10. Other Extensions of the Standard Model

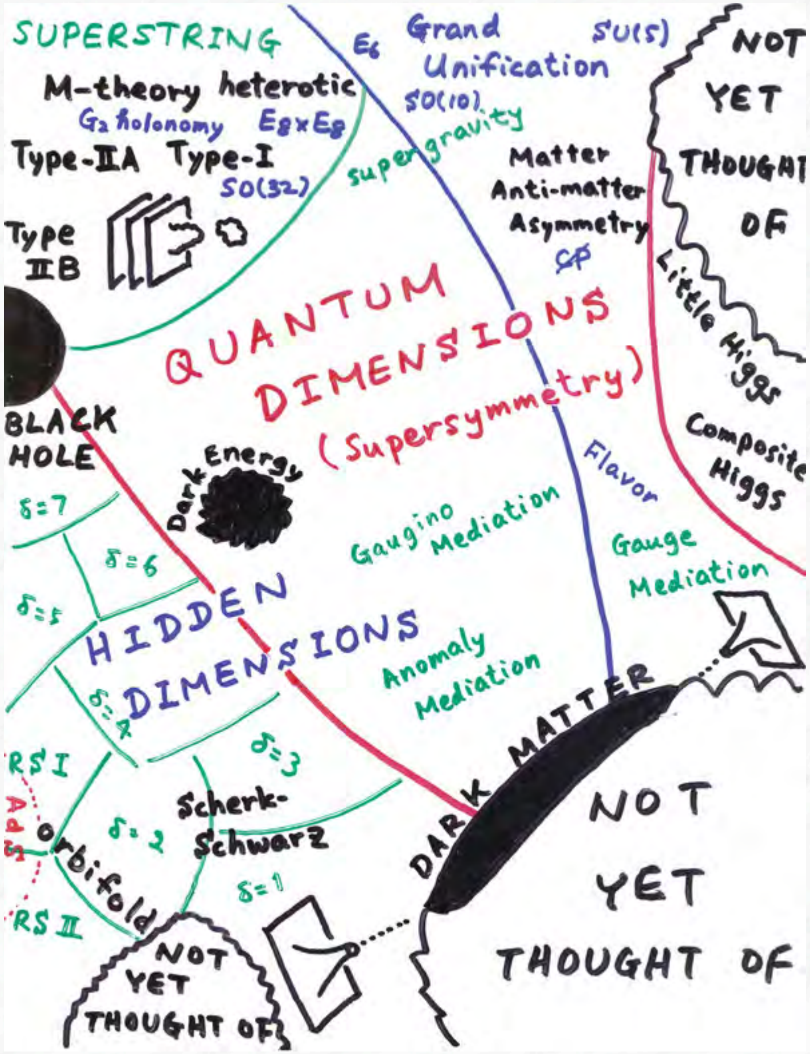
10.1 Introduction to Grand Unified Theories

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) → 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.

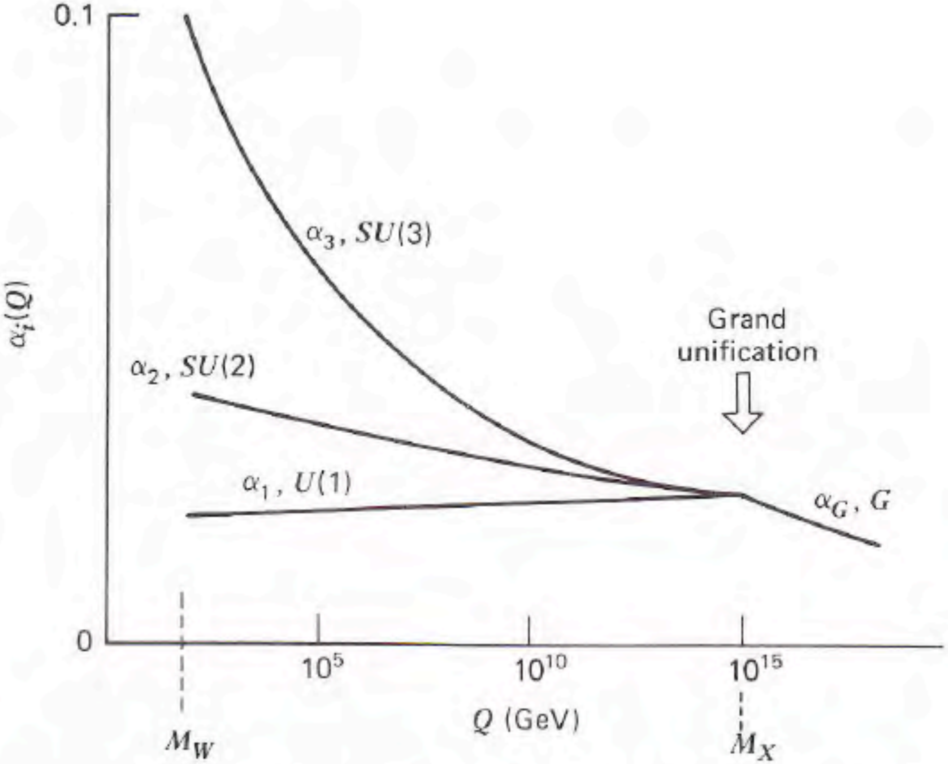


Fig. 15.4 The variation of $\alpha_i \equiv g_i^2/4\pi$ with Q, showing the speculative grand unification of strong $[SU(3)_{color}]$ and electroweak $[SU(2)_L \times U(1)_Y]$ interactions at very short distances $1/Q \approx 1/M_X$.

- 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

$$\text{for } Q > M_X: \quad g_i(Q) = g_G(Q)$$

- 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):

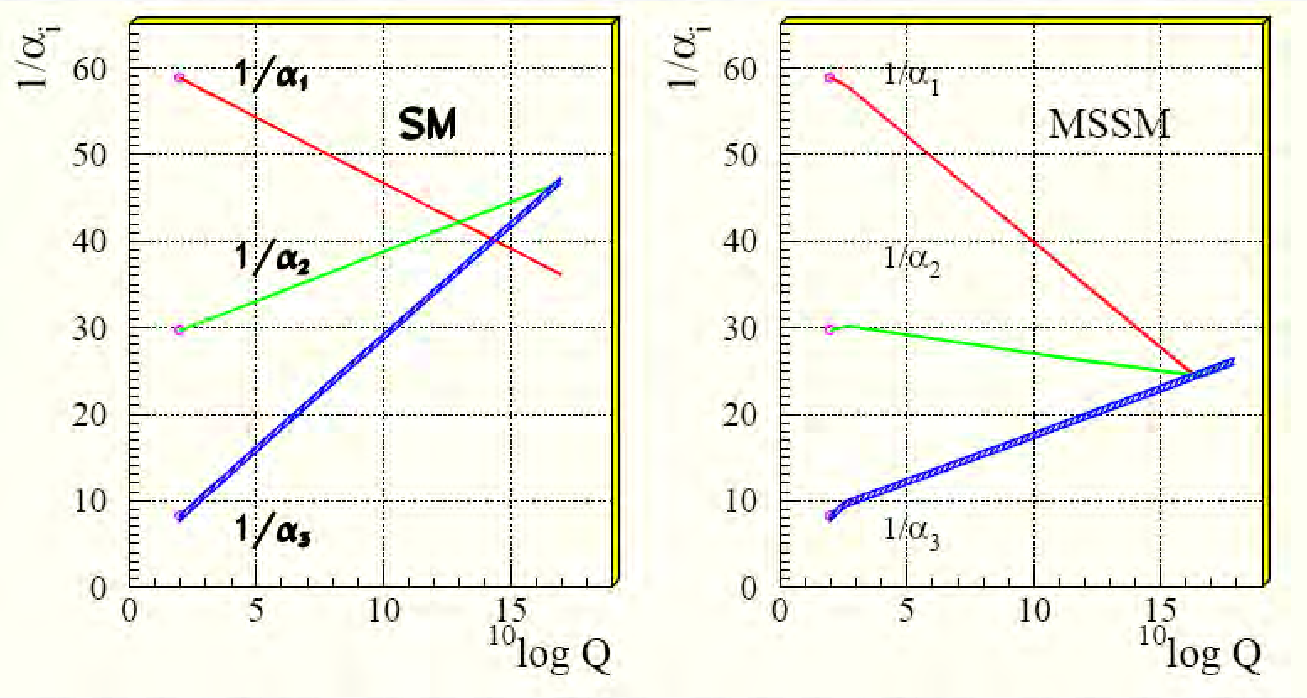
$$b_1 = \frac{1}{(4\pi)^2}\left(\frac{4}{3}n_g\right),$$

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

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

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:

  $(u,d)_L$, $(\nu_e,e^-)_L$ (ubar, 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

<u>The SU(5) Model (Georgi, Glashow, ~1980) (cont):</u>

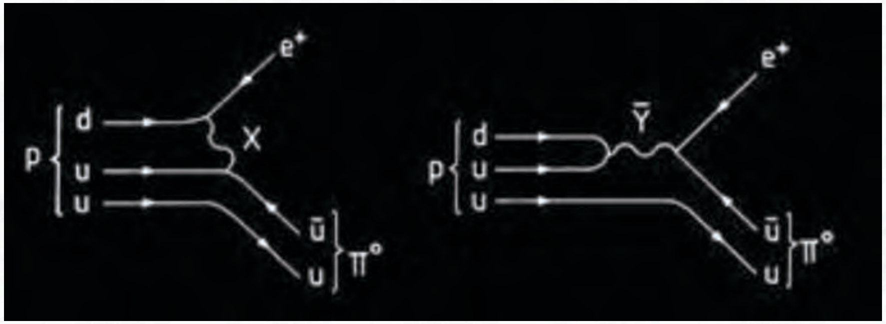
- Transitions mediated by X and Y bosons violate lepton number and baryon number conservation;

  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 disappears. 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: $Q_u = -2\ Q_d$

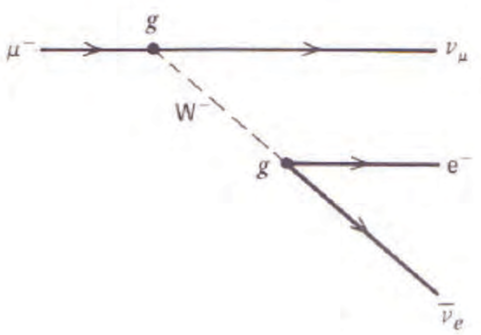
The combined result resolves the mystery of why $Q_p = -Q_e$

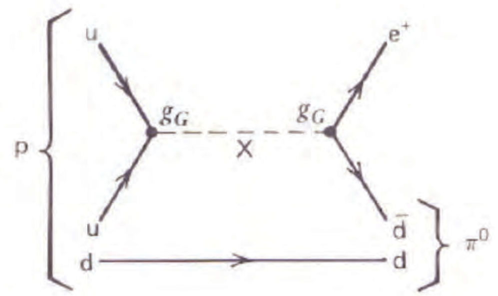
Can proton decay be detected?

- 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 $Q^2 \ll M_X^2$





$$\frac{G}{\sqrt{2}} = \frac{g^2}{8M_W^2} \quad (12.15)$$

$$\Gamma(\mu \to e\bar{\nu}_e\nu_\mu) = \cdots G^2 m_\mu^5 \quad (12.42)$$

$$= \cdots \frac{m_\mu^5}{M_W^4}$$

$$\frac{G_G}{\sqrt{2}} = \frac{g_G^2}{8M_X^2}$$

$$\Gamma(p \to \pi e) = \cdots G_G^2 m_p^5$$

$$= \cdots \frac{m_p^5}{M_X^4}$$

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)

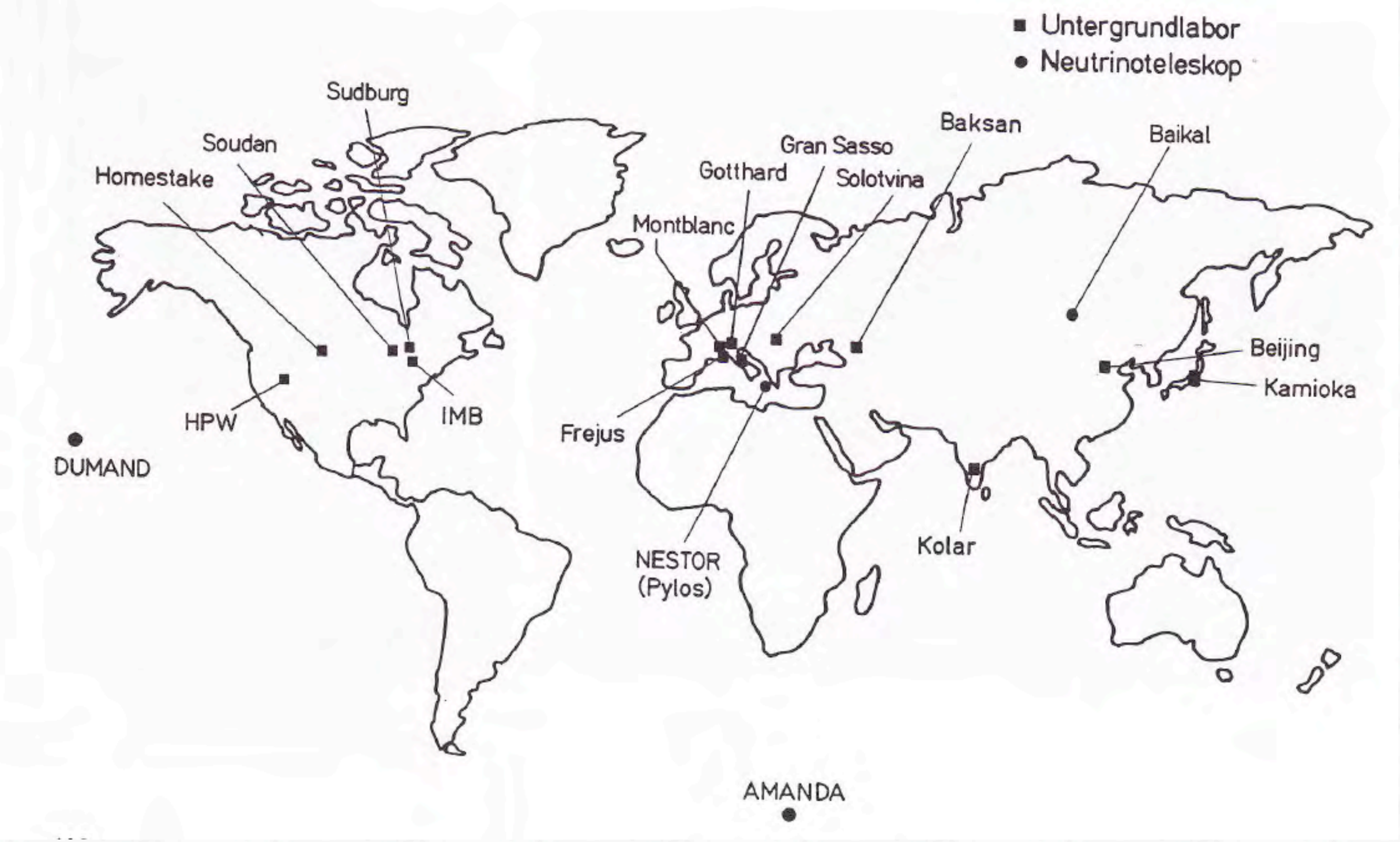
	KGF	NUSEX	Fréjus	Soudan II
M_{tot} [t]	140	150	912	1000
M_{eff} [t]	60	113	550	600
Tiefe [m]	2300	1850	1780	760
Wasseräquivalent [m]	7600	5000	4850	1800
Vertexauflösung [cm]	10	1	0.5	~ 0.5
Ort	Kolar-Goldmine	Mont-Blanc-Tunnel	Fréjus-Tunnel	Soudan-Erzmine

(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 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

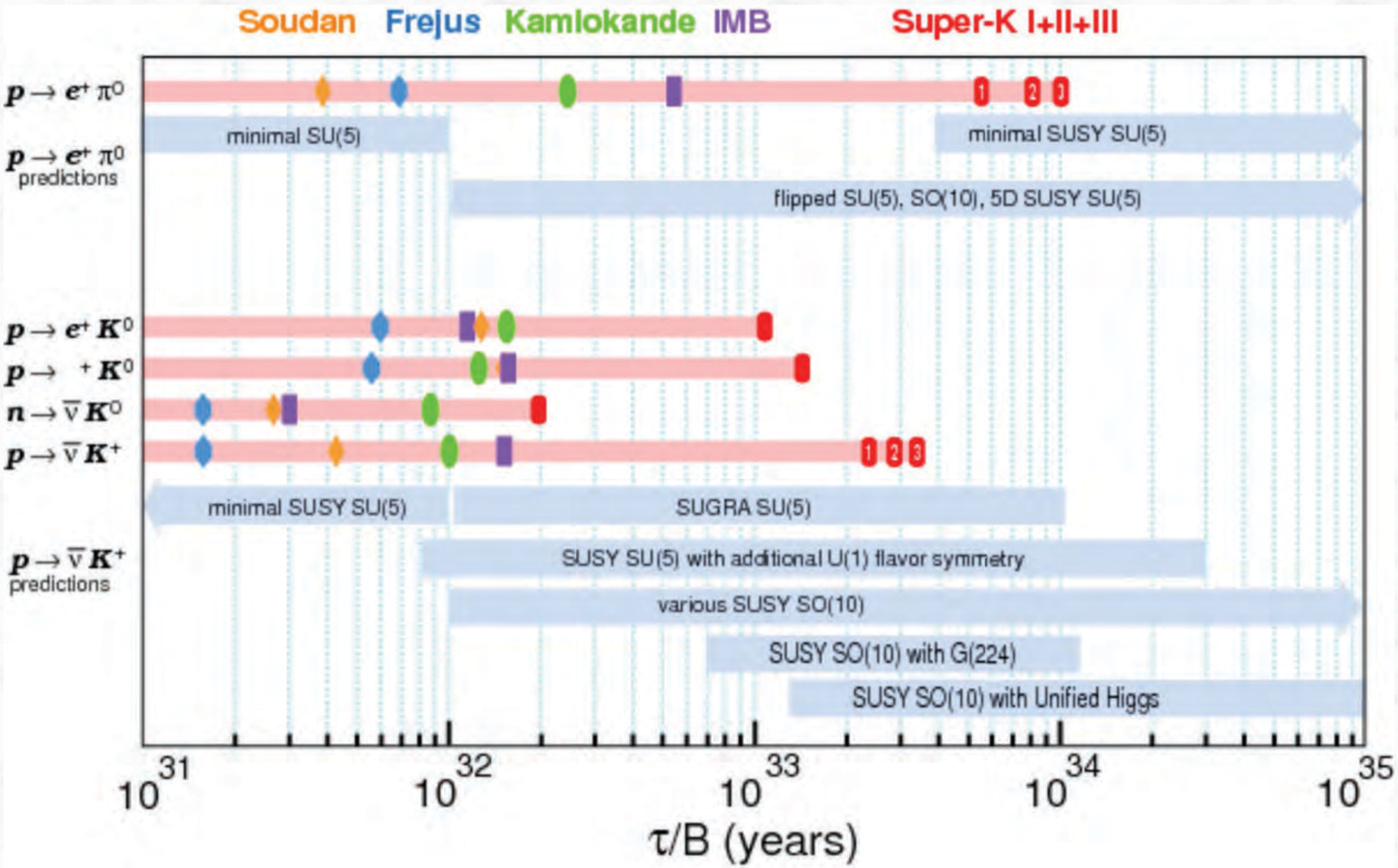
Proton lifetime lower bounds (10^{30} years)			
mesonic $\Delta S = 0$		mesonic $\Delta S \neq 0$	
$p^+ \rightarrow e^+ \pi^0$	8200	$p^+ \rightarrow e^+ K^0_S$	120
$p^+ \rightarrow \mu^+ \pi^0$	6600	$p^+ \rightarrow e^+ K^0_L$	51
$p^+ \rightarrow \tilde{\nu} \pi^+$	25	$p^+ \rightarrow \mu^+ K^0_S$	150
$p^+ \rightarrow e^+ \eta$	313	$p^+ \rightarrow \mu^+ K^0_L$	83
$p^+ \rightarrow \mu^+ \eta$	126	$p^+ \rightarrow \tilde{\nu} K^+$	670
$p^+ \rightarrow e^+ \rho^0$	75	$p^+ \rightarrow e^+ K^{0*}(892)$	84
$p^+ \rightarrow \mu^+ \rho^0$	110	$p^+ \rightarrow \tilde{\nu} K^{+*}(892)$	51
$p^+ \rightarrow \tilde{\nu} \rho^+$	162	inclusive	
$p^+ \rightarrow e^+ \omega$	107	$p^+ \rightarrow e^+$ anything	0.6
$p^+ \rightarrow \mu^+ \omega$	117	$p^+ \rightarrow \mu^+$ anything	12
radiative		multi-body	
$p^+ \rightarrow e^+ \gamma$	670	$p^+ \rightarrow e^+ e^- e^+$	793
$p^+ \rightarrow \mu^+ \gamma$	478	$p^+ \rightarrow e^+ \pi^0 \pi^0$	147

Results:

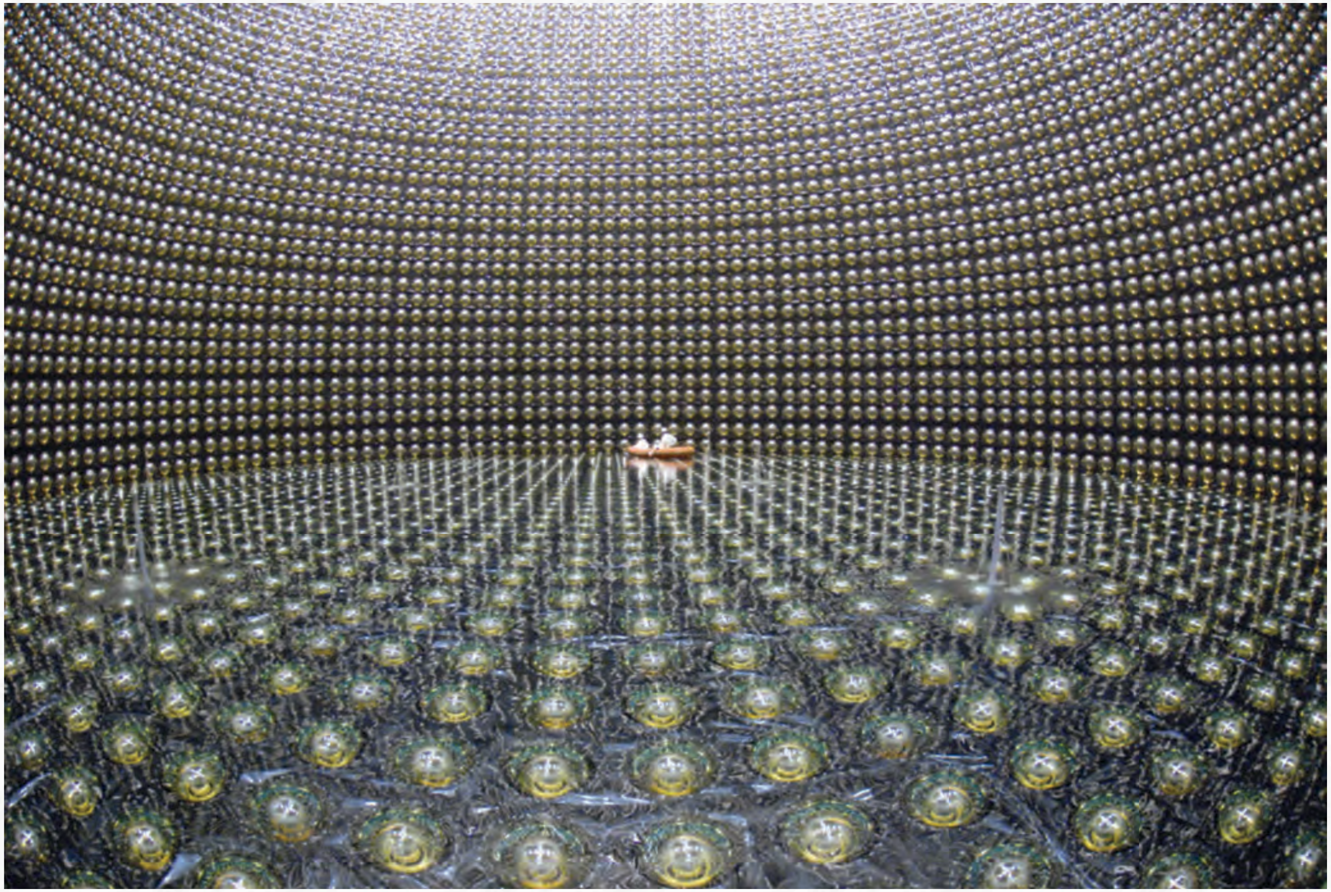
- so far no evidence for proton decay detected
- limits on lifetime in the order of 10^{32} years

