

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

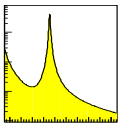
D.Bourilkov

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<http://cern.ch/bourilkov/>

- **Introduction**
- **Fermion-pair production:**
 $e^+e^- \rightarrow f\bar{f}(\gamma)$
- **Photon-pair production:**
 $e^+e^- \rightarrow \gamma\gamma(\gamma)$
- **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

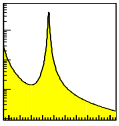
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Year	\sqrt{s} GeV	\mathcal{L} pb^{-1}	$q\bar{q}$ stat. err % single exp. total / HE	Mode
1995 & 97	130	6	2.3/5.2	Above
1995 & 97	136	6	2.6/6.0	M_Z
1996	161	10	2.7/5.9	W pairs
1996	172	10	3.2/7.3	W mass
1997	183	55	1.4/3.3	Z pairs
1998	189	177	0.8/1.8	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**

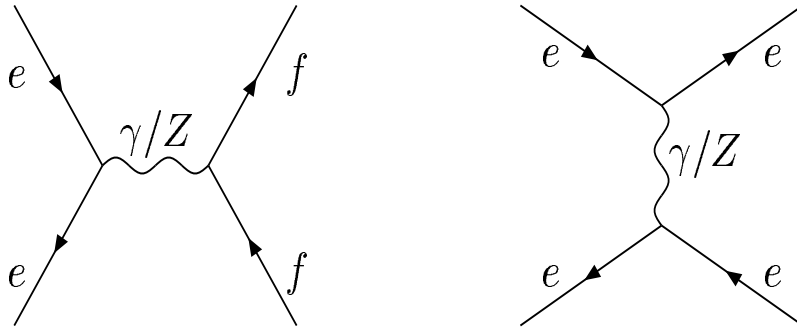
Data 192–209 GeV **preliminary**

Preliminary results on the **full LEP2 data set**

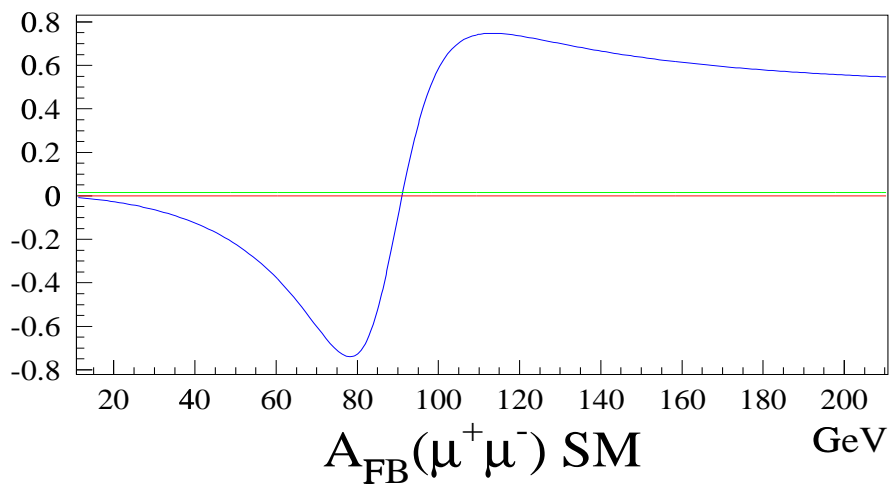
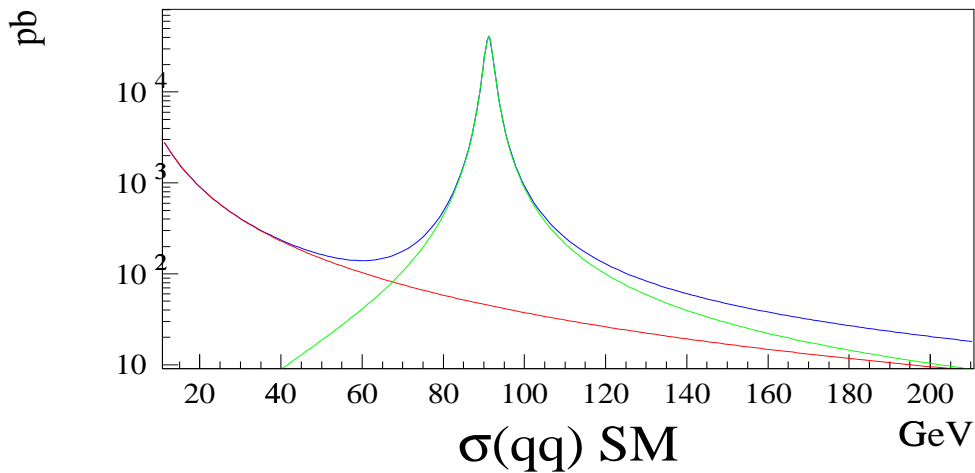


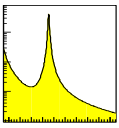
Fermion-pair Production

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



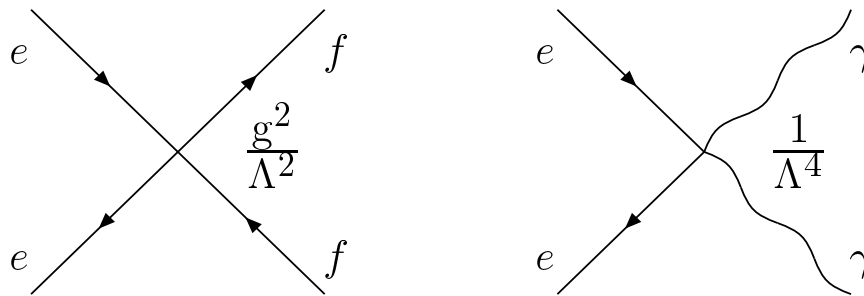


general framework for a new interaction with typical energy scale $\Lambda \gg \sqrt{s}$; operators with canonical dimension $N > 4 \Rightarrow$ coupling $\sim 1/M^{N-4}$

g coupling (by convention $\frac{g^2}{4\pi} = 1$)

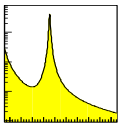
$|\eta_{ij}| \leq 1$ helicity amplitudes

ε $\frac{g^2 \text{sign}(\eta)}{4\pi \Lambda^2}$ for $f\bar{f}$ $\sim \frac{1}{\Lambda^4}$ for $\gamma\gamma$



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

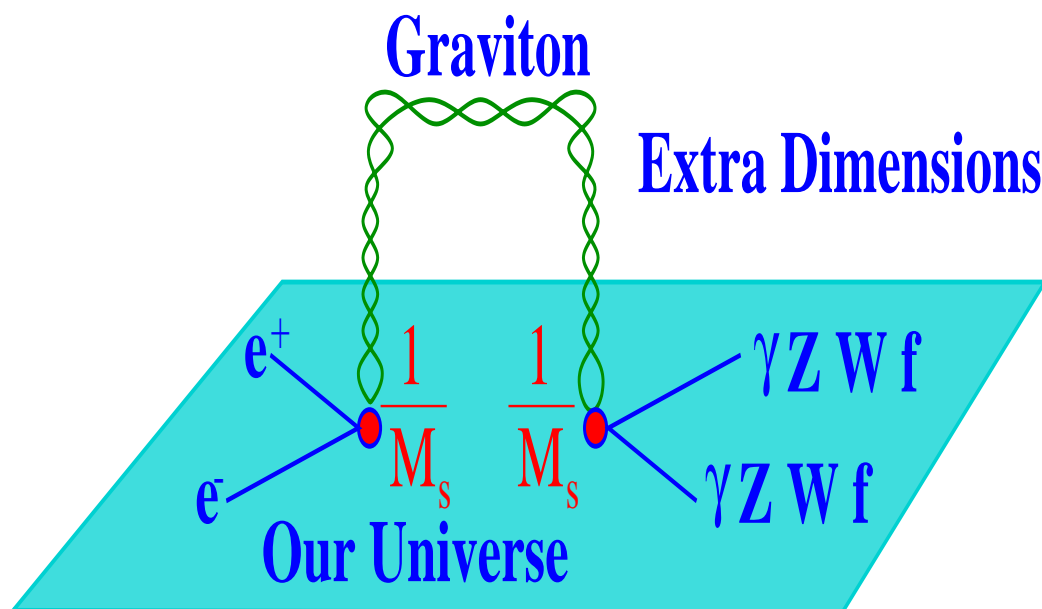
Model	LL	RR	LR	RL	VV	AA	LL+RR	LR+RL
	Non-parity conserving				Parity conserving			
η_{LL}	± 1	0	0	0	± 1	± 1	± 1	0
η_{RR}	0	± 1	0	0	± 1	± 1	± 1	0
η_{LR}	0	0	± 1	0	± 1	∓ 1	0	± 1
η_{RL}	0	0	0	± 1	± 1	∓ 1	0	± 1



Better understanding of space-time?

