Prospects for leptoquark searches with ATLAS at the LHC

N. Benekos (*CERN)*

V. A. Mitsou (*IFIC –Valencia)*

I. Panagoulias, Th. Papadopoulou *(NTUA Athens)*

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Outline

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  - Phenomenology
  - Production of leptoquarks at LHC
- ATLAS sensitivity
  - 2 leptons + 2 jets topology
  - E_T^{miss} + 2 jets topology
- Conclusions

Theoretical motivation

- Leptoquarks (LQ) are hypothetical particles which appear in many SM extensions to explain **symmetry between leptons and quarks**
  - SU(5) GUT model
  - superstring-inspired models
  - 'colour' SU(4) Pati-Salam model
  - composite models
  - technicolor
- LQs are coupled to both leptons and quarks and carry SU(3) color, fractional electric charge, baryon (B) and lepton (L) numbers
- 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: $\kappa_G=1$, $\lambda_G=0$
- Experimental evidence searched:
  - indirectly: LQ-induced 4-fermion interactions
  - directly: production cross sections at collider experiments

Leptoquark classification

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 ► $Q_{em} = \pm 1/3, \pm 2/3, -4/3, -5/3$

- *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)

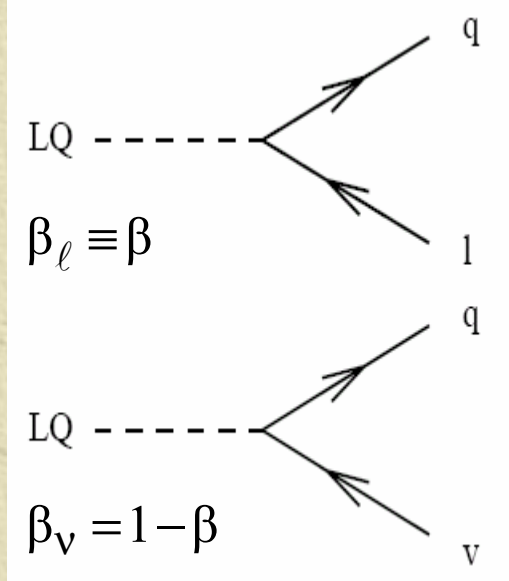
Phenomenology

	F	spin	species
couple to $\ell^- q$, 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 $\ell^+ q$, $\bar{\nu} q$	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 helicity

Decays:

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



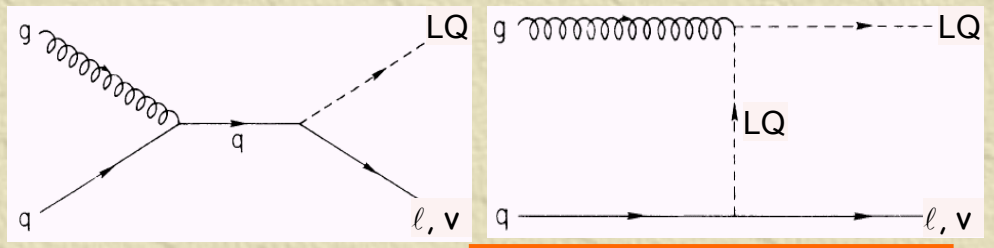
- **Each LQ characterized by two parameters:**
  - LQ mass
  - LQ-ℓ-q Yukawa coupling, λ
- **Resonance width** $\Gamma \sim \lambda^2 \cdot m_{LQ}$

LQ production processes at LHC

Single production

- strongly depends on λ
- possible signatures:
  - $\ell^+\ell^-$ + jet
  - $\ell\nu$ + jet
  - $\nu\nu$ + jet
- Main background: Zjet & tt

$qg \to \ell\, LQ$, $qg \to \nu\, LQ$

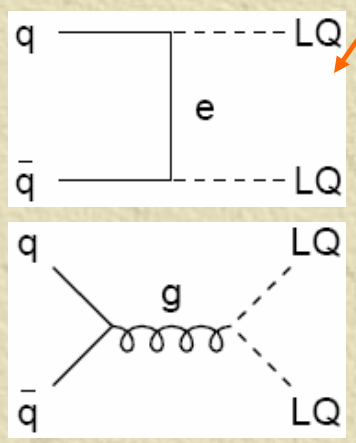


- λ-dependent process
- does not contribute significantly to 2nd & 3rd generation

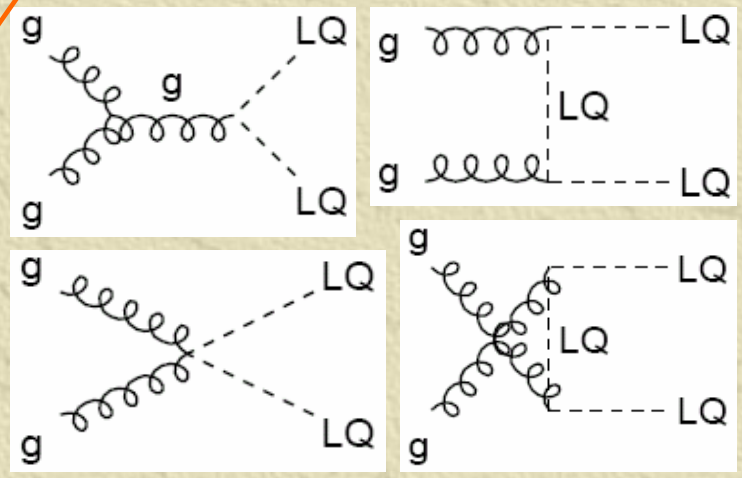
Pair production

- Practically independent of Yukawa coupling λ (only g-LQ-LQ vertex)
- Depends mainly on LQ mass

