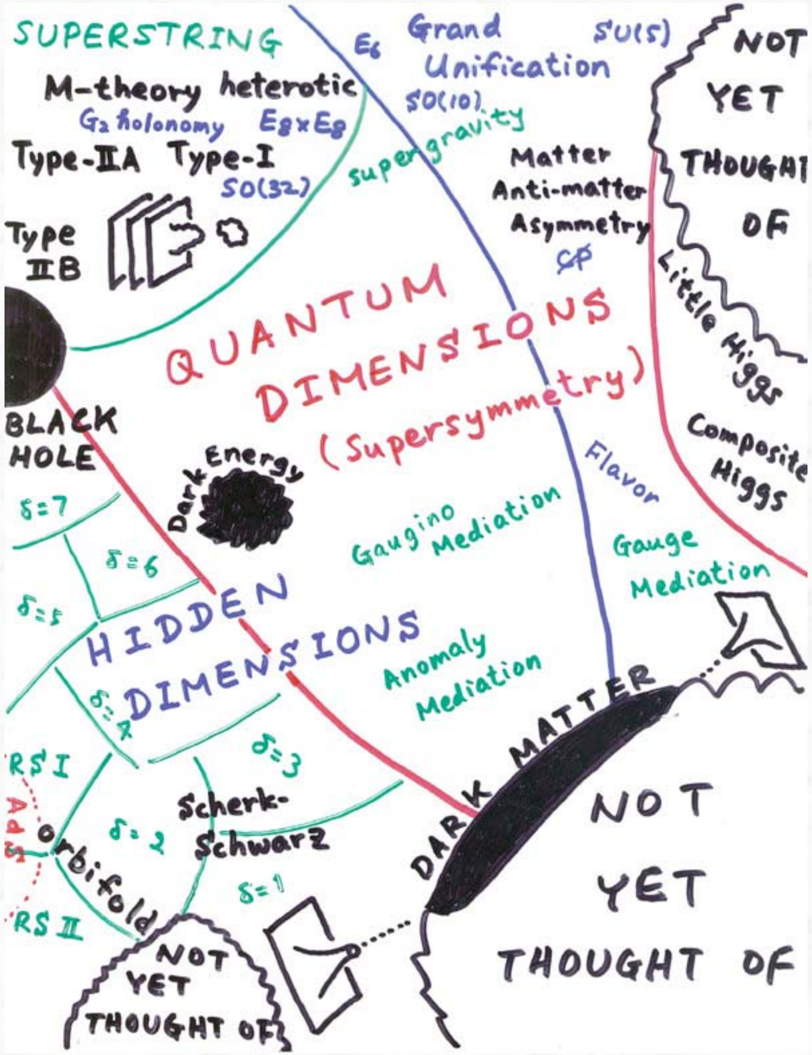
10. Other Extensions of the Standard Model

10.1 Introduction to Grand Unified Theories

10.2 Leptoquarks

10.3 Additional Gauge bosons,
W’ and Z’ searches

10.4 Extra Space dimensions



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.

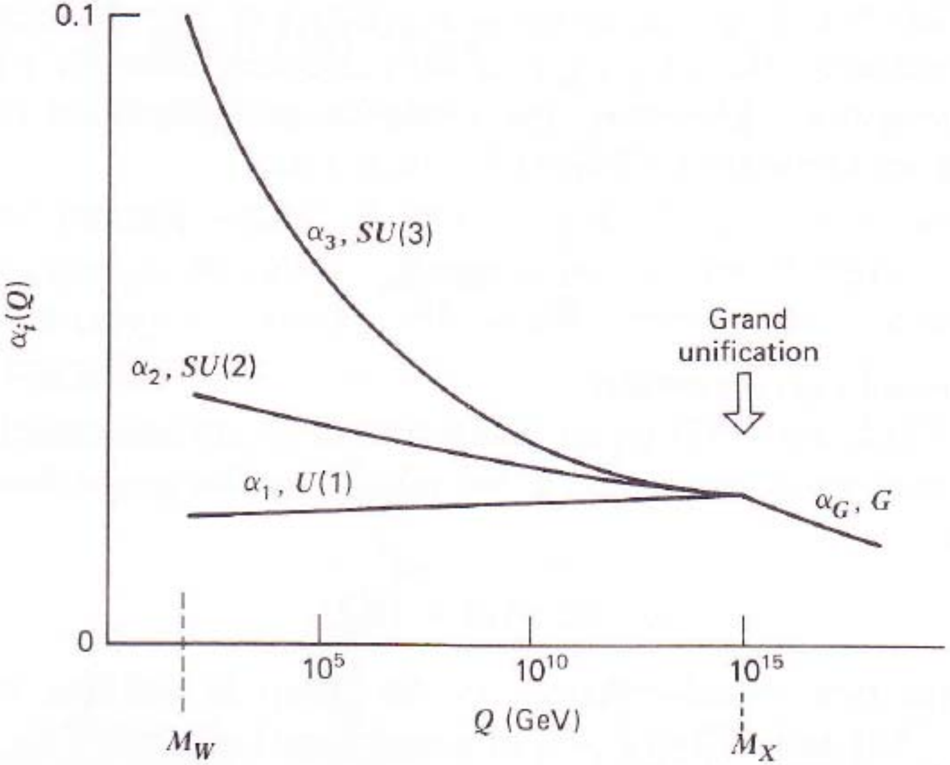


Fig. 15.4 The variation of $\alpha_i \equiv g_i^2/4\pi$ with Q, showing the speculative grand unification of strong $[SU(3)_{\text{color}}]$ and electroweak $[SU(2)_L \times U(1)_Y]$ interactions at very short distances $1/Q \approx 1/M_X$.

- 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 = MX 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 ($i = 3$) :

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

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):

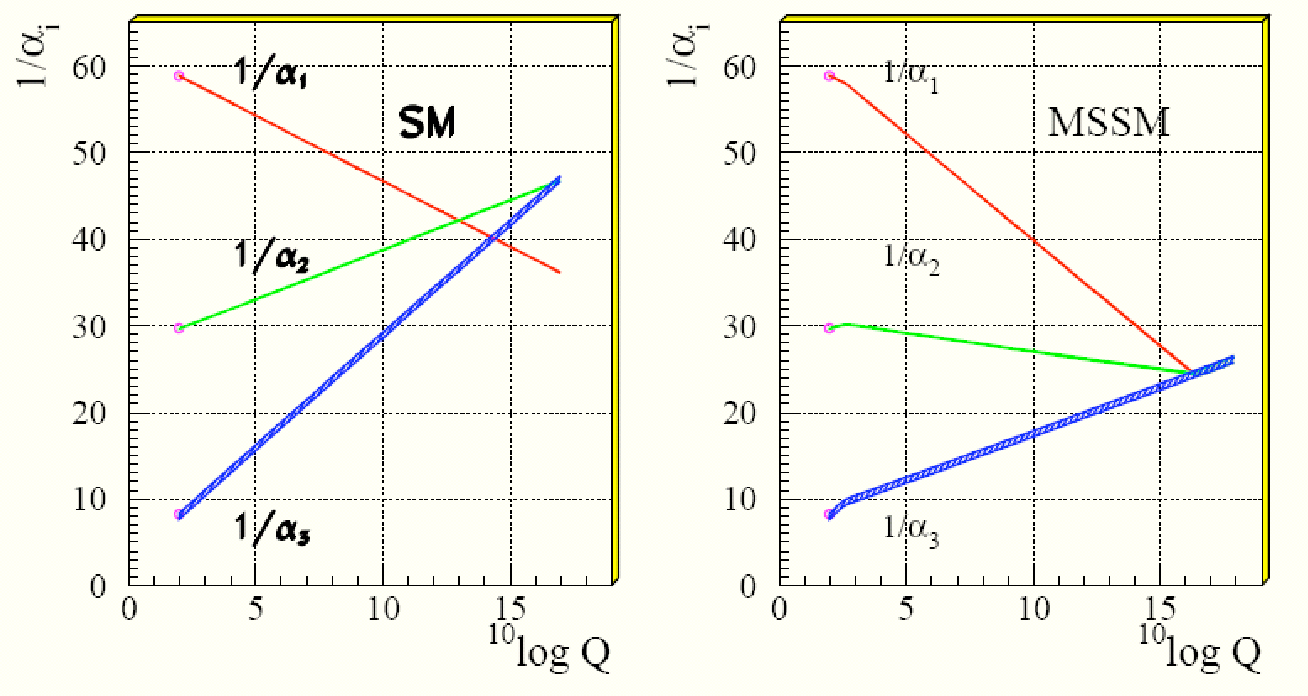
$$b_1 = \frac{1}{(4\pi)^2}\left(\frac{4}{3}n_g\right),$$

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

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

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:

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

  They are arranged in SU(5) multiplets: $(\text{dbar}, \nu_e, e^-)$ 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):

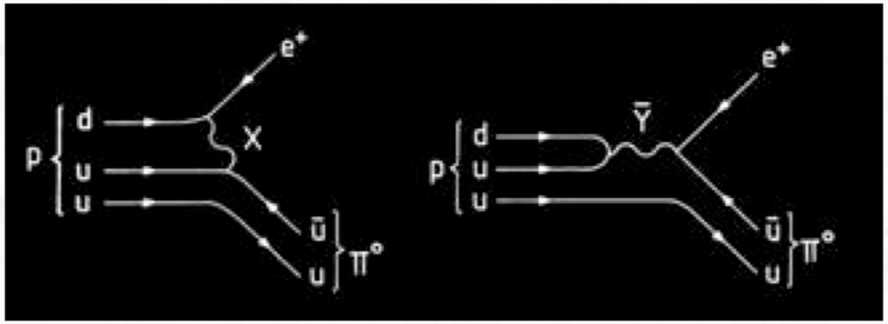
- Transitions mediated by X and Y bosons violate lepton number and baryon number conservation;

  e.g. u + u → X → 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

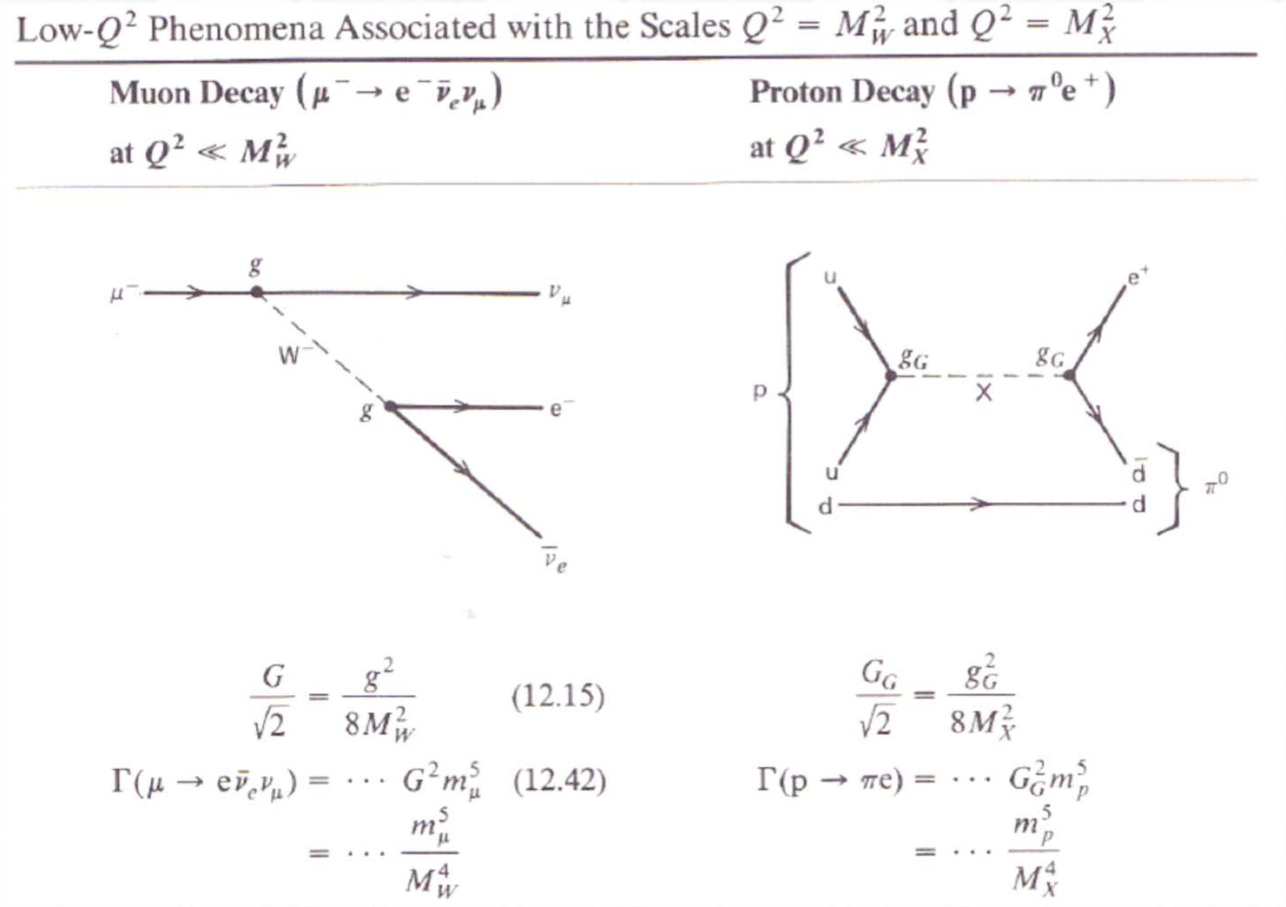
→ $3\,Q_{dbar} + Q_{\nu} + Q_{e-} = 0$ → $Q_d = 1/3\,Q_{e-}$

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:



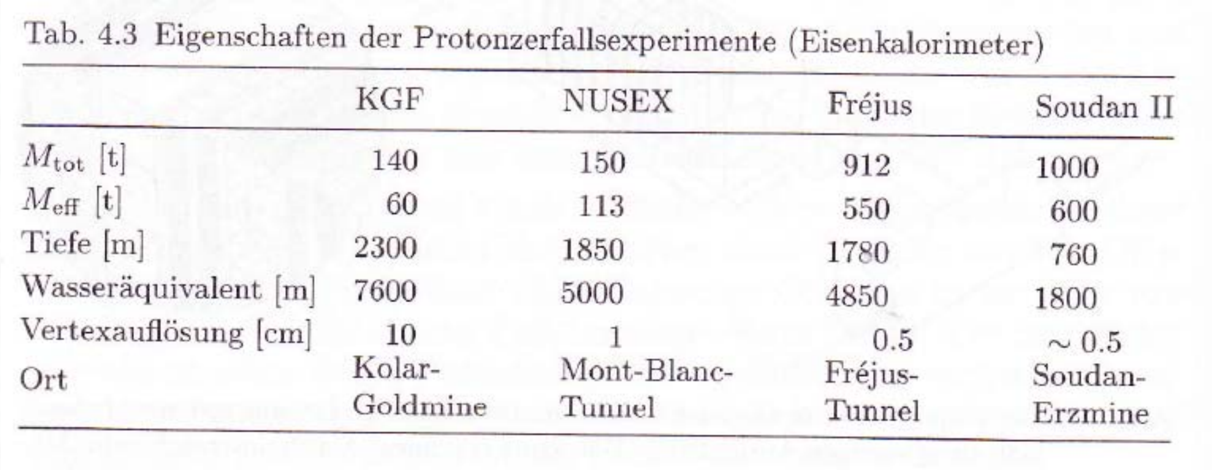
Low-Q^2 Phenomena Associated with the Scales $Q^2 = M_W^2$ and $Q^2 = M_X^2$

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 → τ (p) ~10^{30} years
in SUSY models, lifetime is significantly longer (higher mass scale) > 10^{32} years

Results of experimental searches for proton decay:

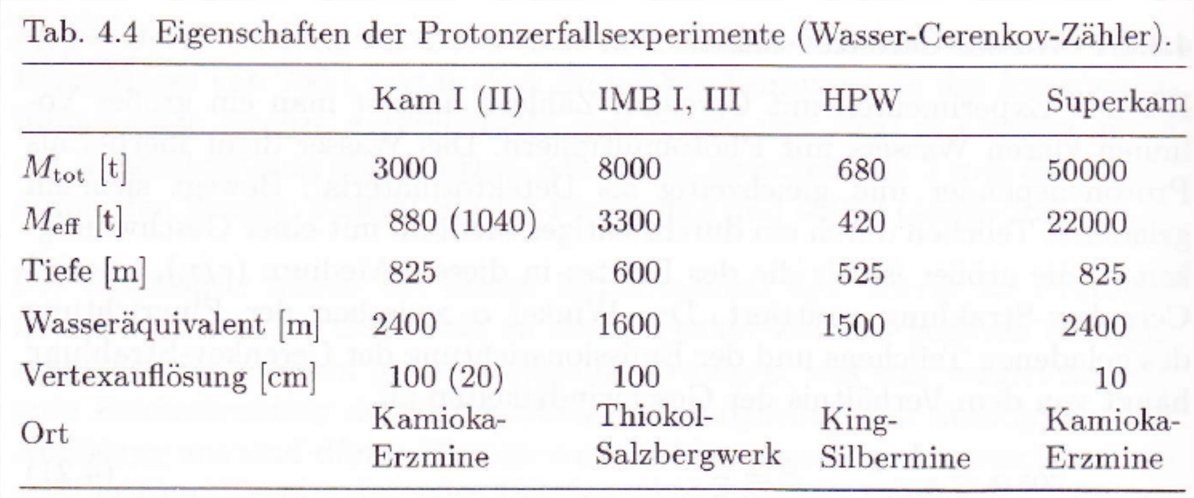
(i) Large mass calorimeter detectors



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

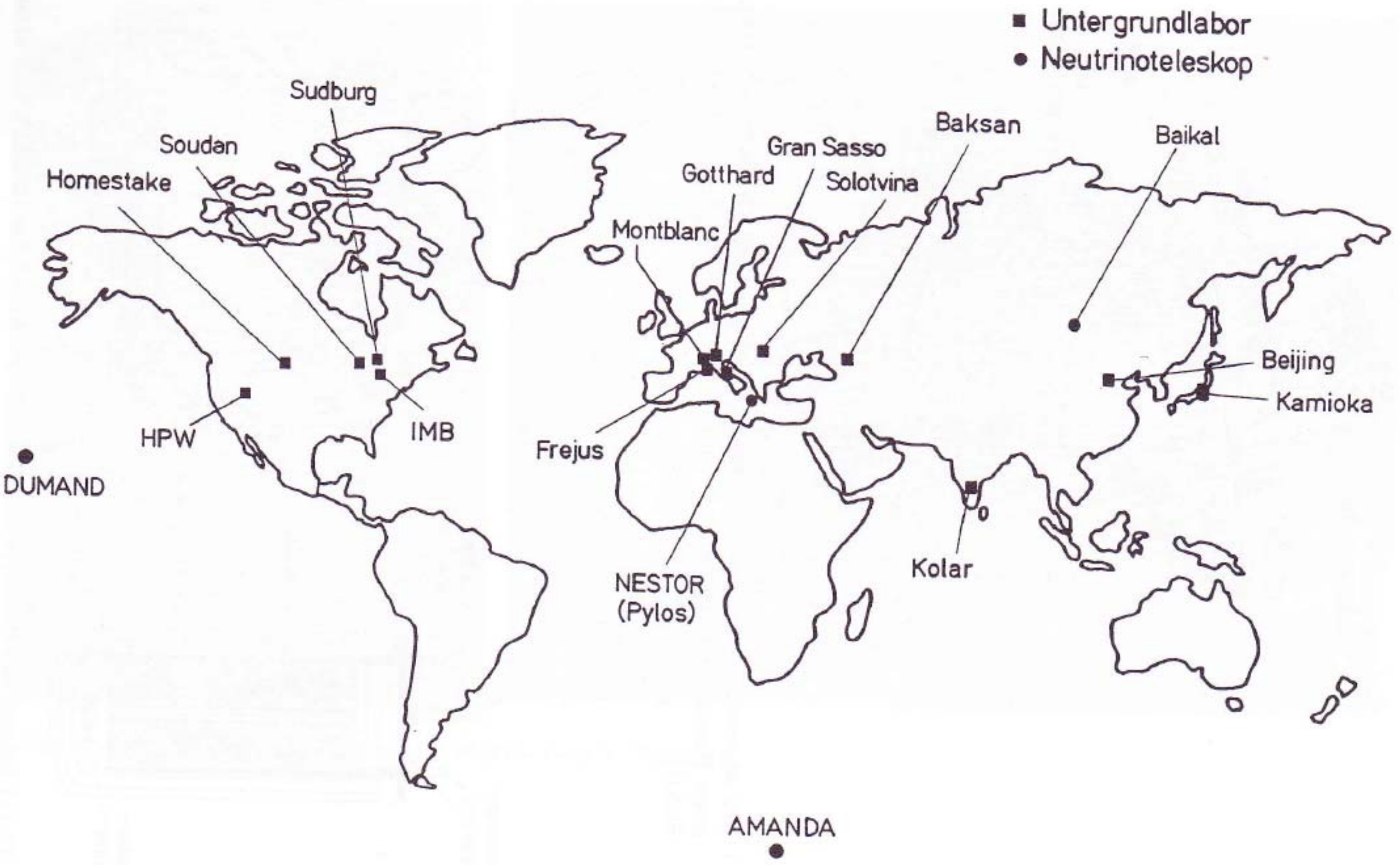
(ii) Large mass water Cherenkov detectors



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

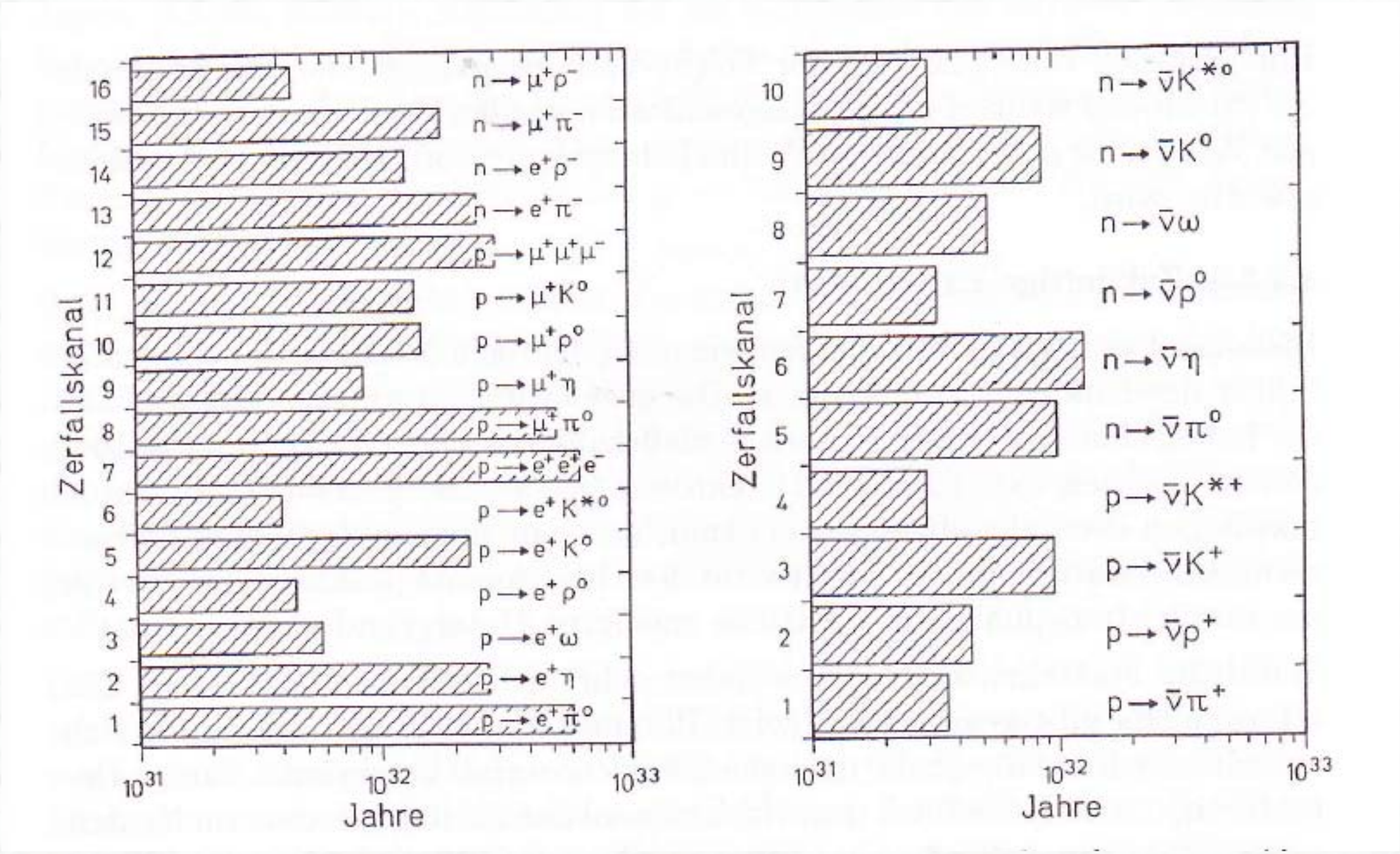
	Kam I (II)	IMB I, III	HPW	Superkam
M_{tot} [t]	3000	8000	680	50000
M_{eff} [t]	880 (1040)	3300	420	22000
Tiefe [m]	825	600	525	825
Wasseräquivalent [m]	2400	1600	1500	2400
Vertexauflösung [cm]	100 (20)	100		10
Ort	Kamioka-Erzmine	Thiokol-Salzbergwerk	King-Silbermine	Kamioka-Erzmine

Overview on locations of proton decay experiments:

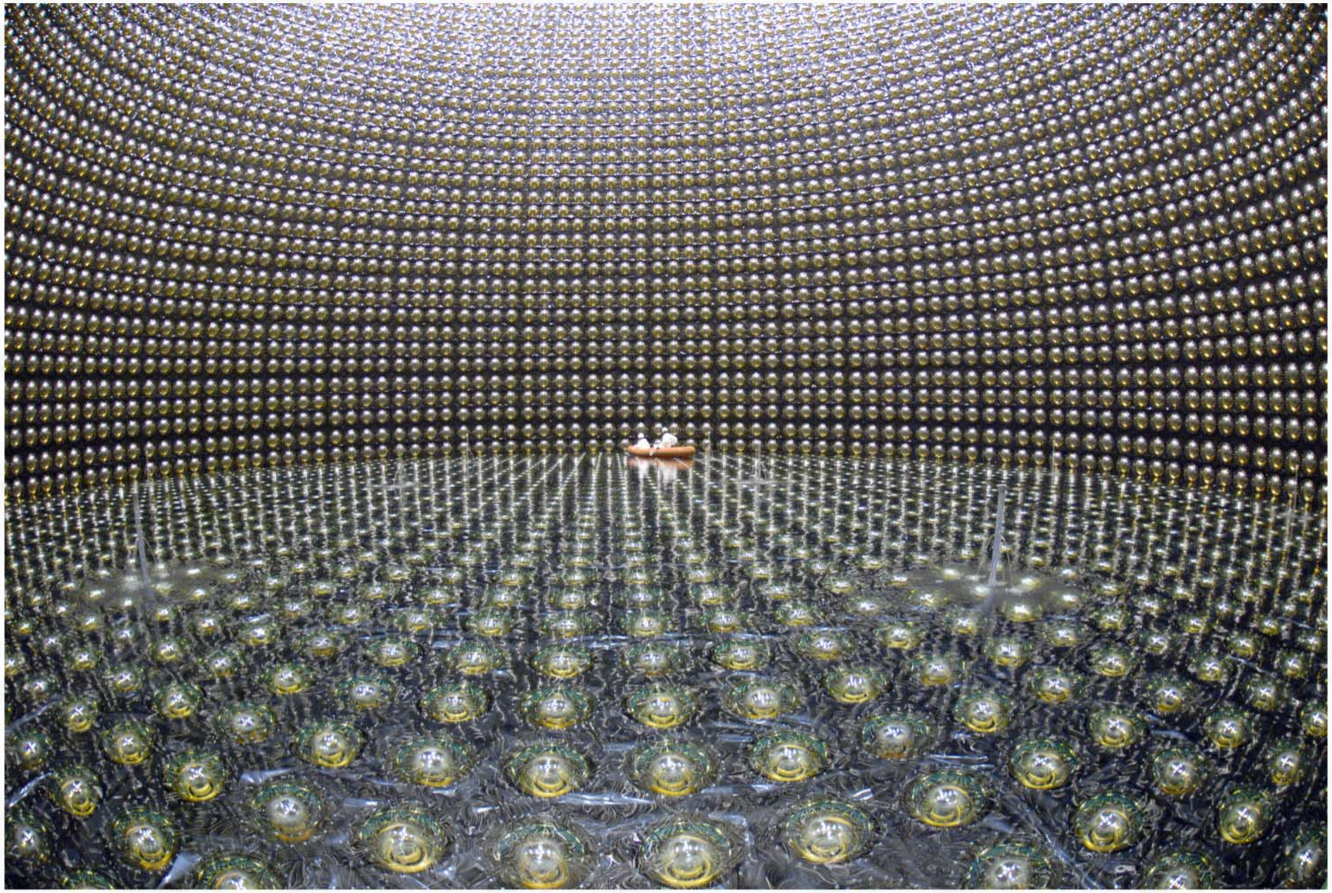


Results:

- so far no significant 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

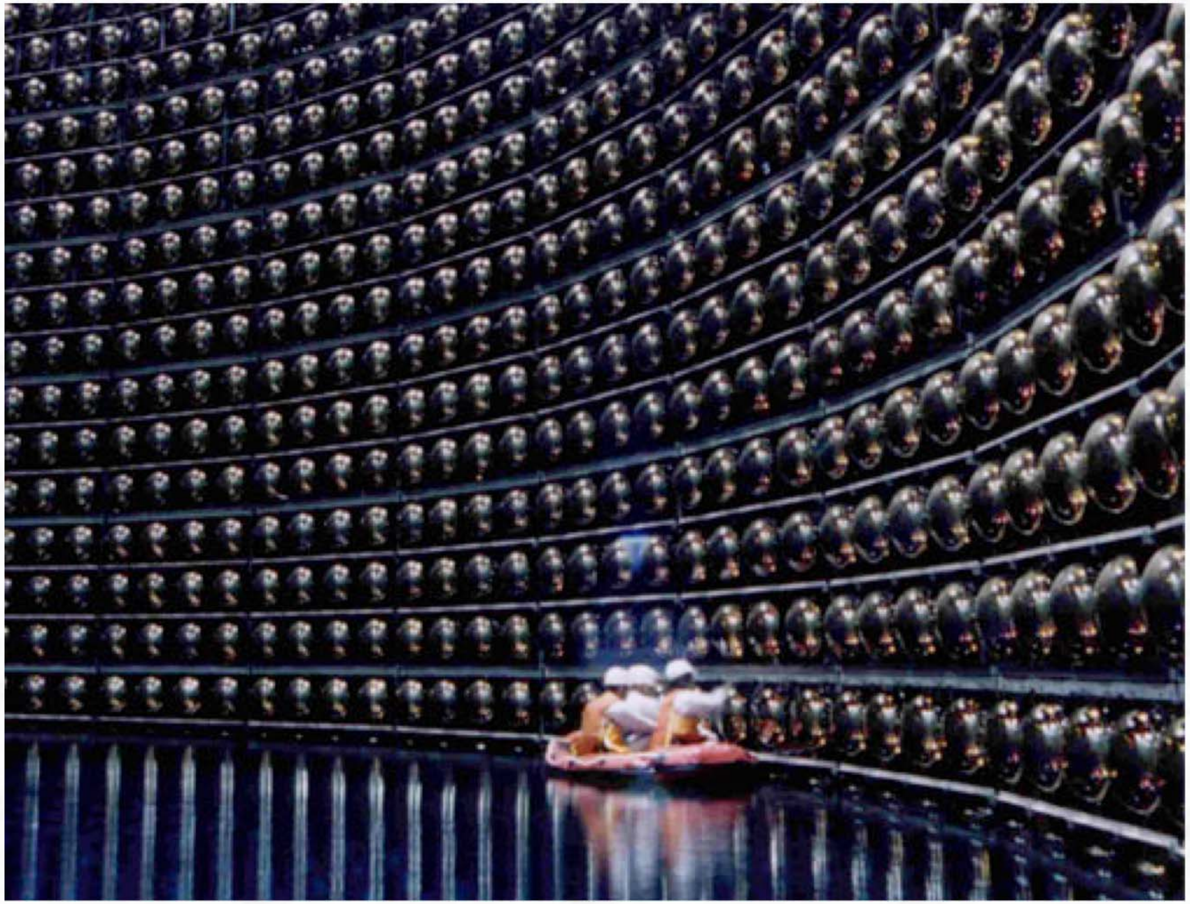


The Super-Kamiokande detector, Kamioka mine, Japan



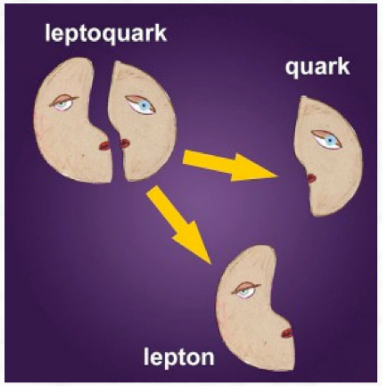
The Super-Kamiokande detector began operating in 1996, more than half a mile underground in a zinc mine in Kamioka, Japan. Japanese and American scientists erected a huge tank of water 138 feet tall to hunt for neutrinos and proton decay. The walls, ceiling, and floor of the 12.5-million-gallon tank 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



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. I.

