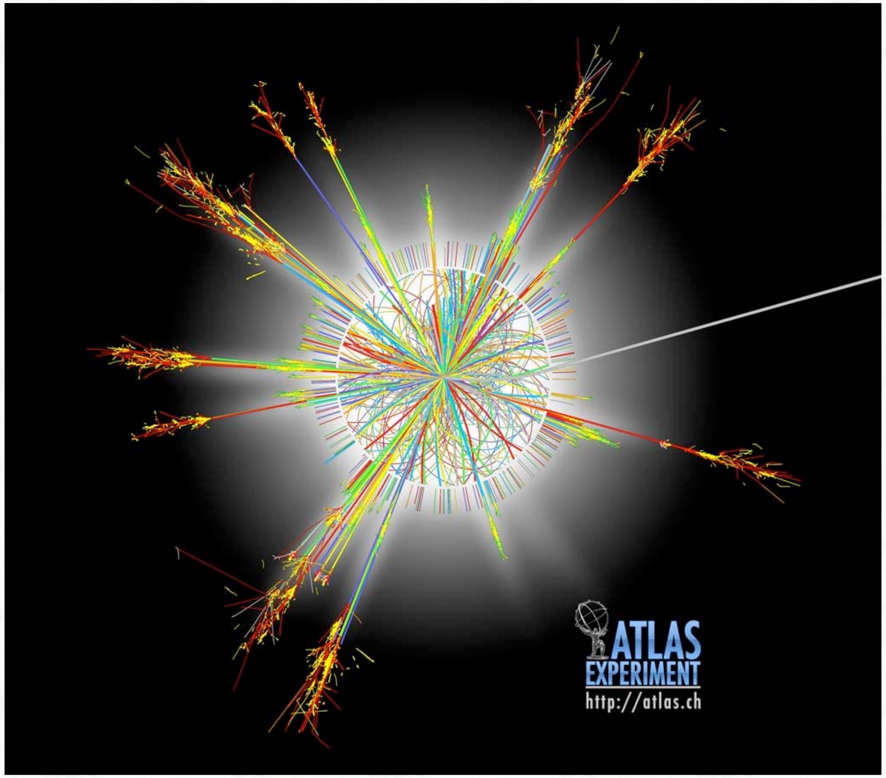
Searches for Physics Beyond the Standard Model at the LHC
-Part 3-



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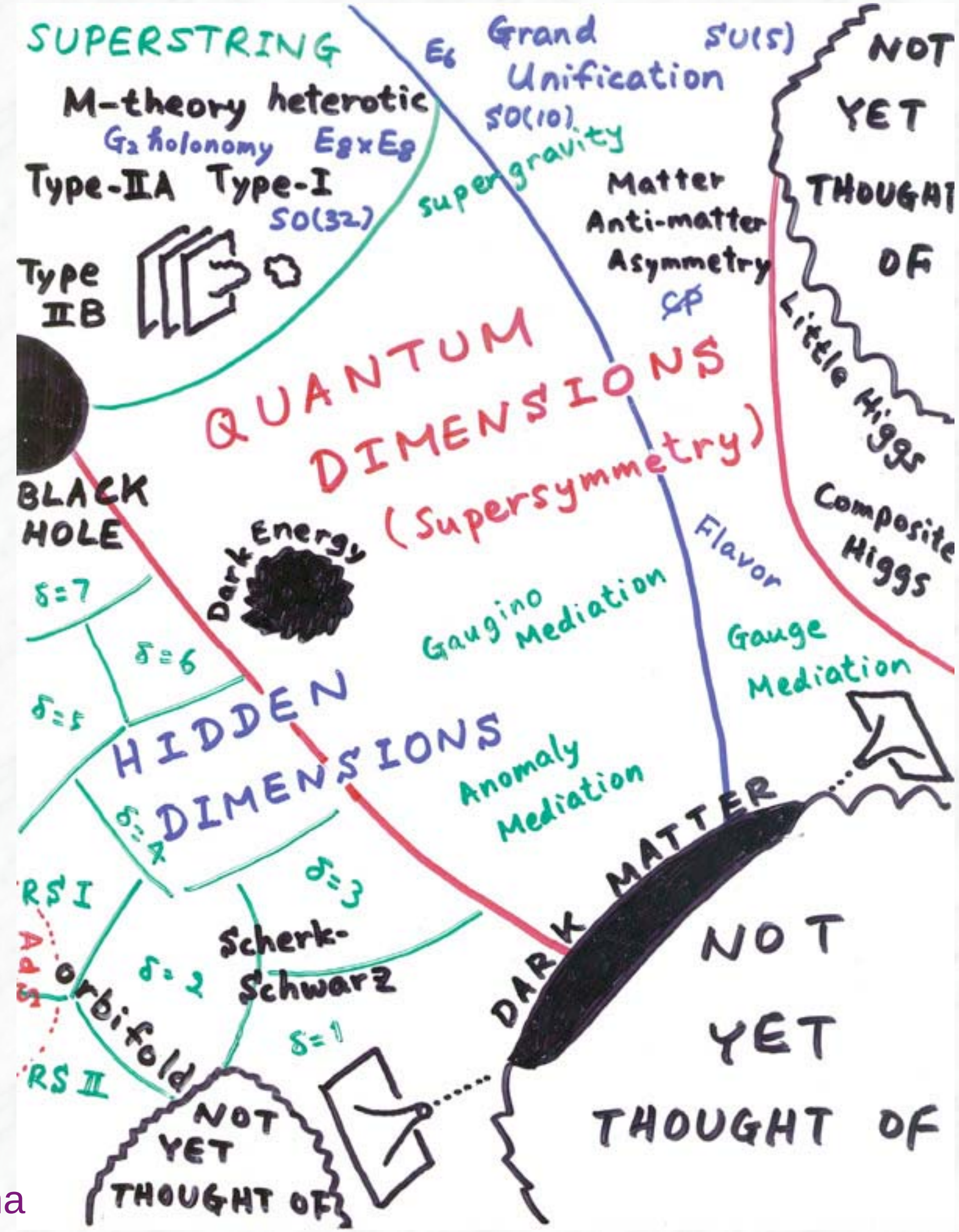
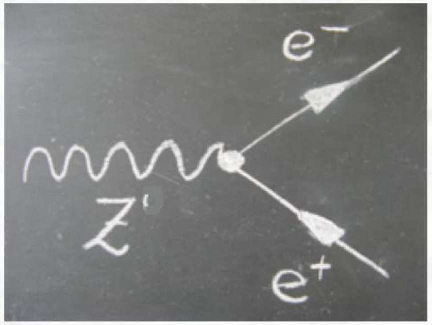
Other Extensions of the Standard Model

- Additional Gauge bosons,
  Z' and W' searches
- Search for compositeness
- Excited quarks
- Leptoquarks
- Search for signals from
  Extra Dimensions

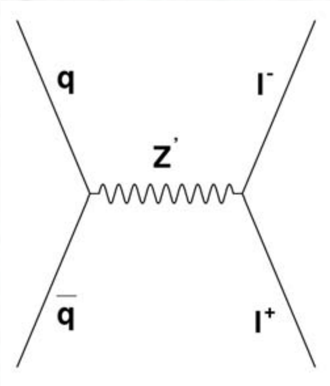


3.1 Additional Gauge Bosons: W' and Z'



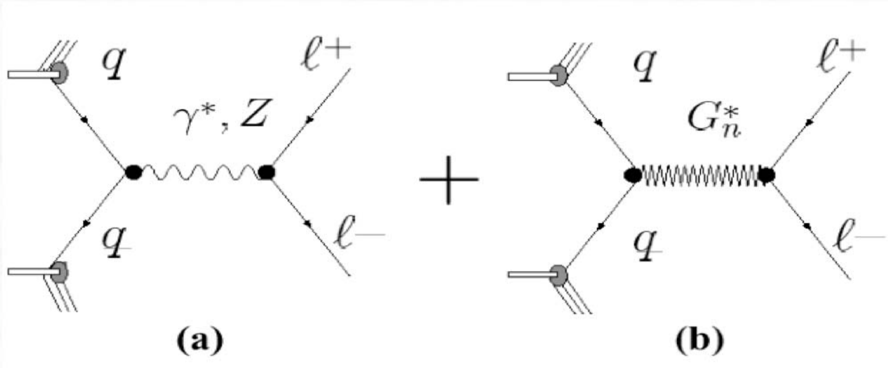
Search for new, high-mass di-lepton resonances

- Additional neutral Gauge Boson Z´



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

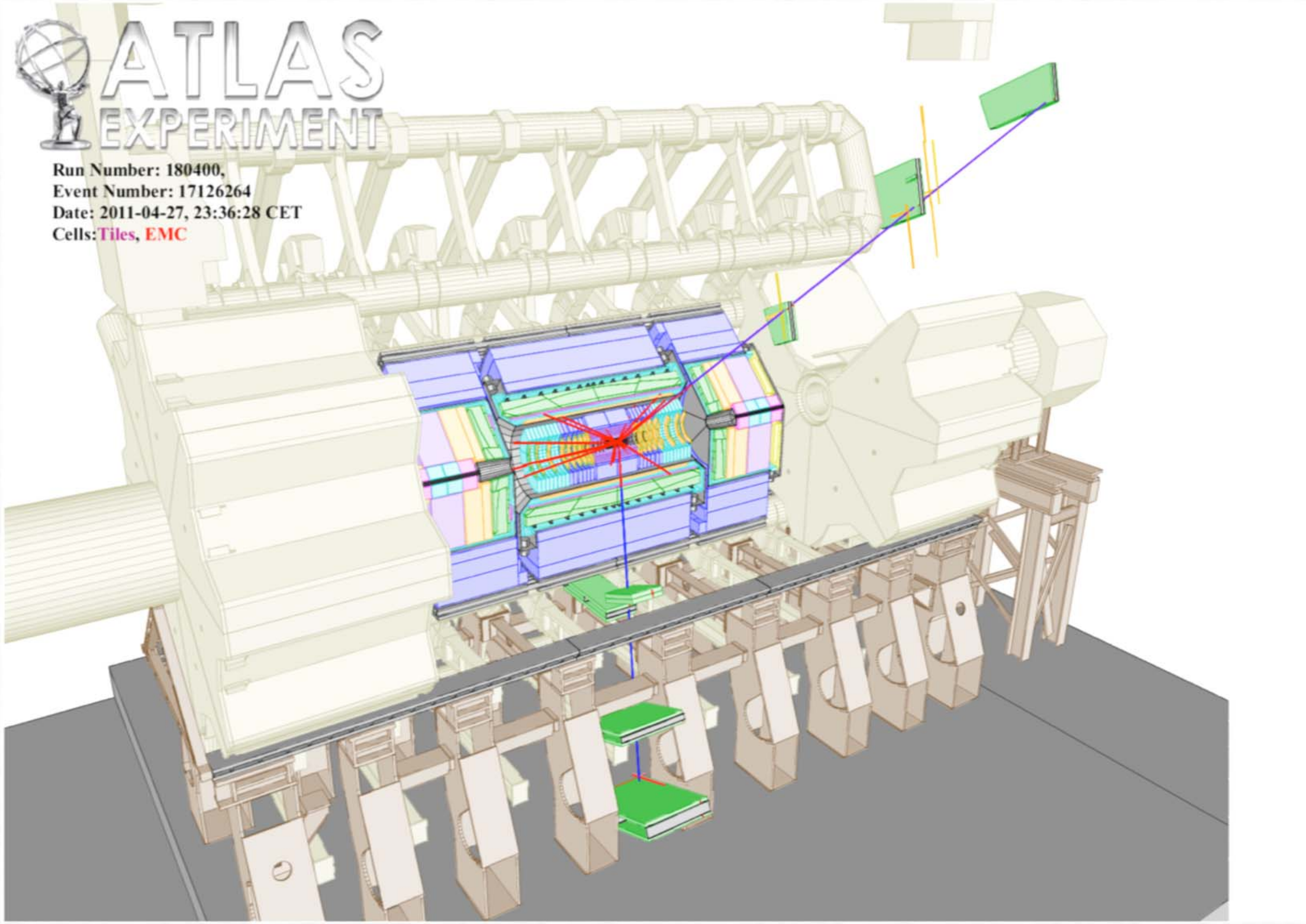
appear in Extra Dim. Scenarios



Standard Model background process

Signal

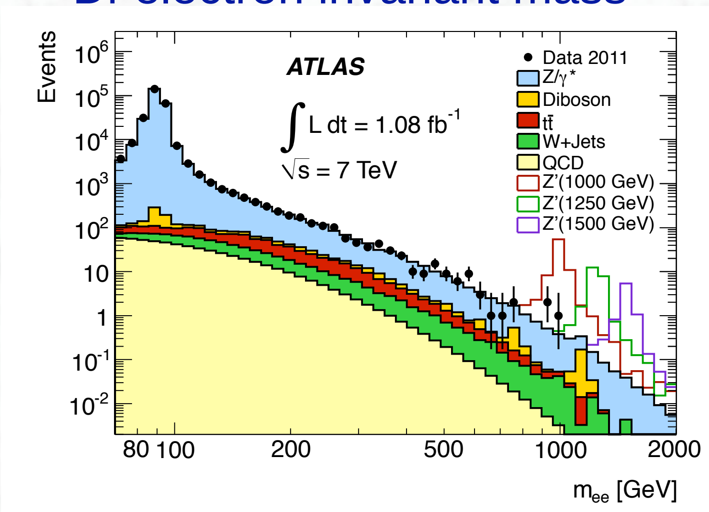
- Identical final state (two leptons), same analysis, interpretation for different theoretical models
- Main background process: Drell-Yan production of lepton pairs



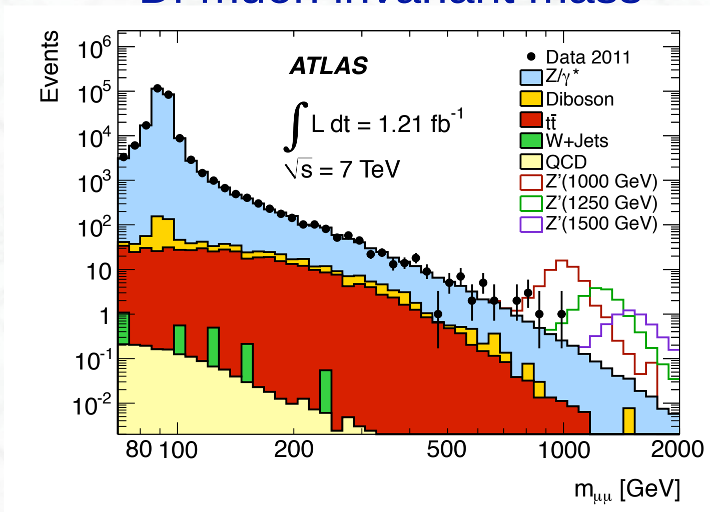
A high invariant mass di-muon event in the ATLAS data. The highest momentum muon has a p_T of 270 GeV and an (eta, phi) of (1.56, 1.30). The subleading muon has a p_T of 232 GeV and an (eta, phi) of (-0.09, -1.82). The invariant mass of the pair is 680 GeV.

Search for 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

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

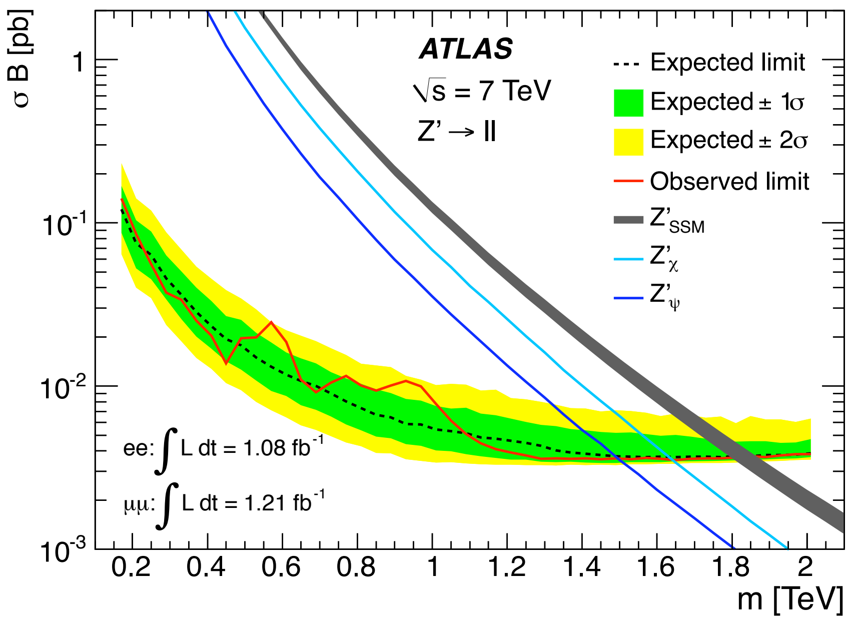
(ii) Models based on the E_6 grand unified symmetry group

- 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

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

- 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 and E6 models:

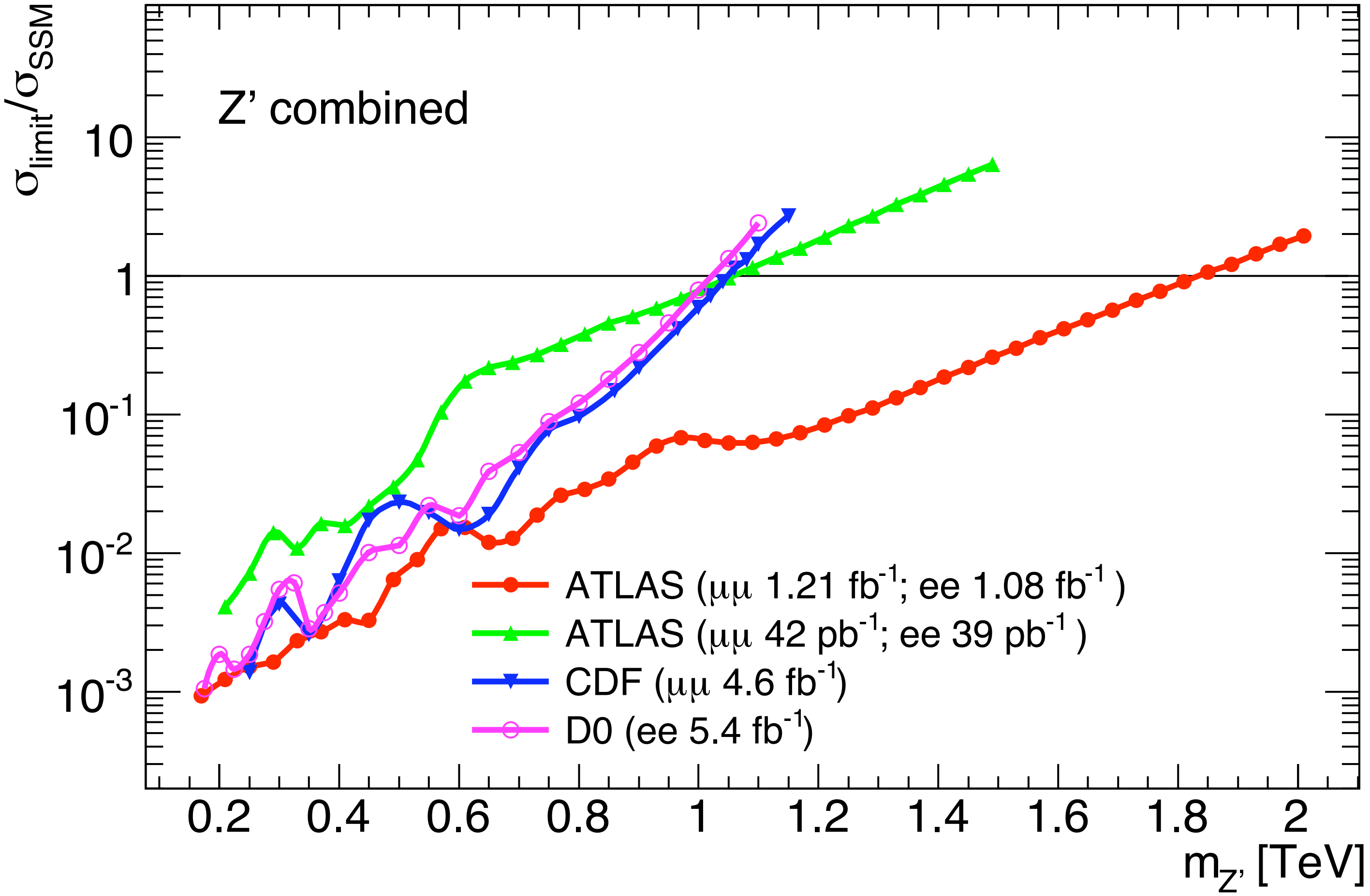


Resulting mass limits: ee + μμ
95% C.L.

