Physics highlights from OPAL

Marco Verzocchi
CERN/EP
for the OPAL Collaboration

27 February 2001
LEP Physics Jamboree

- Recent LEP1 results
- Standard Model measurements @ LEP2
- Searches for the Higgs boson(s)
- Searches for physics beyond the $\mathcal{SM}$

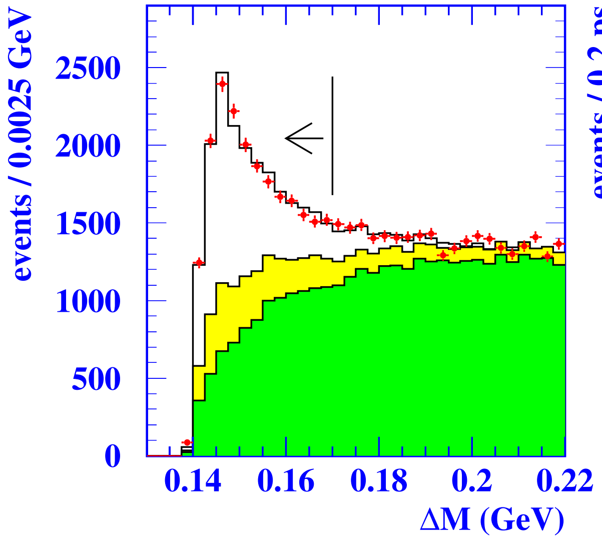
From 1/1/2000:

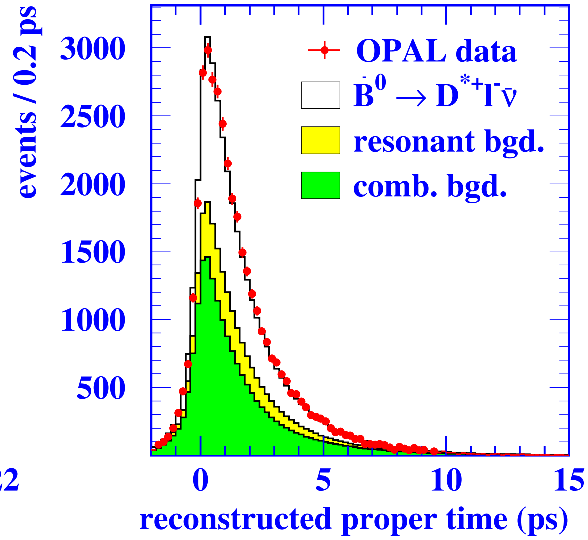
- ✔ 27 articles submitted to journals
- ✔ 15 finished Ph.D. theses
- ✔ still $\approx$50 active Ph.D. students

OPAL is still a lively collaboration

Heavy flavour physics (LEP 1)

$B^0_d \rightarrow D^{*+}\ell\overline{\nu}_\ell$ decays,
tag π_S^+ from $D^{*+} \rightarrow D^0\pi_S^+$,
inclusive reconstruction of D^0 decays.





Initial flavour tag through Q_{jet}, Q_{vtx} and $\ell^\pm$

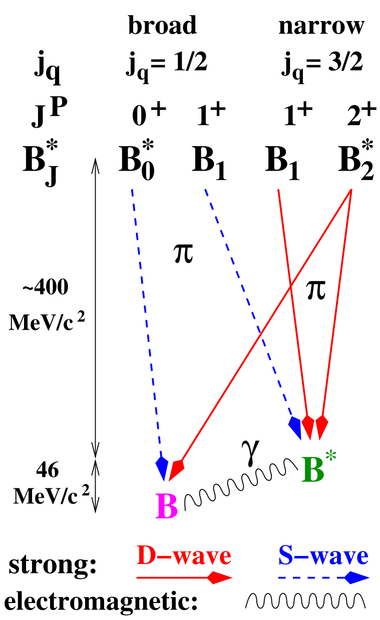
$$\tau_{B^0_d} = (1.541 \pm 0.028 \pm 0.023)\mathrm{ps}$$
$$\Delta m_d = (0.497 \pm 0.024 \pm 0.025)\mathrm{ps}^{-1}$$

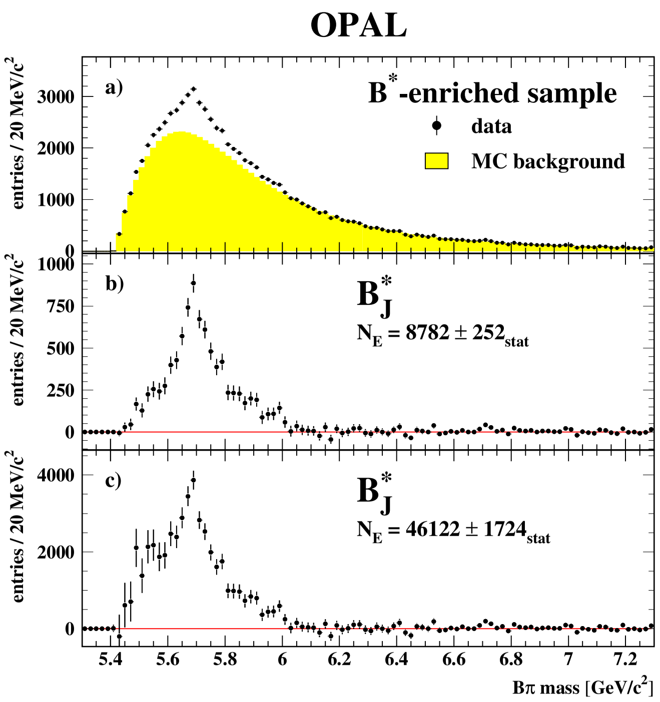
Most precise measurements of $\tau_{B^0_d}$ and Δm_d

Other recent results:

- $g_{b\overline{b}} = (3.07 \pm 0.53 \pm 0.97) \times 10^{-3}$
- $BR(D_s^- \rightarrow \tau^-\overline{\nu}_\tau) = (7.0 \pm 2.1 \pm 2.0)\%$
  - ➥ $f_{D_s} = (286 \pm 44 \pm 41)\,\mathrm{MeV}$ (PRELIMINARY)

First measurement of $\mathrm{BR}(\mathrm{B}_J^* \to \mathrm{B}^*\pi(X))$





N.B. In PDG notation: $\mathrm{B}_J^* = \mathrm{B}^{**}$

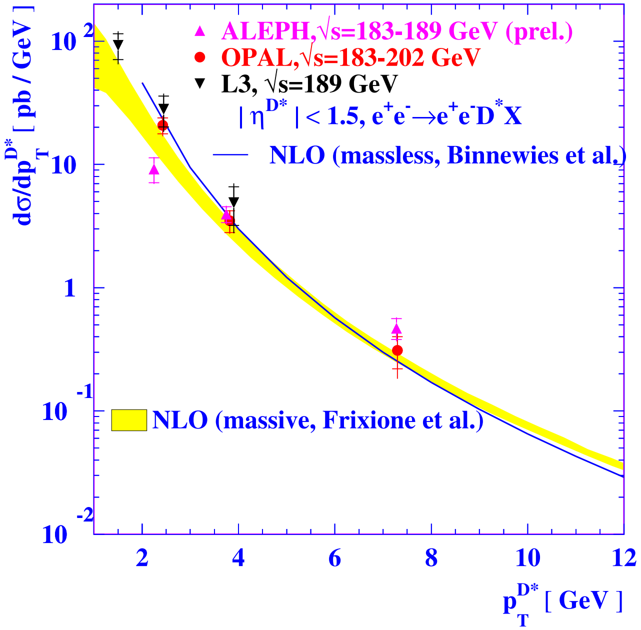
- B^* enriched and depleted mass spectra
- reconstruction ε depends on $\mathrm{M}_{\mathrm{B}\pi}$
- ➥ $\mathrm{BR}(\mathrm{B}_J^* \to \mathrm{B}^*\pi(X)) = 0.85^{+0.26}_{-0.27} \pm 0.12$
- HQET used to fit mass spectra

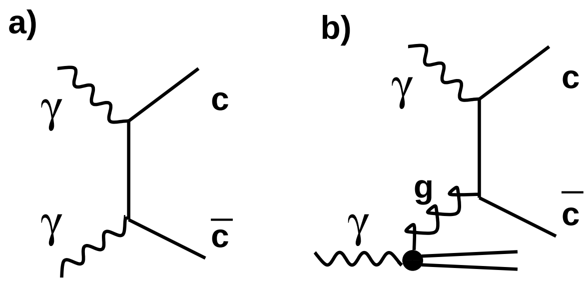
No evidence for $\mathrm{D}^{*\prime\pm}(2369)$

- $f(\mathrm{Z} \to \mathrm{D}^{*\prime\pm}) \times \mathrm{BR}(\mathrm{D}^{*\prime\pm} \to \mathrm{D}^{*\pm}\pi^+\pi^-) < 3.1 \times 10^{-3}$ (95% C.L.)
- ➥ 3.5σ significance for DELPHI signal

$\gamma\gamma$ physics: heavy quark production

Measured $c\bar{c}$ and $b\bar{b}$ production cross sections in untagged $\gamma\gamma$ collisions (183–202 GeV)





Fit $x_T^{D^*}$ and x_γ distributions

➠ extract resolved component

$(54 \pm 10)\%$ due to resolved component

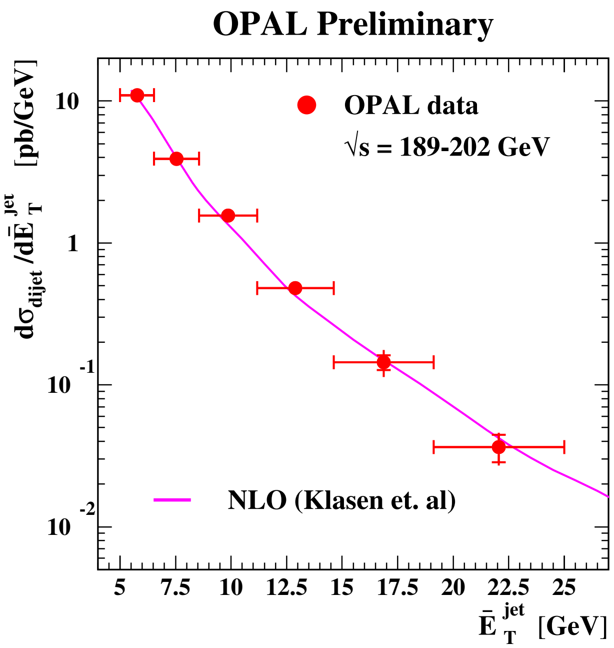
$$\sigma(e^+e^- \to e^+e^- D^{*\pm}X) = 30.7 \pm 2.8 \pm 3.3 \text{ pb}$$

2 GeV $< p_T^{D^*} <$ 12 GeV and $|\eta^{D^*}| < 1.5$

(PRELIMINARY)

$\gamma\gamma$ physics: jets and F_2^γ

$\gamma\gamma \rightarrow jets$

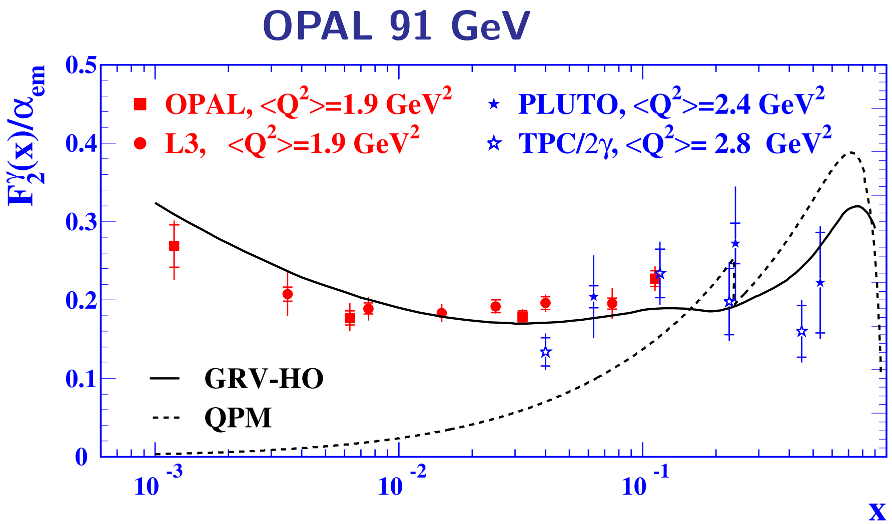


resolved .... direct

NLO predictions tested over 3 orders of magnitude

Study g content of γ

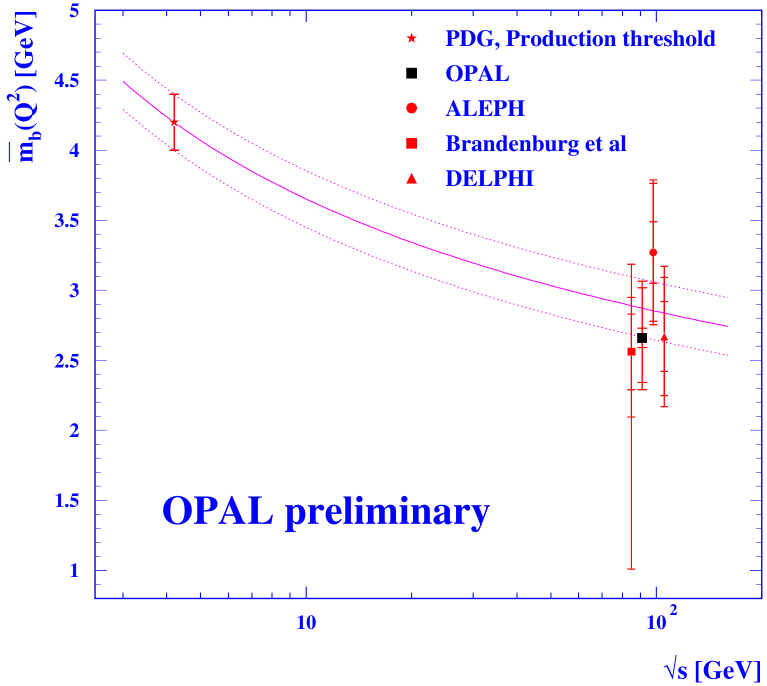
Extended range for F_2^γ measurements at both low x and high Q^2



