



# Supersymmetry – or Alternatives?

**Michael Krämer**

(RWTH Aachen)



## Alternatives?

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# Alternatives?

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# Alternatives...

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- Excited quarks and leptons
- Leptoquarks

# Excited quarks and leptons

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- *Experimental Consequences of Quark - Structure*  
G.B. West & P.M. Zerwas, Phys.Rev.D10:2130,1974.
- *Excited Quarks And Leptons*  
J.H. Kühn & P.M. Zerwas, Phys.Lett.B147:189,1984.
- *Signals Of Excited Quarks And Leptons*  
J.H. Kühn, H.D. Tholl & P.M. Zerwas, Phys.Lett.B158:270,1985.
- *Excited Quark And Lepton Production At Hadron Colliders*  
U. Baur, M. Spira, & P.M. Zerwas, Phys.Rev.D42:815-824,1990.
- *Bounds on radii and magnetic dipole moments of quarks and leptons from LEP, SLC and HERA*  
G. Köpp, D. Schaile, M. Spira & P.M. Zerwas, Z.Phys.C65:545-550,1995

# Excited quarks and leptons

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- Proliferation of quarks and leptons
  - substructure with compositeness scale  $\Lambda \simeq 1 \text{ TeV}$ ?

# Excited quarks and leptons

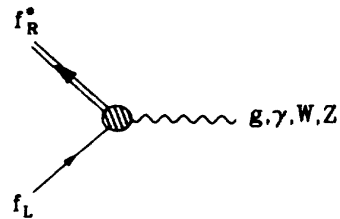
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- Consider simple model where excited fermion has spin and isospin equal to 1/2
- Couplings to gauge bosons and fermions

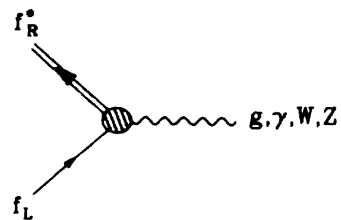


$$\mathcal{L} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} \left[ g_s f_s \frac{\lambda^a}{2} G_\mu^a + g f \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu + g' f' \frac{Y}{2} B_\mu \right] f_L + h.c.$$



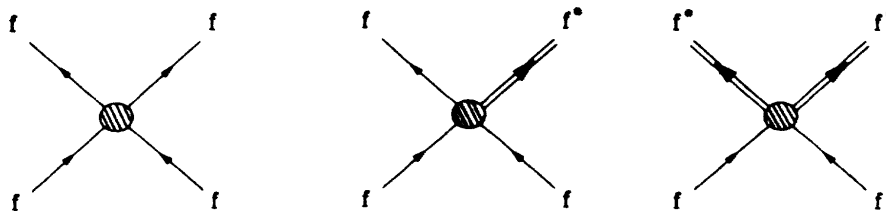
# Excited quarks and leptons

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and contact interactions for  $\sqrt{\hat{s}} \ll \Lambda$



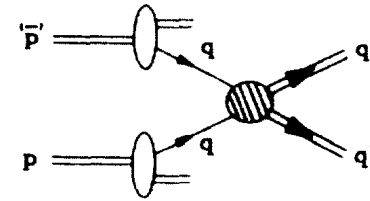
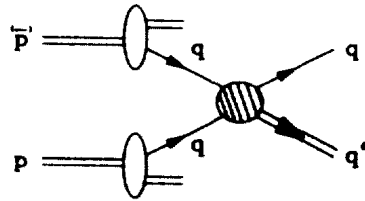
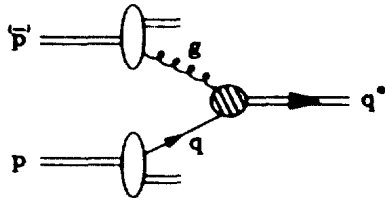
$$\mathcal{L} = \frac{g_*^2}{\Lambda^2} \frac{1}{2} j^\mu j_\mu$$

with 
$$j_\mu = \eta_L \bar{f}_L \gamma_\mu f_L + \eta'_L \bar{f}_L^* \gamma_\mu f_L^* + \eta''_L \bar{f}_L^* \gamma_\mu f_L + h.c. + (L \leftrightarrow R)$$

# Excited quarks

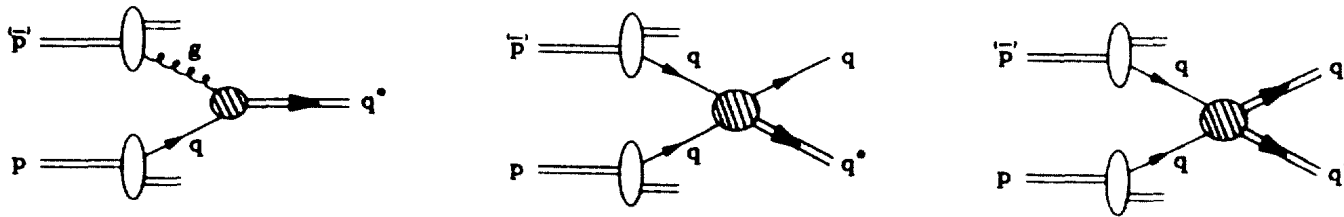
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- Focus on hadron collider phenomenology with production processes

