Search for Leptoquarks

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Outline

- Why Leptoquarks ?
- Current Results from the TeVatron
  - Final Run II results
- LHC prototype analyses
  - Prospects
  - Issues
- Conclusions

1st and 2nd generation scalar LQ only!
Lepton signatures!

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
  - •Isotropic decay
- spin 1 (vector)
  - •anomalous magnetic (k_G) and electric quadrupole (λ_G) model-dependent couplings
    - -Yang-Mills coupling: $k_G = \lambda_G = 0$
    - -Minimal coupling: $K_G = 1$, $\lambda_G = 0$
- -Decay amplitude proportional to $(1 + \cos\theta^*)^2$

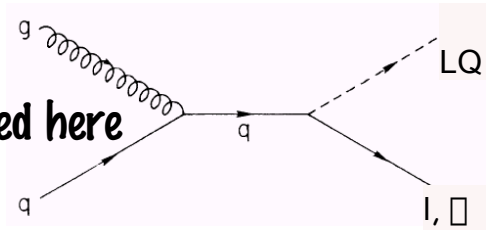
- Experimental evidence searched:
  - indirectly: LQ-induced 4-fermion interactions
  - directly: production cross sections at collider experiments

LQ at Hadron Colliders

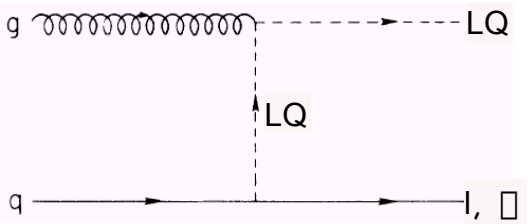
- **Single production**
  - strongly depends on □
  - possible signatures:
    - l^+l^- + jet
    - l□ + jet
    - □□ + jet
  - Main background: Zjet & tt

Not considered here

qg□ ℓ LQ,



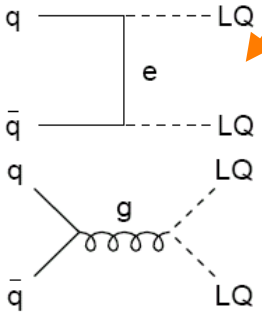
qg□ □LQ



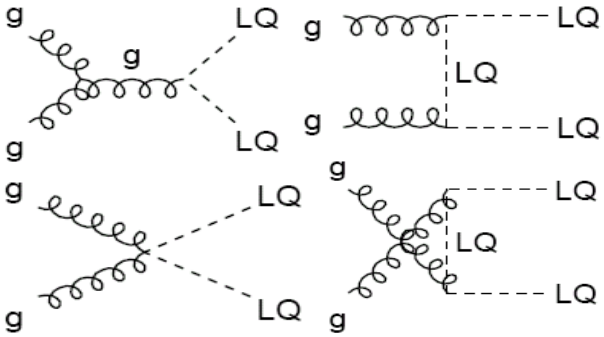
- □dependent process
- does not contribute significantly to 2nd & 3rd generation

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

$q\bar{q}$□ LQ LQ



gg□ LQ LQ



Leptoquark Decay

β = Br(LQβ lq)

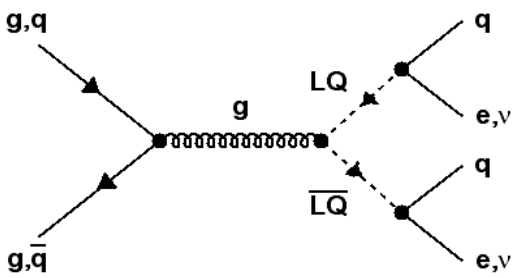
Each generation can decay into 3 final states:

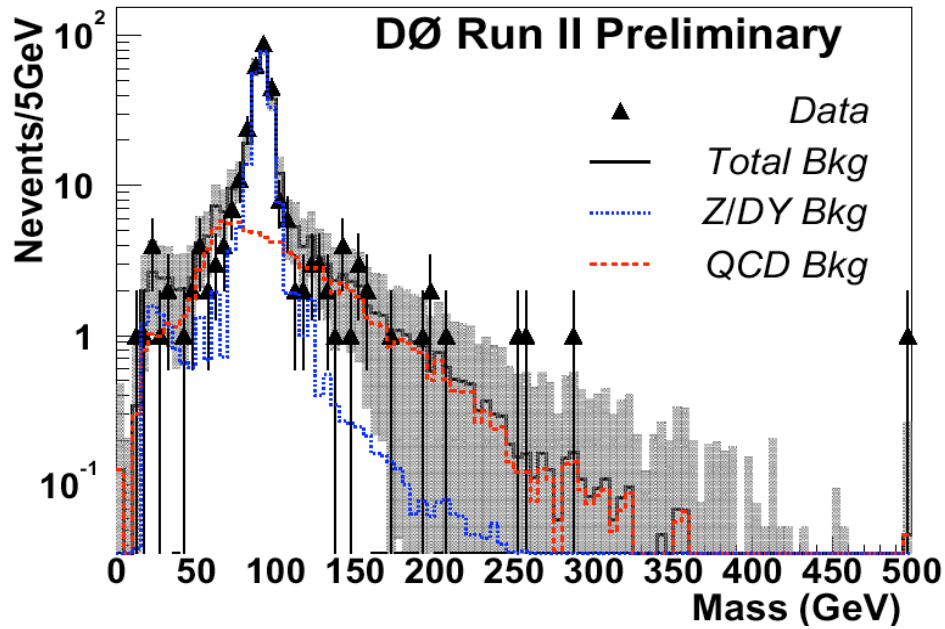
Exclusive to the Tevatron

	1st Generation	2nd Generation	3rd Generation
$\beta = 1$	$LQ\,\overline{LQ} \to e^- e^+ q\bar{q}$	$LQ\,\overline{LQ} \to \mu^+ \mu^- q\bar{q}$	$LQ\,\overline{LQ} \to \tau^+ \tau^- q\bar{q}$
$\beta = 0.5$	$LQ\,\overline{LQ} \to e^\pm \nu_e q_i q_j$	$LQ\,\overline{LQ} \to \mu^\pm \nu_\mu q_i q_j$	$LQ\,\overline{LQ} \to \tau^\pm \nu q_i q_j$
$\beta = 0$	$LQ\,\overline{LQ} \to \nu_e \nu_e q\bar{q}$	$LQ\,\overline{LQ} \to \nu_\mu \nu_\mu q\bar{q}$	$LQ\,\overline{LQ} \to \nu_\tau \nu_\tau q\bar{q}$

This talk! →	LQ LQ β llqq	2l+2j	BR = β^2
	LQ LQ β lβqq	l+MET+2j	BR = $2\beta(1-\beta)$
	LQ LQ β $\beta\beta$qq	MET+2j	BR = $(1-\beta)^2$

First Gen - eejj at DØ





SM background

- Drell-Yan+2jets
- Top (W□ e□)
- QCD/Fakes

Preliminary Selection

✓2 EM clusters E_T > 25 GeV (1 cluster w/ track match)