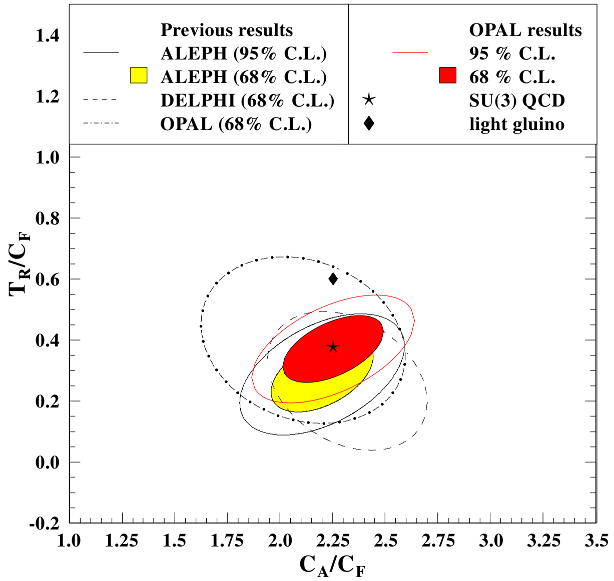
➥ See hint of rise of F_2^γ at lowest x values

QCD: $m_b(m_Z)$ and colour factors

Measure 3-jets rates
in b and $udsc$ events
Compare with $O(\alpha_S^2)$ QCD
predictions (massive quarks)



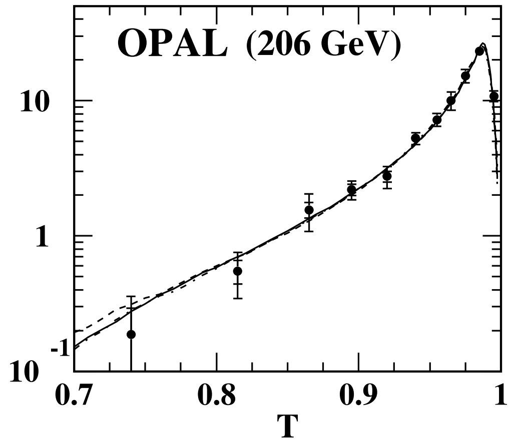
Use jet rates and 4-jets angular correlations. Simultaneous fit to α_S and QCD colour factors. Use NLO theoretical predictions

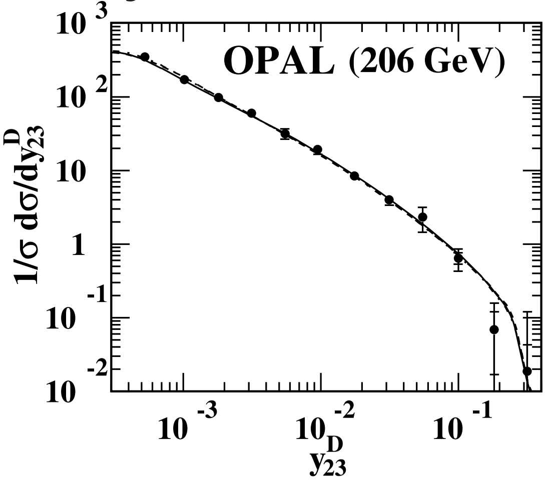


$$C_A = 3.02 \pm 0.25 \pm 0.49 \quad (C_A = 3)$$
$$C_F = 1.34 \pm 0.13 \pm 0.22 \quad (C_F = 4/3)$$

QCD: running of α_S

OPAL Preliminary



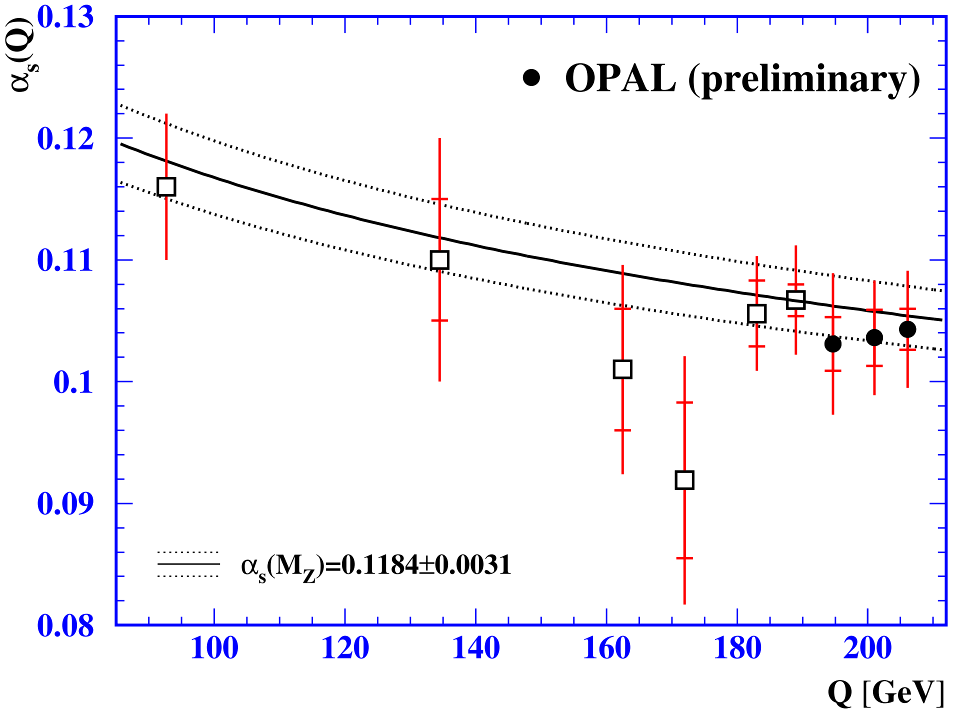


Fit to 6 event shapes variables

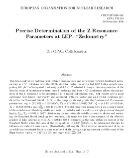
Use $O(\alpha_S^2)$ plus NLLA QCD calculations

$$\alpha_S(206\,\mathrm{GeV}) = 0.107 \pm 0.002 \pm 0.004$$

OPAL measurements of $\alpha_s(Q)$



Electroweak physics at LEP1



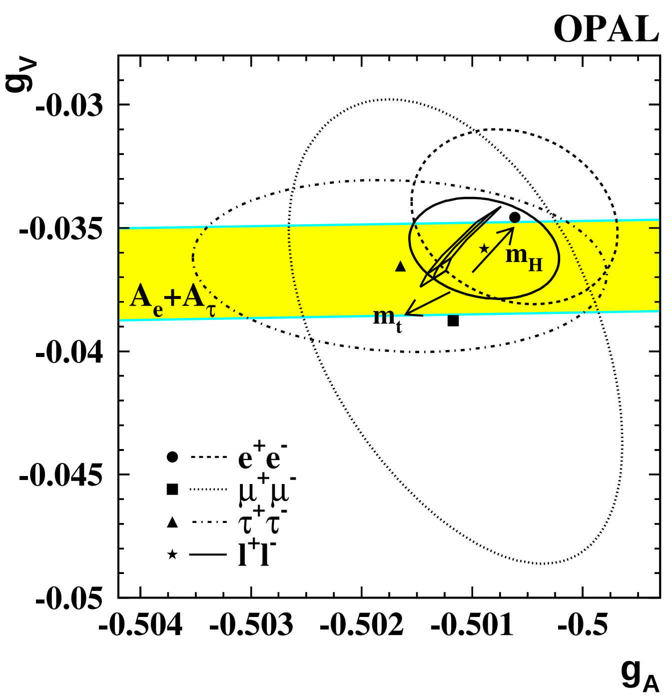
- Finalised lineshape paper

Precise Determination of the Z Resonance Parameters at LEP : Zedometry

$$m_Z = (91.852 \pm 0.0030)\ \mathrm{GeV}$$
$$\Gamma_Z = (2.4948 \pm 0.0041)\ \mathrm{GeV}$$
$$\sigma_h^0 = (41.501 \pm 0.055)\ \mathrm{nb}$$
$$R_\ell = 20.823 \pm 0.044$$
$$A_{FB}^{0,\ell} = 0.0145 \pm 0.0017$$

- Update τ polarisation measurement

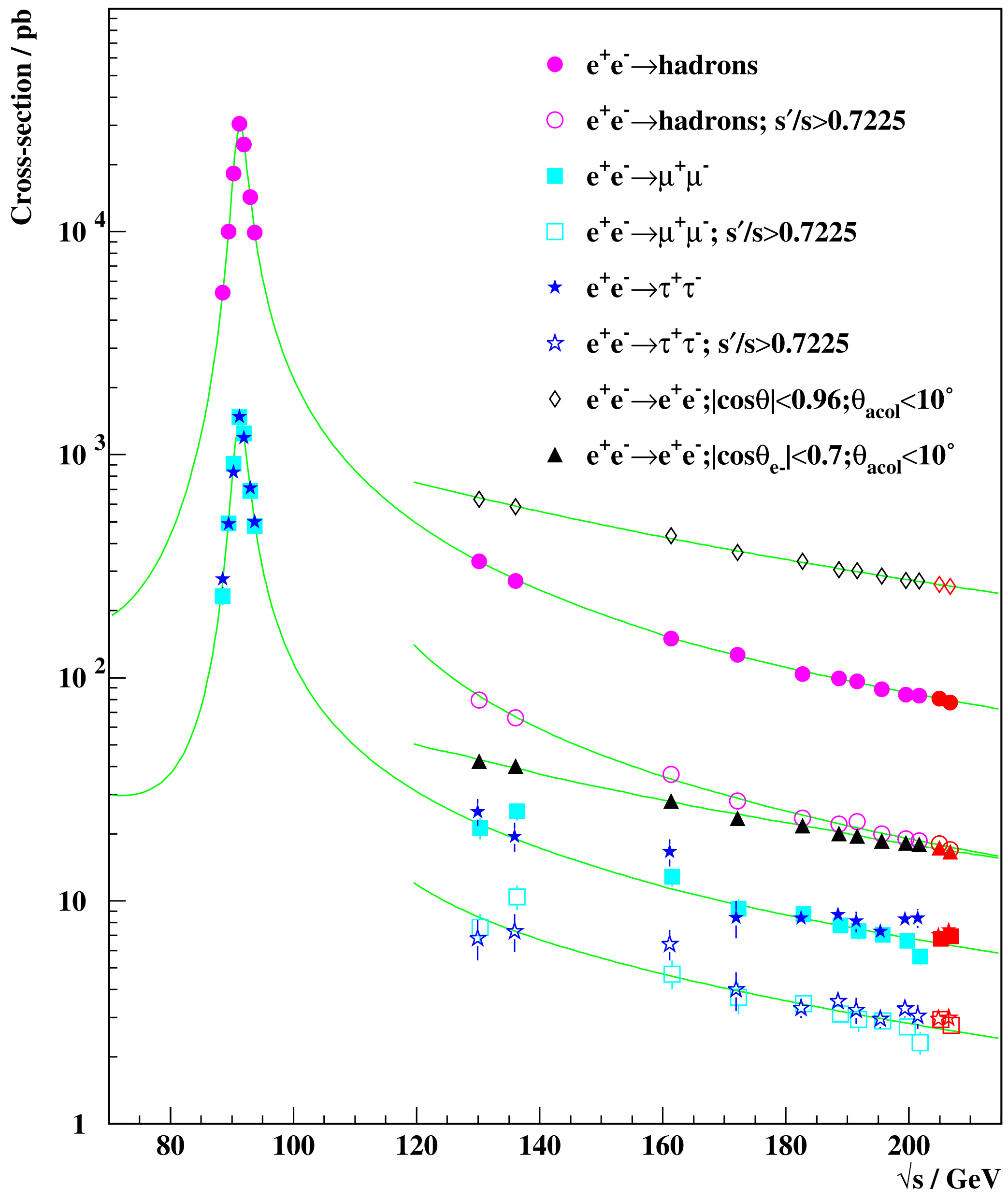
$$< P_\tau > = (-14.10 \pm 0.73 \pm 0.55)\%$$
$$A_{pol}^{FB} = (-10.55 \pm 0.76 \pm 0.25)\%$$



