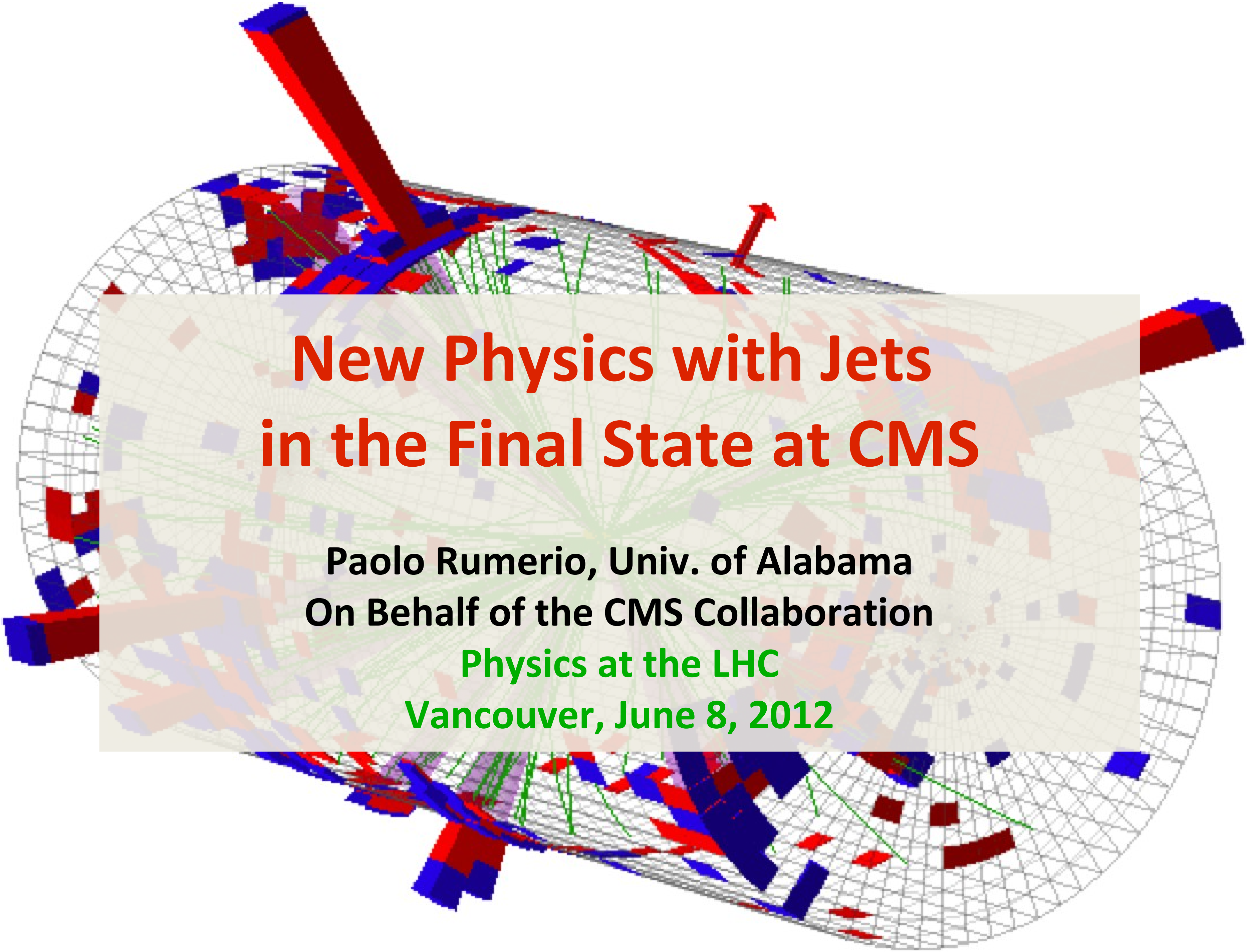


New Physics with Jets in the Final State at CMS

Paolo Rumerio, Univ. of Alabama

On Behalf of the CMS Collaboration

Physics at the LHC

Vancouver, June 8, 2012

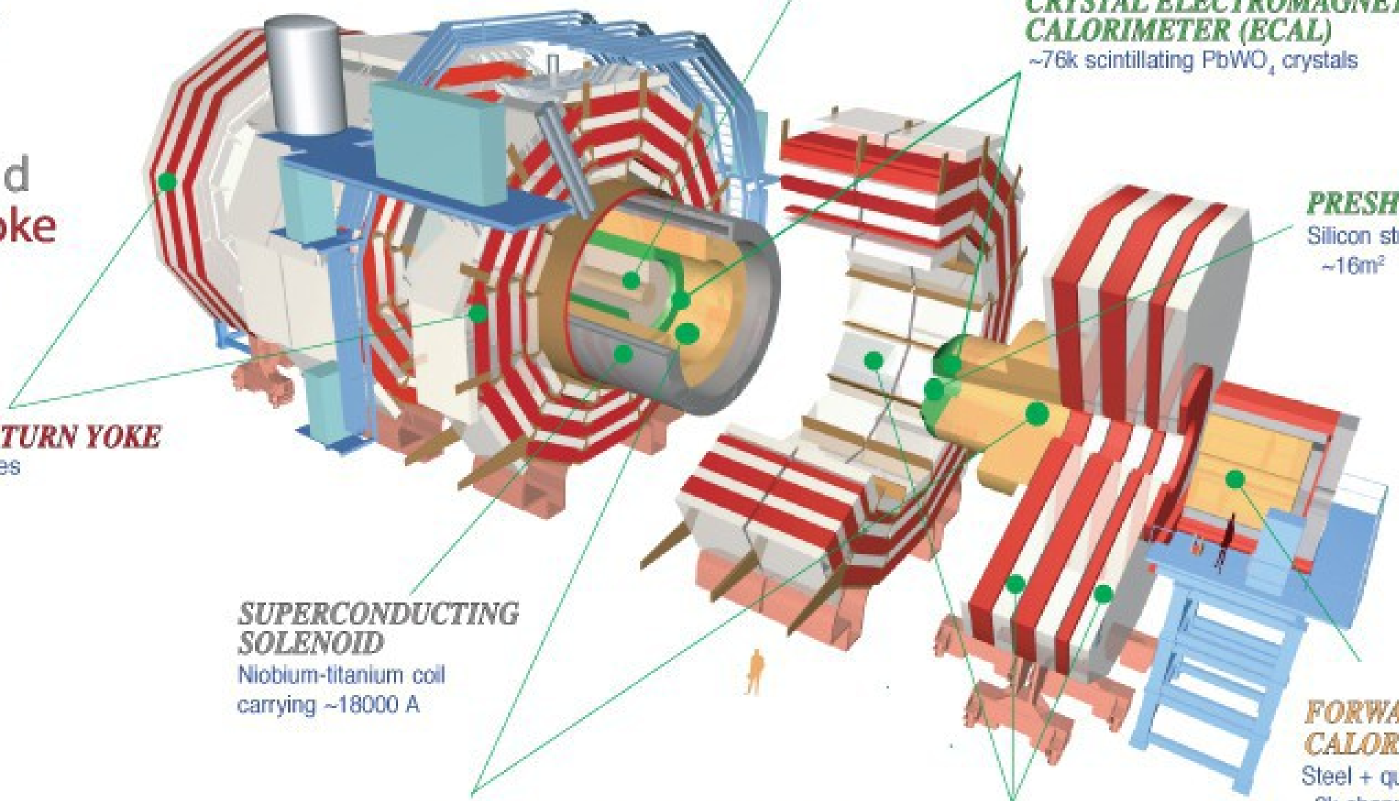
Introduction

- Several BSM searches based on or involving jets and MET have been performed with the 2011 dataset at CMS
  - See Arnd Meyer's talk for lepton-based searches
  - All analyses use the latest techniques refined with the 2011 dataset (dedicated talk by Keti Kaadze on jets and MET).
- Shown here:
  - Highly boosted all-hadronic $t\bar{t}$ (5 fb^{-1})
  - RS Graviton and W' in di-bosons (3 analyses, 4.7 – 5.0 fb^{-1})
  - Black Holes (4.7 fb^{-1})
  - Dark Matter and Large Extra Dimensions (4.7 fb^{-1})
  - Search for three-jet resonances (4.7 fb^{-1})
  - Di-jet resonances (pair produced or using di-jet angular ratio, 2.2 fb^{-1})

  Full list: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

- While the remaining 2011 searches are being finalized/reviewed, the analysis of the 2012 dataset is fully ongoing

The CMS Detector



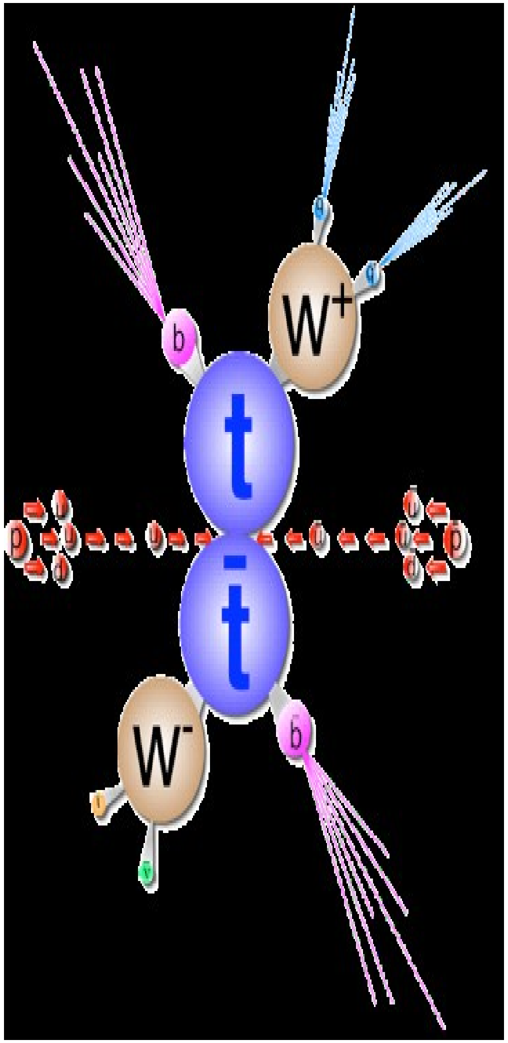
Total weight : **14000 tonnes**
Overall diameter : **15.0 m**
Overall length : **28.7 m**
Magnetic field : **3.8 T**

$t\bar{t}$ Production in Highly Boosted All-Hadronic Final States (EXO-11-006)

arXiv:1204.2488

Boosted $t\bar{t}$

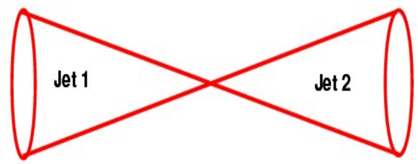
- New physics scenarios often involve enhanced $t\bar{t}$ production at high inv. mass
  - Topcolor Z' and Kaluza-Klein Gluon
  - Models propose enhanced $t\bar{t}$ cross section to resolve the anomalous forward-backward asymmetry measured at the Tevatron
- 46% of $t\bar{t}$ production decays into 3+3 jets
- Due to t and $\bar{t}$ boost, decay products merge
  - Look at jet substructure to recover this phase space
  - Jet reconstruction: Cambridge-Aachen algorithm with R=0.8 – last algo steps reversed to study sub-jet characteristics



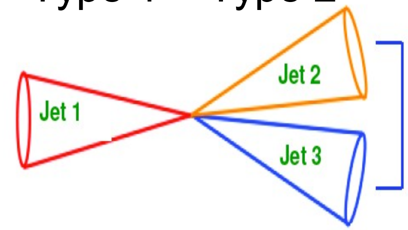
Boosted $t\bar{t}$

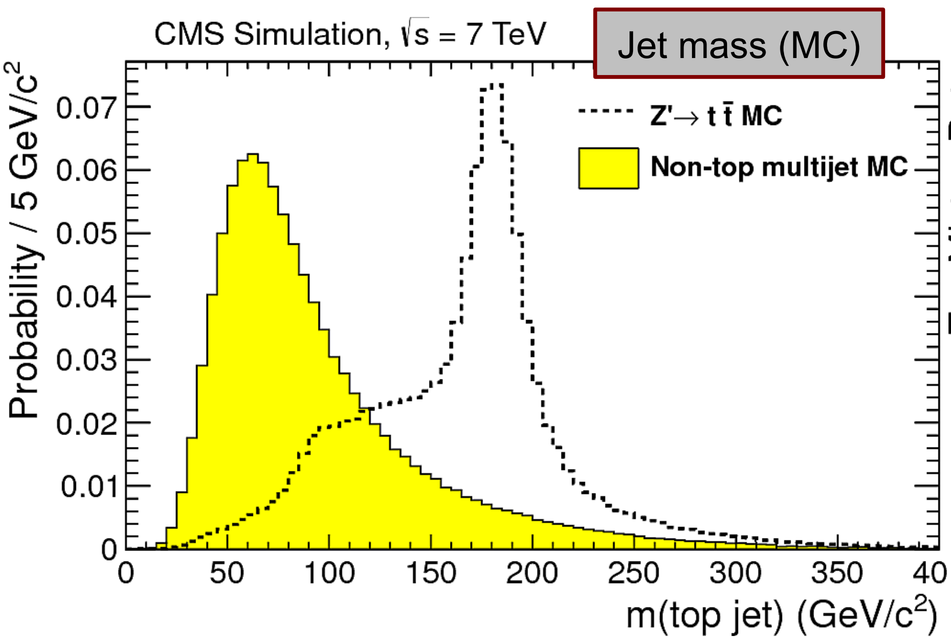
- Type 1: fully merged jet with 3 sub-jets
- Type 2: two jets, one with 2 sub-jets
- Top-tag ($140 < m_{jet} < 250$ GeV) applied to Type 1 and Type 2
- W-tag ($60 < m_{jet} < 100$ GeV and cut on 'mass-drop') applied to the jet with 2 sub-jets in Type 2

