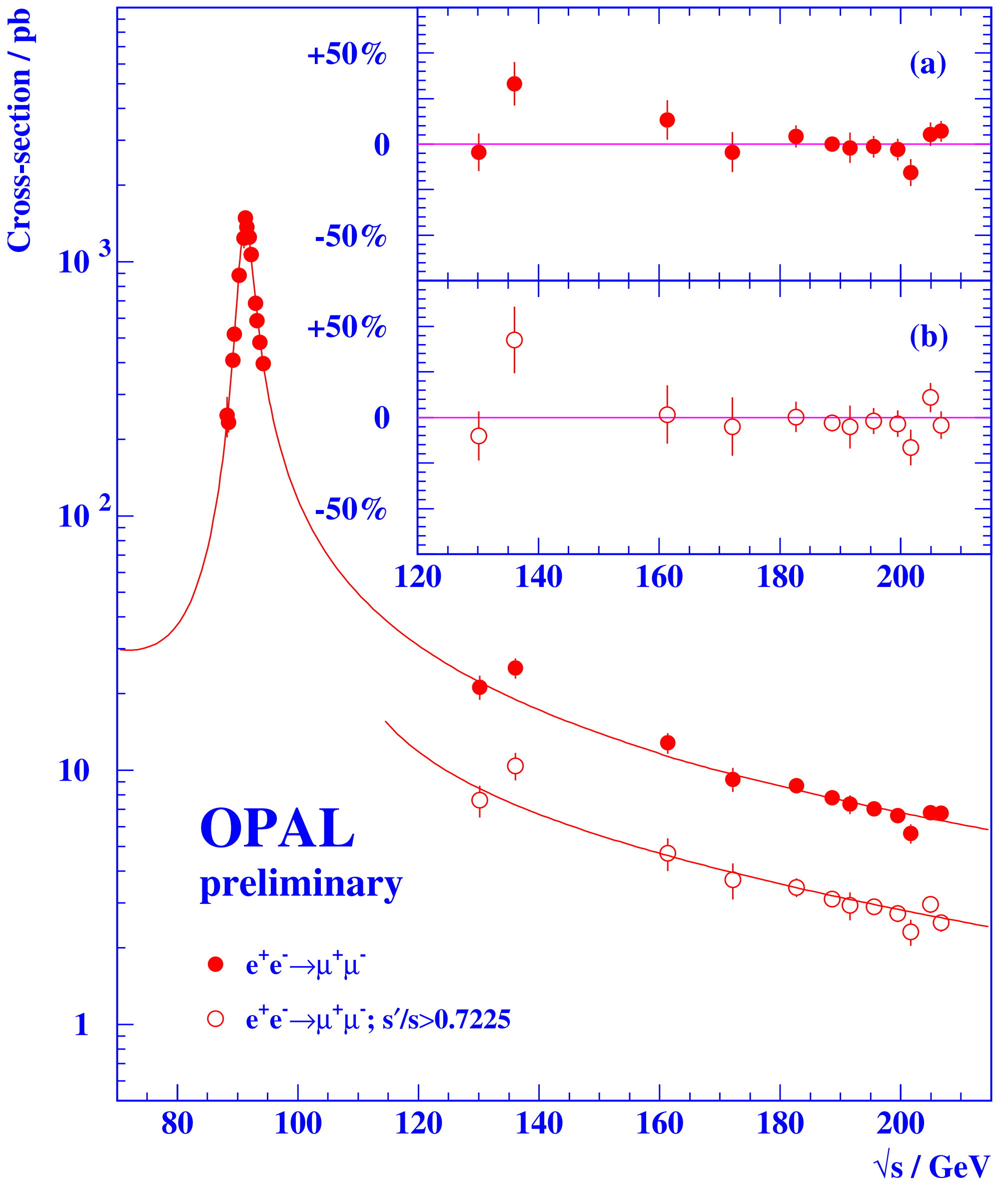
Curve is ZFITTER prediction

Cross-section for mu-pairs

- separate full-energy annihilation events from Z^0 radiative return

211 non-radiative events at $\sqrt{s}$ = 205 GeV

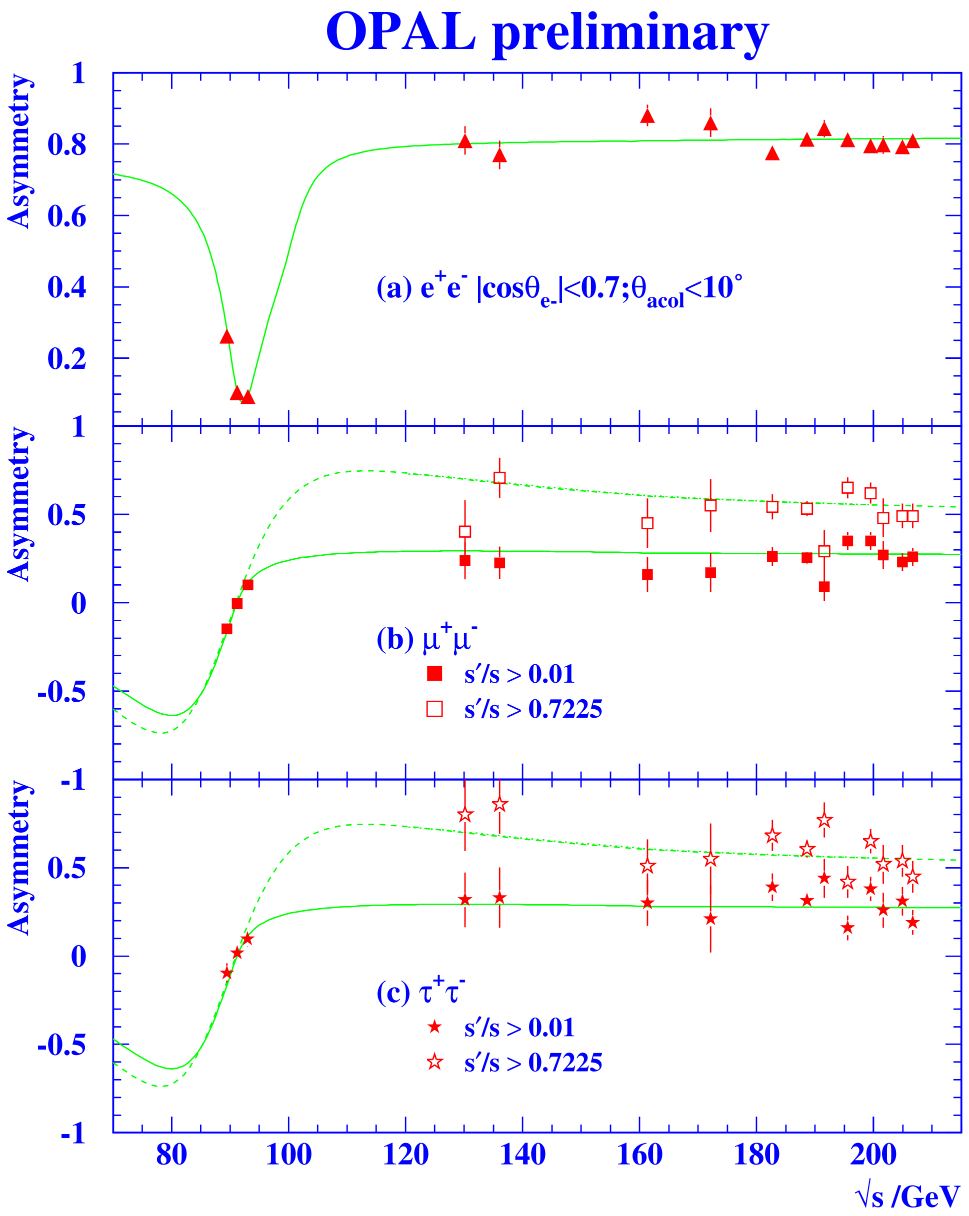
225 non-radiative events at $\sqrt{s}$ = 207 GeV



Curve is ZFITTER prediction

Forward-backward Asymmetries

- Measure A_{fb} for lepton pairs e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$

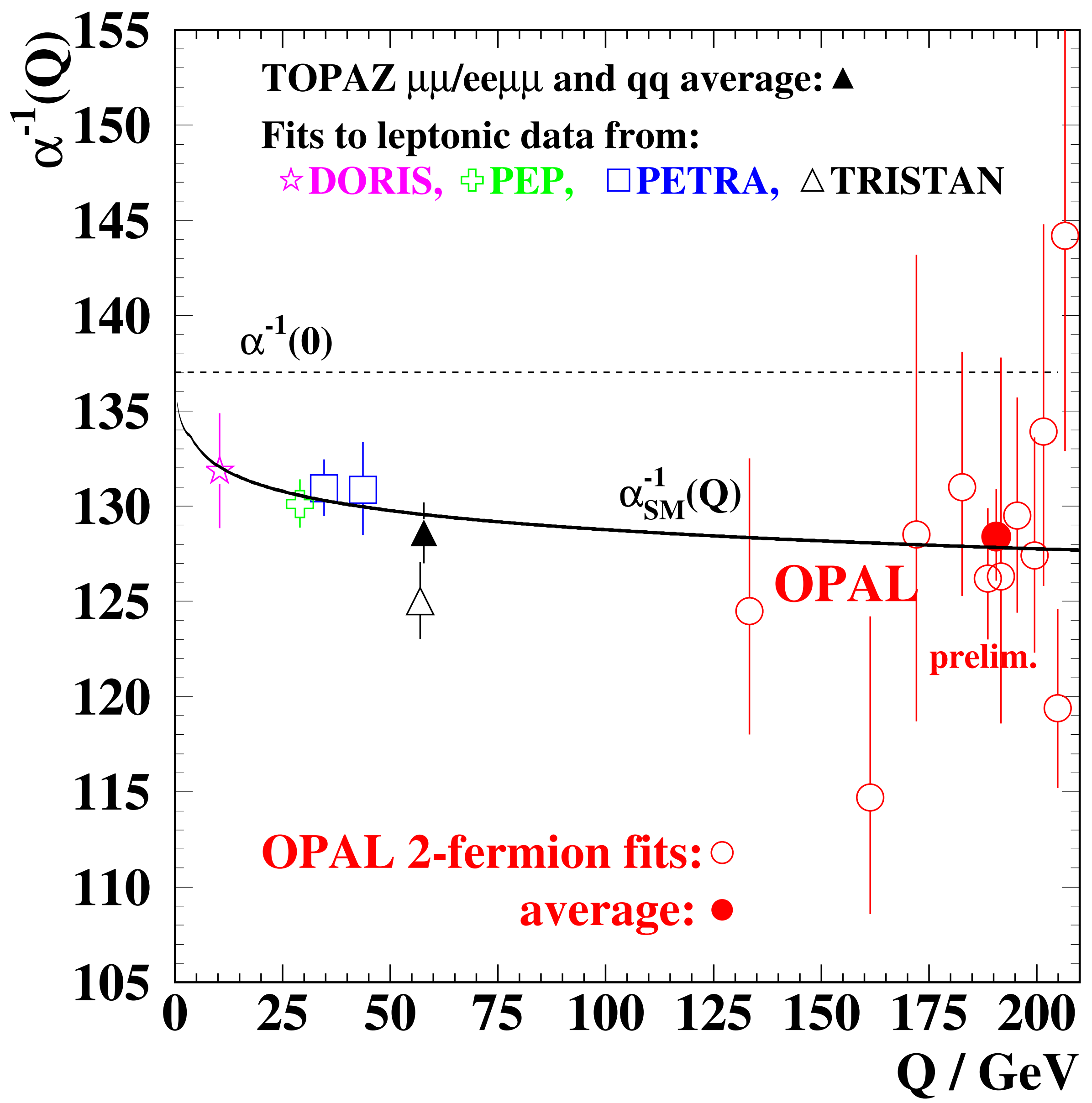


Curve is BHWIDE (e^+e^-), ZFITTER ($\mu^+\mu^-$, $\tau^+\tau^-$) prediction

Fine Structure Constant

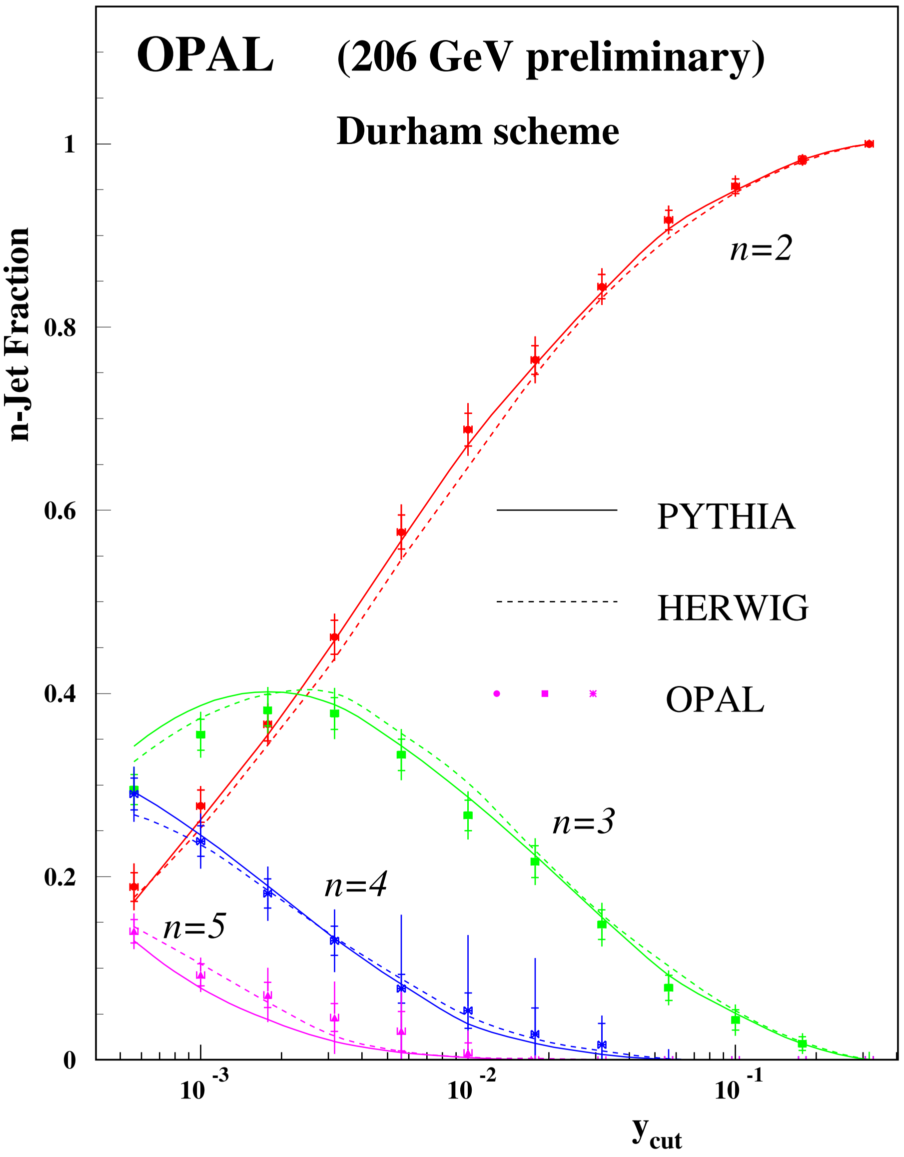
- Use non-radiative cross-sections and asymmetries
- ZFITTER, with all other pars fixed, gives $\alpha_{\rm em}(\sqrt{s})$

$$\alpha_{\rm em}(\sqrt{s} = 190.6\ GeV) = 128.4^{+2.5}_{-2.3}$$ (SM: 127.9)