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)

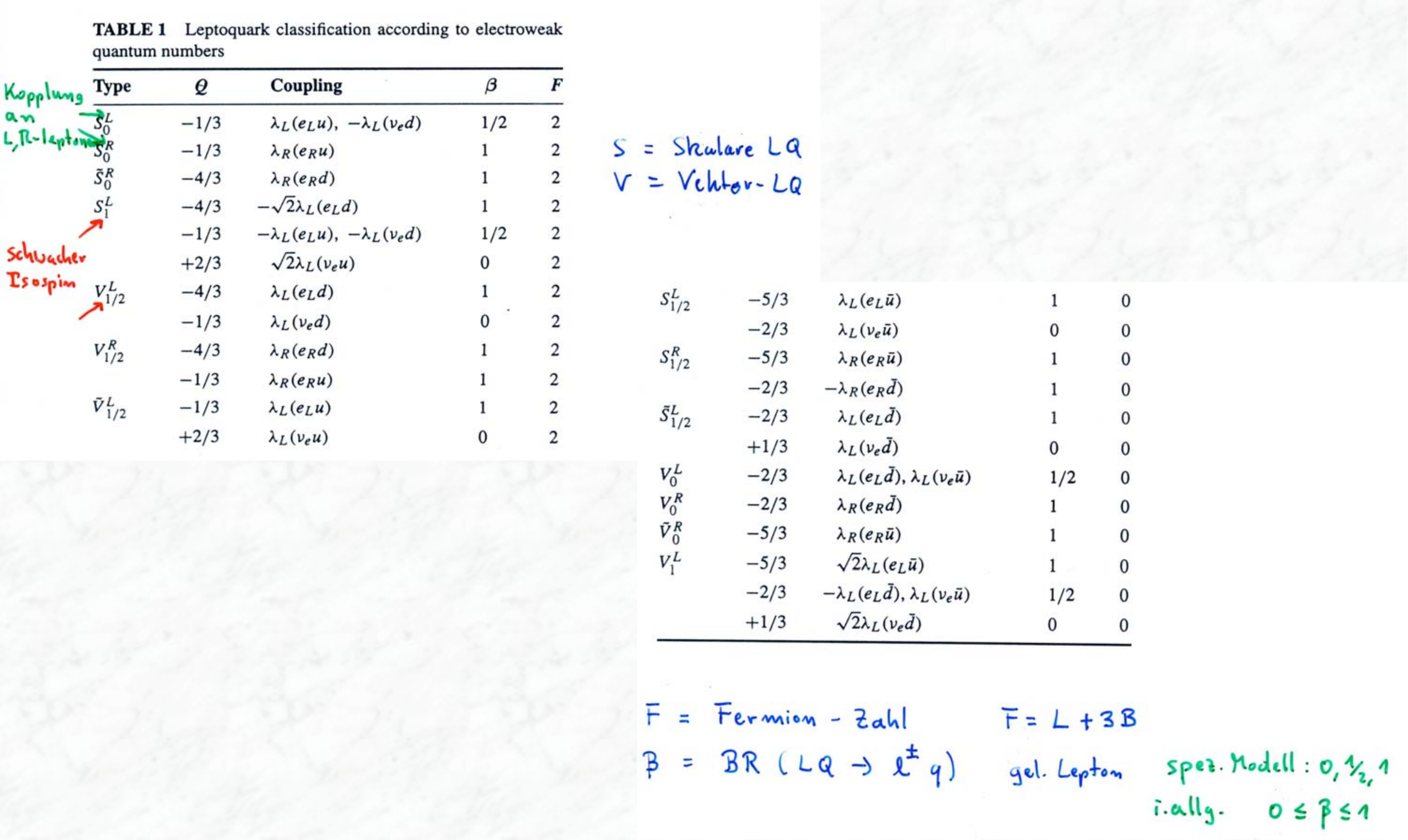


TABLE 1 Leptoquark classification according to electroweak quantum numbers

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 $F = L + 3B$

$\beta = BR(LQ \to \ell^\pm q)$ gel. Lepton

spez. Modell: 0, ½, 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 (-⅓) → $e^- u$, or LQ(-4/3) → $e^- d$
  LQ (-⅓) → $\nu_e d$

  Decays proceed always as: LQ → lepton + quark

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

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

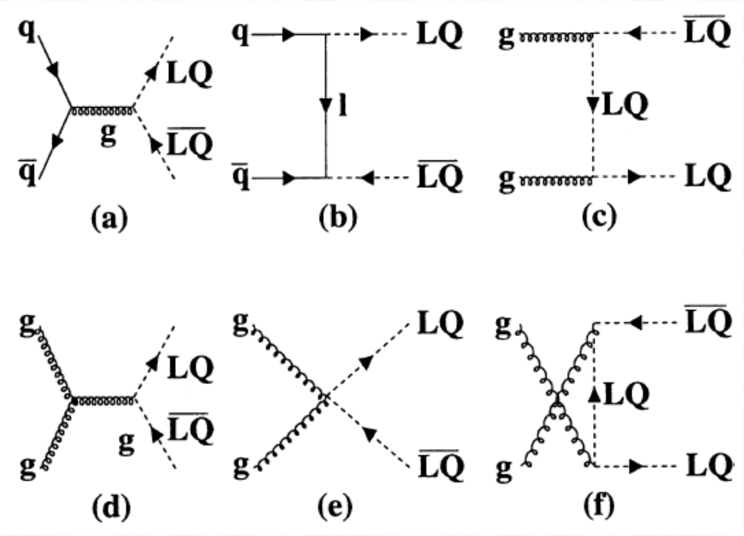
- Leptoquarks (in general form) may enhance flavour-changing neutral currents

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

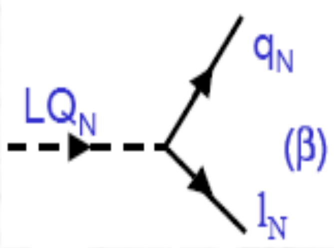
  → LQs of 1st, 2nd, and 3rd generation

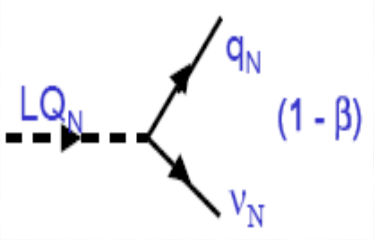
Search for Scalar Leptoquarks (LQ)

- Production:
  pair production via QCD processes
  (qq and gg fusion)



- Decay: 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

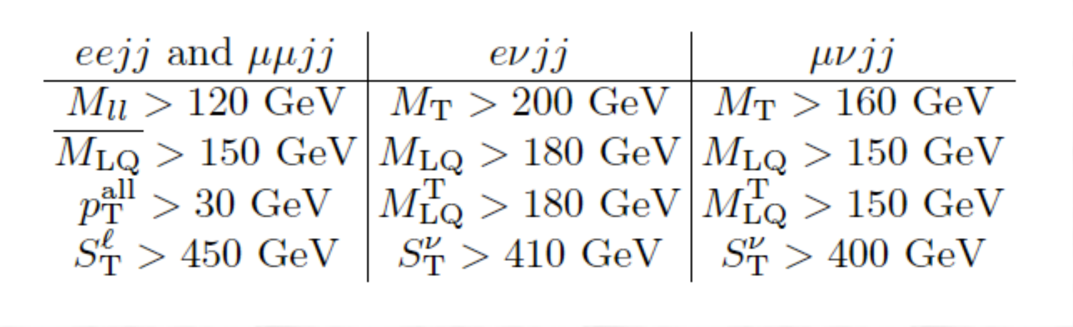
Experimental Signatures:

- 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)

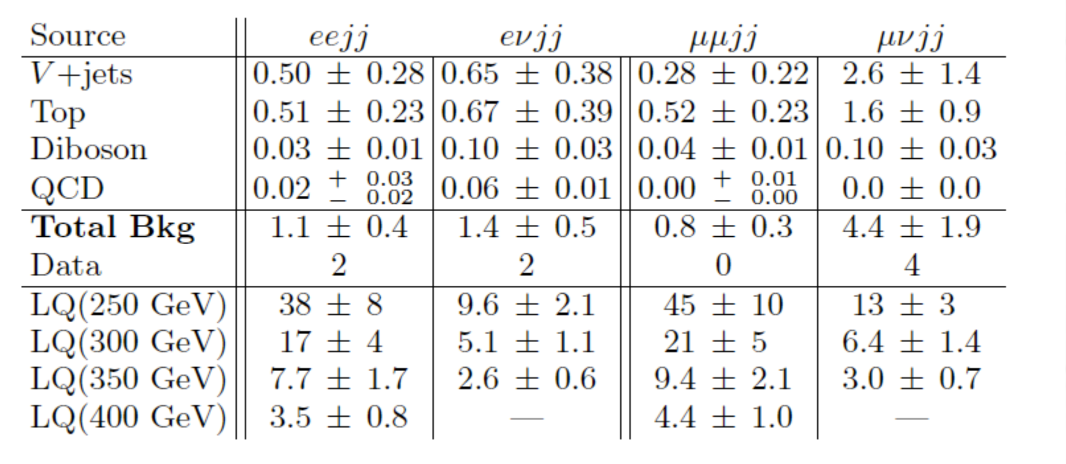
- Additional kinematic requirements:



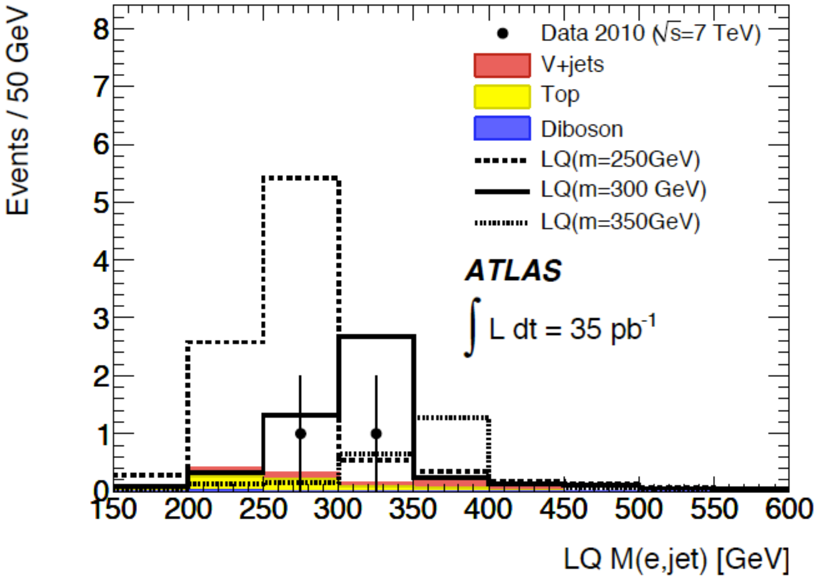
$eejj$ and $\mu\mu jj$	$e\nu jj$	$\mu\nu jj$
$M_{ll} > 120$ GeV	$M_T > 200$ GeV	$M_T > 160$ GeV
$M_{LQ} > 150$ GeV	$M_{LQ} > 180$ GeV	$M_{LQ} > 150$ GeV
$p_T^{all} > 30$ GeV	$M_{LQ}^T > 180$ GeV	$M_{LQ}^T > 150$ GeV
$S_T^\ell > 450$ GeV	$S_T^\nu > 410$ GeV	$S_T^\nu > 400$ GeV

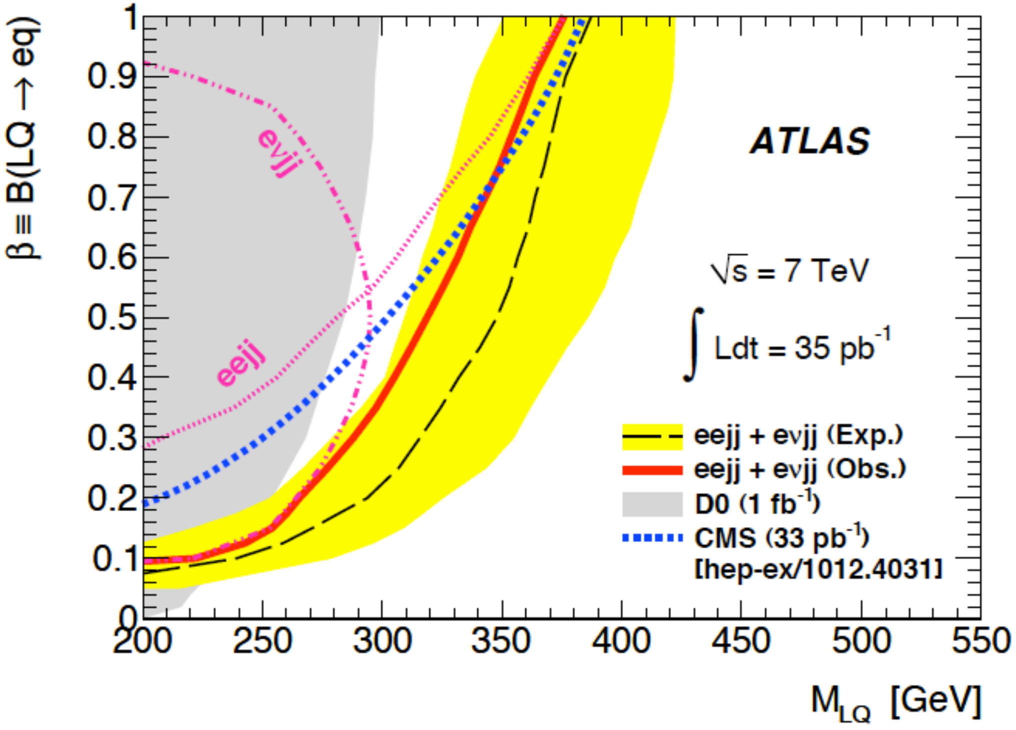
where S_T is the total scalar sum of the transverse momenta (two leptons and two jets)

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

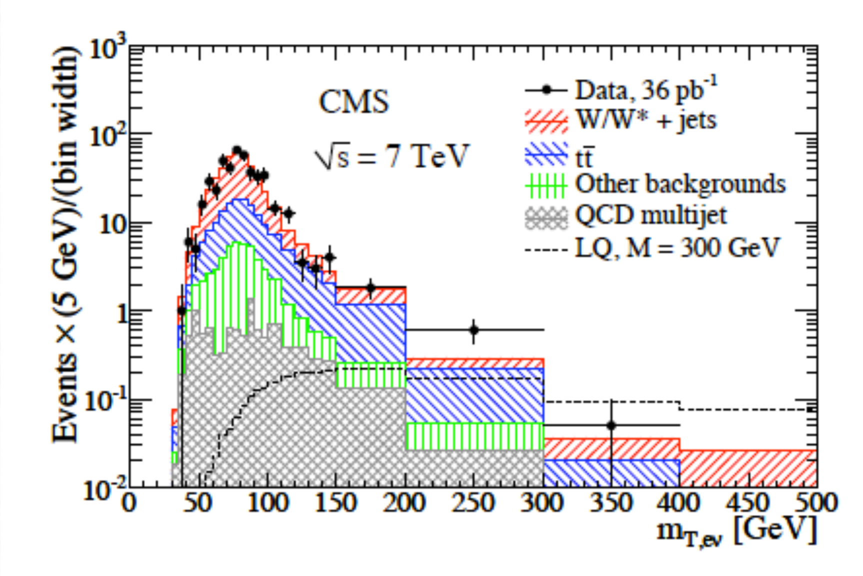


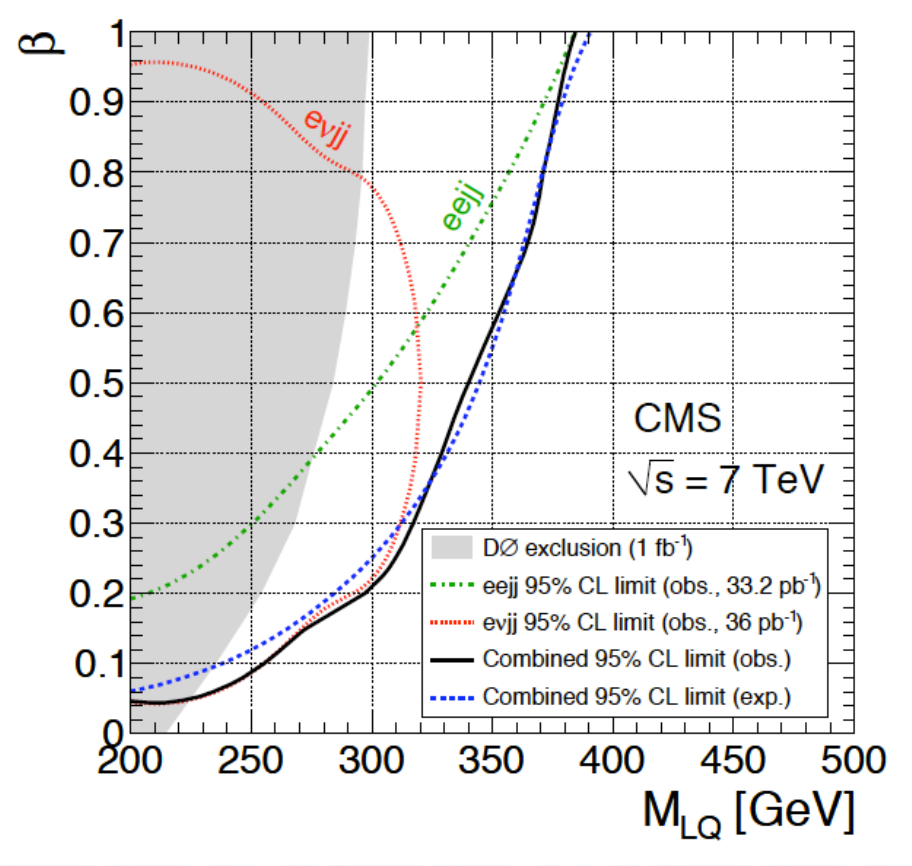
Source	$eejj$	$e\nu jj$	$\mu\mu jj$	$\mu\nu jj$
V+jets	0.50 ± 0.28	0.65 ± 0.38	0.28 ± 0.22	2.6 ± 1.4
Top	0.51 ± 0.23	0.67 ± 0.39	0.52 ± 0.23	1.6 ± 0.9
Diboson	0.03 ± 0.01	0.10 ± 0.03	0.04 ± 0.01	0.10 ± 0.03
QCD	$0.02\,^{+0.03}_{-0.02}$	0.06 ± 0.01	$0.00\,^{+0.01}_{-0.00}$	0.0 ± 0.0
Total Bkg	1.1 ± 0.4	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	—


Events / 50 GeV
0
1
2
3
4
5
6
7
8
150
200
250
300
350
400
450
500
550
600
LQ M(e,jet) [GeV]
Data 2010 (√s=7 TeV)
V+jets
Top
Diboson
LQ(m=250GeV)
LQ(m=300 GeV)
LQ(m=350GeV)
ATLAS
∫ L dt = 35 pb⁻¹


β ≡ B(LQ → eq)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
200
250
300
350
400
450
500
550
M_LQ [GeV]
evjj
eejj
ATLAS
√s = 7 TeV
∫ Ldt = 35 pb⁻¹
eejj + evjj (Exp.)
eejj + evjj (Obs.)
D0 (1 fb⁻¹)
CMS (33 pb⁻¹)
[hep-ex/1012.4031]