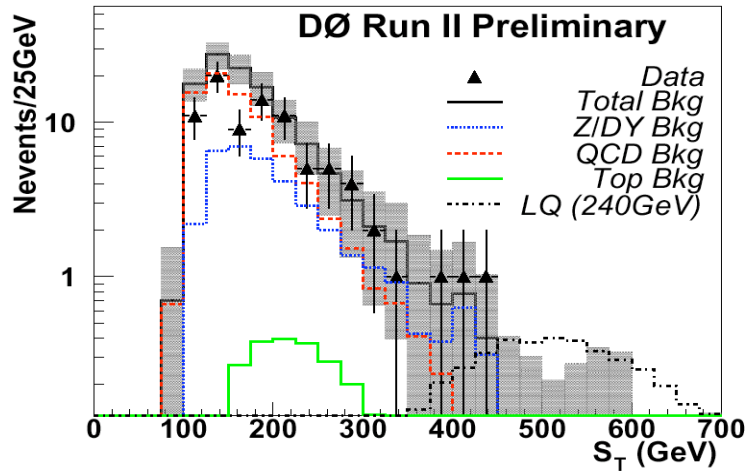
✓2 jets E_T > 20 GeV

✓Z veto (80 < M_{ee} < 102) GeV

DØ – eejj Results

Final event Selection

Scalar Sum of objects E_T $S_T(eejj) > 450$ GeV

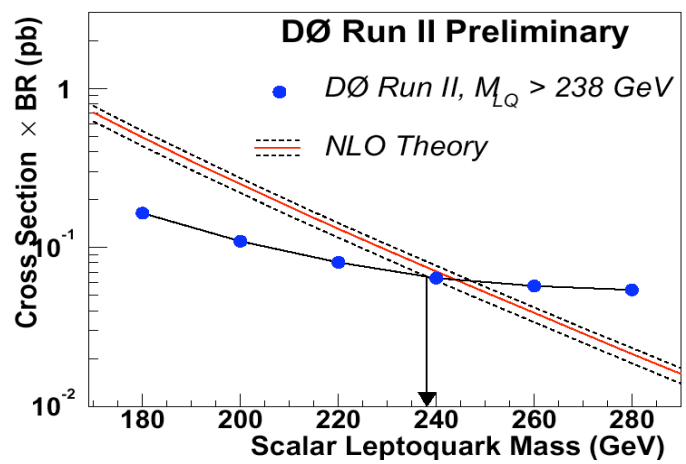


Signal Acceptance ~ (12 - 33)%

M(LQ) ~180 - 280 GeV/c^2

Luminosity	175pb^{-1}
No. Exp.	0.4 ± 0.1
Observed	0

95% CL M_{LQ}<238 GeV/c^2

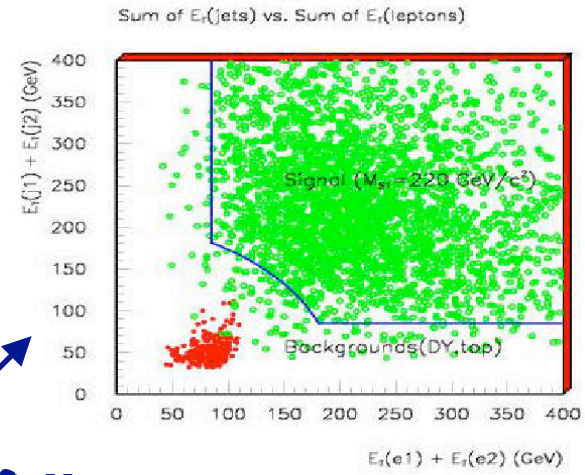


1st Gen - eejj at CDF

Selection

- ✓ 2 electrons (CC,CE) $E_T > 25$ GeV
- ✓ 2 jets, $E_T(j1) > 30$ GeV, $E_T(j2) > 15$ GeV
- ✓ Z Veto ($76 < M_{\mu\mu} < 110$) GeV

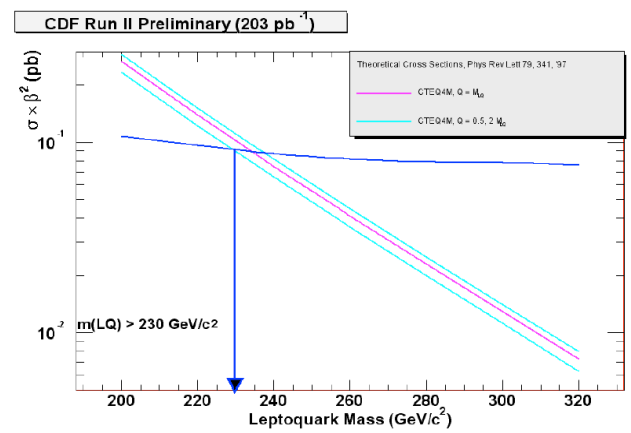
- ✓ Electrons/Jets: $E_T^{j1(e1)} + E_T^{j2(e2)} > 85$ GeV
- ✓ $((E_T(j_1) + E_T(j_2))^2 + (E_T(e_1) + E_T(e_2))^2)^{1/2} > 200$ GeV



Signal Acceptance ~(32 - 40)%

M(LQ) ~200 - 320 GeV/c^2

Luminosity	203 pb^{-1}
Acceptance	(32-42)%
Background	$6.2^{+3.1}_{-2.5}$
Observed	4



Exclude at 95% CL M_{LQ}<230 GeV/c^2

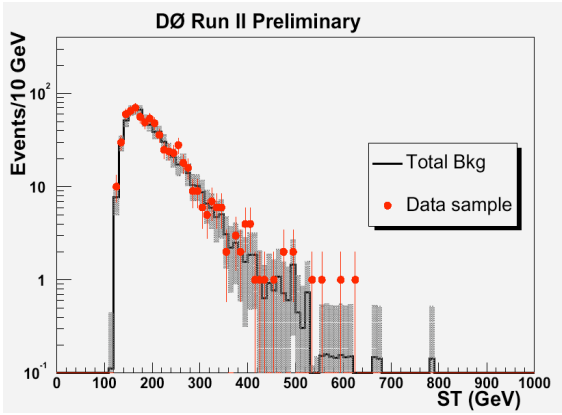
1st Gen -- ej □j at DØ

SM background

- W +2jets
- Top (l + jets and dilepton)
- QCD/Fakes

Selection

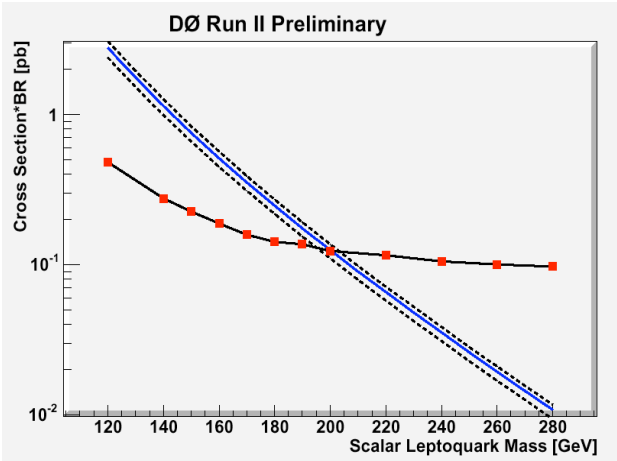
- ✓ 1 electron (w/ em cluster – track match) E_T > 35 GeV
- ✓ MET > 30 GeV
- ✓ 2 jets E_T> 25 GeV
- ✓ DPhi (MET,jet) > 8°
- ✓ S_T(j1,j2,e,MET) > 330 GeV
- ✓ M_T(e,ν) > 130 GeV



Signal Acceptance ~(13 - 25)%

m(LQ) ~160-280 GeV/c^2

Luminosity	175pb^{-1}
Background	4.7 ± 0.8
Observed	2



m_{LQ} < 194 GeV/c^2 @ 95% C.L.

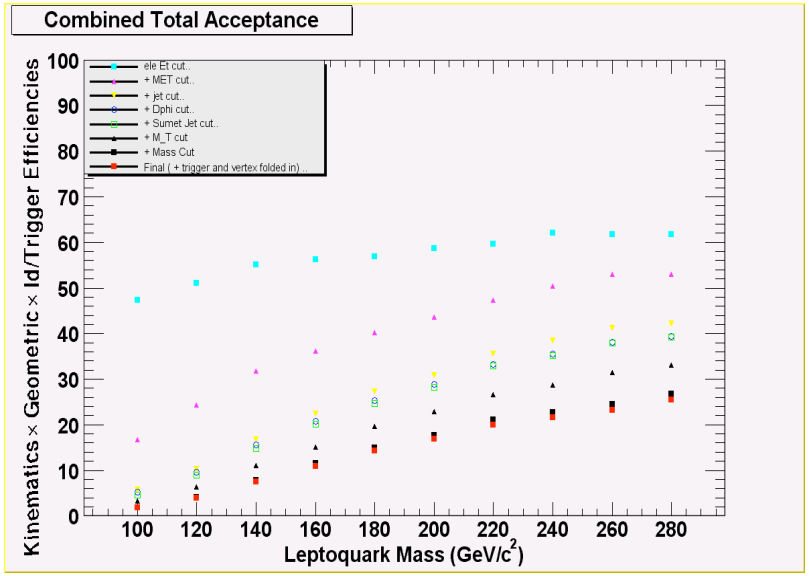
1st Gen - e□jj at CDF

Selection

- 1 central electrons with E_T > 25 GeV
- MET > 60 GeV
- Veto on 2nd electron, central loose or Plug
- 2 jets with E_T > 30 GeV
- □□(MET-jet) > 10°
- $E_T(j1) + E_T(j2)$ > 80 GeV
- $M_T(e-□)$ > 120
- LQ mass combinations

Signal Acceptance ~(2 - 22)%

m(LQ) ~100-280 GeV/c^2



The invariant mass of the electron-jet system and the transverse mass of the neutrino-jet system are selected where the jet assignment is made such that the difference between the electron-jet mass and the neutrino-jet transverse mass is minimized.

