Single Leptoquark Production in pp

Theodora D. Papadopoulou

NTU Athens

1rst ECFA-CERN-LHeC Workshop
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Outline

- About theoretical motivation on LQ studies
- Pair and LQ production at LHC
- Comparison of Single and Pair LQ aspects
- Single LQ studies at LHC
- Preliminary results
- Outlook
- As an Epilogue

Theoretical Motivation

L Q s :

- **appear in many unification theories beyond the SM**
  (GUT, Compositeness, TC, Superstring theories-E_6)

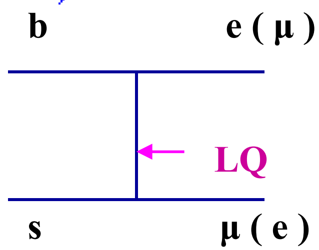
- **Color-triplet bosons with Couplings to quarks and leptons**

- **Scalars (S) and Vectors (V)** ; F=0 $(e^{-1}\ \bar{q})$ and F=2 $(e^{-1}\ q)$
  F=3 B + L

- **Only family diagonal Couplings**
  (to avoid FCNC processes) — LFV also considered (HERA)

- **Chirality conserving LQ** **(Very strong bounds from rare decays)**
  $\Longrightarrow$ 14 species (7 Scalars and 7 Vectors)
  (BRW effective model : 6 isospin singlets,6 doublets and 2 triplets)

- **Pati-Salam LQ**
  Search for $B_s \rightarrow e\ \mu$ decay
  (CDF : $M_{LQ}(B_s) > 19.3$ TeV at 95 % CL)



BRW model

Buchmuller, Rückl, Wyler (BRW) model (1987)

- **Assumptions:**
  - **LQs only couple to quarks, leptons and gauge bosons (with dimensionless couplings)**
  - **LQ interactions invariant under SM gauge group** $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- **LQs are classified by:**
  - **fermion number,** $F=3B+L$ ➔ **F = 0, 2**
  - **spin ➔** ***J=0*** **(scalar) or** ***J=1*** **(vector)**
  - **charge ➔** Q_{em} **= ±1/3, ±2/3, -4/3, -5/3**

- ***Intergenerational mixing is severely restricted by FCNC data*** ➔ **LQ appear in 3 quark/lepton generations**
- ***LQ-mediated π and K helicity-suppressed decays not observed*** ➔ **chiral LQ couplings to fermions**

14 chiral LQ species per generation:

- **7 scalar LQs** (3 singlets, 3 doublets, 1 triplet)
- **7 vector LQs** (3 singlets, 3 doublets, 1 triplet)

About LQ Coupling

- LQs can have:
  - **spin 0 (scalar)** ➔ couplings fixed, i.e., no free parameters
  - **spin 1 (vector)** ➔ anomalous magnetic (κ_G) and electric quadrupole (λ_G) model-dependent couplings
    - Yang-Mills coupling ▶ $\kappa_G=\lambda_G=0$
    - Minimal coupling ▶ $\kappa_G=1$, $\lambda_G=0$

- **Resonance width**

  $\Gamma \sim \lambda^2 \cdot m_{LQ}$

$$\frac{\lambda^2}{4\pi} = \alpha_{em}$$

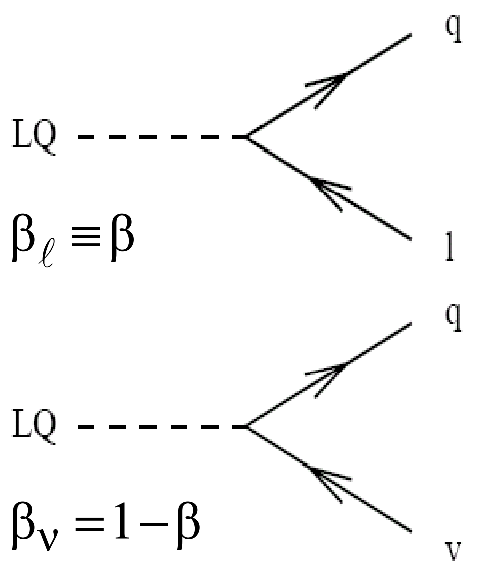
LQ species and decays

	F	spin	species
couple to ℓ^-q, νq	2	0	$S_{0,L}$; $S_{0,R}$; $\tilde{S}_{0,R}$; $S_{1,L}$
	2	1	$V_{1/2,L}$; $V_{1/2,R}$; $\tilde{V}_{1/2,L}$
couple to ℓ^+q, $\bar{\nu}$q	0	0	$S_{1/2,L}$; $S_{1/2,R}$; $\tilde{S}_{1/2,L}$
	0	1	$V_{0,L}$; $V_{0,R}$; $\tilde{V}_{0,R}$; $V_{1,L}$

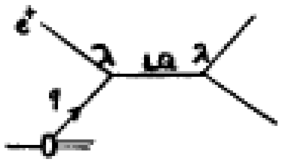
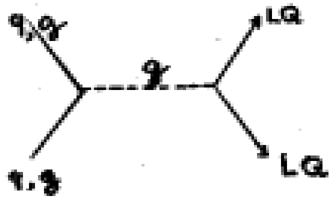
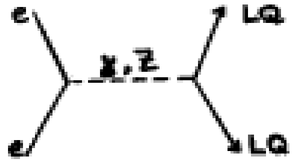
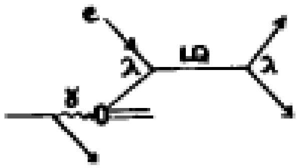
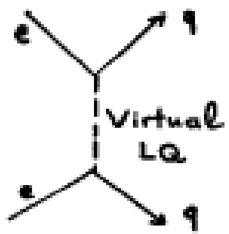
labeled by weak isospin and lepton helicities

Decays:

- **LQs decay to $\ell^{\pm}$q and/or ν^{ℓ}q' with branching ratios β_ℓ, β_ν = 0, 0.5, 1 (depending on the quantum numbers)**
- **Scalar LQs decay isotropically**
- **Vector LQs decay ~ $(1+\cos\theta^*)^2$**