1st, 2nd and 3rd 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	319 GeV/c^2	362 GeV/c^2	
CMS	340 GeV/c^2	290 GeV/c^2	

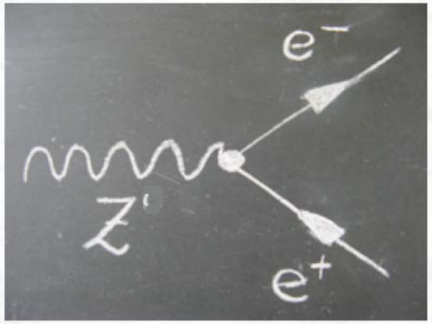
β = 0.5

LHC reach for other BSM Physics

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

	30 fb^{-1}	**100 fb^{-1}**
Excited Quarks $Q^* \to q\,\gamma$	M (q^*) ~ 3.5 TeV	M (q^*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
$Z' \to \ell\ell$, jj $W' \to \ell\,\nu$	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

10.3 Additional Gauge Bosons: W’ and Z’

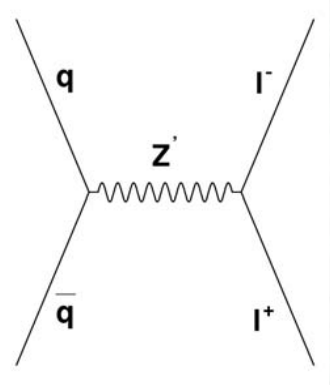


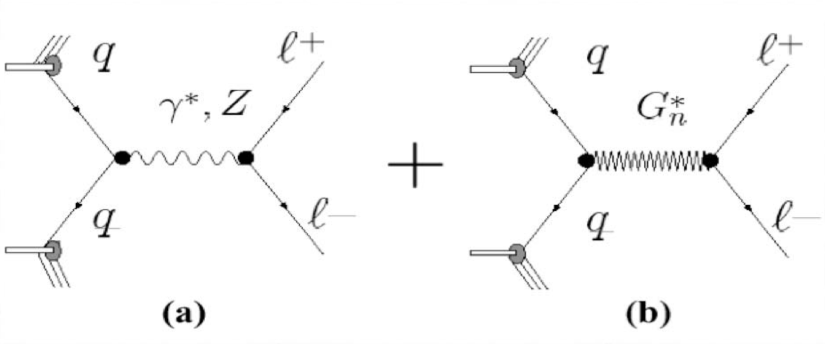
Search for new, high-mass di-lepton resonances

- **Additional neutral Gauge Boson Z´**

- **Randall-Sundrum narrow Graviton resonances decaying to di-lepton**

appear in Extra Dim. Scenarios

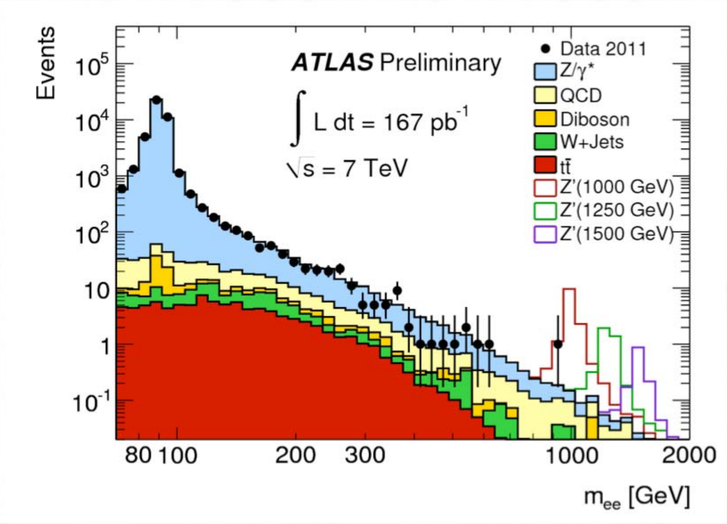




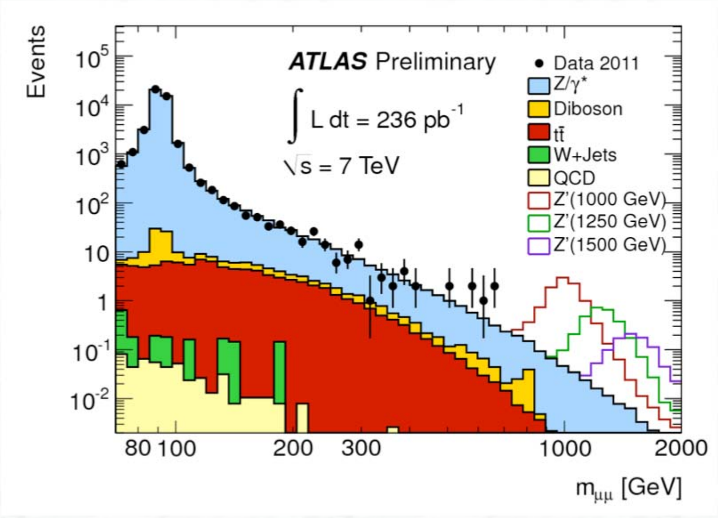
Main background process: Drell-Yan production of lepton pairs

Search for New Resonances in High Mass Di-leptons

Di-electron invariant mass

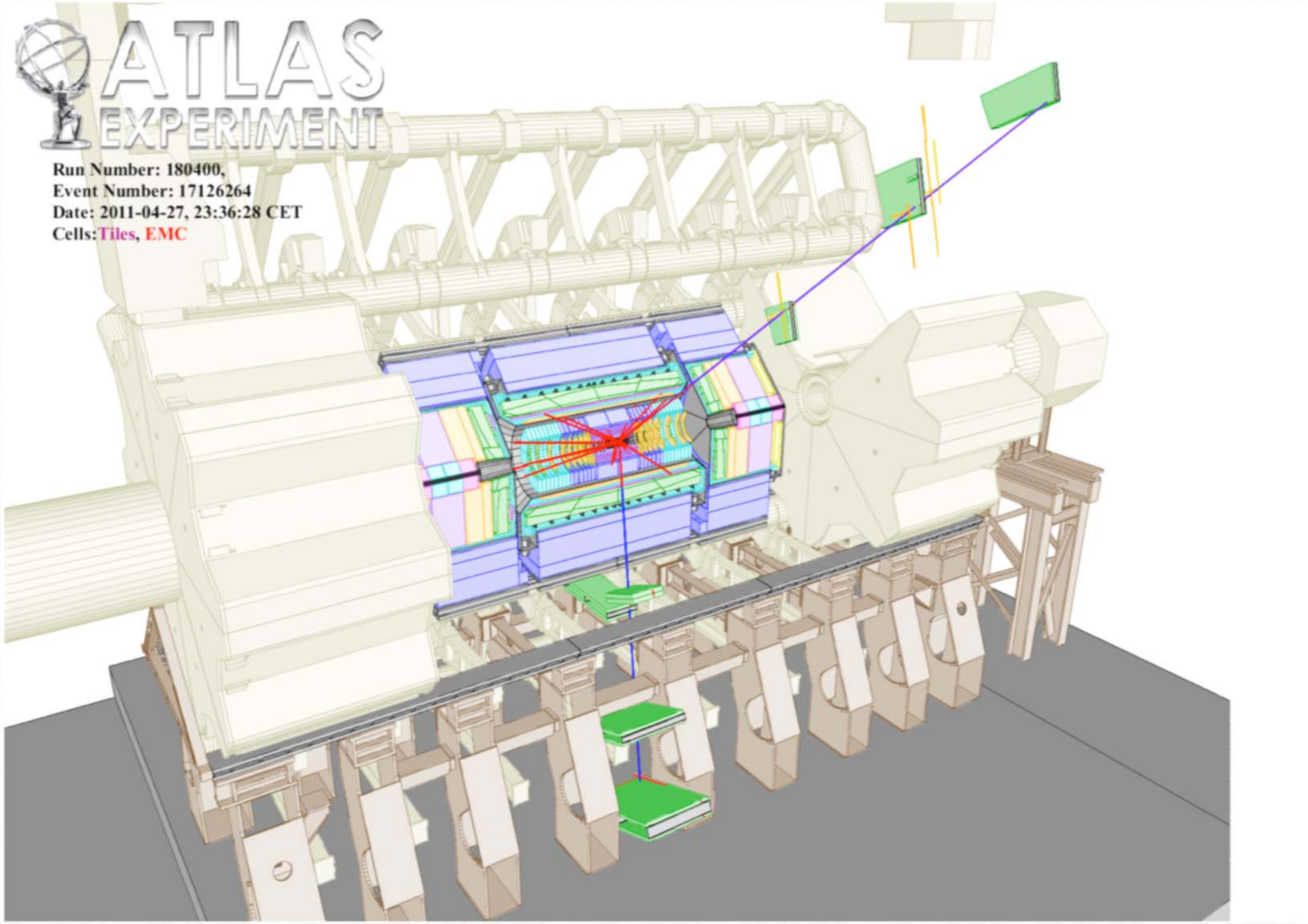


Di-muon invariant mass



Data are consistent with background from SM processes. No excess observed.

95% C.L. limits (SM couplings)	ee	$\mu\mu$	ll combined
CDF / D0 5.3 fb^{-1}			1.07 TeV
ATLAS 36 pb^{-1}	0.96 TeV	0.83 TeV	1.05 TeV
ATLAS 167 / 236 pb^{-1}	1.28 TeV	1.22 TeV	1.41 TeV
CMS 35 / 40 pb^{-1}			1.14 TeV



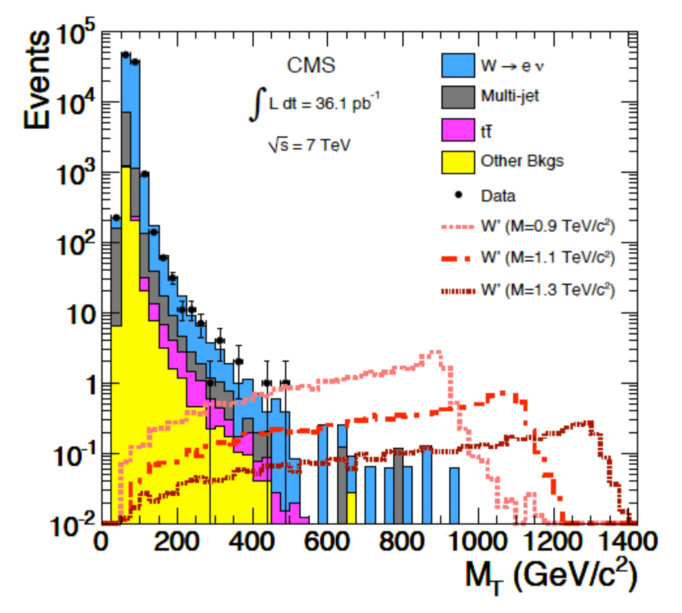
The highest invariant mass di-muon event in the ATLAS data. The highest momentum muon has a p_T of 270 GeV and an (eta, phi) of (1.56, 1.30). The subleading muon has a p_T of 232 GeV and an (eta, phi) of (-0.09, -1.82). The invariant mass of the pair is 680 GeV.

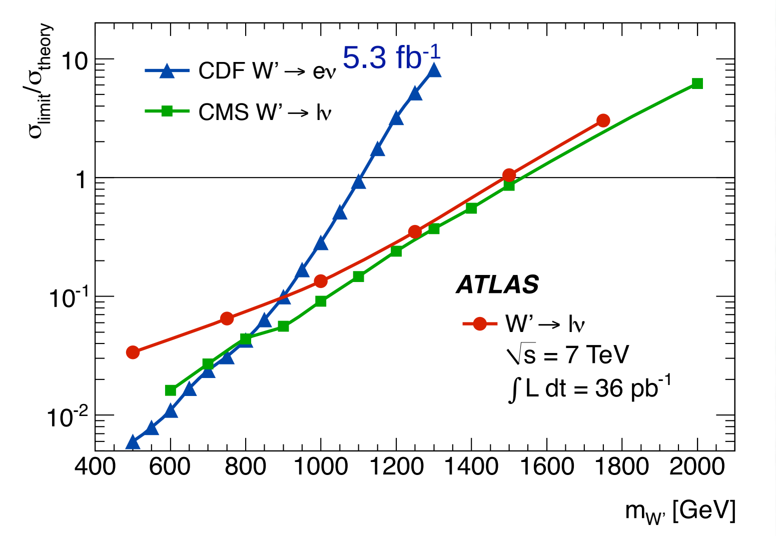
Search for W' → lν

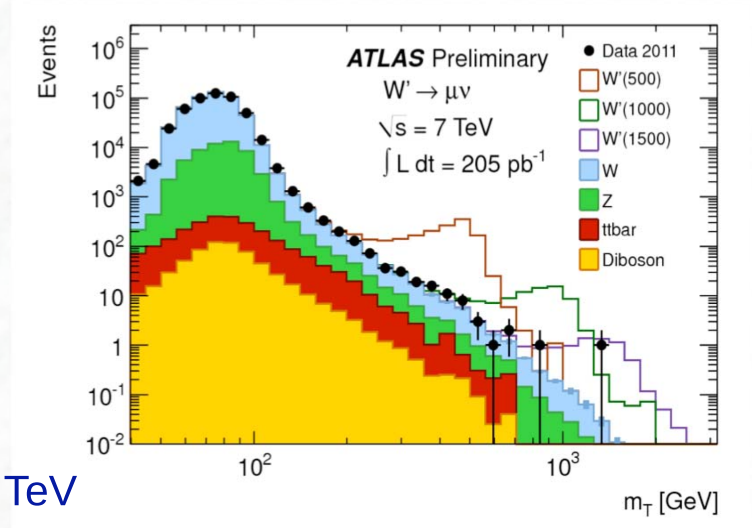
- W': additional charged heavy vector boson
- Appears in theories based on the extension of the gauge group

  e.g. Left-right symmetric models: $SU(2)_R$ W_R
- Assume ν from W' decay to be light and stable, and W' to have the same couplings as in the SM (*"Sequential Standard Model, SSM")*

Signature: high p_T electron + high E_T^{miss}
→ peak in transverse mass distribution





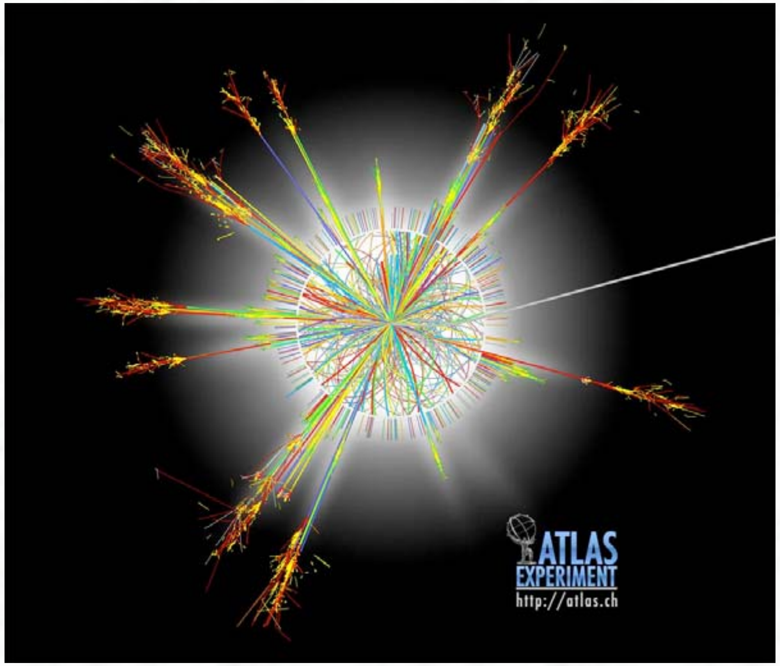


Comparable limits (ATLAS, CMS, 36 pb^{-1}): ~1.49 / 1.58 TeV
New ATLAS limit (W → μν, 205 pb^{-1}): ~1.70 TeV

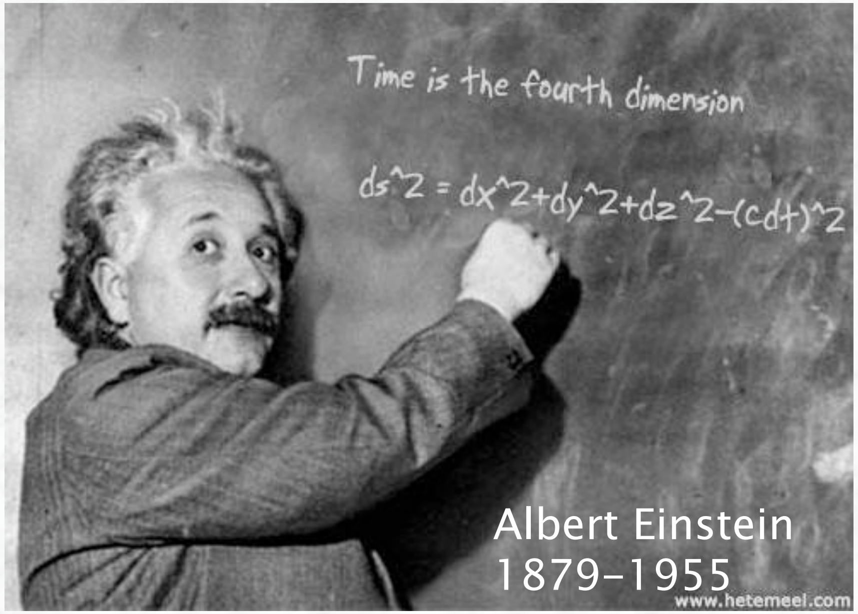
10.4 Extra space dimensions

- Introduction
- Search for escaping gravitons at the LHC
- Serach for Black Hole Production

Microscopic-Black Hole Events at the LHC ?



