Searches for Extra Dimensions at the LHC

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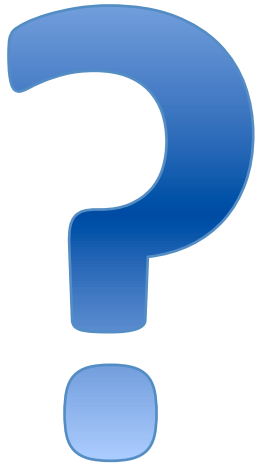
Motivation

Extra dimensions can provide solutions to existing problems.

- Hierarchy problem
- Gauge Coupling Unification
- Dark Matter
- Symmetry Breaking
- Proton Stability



Universal Extra Dimensions

In UED, each particle propagates in all dimensions.

Momentum in higher dimensions is observed as increased mass in Kaluza-Klein particles.

$$E^2 = p_x^2 + p_y^2 + p_z^2 + p_4^2 + \ldots + p_n^2 + m^2$$

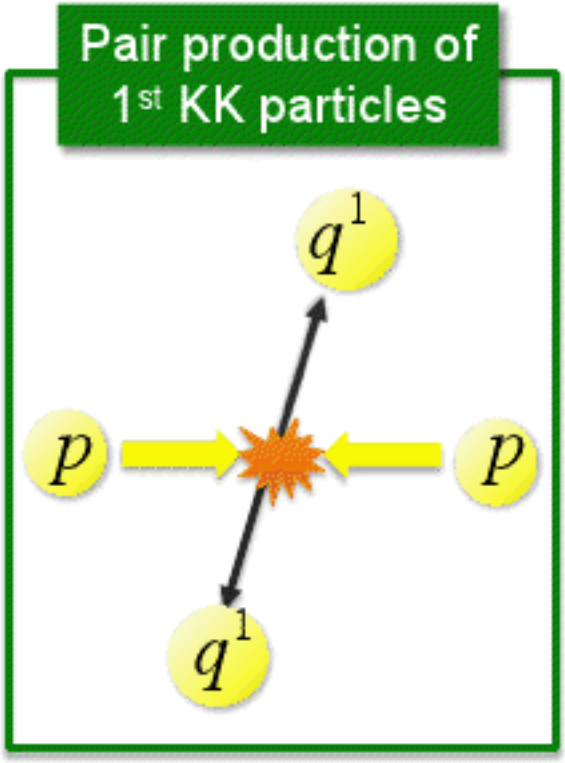
where

$p_4^2 = 1/R^2$ (first-level)

$p_4^2 = (2/R)^2$ (second-level)

KK Parity $P=(-1)^n$ is conserved. The lightest KK particle (γ^*) is stable by KK Parity.

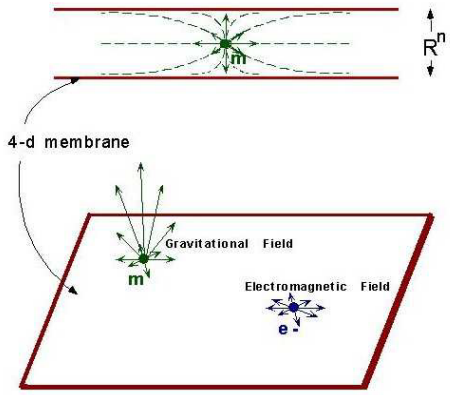
If the space also has n LEDs then the LKP can decay into $\gamma + G^*$



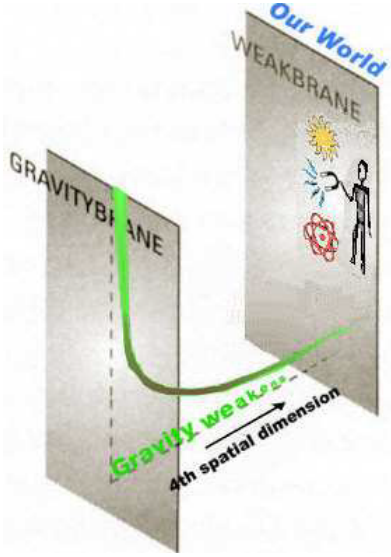
Large Extra Dimensions

Only gravity propagates into extra dimensions

- ADD
  - Multiple compact extra dimensions.
  - Produces tower of KK Gravitons
  - Reduces fundamental Planck scale
    - Black Holes

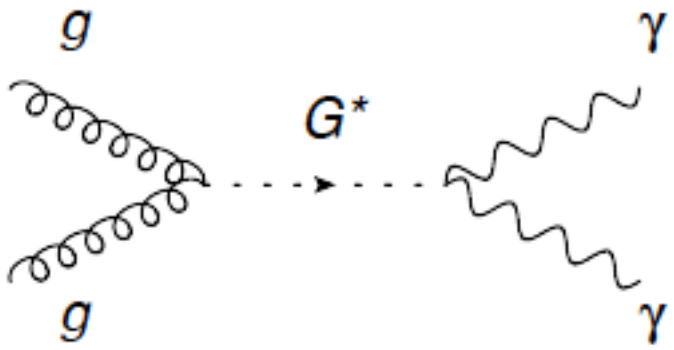


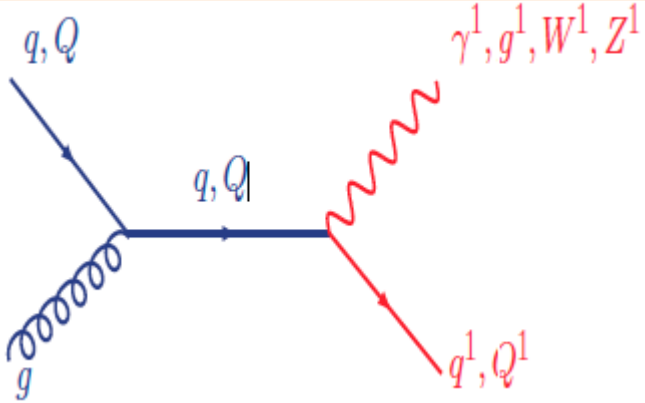
- Randall-Sundrum
  - 5D Warped Geometry
  - Produces tower of KK Gravitons



Photon searches

- UED
  - Photon channel much easier than lepton channel. Diphoton + MET
  - Lepton channel is dominated by ttbar, bbar
  - Photon channel has almost no irreducible background.
  - All decays go through LKP.





- ADD/RS
  - Search for KK graviton decays.
  - Photon channel has twice BR compared to lepton pairs.
  - Small background.
  - Sensitive to both ADD and RS models

Diphoton (UED)

$\int Ldt = 1.07\ fb^{-1}$
$\int Ldt = 4.7\ fb^{-1}$

ATLAS Collaboration: arXiv:1111.4116v2 — Limit: 1/R > 1.23 TeV
CMS Collaboration: CMS-PAS-SUS-12-001 — Limit: 1/R > 1.33 TeV

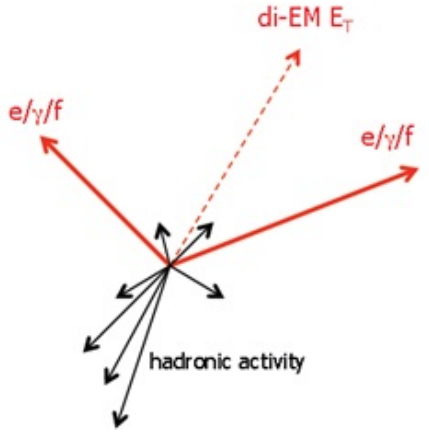
Event Selection

ATLAS

- Two Isolated Photons Et > 25 GeV
- MET > 125 GeV

CMS

- Two Isolated Photons Et > 40/25 GeV
- MET > 75 GeV



Difference in hadronic/EM energy creates fake MET

Background Estimation

QCD

- Shape is determined by reweighting two control samples with no true MET (loose (fake) photons and ee) and normalizing to data.
  - CMS req. both photons to be "loose"
  - ATLAS req. only one
  - Dominated by Z->ee

EW

- Photon Fake rate determined by fitting Z inv. mass peak in eγ.
- Fake rate is used with MC to determine EW contribution
- Irreducible background Zgg, Wgg is negligible.

