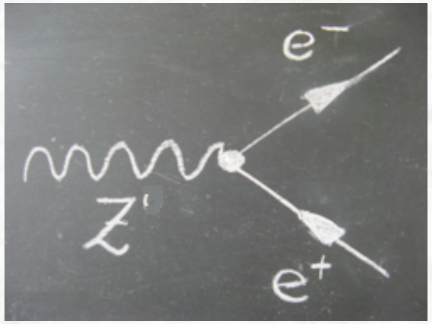
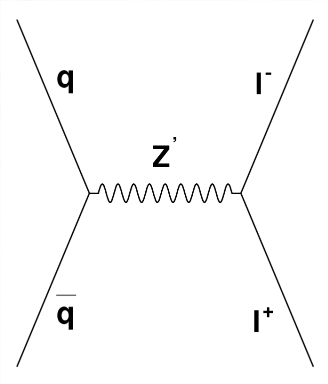
10.3 Additional Gauge Bosons: W' and Z'



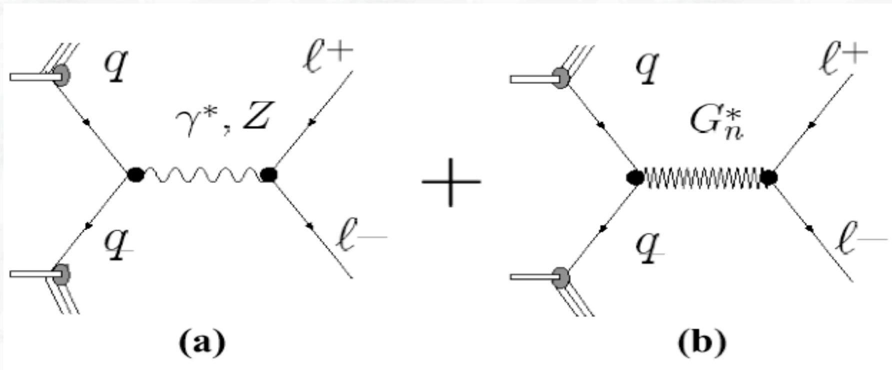
Search for new, high-mass di-lepton resonances

- Additional neutral Gauge Boson Z´



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

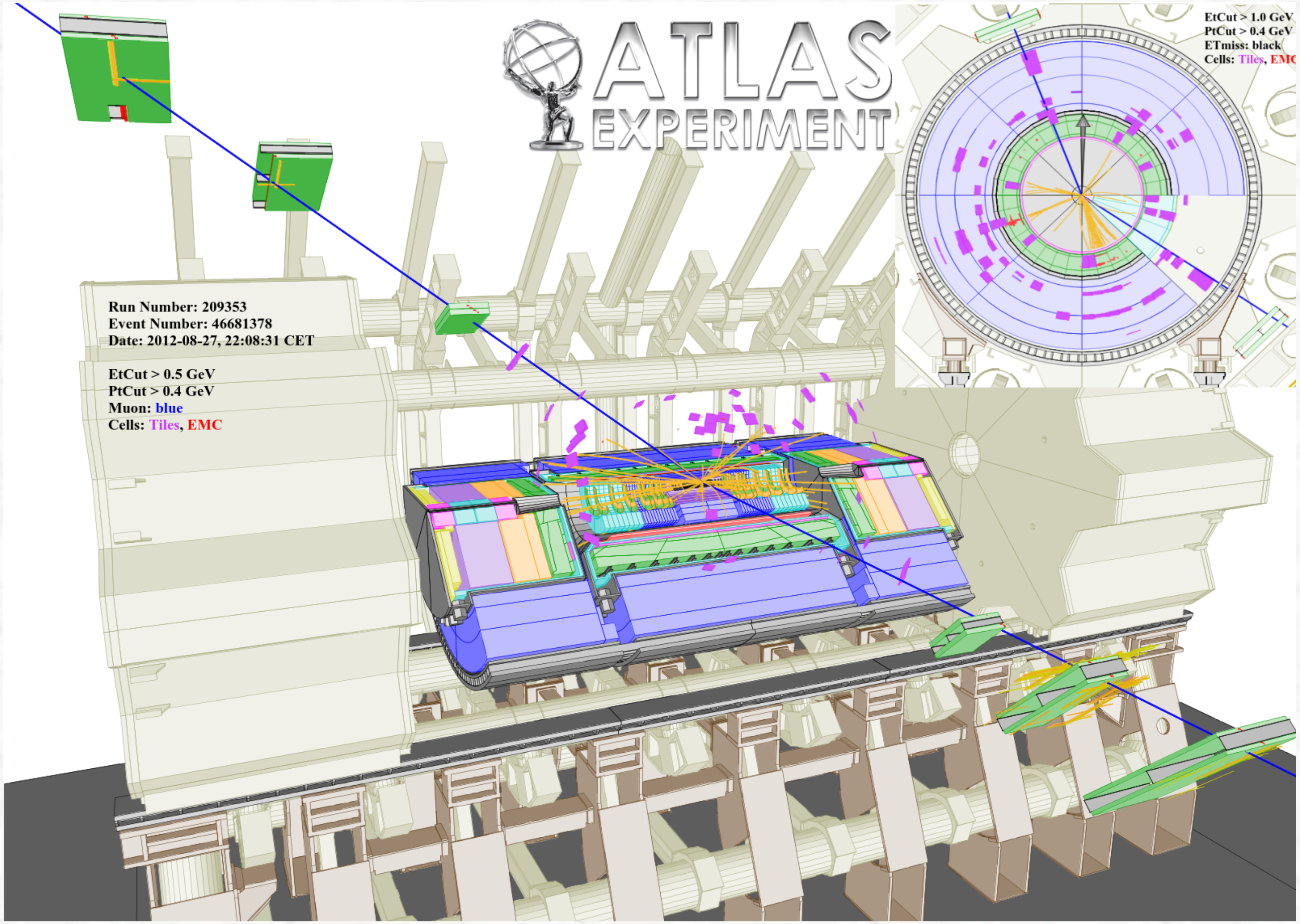
appear in Extra Dim. Scenarios



Standard Model background process

Signal

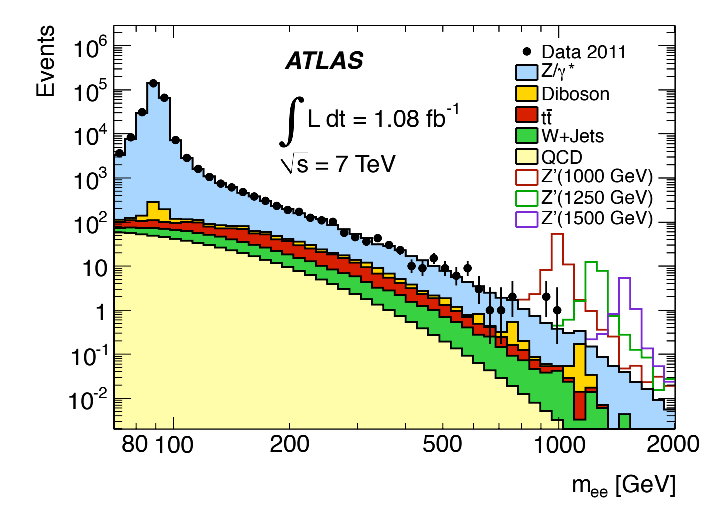
- Identical final state (two leptons), same analysis, interpretation for different theoretical models
- Main background process: Drell-Yan production of lepton pairs



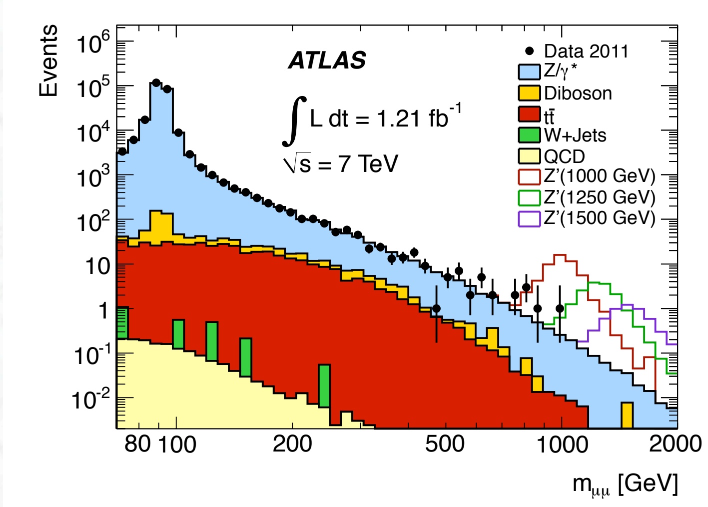
Event display of the selected event with the highest di-muon invariant mass in the ATLAS experiment. The highest momentum muon has a p_T of 653 GeV and an η of 0.99. The subleading muon has a p_T of 646 GeV and an η of -0.85. The invariant mass of the pair is 1844 GeV.

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.

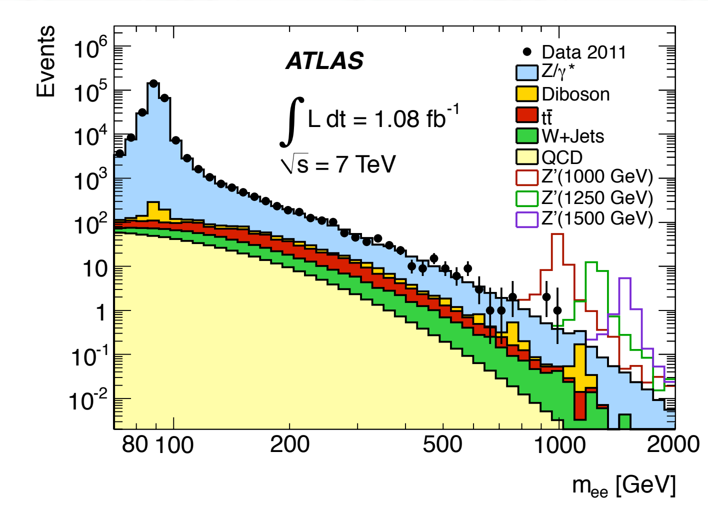
Detailed numbers on signal and background for the ee channel:

$m_{e^+e^-}$ [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

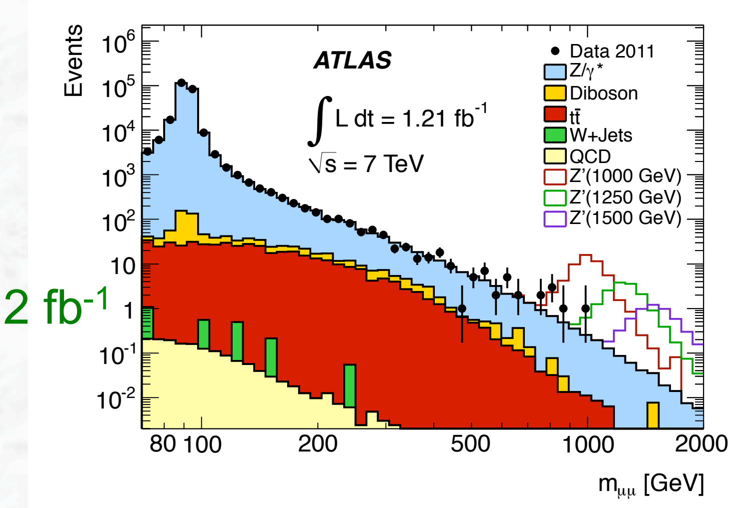
Drell-Yan background can be normalized in the Z peak region, 70-110 GeV

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

Di-electron invariant mass

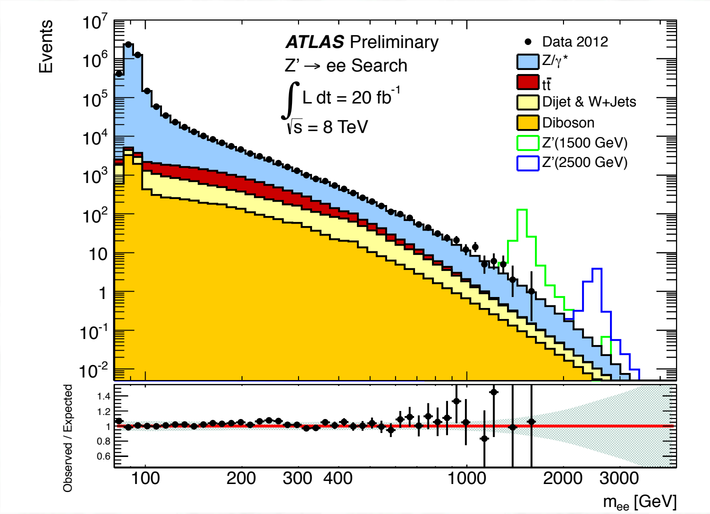


Di-muon invariant mass



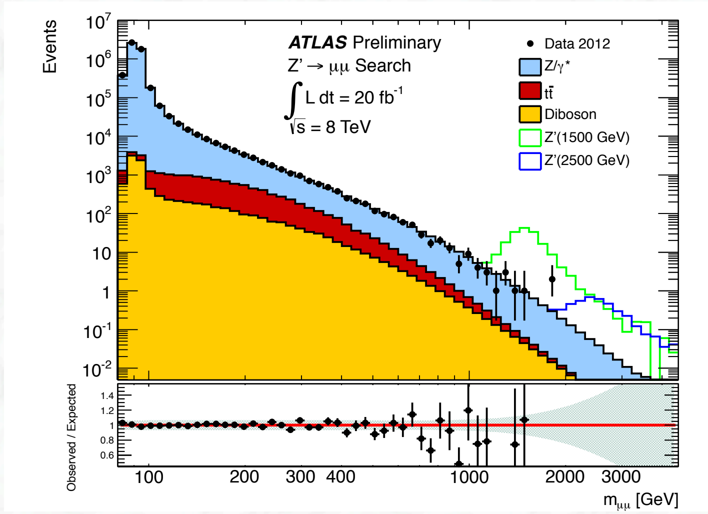
2011:

L = 1.1–1.2 fb^{-1}



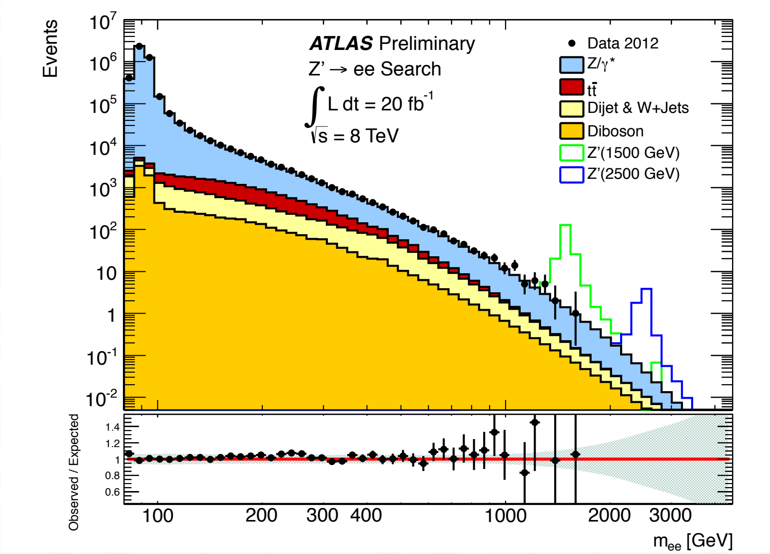
2012:

L = 20 fb^{-1}

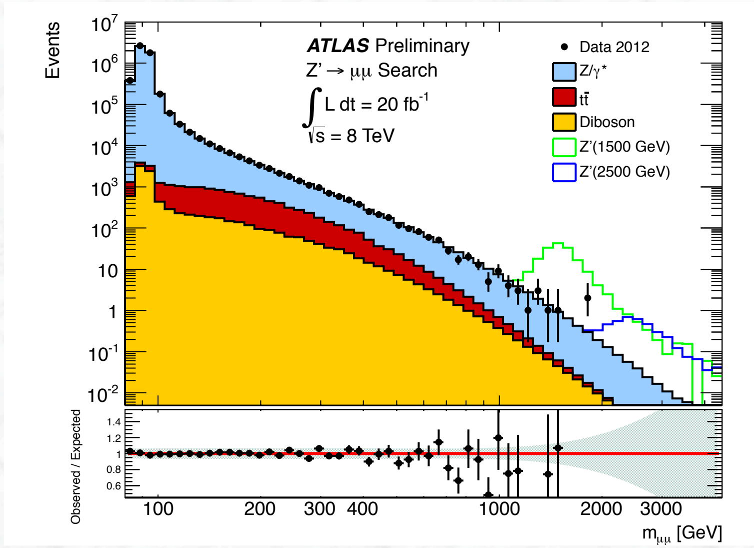


Search for New Resonances in High Mass Di-leptons

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

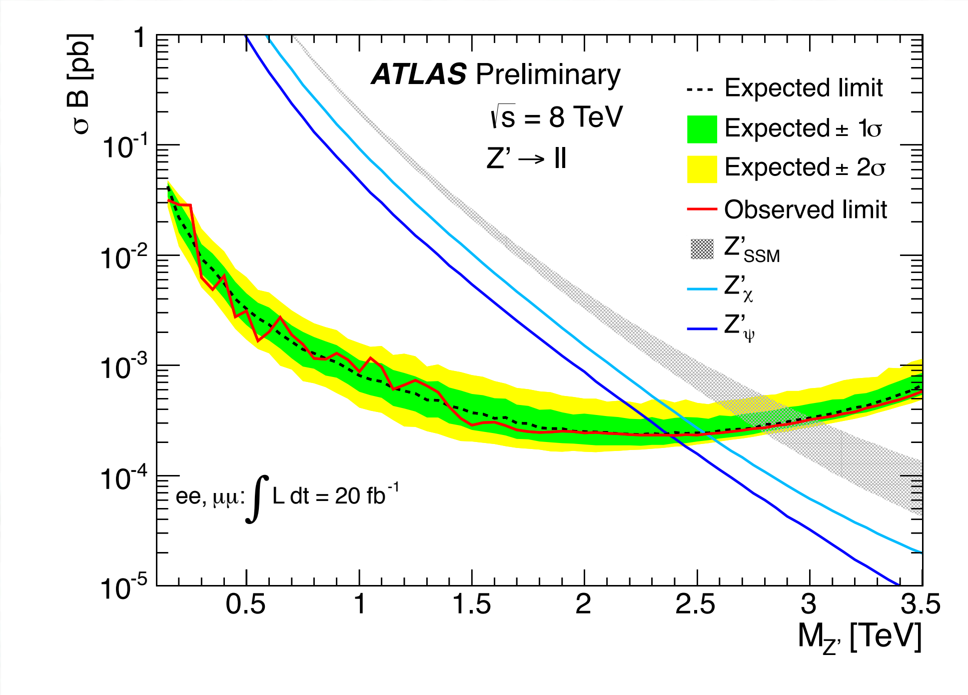
(ii) Models based on the E_6 grand unified symmetry group

- 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

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

- 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:



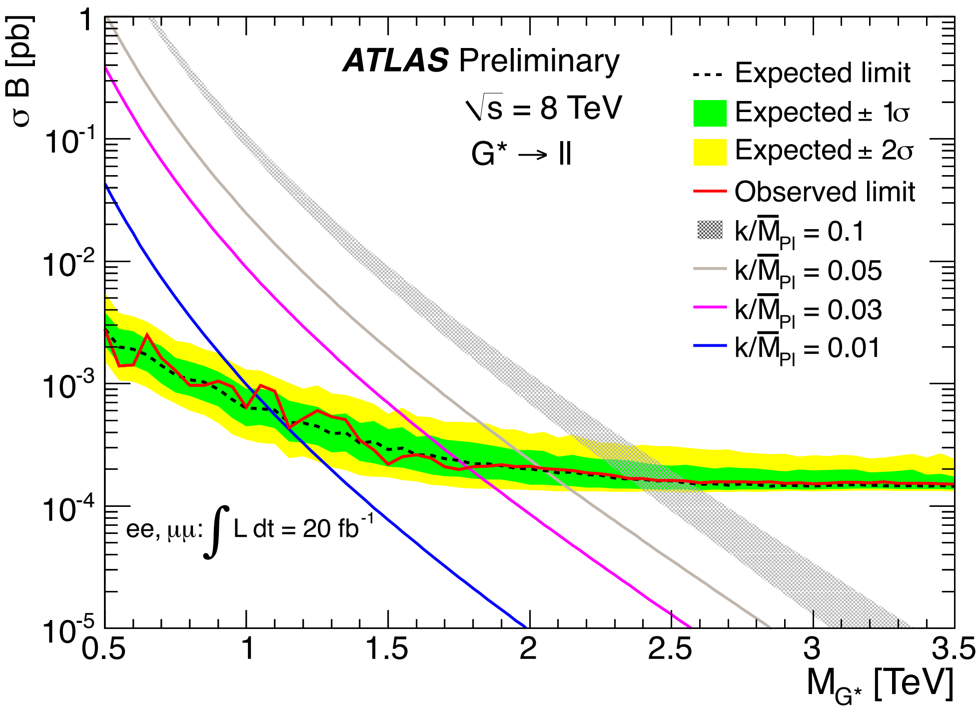
Resulting mass limits: ee + $\mu\mu$
95% C.L., $\sqrt{s}$ = 8 TeV, L = 20 fb^{-1}

Sequential SM: $m_{Z'} > 2.86$ TeV
E_6 models: $m_{Z'} > 2.38 – 2.54$ TeV

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

95% C.L. limits (SM couplings)	ee	$\mu\mu$	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	2.48 TeV	2.86 TeV
CMS 1.1 fb^{-1}			

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

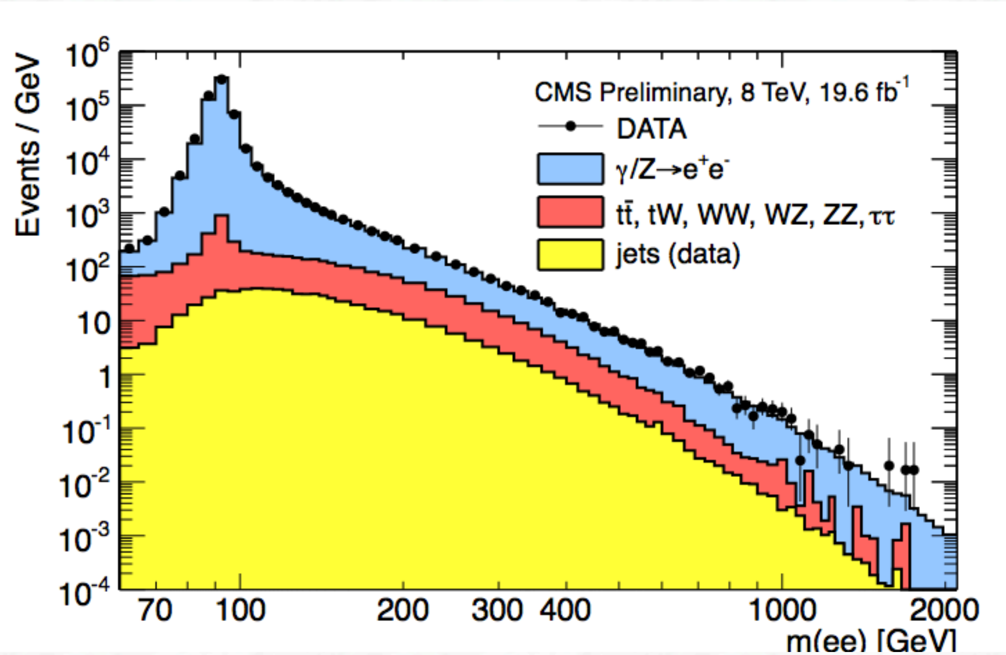


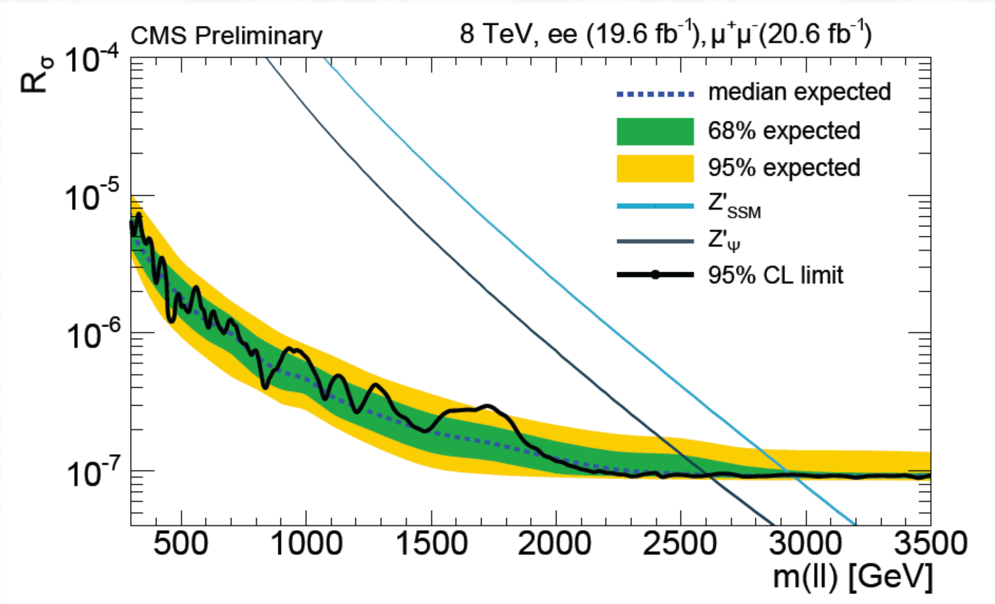
Resulting mass limits: ee + μμ
95% C.L.

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 + $\mu\mu$
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' $\rightarrow$ lν

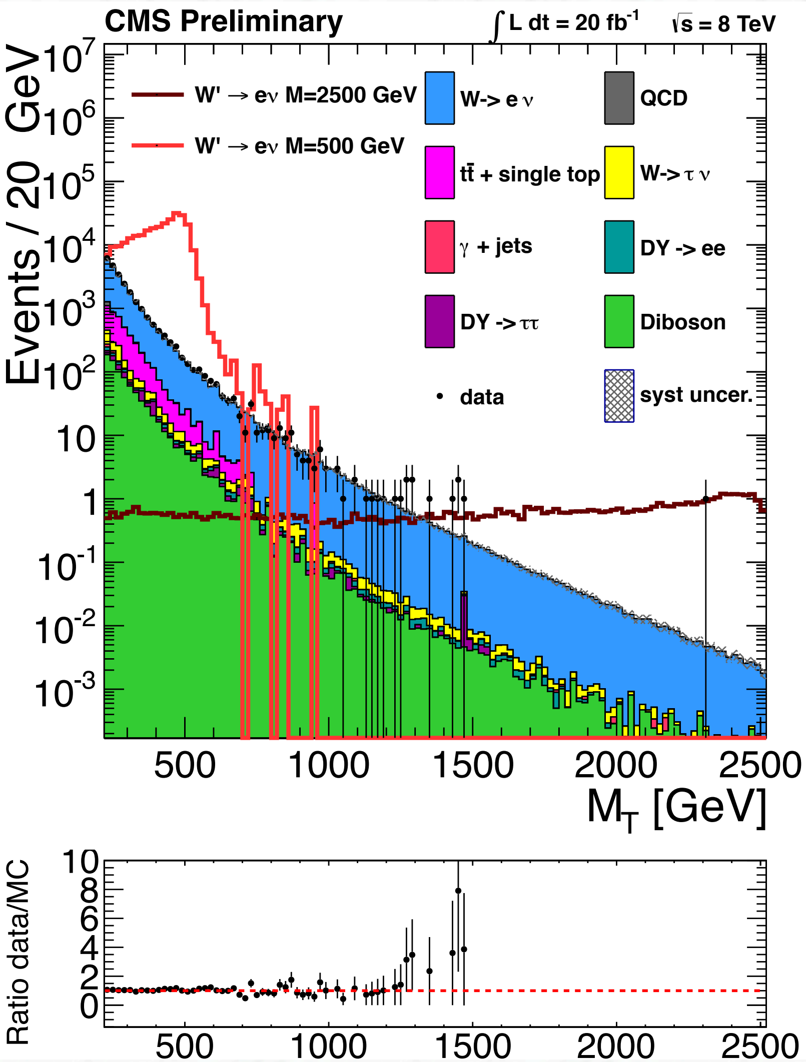
- W': additional charged heavy vector boson
- Appears in theories based on the extension of the gauge group
  e.g. Left-right symmetric models: $SU(2)_R$ ←→ W_R
- Assume ν from W' decay to be light and stable, and W' to have the same couplings as in the SM (*"Sequential Standard Model, SSM"*)

