Fermion-pair Production Above the Z and Limits on New Physics

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- Cross-section and Asymmetry Measurements

  Hadrons: $\mathrm{e^+e^-} \rightarrow \mathrm{q\overline{q}}(\gamma)$

  Leptons: $\mathrm{e^+e^-} \rightarrow \ell^+\ell^-(\gamma) \quad (\ell = \mathrm{e}, \mu, \tau)$

  Flavour-tagged

- Comparisons with SM

  S-matrix fit

  Running of α_{em}

- Searches for new physics

  Z'

  Contact interactions

  Leptoquarks + R-parity violating squarks

  R-parity violating $\tilde{\nu}$

  Light gluinos

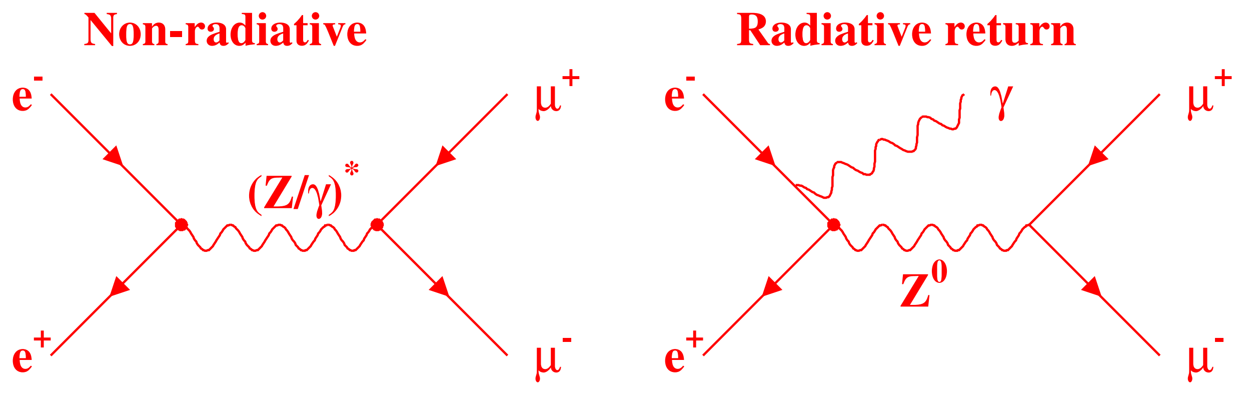
Data from LEP Above the Z

	$\sqrt{s}$ (GeV)	$\int \mathcal{L}\mathrm{d}t$ /expt (pb^{-1})
November 1995	130–136	~ 5
July/August 1996	161	~ 10
October/November 1996	172	~ 10
August 1997	183	~ 6

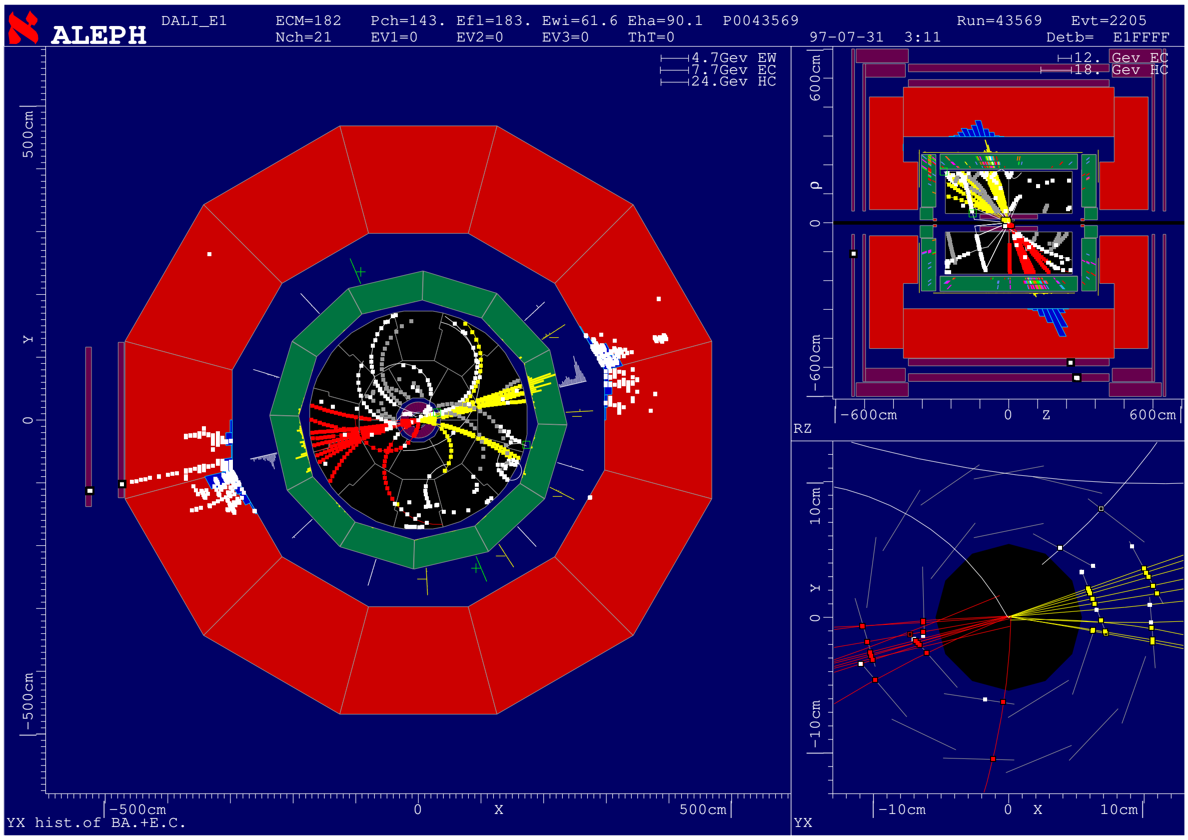
- Results from all four LEP experiments: 130-136 GeV mostly final, 161–172 GeV some final, some preliminary, 183 GeV all very preliminary

Two-fermion production

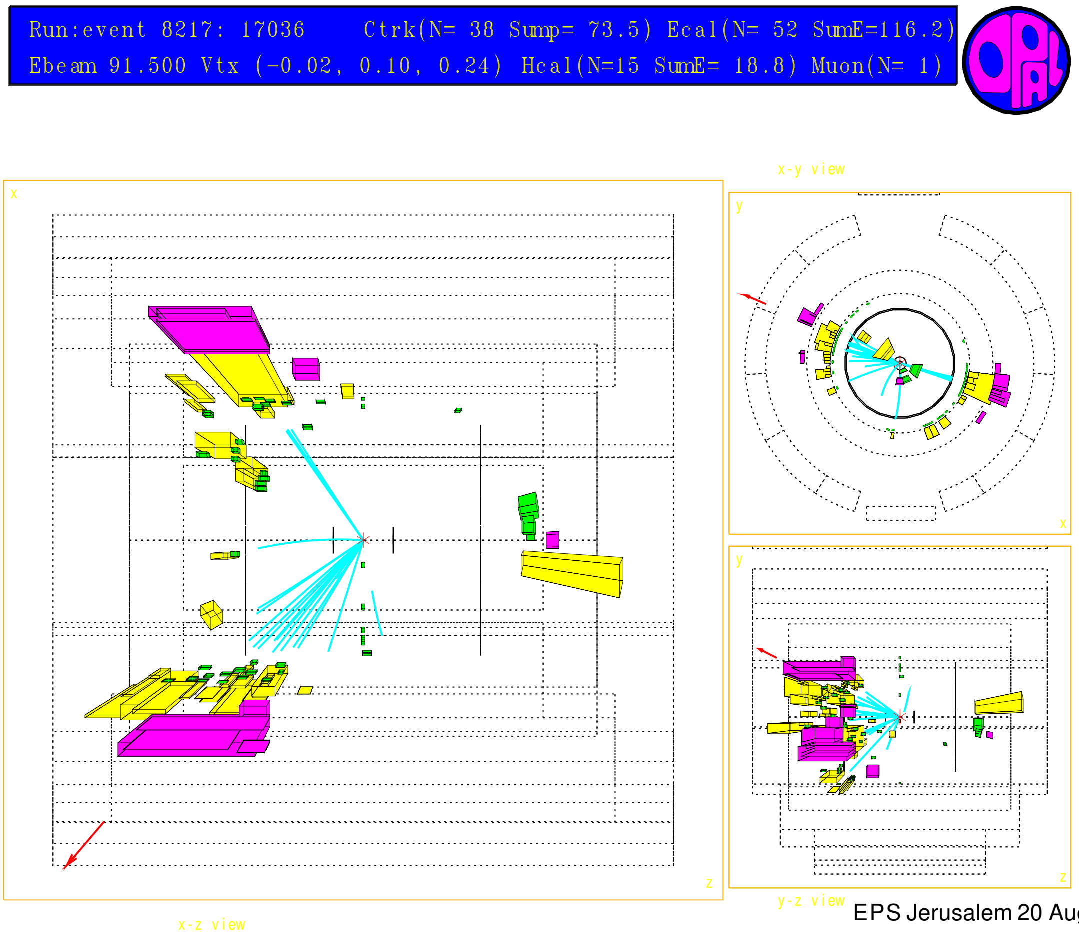
- Event selection generally similar to on Z peak, but
  - radiative return to Z important
  - increased backgrounds from 4-fermion events (WW)
- Radiative return to the Z pole:



$q\bar{q}$ non-radiative

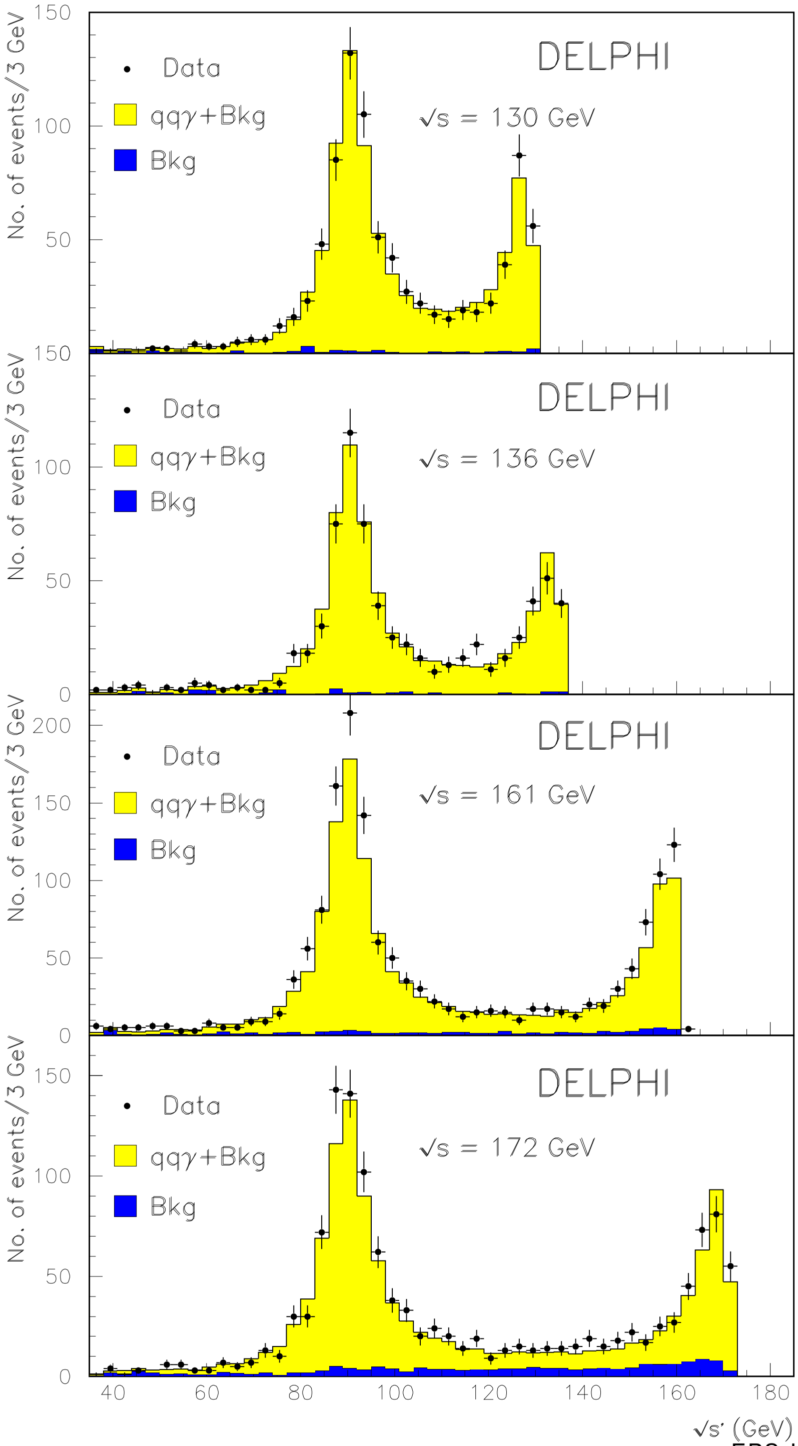


$q\bar{q}$ radiative return



Two-fermion production

- Main interest is in the non-radiative sample, where new physics could show up
- Define s' as effective mass^2 of $\mathrm{e^+e^-}$ system after ISR
- Calculate s' using angles of observed particles or kin. fit



Two-fermion production

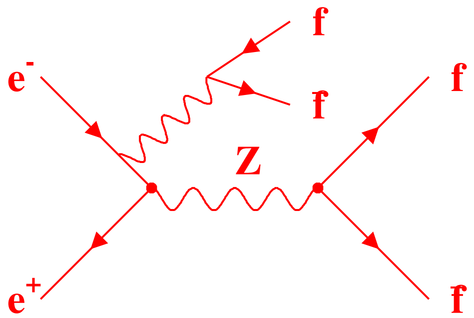
- Measure cross-sections, asymmetries for:
  inclusive events ($s'/s \gtrsim 0.01$)
  'non-radiative' events ($s'/s \gtrsim 0.7 - 0.8$)

- Definition of s' ambiguous because of interference between initial- and final-state radiation

- OPAL has developed well-defined procedure for correcting measurements to 'no interference'; corrections to cross-sections are $<$0.5% for $s'/s > 0.01$, 1–2% for $s'/s > 0.8$

- But corrections rely on theoretical estimate of interference cross-section, only calculated to $\mathcal{O}(\alpha)$

- A second problem is treatment of 4-fermion events, e.g.

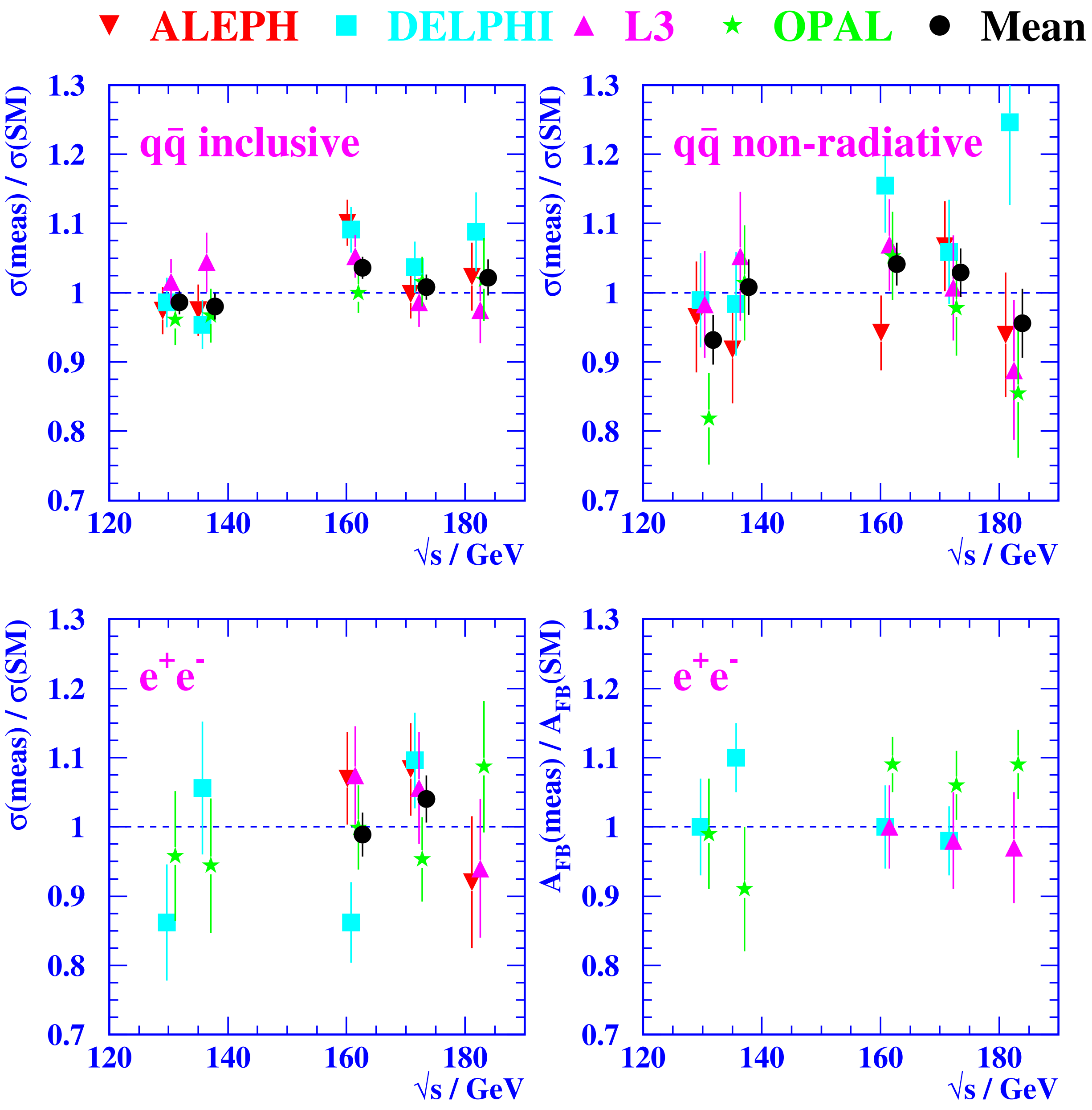


  low mass fermion pairs from s-channel diagrams are signal, like photons

- Corrections to efficiencies 0.5% for $s'/s > 0.01$, negligible for non-radiative case