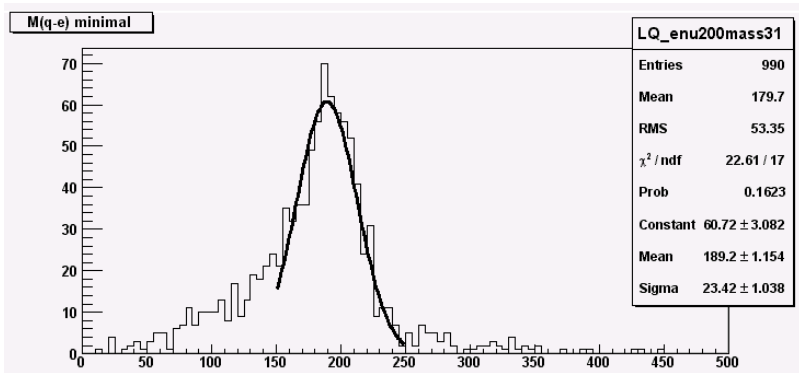
CDF - e□jj - Mass combination

The peak of the *ej* histogram is fitted with a gaussian

rough estimate of the spread of the distribution in the signal region.

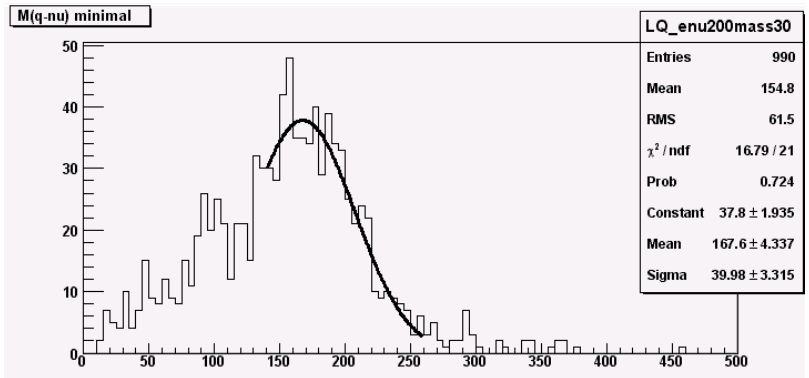
Several masses (120-160-200-240-280) tested:

□$_e$ ~ 15%.



The □-q transverse mass distribution is fitted including the high mass tail end, with a Gaussian to estimate the signal spread.

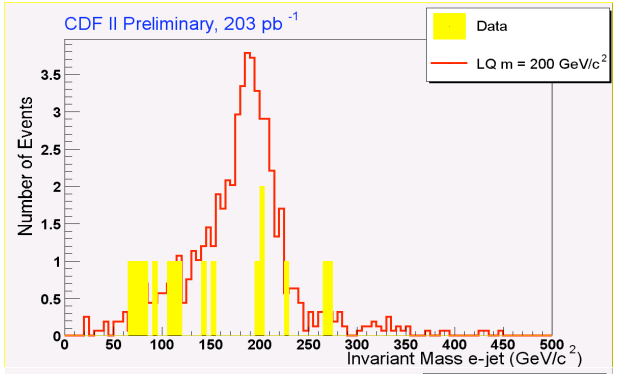
□□ ~ 25%.

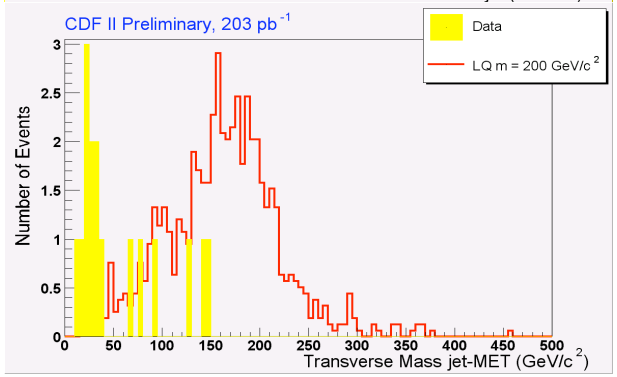


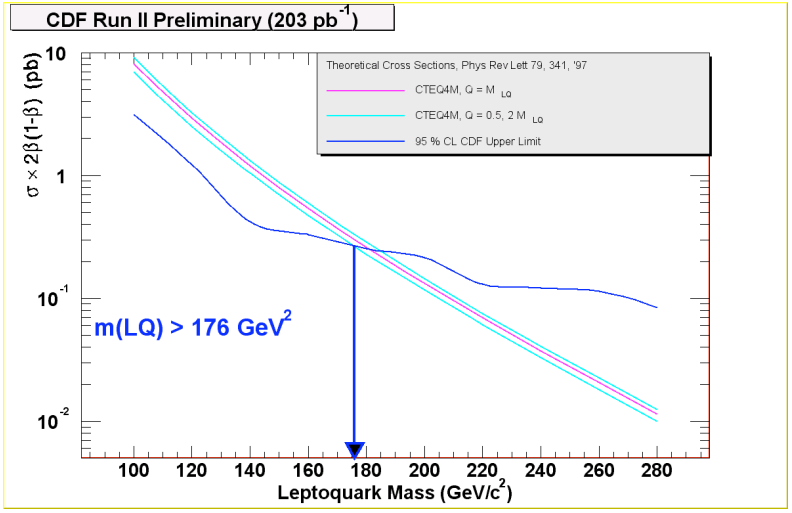
3□ cut around the nominal mass to select LQ candidates of a given mass

CDF - e□jj Results

Mass	100	120	140	160	180	200	220	240	260	280
W+2 jets	1.5±0.9	1.5±0.9	1.5±0.9	2.5±1.13	2.5±1.13	2.5±1.13	2.0±1.0	2.0±1.0	1.5±0.88	0.5±0.5
top	2.7 ±0.6	3.3 ±0.6	3.12 ±0.5	2.8 ±0.5	2.5 ±0.5	2.03 ±0.4	1.63 ±0.4	1.08 ±0.3	0.8 ±0.22	0.6 ±0.21
Z+jets	0.05 ±0.01	0.05±0.01	0.08±0.02	0.08±0.02	0.08±0.02	0.08±0.02	0.06±0.02	0.06±0.02	0.04±0.01	0.04±0.01
Total	4.3±1.03	4.9 ±1.05	4.7 ±1.1	5.4 ±1.2	5.0 ±1.2	4.6 ±1.23	3.7 ±1.06	3.1 ±1.0	2.3 ±0.9	1.1 ±0.6
Data	**7**	**6**	**4**	**4**	**4**	**4**	**2**	**2**	**2**	**1**



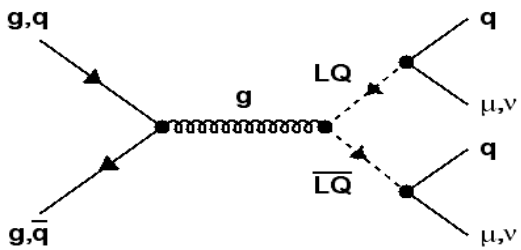




Luminosity 203pb^{-1}

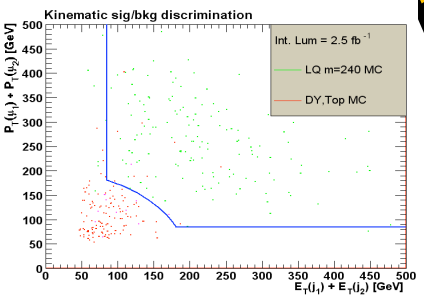
Exclude at 95% CL M_{LQ}<176 GeV/c^2

2nd Gen. -- μj μj at CDF



Selection

- 2 muons with $P_T > 25$ GeV
- 2 jets with $E_T(j1,j2) > 30,15$ GeV
- Dimuon Mass Veto:
- $76 < M_{\mu\mu} < 110$, $M_{\mu\mu} < 15$ GeV

