Two–fermion and Two–photon Final States at LEP2 and Search for Extra Dimensions

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- **Introduction**
- **Fermion-pair production:**
  $\mathbf{e^+e^- \to f\bar{f}(\gamma)}$
- **Photon-pair production:**
  $\mathbf{e^+e^- \to \gamma\gamma(\gamma)}$
- **Searches for new phenomena**
  Contact interactions & Compositeness
  Extra dimensions
- **Outlook**

Les Rencontres de Physique de la Vallée d'Aoste
La Thuile, Aosta Valley, Italy, 4-10 March 2001

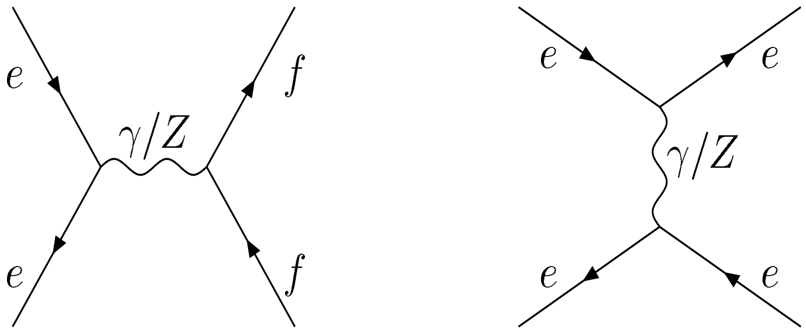
Data

Year	$\sqrt{s}$ GeV	$\mathcal{L}$ pb^{-1}	$q\bar{q}$ stat. err % single exp. total / HE	Mode
1995 & 97	130	6	2.3/5.2	Above
1995 & 97	136	6	2.6/6.0	M_Z
1996	161	10	2.7/5.9	W pairs
1996	172	10	3.2/7.3	W mass
1997	183	55	1.4/3.3	Z pairs
1998	189	177	0.8/1.8	High
1999	192-202	233	0.7/1.6	precision
2000	202-209	220	0.7/1.6	Higgs
1995-2000	130-209	720	0.4/0.8	LEP2

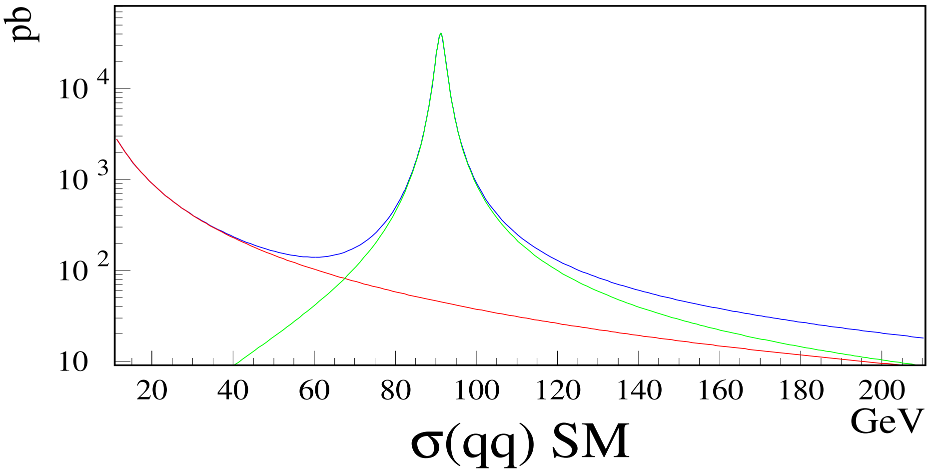
Data up to 189 GeV final

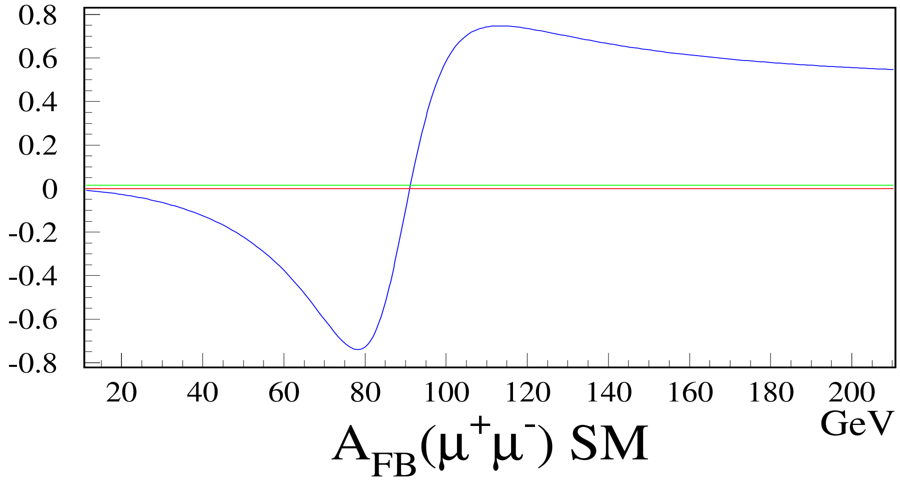
Data 192–209 GeV preliminary

Preliminary results on the full LEP2 data set



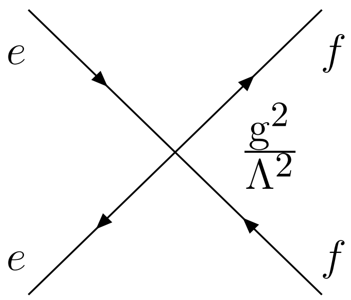
$$\frac{d\sigma}{d\Omega} = |\gamma_s + Z_s + \mathrm{elec} * (\gamma_t + Z_t) + \text{New Physics ?!}|^2$$

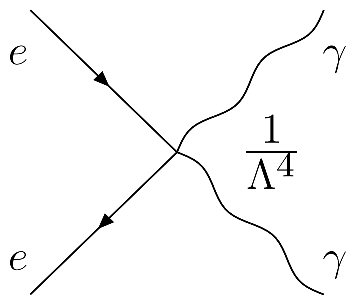




general framework for a new interaction with typical energy scale $\Lambda \gg \sqrt{\mathrm{s}}$; operators with canonical dimension $N > 4 \Rightarrow$ effects $\sim 1/M^{N-4}$

g	coupling (by convention $\frac{g^2}{4\pi} = 1$)
$\vert\eta_{ij}\vert \leq 1$	helicity amplitudes
ε	$\frac{g^2}{4\pi}\frac{sign(\eta)}{\Lambda^2}$ for $f\bar{f}$ $\sim \frac{1}{\Lambda^4}$ for $\gamma\gamma$





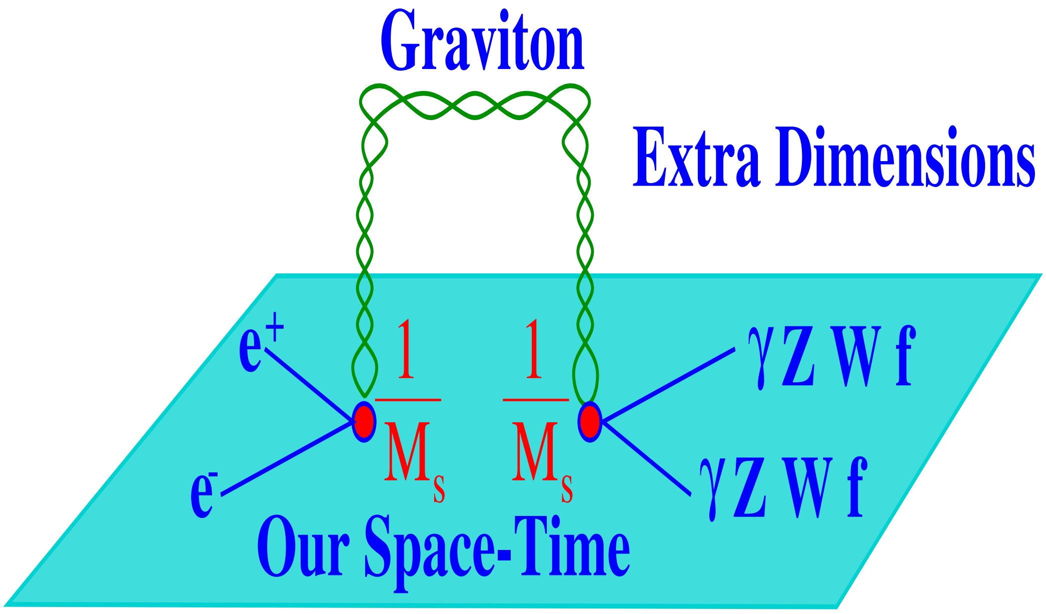
$$\frac{d\sigma}{d\Omega} = \mathrm{SM}(s,t) + \varepsilon \cdot \mathrm{C_{Int}}(s,t) + \varepsilon^2 \cdot \mathrm{C_{NewPh}}(s,t)$$

Model	LL	RR	LR	RL	VV	AA	LL+RR	LR+RL
	Non-parity conserving				Parity conserving			
η_{LL}	±1	0	0	0	±1	±1	±1	0
η_{RR}	0	±1	0	0	±1	±1	±1	0
η_{LR}	0	0	±1	0	±1	∓1	0	±1
η_{RL}	0	0	0	±1	±1	∓1	0	±1

Better understanding of space-time?