Cross-sections and Asymmetries

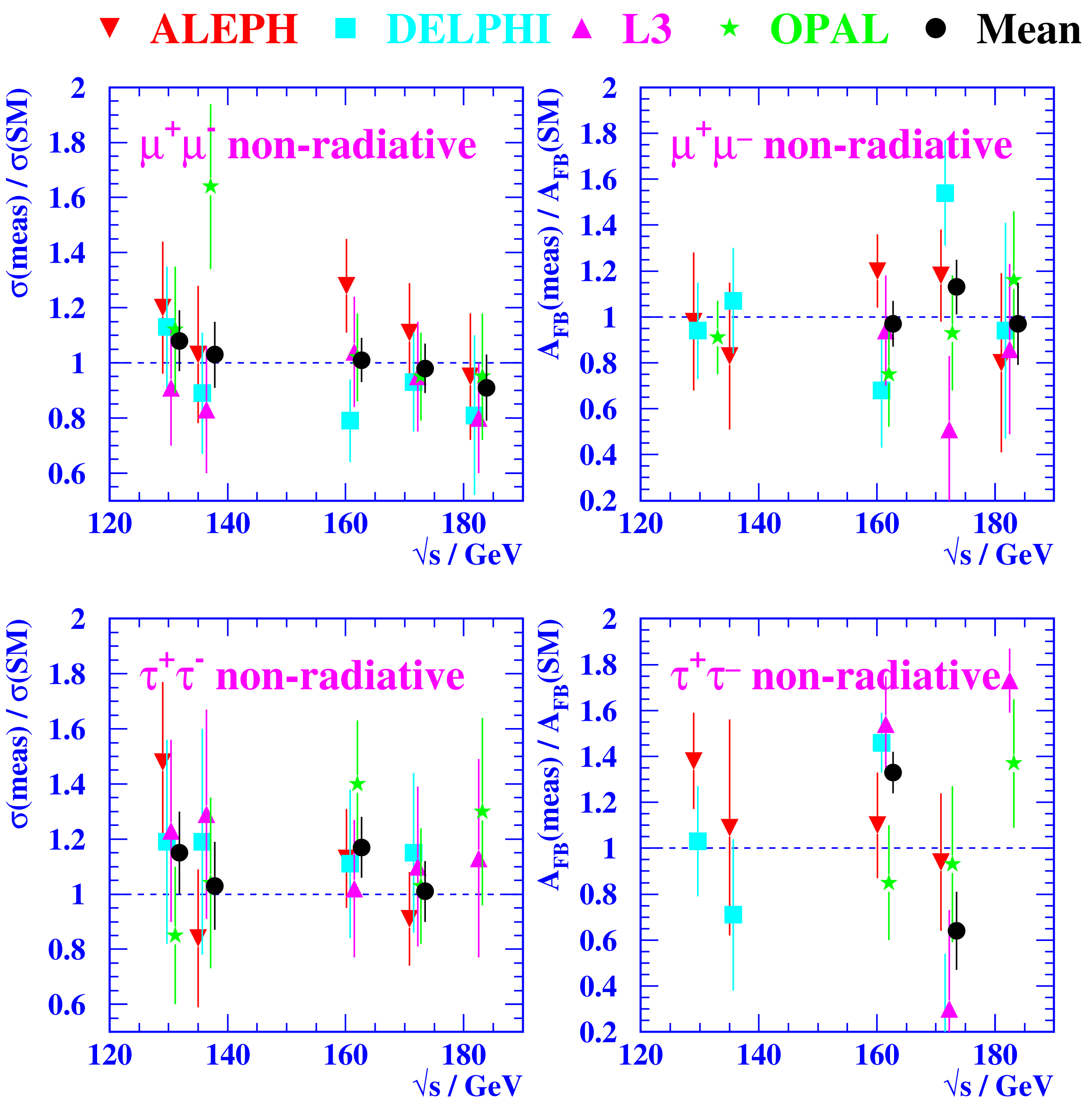
- Measurements generally in good agreement with SM predictions HEP97 #172, 464, 509, 602
- Ratios of measured values to SM predictions for hadrons, electron pairs:



e^+e^- are for barrel region ($|\cos\theta| \lesssim$ 0.7) and acollinearity $\lesssim$ 10–20°

Cross-sections and Asymmetries

- Also for muon and tau pairs:



- N.B. statistical errors dominate systematic errors on ∼ all measurements

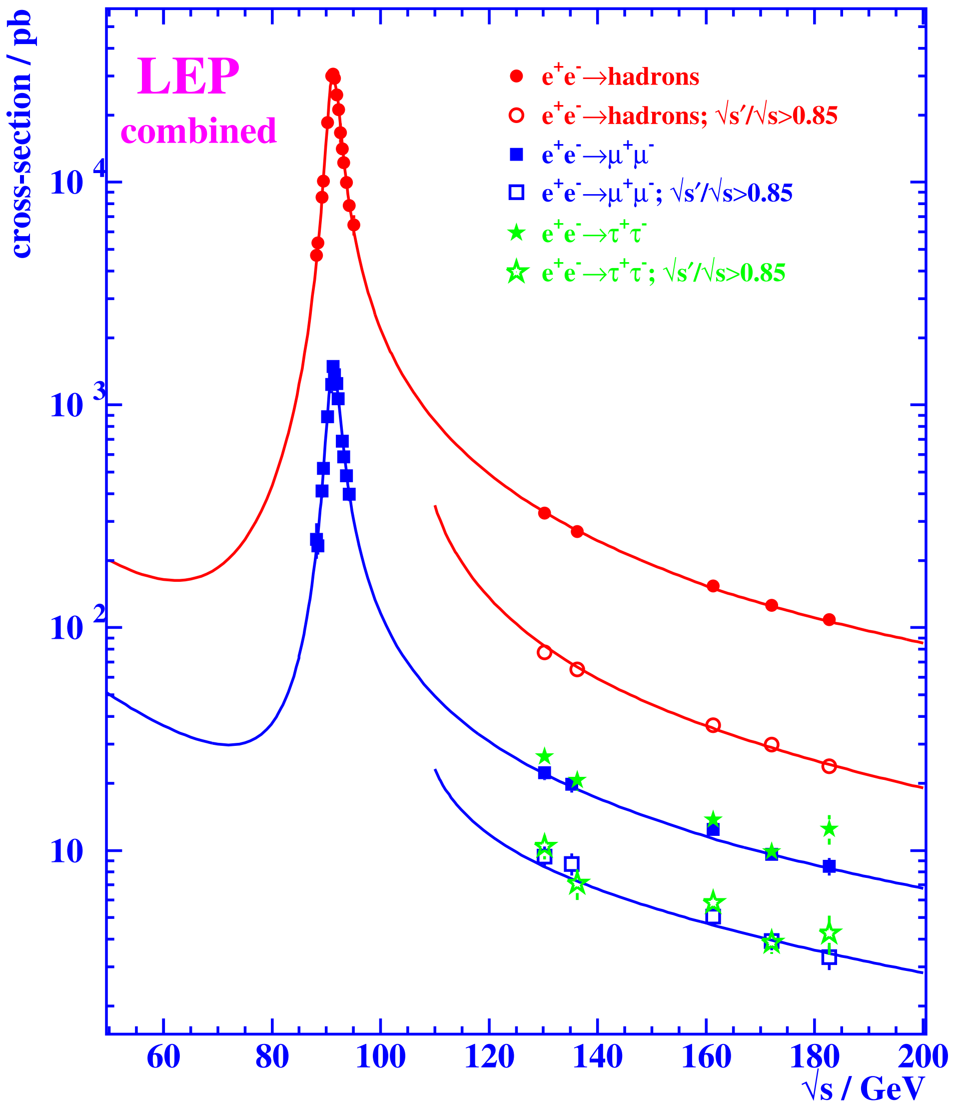
Cross-sections

- Non-radiative cross-sections from all experiments combined:
  - Correct to $\sqrt{s'}/\sqrt{s} > 0.85$ and to mean $\sqrt{s}$ using ZFITTER
  - Take account of all correlated errors
  - Common theory error of 1% not included

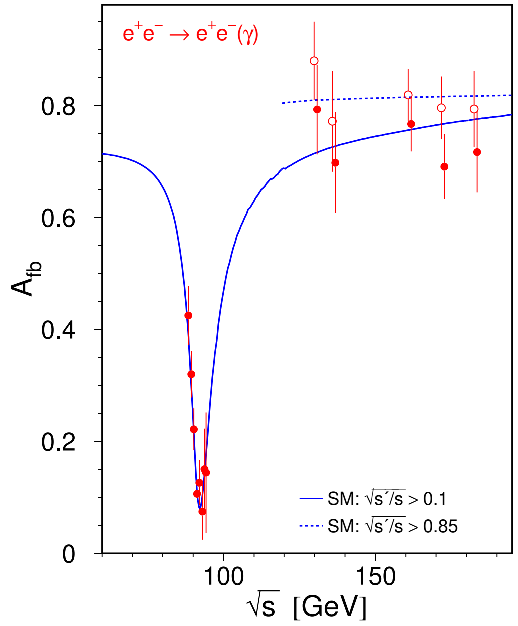
$\sqrt{s}$ (GeV)	σ(pb) $q\bar{q}$	$\mu^+\mu^-$	$\tau^+\tau^-$
130.26	77.6±3.1	9.4 ±1.0	10.4±1.3
SM	82.7	8.4	8.4
136.24	65.1±2.8	8.7 ±1.0	7.1±1.1
SM	66.6	7.3	7.3
161.32	36.5±1.1	5.05±0.41	5.82±0.55
SM	35.3	4.62	4.62
172.10	29.8±1.0	3.92±0.35	3.87±0.44
SM	28.9	3.96	3.96
182.7	23.9±1.2	3.32±0.46	4.25±0.85*
SM	24.3	3.45	3.45