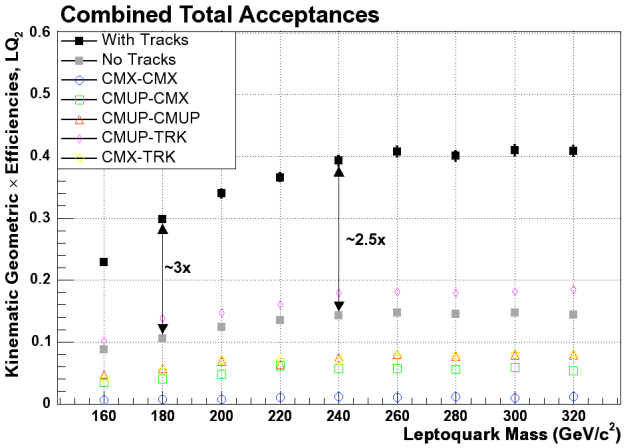


SM Backgrounds

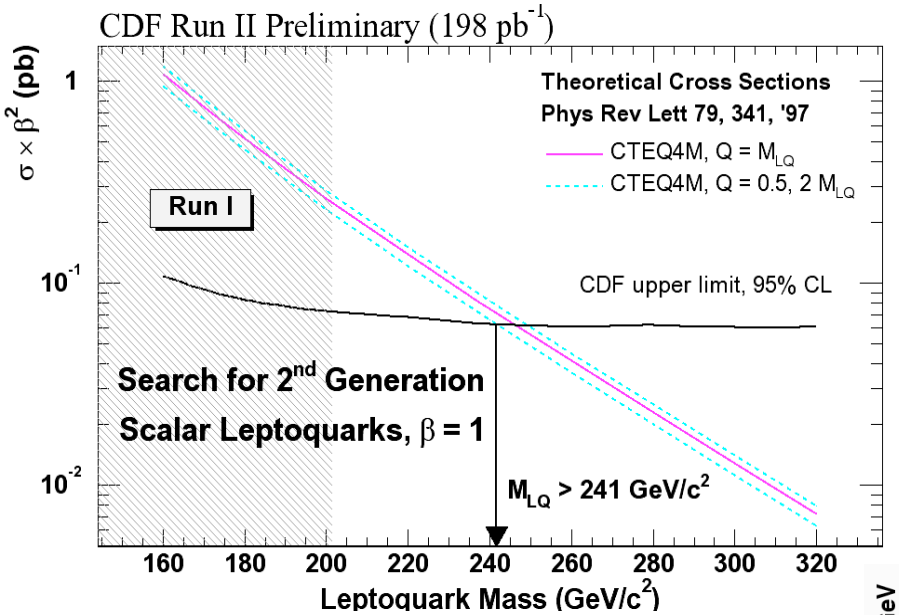
- Drell-Yan+2jets
- Fakes
- Top (W□ □□)

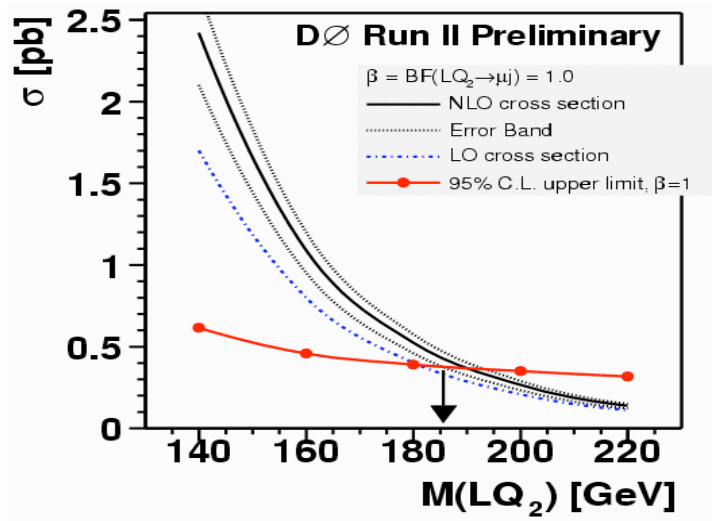
- $E_T(j_1) + E_T(j_2) > 85$ GeV and $P_T(\mu_1) + P_T(\mu_2) > 85$ GeV
- $((E_T(j_1) + E_T(j_2))^2 + (P_T(\mu_1) + P_T(\mu_2))^2)^{1/2} > 200$ GeV

Muons and MIP tracks to increase acceptance



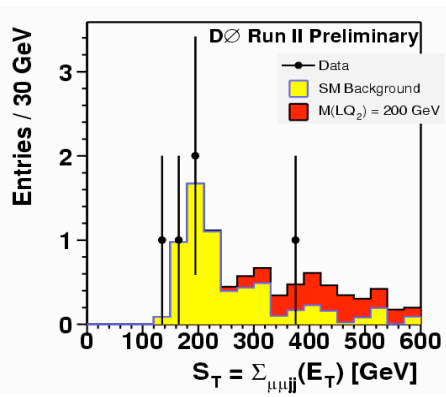
2nd Gen. -- μj μj Results





Luminosity	198pb^{-1}
Background	3.1 ± 1.2
Observed	2

M_{LQ} < 241 GeV/c^2 at 95% CL



Luminosity	104pb^{-1}
Background	1.6 ± 0.5
Observed	1

M_{LQ} < 186 GeV/c^2 at 95% CL

2nd Gen - □□jj at CDF

SM background

- W +2jets
- Top (l + jets and dilepton)
- QCD/Fakes

$|M(\mu,j_1) - M_{LQ}| < 2\sigma_1$

or

$|M(\mu,j_2) - M_{LQ}| < 2\sigma_2$

Sigma's determined from generator-level matched reconstructed objects.

Selection

Z veto (tight/loose pair)

No 2nd muon (CMUP, CMX, or stubless)