Maximum phenomenology with minimum parameters

Study quantum gravity at colliders



Fermion/Boson pair production - Virtual effects
class of theories with virtual graviton exchange
(KK excitations) $\Rightarrow$ effective scale (cut-off) M_s

Guidice, Ratazzi and Wells; Hewett; Rizzo; Agashe and Deshpande ...

Results are model-dependent: $\frac{\lambda}{M_s^4}$

λ not known exactly $\Rightarrow$ assume $\lambda = \pm 1$

- massive string mode oscillations (TeV strings)

Accomando, Antoniadis and Benakli; Cullen, Perelstein and Peskin

dimension-8 operators - M_S - string scale

LSG scale $M \sim 1.6 - 3.0\ M_S$; $\frac{M}{M_S} = \left(\frac{1}{\pi}\right)^{1/8} \alpha'^{-1/4}$

String form factor

$$\mathcal{S}(s,t) = \frac{\Gamma(1 - \frac{s}{M_S^2})\Gamma(1 - \frac{t}{M_S^2})}{\Gamma(1 - \frac{s}{M_S^2} - \frac{t}{M_S^2})}$$

$\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}$

$$\frac{d\sigma}{d\cos\theta} = \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} \cdot |\mathcal{S}(s,t)|^2$$

$\mathrm{e^+e^-} \rightarrow \gamma\gamma$

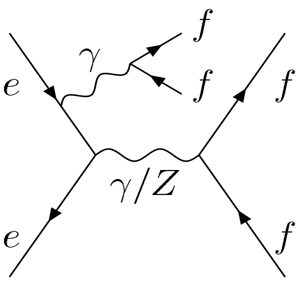
Drell's parametrization (QED cut–off)

$$\Lambda_+^{\mathrm{QED}} = \left(\frac{12}{\pi^2}\right)^{1/4} \cdot \mathrm{M_S} = 1.05\ \mathrm{M_S}$$

- D3 and D7 brane models - can give dimension-6 operators ! Antoniadis, Benakli and Laugier ...

contact interactions induced by massive string oscillators - can be stronger than KK states or winding modes

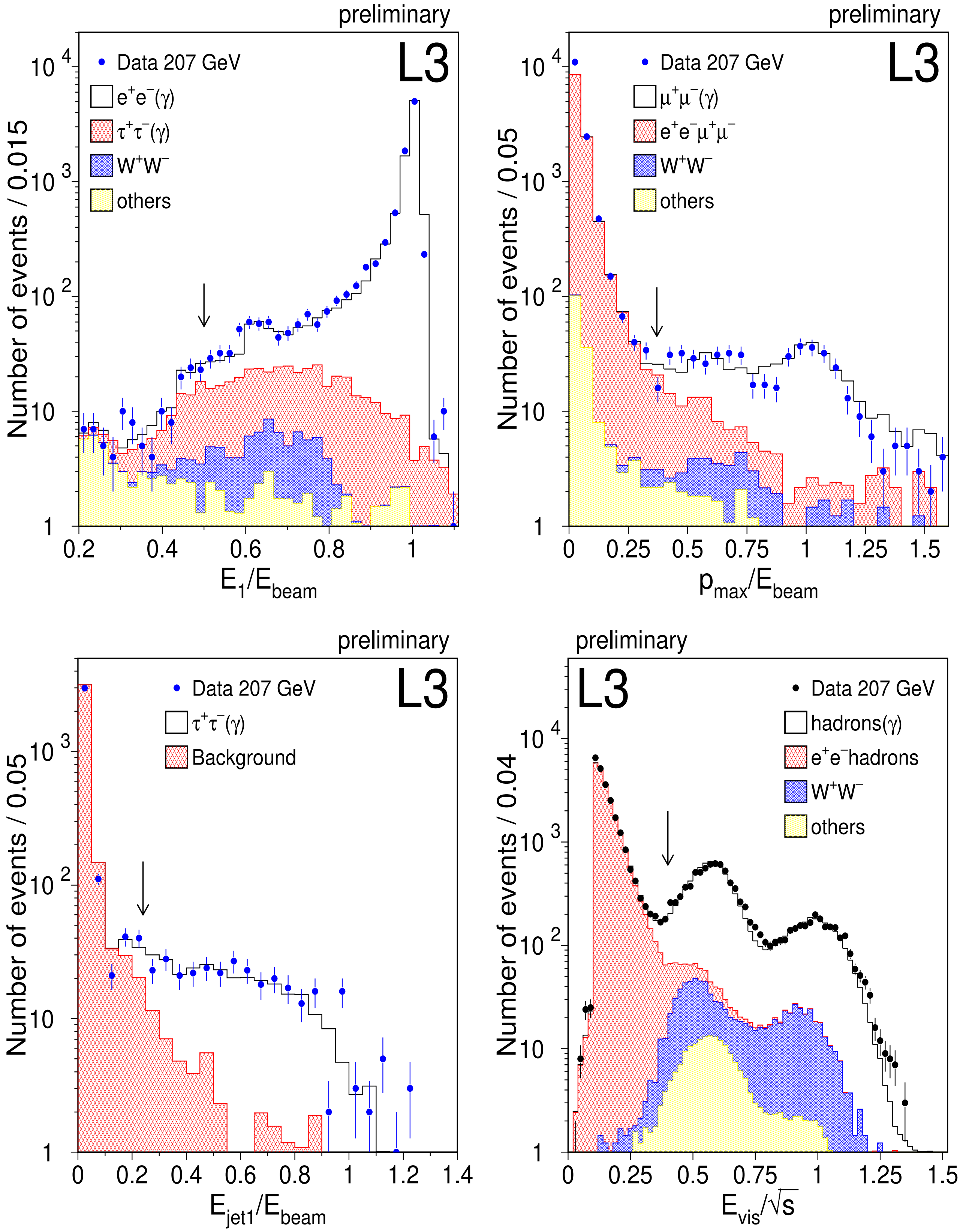
- Interplay between 2-f and 4-f events; radiative corrections, real pairs



low mass fermion pairs are signal, like photons

- Definition of s': not unique due to interference between initial- and final-state radiation
  - interference changes the cross-sections: for $\sqrt{s'}/\sqrt{s} > 0.85$ by $\sim 1.5\%$ for $\mu^+\mu^-$ and $\sim 0.5\%$ for $q\bar{q}$ in $\mathcal{O}(\alpha)$ (efficiency changed by $\leq 50\%$ of this)
  - correct or define $\sqrt{s'}$ as the effective mass of the outgoing fermion pair
- Rising 4-f background (W^+W^-, ZZ, $Z\,e^+e^-$, $We\nu$, ...)

LEP2 Monte Carlo Workshop - Two-fermion Working Group, CERN-YR-2000-009, hep-ph/0007180



preliminary
L3
Data 207 GeV
e+e−(γ)
τ+τ−(γ)
W+W−
others
Number of events / 0.015
E1/Ebeam
preliminary
L3
Data 207 GeV
μ+μ−(γ)
e+e−μ+μ−
W+W−
others
Number of events / 0.05
pmax/Ebeam
preliminary
L3
Data 207 GeV
τ+τ−(γ)
Background
Number of events / 0.05
Ejet1/Ebeam
preliminary
L3
Data 207 GeV
hadrons(γ)
e+e−hadrons
W+W−
others
Number of events / 0.04
Evis/√s

Combines the measurements of σ_{tot}, $\mathrm{A_{FB}}$, R_b, R_c and $\frac{d\sigma}{d\cos\theta}$ for:

$\mu^+\mu^-$, $\tau^+\tau^-$, $\mathrm{q\bar{q}}$ final states

performs combined fits for contact interactions and Z'