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

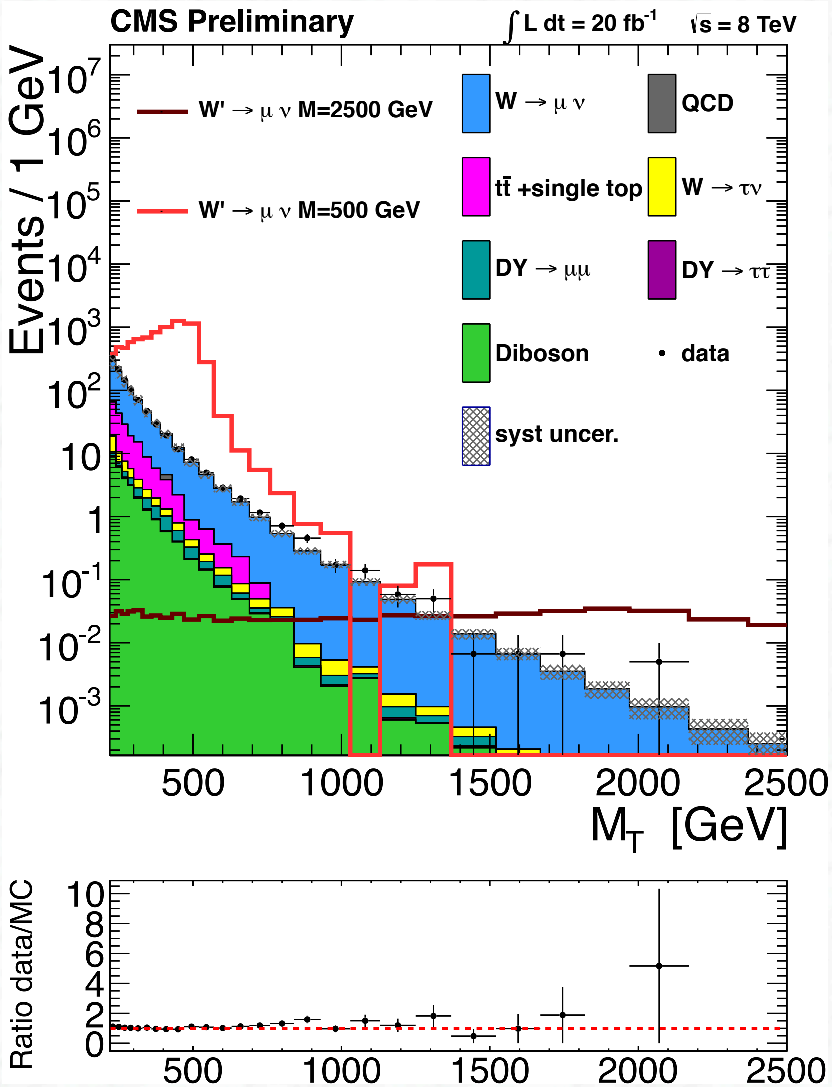
→ peak in transverse mass distribution

Search for New Resonances in High Mass lν events

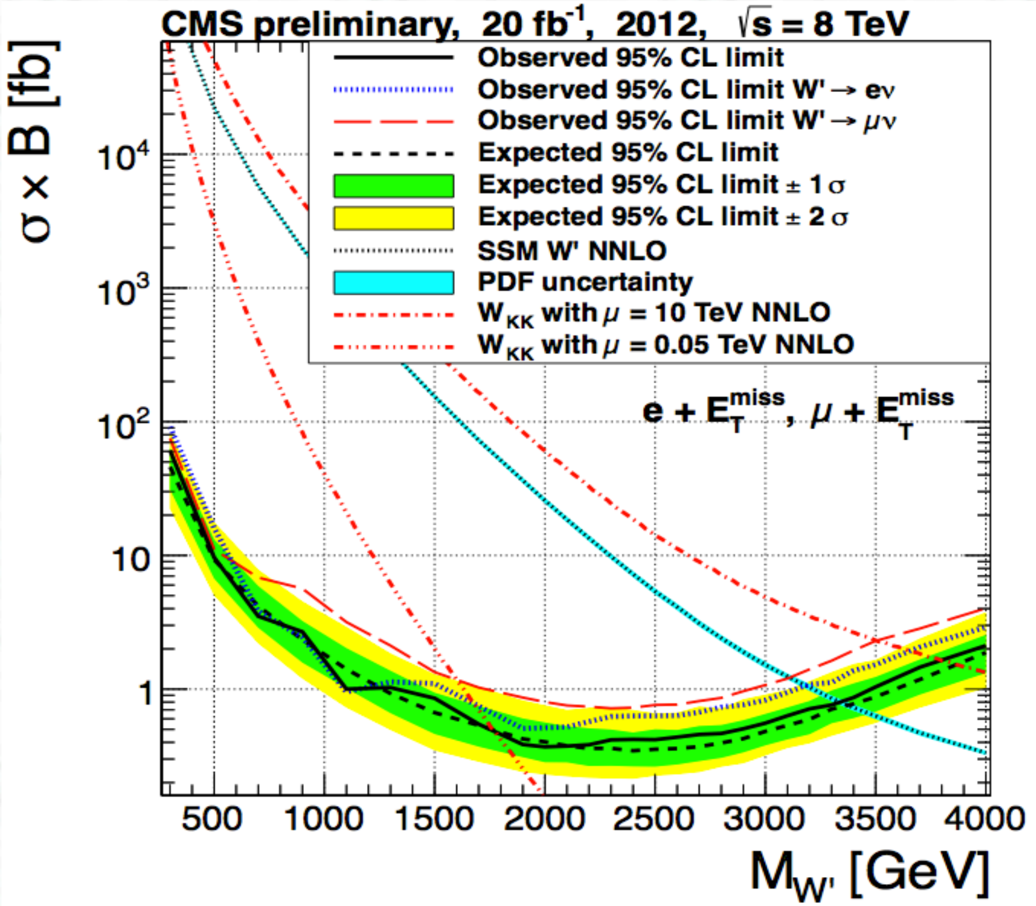
Transverse mass (e, E_T^{miss})



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

10.4 Search for substructure / compositeness of quarks

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

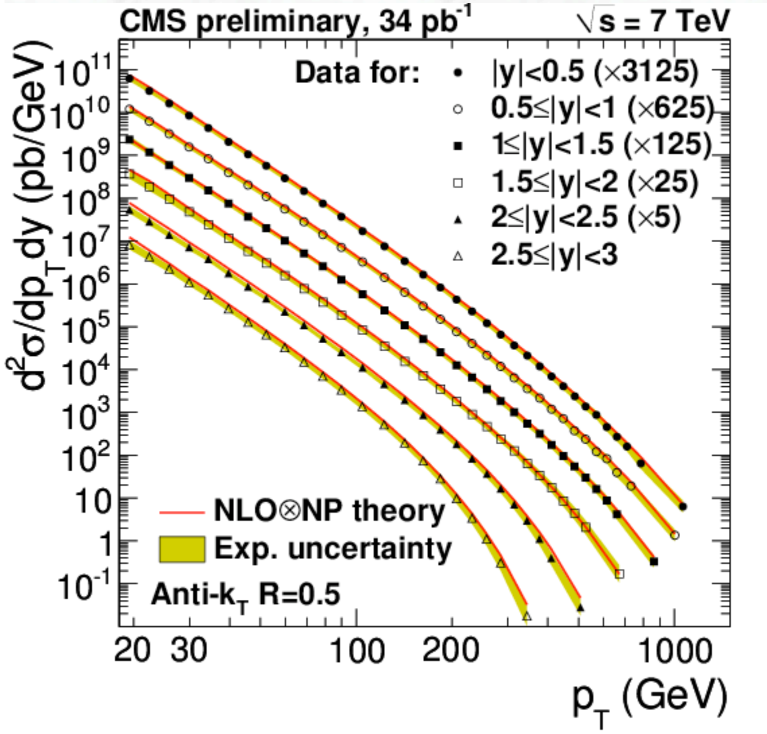
- Such interactions would lead to deviations from the expected QCD scattering behaviour, which would be most visible in:
  - the inclusive jet cross section at high p_T
  - the di-jet invariant mass distribution
    (traditional variables, but very sensitive to uncertainties on the jet energy measurement,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

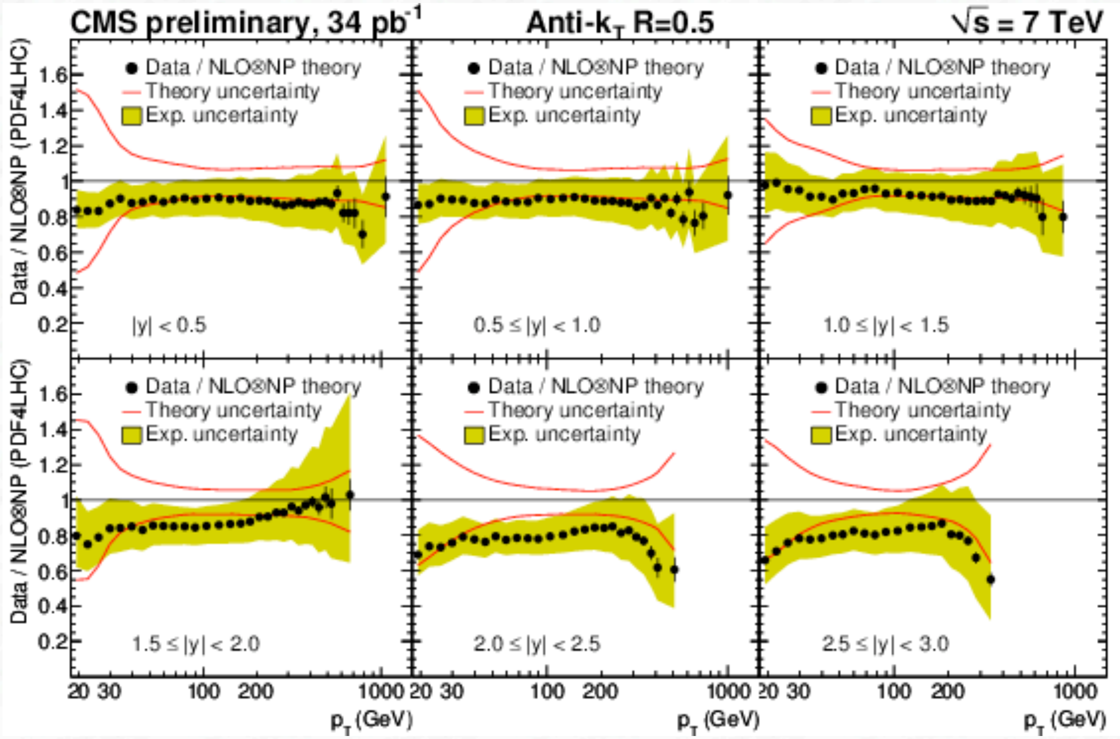
- Parametrize effects by using an effective Lagrangian, in addition to the QCD terms

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

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

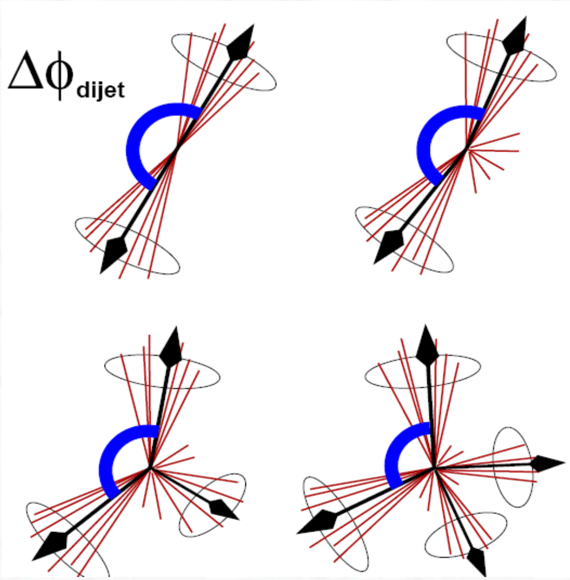
Measured inclusive jet p_T spectrum from CMS (full 2010 dataset)

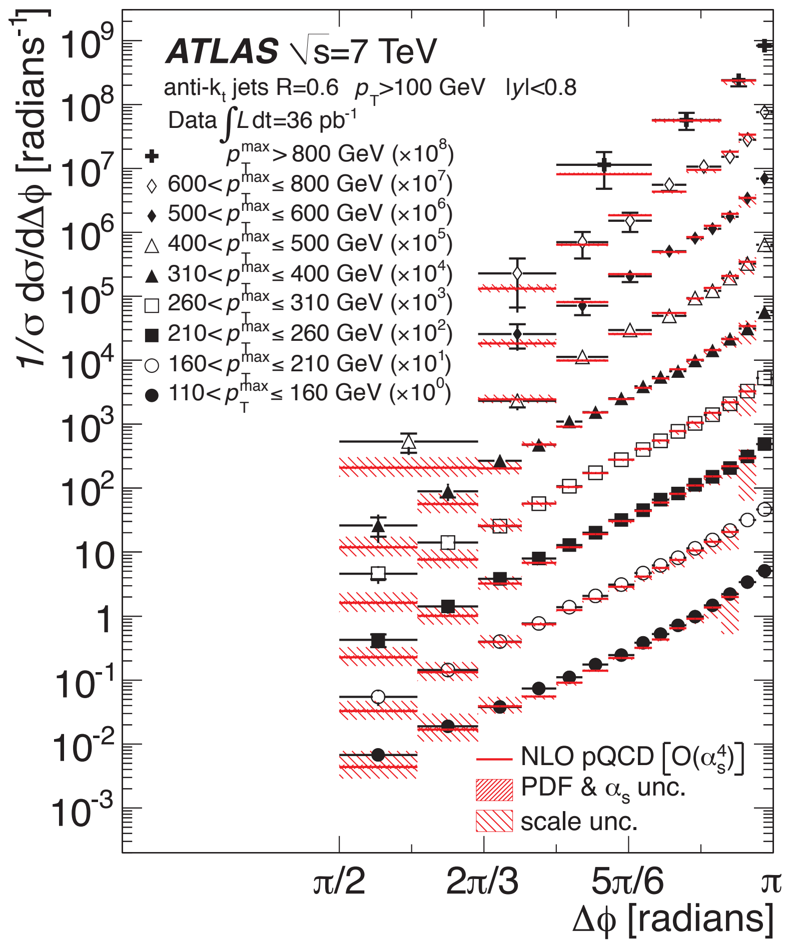




Di-jet angular distributions

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

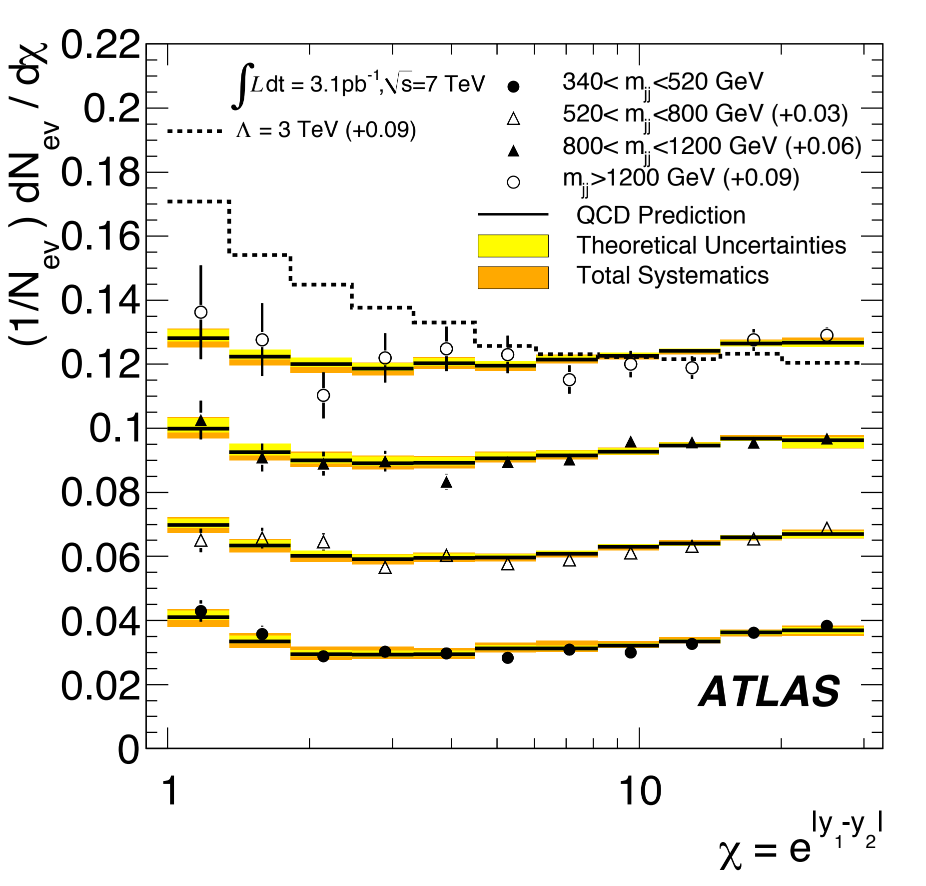




Good agreement with
next-to-leading order QCD predictions

Search for compositeness:

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

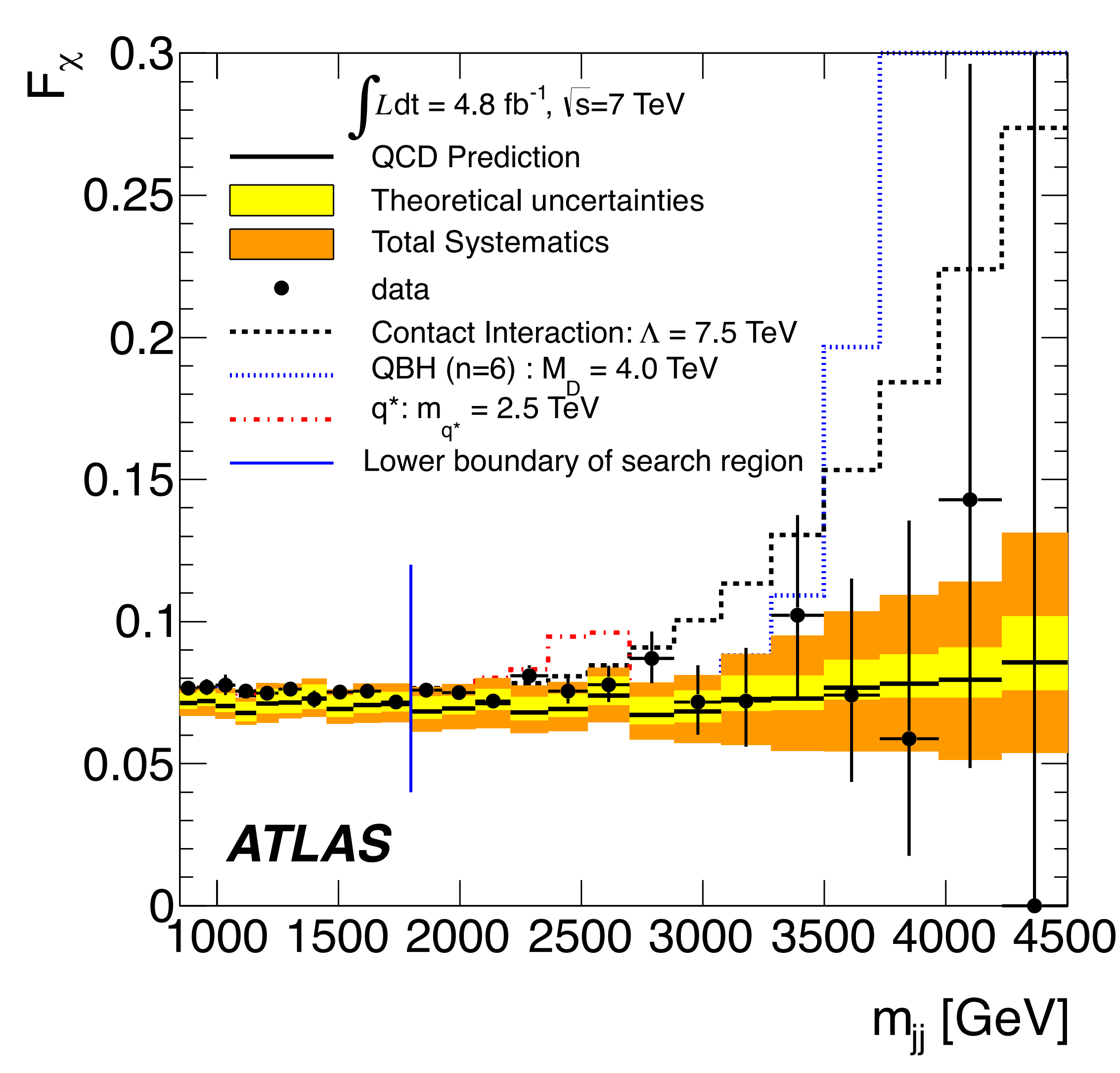


In QCD: gluon exchange diagrams dominate, have the same angular dependence as Rutherford scattering; essentially flat in the variable

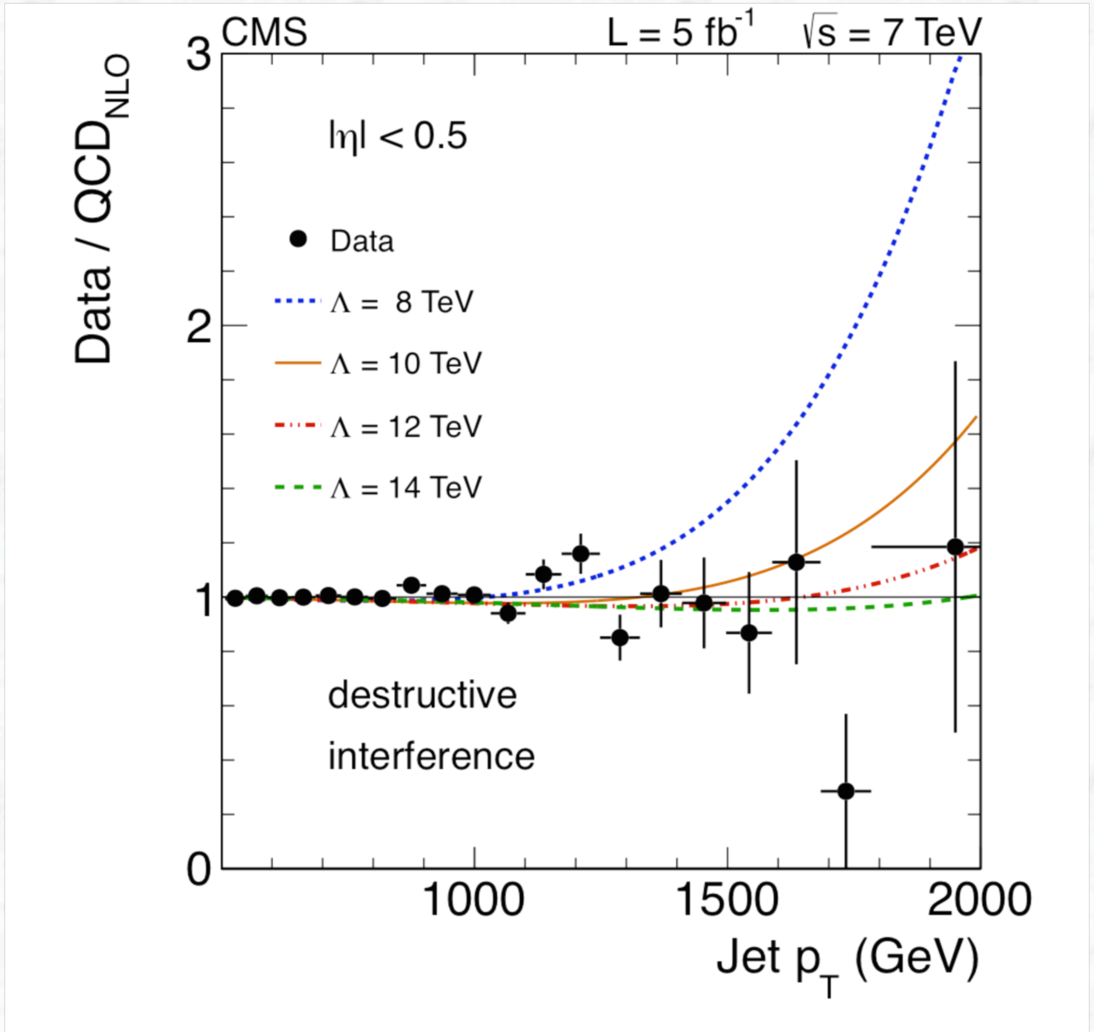
$$\chi = e^{|y_1 - y_2|}$$

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



$$F_\chi(m_{jj}) \equiv \frac{dN_{\text{central}}/dm_{jj}}{dN_{\text{total}}/dm_{jj}},$$



Results on χ measurement from the CMS experiment

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

95% C.L. Limits on scale Λ :

ATLAS:	4.8 fb^{-1}	Λ > 7.6 TeV
CMS:	5 fb^{-1}	Λ > 9.9 TeV

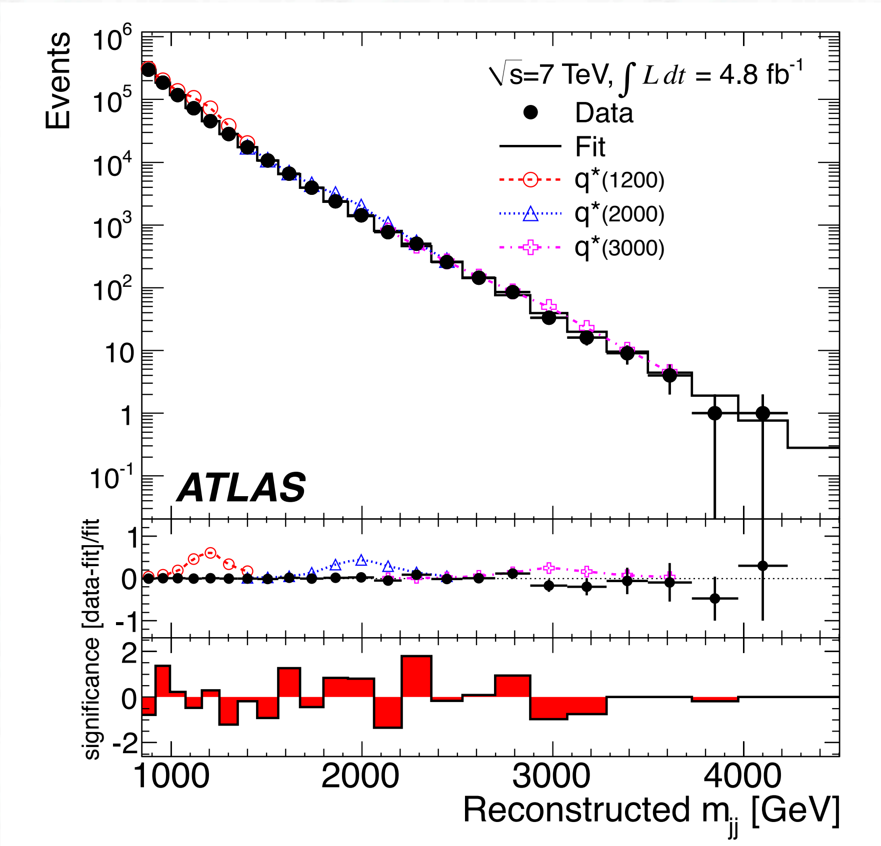
Search for Resonances in the di-jet mass distribution

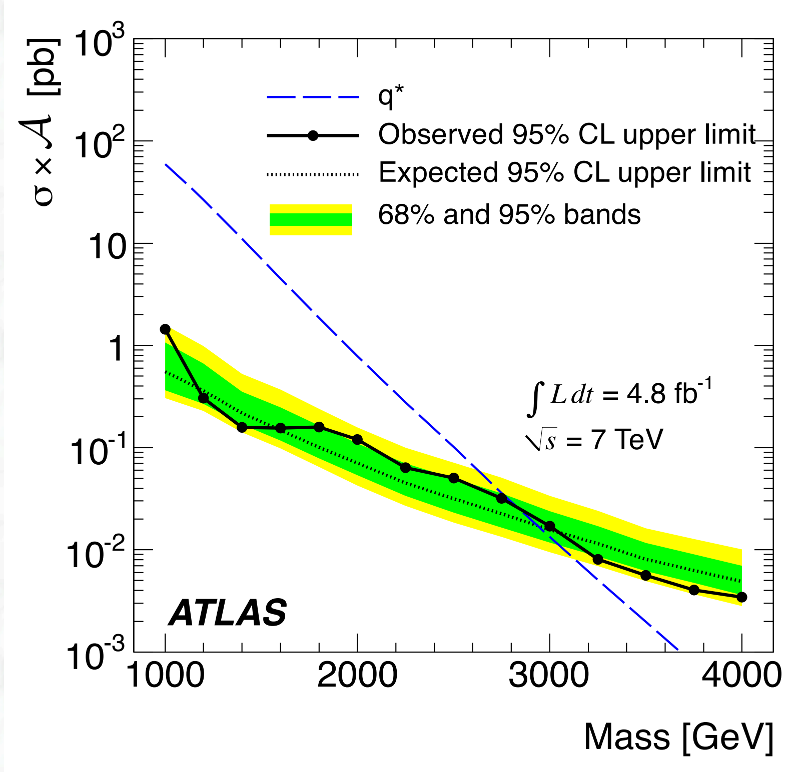
Many extensions of the Standard Model predict the existence of new massive objects that couple to quarks (q) and gluons (g) and result in resonances in the di-jet mass spectrum:

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 $L_{int} = 4.8\ fb^{-1}$





- 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 = 4.8 fb^{-1}):