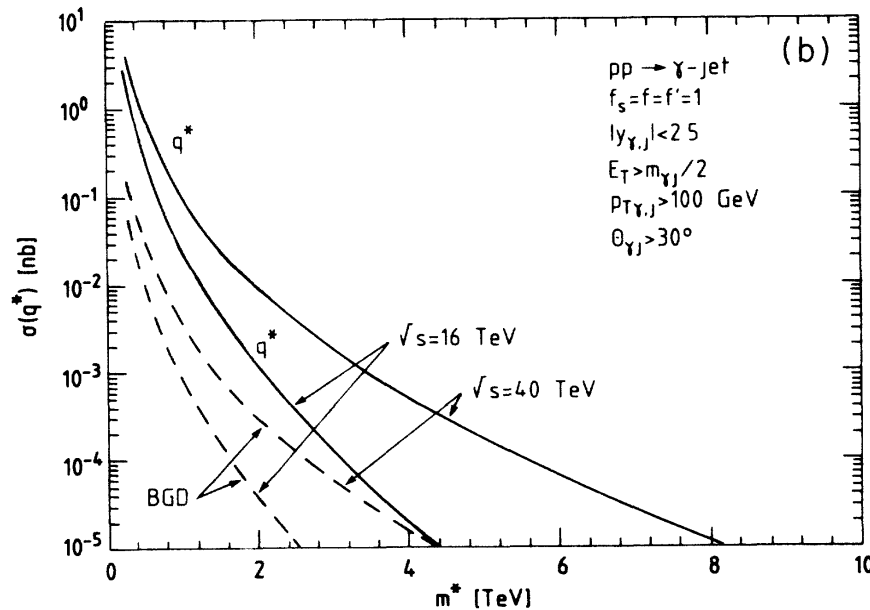


# Excited quarks

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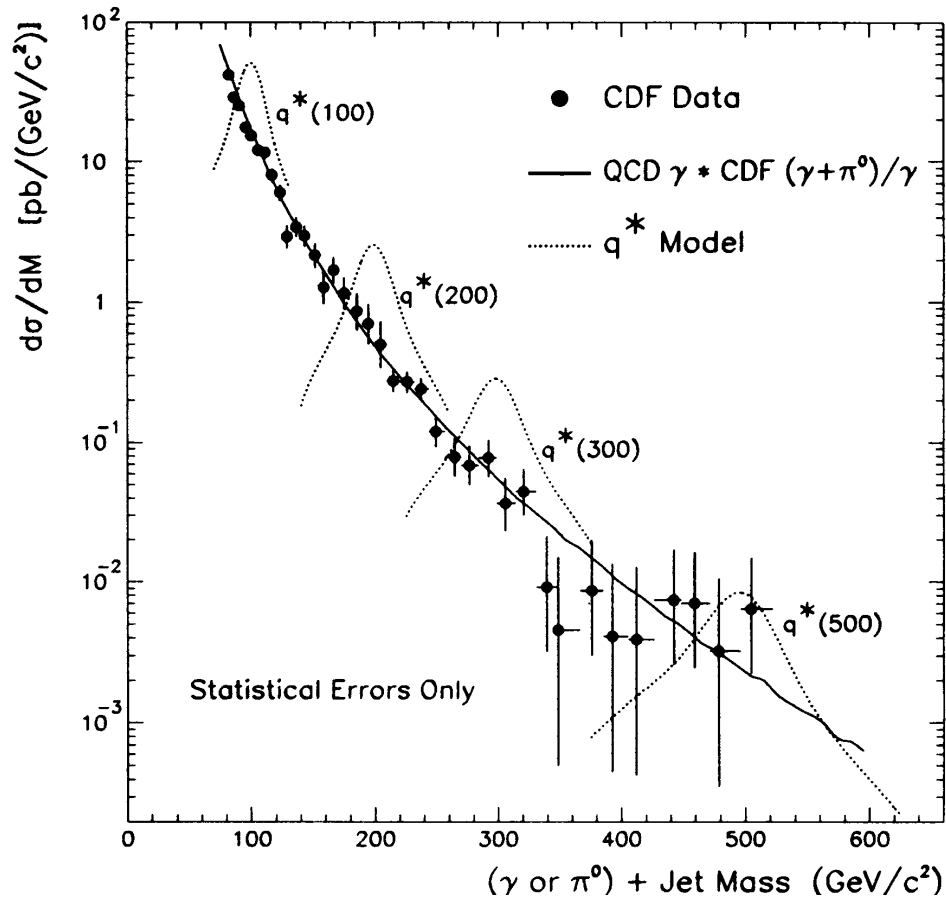


- Promising channel is production via  $qg$  fusion in s-channel:  $qg \rightarrow q^*$  and decay via gauge interactions:  $q^* \rightarrow qg, q\gamma, qZ, q'W$



# Excited quarks: Experimental search

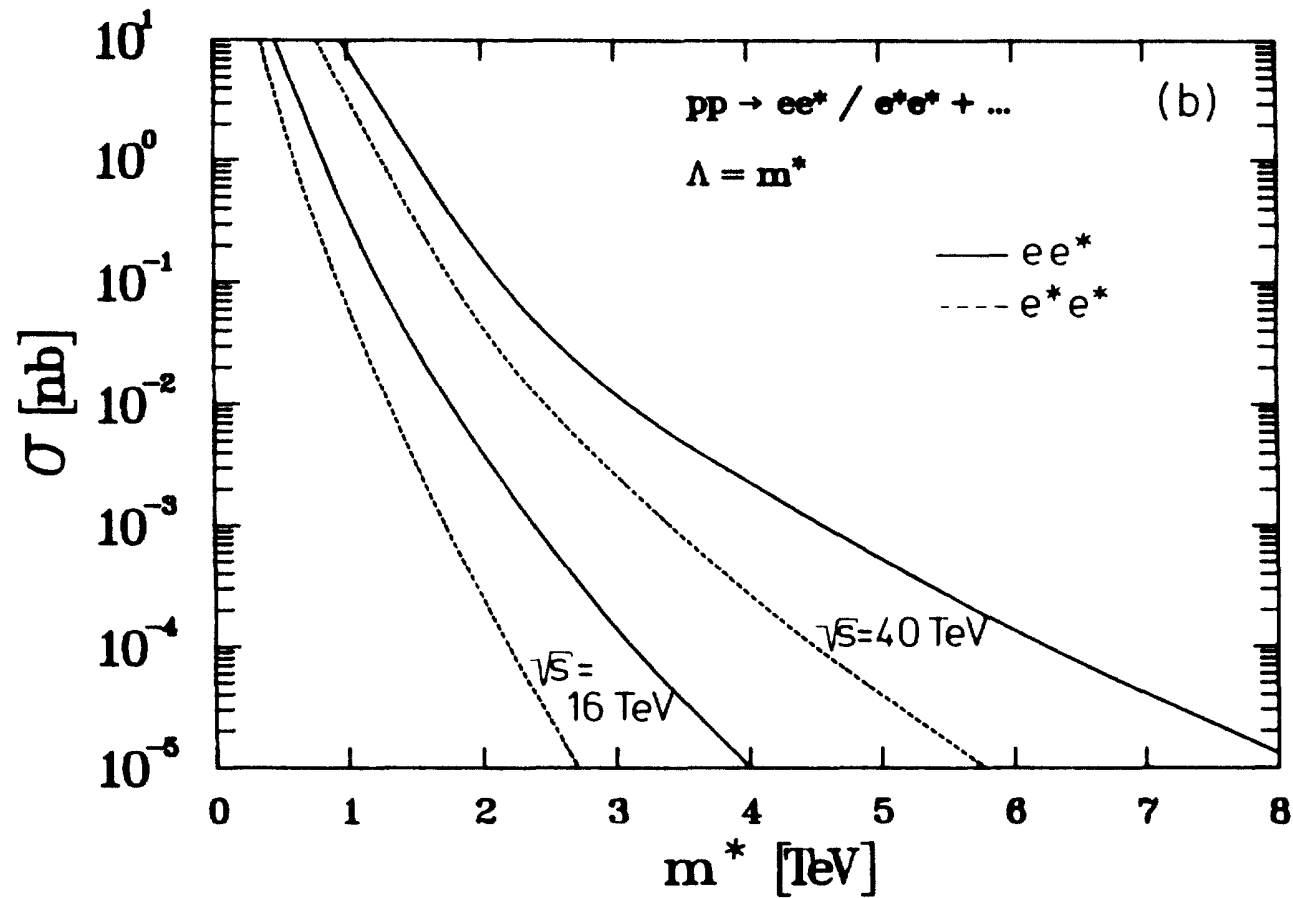
- CDF analysis (Phys.Rev.Lett.72:3004-3008,1994)