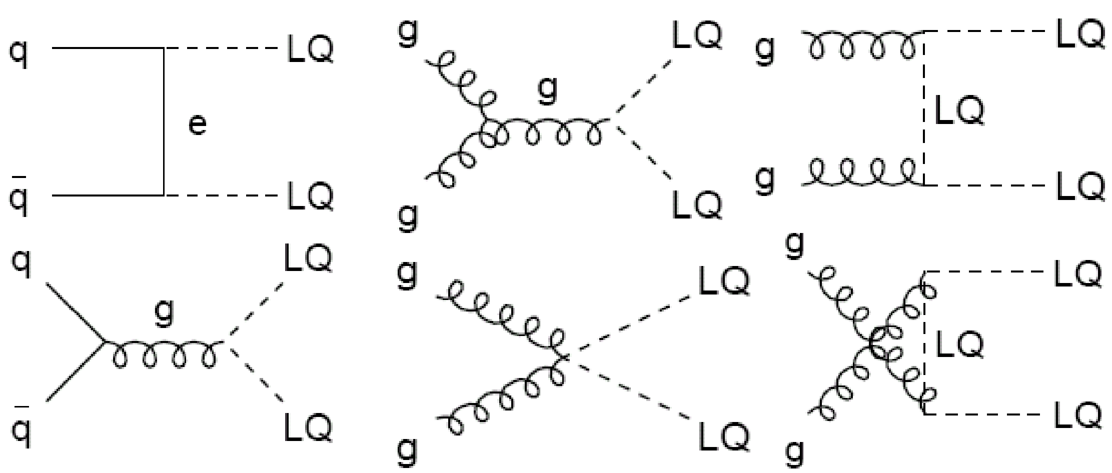


Overview of LQ production mechanisms

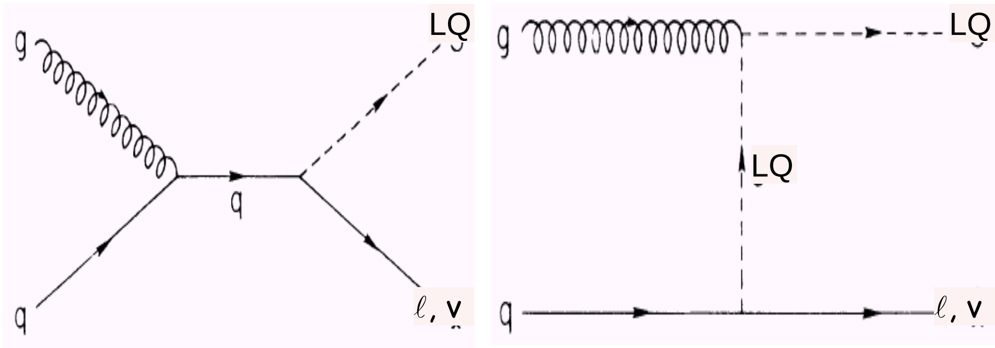
HERA	TEVATRON-LHC	LEP
		
$\sim \lambda^2$	no λ dependence	
β = BR to $\ell^{\pm} q$	β	
first generation	all three generations	
at fixed β, λ vs M		
at fixed λ, β vs μ		
$\frac{\lambda^2}{4\pi} = \alpha_{EM}$		

LQ production at LHC

- **Pair production**
  - Practically independent of Yukawa coupling λ
  - Depends mainly on LQ mass



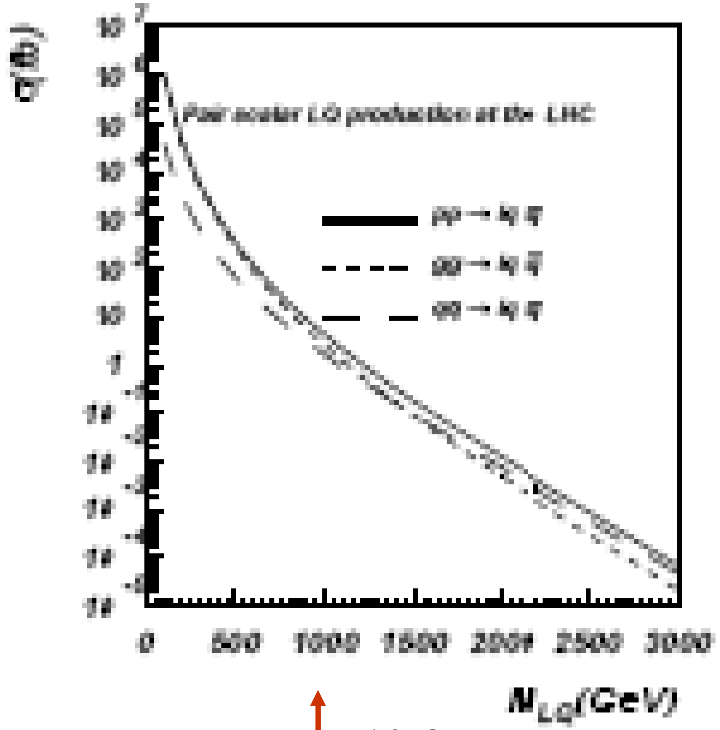
- **Single production**
  - strongly depends on λ
  - possible signatures:
    - $\ell^+\ell^-$ + jet
    - $\ell\nu$ + jet
    - $\nu\nu$ + jet