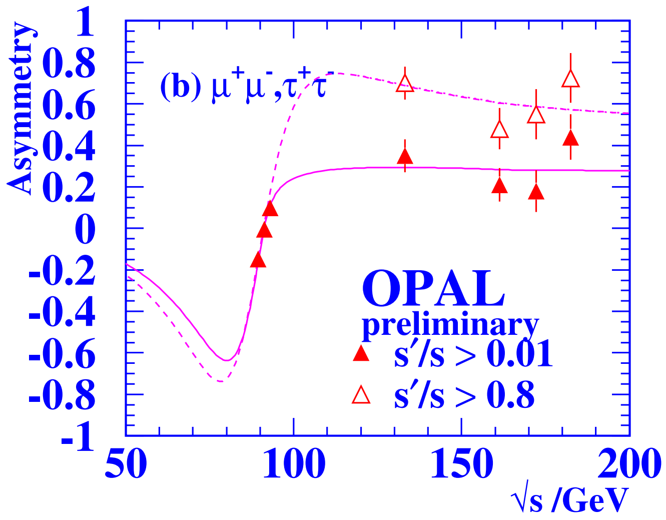
∗ L3 and OPAL only

Cross-sections



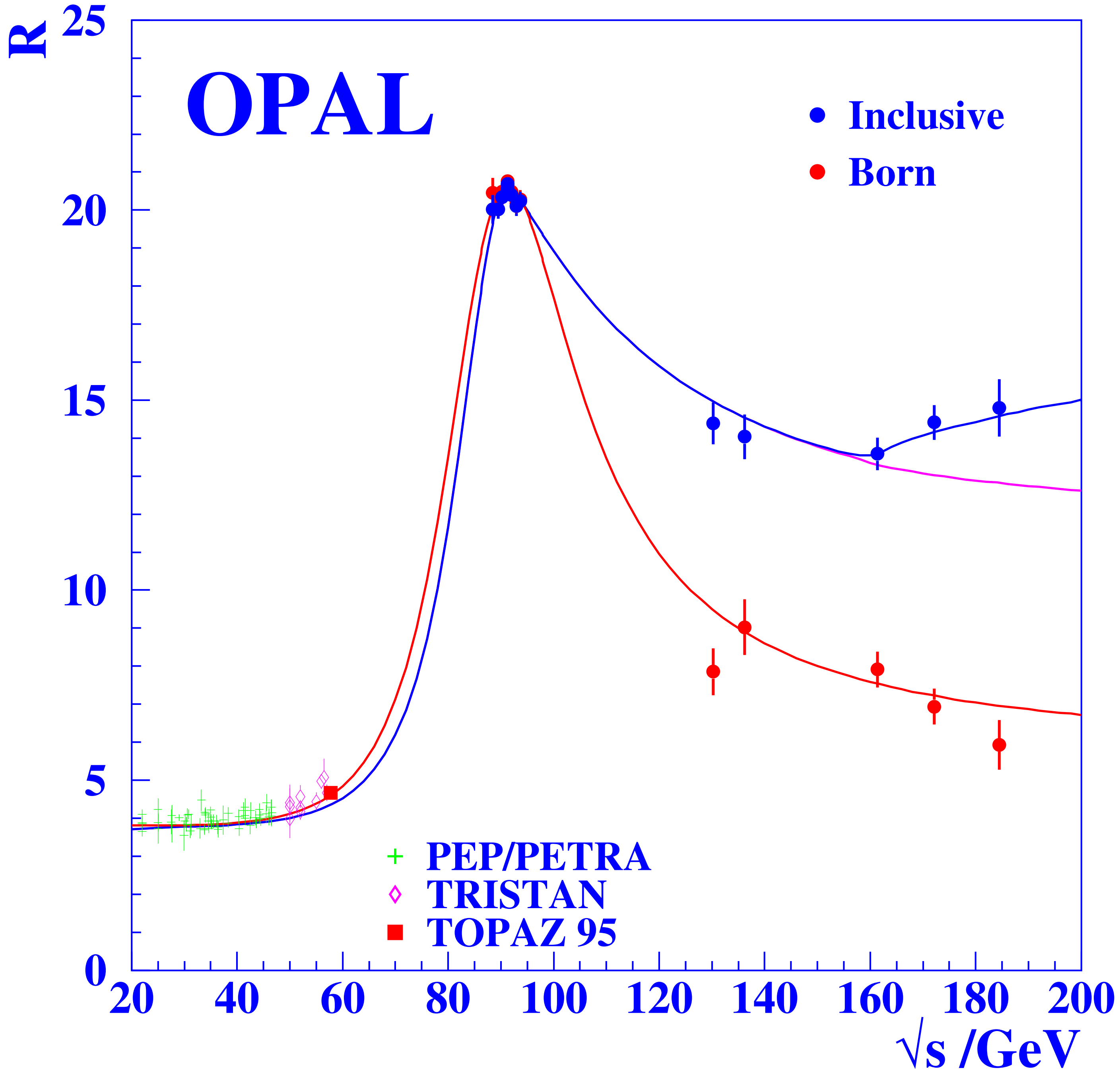
Asymmetries





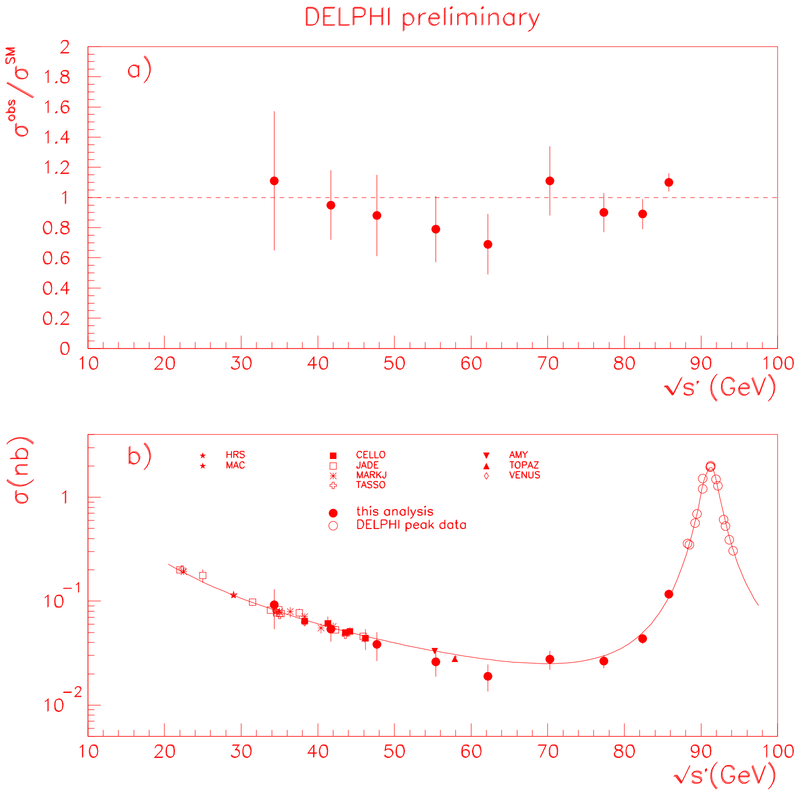
Cross-sections

- OPAL have measured inclusive $q\overline{q}X$ cross-section (no WW subtraction)
- Form ratio of this to theoretical $\mu^+\mu^-$ cross-section $\Rightarrow$ look for production thresholds

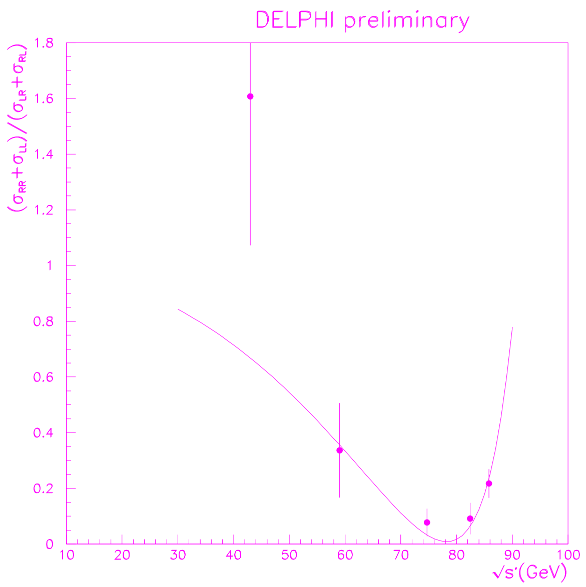


$\sqrt{s'} < m_Z$

- Similar techniques for separating radiative events used on data taken at Z peak to measure cross-sections and asymmetries for $\sqrt{s'} < m_Z$
- DELPHI: updated results on $\mu^+\mu^-\gamma$ including 1995 data



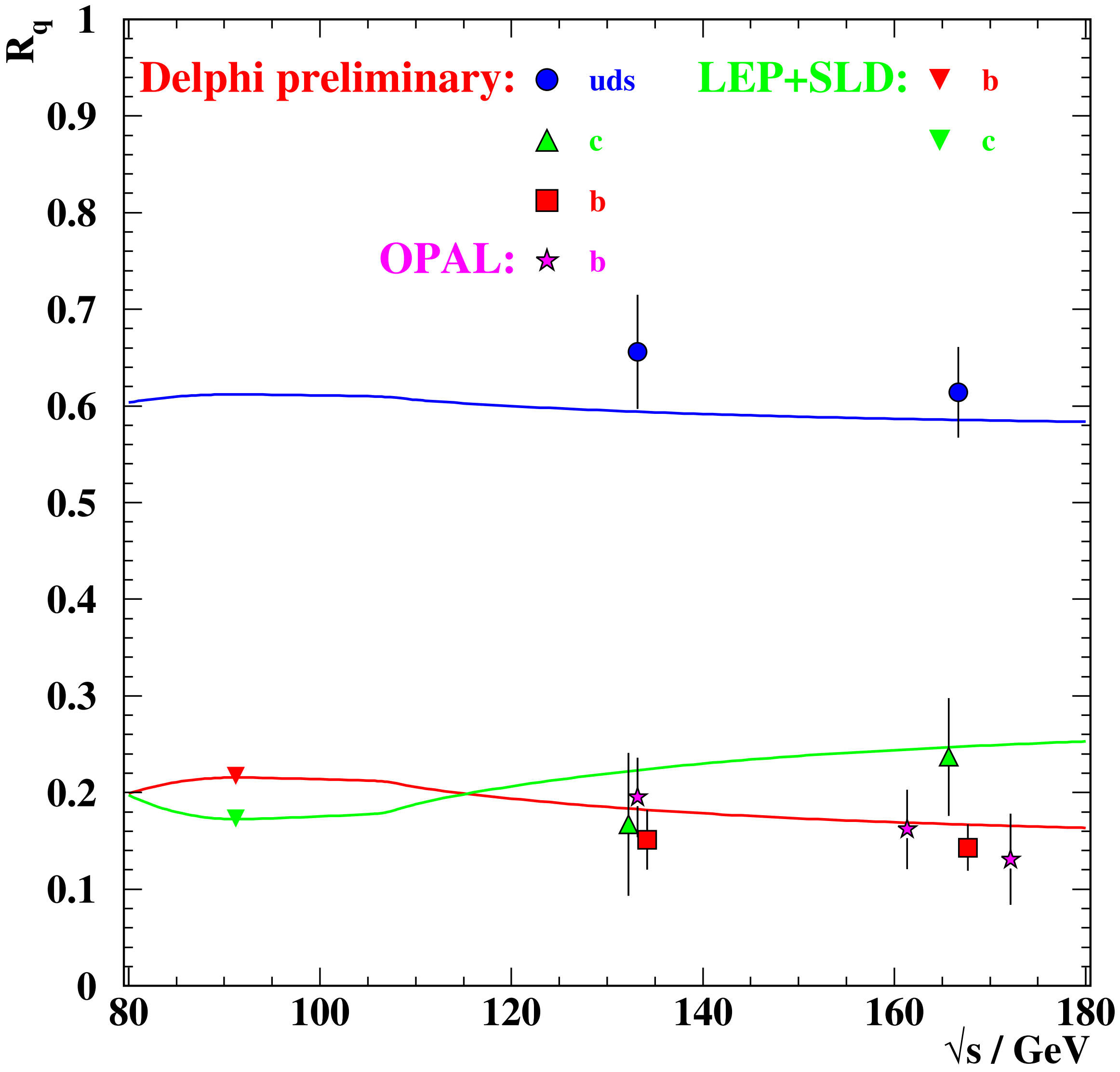
- Also measured ratio of helicity cross-sections; sensitive to new physics as minimum near 80 GeV