⇒ Exclusion  $80 \text{ GeV} \leq m^* \leq 540 \text{ GeV}$

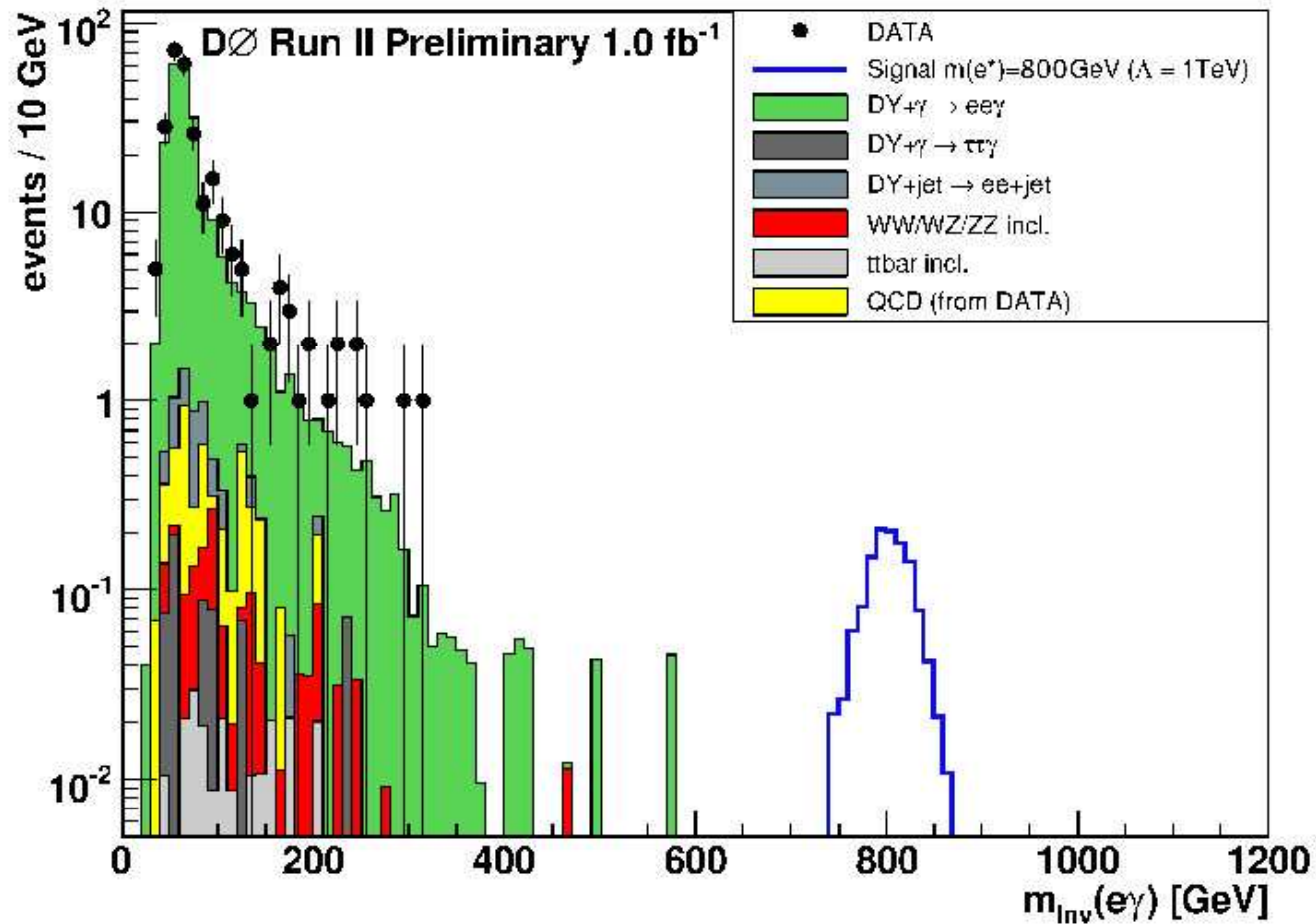
# Excited leptons

- Production via contact interactions:  $q\bar{q} \rightarrow l\bar{l}^*, l^*\bar{l}, l^*\bar{l}^*$   
and decay via gauge interactions  $l^* \rightarrow l\gamma, lZ, \nu W$