❖ Both categories (Pair and Single) LQs are complementary for LHC searches

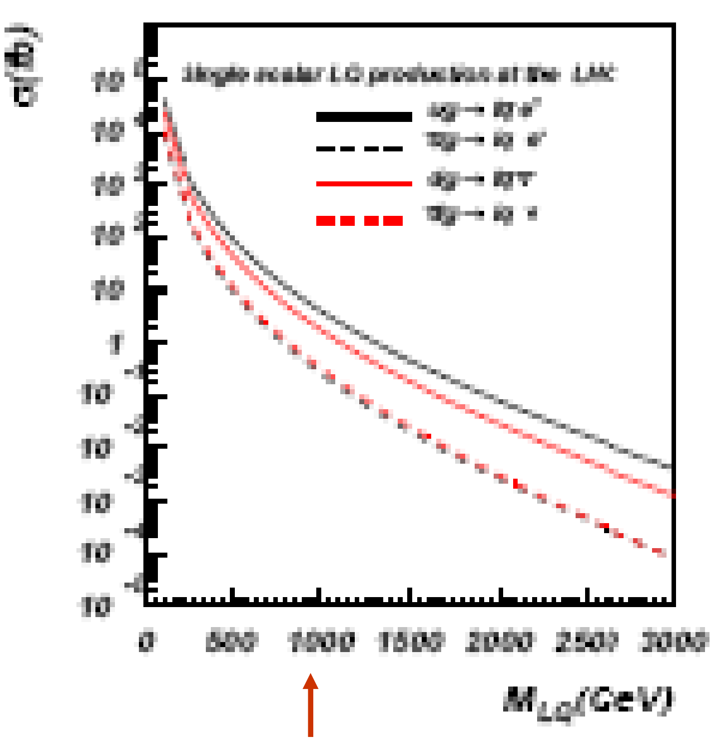
LQ cross sections at LHC

Pair Scalar LQ production



↑ ~10 fb

Single Scalar LQ production



↑ ~10 fb

•Single LQ → valence quarks

•Single $\overline{L}\overline{Q}$ → sea quarks

A. Belyaev, C.Leroy, R.Mehdieyev, A. Pukhov, Phys. Rev. D59 (1999) 075007

❖ If the LQ Coupling is of the order of α_{em} single LQ production should be combined with the studies of LQ pair production

Single LQ studies with

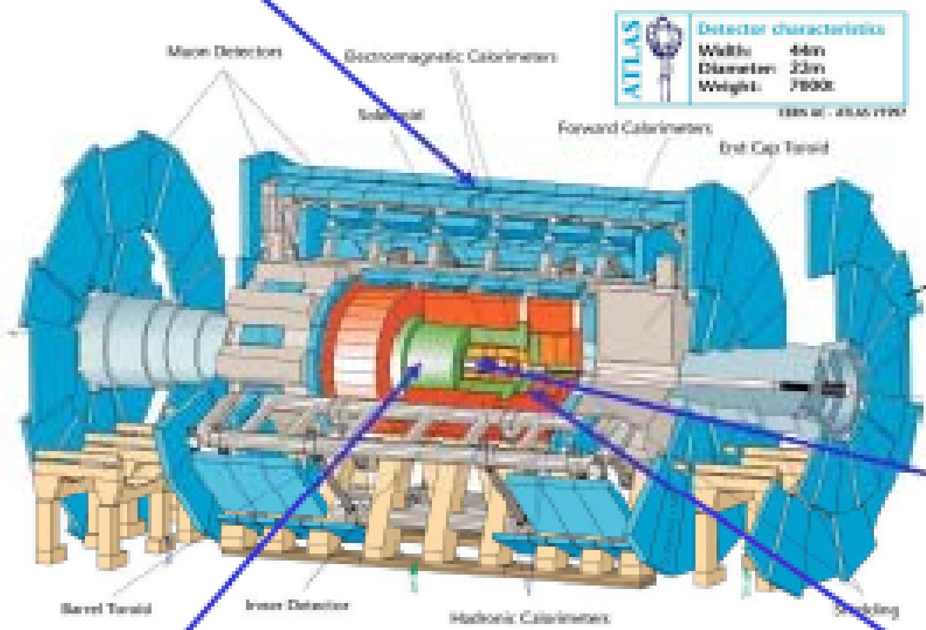
The ATLAS Detector

- Length: ~44 m
- Radius: ~12 m
- Weight: ~ 7000 t
- El. Channels: ~10^8
- Cables: ~3000 km

Precision Muon Spectrometer $\sigma / pT \sim 10\,\%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution (e.g., $A/Z' \rightarrow \mu\mu$, $H \rightarrow 4\mu$)



Inner Detector

$\sigma / p_T \sim 5 \cdot 10^{-4}\, p_T \oplus 0.001$

Good impact parameter res.

(e.g., $H \rightarrow bb$)

EM Calorimeters $\sigma / E \sim 10\% / \sqrt{E(GeV)}$

excellent electron/photon identification

Good *E* resolution (e.g., $H \rightarrow \gamma\gamma$)

Hadron Calorimeters

Good jet and E_T miss performance

(e.g., $H \rightarrow \tau\tau$) $\sigma / E \sim 50\% / \sqrt{E(GeV)} \oplus 0.03$

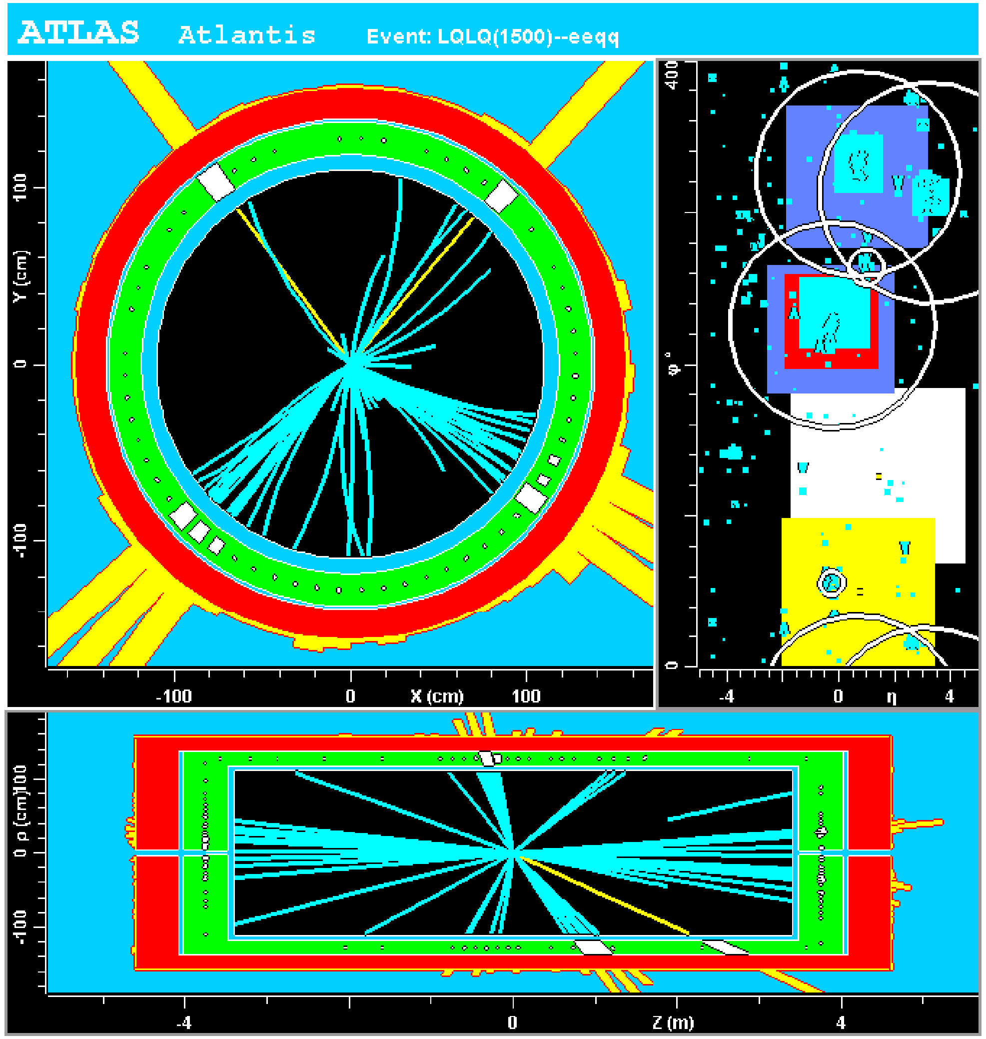
We will probe distances up to 10^{-19} m !