QCD at 206 GeV

- All QCD observables well represented by PYTHIA, HERWIG
- No evidence for anomalous 4-jet production

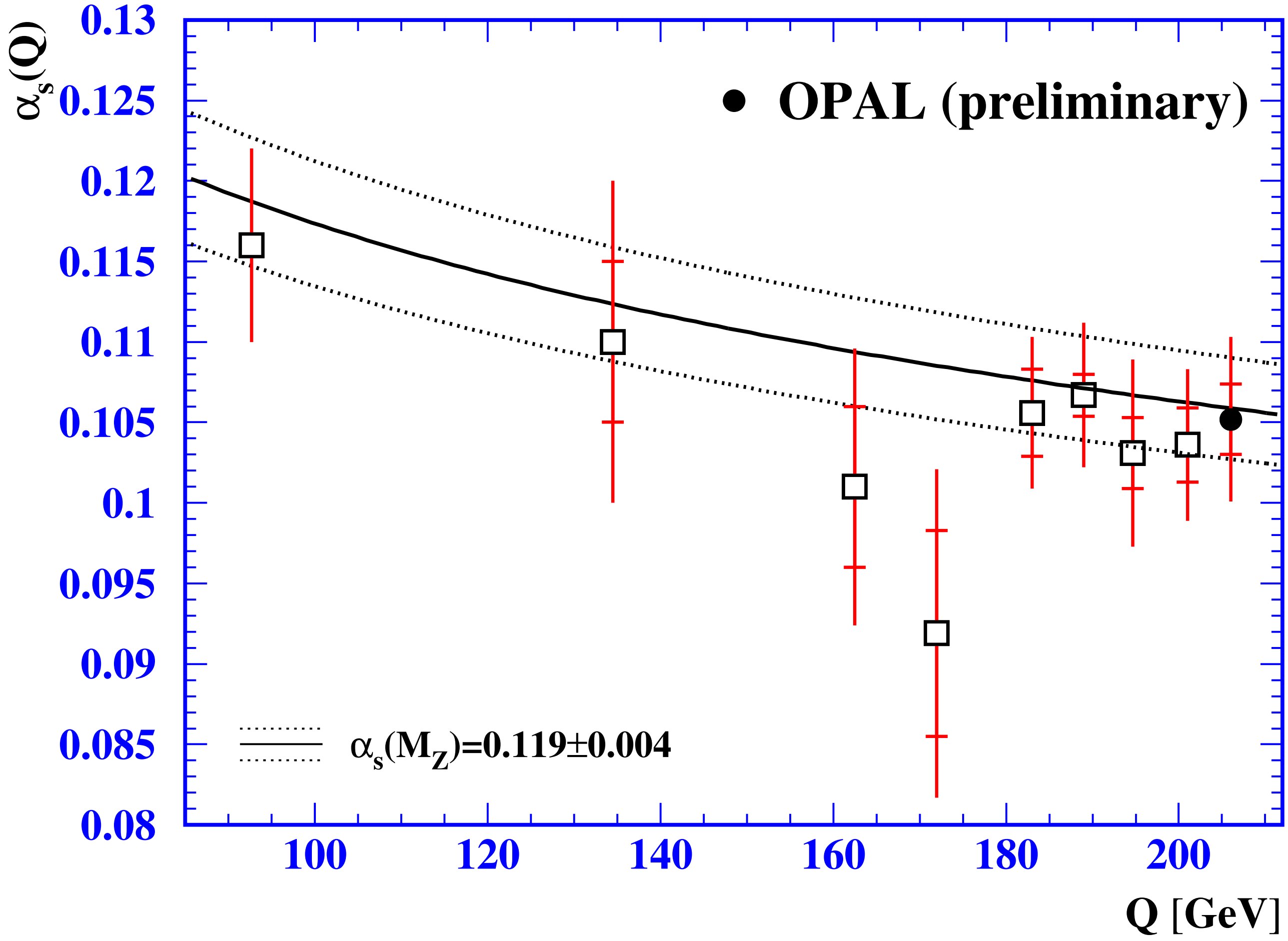


Strong Coupling Constant

- Fit distributions of 1-T, M_H, C, B_W, B_T, and y_{23}^D to NLLA $\mathcal{O}(\alpha_s^2)$QCD calculations
- Results consistent with running of α_s

$$\alpha_s(\sqrt{s} = 205.9\ GeV) = 0.107 \pm 0.002 \pm 0.004$$

Summary of OPAL measurements of α_s(Q)

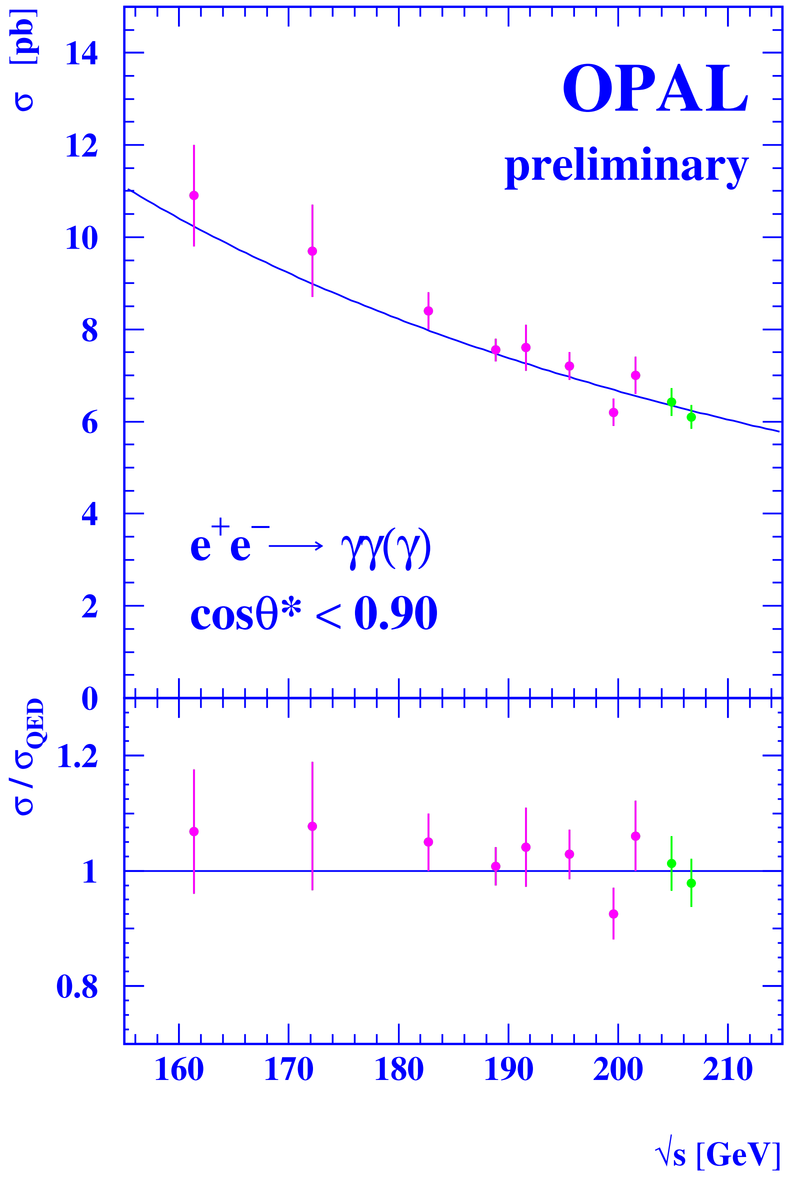


Cross-section for photon-pairs

- A pure QED process at tree level

At $\sqrt{s}$=205 GeV events observed/expected = 467/463

At $\sqrt{s}$=207 GeV events observed/expected = 534/549

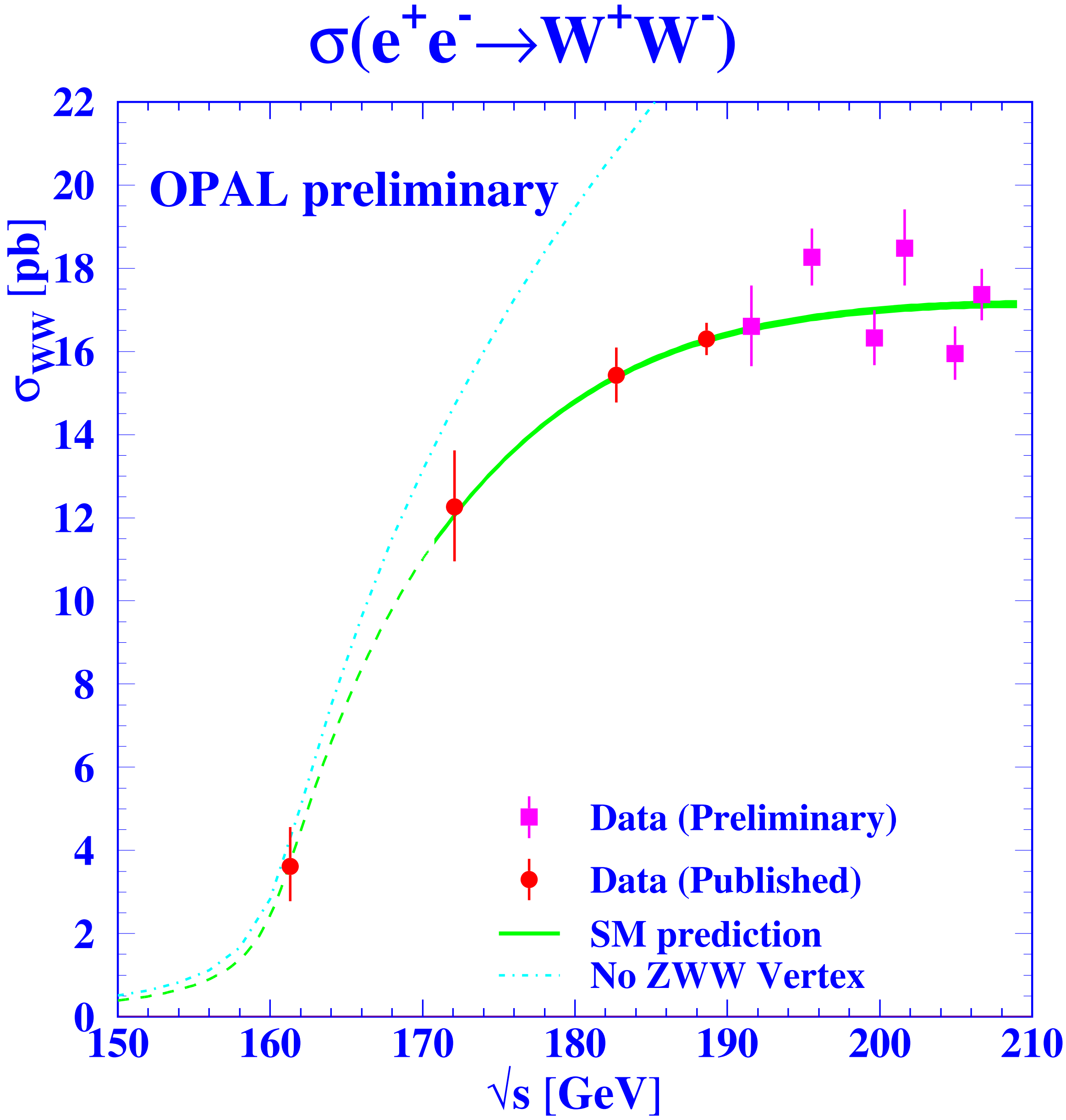


Cross-section for WW-pairs

- Isolate all 3 decay channels WW $\longrightarrow \mathrm{q\overline{q}q\overline{q}}, \mathrm{q\overline{q}}\ell\overline{\nu}_\ell, \ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$
- Cross-sections assume SM W decay fractions