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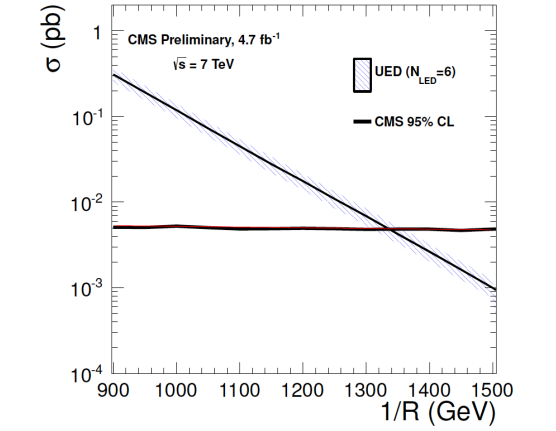
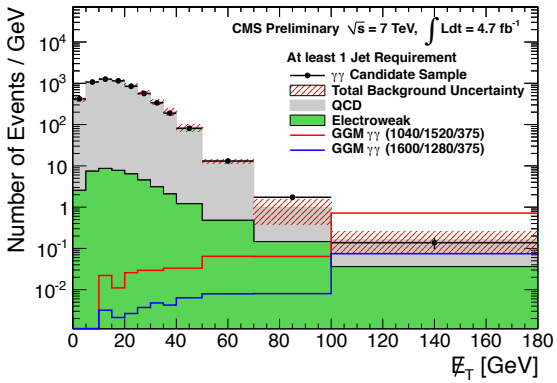
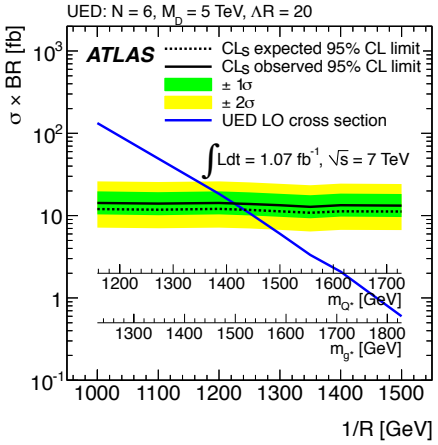
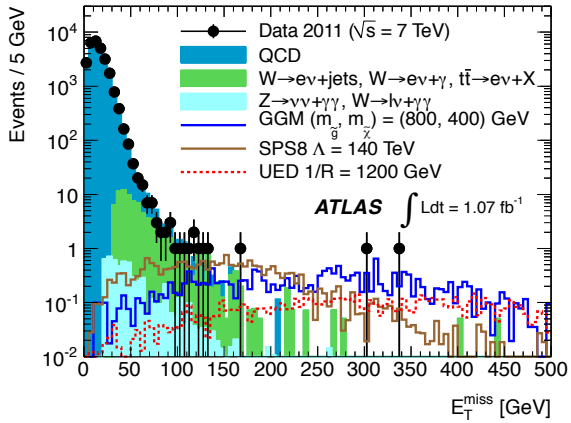




ATLAS





Diphoton (ADD+RS)

$\int Ldt = 2.12\ fb^{-1}$
$\int Ldt = 2.2\ fb^{-1}$

ATLAS Collaboration: arXiv:1111.2194v2 Limit: $M_s > 2.27\text{-}3.53$ TeV; $m\{G_{RS}\} > 1.95$ TeV
CMS Collaboration: arXiv:1112.0688v1 Limit: $M_s > 2.3\text{-}3.8$ TeV ; $m\{G_{RS}\} > 1.84$ TeV

Event Selection

ATLAS

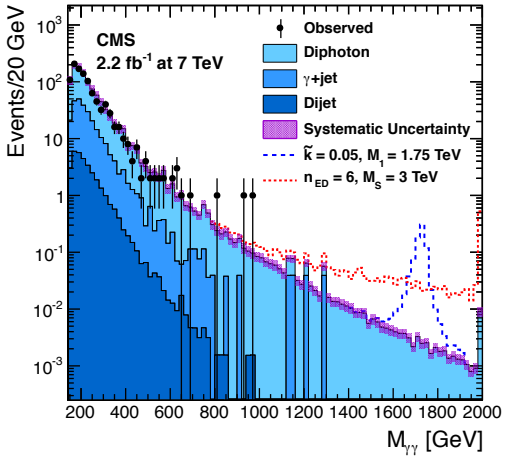
- Two "Tight" photons $E_T > 25$ GeV
- Mγγ > 140 GeV

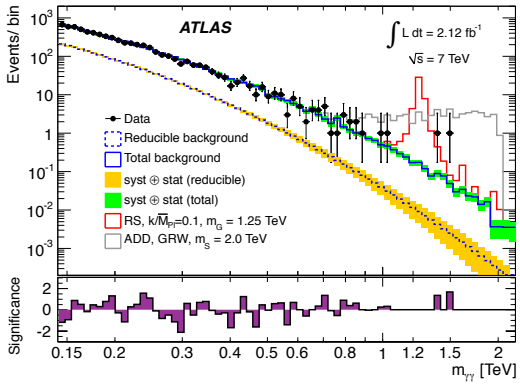
CMS

- Two isolated photons $E_T > 70$ GeV
- Mγγ > 140 GeV

Background Estimation

- SM diphoton is dominant background
  - PYTHIA rescaled using NLO K-factor
- Multi-Jet and photon + jets backgrounds are extrapolated from data.
  - Two background-dominated references regions (jj and jγ)
  - CMS used fake rate from reference regions.
  - ATLAS used sum of control samples and fit to extrapolate to high mass region
- Total background was summed and normalized to data