HEP97 #465

Flavour tagging

- OPAL: vertex tag $\Rightarrow R_{\rm b}$ HEP97 #172
- DELPHI: impact parameter tag to separate b, c, uds $\Rightarrow R_{\rm b}$, $R_{\rm c}$, $R_{\rm uds}$
  + jet charge $\rightarrow A_{\rm FB}^{\rm b}$, $A_{\rm FB}^{\rm c}$, $A_{\rm FB}^{\rm uds}$ HEP97 #466
- Results in agreement with SM, but $A_{\rm FB}^{\rm c}$ low

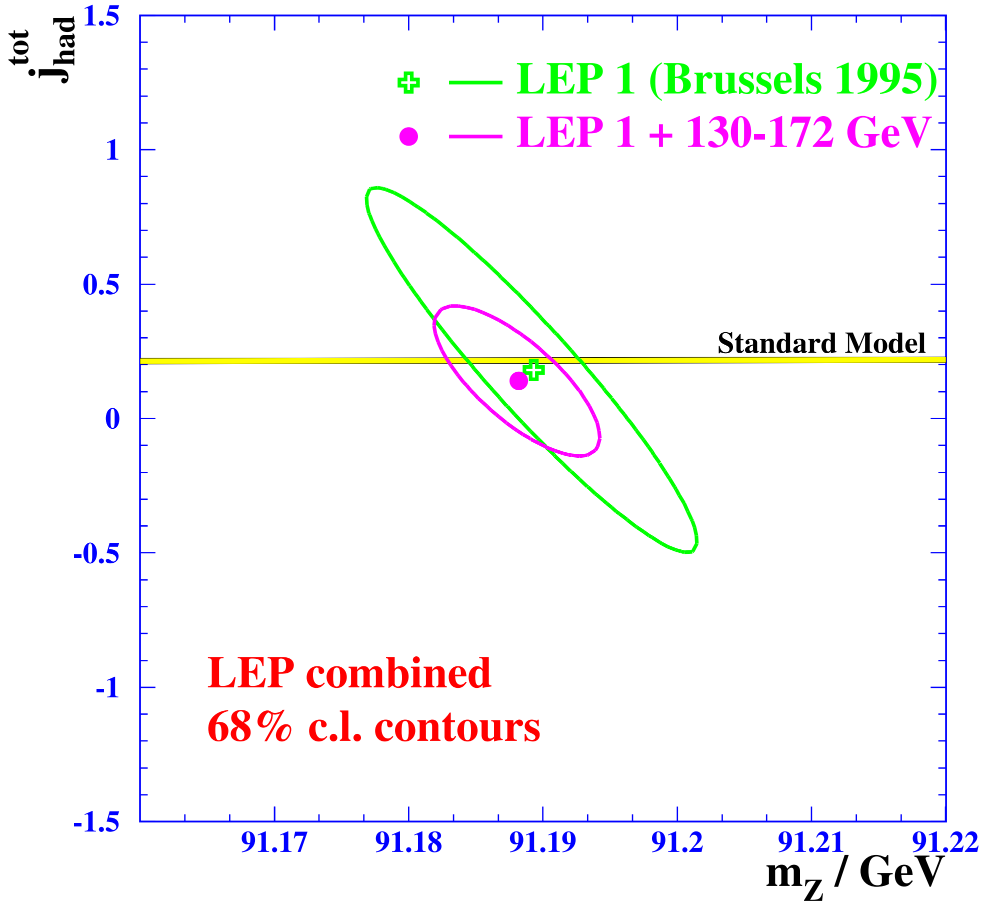


Flavour tagging

		133 GeV	161 GeV	172 GeV
OPAL	R_{b}	0.195±0.041	0.162±0.041	0.131±0.047
DELPHI	R_{b}	0.151±0.031	0.143±0.024	
preliminary	R_{c}	0.167±0.074	0.237±0.061	
	R_{uds}	0.656±0.059	0.614±0.047	
DELPHI	$A^{\mathrm{b}}_{\mathrm{FB}}$ - $A^{\mathrm{SM}}_{\mathrm{FB}}$	0.21±0.52	0.02±0.41	
preliminary	$A^{\mathrm{c}}_{\mathrm{FB}}$ - $A^{\mathrm{SM}}_{\mathrm{FB}}$	–0.75±1.2	–1.91±0.78	
	$A^{\mathrm{s}}_{\mathrm{FB}}$ - $A^{\mathrm{SM}}_{\mathrm{FB}}$	0.78±0.54	–1.25±0.64	
	$A^{\mathrm{u}}_{\mathrm{FB}}$ - $A^{\mathrm{SM}}_{\mathrm{FB}}$	–0.75±0.52	0.75±0.39	
	$A^{\mathrm{d}}_{\mathrm{FB}}$ - $A^{\mathrm{SM}}_{\mathrm{FB}}$	0.95±0.65	–1.19±0.62	

S-matrix fit

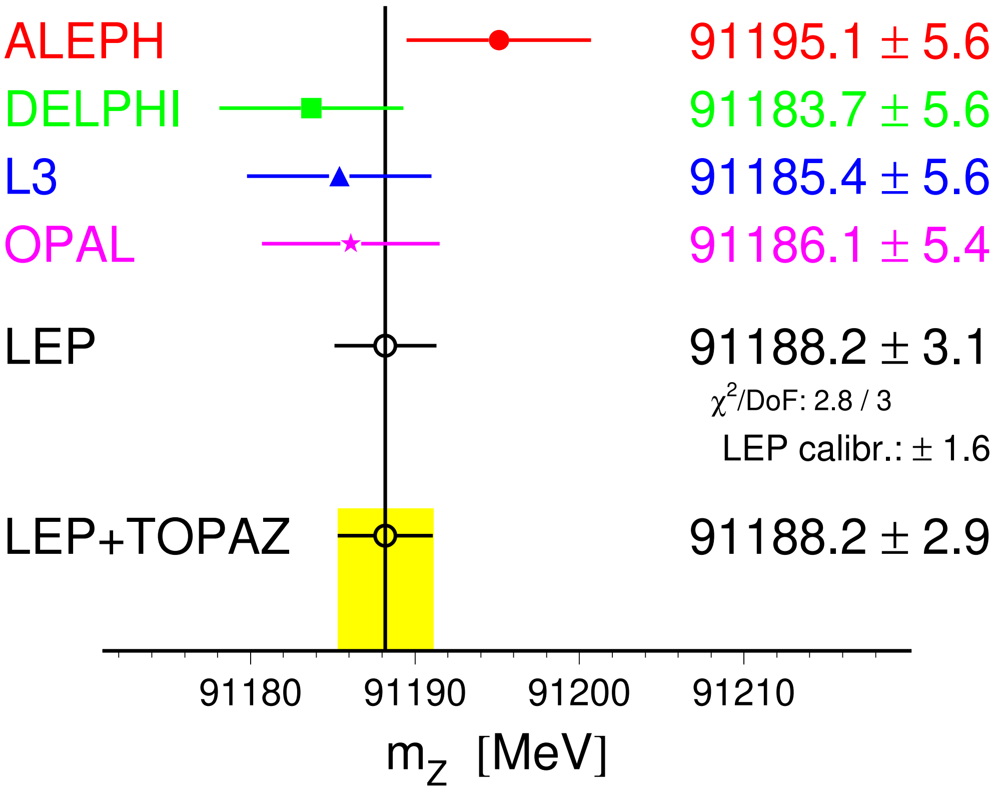
- In electroweak fits at the Z peak, γ-Z interference is not well constrained by the data – often fixed to SM expectation
- Above the Z peak, γ-Z interference important, so data can be used to constrain it
- In the S-matrix formalism, $j_{\mathrm{had}}^{\mathrm{tot}}$ parametrizes the γ-Z interference in the hadronic cross-section.
- Results from all expts, 1990-1996 data, averaged:



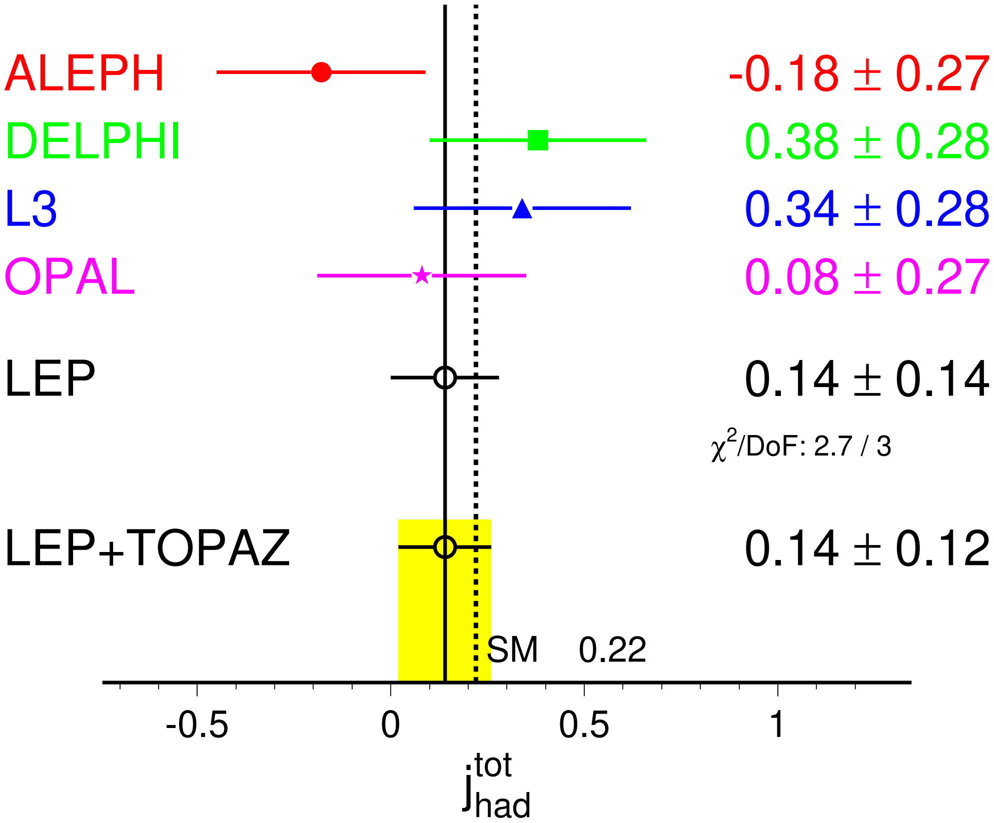
- Adding data above Z reduces error on $j_{\mathrm{had}}^{\mathrm{tot}}$ by $\sim$60%