Time is the Fourth Dimension



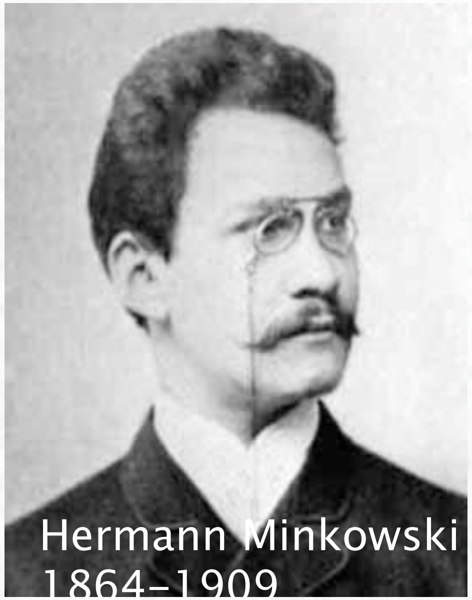
Albert Einstein
1879-1955

www.hetemeel.com

Time:

1. Required by relativity to be a dimension

2. Required, along with three spatial dimensions, to specify the location of an event



Hermann Minkowski
1864-1909

- Spacetime is four dimensional: x, y, z, and t

- Universal constant “c”, which relates measurements of space to measurements of time

A Fifth Dimension?

Theodor Kaluza
1885–1954

- Polish mathematician Kaluza showed in 1919 that gravity and electromagnetism could be unified in a single theory with 5 dimensions – using Einstein's theory of gravity

"The idea of achieving a unified theory by means of five-dimensional world would never have dawned on me…At first glance I like your idea tremendously"

The Fifth Dimension

Oskar Klein
1894–1977

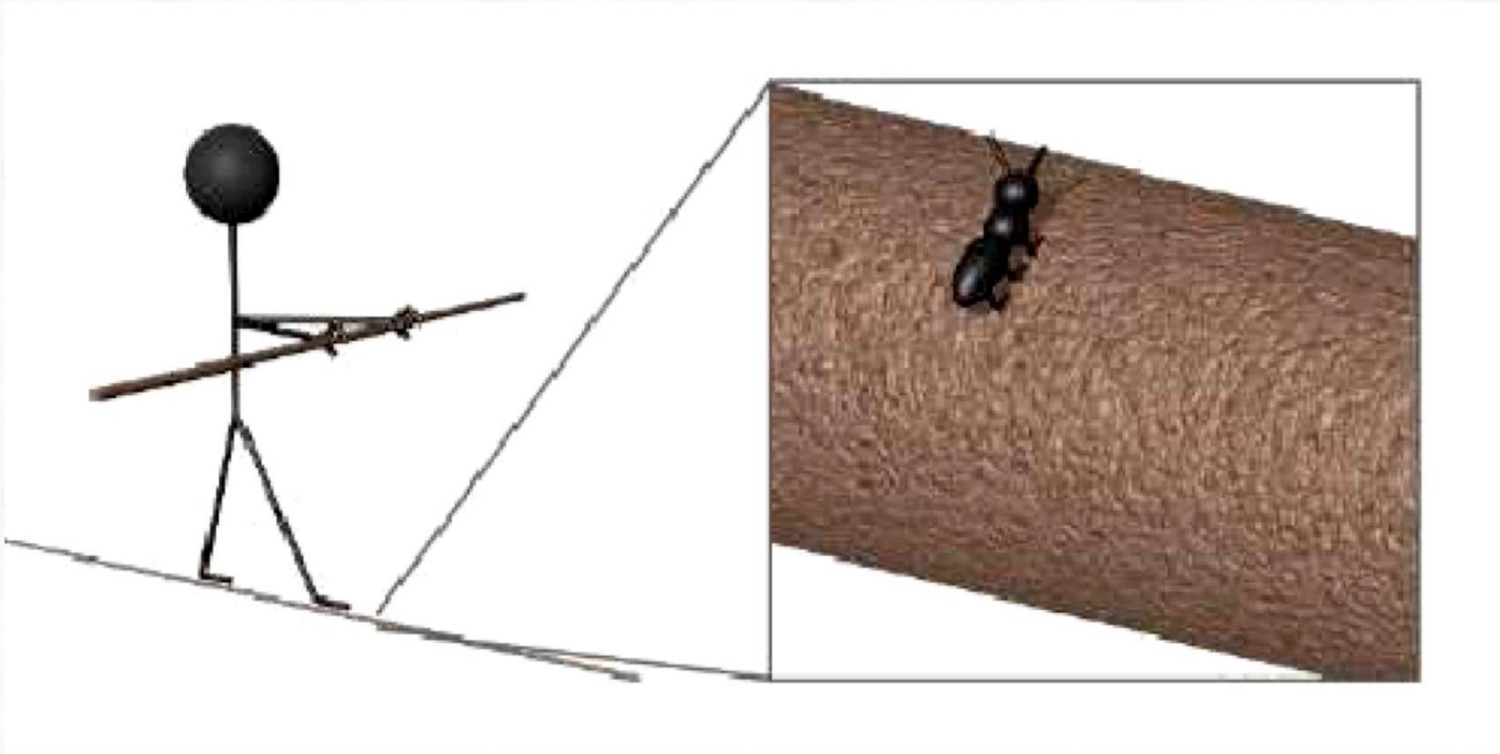
- The Swedish physicist Klein proposed in 1926 that the fifth dimension was real, but too tiny to be observed
- Computed it had a size of 10^{-30} cm to unify gravity with electromagnetism

“Klein’s paper is beautiful and impressive”

Compactified Extra Dimensions

Extra dimensions are too small for us to observe

⇒ they are ‘curled up’ and compact



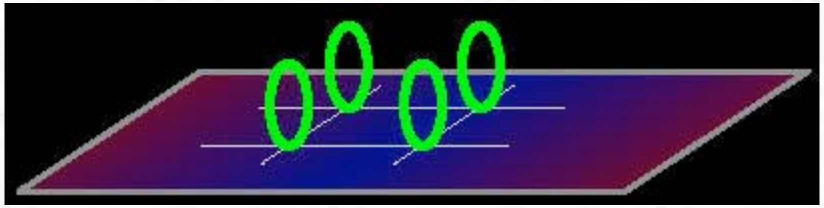
Tightrope walker sees only
one dimension

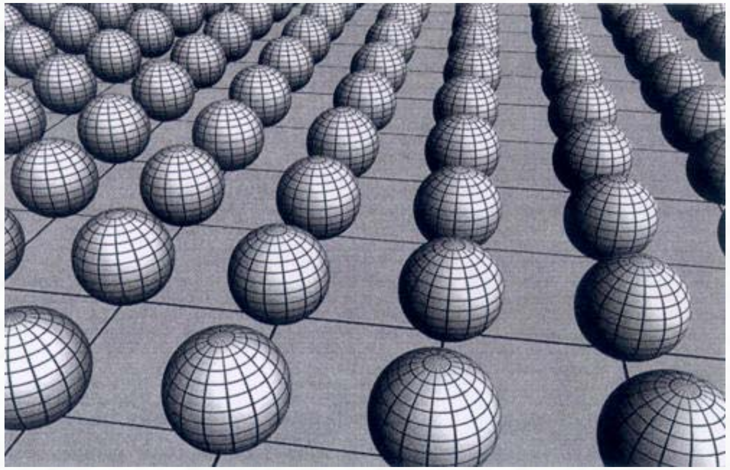
Ant can also go
“around the circle”

“Visualizing” Extra Dimensions

Every point in space-time has curled up extra dimensions associated with it

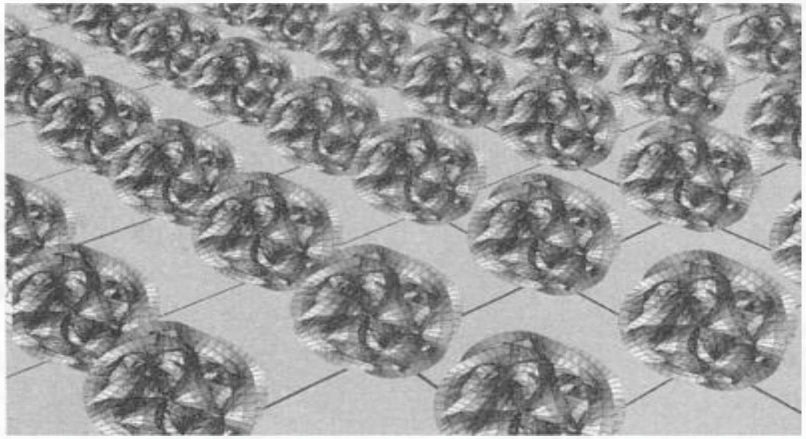
One extra dimension is a circle

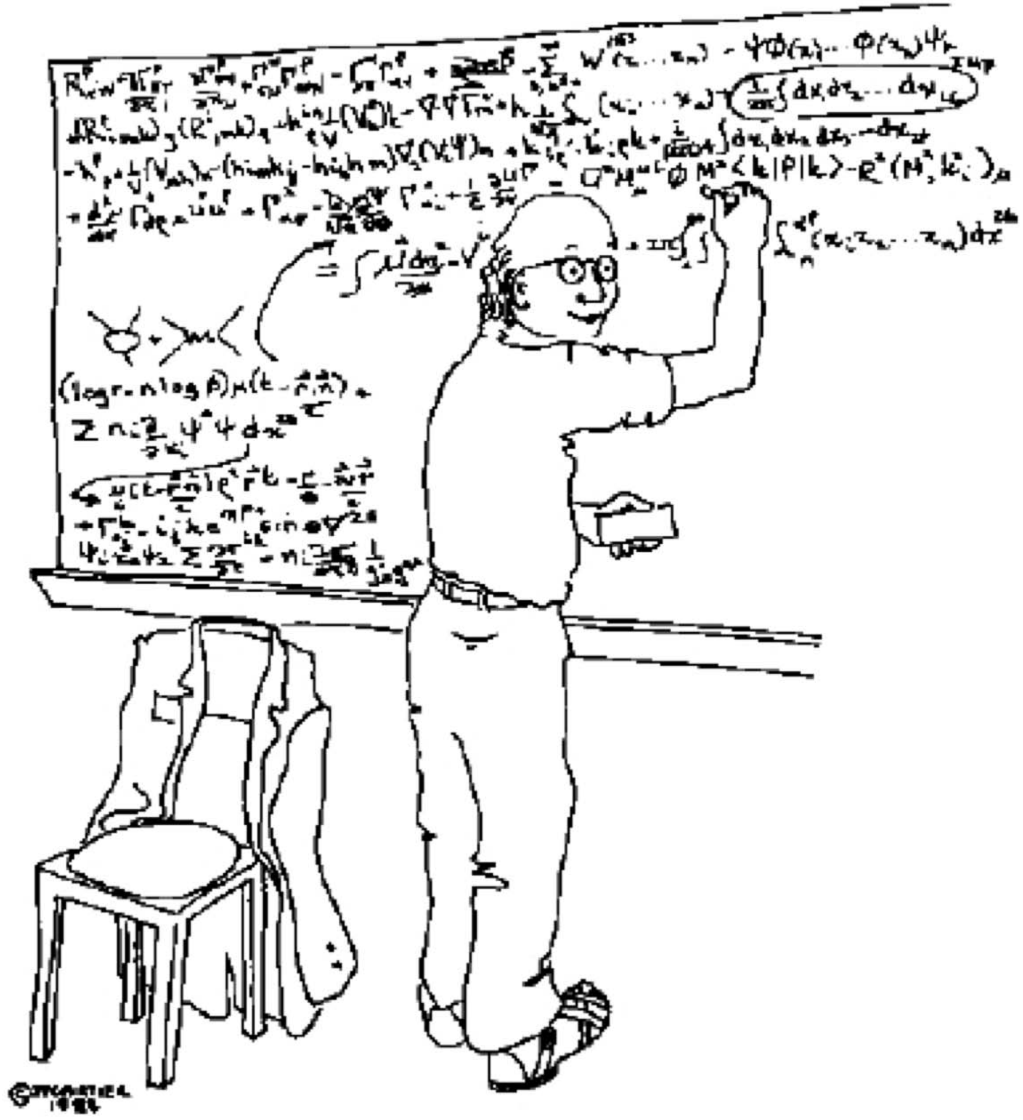




Two extra dimensions can be represented by a sphere

Six extra dimensions can be represented by a Calabi-Yau space





"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

Modifications of Newton’s Law of Gravity

- Newtonian inverse-squared law of gravity is modified with extra dimensions

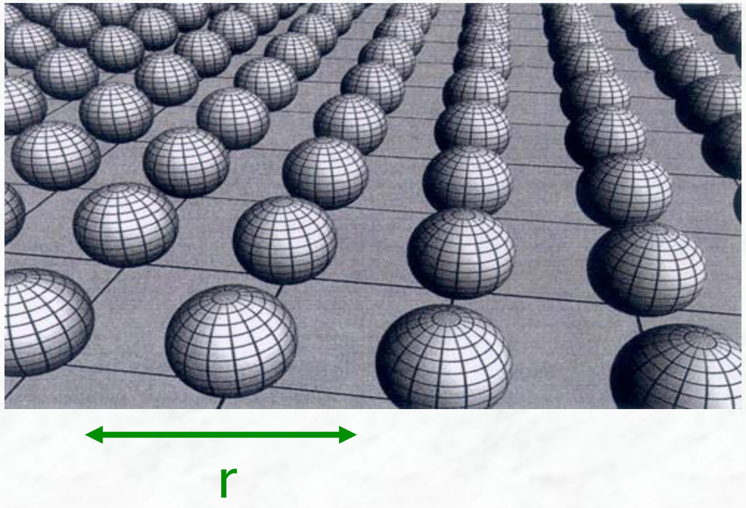
- Example: 2 extra dimensions of size R

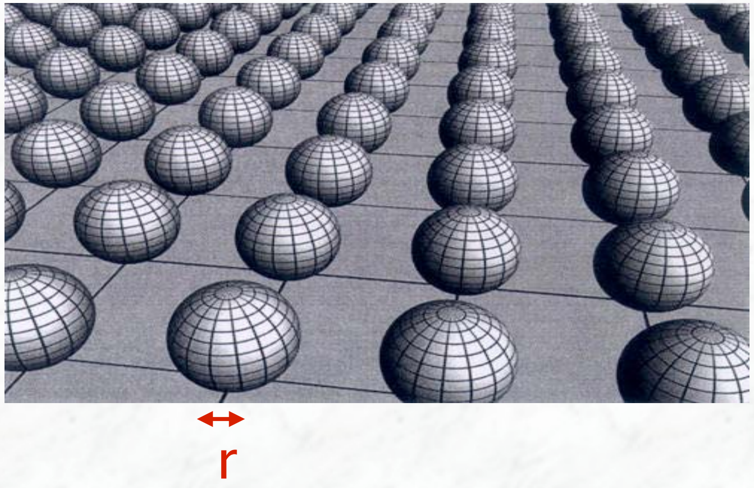
- Distances $r > R$

$$F \sim \frac{1}{r^2}$$

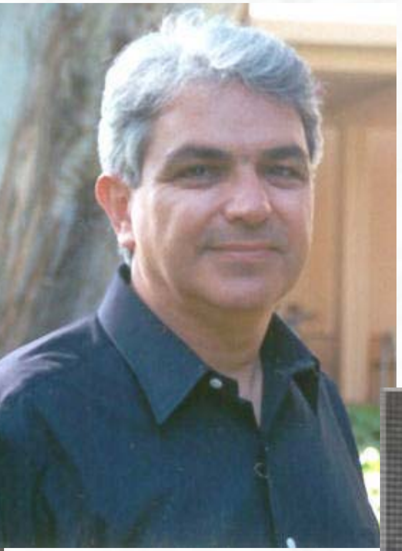
- Distances $r < R$

$$F \sim \frac{1}{r^4}$$





Creators of New Extra-Dimensional Ideas!