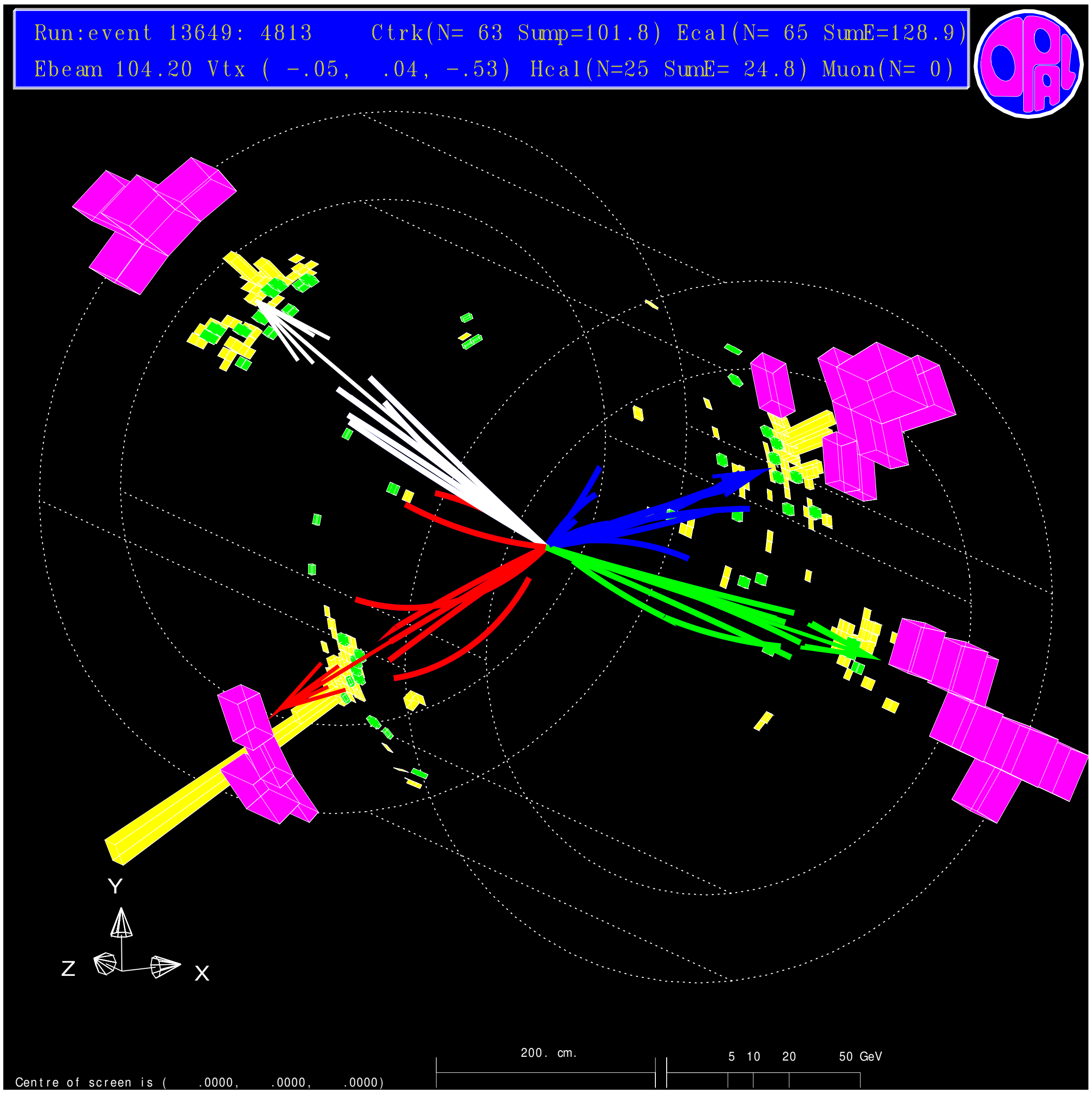
At $\sqrt{s}$=205 GeV obtain 651, 545, 125 events resp.

At $\sqrt{s}$=207 GeV obtain 887, 708, 162 events resp.



SM prediction via RACOONWW and YFSWW

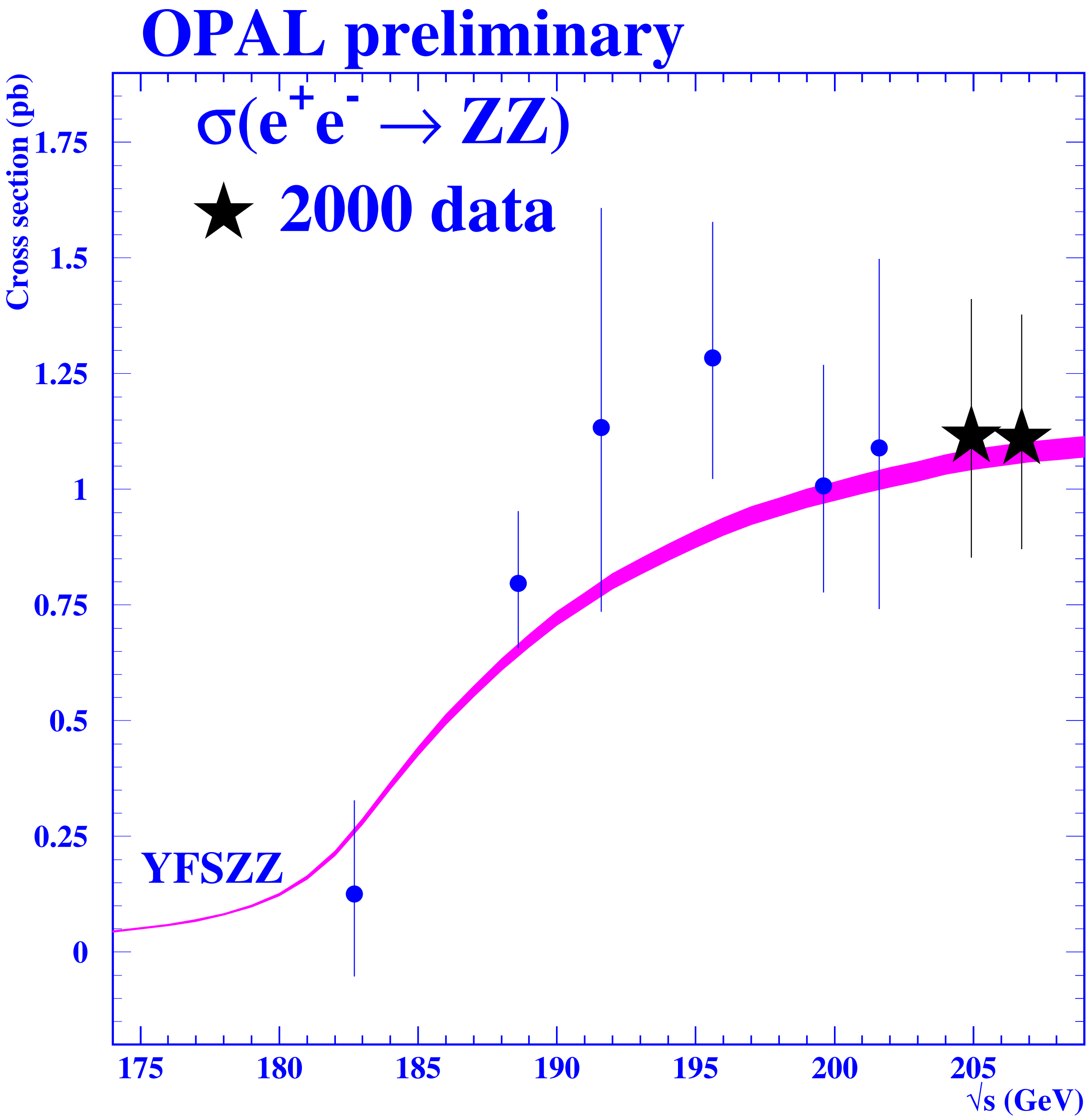
A WW $\longrightarrow$ qqqq event at 208 GeV



Cross-section for ZZ-pairs

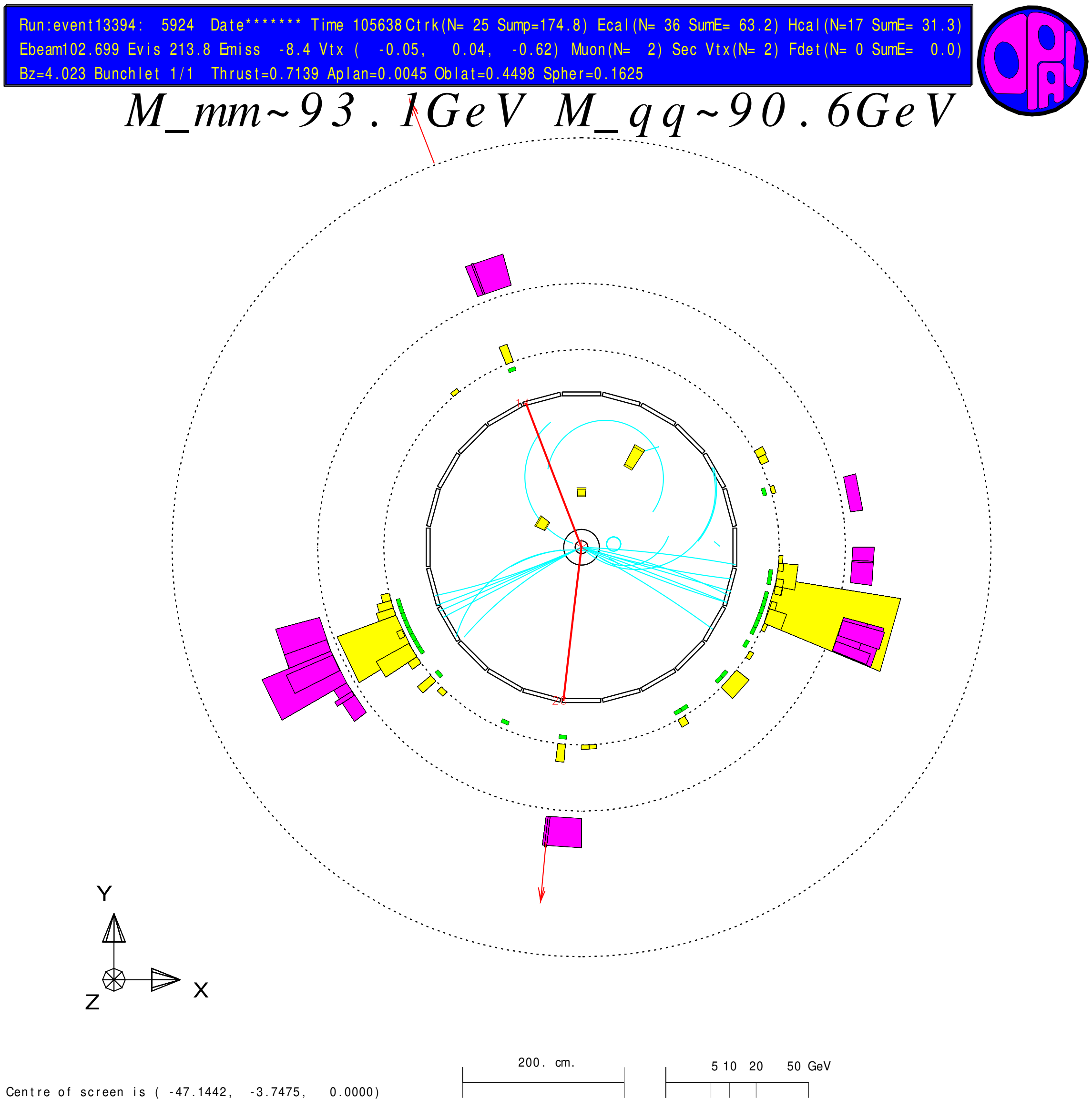
- Isolate decay channels $llll, ll\nu\nu, qqll, qq\nu\nu, qqqq$
- Cross-sections assume SM Z decay fractions

At $\sqrt{s}$=205 GeV obtain 77 candidates, expected SM bkgd = 37
At $\sqrt{s}$=207 GeV obtain 85 candidates, expected SM bkgd = 45