Maximum phenomenology with minimum parameters

Study quantum gravity at colliders

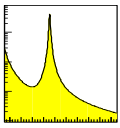


Fermion/Boson pair production - Virtual effects
class of theories with virtual graviton exchange
(KK excitations) \Rightarrow effective scale (cut-off) M_s

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

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

$e^+e^- \rightarrow e^+e^-$

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

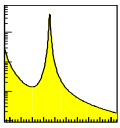
$e^+e^- \rightarrow \gamma\gamma$

Drell's parametrization (QED cut-off)

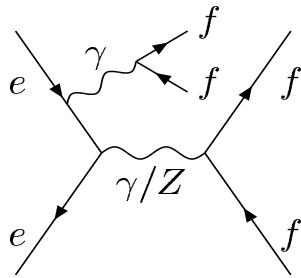
$$\Lambda_+^{\text{QED}} = \left(\frac{12}{\pi^2}\right)^{1/4} \cdot M_S = 1.05 M_S$$

- 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



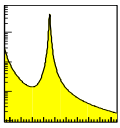
- Interplay between 2-f and 4-f events; radiative corrections, real pairs



low mass fermion pairs are signal, like photons

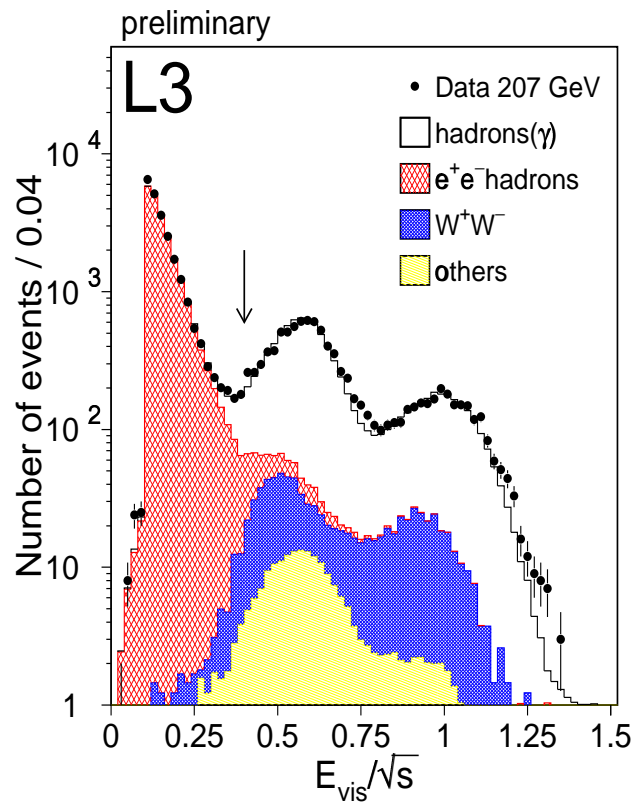
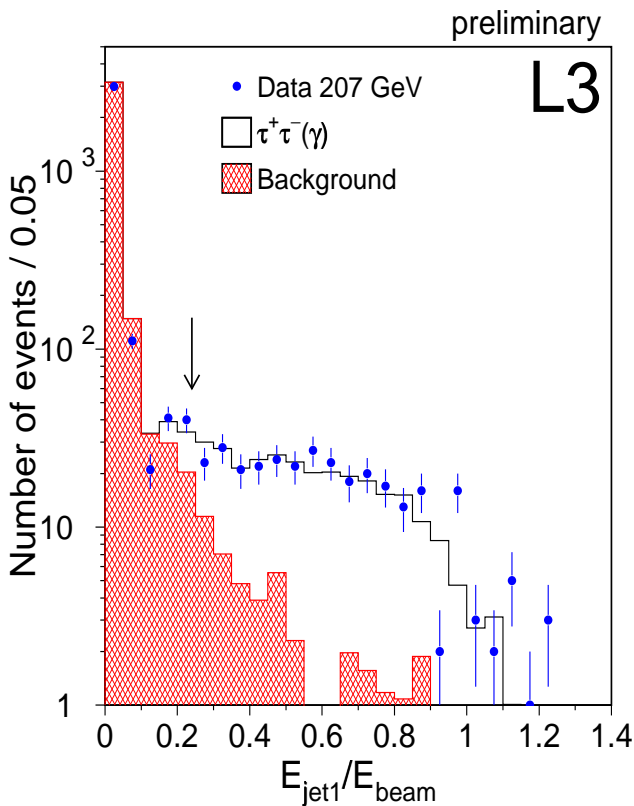
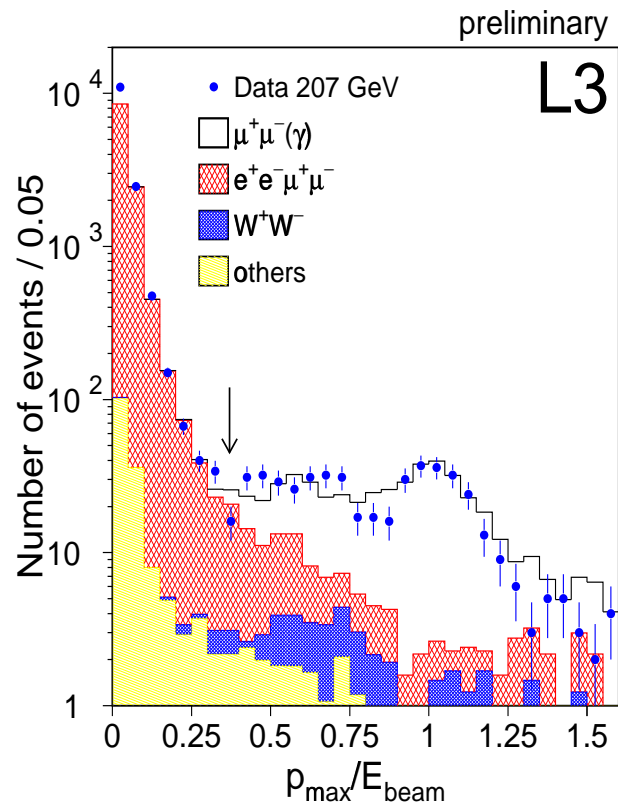
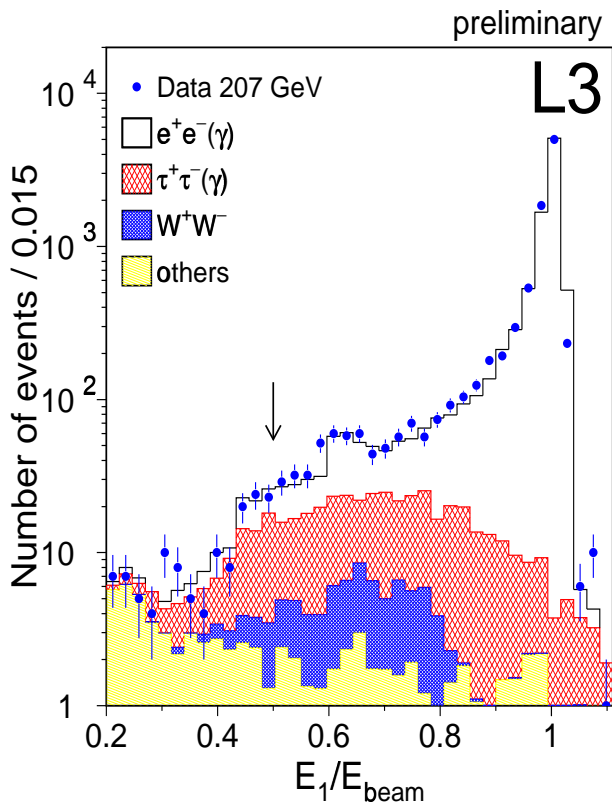
- Definition of s' : not unique due to interference between initial- and final-state radiation
 - interference changes the cross-sections: for $\sqrt{s'}/\sqrt{s} > 0.85$ by $\sim 1.5\%$ for $\mu^+\mu^-$ and $\sim 0.5\%$ for $q\bar{q}$ in $\mathcal{O}(\alpha)$ (efficiency changed by $\leq 50\%$ of this)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