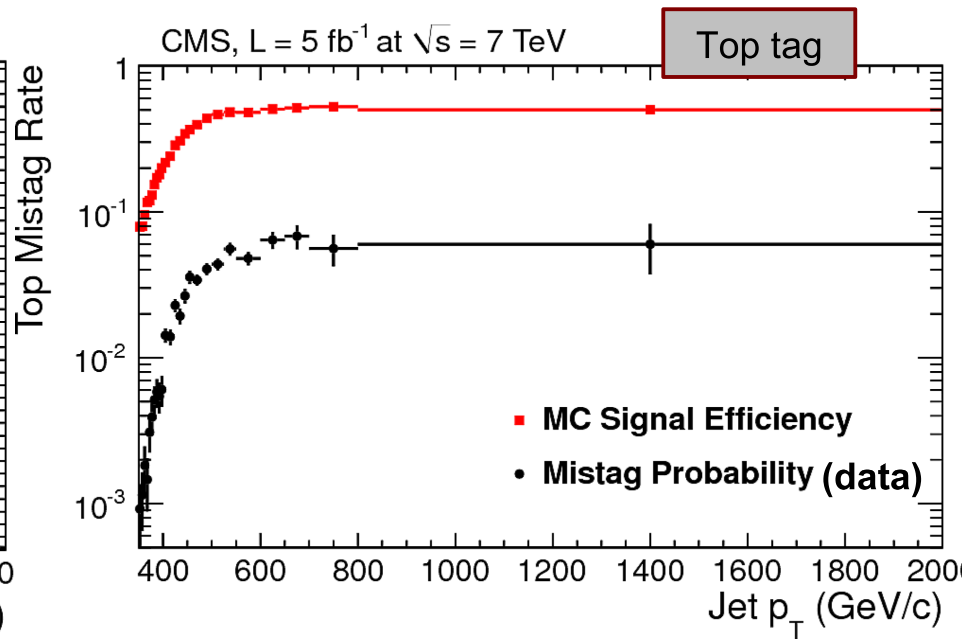
Type 1 + Type 1



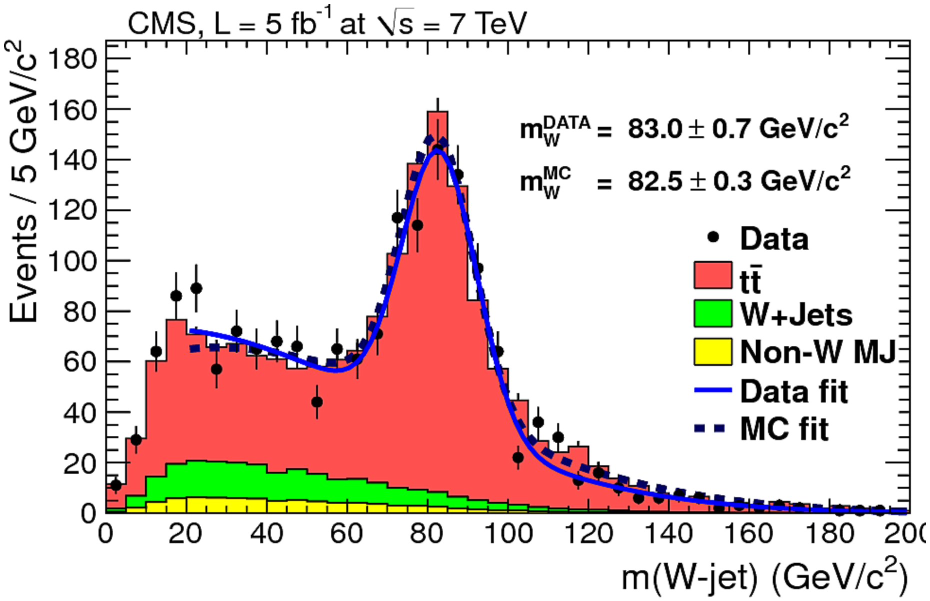
Type 1 + Type 2

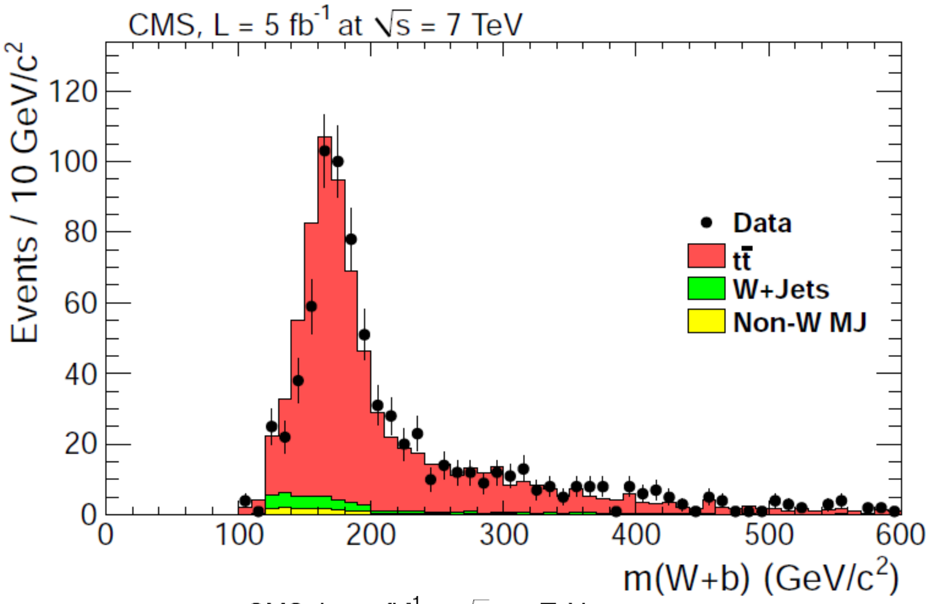




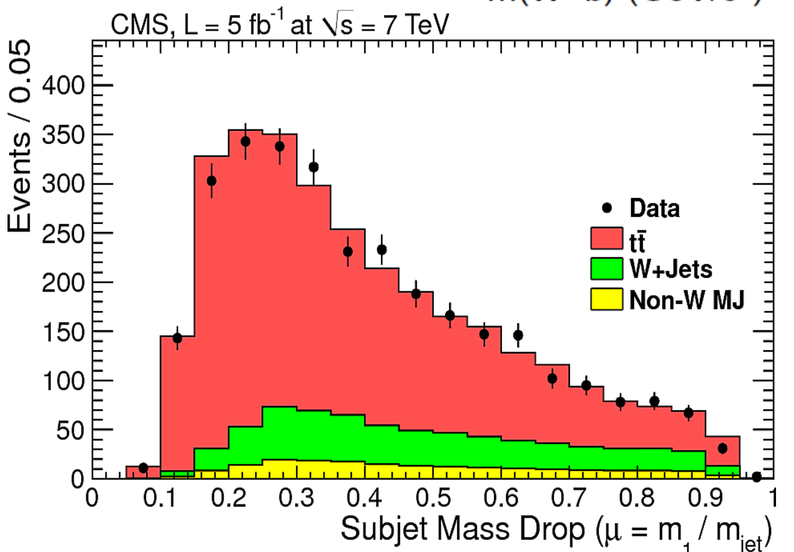


Boosted $t\bar{t}$

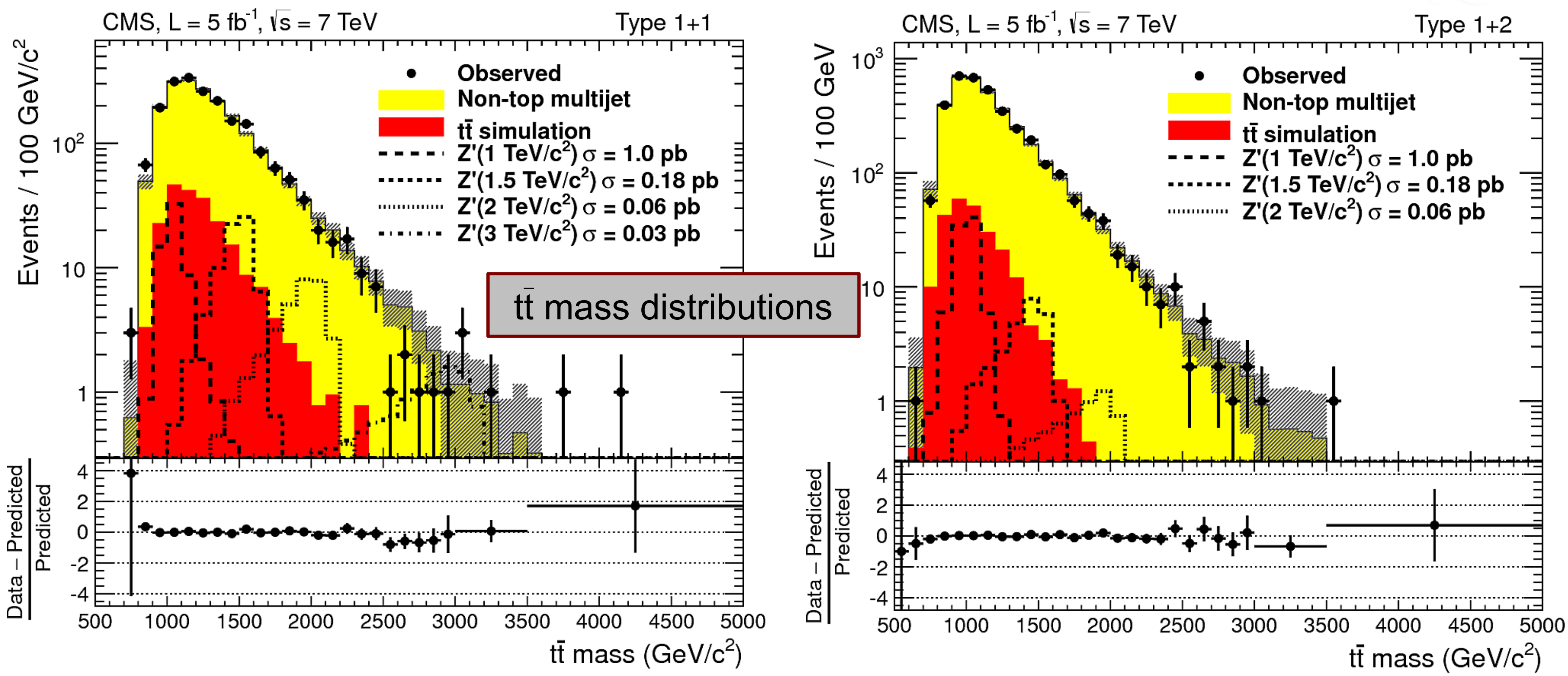




- Type 2 candidates:
  - W-jet mass (top-left)
  - W+b mass (top-right)
  - Mass drop variable (bottom-right), used in the W-jet tagging and defined as the mass of the highest mass sub-jet divided by the mass of the jet



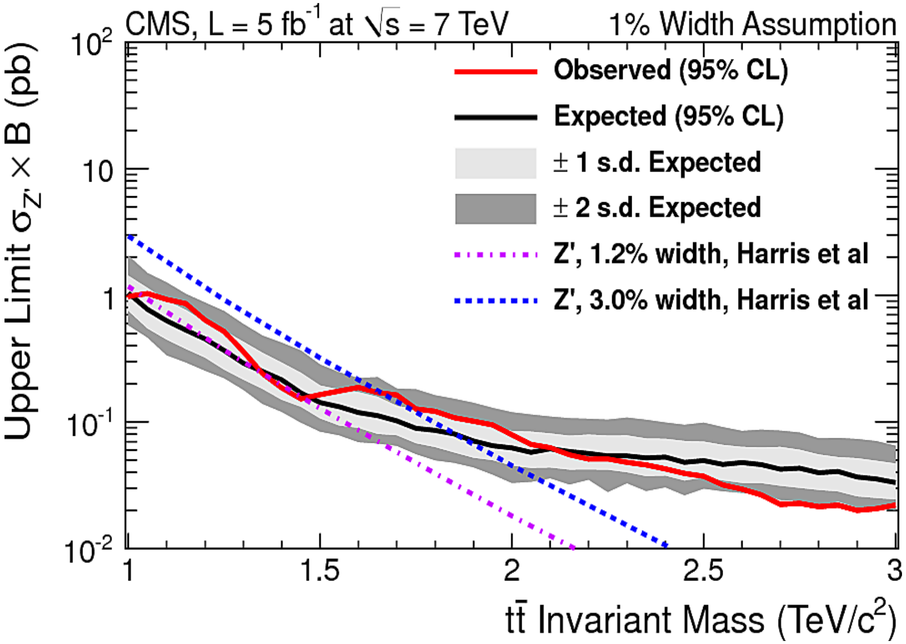
Boosted $t\bar{t}$

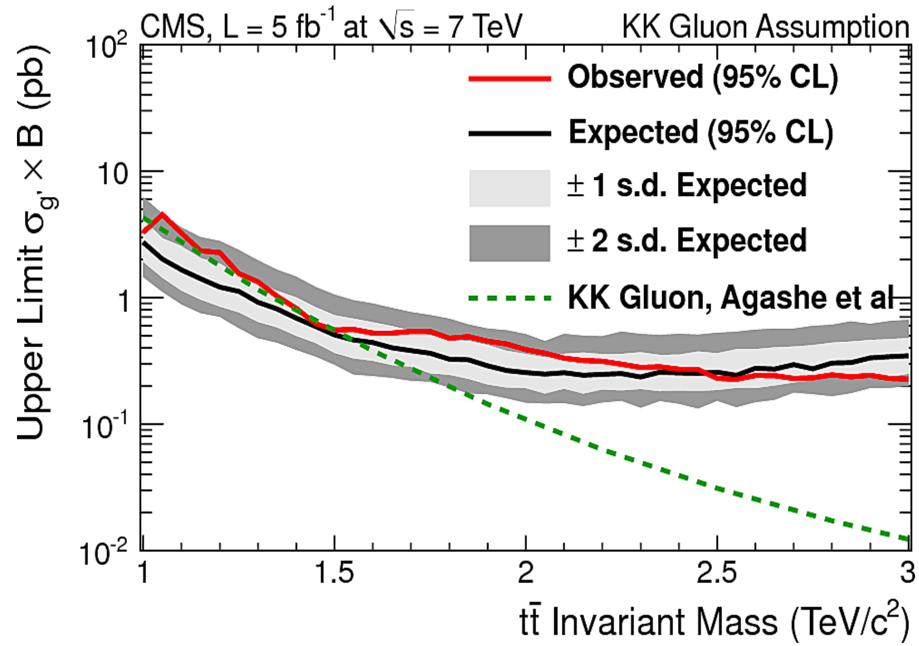


	$m_{t\bar{t}}$ =0.9–1.1 TeV/c^2 1+1	$m_{t\bar{t}}$ =0.9–1.1 TeV/c^2 1+2	$m_{t\bar{t}}$ =1.3–2.4 TeV/c^2 1+1	$m_{t\bar{t}}$ =1.3–2.4 TeV/c^2 1+2
Expected SM $t\bar{t}$ events	69 ± 36	110 ± 62	65 ± 42	24 ± 15
Expected non-top multijet events	443 ± 23	1239 ± 32	741 ± 32	817 ± 38
Total expected events	512 ± 43	1349 ± 70	806 ± 53	841 ± 41
Observed events	506	1383	809	841