Excited quarks: m_{q*} > 2.83 TeV

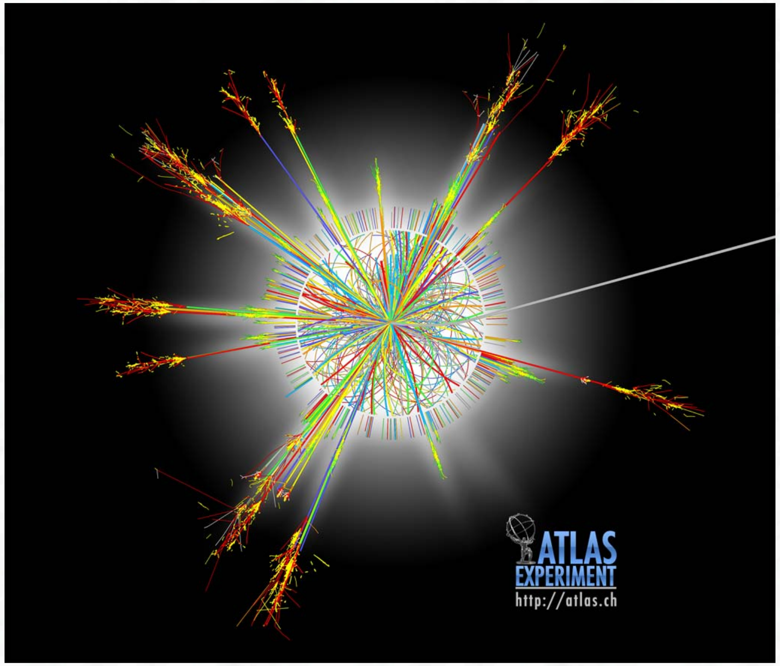
Axigluons: m_A > 1.68 TeV

10.5 Extra space dimensions

- Introduction

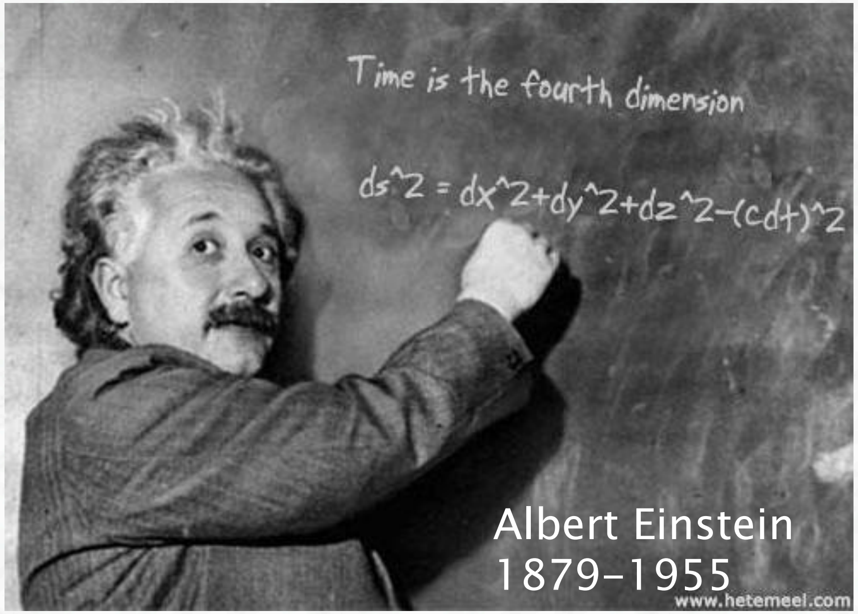
- Search for escaping gravitons at the LHC

- Search for Black Hole Production



Microscopic-Black Hole Events at the LHC ?

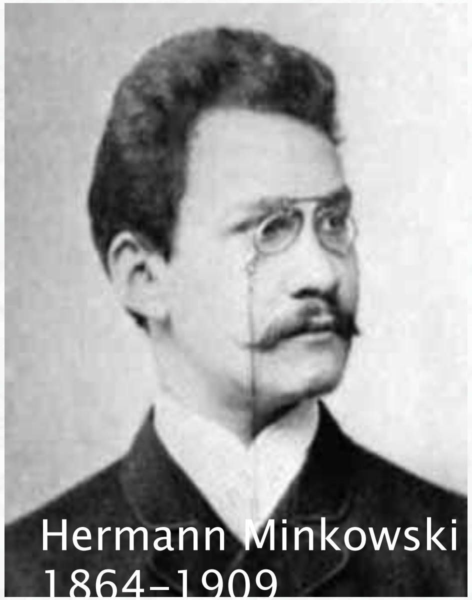
Time is the fourth Dimension



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

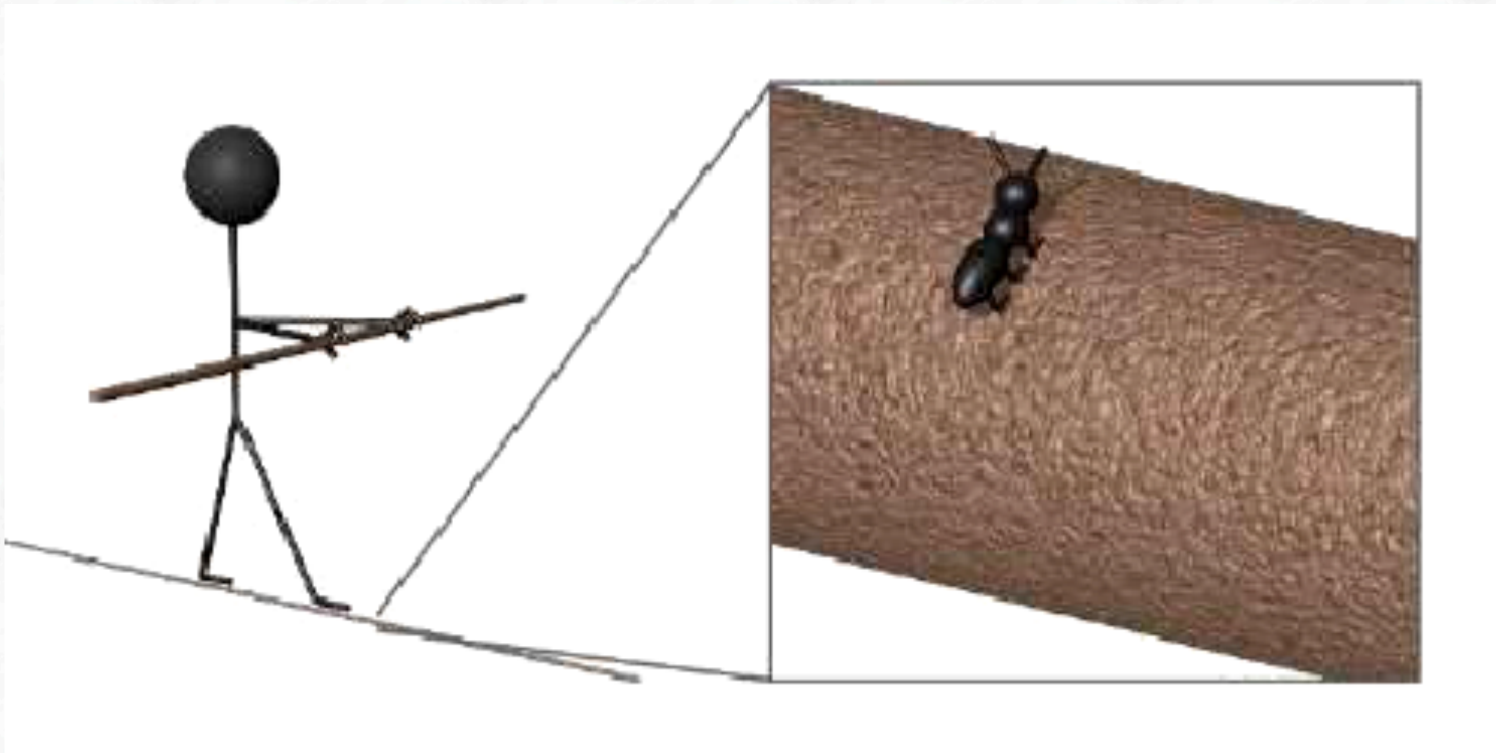
- The Swedish physicist O. Klein proposed in 1926 that the fifth dimension was real, but too tiny to be observed
- Computed to be of a size of 10^{-30} cm to unify gravity with electromagnetism

"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



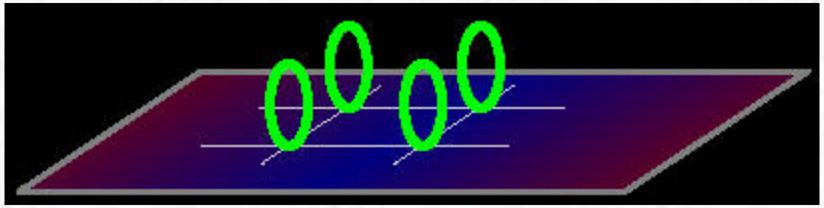
Tightrope walker sees only one dimension

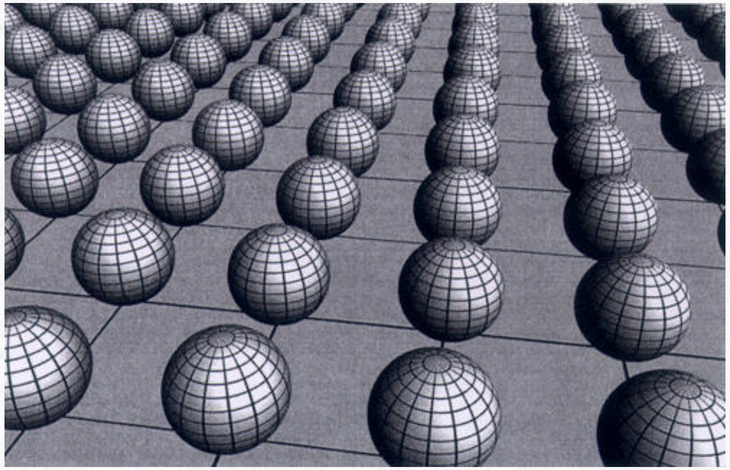
Ant can also go "around the circle"

“Visualizing” Extra Dimensions

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

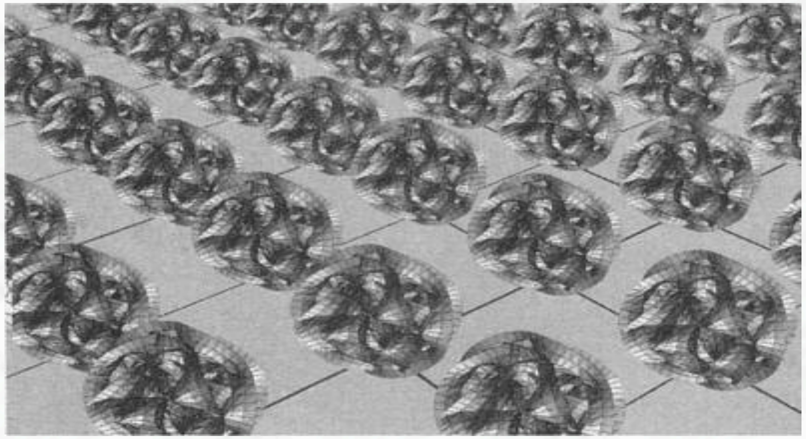
One extra dimension is a circle





Two extra dimensions can be represented by a sphere

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



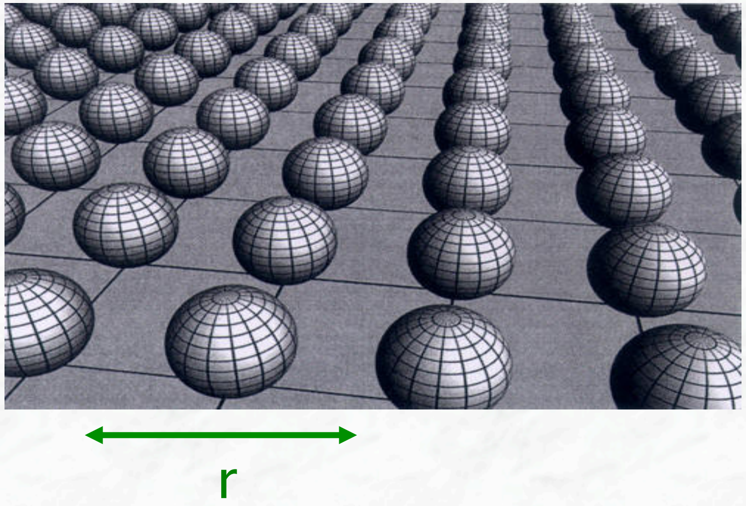
Modifications of Newton's Law of Gravity

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

- Example: 2 extra dimensions of size R

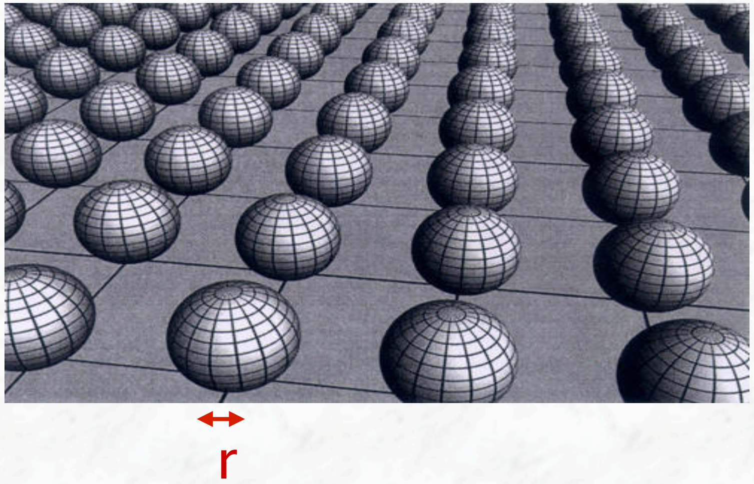
- Distances r > R

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

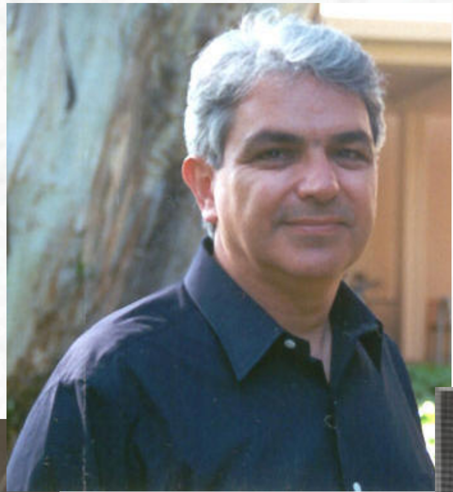


- Distances r < R

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



Creators of New Extra-Dimensional Ideas!