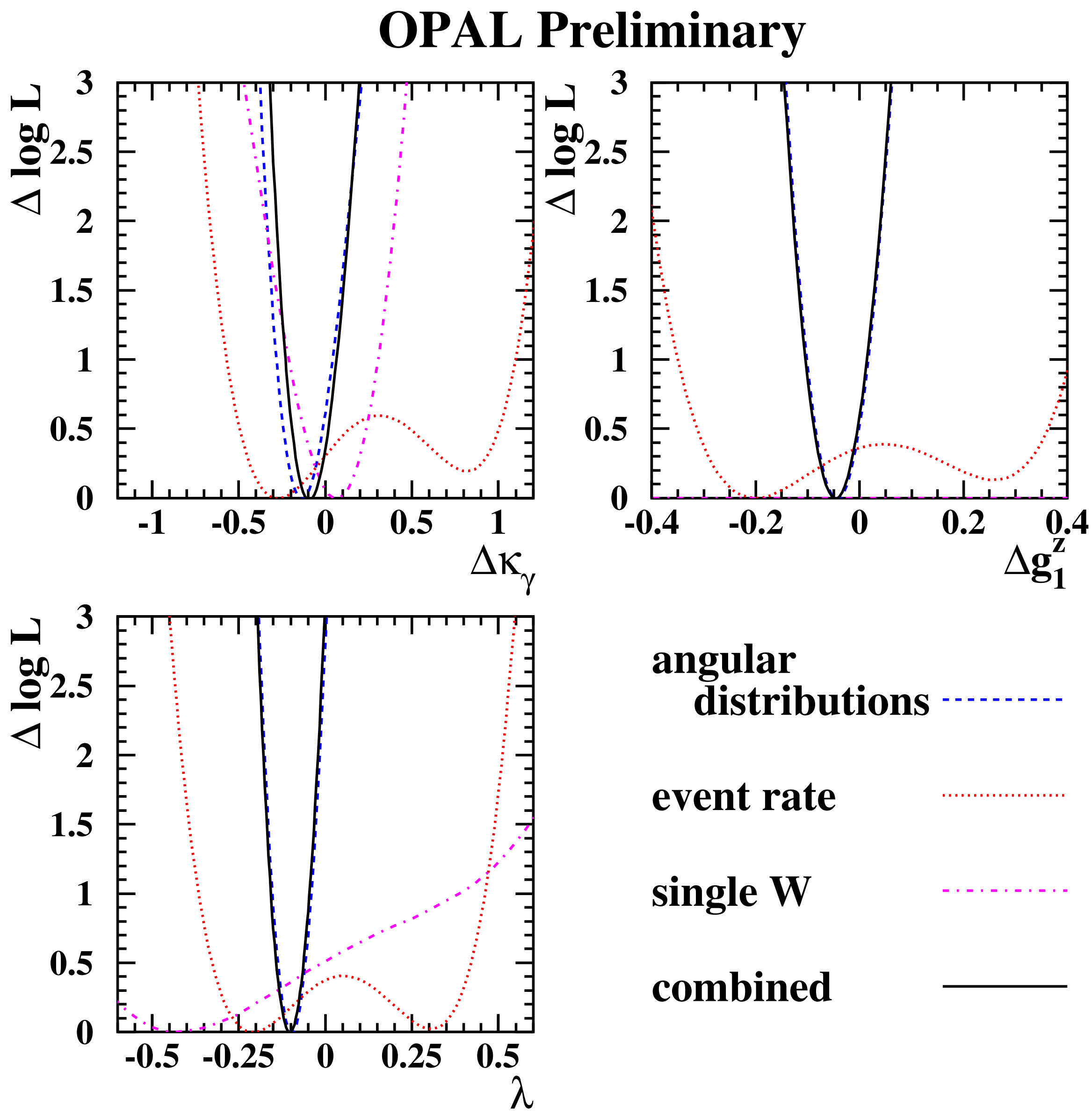
No evidence for non-zero neutral TGCs (ZZγ, ZZZ)

A ZZ event at 205 GeV



Charged Current TGCs

- Combine WW cross-section and angular distributions with single-W cross-section



No anomalous behaviour: SM values look OK.

Obtain limits on CP-violating TGCs via spin density matrix.

No evidence for anomalous QGCs, eg WW$\gamma\gamma$.

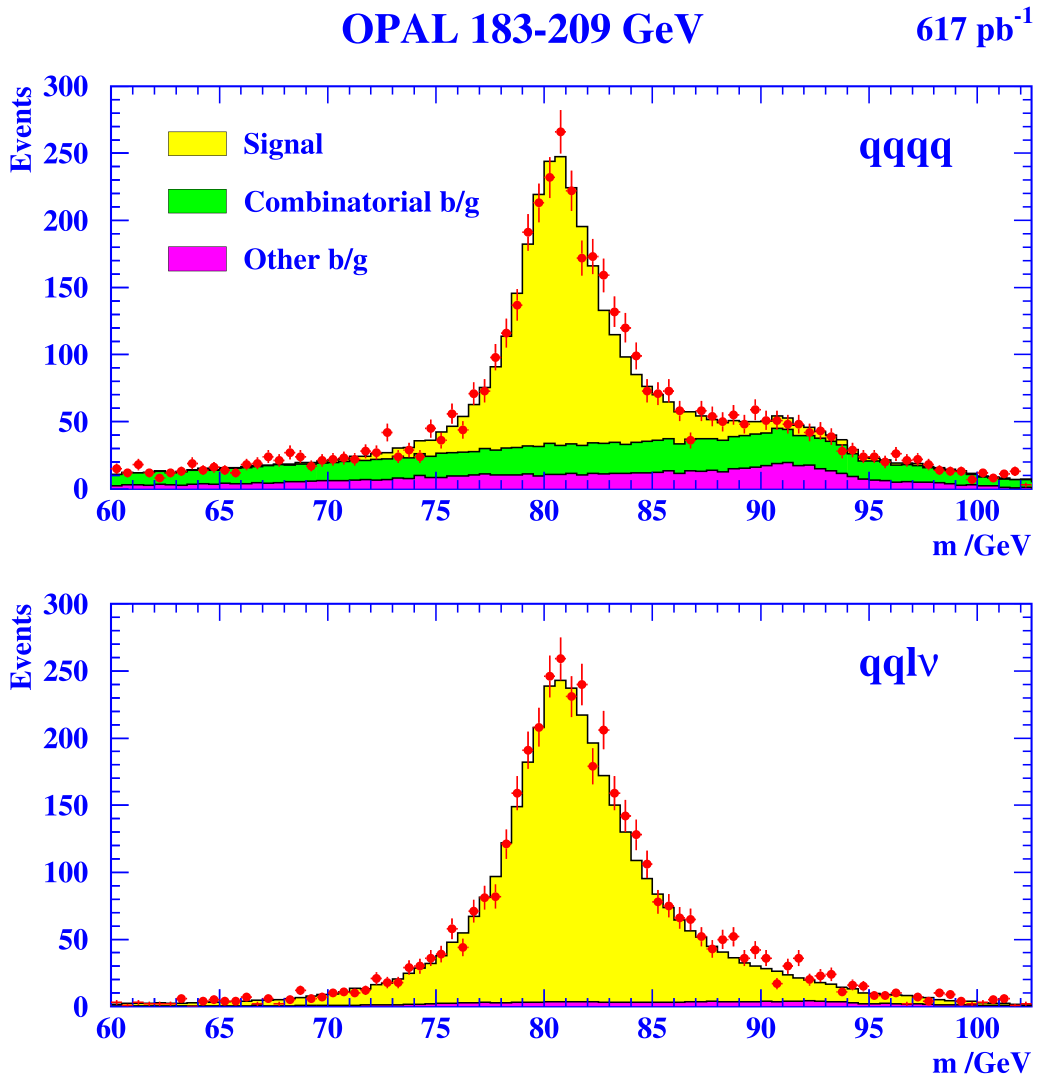
Precision M_W Measurement

- With 480pb^{-1} (prior to Y2K)

$$m_{\mathrm{W}} = 80.485 \pm 0.052(stat) \pm 0.039(sys)\ GeV$$

- With final statistics, expect

$$m_{\mathrm{W}} = 80.xxx \pm 0.040(stat) \pm 0.025(sys)\ GeV$$



Data shows no FSI (BEC,CR), $M(qqqq) = M(qql\nu)$.

Emphasise need for good LEP energy determination.

Estimate all-LEP error 30-35 MeV (SM indirect = 26 MeV).

Non-SM Physics ...indirect limits

$\mathrm{f\bar{f}}, \gamma\gamma, \mathrm{ZZ}$, ... cross-sections and couplings in agreement with SM. They provide limits on possible new physics (generally model dependent).

- 4-fermion Contact Interactions

  Mass limits 8-15 TeV with $g^2/4\pi = 1$

- Sneutrino exchange (RPV) in s-channel

  $\lambda_{131}, \lambda_{121}$ coupling limits within 100-300 GeV range

- Z' exchange in s-channel

  Exclusion limits in 400-750 GeV range

- QED Λ cut-off parameters in $\mathrm{e^+e^-} \rightarrow \gamma\gamma$

  Both Λ_+, Λ_- above 330 GeV

- Excited electron in t-channel $\gamma\gamma$

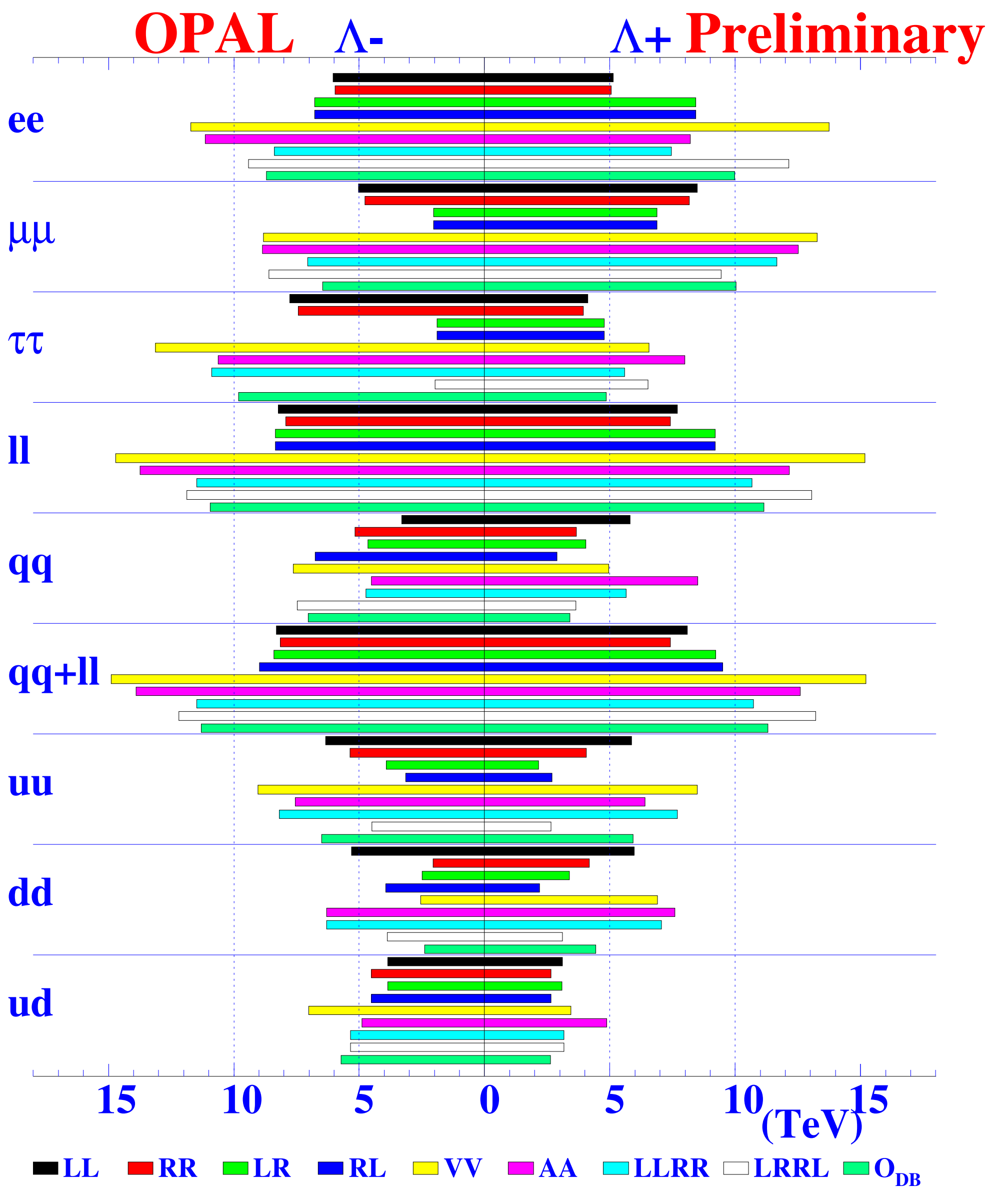
  Mass limit ~ 300 GeV assuming $e^*e\gamma = ee\gamma$ coupling

- Low scale quantum gravity in $\mu^+\mu^-, \tau^+\tau^-, \gamma\gamma, \mathrm{ZZ}$