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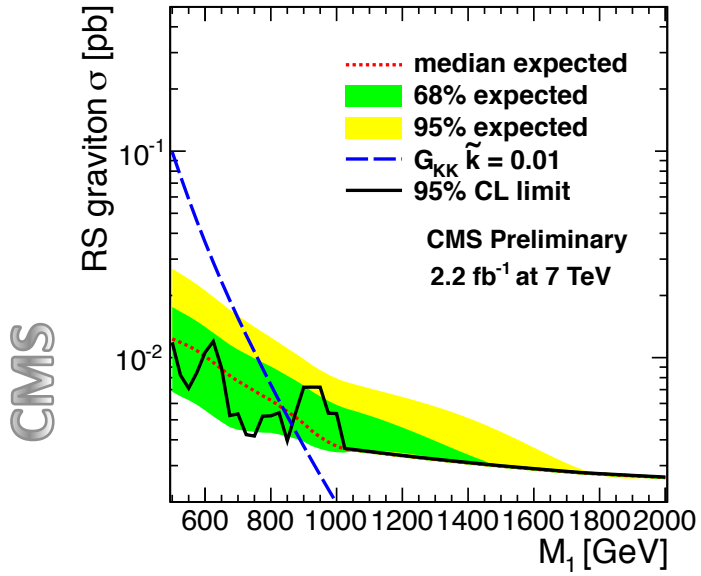
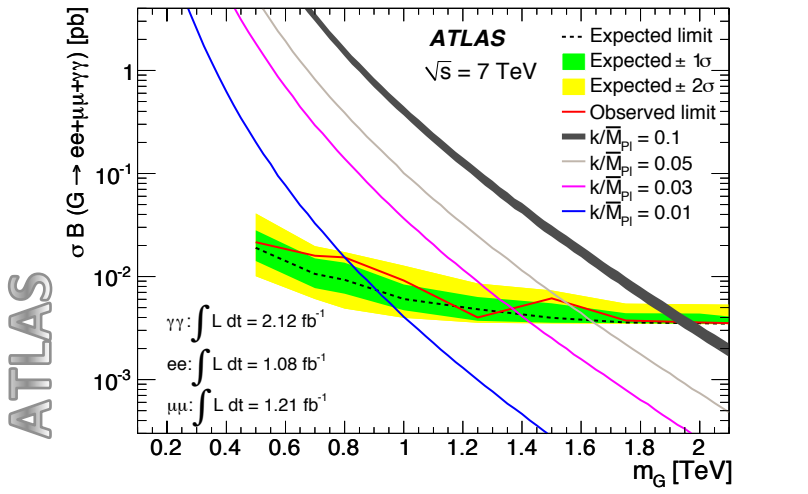


k-factor Value	GRW	Hewett Pos	Hewett Neg	HLZ $n=3$	HLZ $n=4$	HLZ $n=5$	HLZ $n=6$	HLZ $n=7$
1	2.73	2.44	2.16	3.25	2.73	2.47	2.30	2.17
1.70	2.97	2.66	2.27	3.53	2.97	2.69	2.50	2.36



K factor	GRW	Hewett pos.	Hewett neg.	HLZ (n_{ED}) 2	3	4	5	6	7
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
1.6	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53

95% CL limits on M_S in GRW, Hewett, and HLZ conventions.

Photon + MET (ADD)

$\int Ldt = 5.0\ fb^{-1}$

CMS Collaboration: arXiv:1204.0821v1

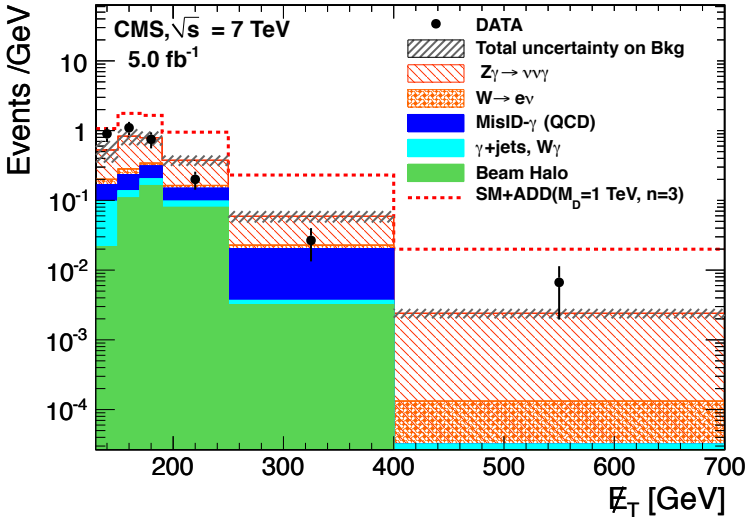
Limit: $M_D < 1.59\text{-}1.66$ TeV; n=3-6

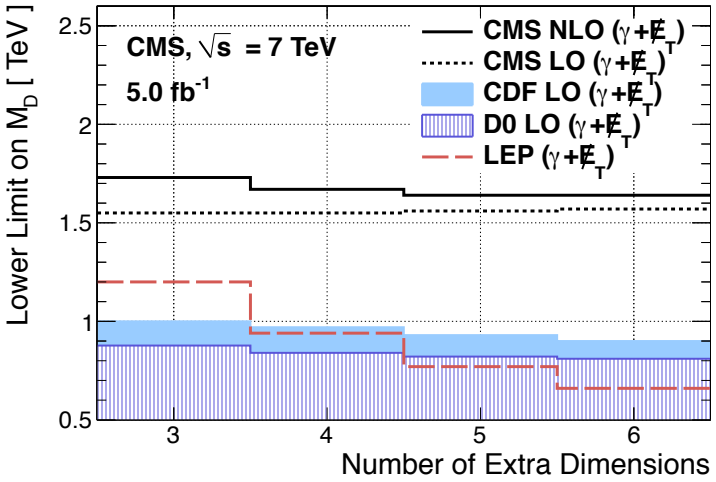
Event Selection

- Isolated photon $p_T > 145$ GeV
- MET > 130 GeV

Background Estimation

- Primary background is Zγ -> γ + MET
- Zγ, γ+jet, γγ estimated from PYTHIA MC
- Wγ estimated from MADGRAPH
  - NLO corrected via k-factor
- Electron/photon fake rate from data (Z->ee) used to estimate W->eυ
- Jet/photon fake rate was determined using QCD-enriched data sample.
  - Ratio of tight/loose candidates.





Dilepton (ADD/RS)

$\int Ldt = 4.9\text{-}5.0\ fb^{-1}$

$\int Ldt = 2.1\text{-}2.3\ fb^{-1}$

ATLAS Collaboration: ATLAS-CONF-2012-007 Limit: $m\{G_{RS}\} > 2.16$ TeV

CMS Collaboration: arXiv:1202.3827v1 Limit: $M_S > 2.5$ TeV - 3.8 TeV

Event Selection

ATLAS

Muons	Electrons
• $p_T > 25$ GeV	• $p_T > 25$
• Oppositely charged pairs	• No charge req.

CMS

Muons	Electrons
• $p_T > 45$ GeV	• $p_T > 35/40$ GeV (Barrel/Endcaps)
• No charge req.	• Oppositely charged pairs

Signal Region: $M_{ee/\mu\mu} > 1.1$ TeV

Background Estimation

- SM DY process is dominant background
  - Dimuon channel used MC@NLO+NNLO corrections
  - Dielectron channel used PYTHIA6+NLOcorrection, normalized to data around M_Z
- ttbar & diboson estimated with PYTHIA/MADGRAPH
- QCD, estimated from data

Dilepton (ADD/RS)