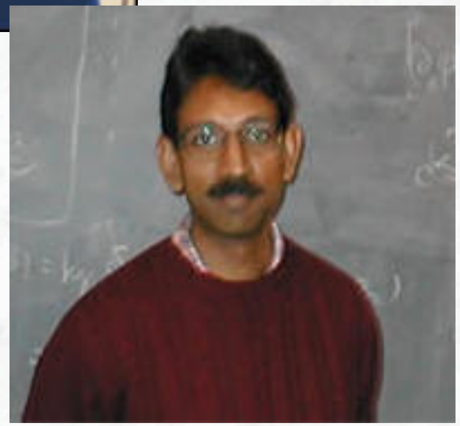


Savas
Dimopoulos
Stanford

Lisa Randall
Harvard

Nima Arkani-Hamed
Princeton

Gia Dvali
New York Univ.



Raman Sundrum
Johns Hopkins

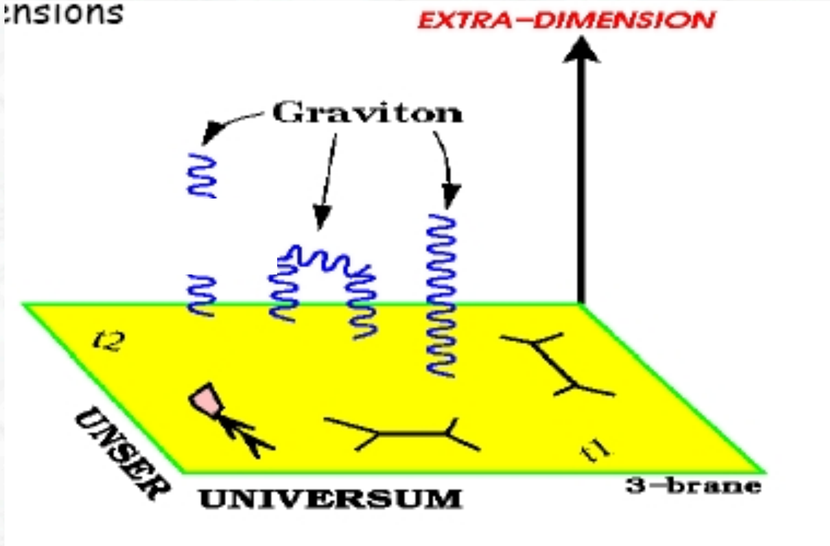
Large Extra Dimensions & the ADD Model

- 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:

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

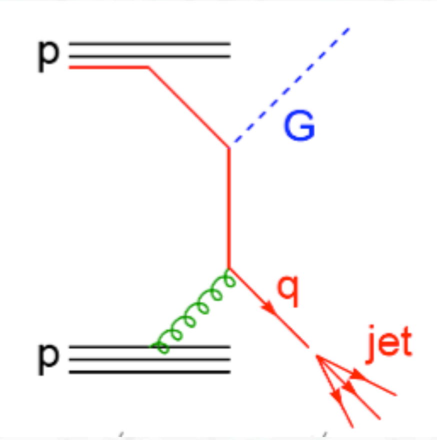
- The Standard Model interactions and all matter particles are confined to our 3-dimensional world



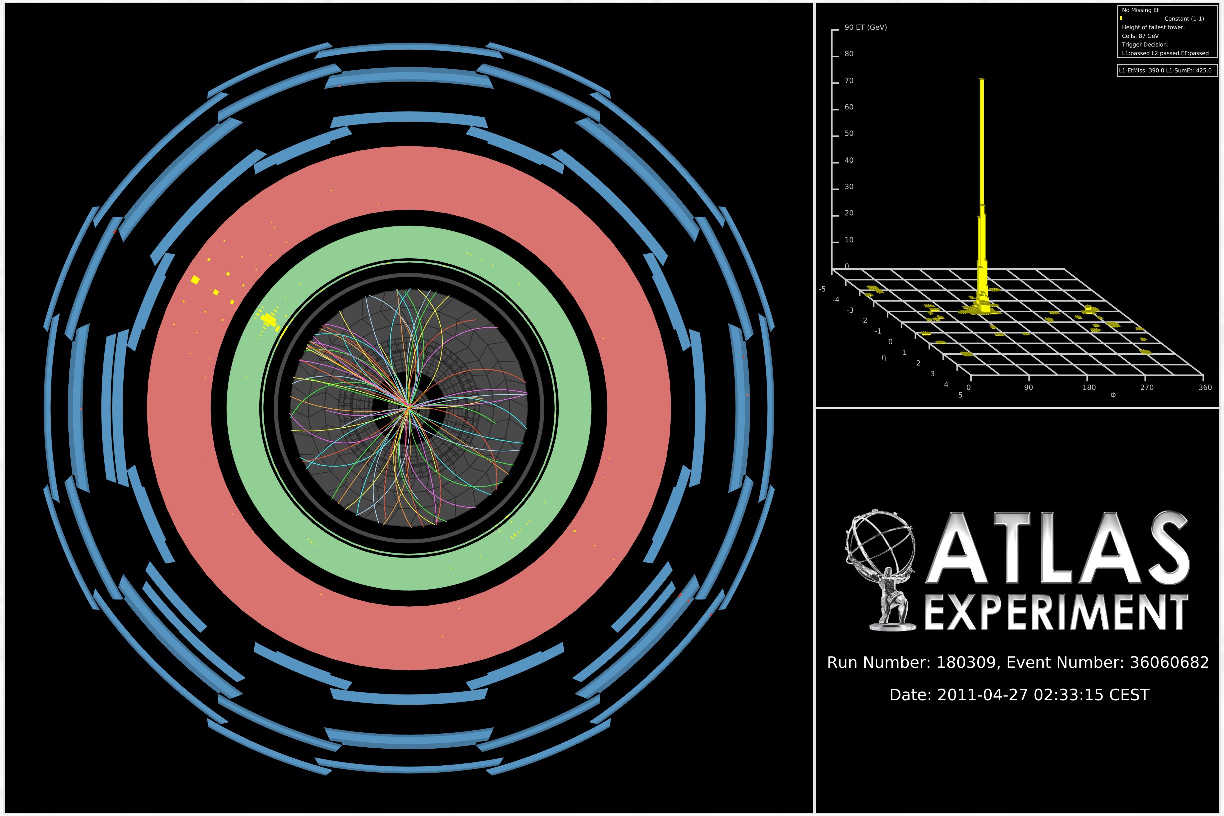
Arkani-Hamed, Dimopoulos, Dvali: hep-ph/9803315, 9804398, 9807344

Experimental Signature: Mono-jets from graviton production

Signal: single jet, E_T^{miss}

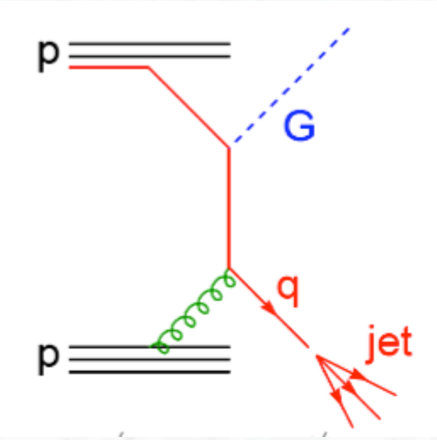


A nice candidate event: 1 jet with p_T = 602 GeV
E_T^{miss} = 523 GeV



Experimental Signature: Monojets

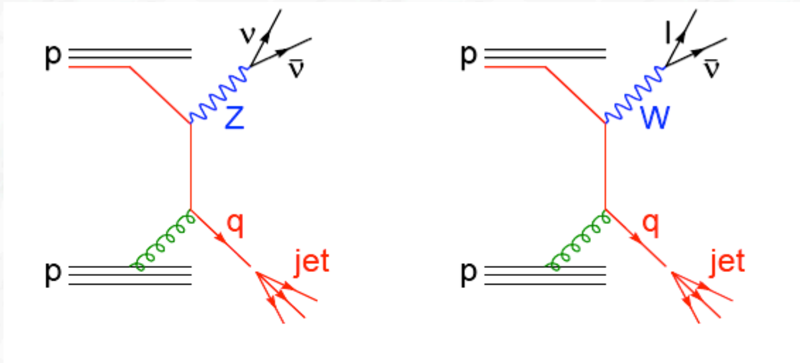
Signal: single jet, E_T^{miss}



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, 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

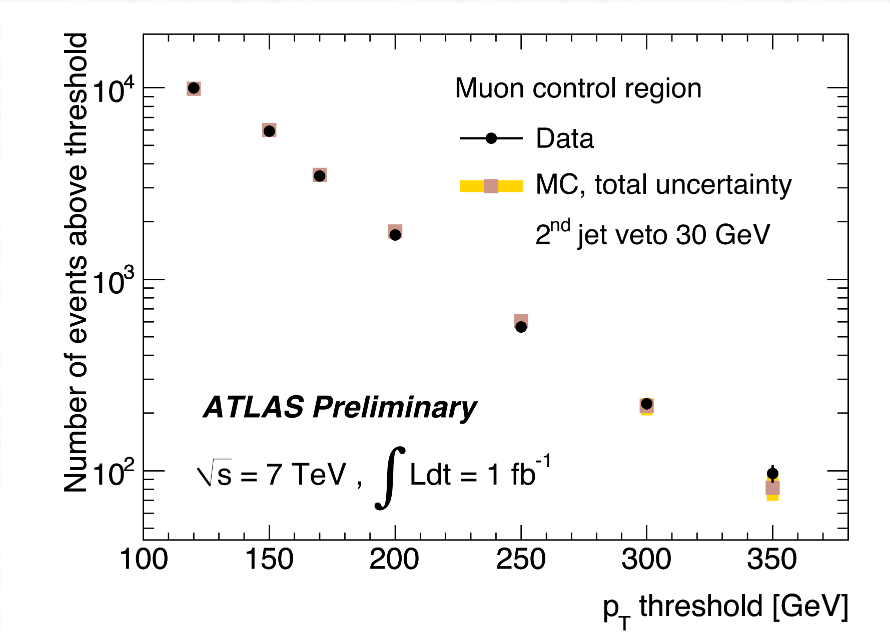
W/Z + jet background estimate from data:

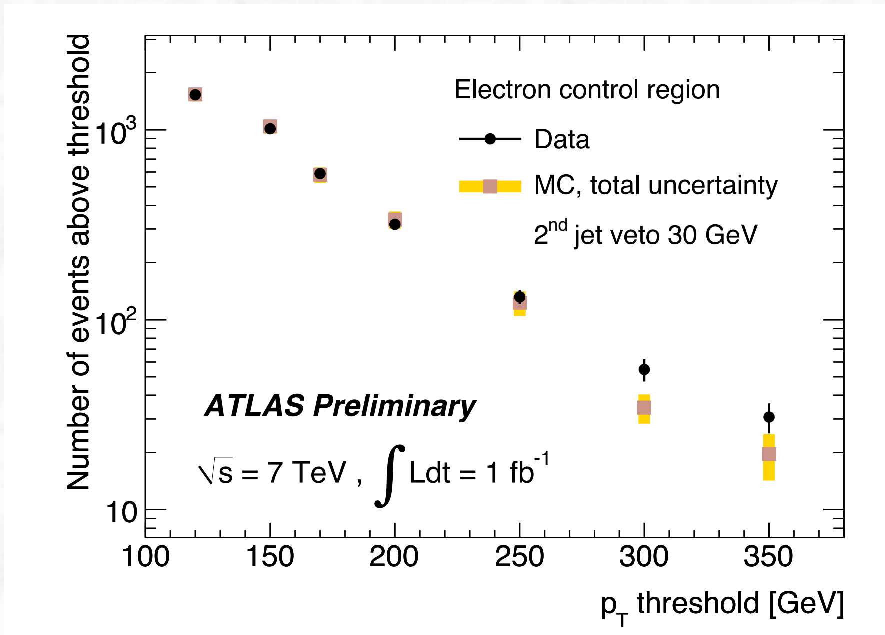
- Control sample, require an identified lepton (disjunct with the signal sample); all other cuts identical; done separately for the electron and the muon channels

  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

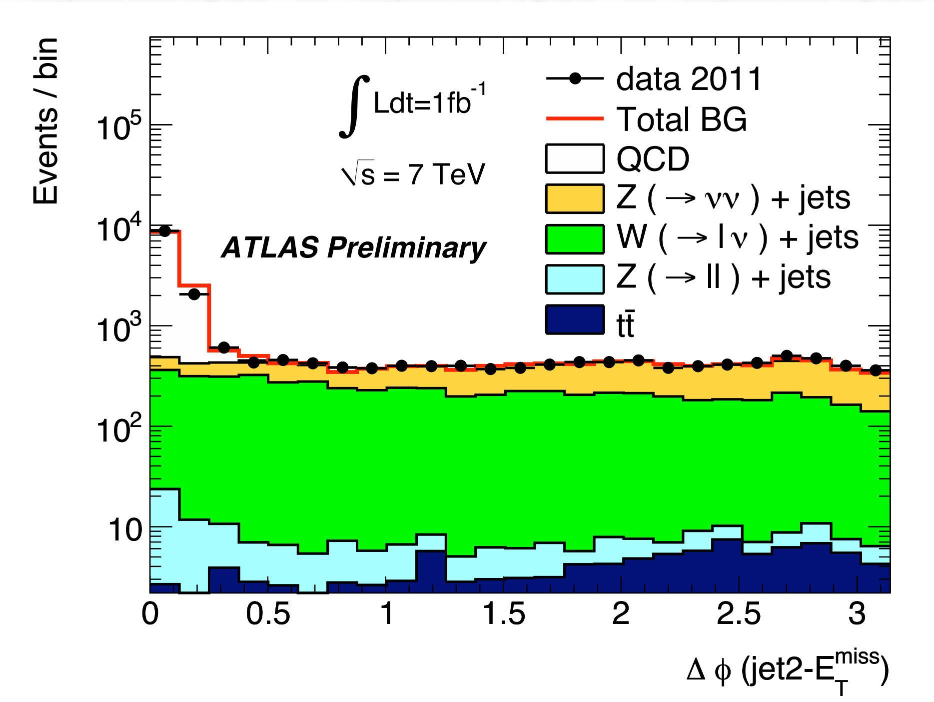




Estimate of multijet background from data:

- 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)



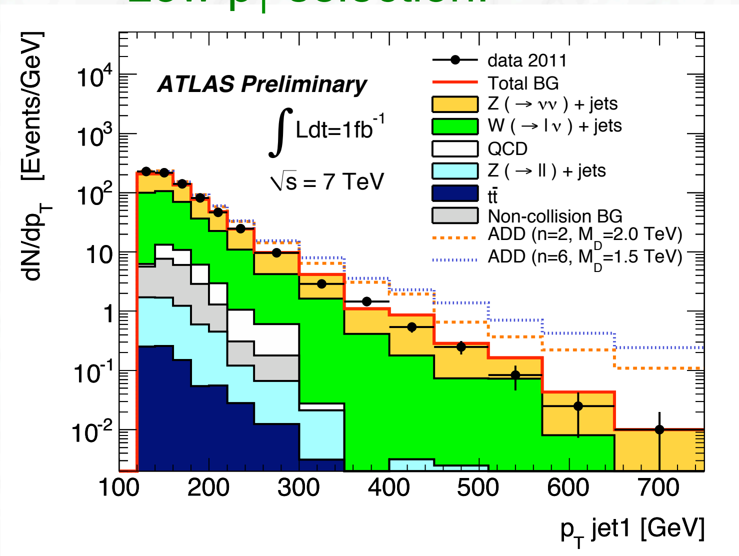
Good description of data, except in low $\Delta\phi$ region → QCD background component from data