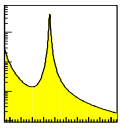
LEP2 Monte Carlo Workshop - Two-fermion Working Group, CERN-YR-2000-009, hep-ph/0007180



Fermion Pairs - Selection

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Combines the measurements of σ_{tot} , A_{FB} , R_b ,

R_c and $\frac{d\sigma}{d\cos\theta}$ for:

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

performs combined fits for contact interactions and Z'

Note LEP2FF/01-01 for Winter Conf. 2001

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

LEPEWWG $f\bar{f}$ Subgroup

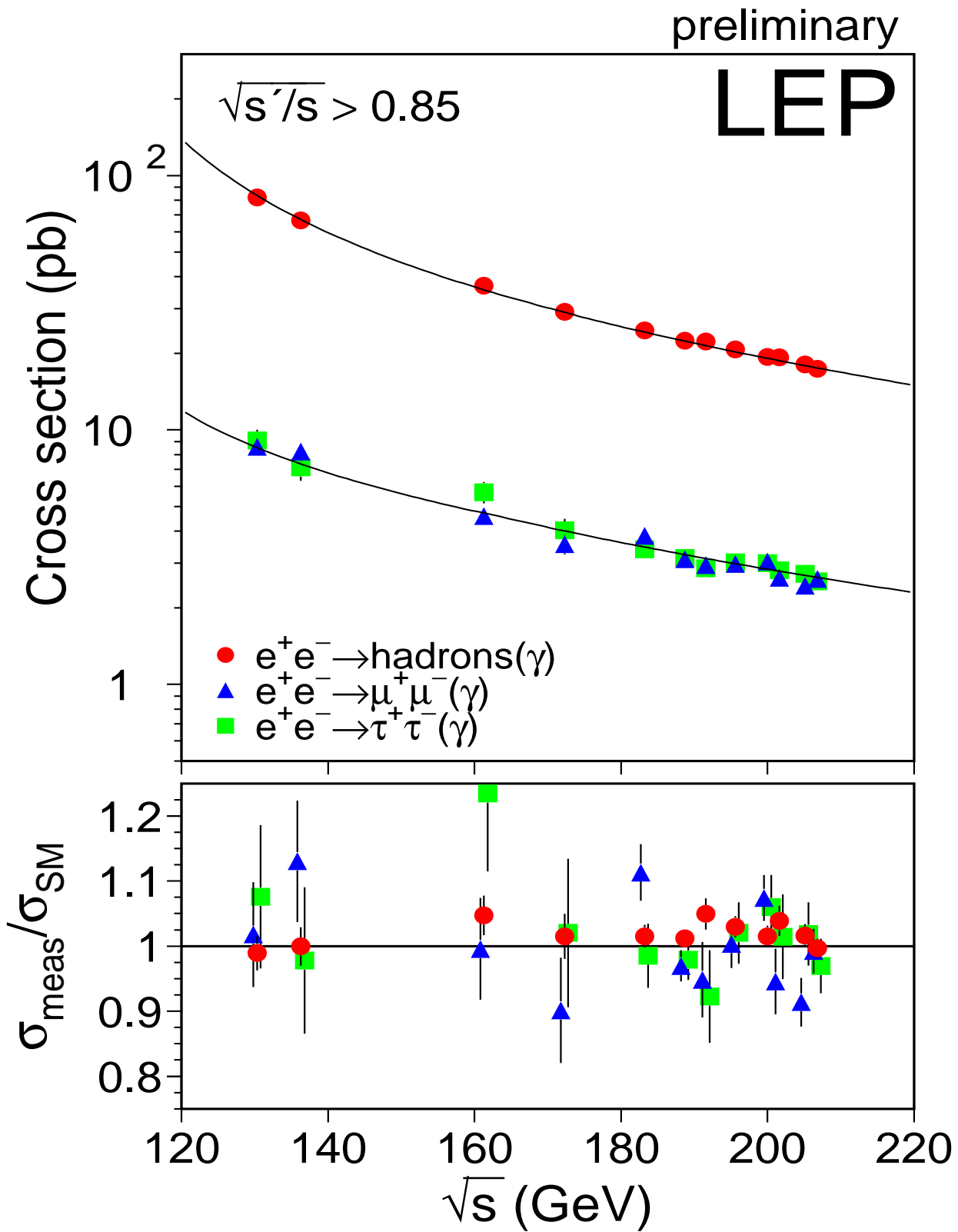
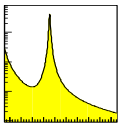
Members :

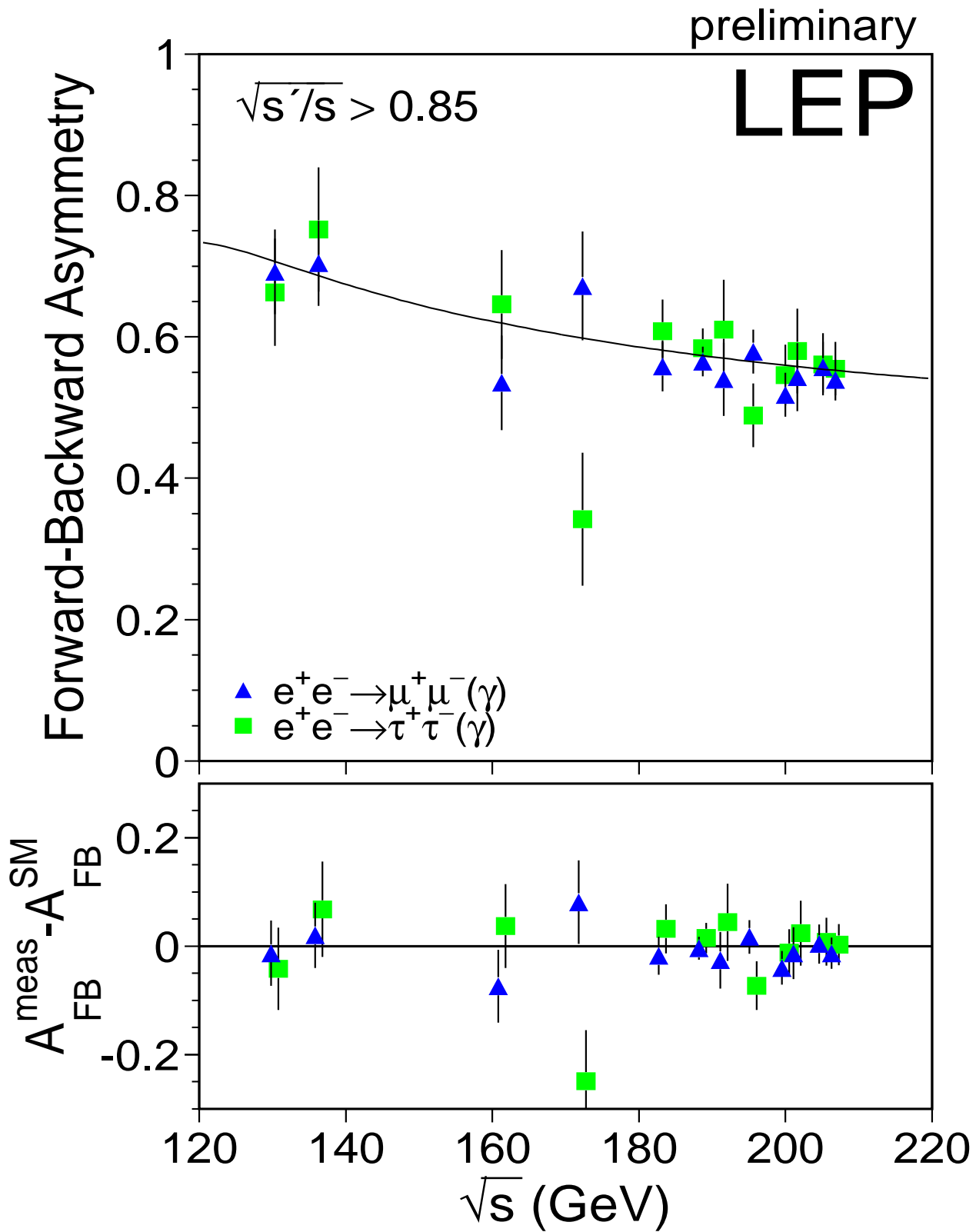
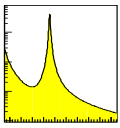
C. Geweniger, C. Goy, M-N Minard
M. Elsing, J. Holt, W. Liebig, A. Olshevski, P. Renton
S. Blyth, D. Bourilkov, S. Riemann, S. Wynnhoff
F. Fiedler, M. Kobel, S. Marcellini, K. Sachs, P. Ward

