10. Other Extensions of the Standard Model

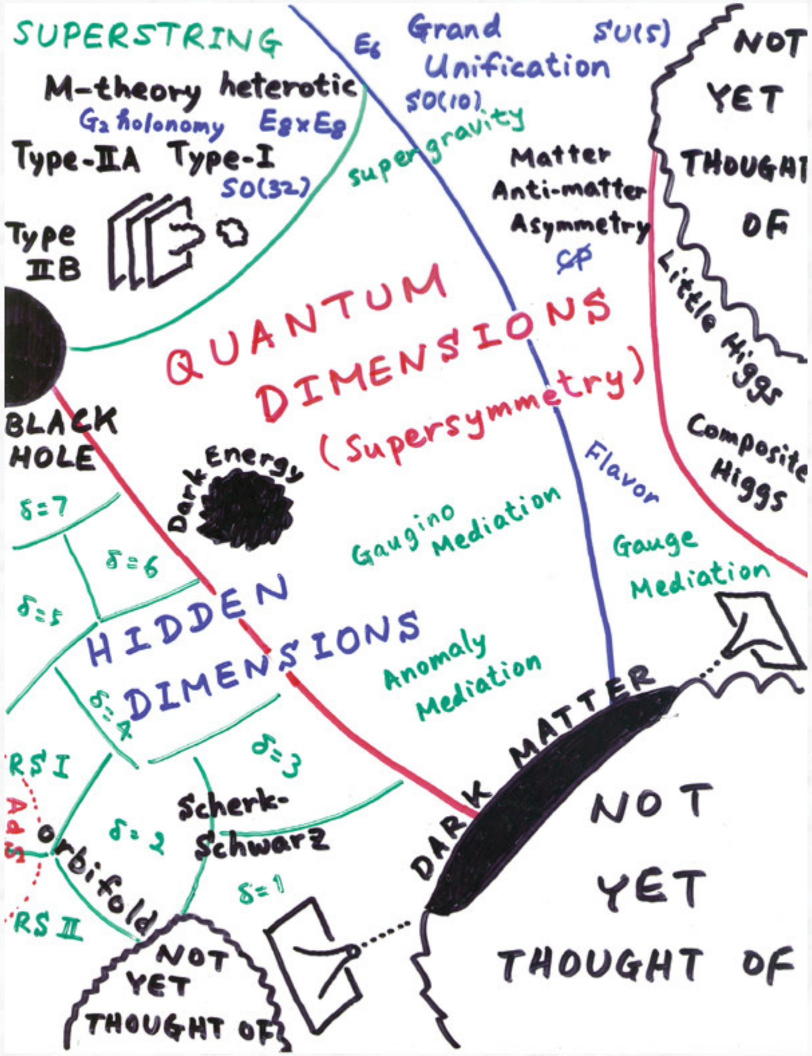
10.1 Introduction to Grand Unified Theories

10.2 Leptoquarks

10.3 Additional Gauge bosons,
W' and Z' searches

10.4 Compositeness and excited
quarks

10.5 Extra Space dimensions



Why Physics Beyond the Standard Model ?

1. Gravity is not yet incorporated in the Standard Model

2. Dark Matter not accomodated

3. Many open questions in the Standard Model
   - Hierarchy problem: m_W (100 GeV) $\rightarrow$ m_{Planck} (10^{19} GeV)
   - Unification of couplings
   - Flavour / family problem
   - …..

All this calls for a ***more fundamental theory*** of which the Standard Model is a low energy approximation → **New Physics**

Candidate theories: Supersymmetry
Extra Dimensions
New gauge bosons
…….

Many extensions predict new physics at the TeV scale !!

Strong motivation for LHC, mass reach ~ 3 TeV

10.1 Introduction to Grand Unified Theories (GUT)

- The SU(3) x SU(2) x U(1) gauge theory is in impressive agreement with experiment.

- However, there are still three gauge couplings (g, g', and α_s) and the strong interaction is not unified with the electroweak interaction

- Is a unification possible ?

  Is there a larger gauge group G, which contains the SU(3) x SU(2) x U(1) ?
  Gauge transformations in G would then relate the electroweak couplings g and g' to the strong coupling α_s.

  For energy scales beyond M_{GUT}, all interactions would then be described by a grand unified gauge theory (GUT) with a single coupling g_G, to which the other couplings are related in a specific way.

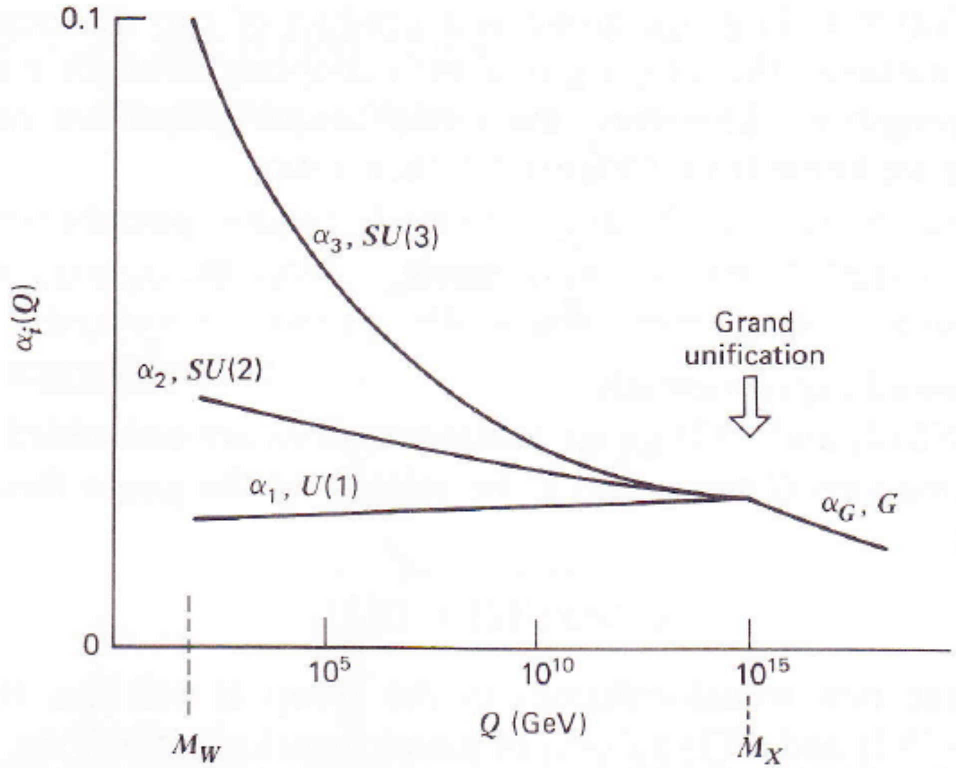


Fig. 15.4 The variation of $\alpha_i \equiv g_i^2/4\pi$ with Q, showing the speculative grand unification of strong [$SU(3)_{\text{color}}$] and electroweak [$SU(2)_L \times U(1)_Y$] interactions at very short distances $1/Q \approx 1/M_X$.