  → simple SM + GUT models ruled out

  SUSY + GUT models still alive

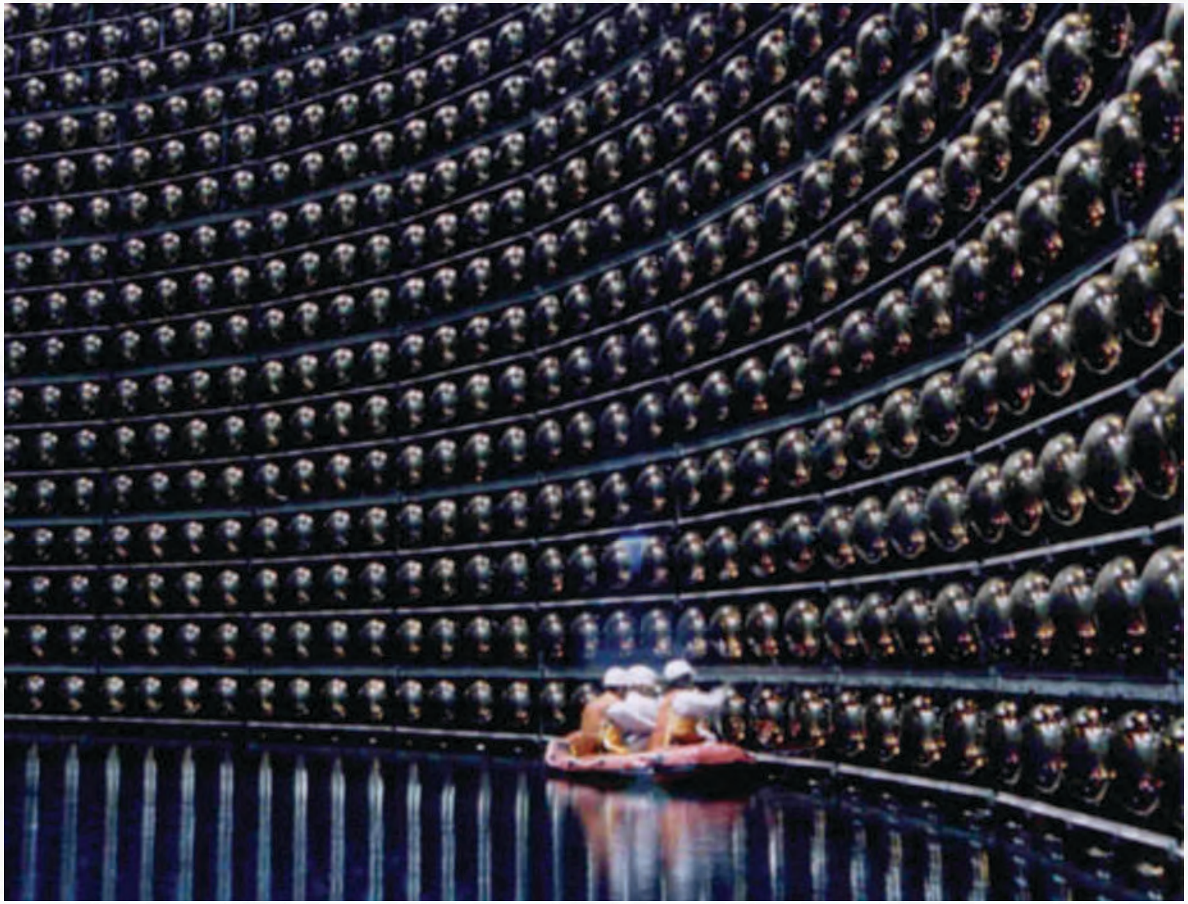


The Super-Kamiokande detector, Kamioka mine, Japan



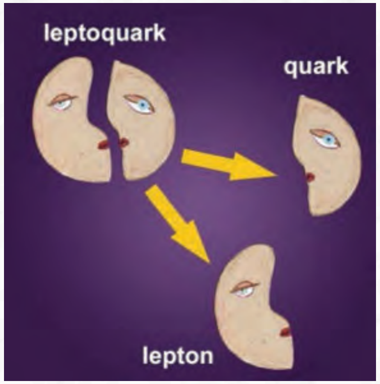
The Super-Kamiokande detector began operating in 1996, more than half a mile underground in a zinc mine in Kamioka, Japan. Japanese and American scientists erected a huge tank of water 138 feet tall to hunt for neutrinos and proton decay. The walls, ceiling, and floor of the 12.5-million-gallon tank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



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 : $0, \frac{1}{2}, 1$

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 ($-\frac{1}{3}$) → $e^- u$, or LQ($-4/3$) → $e^- d$
  LQ ($-\frac{1}{3}$) → $\nu_e d$

  Decays proceed always as: LQ → lepton + quark

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

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

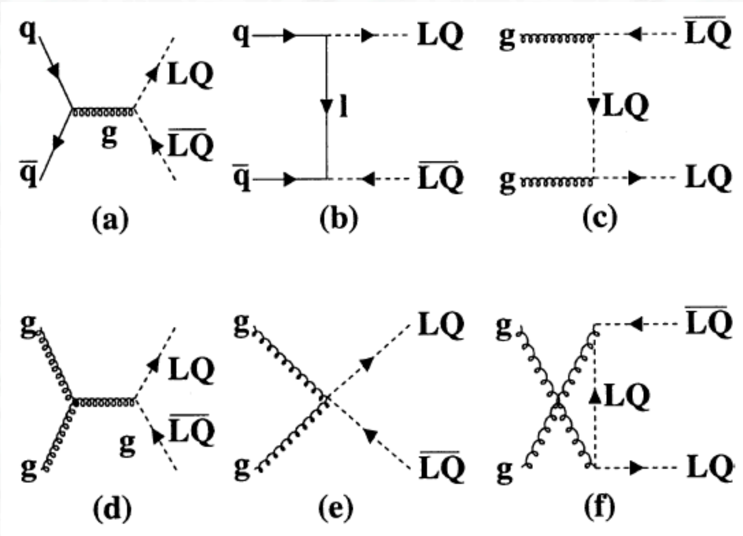
- Leptoquarks (in general form) may enhance flavour-changing neutral currents

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

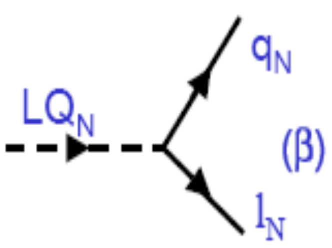
  → LQs of 1st, 2nd, and 3rd generation

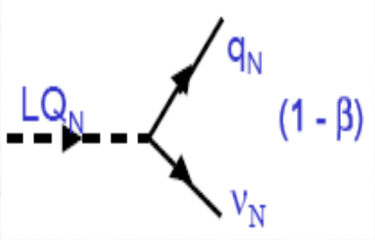
Search for Scalar Leptoquarks (LQ)

- 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
$\overline{M_{LQ}} > 150$ 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

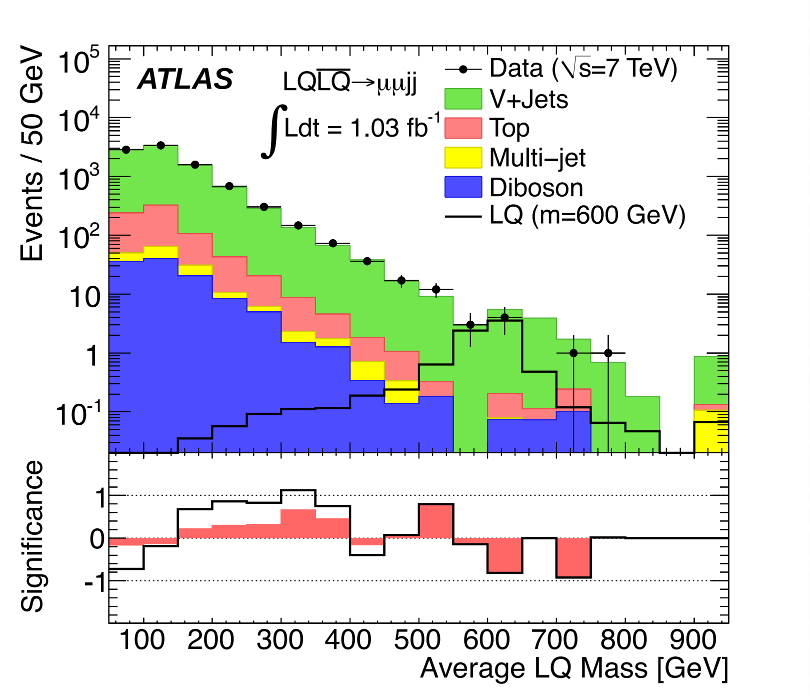
where S_T is the total scalar sum of the transverse momenta (two leptons and two jets)

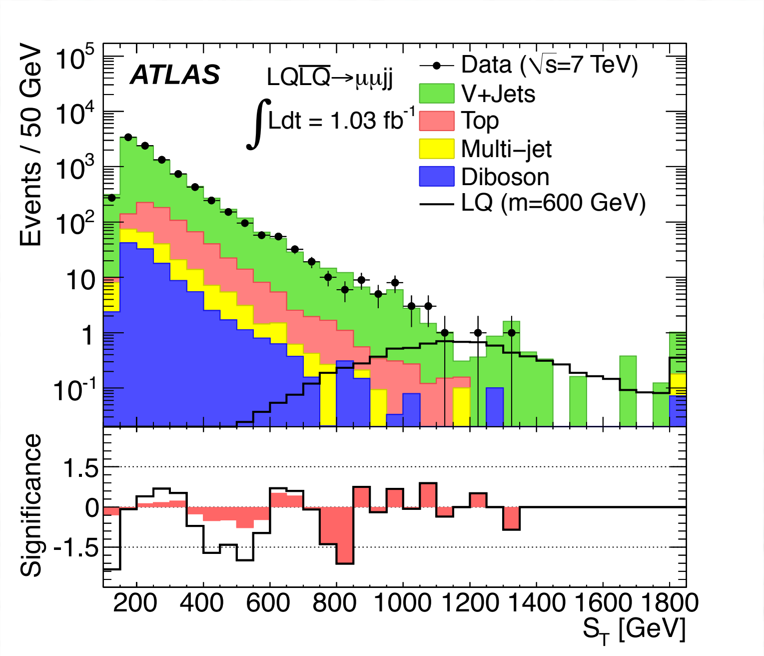
- Data, backgrounds and signal expectation (36 pb^{-1})

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 → μ μ j j

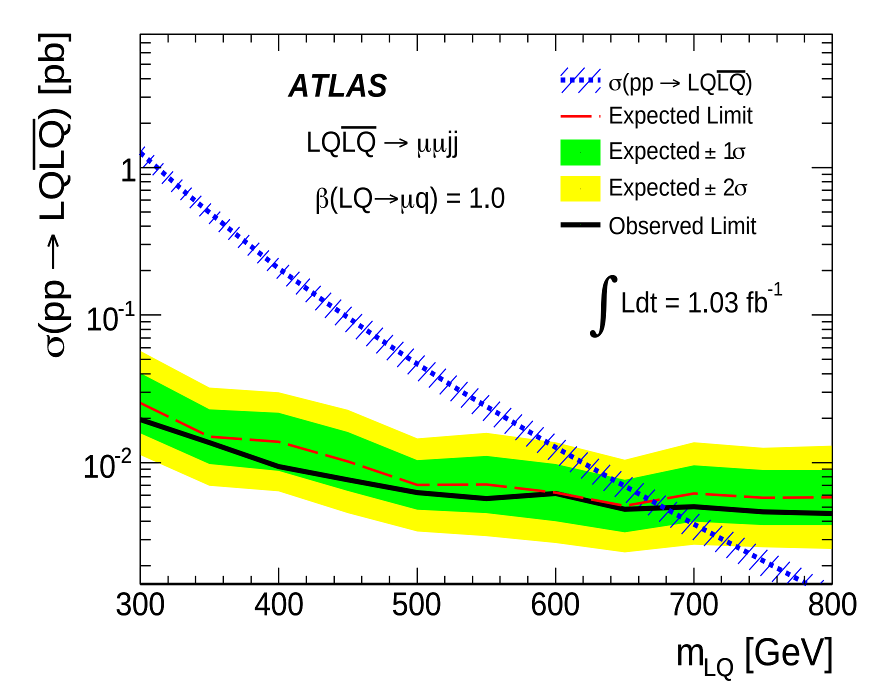


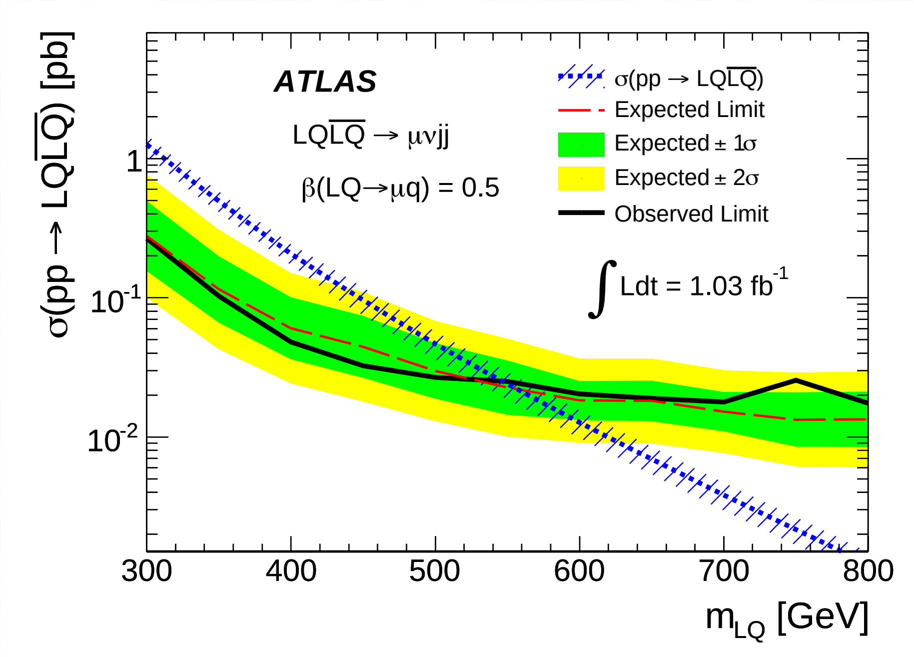


Left: invariant mass of $m(\mu_1, j_1)$, $m(\mu_2, j_2)$

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

Excluded cross sections:





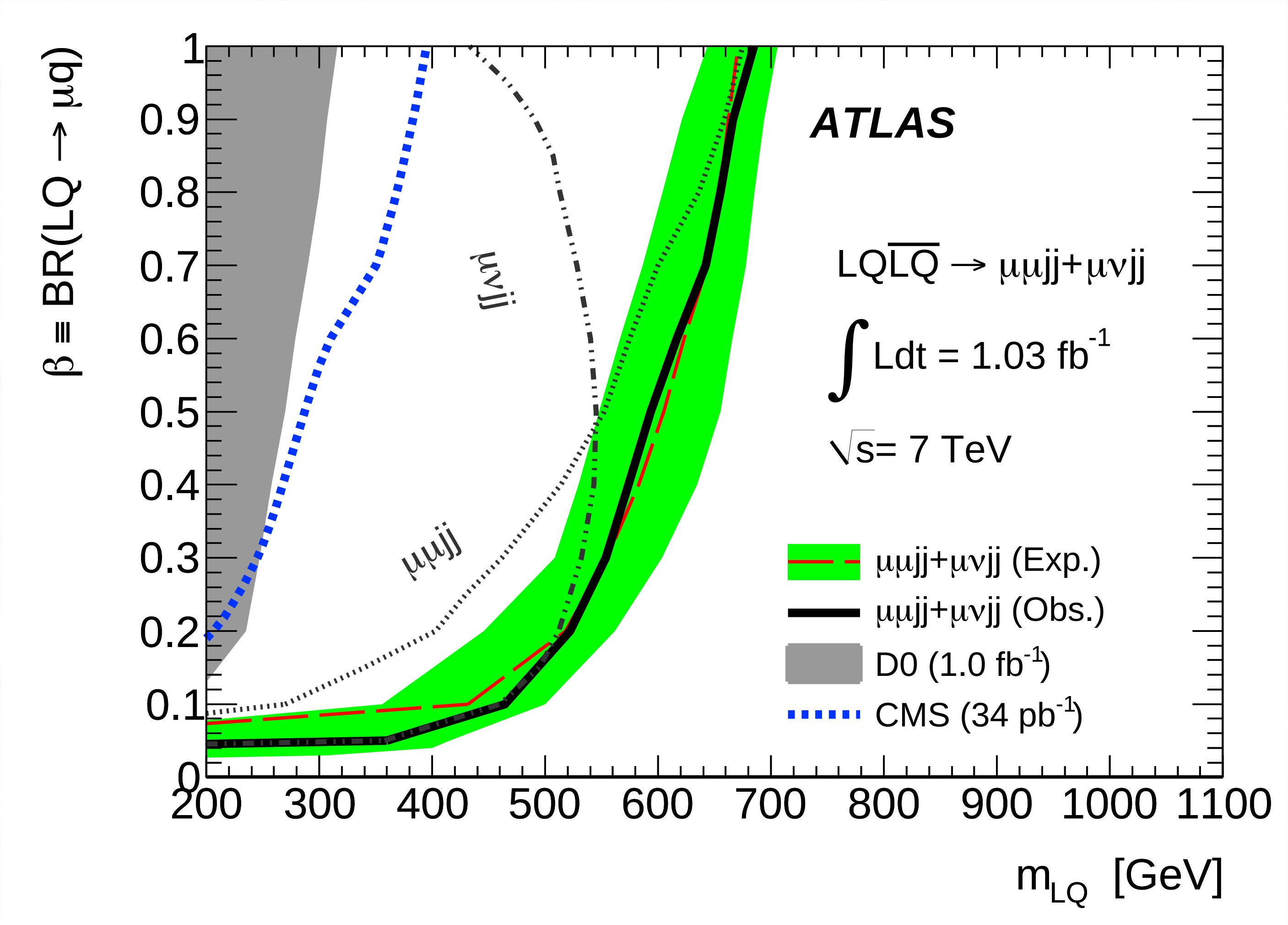
$\beta = 1.0$

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

$\beta = 0.5$

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

Excluded regions of parameter space:



Current mass limits for 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	
HERA	699 GeV/c^2 (λ = 0.3)		
ATLAS	606 GeV/c^2 (1 fb^{-1})	594 GeV/c^2 (1 fb^{-1})	534 GeV/c^2 (4.7 fb^{-1})
CMS	845 GeV/c^2 (19.6 fb^{-1})	785 GeV/c^2 (19.6 fb^{-1})	550 GeV/c^2 (19.7 fb^{-1})

$\beta = 0.5$

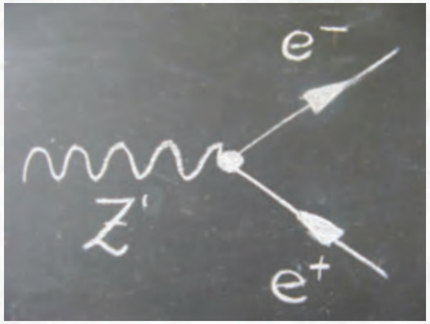
LHC reach for other BSM Physics

(expected discovery sensitivity for 30 and 100 fb^{-1} @ 14 TeV)

:·

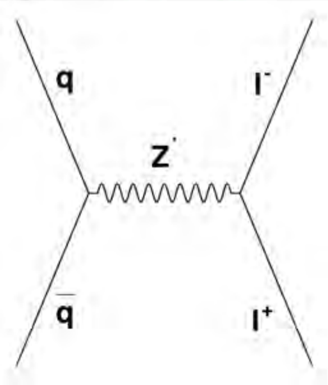
	30 fb^{-1}	**100 fb^{-1}**
Excited Quarks $Q^* \rightarrow q\,\gamma$	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
Z ‘ $\rightarrow \ell\ell$, jj W ‘ $\rightarrow \ell\,\nu$	M (Z ‘) ~ 3 TeV M (W ‘) ~ 4 TeV	M (Z ‘) ~ 5 TeV M (W ‘) ~ 6 TeV
Compositeness (from Di-jet)	Λ ~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

10.3 Additional Gauge Bosons: W’ and Z’



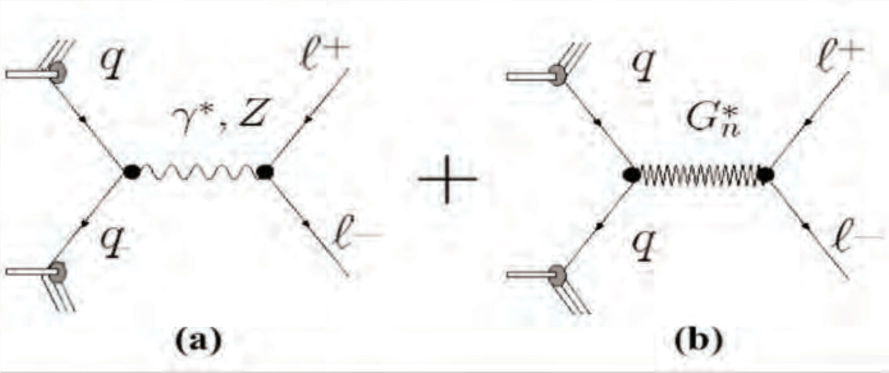
Search for new, high-mass di-lepton resonances

- Additional neutral Gauge Boson Z´



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

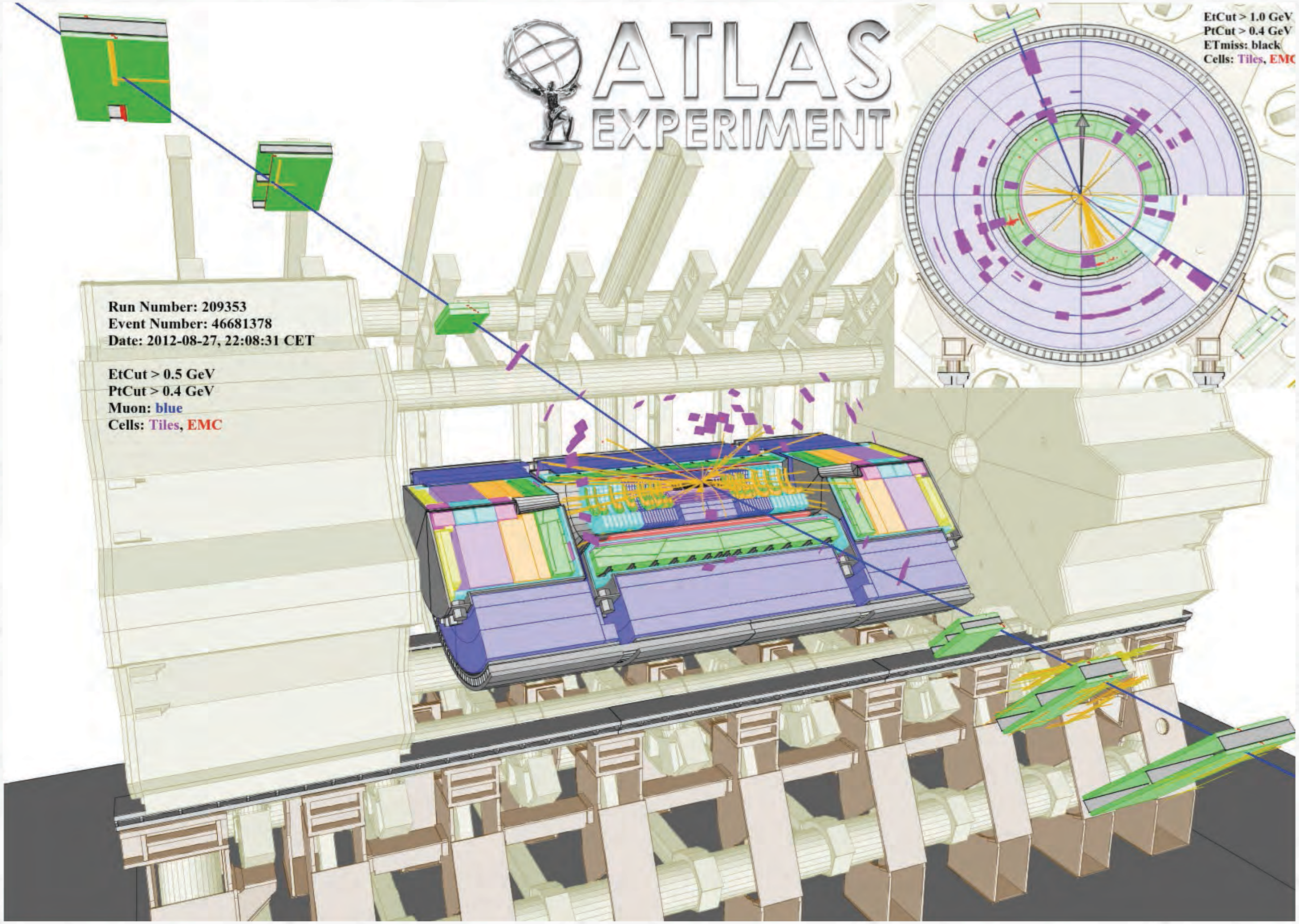
appear in Extra Dim. Scenarios



Standard Model background process

Signal

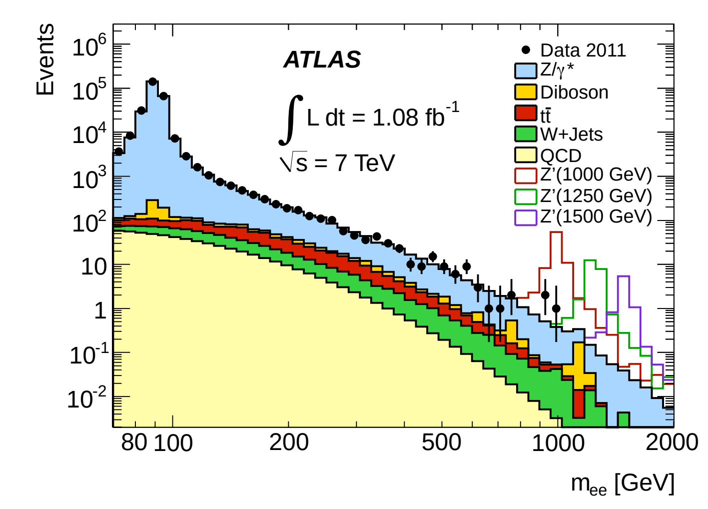
- Identical final state (two leptons), same analysis, interpretation for different theoretical models
- Main background process: Drell-Yan production of lepton pairs



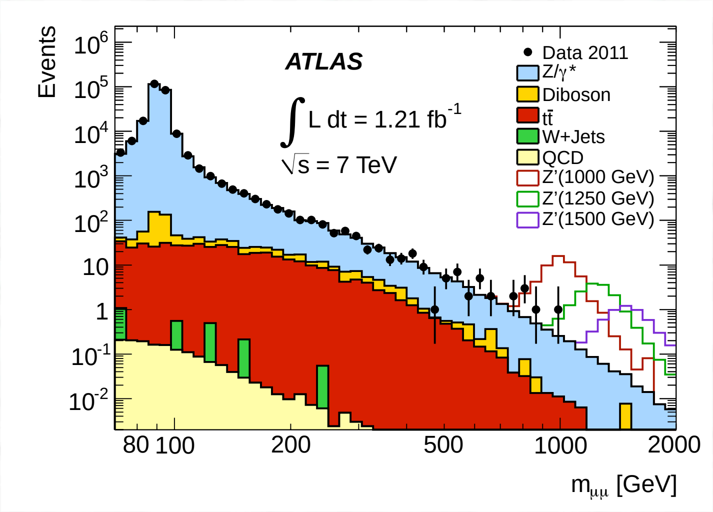
Event display of the selected event with the highest di-muon invariant mass in the ATLAS experiment. The highest momentum muon has a p_T of 653 GeV and an η of 0.99. The subleading muon has a p_T of 646 GeV and an η of -0.85. The invariant mass of the pair is 1844 GeV.