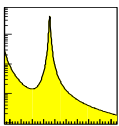
Abstract

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

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

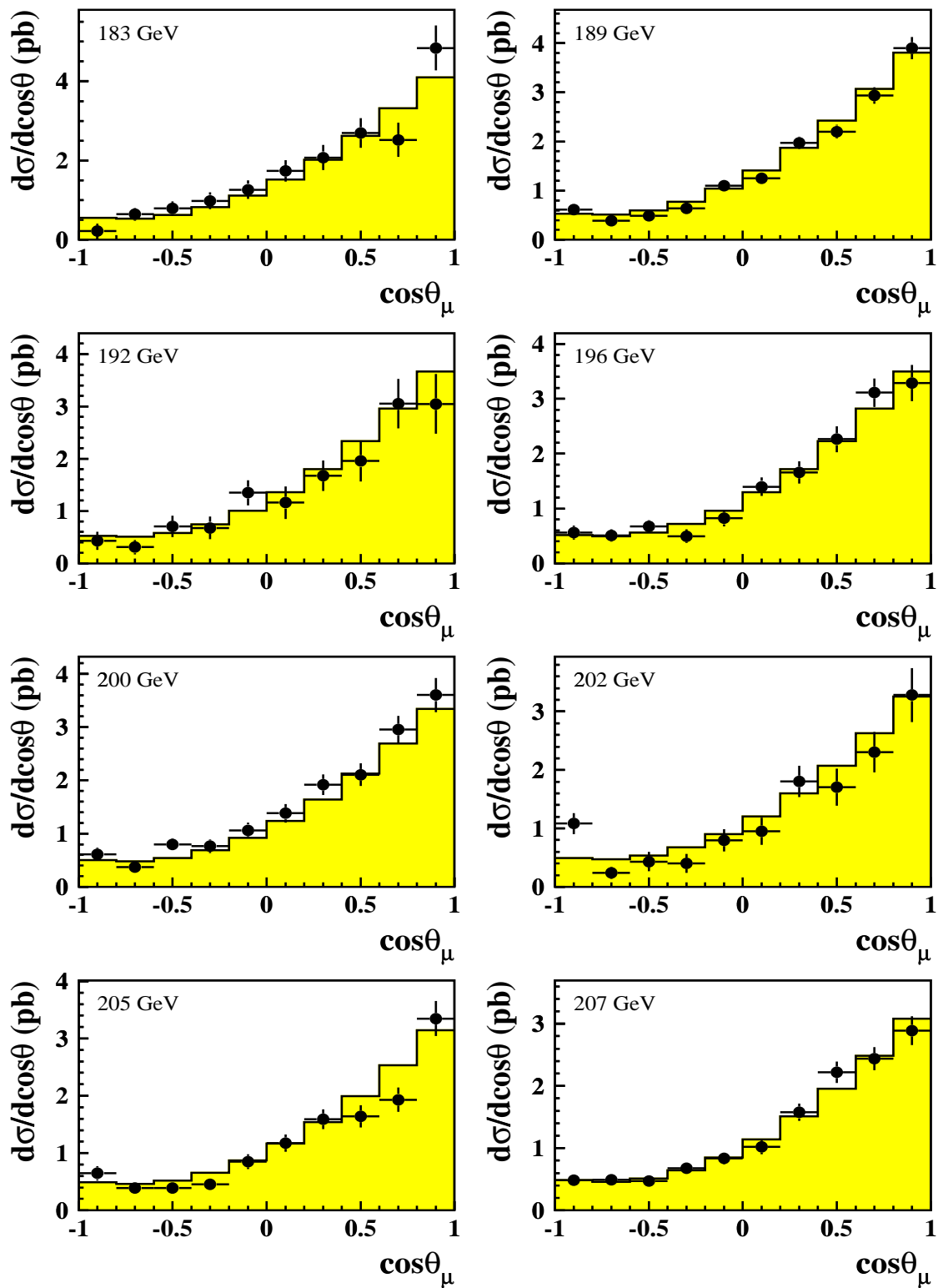


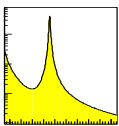




Fermion Pairs - $\frac{d\sigma}{d\cos\theta}(\mu^+\mu^-)$ *D. Bourilkov*

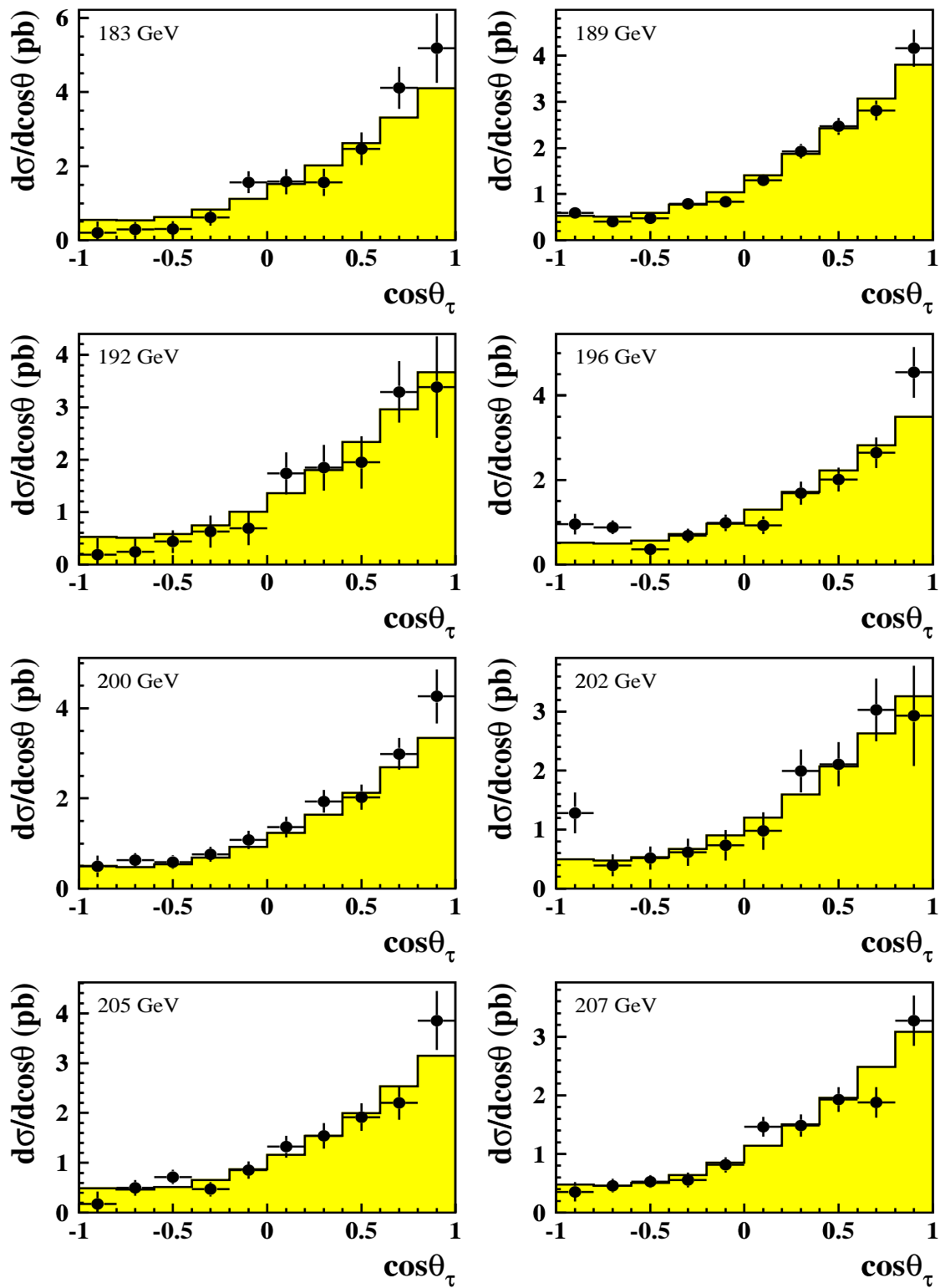
Preliminary LEP Averaged $d\sigma/d\cos\theta$ ($\mu\mu$)