S-matrix fit

Z-Boson Mass [MeV], S-Matrix



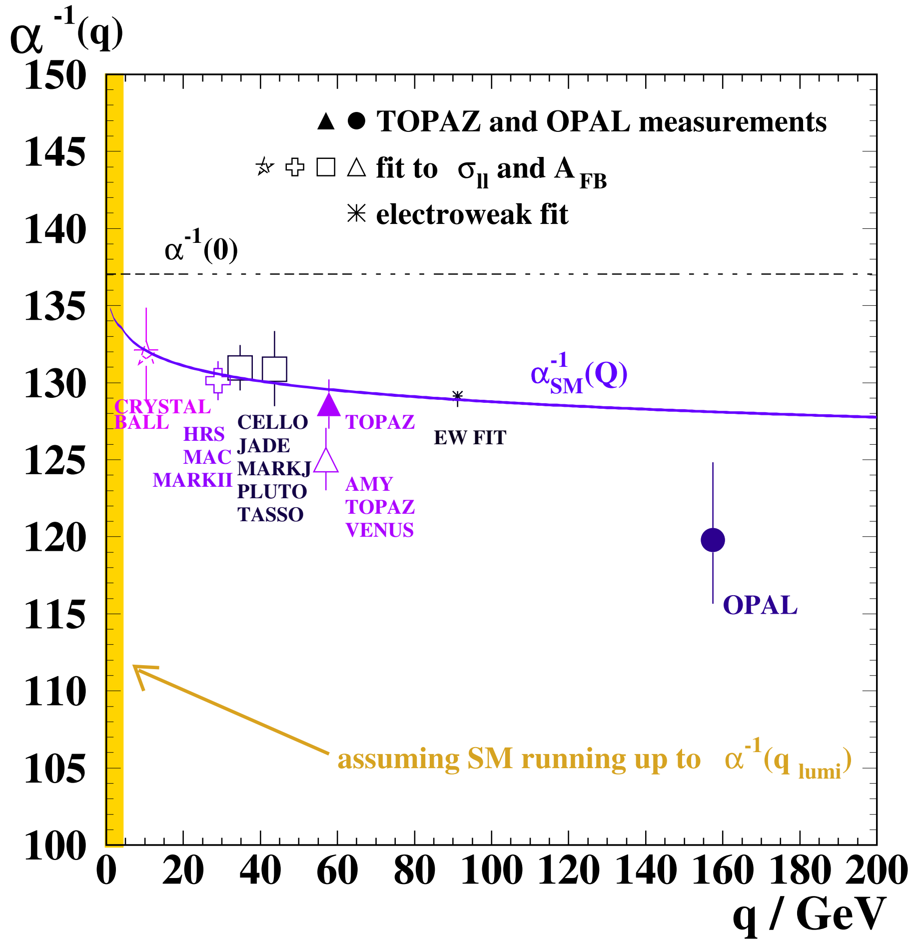
Hadronic γZ interference term



Running of $\alpha_{\rm em}$

- At 130–172 GeV, s-channel $\gamma \simeq$ 2–4 times $\rm Z$ for $\mu^+\mu^-$ and $\tau^+\tau^-$ with $s' \simeq s$
- OPAL used 130–172 GeV cross-section and asymmetry measurements to measure $\alpha_{\rm em}$
- Form χ^2 between measurements and theory (ZFITTER) varying $\alpha_{\rm em}$

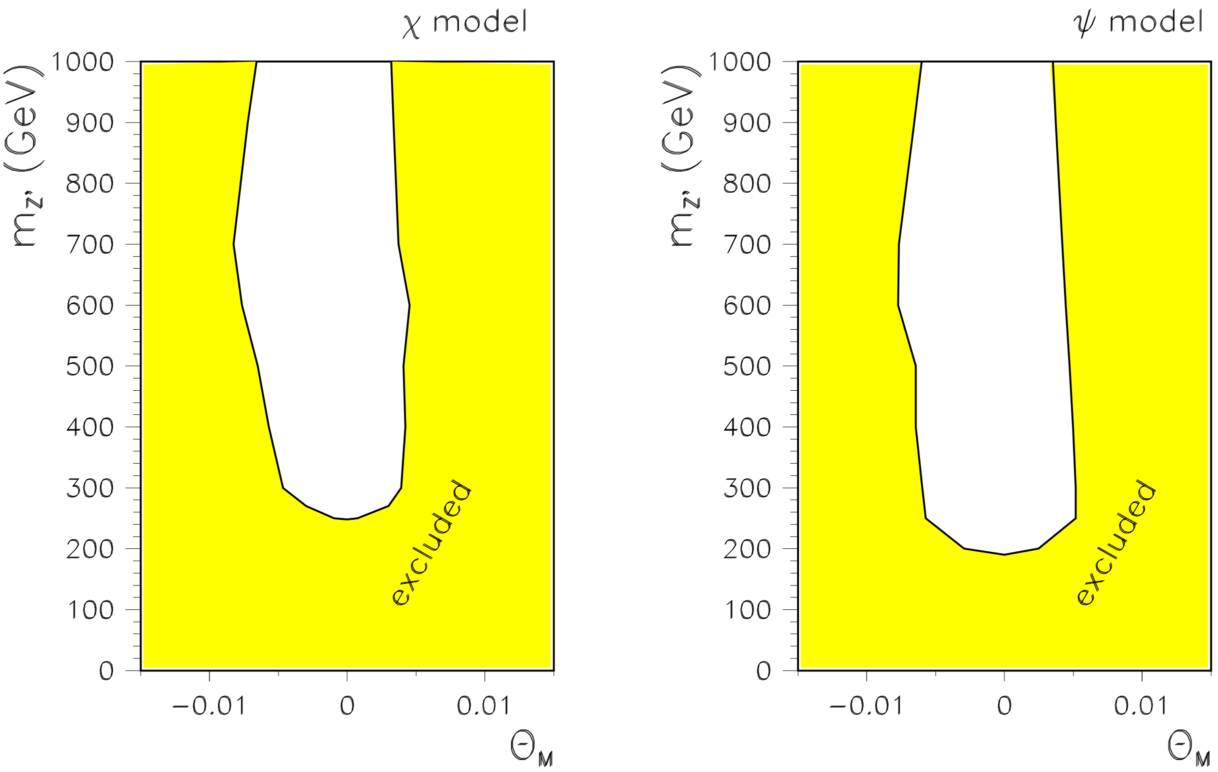
$$1/\alpha_{\rm em}(157.42\ {\rm GeV}) = 119.2\pm^{5.1}_{4.1}$$



- Assumes SM running of $\alpha_{\rm em}$ below $\simeq$ 10 GeV, but remove this by fitting ratios of cross-sections $\rightarrow$ result nearly unchanged

Search for Z'

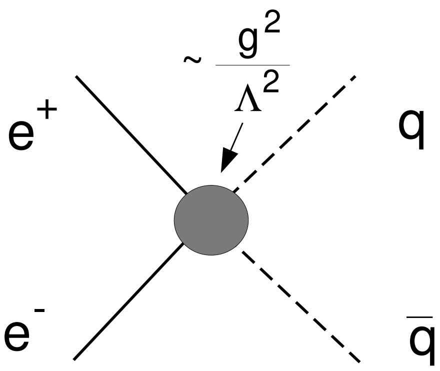
- New results from L3 including Z and 130–172 GeV data
  HEP97 #510
- Z data constrain Z-Z' mixing angle θ_{M}, high energy data constrain Z' mass if mixing is small
- 95% confidence limits for various models, e.g.



- For E6 and LR models, $m_{\mathrm{Z}'} \gtrsim 250$ GeV @ 95% c.l.
- If $\theta_{\mathrm{M}} = 0$ and SM couplings, $m_{\mathrm{Z}'} > 550$ GeV @ 95% c.l.
  c.f. similar CDF limit 690 GeV
- Also model independent limits on $\mathrm{Z}'\ell\bar{\ell}$ couplings