Sequential SM: $m_{Z'} > 1.83$ TeV
E_6 models: $m_{Z'} > 1.49 – 1.63$ TeV

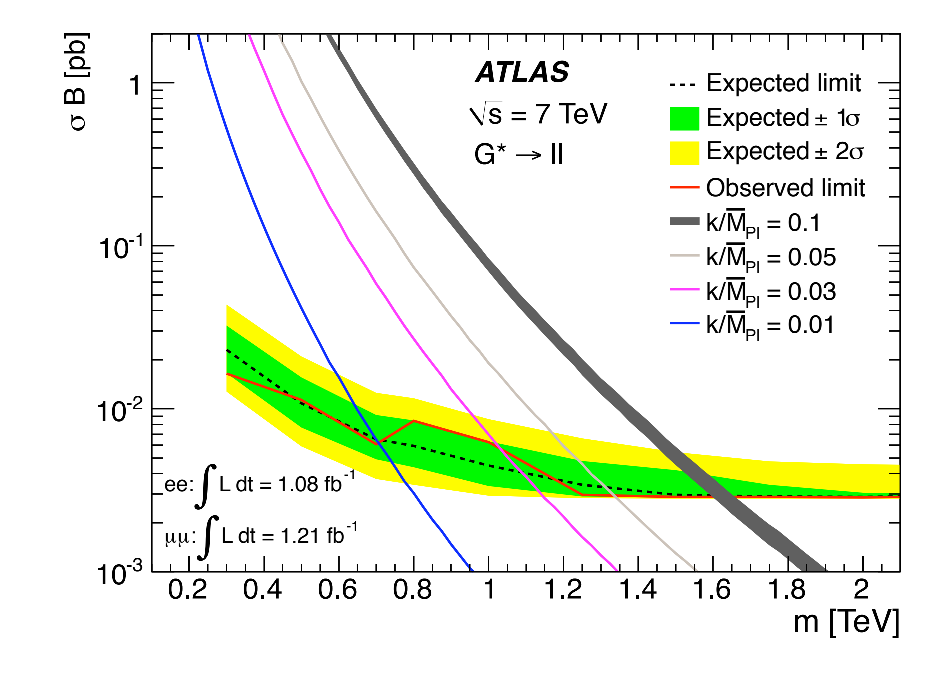
Summary of 95% C.L. SSM exclusion limits from various experiments:

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 1.1 / 1.2 fb^{-1}	1.70 TeV	1.61 TeV	1.83 TeV
CMS 1.1 fb^{-1}			1.94 TeV



Ratio of observed combined limit for the Z' search using both channels divided by the SSM Z' cross section time branching ratio.

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

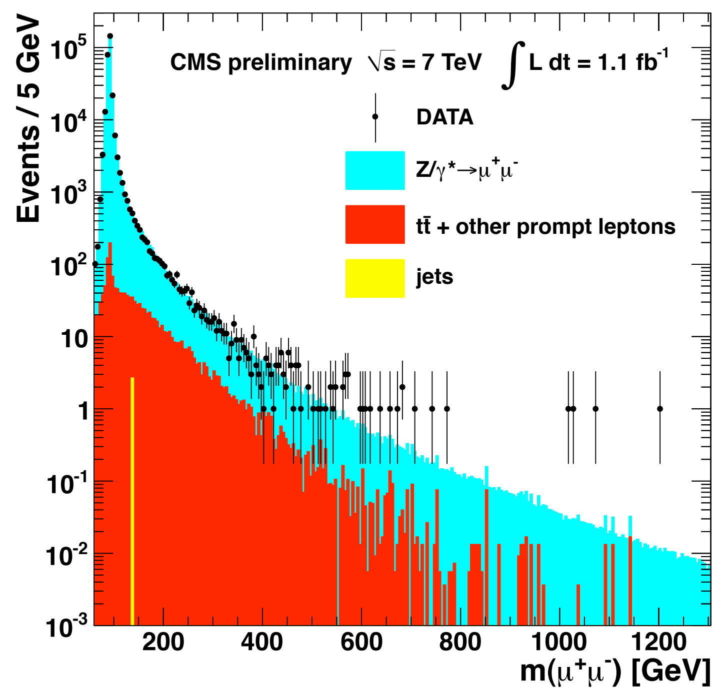


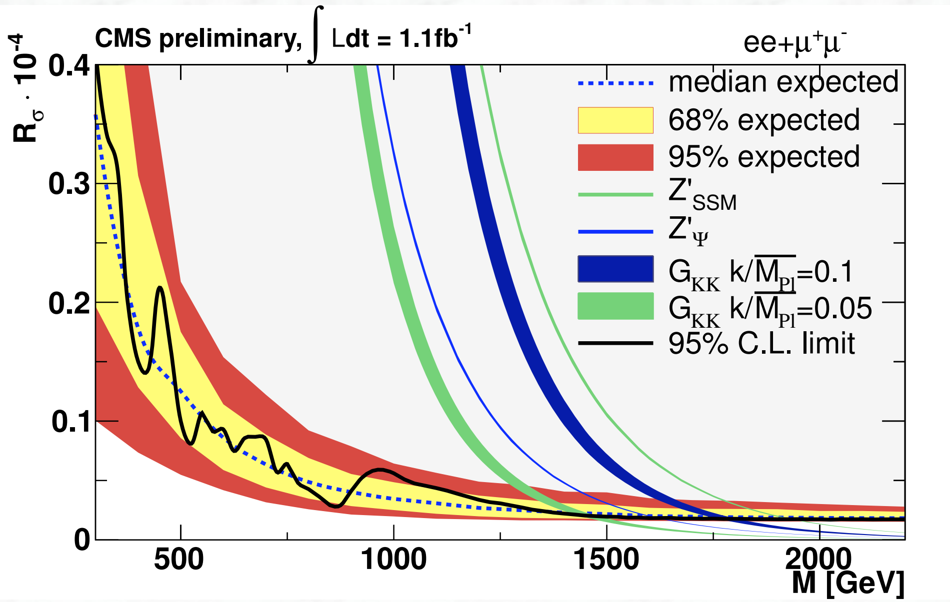
Resulting mass limits: ee + μμ
95% C.L.

k/M'_{Pl} = 0.01: $m_{Z'}$ > 0.71 TeV
k/M'_{Pl} = 0.03: $m_{Z'}$ > 1.03 TeV
k/M'_{Pl} = 0.05: $m_{Z'}$ > 1.33 TeV
k/M'_{Pl} = 0.10: $m_{Z'}$ > 1.63 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: $m_{Z'} > 1.94$ TeV
E_6 models: $m_{Z'\Psi} > 1.62$ TeV

Kaluza-Klein Gravitons:
$k/M'_{Pl} = 0.05$: $m_{Z'} > 1.45$ TeV
$k/M'_{Pl} = 0.10$: $m_{Z'} > 1.78$ TeV

Search for W' $\rightarrow$ 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

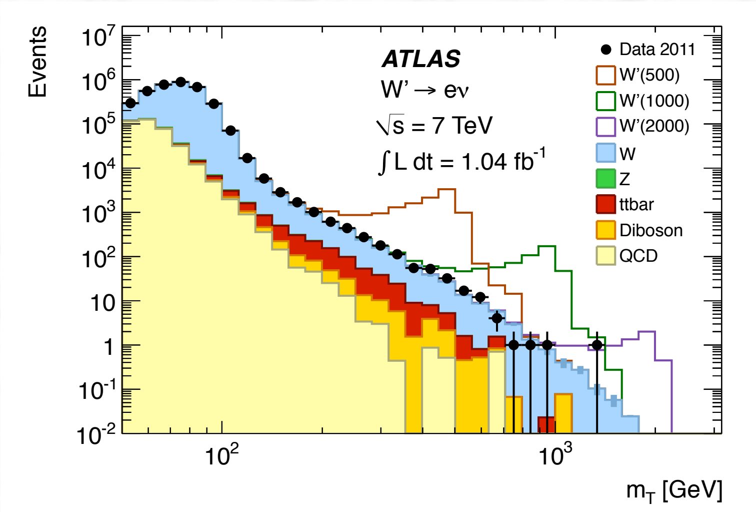
- Assume ν from W' decay to be light and stable, and W' to have the same couplings as in the SM (*"Sequential Standard Model, SSM")*

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

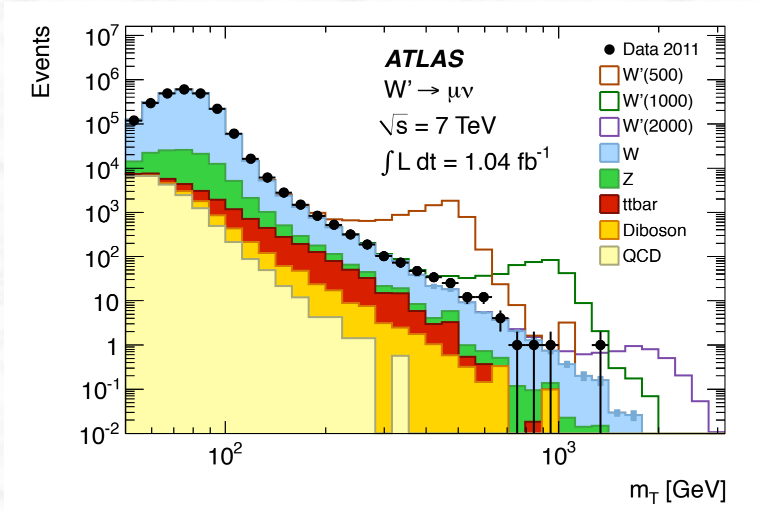
$\rightarrow$ peak in transverse mass distribution

Search for New Resonances in High Mass lν events

Transverse mass (e, E_T^{miss})



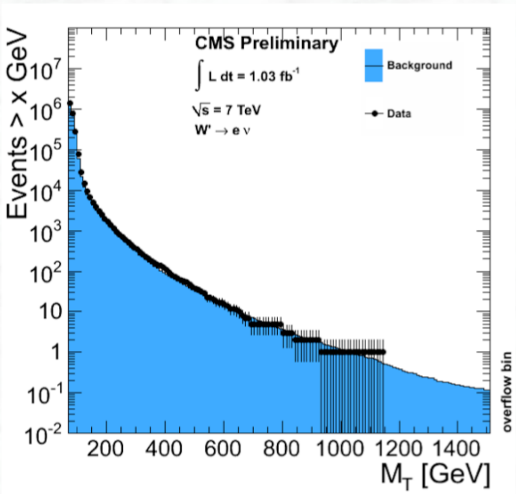
Transverse mass (μ, E_T^{miss})

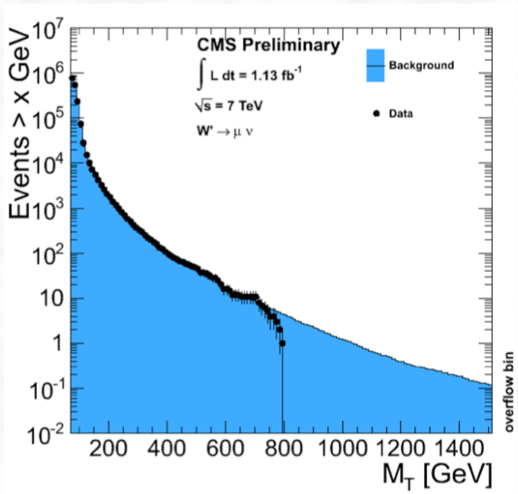


Data are consistent with background from SM processes. No excess observed.

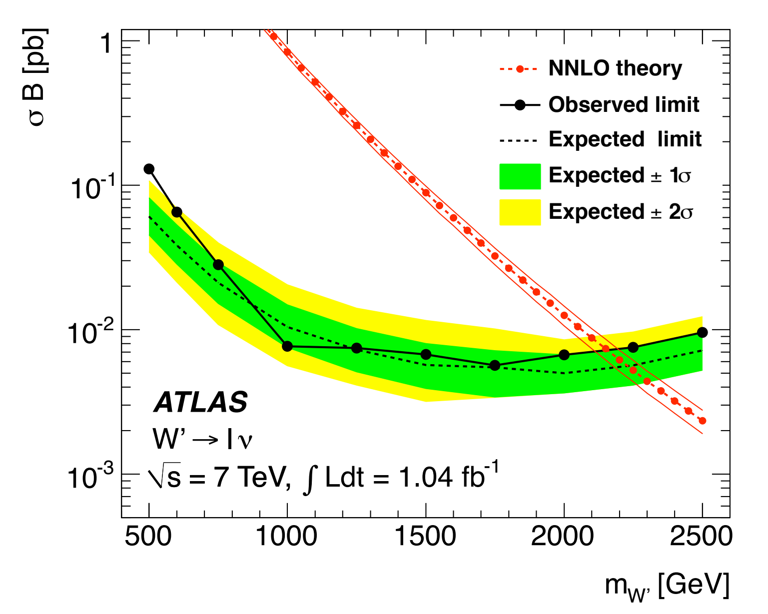
Above: Differential transverse mass distributions from ATLAS in the eν and μν channels

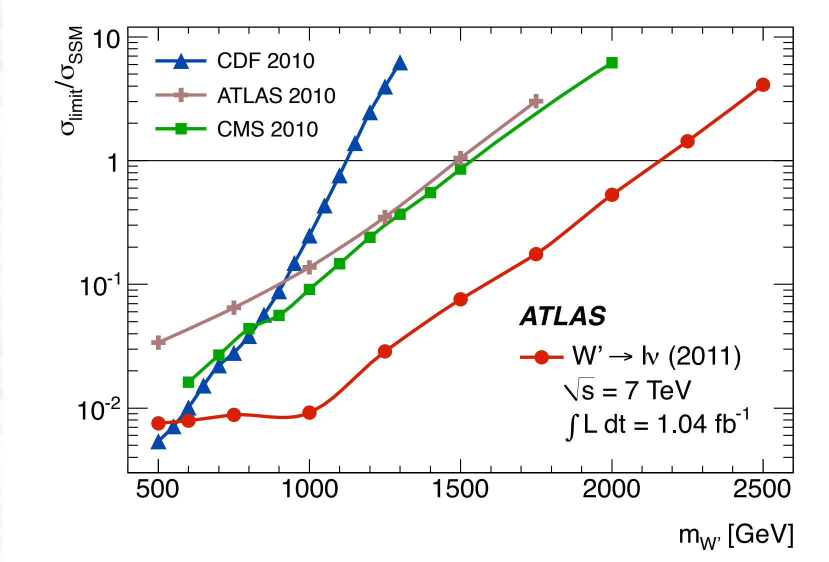
Below: Cumulative transverse mass distributions from CMS in the eν and μν channels

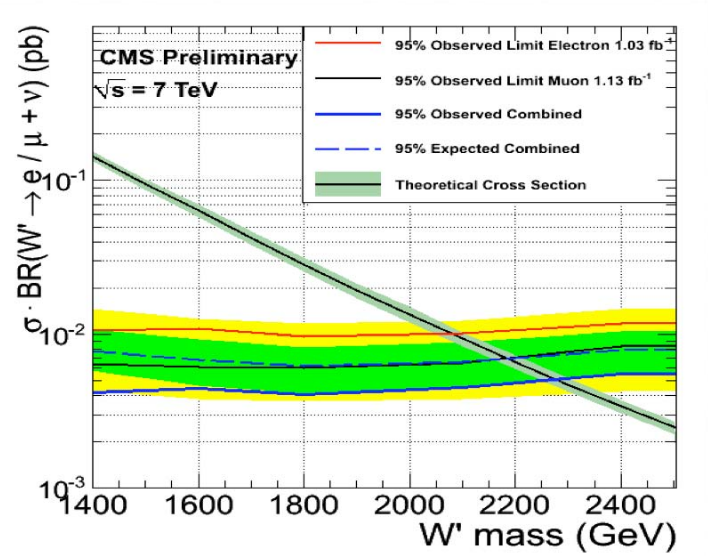




Interpretation in the Sequential SM







Summary of 95% C.L. SSM exclusion limits from ATLAS and CMS:

95% C.L. limits (SM couplings)		ll combined
ATLAS	$1.1\ fb^{-1}$	2.23 TeV
CMS	$1.1\ fb^{-1}$	2.27 TeV

3.2 Search for substructure / compositeness of quarks

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

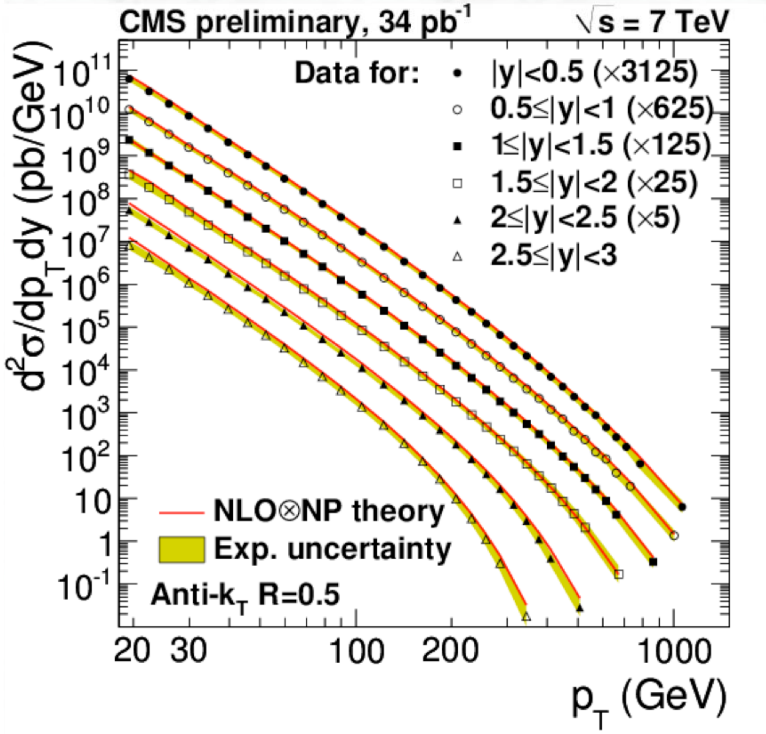
- Such interactions would lead to deviations from the expected QCD scattering behaviour, which would be most visible in:
  - the inclusive jet cross section at high p_T
  - the di-jet invariant mass distribution
    (traditional variables, but very sensitive to uncertainties on the jet energy measurement, i.e. jet energy scale)
  - the di-jet angular distributions of jets in the parton-parton centre-of-mass system

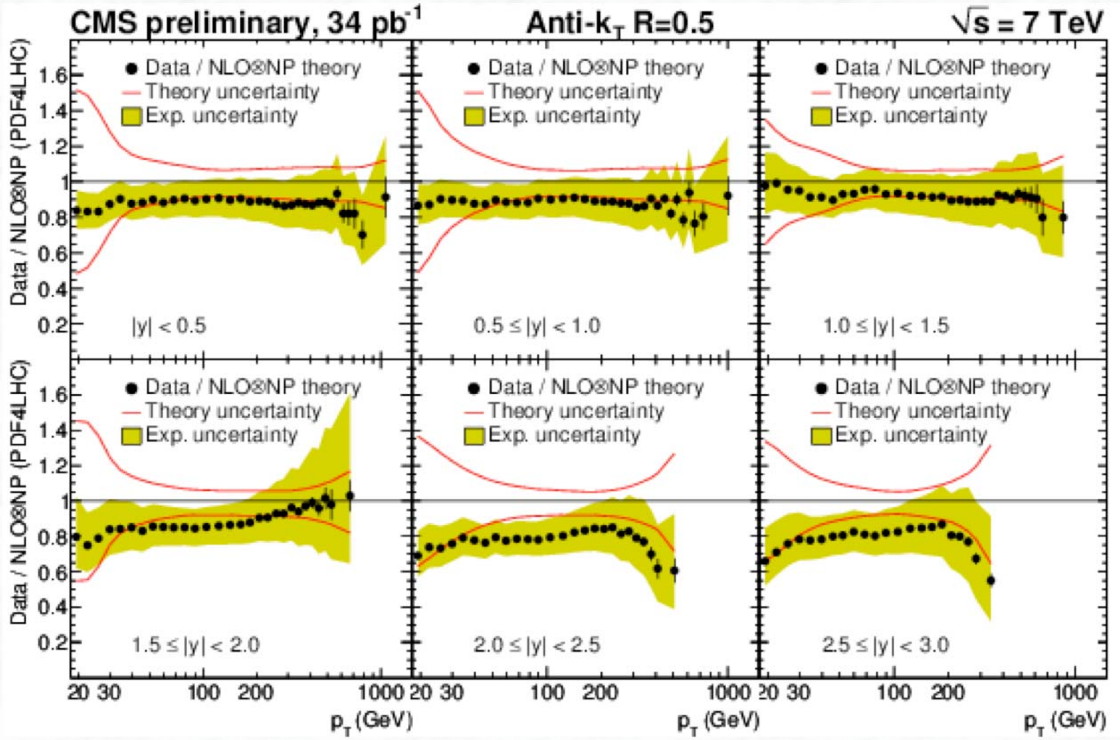
- Parametrize effects by using an effective Lagrangian, in addition to the QCD terms

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

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

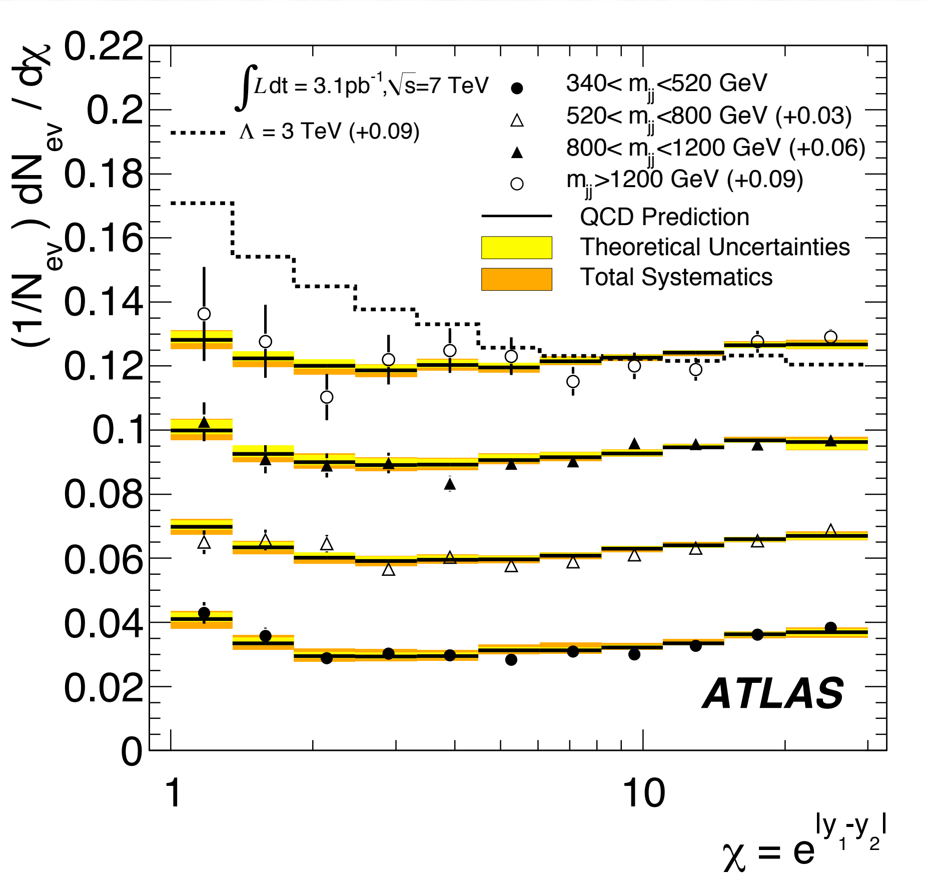
Measured inclusive jet p_T spectrum from CMS (full 2010 dataset)





Search for compositeness:

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

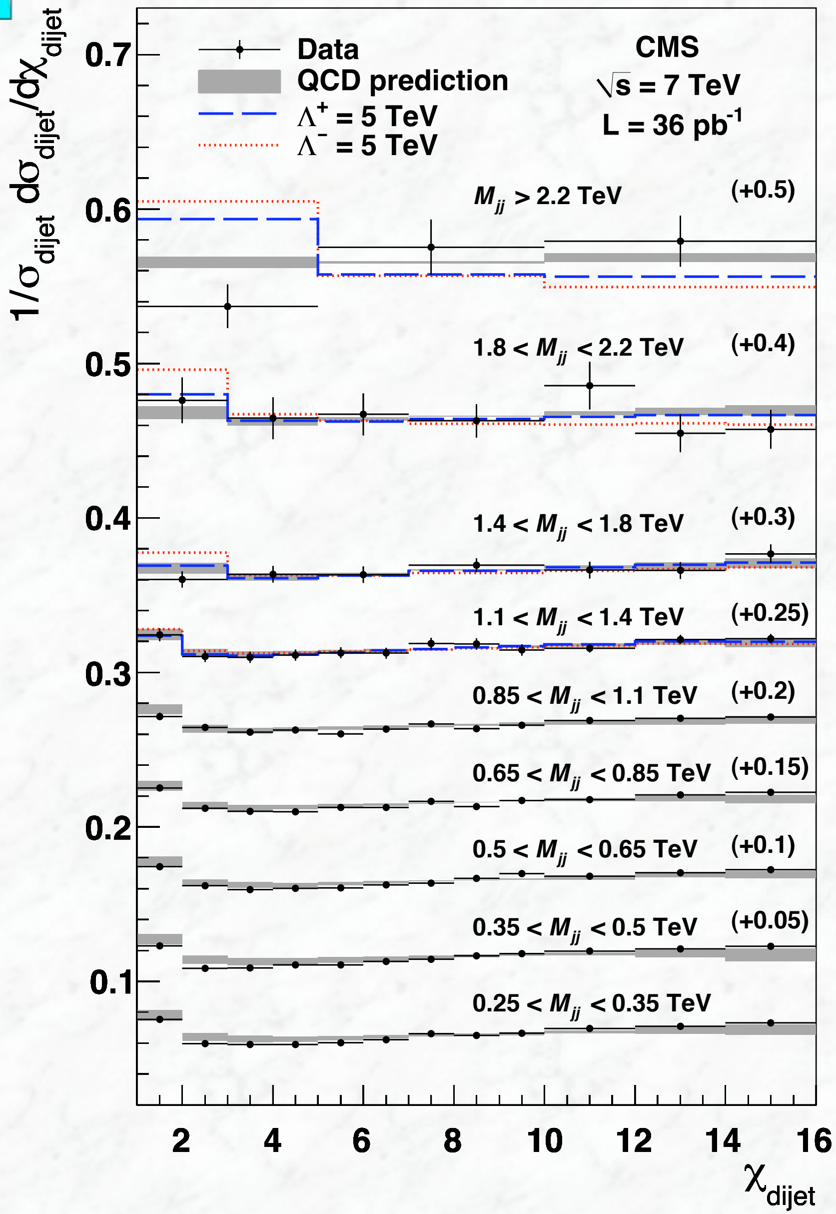


In QCD: gluon exchange diagrams dominate, have the same angular dependence as Rutherford scattering; essentially flat in the variable

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

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



Results on χ measurement from the CMS experiment

based on full 2010 dataset, 36 pb^{-1}

95% C.L. Limits on scale Λ :

ATLAS	3.1 pb^{-1}	Λ > 3.4 TeV
CMS:	36 pb^{-1}	Λ^+ > 5.6 TeV Λ^- > 6.7 TeV

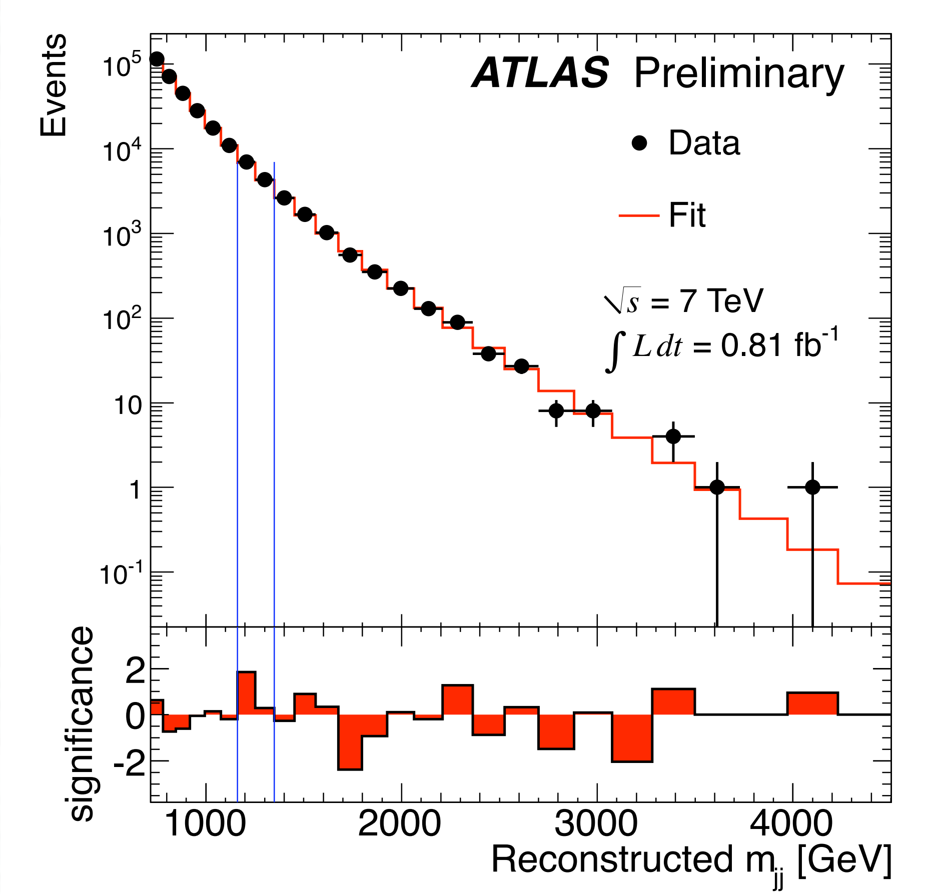
3.3 Search for Resonances in the di-jet mass distribution

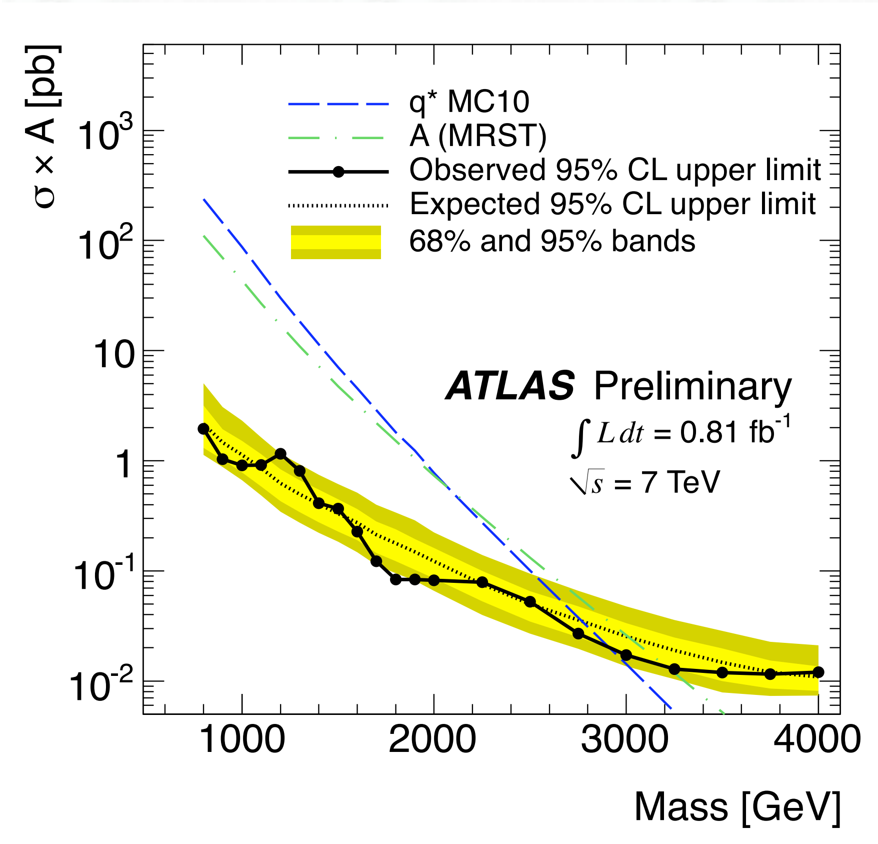
Many extensions of the Standard Model predict the existence of new massive objects that couple to quarks (q) and gluons (g) and result in resonances in the di-jet mass spectrum:

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 $SU(3)_L \times SU(3)_R$
- 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} = 0.81 fb^{-1}