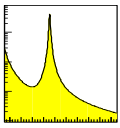




Fermion Pairs - $\frac{d\sigma}{d\cos\theta}(\tau^+\tau^-)$ *D. Bourilkov*

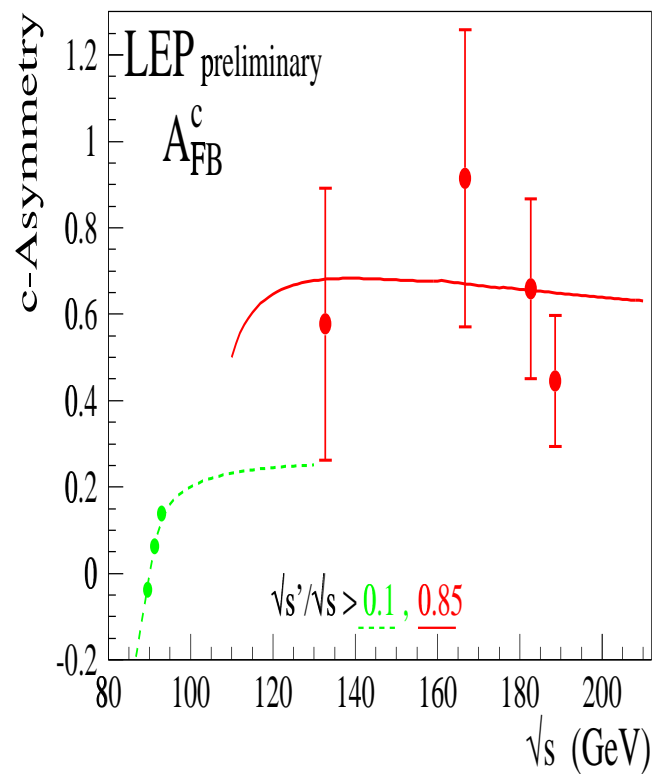
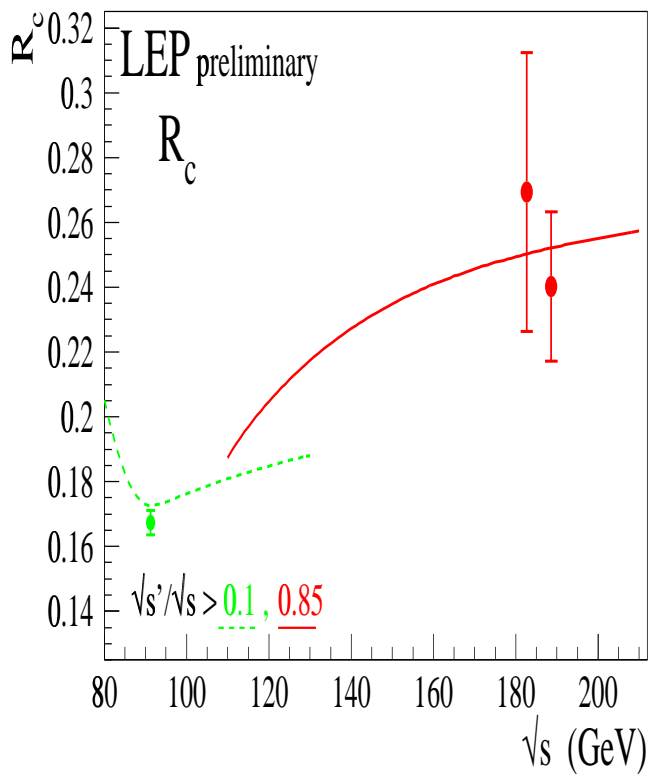
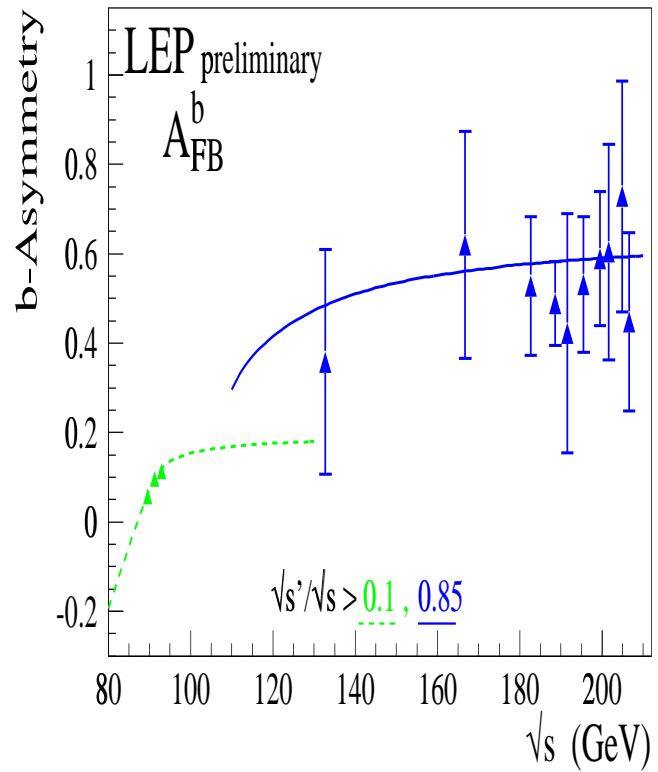
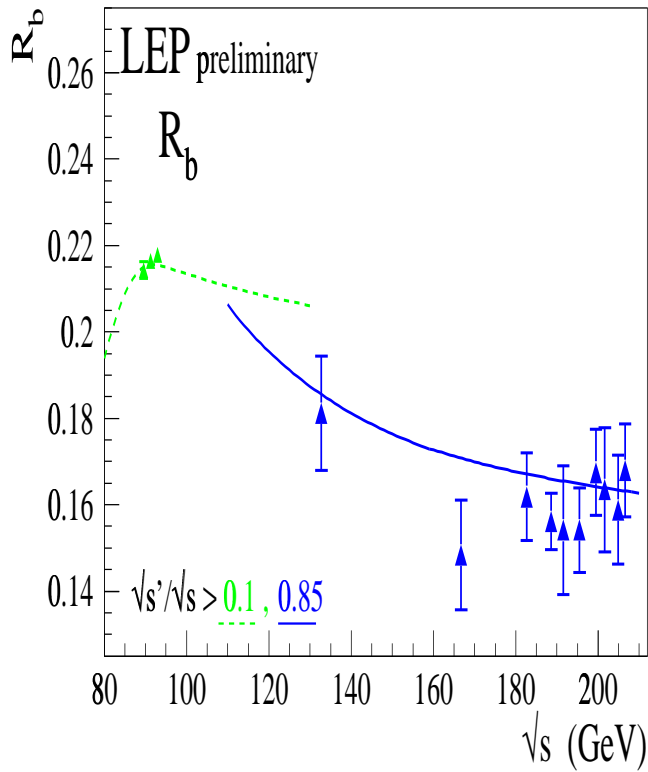
Preliminary LEP Averaged $d\sigma/d\cos\theta(\tau\tau)$