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.

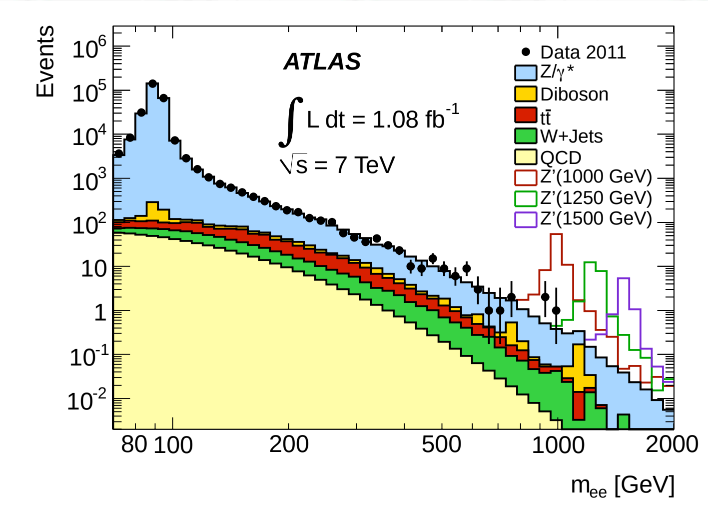
Detailed numbers on signal and background for the ee channel:

$m_{e^+e^-}$ [GeV]	70-110	110-200	200-400	400-800	800-3000
DY	258482 ± 410	5449 ± 180	613 ± 26	53.8 ± 3.1	2.8 ± 0.1
$t\bar{t}$	218 ± 36	253 ± 10	82 ± 3	5.4 ± 0.3	0.1 ± 0.0
Diboson	368 ± 19	85 ± 5	29 ± 2	3.1 ± 0.5	0.3 ± 0.1
W+jets	150 ± 100	150 ± 26	43 ± 10	4.6 ± 1.8	0.2 ± 0.4
QCD	332 ± 59	191 ± 75	36 ± 29	1.8 ± 1.4	< 0.05
Total	259550 ± 510	6128 ± 200	803 ± 40	68.8 ± 3.9	3.4 ± 0.4
Data	259550	6117	808	65	3

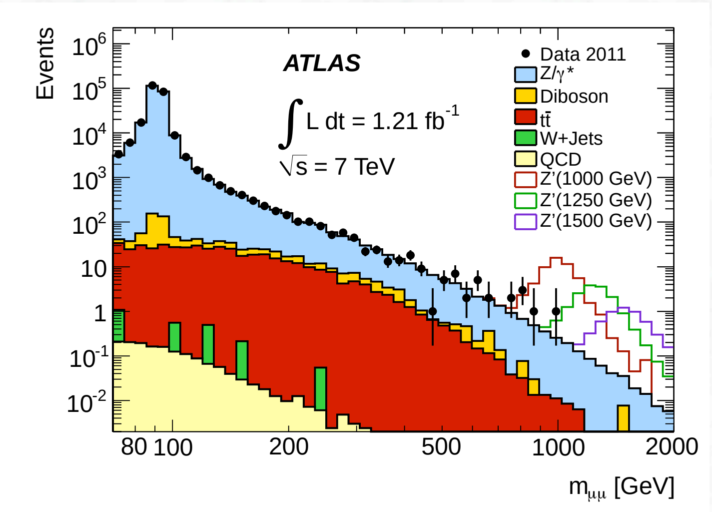
Drell-Yan background can be normalized in the Z peak region, 70-110 GeV

Development with more data: from 1.1 fb^{-1} to 20 fb^{-1}

Di-electron invariant mass

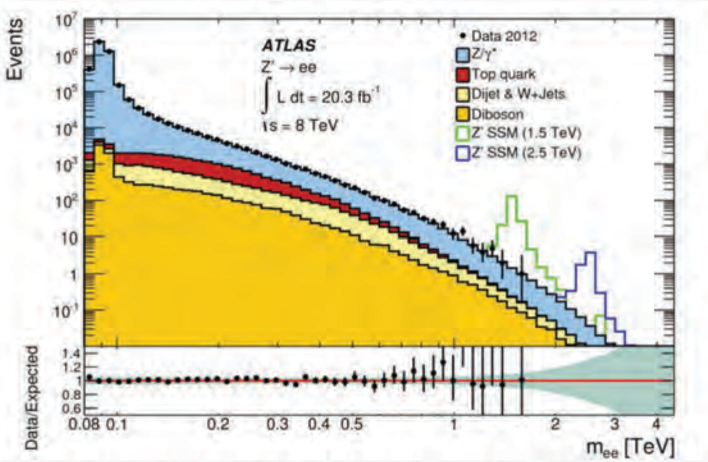


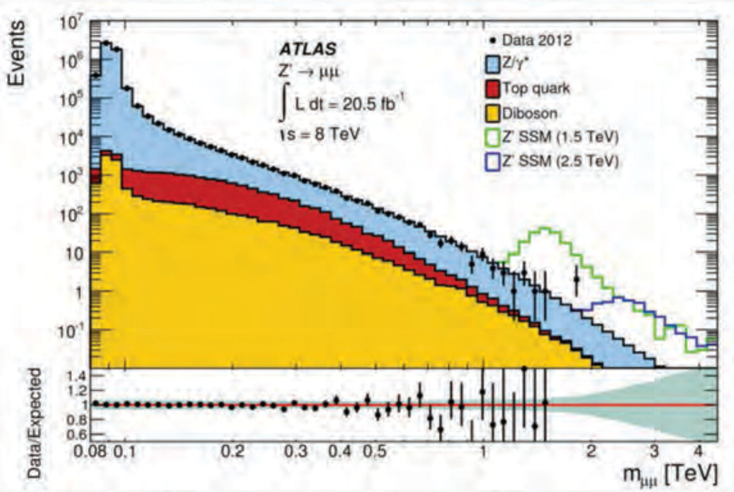
Di-muon invariant mass



2011:

L = 1.1–1.2 fb^{-1}



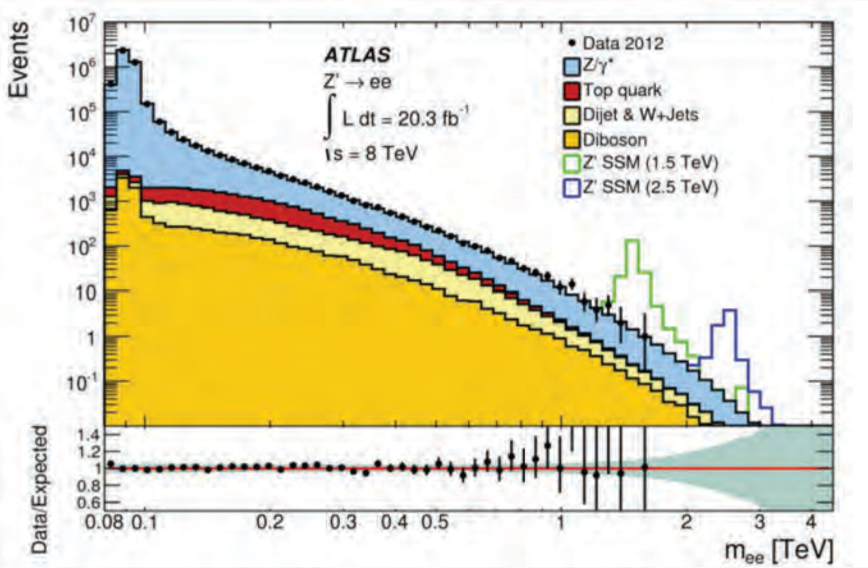


2012:

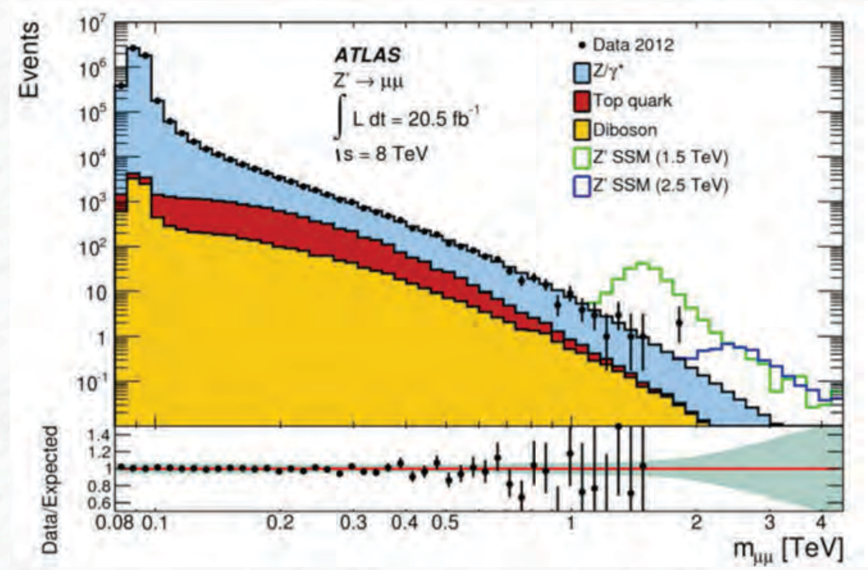
L = 20 fb^{-1}

Search for New Resonances in High Mass Di-leptons

Di-electron invariant mass



Di-muon invariant mass



Data are still consistent with background from SM processes (no excess).

Detailed numbers on signal and background for the ee channel:

m_{ee} [GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000	3000 - 4500
Z/γ^*	119000 ± 8000	13700 ± 900	1290 ± 80	68 ± 4	9.8 ± 1.1	0.008 ± 0.005
$t\bar{t}$	7000 ± 800	2400 ± 400	160 ± 60	2.5 ± 0.6	0.11 ± 0.04	< 0.001
Diboson	1830 ± 210	660 ± 160	93 ± 33	4.8 ± 0.8	0.79 ± 0.26	0.005 ± 0.004
Dijet, W + jet	3900 ± 800	1260 ± 310	230 ± 110	8.6 ± 2.4	0.9 ± 0.6	0.004 ± 0.006
Total	131000 ± 8000	18000 ± 1100	1780 ± 150	84 ± 5	11.6 ± 1.3	0.017 ± 0.009
Data	133131	18570	1827	98	10	0

Drell-Yan background can be normalized in the Z peak region, 70-110 GeV

Z' models used in the interpretation

(i) Sequential Standard Model Z'

- Z' has the same couplings to fermions as the Standard Model Z, width of the Z' increases proportional to its mass

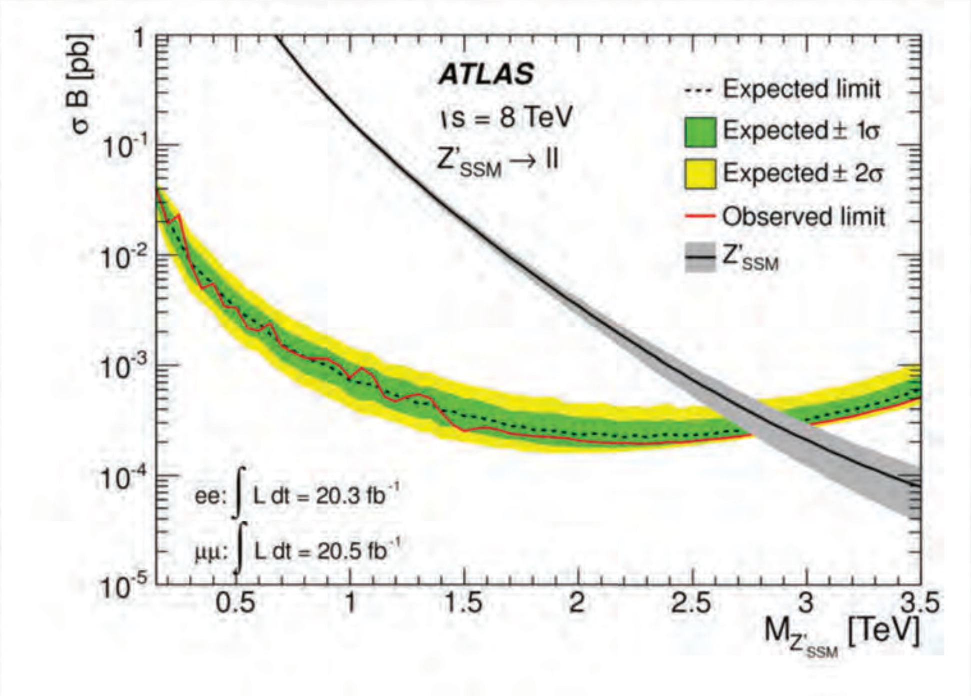
(ii) Models based on the E_6 grand unified symmetry group

- Broken into SU(5) and two additional U(1) groups, leading to two new neutral gauge fields, denoted Ψ and χ.
  The particles associated with the additional fields can mix to form the Z' candidates

  $Z' = Z'_{\Psi} \cos \theta_{E6} + Z'_{X} \sin \theta_{E6}$

- The pattern of symmetry breaking and the value of θ_{E6} determine the Z' couplings to fermions
  (several choices are considered)

Interpretation in the SSM:



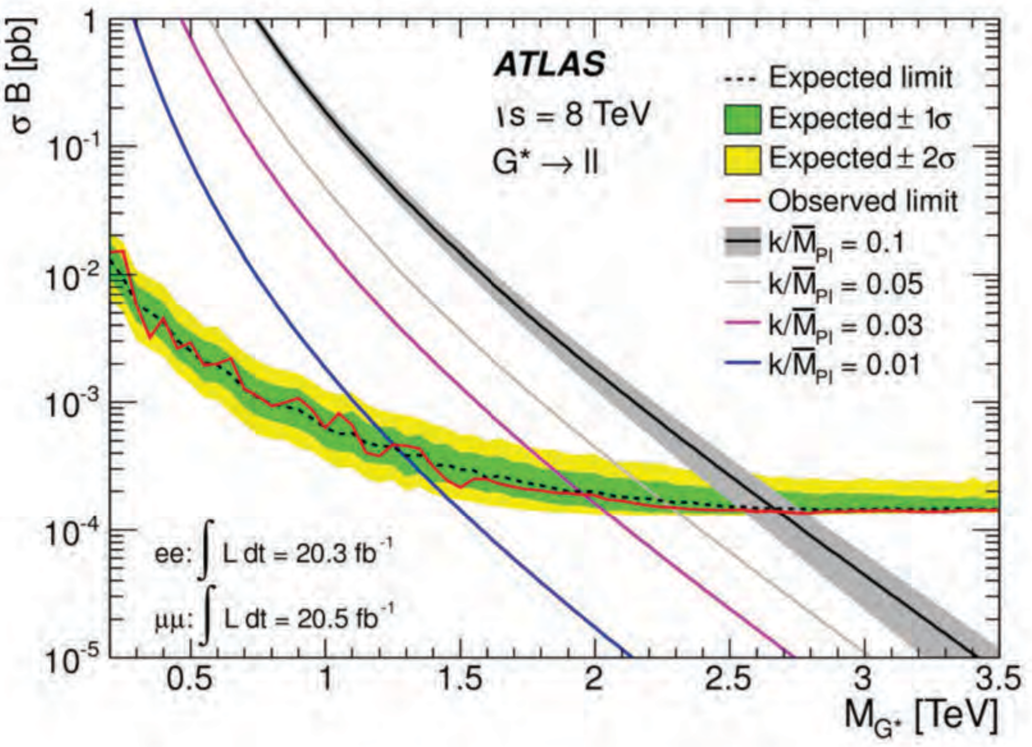
Resulting mass limits: ee + μμ
95% C.L., $\sqrt{s}$ = 8 TeV, L = 20 fb^{-1}

Sequential SM: $m_{Z'}$ > 2.90 TeV
E_6 models: $m_{Z'}$ > 2.43 – 2.73 TeV

Summary of 95% C.L. SSM exclusion limits from various experiments:

95% C.L. limits (SM couplings)	ee	μμ	ll combined
CDF / D0 5.3 fb^{-1}			1.07 TeV
ATLAS 0.036 fb^{-1}	0.96 TeV	0.83 TeV	1.05 TeV
ATLAS $\sqrt{s}$= 7 TeV, L =1.1 / 1.2 fb^{-1}	1.70 TeV	1.61 TeV	1.83 TeV
ATLAS $\sqrt{s}$= 8 TeV, 20 fb^{-1}	2.79 TeV	2.53 TeV	2.90 TeV

Interpretation in the Randall-Sundrum models: Graviton resonances: G → ll
(Kaluza-Klein modes)

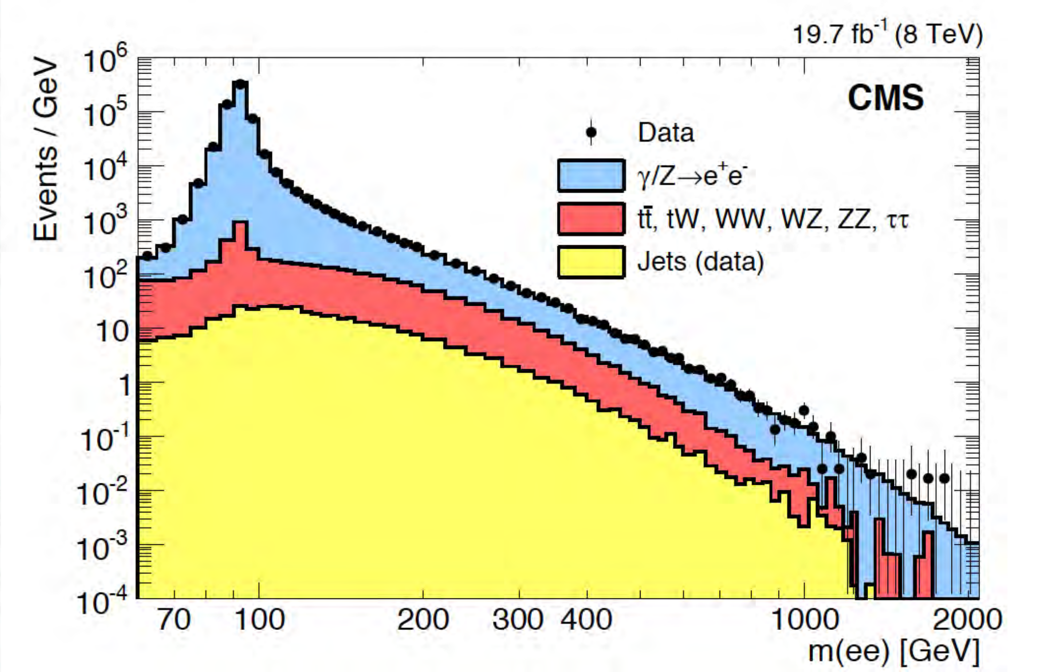


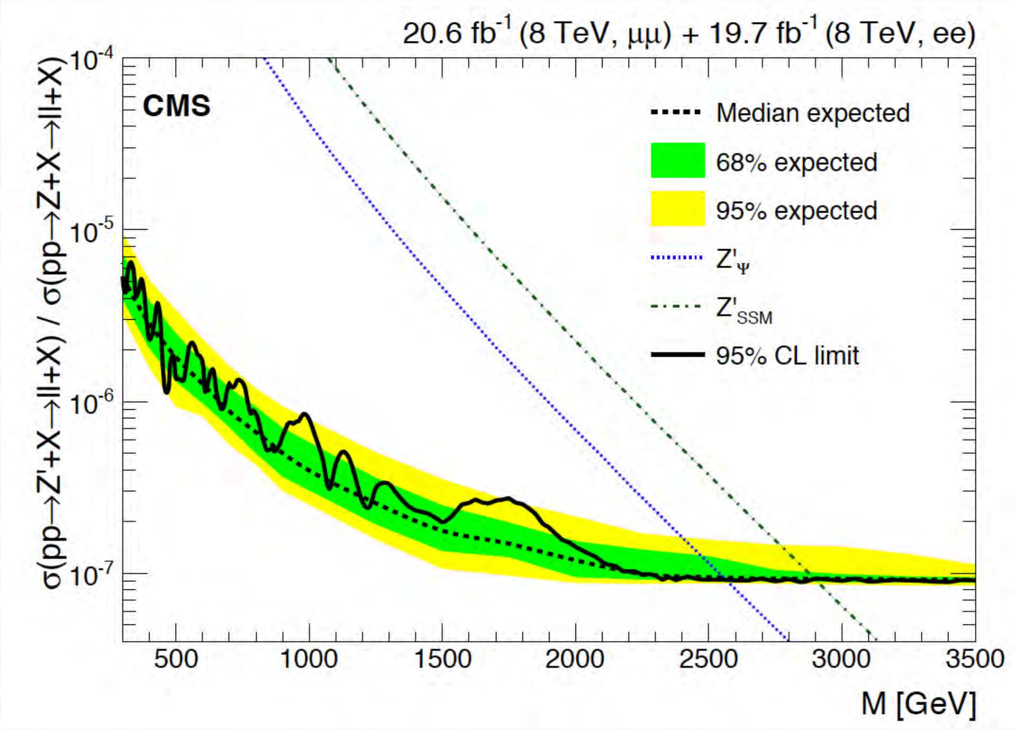
Resulting mass limits: ee + μμ
95% C.L.

k/M'_{Pl} = 0.10: $m_{Z'}$ > 2.47 TeV

Limits as a function of the coupling strength k/M'_{Pl}

k : = space-time curvature in the extra dimension
$M'_{Pl} = M_{Pl} / \sqrt{8\pi}$ (reduced Planck scale)





Resulting mass limits: ee + μμ
95% C.L. from the CMS analyses

Sequential SM: $m_{Z'}$ > 2.96 TeV
E_6 models: $m_{Z'\psi}$ > 2.60 TeV

Search for W' $\rightarrow l\nu$

- 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

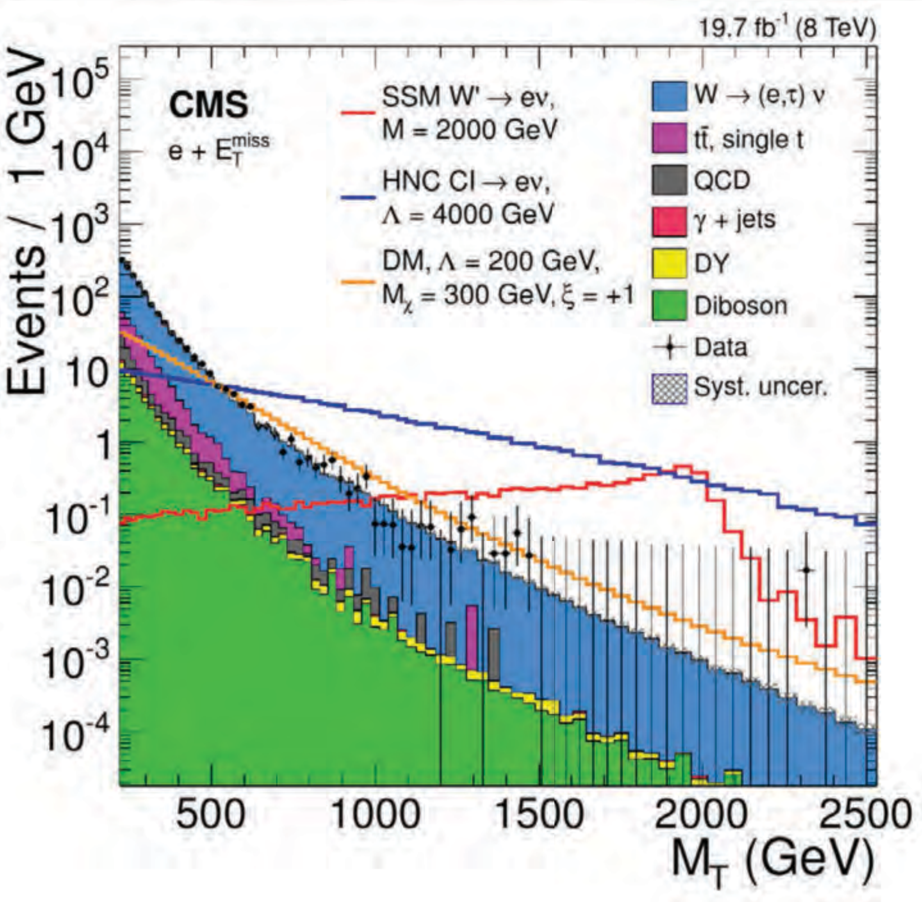
- Assume ν from W' decay to be light and stable, and W' to have the same couplings as in the SM (*"Sequential Standard Model, SSM")*