$P_T(\mu) > 25$ GeV

$\not{E}_T > 60$ GeV

2 jets, @ $E_T > 30$GeV

$\Delta\phi(\mu,\not{E}_T) < 175°$, $\Delta\phi(\not{E}_T,\text{jets}) > 5°$

$E_T(\text{jet1}) + E_T(\text{jet2}) > 80$ GeV

$M_T(\not{E}_T,\text{Muon}) > 120$ GeV/c²

Mass Cut

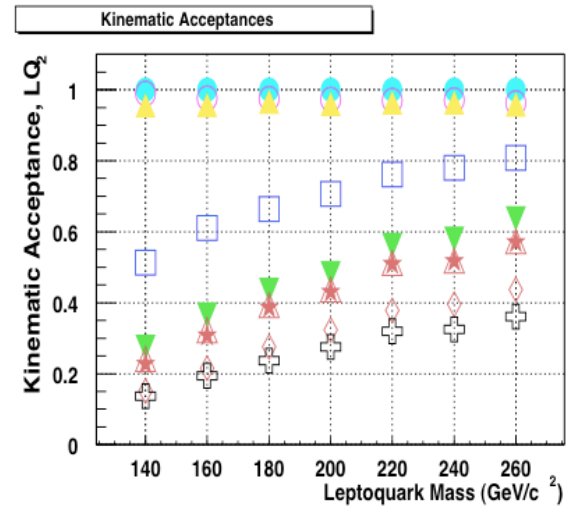
$M_T(\not{E}_T,j_1) > T_1(\min)$

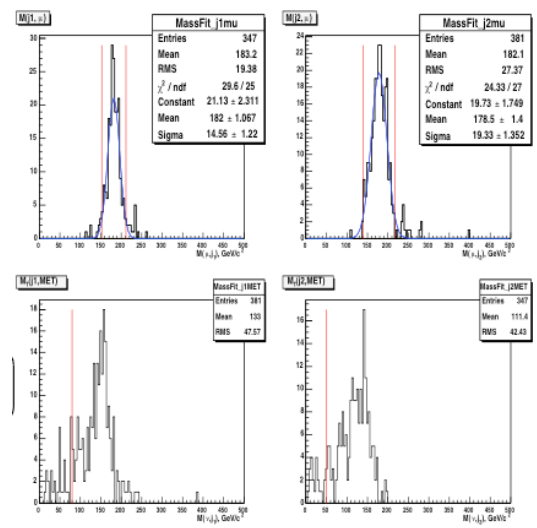
or

$M_T(\not{E}_T,j_2) > T_2(\min)$

$T_1(\min) = 20 + (M_{LQ} - 120)$ GeV/c²

$T_2(\min) = 20 + (M_{LQ} - 120)/2$ GeV/c²





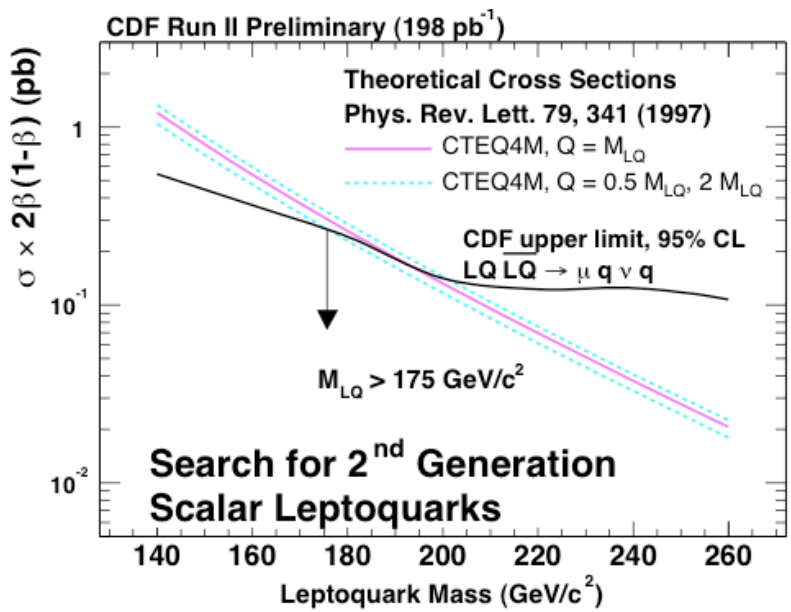
□□jj at CDF - Results

Final Selection

	140	160	180	200	220	240	260
W	0.92 ± 0.06	1.44 ± 0.10	1.44 ± 0.10	1.67 ± 0.11	1.65 ± 0.11	0.93 ± 0.06	0.44 ± 0.03
Top	1.69 ± 0.21	1.84 ± 0.23	1.35 ± 0.17	1.00 ± 0.39	0.80 ± 0.29	0.67 ± 0.08	0.52 ± 0.06
Z	0.18 ± 0.01	0.22 ± 0.02	0.19 ± 0.01	0.18 ± 0.01	0.14 ± 0.01	0.05 ± 0.00	0.04 ± 0.00
QCD	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.00
Total	3.09 ± 0.57	3.74 ± 0.62	3.22 ± 0.56	3.08 ± 0.53	2.83 ± 0.51	1.94 ± 0.44	1.30 ± 0.39
Data	3	3	2	0	0	0	0

Luminosity **198pb^{-1}**

Exclude at 95% CL
$M_{LQ} < 175$ GeV/c^2



At the End of TeVatron Run II

Assumptions:

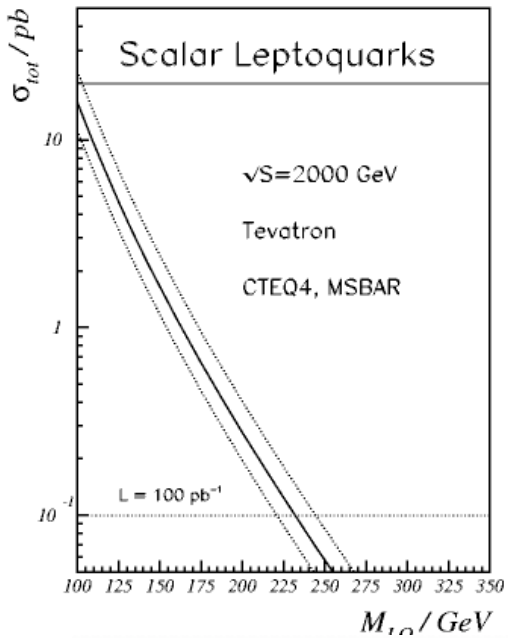
Same acceptances as now
Number of events observed = number of predicted background
Same errors

$\square$= 1 mass limit up to 250-300 GeV/c^2
$\square$ = 0.5 mass limit up to 230-280 GeV/c^2

Preliminary

New analysis strategy
(not counting experiment anymore?)
might be necessary.....

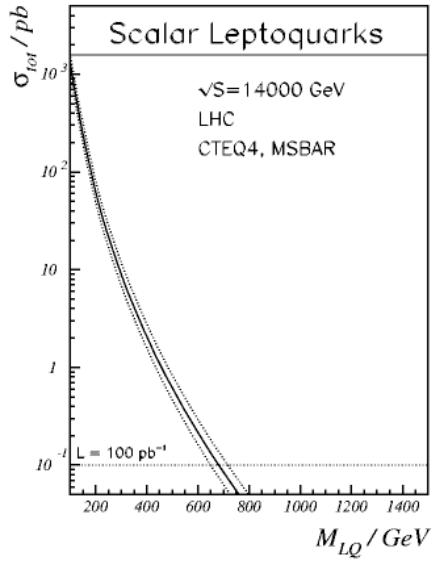
From the TeVatron to LHC

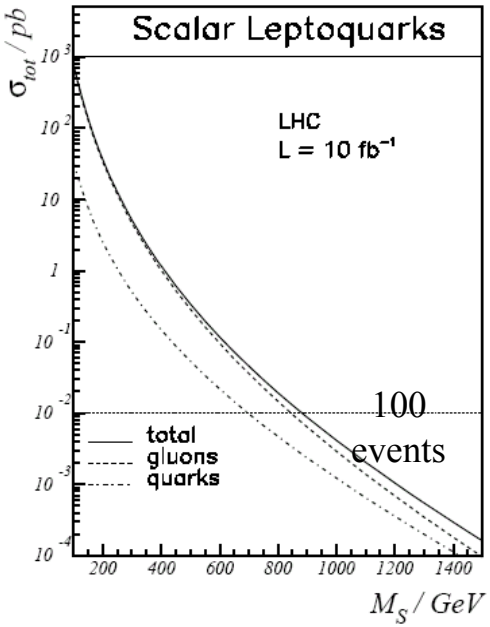


Theoretical Cross Sections

Phys. Rev. Lett. 79, 341 (1997)

$\sigma(pb)$: $p\,\bar{p} \rightarrow LQ_s + \overline{LQ}_s + X$

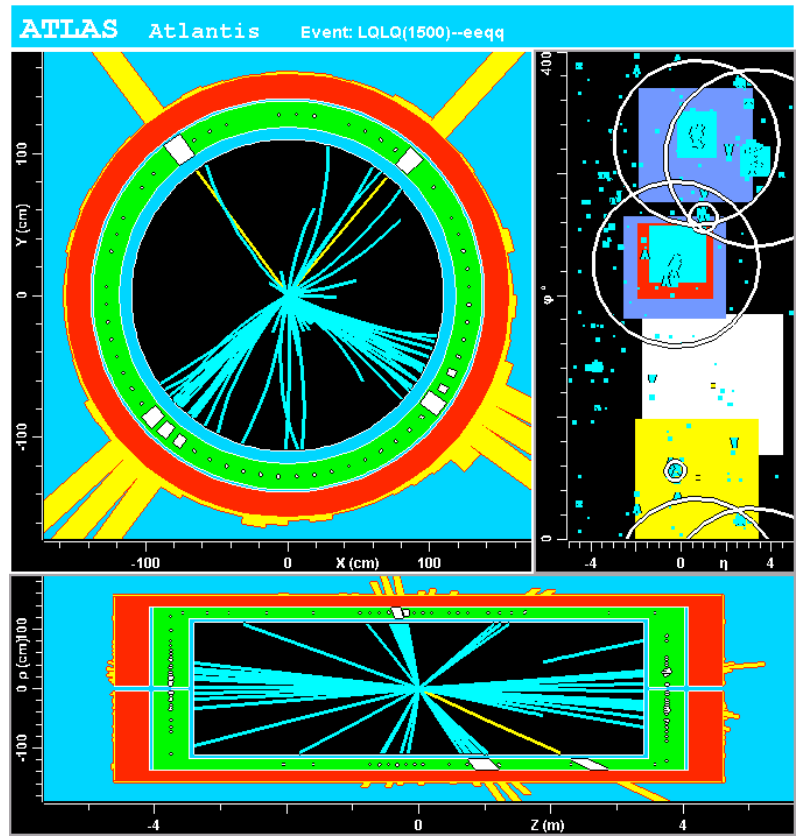




Leptoquarks in ATLAS

V.A. Mitsou, I. Panagoulias, Th. Papadopolou, Physics at LHC, Vienna 2004

- Scalar leptoquarks production studied
- Pair production
  - lljj channel
  - □□ jj channel
- Simulation tools:
  - PYTHIA
    - qq □ LQ LQ
    - gg □ LQ LQ
  - ATLAS fast simulation *(ATHENA-ATLFAST)*