Boosted $t\bar{t}$

- Likelihood fit to $t\bar{t}$ mass distribution
- 95% CL limit on σ x B.R. Extracted using CLs method





- Topcolor Z' excluded between masses of: 1.3-1.5 TeV for 1% width
  1.0-1.6 TeV for 3% width
  1.0-2.0 TeV for 10% width
- Randall-Sundrum Kaluza-Klein gluon excluded in 1.4-1.5 TeV and small region close to 1 TeV
- Counting technique poses a <2.6 limit on possible cross section enhancement w.r.t SM expectation for $t\bar{t}$ mass > 1 TeV (a priori most probable value is 2.5)

Search for Randall-Sundrum Gravitons

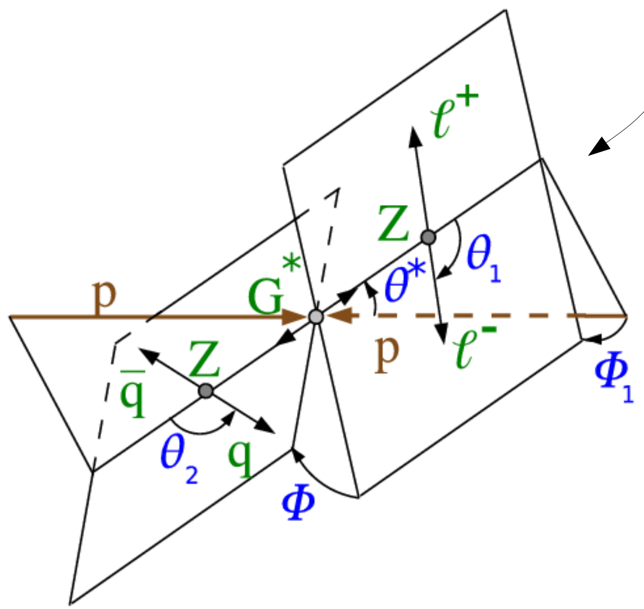
$G^* \rightarrow ZZ \rightarrow q\bar{q}\nu\bar{\nu}$ (EXO-11-061)

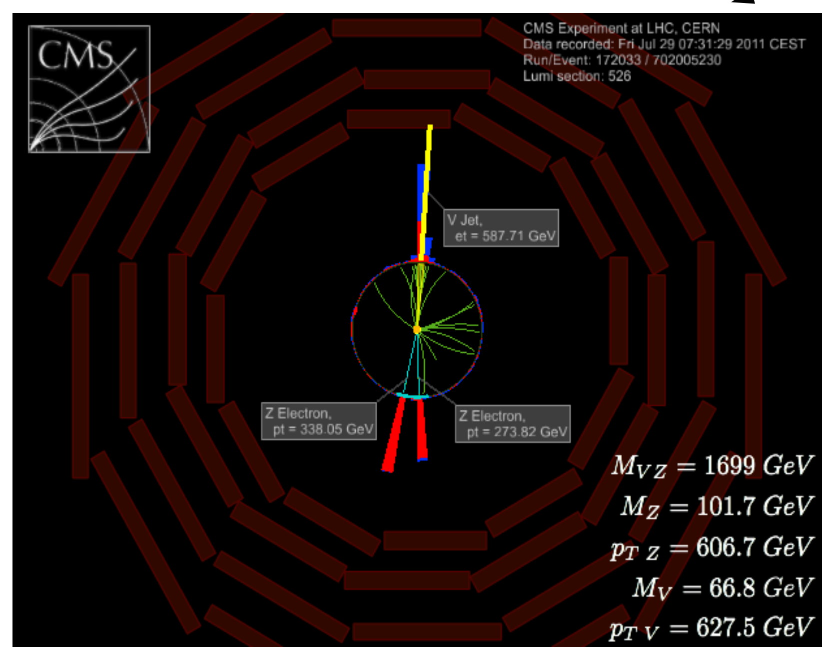
$G^*/W' \rightarrow VZ \rightarrow q\bar{q}ll$ (EXO-11-081)

$G^* \rightarrow ZZ \rightarrow q\bar{q}ll$ (EXO-11-102)

RS Graviton

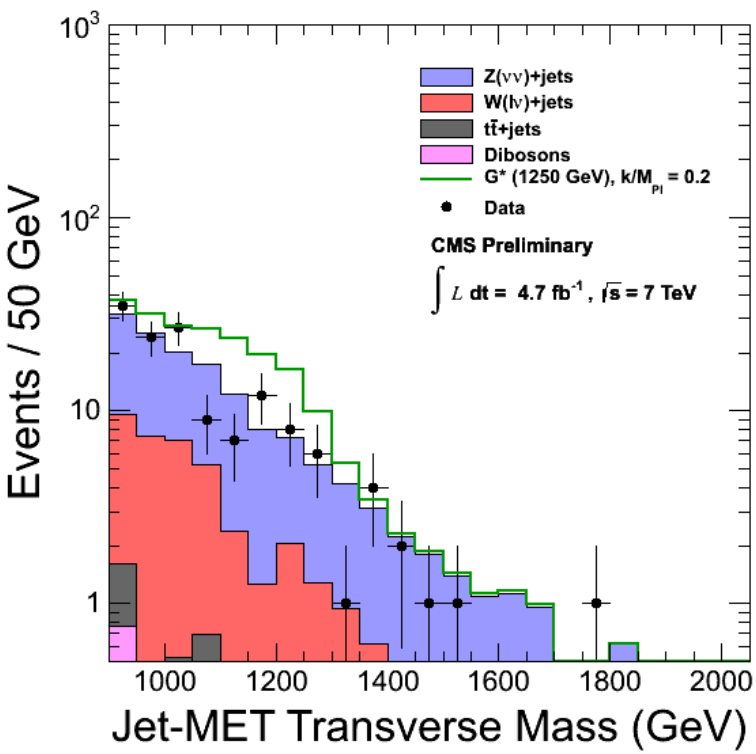
- Warped Extra Dimension to solve hierarchy problem
  - Leads to a Kaluza-Klein tower of states, k/M_{Pl} = coupling parameter
- To be detected as massive, universally coupled, spin-2 resonances
  - $G^* \to ZZ \to q\bar{q}\nu\bar{\nu}$ (with $q\bar{q}$ merged in a single jet)
  - $G^*/W' \to VZ \to q\bar{q}ll$ (with $q\bar{q}$ merged in a single jet)
  - $G^* \to ZZ \to q\bar{q}ll$ (uses angular spin correlations to discriminate S and B)

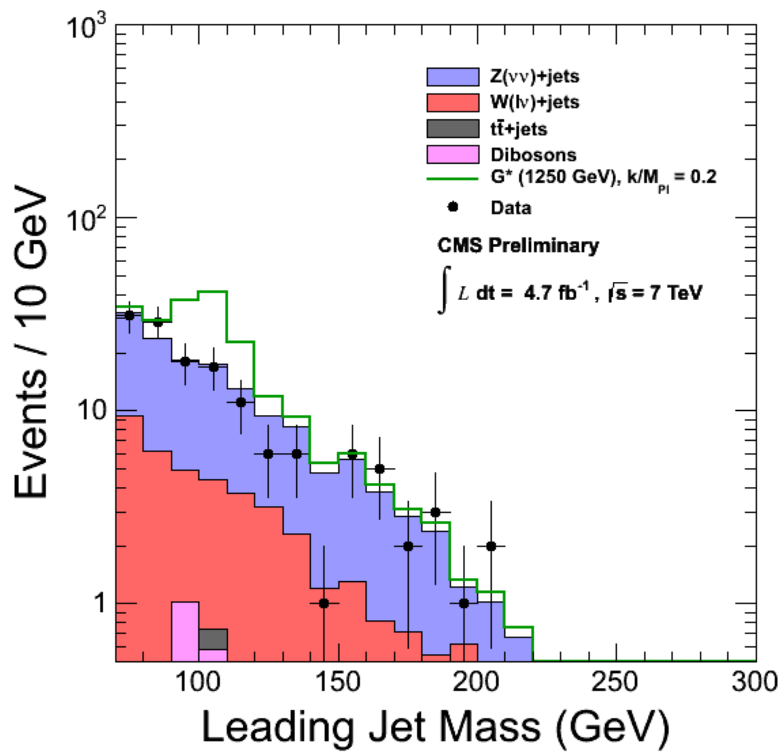




RS G* → ZZ → jet+MET

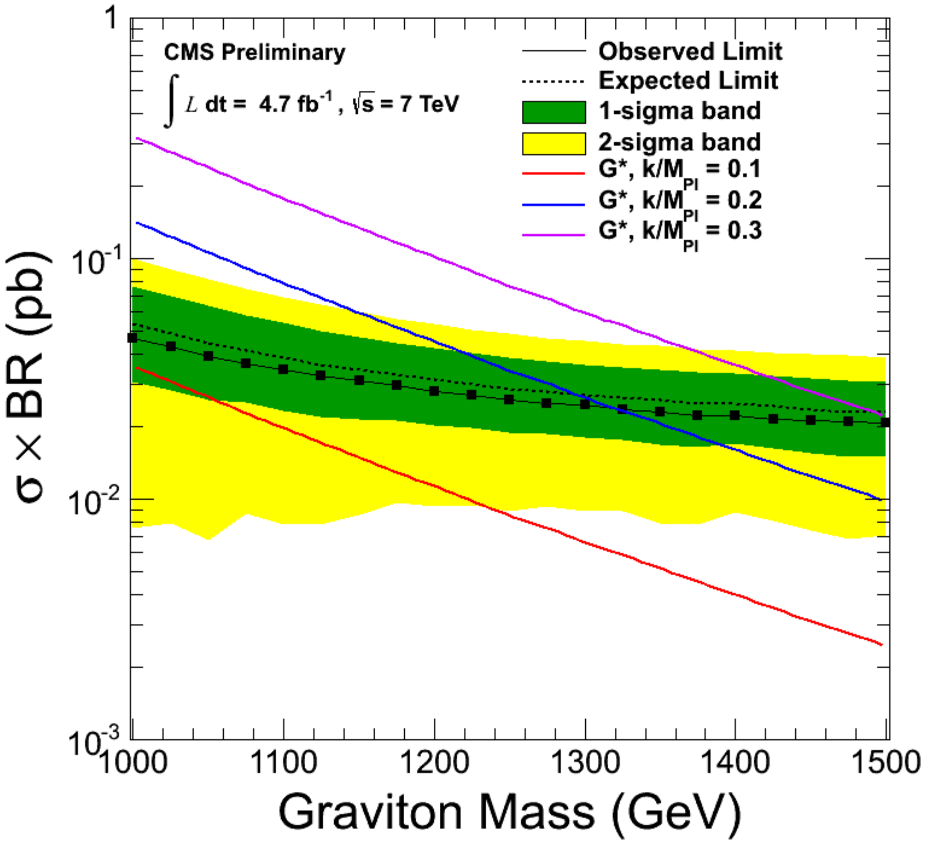
- Jet algo: anti-kT with cone size R=0.7
- Main selection: jet p_T and MET >300 GeV; m_{jet}>70 GeV; M_T(jet,MET)>900 GeV; no more than 2 jets pT>30 GeV (2-jet evts kept if $\Delta\varphi$<2.8); no isolated leptons.
- Bkg determined from data side bands in m_{jet} vs M_T(jet,MET) ('ABCD' method)
- SM background estimate = 153±29 events; observed in data = 138 events

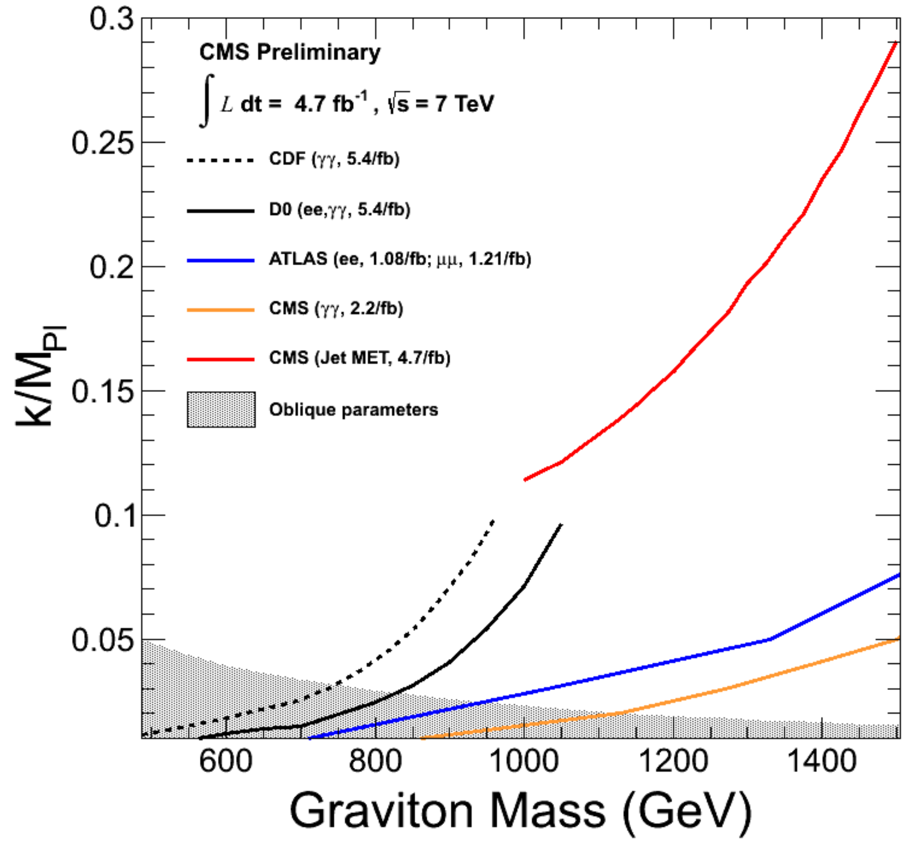




RS G* → ZZ → jet+MET

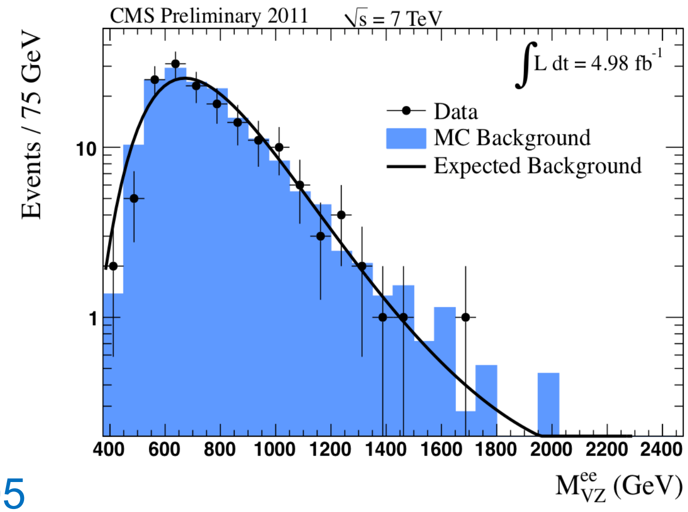
- Likelihood fit performed on signal and side bands regions of m_{jet} vs M_T(jet,MET)
- Upper limit on σ x BR set using CLs method
- RS Graviton excluded in mass range of 1.0-1.5 TeV for k/M_{Pl} above [0.11, 0.29]