Note LEP2FF/01-01 for Winter Conf. 2001

Combination of the LEP II $\mathrm{f\bar{f}}$ Results

LEPEWWG $\mathrm{f\bar{f}}$ Subgroup

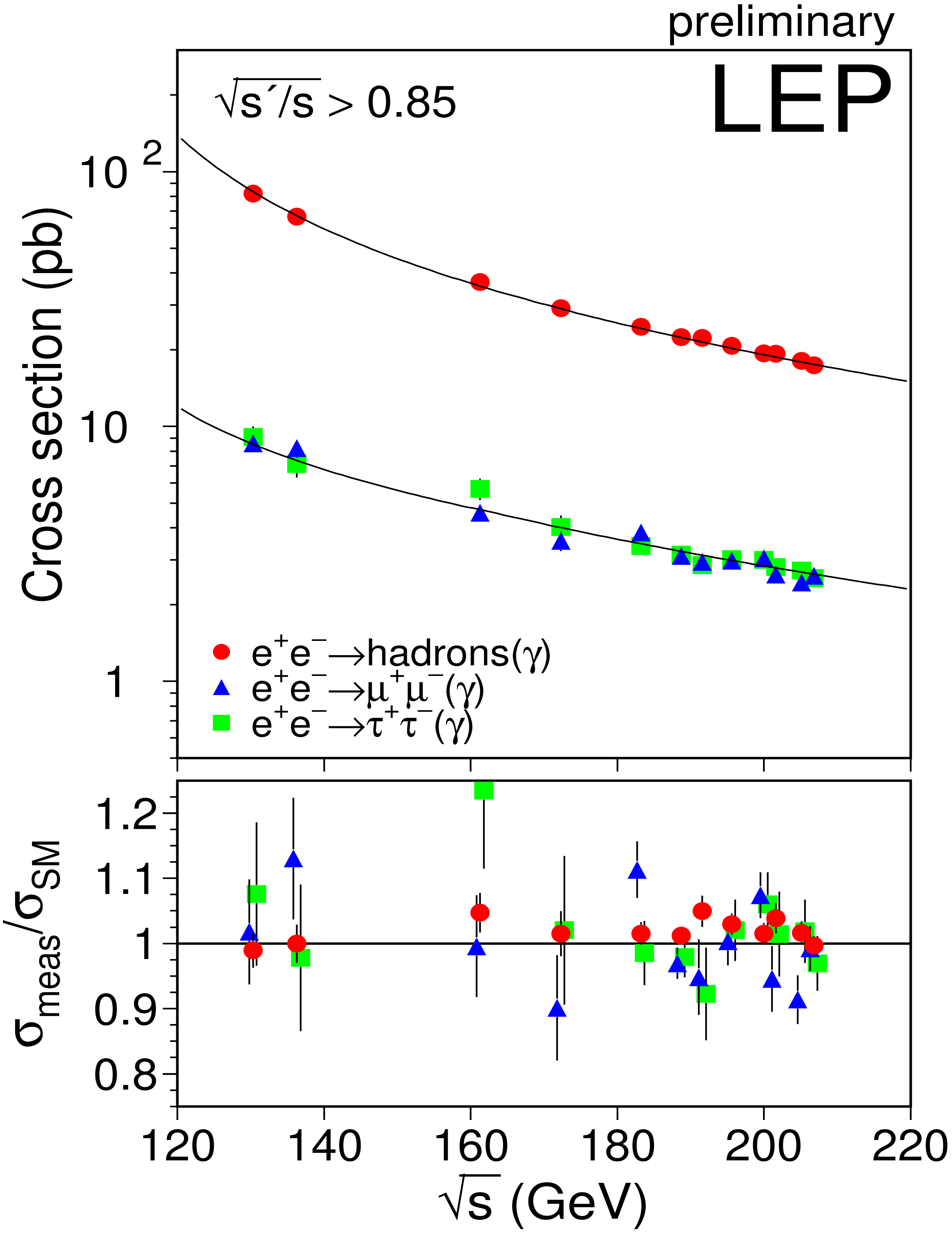
Members :

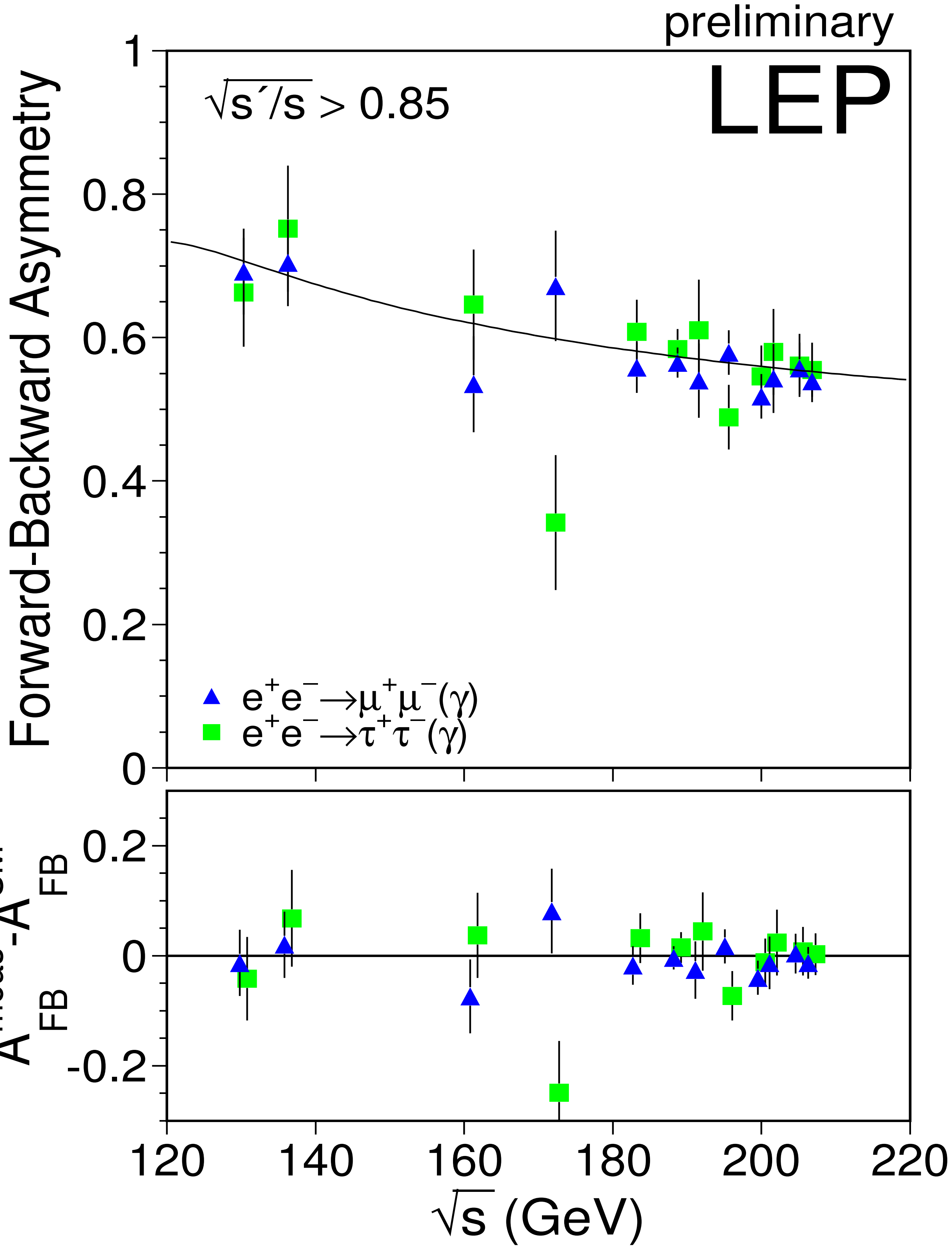
C. Geweniger, C. Goy, M-N Minard
M. Elsing, J. Holt, W. Liebig, A. Olshevski, P. Renton
S. Blyth, D. Bourilkov, S. Riemann, S. Wynhoff
F. Fiedler, M. Kobel, S. Marcellini, K. Sachs, P. Ward