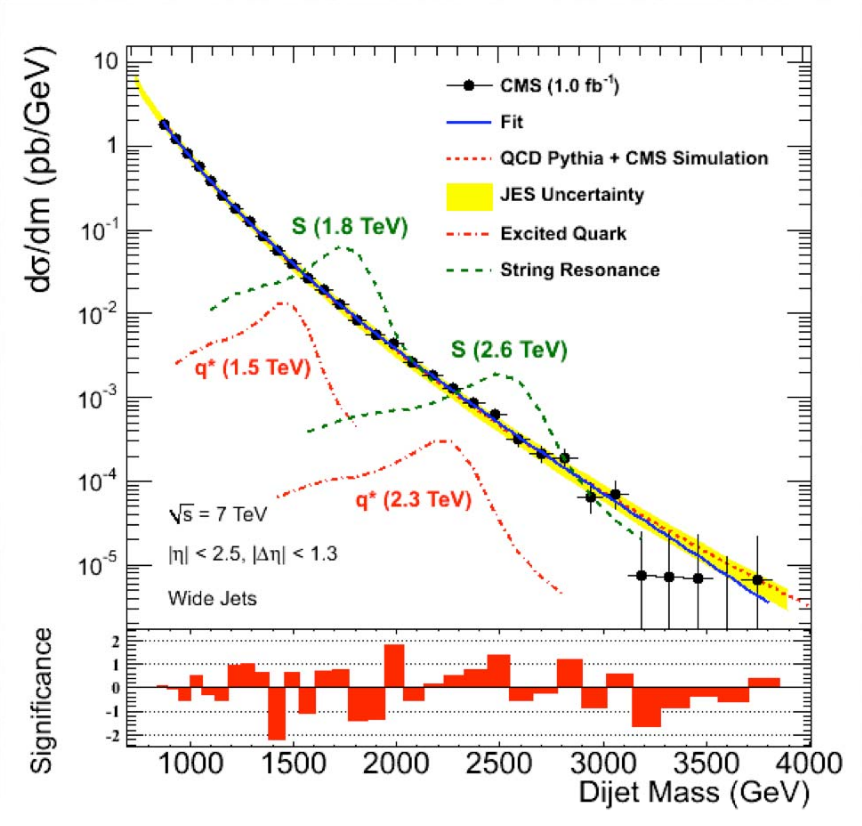


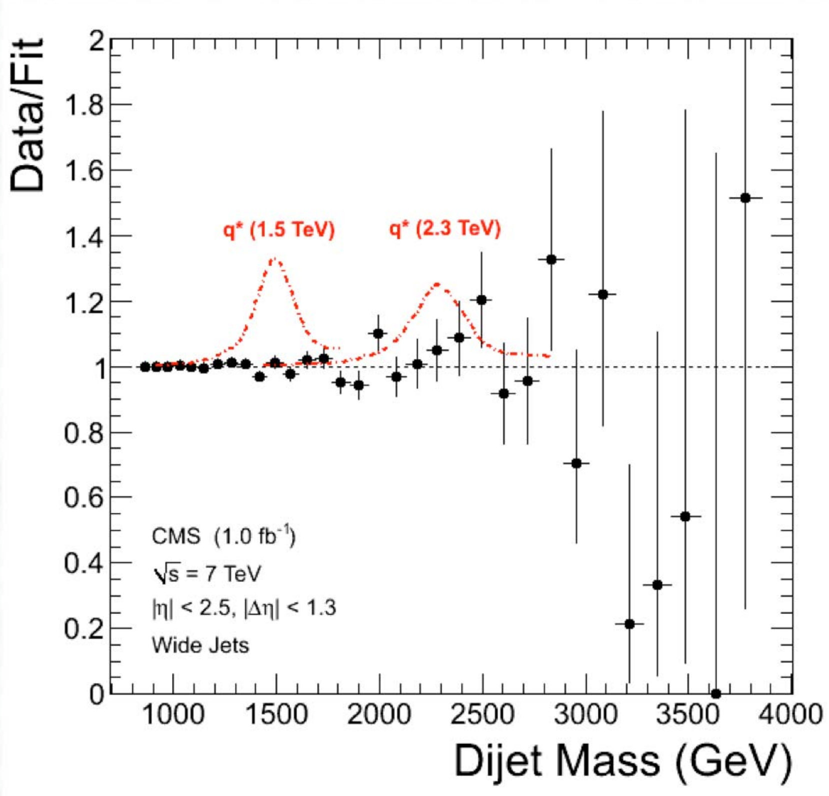


- Search for resonance / bump in the invariant dijet mass spectrum
- Assume smooth functional form of the QCD mass spectrum
- No evidence for a resonance → exclusion limits

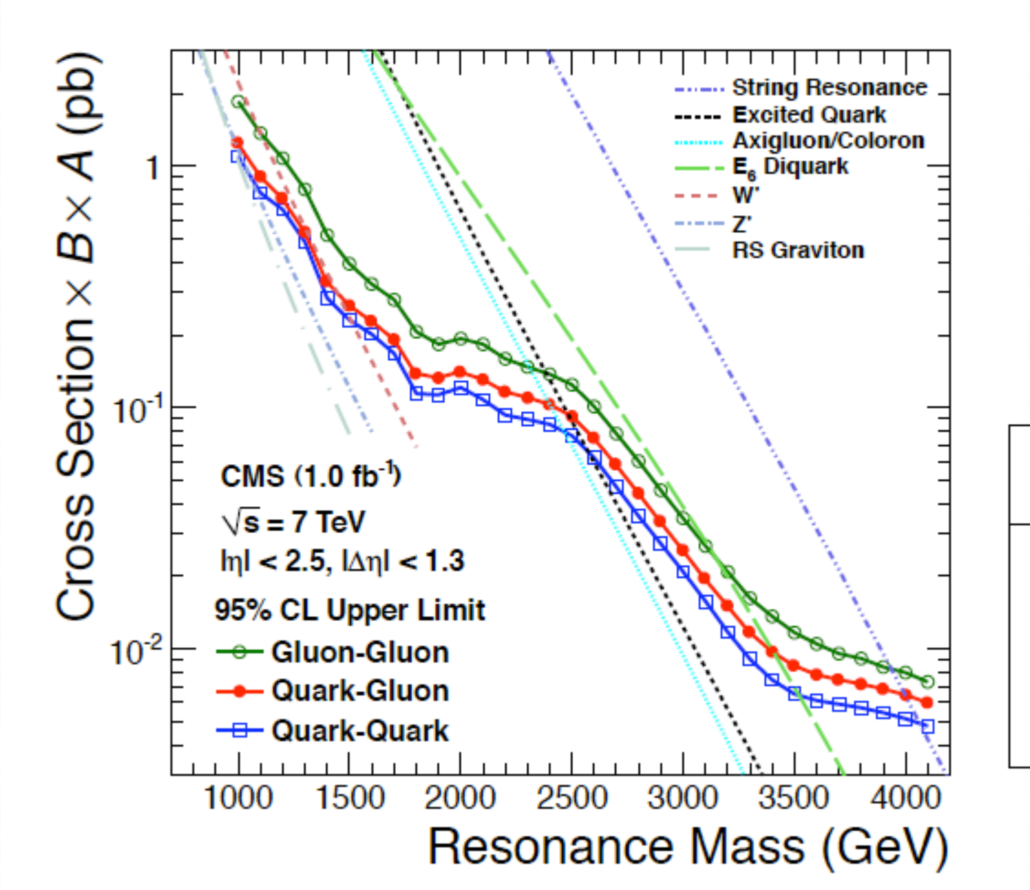
Model	95% CL Limits (TeV)	
	Expected	Observed
Excited Quark q^*	2.77	2.91
Axigluon	3.02	3.21

CMS search in data corresponding to L_{int} = 0.81 fb^{-1}





- Search for resonance / bump in the invariant dijet mass spectrum
- Compare to PYTHIA QCD model
- No evidence for a resonance → exclusion limits



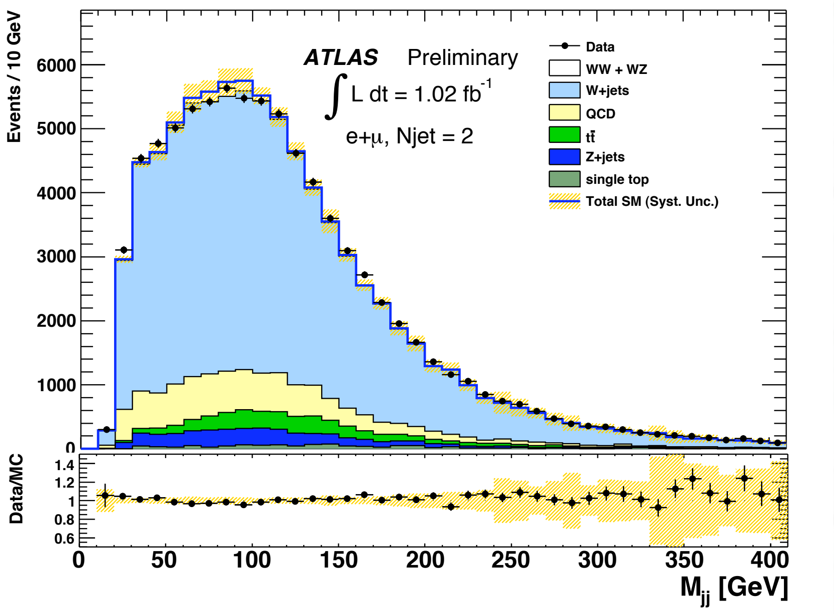
Model	Excluded Mass (TeV)	
	Observed	Expected
String Resonances	4.00	3.90
E_6 Diquarks	3.52	3.28
Excited Quarks	2.49	2.68
Axigluons/Colorons	2.47	2.66
W′ Bosons	1.51	1.40

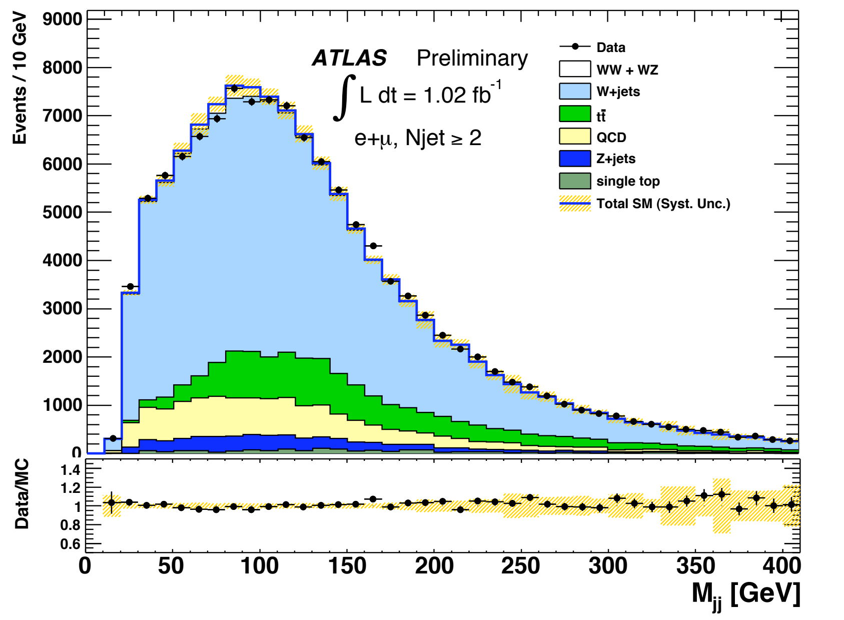
No exclusion limits set yet on
RS gravitons and Z’ → qq decays

More resonance searches ??

What about a bump in the di-jet mass in Wjj events ?

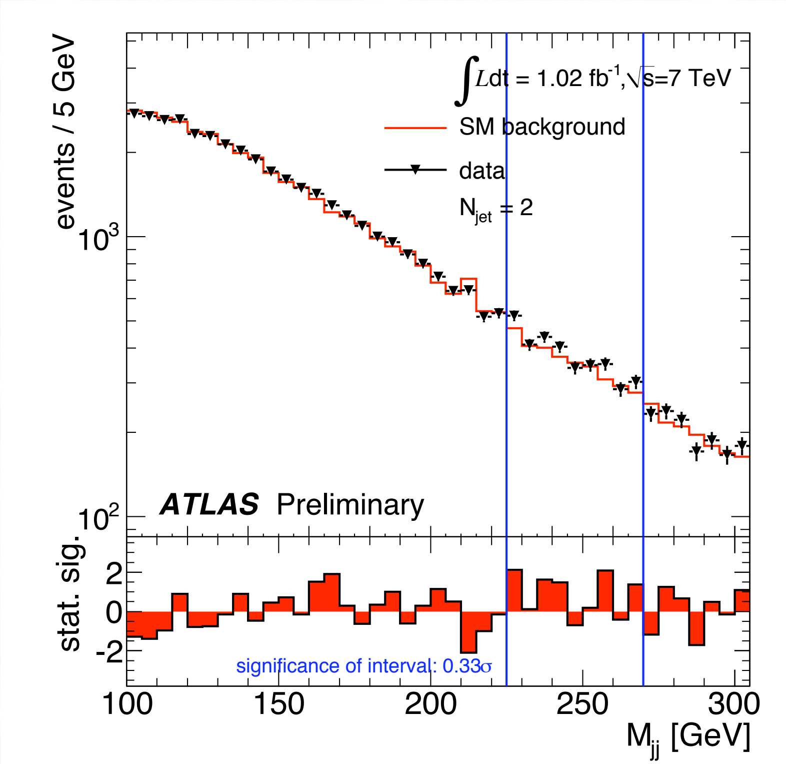
ATLAS analysis, $L_{int} = 1.02\ fb^{-1}$

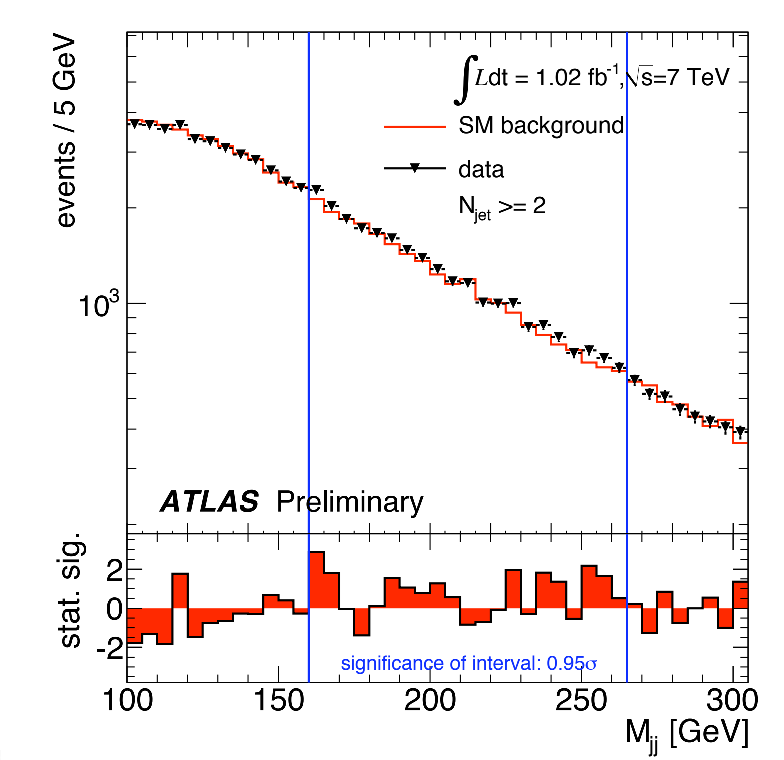




Di-jet mass distributions for Wjj events, with $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$, with $N_{jet} = 2$ (left) and for $N_{jet} \geq 2$ (right)

No significant excess above the Standard Model expectation seen !

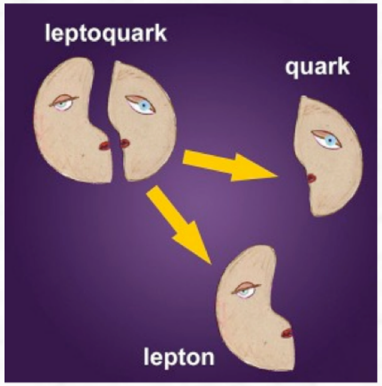




Fine binned comparison of the di-jet invariant mass obtained with $N_{jet} = 2$ (left) and for $N_{jet} \geq 2$ (right), to the background hypothesis and the resulting bin-to-bin significance

No significant excess above the Standard Model expectation seen !

3.4 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 $\quad F = L + 3B$

β = BR (LQ → $\ell^\pm q$) $\quad$ gel. Lepton $\quad$ spez. Modell : 0, ½, 1

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

Leptoquarks at the electroweak scale ?

- Leptoquarks may also be light, with masses at the electroweak scale;

  allowed decays: LQ (-⅓) → e^- u, or LQ(-4/3) → e^- d
  LQ (-⅓) → ν_e d

  Decays proceed always as: LQ → lepton + quark

  Branching ratio β : = BR (LQ → l q) charged lepton decay
  (1-β) = 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

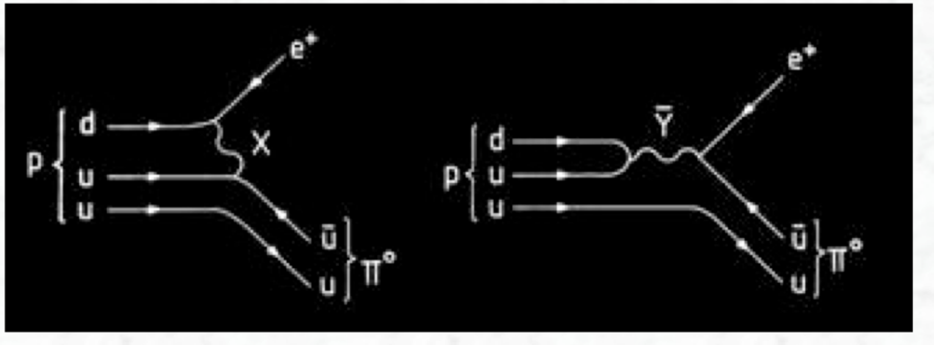
  → LQs of 1st, 2nd, and 3rd generation

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

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

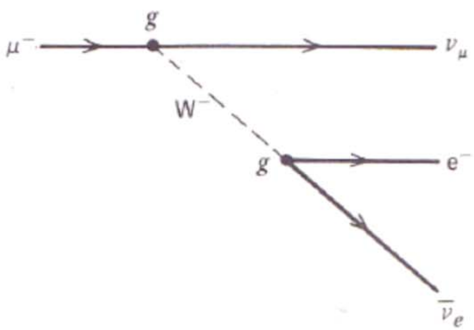


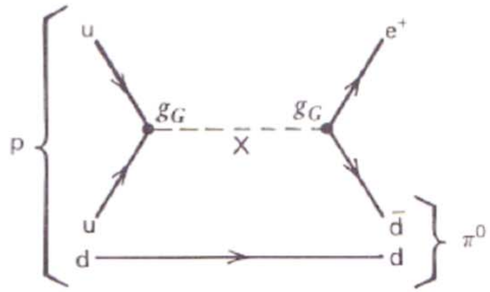
Can proton decay be detected?