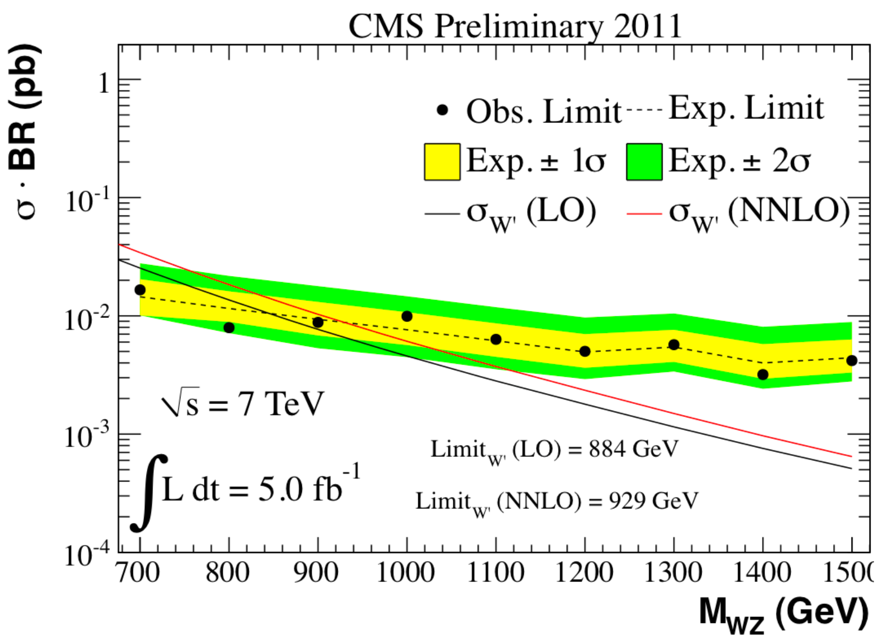


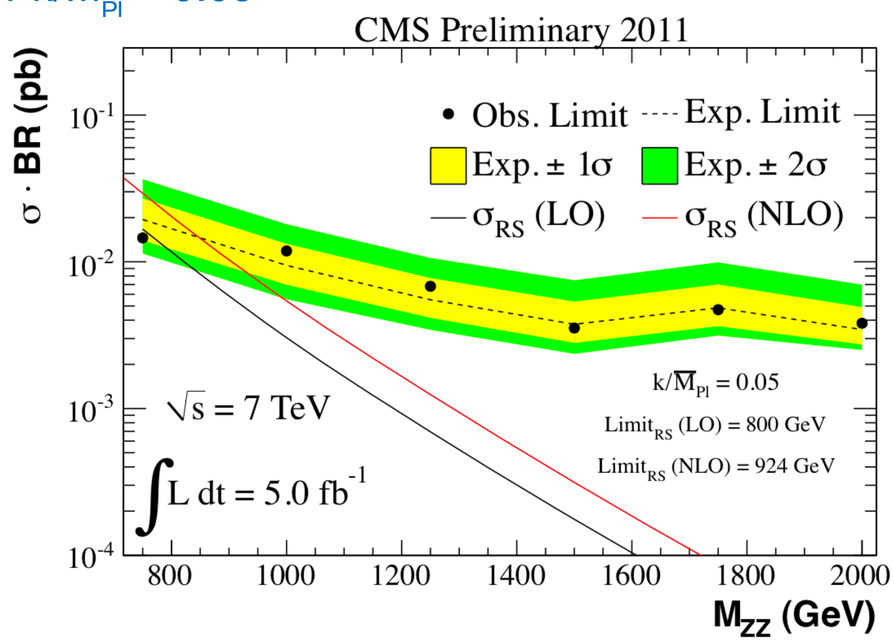


$G^*/W' \to VZ \to q\bar{q}ll$

- Heavy Resonance assumption: boosted decay products
  - $q\bar{q}$ merged into a single jet → $65 < m_{jet} < 120$ GeV
  - Leptons (ee or μμ) with small opening angle → care in applying isolation
- Dominant bkg is Z+jets, then tt → determined from data in side band $30 < m_{jet} < 65$ GeV
- W'_{SSM} excluded between 700 and 929 GeV
- RS Graviton excluded between 700 and 924 for $k/\overline{M}_{Pl} = 0.05$

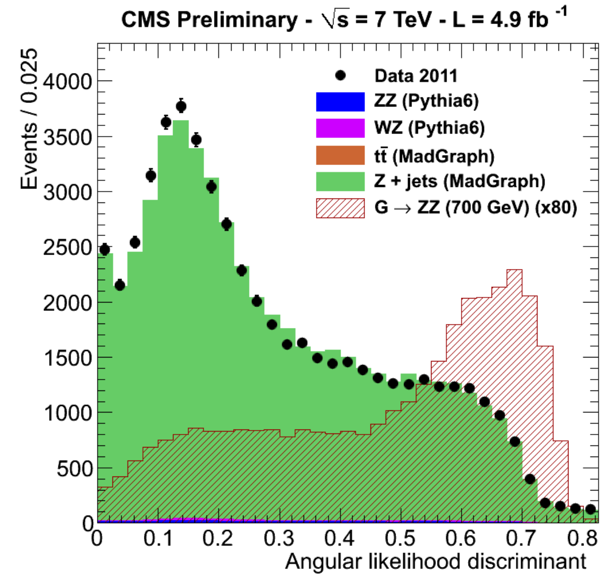


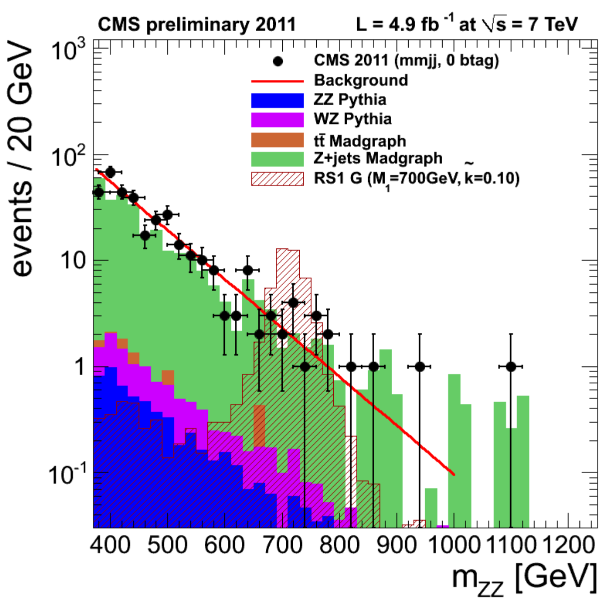


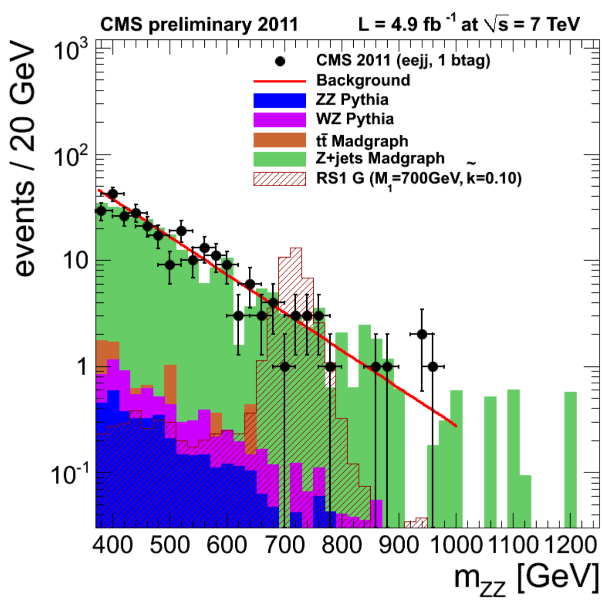


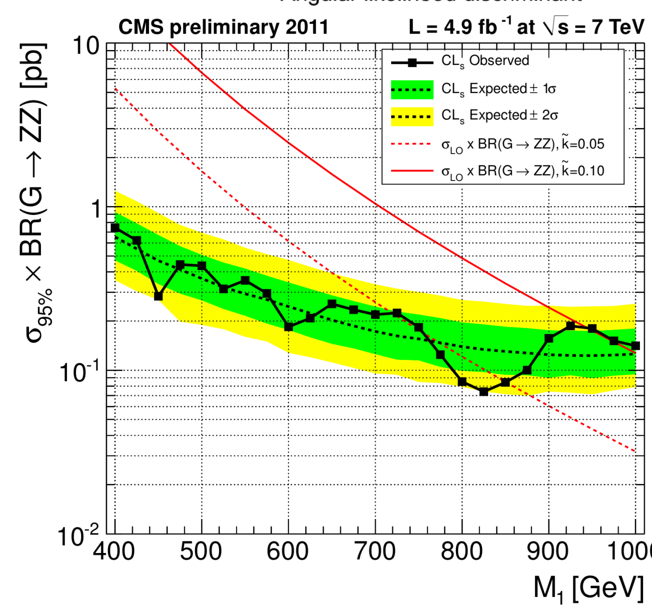
RS G* → ZZ → $q\bar{q}ll$

- Explores the M_{ZZ} region between 400 and 1000 GeV
- Uses angular likelihood discriminant to suppress bkg
- Events categorized according to 0, 1, 2 b-tagged jets
- Di-jet and di-lepton masses consistent with Z
- Jet kinematics corrected by fitting imposing $m_{jj}=m_Z$
- Excluded Gravitons with mass $M_1 < 945$ GeV for $\tilde{k}=0.1$, and $M_1 < 720$ GeV and $760 < M_1 < 850$ GeV for $\tilde{k}=0.05$







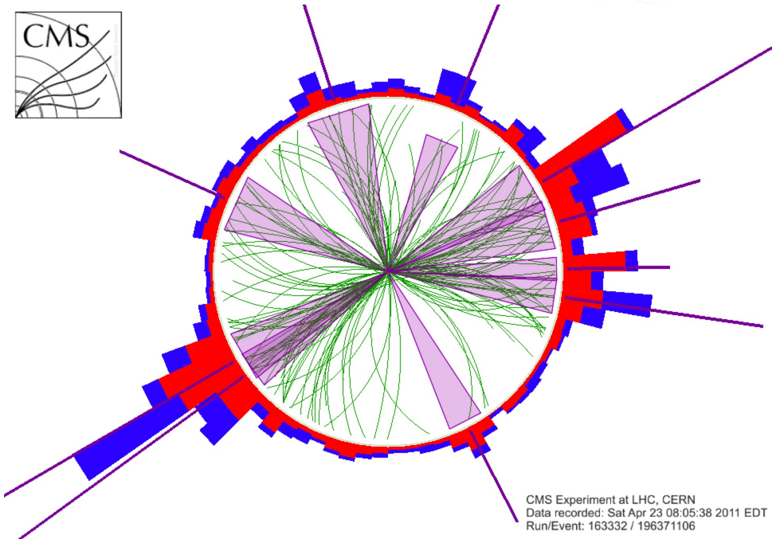


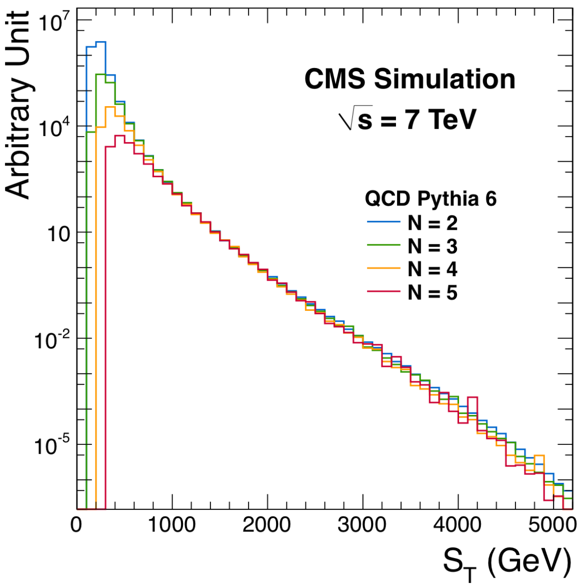
Search for Microscopic Black Holes
(EXO-11-071)

10.1007/JHEP04(2012)061

Black Holes

- ADD model proposed to solve the hierarchy problem:
  - By introducing n large, flat, extra spatial dimensions
  - Scale for new physics given in terms of multi-dim Planck scale M_D
- One prediction is the formation of microscopic Black Holes
  - Spectacular signature with large number (N) of energetic particles (75% jets, 25% W/Z/γ/leptons)
- Selection requires $S_T = \sum p_T$ of jets, γ's, l's + MET above a 50 GeV threshold
- Dominant background at high S_T is QCD multijet production
  - Determined from data exploiting the empirically observed S_T multiplicity invariance