$q\bar{q} \to LQ\ LQ$

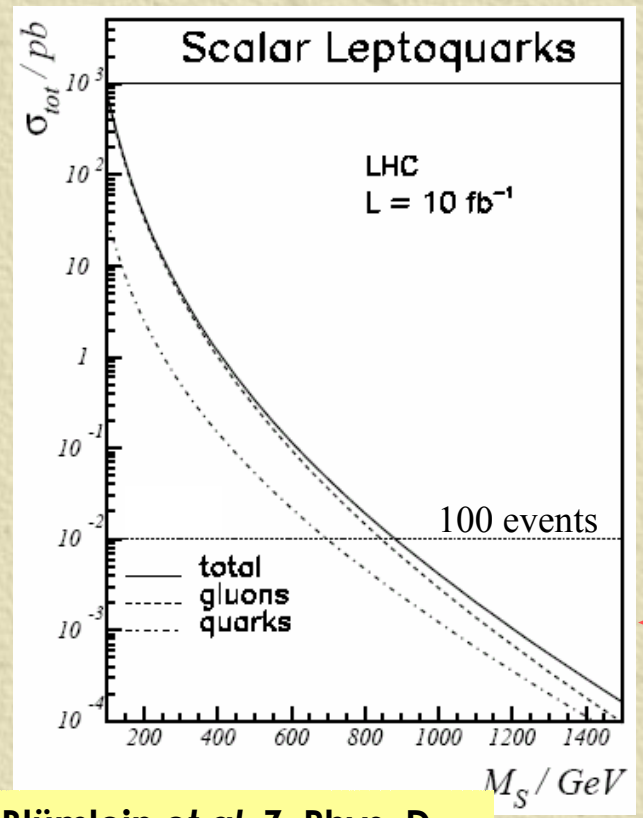


$gg \to LQ\ LQ$



LQ production rates at LHC

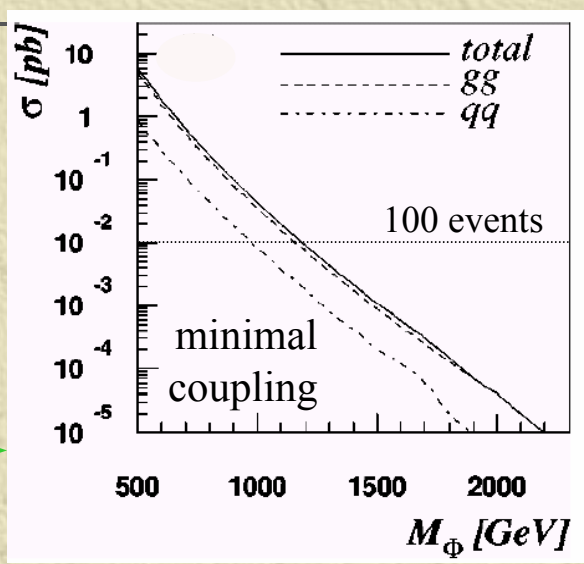
- Pair production cross sections
  - $q\bar{q} \rightarrow LQ\,LQ$: ~30% of total production (for $m_{LQ} \approx 1$TeV)