$\Rightarrow$ $$\sin^2\theta_{eff}^{lept} = 0.23211 \pm 0.00068$$

Electroweak physics at LEP2

OPAL preliminary

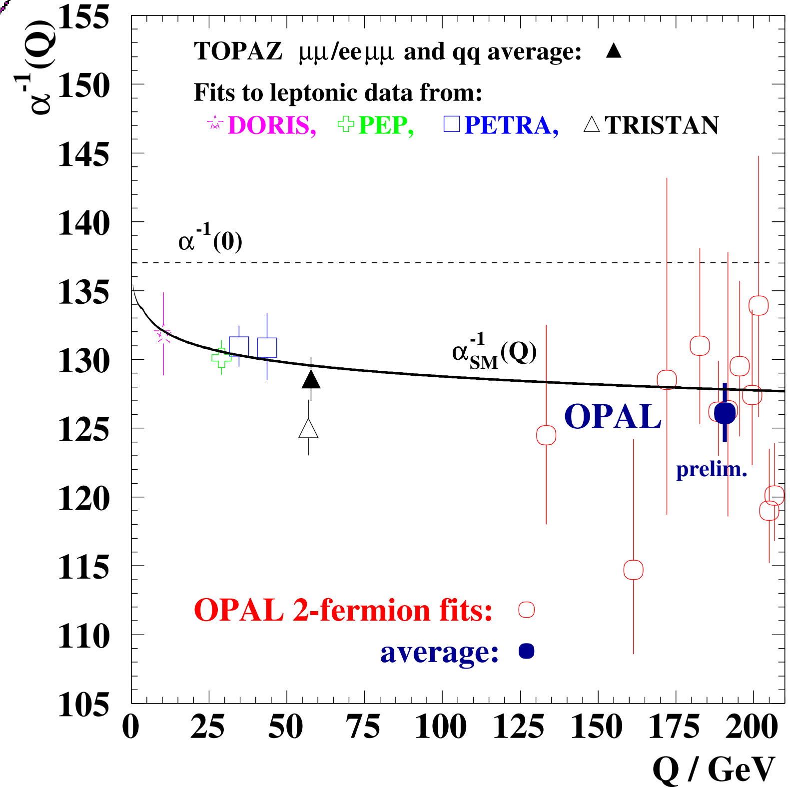


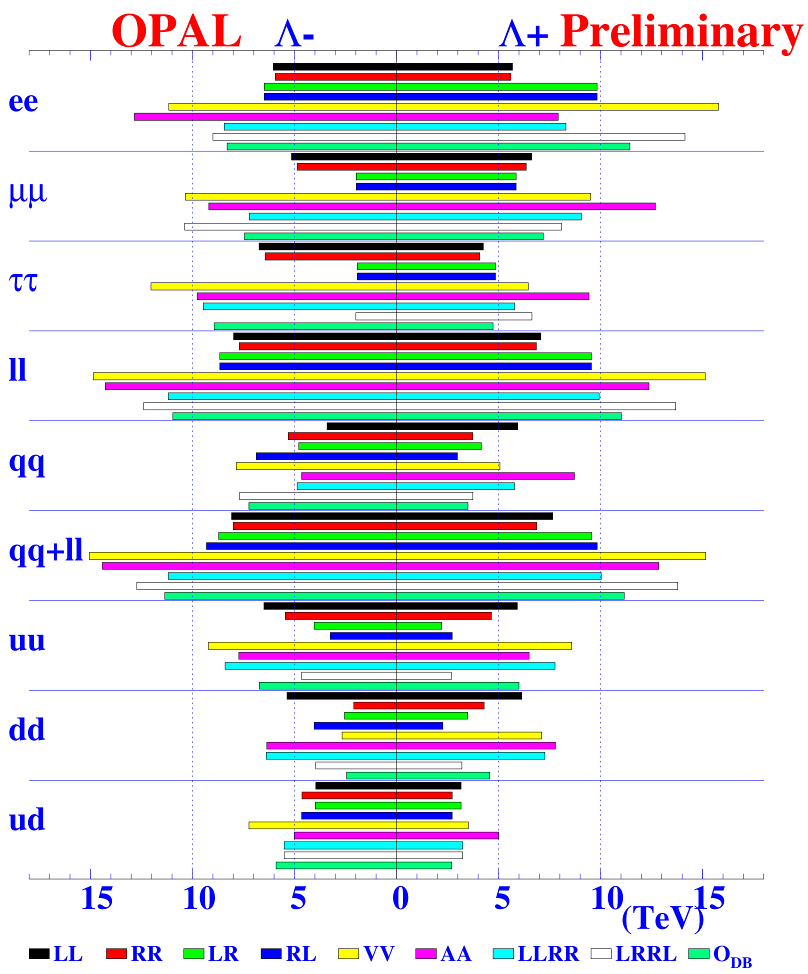
Cross sections and asymmetries in agreement with $\mathcal{SM}$ except

2.5σ excess for τ pairs at $\sqrt{s} \geq 200$ GeV

- Measure $\mathcal{SM}$ parameters
- Set constraints on new physics

Running of α_{em} and contact interactions



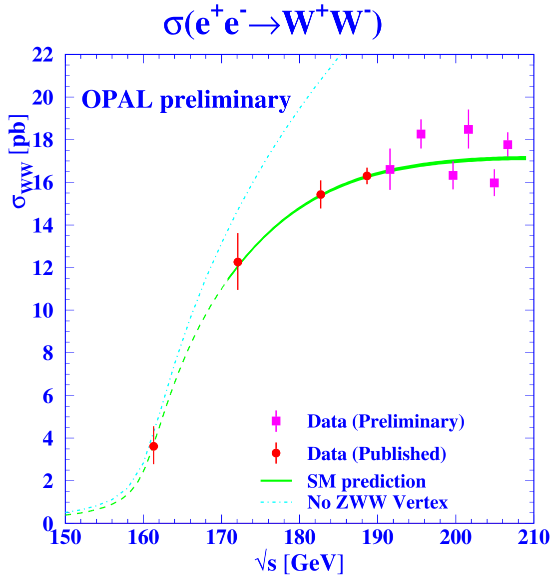


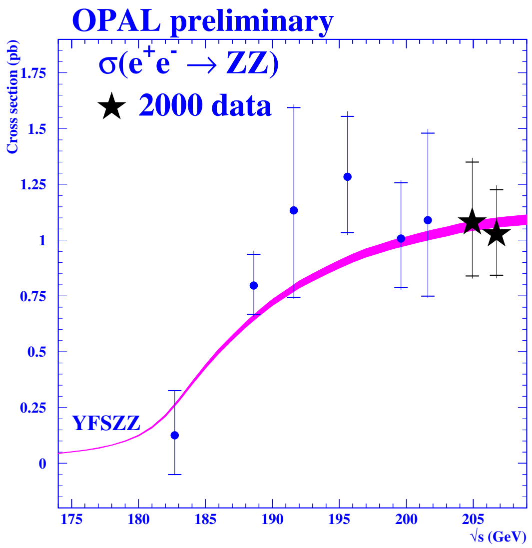
$$\alpha_{em}(191\ \mathrm{GeV}) = 126.1^{+2.2}_{-2.1}$$

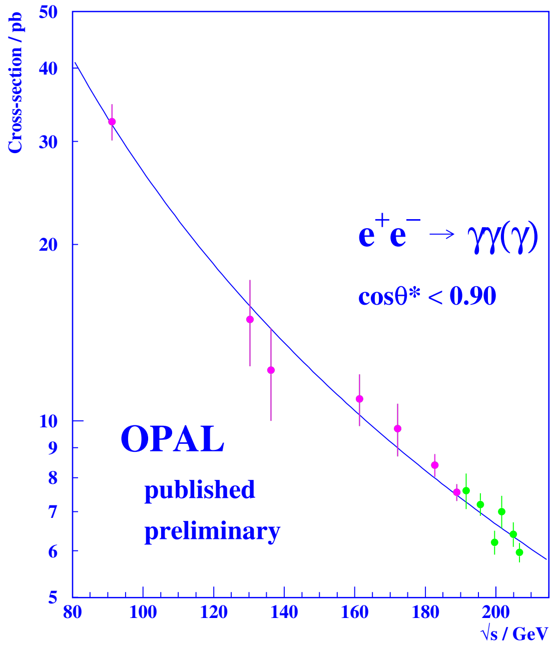
$$127.9 \quad (\mathcal{SM})$$

➥ 5σ difference from $\alpha_{em}(0)$

Diboson production



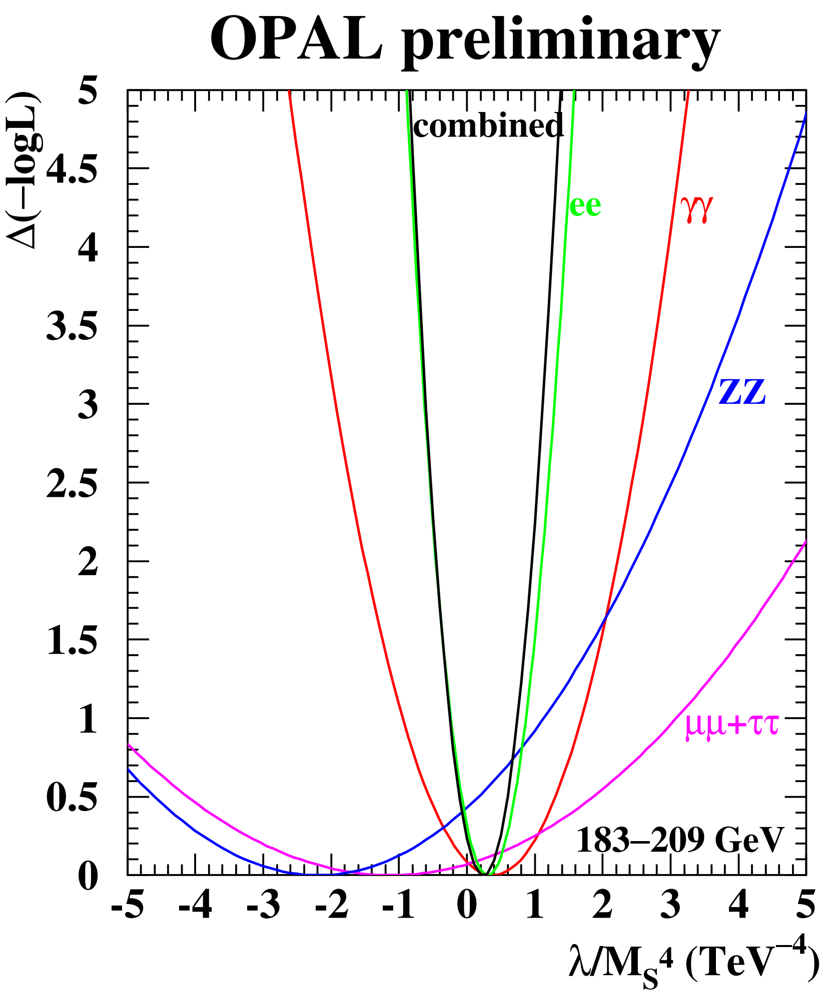




- 9.5K W-pair events (183–208 GeV)
  - ➥ branching ratios, W mass, gauge couplings, QCD
- $\mathrm{BR}(Z \to b\bar{b}) = 0.197 \pm 0.033$ (0.151 in the $\mathcal{SM}$)
- Limit on contact terms $\Lambda_+ > 344$ GeV, $\Lambda_- > 325$ GeV

Gravity in n+4 dimensions

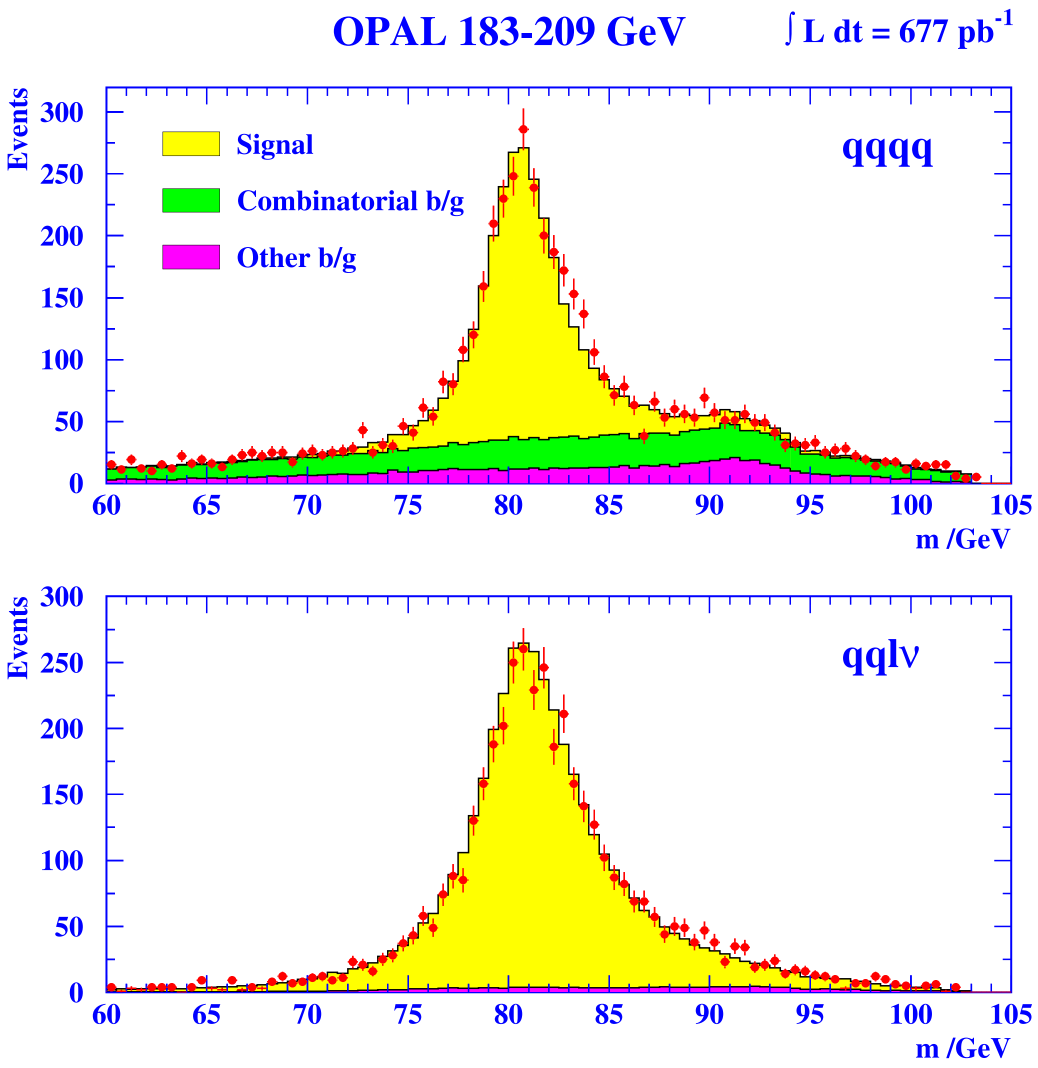
- Use $\mu^+\mu^-$, $\tau^+\tau^-$, $\gamma\gamma$ and ZZ final states
- Add e^+e^- final state
  - ✔ Interference of t–channel and G exchange
    - ➥ Stronger constraints



Limits at the 95% C.L.