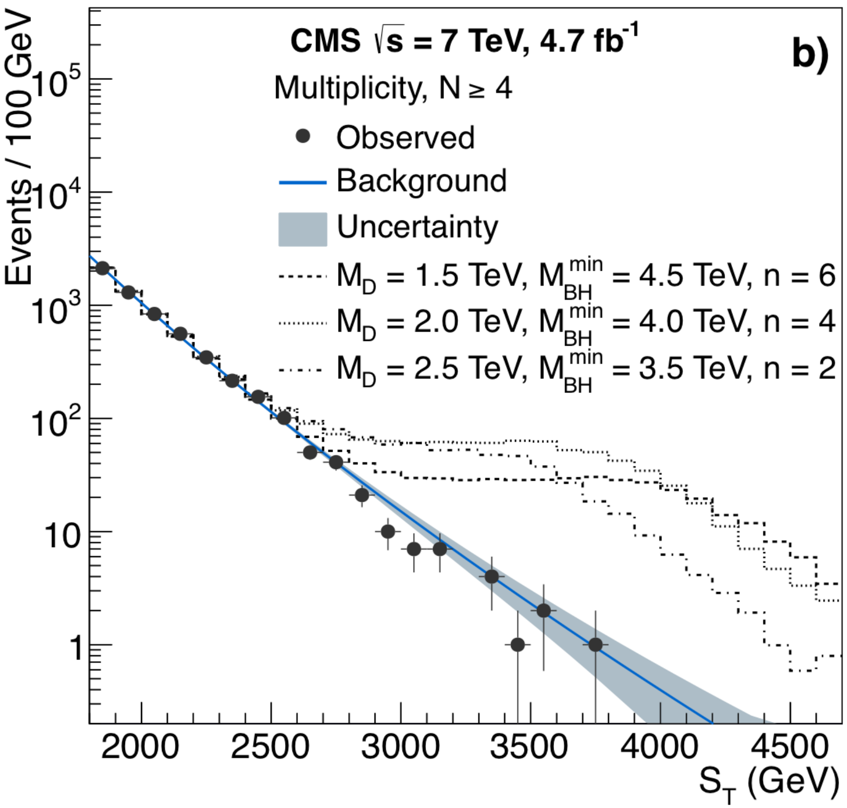


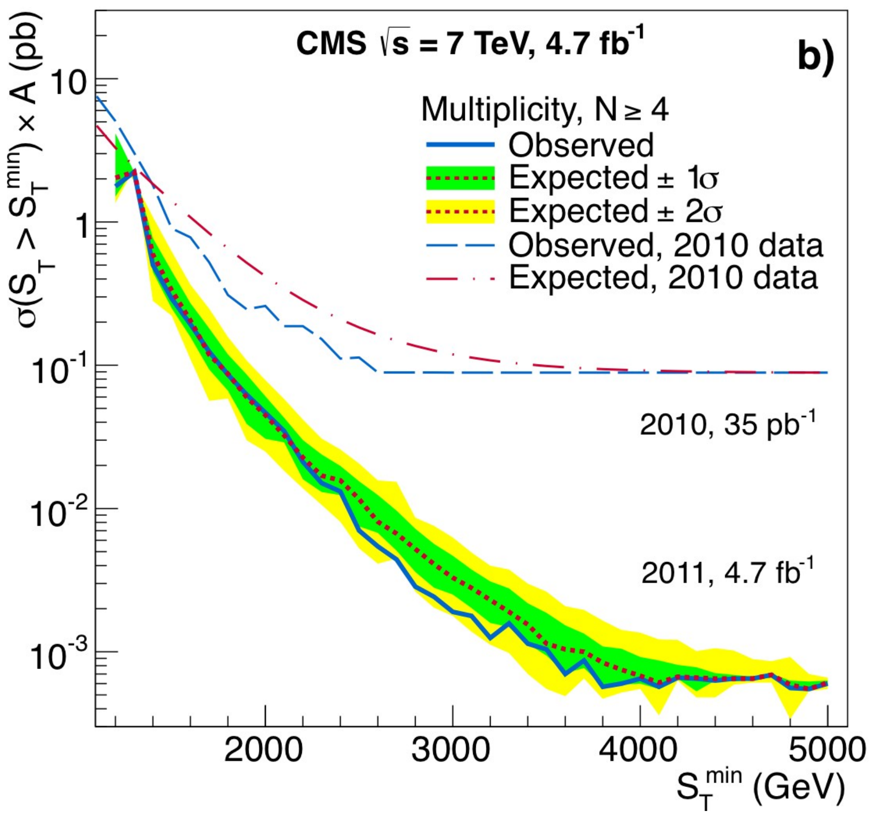
Black Holes

- Total transverse energy (S_T) distribution for multiplicity N ≥ 4 events, and expected semiclassical BH signals

- Model-independent 95% CL limits (CLs method) on N ≥ 4 cross section for $S_T > S_T^{min}$ versus S_T^{min} (limits provided for N ≥ 3,4,5,6,7,8)

new

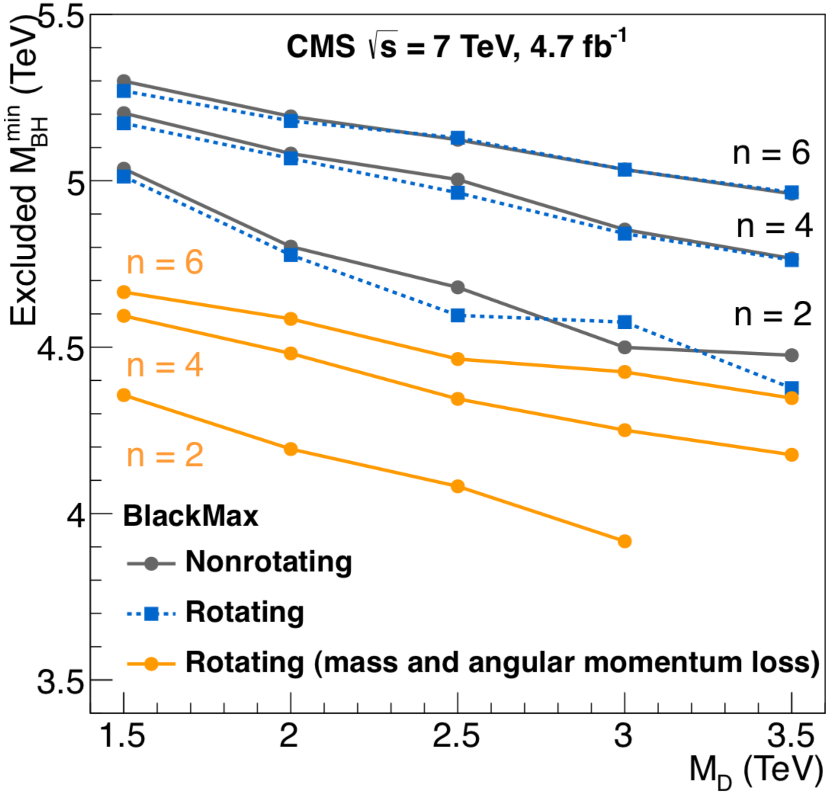




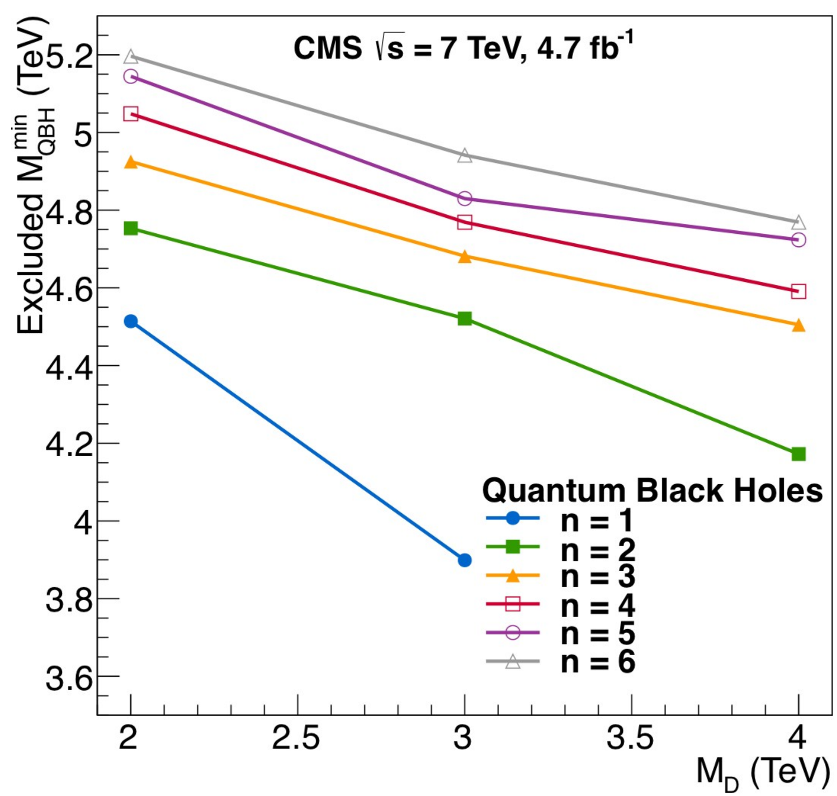
Black Holes

- Limits are set on specific subsets of the probed models using optimized S_T and N selections. For example:

Minimum BH mass excluded at 95% CL vs. reduced Planck scale M_D for n=2,4,6



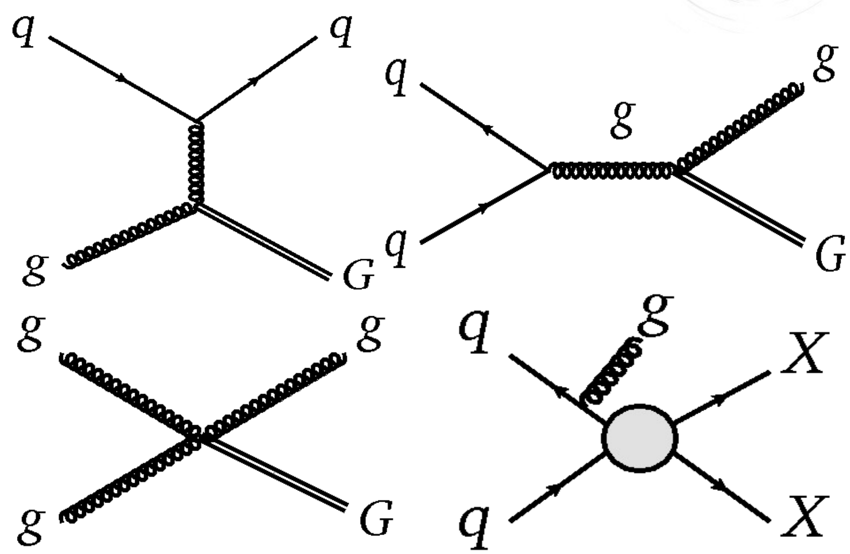
Minimum Quantum BH mass excluded at 95% CL vs. reduced Planck scale M_D for n=1 (RS model) and n=2-6 (ADD model)

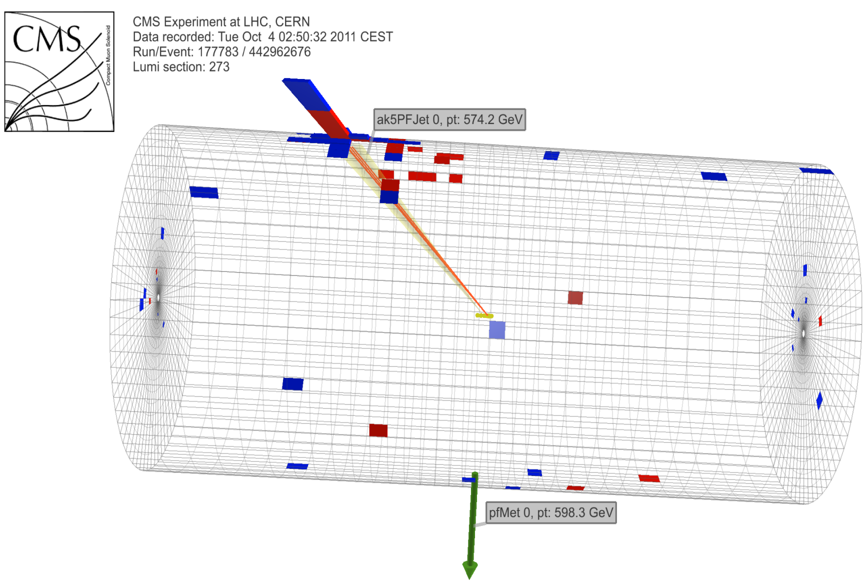


Dark Matter and Large Extra Dimensions in Monojet Events (EXO-11-059)

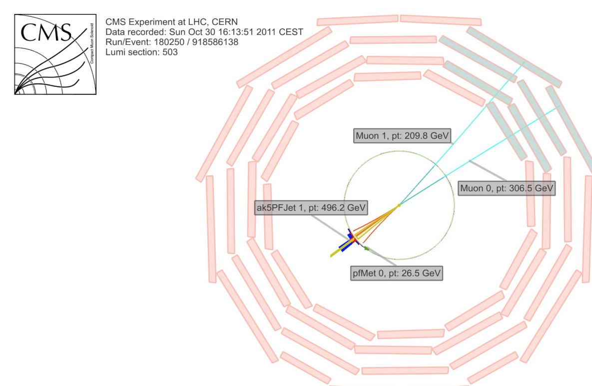
DM and LED

- A monojet + MET signature arises in
  - Large Extra Dimenstions (LED) of ADD model → G escapes in extra dim. space
  - Dark Matter interaction with SM mediated by very heavy particles
- Selection: jet (anti-k_T R=0.5) p_T > 110 GeV; MET > 350 GeV; ≤2 jets pT>30 GeV (2-jet evts kept if Δφ<2.5); no isolated leptons.