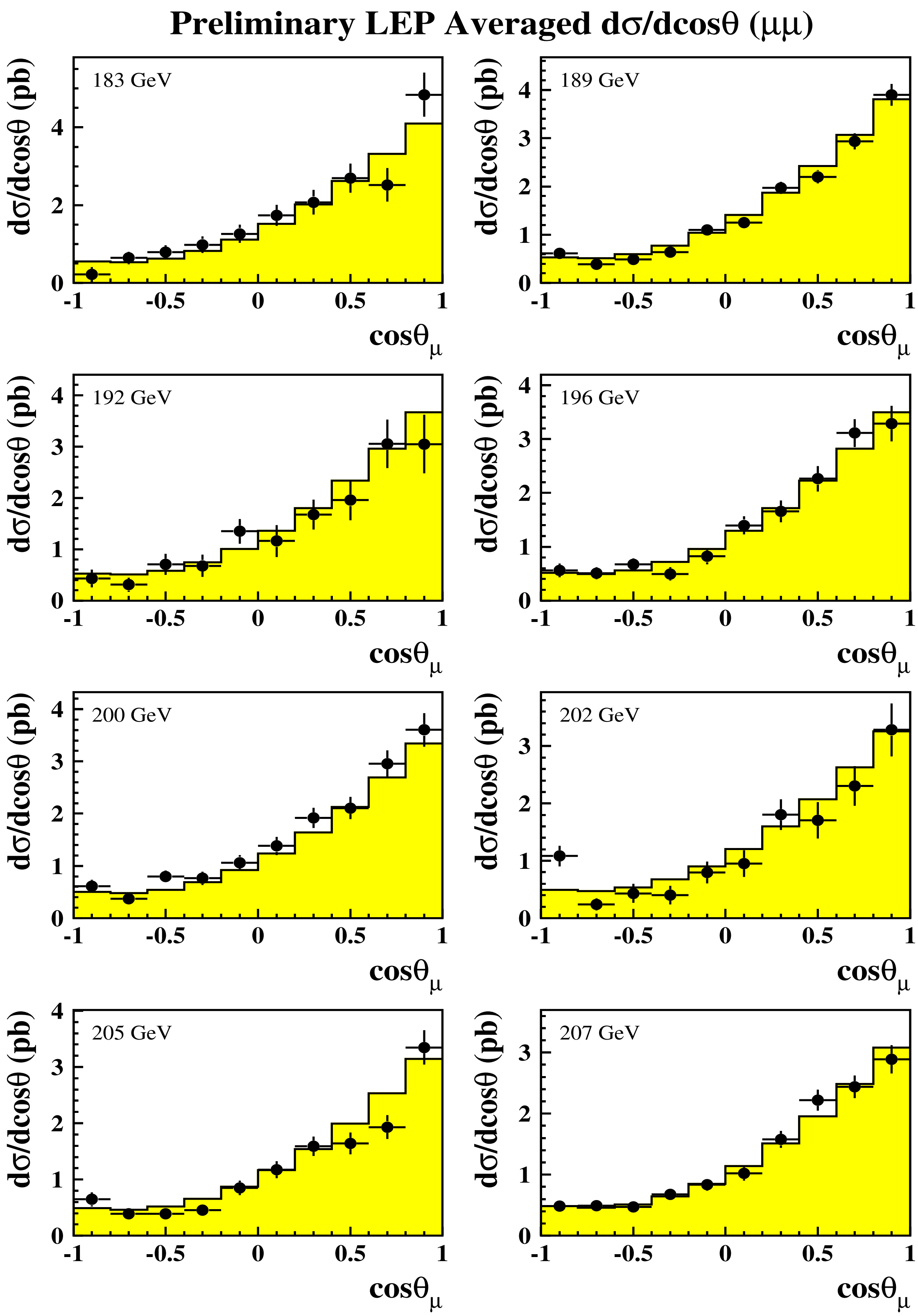
Abstract

Preliminary combinations of measurements of the 4 LEP collaborations of the process

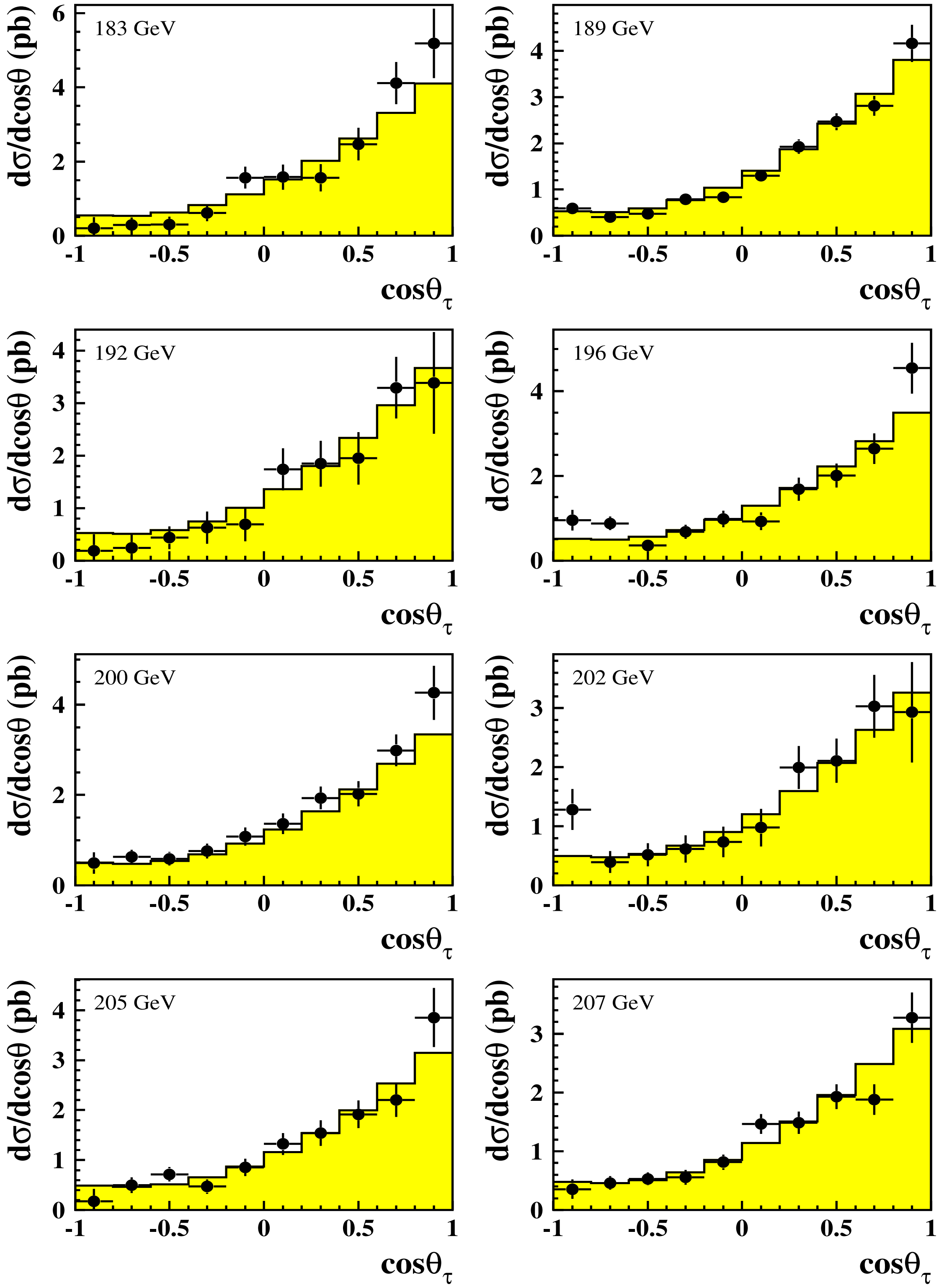
Future plans: combine $\mathrm{e^+e^-}$ and $\gamma\gamma$ final states