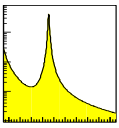




$f\bar{f}$ - Heavy Flavors

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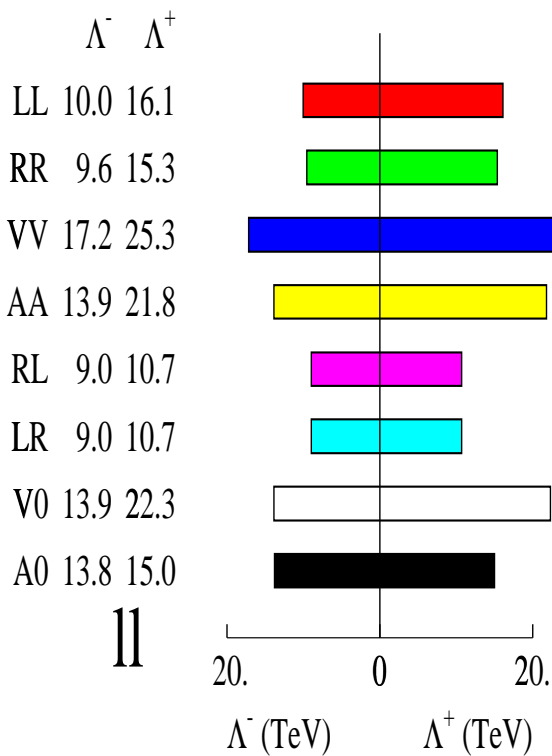
Contact Interactions

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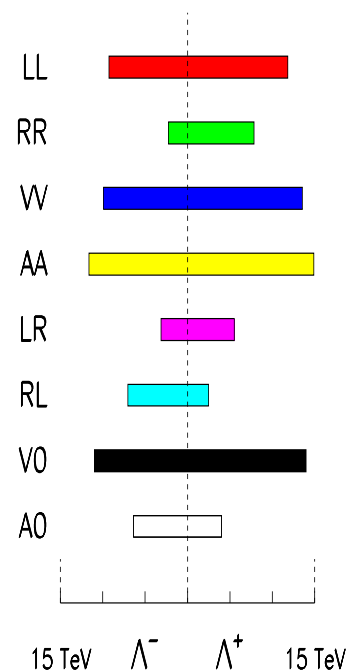
LEP2 $f\bar{f}$ group: limits for $\mu^+\mu^-$, $\tau^+\tau^-$, l^+l^- , $q\bar{q}$, $b\bar{b}$, $c\bar{c}$ (95% CL)

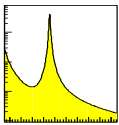
Model	$e^+e^- \rightarrow \mu^+\mu^-$			$e^+e^- \rightarrow \tau^+\tau^-$		
	ϵ [TeV ⁻²]	Λ^- [TeV]	Λ^+ [TeV]	ϵ [TeV ⁻²]	Λ^- [TeV]	Λ^+ [TeV]
LL	$-0.0056^{+0.0040}_{-0.0040}$	8.6	14.7	$-0.0016^{+0.0054}_{-0.0047}$	9.4	10.6
RR	$-0.0077^{+0.0053}_{-0.0030}$	8.3	14.1	$-0.0008^{+0.0049}_{-0.0060}$	9.0	10.2
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

LEP Combined Preliminary



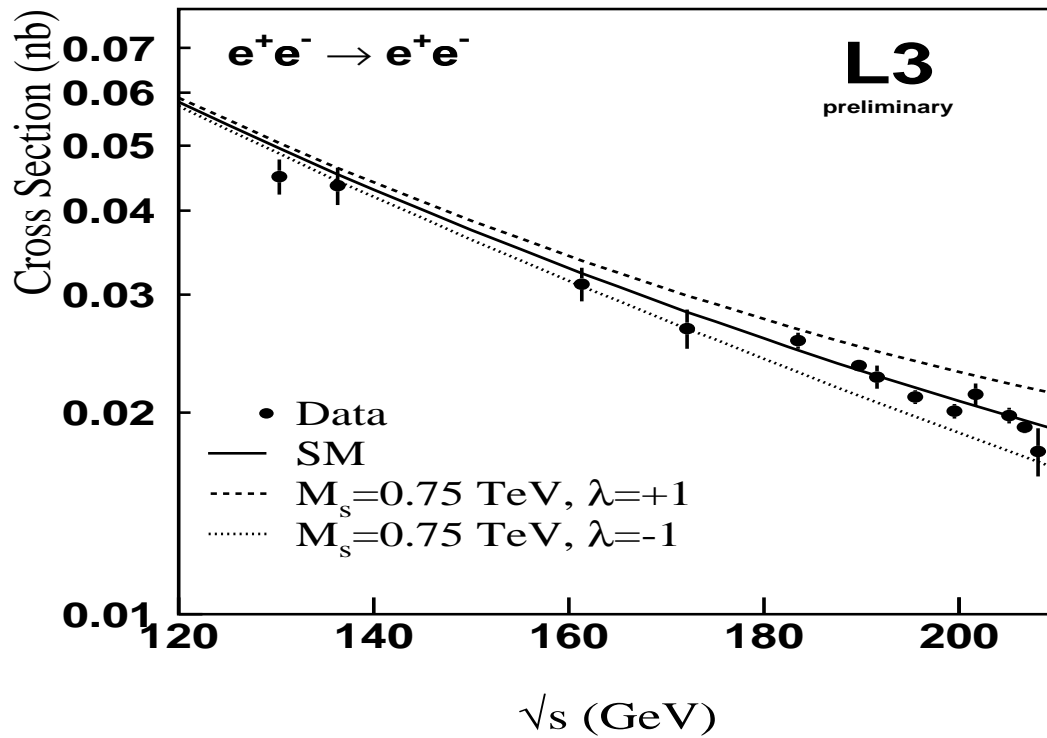
bb – LEP Combined Preliminary



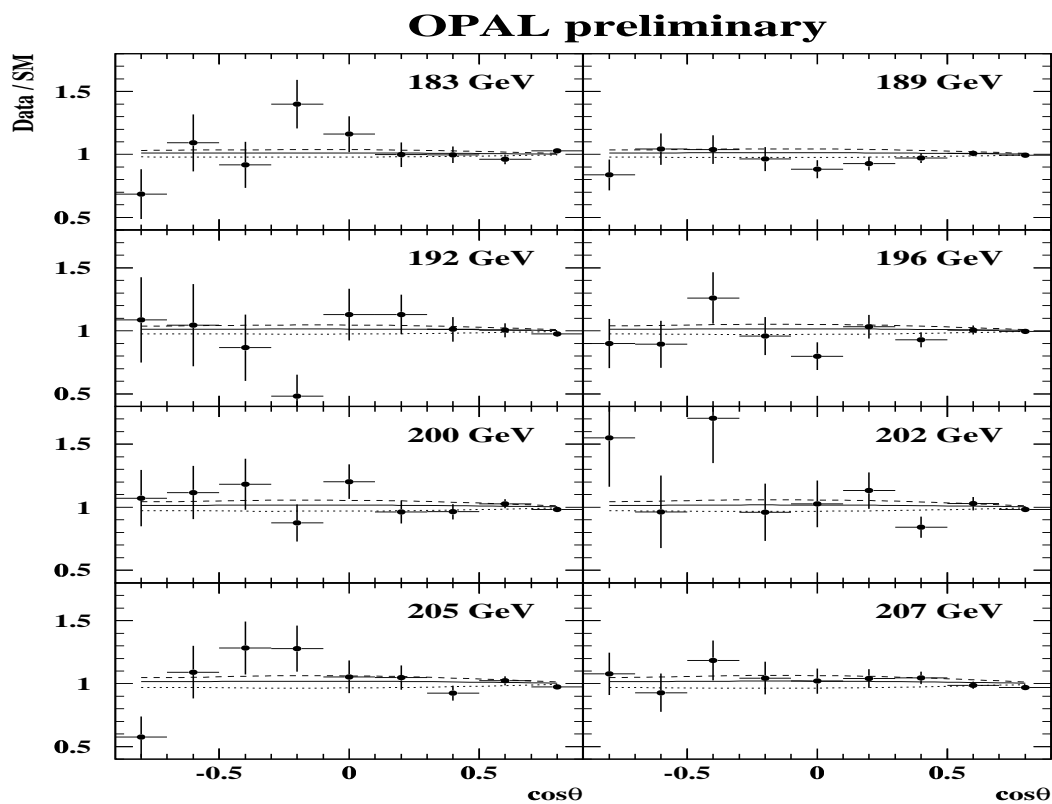


Extra Dimensions

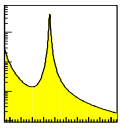
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$M_s^+ > 1.06$ TeV $M_s^- > 0.98$ TeV TeV Strings: $M_s > 0.57$ TeV