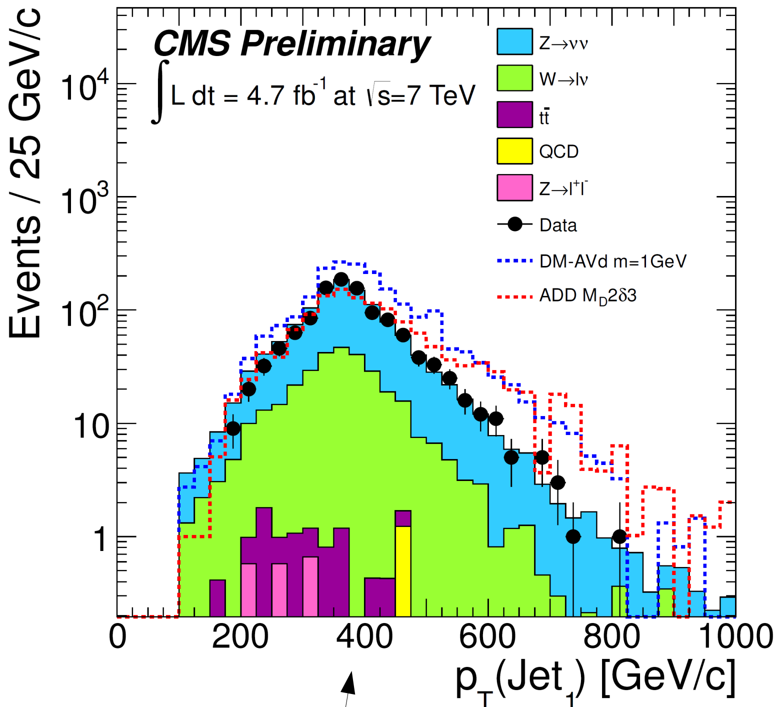


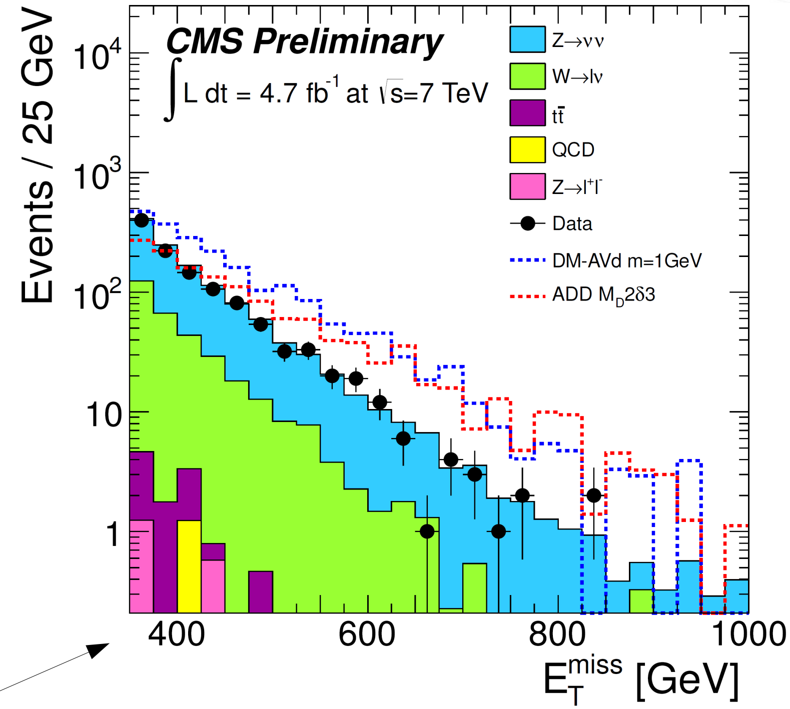


- Main backgrounds: Z(→νν)+jets and W+jets – determined from data using Z(→μμ)+jets and W(→μν)+jets



DM and LED

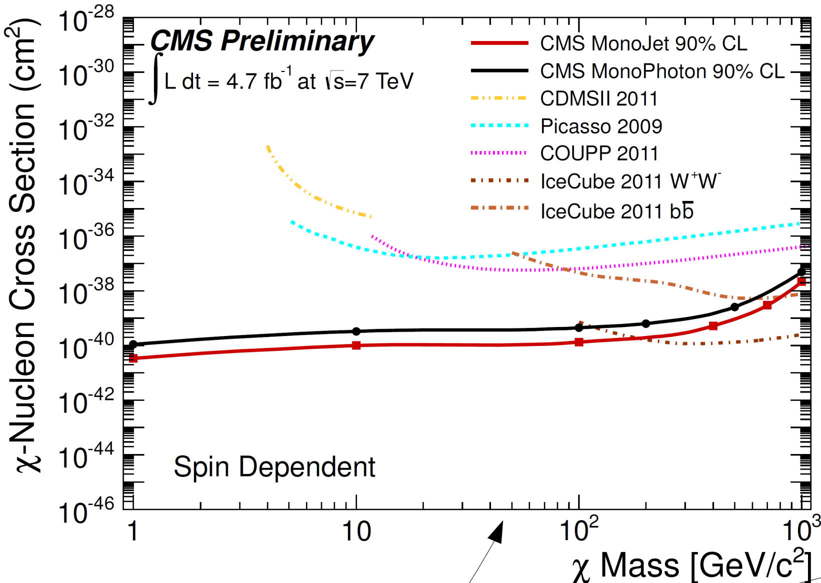


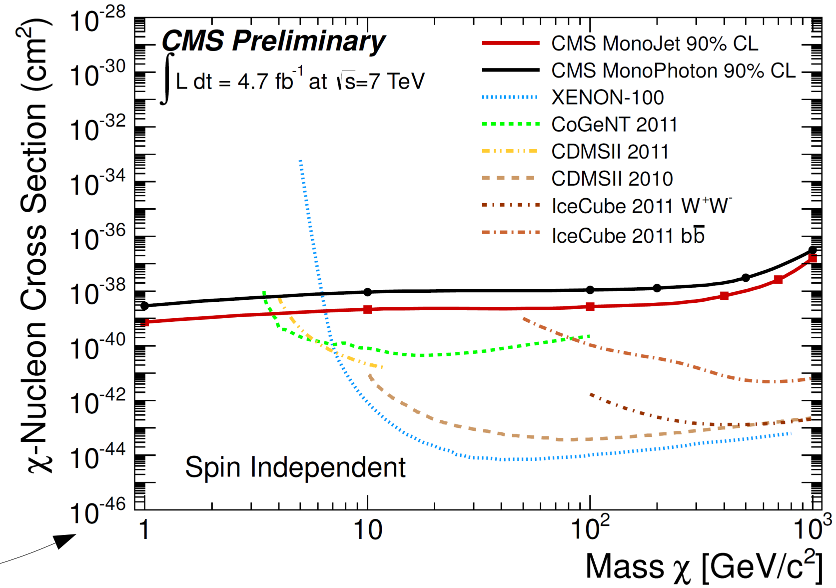


Background process	Events
$Z \to \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142

- P_T leading jet and MET distributions after final event selection
- SM background prediction and comparison with data

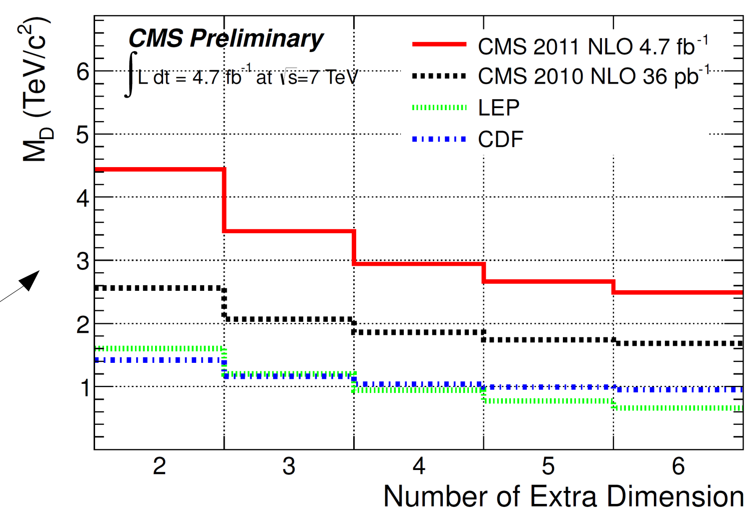
DM and LED





- 90% CL upper limits on dark matter-nucleon cross section for spin dependent and spin independent models – and comparison with direct detection limits

- 95% CL lower limits on fundamental mass scale M_D of ADD model versus number of extra dimensions

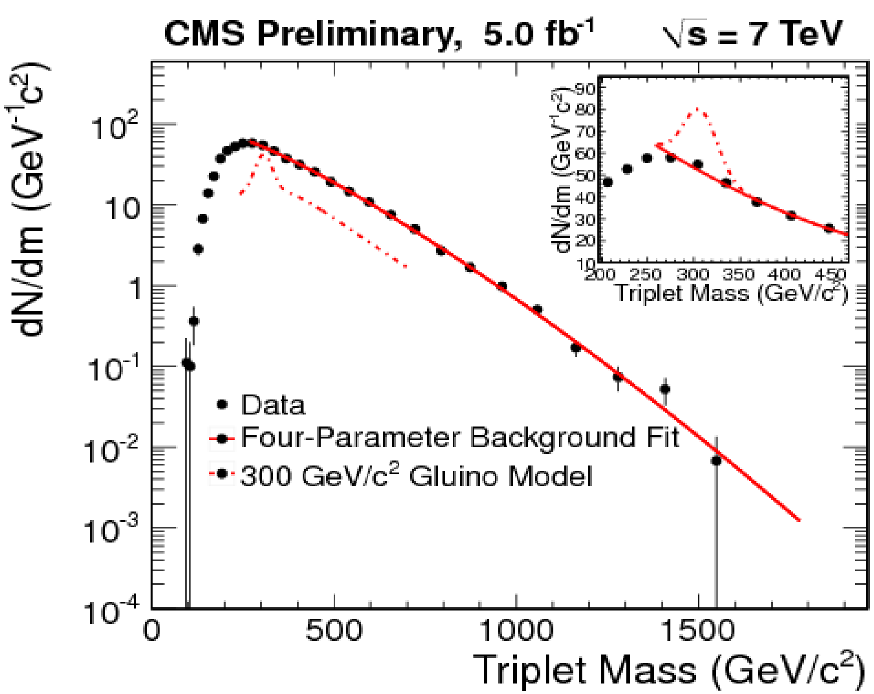


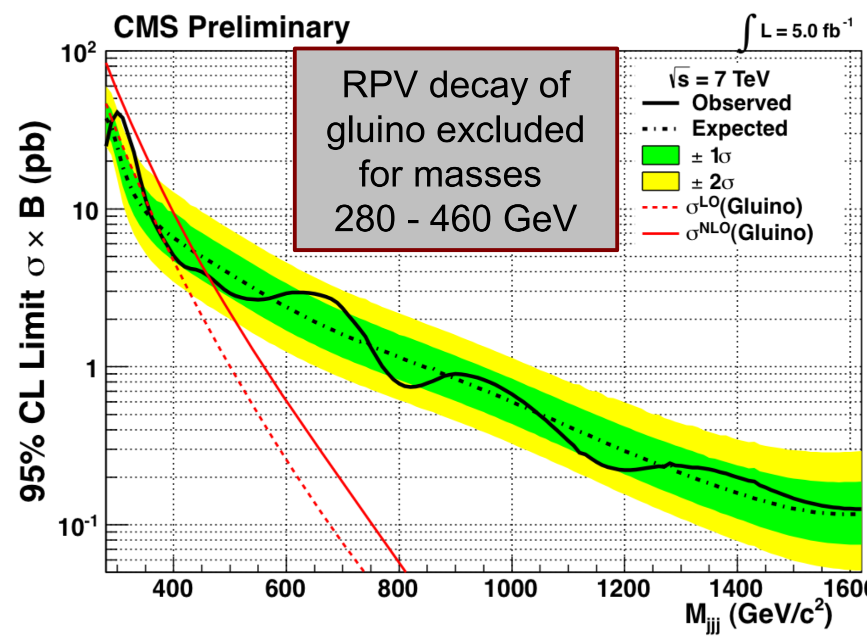
Search for Three-Jet Resonances (EXO-11-060)

Three-Jet Resonances

- Various extensions of SM predict resonances that decay into multi-jet states:
  - Heavy colored fermions
  - RPV decay of SUSY gluinos
- Benchmark model: gluino pair production, each decaying into 3 jets
- Jet ensemble technique used to select jet-triplet combinations out of 6 selected high-pT jets
  - Large signal combinatoric and SM multijet background
- Triplet mass distribution fit to functional form + a gaussian
- $$\frac{d\sigma}{dM_{jjj}} = \frac{P_0(1 - M_{jjj}/\sqrt{s})^{P_1}}{(M_{jjj}/\sqrt{s})^{P_2+P_3 \ln(M_{jjj}/\sqrt{s})}}$$

  to set ... ction





Searches for:

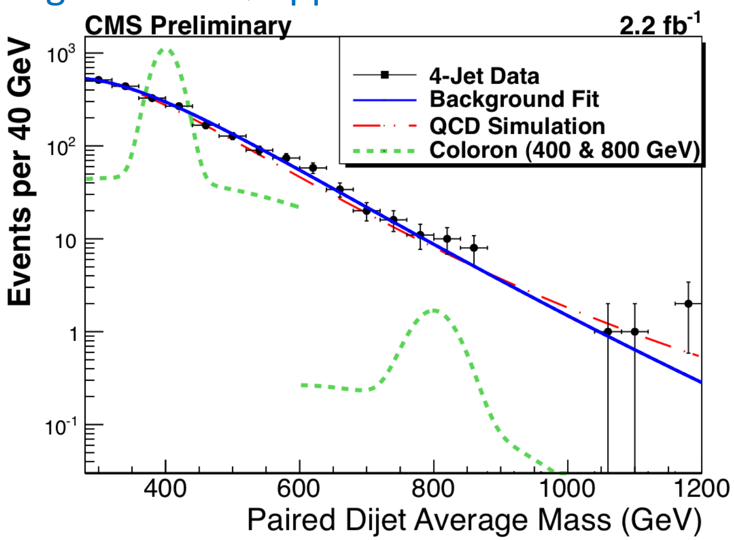
Pair-Produced Di-Jet Resonances (EXO-11-016, 2.2 fb^{-1})

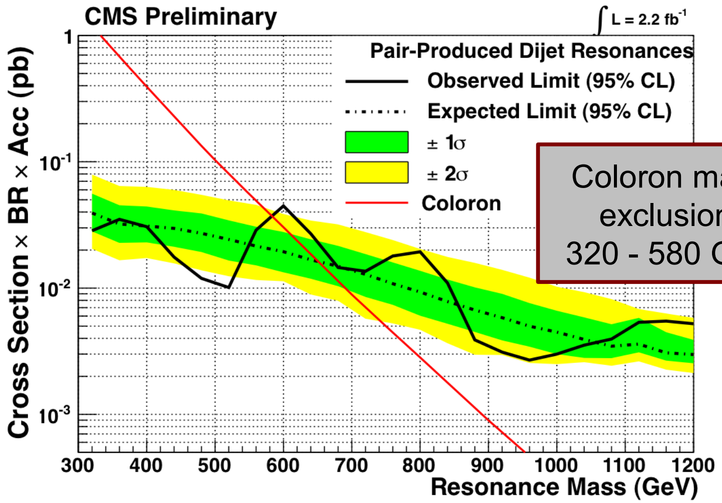
Di-Jet Resonances using Di-Jet Angular Ratio (EXO-11-026, 2.2 fb^{-1})

Di-Jet Resonance Searches (2.2 fb^{-1})

Pair-Produced di-jet resonances

– e.g. coloron → $q\bar{q}$

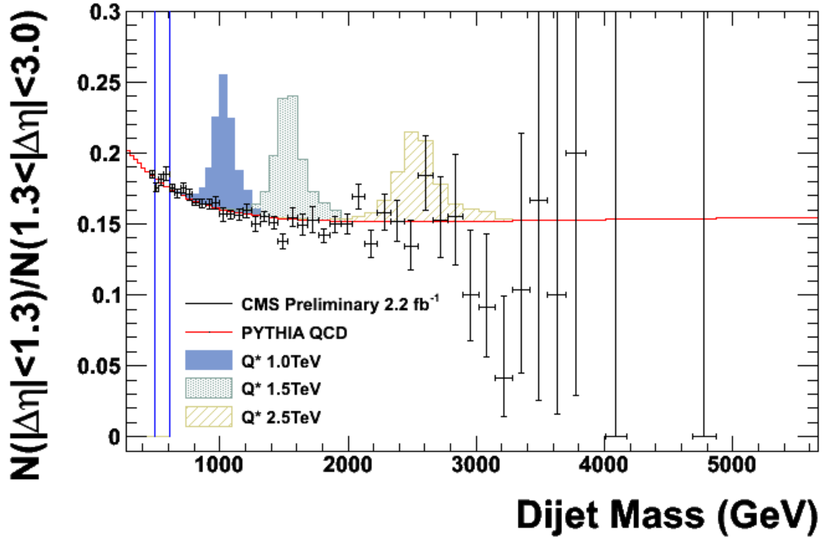


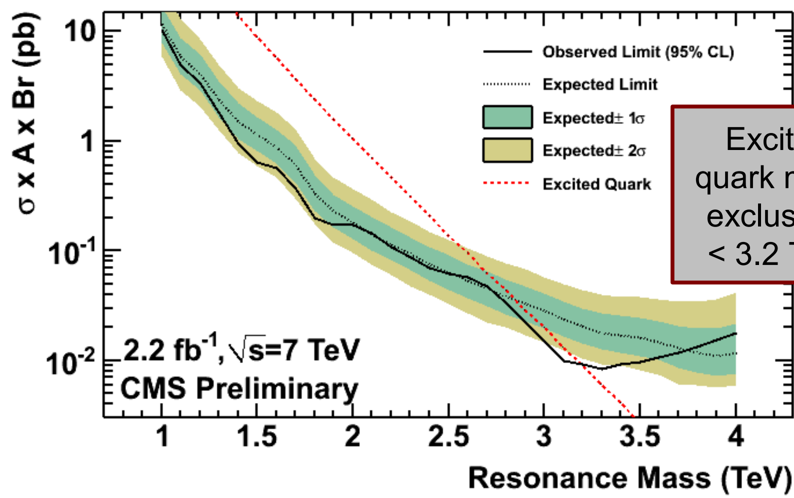


Coloron mass exclusion 320 - 580 GeV

Di-jet resonances using Δη ratio distrib.