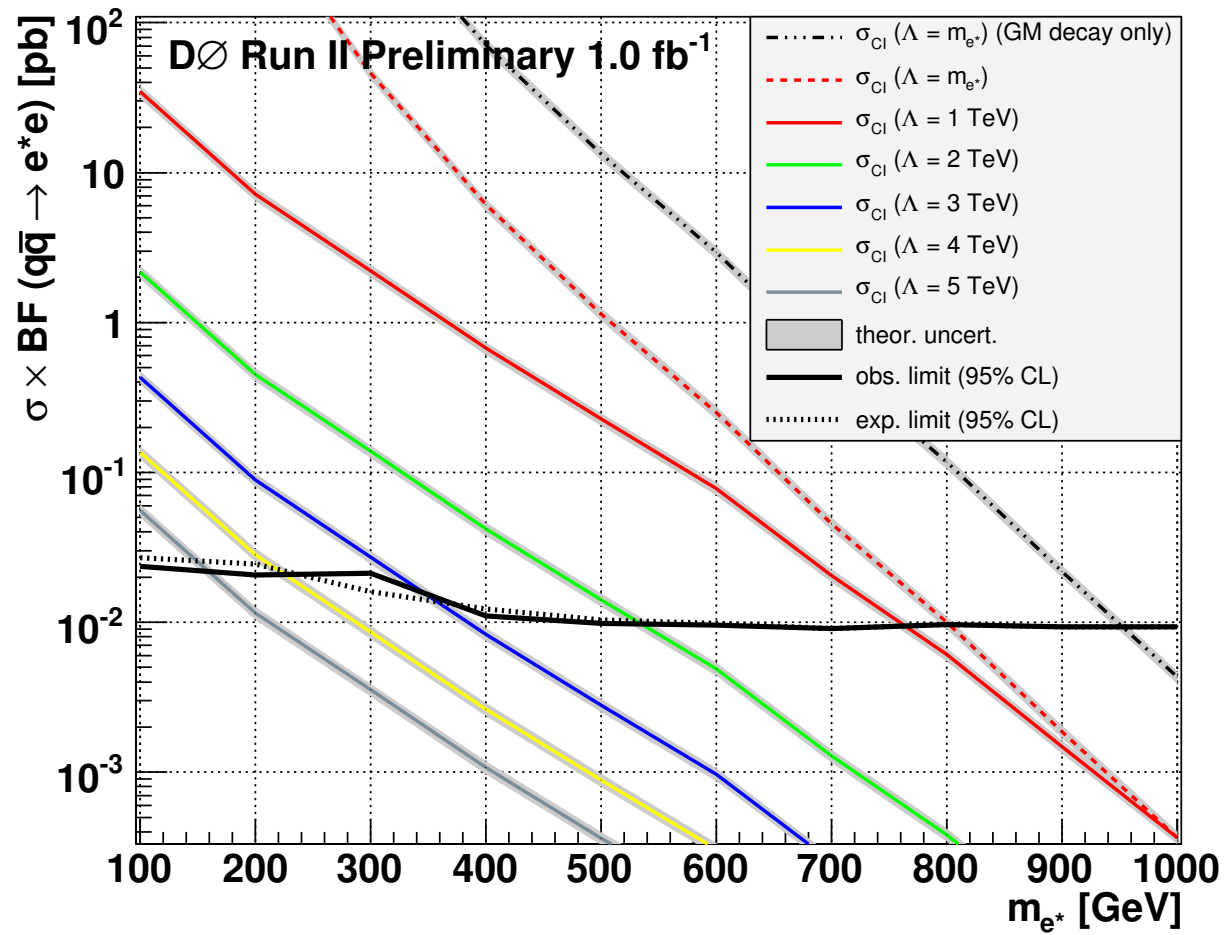
# Excited leptons: Experimental search

- recent D0 analysis:  $p\bar{p} \rightarrow ee^* \rightarrow ee\gamma$  (5349-CONF)



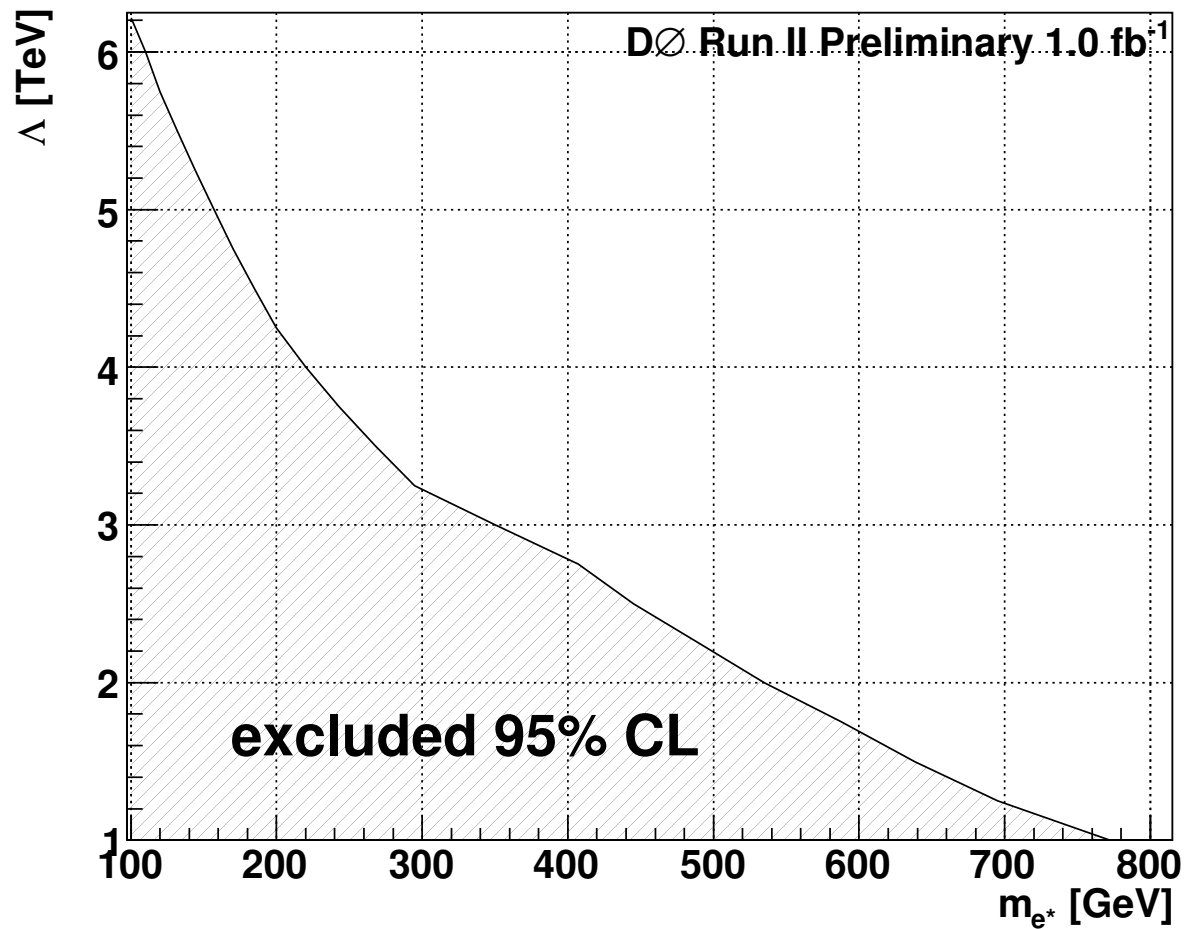
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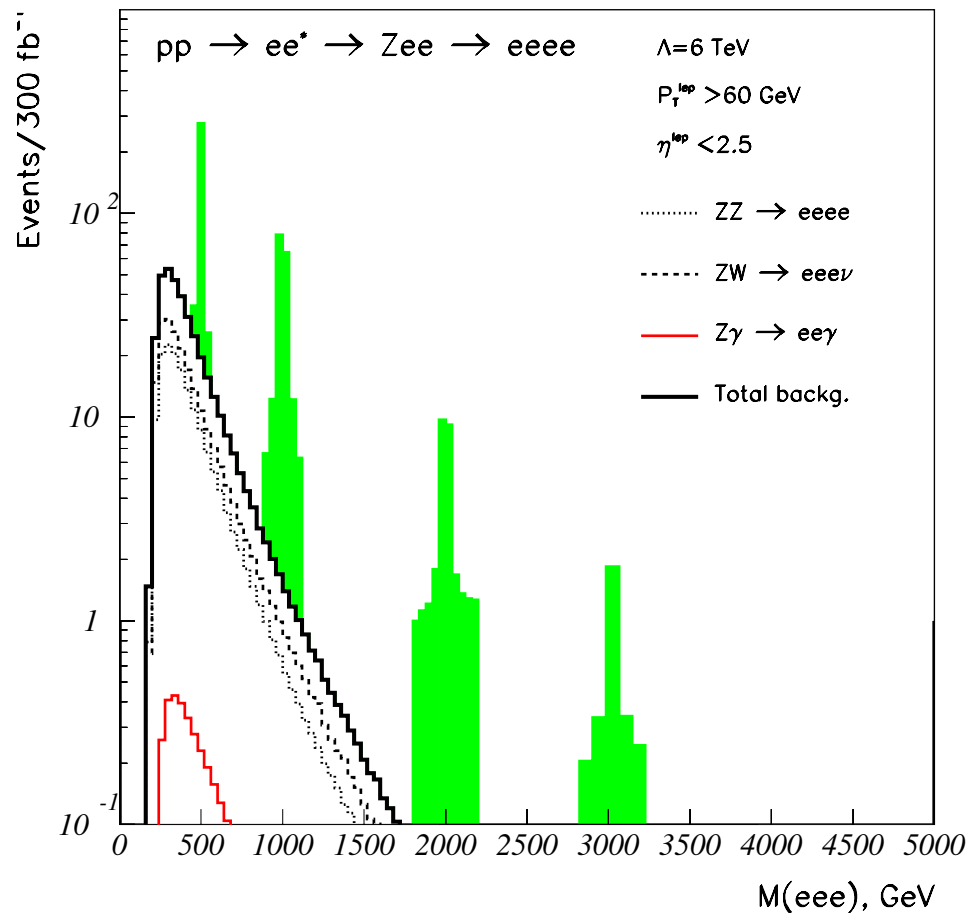
- recent D0 analysis:  $p\bar{p} \rightarrow ee^* \rightarrow ee\gamma$  (5349-CONF)