- Gauge couplings are energy-dependent, g_2 and g_3 are asymptotically free, i.e. their value decreases with energy, g_1 increases with energy
- Figure suggests that for some large energy scale $Q = M_X$ the three couplings merge into a single grand unified coupling g_G

for $Q > M_X$: $g_i(Q) = g_G(Q)$

- Assuming that there exists unification, the known / measured values of the coupling constants at low energy, i.e. at an energy scale m, can be used to estimate the Grand Unification Mass scale M_X
- The energy dependence of the three couplings is theoretically known, from the renormalization group equations.

Example: running of the strong coupling constant α_s:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(33 - 2n_f)\log(Q^2/\mu^2)}.$$

This can be written in the form:

$$\frac{1}{g_3^2(\mu)} = \frac{1}{g_3^2(Q)} + 2b_3 \log\frac{Q}{\mu},$$

where:

$$\alpha_s(Q) = \frac{g_3^2(Q)}{4\pi}$$

and

$$b_3 = \frac{1}{(4\pi)^2}\left(\frac{2}{3}n_f - 11\right)$$

- For $Q = M_X$ and $g_3 = g_G$ follows (i = 3) :

$$\frac{1}{g_i^2(\mu)} = \frac{1}{g_G^2} + 2b_i \log\frac{M_X}{\mu}$$

This relation is valid also for the SU(2) and U(1) gauge groups (i = 1,2).
The b_i terms for these gauge couplings are given by (see textbooks):

$$b_1 = \frac{1}{(4\pi)^2}\left(\frac{4}{3}n_g\right),$$

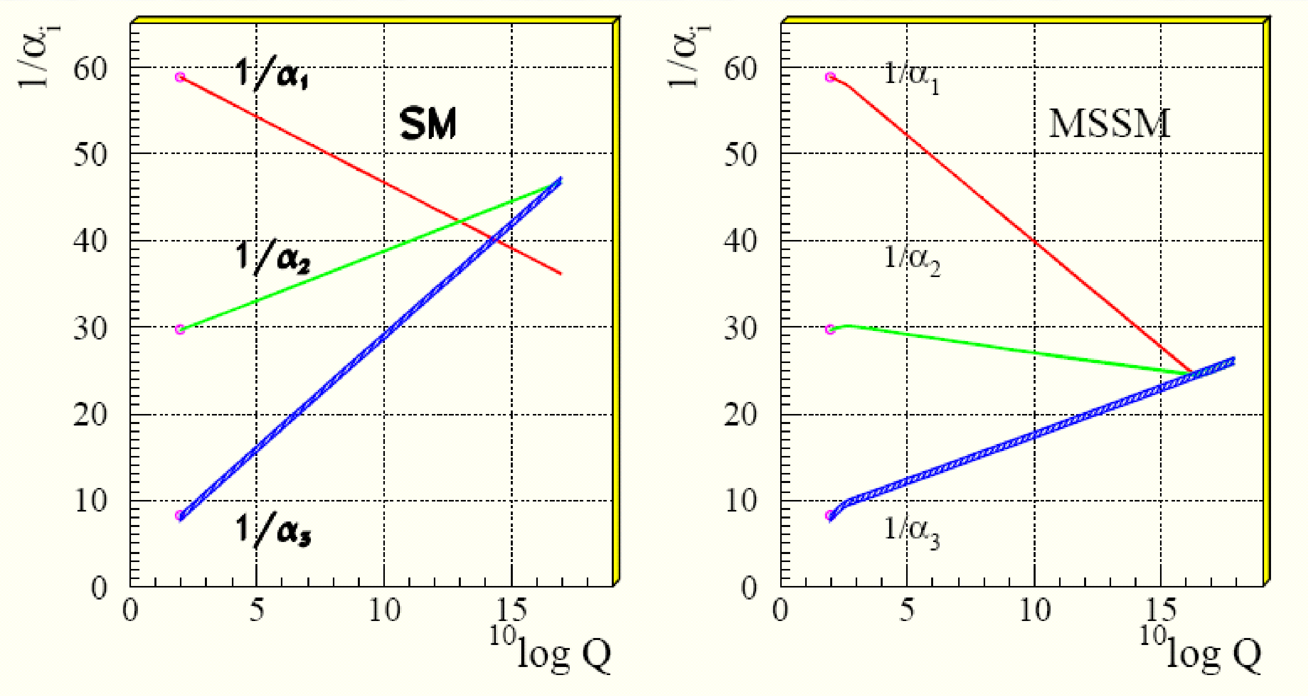
$$b_2 = \frac{1}{(4\pi)^2}\left(-\frac{22}{3}\right) + b_1,$$

$$b_3 = \frac{1}{(4\pi)^2}(-11) + b_1,$$

where n_g is the number of generations

- From these relations and the experimental measurements of the couplings, the mass scale M_X can be calculated.

- Within the Standard Model a mass scale of $M_X \sim 10^{15}$ GeV is obtained, however, the coupling unification is not possible….



…. in contrast to the Supersymmetric extension of the Standard Model assuming a SUSY mass scale at the TeV-scale

for SUSY scenarios: $M_X \sim 10^{16}$ GeV

The SU(5) Model (Georgi, Glashow, ~1980):

- Georgi and Glashow have shown that SU(5) is the smallest gauge group that can contain the SU(3) x SU(2) x U(1) as subgroups
  (this is also possible for larger gauge groups)

- In SU(5) quarks and leptons are assigned to one multiplet

  e.g. in the Stadard Model we have 15 left handed states:

  $(u,d)_L$, $(\nu_e,e^-)_L$ $(\text{ubar}, \text{dbar})_L$ e^+_L

  They are arranged in SU(5) multiplets: (dbar, ν_e , e^-) and (e^+, u, d, ubar)

- Transitions between SU(5) multiplets are mediated by new gauge bosons, X and Y

- There should be 24 gauge bosons in total (N^2 -1), i.e. 12 X and Y bosons in addition to the 8 gluons, and 4 el.weak gauge bosons (W^+,W^-,Z, γ)

  These gauge bosons carry weak isospin, electric charge and colour charge

The SU(5) Model (Georgi, Glashow, ~1980) (cont):

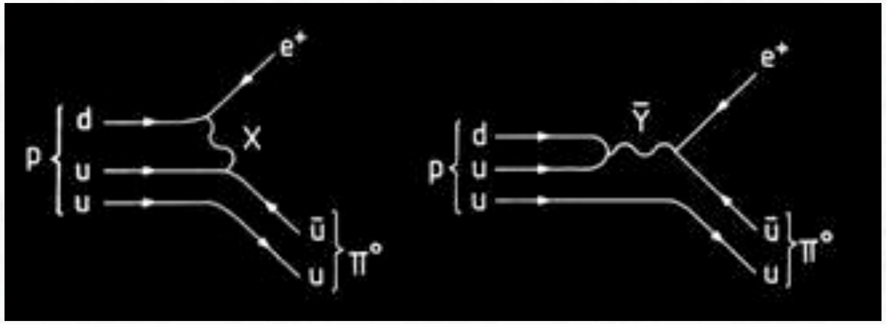
- Transitions mediated by X and Y bosons violate lepton number and baryon number conservation;

  e.g. $u + u \rightarrow X \rightarrow e^{+}$ dbar

- At energies $Q > M_X$ the strong colour force merges with the electroweak force and the sharp separation of particles into coloured quarks and colourless leptons disppears. This leads to lepton / baryon number-violating interactions.

