Institute for Research in Fundamental Sciences

The Results of CMS Experiment Searches for Gravitational Effects

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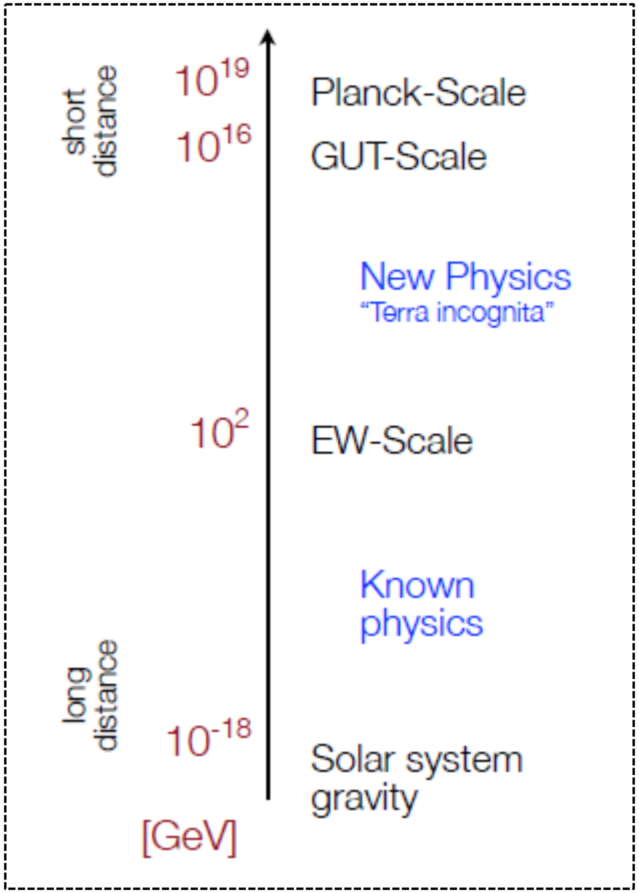
Outlines

- Extra Dimensions:
  - Large Extra Dimensions ADD
  - Randall-Sundrum
- Consequences of Extra Dimensions
- The Results of CMS Experiment on Extra Dimensions
- Mini Black Holes
- Jet Extinction

The main aim is to point out where the CMS experiment is in the search for the low-scale gravity.

Why Extra Dimensions: Hierarchy Problem



Planck Scale: 10^{19} GeV

Scale at which the gravitational force becomes as strong as the other forces;
effects of quantum gravitation become relevant ...

GUT Scale: 10^{16} GeV

Unification scale where strong, weak and electromagnetic forces become equal ...

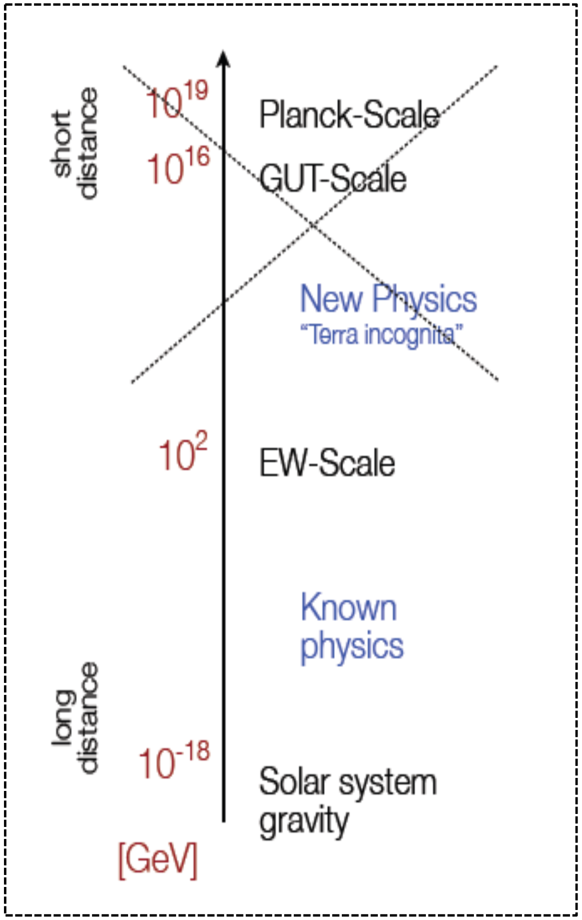
Electroweak Scale: 10^{2} GeV

Scale of electroweak symmetry breaking ...