Savas
Dimopoulos
Stanford

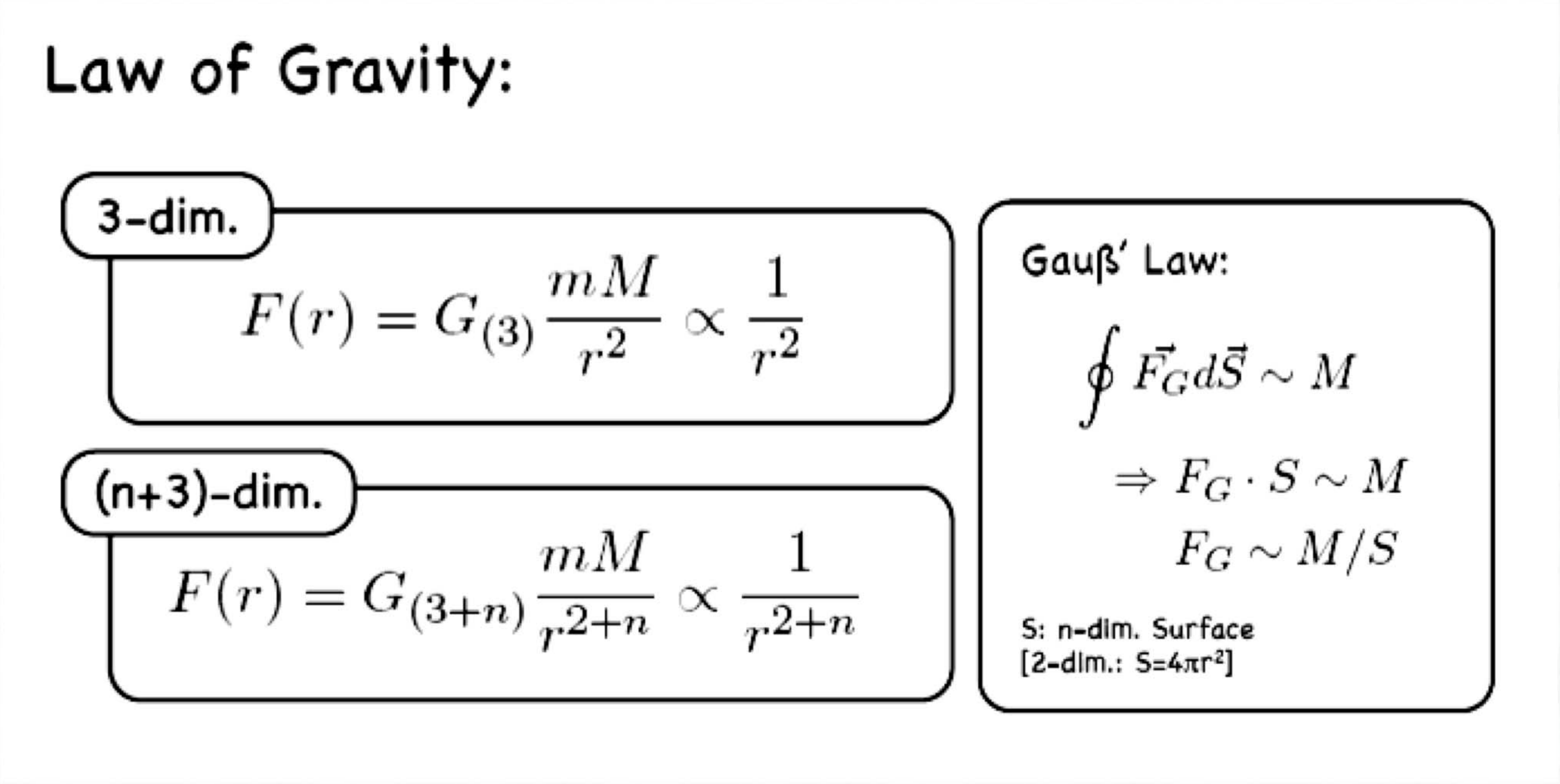
Lisa Randall
Harvard

Nima Arkani-Hamed
Princeton

Gia Dvali
New York Univ.

Raman Sundrum
Johns Hopkins

Extra Dimensions & the Law of Gravity



Law of Gravity:

3-dim.

$$F(r) = G_{(3)} \frac{mM}{r^2} \propto \frac{1}{r^2}$$

(n+3)-dim.

$$F(r) = G_{(3+n)} \frac{mM}{r^{2+n}} \propto \frac{1}{r^{2+n}}$$

Gauß' Law:

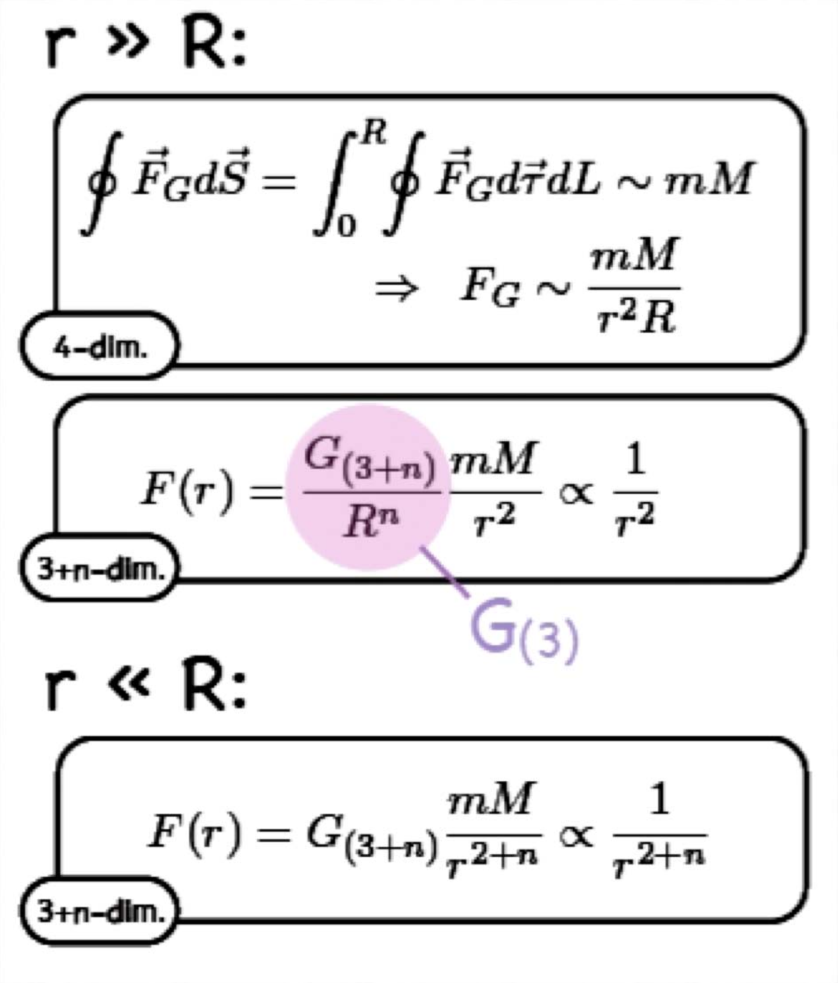
$$\oint \vec{F_G} d\vec{S} \sim M$$

$$\Rightarrow F_G \cdot S \sim M$$

$$F_G \sim M/S$$

S: n-dim. Surface
[2-dim.: $S=4\pi r^2$]

Compactified Extra Space Dimensions



r » R:

$$\oint \vec{F}_G d\vec{S} = \int_0^R \oint \vec{F}_G d\vec{r} dL \sim mM$$

$$\Rightarrow \quad F_G \sim \frac{mM}{r^2 R}$$

4-dim.

$$F(r) = \frac{G_{(3+n)}}{R^n} \frac{mM}{r^2} \propto \frac{1}{r^2}$$

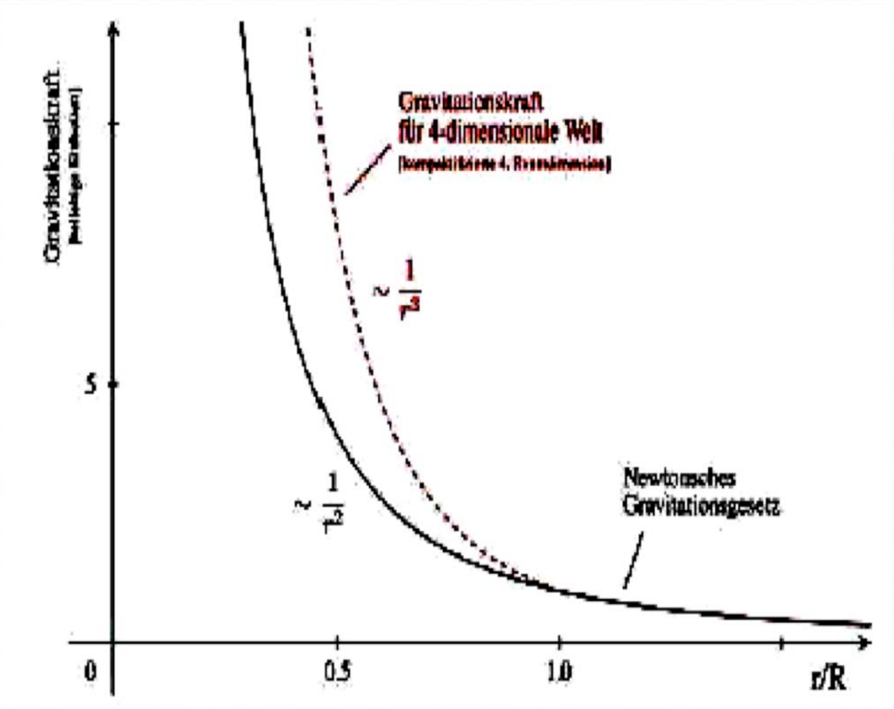
3+n-dim.

$G_{(3)}$

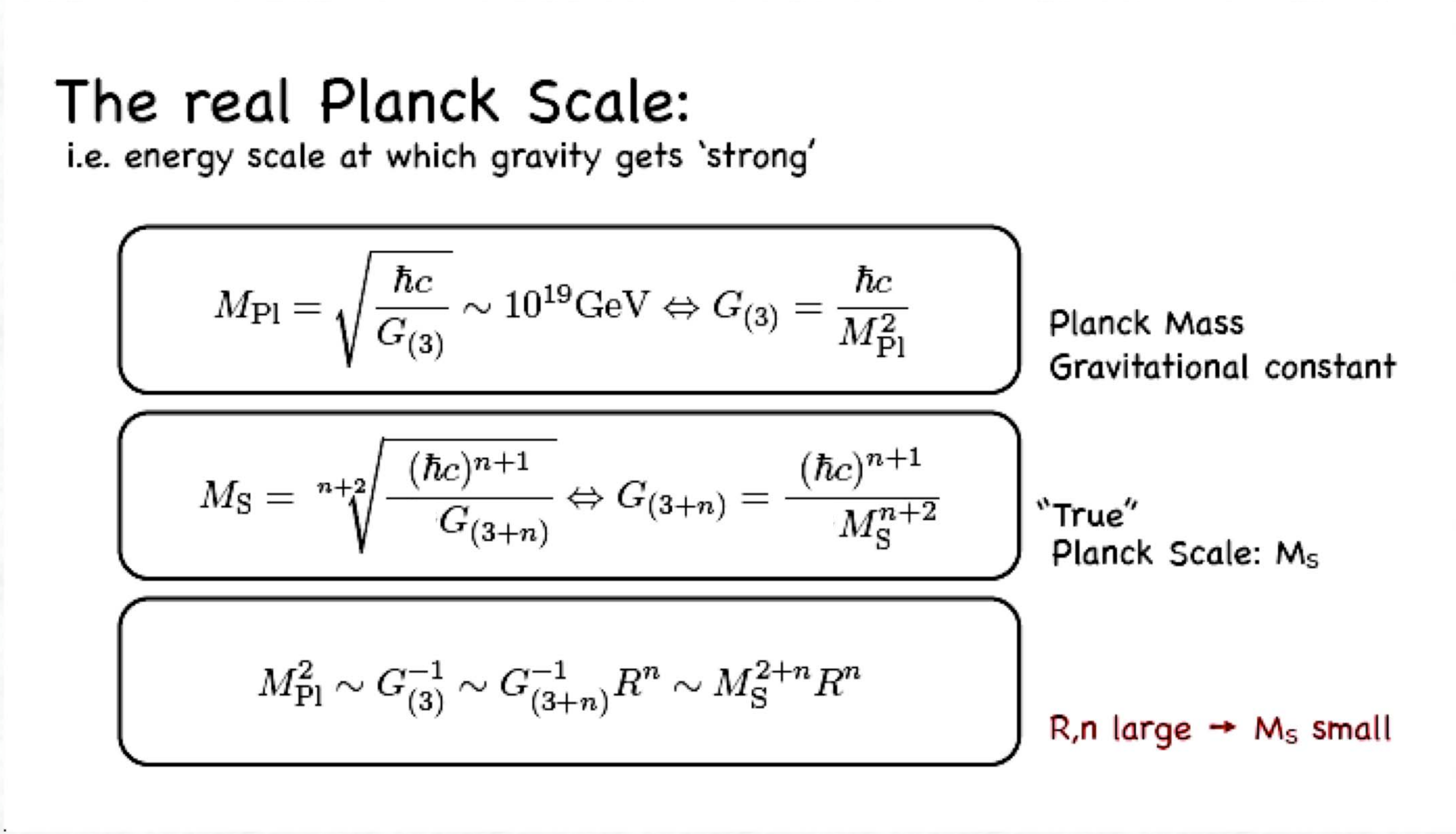
r « R:

$$F(r) = G_{(3+n)} \frac{mM}{r^{2+n}} \propto \frac{1}{r^{2+n}}$$

3+n-dim.



The Scale of Gravity



The real Planck Scale:

i.e. energy scale at which gravity gets 'strong'

$$M_{\rm Pl} = \sqrt{\frac{\hbar c}{G_{(3)}}} \sim 10^{19}{\rm GeV} \Leftrightarrow G_{(3)} = \frac{\hbar c}{M_{\rm Pl}^2}$$

Planck Mass
Gravitational constant

$$M_{\rm S} = \sqrt[n+2]{\frac{(\hbar c)^{n+1}}{G_{(3+n)}}} \Leftrightarrow G_{(3+n)} = \frac{(\hbar c)^{n+1}}{M_{\rm S}^{n+2}}$$

"True"
Planck Scale: M_S

$$M_{\rm Pl}^2 \sim G_{(3)}^{-1} \sim G_{(3+n)}^{-1} R^n \sim M_{\rm S}^{2+n} R^n$$

R,n large → M_S small

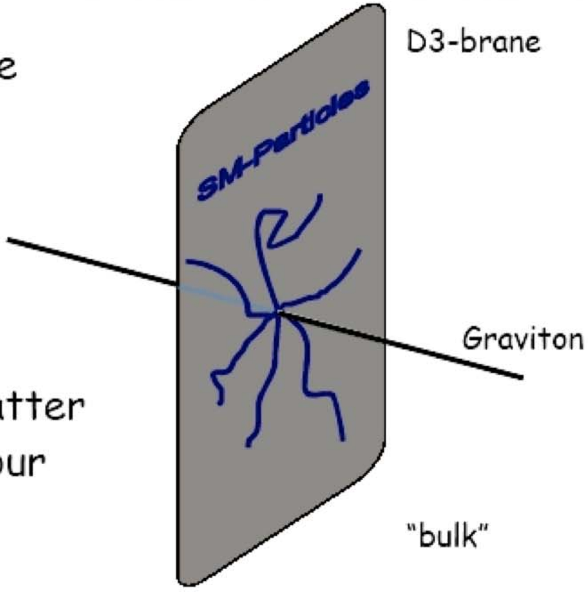
Large Extra Dimensions & ADD Model

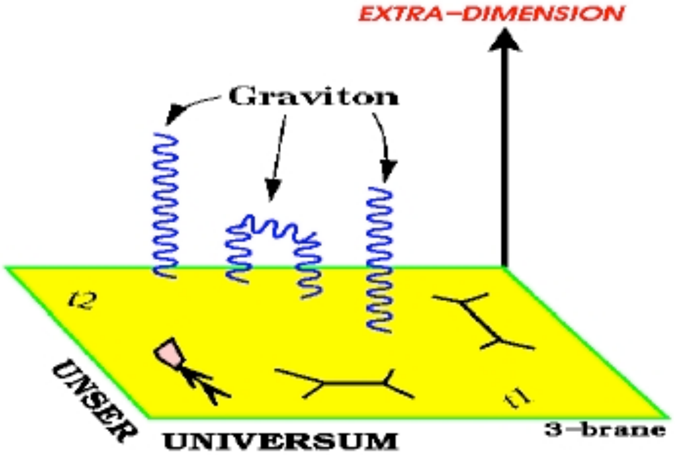
ADD approach — Antoniadis, Arkani-Hamed, Dimopoulos, Dvali: hep-ph/9803315, 9804398, 9807344

There are n compactified extra dimensions

Only gravity can propagate in extra dimensions

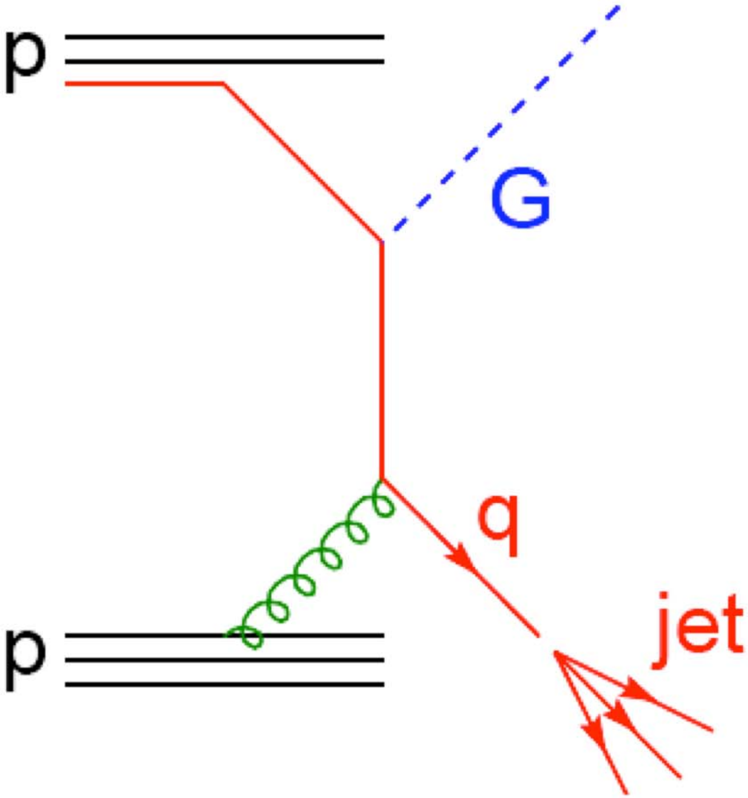
- n compactified extra space dimensions with size R
- gravity in all n+3 space dimensions
- SM interactions and all matter particles are confined to our 3-dimensional world.