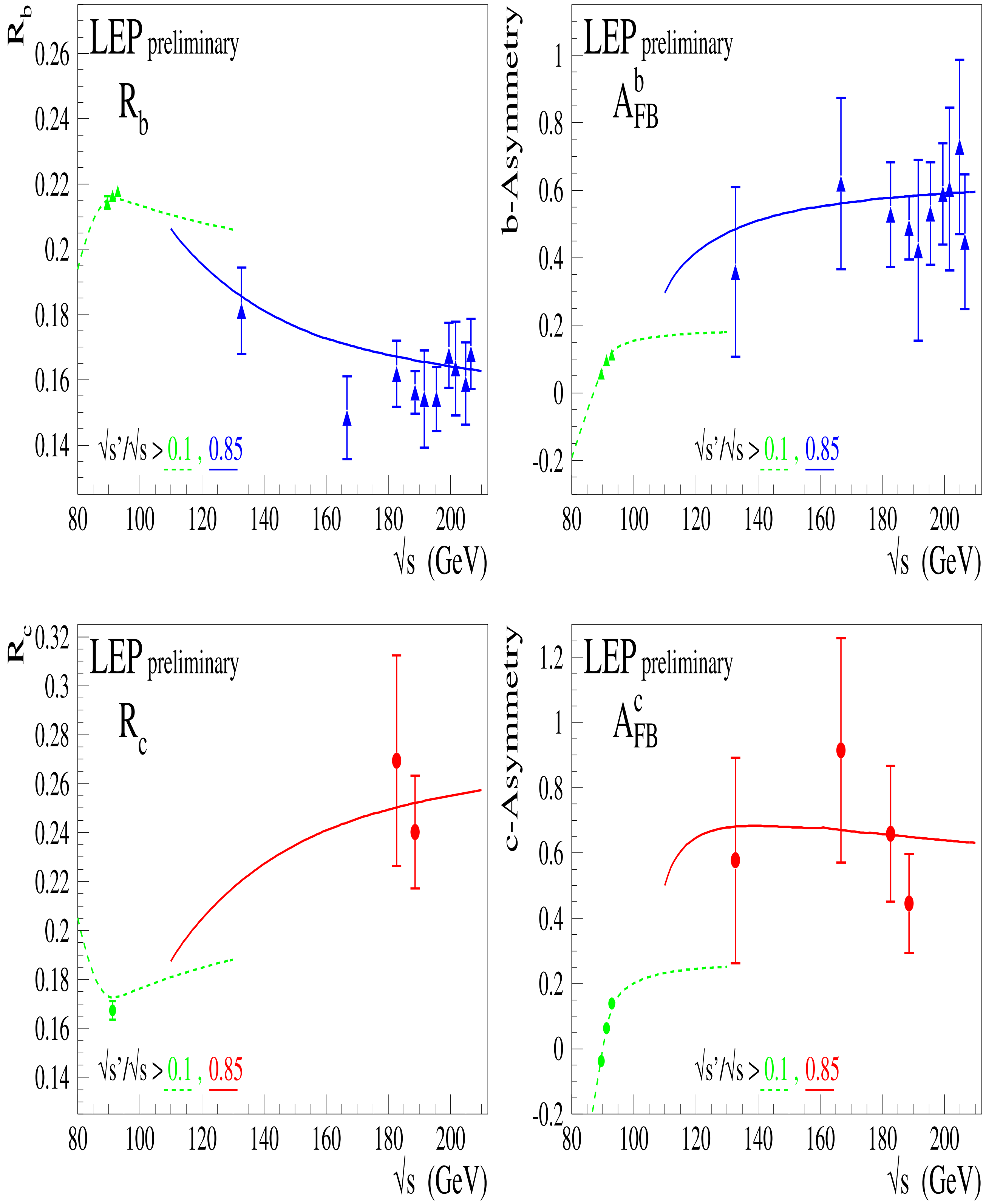

preliminary
LEP
$\sqrt{s'/s} > 0.85$
Cross section (pb)
$e^+e^- \to hadrons(\gamma)$
$e^+e^- \to \mu^+\mu^-(\gamma)$
$e^+e^- \to \tau^+\tau^-(\gamma)$
$\sigma_{meas}/\sigma_{SM}$
$\sqrt{s}$ (GeV)


preliminary
LEP
$\sqrt{s'/s} > 0.85$
Forward-Backward Asymmetry
$e^+e^- \to \mu^+\mu^-(\gamma)$
$e^+e^- \to \tau^+\tau^-(\gamma)$
$A_{FB}^{meas}-A_{FB}^{SM}$
$\sqrt{s}$ (GeV)
1
0.8
0.6
0.4
0.2
0
-0.2
120
140
160
180
200
220


Preliminary LEP Averaged dσ/dcosθ (μμ)
183 GeV
189 GeV
192 GeV
196 GeV
200 GeV
202 GeV
205 GeV
207 GeV
dσ/dcosθ (pb)
cosθ_μ

Preliminary LEP Averaged dσ/dcosθ (ττ)

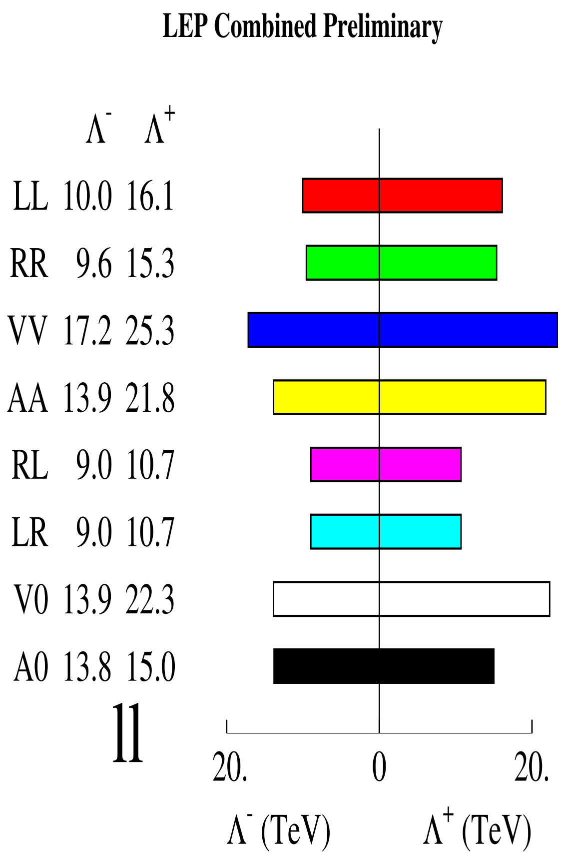


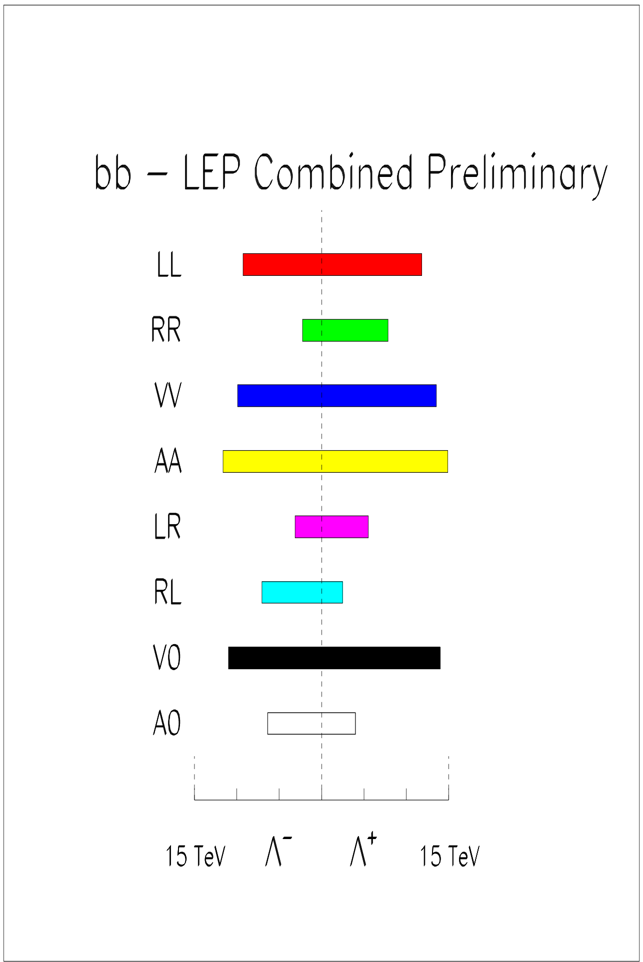


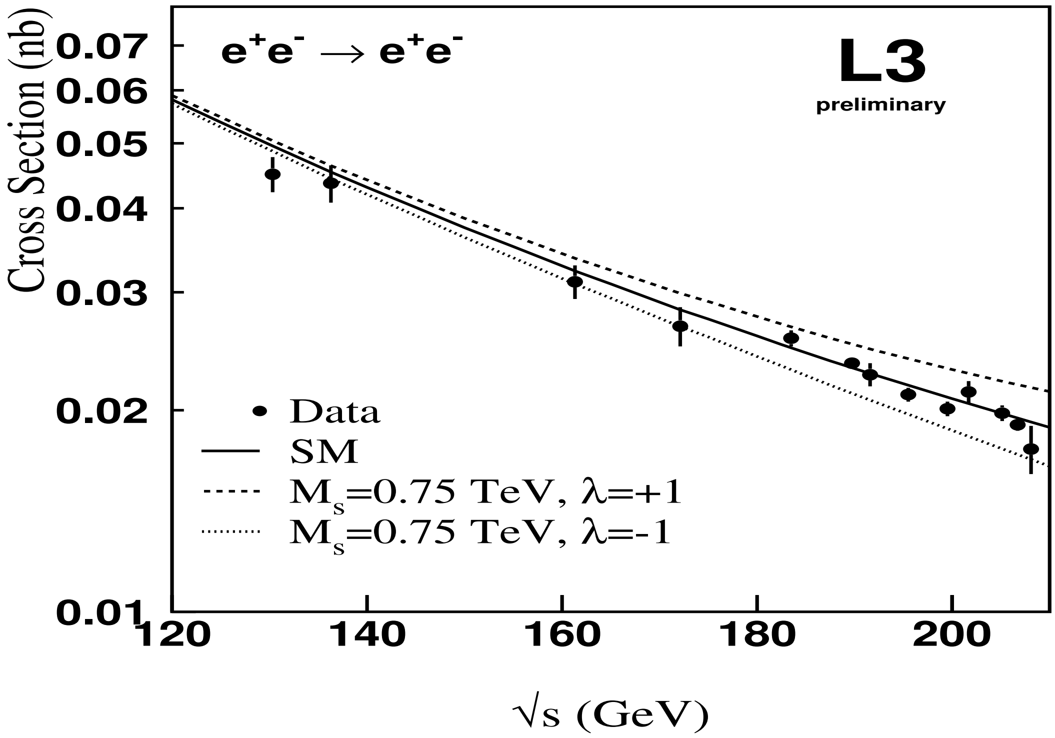
LEP preliminary
R_b
R_b
$\sqrt{s'}/\sqrt{s} > 0.1$, 0.85
$\sqrt{s}$ (GeV)
LEP preliminary
A^b_{FB}
b-Asymmetry
$\sqrt{s'}/\sqrt{s} > 0.1$, 0.85
$\sqrt{s}$ (GeV)
LEP preliminary
R_c
R_c
$\sqrt{s'}/\sqrt{s} > 0.1$, 0.85
$\sqrt{s}$ (GeV)
LEP preliminary
A^c_{FB}
c-Asymmetry
$\sqrt{s'}/\sqrt{s} > 0.1$, 0.85
$\sqrt{s}$ (GeV)