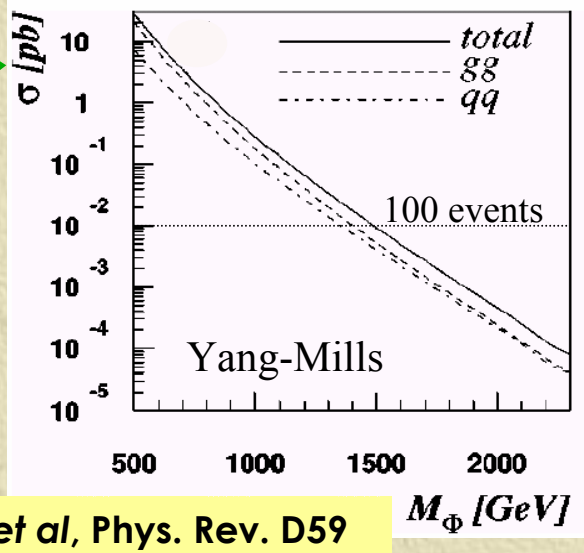


Blümlein *et al*, Z. Phys. D 76 (1997) 137

Vector LQs

Scalar LQs



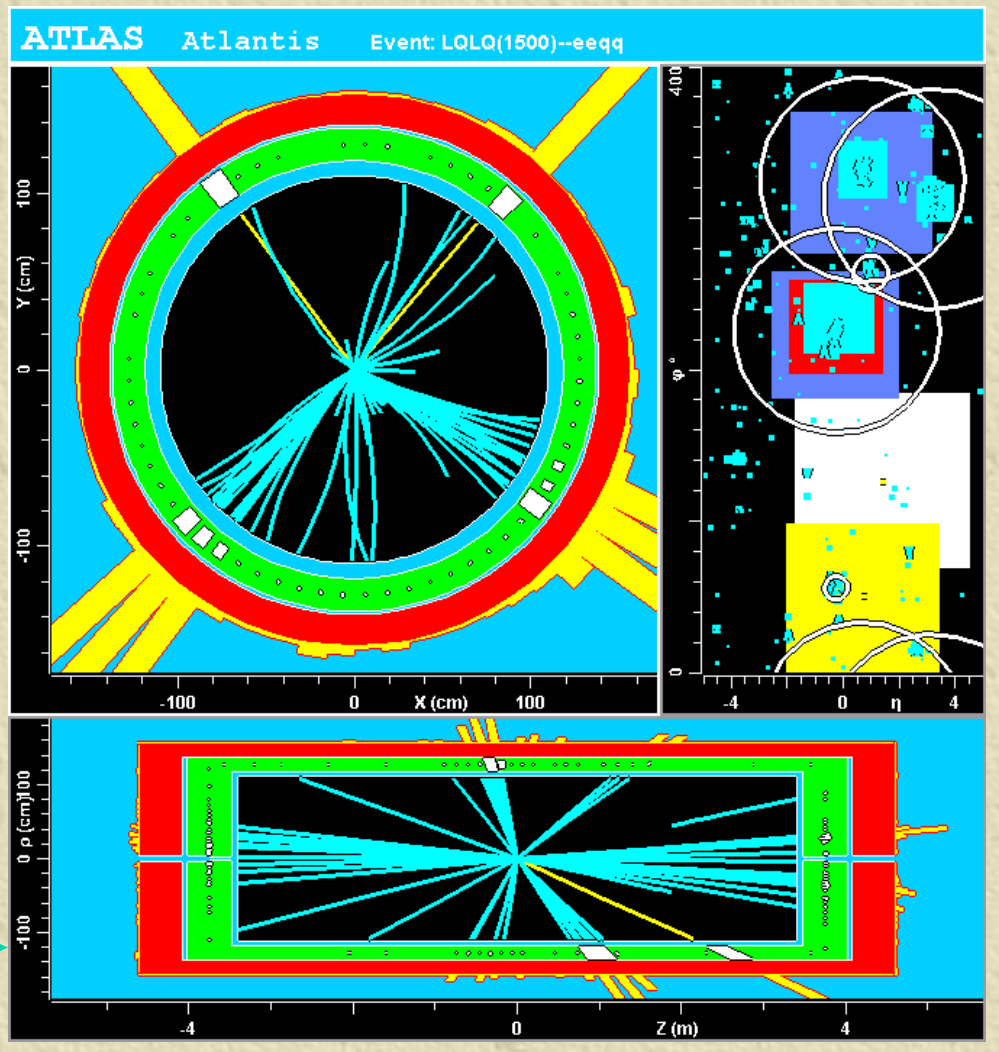


Belyaev *et al*, Phys. Rev. D59 (1999) 075007

Leptoquarks in ATLAS

- Scalar leptoquarks
- Pair production
  - $\ell\ell jj$ channel
  - $\nu\nu jj$ channel
  - independent of λ!
- Simulation tools:
  - PYTHIA
    - $qq \rightarrow LQ\,LQ$
    - $gg \rightarrow LQ\,LQ$
  - ATLAS fast simulation *(ATHENA-ATLFAST)*

$LQ\,LQ \rightarrow e^+e^-qq$
m_{LQ}=1500 GeV
(schematic view)



2 leptons + 2 jets topology

- **Signal**
  - LQ LQ $\rightarrow \ell^+q\ell^-q$
  - 1st and 2nd generation LQs
  - Scalar e^-u & μ^-c
  - $\beta=1 \rightarrow S_0^R(^{-1}/_3)$
  - $\beta=0.5 \rightarrow S_0^L(^{-1}/_3),\ S_1(^{-1}/_3)$
  - $\lambda \geq 10^{-6}$ (LQ : resonance)

M_{LQ} (TeV)	σ (fb)	
	1st gener.	2nd gener.
1.0	5.0	4.8
1.2	1.3	1.3
1.3	0.71	0.68
1.5	0.22	0.21
1.7	0.074	0.070
2.0	0.015	0.014