# Excited leptons: Prospects at the LHC

● eg.  $pp \rightarrow ee^* \rightarrow eeZ$  (ATLAS 2002-014)



● LHC reach:  $M^* \lesssim 4 \text{ TeV}$  for  $\Lambda = 6 \text{ TeV}$

# Leptoquarks

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- “Atom smasher hurls particle theory into chaos!” (Daily Telegraph 20 February 1997)

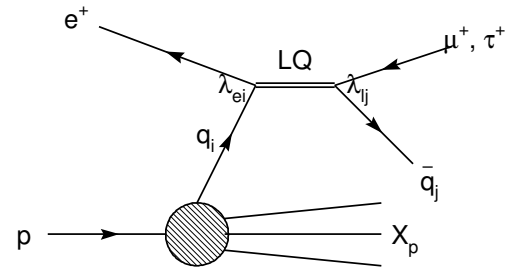
*The accepted perception of the universe was called into question again yesterday by results from an international atom smasher experiment.*



# Leptoquarks: HERA excess of high $Q^2$ events

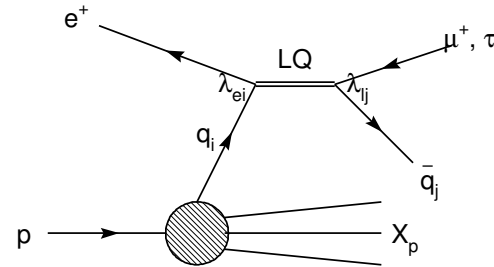
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- Leptoquark search at HERA

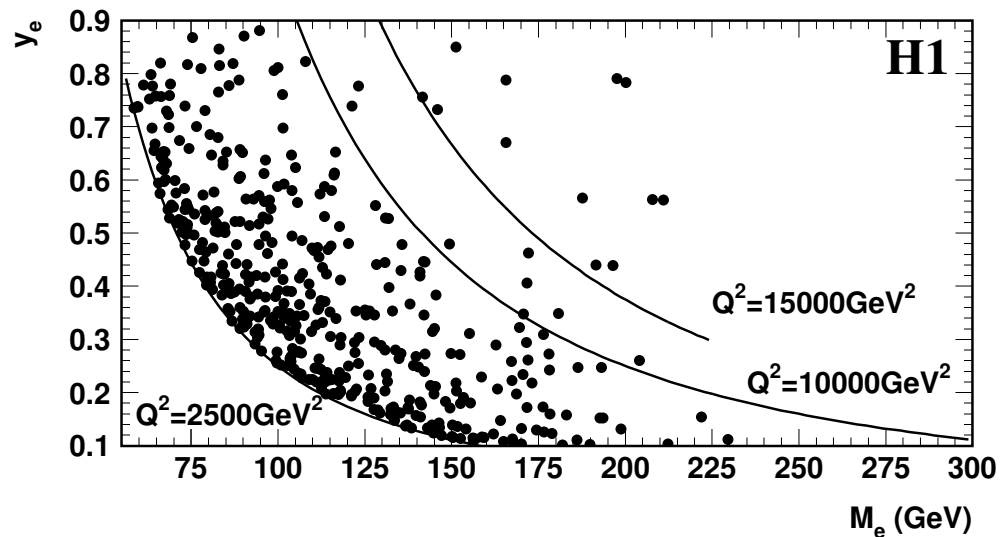


# Leptoquarks: HERA excess of high $Q^2$ events

- Leptoquark search at HERA



- HERA excess of events at  $Q^2 > 15000 \text{ GeV}^2$  (1997)



H1 observed 12 events (SM expectation  $4.71 \pm 0.76$ )

ZEUS observed 12 events (SM expectation  $8.66 \pm 0.66$ )

# Leptoquarks

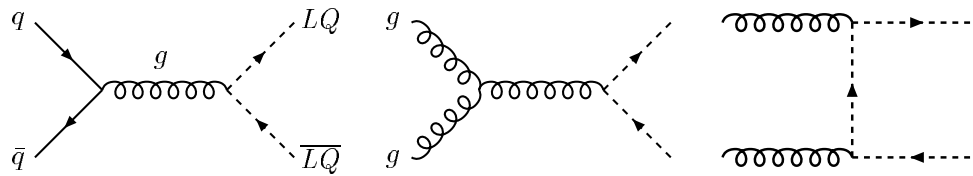
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- *Leptoquarks and diquarks in  $e^+ e^-$  collisions up to 2-TeV.*  
D. Schaile & P.M. Zerwas, La Thuile Workshop 1987
- *Virtual Leptoquark Effects On The Drell-Yan Process*  
R. Rückl & P.M. Zerwas, La Thuile Workshop 1987
- *( $e b$ ), ( $e t$ ) type leptoquarks*  
C. Berger, J. Tutas, M. Spira & P.M. Zerwas, DESY HERA Workshop 1987
- *Single leptoquark production at hadron colliders*  
J. Ohnemus, S. Rudaz, T.F. Walsh & P.M. Zerwas, Phys.Lett.B334:203-207,1994
- *Leptoquark / squark interpretation of HERA events: Virtual effects in  $e^+ e^-$  annihilation to hadrons*  
J. Kalinowski, R. Rückl, H. Spiesberger & P.M. Zerwas, Z.Phys.C74:595-603,1997
- *Formation and decay of scalar leptoquarks / squarks in  $e p$  collisions*  
T. Plehn, H. Spiesberger, M. Spira, & P.M. Zerwas, Z.Phys.C74:611-614,1997
- *Pair production of scalar leptoquarks at the Tevatron*  
M. Krämer, T. Plehn, M. Spira & P.M. Zerwas, Phys.Rev.Lett.79:341-344,1997
- *Pair production of scalar leptoquarks at the LHC*  
M. Krämer, T. Plehn, M. Spira & P.M. Zerwas, Phys.Rev.D71:057503,2005