$\lambda = +1$	$M_S > 1.03\,\text{TeV}$
$\lambda = -1$	$M_S > 1.17\,\text{TeV}$

W mass measurement

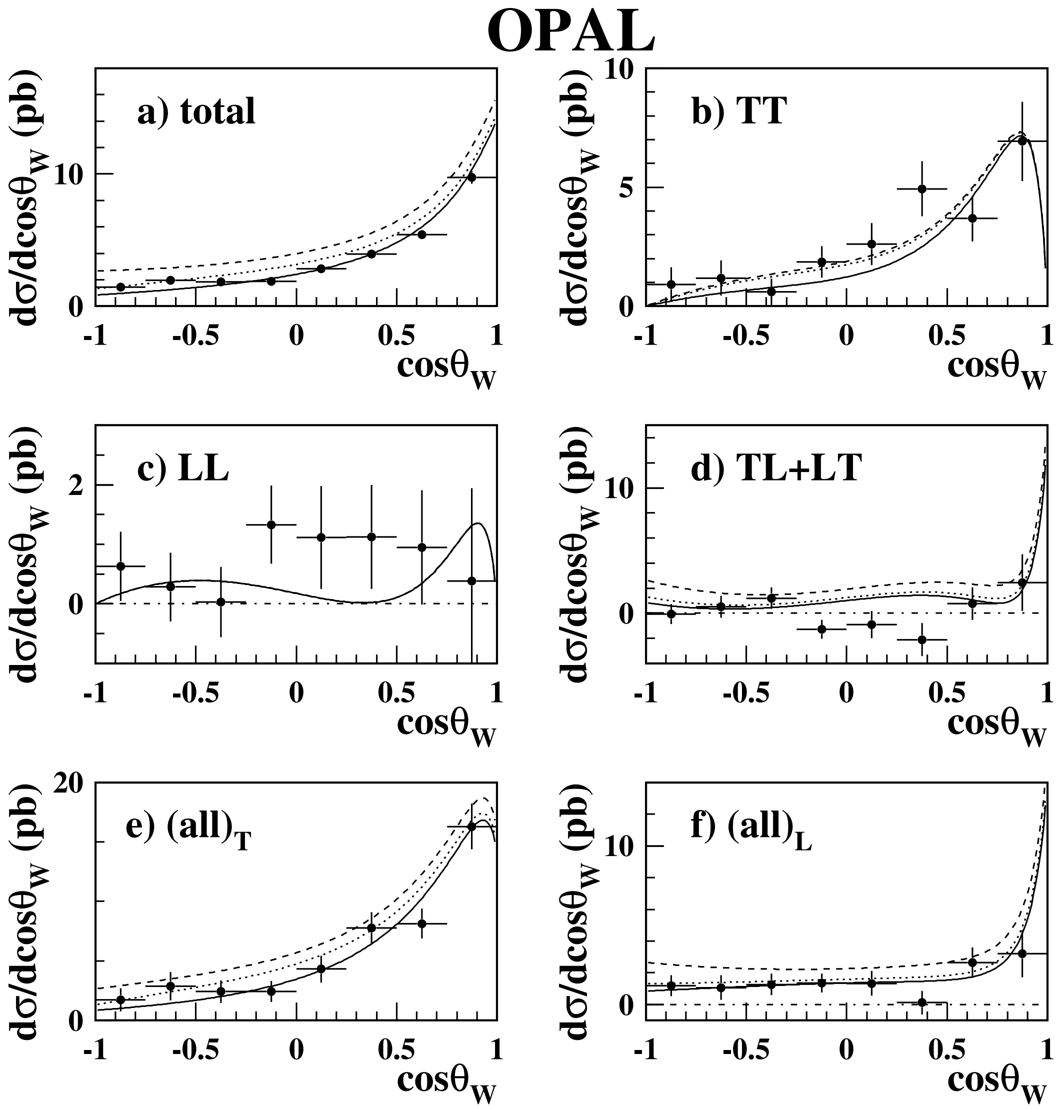


- **Understand systematic uncertainties**
  - Work toward final result
- Compare E_{beam} from radiative returns with LEP Calibration

$$\Delta E = -88 \pm 44 \pm 51 \text{ MeV}$$

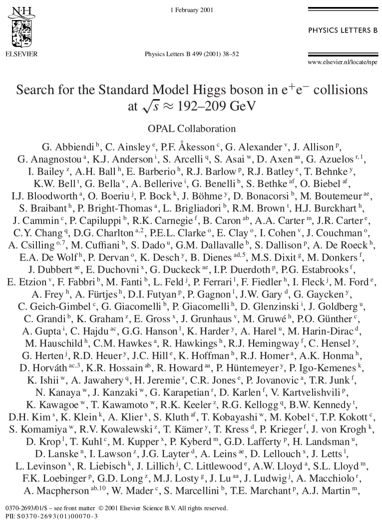
- Still need support from theoretical community in many areas

W Polarisation



$\sigma_{\rm T}/\sigma_{\rm total}$	$0.790 \pm 0.033 \pm 0.016$	0.74
$\sigma_{\rm L}/\sigma_{\rm total}$	$0.210 \pm 0.033 \pm 0.016$	0.26
$\sigma_{\rm TT}/\sigma_{\rm total}$	$0.781 \pm 0.090 \pm 0.033$	0.57
$\sigma_{\rm LL}/\sigma_{\rm total}$	$0.201 \pm 0.072 \pm 0.018$	0.09
$\sigma_{\rm TL}/\sigma_{\rm total}$	$0.018 \pm 0.147 \pm 0.038$	0.34

SM Higgs search (192-209 GeV)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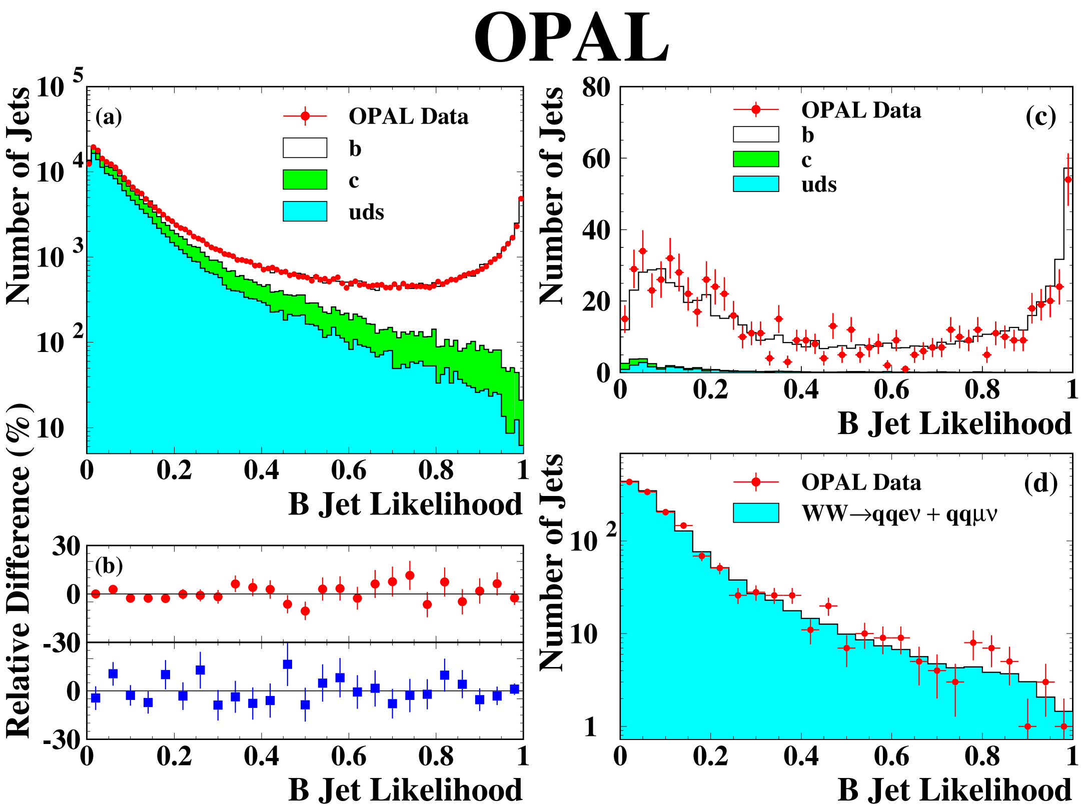
PHYSICS LETTERS B

Search for the Standard Model Higgs boson in e^+e^- collisions at $\sqrt{s} \approx 192$–209 GeV

OPAL Collaboration

Search channels

- $HZ \rightarrow b\bar{b}q\bar{q}$
- $HZ \rightarrow b\bar{b}\ell^+\ell^-$ $(\ell = e, \mu)$
- $HZ \rightarrow b\bar{b}\tau^+\tau^-$
- $HZ \rightarrow b\bar{b}\nu\bar{\nu}$
- $HZ \rightarrow \tau^+\tau^- q\bar{q}$
- WW, ZZ fusion



Final calibrations/alignments not used

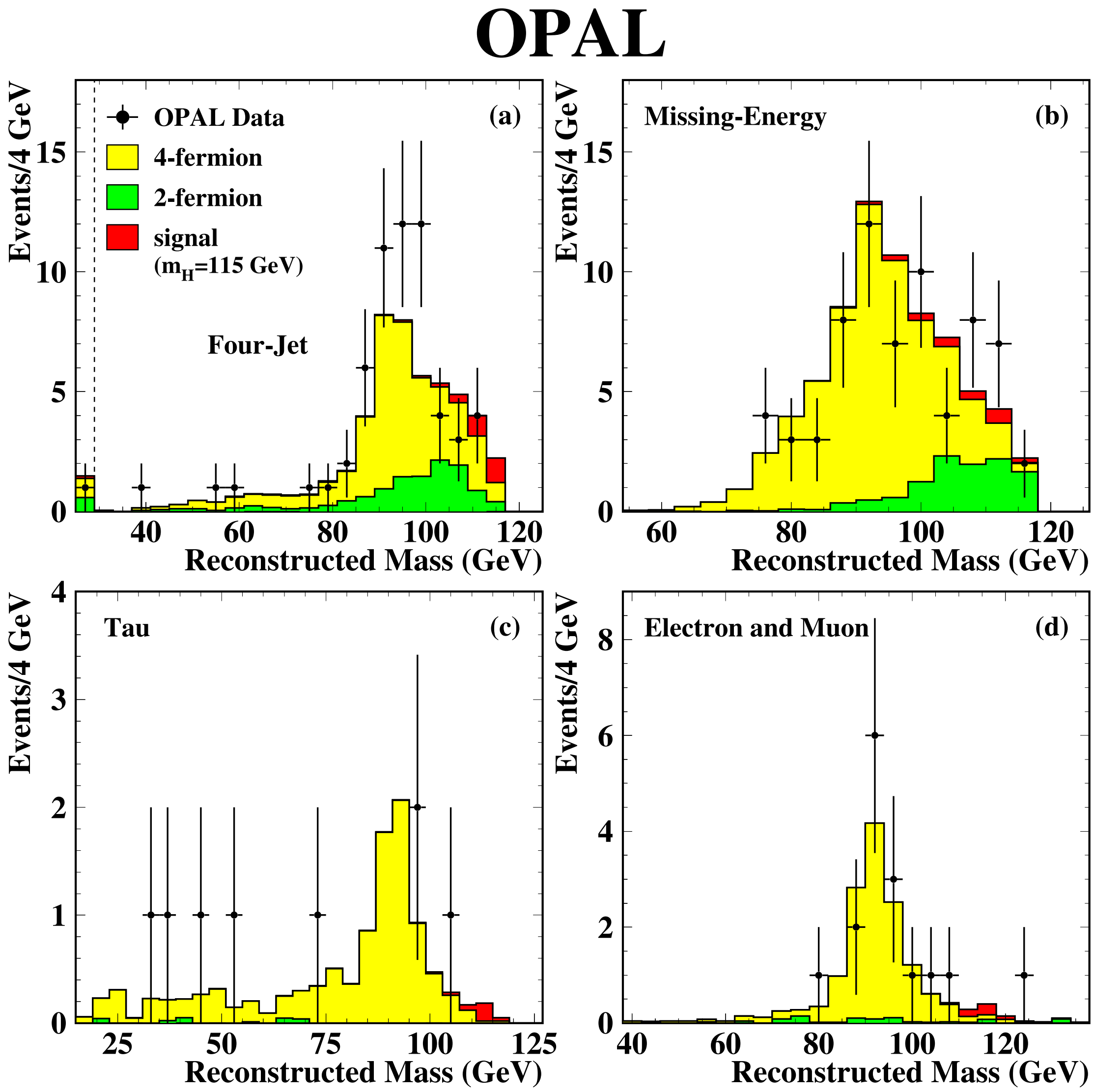
Total systematics:

Background 11–15%

Signal 5–6%

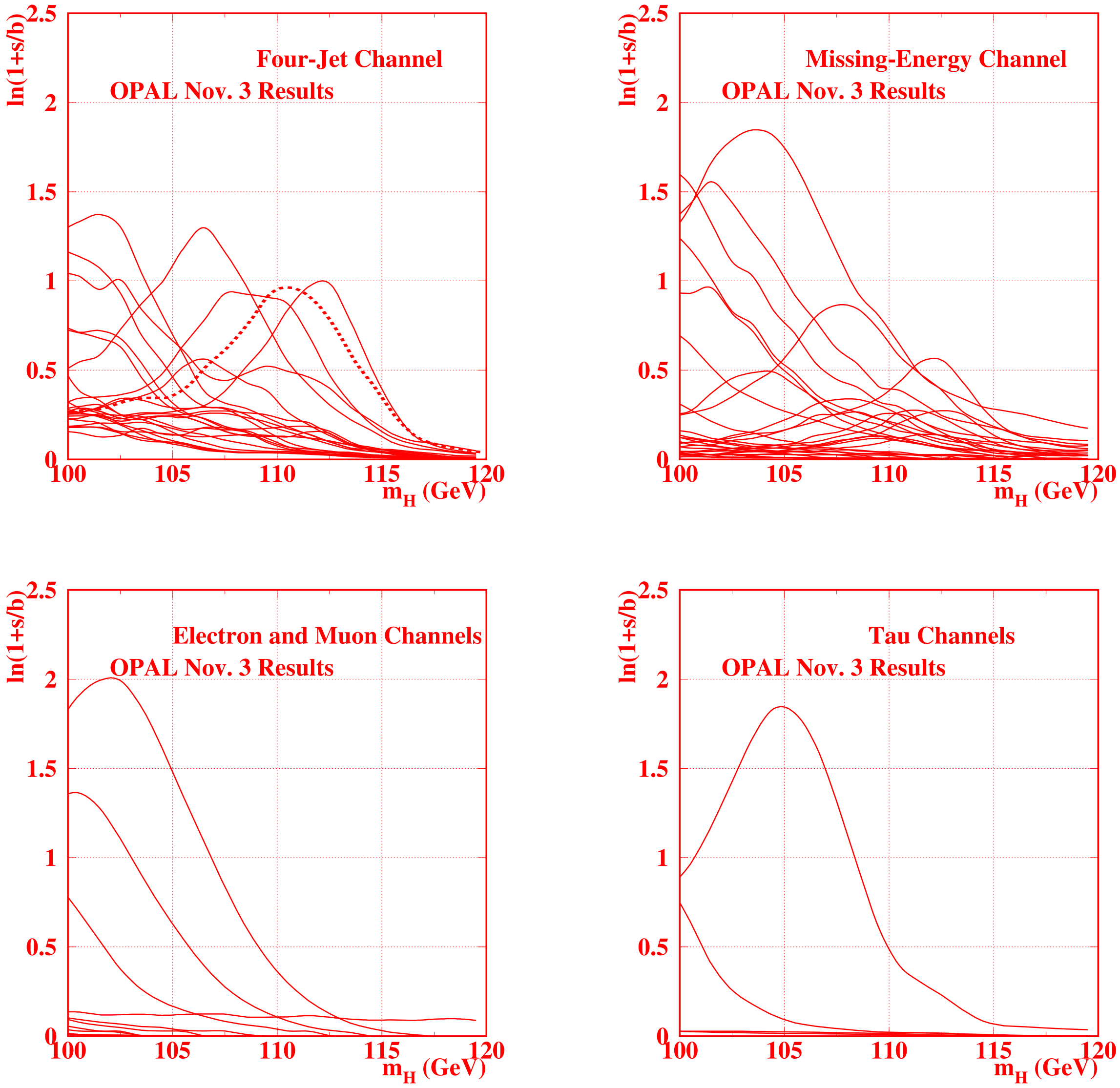
Selected events (192-209 GeV)

	data	bg	signal events $m_H = 115$ GeV
4 jets	60	49.8 ± 6.0	2.24 ± 0.10
$\not{E}$	68	69.7 ± 8.6	1.68 ± 0.10
τ	8	11.1 ± 1.2	0.25 ± 0.01
$e + \mu$	16	15.5 ± 1.6	0.40 ± 0.007



Event weights

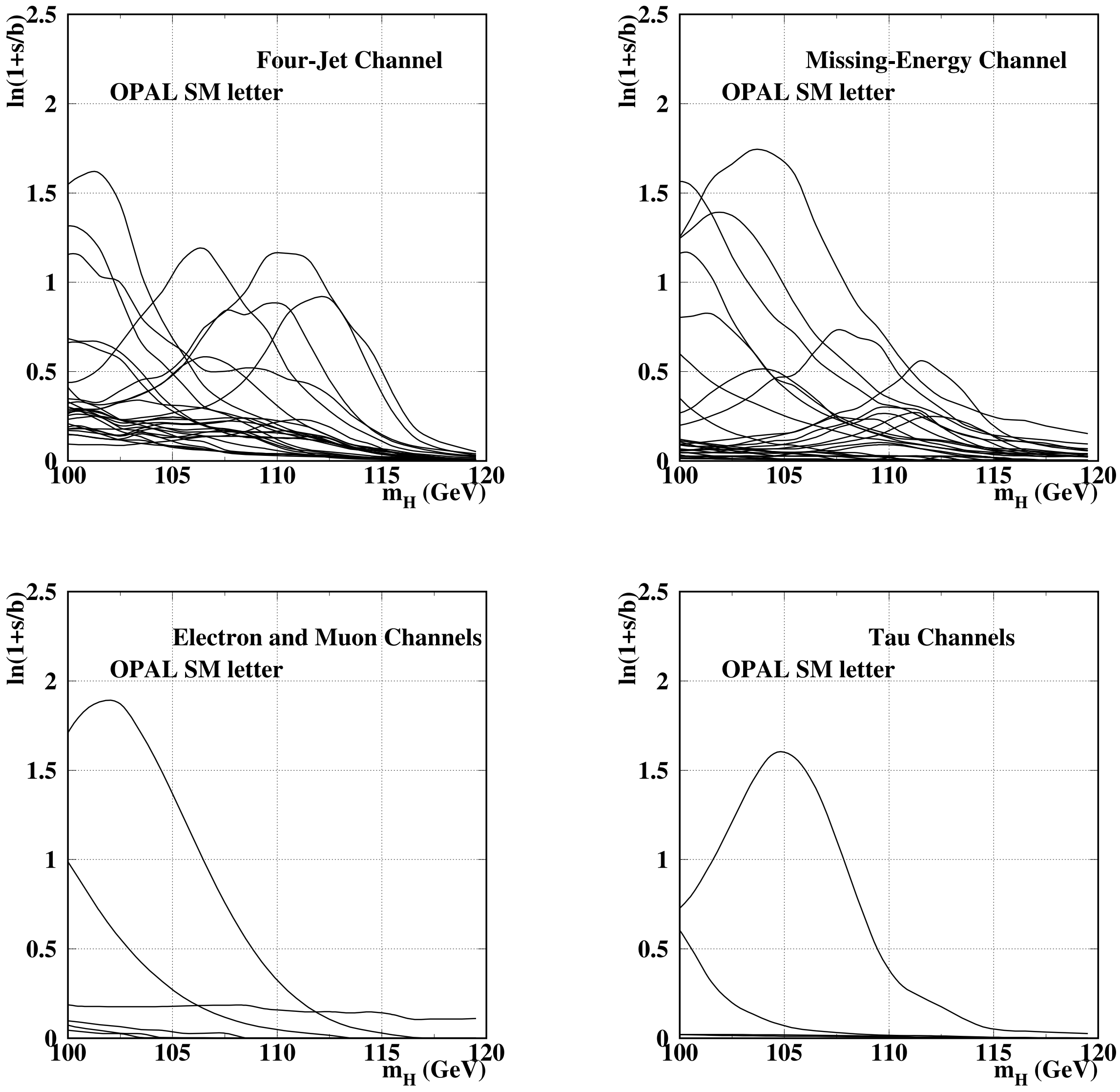
Only year 2000 data



LEPC presentation - 3 Nov 2000
Include candidates from last days of run

Results are stable

Only year 2000 data



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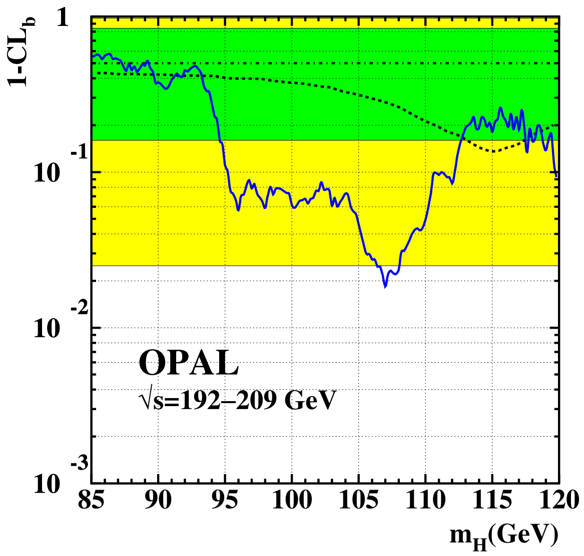
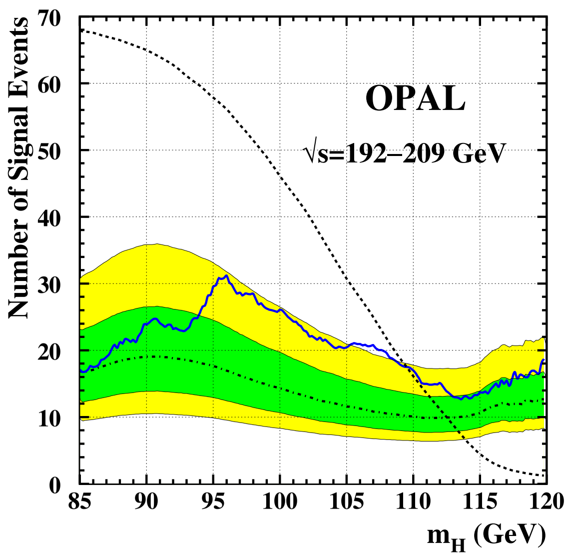
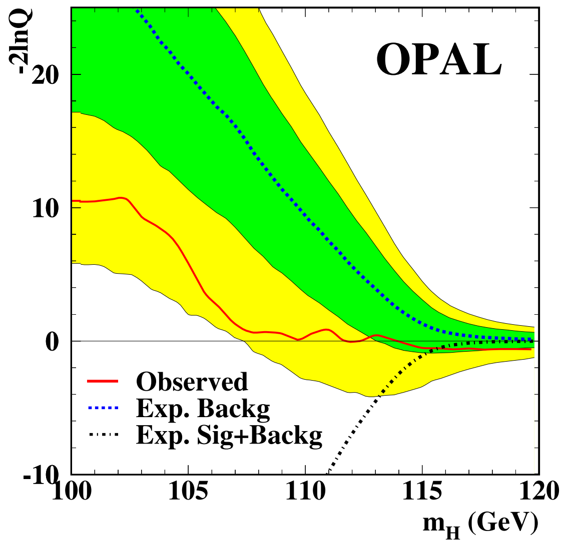
- Reprocess last 3 weeks of data
- Improve MC description of b tagging
- Analysis improvements for $b\bar{b}\nu\bar{\nu}$ and $b\bar{b}\ell\ell$

All within systematics

SM Higgs search – Results







$m_H > 109.7$ GeV
(exp. 112.5 GeV)

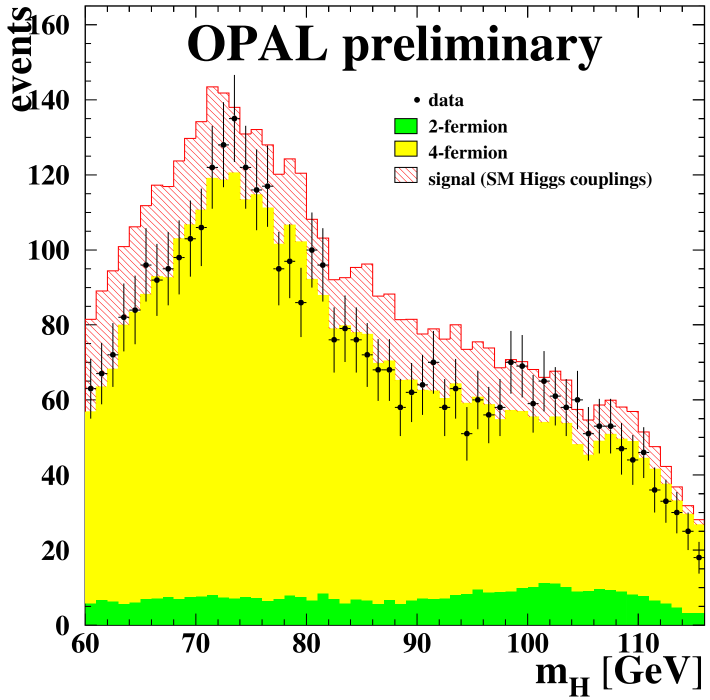
At $m_H = 115$ GeV:

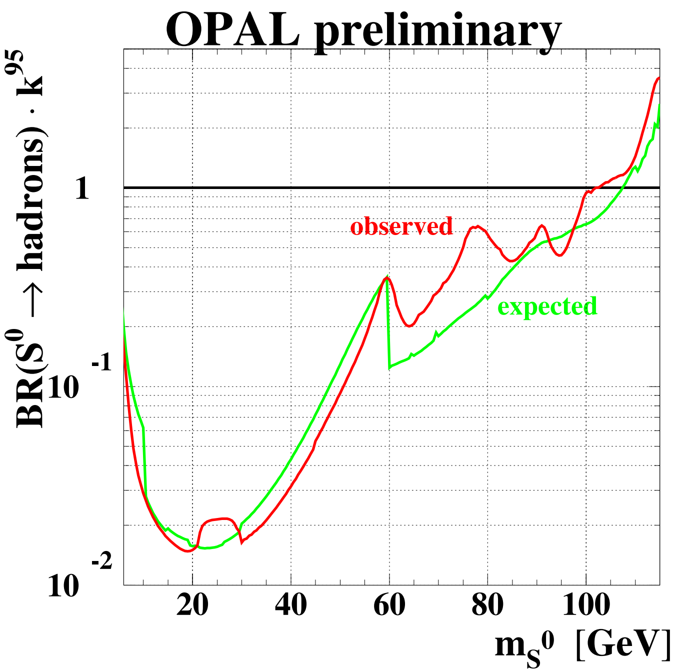
$1 - CL_b = 0.2$

$CL_{s+b} = 0.4$

- ✔ Data reprocessing finished 15 December
  - ➥ Only small changes observed
- ✔ Analysis improvements
  - ➥ Final results before the autumn