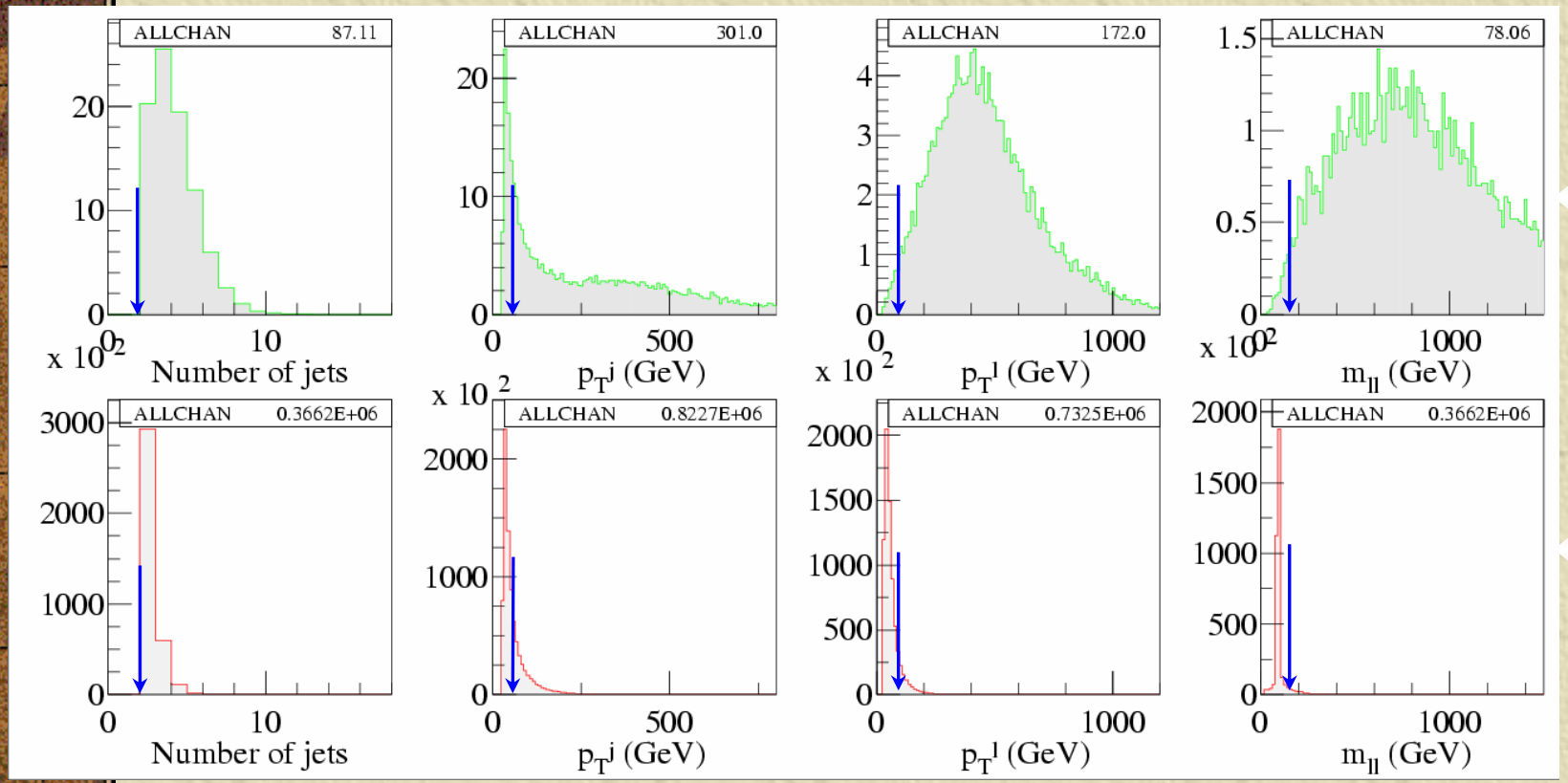
- **Background**
  - QCD: huge, but eliminated after high-p_T isolated leptons and high-$m_{\ell j}$ cuts are applied
  - Drell-Yan: eliminated by high-$m_{\ell j}$ cut

Process	σ×BR (pb)
Zjet ($\ell\ell jj$)), $p_T > 20$ GeV	1 380
tt ($\ell\nu j\ell\nu j$)	11
ZZ ($\ell\ell jj$)	1.2
ZW ($\ell\ell jj$)	1.2
WW ($\ell\nu\ell\nu$)	3.3

- First level cuts:
  - At least 2 jets with p_T>30 GeV and $|\eta|$<5.0
  - 2 same-flavour, opposite- sign leptons with p_T>30 GeV and $|\eta|$<2.5