The Standard Model of elementary particle physics gives no explanation for this hierarchy

Why Extra Dimensions: ADD Scenario

The existence of New Spatial Dimensions is proposed.



-If Large Extra Dimensions exist the 4D Planck Scale (M_P) **is not a fundamental scale** and the 4+n Planck Scale (M_S) is the Fundamental Scale.

- To solve the Hierarchy Problem: $M_S \sim M_{EW}$

The Planck scale $M_P \sim G^{-1/2}$ is not a fundamental scale; its enormity is simply a consequence of the large size of the new dimensions. While gravitons can freely propagate in the new dimensions, at sub-weak energies the Standard Model SM. Fields must be localized to a 4-dimensional manifold of weak scale "thickness" in the extra dimensions.

ADD- Physics Letters B 429 1998. 263–272

Why Extra Dimensions: ADD Scenario

The effect of Extra Dimensions or the strength of gravity can be parameterized in terms of a single parameter:

$$\eta = F/M_s^4$$

η describes the strength of gravity in the presence of extra dimensions.
F is a dimensionless parameter and in different in ADD conventions:

-HLZ (Han, Lykken and Zhang) Conventions→

$$F = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right), for \quad n=2 \\ \frac{2}{2-n} \quad for \;\; n>2 \end{cases}$$

-GRW (Guidice-Rattazzi-Wells)→

$$F = 1$$

$$F = \frac{\pm 2}{\pi}$$

-Hewett→

Why Extra Dimensions: RS Scenario

Critics on ADD: Hierarchy of gauge fields replaced by new hierarchy of length scales

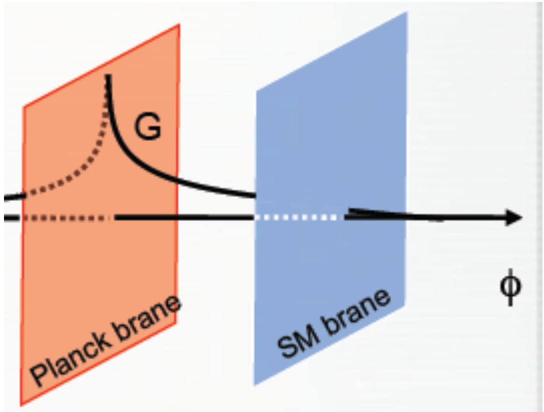
Alternative: Randall-Sundrum Model(s)

The Warped Extra Dimensions scenario was created by Randall and Sundrum (RS) and is quite different and more flexible than the ADD model. The basic RS model assumes the existence of only one highly curved ED. In this setup there are two branes, one at y = 0 (called the Planck brane) while the other is at $y = \pi r_c$ (called the TeV or SM brane). What makes this model special is the metric:

$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$

Warp Factor:

$$\Lambda_\pi \sim M_{\rm Pl} e^{-\pi k r_c}$$



Phys. Rev. Lett. 83 (99)

Why Extra Dimensions: RS Scenario

-In spite of ADD, light KK modes might be accessible and are well separated.

-Low energy effects on the SM brane are given by Λ_π; for $kr_c \sim 11\text{-}12$: $\Lambda_\pi \sim 1$ TeV and the hierarchy problem is solved naturally.

-Need only two parameters to define the model: k (curvature of the space) and r_c (compactification radius of the extra dim.)
Equivalent set of parameters:

- The mass of the first KK mode, M_1
- Dimensionless coupling k/M_{Pl}, which determines the graviton width.

Experimental Consequences of EDs

The ED models predict a number of observable signatures at the Large Hadron Collider (LHC).