LEP2 $f\bar{f}$ group: limits for $\mu^+\mu^-$, $\tau^+\tau^-$, l^+l^-, $q\bar{q}$, $b\bar{b}$, $c\bar{c}$ (95% CL)

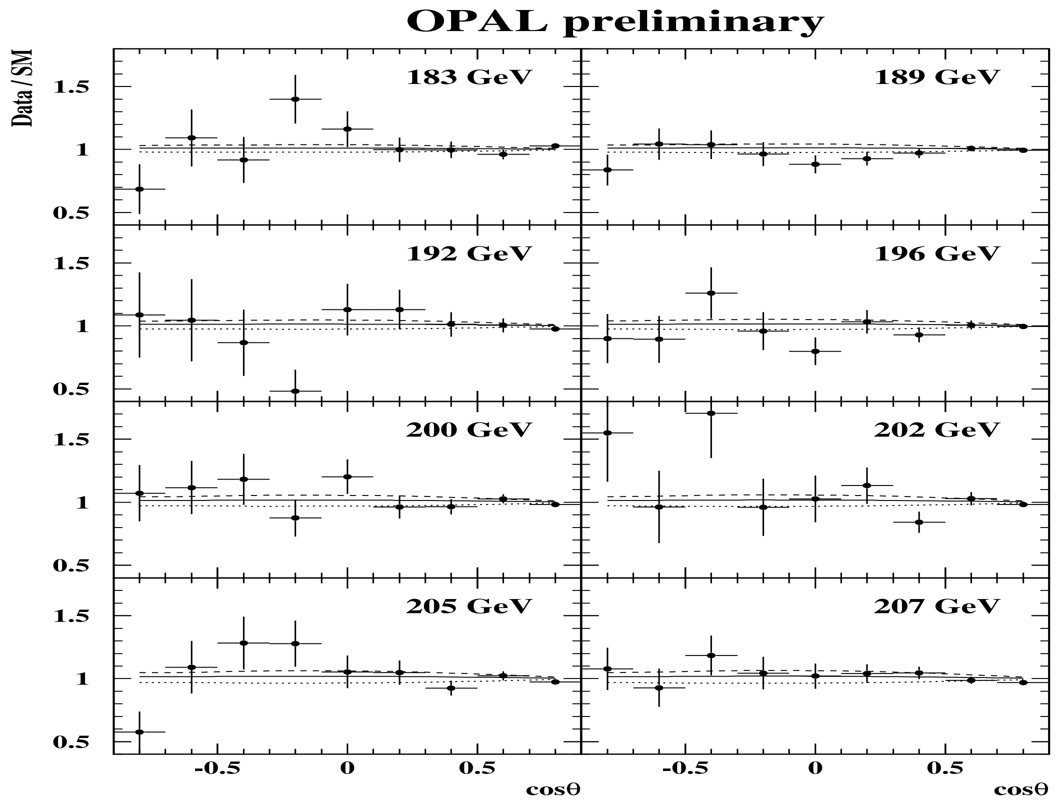
	$e^+e^- \rightarrow \mu^+\mu^-$			$e^+e^- \rightarrow \tau^+\tau^-$		
Model	ϵ [TeV^{-2}]	Λ^- [TeV]	Λ^+ [TeV]	ϵ [TeV^{-2}]	Λ^- [TeV)]	Λ^+ [TeV]
LL	$-0.0056^{+0.0040}_{-0.0040}$	8.6	14.7	$-0.0016^{+0.0054}_{-0.0047}$	9.4	10.6
RR	$-0.0077^{+0.0053}_{-0.0030}$	8.3	14.1	$-0.0008^{+0.0049}_{-0.0060}$	9.0	10.2
VV	$-0.0014^{+0.0016}_{-0.0017}$	15.3	22.4	$-0.0002^{+0.0016}_{-0.0023}$	15.2	17.5
AA	$-0.0036^{+0.0027}_{-0.0013}$	11.8	20.4	$-0.0004^{+0.0032}_{-0.0025}$	13.2	13.8
LR	$0.0014^{+0.0043}_{-0.0061}$	7.8	9.3	$-0.0014^{+0.0075}_{-0.2283}$	2.1	8.6
RL	$0.0014^{+0.0043}_{-0.0061}$	7.8	9.3	$-0.0014^{+0.0075}_{-0.2283}$	2.1	8.6
V0	$-0.0036^{+0.0025}_{-0.0014}$	12.1	20.2	$-0.0003^{+0.0023}_{-0.0030}$	13.0	14.7
A0	$0.0008^{+0.0020}_{-0.0031}$	12.7	12.9	$-0.0008^{+0.0038}_{-0.0046}$	9.9	11.9



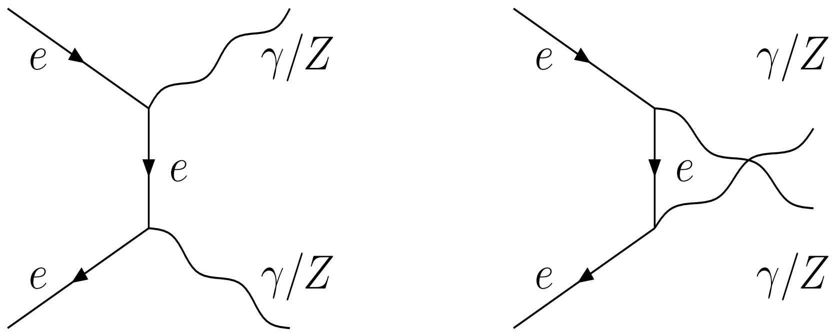




$M_s^+ > 1.06$ TeV $M_s^- > 0.98$ TeV   TeV Strings: $M_S > 0.57$ TeV



$M_s^+ > 1.00$ TeV $M_s^- > 1.15$ TeV



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = |\mathrm{e_t} + \mathrm{e_u} + \text{New Physics ?!}|^2$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\alpha^2}{2\mathrm{s}}\left[\frac{\mathrm{t}}{\mathrm{u}} + \frac{\mathrm{u}}{\mathrm{t}}\right] = \frac{\alpha^2}{\mathrm{s}} \cdot \frac{1+\cos^2\theta}{1-\cos^2\theta}$$

many deviations from QED investigated

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{QED} \cdot \left(1 \pm \frac{s^2}{2(\Lambda_\pm^{\mathrm{QED}})^4}\sin^2\theta\right)$$