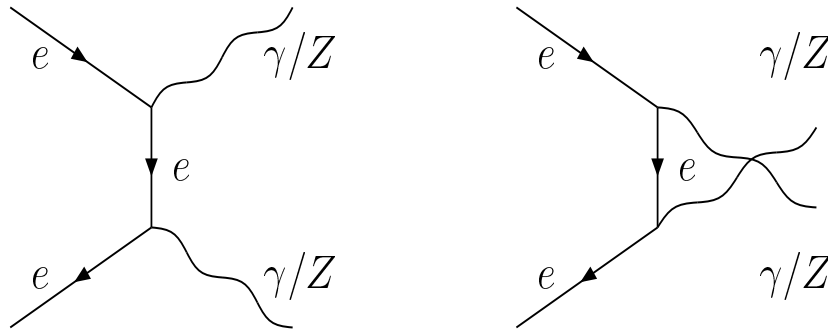


$M_s^+ > 1.00$ TeV $M_s^- > 1.15$ TeV



Photon-pair Production

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

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

many deviations from QED investigated

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

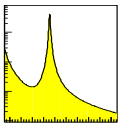
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{QED} \cdot \left(1 \mp \frac{\lambda}{\pi\alpha} \cdot \frac{s^2}{2(M_s)^4} \sin^2 \theta + \dots \right)$$

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

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

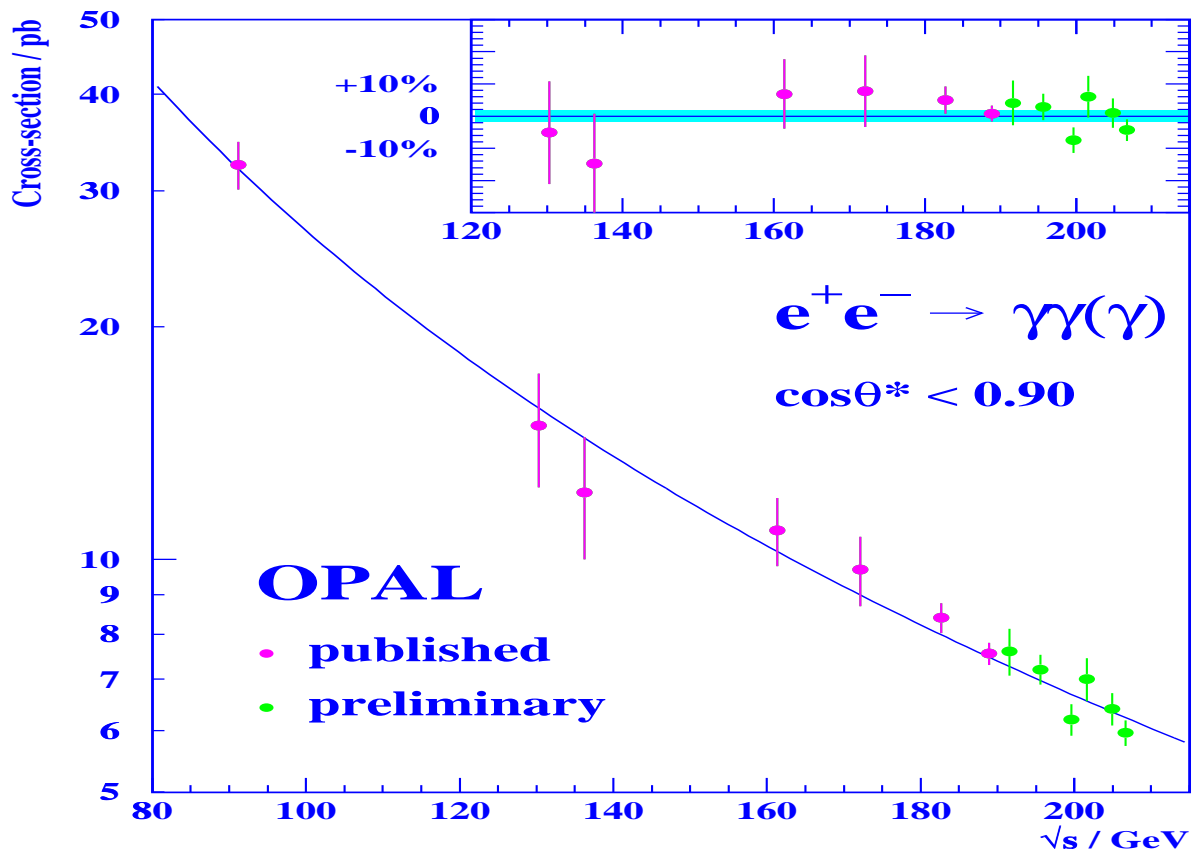
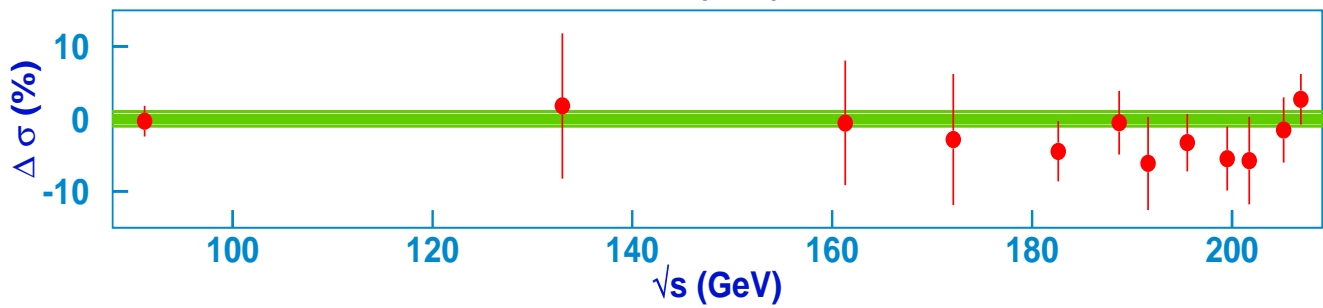
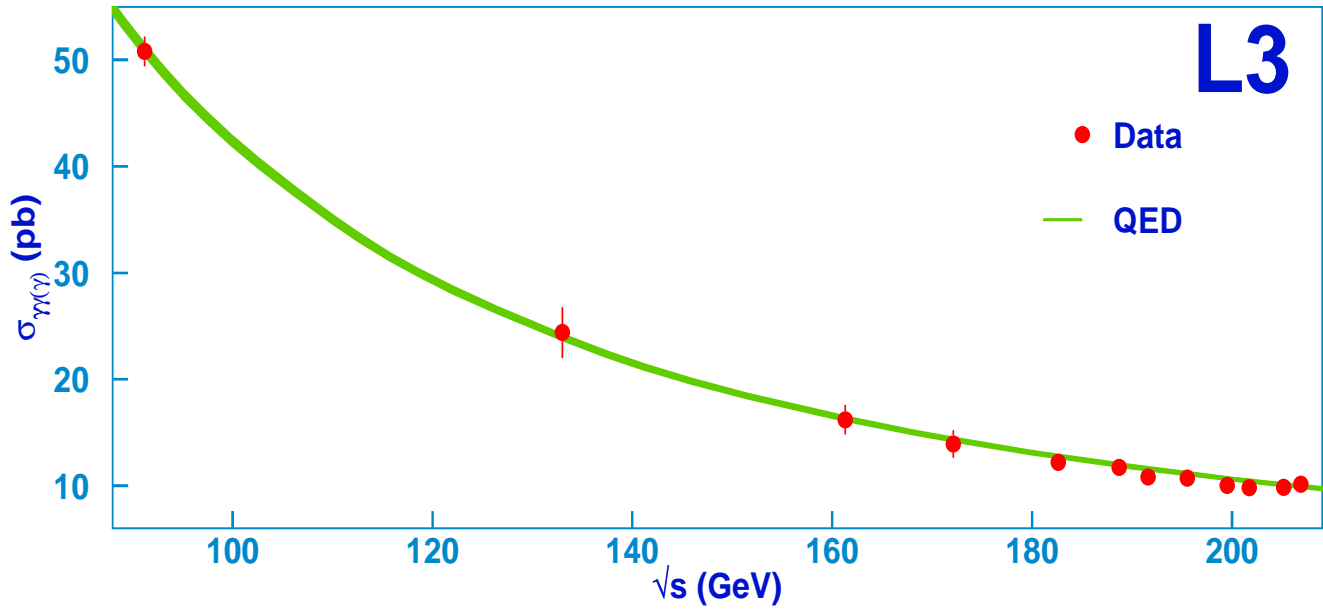
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{QED} \cdot \left(1 + \frac{2}{\alpha} \cdot \frac{s^2}{2(\Lambda_6)^4} \sin^2 \theta + \dots \right)$$