Contact Interactions

- General framework for searching for new physics with energy scale Λ



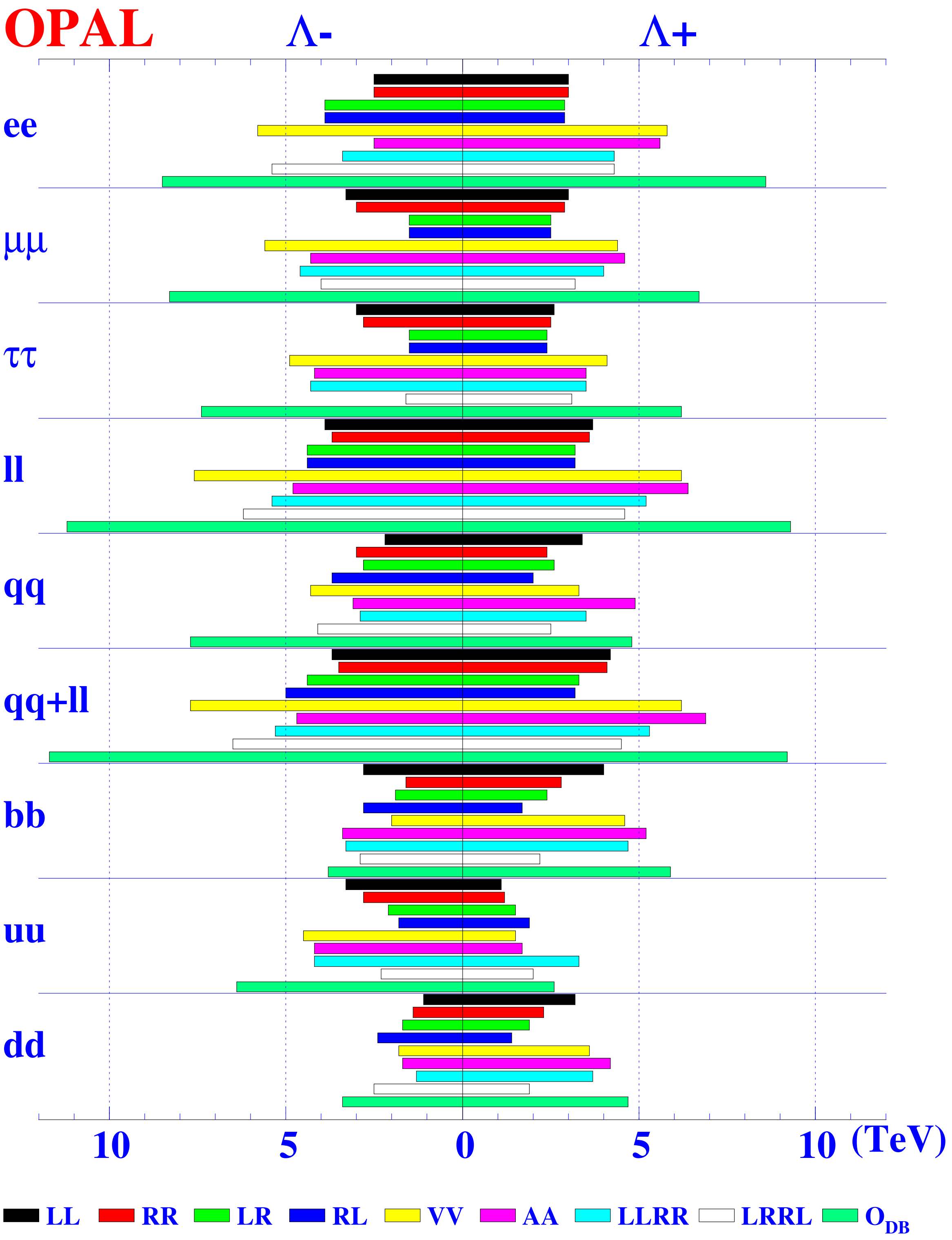
$$\mathcal{L}^{\text{contact}} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{i,j=\mathrm{L,R}} \eta_{ij} [\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_i][\bar{\mathrm{f}}_j \gamma_\mu \mathrm{f}_j]$$

- Many different models depending on η_{ij}
- Sensitivity increases with c.m. energy
- Results from ALEPH, DELPHI, OPAL; HEP97 #172, 466, 467, 602

  Recent update from ALEPH using 183 GeV data
- Fit lepton angular distributions, hadronic cross-sections and R_b (O, D), R_c, R_uds, $A_\mathrm{FB}^{\mathrm{b,c,uds}}$ (D)
- Limits Λ_+, Λ_- depending on sign of η_{ij}

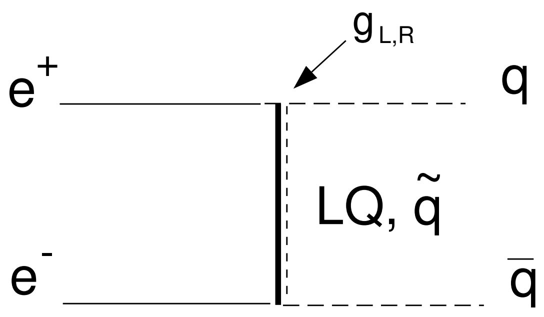
Contact Interactions

- 95% confidence limits on Λ assuming $g^2 = 4\pi$
- Typical limits in range 3–8 TeV for all channels combined

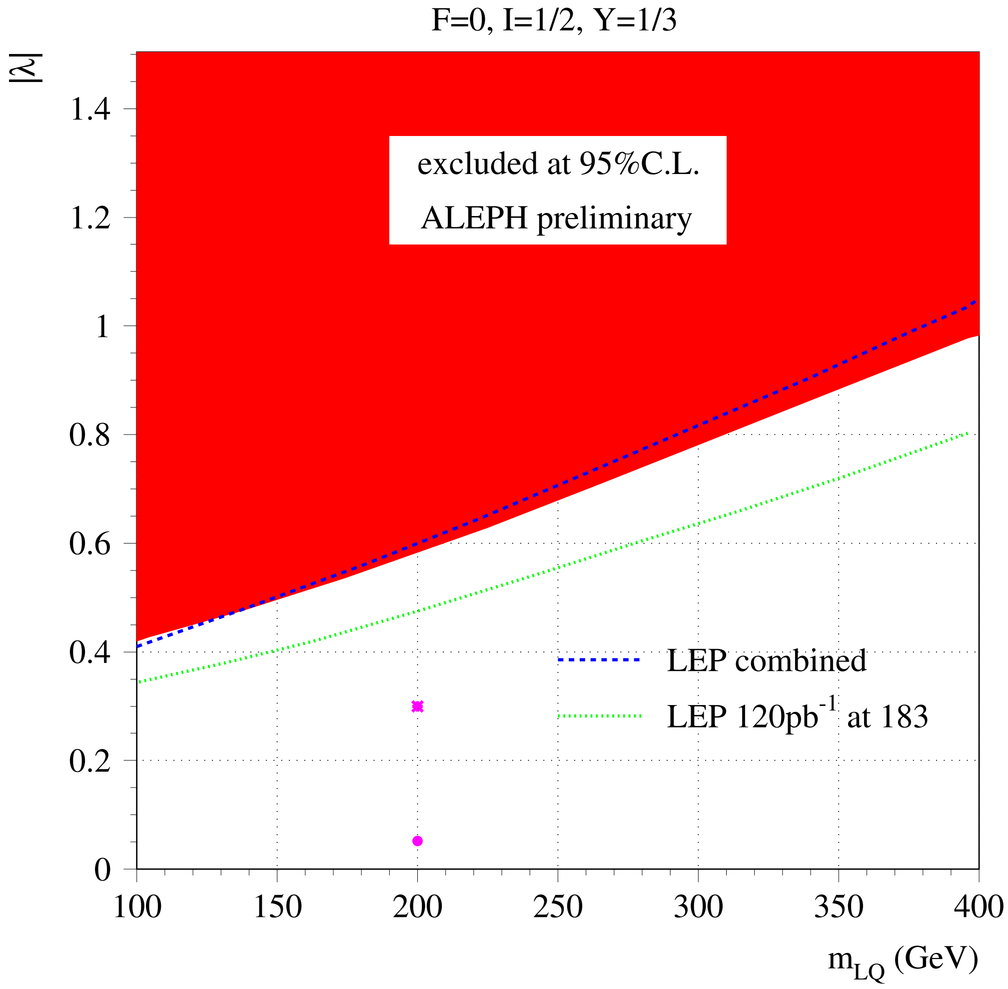


Leptoquarks / RPV squarks

- t-channel exchange of new heavy particle, e.g. leptoquark, squark in R-parity violating SUSY, may alter hadronic cross-section

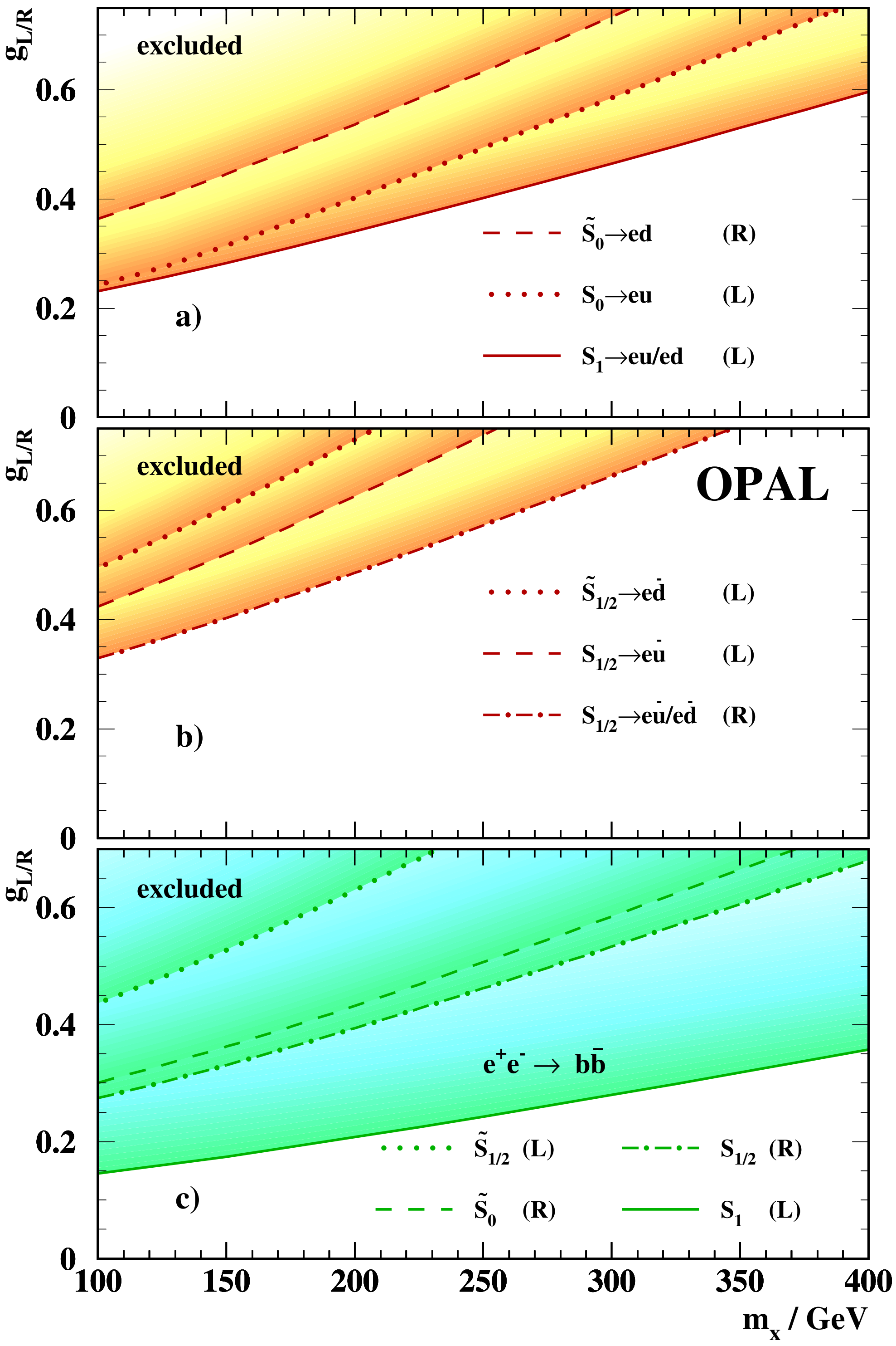


- Results from ALEPH, DELPHI, OPAL: HEP97 # 172, 466, 602; ALEPH results updated using 183 GeV data