  (similar to the unification of the weak and electromagnetic interaction for energy scales $Q > m_W$, see HERA results on charged and neutral currents)

- This has profound implications: The proton is predicted to decay!



The model has several nice features, among them: it predicts equality of electron and proton charge:

- Charge in each multiplett must be zero

  → $3\,Q_{dbar} + Q_{\nu} + Q_{e-} = 0$ → $Q_d = 1/3\,Q_{e-}$

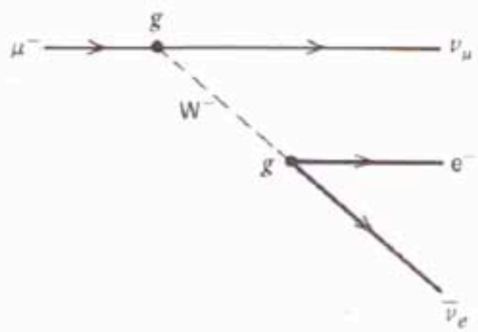
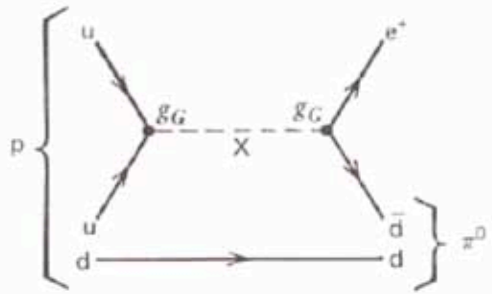
  2nd multiplett: $Q_u = -\,2\,Q_d$

  The combined result resolves the mystery of why $Q_p = -\,Q_e$

Can proton decay be detected?

- Similar to the muon lifetime (which depends on m_W), the proton lifetime can be estimated:

Low-Q^2 Phenomena Associated with the Scales $Q^2 = M_W^2$ and $Q^2 = M_X^2$

Muon Decay ($\mu^- \to e^- \bar{\nu}_e \nu_\mu$) at $Q^2 \ll M_W^2$	Proton Decay ($p \to \pi^0 e^+$) at $Q^2 \ll M_X^2$
	
$\frac{G}{\sqrt{2}} = \frac{g^2}{8M_W^2}$ (12.15)	$\frac{G_G}{\sqrt{2}} = \frac{g_G^2}{8M_X^2}$
$\Gamma(\mu \to e\bar{\nu}_e\nu_\mu) = \cdots G^2 m_\mu^5$ (12.42)	$\Gamma(p \to \pi e) = \cdots G_G^2 m_p^5$
$= \cdots \frac{m_\mu^5}{M_W^4}$	$= \cdots \frac{m_p^5}{M_X^4}$

Estimated lifetime: $M_X = 10^{14}$ GeV $\rightarrow$ τ (p) $\sim 10^{30}$ years
in SUSY models, lifetime is significantly longer (higher mass scale) > 10^{32} years

Results of experimental searches for proton decay:

(i) Large mass calorimeter detectors

Tab. 4.3 Eigenschaften der Protonzerfallsexperimente (Eisenkalorimeter)

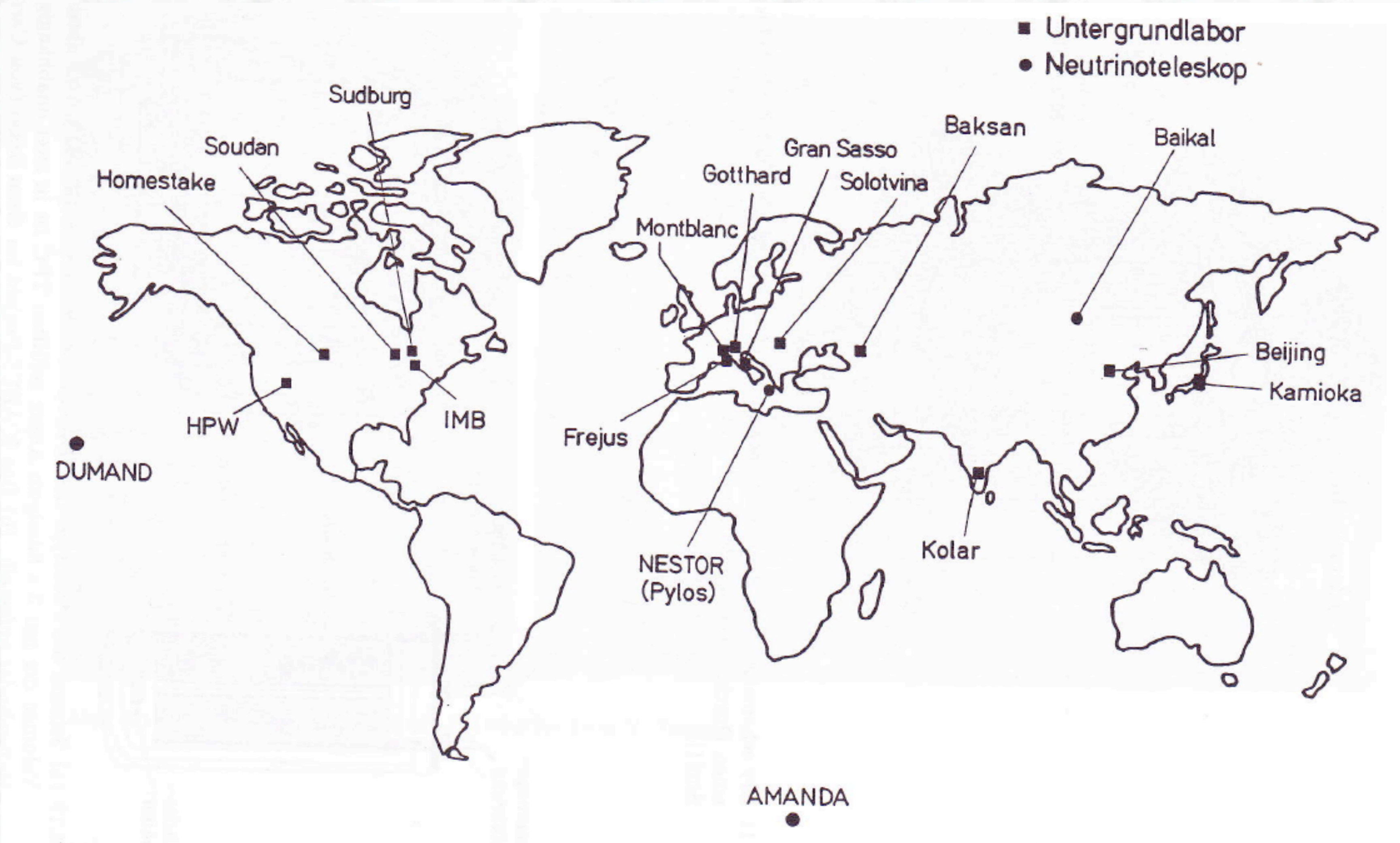
	KGF	NUSEX	Fréjus	Soudan II
M_{tot} [t]	140	150	912	1000
M_{eff} [t]	60	113	550	600
Tiefe [m]	2300	1850	1780	760
Wasseräquivalent [m]	7600	5000	4850	1800
Vertexauflösung [cm]	10	1	0.5	~ 0.5
Ort	Kolar-Goldmine	Mont-Blanc-Tunnel	Fréjus-Tunnel	Soudan-Erzmine

(ii) Large mass water Cherenkov detectors

Tab. 4.4 Eigenschaften der Protonzerfallsexperimente (Wasser-Cerenkov-Zähler).