LQ LQ □ e^+e^-qq
m_{LQ}=1500 GeV
(schematic view)

2 leptons + 2 jets topology

Signal

LQ LQ □ l^+ql^-q

1st and 2nd generation LQs

M_{LQ} (TeV)	□□□(fb)
1.0	5.0
1.2	1.3
1.3	0.7
1.5	0.2
1.7	0.07
2.0	0.015

Background

- QCD: huge, but eliminated after high-p_T isolated leptons and high-m_{lj} cuts are applied
- Drell-Yan: eliminated by high-m_{lj} cut

Process	□□BR (pb)
Zjet (lljj)), p_T > 20 GeV	1 380
tt (l□j l□j)	11
ZZ (lljj)	1.2
ZW (lljj)	1.2
WW (l□l□)	3.3

First level cuts:

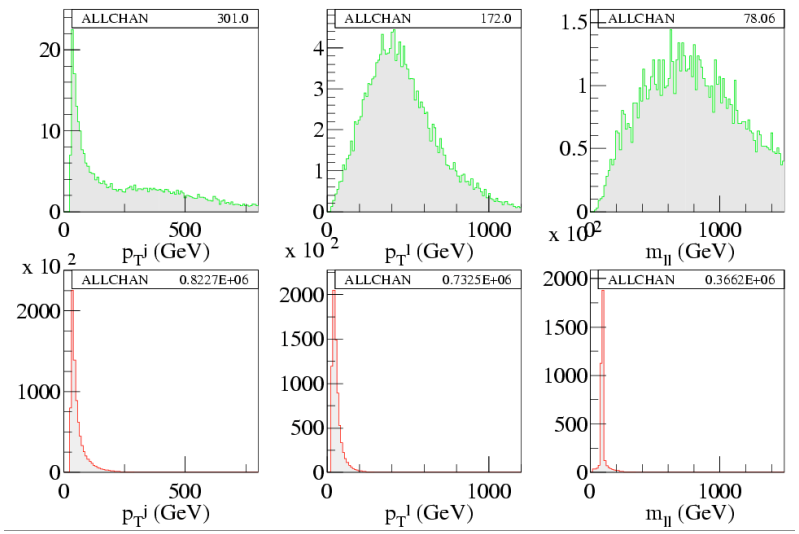
- At least 2 jets with p_T>30 GeV and |□|<5.0
- 2 same-flavour, opposite- sign leptons with p_T>30 GeV and |□|<2.5

2 letpons & 2 jets topology

First level cuts:

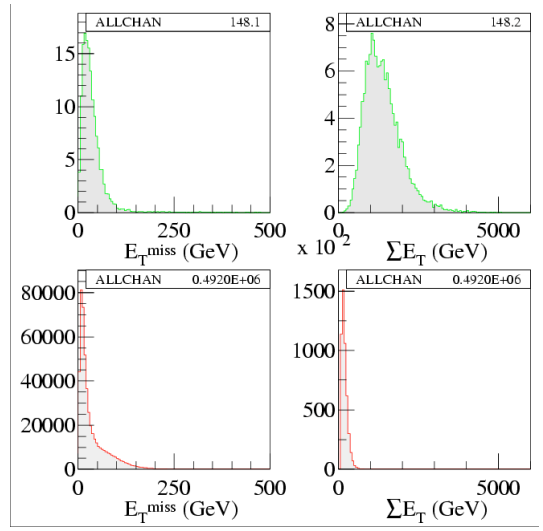
At least 2 jets with p_T>30 GeV and |□|<5.0

2 same-flavour, opposite- sign leptons with p_T>30 GeV and |□| < 2.5



signal

backgrnd

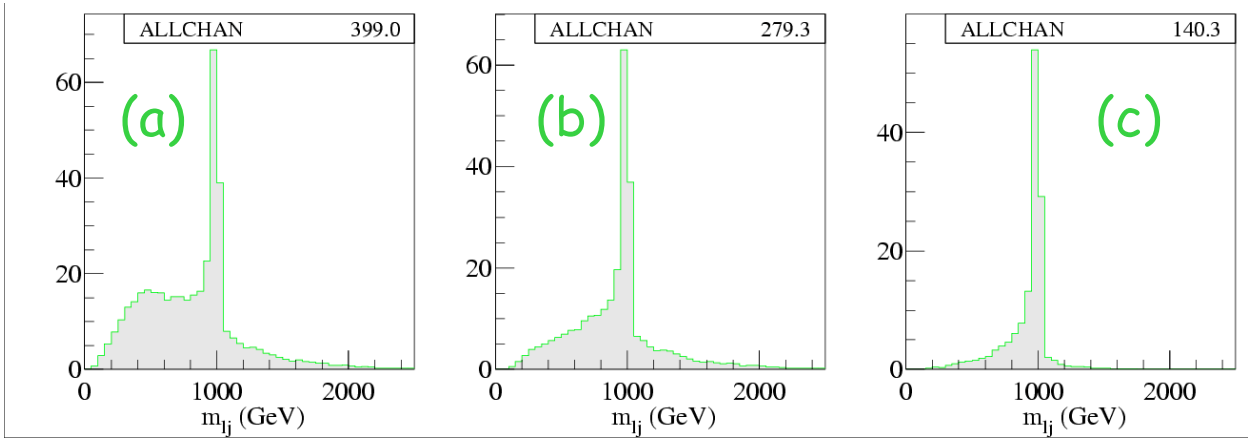


ΣE_T: sum of transverse energy in the calorimeters

M_{ljj} Invariant Mass

m_{lj} combination	$\lvert m_{lj}-m_{LQ}\rvert < 100$ GeV	
	# events	%
(a) all combinations	136/399	35%
(b) two leading jets	126/279	45%
(c) two leading jets; minimum-Δm_{lj} combination	98/140	70%

Provides clearest signal



m_{LQ}=1 TeV

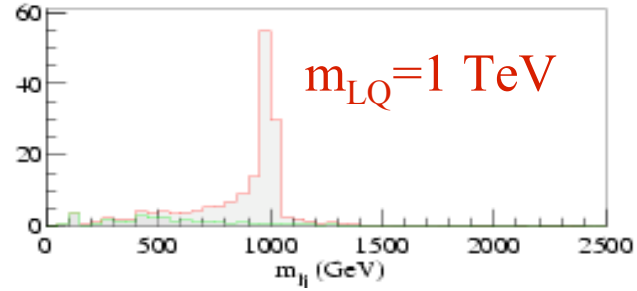
lljj: Selection Cuts

- Similar cuts imposed for both eejj & □□jj channels
- Cuts optimized to maximize significance for all leptoquark masses
  - at least 2 jets with p_T>70 GeV and |□|<5.0
  - 2 same-flavour, opposite- sign leptons with p_T>100 GeV and |□|<2.5
  - M_{ll} > 180 GeV *(to remove Z events)*
  - E_T^{miss} < 70 GeV *(for tt background)*
  - ΣE_T > 570 GeV
  - $E_T^{miss}/\Sigma E_T$ < 0.05
  - mass window: $|m_{lj}-m_{LQ}|$ < 100 GeV
  - m_{LQ} reconctructed from two leading jets with minimum-Δm_{lj} combination