Leptoquarks / RPV squarks

Limits on the coupling for Scalar Leptoquarks

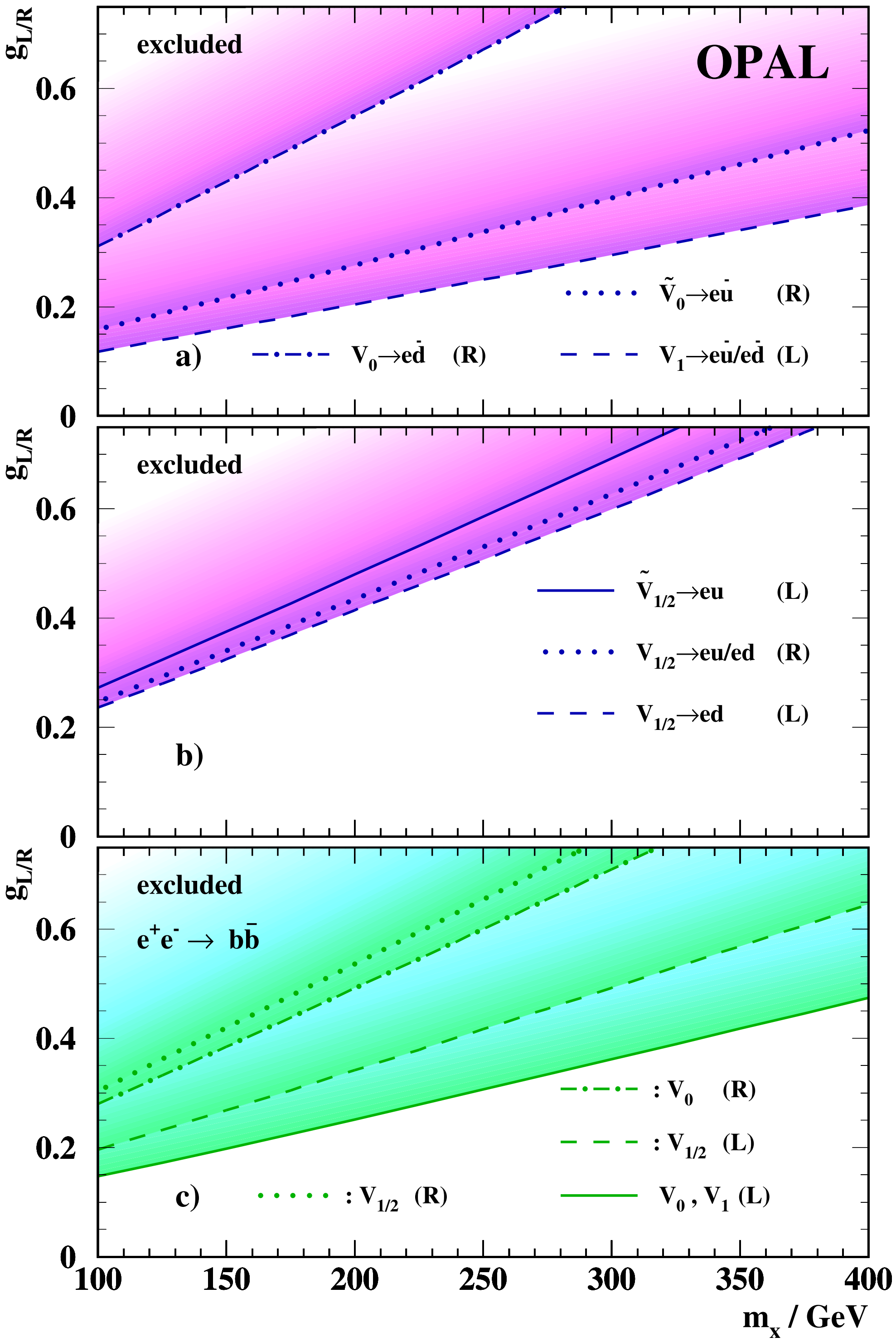


- $S_0 \equiv \tilde{d}_R$

  $\tilde{S}_{1/2} \equiv \tilde{u}_L$

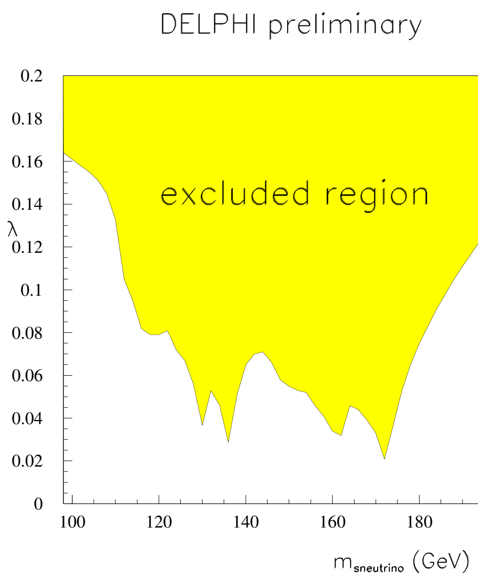
Leptoquarks

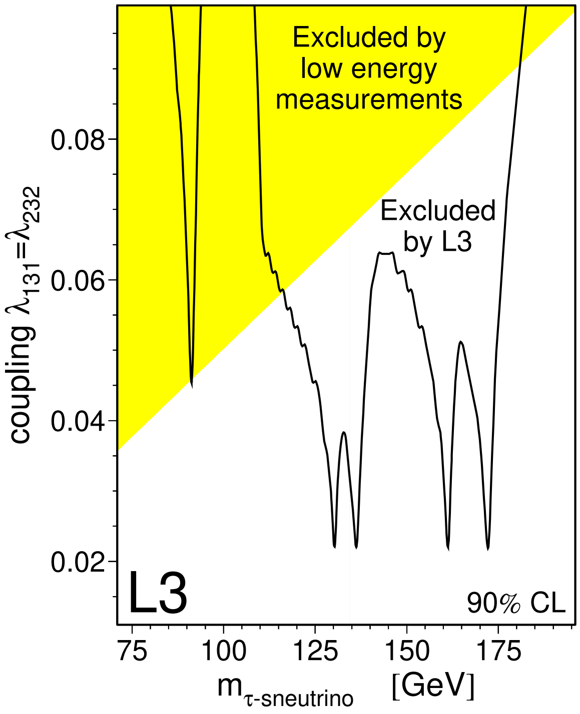
Limits on the coupling for Vector Leptoquarks



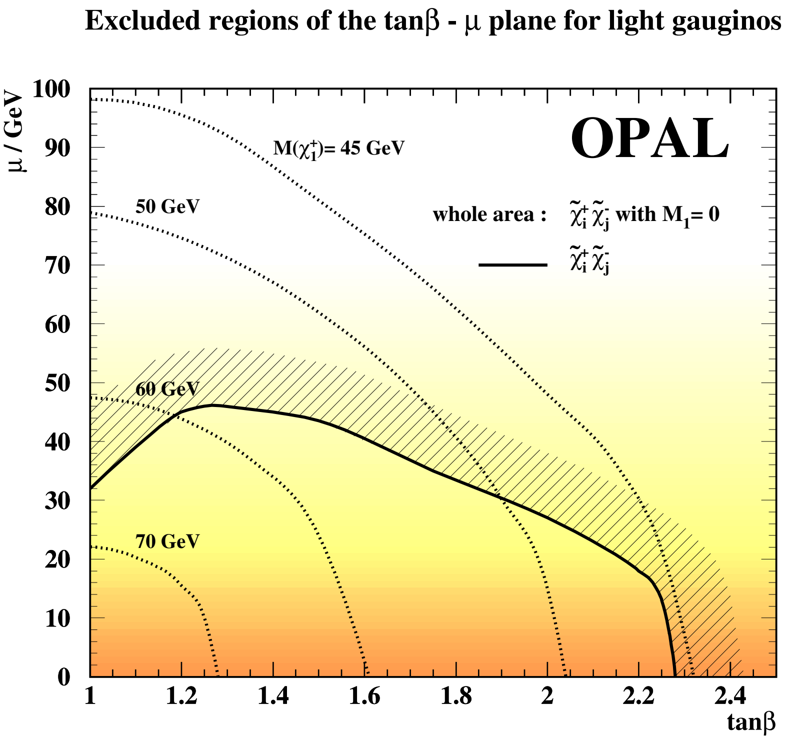
Other Limits

- L3, DELPHI have used lepton pair data to put limits on sneutrinos in R-parity violating SUSY models, e.g. for $\lambda_{131} = \lambda_{232} = \lambda$: HEP97 #467





- OPAL have used hadronic cross-sections to place limits on light gluinos: HEP97 #172



Summary

- Cross-section and lepton asymmetry measurements at 130-172 GeV in agreement with SM predictions
- First results at 183 GeV also consistent with SM
- Data above the Z constrain γ-Z interference
- Running of α_{em} investigated
- Measurements used to put limits on new physics:
  Z', contact interactions, leptoquarks/squarks, $\tilde{\nu}$, light gluinos
- We look forward to pursuing these studies at even higher energies