First LQ study in ATLAS

Pair LQ production -ATLAS

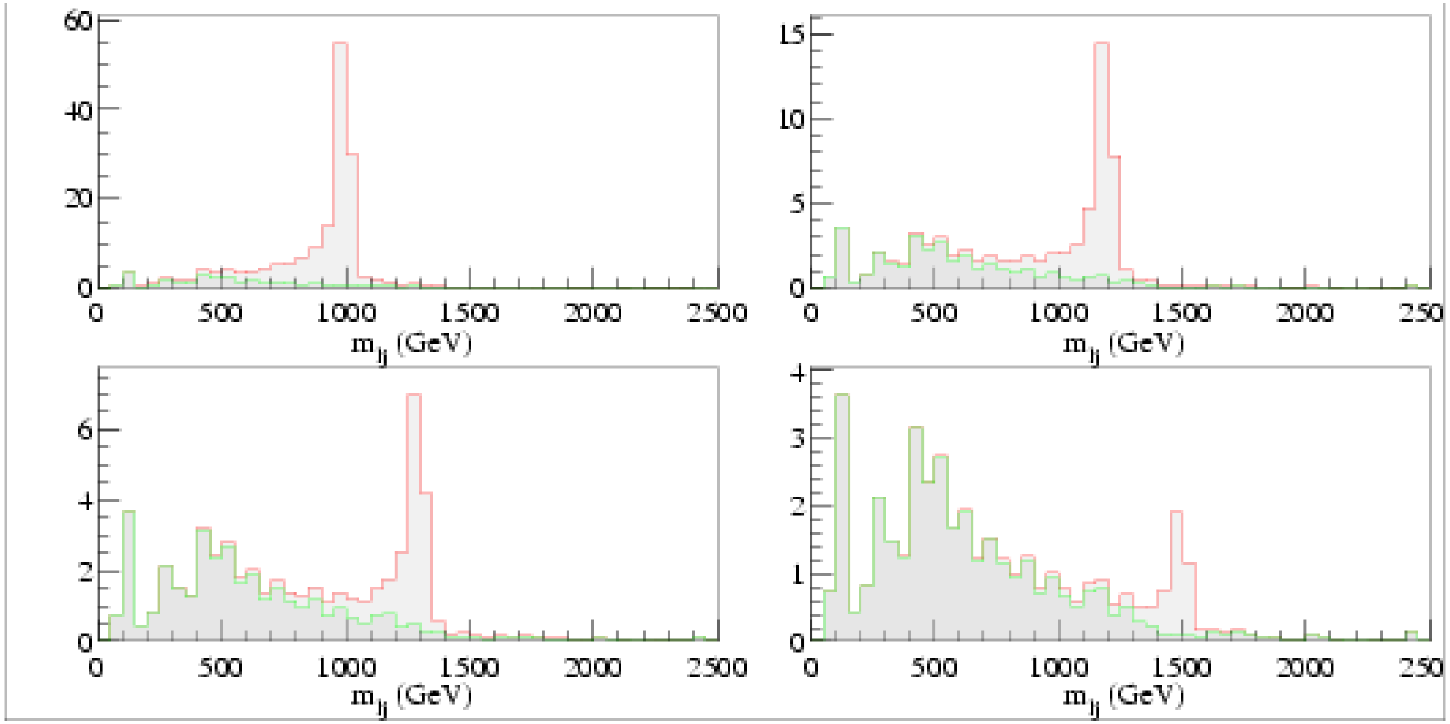
- Scalar leptoquarks
- PAIR Production
  - ℓℓjj channel
  - ννjj channel
  - independent of λ
- Simulation tools:
  - PYTHIA
    - qq → LQ LQ
    - gg → LQ LQ
  - ATLAS fast simulation *(ATHENA-ATLFAST)*

LQ LQ → e+e-qq (m_LQ=1500 GeV)



V.Mitsou, N.Benekos, I.Panagoulias, Th.Papadopoulou, ATL-COM-PHYS-2004-071, Cz. J. of Physics,Vol. 54(2004), Suppl. A

lljj Signal and Background

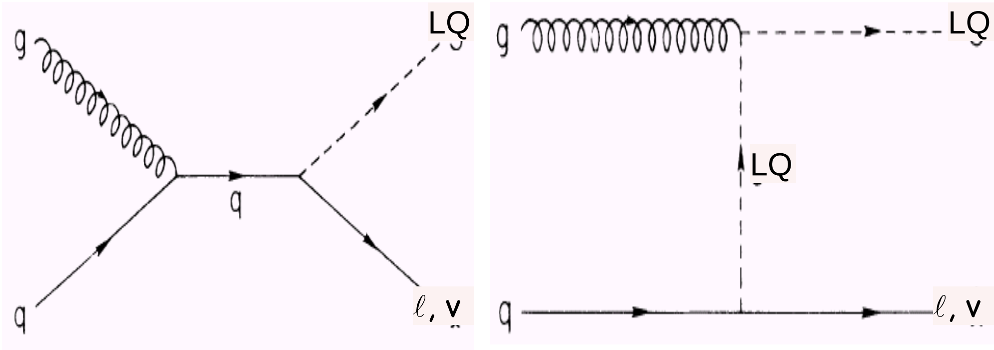


L=30 fb^{-1}

Signal can be observed for **MLQ ~ 1.3 TeV (5σ)**

Results are presented by V.Mitsou in "Physics at LHC" Conference, Vienna 2004

Single LQ at LHC



Interesting aspects !!