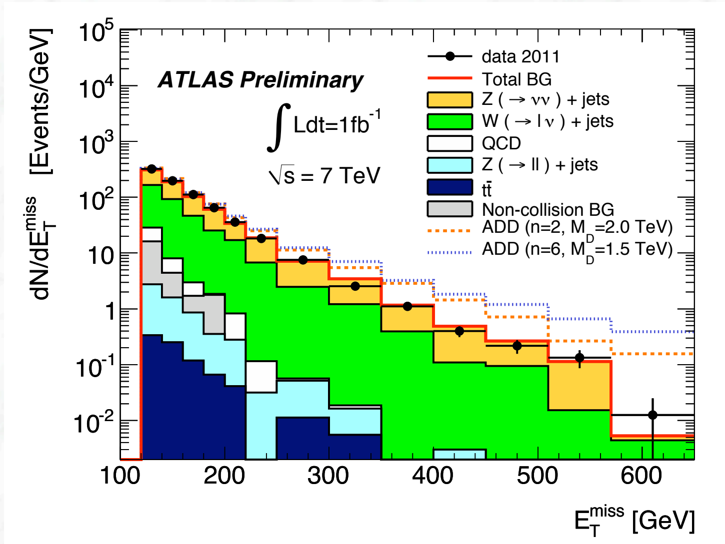
Numbers of observed events in data in comparison to expectations from Standard Model background:

	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

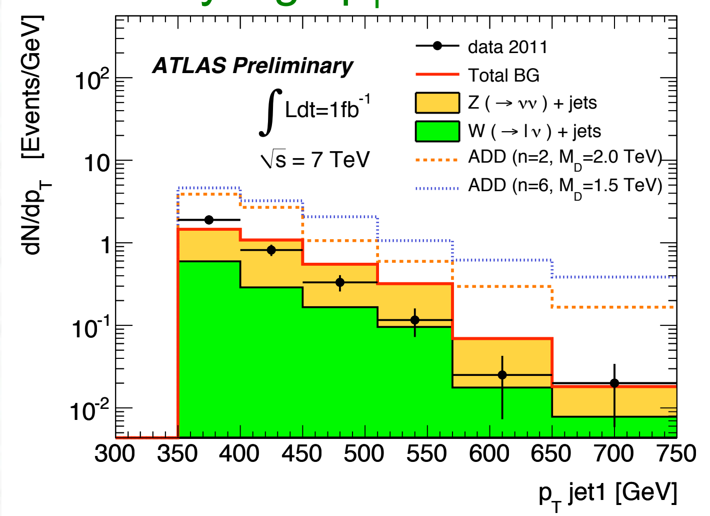
Agreement between data and expectations for the p_T(jet) and E_T^{miss} spectra:

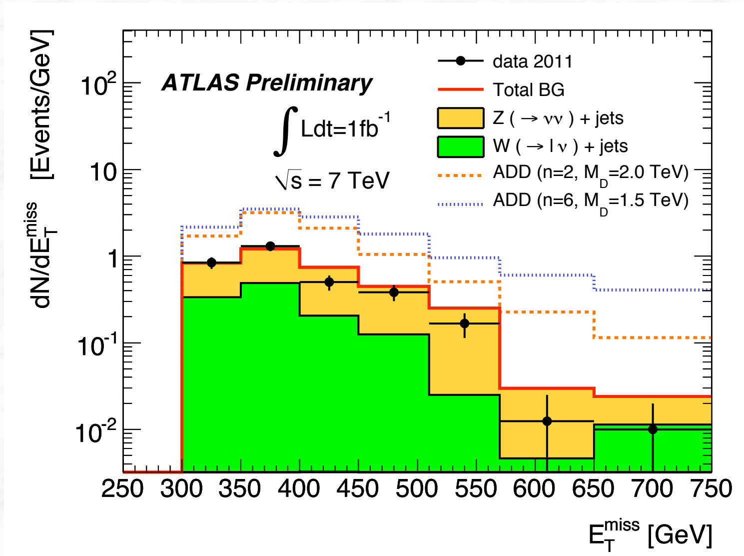
Low p_T selection:



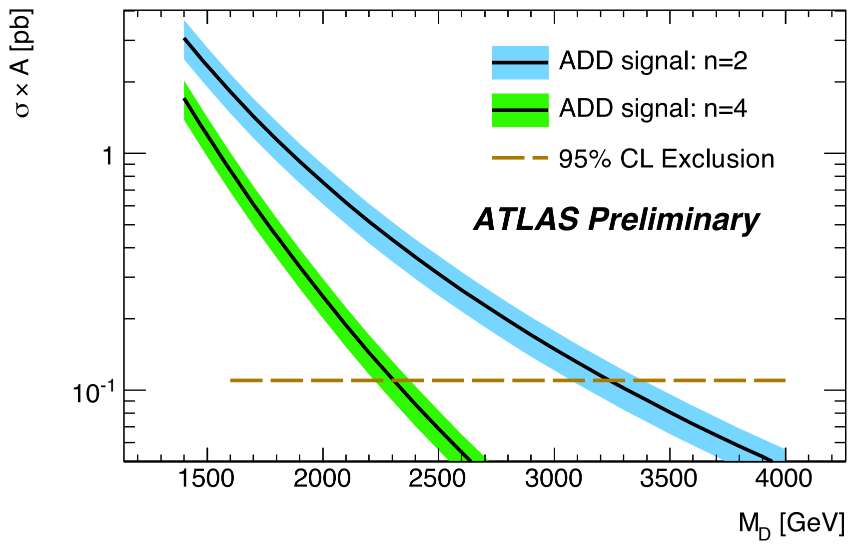


Very high p_T selection:

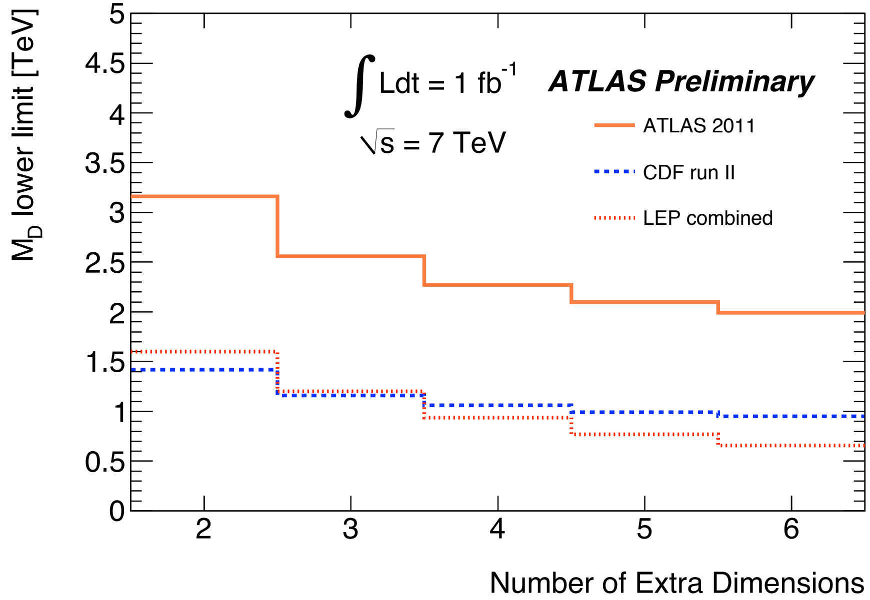




Constraints on the ADD model parameters:



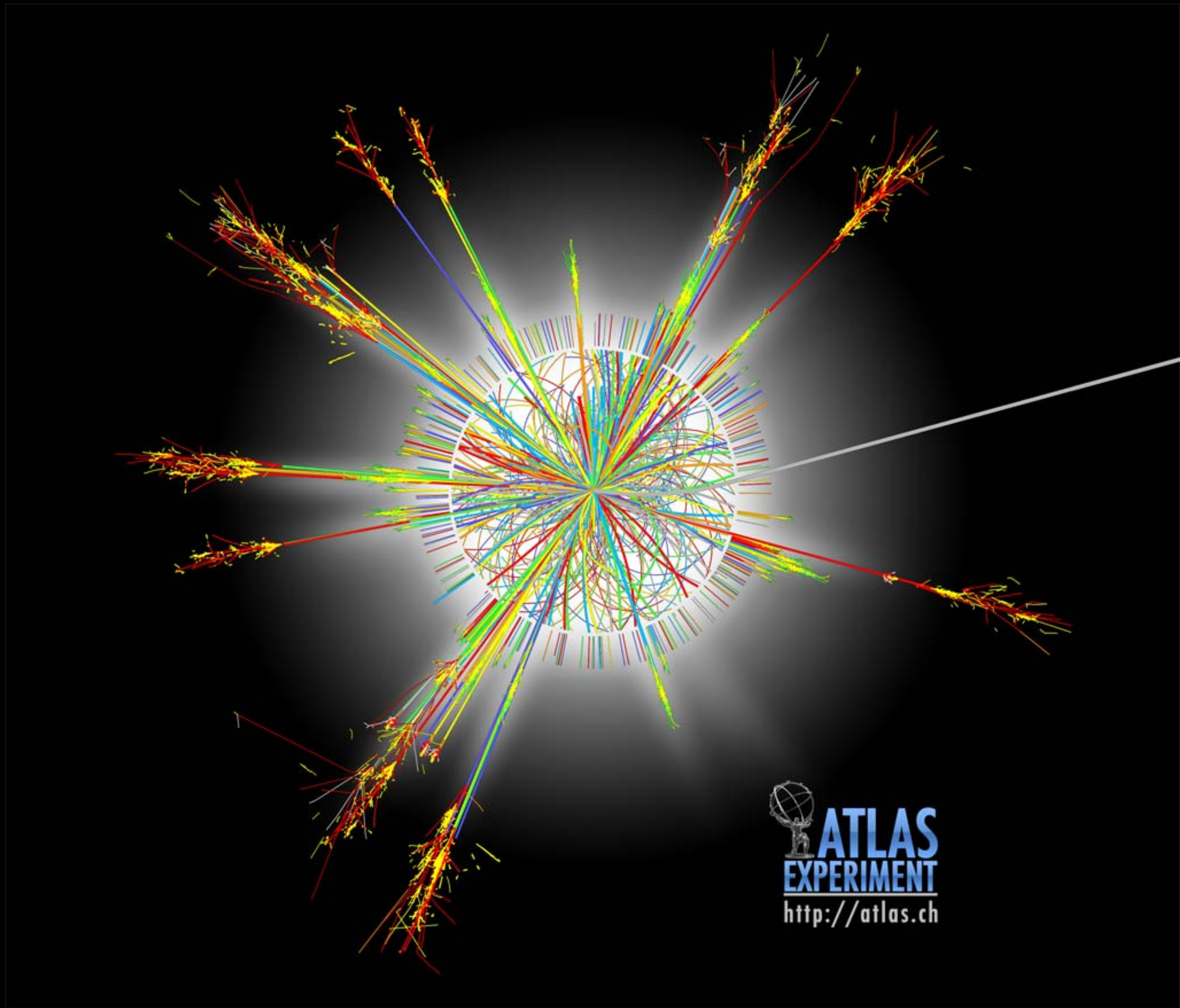
Cross sections as a function of M_D for n=2 and n=4 extra dimensions (cutoff for s^ < M^2_D)



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

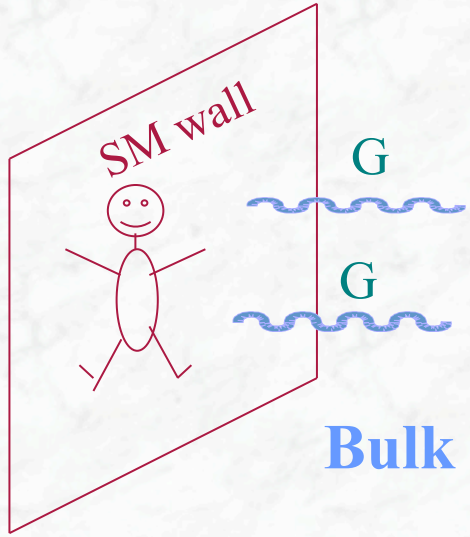
Microscopic Black Holes at the LHC ?



- 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:

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

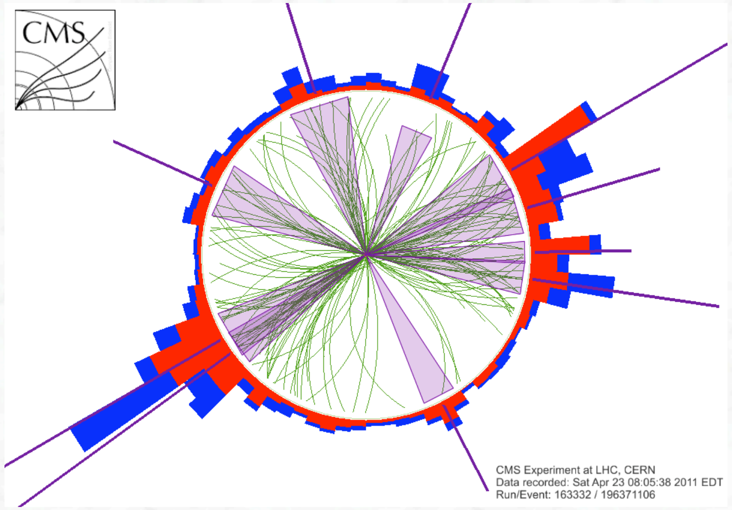


- Black hole formation at energies greater than M_D, (above a threshold mass, M_{th})

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

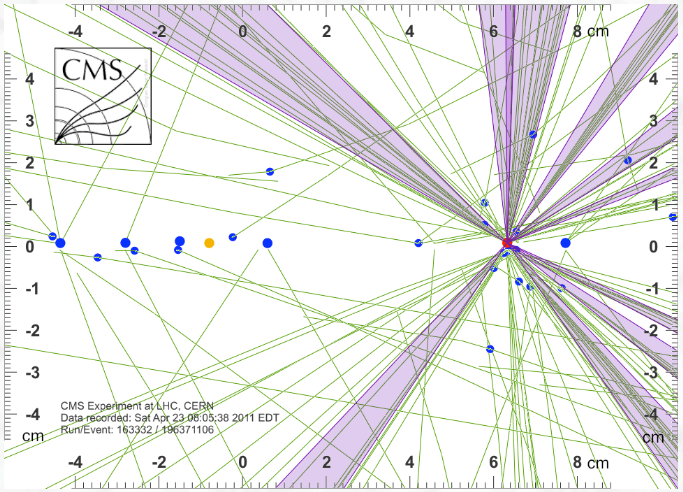
- Once produced, the black hole is expected to decay via Hawking radiation, democratically to all Standard Model particles (quarks and gluons dominant,75%)
  → multijet events with large mass and total transverse energy

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



Candidate events exist….

event with high multiplicity of jets,
high mass….