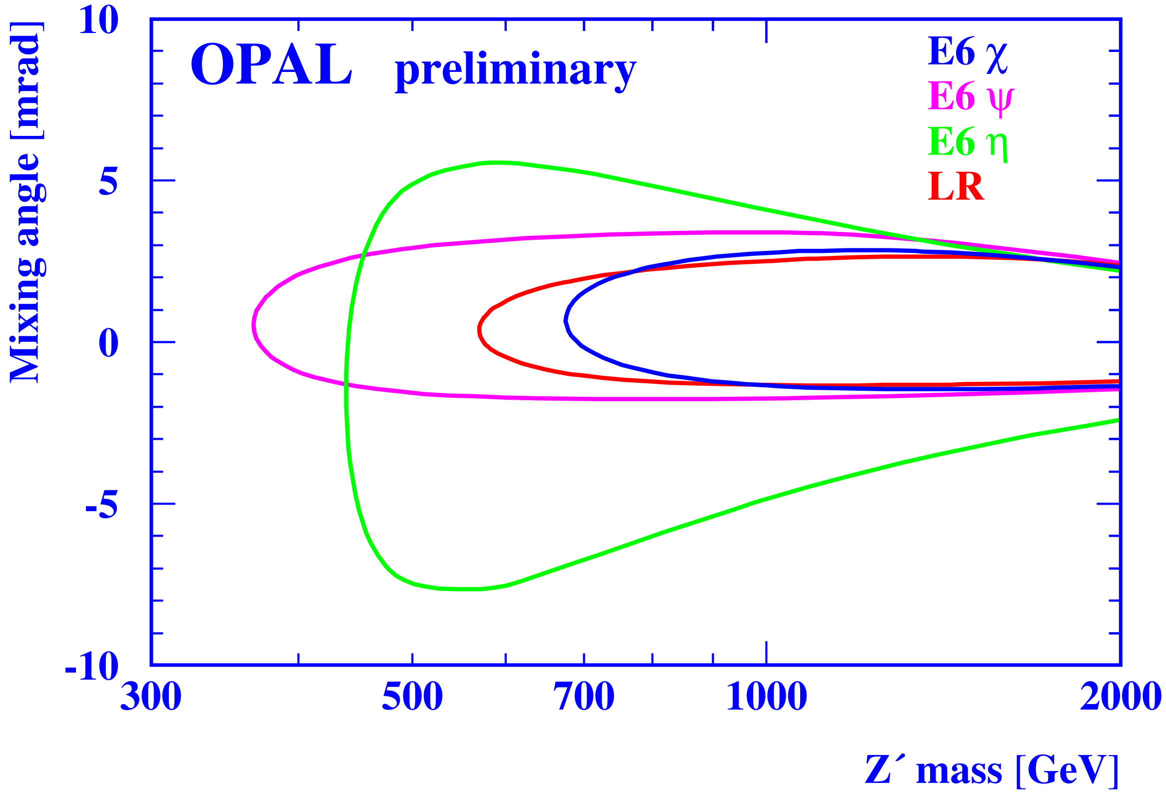
  Mass limits 830-900 GeV

General conclusion: New Physics is far beyond EW scale

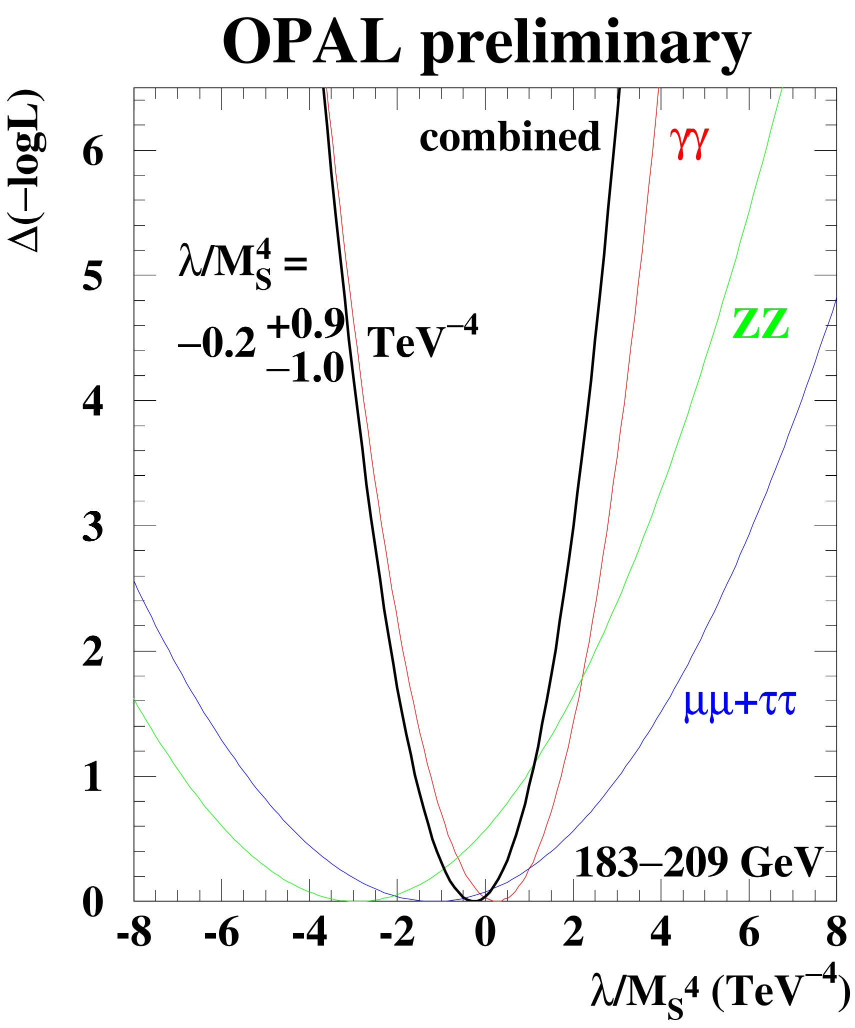
Contact Interactions



Limits on possible Z'