Signature: high p_T electron + high E_t^{miss}

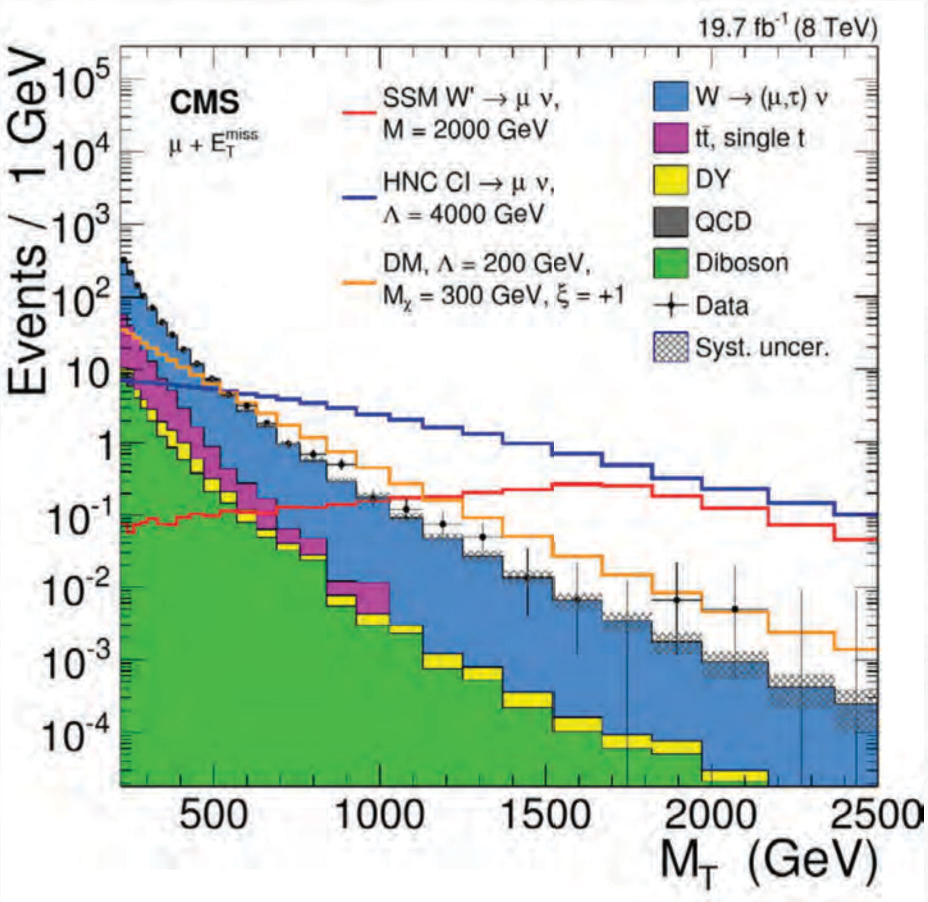
→ peak in transverse mass distribution

Search for New Resonances in High Mass lν events

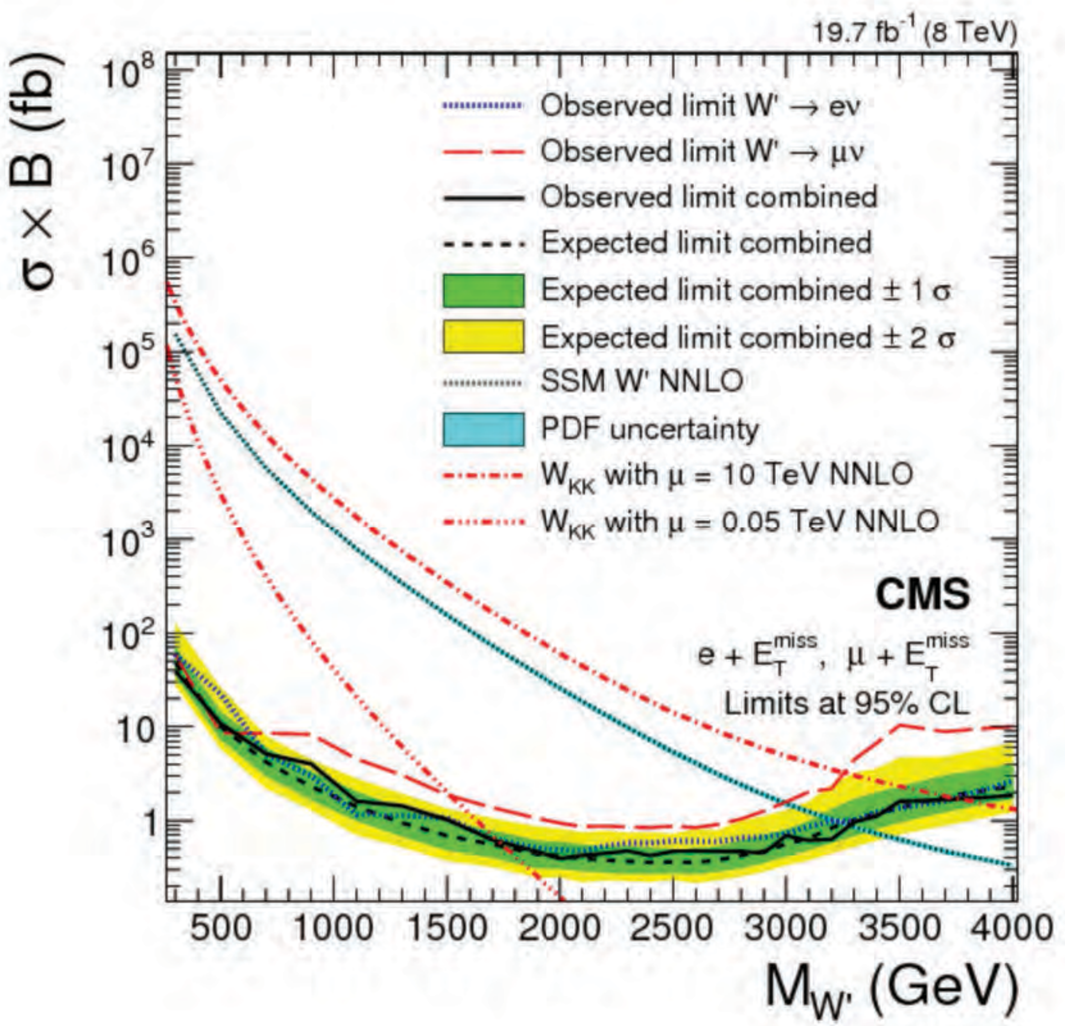
Transverse mass (e, E_T^{miss})



Transverse mass (μ, E_T^{miss})



Interpretation in the Sequential SM

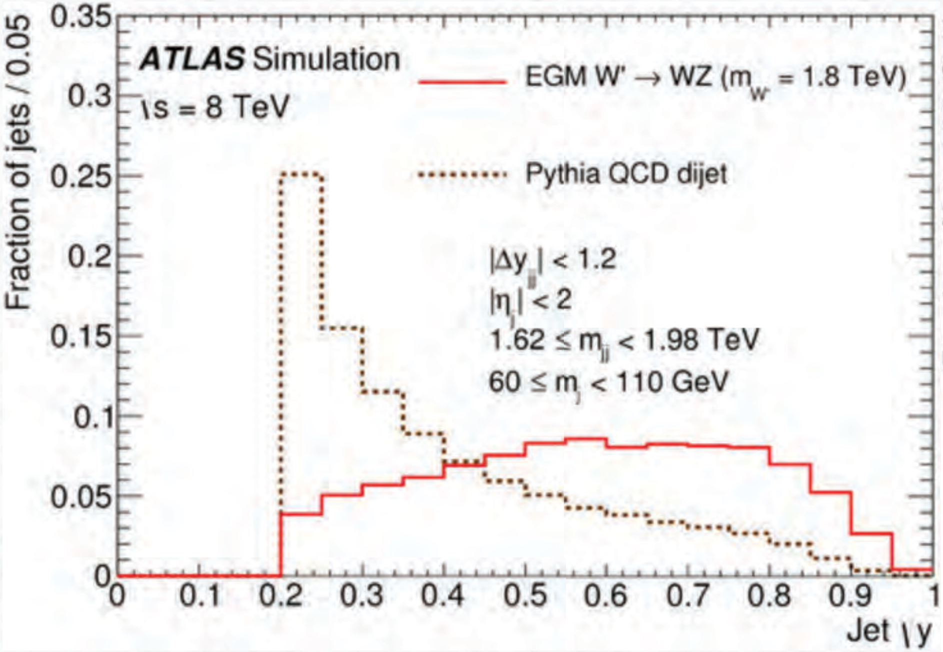


Resulting mass limits: eν + μν
95% C.L. from the CMS analyses

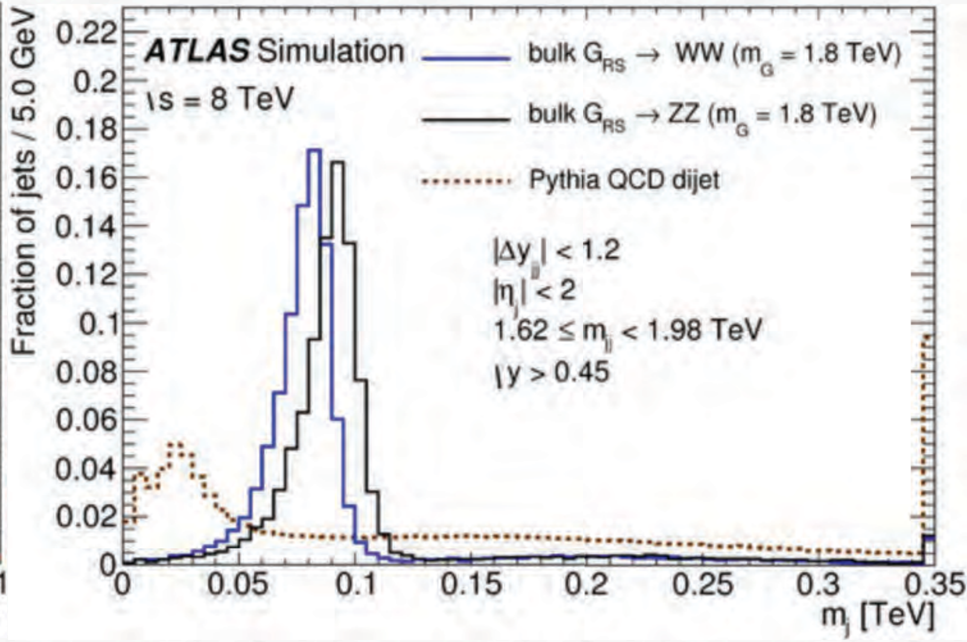
Sequential SM: $m_{W'}$ > 3.35 TeV

Search for WW, WZ, and ZZ resonances

Fully hadronic final state
Use jet substructure techniques

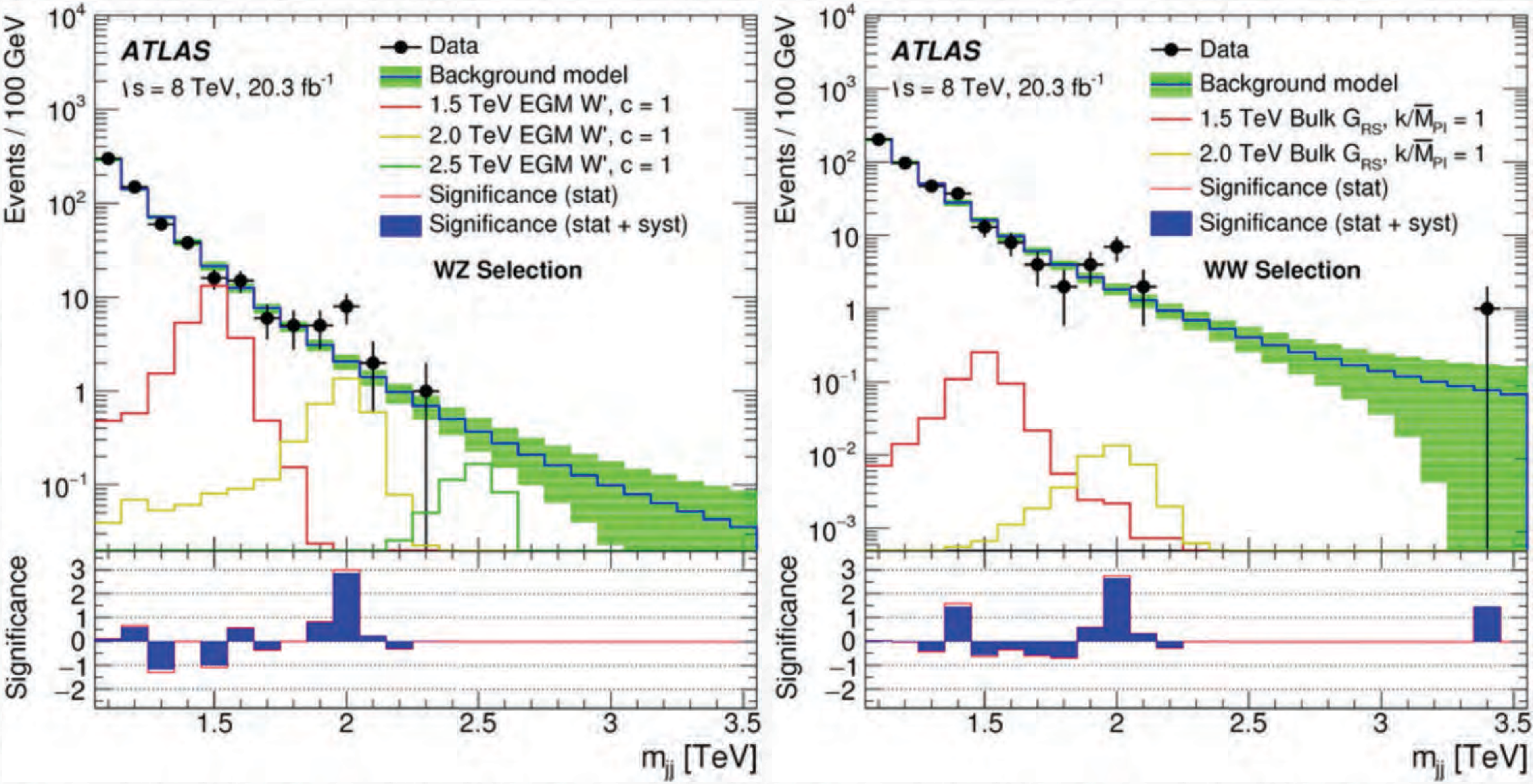


subjet momentum balance



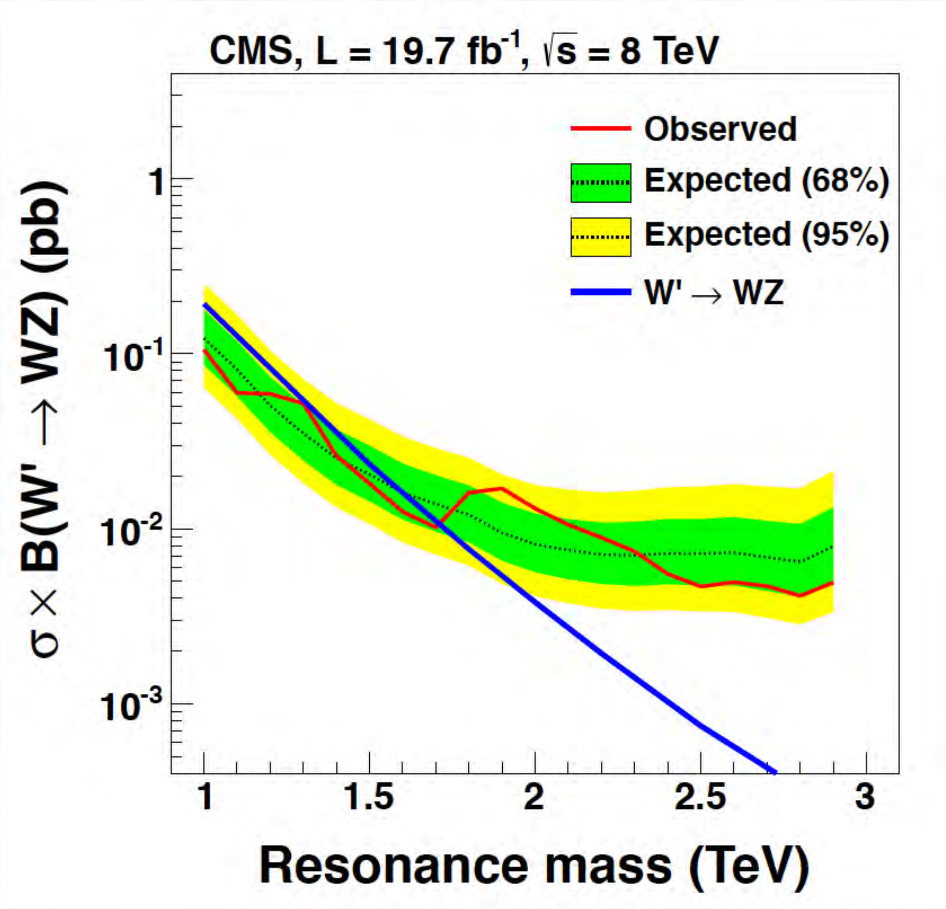
mass m_j of the groomed jet

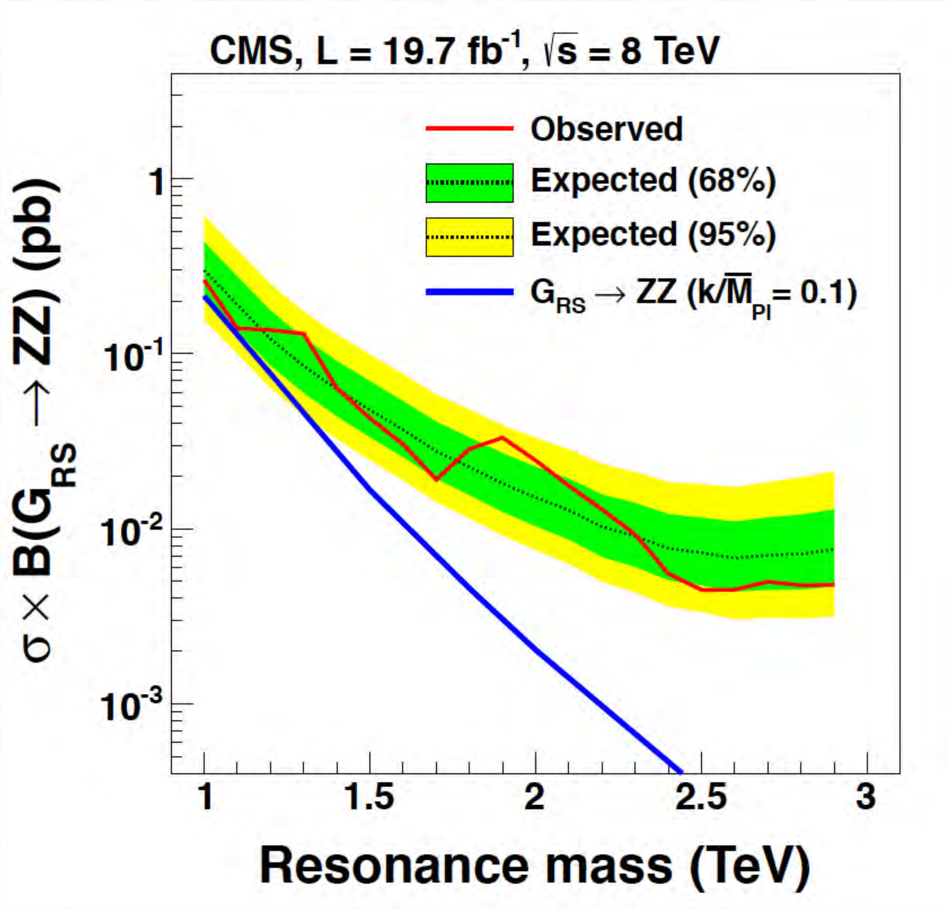
Search for WW, WZ, and ZZ resonances



Search for WW, WZ, and ZZ resonances

Fully hadronic final state
Use jet substructure techniques





10.4 Search for substructure / compositeness of quarks

- Substructure of quarks would lead to contact interactions at high energy scales between the constituents

- Such interactions would lead to deviations from the expected QCD scattering behaviour, which would be most visible in:
  - the inclusive jet cross section at high p_T
  - the di-jet invariant mass distribution

    (traditional variables, but very sensitive to uncertainties on the jet energy measurement, i.e. jet energy scale)
  - the di-jet angular distributions of jets in the parton-parton centre-of-mass system

- Parametrize effects by using an effective Lagrangian, in addition to the QCD terms

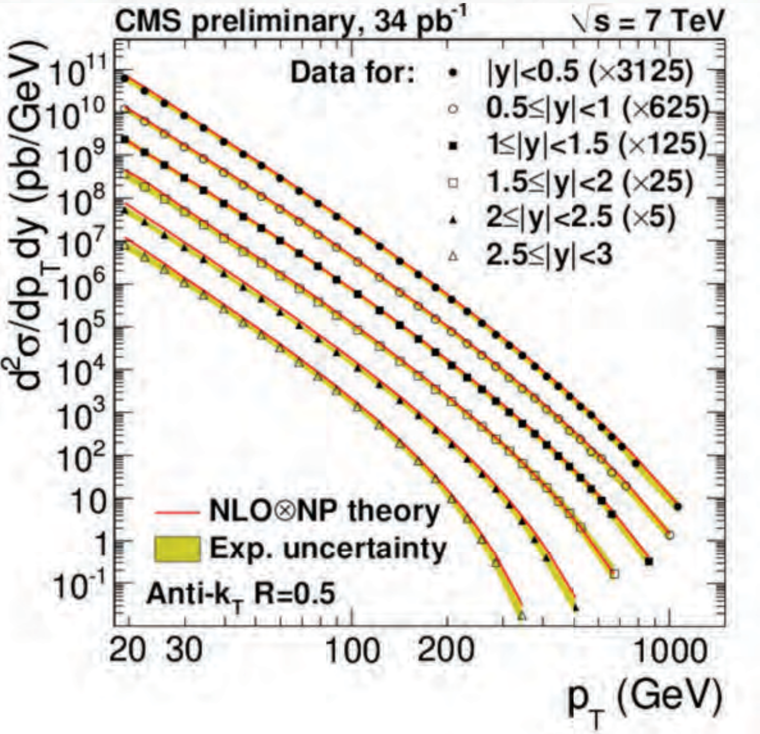
$$L_{qqqq}(\Lambda) = \frac{\xi g^2}{2\Lambda^2} \psi_q^L \gamma^\mu \psi_q^L \;\; \psi_q^L \gamma^\mu \psi_q^L \qquad \text{where} \qquad \frac{g^2}{4\pi} = 1$$

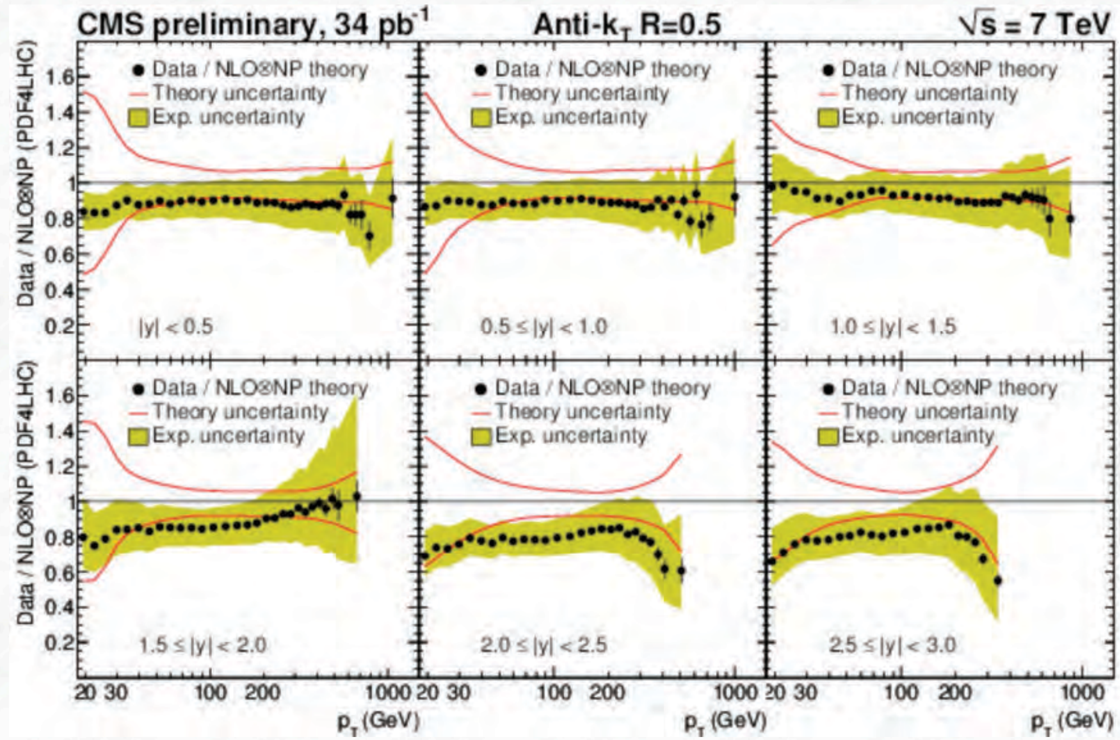
corresponds to a 4-fermion interaction (analogue to Fermi theory) ;

$\xi = \pm 1$, interference parameter, relative phase between QCD terms and contact terms

Λ = scale parameter of new interaction, to be determined in experiment

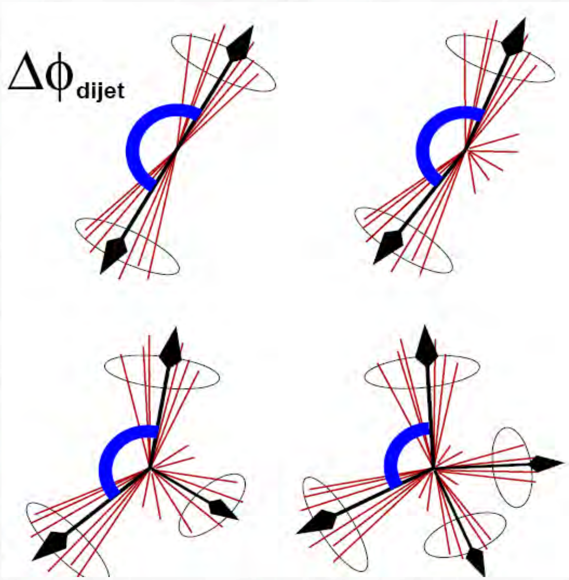
Measured inclusive jet p_T spectrum from CMS (full 2010 dataset)

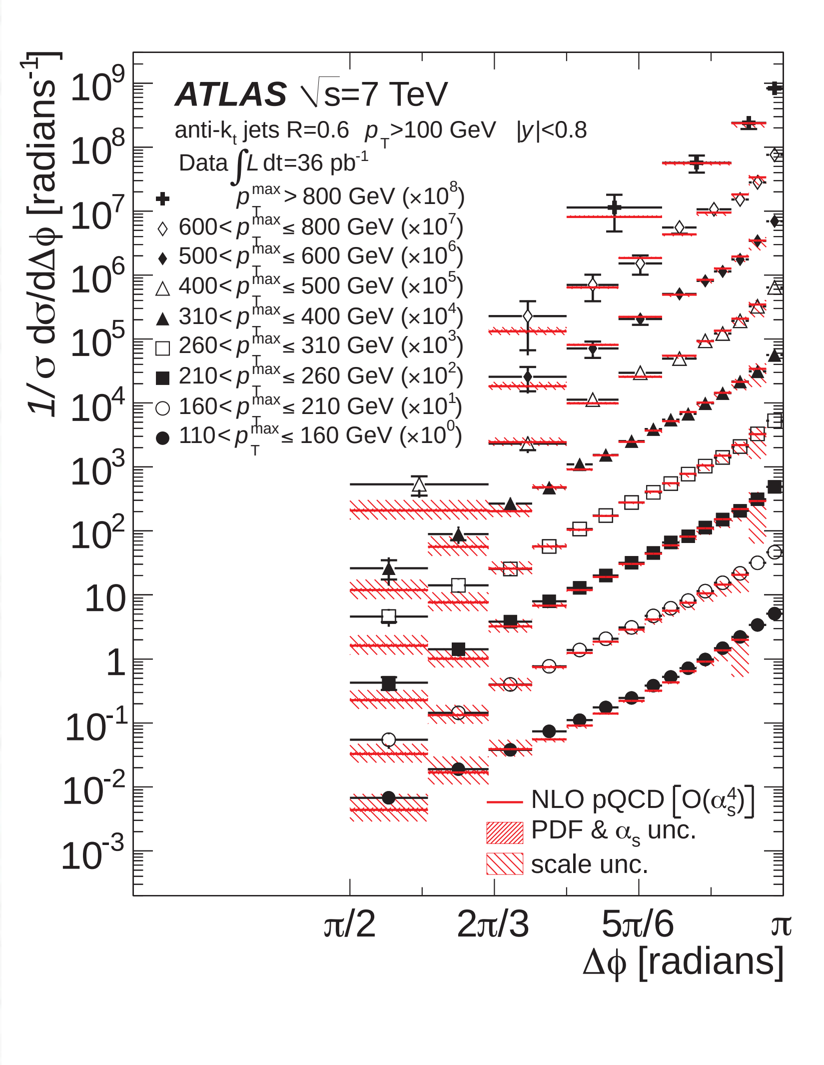




Di-jet angular distributions

- Reduced sensitivity to Jet energy scale
- Sensitivity to higher order QCD corrections preserved