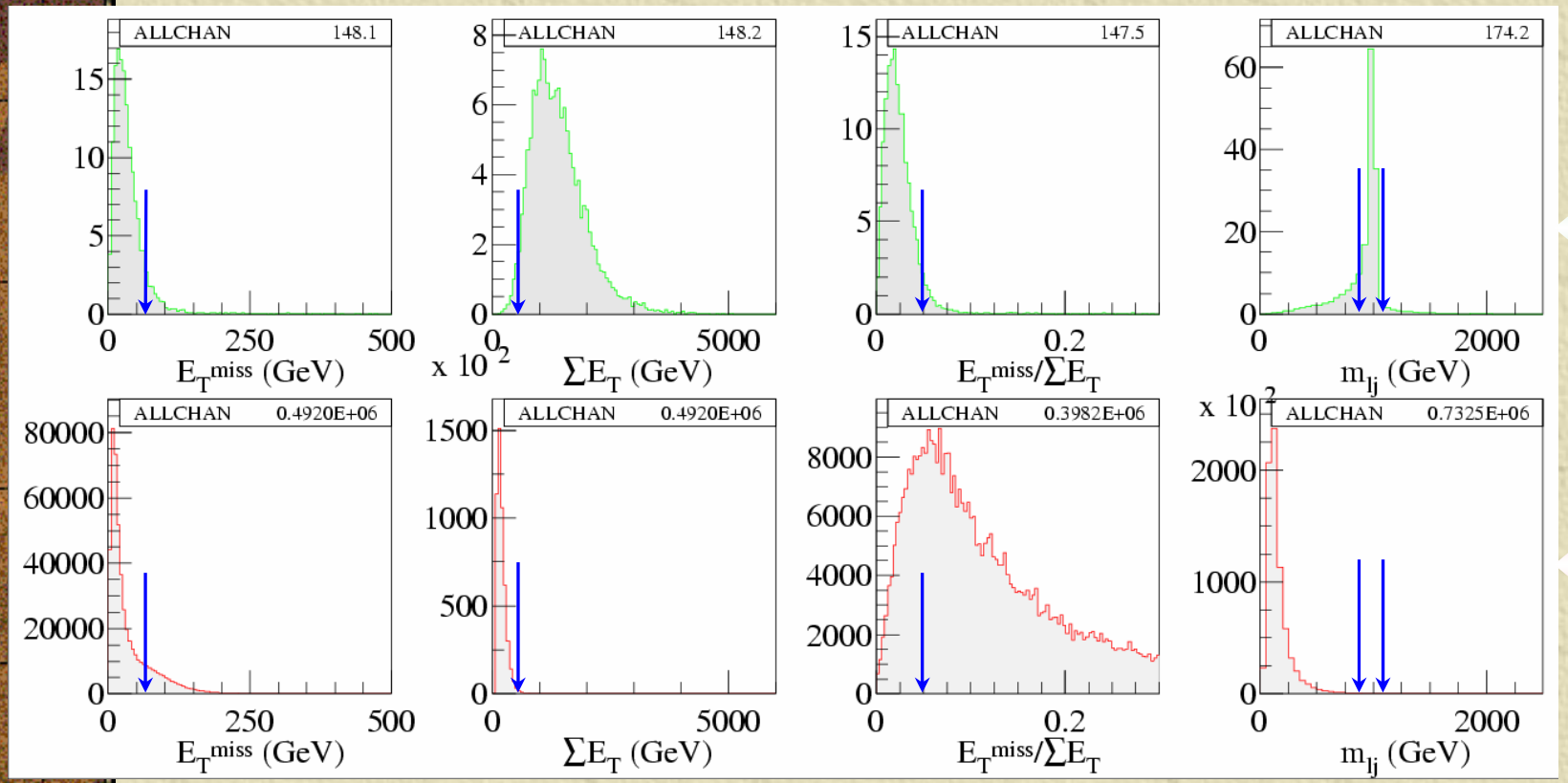
$\ell\ell jj$: selection variables I

- Signal (m_{LQ}=1 TeV):
  - Many high-p_T jets
  - Two high-p_T leptons
- Background:
  - $Z \rightarrow \ell^+\ell^-$ peak at $m_{\ell\ell} \approx 90$ GeV
- After first-level cuts



$\ell\ell jj$: selection variables II

- $\sum E_T$: sum of transverse energy in the calorimeters
- $m_{\ell j}$: lepton-jet invariant mass for two leading jets (minimum- $\Delta m_{\ell j}$ combination)



signal

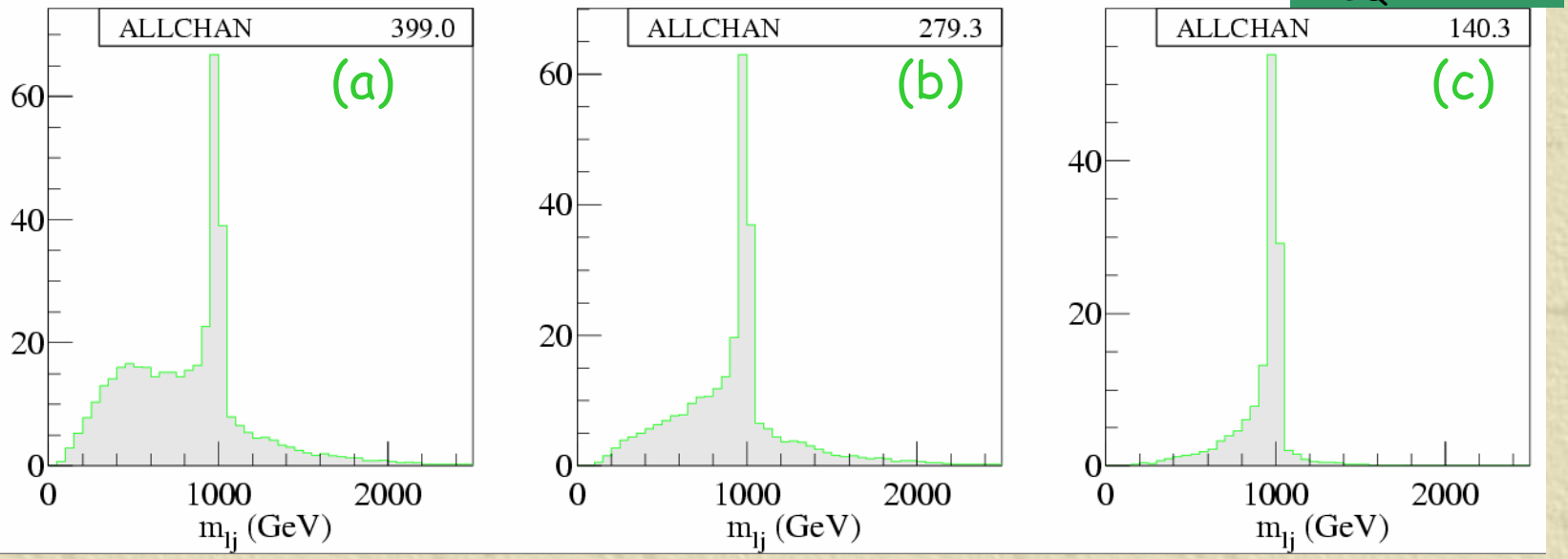
backgrnd

$\ell\ell jj$: $m_{\ell j}$ invariant mass

$m_{\ell j}$ combination	$\lvert m_{\ell j}-m_{LQ}\rvert < 100$ GeV	
	# events	%
(a) all combinations	136	34%
(b) two leading jets	126	45%
(c) two leading jets; minimum-$\Delta m_{\ell j}$ combination	98	70%