❖ **it is possible to probe LQ masses greater than half of the center-of-mass-energy of the experiment (Ecm/2)**

❖ **this process gives high PT leptons and jets (clear signal)**

BUT

❖ **the signal extraction is very difficult due to low cross-section !**

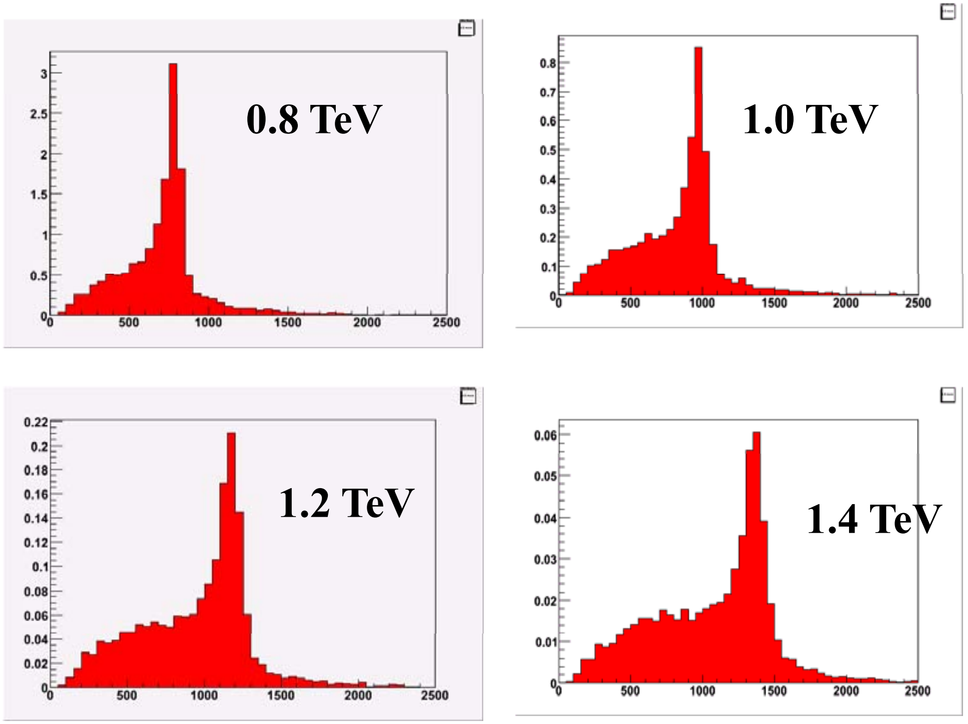
Single LQ production with ATLAS

PRELIMINARY RESULTS

Evgenia Panagiotopoulou

PhD studies-NTU Athens

➢ **reconstruction of invariant mass LQ**



(1) Study of the 2nd gen

Single LQ → c μ

Topology : μ μ jet

and (later)

(2) Study of the 1st gen

Single LQ → u e , d e

Topology : e e jet

- **ATLFAST studies 1st step**

- **Studies with fully simulated events 2nd step→**

Baseline selections

(common for all ATLAS LQ analyses)

Muons	Combined muons (reconstructed containing track in both inner + muon detectors)
	Muon pT ≥ 20 GeV
	Muon $\|\eta\| \leq 2.5$
Jets	Reconstructed calorimeter towers with $\Delta R = 0.4$ cone algorithm
	Jet pT ≥ 20 GeV
	Jet $\|\eta\| \leq 4.5$

Individual analysis cuts

Select the 2 highest pT muons (pTmax$_{\mu 1}$, pTmax$_{\mu 2}$) and the highest pT jet (pTmax$_{j}$)

all max pTs ≥ 100 GeV for low LQmass (300, 400 GeV)	all max pTs ≥ 170, 230 GeV for high LQmass (600, 800 GeV respectively)

Cut b-jets (jets who's weight is > 4)

Invariant mass of the 2 selected muons $M_{\mu\mu} \geq 200$ GeV

Sum of max pTs: SPT = pTmax$_{\mu 1}$ + pTmax$_{\mu 2}$ + pTmax$_{j}$

SPT ≥ LQmass+100 GeV for low LQmass (300, 400 GeV)	SPT ≥ LQmass+200 GeV for high LQmass (600, 800 GeV)

Single LQ Signal efficiencies

PRELIMINARY RESULTS

Single LQ mass (GeV)	Signal efficiency	
	LQ → u μ (good statistics)	**LQ → c μ** (poor statistics)
300	13.3% ± 0.9%	12.2% ± 2.1%
400	12.4% ± 0.4%	17.5% ± 2.5%
600	15.2% ± 0.9%	11% ± 1.6%
800	15.7% ± 0.7%	10.9% ± 1.4%

- **for Single Scalar LQ (Q = -1/3)**

Single LQ Discovery Luminosities

PRELIMINARY RESULTS

M_{LQ} (GeV)	$\sigma * \mathcal{B}$ LQ → u μ (pb)	Generated single LQ events	Signal events	Background events	Signal significance	5σ Discovery **Expected** Luminosity (fb-1)
300	1.234	1809	1153	199	45	0.71
400	0.368	7541	402	132	23	1.67
600	0.0647	2355	59	11	10	4.6
800	0.0173	3476	14	3.7	5.1	14

Cut flow for Single LQ (m=400 GeV)