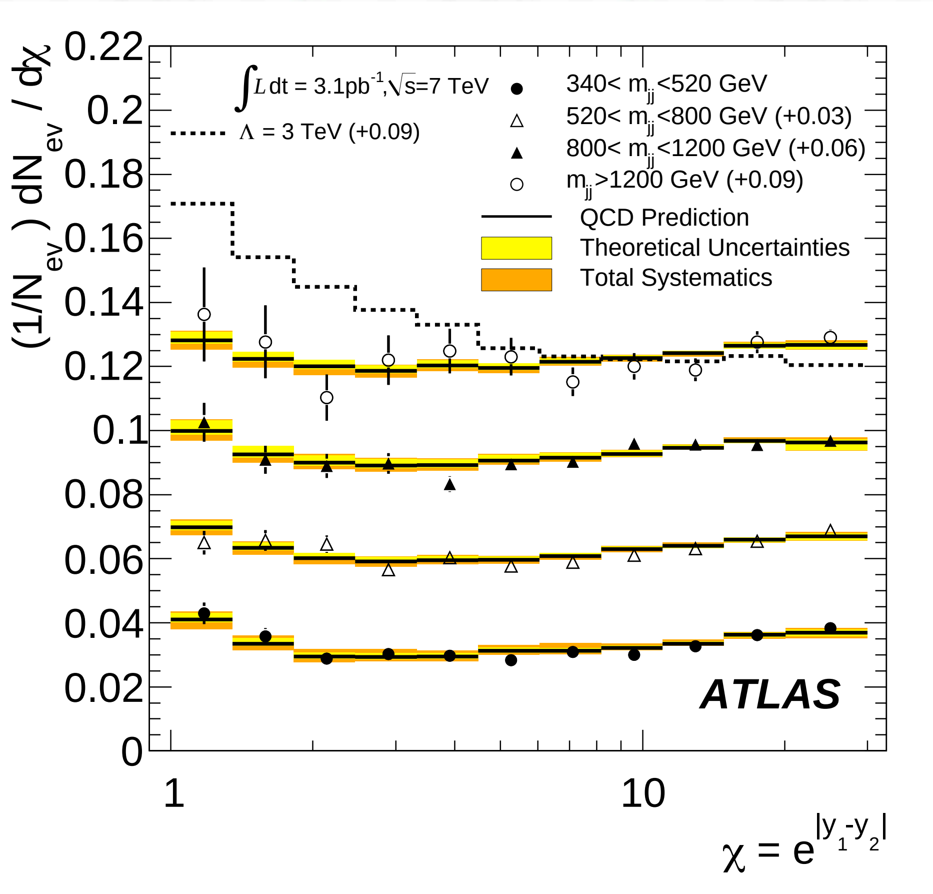




Good agreement with
next-to-leading order QCD predictions

Search for compositeness:

Measurements of the di-jet angular distributions with early ATLAS data (L_{int} = 3.1 pb^{-1})



In QCD: gluon exchange diagrams dominate, have the same angular dependence as Rutherford scattering; essentially flat in the variable

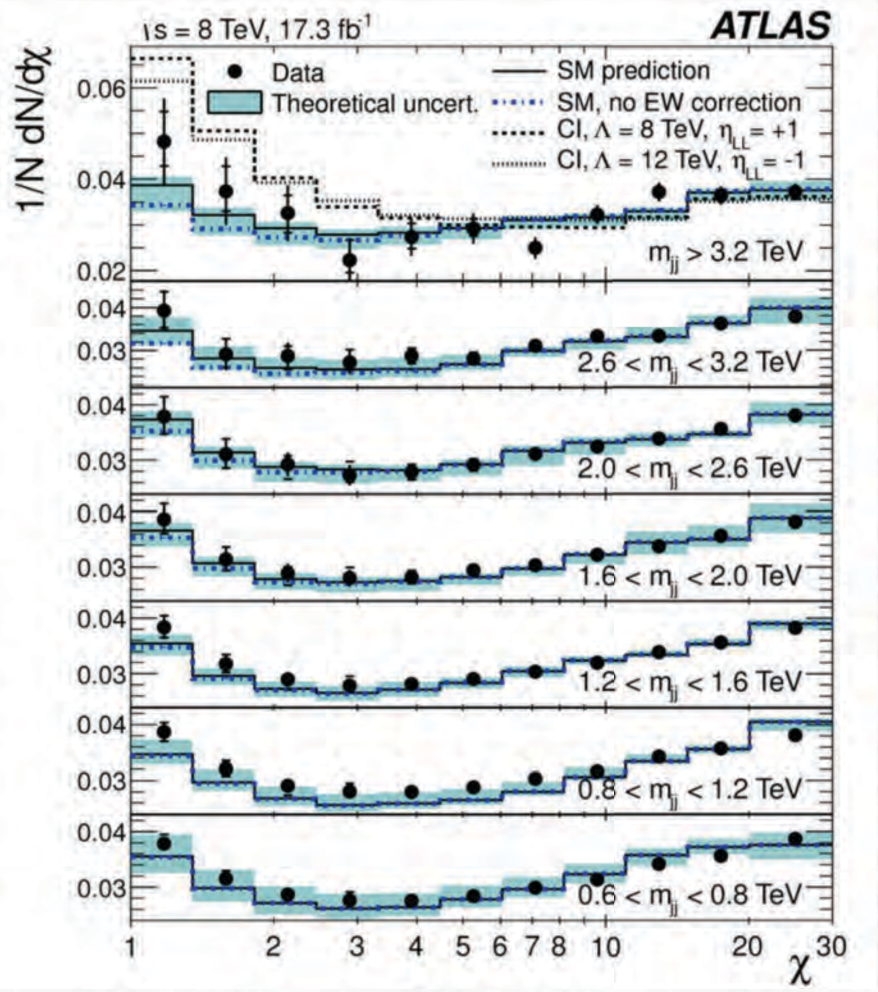
$$\chi = e^{|y_1 - y_2|}$$

y_1, y_2 = rapidities of the two jets

This variable (angular measurement) is less sensitive to the syst. uncertainties on the jet energy measurement (jet energy scale) than the di-jet invariant mass spectrum

Search for compositeness:

Measurements of the di-jet angular distributions
with full ATLAS data (L_{int} = 17.3 fb^{-1}; lower than 20 due to trigger pre-scales)



In QCD: gluon exchange diagrams dominate, have the same angular dependence as Rutherford scattering; essentially flat in the variable

$$\chi = e^{|y_1 - y_2|}$$

y_1, y_2 = rapidities of the two jets

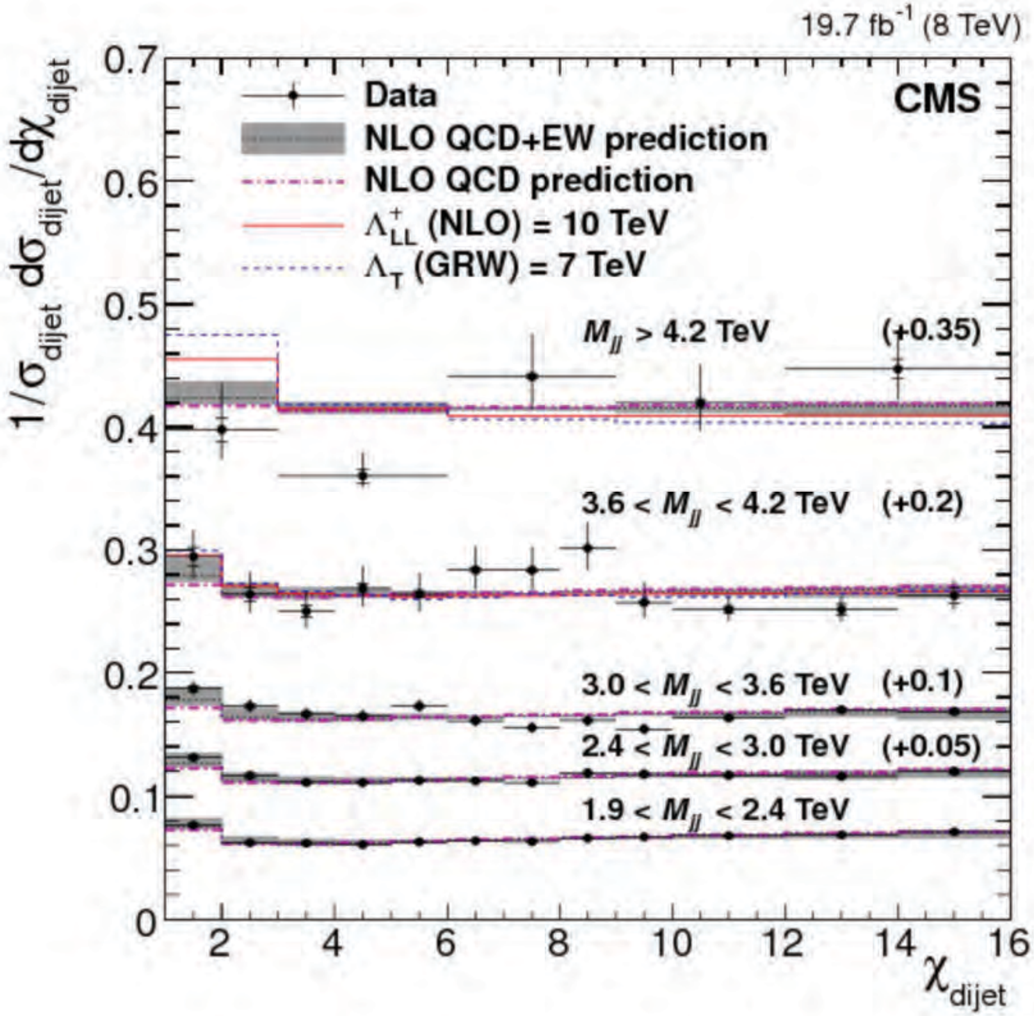
95% C.L. Limits on composite scale Λ :

- 8.1 TeV (destructive interference)
- 12.0 TeV (constructive interference)

This variable (angular measurement) is less sensitive to the syst. uncertainties on the jet energy measurement (jet energy scale) than the di-jet invariant mass spectrum

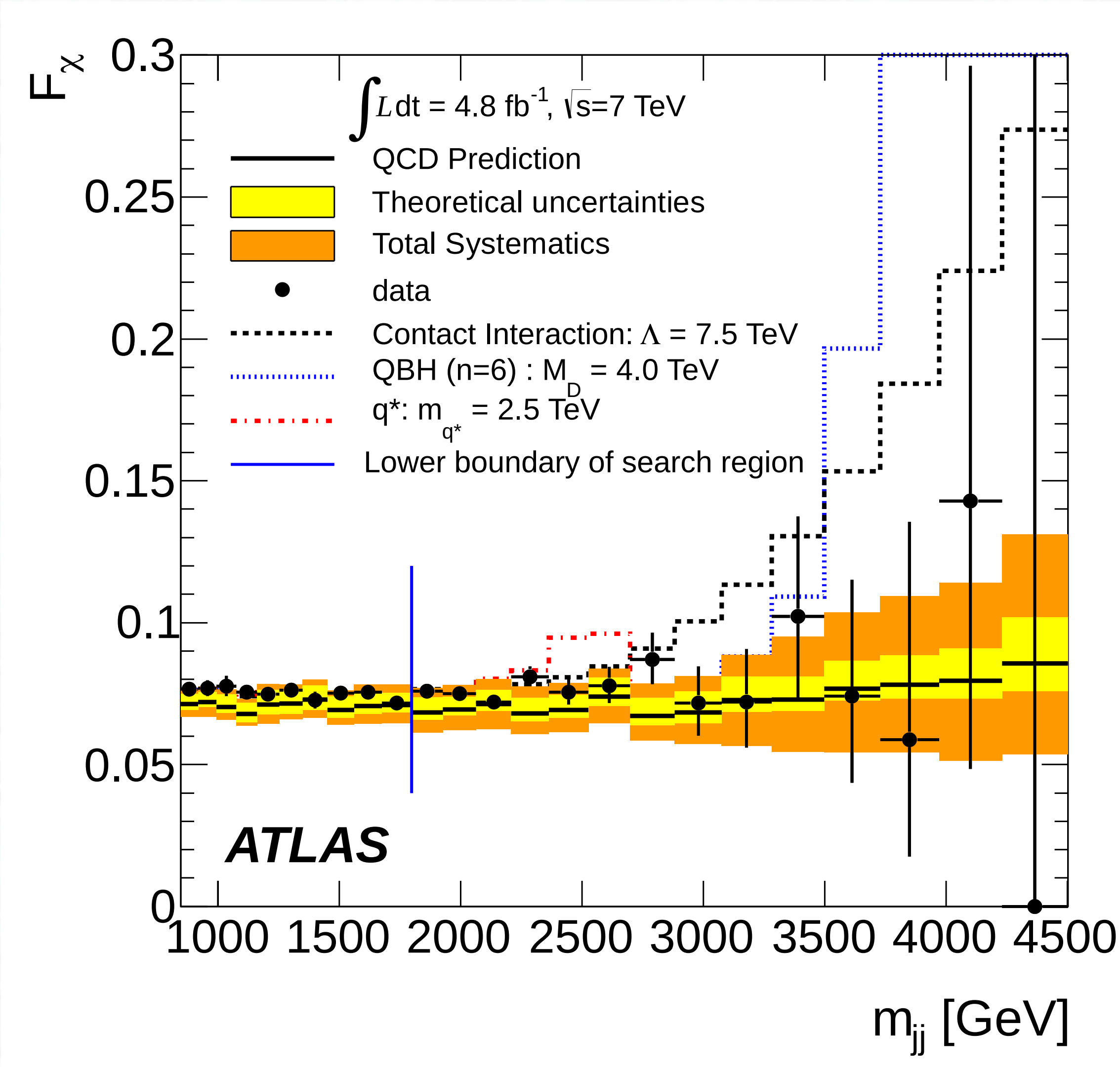
Results on χ measurement from the CMS experiment

based on full dataset



95% C.L. Limits on composite scale Λ :

- 9.0 TeV (destructive interference)
- 11.7 TeV (constructive interference)



$$F_\chi(m_{jj}) \equiv \frac{\mathrm{d}N_{\mathrm{central}}/\mathrm{d}m_{jj}}{\mathrm{d}N_{\mathrm{total}}/\mathrm{d}m_{jj}}$$

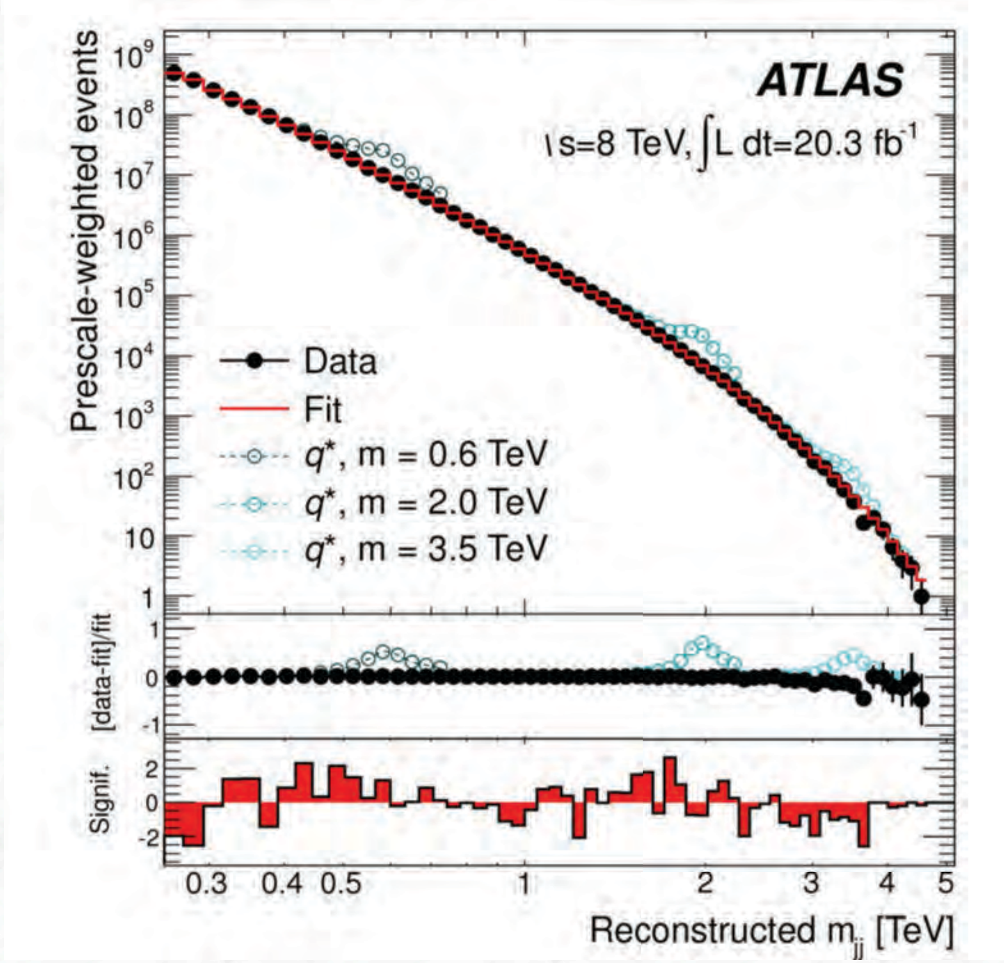
Search for Resonances in the di-jet mass distribution

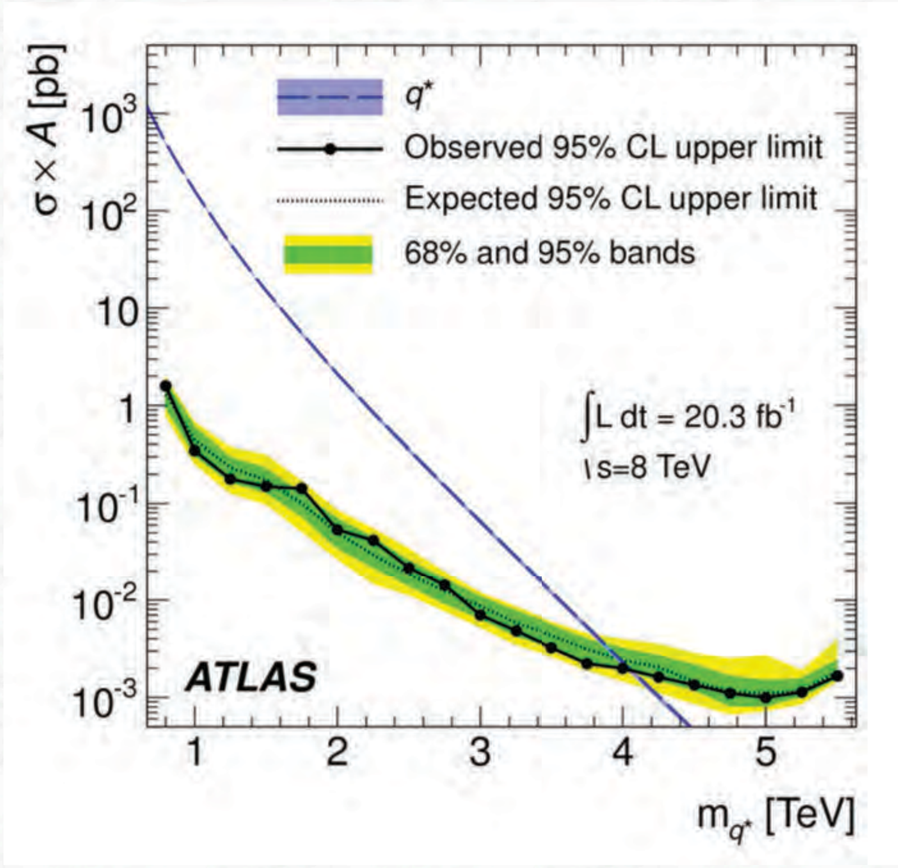
Many extensions of the Standard Model predict the existence of new massive objects that couple to quarks (q) and gluons (g) and result in resonances in the di-jet mass spectrum:

Some examples searched for by ATLAS and CMS:

- Excited quarks q*, which decay to qg, predicted if quarks are composited objects
- Axial-vector particles called axigluons (A), which decay to qq, predicted in a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry $SU(3)_L$ x $SU(3)_R$
- New gauge bosons (W' and Z'), which decay into qq, predicted by models that include new gauge symmetries; the W' and Z' are assumed to have Standard Model couplings
- Randall-Sundrum (RS) gravitons (G), which decay to qq and gg, predicted in the RS model of extra dimensions; the value of the dimensionless coupling k/M'_{Pl} is chosen to be 0.1.
- ....

ATLAS search in data corresponding to L_{int} = 20.3 fb^{-1}





- Search for resonance / bump in the invariant dijet mass spectrum
- Assume smooth functional form of the QCD mass spectrum
- No evidence for a resonance → exclusion limits

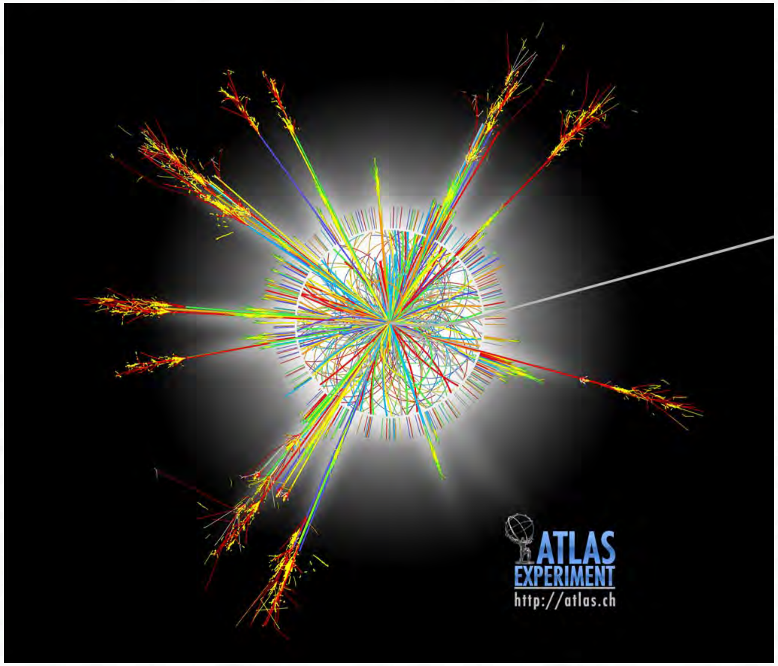
95% C.L. Limits (ATLAS, L = 20.3 fb^{-1}):

Excited quarks: $m_{q*} > 4.06$ TeV

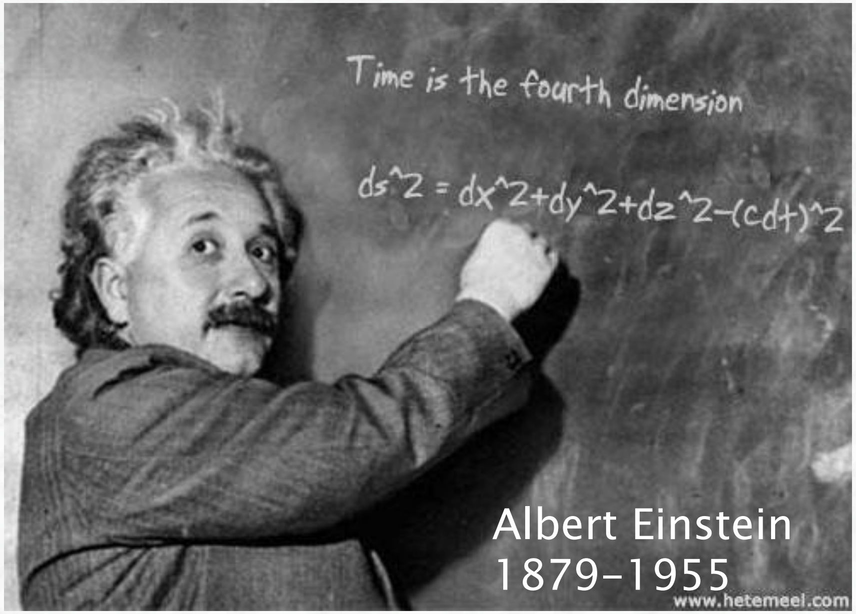
10.5 Extra space dimensions

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

Microscopic-Black Hole Events at the LHC ?