	Kam I (II)	IMB I, III	HPW	Superkam
M_{tot} [t]	3000	8000	680	50000
M_{eff} [t]	880 (1040)	3300	420	22000
Tiefe [m]	825	600	525	825
Wasseräquivalent [m]	2400	1600	1500	2400
Vertexauflösung [cm]	100 (20)	100		10
Ort	Kamioka-Erzmine	Thiokol-Salzbergwerk	King-Silbermine	Kamioka-Erzmine

Overview on locations of proton decay experiments:

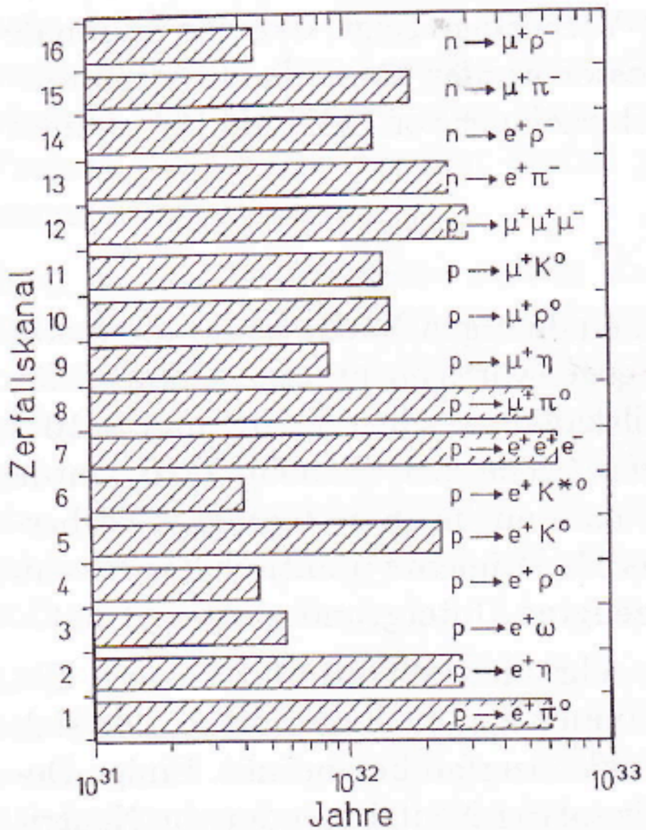


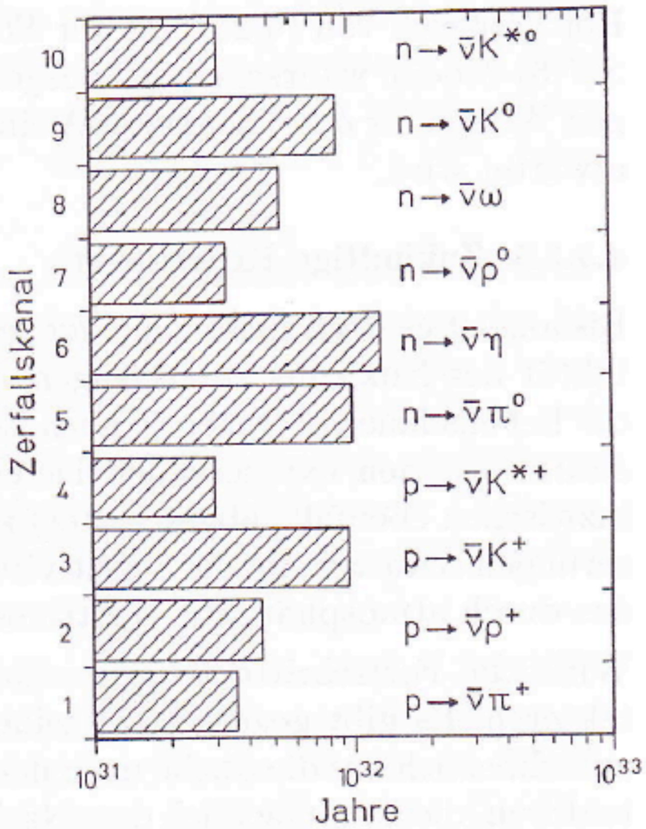
Results:

- so far no evidence for proton decay detected
- limits on lifetime in the order of 10^{32} years