Preliminary

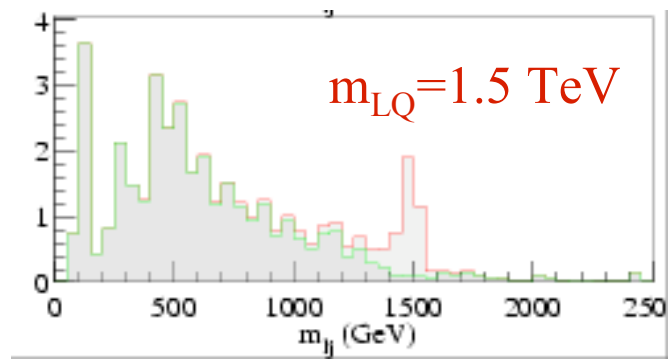
lljj: Expected Significance

- First generation leptoquarks
- Integrated luminosity ∫L=30 fb^{-1}



M_{LQ} (TeV)	Signal	Background	S/√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

Preliminary



Signal can be clearly observed for m_{LQ} = 1.3 TeV
Similar results obtained for □□jj channel

LQ at CMS

S. Abdullin, F. Charles
hep-ph/9905396

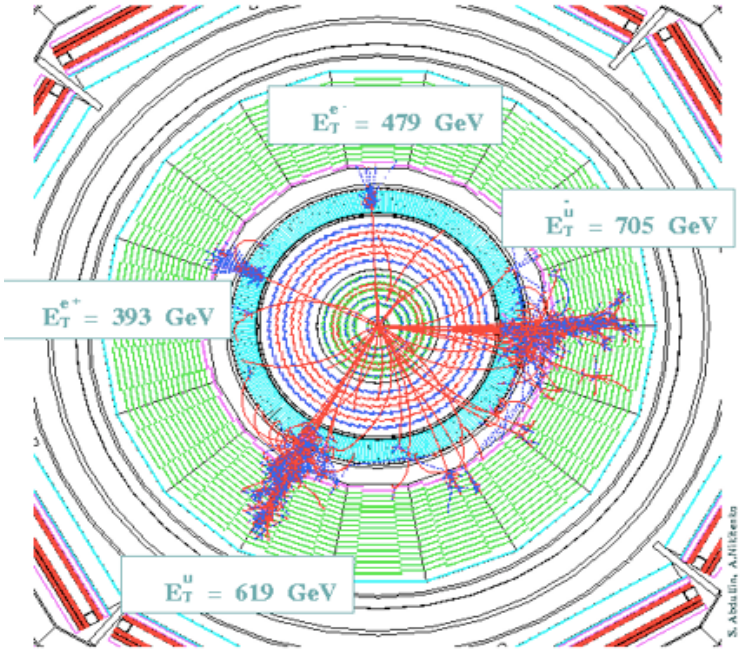
Scalar leptoquarks production studied

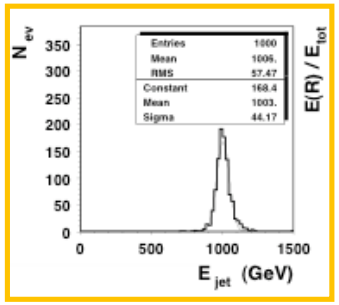
Pair production

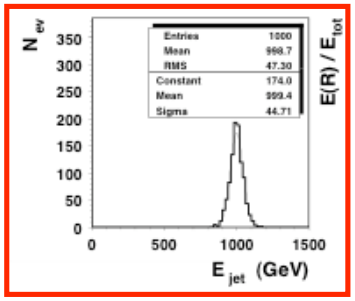
- lljj channel
- l□j channel

Simulation tools:

- PYTHIA
  - qq □ LQ LQ
  - gg □ LQ LQ
- CMSJET fast simulation *(compared to CMSIM)*





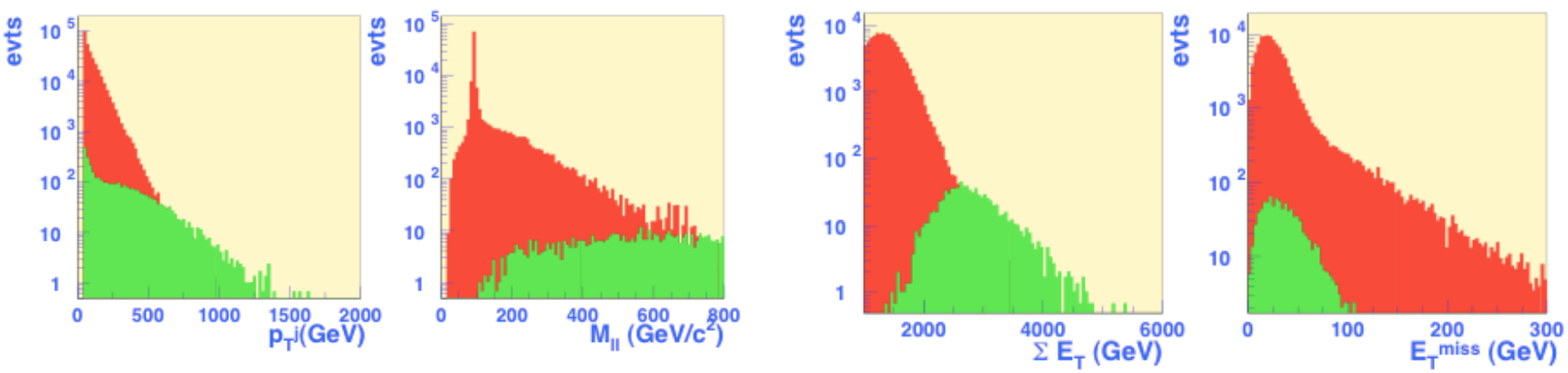


LQ at CMS - Selection

Selection cuts

- 2 isolated leptons (SF OS) with $p_T > 40$ GeV, $|\eta| < 2.4$; $m_{ll} > 150$ GeV
- At least 2 jets with $E_T > 60$ GeV , $|\eta| < 4.5$
- $E_T^{miss} < 185$ GeV, $\Sigma\ E_T > 1700$ GeV, $E_T^{miss}/\Sigma\ E_T < 0.04$
- $\Delta\ m_{lj} < 310$ GeV, the peak window $\Delta m = 210$ GeV

m(LQ) = 1.4 TeV



LQ at CMS - Sensitivity

Accepted lj combinations and significance for L = 100 fb^{-1}
eejj channel

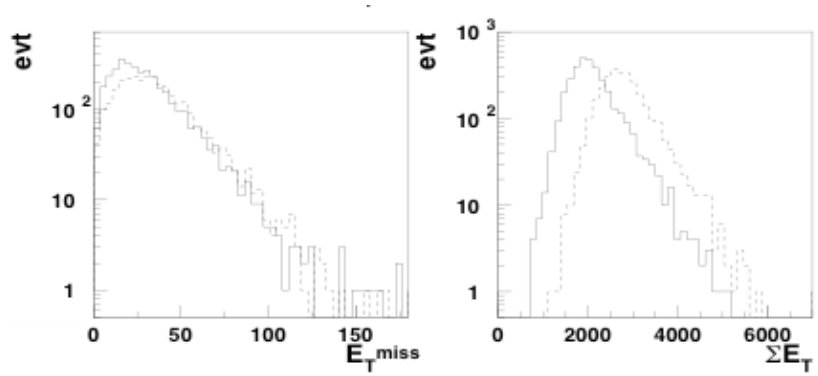
M_{LQ} (GeV)	900	1200	1400	1500
Signal	2584	174.4	49	24.6
Background	240	45.27	11.3	7.5
$\sigma = \frac{S}{\sqrt{S+B}}$	49	11.8	6.3	4.34
$\sigma = \frac{S}{\sqrt{B}}$	167	25.9	14.6	9.0