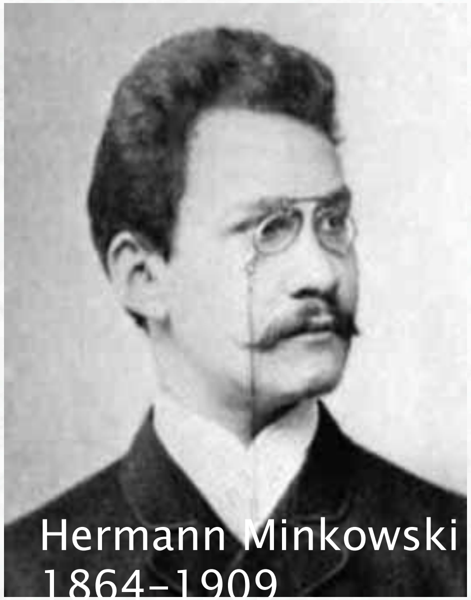
Time is the fourth Dimension



Time:

1. Required by relativity to be a dimension

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



- Space-time 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

- The Polish mathematician T. 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 a five-dimensional world would never have dawned on me…At first glance I like your idea tremendously"

The fifth dimension

Oskar Klein
1894–1977

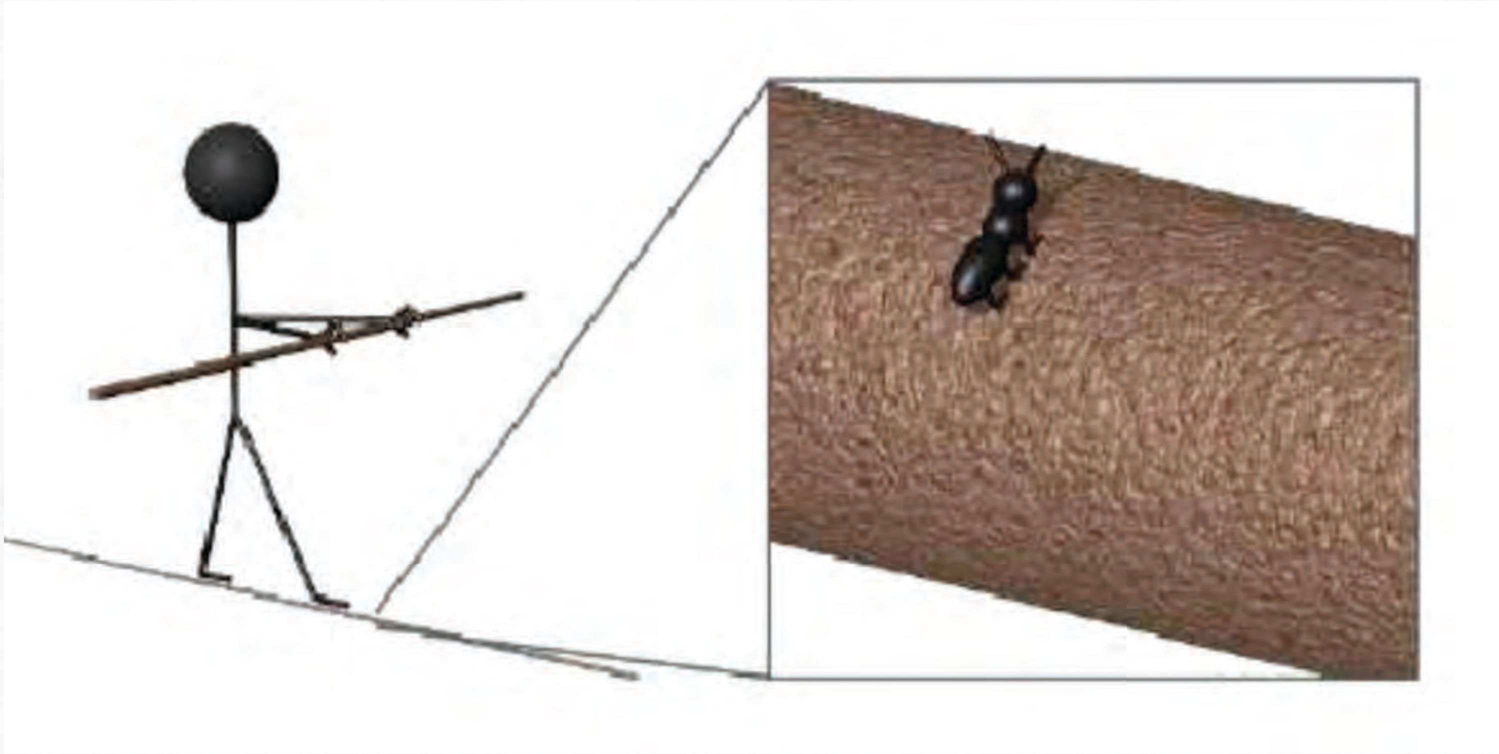
- The Swedish physicist O. Klein proposed in 1926 that the fifth dimension was real, but too tiny to be observed
- Computed to be of a size of 10^{-30} cm to unify gravity with electromagnetism

"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



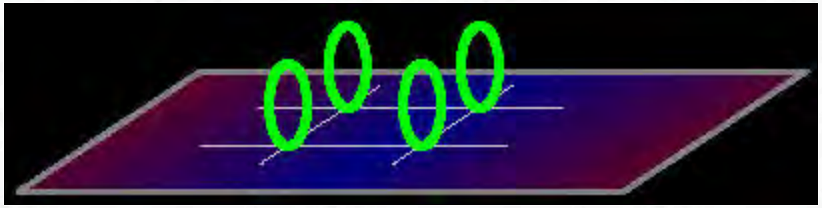
Tightrope walker sees only one dimension

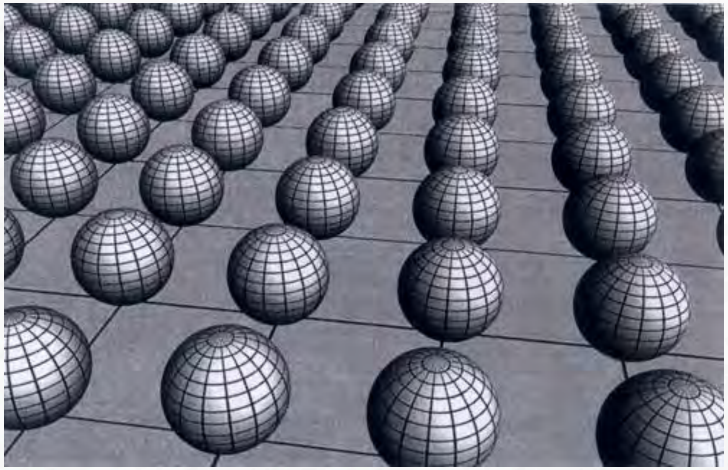
Ant can also go “around the circle”

“Visualizing” Extra Dimensions

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

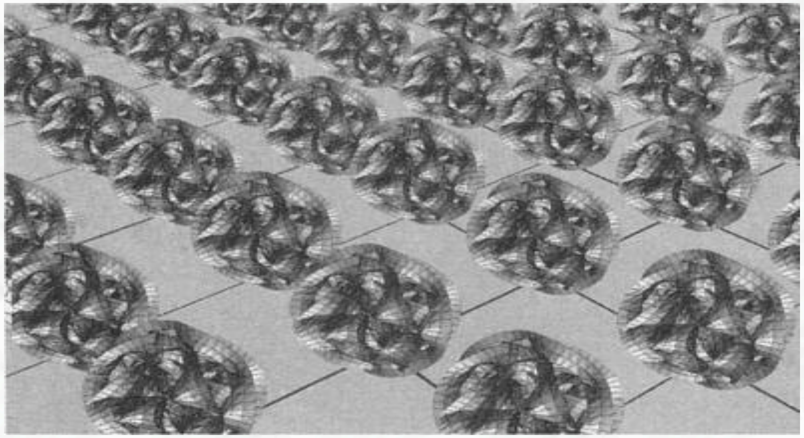
One extra dimension is a circle





Two extra dimensions can be represented by a sphere

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



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

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

r

r

Creators of New Extra-Dimensional Ideas!

Lisa Randall
Harvard

Savas
Dimopoulos
Stanford

Nima Arkani-Hamed
Princeton

Gia Dvali
New York Univ.

Raman Sundrum
Johns Hopkins

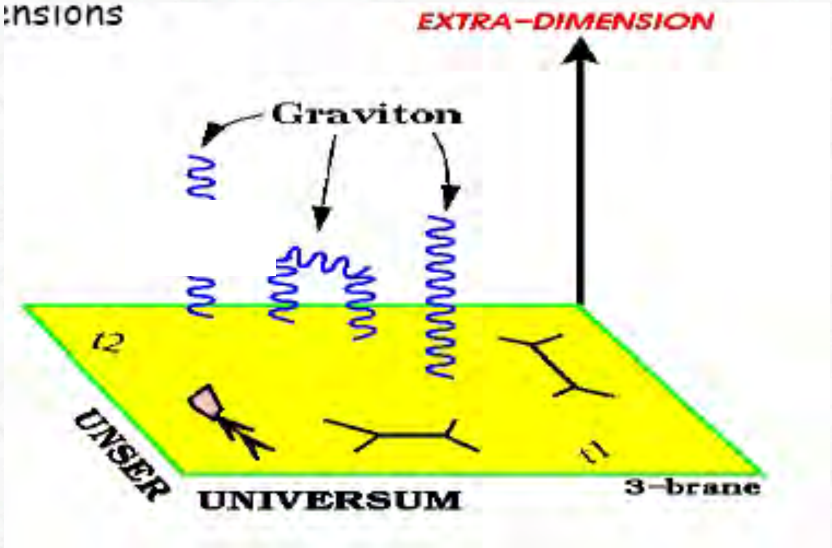
Large Extra Dimensions & the ADD Model

- Assume that there are n compactified extra space dimensions, with size r
- Only gravity can propagate in the extra dimensions;

Relation between Planck mass M_{Pl} in 4 and (4+n) dimensions M_D:

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

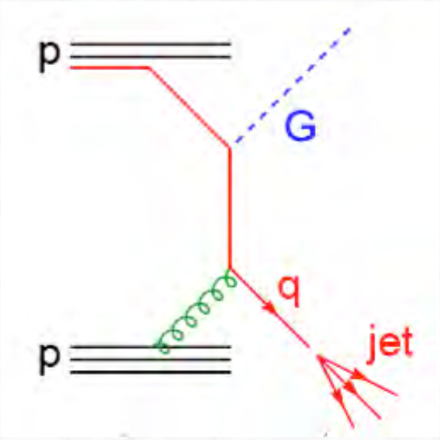
- The Standard Model interactions and all matter particles are confined to our 3-dimensional world



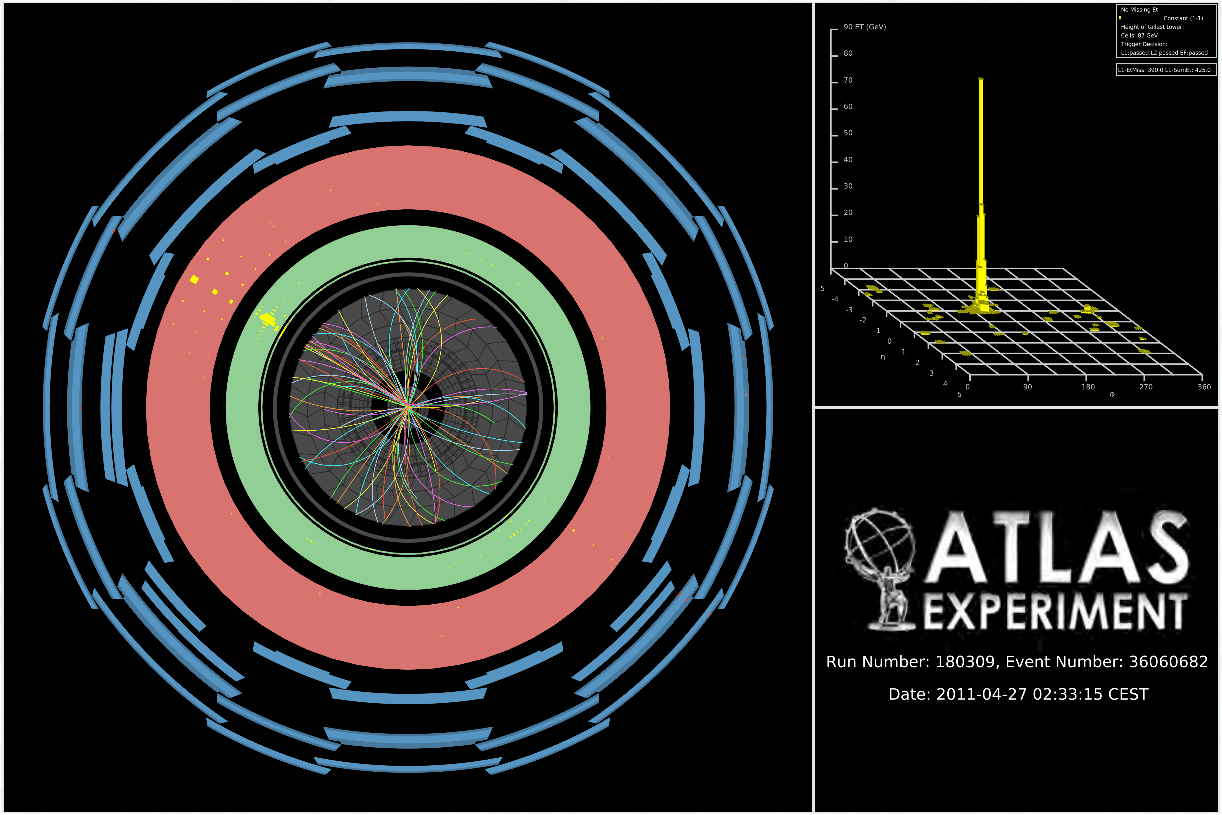
Arkani-Hamed, Dimopoulos, Dvali: hep-ph/9803315, 9804398, 9807344

Experimental Signature: Mono-jets from graviton production

Signal: single jet, E_T^{miss}

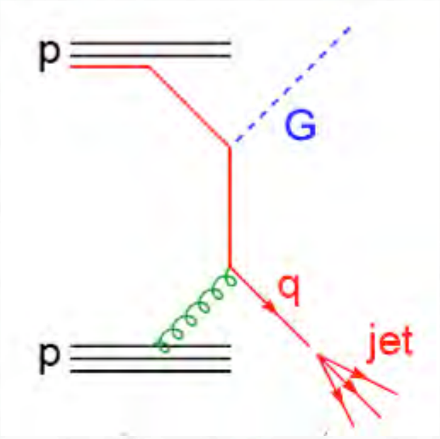


A nice candidate event: 1 jet with p_T = 602 GeV
E_T^{miss} = 523 GeV



Experimental Signature: Monojets

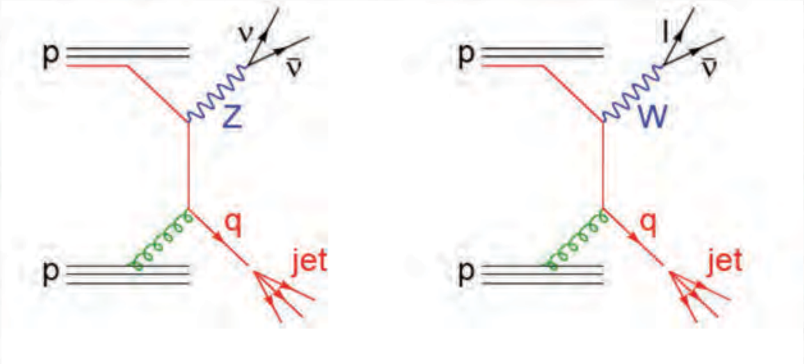
Signal: single jet, E_T^{miss}



Physics background:

- Z + jet, Z → νν (irreducible)

- W+ jet, W → lν, l not detected
- QCD jet background, jet mis-measured



In addition, there could be a sizeable "instrumental / non-physics" background:

- Calorimeter noise, coherent noise in one region of the calorimeter
- Beam induced background
- Background from cosmic rays
  (e.g. high energy muon showers)

Typical selection: ATLAS, 2012 data, $L_{int} = 20.3\ fb^{-1}$

- require strict vertex cuts (five tracks associated to a primary vertex) suppresses beam-related background and cosmic ray backgrounds

- apply tight cuts on the shape of the calorimeter energy depositions, i.e. fraction of el.magn. energy, timing cuts, … (to suppress jets from "correlated noise in the calorimeter")

- Require 1 jet with $p_T > 120$ GeV in the central detector region, $|\eta| < 2.0$ No further jets in the event with $p_T > 30$ GeV within $|\eta| < 4.5$

- $\Delta\phi$ (jet, E_T^{miss}) > 1.0

- E_T^{miss} > 150 GeV, 200 GeV, 250 GeV, 300 GeV, 350 GeV, 400 GeV, 500 GeV, 600 GeV, 700 GeV

- Lepton veto: reject all events with an identified lepton, electrons with $p_T > 20$ or muons with $p_T > 10$ GeV

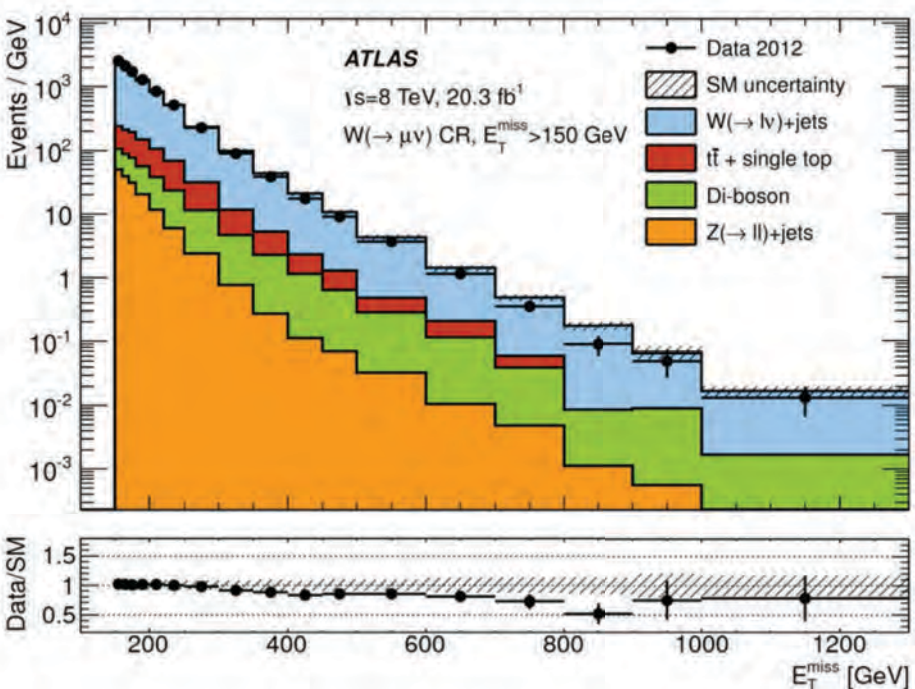
W/Z + jet background estimate from data:

- Control sample, require one or two identified leptons (disjoint to the signal sample); all other cuts identical; done separately for the electron and the muon channels

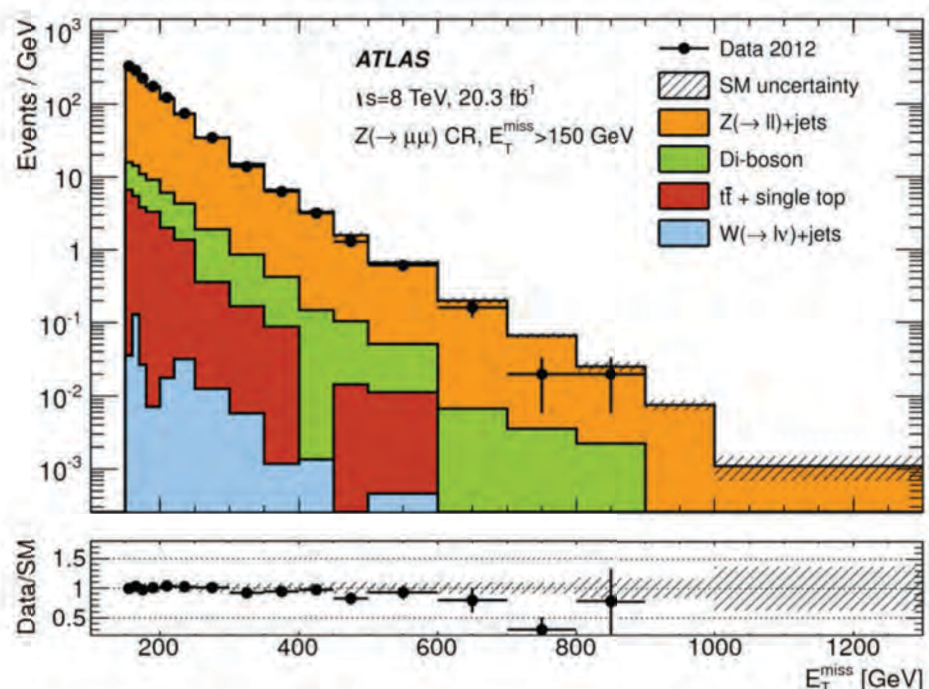
  These control sample contain contributions from Z → ll (two leptons), as well as W → lν, and W → τν (one lepton), plus some pollution by tt background; the latter one is subtracted using the theory prediction (Monte Carlo)

- Normalize the NNLO MC background cross section in each signal region separately according to the ratio found in the individual data/MC control regions

W → μν control region



Z → μμ control region to constrain Z → νν

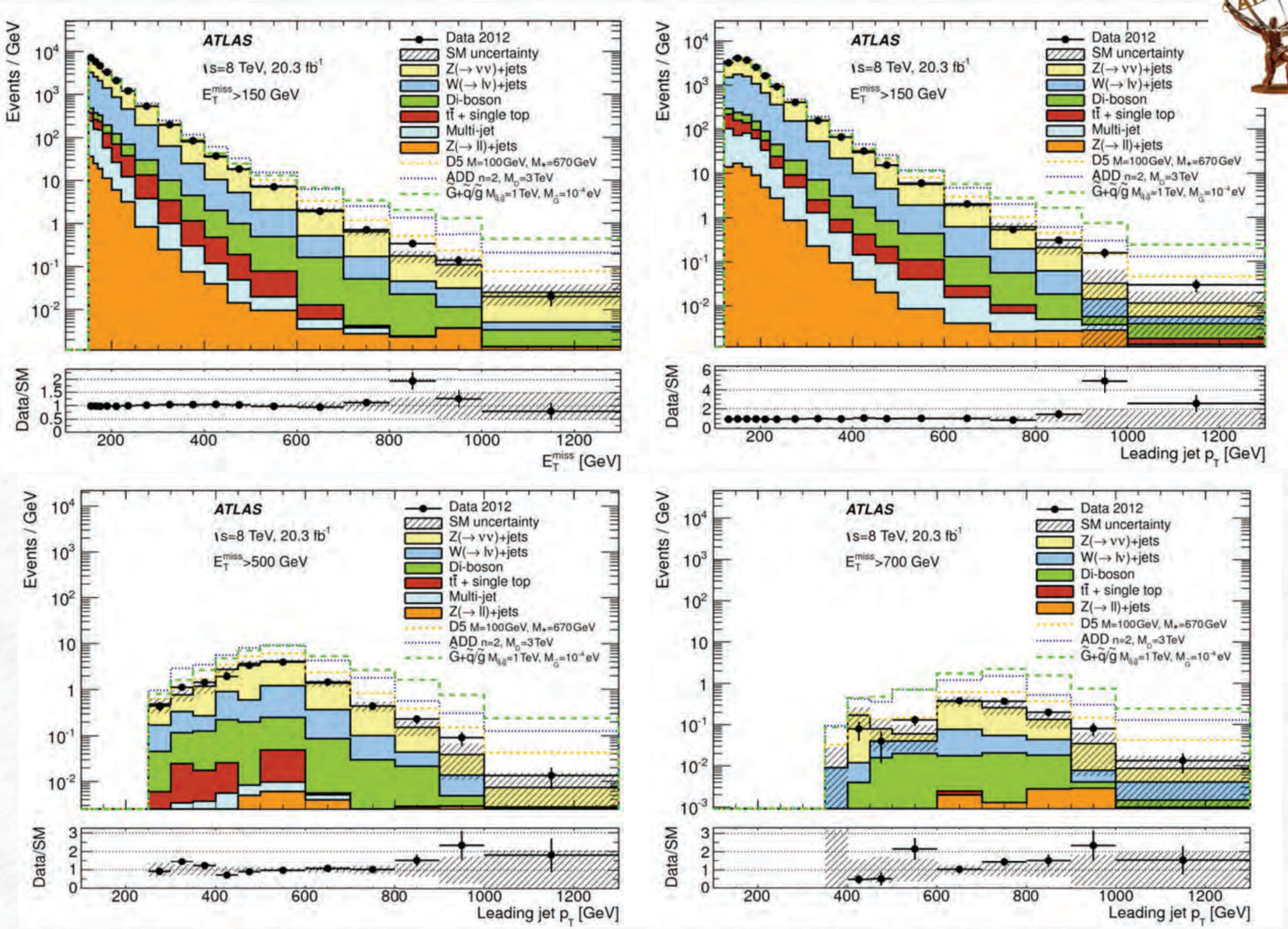


Numbers of observed events in data in comparison to expectations from Standard Model background for most sensitive signal regions:

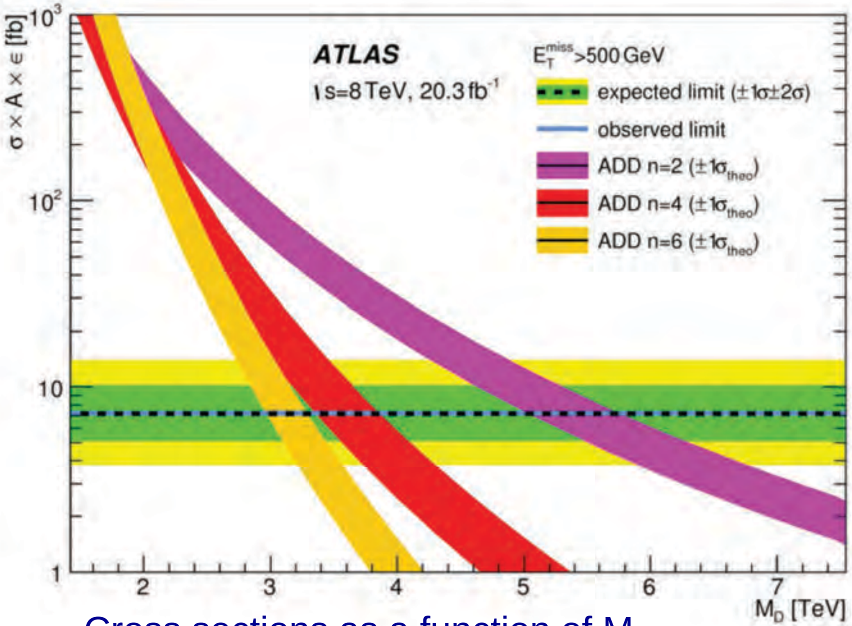
Table 5 Data and SM background expectation in the signal region for the SR6–SR9 selections. For the SM expectations both the statistical and systematic uncertainties are included. In each signal region, the individual uncertainties for the different background processes can be correlated, and do not necessarily add in quadrature to the total background uncertainty.