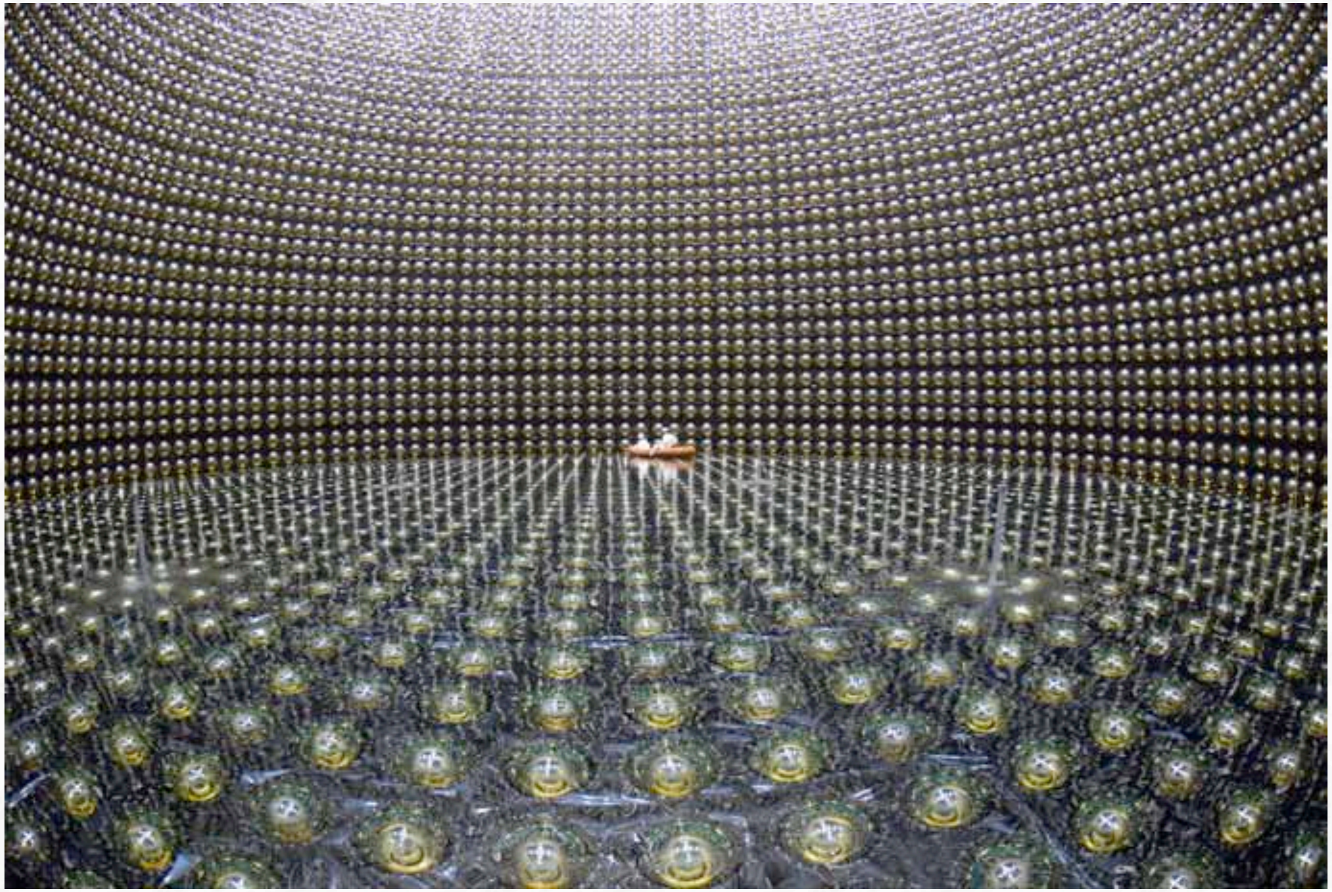
  → simple SM + GUT models ruled out

  SUSY + GUT models still alive



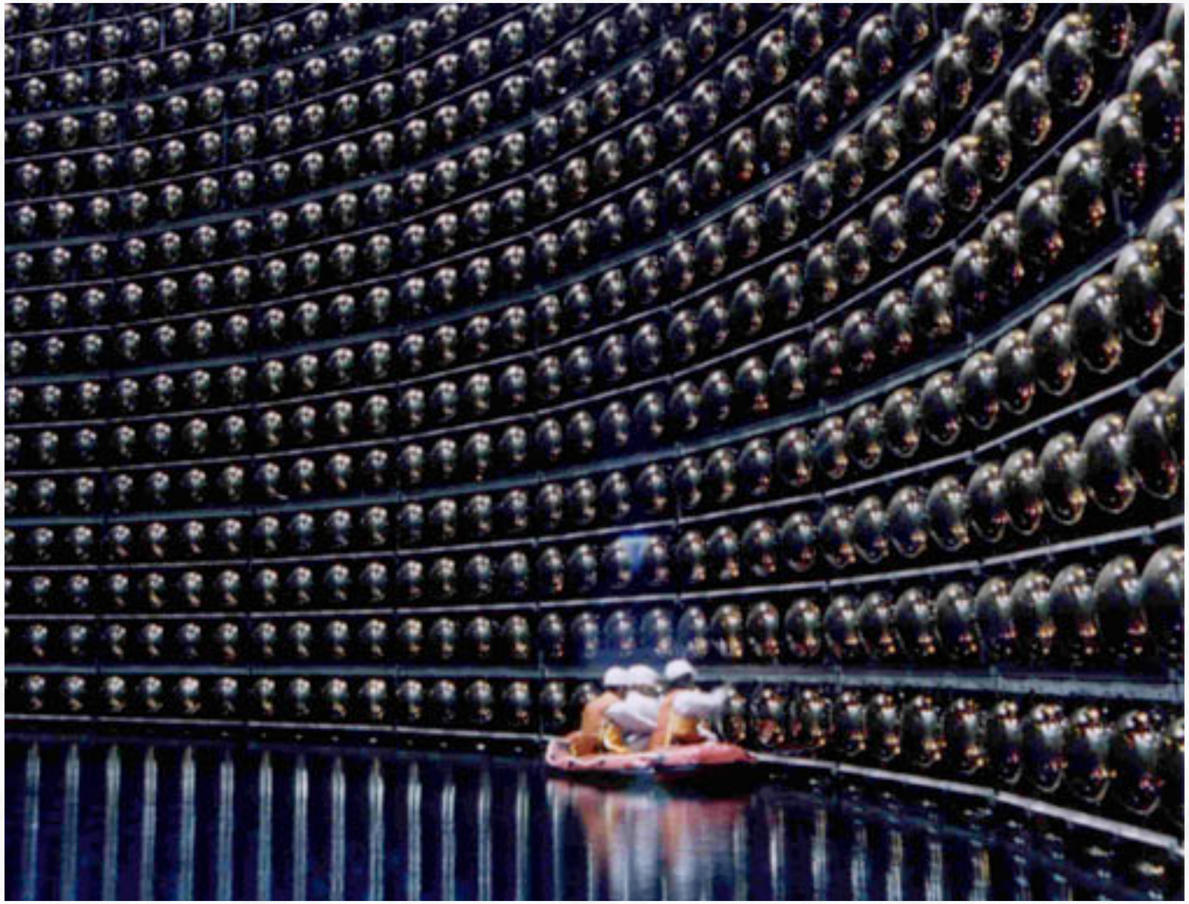


The Super-Kamiokande detector, Kamioka mine, Japan



The Super-Kamiokande detector began operating in 1996, more than half a mile underground in a zinc mine in Kamioka, Japan. Japanese and American scientists erected a huge tank of water 138 feet tall to hunt for neutrinos and proton decay. The walls, ceiling, and floor of the 12.5-million-gallon tank are lined with 11,242 light-sensitive phototubes. These pick up and measure bluish streaks of light called Cherenkov radiation. Super-Kamiokande detects neutrinos that nuclear interactions in the sun and atmosphere produce.

The Super-Kamiokande detector, Kamioka mine, Japan



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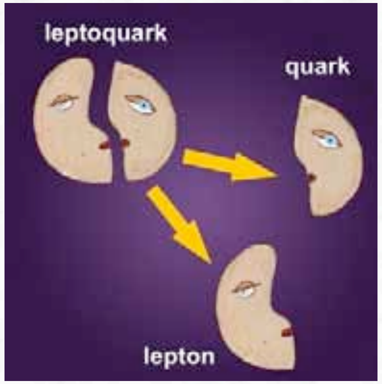
10.2 The Search for Leptoquarks



- Leptoquarks are particles that couple to leptons and quarks, motivated by Grand Unified Theories (or any theory that "unifies" quarks and leptons in the same particle multiplet)

- They carry colour charge, weak isopin and electric charge, and are bosons (spin-0 or spin-1)

  Example: X and Y bosons in GUTs

- Generalization: Leptoquarks LQ (see classification)

  Bosons: spin-0 or spin-1
  el. charge: -5/3, -4/3, -2/3, -1/3, 1/3, 2/3
  weak isospin: 0, ½, 1
  Lepton .and. baryon number ≠ 0

Leptoquark classification
(Buchmüller, Rückl, Wyler)