Provides clearest signal

m_{LQ}=1 TeV



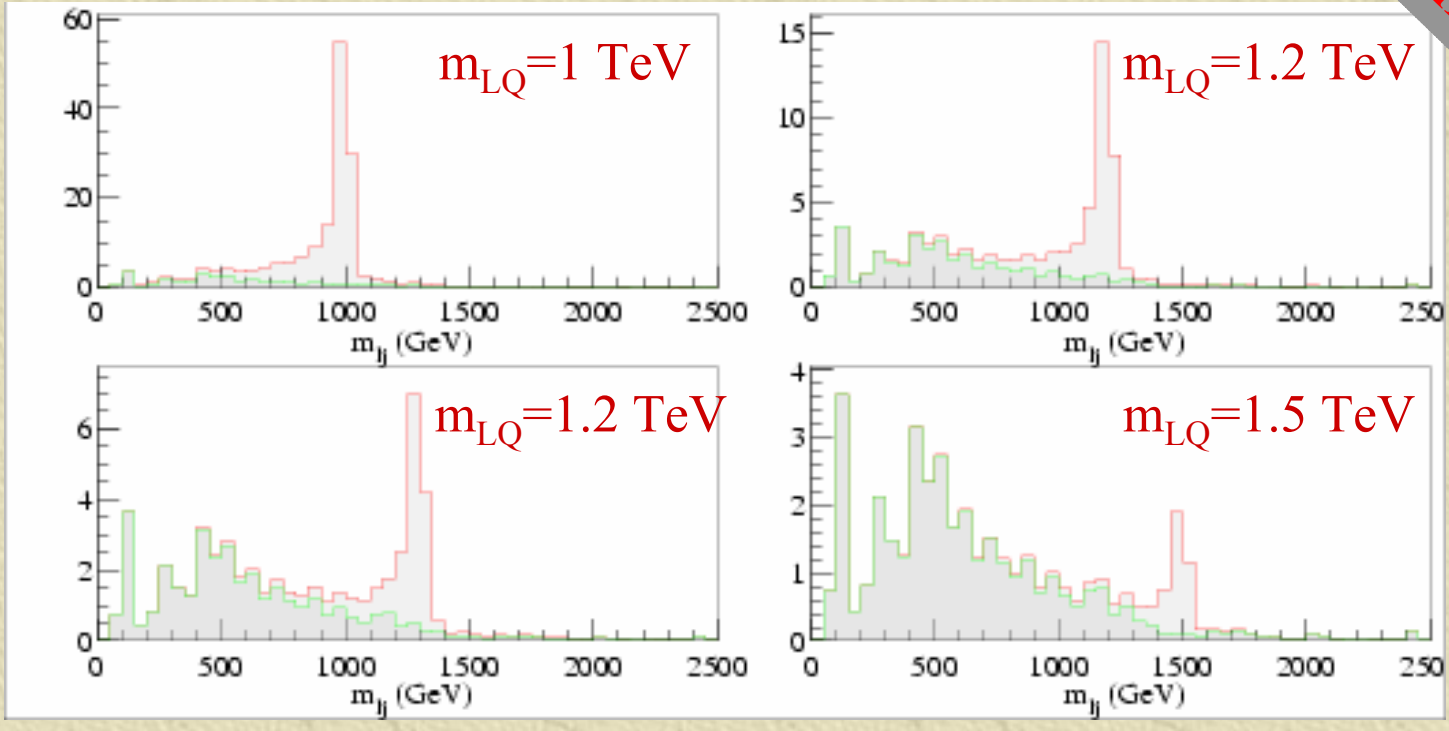
$\ell\ell$jj: selection cuts (tentative)

- Similar cuts imposed for both eejj & μμjj channels
- Cuts optimized to maximize significance for all leptoquark masses
  - at least 2 jets with p_T>70 GeV and $|\eta|$<5.0
  - 2 same-flavour, opposite- sign leptons with p_T>100 GeV and $|\eta|$<2.5
  - $m_{\ell\ell}$ > 180 GeV *(for Z peak)*
  - E_T^{miss} < 70 GeV *(for tt background)*
  - $\sum E_T$ > 570 GeV
  - $E_T^{miss}/\sum E_T$ < 0.05
  - mass window: $|m_{\ell j}-m_{LQ}|$ < 100 GeV
  - **m_{LQ} reconctructed from two leading jets with minimum-$\Delta m_{\ell j}$ combination**

$\ell\ell jj$: signal and background

- After all selection criteria
- S+B and B is shown for 1st generation (e^+e^-jj)

Preliminary



- Signal can be observed for $M_{LQ} \sim 1.3$ TeV
- Channel background-free for M_{LQ}>1.8 TeV but signal cross section very small (<0.07 fb)

$\ell\ell jj$: signal significance

- First generation leptoquarks
- Integrated luminosity $\int \mathcal{L}=30\ fb^{-1}$

Preliminary

M_{LQ} (TeV)	Signal	Background	$S/\sqrt{B}$
1.0	126	4.65	58
1.2	27.6	4.14	14
1.3	16.1	3.46	10.7
1.5	4.49	1.86	5.9

- Signal can be clearly observed for $m_{LQ} = 1.3$ TeV
- Similar results obtained for $\mu\mu jj$ channel