Flavour independent search for HZ, H$\rightarrow q\bar{q}$





- Search for a scalar boson S^0 produced with a Z^0 and with 100% branching ratio to hadrons
- No b–tag requirement in the analyses
- Mass dependent analysis for the 4–jet channel
- For $\mathrm{BR}(\mathrm{S}^0 \rightarrow \mathrm{hadrons}) = 100\%$

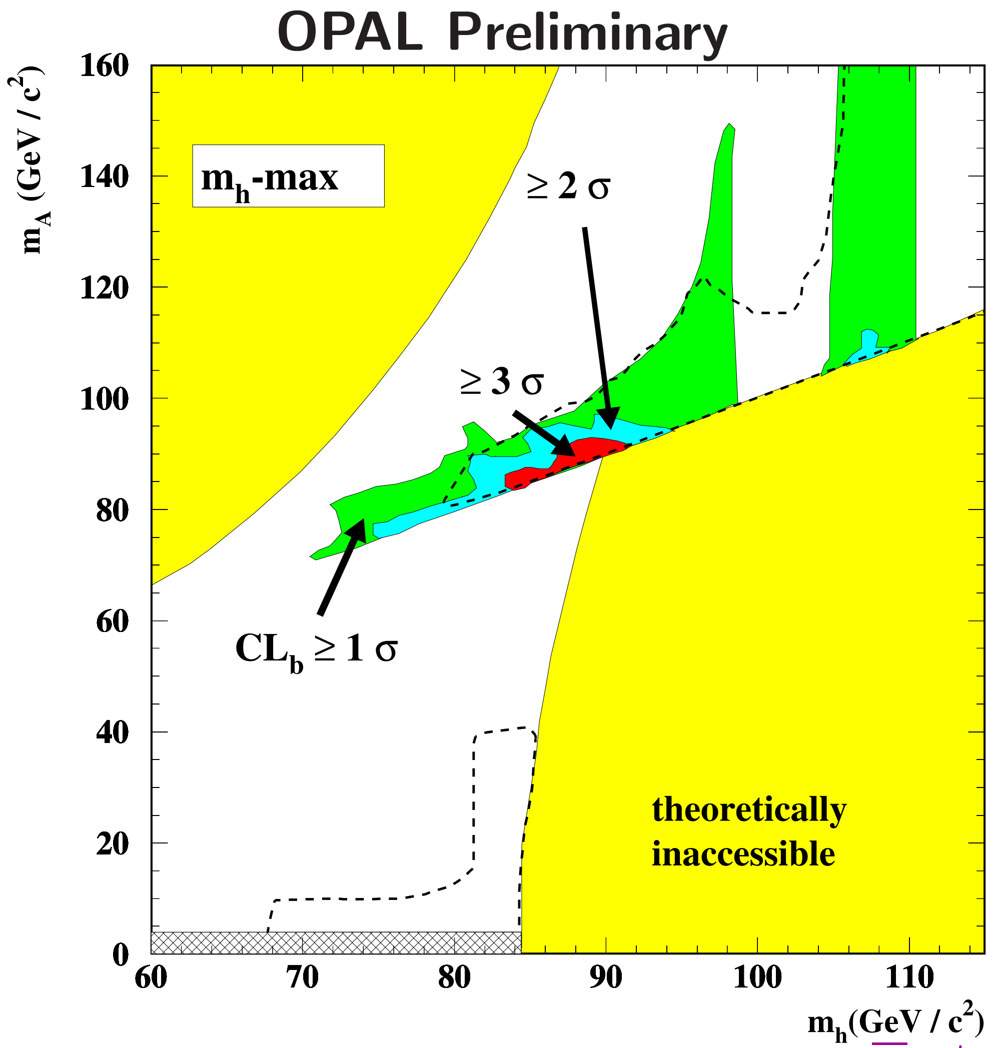
$$m_{\mathrm{S}^0} > 101.8\ \mathrm{GeV} \qquad \text{at } 95\%\ \mathrm{C.L.}$$

MSSM Higgs boson(s) searches

❶ Reuse $\mathcal{SM}$ results for Zh

❷ Search for $hA \rightarrow b\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-$:

16 events observed, 14.8 ± 1.7 expected



☛ Excess at $m_h \approx m_A \approx 83$ GeV: $b\bar{b}\tau^+\tau^-$ candidates at 189 GeV

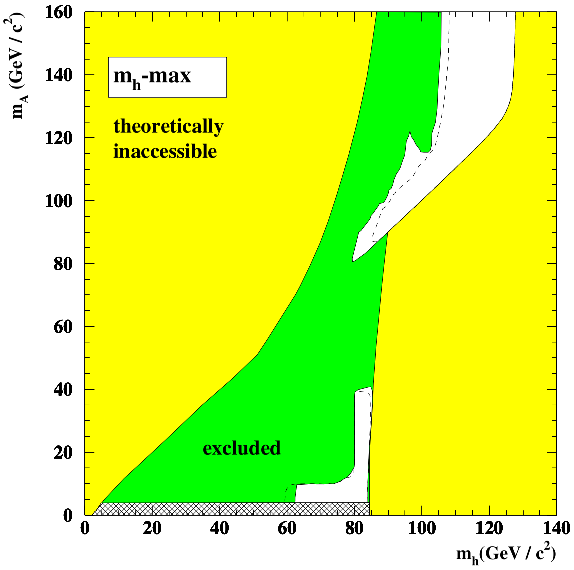
☛ $m_h \approx m_A \approx 91$ GeV: $b\bar{b}b\bar{b}$ candidates at 196 GeV

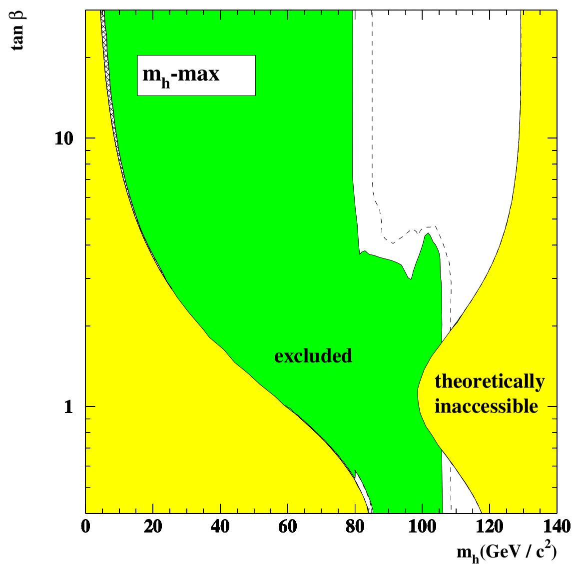
Both regions excluded by LEP combination

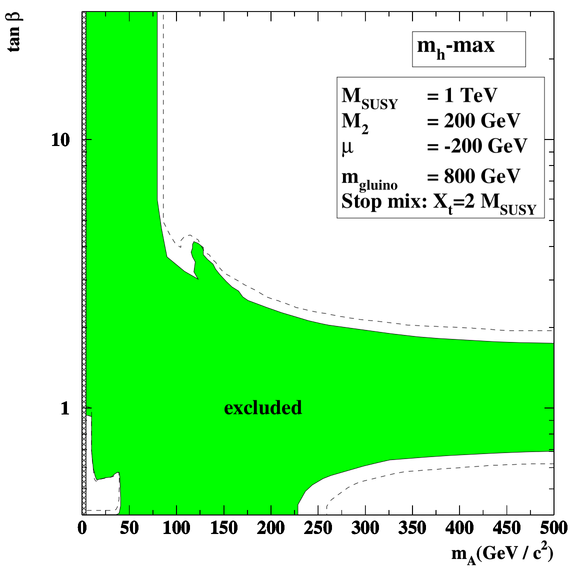
MSSM parameters scan

- no mixing
- maximal m_h ➠ conservative $\tan\beta$ limits
- large μ ➠ no $h \rightarrow b\bar{b}$

Maximal m_h scan







for $\tan\beta > 1.2$:

$m_h > 79.3$ GeV
(exp. 85.1 GeV)

$m_A > 80.6$ GeV
(exp. 86.9 GeV)

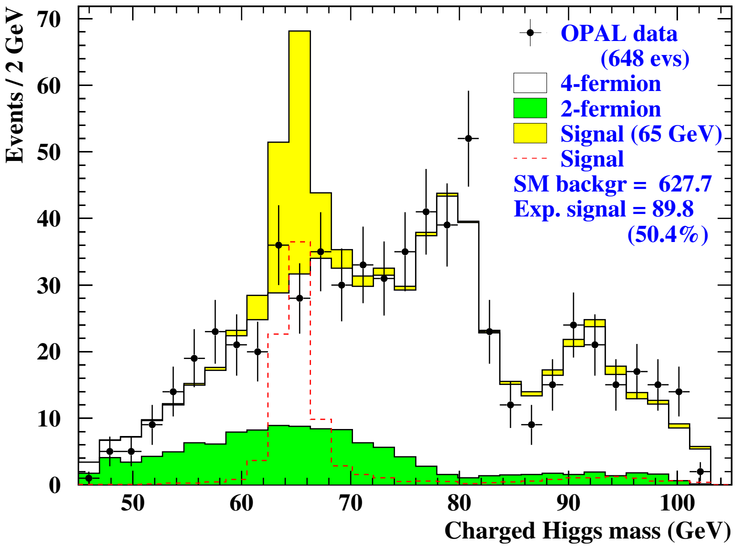
$0.9 < \tan\beta < 1.7$
(exp. $1.0 < \tan\beta < 1.9$)

Charged Higgs boson searches

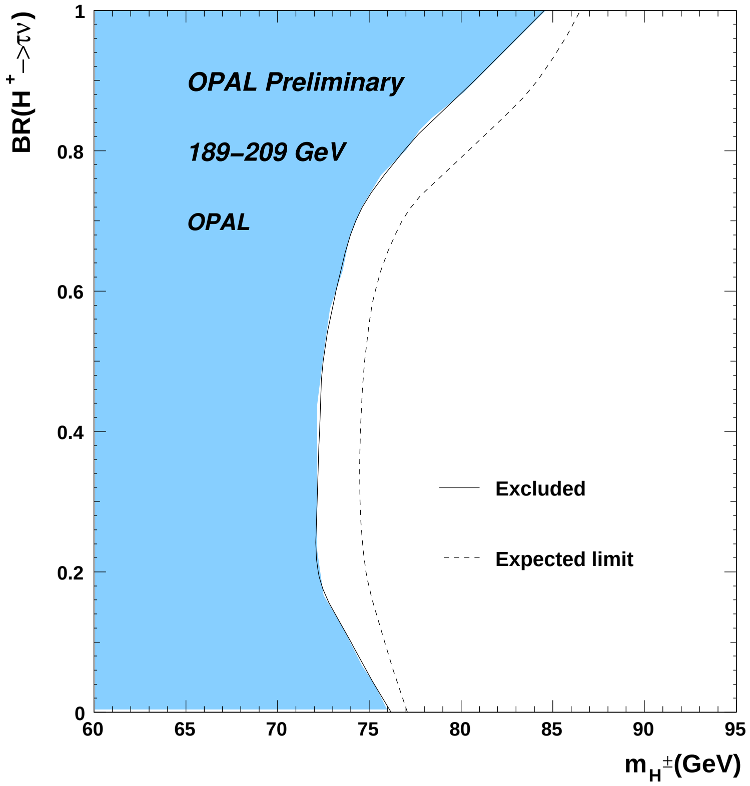
Search $e^+e^- \rightarrow H^+H^-$ in:

- $q\bar{q}'q''\bar{q}'''$ (4 jet final state)
- $\tau^+\nu_\tau q'\bar{q}$
- $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$

OPAL Preliminary: $H^+H^- \rightarrow qqqq$, 189 - 206 GeV, 615.0 pb^{-1}



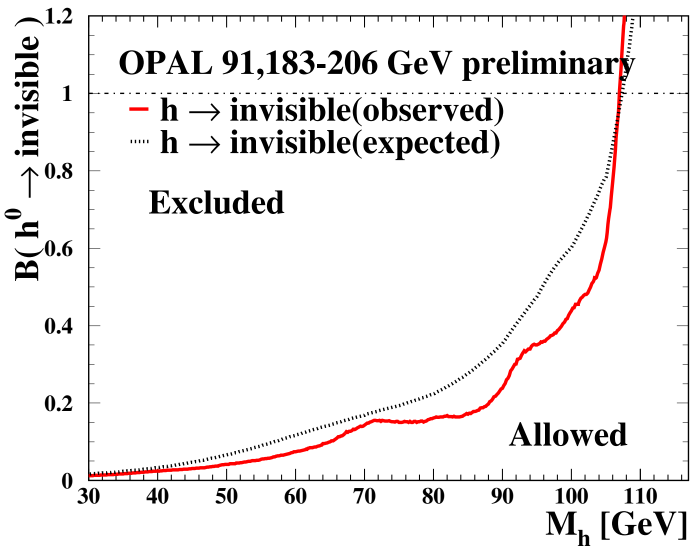
4jet–channel for $m_{H^\pm} = 65$ GeV



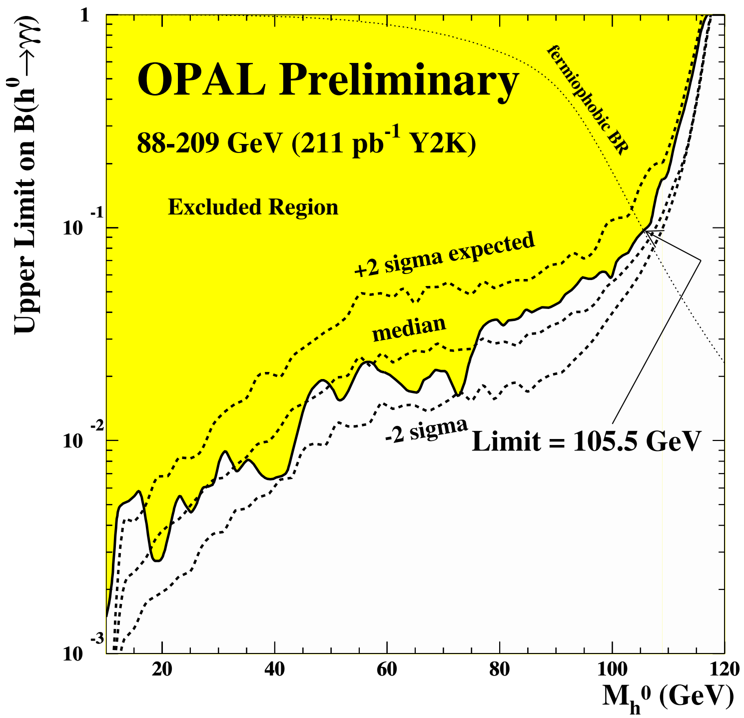
- Excluded $m_{H^\pm} < 72.2$ GeV at 95% C.L.
  < 74.5 GeV (expected)