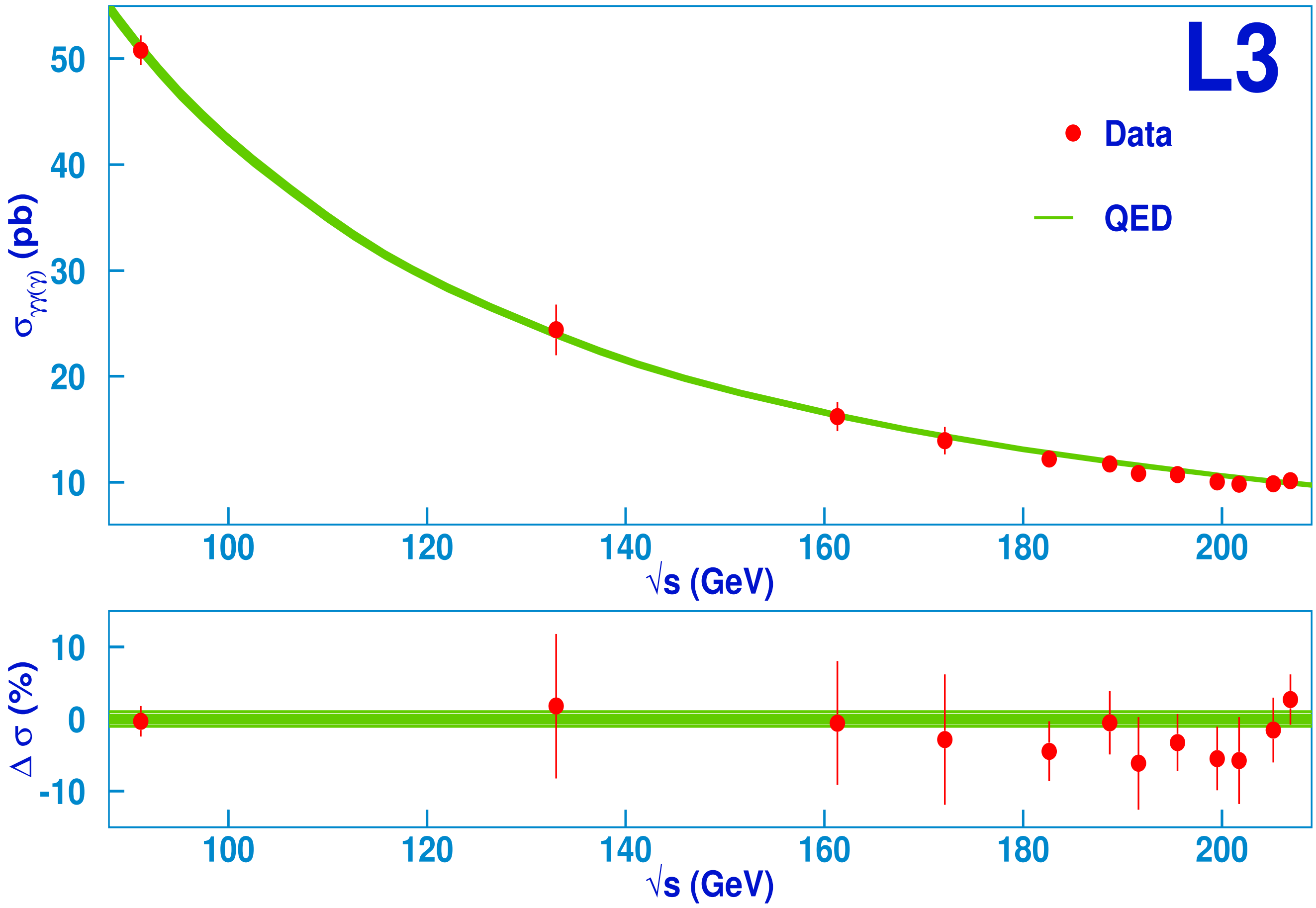
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{QED} \cdot \left(1 \mp \frac{\lambda}{\pi\alpha} \cdot \frac{s^2}{2(M_s)^4}\sin^2\theta + \ldots\right)$$

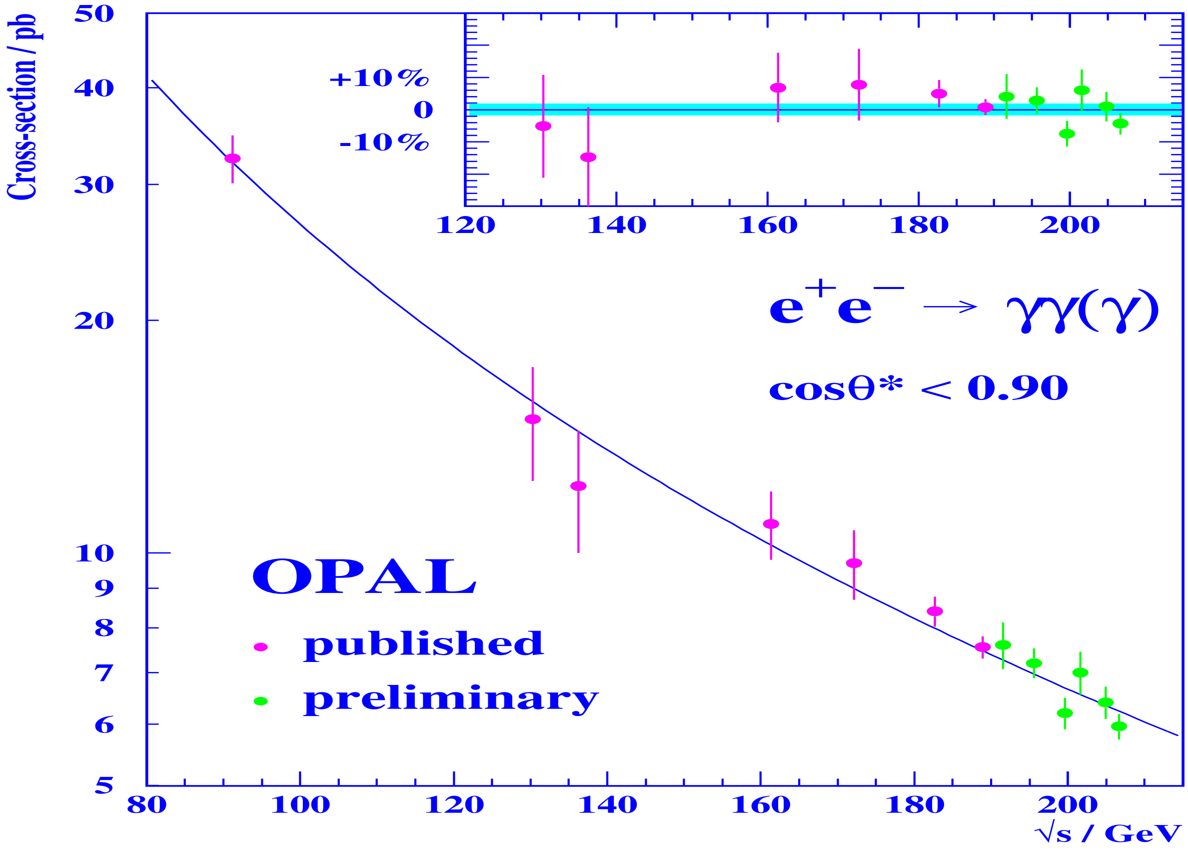
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{QED} \cdot \left(1 + \frac{\pi^2}{12} \cdot \frac{s^2}{2(M_S)^4}\sin^2\theta\right)$$

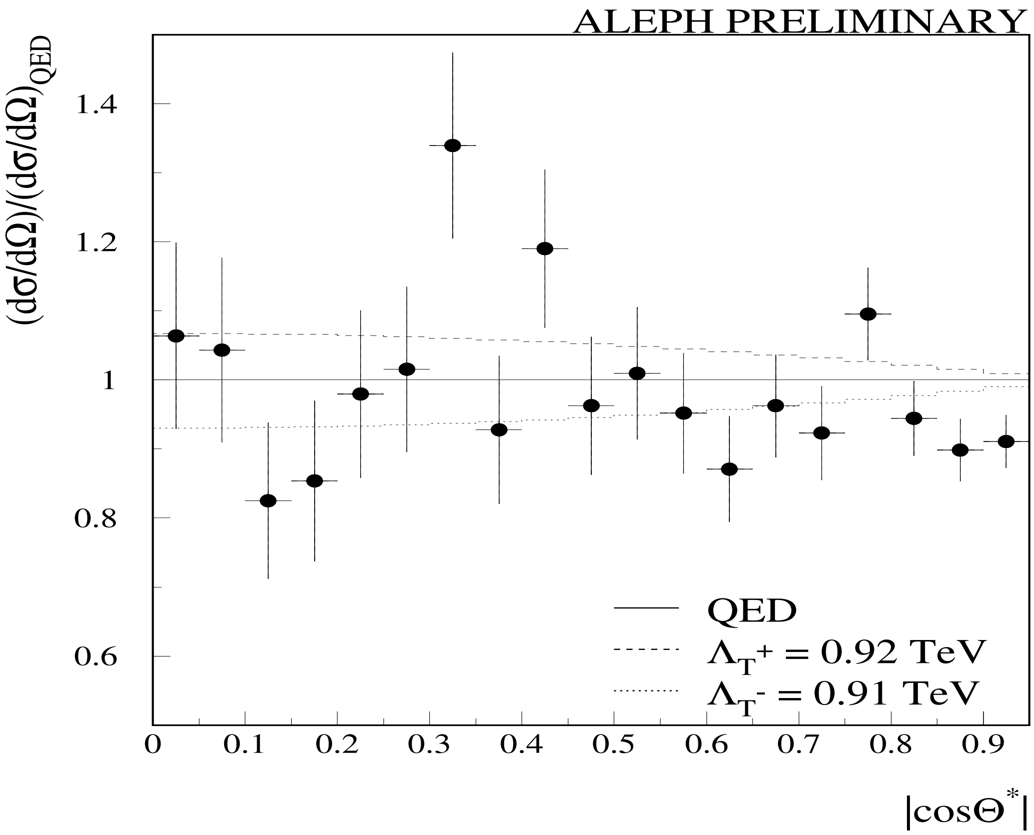
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{QED} \cdot \left(1 + \frac{(\eta_L + \eta_R)}{2} \cdot \frac{s^2}{2(\Lambda^{\mathrm{CI}})^4}\sin^2\theta + \ldots\right)$$