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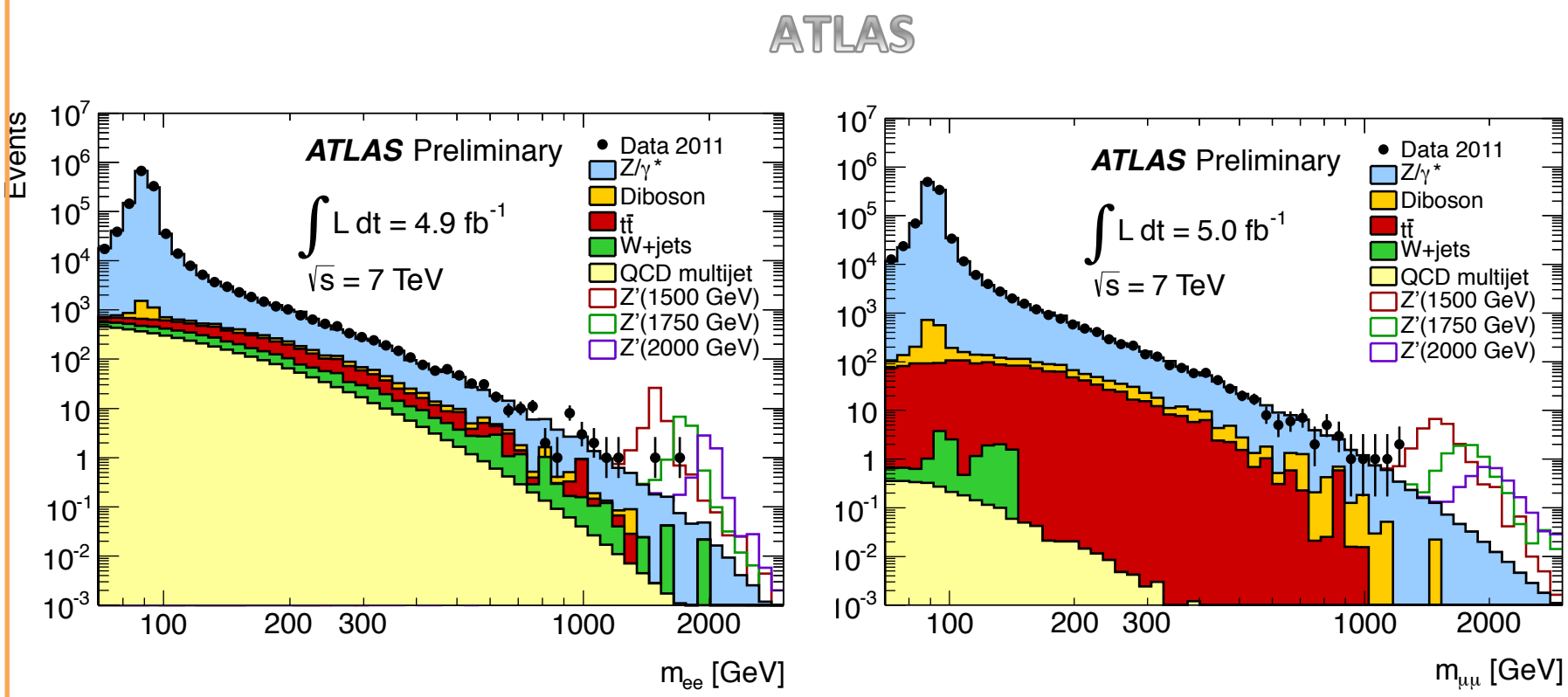

Z`

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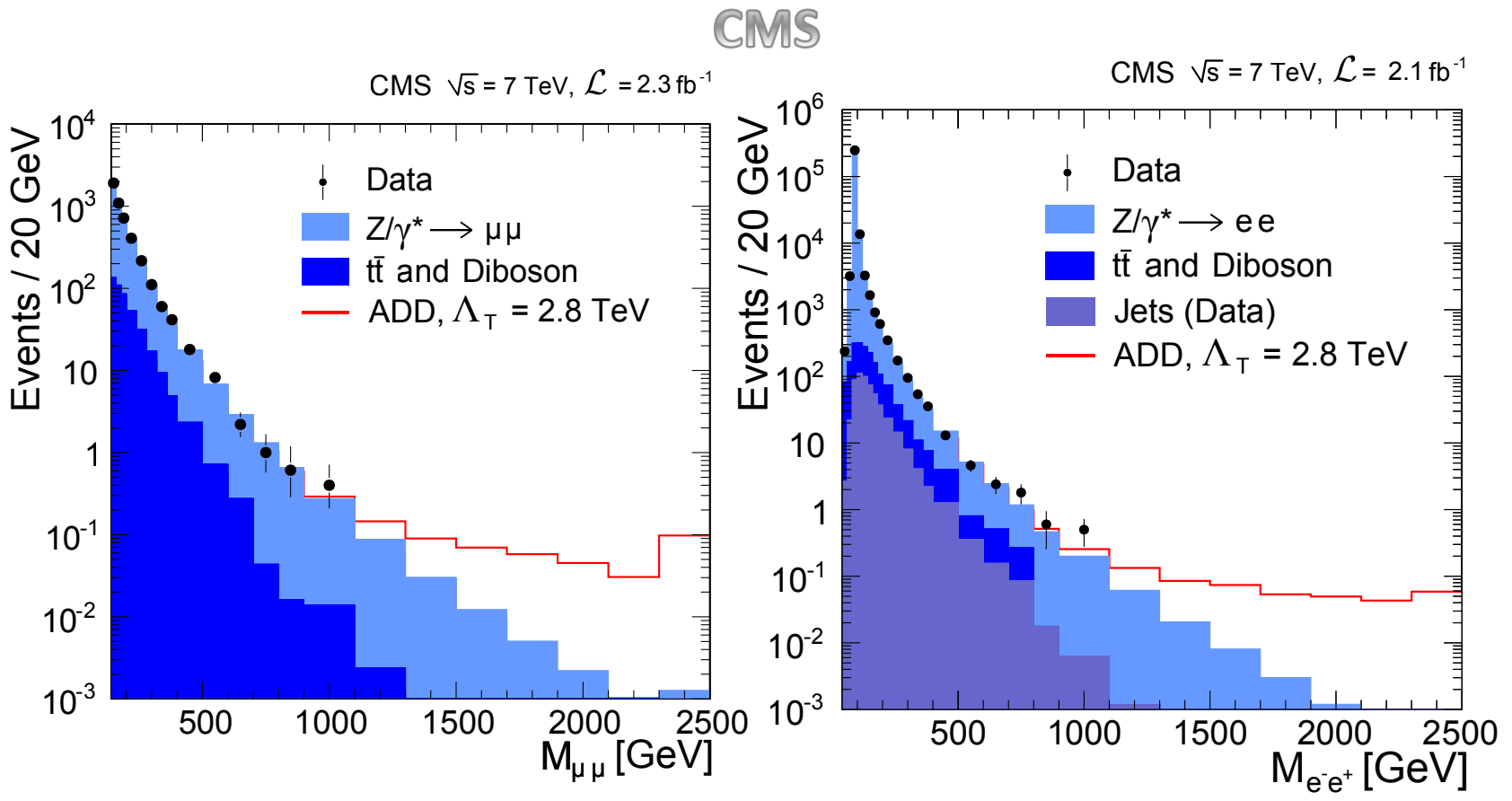