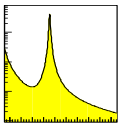
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{QED} \cdot \left(1 + \frac{s^3}{32\pi\alpha^2(\Lambda')^6} \frac{\sin^2 \theta}{1 + \cos^2 \theta} + \dots \right)$$



$\gamma\gamma$

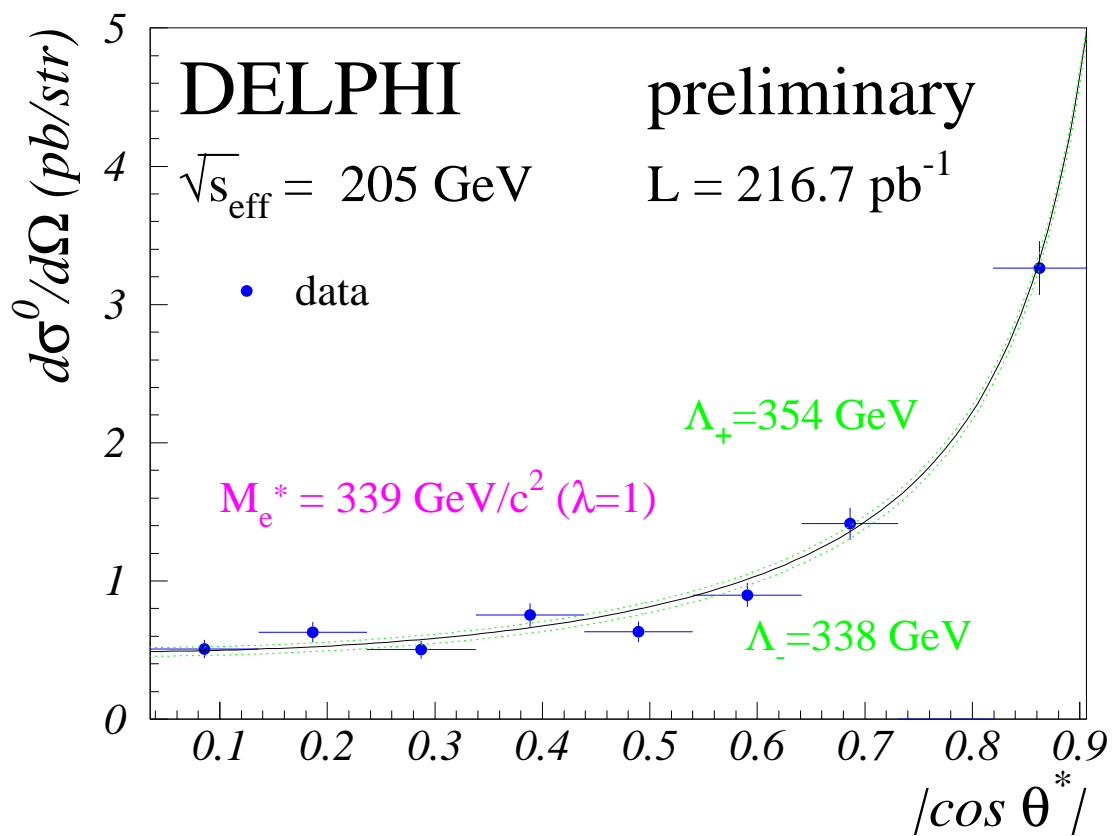
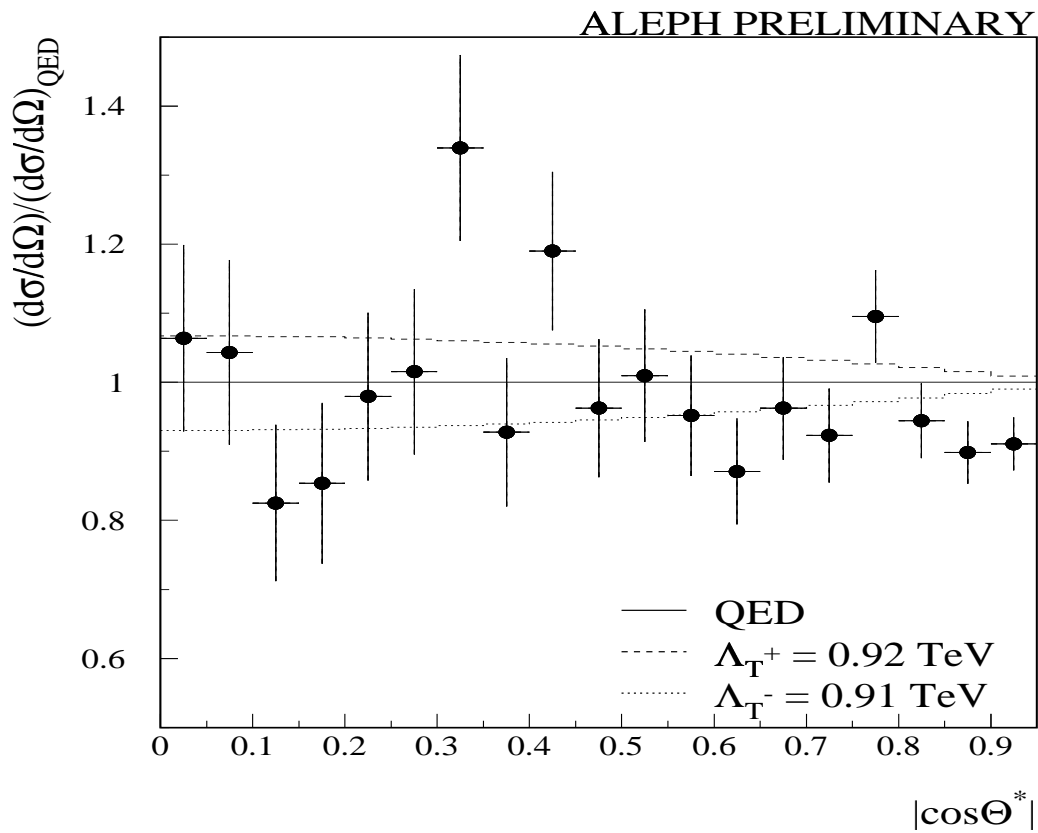
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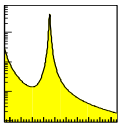




$\gamma\gamma$

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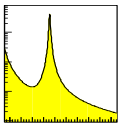


$\gamma\gamma$ - Limits

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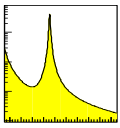
Model	ALEPH [TeV]	DELPHI [TeV]	L3 [TeV]	OPAL [TeV]	Combined [TeV](*)
QED cut-off - $\Lambda_{\pm}^{\text{QED}}$					
Λ_+	0.319	0.355	0.385	0.344	0.44
Λ_-	0.317	0.321	0.325	0.325	0.37
excited electron: $m_{e^*}^2/\lambda \sim (\Lambda^{\text{QED}})^2$					
M_{e^*}	0.337	0.339	0.325	0.354	-
low scale gravity: $M_S = 2.57 \Lambda^{\text{QED}}$; $\Lambda_T = 1.12 M_S$					
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: $M_S = 0.952 \Lambda^{\text{QED}}$					
M_S	0.304	0.338	0.367	0.328	0.42
contact interactions: $\Lambda_6 = 4.069 \Lambda^{\text{QED}}$					
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		
$e^+e^- \rightarrow \text{bosons}$	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 (*)		
$e^+e^- \text{ and } \gamma\gamma$	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:

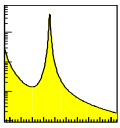
$$\Lambda_{VV}^+ \simeq \sqrt{\frac{4\pi}{0.59g_s}} \cdot M_S$$

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

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

Process	D-brane string scale M_S (TeV)	
	$g_s = g_{YM}^2 \sim \frac{1}{2}$	$\frac{g_s}{4\pi} = \frac{1}{128}$
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



- ♣ 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 results

LHC NEWS : STRING DISCOVERY?