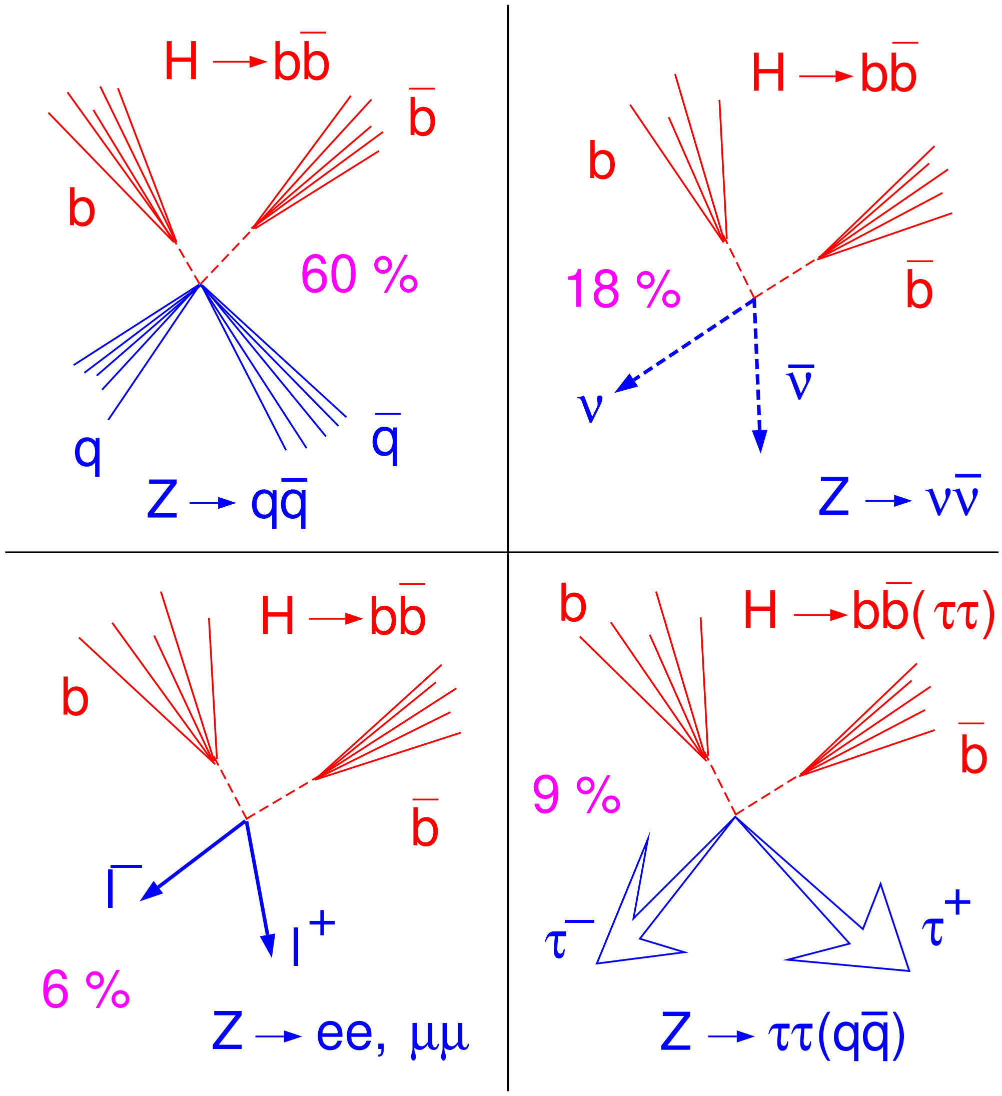
Gravity in Extra Dimensions



95% CL lower limit on M_S is

0.83 TeV with $\lambda = -1$ and 0.90 TeV with $\lambda = +1$

Standard Model Higgs Decays



4-jet channel, data=18, bkgd=19.1+-2.4

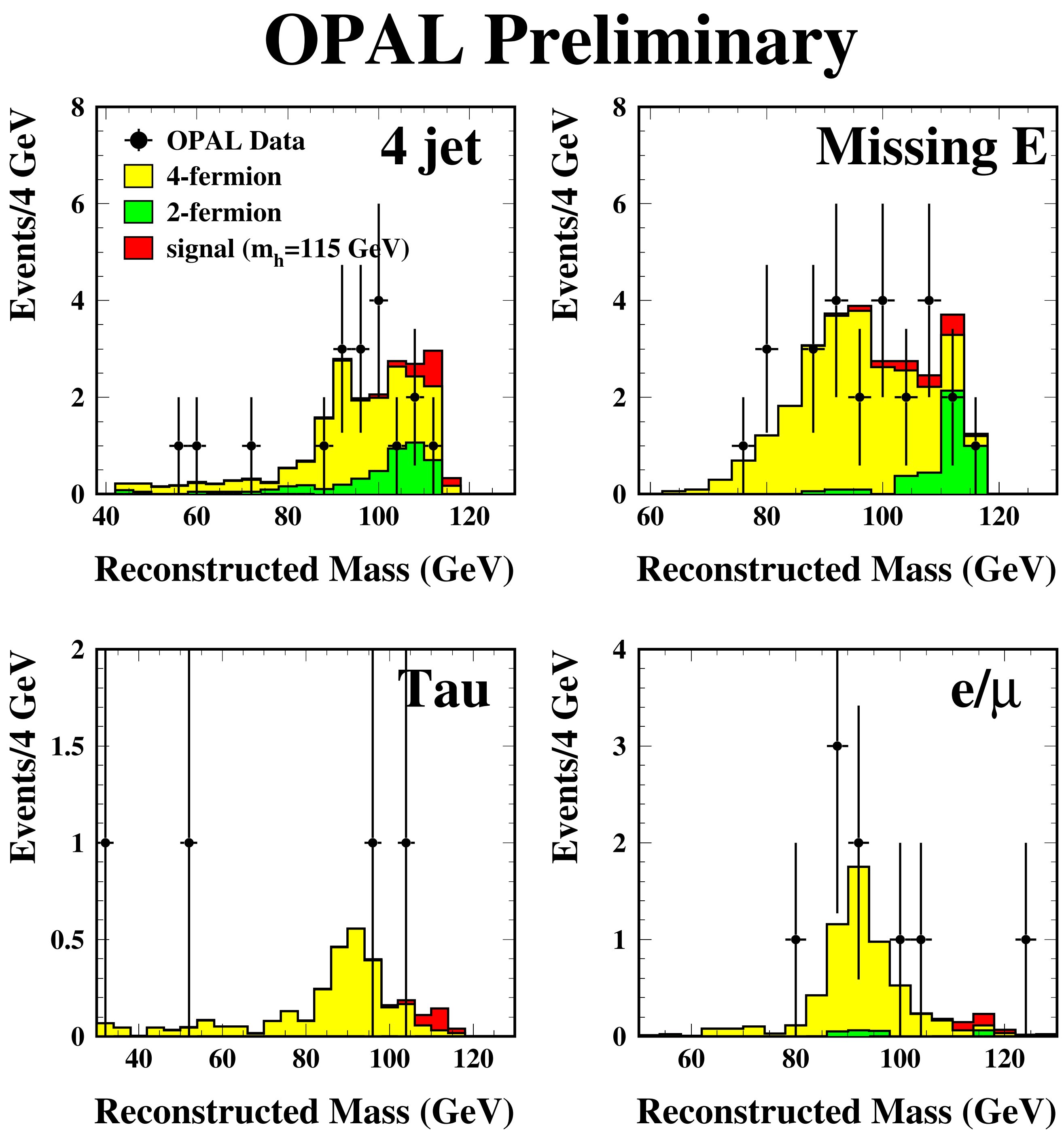
Missing E ch, data=26, bkgd=28.1+-2.9

Tau channel, data=4, bkgd=2.7+-0.4

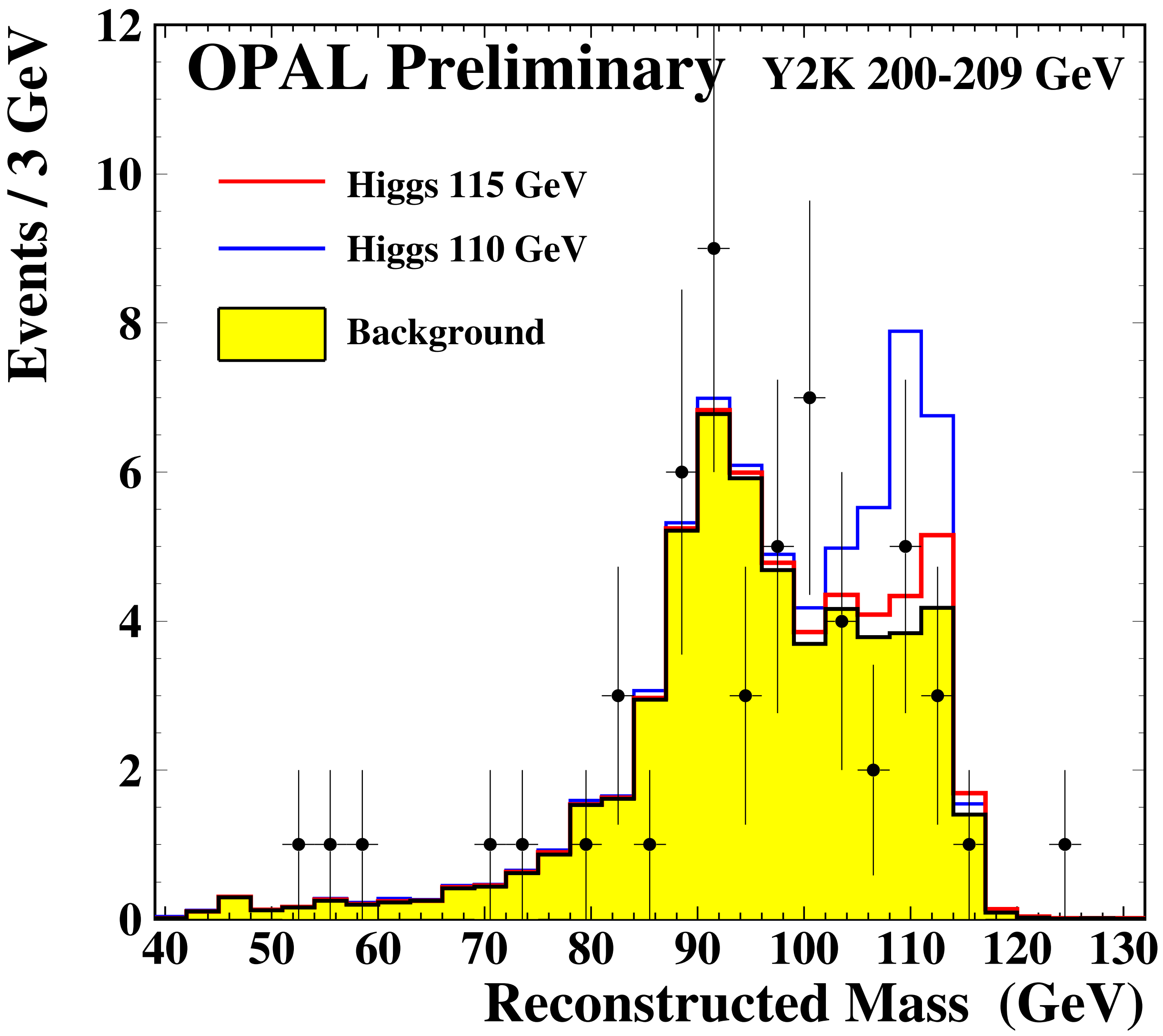
e/mu channel, data=9, bkgd=5.9+-1.0

TOTAL, data=57, bkgd=55.7+-5.8

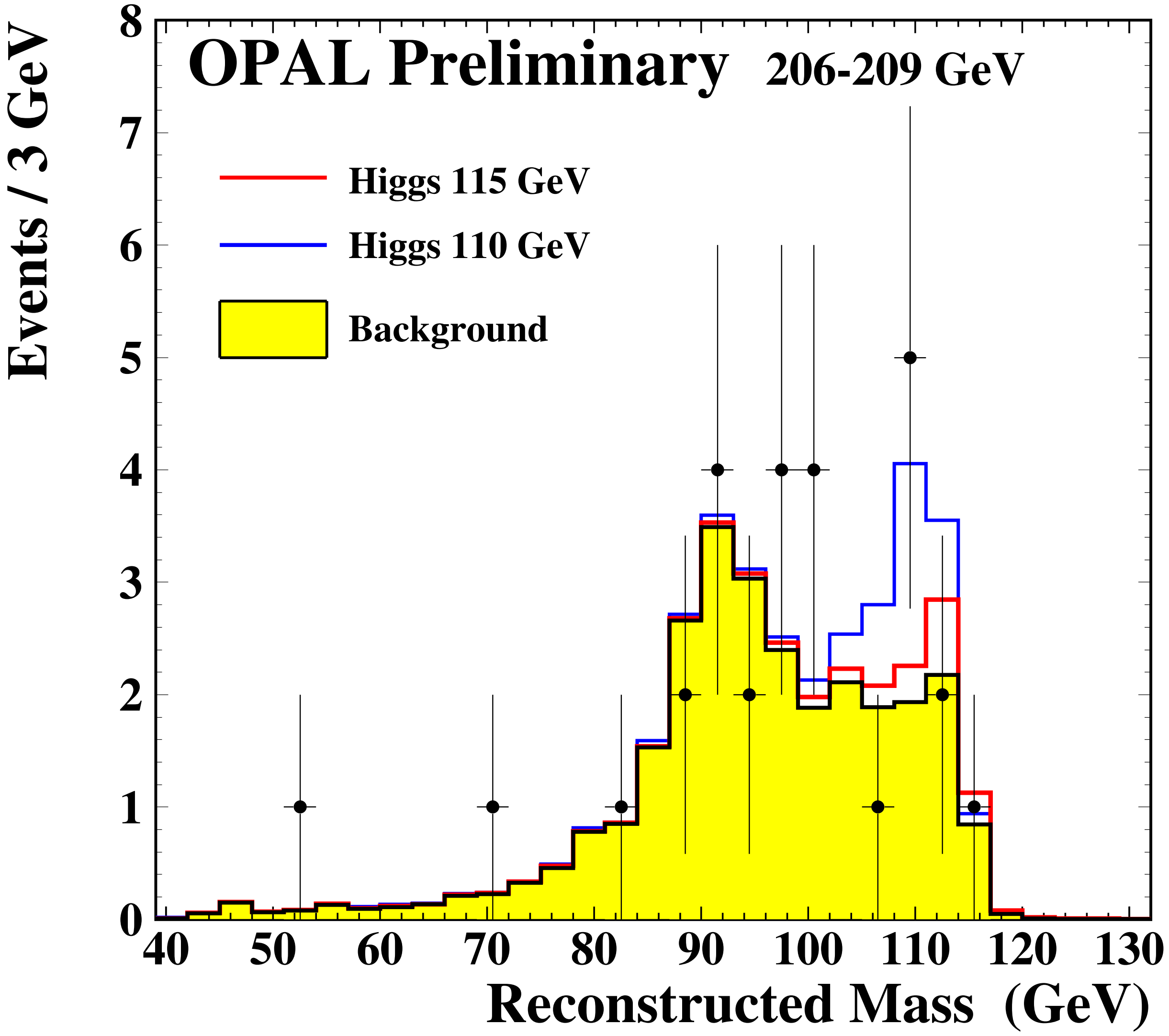
Higgs: Individual Channel Mass Distributions



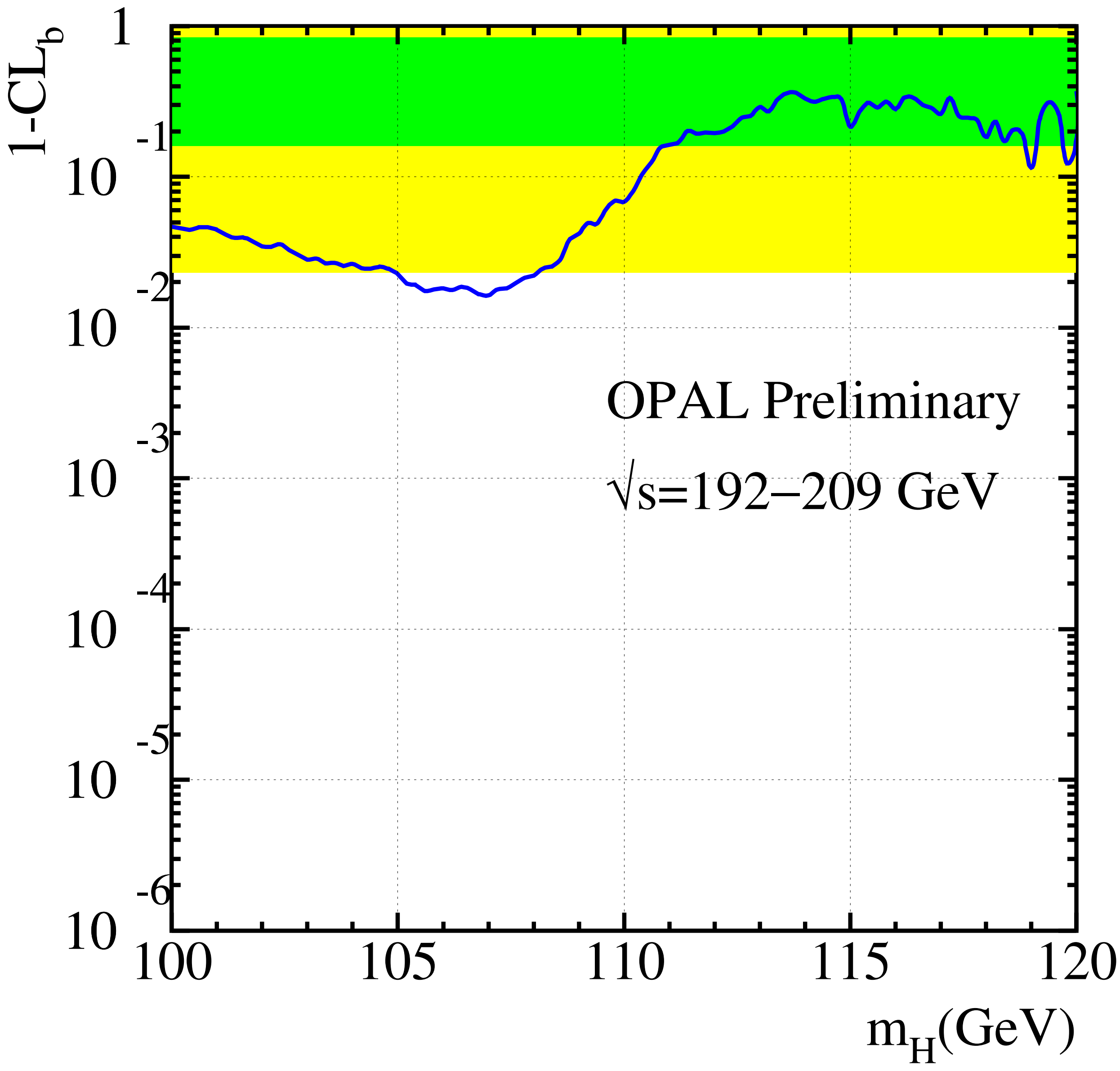
Higgs: Mass Distribution, all Y2K data



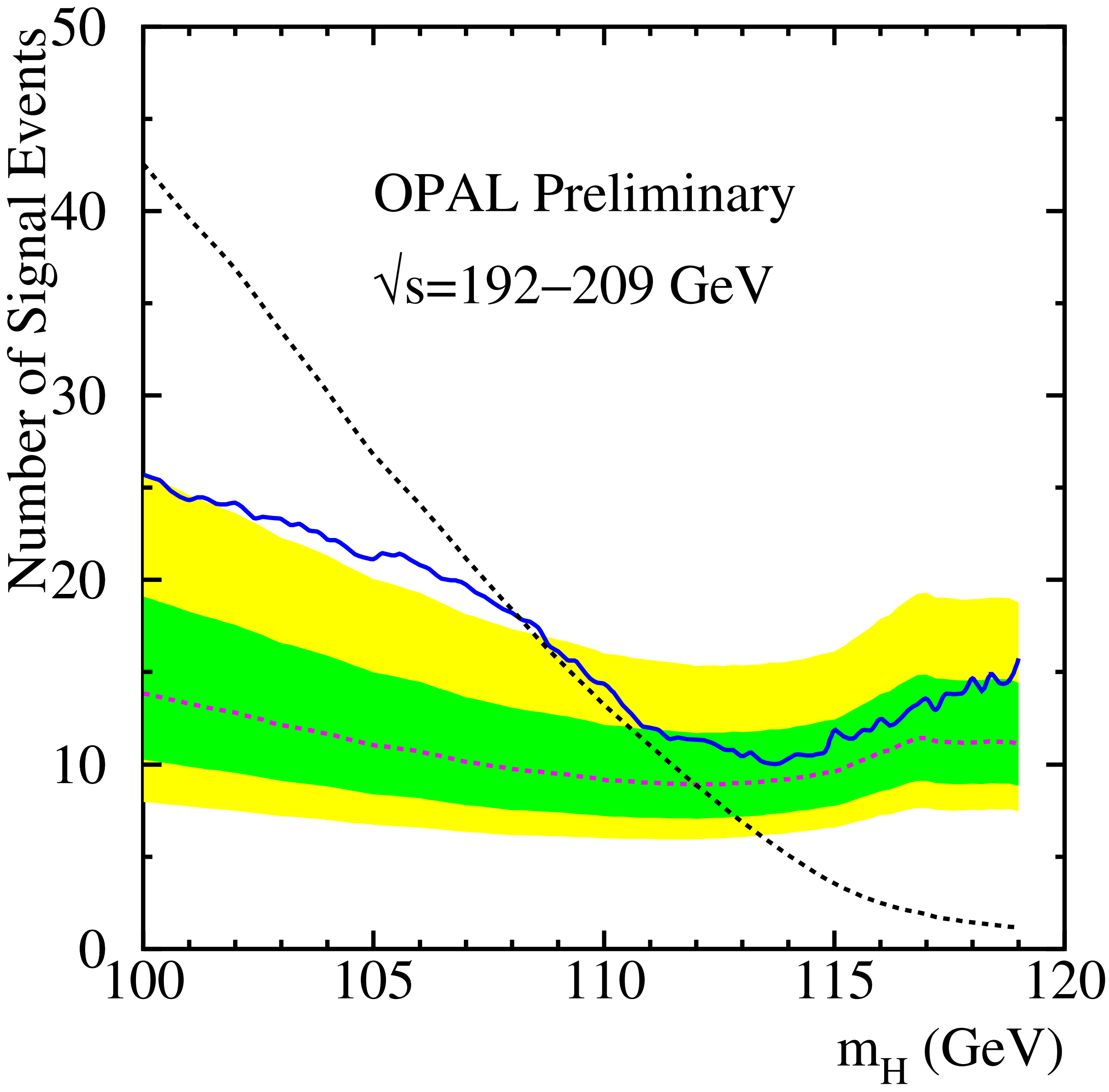
Higgs: Mass Distribution, only 207 GeV data



Higgs: 1-CL_b: background-only hypothesis



SM Higgs Mass .. 95% CL lower limit



$m_H > 107.9$ GeV at 95% CL

More Higgs Searches

- SUSY Higgs
  - $e^+e^- \to h^0Z^0$: as HZ search
  - $e^+e^- \to A^0h^0 \to b\bar{b}b\bar{b}$: Data=7, Bkgd=8.4+-1.3
  - $e^+e^- \to A^0h^0 \to \tau^+\tau^-b\bar{b}$: Data=5, Bkgd=3.4+-0.5

  For tan$(\beta) > 1.2$, determine $m_h > 80.7$ GeV, $m_A > 83.2$ GeV.