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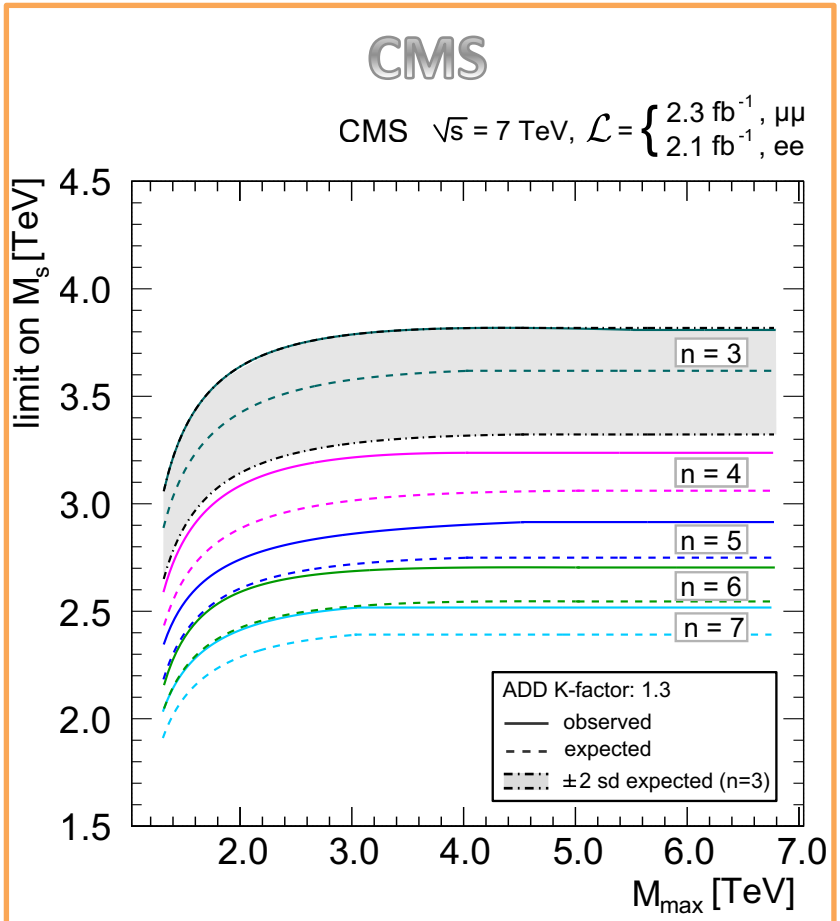
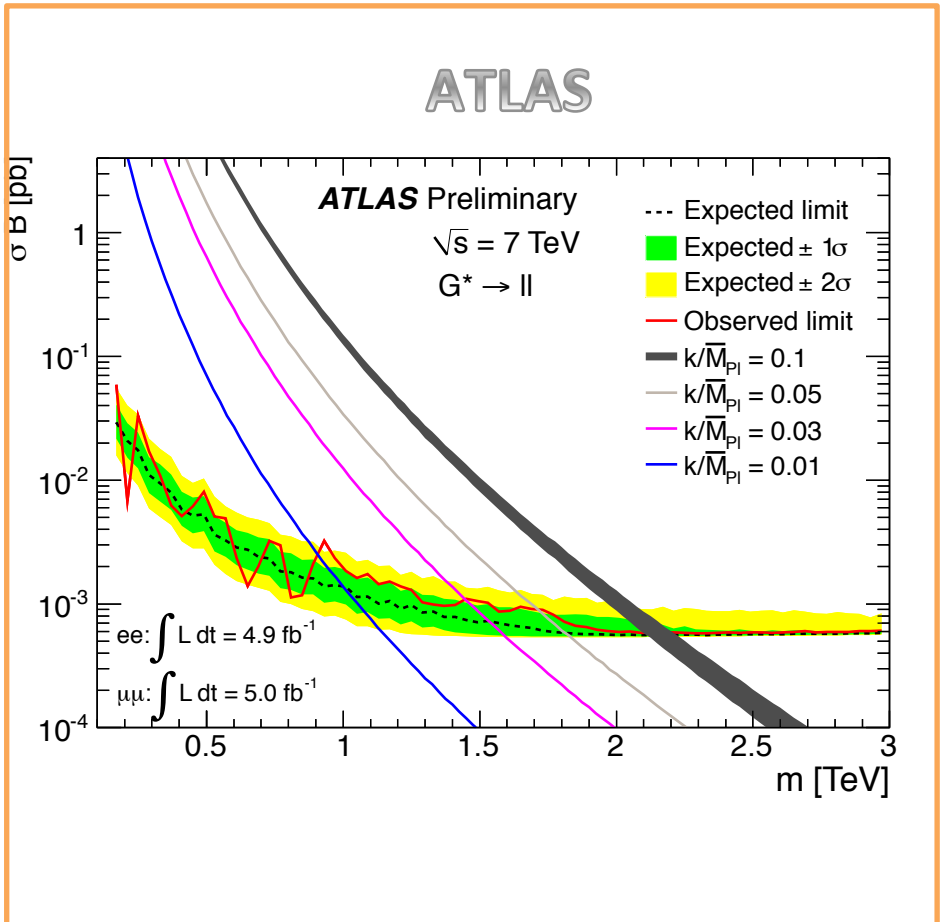




Lepton+Jets(RS)

$\int Ldt = 2.05\ fb^{-1}$

ATLAS Collaboration: arXiv:1205.5371v1

Limit: 500 GeV >m{g_{kk}}>1070 GeV

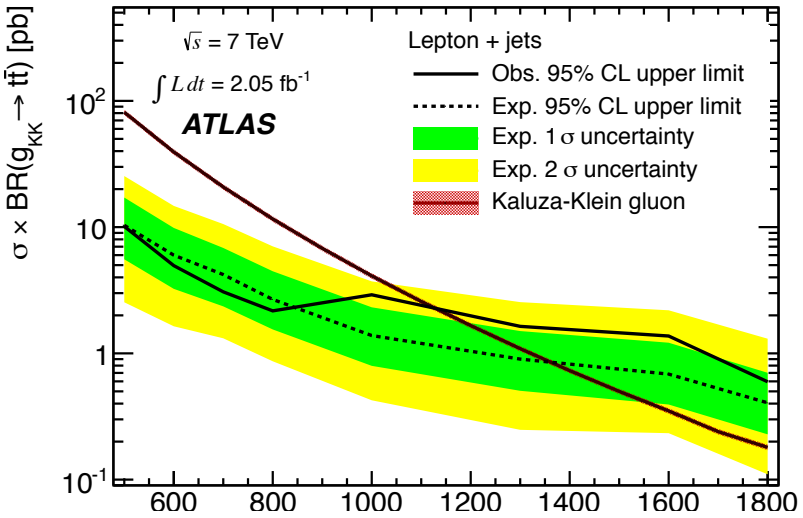
Search for ttbar resonances (KK gluon)

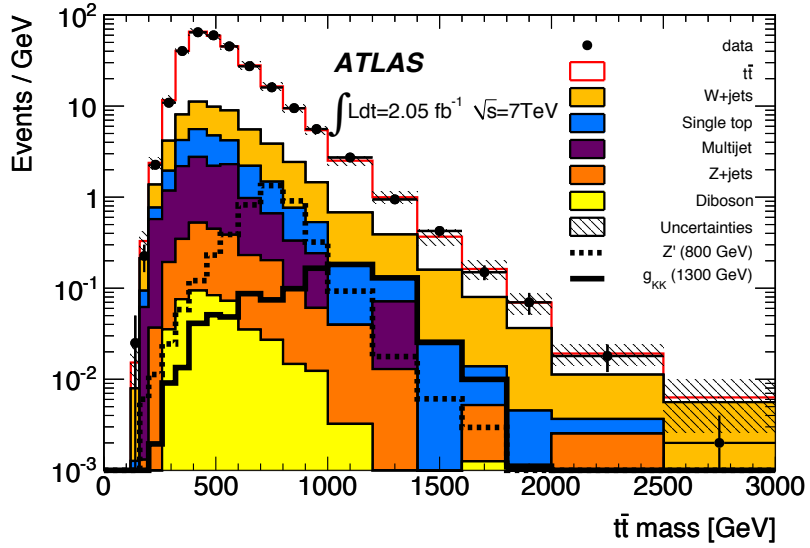
Event Selection

- Exactly one isolated lepton
- Electron Channel
  - MET > 35 GeV; M_T(lepton-MET)> 25 GeV
- Muon Channel
  - MET > 20 GeV; M_T(lepton-MET)>60 GeV
- At least three or four jets, depending on p_T
  - Jet pT >25 GeV; $|\eta| < 2.5$

Background Estimation

- ttbar and single top simulated w/ MC@NLO
  - Corrections based on data
- W+jets simulated with ALPGEN
  - Corrections based on data
- QCD Multijet estimated from data
  - Template is created using sample with exactly one jet with a high EM fraction and at least four tracks. Normalized to data.