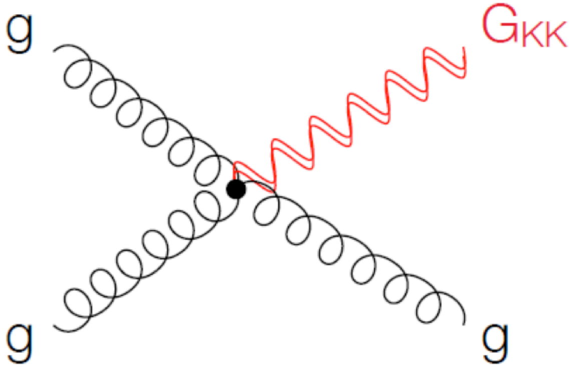
- One of the direct signatures is the production of a graviton in the final state of pp collisions. Graviton is emitted into the hidden space dimensions and appears as missing energy.
- Exchange of virtual gravitons: Change of cross sections
- New Particles: Kaluza-Klein excitations
- Production of Mini Black Holes

Gravitational Radiation

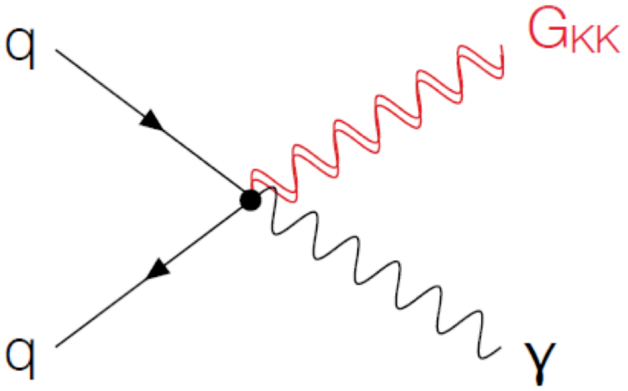
Graviton can be produced along with a jet (or a photon).
Gravitons interact weakly with the detector and radiate into the bulk appearing as missing energy.

Two clean signatures of the ED are:

- High-energy monojet & missing energy

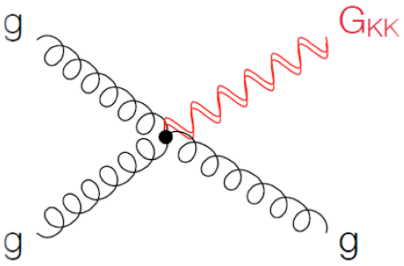


- High-energy single photon & missing energy



Monojet + Missing Energy

Signal: An energetic jet + large missing energy



Backgrounds:

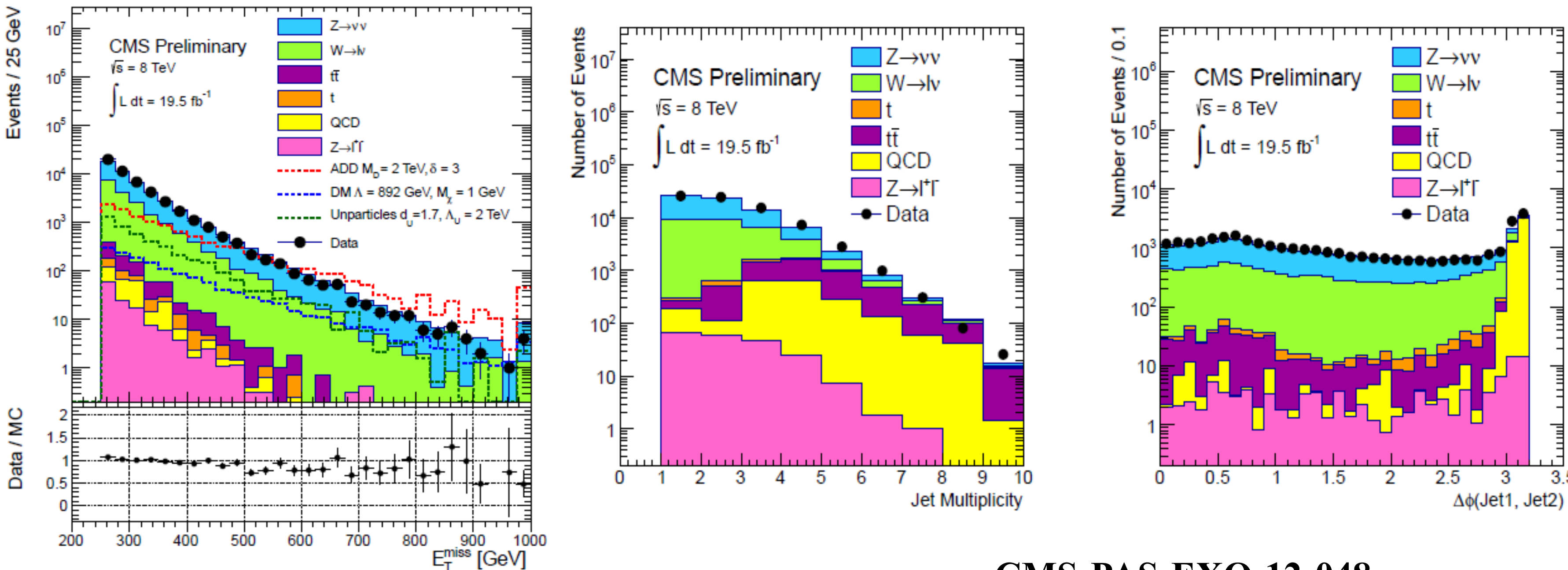
✧ Z(invisible)+Jet→Missing Energy+Jet.
✧ Z+Jets, W+Jets, Top pair, Single top, multijet

The signal events are selected by requiring:

CMS-PAS-EXO-12-048

- E^{miss}_T > 200 GeV.
- $P_{T,j1}$ > 110 GeV with $|\eta|<2.4$.
- Jet veto: Events with more than two jets (Njets > 2) with p_T above 30 GeV/c are discarded.
- The angular separation of the two jets should be less than 2.5.
- Isolated electron and muon veto as well as tau veto

Monojet + Missing Energy



CMS-PAS-EXO-12-048

Missing transverse momentum E^{miss}_T after all selection cuts for data and SM backgrounds.

Representative signal distributions ADD is also overlaid. Events with E^{miss}_T > 1 TeV are included in the overflow bin.

Monojet + Missing Energy

SM background predictions compared with data after passing the selection requirements for various E^{miss}_T thresholds, corresponding to an integrated luminosity of 19.5/fb.
The uncertainties include both statistical and systematic terms and are considered to be uncorrelated.

In the last two rows, expected and observed 95% confidence level upper limits on possible contributions from new physics passing the selection requirements are given

E_T^{miss} (GeV) →	> 250	> 300	> 350	> 400	> 450	> 500	> 550
$Z(\nu\nu)$+jets	30600 ± 1493	12119 ± 640	5286 ± 323	2569 ± 188	1394 ± 127	671 ± 81	370 ± 58
W+jets	17625 ± 681	6042 ± 236	2457 ± 102	1044 ± 51	516 ± 31	269 ± 20	128 ± 13
$t\bar{t}$	470 ± 235	175 ± 87.5	72 ± 36	32 ± 16	13 ± 6.5	6 ± 3.0	3 ± 1.5
$Z(\ell\ell)$+jets	127 ± 63.5	43 ± 21.5	18 ± 9.0	8 ± 4.0	4 ± 2.0	2 ± 1.0	1 ± 0.5
Single t	156 ± 78.0	52 ± 26.0	20 ± 10.0	7 ± 3.5	2 ± 1.0	1 ± 0.5	0 ± 0
QCD Multijets	177 ± 88.5	76 ± 38.0	23 ± 11.5	3 ± 1.5	2 ± 1.0	1 ± 0.5	0 ± 0
Total SM	49154 ± 1663	18506 ± 690	7875 ± 341	3663 ± 196	1931 ± 131	949 ± 83	501 ± 59
Data	50419	19108	8056	3677	1772	894	508
Exp. upper limit	3580	1500	773	424	229	165	125
Obs. upper limit	4695	2035	882	434	157	135	131