  - $e^+e^- \to H^+H^- \to \tau^+\nu_\tau q\bar{q}'$: Data=160, Bkgd=168
  - $e^+e^- \to H^+H^- \to q\bar{q}'q\bar{q}'$: Data=279, Bkgd=302

  $m_{H^\pm} > 72.3$ GeV assuming Br$(\tau\nu + q\bar{q}) = 1$

- Special Higgs Decays
  - Invisible h^0, eg.$\to \tilde{\chi}_1^0\tilde{\chi}_1^0$: Data=35, Bkgd=53

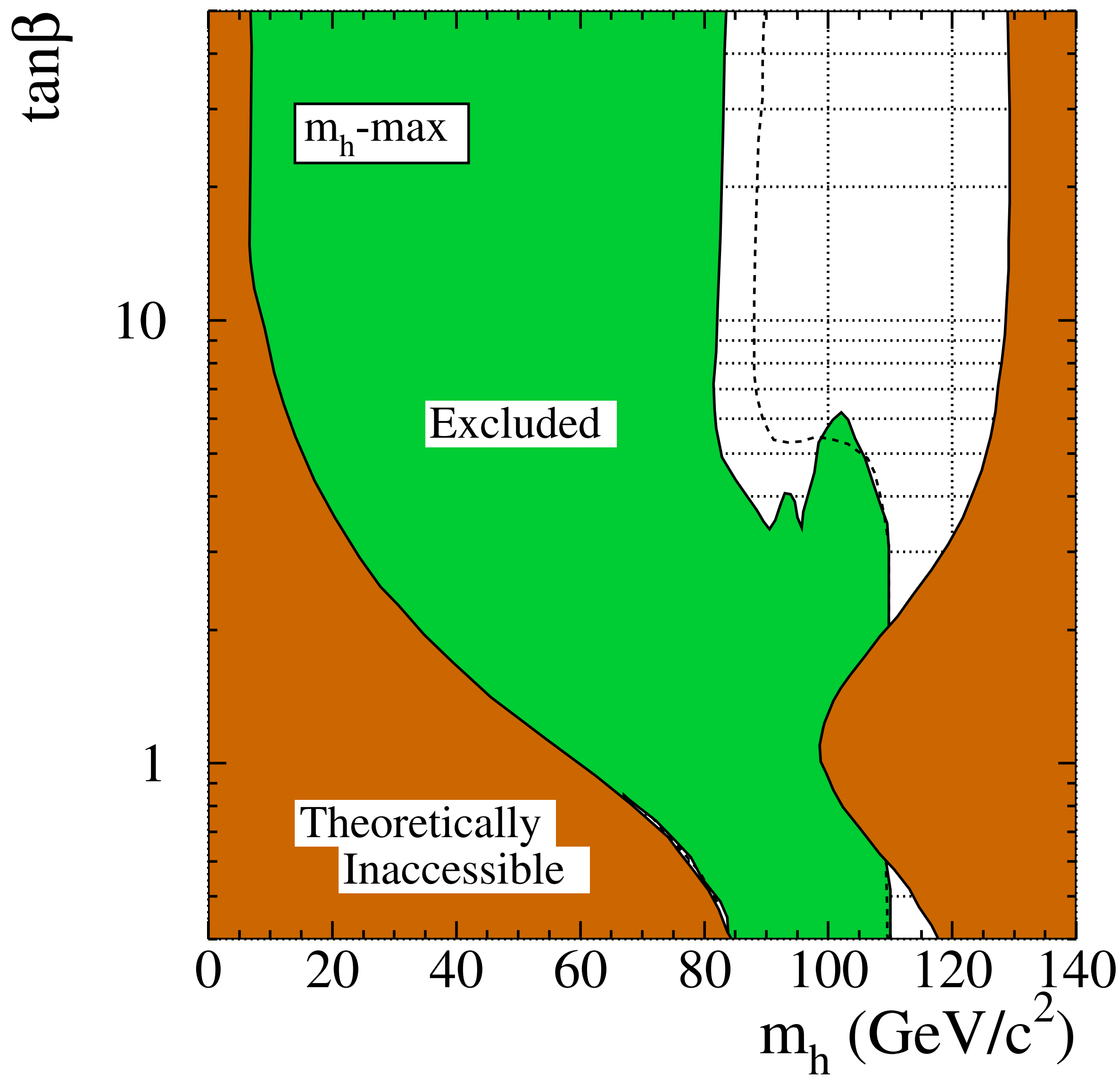
  $m_{h^0} > 107.2$ GeV assuming SM prod rate

  - Fermiophobic $h^0 \to \gamma\gamma$: Data=16, Bkgd=19

  $m_{h^0} > 104.6$ GeV assuming SM prod rate

Limits in CMSSM parameter space

m_h-max: A specific benchmark MSSM scan which provides the most conservative range of excluded tan(β) values.



Exclusion: tan(β) region 0.8-2.0

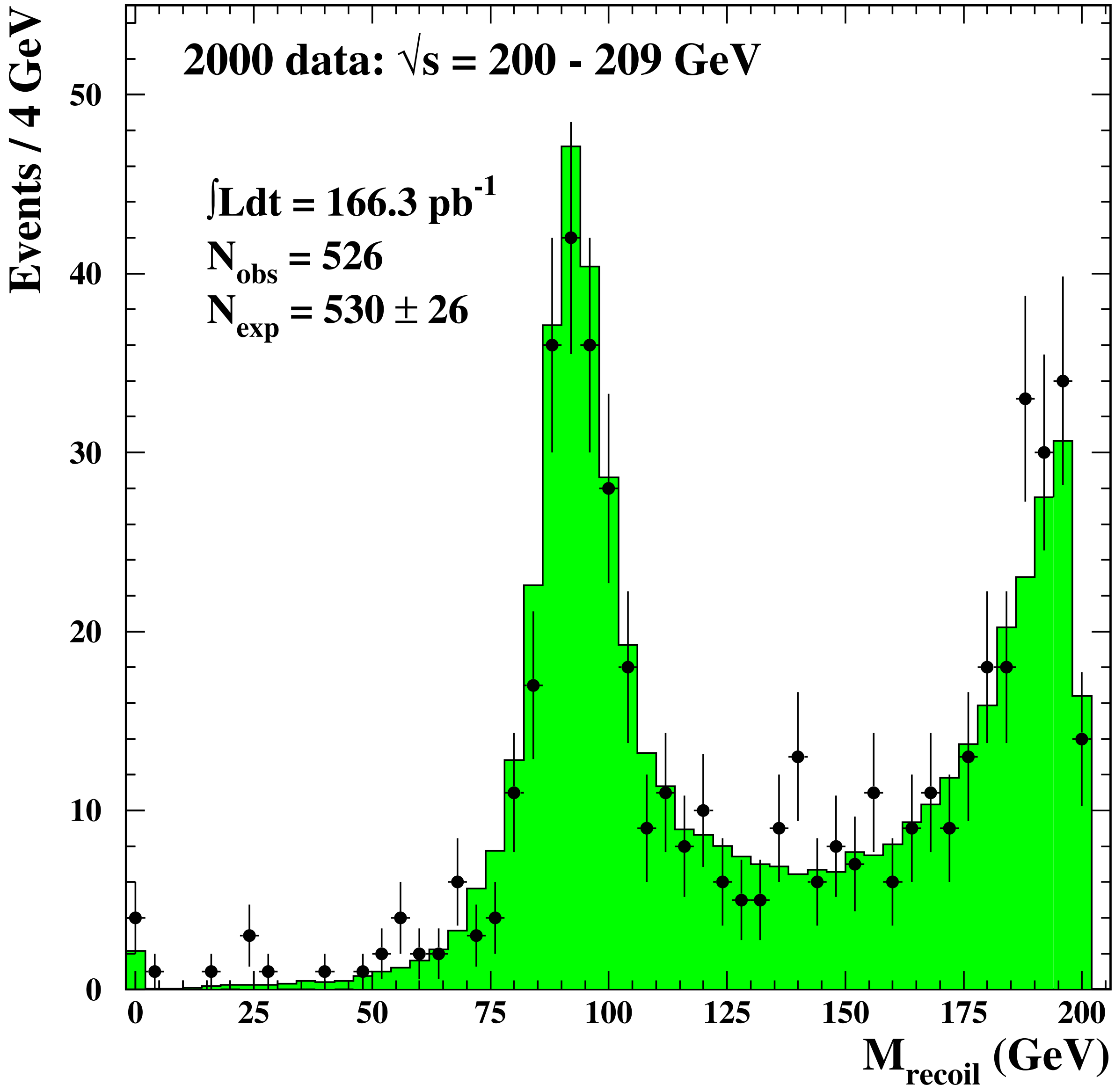
Search Channel List

$e^+e^- \to hZ$	$h \to b\bar{b}$	$b\bar{b}q\bar{q}$, $b\bar{b}\nu\bar{\nu}$, $b\bar{b}\ell^+\ell^-$
	$h \to \gamma\gamma$	$(q\bar{q}, \ell^+\ell^-, \nu\bar{\nu})+\gamma\gamma$
	$h \to \tilde{\chi}^0\tilde{\chi}^0$	$q\bar{q}, \ell^+\ell^- + \not{E}$
$e^+e^- \to hA$	$h, A \to b\bar{b}, \tau\tau$	$b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$
	$h \to AA$	$b\bar{b}b\bar{b}b\bar{b}$
$e^+e^- \to H^+H^-$	$H^+ \to q\bar{q}, \tau\nu$	$q\bar{q}q\bar{q}, q\bar{q}\tau\nu, \tau\nu\tau\nu$
$e^+e^- \to \tilde{\chi}^+\tilde{\chi}^-$	$\tilde{\chi}^- \to W^*\tilde{\chi}^0$	jets $(+\ell^\pm)$, $\ell^+\ell^- + \not{E}$
	(In)Direct RPV	jets, $\ell^\pm$, ν
	$(\tilde{\chi}^0 \to \gamma\tilde{G})$	jets, $\ell^+\ell^-$, $\gamma\gamma + \not{E}$
$e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_1$	$\tilde{\chi}^0_2 \to Z^0\tilde{\chi}^0_1$	2 jets $+ \not{E}$
	$\tilde{\chi}^0_2 \to \gamma\tilde{\chi}^0_1$	$\gamma + \not{E}$
$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$	$\tilde{\chi}^0_1 \to \gamma\tilde{G}$	$\gamma\gamma + \not{E}$
	$\tilde{\chi}^0_1$ Lifetime	non-pointing γ
	RPV Decays	jets, $\ell^\pm$, ν
$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$	$\tilde{\ell}^- \to \ell^-\tilde{\chi}^0_1$	$\ell^+\ell^- + \not{E}$
	$(\tilde{\chi}^0 \to \gamma\tilde{G})$	$\ell^+\ell^-\gamma\gamma + \not{E}$
	(In)Direct RPV	2,4,6$\times\ell^\pm + \not{E}$
	$\tilde{\ell}^\pm$ Lifetime	Kinked Tracks
		Stable, Charged
$e^+e^- \to \tilde{\nu}\tilde{\nu}$	(In)Direct RPV	$\ell^+\ell^-\ell^+\ell^-$
		jets $+ \not{E}$
$e^+e^- \to \tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}^0_1$	2 jets $+ \not{E}$
	$\tilde{t}_1 \to b\ell^+\tilde{\nu}$	2 jets $+ \ell^+\ell^- + \not{E}$
	(In)Direct RPV	$\ell^+q\ell^-q$
$e^+e^- \to N\bar{N}$	$N \to \ell W$	jets $+\ell^\pm$
$e^+e^- \to L^+L^-$	$L^+ \to \nu W$	jets, $\ell^\pm + \not{E}$
$e^+e^- \to \ell^{*+}\ell^{(*)-}$	$\ell^{*+} \to \ell^+\gamma$	$\ell^+\ell^-\gamma(\gamma)$
$e^+e^- \to \nu^*\bar{\nu}^*$	$\nu^* \to \nu\gamma$	$\gamma(\gamma) + \not{E}$
$e^+e^- \to \ell^*\ell, \nu^*\nu$	$\ell^* \to \ell Z$	jets, $\ell^\pm$, ν

Single Photon Recoil Mass

Sensitive to Gravity in Extra Dimensions, GMSB scenarios, eg. $\tilde{\chi}^0_1 \rightarrow \gamma\tilde{\mathrm{G}}$, and MSSM $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1\gamma$, and excited neutrinos, eg. $\nu^* \rightarrow \nu\gamma$.

Standard Model process is $\mathrm{e^+e^-} \rightarrow \nu\bar{\nu}\gamma(\gamma)$.



Non-SM Physics ...direct searches

In general a null search provides limits on cross-sections, couplings, masses, ...