PRELIMINARY RESULTS

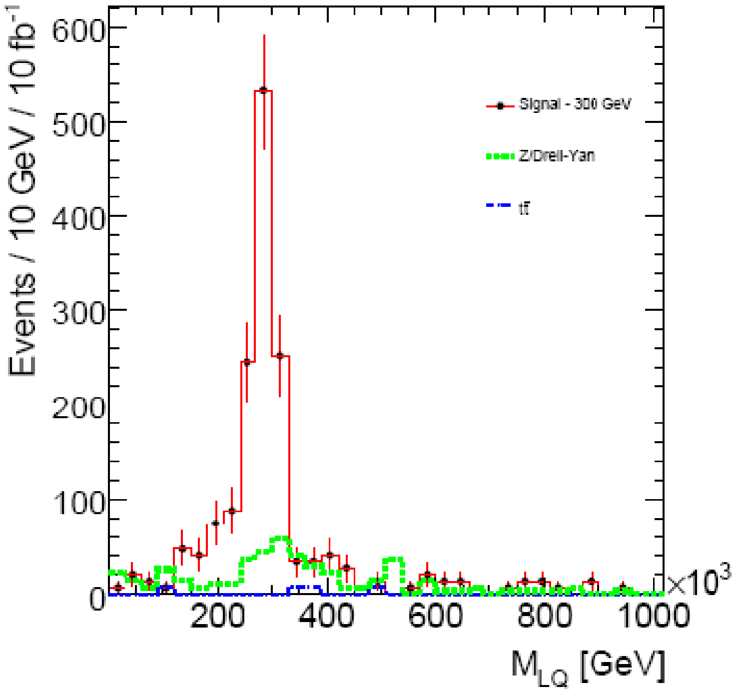
Physics sample	Before cuts	Baseline cuts	$pTmax\mu_{1,2} \geq 100$ GeV $pTmaxj \geq 100$ GeV b-tag weight ≤ 4	SPT $\geq$ 500 GeV	$M\mu\mu \geq$ 200 GeV	LQ mass window ($\pm 2\sigma$)
MLQ = 400 GeV	3680	2432	666	613	457	402
Z/DY $\geq$ 150 GeV	72780	33626	689	586	360	118
t tbar	420000?	86581	42	28	28	14

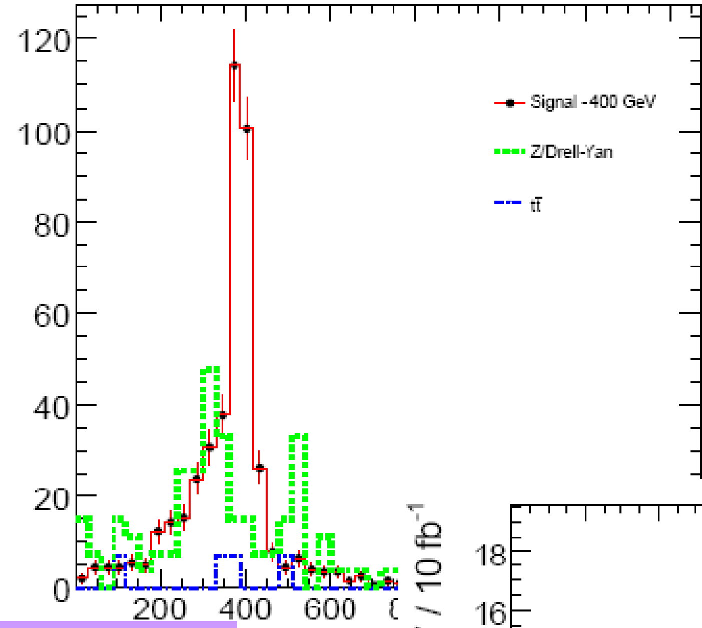
- **Single Scalar LQ → u μ (Q = -1/3)**
- **Optimized for the smallest integrated luminosity needed for a discovery with 5σ and normalized for an integrated luminosity of 10 fb^{-1}**
- **All other background are negligible**

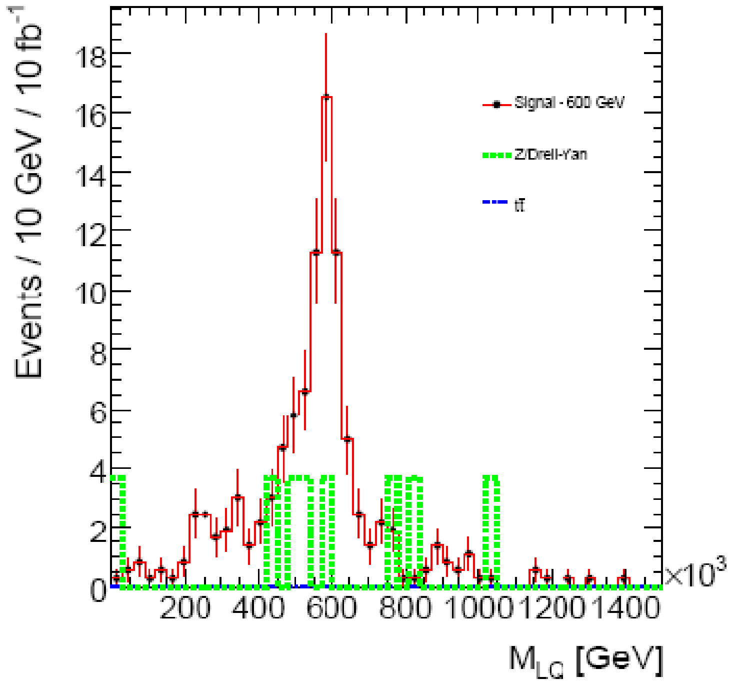
VERY PRELIMINARY RESULTS

Systematic error	effect on signal	effect on background
Integrated luminosity	20% ??	20% ??
LQ cross-section	10%	-
High mass DY cross-section (main background)	-	1.2%
t tbar cross-section (secondary background)	-	7.2%
Muon identification and trigger	10%	10%
Muon resolution	8%	8%
Jet energy scale	6%	7%
Jet resolution	5%	6%
Statistical uncertainty of MC	2%	6%
B-tagging uncertainty	10%	10%
Quadratic sum of all uncertainties	28.8%	28.9%

Invariant mass μj pair







PRELIMINARY RESULTS

Early LHC Single LQ searches !