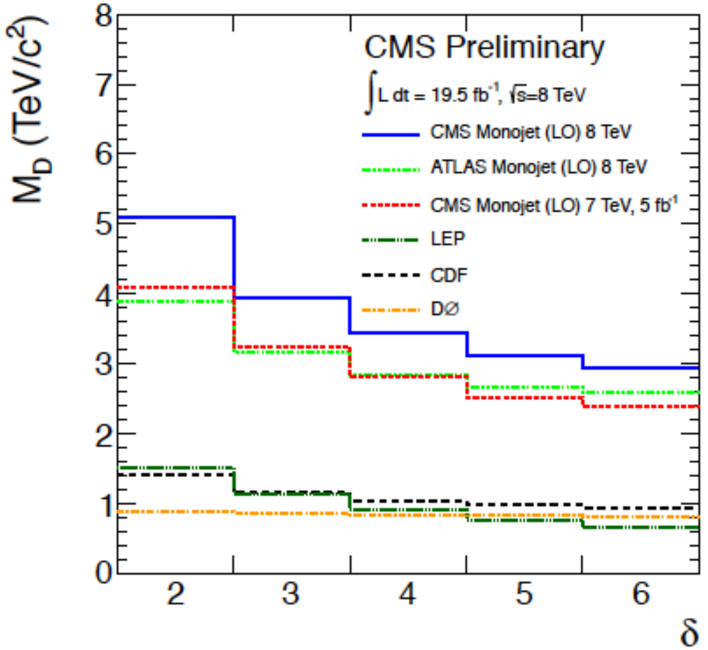
The total number of background events for $E^{miss}_T > 400$ GeV is measured to be 3663+/-196.

CMS-PAS-EXO-12-048

Monojet + Missing Energy: Results

The limits on the ADD model E^{miss}_T > 400 GeV where we have the **greatest sensitivity**.

δ	LO Exp. Limit	LO Obs. Limit	NLO Exp. Limit	NLO Obs. Limit
2	5.12	5.10	5.70	5.67
3	3.96	3.94	4.31	4.29
4	3.46	3.44	3.72	3.71
5	3.11	3.10	3.32	3.31
6	2.95	2.94	3.13	3.12



Limits at 95% CL on ADD model parameters are M_S > 5.1 TeV for n_{ED} = 2 at Leading Order and 5.67 TeV at NLO.