# Leptoquarks: Hadroproduction

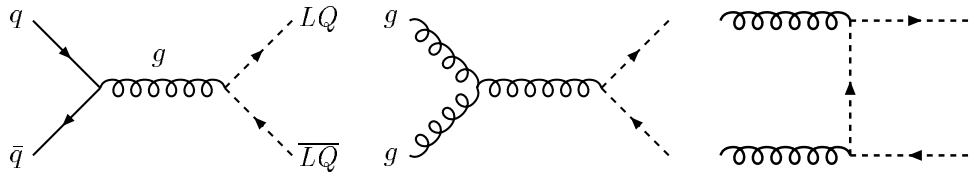
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- potentially large hadron collider cross section:



# Leptoquarks: Hadroproduction

- potentially large hadron collider cross section:



- cross section prediction depends only on  $m_{LQ}$ :

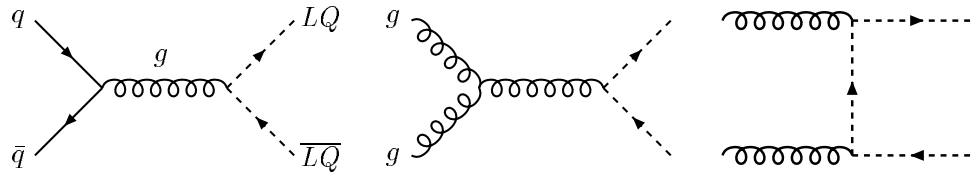
$$\hat{\sigma}_{LO}[q\bar{q} \rightarrow LQ + \bar{L}\bar{Q}] = \frac{\alpha_s^2 \pi}{\hat{s}} \frac{2}{27} \beta^3$$

$$\hat{\sigma}_{LO}[gg \rightarrow LQ + \bar{L}\bar{Q}] = \frac{\alpha_s^2 \pi}{96 \hat{s}} \left[ \beta (41 - 31\beta^2) + (18\beta^2 - \beta^4 - 17) \log \frac{1 + \beta}{1 - \beta} \right]$$

where  $\beta = \sqrt{1 - 4m_{LQ}/\hat{s}}$

# Leptoquarks: Hadroproduction

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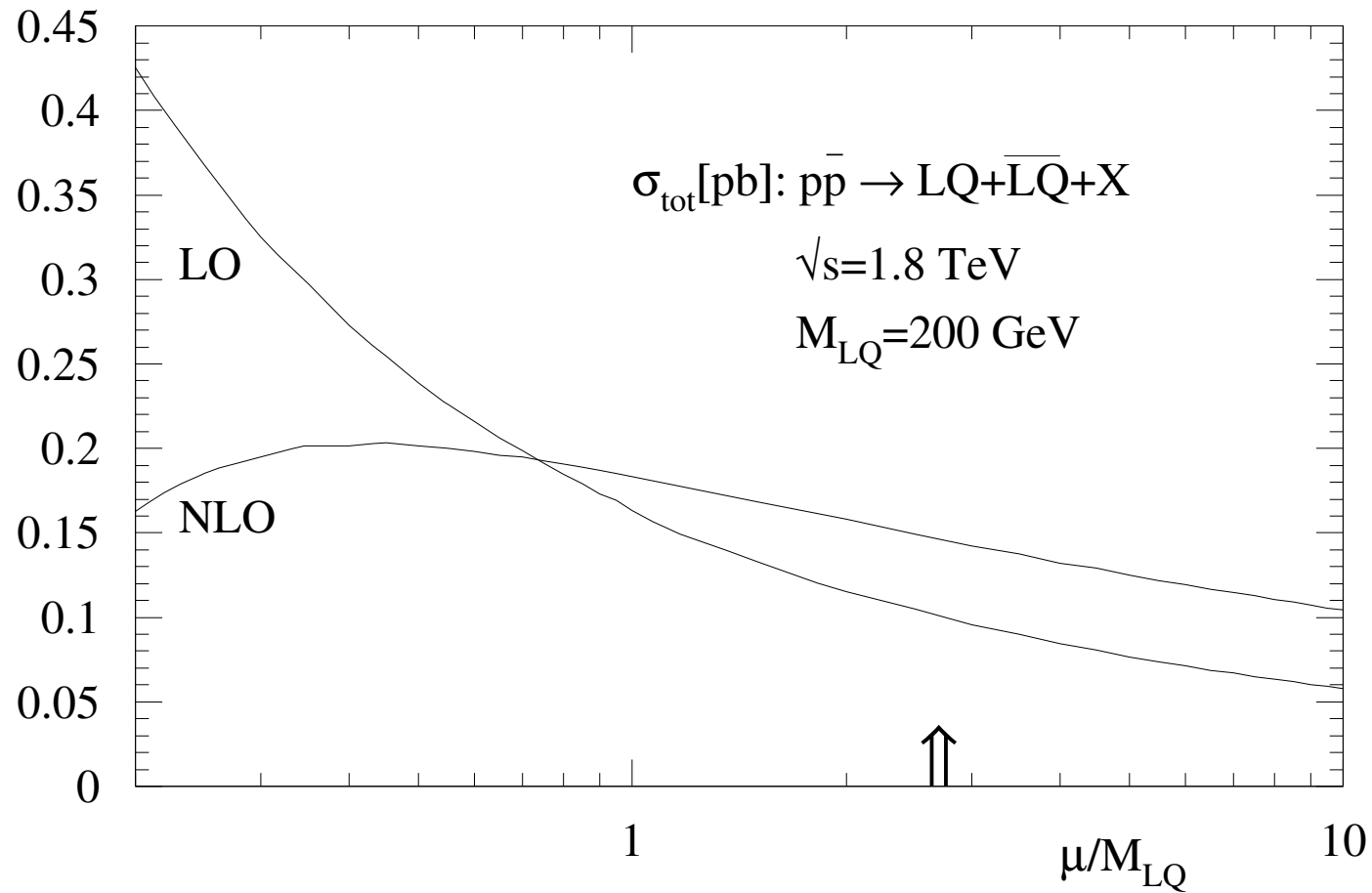
- Cross section coincides with squark-pair production for  $m_{\tilde{g}} \rightarrow \infty$

$$\sigma(p\bar{p} \rightarrow \tilde{t}\bar{\tilde{t}}) \xrightarrow[4\tilde{g}\text{-coupling} \rightarrow 0]{m_{\tilde{g}} \rightarrow \infty} \sigma(p\bar{p} \rightarrow LQ \overline{LQ})$$