– e.g. excited quarks → qg





Excited quark mass exclusion < 3.2 TeV

Conclusions

- Analyses based on jets and MET play an important role in searches for new physics
  - New techniques (e.g. jet substructure) are being used with remarkable results
  - Methods to deal with high pileup have proved to be effective

- The impressive performances of accelerator and experiment are making possible to continuously extend the range of the searches
  - The data has reserved no surprises so far

- The search continues with the closing of the 2011 effort and – full steam – with the analysis of the 2012 dataset

BACKUP

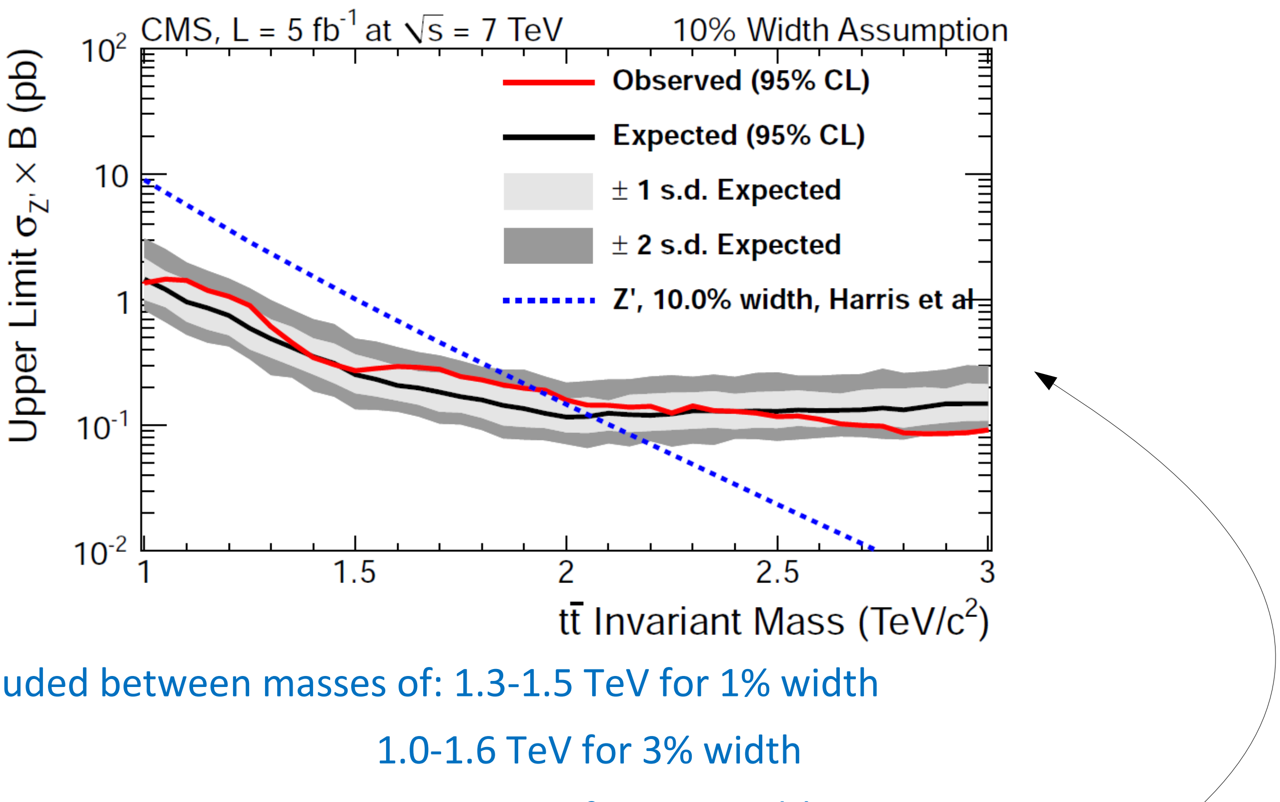
Boosted $t\bar{t}$ - Systematics

Table 3: Summary of relative systematic uncertainties on signal efficiency for two $t\bar{t}$ mass windows. All values are in percent. The central value of the subjet selection scale factor is 0.94, it is the only scale factor that has a non-unit mean.

Source	Variation	$m_{t\bar{t}}$ =0.9–1.1 TeV/c^2		$m_{t\bar{t}}$ =1.3–2.4 TeV/c^2	
		1+1	1+2	1+1	1+2
MC Statistical		2.0	1.6	0.7	1.6
Trigger	See text	13	20	<1	3
Jet energy scale	$\approx \pm 5$	19	19	2	2
Subjet efficiency scale factor	± 6	6	6	6	6
Luminosity	± 2.2	2.2	2.2	2.2	2.2
Total		24	28	7	8

Boosted $t\bar{t}$

- Likelihood fit to $t\bar{t}$ mass distribution
- 95% CL limit on σ x B.R. Extracted using CLs method



- Topcolor Z' excluded between masses of: 1.3-1.5 TeV for 1% width

  1.0-1.6 TeV for 3% width

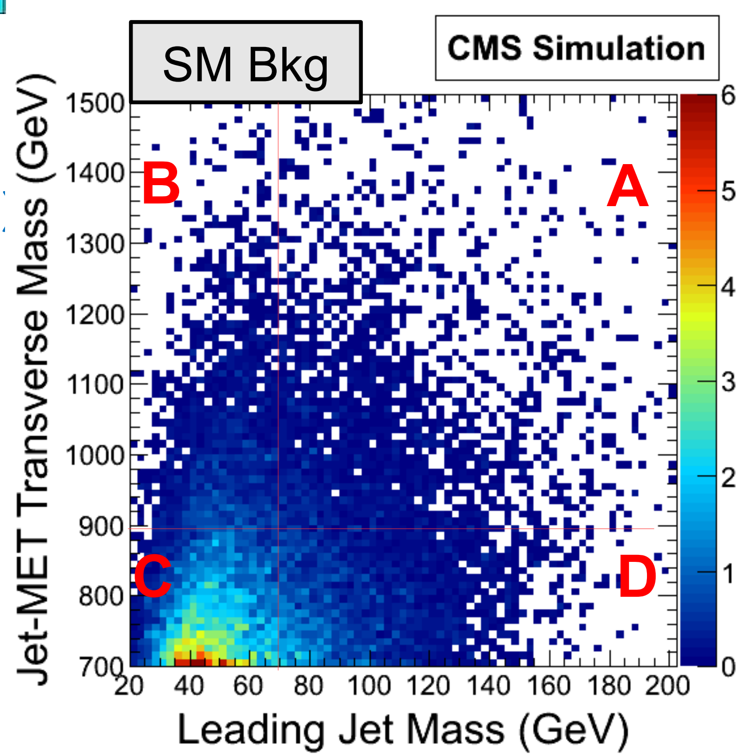
  1.0-2.0 TeV for 10% width
- Randall-Sundrum Kaluza-Klein gluon excluded in 1.4-1.5 TeV and small region close to 1 TeV
- Counting technique poses a <2.6 limit on possible cross section enhancement w.r.t SM expectationfor $t\bar{t}$ mass > 1 TeV (a priori most probable value is 2.5)

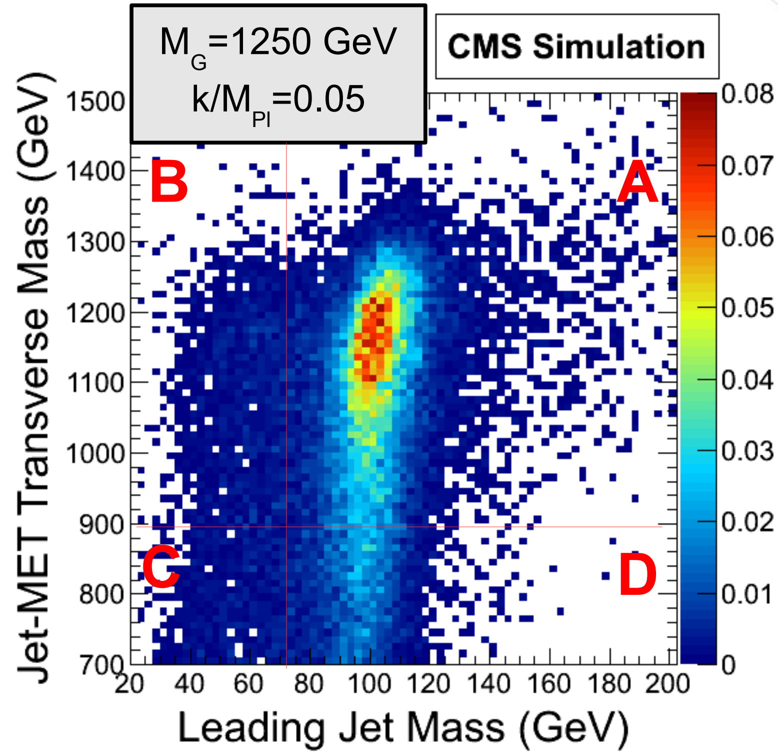
Boosted $t\bar{t}$ – Results

Table 4: Expected number of events with $m_{t\bar{t}} > 1\,\mathrm{TeV}/c^2$ from SM $t\bar{t}$ and non-top multijet backgrounds, along with their total, compared to the observed number of events. The efficiency for SM $t\bar{t}$ production, which is used in the limit setting procedure described in the text, is shown on the final line.

	1+1	1+2
Expected SM $t\bar{t}$ events	194 ± 106	129 ± 80
Expected non-top multijet events	1546 ± 45	2271 ± 130
Total expected events	1740 ± 115	2400 ± 153
Observed events	1738	2423
$t\bar{t}$ efficiency	$(2.5 \pm 1.3) \times 10^{-4}$	$(1.6 \pm 1.0) \times 10^{-4}$

RS G* → jet+MET





Yield	Run2011 Data	SM Prediction	Ratio
N_A	138	131 ± 3	1.05 ± 0.02
N_B	125	125 ± 3	1.00 ± 0.03
N_C	542	579 ± 7	0.94 ± 0.01
N_D	283	259 ± 5	1.09 ± 0.02

$$B_{est} = N_D \cdot \frac{N_B}{N_C} \cdot \frac{1}{\rho}$$

$$\rho_{MC} = 0.42 \pm 0.06 \text{ stat.} \pm 0.02 \text{ syst.}$$

RS G* → jet+MET

Table 1: Signal selection efficiency as function of the graviton mass M_G.

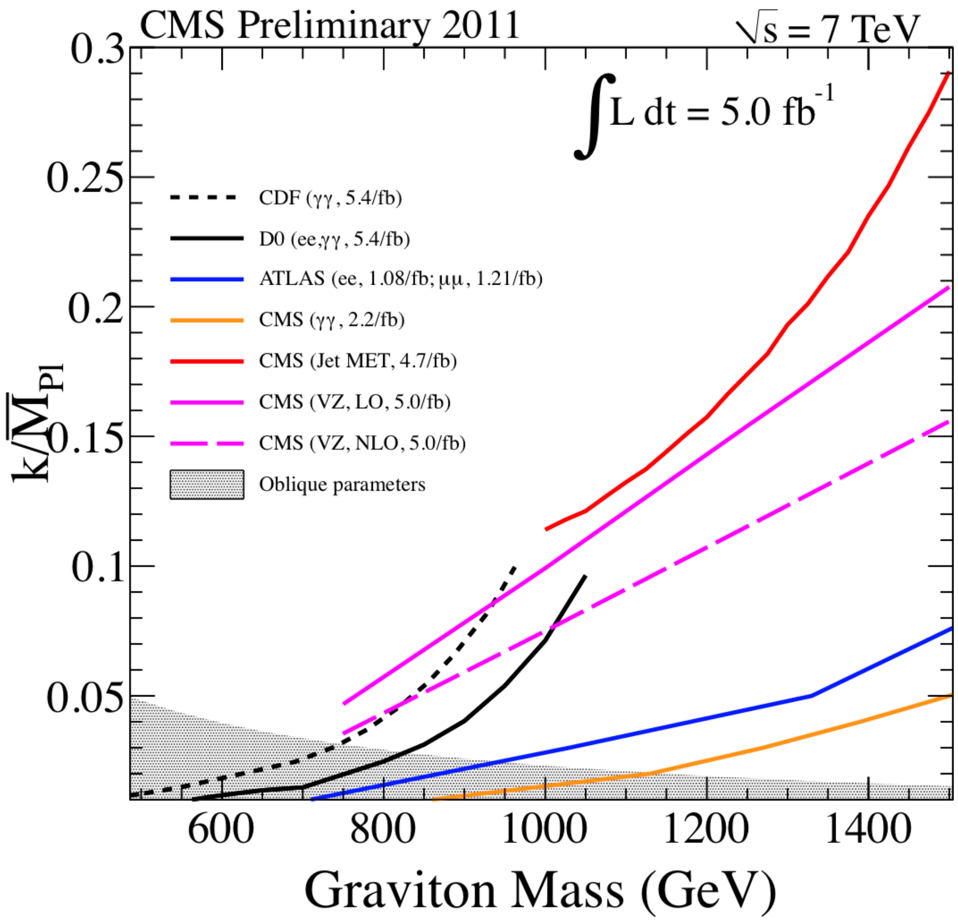
M_G (GeV)	Efficiency	Eff. Uncertainty
1000	0.22	0.02
1250	0.46	0.02
1500	0.56	0.03
1750	0.58	0.03
2000	0.63	0.03

Table 3: Systematic uncertainties in the signal efficiency, for the graviton mass range $M_G = [1000, 2000]$ GeV.