TABLE 1 Leptoquark classification according to electroweak quantum numbers

Type	Q	Coupling	β	F
S_0^L	$-1/3$	$\lambda_L(e_L u),\ -\lambda_L(\nu_e d)$	1/2	2
S_0^R	$-1/3$	$\lambda_R(e_R u)$	1	2
$\tilde{S}_0^R$	$-4/3$	$\lambda_R(e_R d)$	1	2
S_1^L	$-4/3$	$-\sqrt{2}\lambda_L(e_L d)$	1	2
	$-1/3$	$-\lambda_L(e_L u),\ -\lambda_L(\nu_e d)$	1/2	2
	$+2/3$	$\sqrt{2}\lambda_L(\nu_e u)$	0	2
$V_{1/2}^L$	$-4/3$	$\lambda_L(e_L d)$	1	2
	$-1/3$	$\lambda_L(\nu_e d)$	0	2
$V_{1/2}^R$	$-4/3$	$\lambda_R(e_R d)$	1	2
	$-1/3$	$\lambda_R(e_R u)$	1	2
$\tilde{V}_{1/2}^L$	$-1/3$	$\lambda_L(e_L u)$	1	2
	$+2/3$	$\lambda_L(\nu_e u)$	0	2
$S_{1/2}^L$	$-5/3$	$\lambda_L(e_L \bar{u})$	1	0
	$-2/3$	$\lambda_L(\nu_e \bar{u})$	0	0
$S_{1/2}^R$	$-5/3$	$\lambda_R(e_R \bar{u})$	1	0
	$-2/3$	$-\lambda_R(e_R \bar{d})$	1	0
$\tilde{S}_{1/2}^L$	$-2/3$	$\lambda_L(e_L \bar{d})$	1	0
	$+1/3$	$\lambda_L(\nu_e \bar{d})$	0	0
V_0^L	$-2/3$	$\lambda_L(e_L \bar{d}), \lambda_L(\nu_e \bar{u})$	1/2	0
V_0^R	$-2/3$	$\lambda_R(e_R \bar{d})$	1	0
$\tilde{V}_0^R$	$-5/3$	$\lambda_R(e_R \bar{u})$	1	0
V_1^L	$-5/3$	$\sqrt{2}\lambda_L(e_L \bar{u})$	1	0
	$-2/3$	$-\lambda_L(e_L \bar{d}), \lambda_L(\nu_e \bar{u})$	1/2	0
	$+1/3$	$\sqrt{2}\lambda_L(\nu_e \bar{d})$	0	0

Kopplung an L,R-Leptonen

schwacher Isospin

S = Skalare LQ
V = Vektor-LQ

F = Fermion-Zahl $F = L + 3B$

β = BR (LQ $\to \ell^{\pm} q$)   gel. Lepton   spez. Modell: $0, \frac{1}{2}, 1$

i. allg. $0 \le \beta \le 1$

Leptoquarks at the electroweak scale ?

- Leptoquarks may also be light, with masses on the electroweak scale; (consistent with proton lifetime, if baryon and lepton number are separately conserved)

  allowed decays: $LQ\,(-\tfrac{1}{3}) \rightarrow e^- u$, or $LQ(-4/3) \rightarrow e^- d$
  $LQ\,(-\tfrac{1}{3}) \rightarrow \nu_e\, d$

  Decays proceed always as: LQ → lepton + quark

  Branching ratio β : $= BR\,(LQ \rightarrow l\, q)$ charged lepton decay
  $(1-\beta) = BR\,(LQ \rightarrow \nu\, q)$ neutral lepton decay

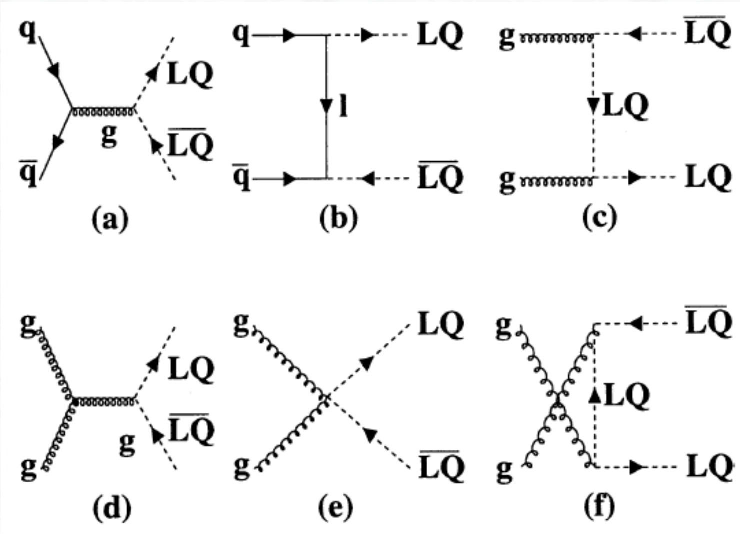
  β ist a free parameter $(0 \leq \beta \leq 1)$, in general not fixed by the theory

- Leptoquarks (in general form) may enhance flavour-changing neutral currents

  to suppress these contributions: require that leptoquarks only couple to one generation of fermions

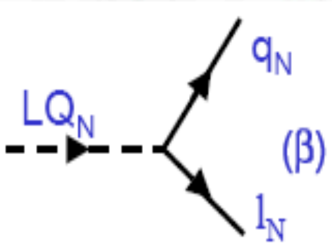
  → LQs of 1st, 2nd, and 3rd generation

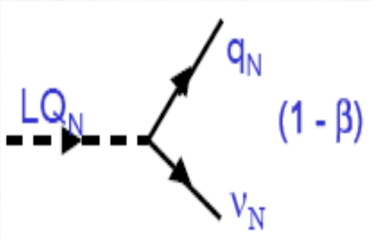
Search for Scalar Leptoquarks (LQ)



- <u>Production:</u>
  pair production via QCD processes
  (qq and gg fusion)

- <u>Decay:</u> into a lepton and a quark





β = LQ branching fraction to charged lepton and quark
N = Generation index
Leptoquarks of 1., 2., and 3. generation

<u>Experimental Signatures:</u>

- Two high p_T isolated leptons + jets .OR.
- One isolated lepton + E_T^{miss}+ jets .OR.
- E_T^{miss} + jets

Results from the ATLAS and CMS searches for leptoquarks

- Require two high P_T leptons and two high P_T jets (ll qq channel)
  .or. one high P_T lepton, E_T^{miss}, and two high P_T jets (lν qq channel)

- Additional kinematic requirements:

$eejj$ and $\mu\mu jj$	$e\nu jj$	$\mu\nu jj$
$M_{ll} > 120$ GeV	$M_T > 200$ GeV	$M_T > 160$ GeV
$\overline{M}_{LQ} > 150$ GeV	$M_{LQ} > 180$ GeV	$M_{LQ} > 150$ GeV
$p_T^{all} > 30$ GeV	$M_{LQ}^T > 180$ GeV	$M_{LQ}^T > 150$ GeV
$S_T^{\ell} > 450$ GeV	$S_T^{\nu} > 410$ GeV	$S_T^{\nu} > 400$ GeV