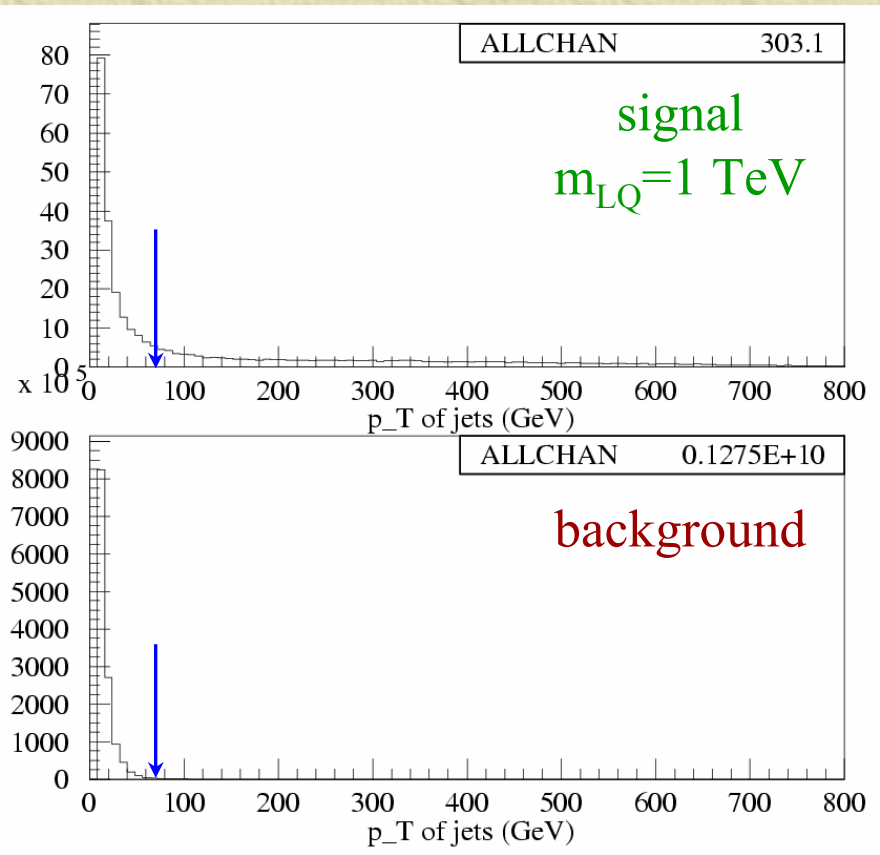
E_T^{miss} +2 jets topology

- 1st and 2nd generation LQs
  - Scalar νd & νs
  - LQ LQ → νν qq
  - Signal is difficult to be separated from SM background (Z jet irreducible background)
- 3rd generation LQs
  - LQ LQ → νν bb
  - β = 0 ➡ $\tilde{S}_{1/2}(^{+1}/_{3})$ $S_1(^{+2}/_{3})$,
  - β = 0.5 ➡ $S_0^L(^{-1}/_{3})$, $S_1(^{-1}/_{3})$
- Background
  - Zjet background irreducible
  - Main backgrounds: tt, ZZ, ZW(bbℓν)
  - All other SM backgrounds are eliminated from b-tagging and lepton-veto

Process	σ×BR (pb)
Zjet (ννjj)	22 000
Wjet (ℓνjj)	38 400
tt (ℓνbℓνb)	51.6
ZZ (ννbb)	0.6
ZW (bblν)	1.3
ZW (ννjj)	3.6
WW (ℓνjj)	30.5

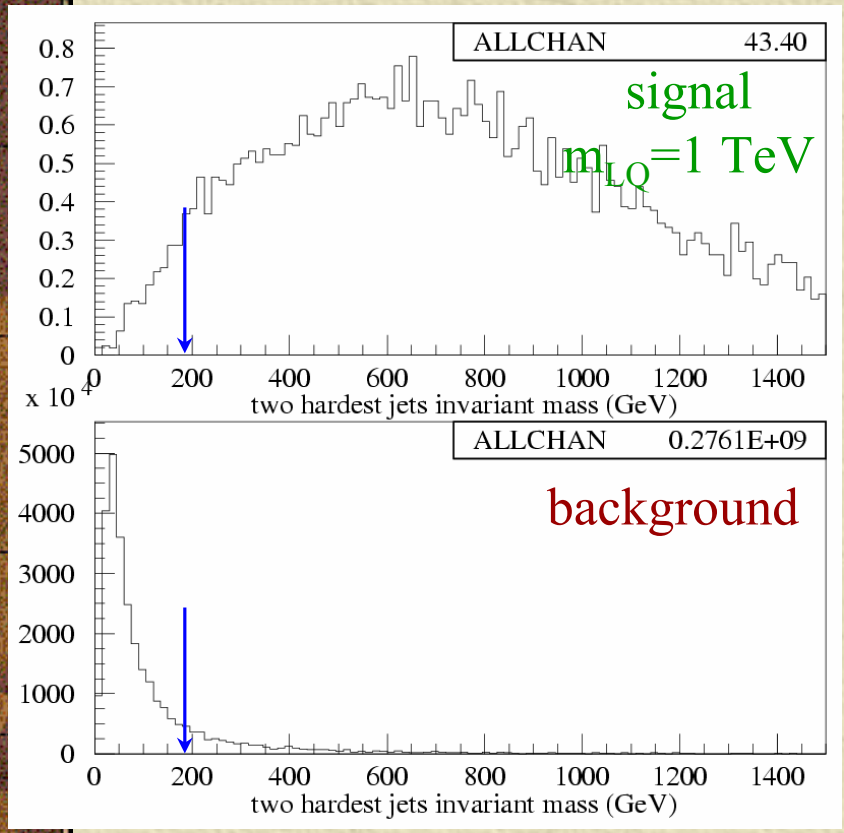
vvjj: selection criteria (tentative)