- **LQ mass from 300 – 600 GeV**
- **plots are normalized to L= 10 fb^{-1}**

Beyond minimal LQs: SUSY quarks

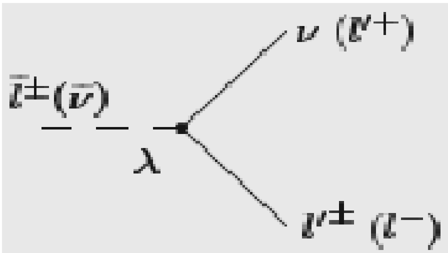
- Rp can be explicitly broken by trilinear terms in the superpotential

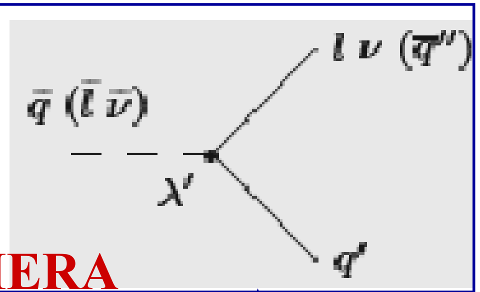
$$W = \lambda_{ijk} L_i L_j \overline{E}_k \quad + \lambda'_{ijk} L_i Q_j \overline{D}_k \quad + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k$$

$\Delta L \neq 0$ — 9 Couplings $(i \neq j)$

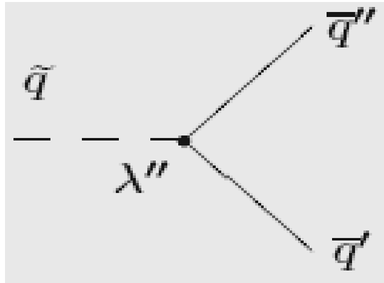
$\Delta L \neq 0$ — 27 Couplings

$\Delta B \neq 0$ — 9 Couplings $(j \neq k)$





HERA



- o **single sparticle production** **via a $\Delta L \neq 0$ or a $\Delta B \neq 0$ operator**
- o **Unstable LSP !**

- **Resonant squark production**
- **l +(l) + multijets**

→ **fast proton decay is suppressed if Lepton and Baryon number Violating Couplings not simultaneously present**

Outlook

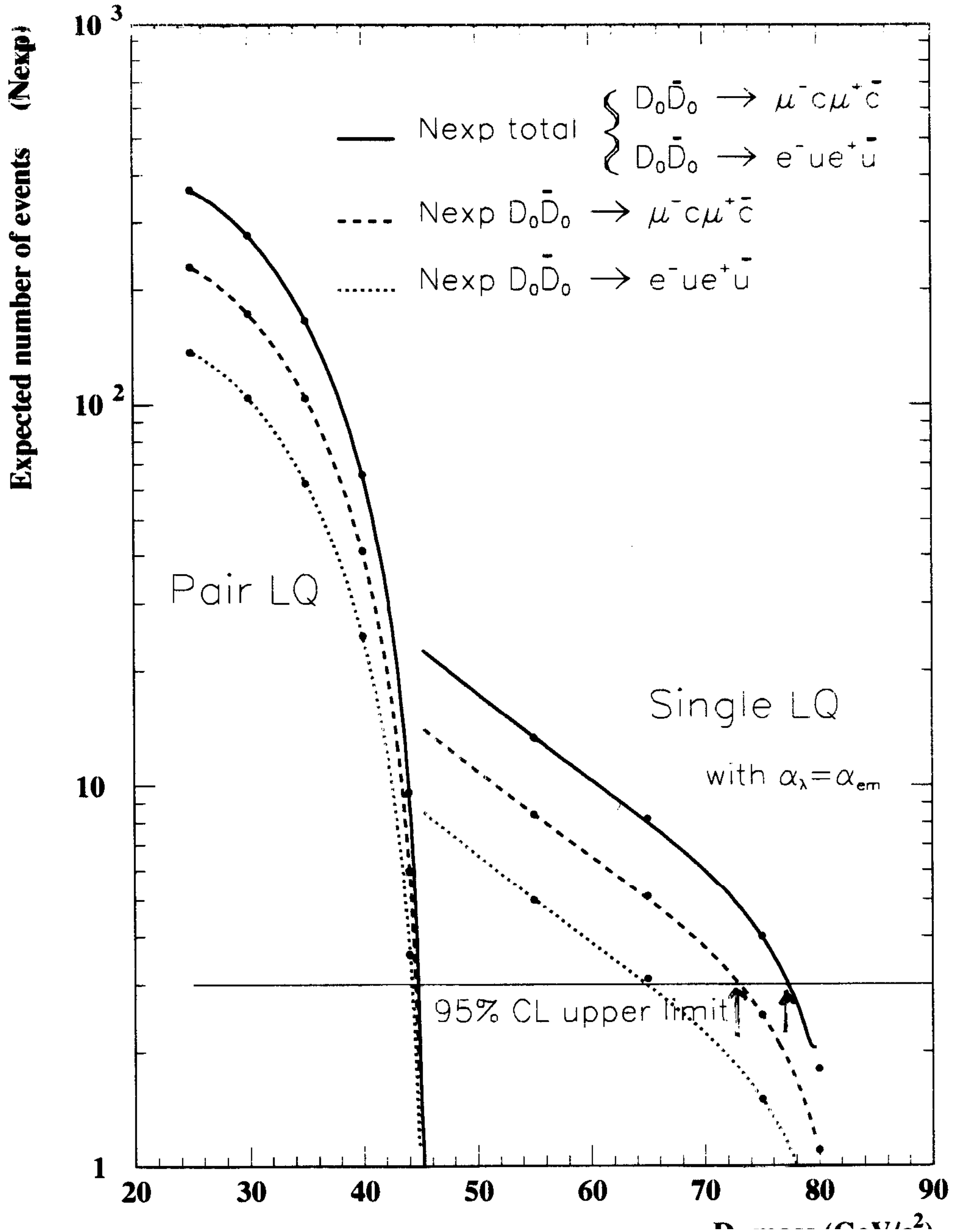
- **Pair and Single LQ studies at LHC are complementary**
- **First studies on Single LQ with ATLAS/LHC are underway towards the final results at early LHC**
- **Results presented are PRELIMINARY**
- **Use of the LHC results to predictions for the LHeC are important for the LHeC expectations on the potential of**