M_G	PDF	JES	MET	Total
1000 GeV	4%	7%	7%	10%
1250 GeV	4%	1%	3%	5%
1500 GeV	4%	1%	3%	5%
1750 GeV	4%	1%	3%	5%
2000 GeV	4%	1%	3%	5%

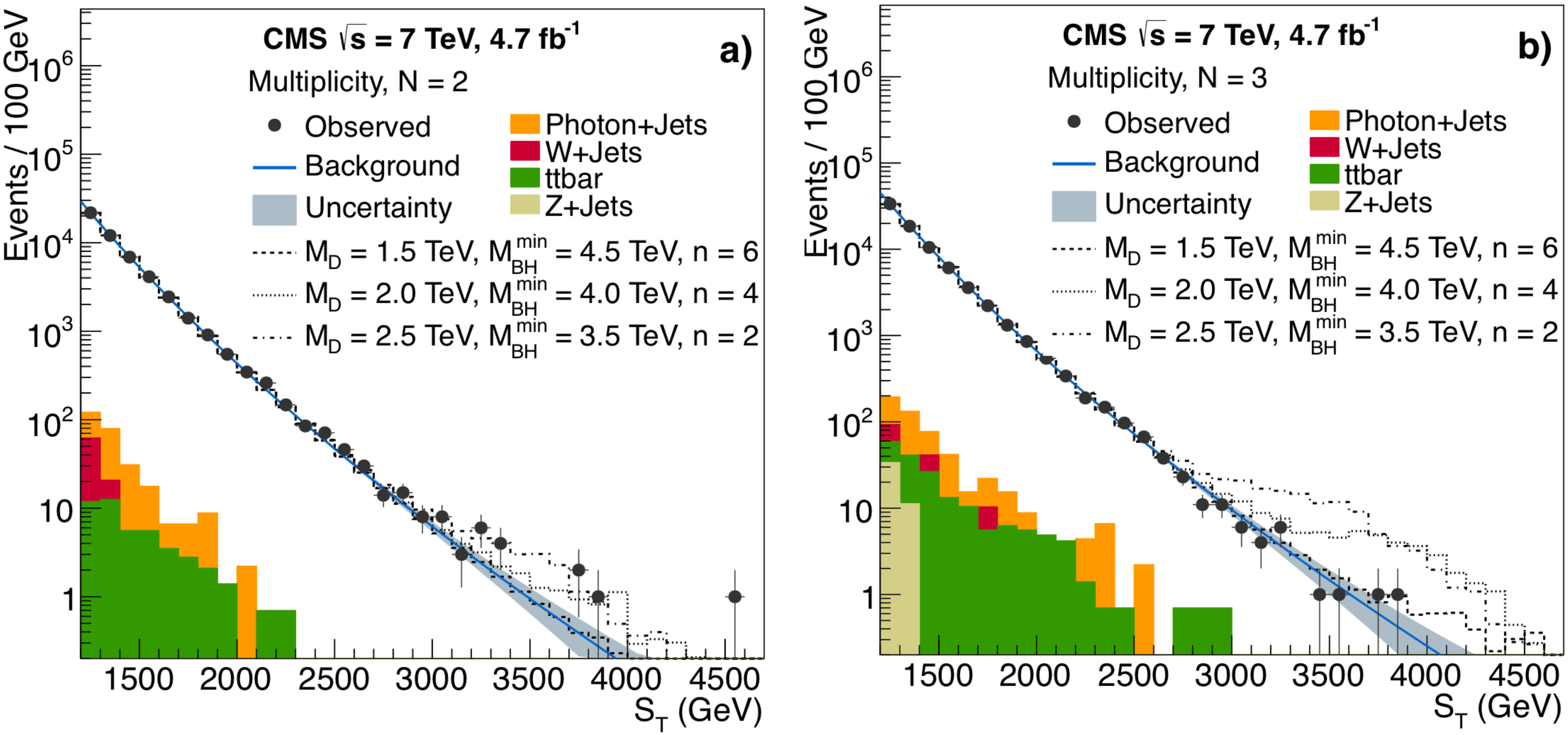
$G^*/W' \rightarrow VZ \rightarrow q\bar{q}ll$

- The results for the RS Graviton can be extended to other values of $k/\overline{M}_{Pl}$ assuming that the resonance width is much smaller than experimental resolution and the signal efficiency does not change



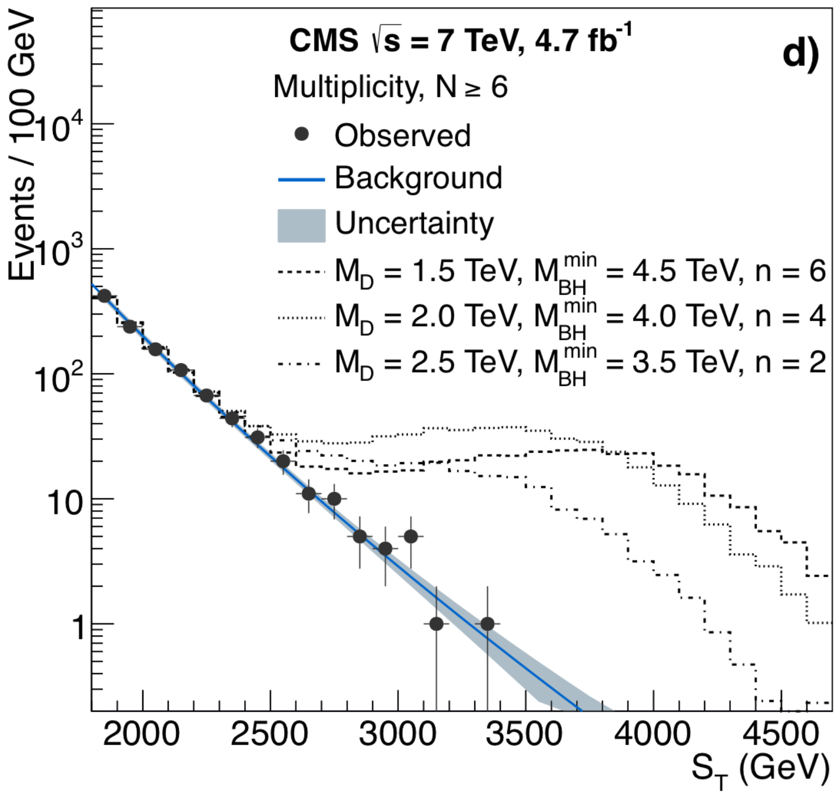
Black Holes

- Total transverse energy (S_T) distributions for low multiplicity (N=2, 3) events

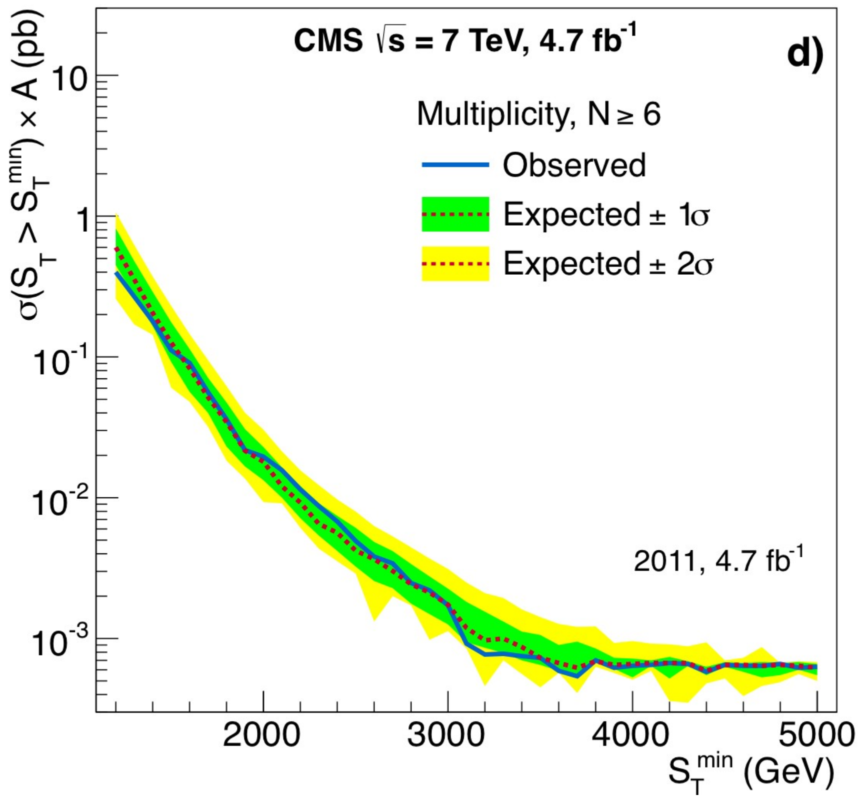


Black Holes

- Total transverse energy (S_T) distribution for multiplicity N ≥ 6 events, and expected semiclassical BH signals

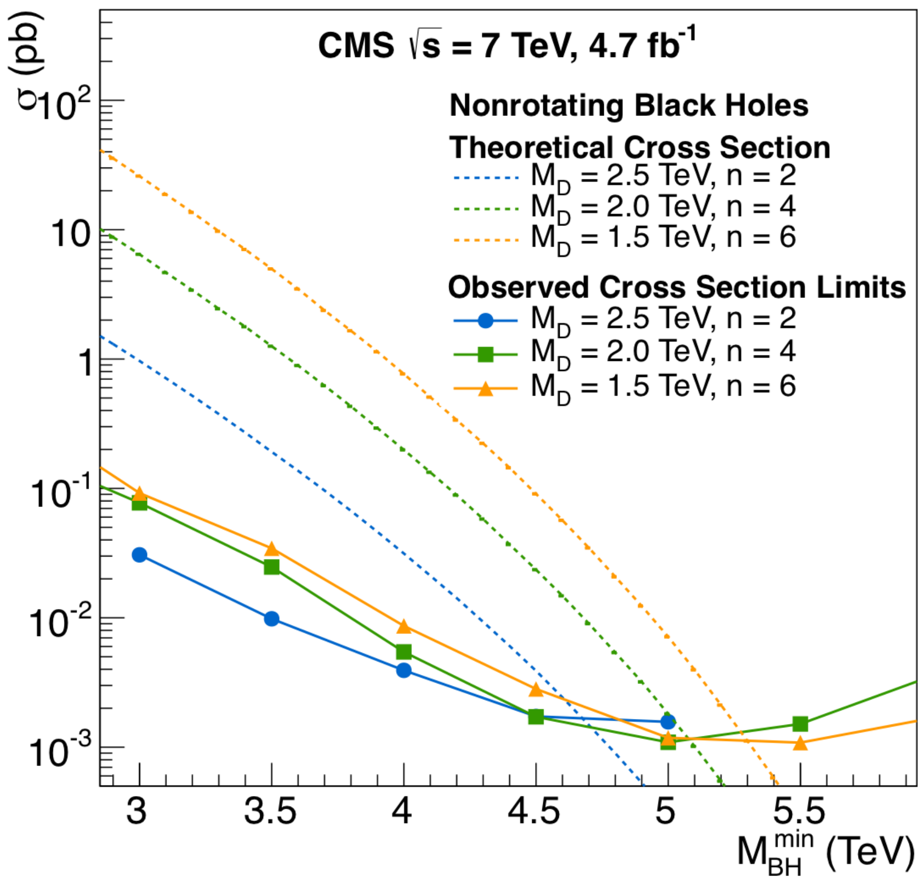


- Model-independent 95% CL limits on N ≥ 6 cross section for $S_T > S_T^{min}$ versus S_T^{min}



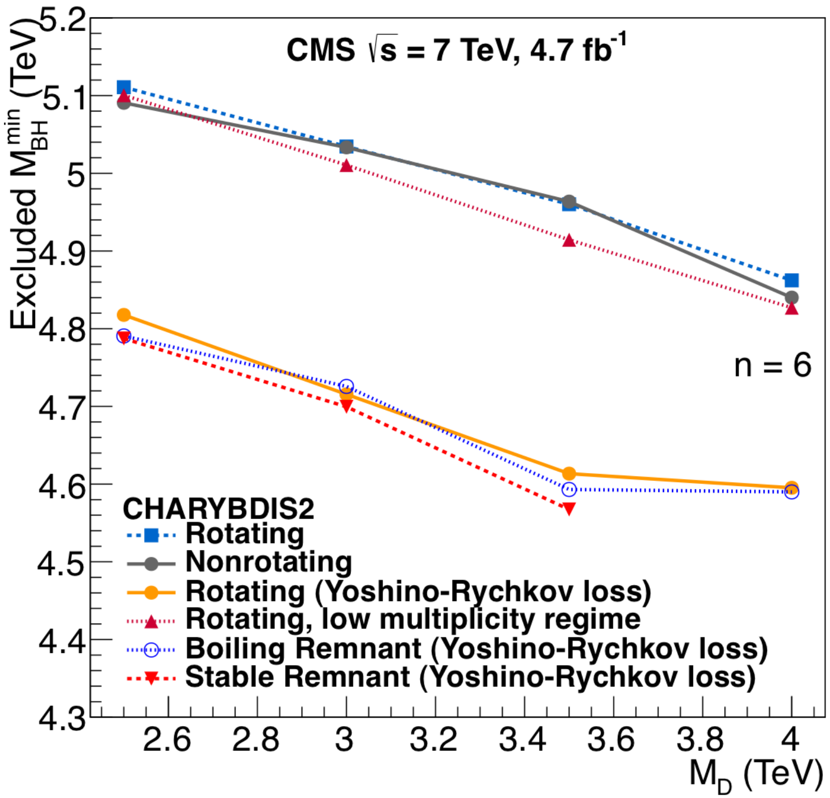
Black Holes

- 95% CL cross section limits for counting experiments optimized for various BH parameters compared with signal cross sections vs. BH mass



Black Holes

- Minimum BH mass excluded at 95% CL vs. reduced Planck scale M_D for n=6



- Cross section limits for various string ball parameters compared with signal production cross section vs. minimum string ball mass