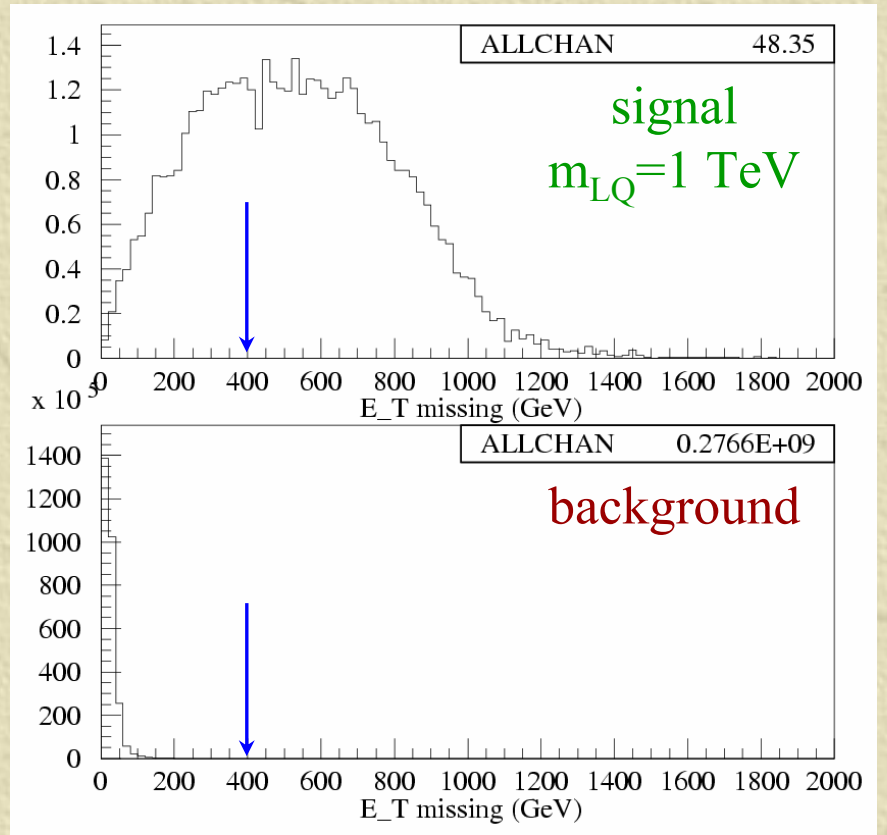
- Selection criteria maximize significance for high leptoquark masses
  - At least **2 b-jets** with p_T>70 GeV and $|\eta|$<5.0
  - No isolated leptons
  - **m_{jj} > 180 GeV**
  - **E_T^{miss} > 400 GeV**
  - **$30^o<\varphi_{j-j}<150^o$** for the two leading jets
  - **$\varphi_{j-pTmiss}>60^o$** for the two leading jets



vvjj: selection variables

- Variables shown before applied cuts (p_T^{jet}>10 GeV)
- Main cut: **large E_T^{miss}** due to escaping neutrinos



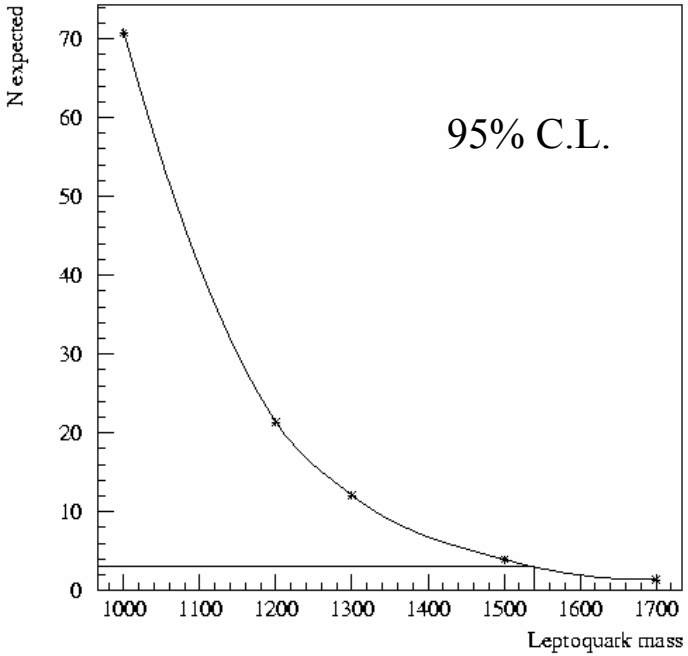


ννjj: significance

- Third generation leptoquarks: LQ LQ → νbνb
- Integrated luminosity ∫**L=30 fb^{-1}**
- No mass peak is reconstructed (only excess of events)
- Signal observable for masses up to m_{LQ}=1.3 TeV
- Exclusion limits (95% C.L.) up to m_{LQ} ~1.5 TeV

Preliminary

m_{LQ} (TeV)	σ x BR (fb)	eff. (%)	signal	SM bgd	S/√B
1.0	4.84	48.7	70.7	3.4	38.3
1.2	1.28	55.5	21.3	3.4	11.5
1.3	0.68	59.1	12.1	3.4	6.5
1.5	0.21	61.6	3.9	3.4	2.1
1.7	0.07	64.3	1.4	3.4	0.7



Conclusions

- ATLAS at the LHC is going to explore the existence of leptoquarks with masses up to $m_{LQ} \sim 1.5$ TeV independently of the Yukawa coupling
- 1st- or 2nd-generation scalar leptoquarks can be observed up to $m_{LQ} \approx 1.3$ TeV, in the $LQ\,LQ \rightarrow \ell\ell qq$ channel (if $\beta=1$)
- 3rd-generation LQs are observable up to $m_{LQ} \approx 1.3$ TeV, if they only couple to a **neutrino** & a **b-quark**, via the $LQ\,LQ \rightarrow \nu\nu bb$ channel
- Possibility to study other species of LQs by combining/investigating other channels