Signal Region	SR6	SR7	SR8	SR9
Observed events	3813	1028	318	126
SM expectation	4000 ± 160	1030 ± 60	310 ± 30	97 ± 14
$Z(\rightarrow \nu\bar{\nu})$	3000 ± 150	740 ± 60	240 ± 30	71 ± 13
$W(\rightarrow \tau\nu)$	540 ± 60	130 ± 20	34 ± 8	11 ± 3
$W(\rightarrow e\nu)$	170 ± 20	43 ± 7	9 ± 3	3 ± 1
$W(\rightarrow \mu\nu)$	140 ± 20	35 ± 6	10 ± 2	2 ± 1
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$	3 ± 1	2 ± 1	1 ± 1	1 ± 1
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$	2 ± 1	0 ± 0	0 ± 0	0 ± 0
$t\bar{t}$, single top	30 ± 20	7 ± 7	1 ± 1	0 ± 0
Dibosons	183 ± 70	65 ± 35	23 ± 16	8 ± 7
Multijets	6 ± 6	1 ± 1	0 ± 0	0 ± 0

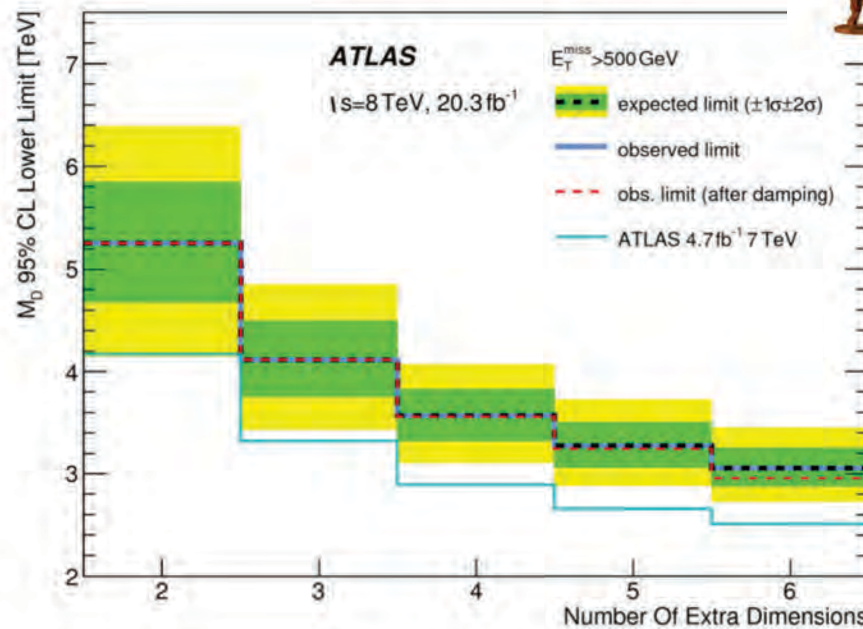
Agreement between data and expectations for the p_T(jet) and E_T^{miss} spectra:

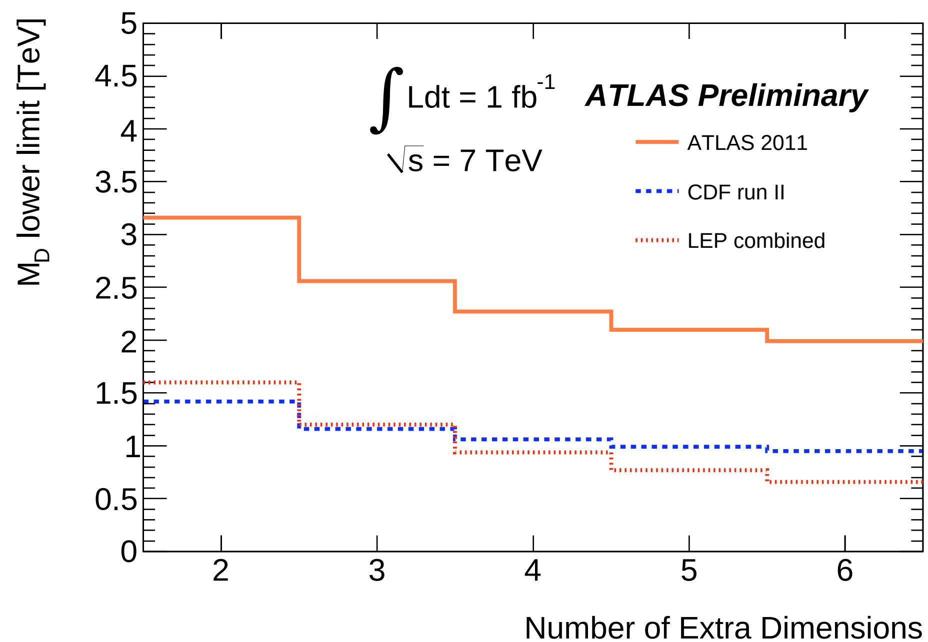


Constraints on the ADD model parameters: Excluded M_D values (95% C.L.):

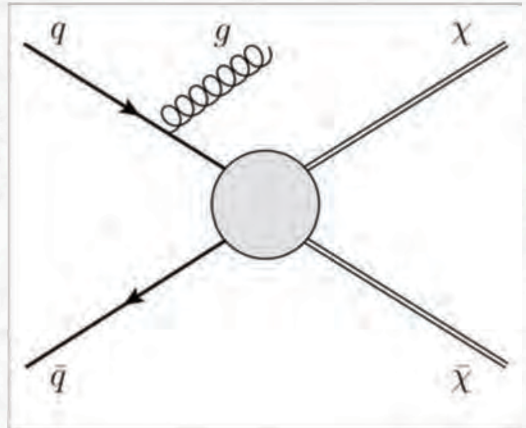


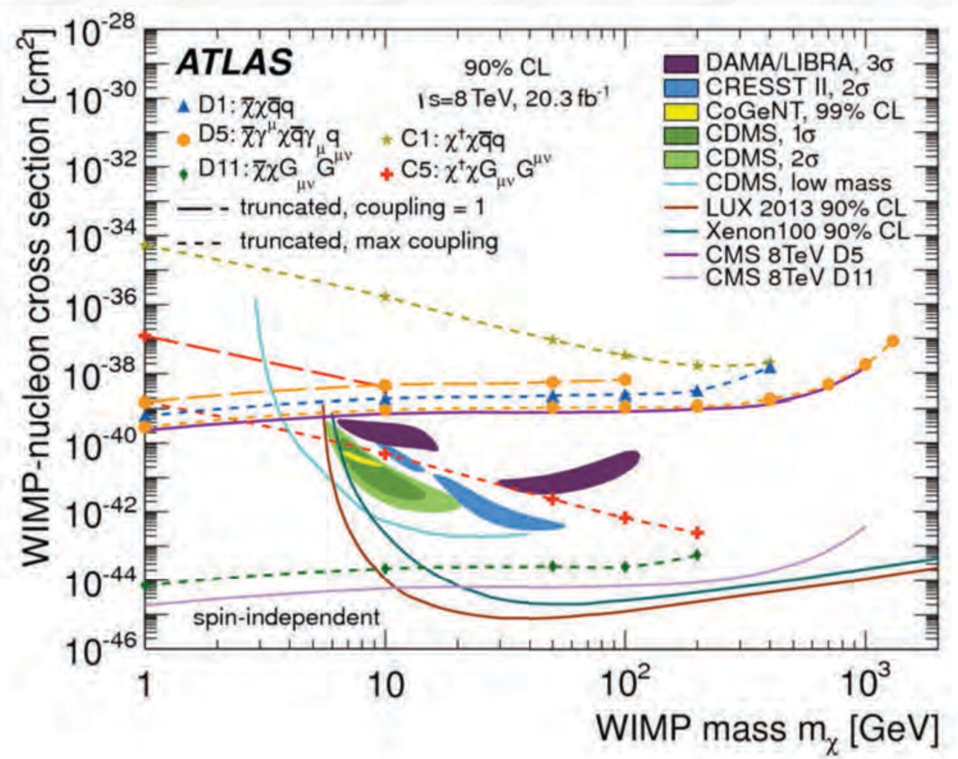
Cross sections as a function of M_D
for n=2, n=4, and n=6 extra dimensions
(cutoff for $\hat{s} < M^2_D$)



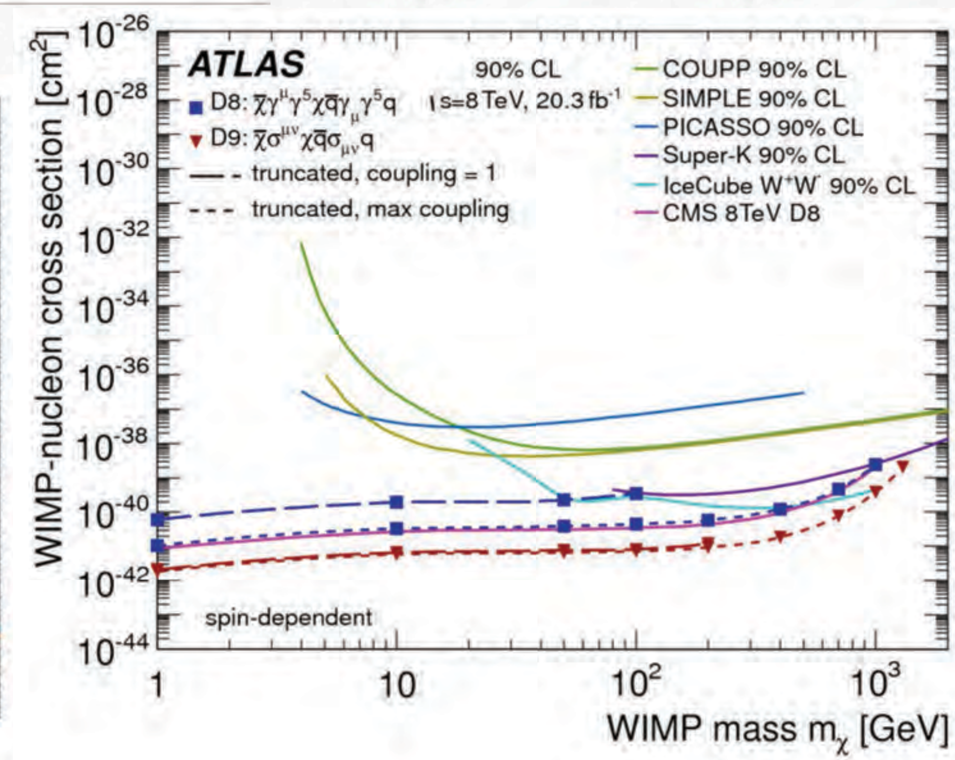


Use same analysis to also constrain Dark Matter production cross sections



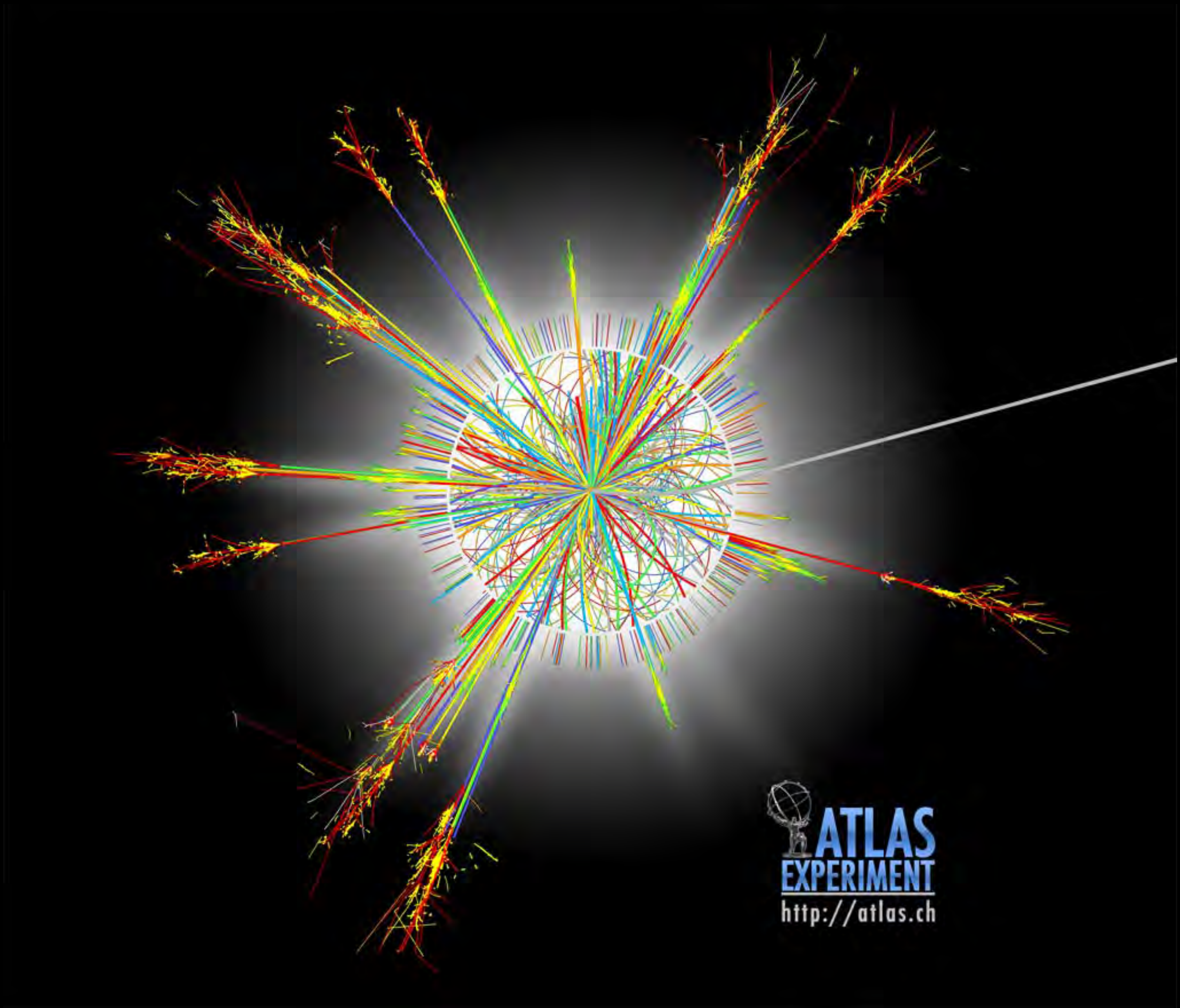


Spin-independent couplings



Spin-dependent couplings

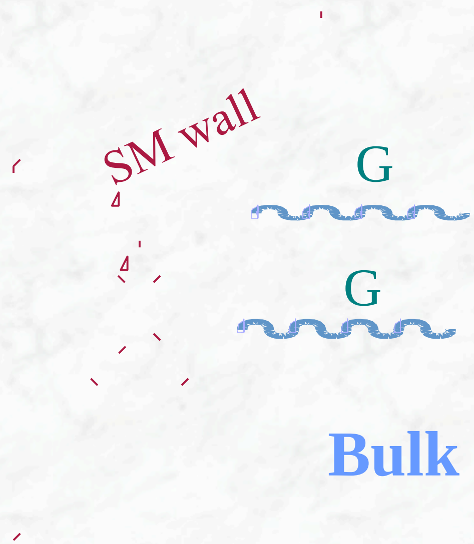
Microscopic Black Holes at the LHC ?



- 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 (fundamental scale $M_D << M_{Pl}$):

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



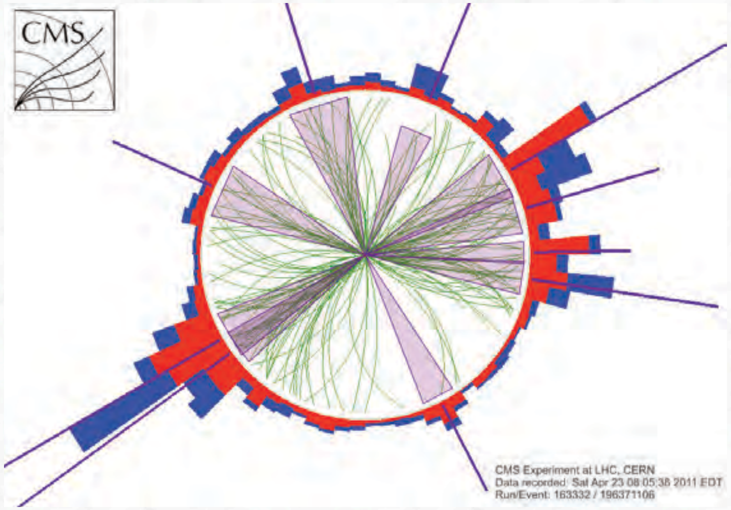
- Black hole formation at energies greater than M_D, (above a threshold mass, M_{th})

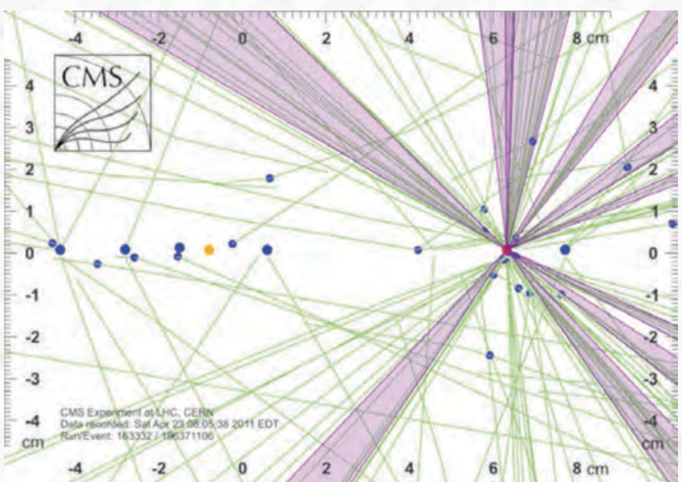
  Production cross section can be in the order of 100 pb for M_D ~1 TeV (large model dependence)

- Once produced, the black hole is expected to decay via Hawking radiation, democratically to all Standard Model degrees of freedom (quarks and gluons dominant, 75%, because N_C=3)
  → multijet events with large mass and total transverse energy

- However, near production threshold, quantum effects play a role (quantum black holes); democratic decay is not valid any more

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





Candidate events exist….

event with high multiplicity of jets, high mass….

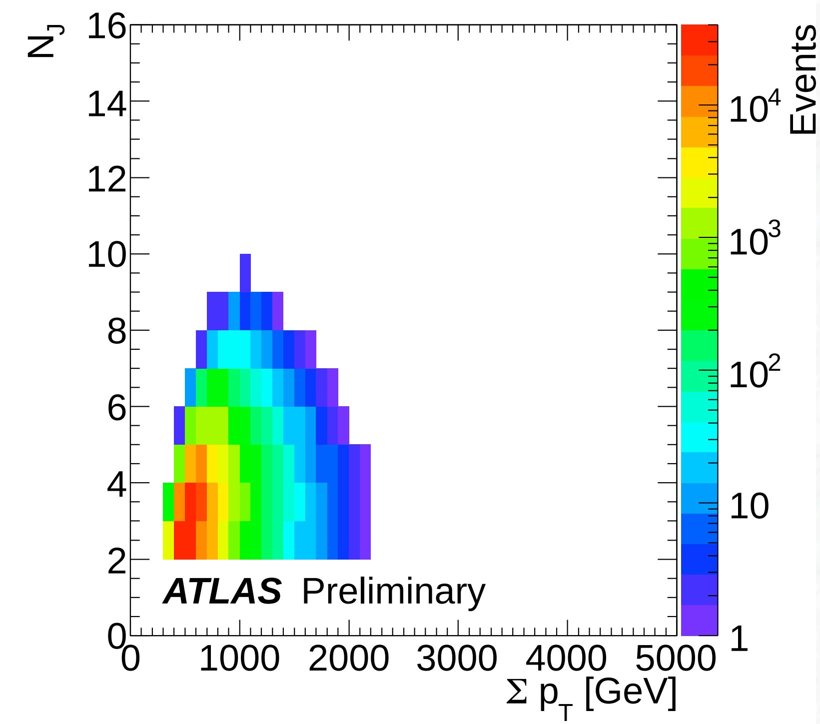
all particles coming from one interaction vertex

Is there an excess above the expectation from QCD production?

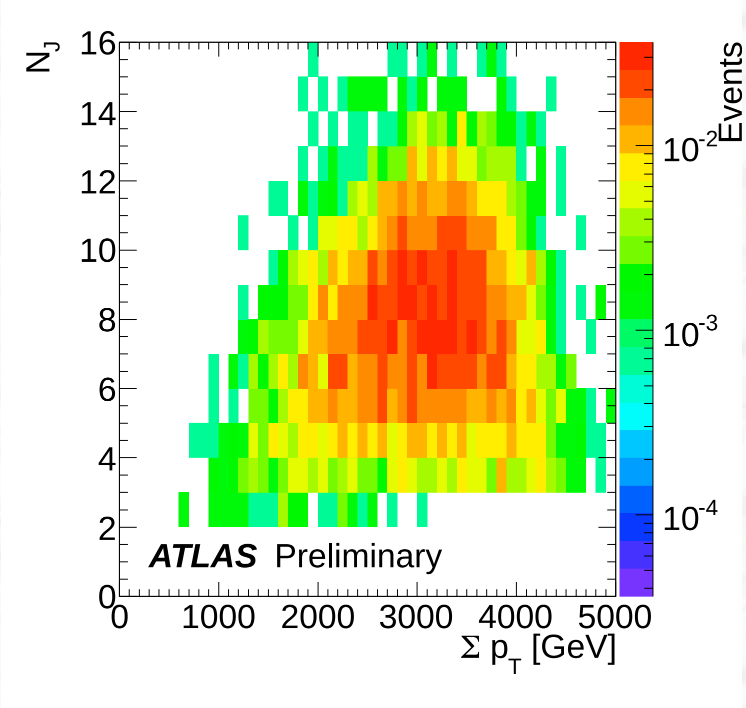
Discriminating variables between QCD background and black hole signals:

- jet multiplicity N_J
- total transverse momentum/energy (scalar sum) in the event, Σp_T =: S_T

Results of an ATLAS Monte Carlo simulation:



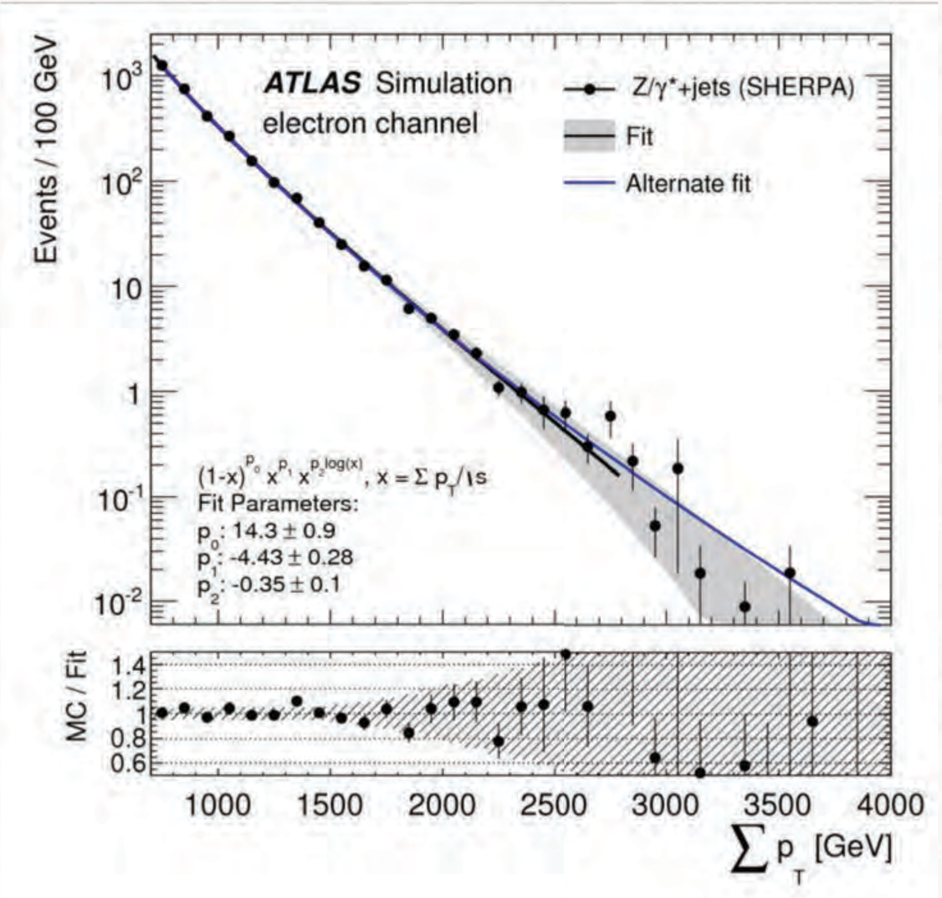
QCD multijet “background”