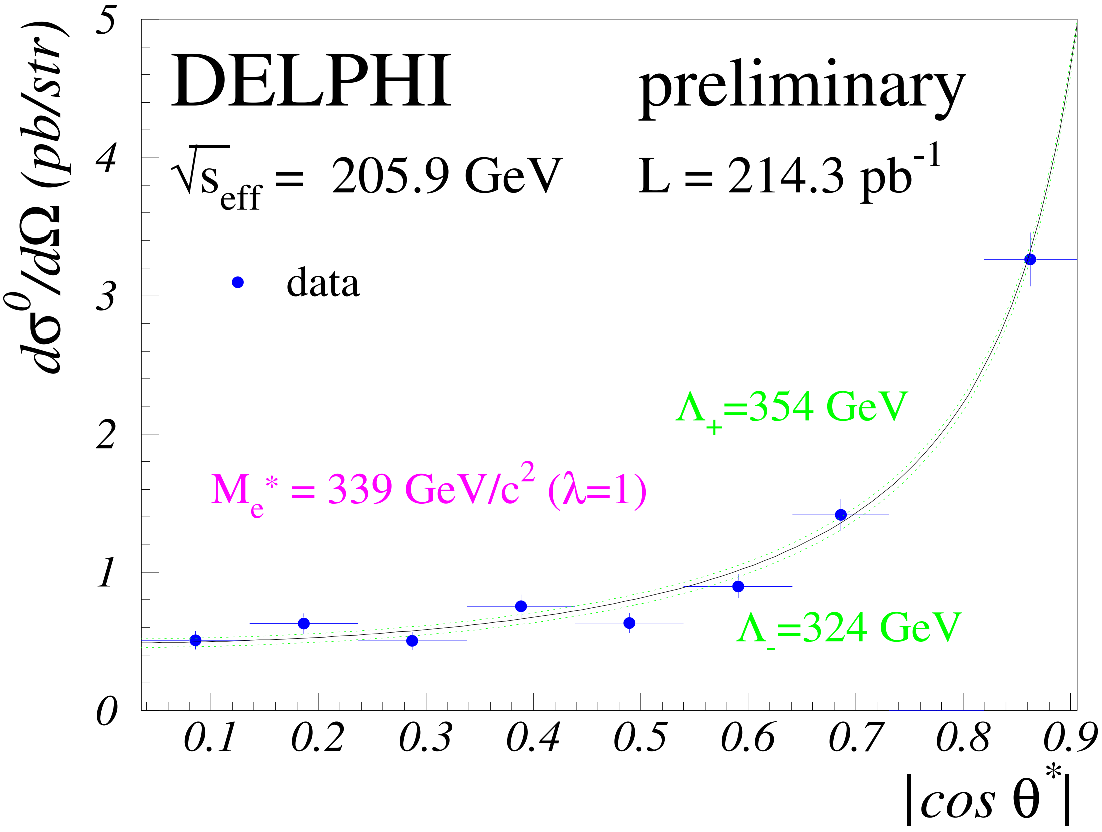
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{QED} \cdot \left(1 + \frac{2}{\alpha} \cdot \frac{s^2}{2(\Lambda_6)^4}\sin^2\theta + \ldots\right)$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{QED} \cdot \left(1 + \frac{s^3}{32\pi\alpha^2(\Lambda')^6}\frac{\sin^2\theta}{1+\cos^2\theta} + \ldots\right)$$


L3
Data
QED
$\sigma_{\gamma\gamma(\gamma)}$ (pb)
50
40
30
20
10
100
120
140
160
180
200
$\sqrt{s}$ (GeV)
$\Delta\sigma$ (%)
10
0
-10
100
120
140
160
180
200
$\sqrt{s}$ (GeV)


Cross-section / pb
50
40
30
20
10
9
8
7
6
5
80
100
120
140
160
180
200
$\sqrt{s}$ / GeV
+10%
0
-10%
120
140
160
180
200
$e^+e^- \rightarrow \gamma\gamma(\gamma)$
$\cos\theta^* < 0.90$
OPAL
published
preliminary


ALEPH PRELIMINARY
$(d\sigma/d\Omega)/(d\sigma/d\Omega)_{QED}$
QED
$\Lambda_T^+ = 0.92$ TeV
$\Lambda_T^- = 0.91$ TeV
$|\cos\Theta^*|$


DELPHI
preliminary
$\sqrt{s}_{eff} = 205.9$ GeV
$L = 214.3\ pb^{-1}$
data
$\Lambda_+ = 354$ GeV
$M_{e^*} = 339\ GeV/c^2\ (\lambda=1)$
$\Lambda_- = 324$ GeV
$d\sigma^0/d\Omega\ (pb/str)$
$|\cos\theta^*|$

Model	ALEPH [TeV]	DELPHI [TeV]	L3 [TeV]	OPAL [TeV]	Combined [TeV](*)
QED cut–off - $\Lambda_{\pm}^{\mathrm{QED}}$					
Λ_+	0.319	0.355	0.385	0.344	0.44
Λ_-	0.317	0.321	0.325	0.325	0.37
excited electron: $\mathrm{m}_{\mathrm{e}*}^2/\lambda \sim (\Lambda^{\mathrm{QED}})^2$					
M_{e*}	0.337	0.339	0.325	0.354	-
low scale gravity: $\mathrm{M_s} = 2.57\ \Lambda^{\mathrm{QED}}$; $\Lambda_{\mathrm{T}} = 1.12\ \mathrm{M_s}$					
M_s^+	0.81	0.82	0.83	0.83	0.95
M_s^-	0.82	0.91	0.99	0.89	1.14
TeV strings: $\mathrm{M_S} = 0.952\ \Lambda^{\mathrm{QED}}$					
M_S	0.304	0.338	0.367	0.328	0.42
contact interactions: $\Lambda_6 = 4.069\ \Lambda^{\mathrm{QED}}$					
Λ_6	1.299		1.566		
more contact interactions: Λ'					
Λ'			0.810	0.763	

* Combined by DB

Process	LSG scale M_s (TeV)	
	$\lambda = -1$	$\lambda = +1$
D.Bourilkov, JHEP 08 (1999) 006		
$e^+e^- \rightarrow e^+e^-$	0.96	1.26
S.Mele, E.Sanchez, PRD 61(2000)117901		
$e^+e^- \rightarrow$ bosons	0.96	0.93
WC2001 - L3 preliminary		
$e^+e^- \rightarrow e^+e^-$	0.98	1.06
WC2001 - OPAL preliminary		
$e^+e^- \rightarrow e^+e^-$	1.15	1.00
WC2001 - LEP combined preliminary (*)		
$e^+e^- \rightarrow e^+e^-$	1.28	1.13
WC2001 - LEP combined preliminary (*)		
$e^+e^- \rightarrow \gamma\gamma$	1.14	0.95
WC2001 - LEP combined preliminary (*)		
e^+e^- and $\gamma\gamma$	1.39	1.13

* Combined by DB

Process	TeV strings scale M_S (TeV)
D.Bourilkov, PRD 62(2000)076005; hep-ph/0002172	
$e^+e^- \rightarrow e^+e^-$	0.63
WC2001 - L3 preliminary	
$e^+e^- \rightarrow e^+e^-$	0.57
WC2001 - LEP combined preliminary (*)	
$e^+e^- \rightarrow \gamma\gamma$	0.42

D-branes: contact interactions:

$$\Lambda^+_{VV} \simeq \sqrt{\frac{4\pi}{0.59 g_s}} \cdot M_S$$

$e^+e^- \rightarrow \mu^+\mu^-$, $\tau^+\tau^-$: $\eta_{LL} = \eta_{RR} = \eta_{LR} = \eta_{RL} = 1$

$e^+e^- \rightarrow e^+e^-$: $0.75\eta_{LL} = 0.75\eta_{RR} \simeq \eta_{LR} = \eta_{RL} = 1$

Process	D-brane string scale M_S (TeV)	
	$g_s = g^2_{YM} \sim \frac{1}{2}$	$\frac{g_s}{4\pi} = \frac{1}{128}$
WC2001 - LEP combined preliminary		
$e^+e^- \rightarrow \mu^+\mu^-$ $e^+e^- \rightarrow \tau^+\tau^-$	3.9	1.7
WC2001 - LEP combined preliminary (*)		
$e^+e^- \rightarrow e^+e^-$	3.5	1.5

* Combined by DB

Outlook

♣ the Standard Model has no difficulty to describe the full set of precise LEP2 measurements from 130-209 GeV (results at 192–209 GeV preliminary)

♢ the extra dimensions remain hidden so far ... in spite of sensitive searches!

♡ many new limits (TeV scale!) for physics beyond the Standard Model

♠ thanks to the 4 LEP collaborations for providing their latest results

LHC NEWS : STRING DISCOVERY?