More exotic Higgses

H $\longrightarrow$ *invisible*



Fermiophobic H $\longrightarrow \gamma\gamma$



- Deficit below 100 GeV
- Excess above 105 GeV (2.3σ at 112 GeV)
- Observed limit: 107.0 GeV
- Expected limit: 107.4 GeV

- Excluded $m_H < 105.5$ GeV at 95% C.L.
  < 106.4 GeV (expected)

Nada/Nichts/Niente/Rien/Nothing

Search Channel List

$e^+e^- \to hZ$	$h \to b\bar{b}$	$b\bar{b}q\bar{q}$, $b\bar{b}\nu\bar{\nu}$, $b\bar{b}\ell^+\ell^-$
	$h \to \tau^+\tau-$	$\tau^+\tau^-q\bar{q}$
	$h \to q\bar{q}$	$q\bar{q}q\bar{q}$, $q\bar{q}\nu\bar{\nu}$, $q\bar{q}\ell^+\ell^-$
	$h \to \gamma\gamma$	$(q\bar{q}, \ell^+\ell^-, \nu\bar{\nu})+\gamma\gamma$
	$h \to WW^*$	$(\ell\nu q\bar{q}, q\bar{q}q\bar{q})+(q\bar{q}, \nu\bar{\nu})$
	$h \to \tilde{\chi}^0\tilde{\chi}^0$	$q\bar{q}$, $\ell^+\ell^- + \not{E}$
$e^+e^- \to hA$	$h, A \to b\bar{b}, \tau\tau$	$b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$
	$h \to AA$	$b\bar{b}b\bar{b}b\bar{b}$
$e^+e^- \to H^+H^-$	$H^+ \to q\bar{q}, \tau\nu$	$q\bar{q}q\bar{q}$, $q\bar{q}\tau\nu$, $\tau\nu\tau\nu$
	$H^+ \to A^0W^{+(*)}$	$b\bar{b}b\bar{b} + (\ell\nu q\bar{q}, q\bar{q}q\bar{q})$
$e^+e^- \to \tilde{\chi}^+\tilde{\chi}^-$	$\tilde{\chi}^- \to W^*\tilde{\chi}^0$	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
$e^+e^- \to LQ\bar{L}\bar{Q}$	LQ$\to \ell q$ (νq)	jets, $\ell^\pm$, ν

YEAR 2000

Reported excesses in:

❶ $\nu\bar{\nu}q\bar{q}$ (neutralino, low Δm)

❷ $\ell\ell\gamma\gamma + \not{E}_T$

❸ Low multiplicity ($N_{ch} \leq 4$), $\Delta m < 10$ GeV chargino

Full data set (200–220 pb^{-1})

Latest news

❶ and ❷ not confirmed by further data (at higher $\sqrt{s}$)

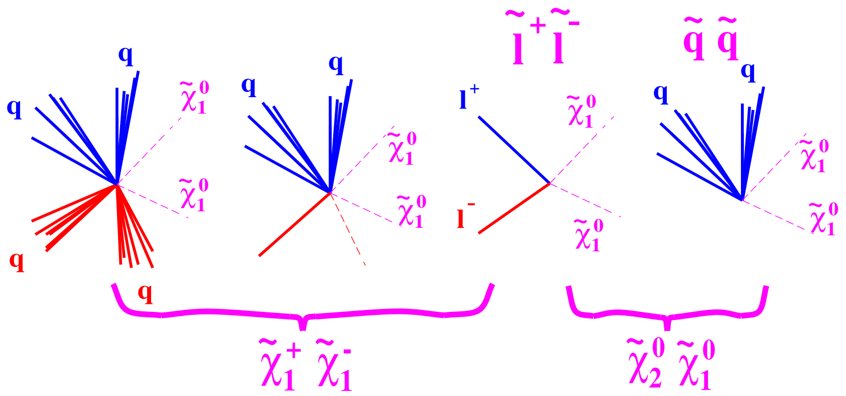
❸ currently under investigation

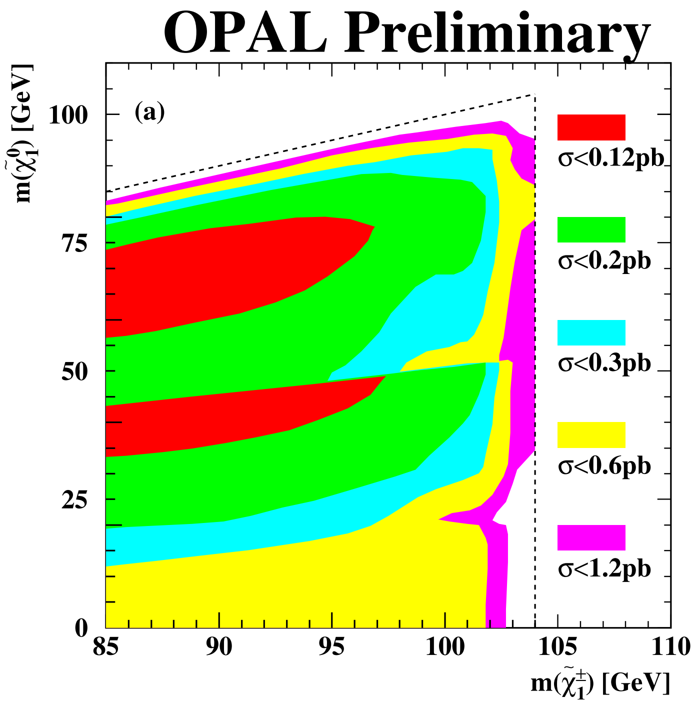
NO SIGNIFICANT EXCESS

Limits, limits, limits ....

Charginos

Search topologies





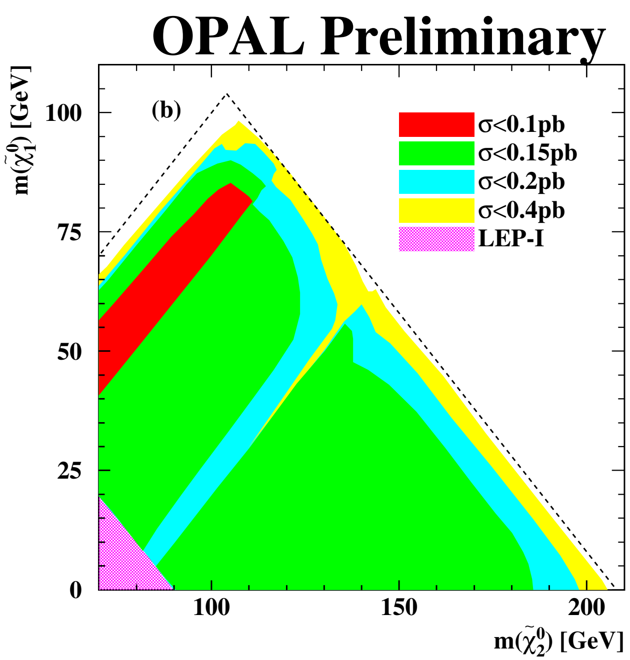
(C)MSSM parameters scan

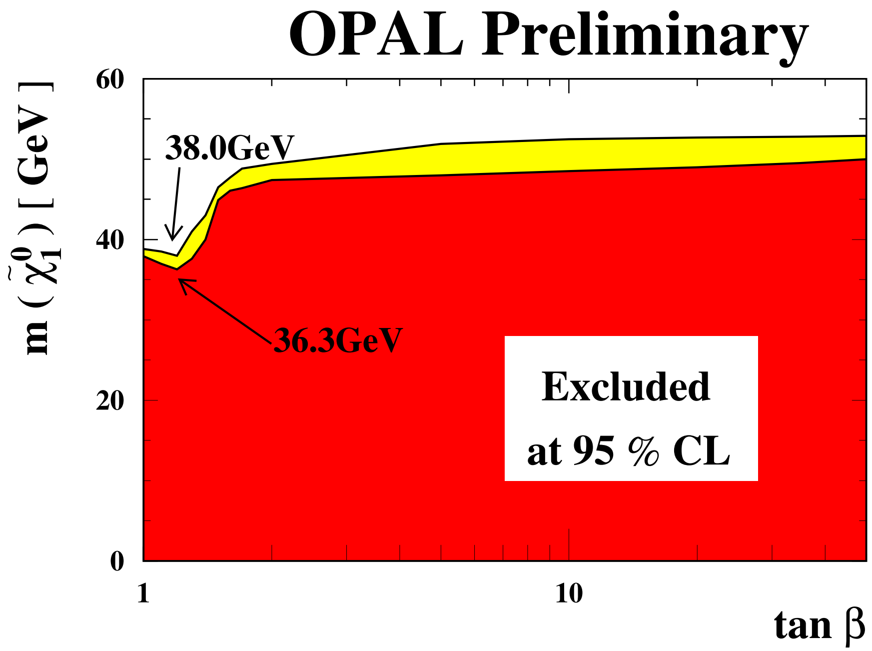
❶ $m(\tilde{\chi}_1^\pm) > \ 93.9\ \mathrm{GeV}$ ❷ $m(\tilde{\chi}_1^\pm) > 100.7\ \mathrm{GeV}$

Limits obtained for $|\mu| < 09.5\ \mathrm{TeV}$, $\Delta m > 5\ \mathrm{GeV}$ and

❶ any m_0 or ❷ $m_0 > 500\ \mathrm{GeV}$

Neutralinos





(C)MSSM parameters scan

❶ $m(\tilde{\chi}^0_1) > \ 36.3$ GeV ❷ $m(\tilde{\chi}^0_1) > \ 38.0$ GeV

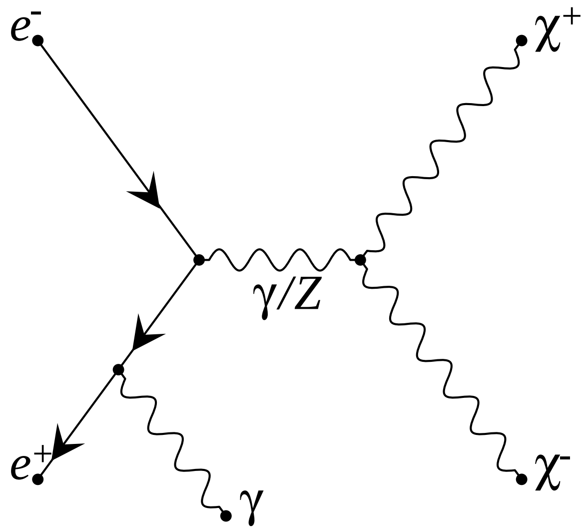
Limits obtained for $|\mu| < 0.5$ TeV, $\Delta m > 5$ GeV and

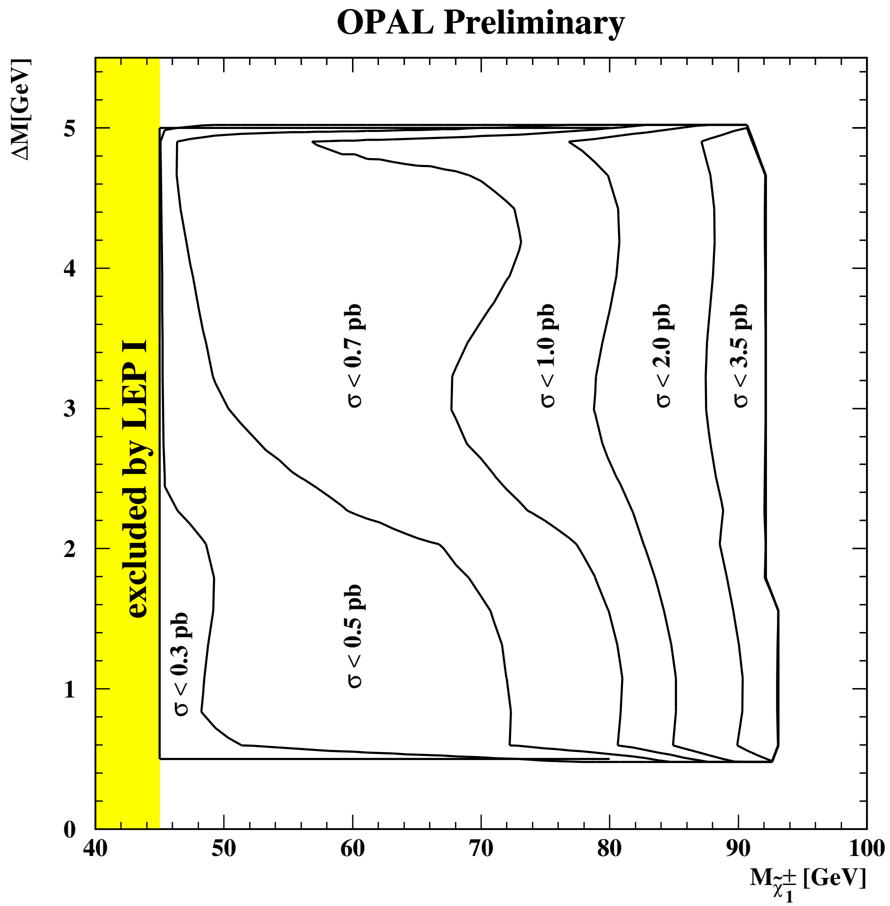
❶ any m_0 or ❷ $m_0 > 500$ GeV

Combining with Higgs analysis ($\tan\beta$), ➡ stronger exclusion of low LSP masses