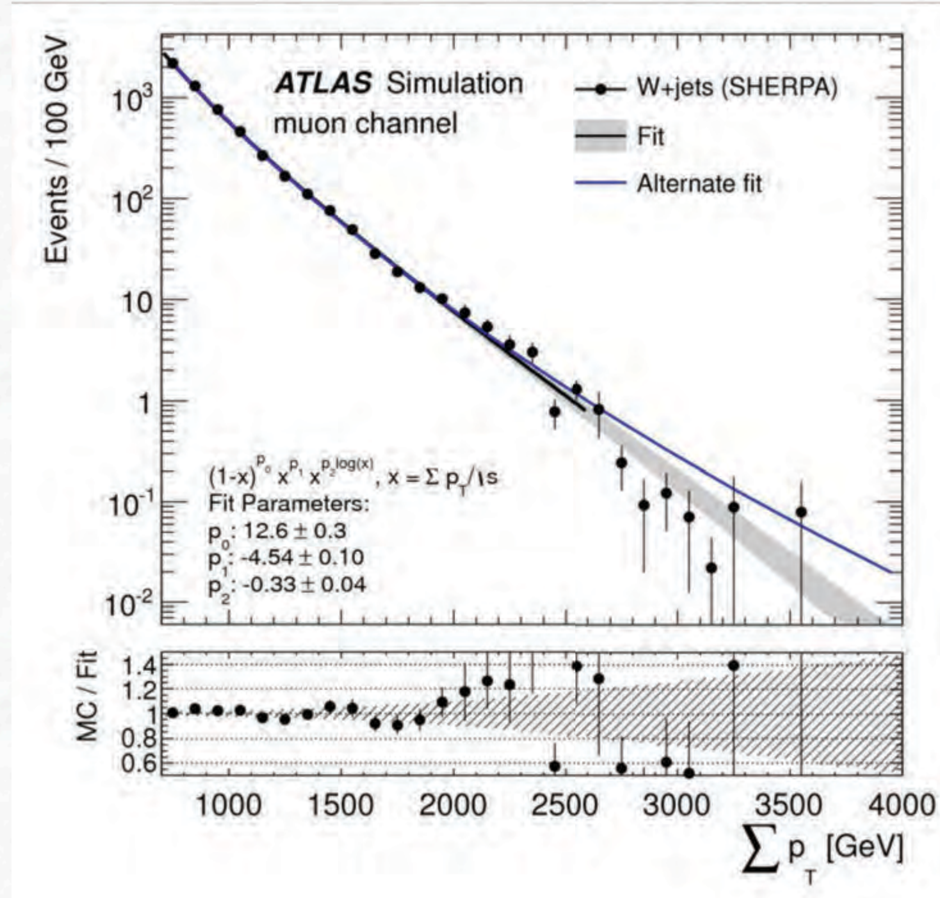


Black hole signal events with Planck scale M_D = 1 TeV and n = 2, threshold production mass 4.3 TeV

ATLAS analysis with 20.3 fb^{-1} at 8 TeV:

- One or more high-p_T lepton (electron or muon), plus 2 or more leptons or jets
- Total transverse momentum/energy (scalar sum) in the event, Σp_T =: S_T

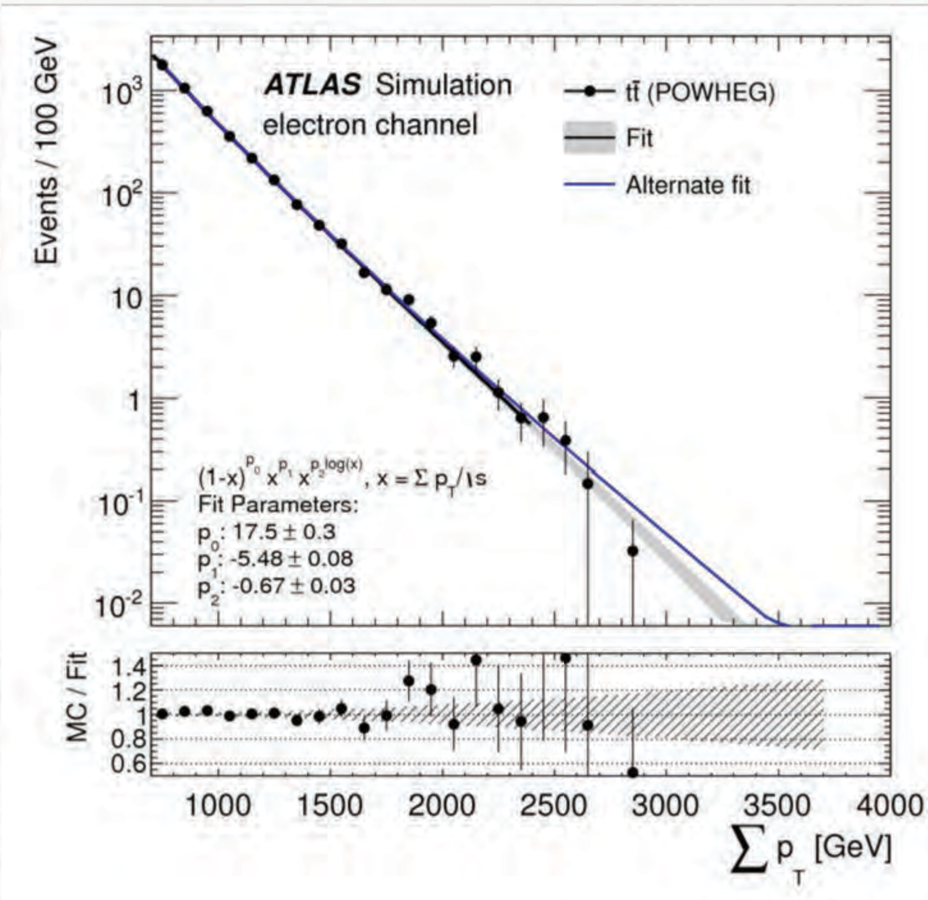


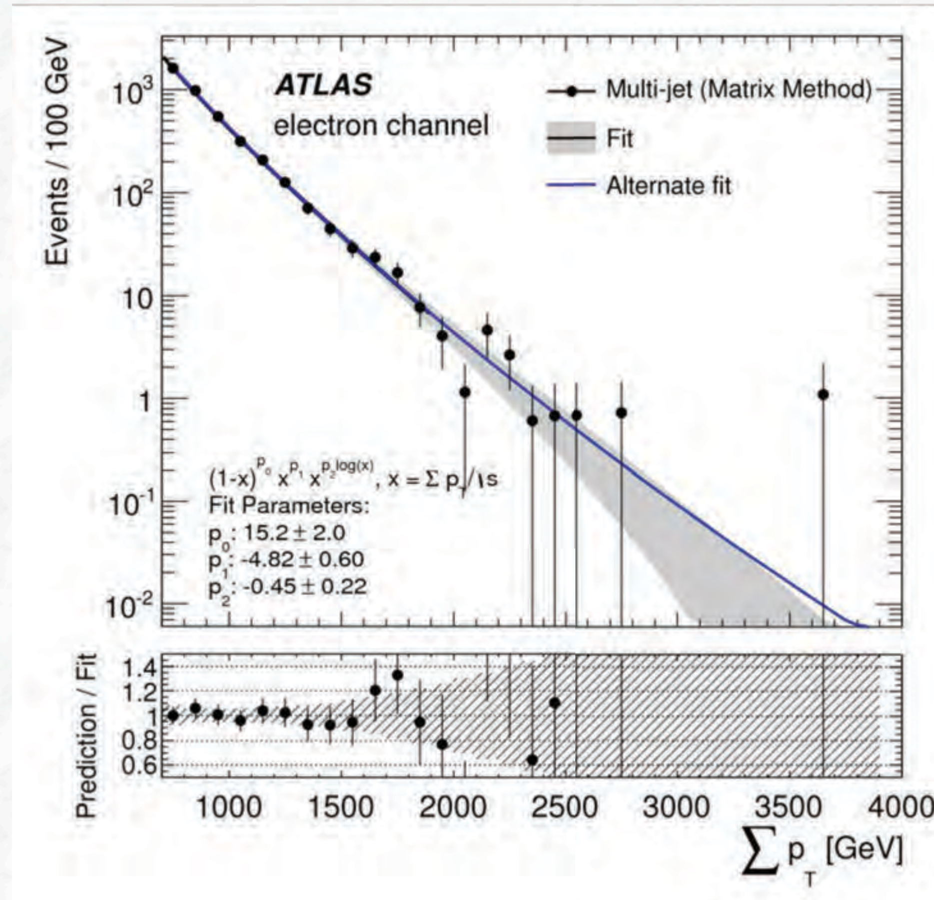


Shape of ST distribution cannot be reliably calculated in Monte Carlo simulation.
Problem: high jet multiplicities
Extrapolate each background individually with a fit to data from low-S_T to high-S_T region

ATLAS analysis with 20.3 fb^{-1} at 8 TeV:

- One or more high-p_T lepton (electron or muon), plus 2 or more leptons or jets
- Total transverse momentum/energy (scalar sum) in the event, Σp_T =: S_T

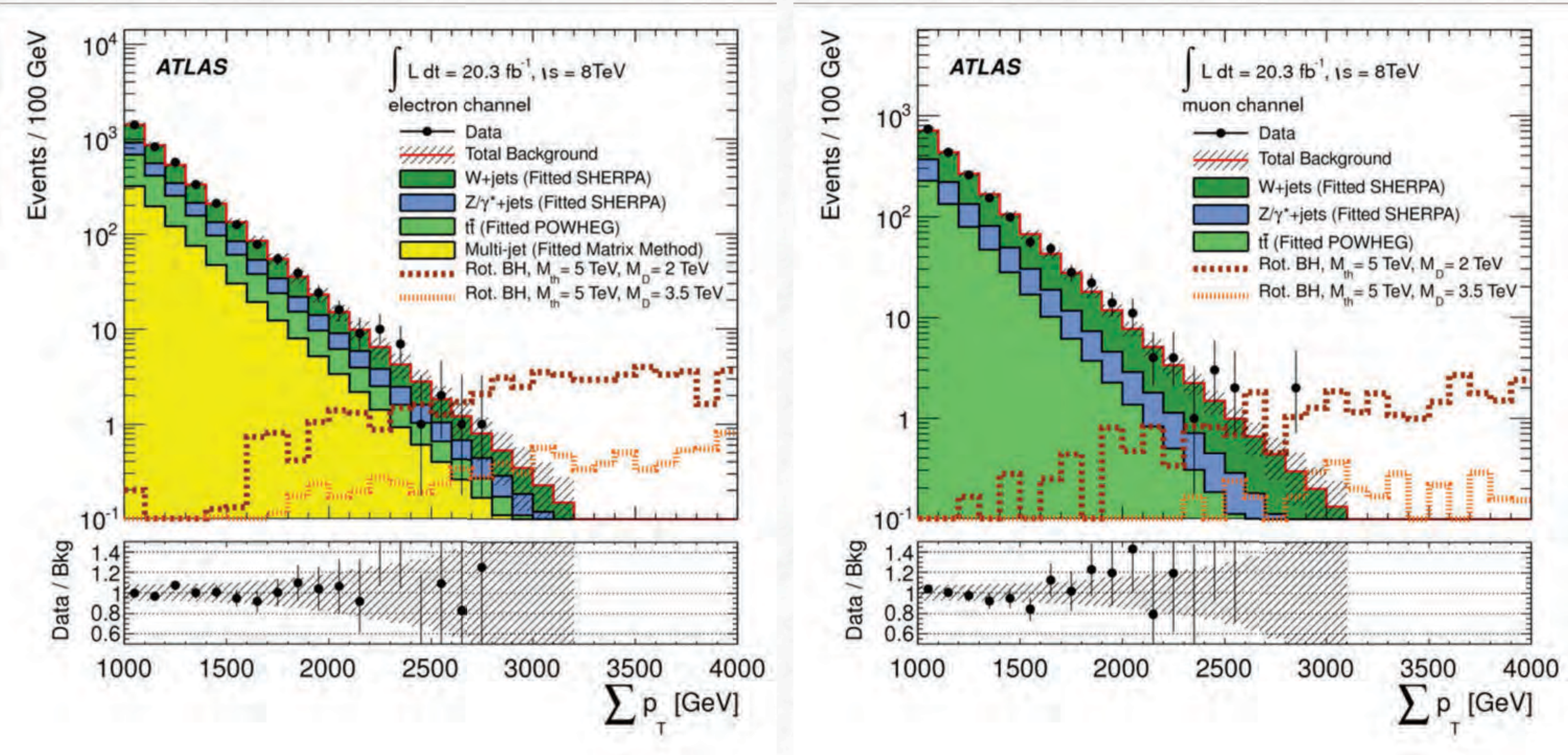




Shape of ST distribution cannot be reliably calculated in Monte Carlo simulation.
Problem: high jet multiplicities
Extrapolate each background individually with a fit to data from low-S_T to high-S_T region

ATLAS analysis with 20.3 fb^{-1} at 8 TeV:

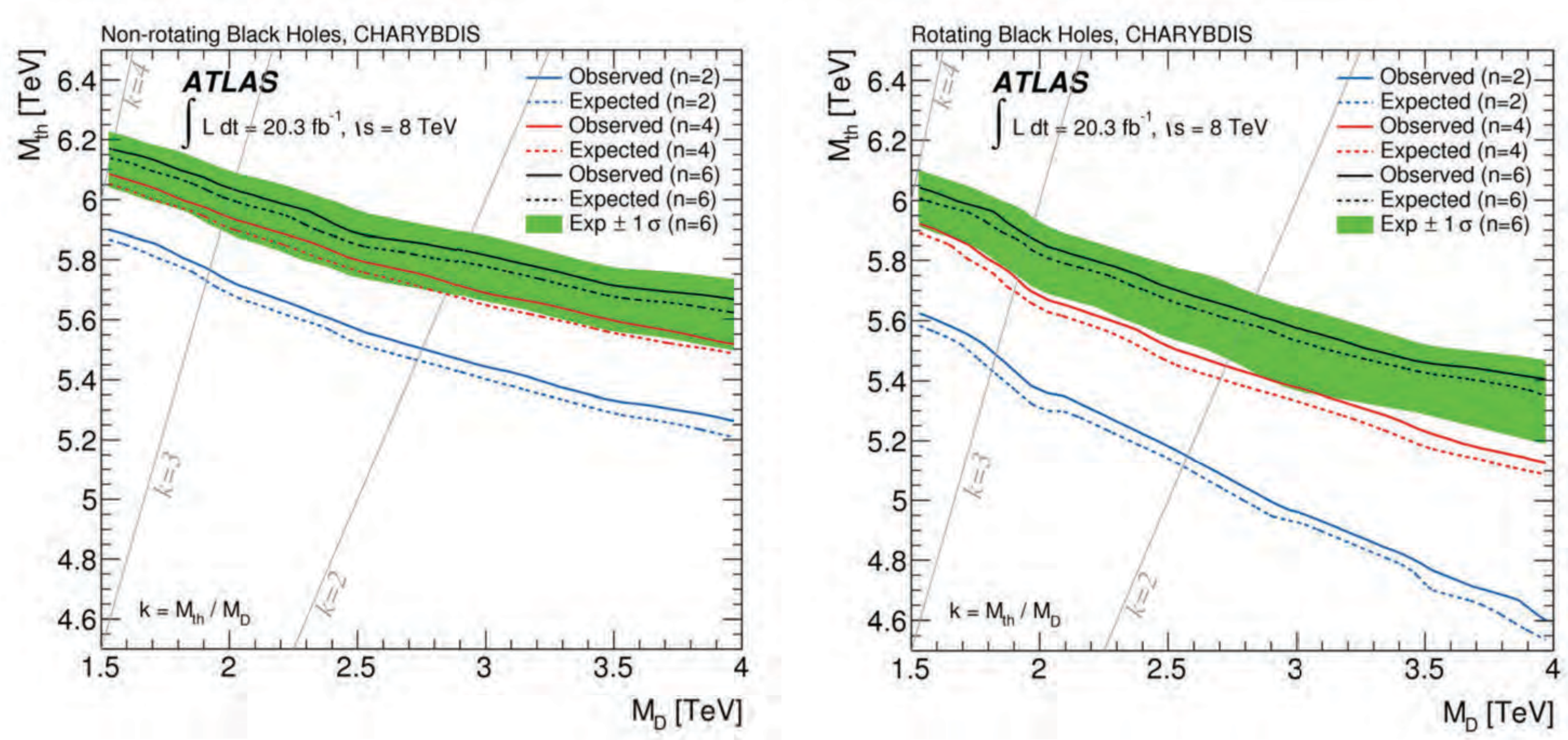
- One or more high-p_T lepton (electron or muon), plus 2 or more leptons or jets
- Total transverse momentum/energy (scalar sum) in the event, Σp_T =: S_T



→ No evidence for the formation of micro Black Holes… limits

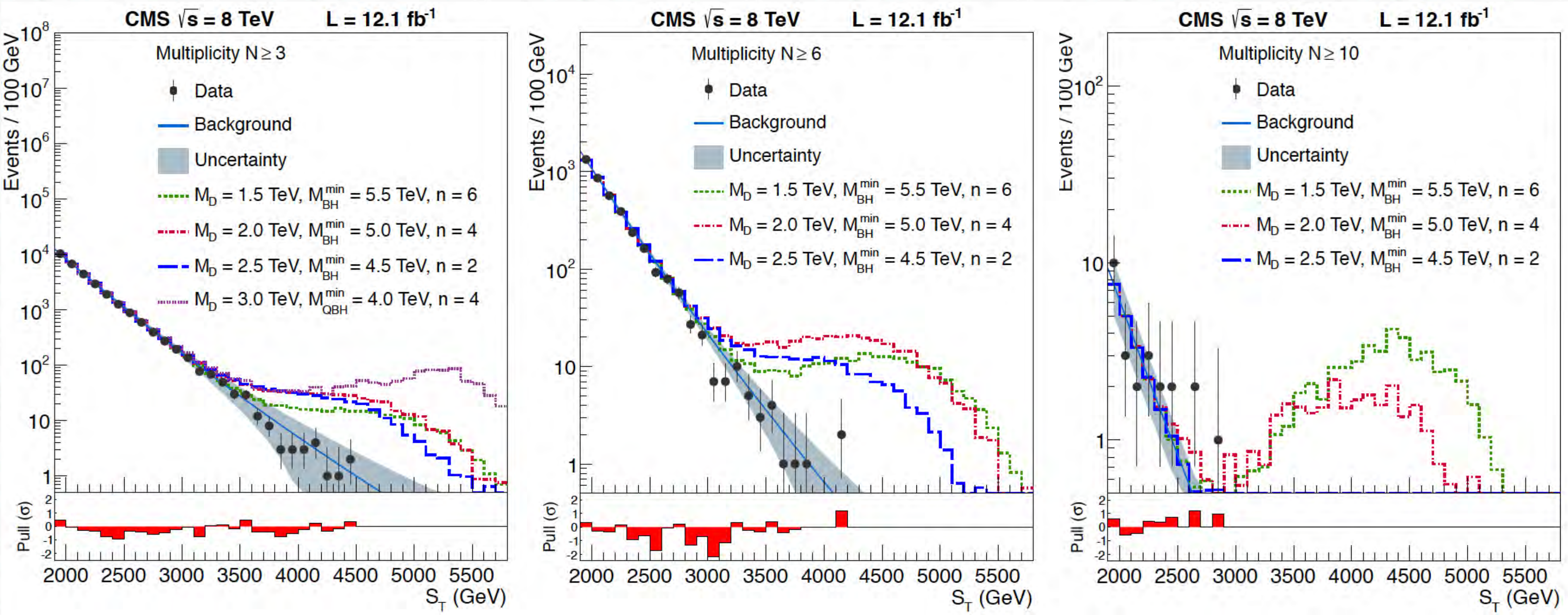
However, near production threshold, quantum effects play a role (quantum black holes); democratic decay is not valid any more

- Use production threshold $M_{th} > M_D$ above which semi-classical approximations work
- Between M_{th} and M_D, quantum-gravitations effects become important and evaporation by emission of Hawking radiation is no longer a suitable model



→ No evidence for the formation of micro Black Holes… limits

CMS analysis, use large part of the 8 TeV 2012 data, $L_{int} = 12.1\ fb^{-1}$



Total transverse energy S_T for events with N > 3, 5, 10 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).

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2015

ATLAS Preliminary

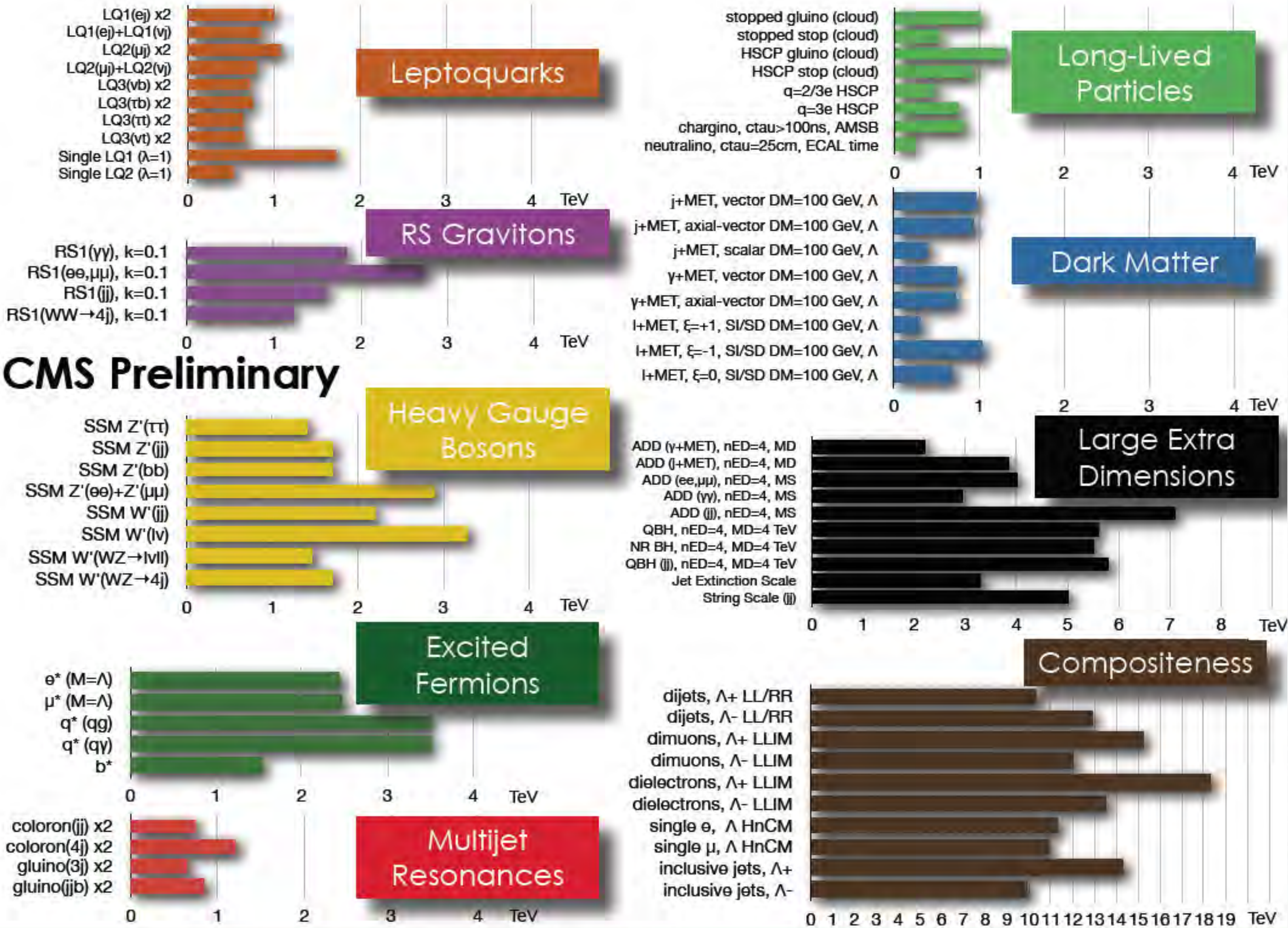
$\int \mathcal{L}\,dt = (1.0 - 20.3)$ fb^{-1} $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt$[fb^{-1}]	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	$2 e, \mu$	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	$1 e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2μ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	Preliminary
	RS1 $G_{KK} \to \ell\ell$	$2 e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	Preliminary
	Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	$2 e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1 e, \mu$	2 j / 1 J	Yes	20.3	W' mass 700 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1 e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	ATLAS-CONF-2015-009
	2UED / RPP	$2 e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		Preliminary
Gauge bosons	SSM $Z' \to \ell\ell$	$2 e, \mu$	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	2τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	SSM $W' \to \ell\nu$	$1 e, \mu$	–	Yes	20.3	W' mass 3.24 TeV		1407.7494
	EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$	$3 e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2 e, \mu$	2 j / 1 J	–	20.3	W' mass 1.59 TeV		1409.6190
	HVT $W' \to WH \to \ell\nu bb$	$1 e, \mu$	2 b	Yes	20.3	W' mass 1.47 TeV	$g_V = 1$	Preliminary
	LRSM $W'_R \to t\bar{b}$	$1 e, \mu$	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to t\bar{b}$	$0 e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL} = -1$	Preliminary
	CI $qq\ell\ell$	$2 e, \mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	$2 e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.35 TeV	$\lvert C_{LL}\rvert = 1$	Preliminary
DM	EFT D5 operator (Dirac)	$0 e, \mu$	≥ 1 j	Yes	20.3	M_* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	$0 e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1^{st} gen	$2 e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2^{nd} gen	2μ	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3^{rd} gen	$1 e, \mu, 1 \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	VLQ $TT \to Ht + X, Wb + X$	$1 e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	T mass 785 GeV	isospin singlet	ATLAS-CONF-2015-012
	VLQ $TT \to Zt + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	1409.5500
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $BB \to Wt + X$	$1 e, \mu$	≥ 1 b, ≥ 5 j	Yes	20.3	B mass 640 GeV	isospin singlet	Preliminary
	$T_{5/3} \to Wt$	$1 e, \mu$	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		Preliminary
Excited fermions	Excited quark $q^* \to q\gamma$	1γ	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2 e, \mu, 1 \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \to \ell W, \nu Z$	$3 e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	$1 e, \mu, 1 \gamma$	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	$2 e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2 e, \mu$ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3 e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	$1 e, \mu$	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	Preliminary
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g\rvert = 1 g_D$	1207.6411

$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

Mass scale [TeV] (10^{-1}, 1, 10)

*Only a selection of the available mass limits on new states or phenomena is shown.


Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
0 1 2 3 4 TeV
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
0 1 2 3 4 TeV
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
0 1 2 3 4 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4 TeV
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4 TeV
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
chargino, ctau>100ns, AMSB
neutralino, ctau=25cm, ECAL time
0 1 2 3 4 TeV
Dark Matter
j+MET, vector DM=100 GeV, Λ
j+MET, axial-vector DM=100 GeV, Λ
j+MET, scalar DM=100 GeV, Λ
γ+MET, vector DM=100 GeV, Λ
γ+MET, axial-vector DM=100 GeV, Λ
l+MET, ξ=+1, SI/SD DM=100 GeV, Λ
l+MET, ξ=-1, SI/SD DM=100 GeV, Λ
l+MET, ξ=0, SI/SD DM=100 GeV, Λ
0 1 2 3 4 TeV
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 1 2 3 4 5 6 7 8 TeV
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV

End of lectures