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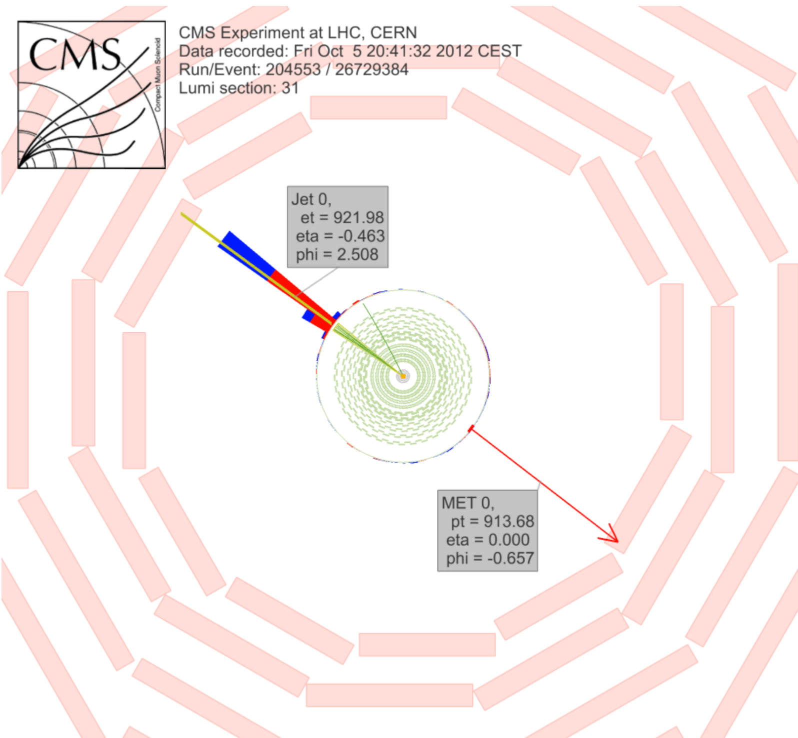
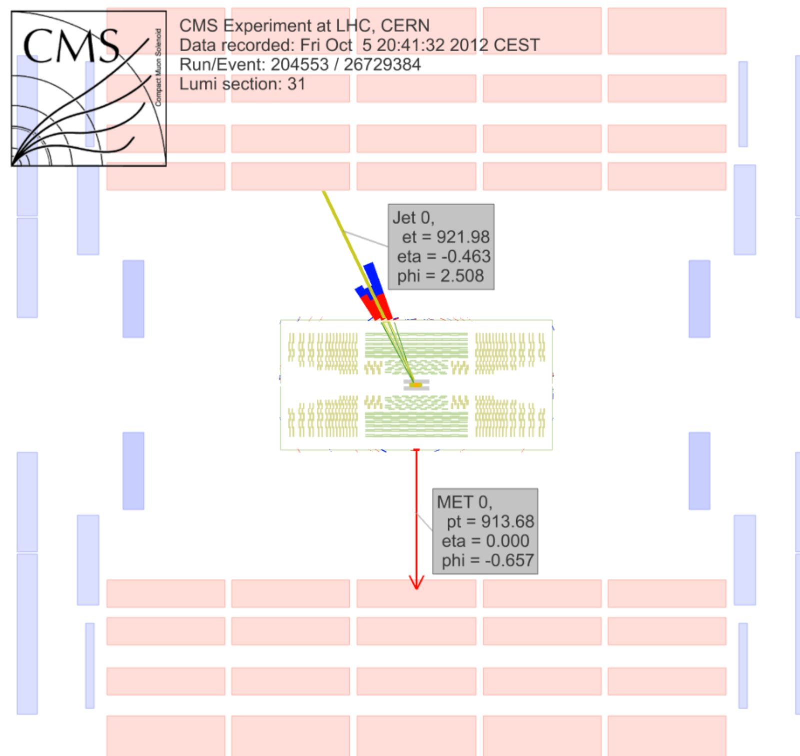
Interesting CMS Single Jet event Candidate

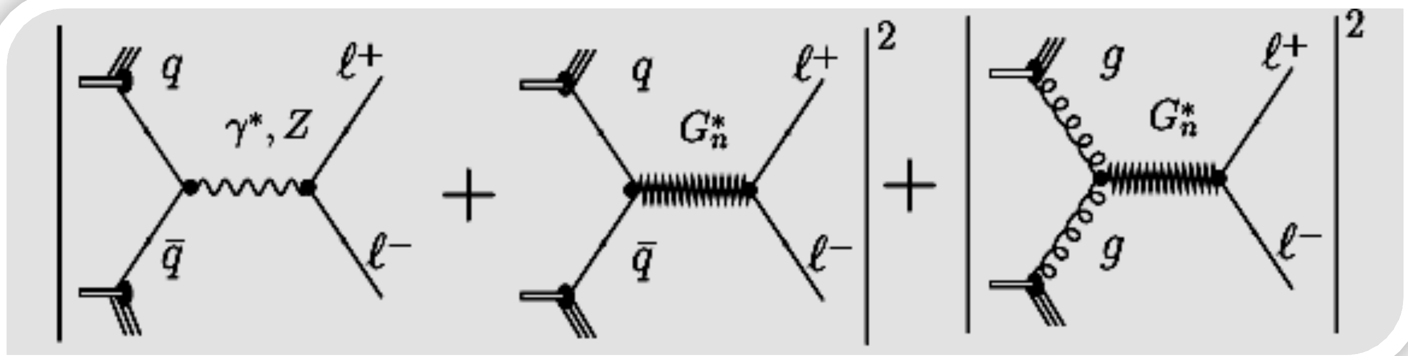


Rho-phi view of a monojet event



Rho-z view of a monojet event

Exchange of Virtual Gravitons: Di-lepton Production: P+P→l+l+X



$$\sigma = \sigma_{SM} + \eta_G \sigma_{int} + \eta_G^{\,2} \sigma_{KK} \qquad \eta_G = F / M_s^{\,4}$$