Monojet(ADD)

$\int Ldt = 1.0\ fb^{-1}$

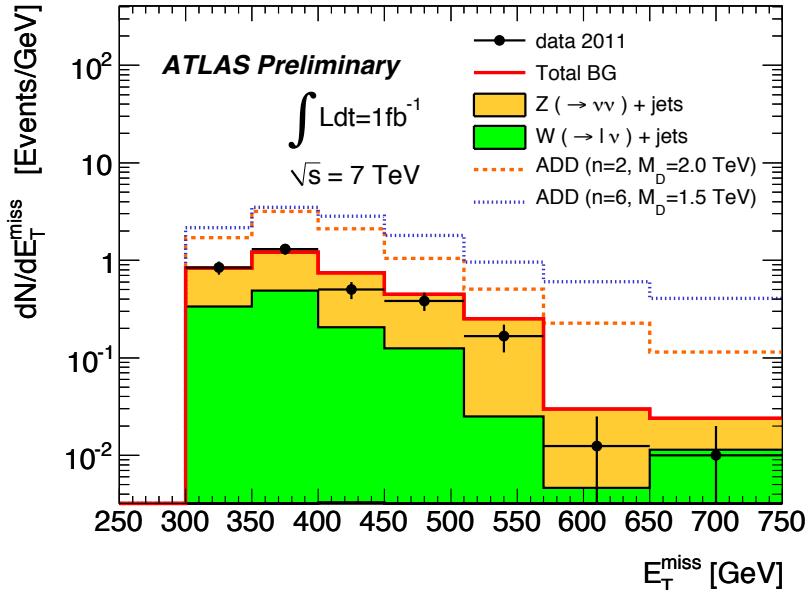
ATLAS Collaboration: ATLAS-CONF-2011-096 Limit:$M_D > 3.2$ TeV; n=2

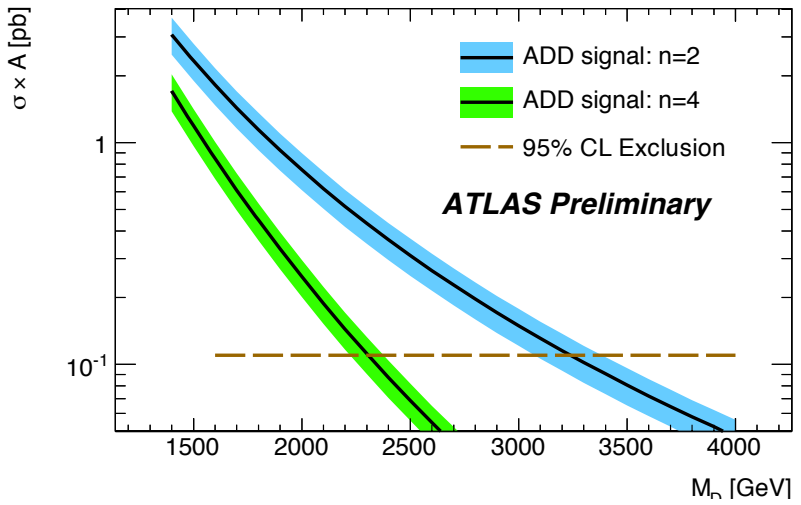
Event Selection

- Isolated Jet $p_T > 120$
- MET > 220 GeV
- No remaining electrons or muons after cleaning

Background Estimation

- Background from Z(νν)+jets,W +jets estimated using MC normalized to data.
  - Muon and electron sample, orthogonal to signal is used for normalization.
- Ttbar and γ+jets determined from MC.
  - Contributes less than 0.2% (Negligible)





MonoJet(ADD)

$\int Ldt = 4.7\ fb^{-1}$

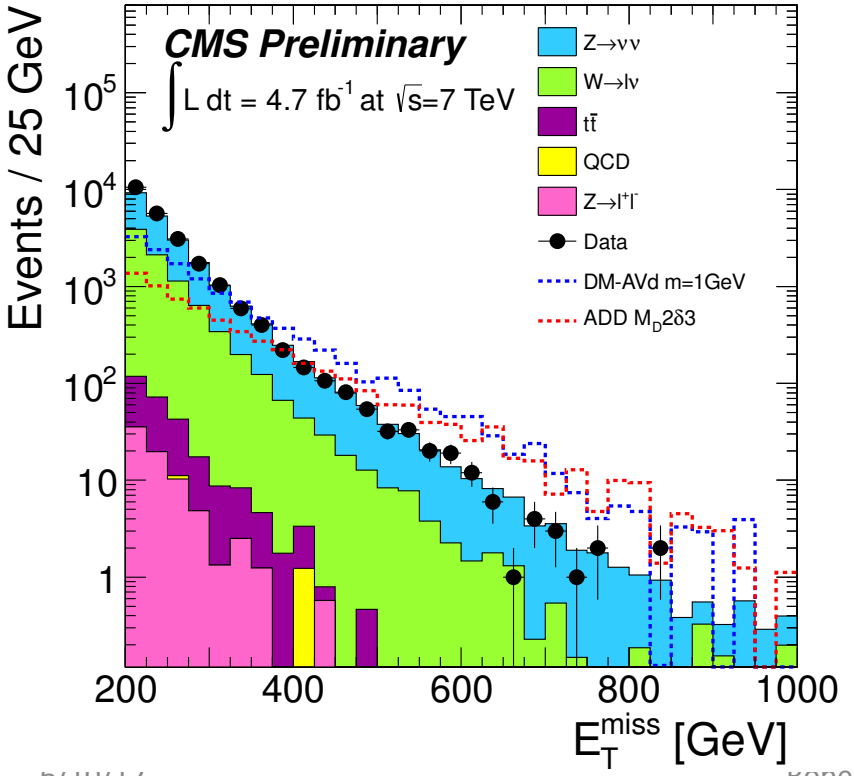
CMS Collaboration: CMS-PAS-EXO-11-59 Limit: $M_D > 4.0$ TeV; n=2