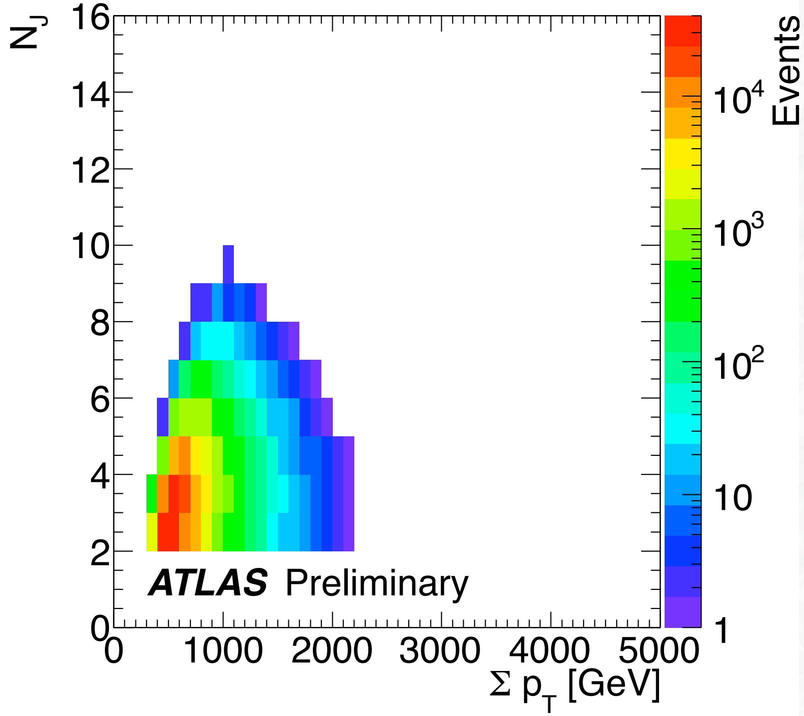
all particles coming from one interaction vertex

Is there an excess above the expectation from QCD production?

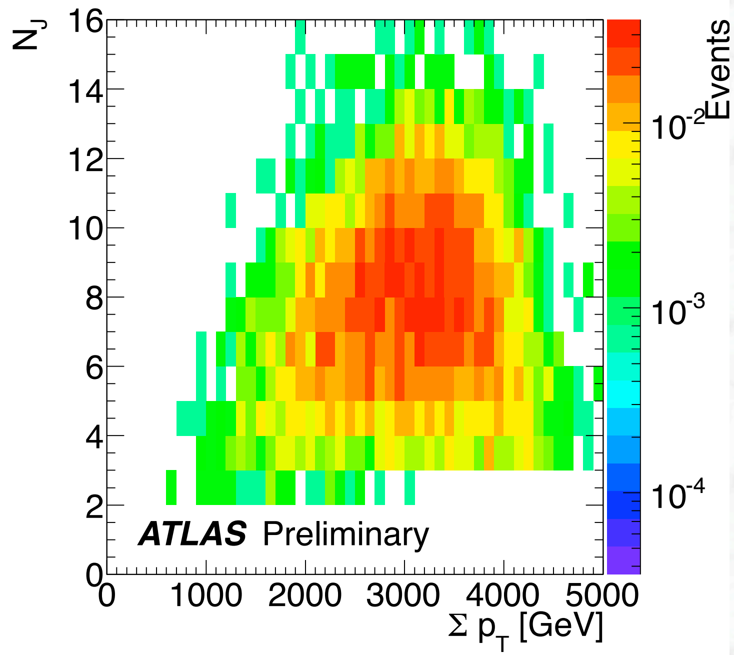
Discriminating variables between QCD background and black hole signals:

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

Results of an ATLAS Monte Carlo simulation:

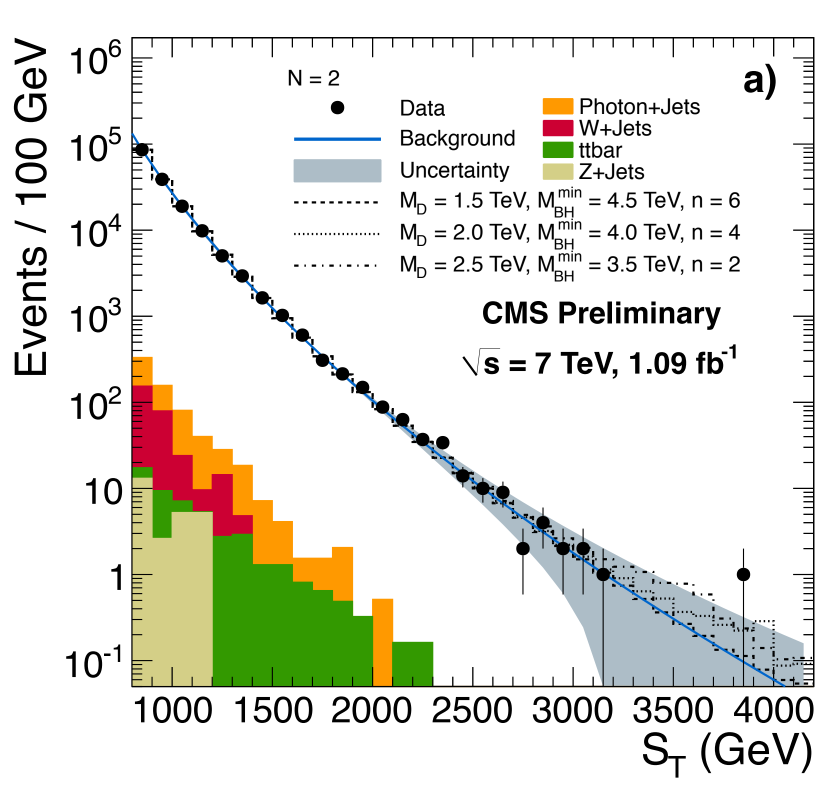


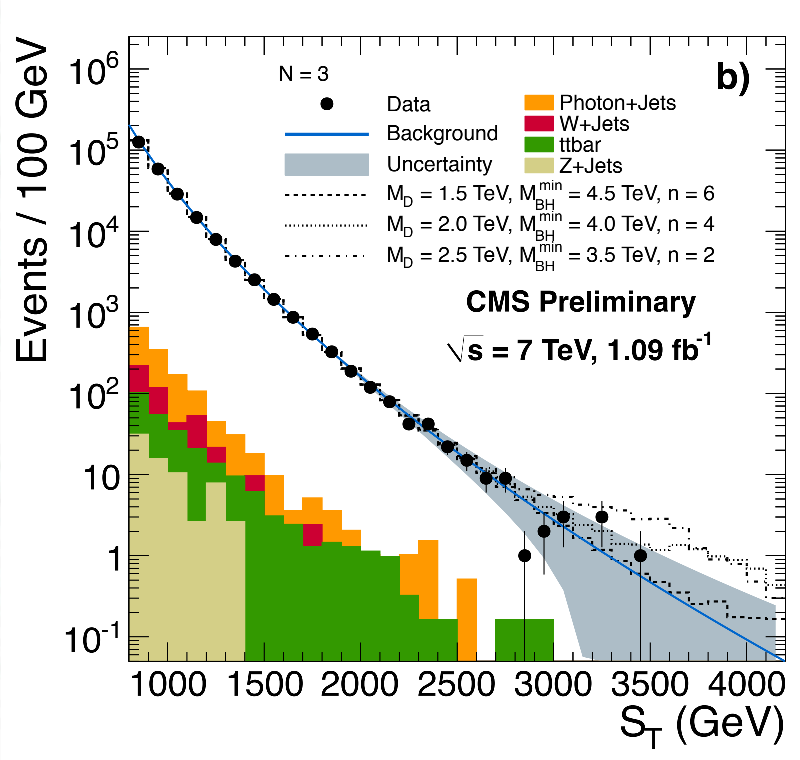
QCD multijet "background"



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



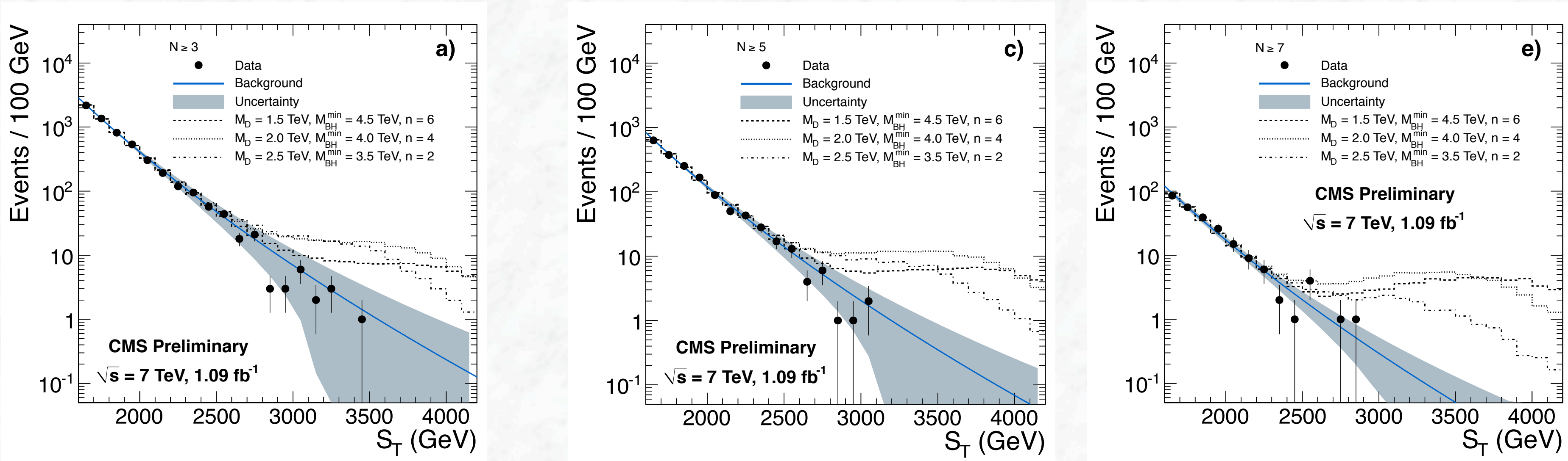


Shape of S_T distribution cannot be reliably calculated in Monte Carlo simulation

problem: high jet multiplicities

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

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

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

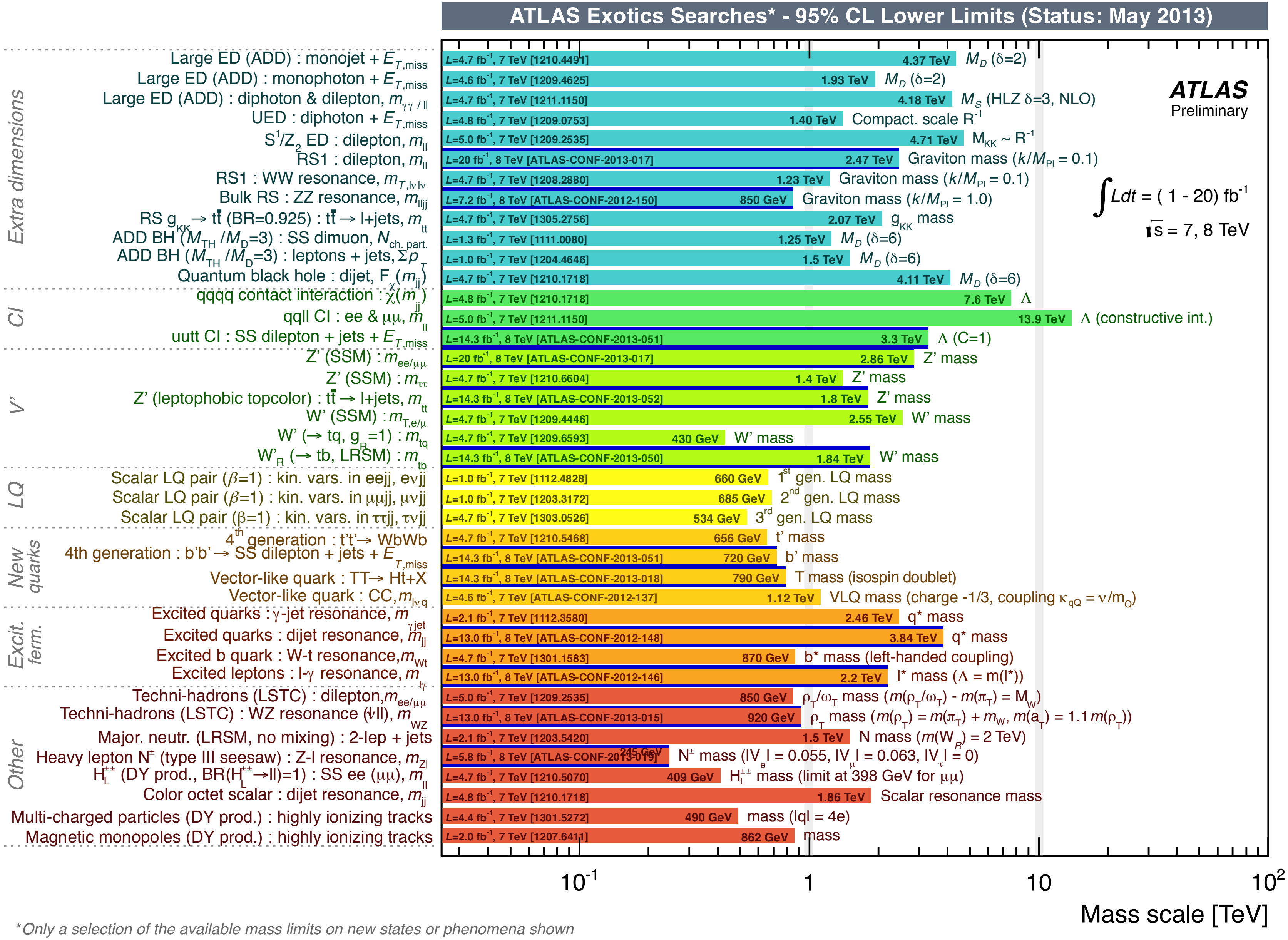
- **K. Cheung, “Collider Phenomenology for Models of Extra Dimensions”, hep-ph/0305003**
  http://arxiv.org/abs/hep-ph/0305003

- **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).**

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



End of lectures