- 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 $Q^2 \ll M_X^2$





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

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

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

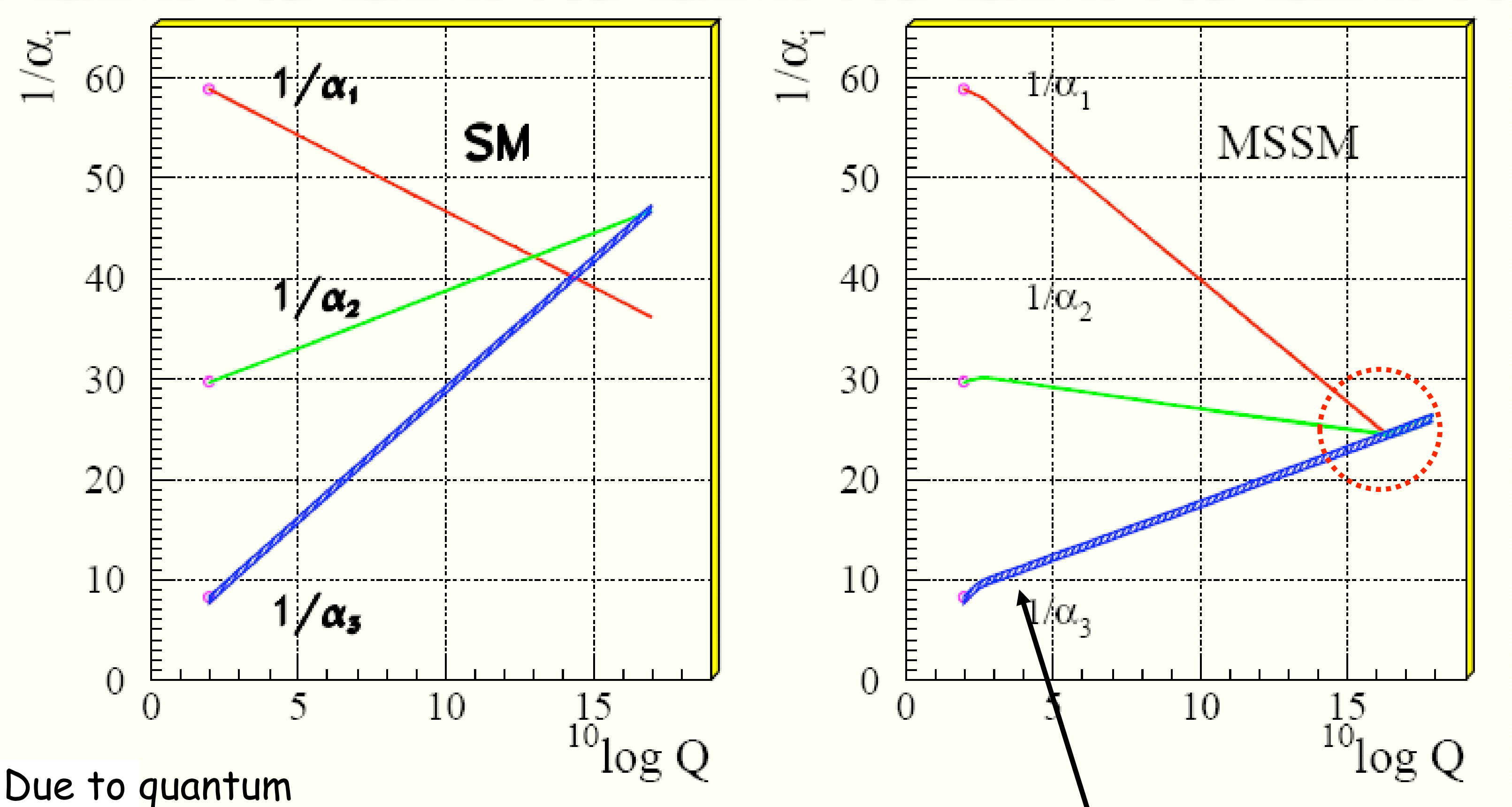
$$\frac{G_G}{\sqrt{2}} = \frac{g_G^2}{8M_X^2}$$

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

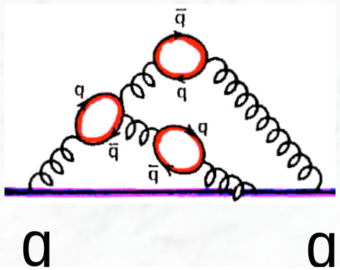
$$= \cdots \frac{m_p^5}{M_X^4}$$

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

The unification of the couplings of the three interactions seems possible in a SUSY model



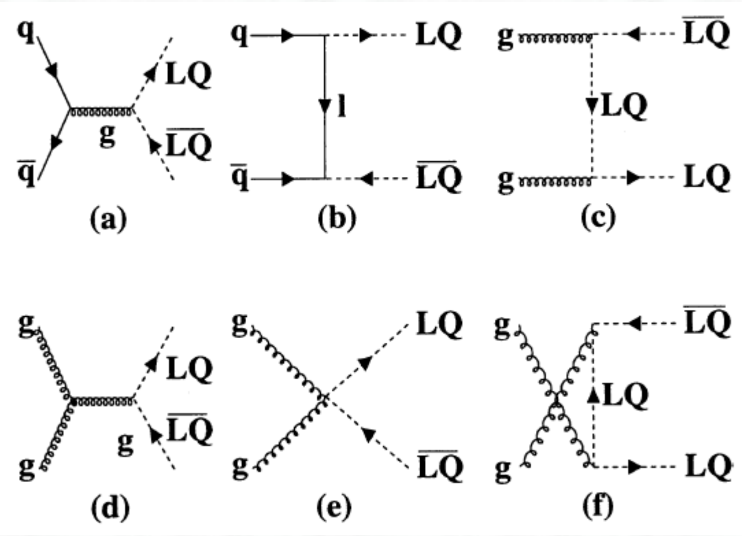
Due to quantum corrections, e.g.



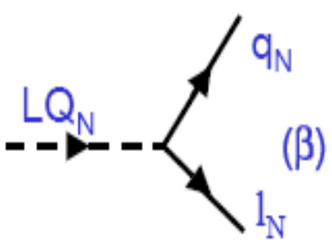
slope is changed due to contributions from SUSY particles

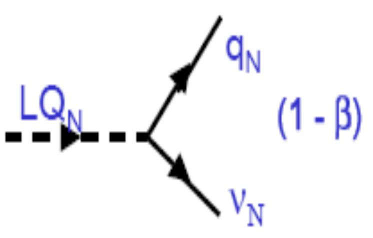
Search for Scalar Leptoquarks (LQ)

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



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





β= LQ branching fraction to charged lepton and quark
N = generation index
Leptoquarks of 1st, 2nd, and 3rd 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)

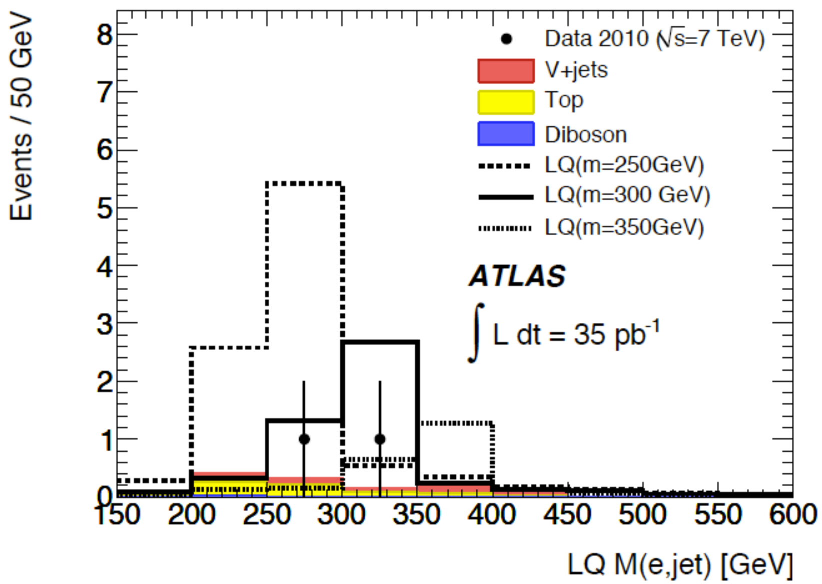
- Additional kinematic requirements:

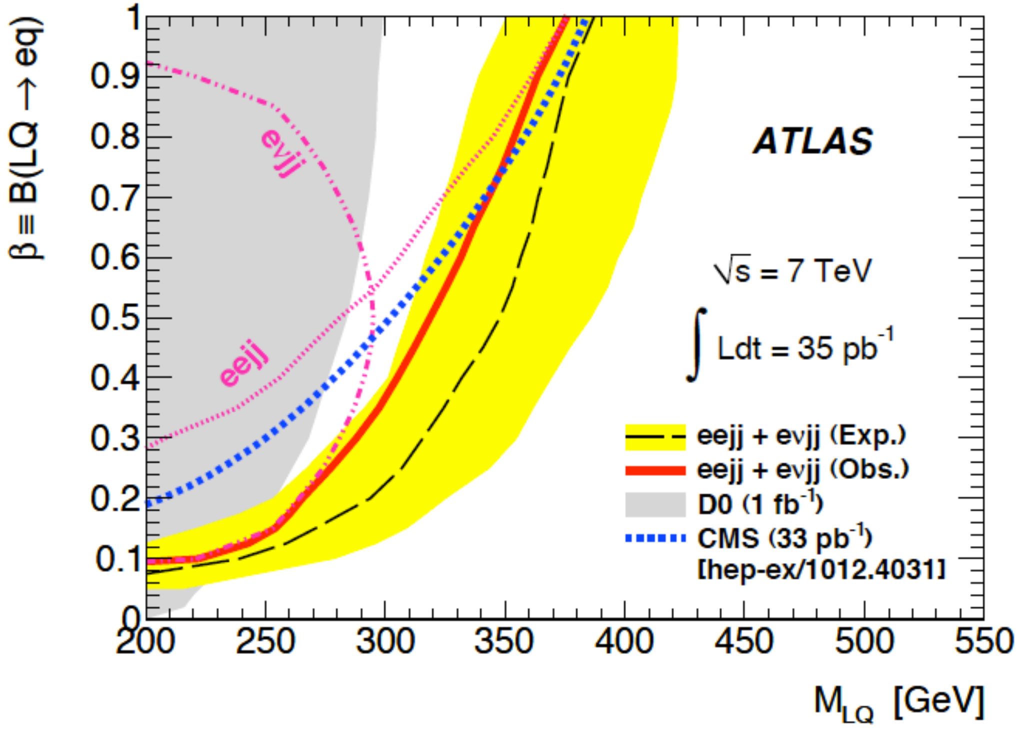
$eejj$ and $\mu\mu jj$	$e\nu jj$	$\mu\nu jj$
$M_{ll} > 120$ GeV	$M_T > 200$ GeV	$M_T > 160$ GeV
$M_{LQ} > 150$ GeV	$M_{LQ} > 180$ GeV	$M_{LQ} > 150$ GeV
$p_T^{all} > 30$ GeV	$M_{LQ}^T > 180$ GeV	$M_{LQ}^T > 150$ GeV
$S_T^\ell > 450$ GeV	$S_T^\nu > 410$ GeV	$S_T^\nu > 400$ GeV

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

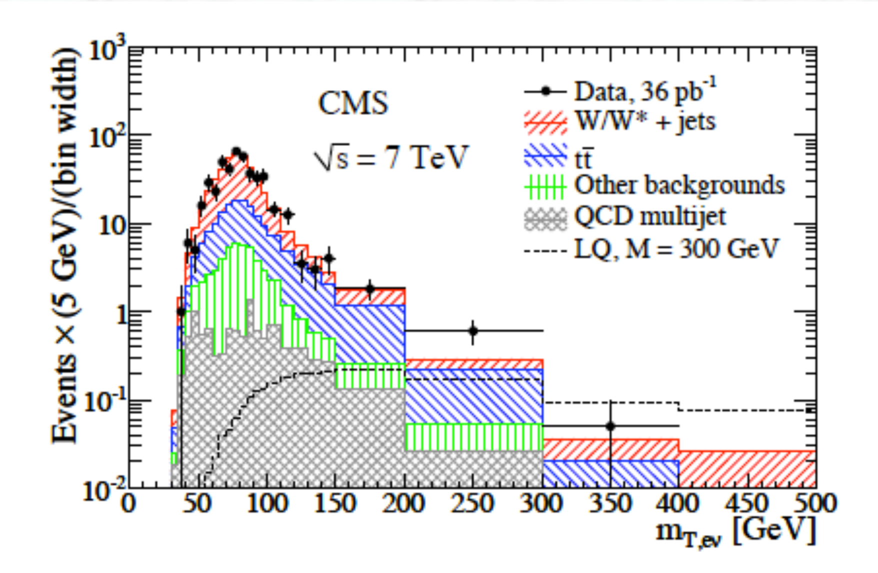
- Data, backgrounds and signal expectation (36 pb^{-1})

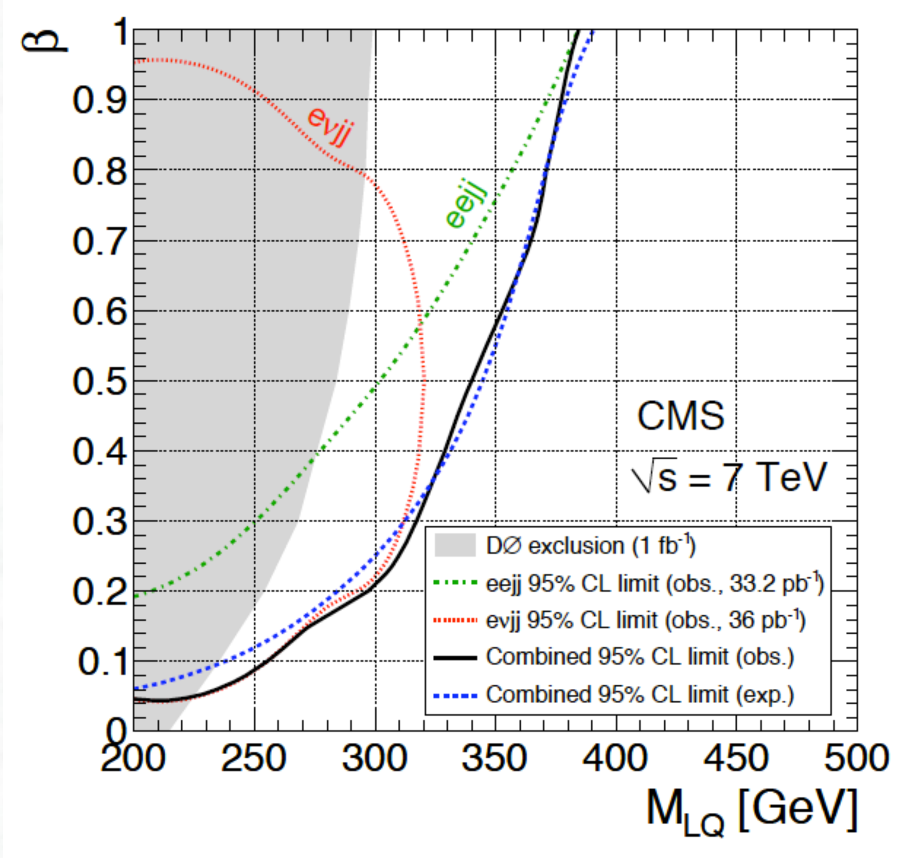
Source	$eejj$	$e\nu jj$	$\mu\mu jj$	$\mu\nu jj$
V+jets	0.50 ± 0.28	0.65 ± 0.38	0.28 ± 0.22	2.6 ± 1.4
Top	0.51 ± 0.23	0.67 ± 0.39	0.52 ± 0.23	1.6 ± 0.9
Diboson	0.03 ± 0.01	0.10 ± 0.03	0.04 ± 0.01	0.10 ± 0.03
QCD	$0.02 \,^{+0.03}_{-0.02}$	0.06 ± 0.01	$0.00 \,^{+0.01}_{-0.00}$	0.0 ± 0.0
Total Bkg	1.1 ±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


β ≡ B(LQ → eq)
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]
MLQ [GeV]

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/c²	224 GeV/c²	129 GeV/c²
D0 (Run I + II)	282 GeV/c²	200 GeV/c²	
ATLAS	319 GeV/c²	362 GeV/c²	
CMS	340 GeV/c²	290 GeV/c²	

β = 0.5

LHC reach for other BSM Physics

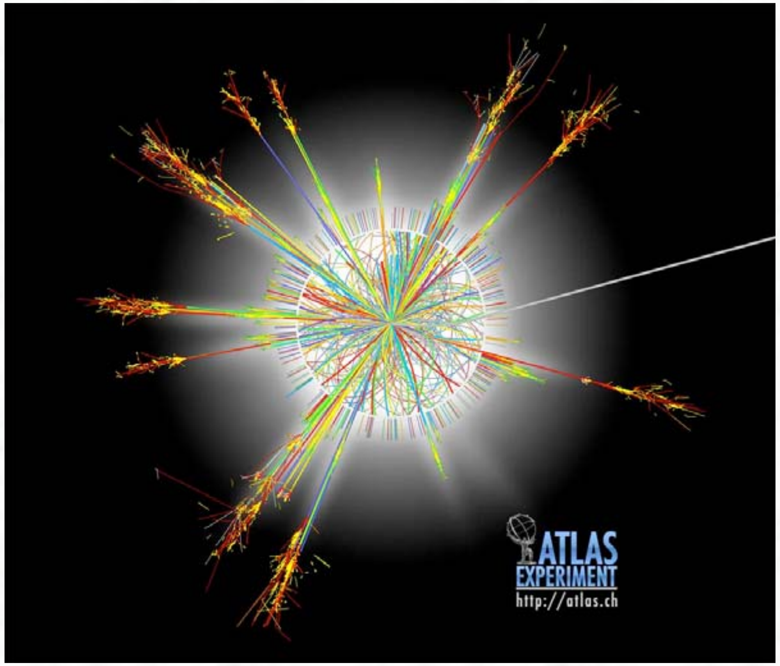
(expected discovery sensitivity for 30 and 100 fb^{-1})

	30 fb^{-1}	**100 fb^{-1}**
Excited Quarks $Q^* \rightarrow q\,\gamma$	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

3.5 Search for signals from extra dimensions

- Search for escaping gravitons at the LHC

- Search for Black Hole Production



Microscopic-Black Hole events at the LHC ?