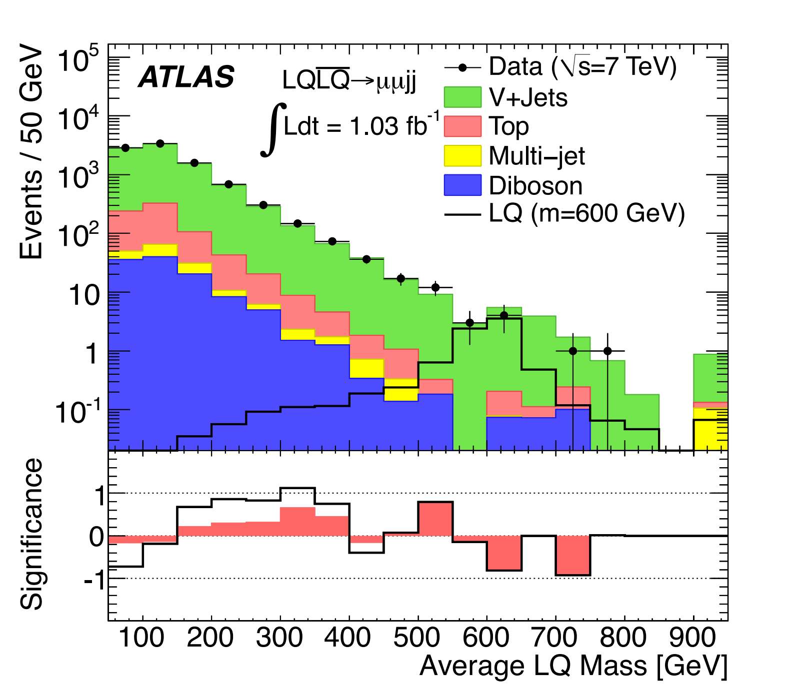
where S_T is the total scalar sum of the transverse momenta (two leptons and two jets)

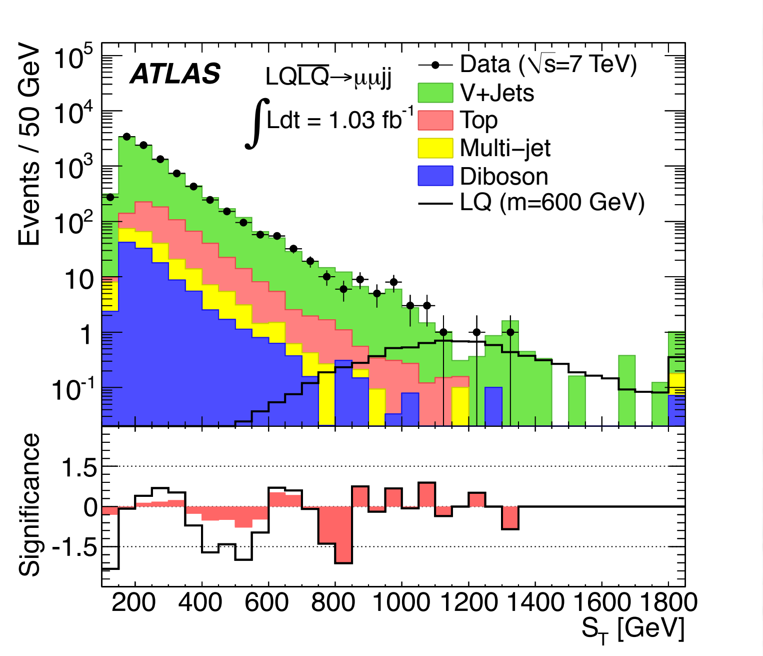
- Data, backgrounds and signal expectation (36 pb^{-1})

Source	$eejj$	$e\nu jj$	$\mu\mu jj$	$\mu\nu jj$
V+jets	0.50 ± 0.28	0.65 ± 0.38	0.28 ± 0.22	2.6 ± 1.4
Top	0.51 ± 0.23	0.67 ± 0.39	0.52 ± 0.23	1.6 ± 0.9
Diboson	0.03 ± 0.01	0.10 ± 0.03	0.04 ± 0.01	0.10 ± 0.03
QCD	$0.02\,^{+0.03}_{-0.02}$	0.06 ± 0.01	$0.00\,^{+0.01}_{-0.00}$	0.0 ± 0.0
Total Bkg	1.1 ± 0.4	1.4 ± 0.5	0.8 ± 0.3	4.4 ± 1.9
Data	2	2	0	4
LQ(250 GeV)	38 ± 8	9.6 ± 2.1	45 ± 10	13 ± 3
LQ(300 GeV)	17 ± 4	5.1 ± 1.1	21 ± 5	6.4 ± 1.4
LQ(350 GeV)	7.7 ± 1.7	2.6 ± 0.6	9.4 ± 2.1	3.0 ± 0.7
LQ(400 GeV)	3.5 ± 0.8	—	4.4 ± 1.0	—