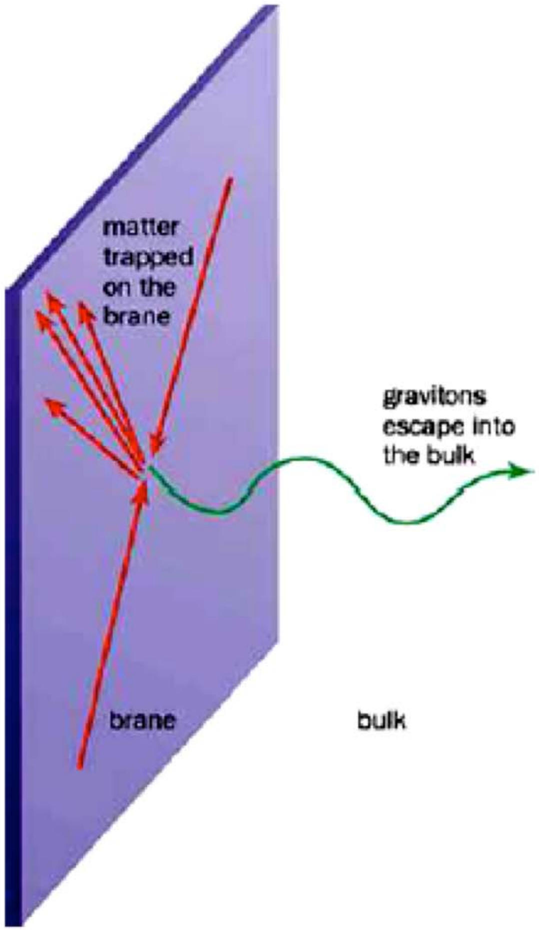




Experimental Signature: Monojets

Real graviton production



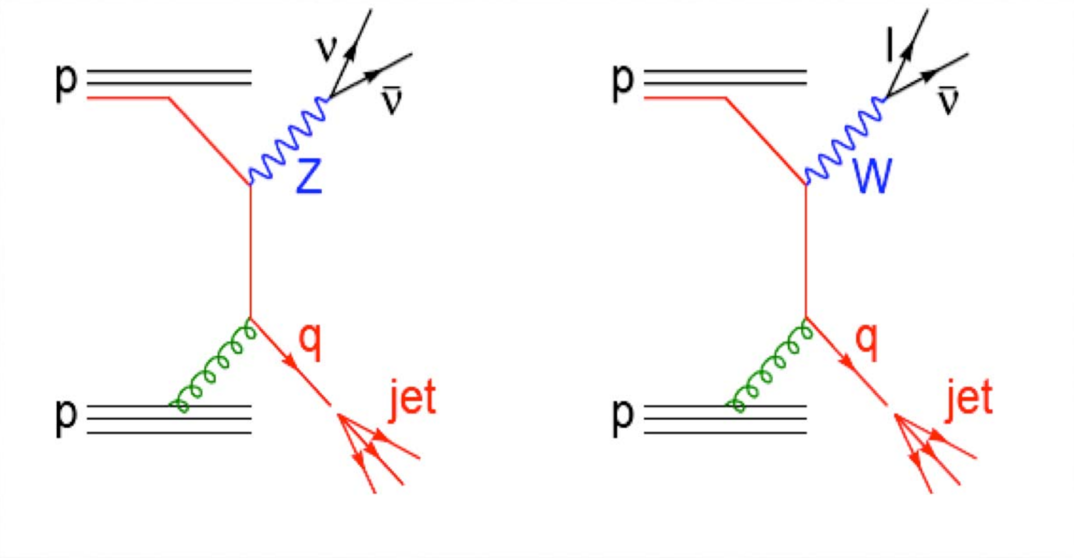


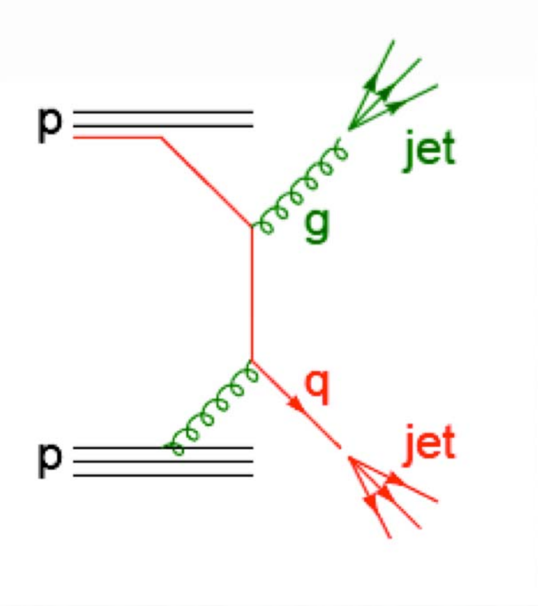
Signal: high E_T jet + missing E_T

Monojets: Standard-Model Backgrounds

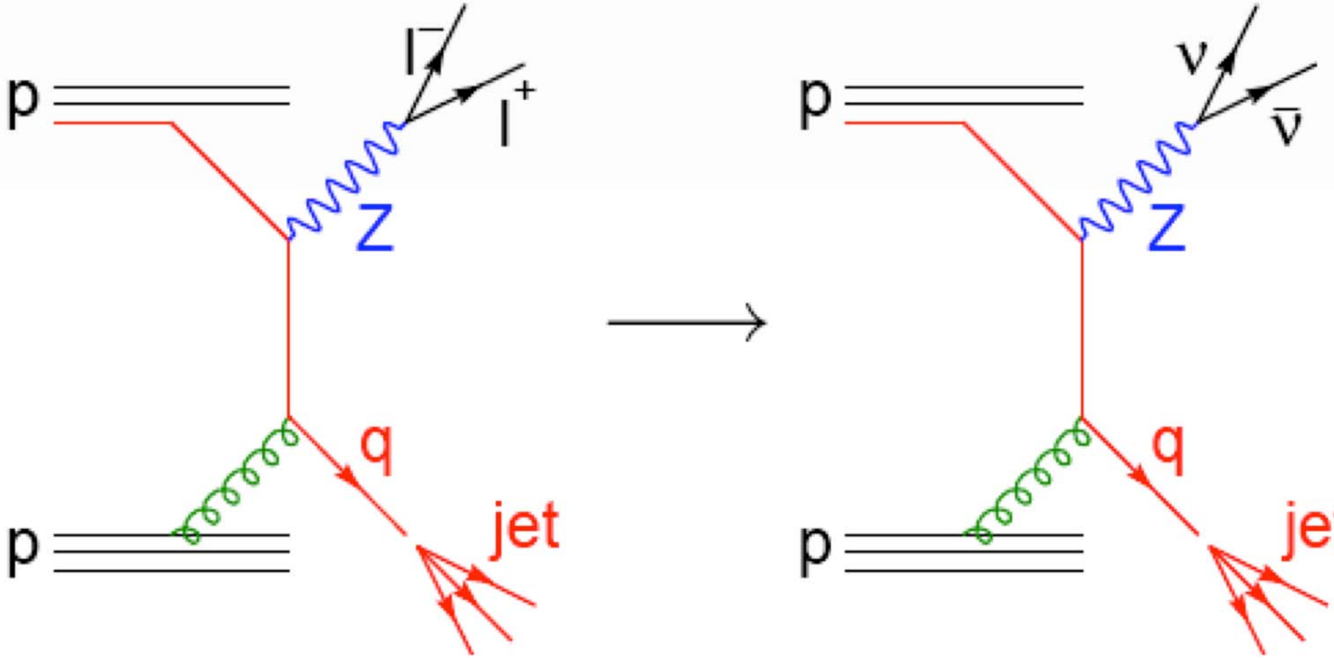
- Jet + Z → $\nu\nu$
- Jet + $W \rightarrow \nu e, \nu\mu, \nu\tau$ with lepton lost (lepton with low energy, lepton in dead region)

- Instrumentation + QCD
  - QCD dijets with one jet lost in dead region, or due to energy fluctuations, or multijets
  - Calorimeter noise
  - Beam induced signals
  - Cosmics





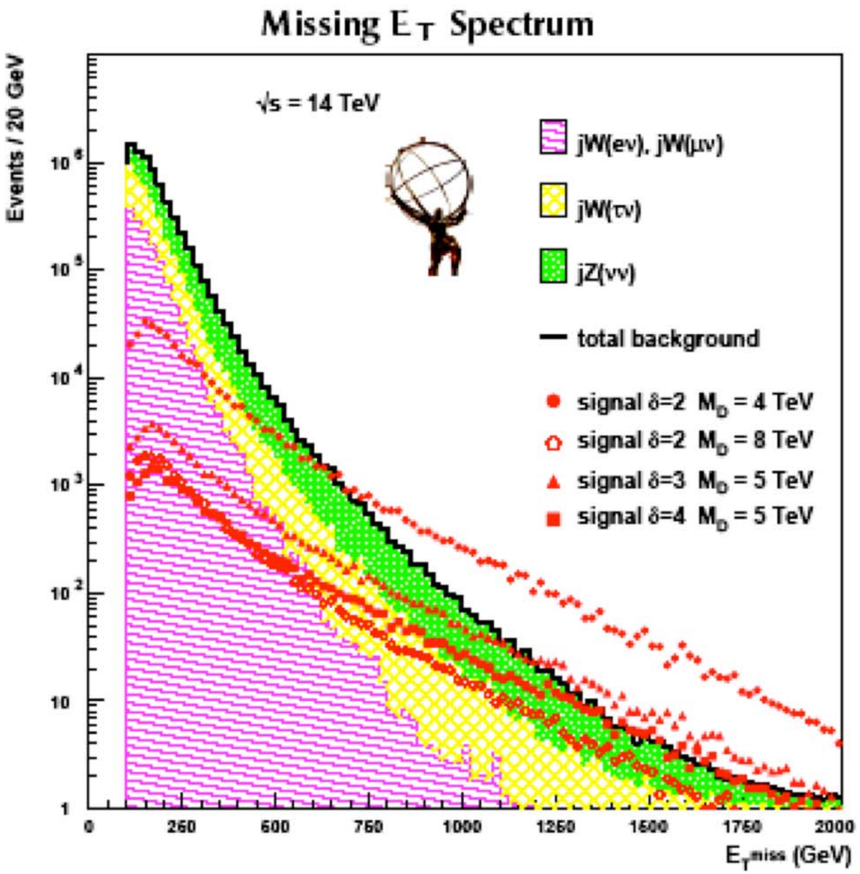
Monojets: Understanding Z+Jet Background



Using known branching ratio $\frac{\sigma(Z \to \nu\nu)}{\sigma(Z \to l^+ l^-)}$

Monojet Searches at the LHC

Vacavant, Hinchliffe: ATLAS-PHYS-2000-016, SN-ATLAS-2001-005



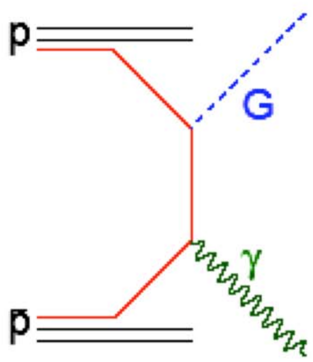
- ATLAS MC based feasibility studies

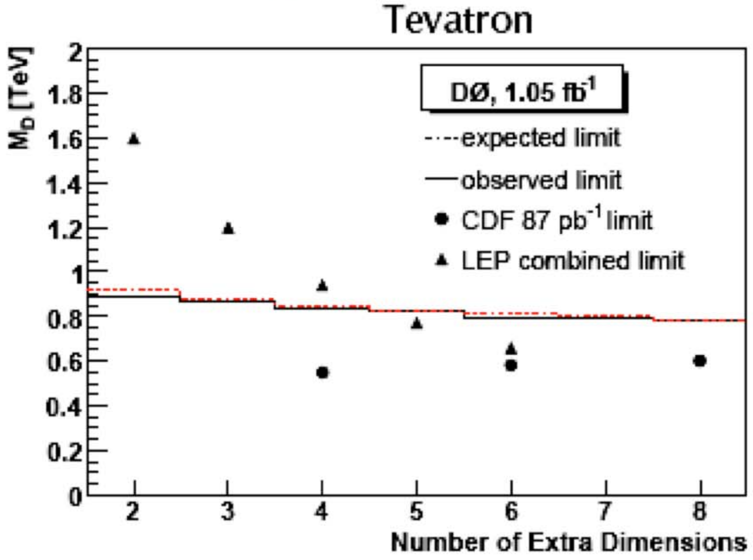
5σ discovery sensitivity for $100\,\text{fb}^{-1}$:

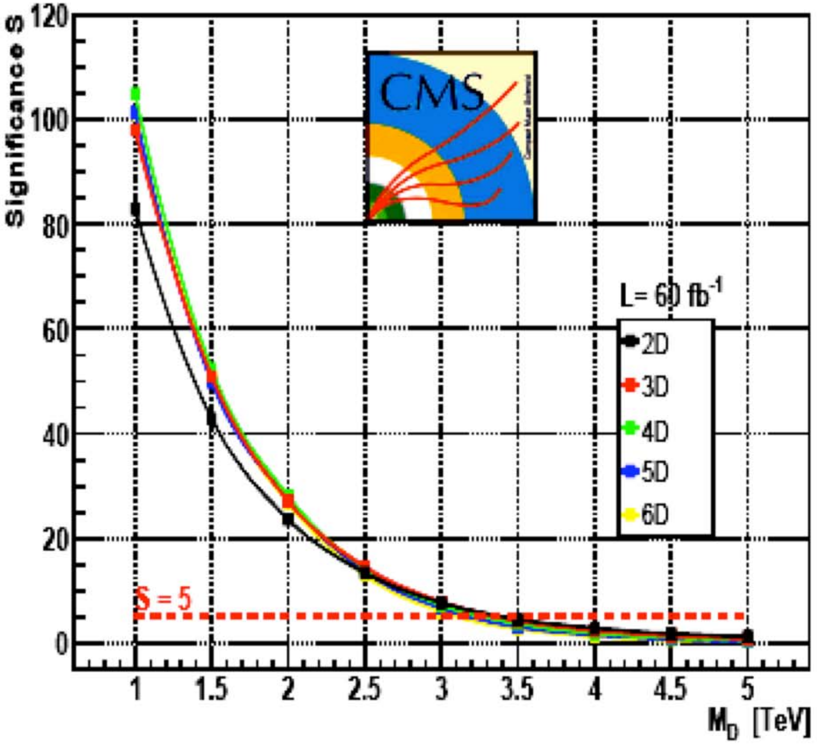
n	2	3	4
M_D / TeV	9	7	6

- No instrumentation effects included

Monophoton Searches:







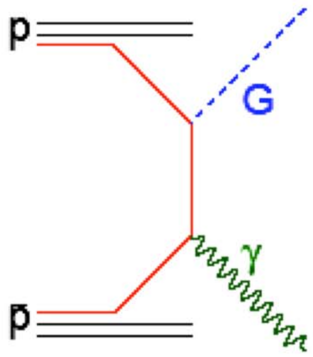
5σ discovery sensitivity for $100\,\text{fb}^{-1}$:

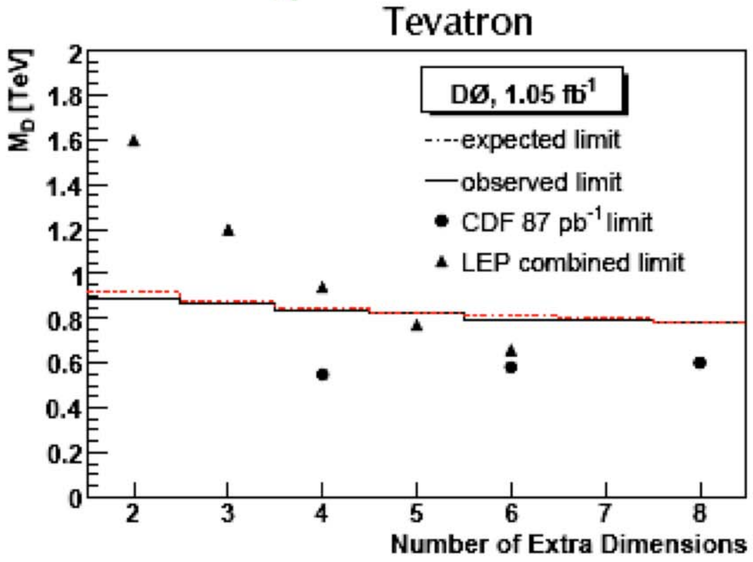
For $n = 2$: $M_D \sim 4\,\text{TeV}$

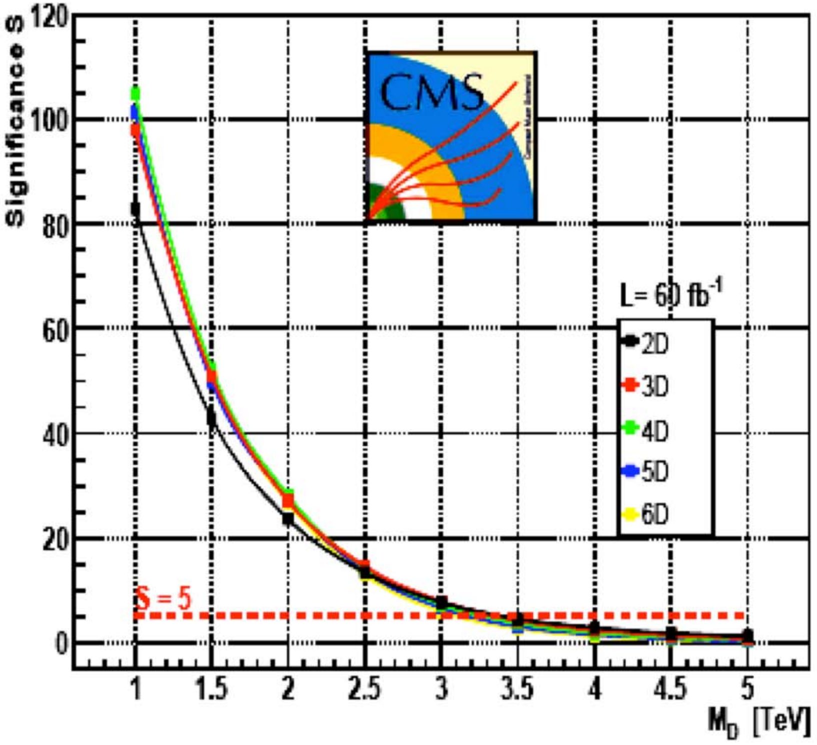
arXiv:0803.2137, hep-ex/0205057

ATLAS-PHYS-2000-016, CMS-NOTE-2006-129

Monophoton Searches: Tevatron and LHC







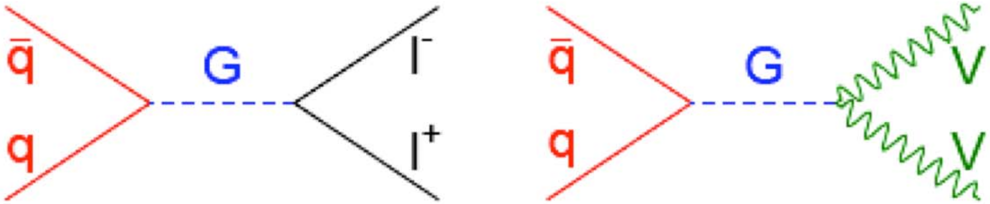
5σ discovery sensitivity for 100 fb^{-1}:
For $n = 2$: $M_D \sim 4$ TeV