Expected 95% C.L. limit
m(LQ) < 1.47 TeV for □ = 1
m(LQ) < 1.2 TeV for □ = 0.5

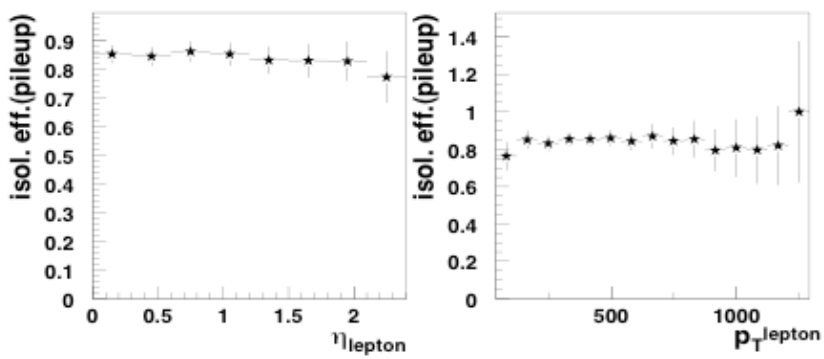
LQ at CMS - Effects of Pile-up

~25 interactions per bunch crossing at 10^{34} cm^{-2} s^{-1}

ΣE_T increase ~ 800 GeV;
No considerable effect on MET
Degradation of lepton isolation (both track-based and calo-based)



15% degradation
(p_T and η dependence)



LQ at CMS - Mass Resolution

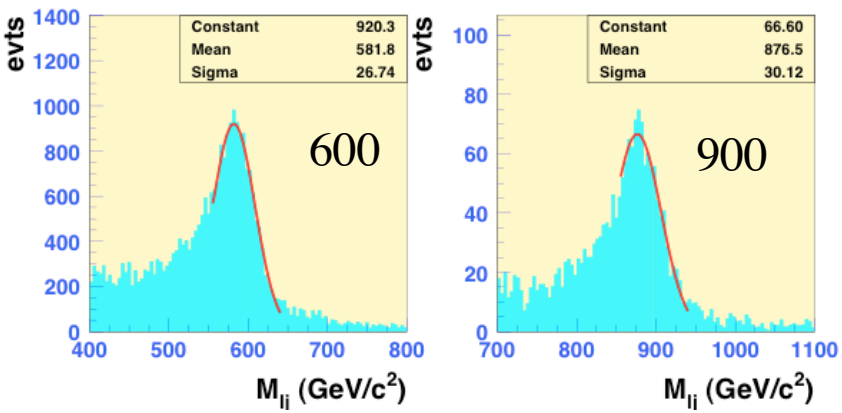
$$M_{LQ} = \sqrt{(\tilde{p_l} + \tilde{p_{jet}})^2} \simeq \sqrt{2E_l E_j (1 - cos\theta)}$$

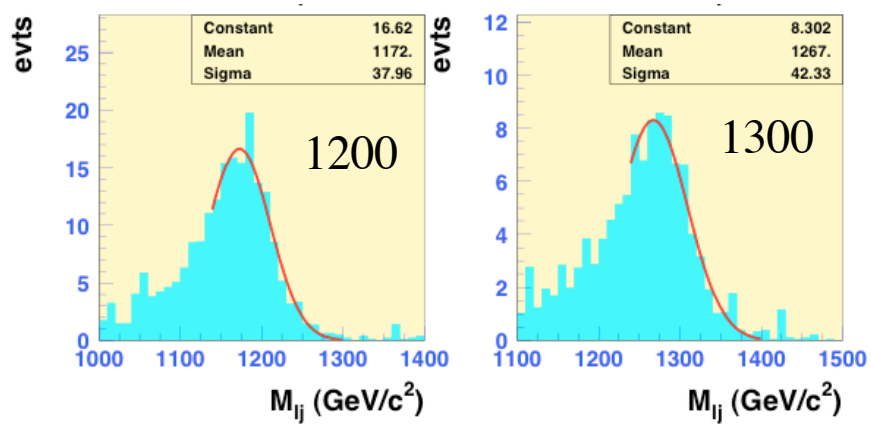
$$\frac{\sigma(M_{LQ})}{M_{LQ}} \simeq \frac{\sigma(E_j)}{2E_j}$$

due to the excellent lepton energy resolution in CMS

For high mass LQ and high energy jets the constant term dominates

$$\frac{\sigma(M_{LQ})}{M_{LQ}} \simeq \frac{6.5\%}{2} = 3.25\%.$$





Conclusions

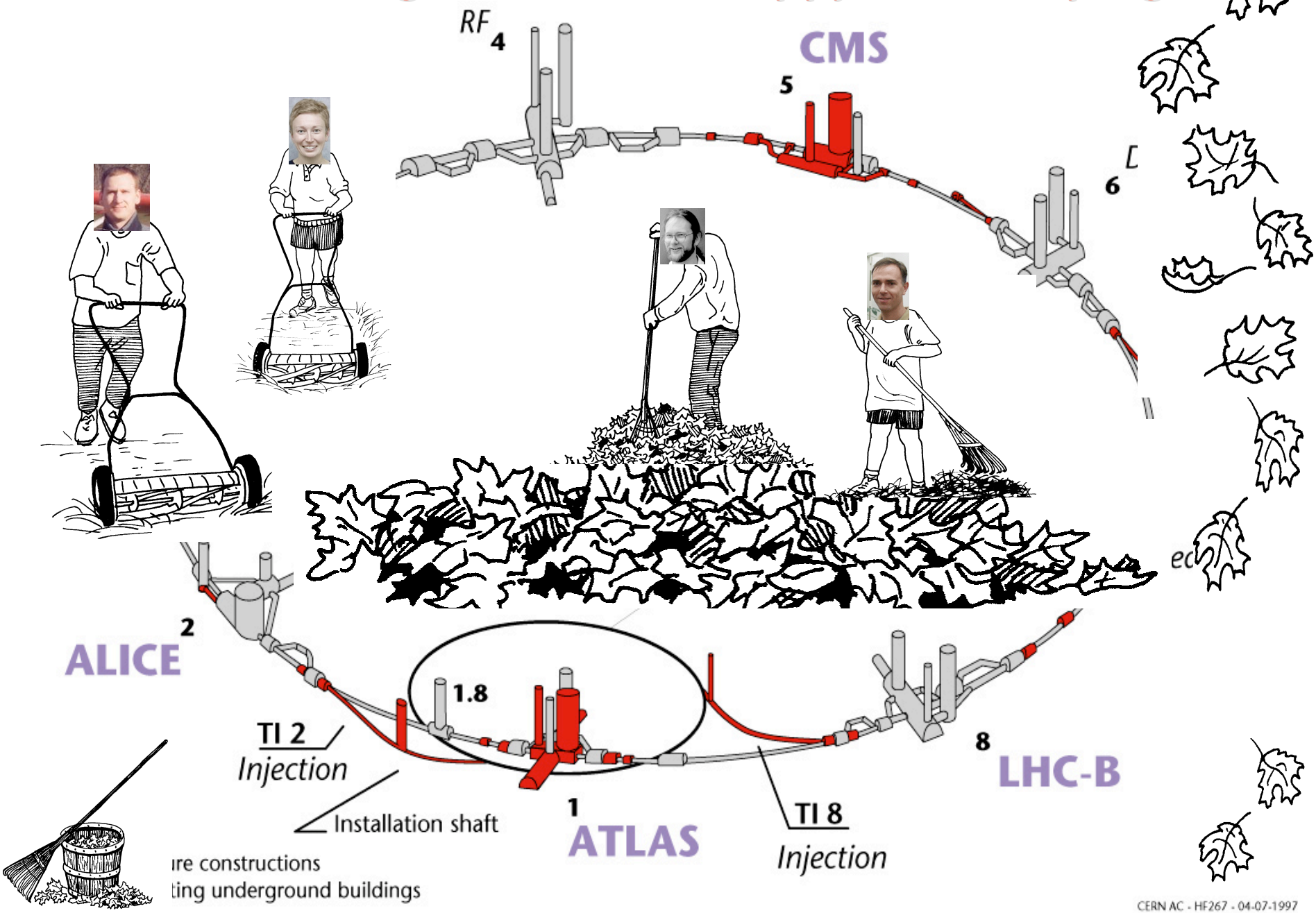
Searches for 1st and second generation LQ's are currently well established at the TeVatron;
Current limits are superseding the existing ones from Run I
Choice of cuts very similar among the 2 experiments

Final reach ~300 GeV/c^2

Both ATLAS and CMS have carried on feasibility studies for searches for 1st and 2nd generation LQ
Cuts very similar to TeVatron
Issue of pile-up discussed in CMS

Final reach ~1500 GeV/c^2

Thanks to the Organizers and Happy Landscaping !



Backup Slides

Comparison with Other Colliders