Example: results of the search for second generation leptonquarks

Final states: LQ LQ → $\mu\,\mu\,j\,j$

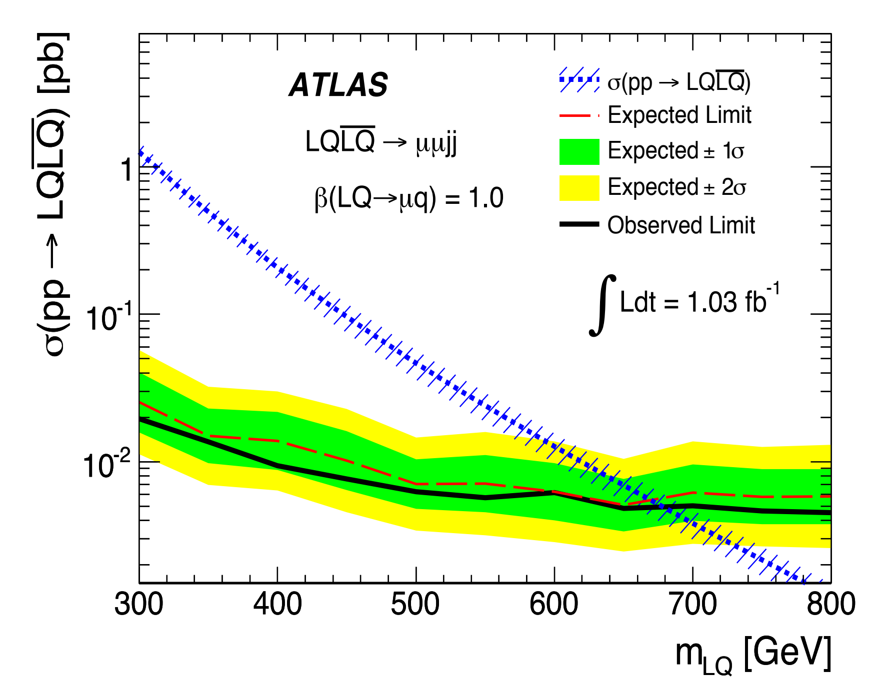


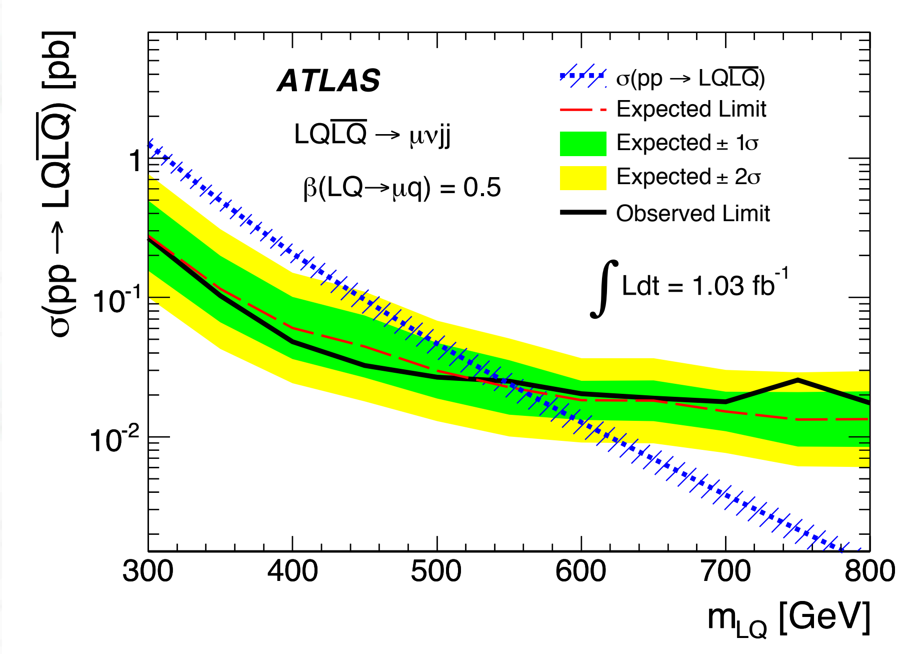


Left: invariant mass of $m(\mu_1, j_1)$, $m(\mu_2, j_2)$

Right: $S_T := p_T(\mu_1) + p_T(\mu_2) + E_T(j_1) + E_T(j_2)$ scalar sum

Excluded cross sections:





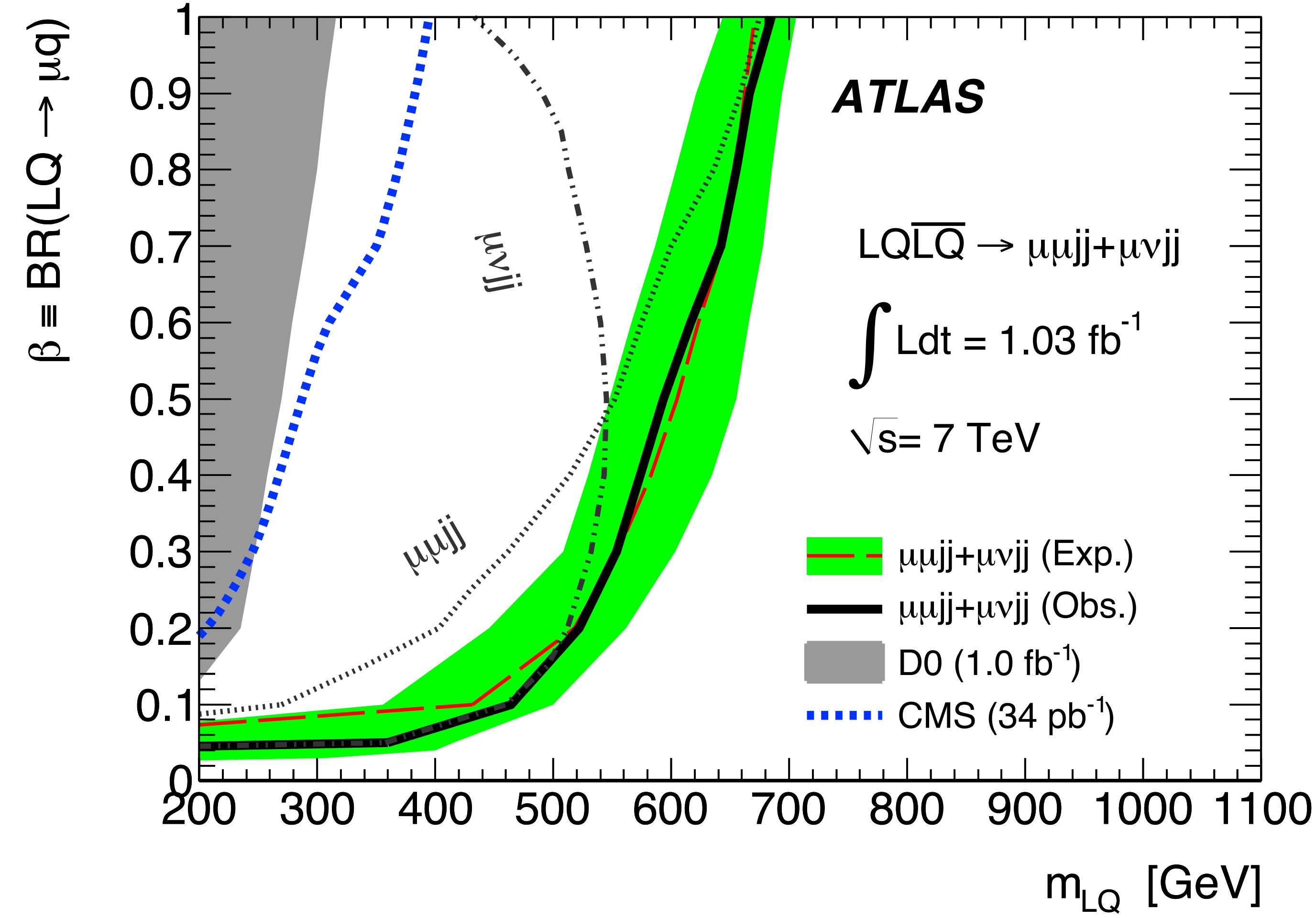
$\beta = 1.0$

$m_{LQ} > 685$ GeV (95% C.L.)

$\beta = 0.5$

$m_{LQ} > 594$ GeV (95% C.L.)

Excluded regions of parameter space:



Current mass limits for
1^{st}, 2^{nd} and 3^{rd} generation Leptoquarks

95% C.L. Mass Limits	1. Generation LQ	2. Generation LQ	3. Generation LQ
CDF (Run II)	235 GeV/c^2	224 GeV/c^2	129 GeV/c^2
D0 (Run I + II)	282 GeV/c^2	200 GeV/c^2	
ATLAS	606 GeV/c^2	594 GeV/c^2	534 GeV/c^2
CMS	597 GeV/c^2	585 GeV/c^2	

$\beta = 0.5$

LHC reach for other BSM Physics

(expected discovery sensitivity for 30 and 100 fb^{-1})

	30 fb^{-1}	**100 fb^{-1}**
Excited Quarks $Q^* \rightarrow q\,\gamma$	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
$Z' \rightarrow \ell\ell$, jj $W' \rightarrow \ell\,\nu$	M (Z') ~ 3 TeV M (W') ~ 4 TeV	M (Z') ~ 5 TeV M (W') ~ 6 TeV
Compositeness (from Di-jet)	Λ ~ 25 TeV	Λ ~ 40 TeV