LHeC New physics

Hunting LQs (!) from

Single LQ

at LEP 1



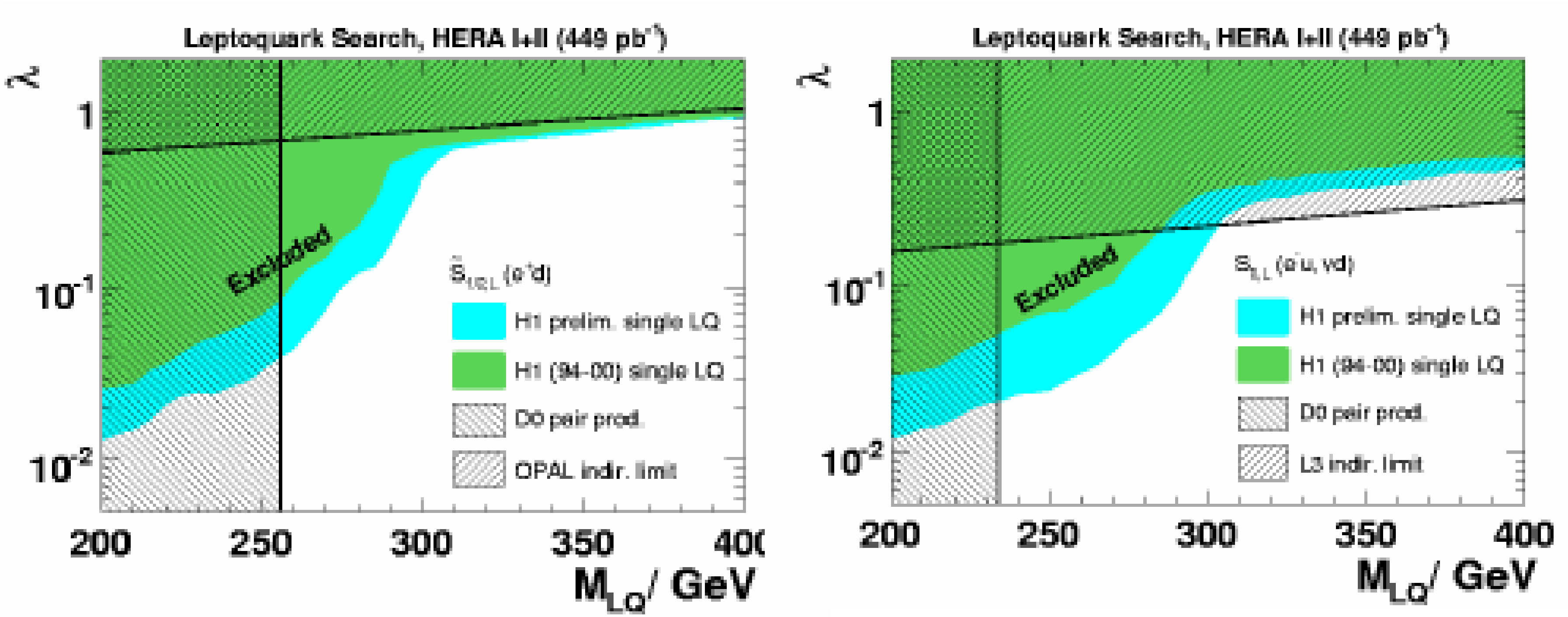
Th.Papadopoulou

DELPHI Collaboration

Phys. Lett B316 (1993)620

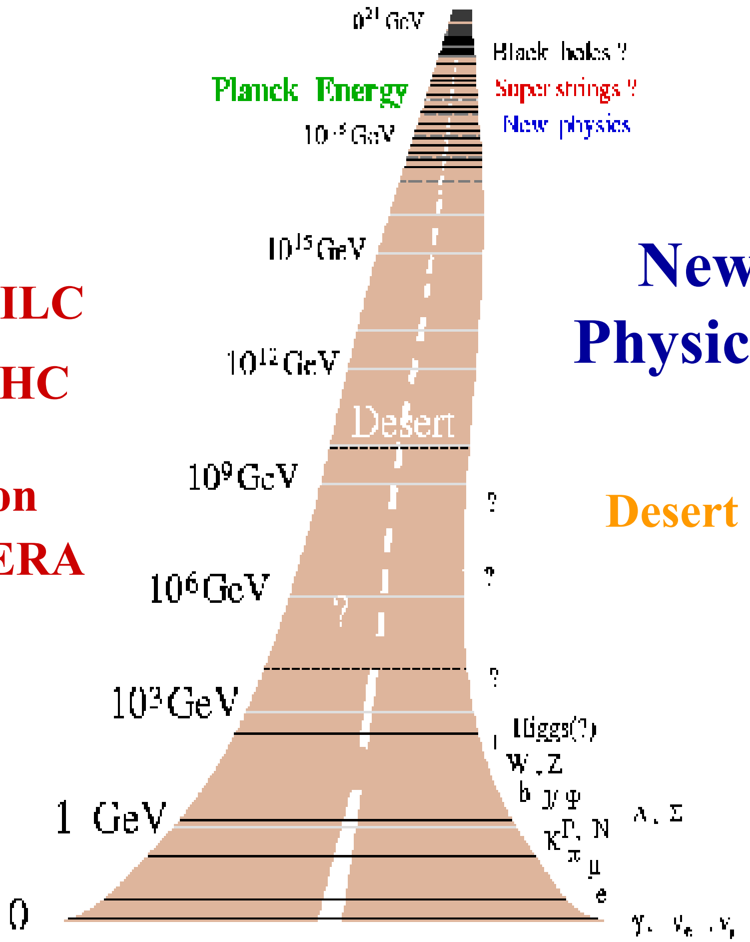
LQ Exclusion Limits -- comparison with LEP and Tevatron

from I. Panagoulias' talk at DIS2008 – work on PhD / NTUA & DESY



HERA extends the exclusion region

As an Epilogue



ILC

LHC

Tevatron

HERA

LEP2

New Physics ?

Desert ?

Future Perspectives !

LHeC Collider ?