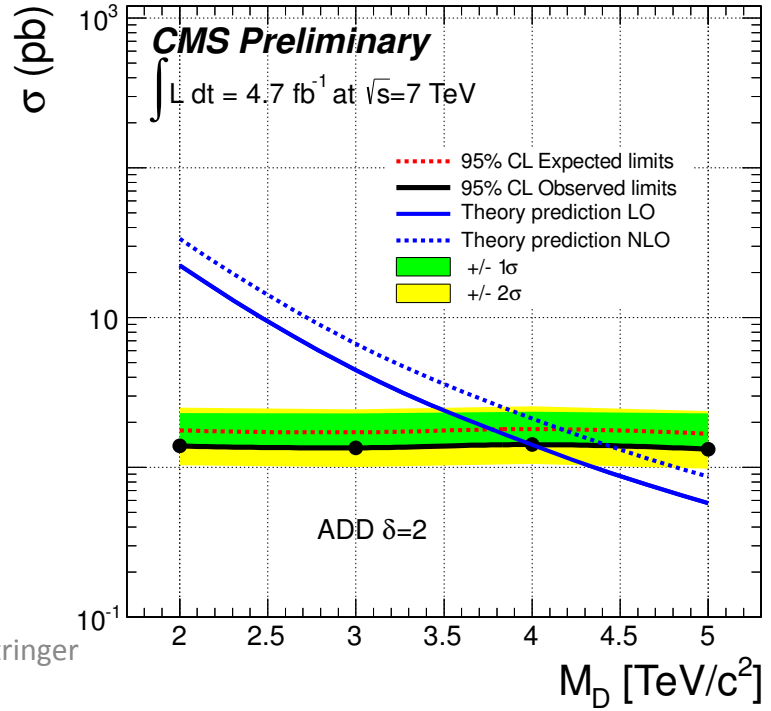
Event Selection

- MET > 200 GeV
- Lead jet pT>110 GeV

Background Estimation

- Data Driven Background estimate for
  - Z(νν)+jets
  - W+jets
- Estimated using μ+jets events.
  - Scaled by xsec
  - Efficiency of the lepton veto.





Dijet (ADD BH)

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

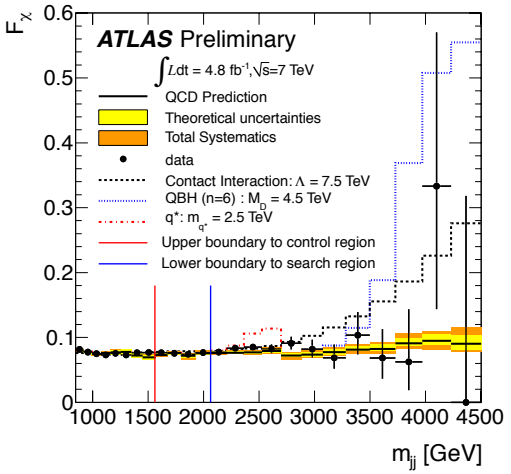
ATLAS Collaboration: ATLAS-CONF-2012-038 Limit: $M_D > 4.11$ TeV; n=6

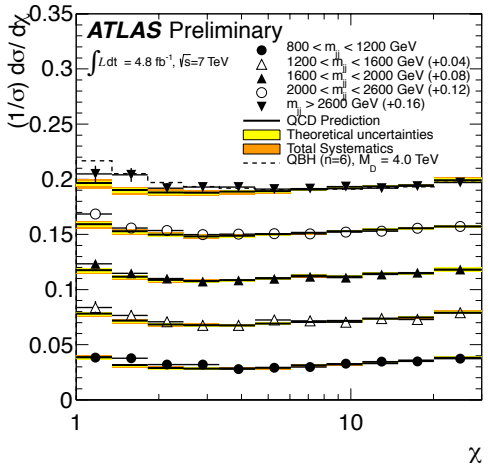
- Two analysis methods
  - Dijet mass
  - Angular distributions

$$\chi \equiv \exp(|y1 - y2|) = \exp(2|y^*|)$$

Event Selection

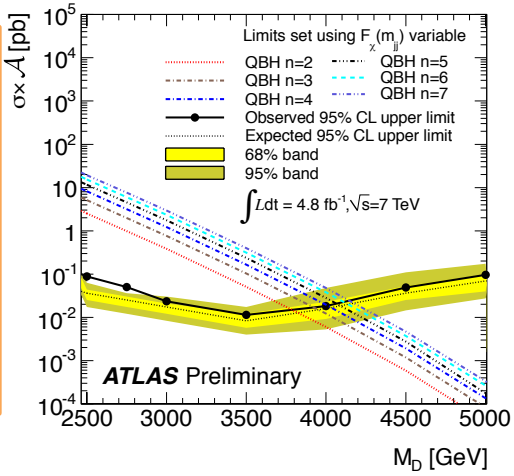
- At least two jets
  - No poorly measured jet with $p_T > 30\%$ of 2nd jet
- Mass analysis
  - $|y^*| < 0.6$, $|y_{1,2}| < 2.8$
  - $M_{jj} > 850$ GeV
- Angular analysis
  - $|y^*| < 1.7, |y_B| < 1.1, |y_{1,2}|$
  - $M_{jj} > 800$ GeV





QCD Background

- Mass analysis
  - Dijet mass dist. fit to smooth background
  - $f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x}$
- Angular analysis
  - Based on MC preditions
  - k-factors applied for NLO



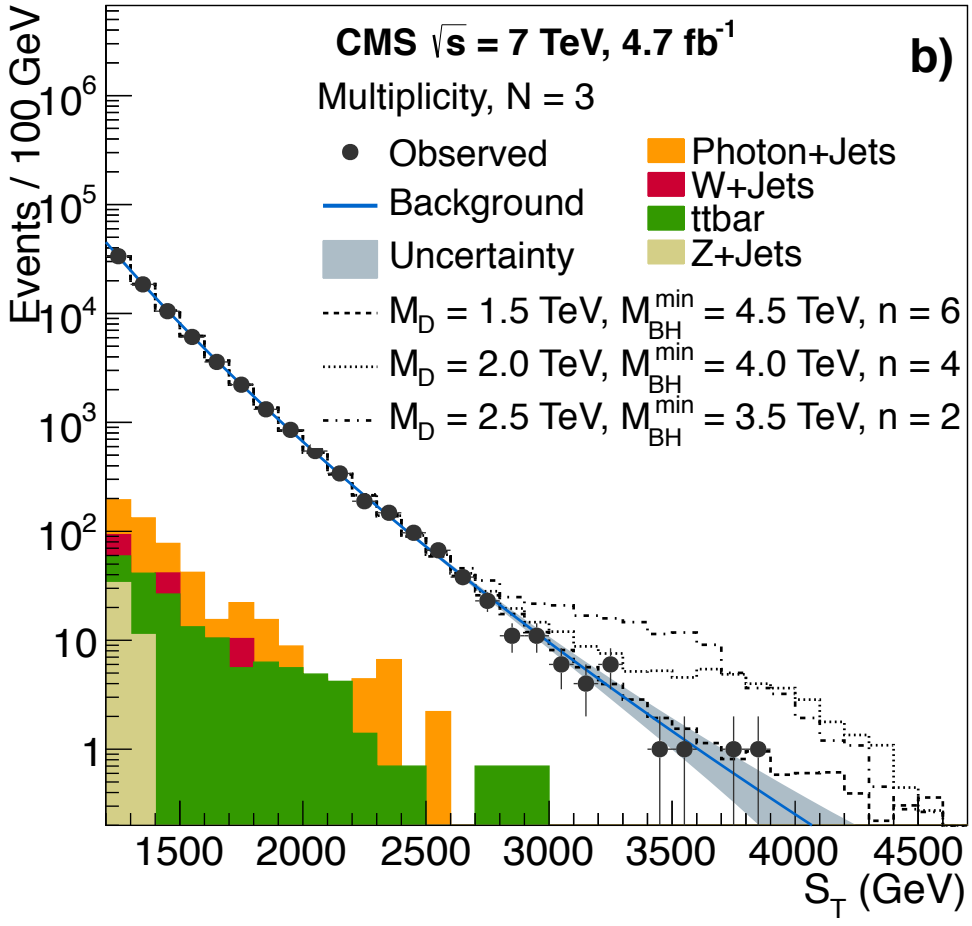
S_T Scaling (ADD BH)