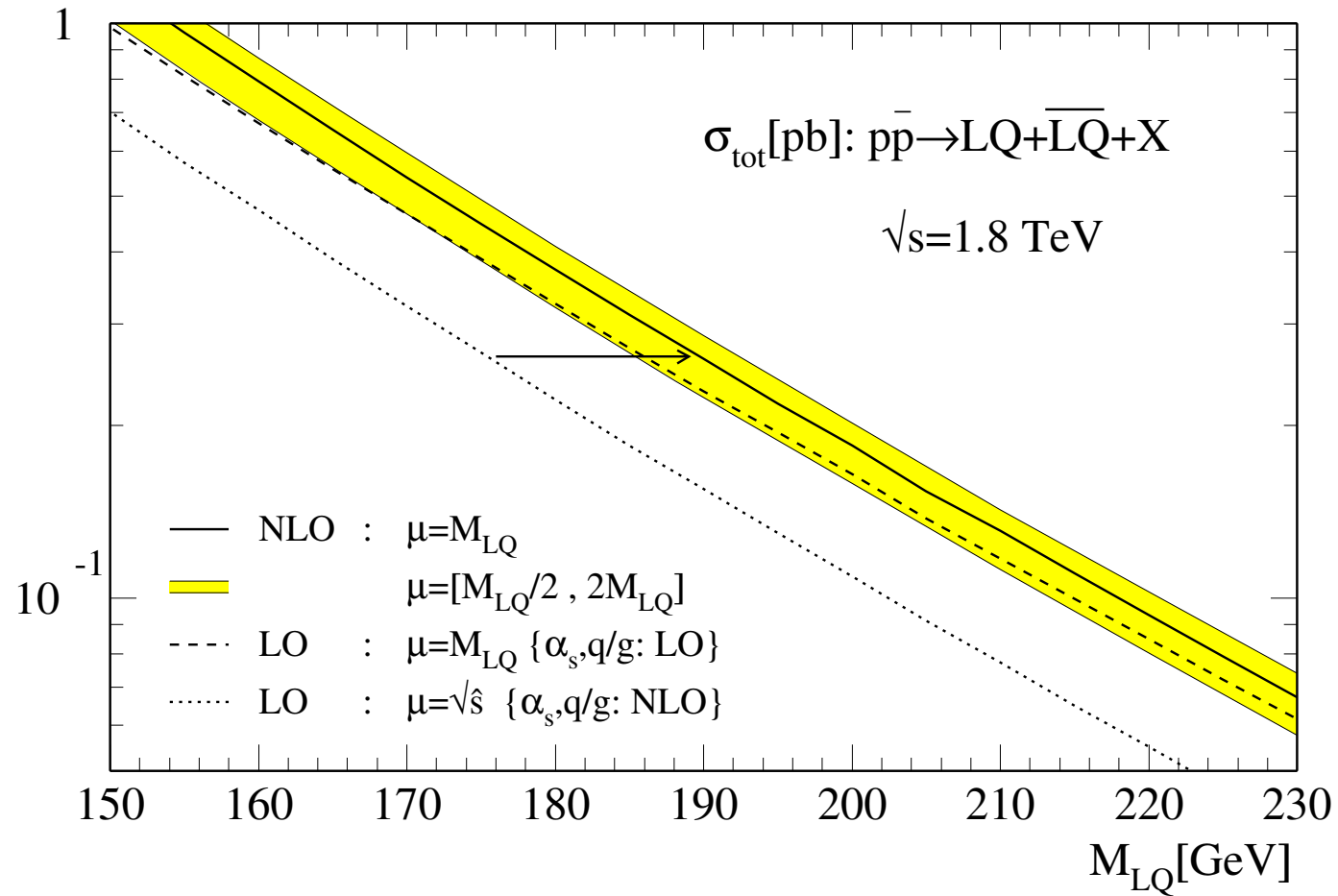
# Leptoquarks: Hadroproduction at NLO

- Reduction of scale uncertainty at NLO



# Leptoquarks: Hadroproduction at NLO

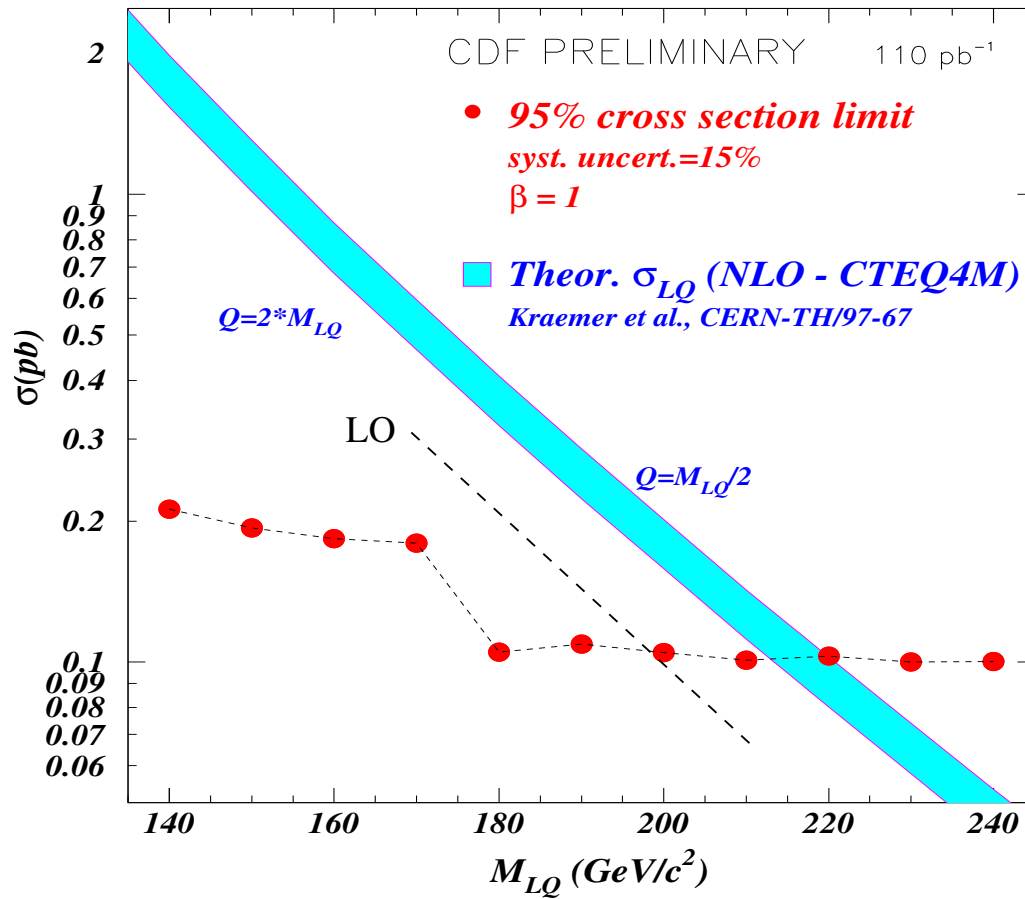
- Improved mass bounds at NLO



# Leptoquarks: Experimental searches

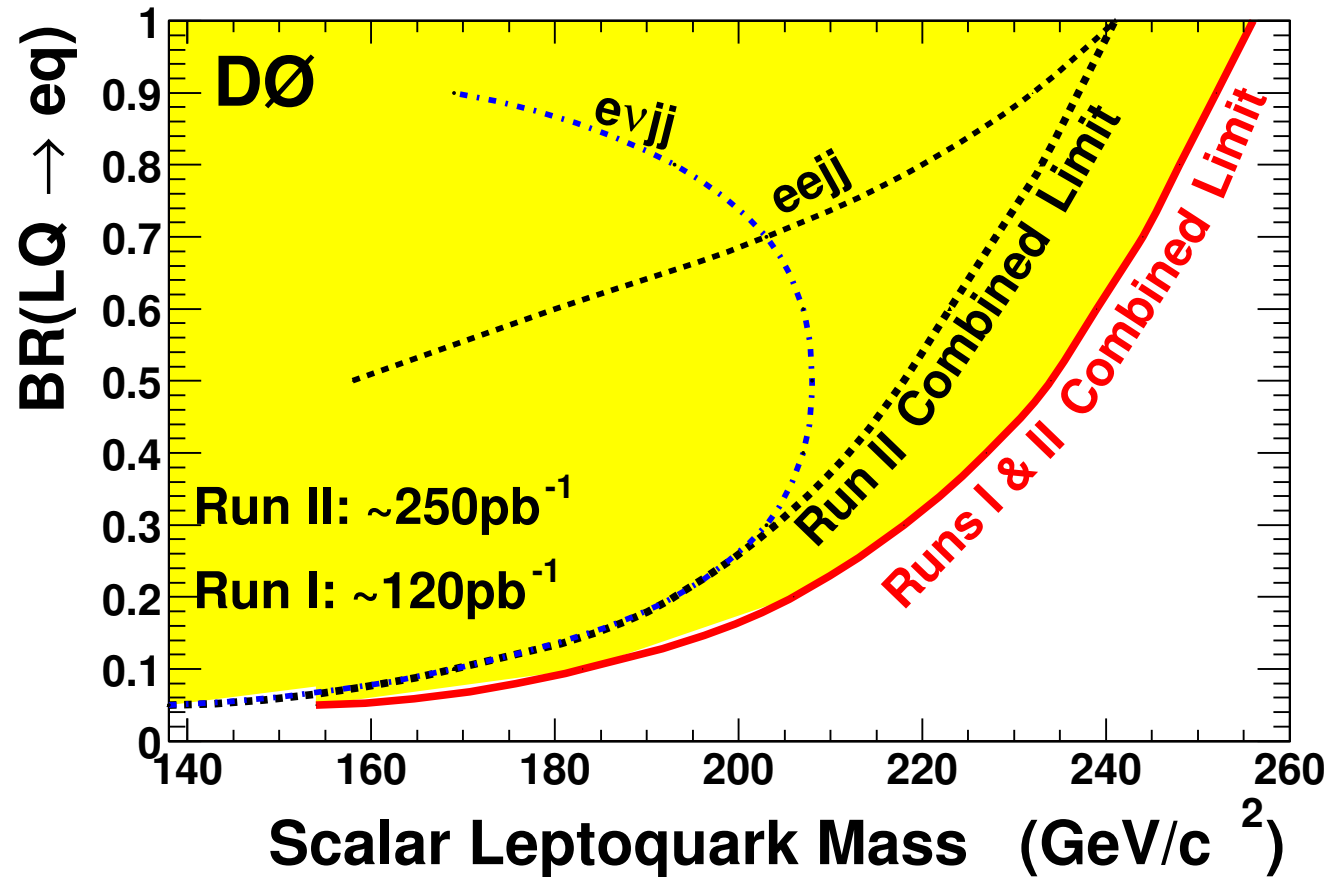
- Improved mass bounds at NLO