Investigate small Δm values

- ✘ Low Δm ➠ background from $\gamma\gamma \rightarrow$ hadrons
- ✘ Antitag $\gamma\gamma$ events with ISR photons (low signal $\varepsilon \approx$ few%)

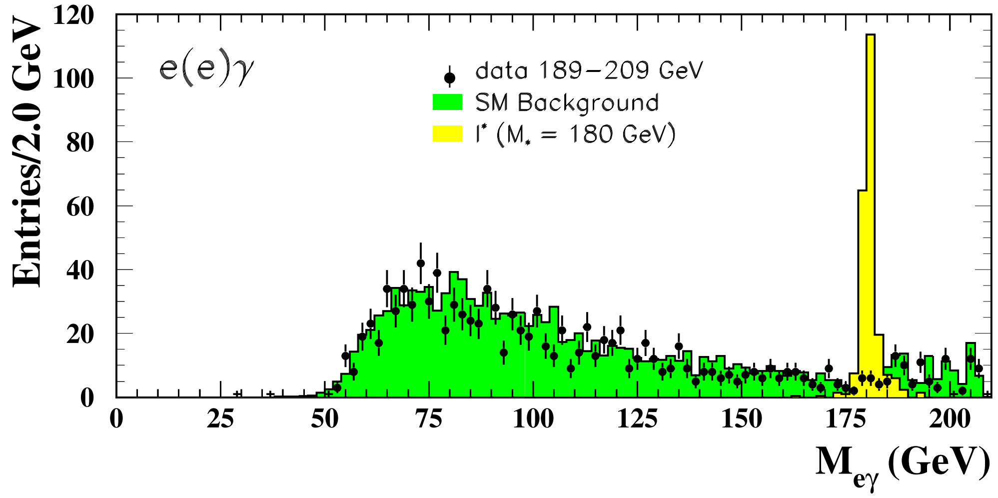


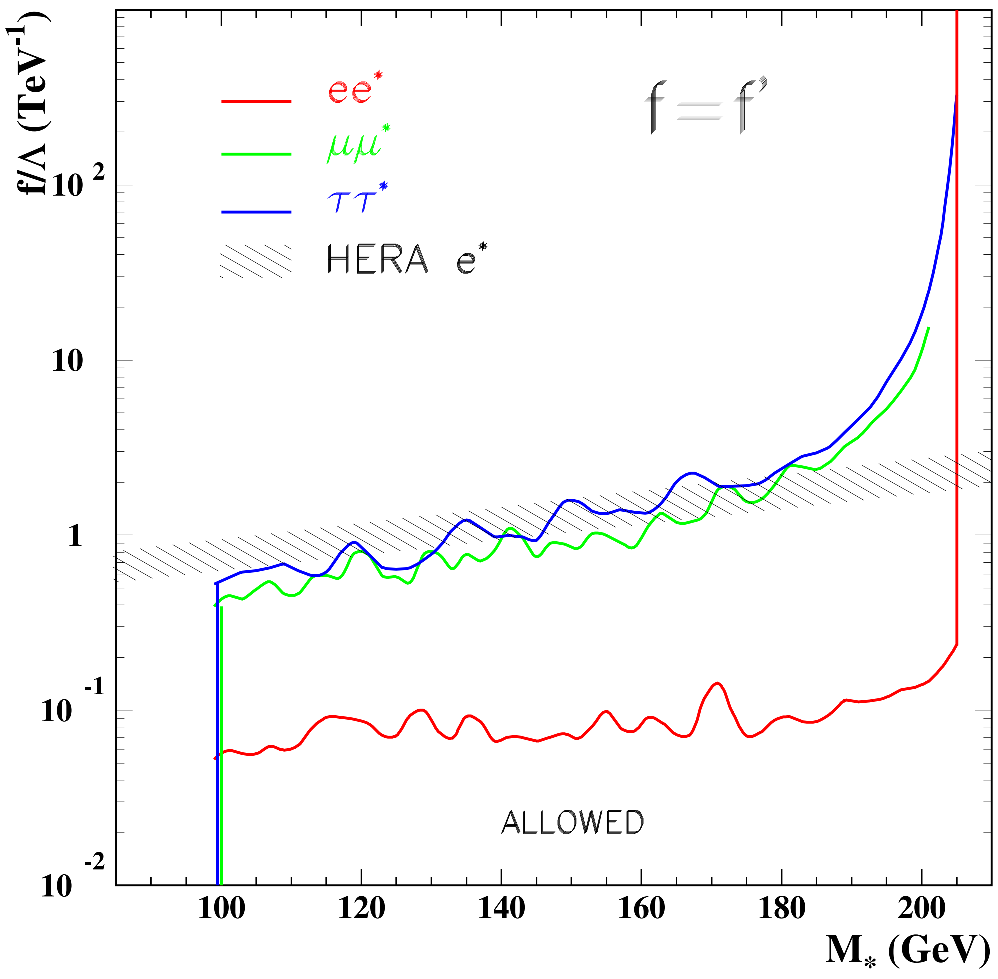


- ✘ Exclude $m(\tilde{\chi}_1^\pm) < 91$ GeV (assuming $m_{\tilde{\nu}} = 1$ TeV) for $0.5 < \Delta m < 5$ GeV

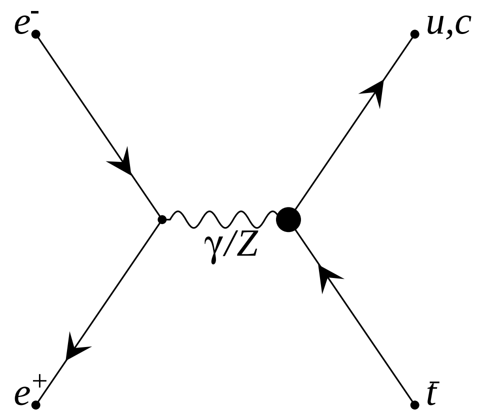
Excited leptons

Pair production ➡ kinematic limit
Single production ➡ limit on f/Λ

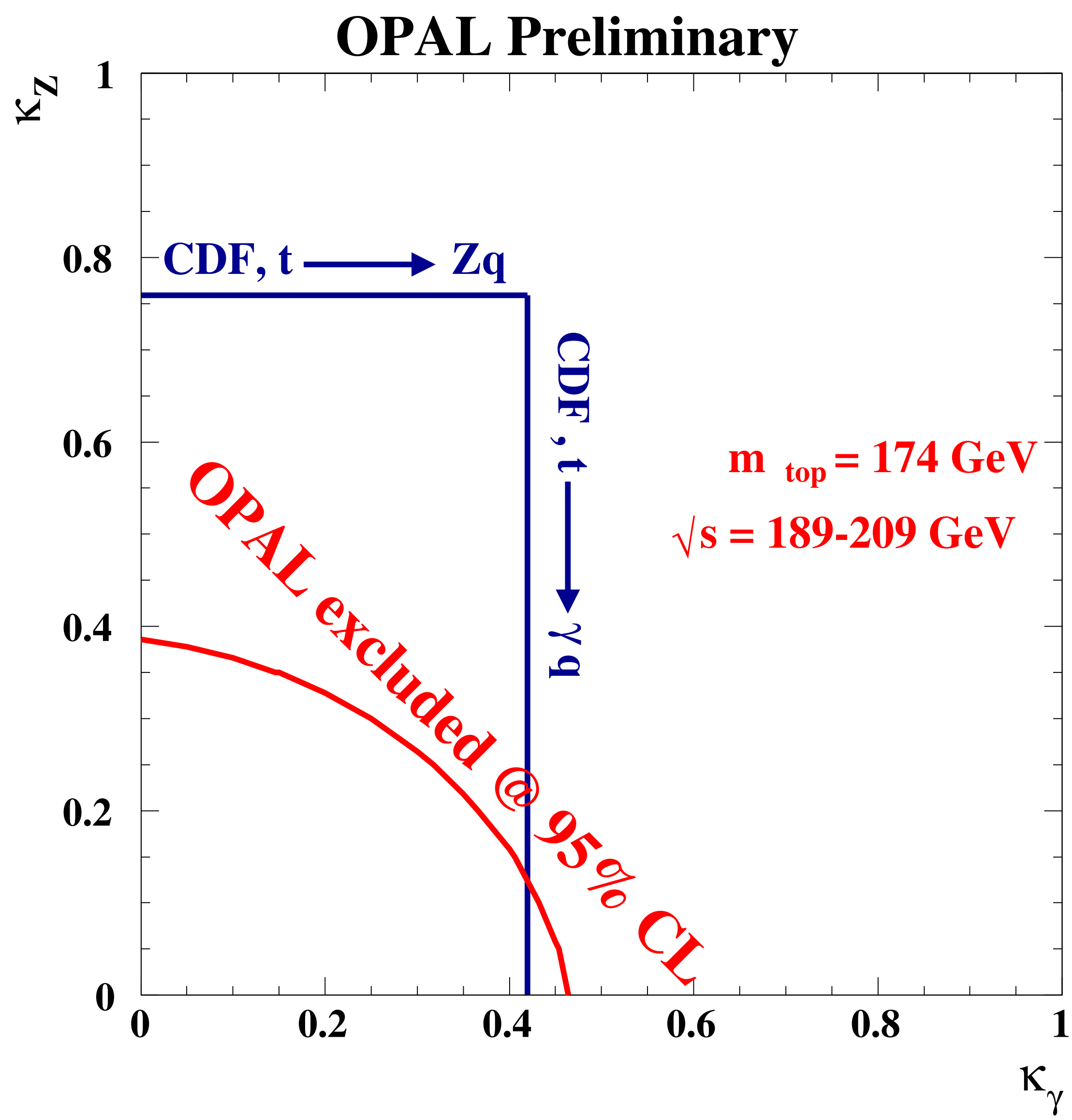




FCNC and single top

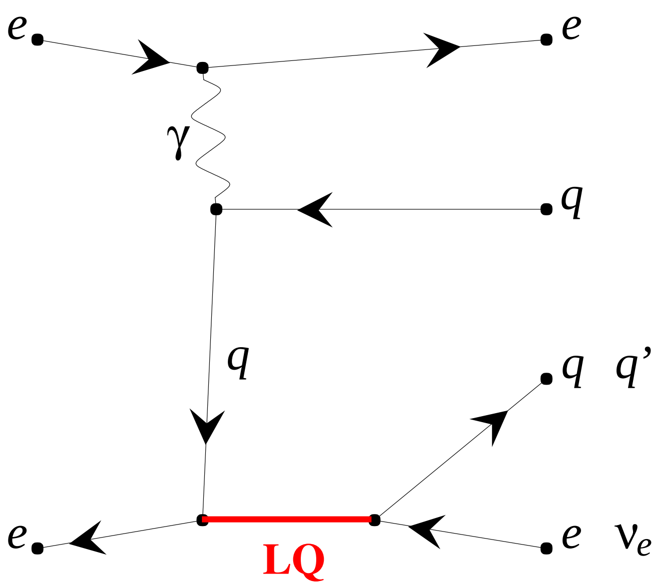


- Invisible in the $\mathcal{SM}$
- Signals new physics
- No excess observed
- Limit on anomalous top couplings κ_γ and κ_Z

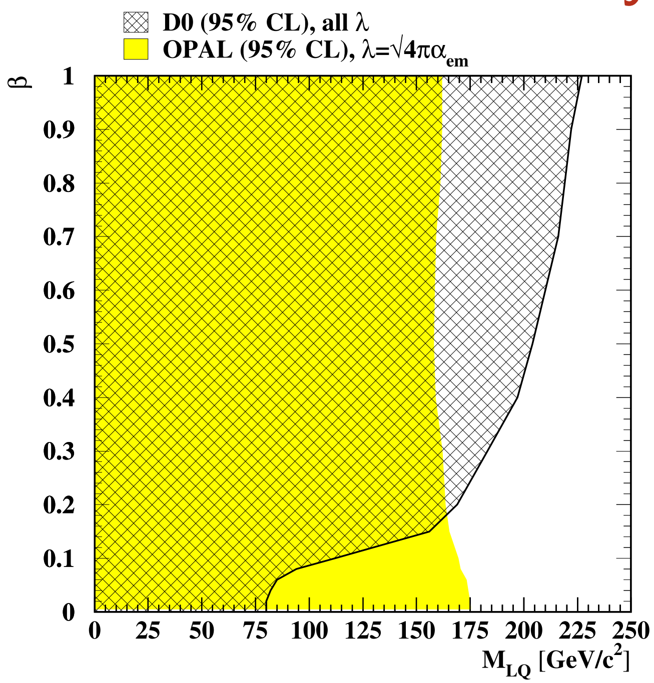


Single leptoquarks

- **Pair production** ➠ depending on quantum numbers, branching ratios, lower m_{LQ} between 76 GeV and kinematic limit
- Single production ➠ Probe higher masses
- Final states: electron + jet or monojet, plus $\not{p}_L$



OPAL 189 GeV data only



Conclusions

http://opalweb.cern.ch/Opal/PPwelcome.html

- PN469 Measurements of Standard Model Processes in e^+e^- Collisions at $\sqrt{s} \approx 203 - 209$ GeV
- PN470 New Particle Searches in e^+e^- Collisions at $\sqrt{s} \approx 200 - 209$ GeV
- PN472 Searches for Higgs Bosons in Extensions to the Standard Model in e^+e^- at the Highest LEP Energies
- PLB 499 (2001) 38 Search for the Standard Model Higgs Boson in e^+e^- Collisions at $\sqrt{s} \approx 192 - 209$ GeV

Many thanks to the OPAL colleagues who helped preparing this talk

Apologies for results which were not shown

We are working toward final results

Stay tuned !!!!