$\int Ldt = 4.7\ fb^{-1}$

CMS Collaboration: arXiv:1202.6396v1 Limit: $m_{BH} > 3.9\text{-}5.3$ TeV ; n=6; $M_D <= 4$ TeV

Analysis Method

- S_T is defined as the scalar sum of the E_T of photons, electrons, muons, and jets.
  - Only objects with E_T>50 GeV included in S_T
  - MET if greater than 50 GeV is also included.
- Background is determined using multiplicity N=2 and N=3 events
  - 1200 GeV < S_T < 2800 GeV
  - Fitted with $f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x}$
- Limits are determined using events of higher multiplicity (N≥3)



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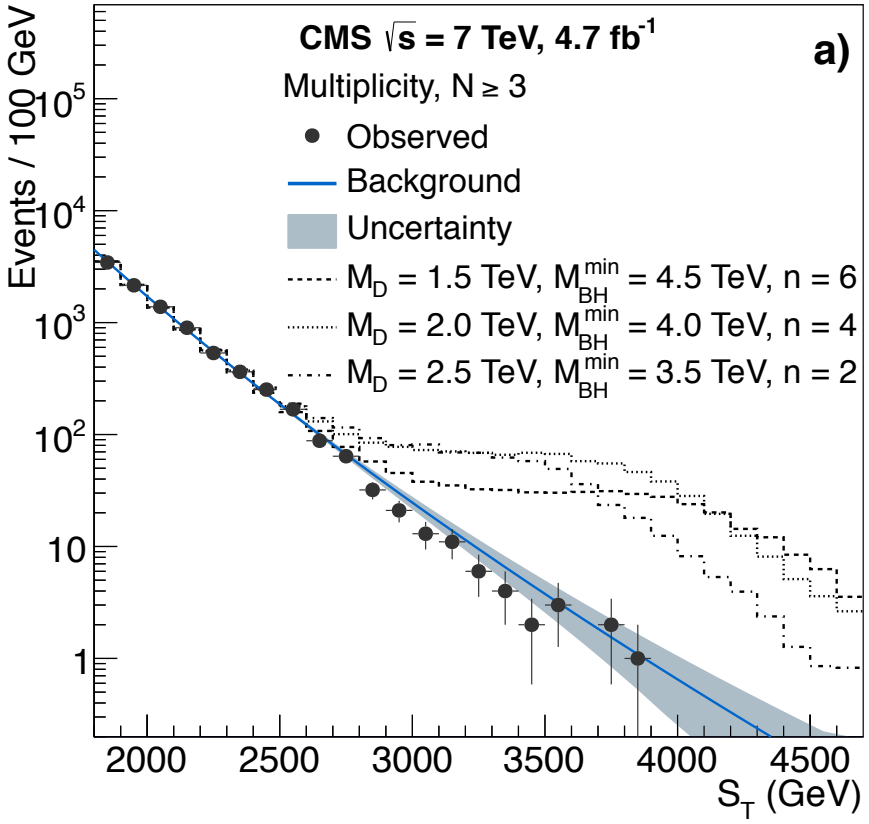

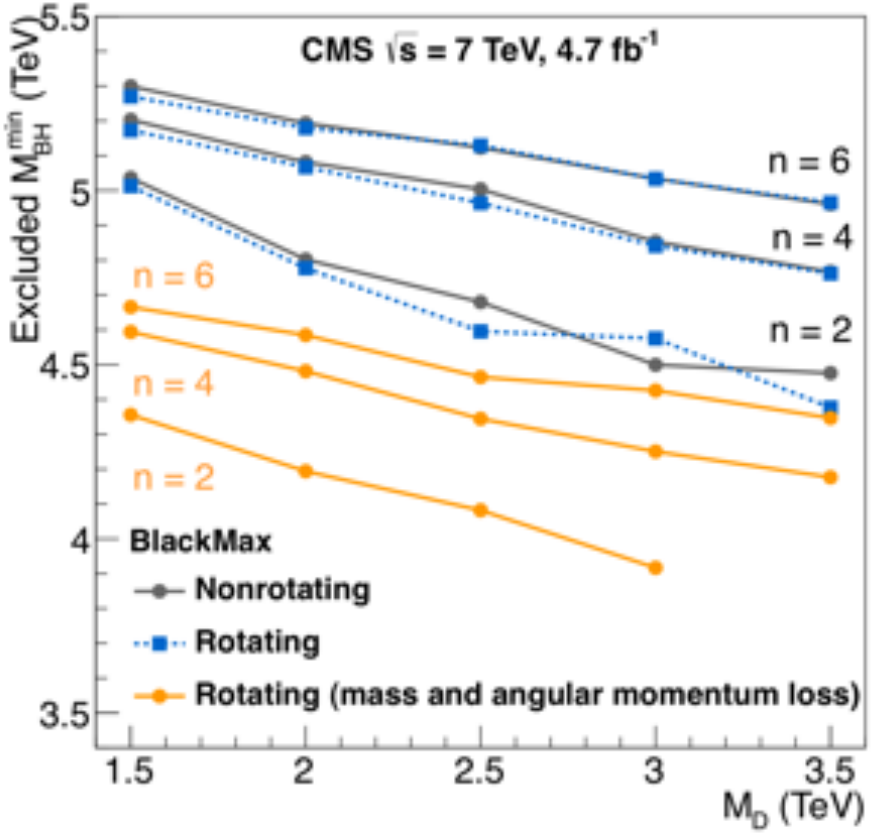

Summary

Photons	ATLAS Collaboration: arXiv:1111.4116v2	UED: 1/R < 1.23 TeV
	CMS Collaboration: SUS-12-001	UED: 1/R < 1.33 TeV
	ATLAS Collaboration: arXiv:1111.2194v2	M_s > 2.27-3.53 TeV ; m{G_{RS}}>1.95 TeV
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	CMS Collaboration: arXiv:1112.0688v1	M_D > 1.59-1.66 TeV; n=3-6
Leptons	CMS Collaboration: arXiv:1202.3827v1	M_S > 2.5 TeV - 3.8 TeV
	ATLAS Collaboration: ATLAS-CONF-2012-007	m{G_{RS}}>2.16 TeV
	ATLAS Collaboration: arXiv:1205.5371v1	500 GeV >m{g_{kk}}>1070 GeV
Jets	ATLAS Collaboration: ATLAS-CONF-2011-096	M_D > 3.2 TeV; n=2
	CMS Collaboration: CMS-PAS-EXO-11-059	M_D > 4.0 TeV; n=2
	ATLAS Collaboration: ATLAS-CONF-2012-038	M_D > 4.11 TeV; n=6
	CMS Collaboration: arXiv:1202.6396v1	m_{BH} > 3.9-5.3 TeV ; n=6; M_D<=4 TeV

Conclusions

- There have been many different searches using varied methods/channels/models
  - Photons/Leptons/Jets
  - ADD/RS/UED
  - Resonances (Bumphunt)/MET/S_T Scaling
- No excesses were observed in any of the searches.
- Limits were set/improved for many ED models.
- ATLAS and CMS limits are in good agreement.

THANK YOU FOR YOUR ATTENTION.