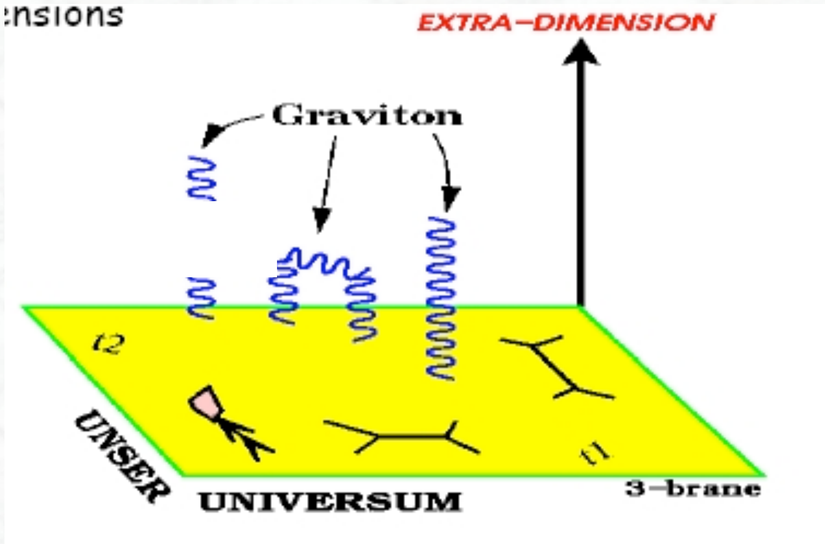
Large Extra Dimensions & the ADD Model

- 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:

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

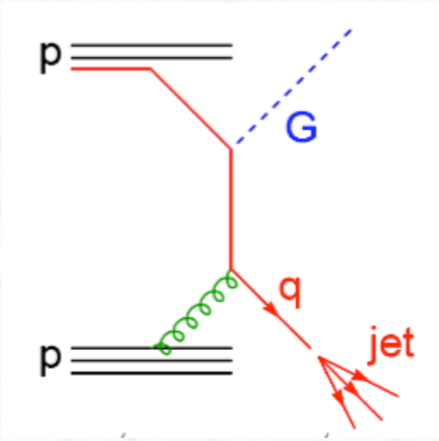
- The Standard Model interactions and all matter particles are confined to our 3-dimensional world



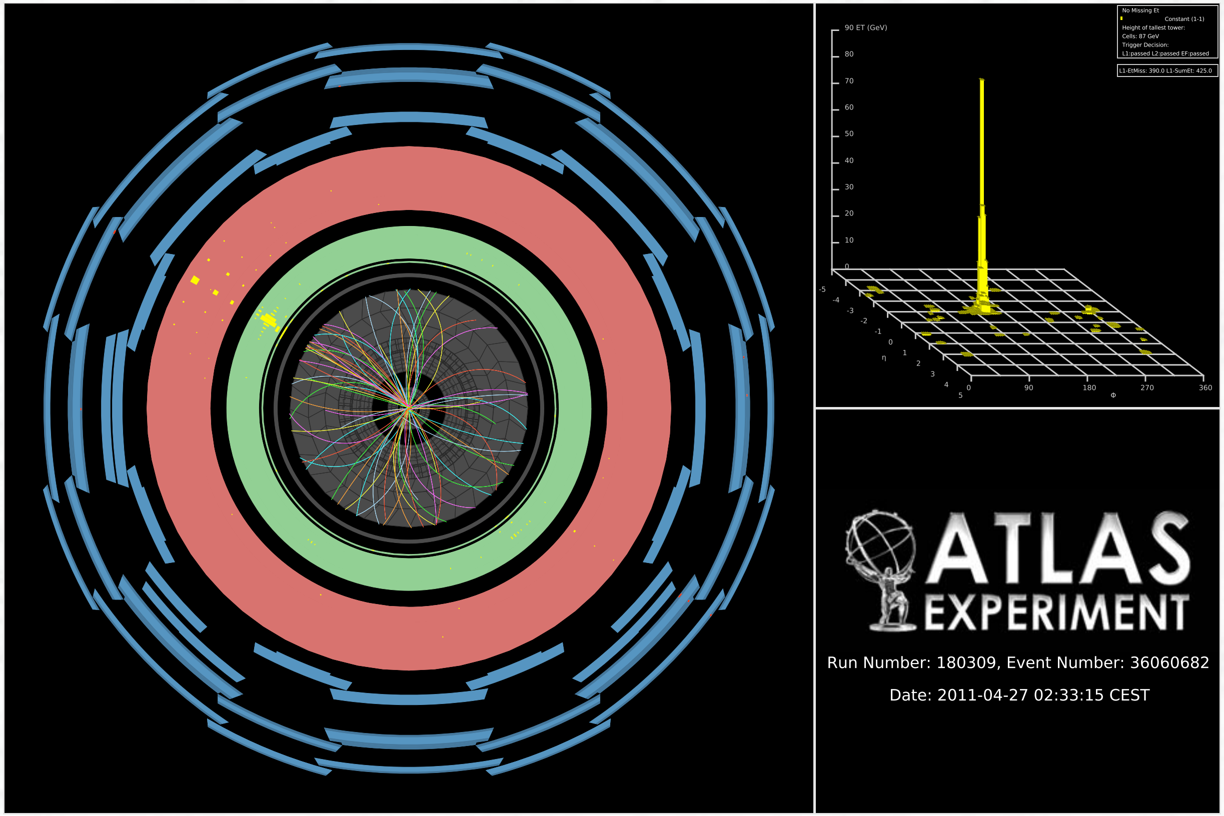
Arkani-Hamed, Dimopoulos, Dvali: hep-ph/9803315, 9804398, 9807344

Experimental Signature: Mono-jets from graviton production

Signal: single jet, E_T^{miss}

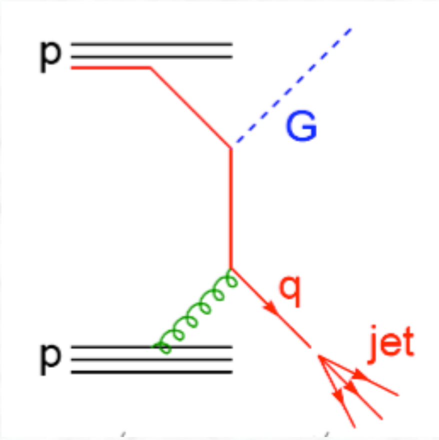


A nice candidate event: 1 jet with p_T = 602 GeV
E_T^{miss} = 523 GeV



Experimental Signature: Monojets

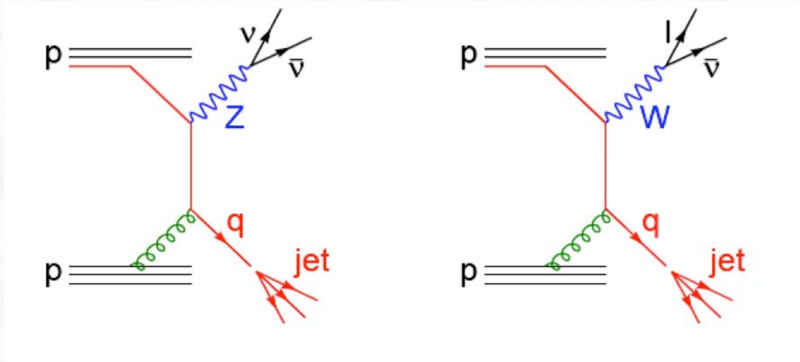
Signal: single jet, E_T^{miss}



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, 2011 data, L_{int} = 1.0 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 (low p_T), 250 GeV (high p_T), 350 GeV (very high) in the central detector region, $|\eta| < 2.0$

  No further jets in the event with p_T > 30 GeV within $|\eta| < 4.5$

- E_T^{miss} > 120 GeV (low), 220 GeV (high) and 300 GeV (very high) and $\Delta\phi$ (jet, E_T^{miss}) > 0.5

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

➔ 15750, 965 and 167 events observed in ATLAS data for the low, high and very high selections, respectively

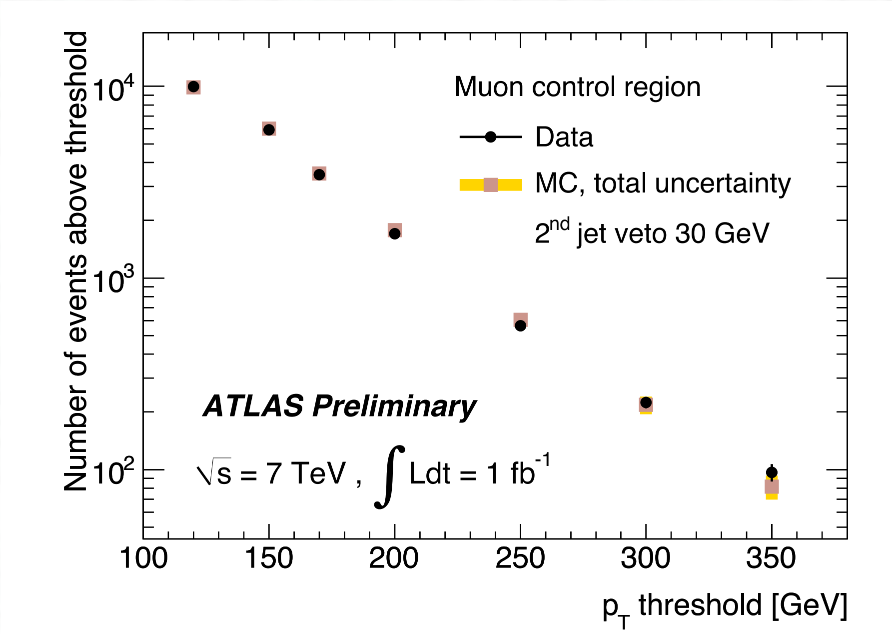
W/Z + jet background estimate from data:

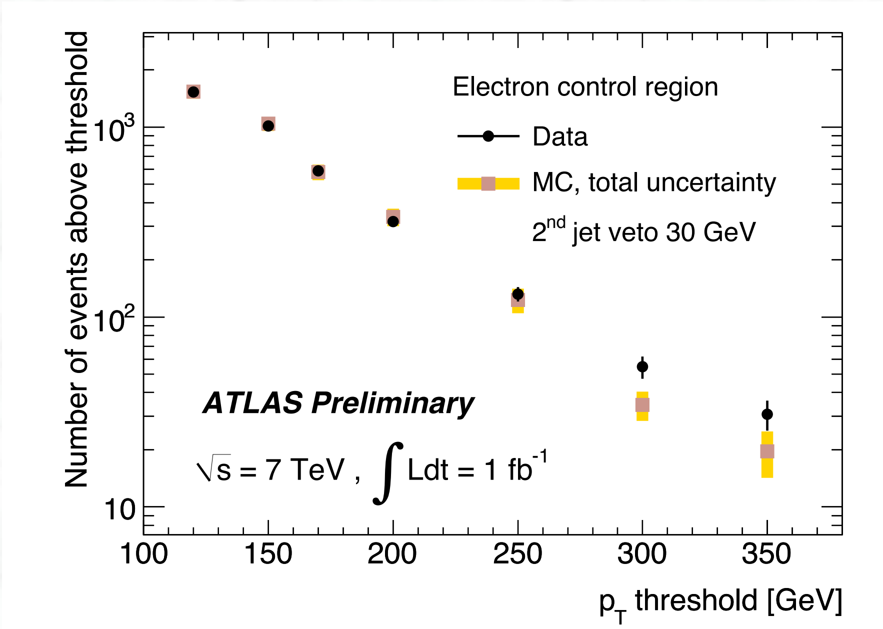
- Control sample, require an identified lepton (disjunct with the signal sample); all other cuts identical; done separately for the electron and the muon channels

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

- Total sum is normalized to the data; normalization factors found are: e.g. low p_T selection: 0.95 ± 0.02 (muons) and 0.90 ± 0.04 (electrons) (on top of the NNLO theory prediction for inclusive W/Z cross section)

After normalization: very good agreement between data and Monte Carlo simulation

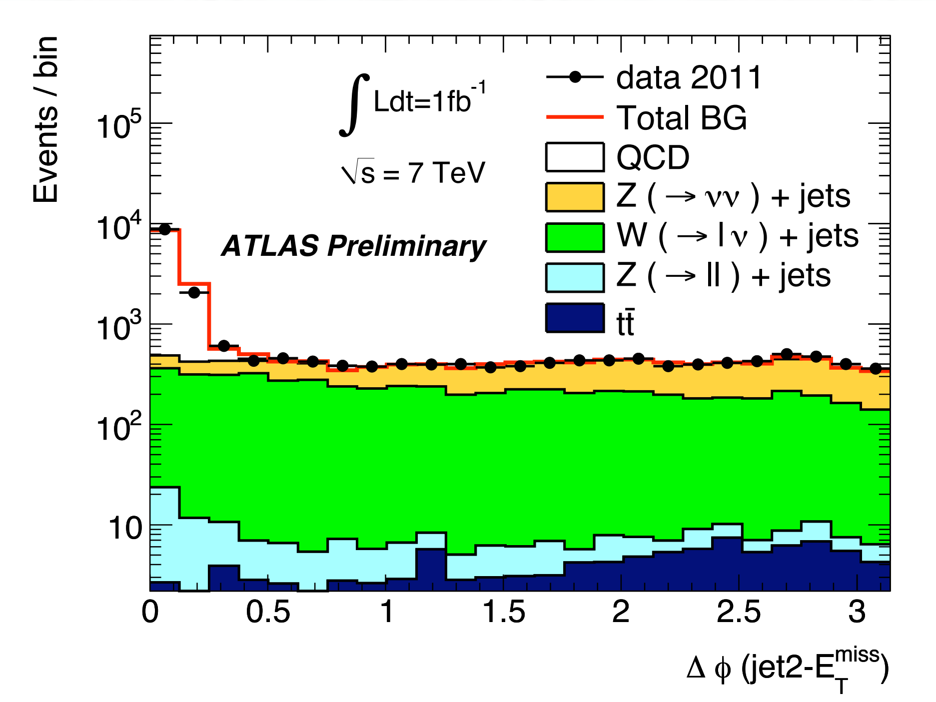




Estimate of multijet background from data:

- Control sample: give up veto on 2nd jet and $\Delta\phi$ (jet, E_T^{miss}) requirement ("fake" E_T^{miss} will most likely result from a mis-measured second jet)

- Look at the $\Delta\phi$ distribution for the second jet: (for physics backgrounds the same normalization factors as determined before are used)



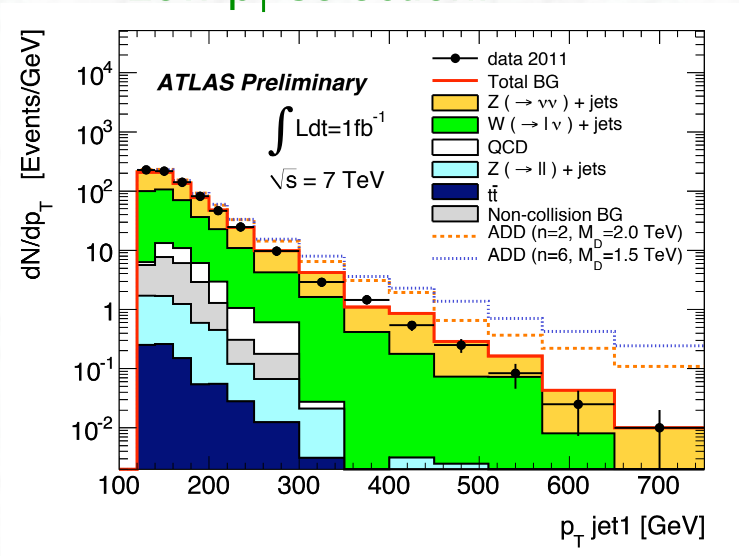
Good description of data, except in low $\Delta\phi$ region → QCD background component from data

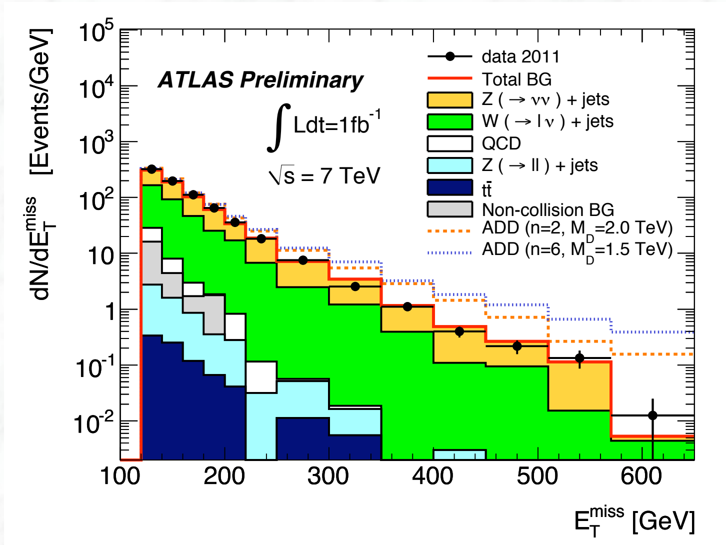
Numbers of observed events in data in comparison to expectations from Standard Model background:

	Background Predictions ± (stat.) ± (syst.)		
	LowPt Selection	HighPt Selection	veryHighPt selection
$Z(\rightarrow \nu\bar{\nu})$+jets	$7700 \pm 90 \pm 400$	$610 \pm 27 \pm 47$	$124 \pm 12 \pm 15$
$W(\rightarrow \tau\nu)$+jets	$3300 \pm 90 \pm 220$	$180 \pm 16 \pm 22$	$36 \pm 7 \pm 8$
$W(\rightarrow e\nu)$+jets	$1370 \pm 60 \pm 90$	$68 \pm 10 \pm 8$	$8 \pm 1 \pm 2$
$W(\rightarrow \mu\nu)$+jets	$1890 \pm 70 \pm 100$	$113 \pm 14 \pm 9$	$18 \pm 4 \pm 2$
Multi-jets	$360 \pm 20 \pm 290$	$30 \pm 6 \pm 11$	$3 \pm 2 \pm 2$
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$+jets	$59 \pm 3 \pm 4$	$2.0 \pm 0.6 \pm 0.2$	-
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$+jets	$45 \pm 3 \pm 2$	$2.0 \pm 0.6 \pm 0.1$	-
$t\bar{t}$	$17 \pm 1 \pm 3$	$1.7 \pm 0.3 \pm 0.3$	-
γ+jet	-	-	-
$Z/\gamma^*(\rightarrow e^+e^-)$+jets	-	-	-
Non-collision Background	$370 \pm 40 \pm 170$	$8.0 \pm 3.3 \pm 4.1$	$4.0 \pm 3.2 \pm 2.1$
Total Background	$15100 \pm 170 \pm 680$	$1010 \pm 37 \pm 65$	$193 \pm 15 \pm 20$
Events in Data (1.00 fb^{-1})	15740	965	167

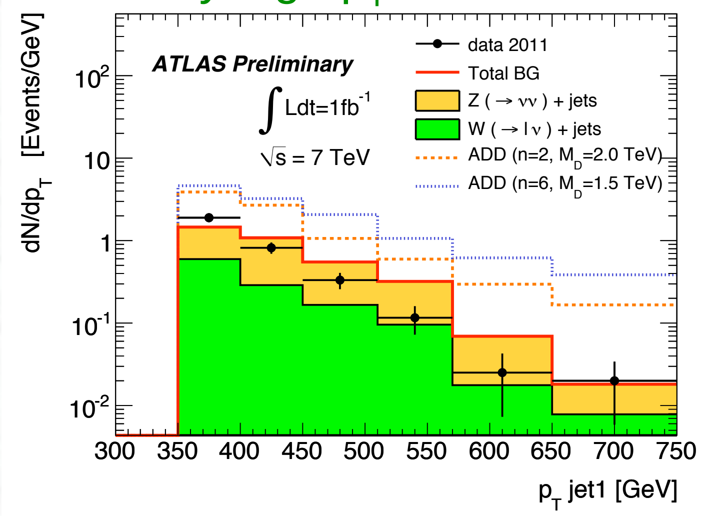
Agreement between data and expectations for the p_T(jet) and E_T^{miss} spectra:

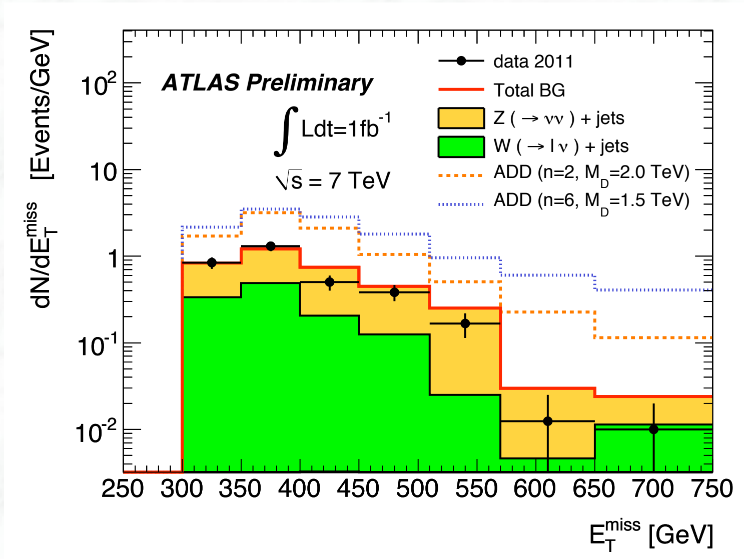
Low p_T selection:



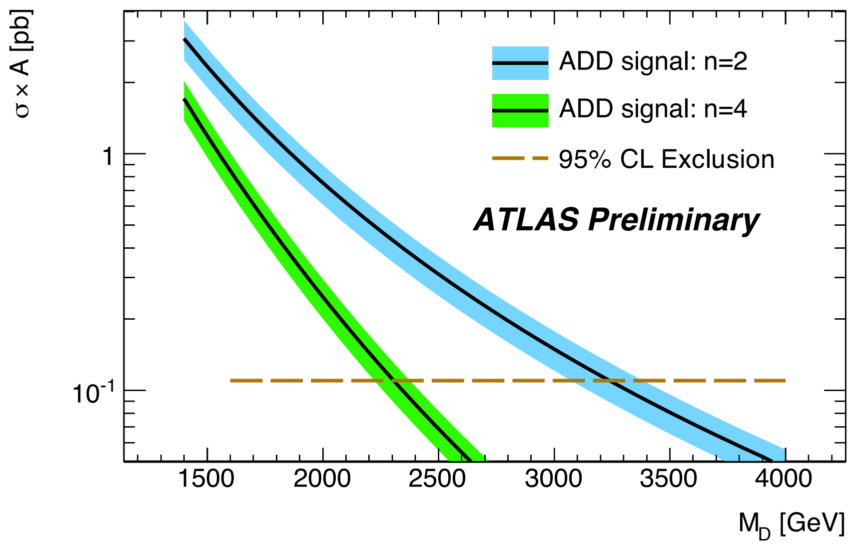


Very high p_T selection:

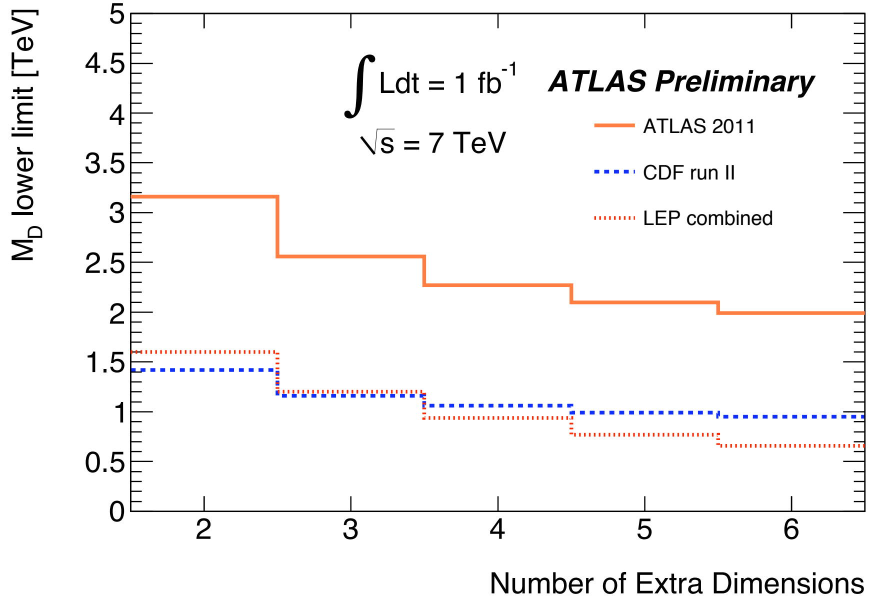




Constraints on the ADD model parameters:



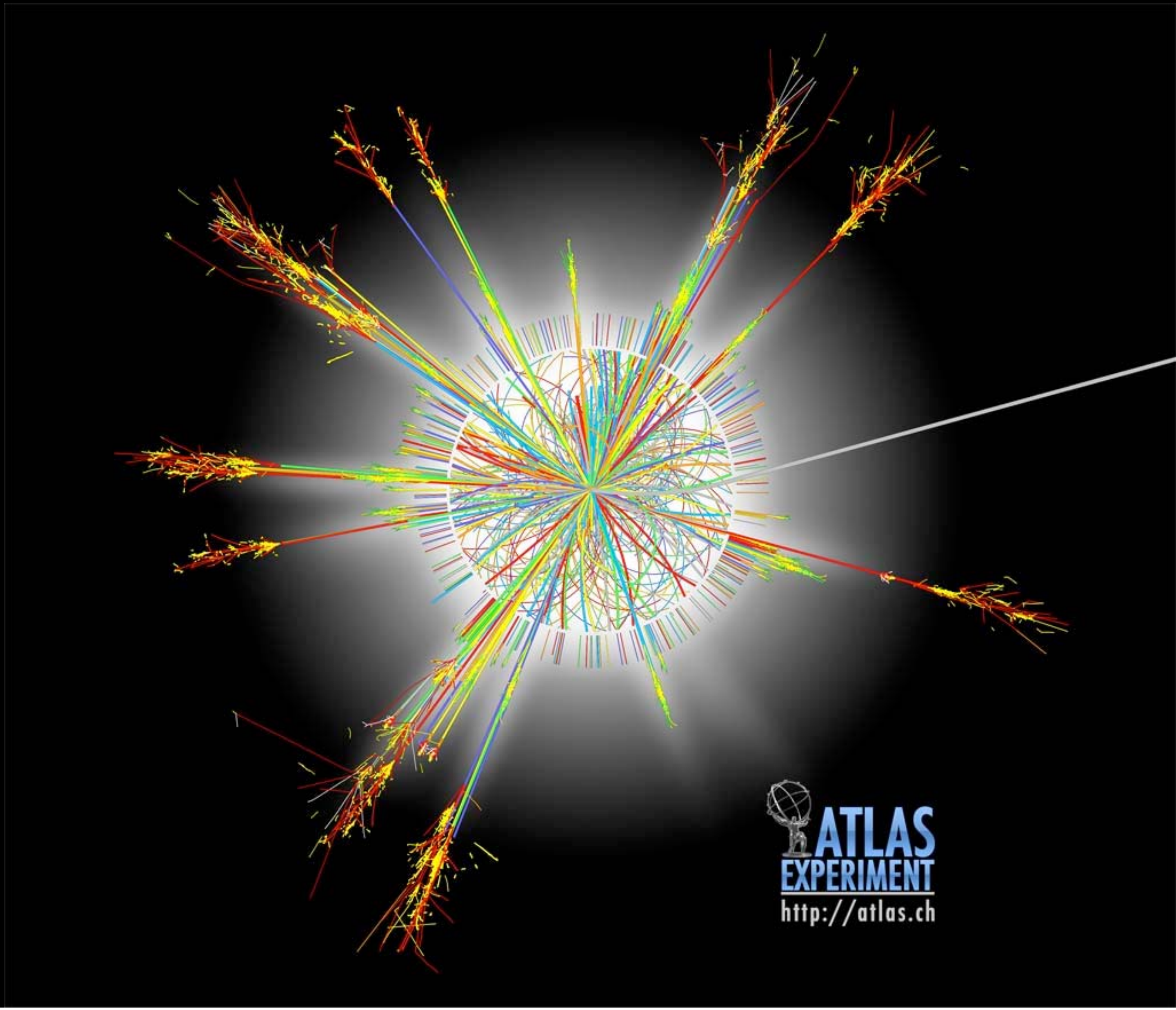
Cross sections as a function of M_D for n=2 and n=4 extra dimensions (cutoff for s^ < M^2_D)



Excluded M_D values (95% C.L.):

95% CL limits on M_D for the ADD model ($\hat{s} < M_D^2$)			
	LowPt selection	HighPt selection	veryHighPt selection
n	observed [TeV]	observed [TeV]	observed [TeV]
2	2.20	3.16	3.39
3	1.76	2.50	2.55
4	1.54	2.15	2.26
5	1.37	1.89	1.90
6	1.24	1.68	1.58

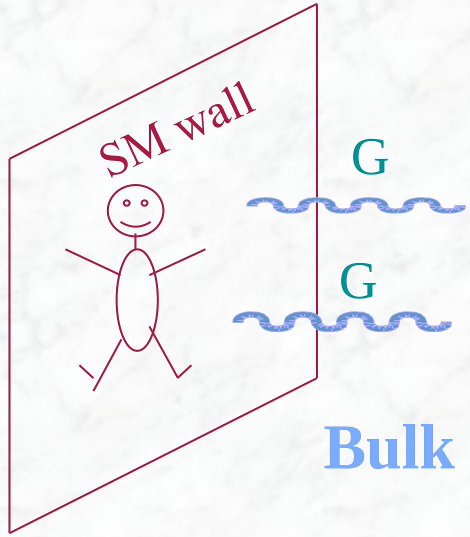
Microscopic Black Holes at the LHC ?



- 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:

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

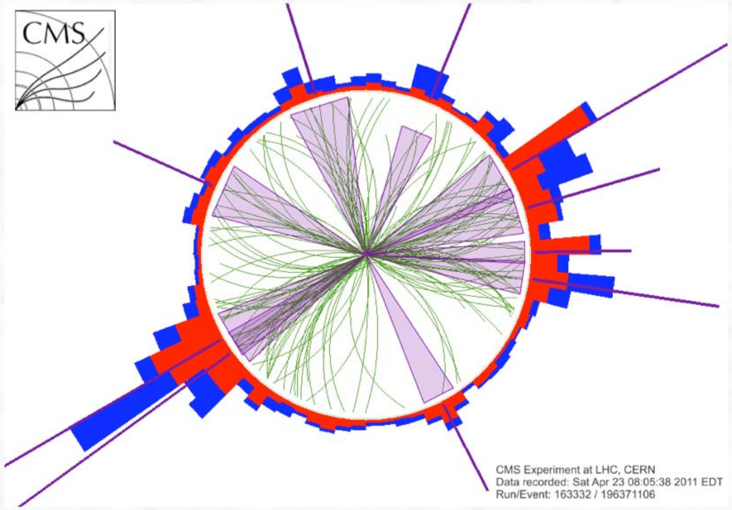


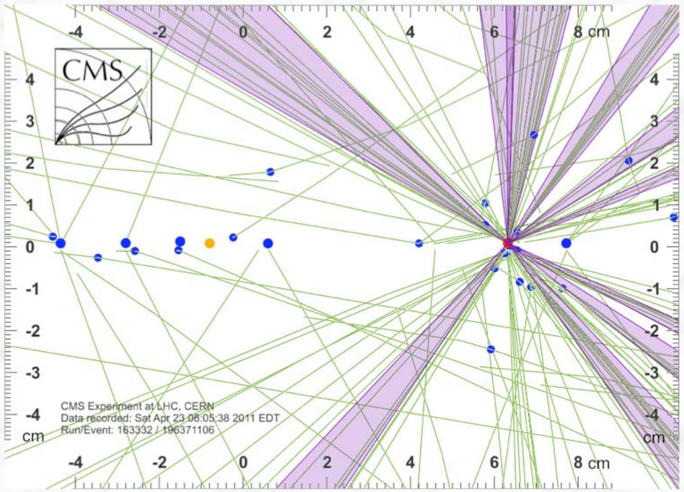
- Black hole formation at energies greater than M_D, (above a threshold mass, M_{th})

  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 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….

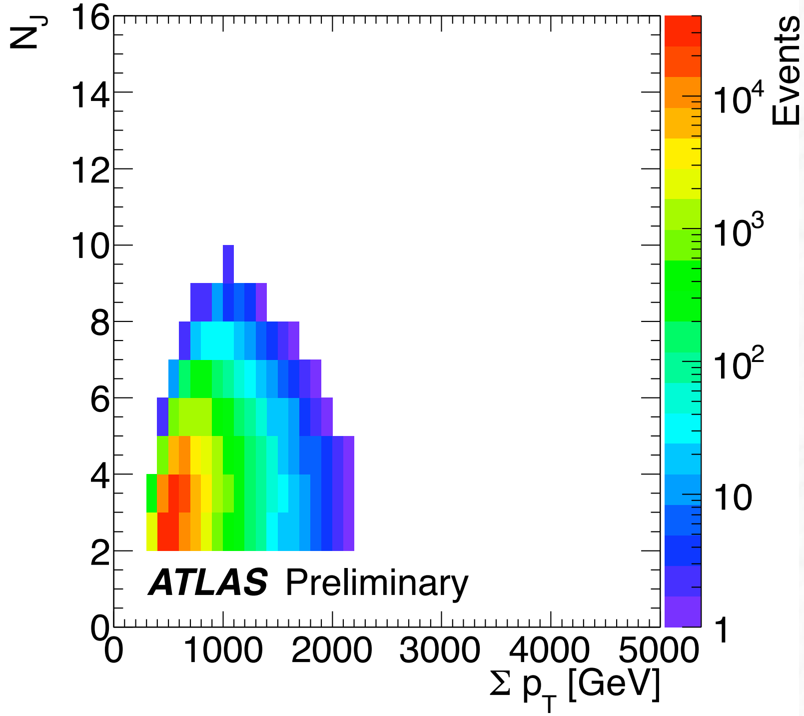
all particles coming from one interaction vertex

Is there an excess above the expectation from QCD production?