- Leptoquarks
  $e^+e^- \rightarrow L_q\overline{L_q}, L_q \rightarrow lq$ Data=54, Bkgd=55
- Heavy Leptons
  $e^+e^- \rightarrow N\overline{N}, N \rightarrow lW$ Data=63, Bkgd=51
- Excited Leptons
  $e^+e^- \rightarrow l^{*+}l^{*-}, l^* \rightarrow l\gamma$ Data=6, Bkgd=4
  $e^+e^- \rightarrow l^{*+}l^-, l^* \rightarrow l\gamma$ Data=642, Bkgd=691
- Stable, long-lived, massive particles
  Sensitive to $Q/e = \pm 1, \pm 2/3$ Data=0, Bkgd=1
- Single top via FCNC
  $e^+e^- \rightarrow t\overline{c}(\overline{u})$ Data=21, Bkgd=23

$$M(l^*) > 103\; GeV$$

$M(\tilde{\ell}) > 97\; GeV, M(\tilde{\chi}^{\pm}) > 101\; GeV$, for long-lived

$\sigma_{top} < 0.36$ pb, assuming Br$(t \rightarrow bW) = 1$

Non-SM Physics ...direct SUSY searches

MSSM searches of two types are conducted

(A) MSUGRA, with/without RPC, where LSP = $\tilde{\chi}^0_1$ (stable),

which leads to topologies with jets, leptons, AND Missing Energy

(B) GMSB, where LSP = $\tilde{\mathrm{G}}$ [$\tilde{\chi}^0_1 \rightarrow \gamma\tilde{\mathrm{G}}, \tilde{\ell} \rightarrow l\tilde{\mathrm{G}}$], which give

MORE leptons and photons

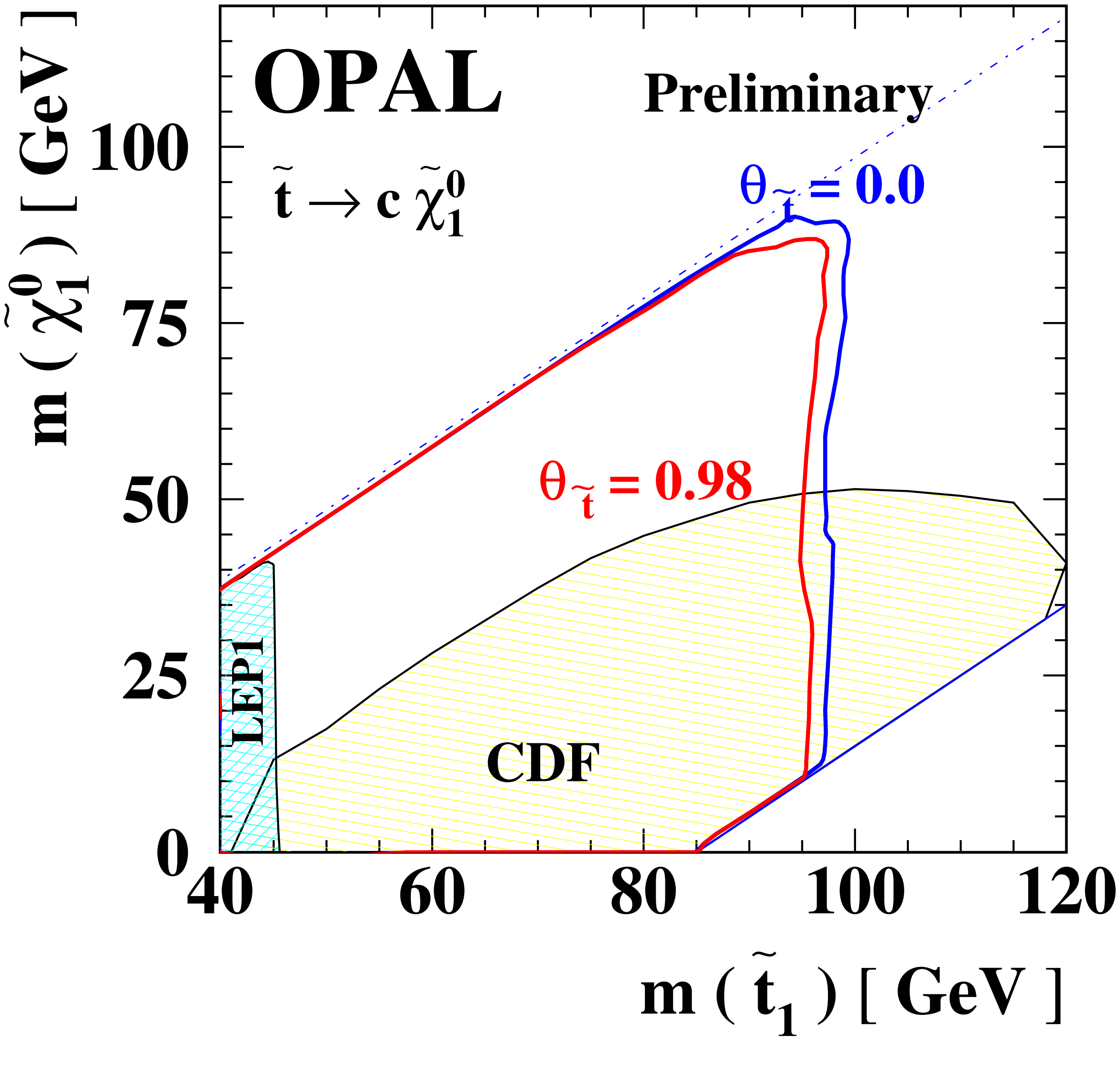
- Scalar Leptons
  $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-, \tilde{\ell} \rightarrow l\tilde{\chi}^0_1$
- Scalar top/bottom quarks
  $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\mathrm{t}}\bar{\tilde{\mathrm{t}}}, \tilde{\mathrm{t}} \rightarrow c\tilde{\chi}^0_1, b\tilde{\chi}^{\pm}$
  $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\mathrm{b}}\bar{\tilde{\mathrm{b}}}, \tilde{\mathrm{b}} \rightarrow b\tilde{\chi}^0_1$
- Charginos
  $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\chi}^{\pm}\tilde{\chi}^{\mp}, \tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^0_1 W^{\pm}$
- Neutralinos
  $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_1, \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 Z^0$

No compelling evidence for data in excess of SM bkgd

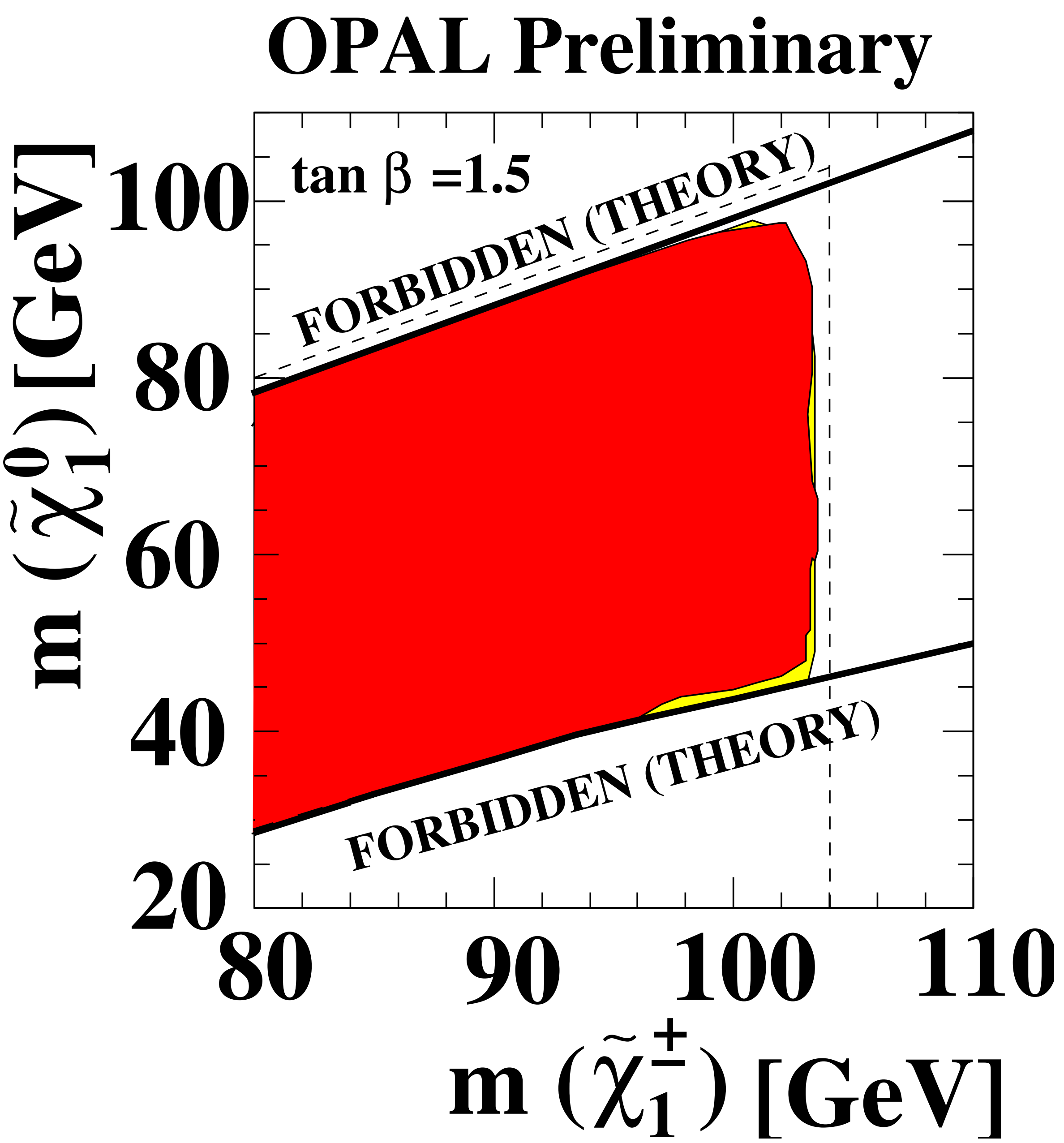
Cross-section limits are determined

Calculate exclusion regions in MSSM parameter space

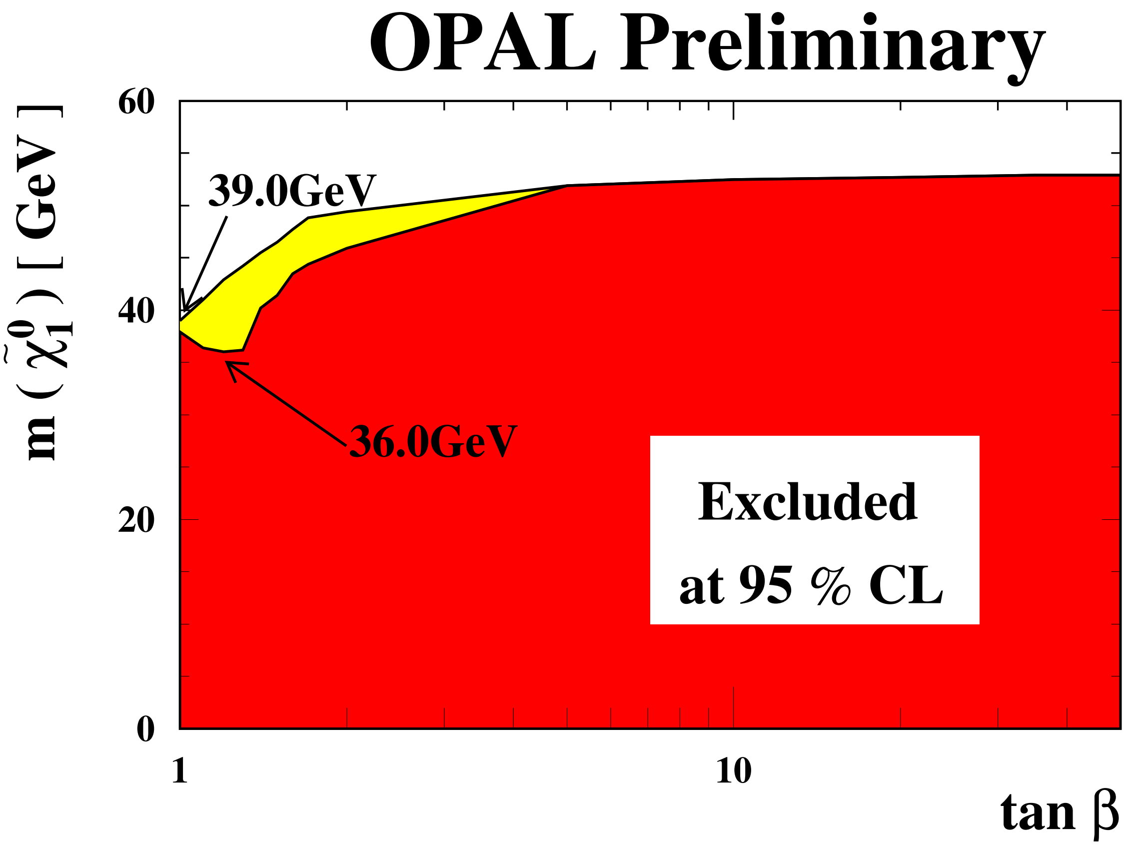
MSSM exclusion limit for stop



MSSM exclusion limit for gauginos



MSSM exclusion limit for neutralino



Absolute lower limit on lightest neutralino

$m_{\tilde{\chi}^0_1} > 39.0$ GeV for $m_0 > 500$ GeV

$m_{\tilde{\chi}^0_1} > 36.0$ GeV for any m_0

Summary

- OPAL data taking in 2000 very successful
  $\int \mathcal{L}\mathrm{d}t$ almost 200 pb^{-1}
- Many ongoing physics analyses, both LEP1 and LEP2
- All results from LEP data in good agreement with SM predictions.
- We look forward to several years of continuing physics analysis and
  .....perhaps, in some forgotten corner, unexpected new physics