## First Generation Scalar LQ Search

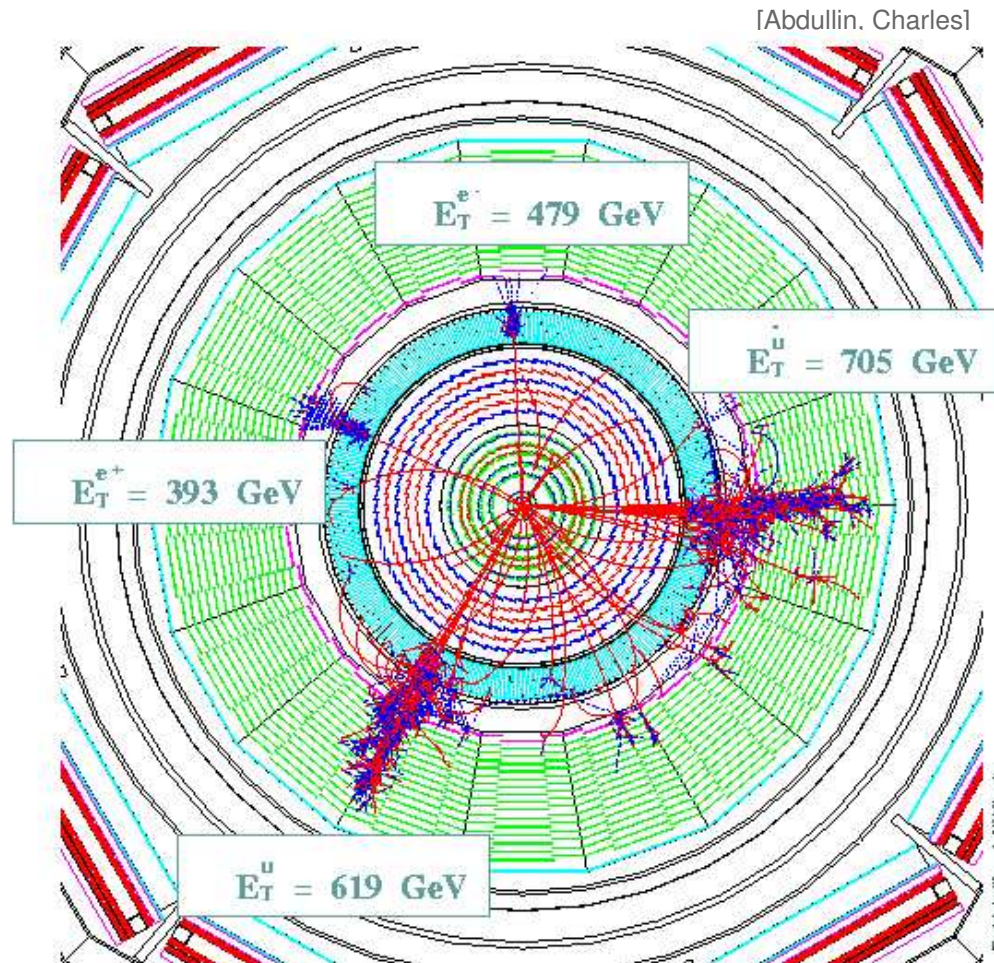


# Leptoquarks: Experimental searches

- Current status (D0 Fermilab-Pub-04-389-E)



# Leptoquarks: Prospects for the LHC



- LHC reach:  $m_{LQ} \lesssim 1.5 \text{ TeV}$  for  $\beta = 1$

# In Summa

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