arXiv:0803.2137, hep-ex/0205057

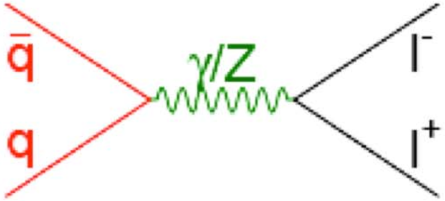
ATLAS-PHYS-2000-016, CMS-NOTE-2006-129

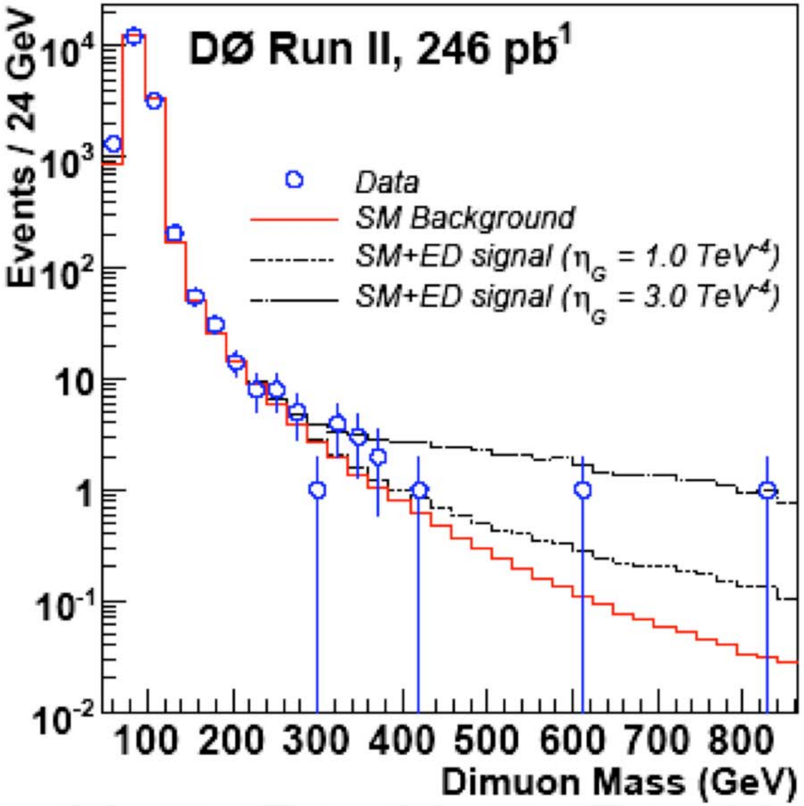
Virtual Graviton Exchange in ADD Model

- e^+e^- and $\gamma\gamma$ from calorimeter measurements
- $\mu^+\mu^-$ momentum reconstruction in central and muon chambers



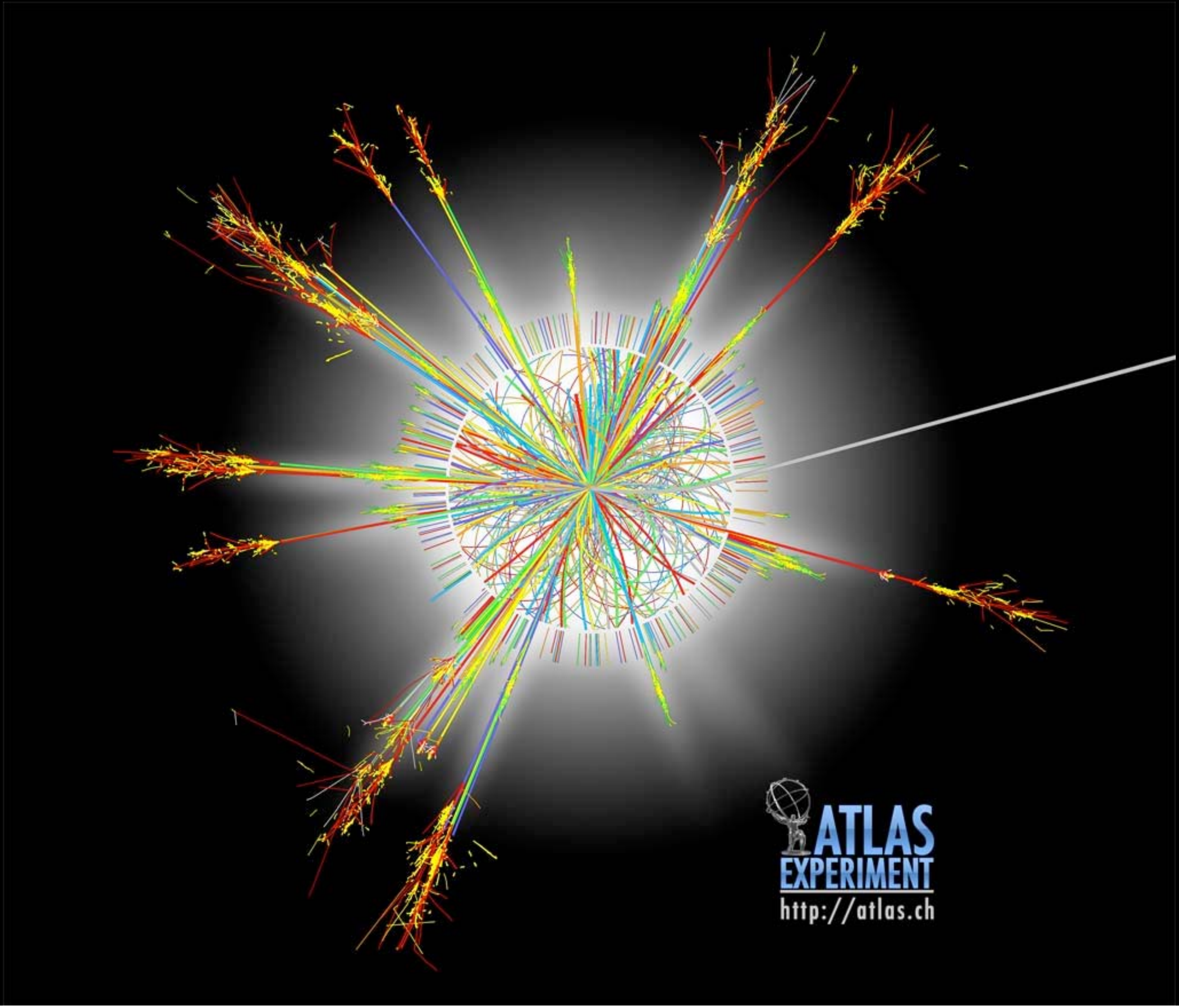
Look for deviations from SM
in Drell-Yan scattering for e^+e^- and $\mu^+\mu^-$



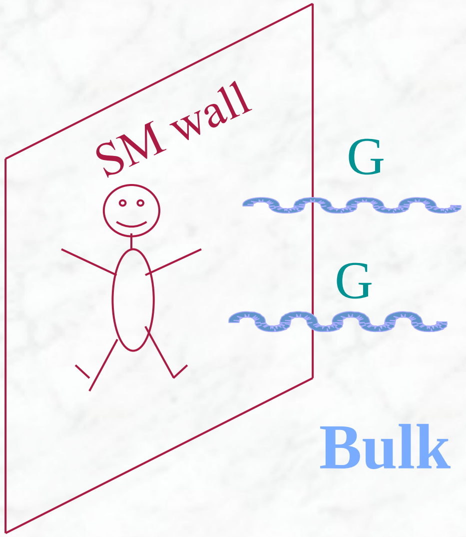


Deviations expected at high invariant masses
as KK gravitons appear "massive"
No deviations observed

Microscopic Black Holes at the LHC ?



Can LHC probe Black Hole production ?



- New physics, scale of gravity M_D, can appear at the TeV-mass scale, i.e. accessible at the LHC

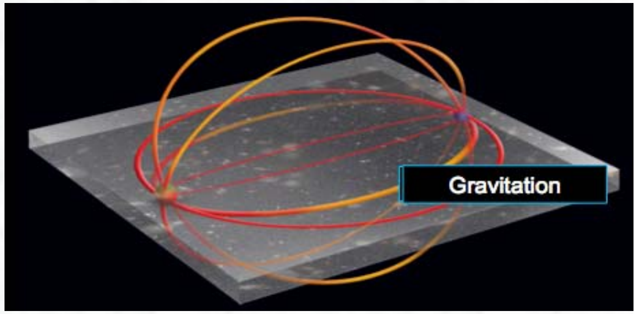
- Extra dimensions are compactified on a torus or sphere with radius r

  relation between Planck mass in 4 and (4+n) dimensions:

$$M_{\mathrm{Pl}}^2 = 8\pi M_D^{n+2} r^n$$

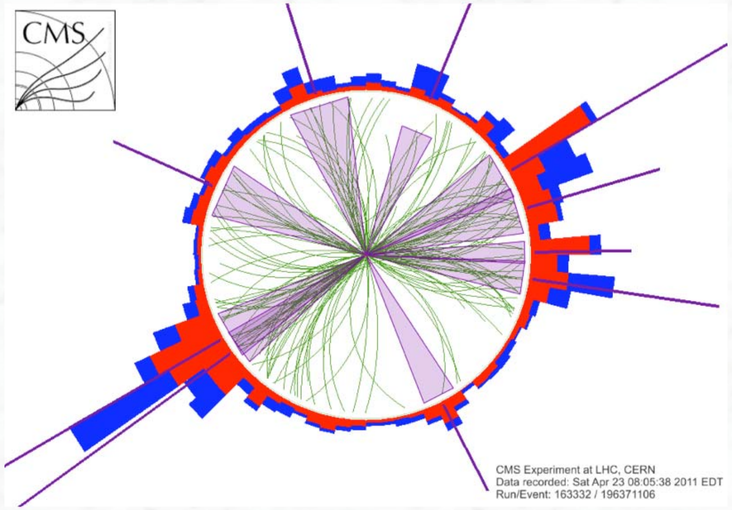
- Black hole formation at energies greater than M_D

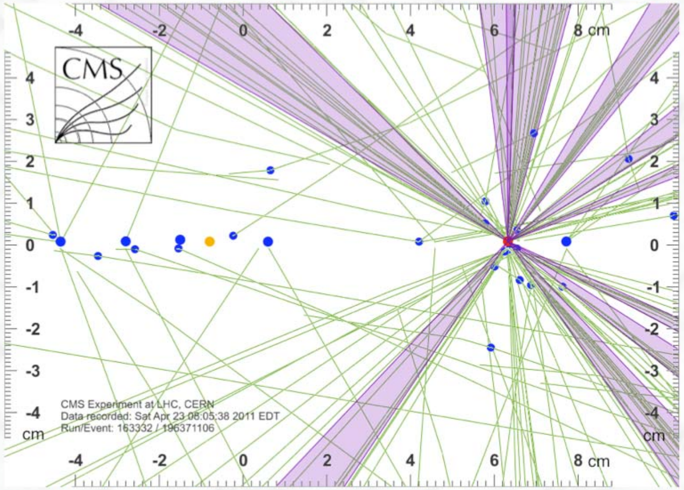
  Production cross section can be in the order of 100 pb for M_D ~1 TeV (large model dependence)



- Once produced, the black hole is expected to decay via Hawking radiation, democratically to all Standard Model particles (quarks and gluons dominant,75%)
  → multijet events with large mass and total transverse energy

CMS search for events with high jet multiplicity and large transverse energy



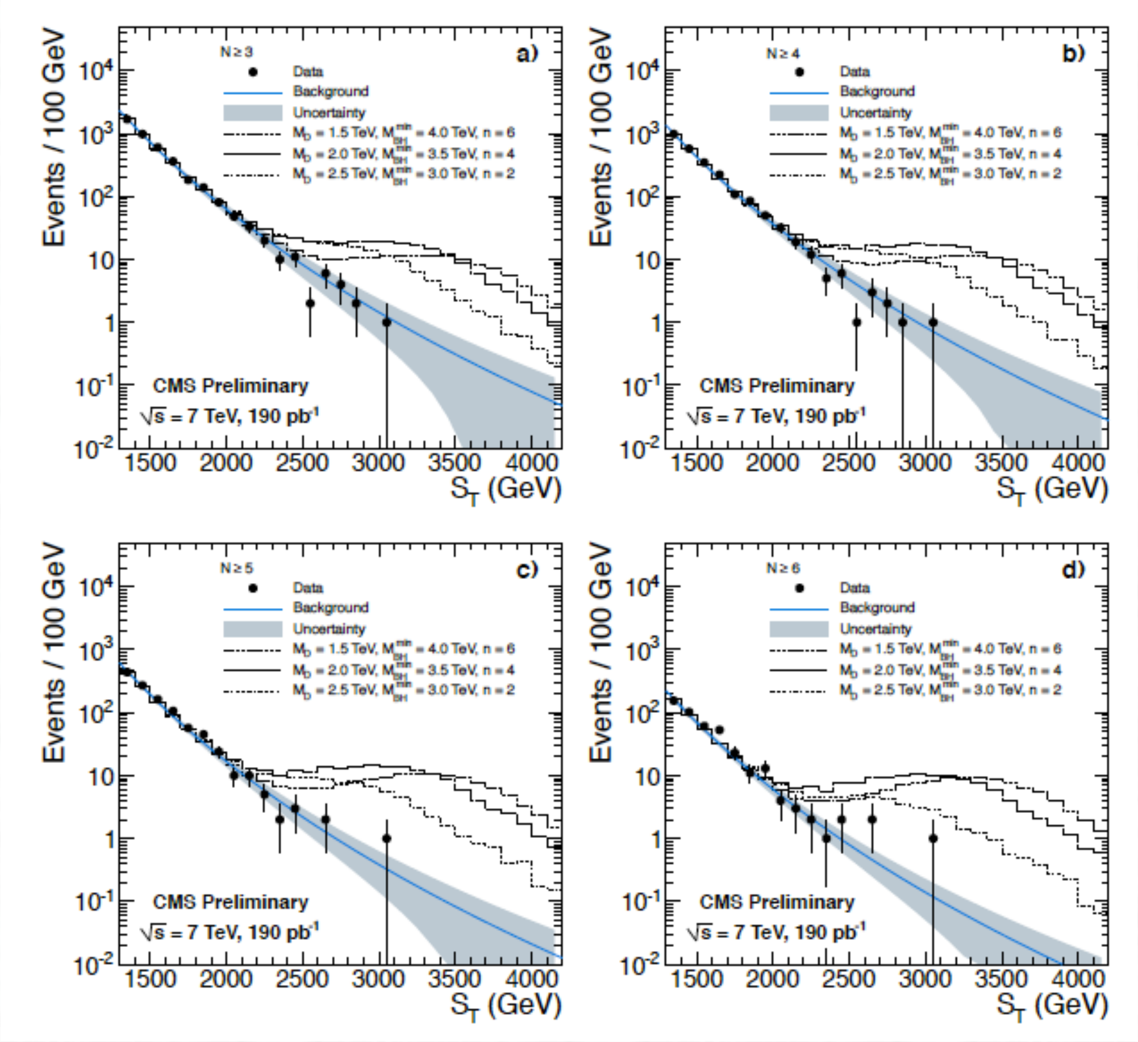


Candidate events exist….

event with high multiplicity of jets,
high mass….

all particles coming from one interaction vertex

Is there an excess above the expectation from QCD production?



Total transverse energy S_T for events with N>3, 4, 5, 6 objects

No evidence for excess above the QCD expectations
→ No evidence for the formation of micro Black Holes

Literature

Available on the web:

- R. Rattazzi, “Cargese Lectures on Extra Dimensions”, hep-ph/0607055
  http://arxiv.org/abs/hep-ph/0607055

- T. Rizzo, „Pedagogical Introduction to Extra Dimensions“, hep-ph/0409309
  http://arxiv.org/abs/hep-ph/0409309

- K. Cheung, “Collider Phenomenology for Models of Extra Dimensions”, hep-ph/0305003
  http://arxiv.org/abs/hep-ph/0305003

- G. Landsberg, “Black Holes at Future Colliders and Beyond”, hep-ph/0607297
  http://arxiv.org/abs/hep-ph/0607297

Books (popular science):

- L. Randall, „Verborgene Universen: Eine Reise in den extradimensionalen Raum“, Fischer Taschenbuchverlag (2006).

End of lectures