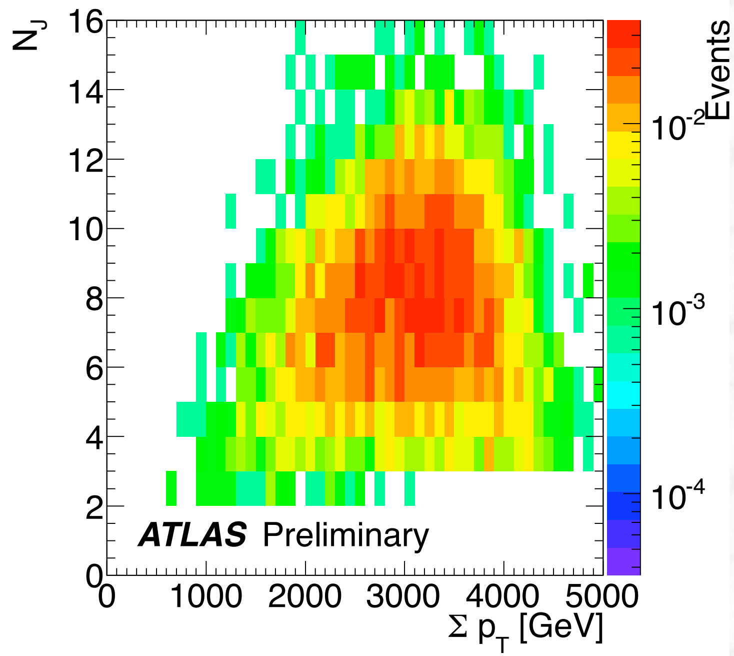
Discriminating variables between QCD background and black hole signals:

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

Results of an ATLAS Monte Carlo simulation:

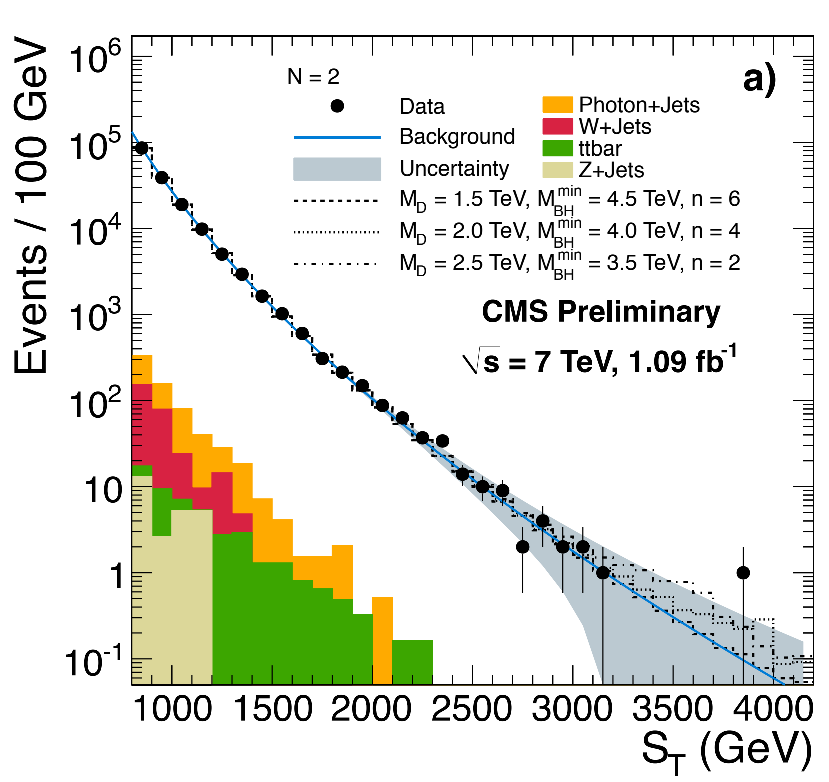


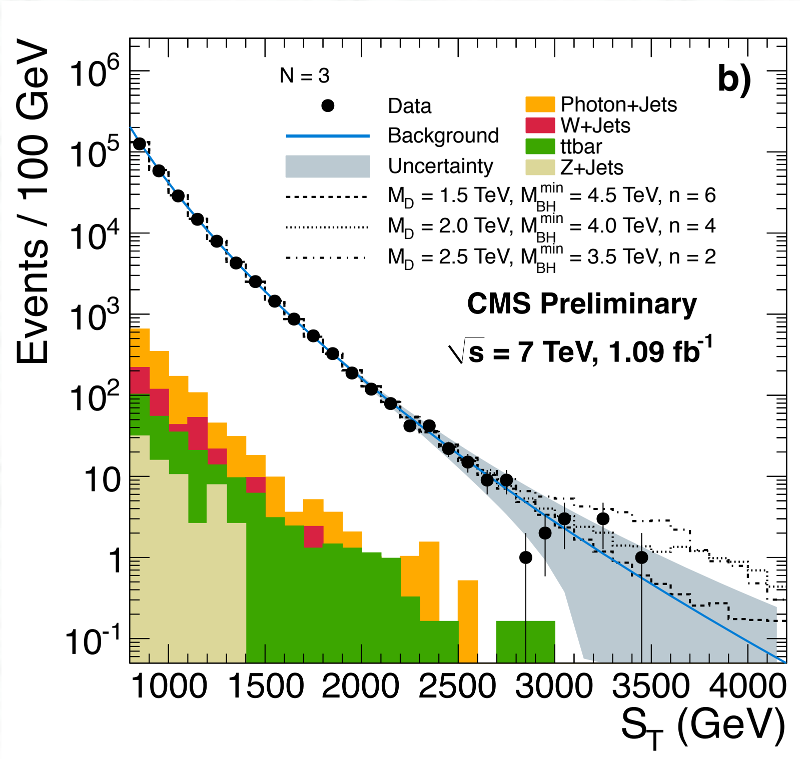
QCD multijet “background”



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

Background model / "calibration" of QCD multijet background





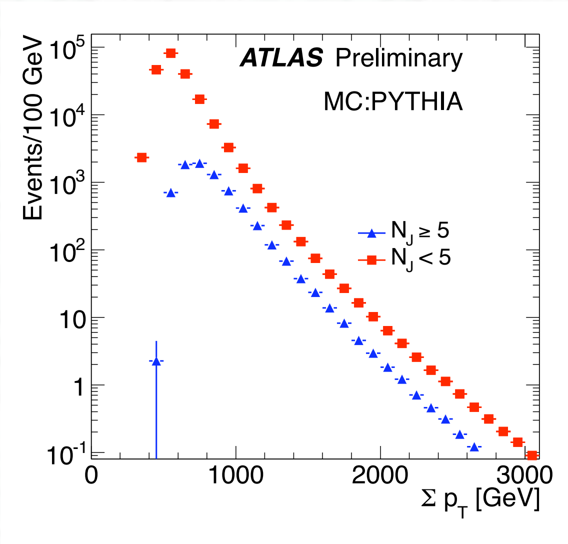
Shape of ST distribution cannot be reliably calculated in Monte Carlo simulation

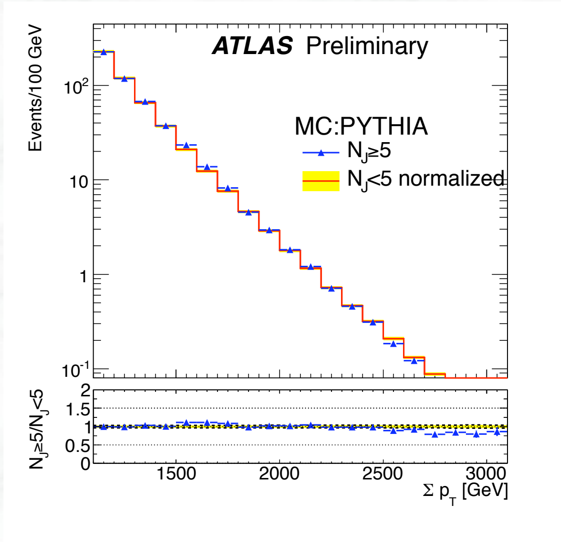
problem: high jet multiplicities

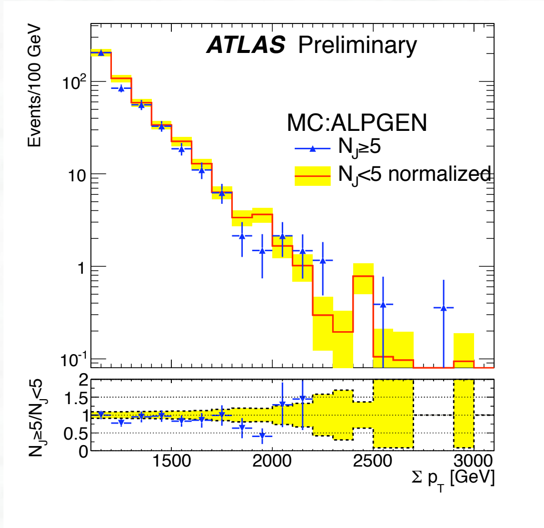
→ Fit a smooth QCD model to data in low ST region, determine parametrization (functional form) at low multiplicities (n=2)

ATLAS: take shape of QCD background from Monte Carlo (PYTHIA and ALPGEN)
(shape does not seem to vary strongly as function of jet multiplicity
in high S_T region)

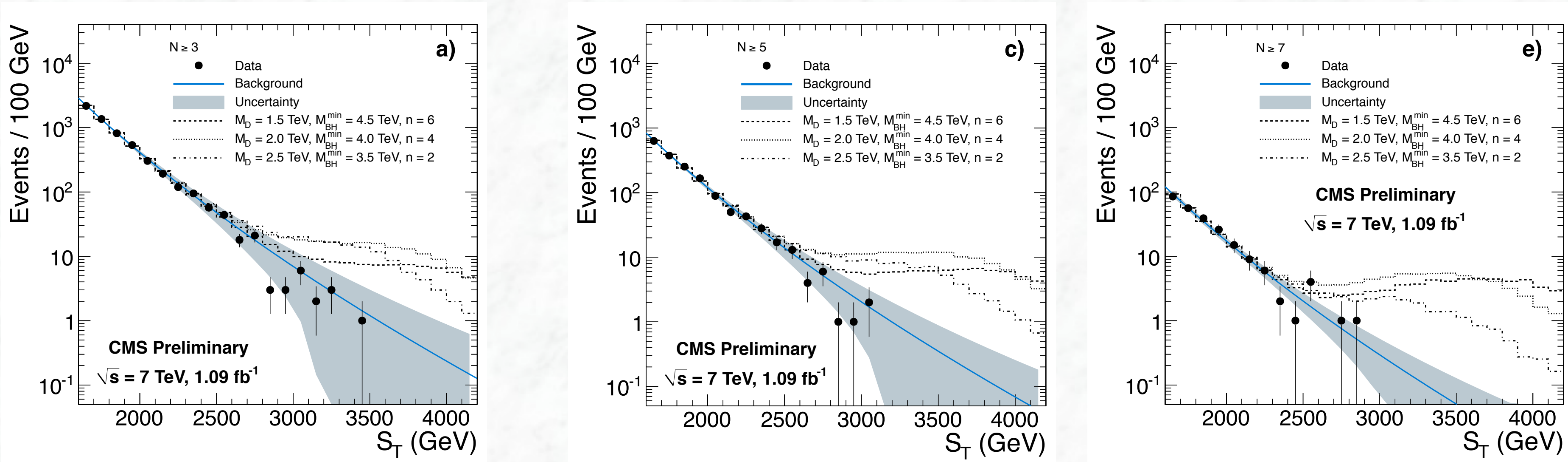
Take normalization from data in low S_T region (< 1.2 TeV)







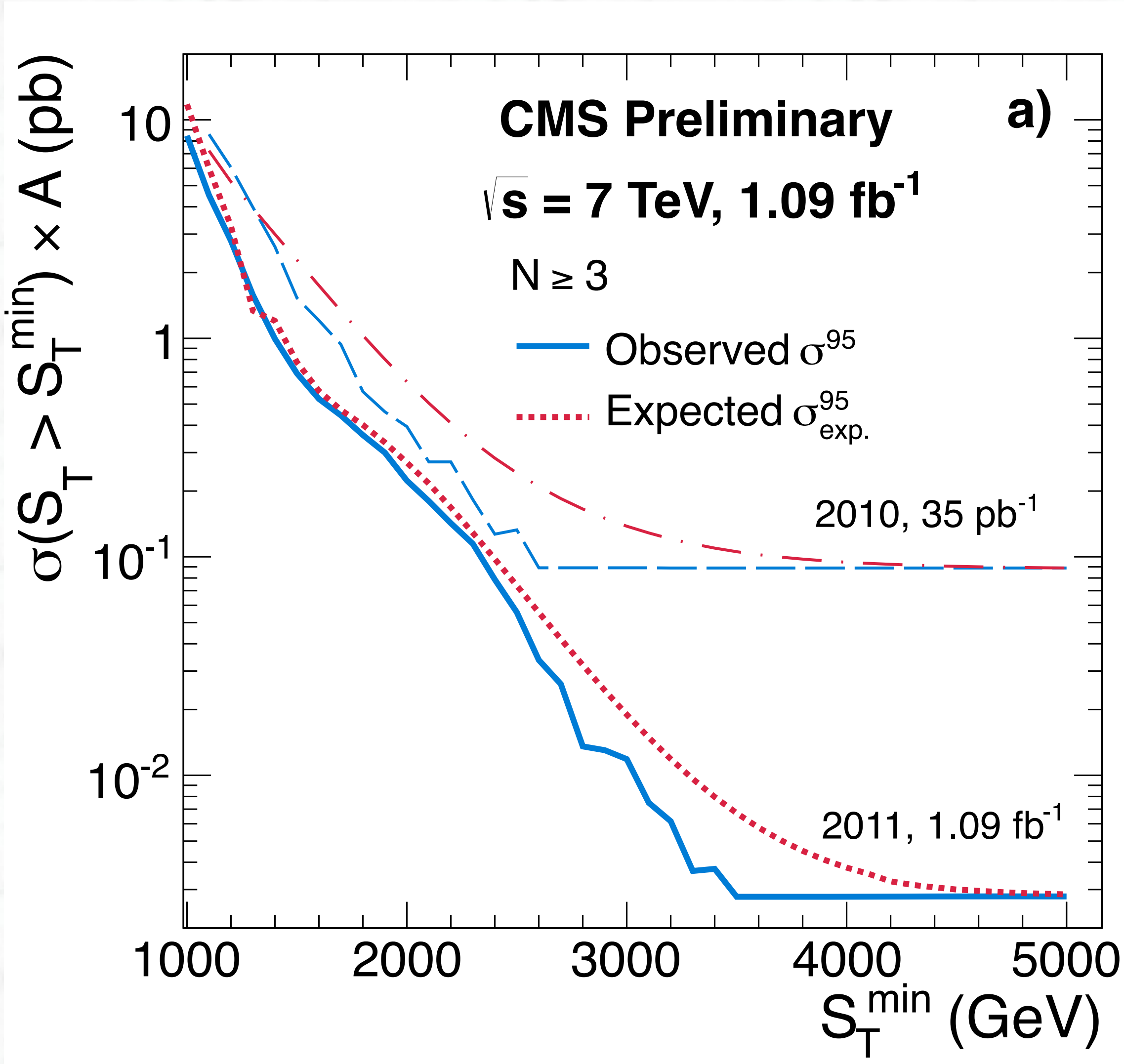
CMS analysis, use large part of the 2011 data, $L_{int} = 1.09\ fb^{-1}$



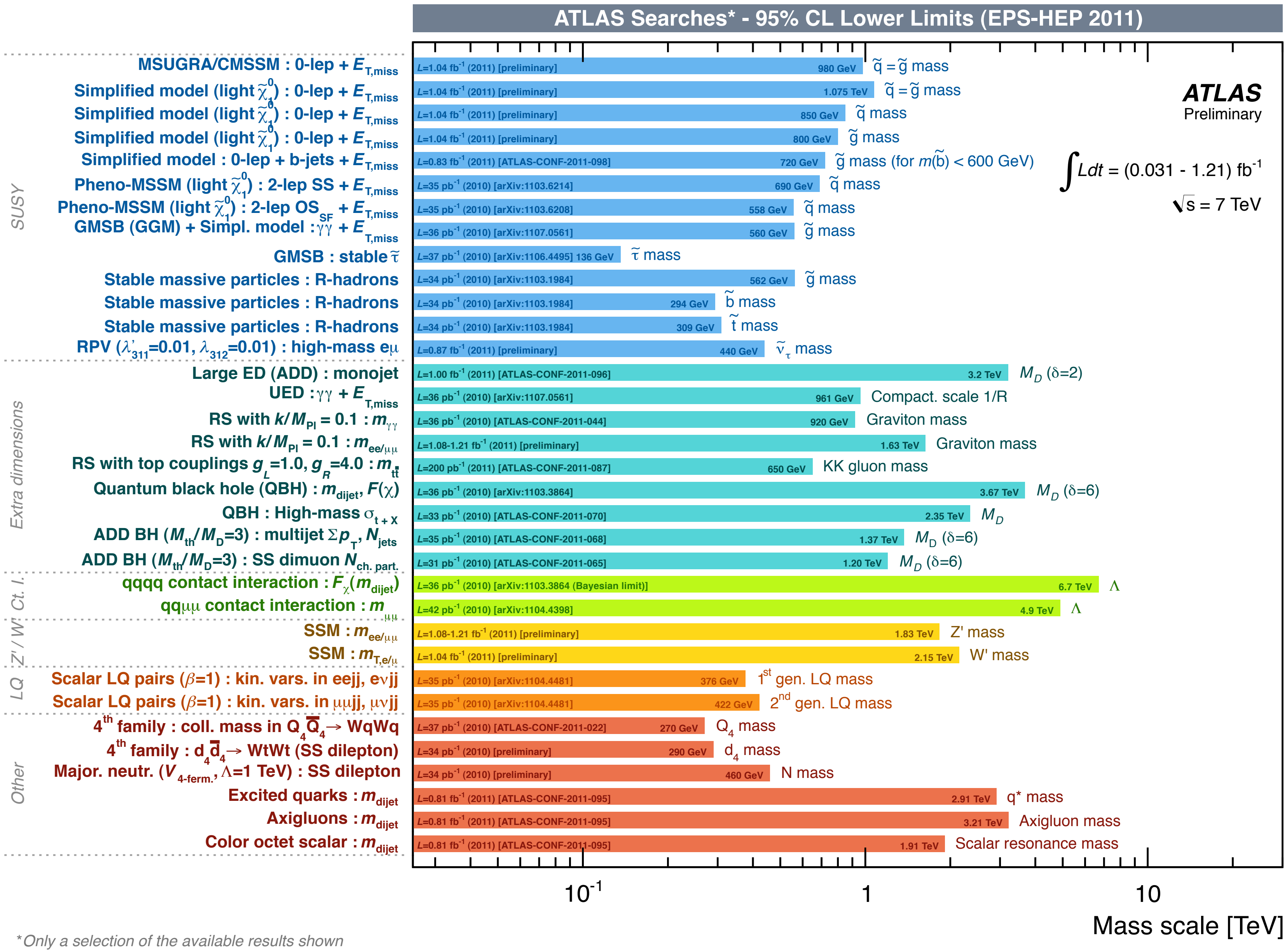
Total transverse energy S_T for events with N > 3, 5, 7 objects

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

Extracted limits (at 95% C.L.) on the excluded cross section times acceptance for $S_T > S_T^{min}$



Summary of results on searches for Physics Beyond the Standard Model in ATLAS in ATLAS



End of lectures