Signal: Two opposite sign same flavor leptons

Backgrounds:

Irreducible: Standard Model Drell-Yan

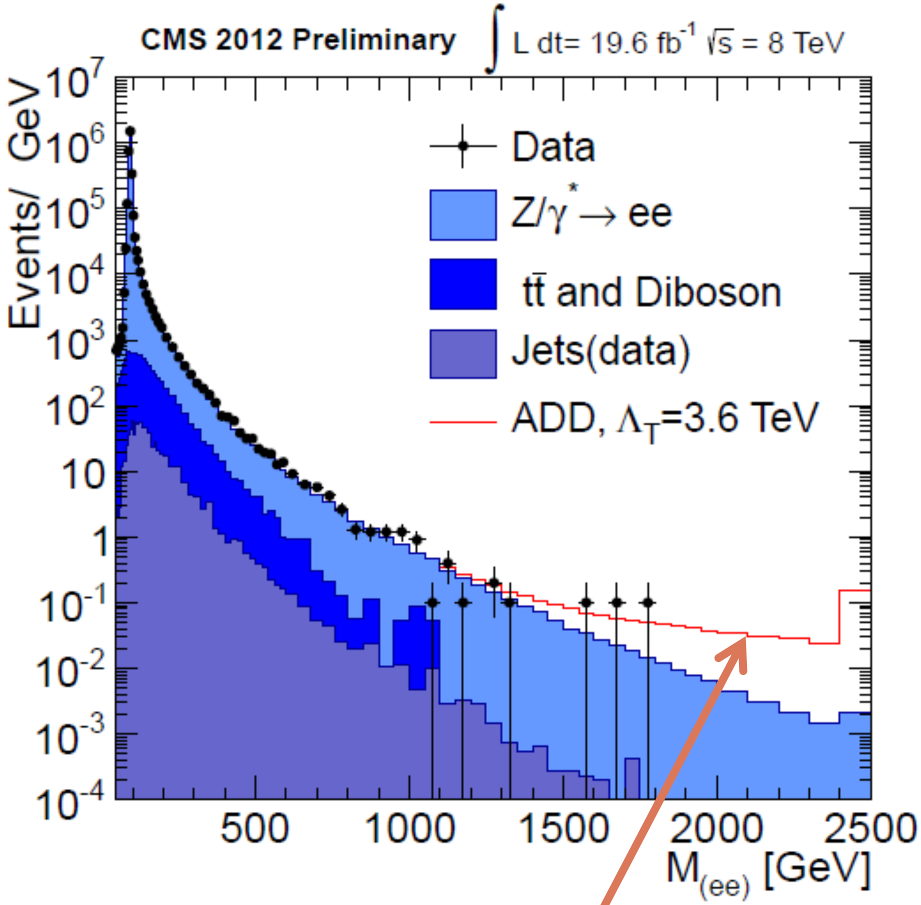
Other backgrounds:

- Top pair (specially dileptonic), WW,WZ,ZZ
- Multijet
- Photon+Jet

Exchange of Virtual Gravitons: Di-electron

-Two isolated electrons with:
P_T > 33 GeV and |eta| < 2.5
-Signal events above an invariant mass cut are used for the analysis.
-The optimal invariant mass cut is found to be 1.8 TeV
There are only contributions from DY above 1.8 TeV.

CMS-PAS-EXO-12-031



ee, $\mathcal{L} = 19.6$ fb^{-1}			
Mass region [TeV]	N_{obs}	Background expectation	Signal exp. $\Lambda_T = 3.6$ TeV
Control regions			
0.12–0.40	85851	82497 ±12374	
0.40–0.60	1251	1131±169	
0.60–0.90	249	232 ±35	
0.90–1.30	41	36 ±6	
1.30–1.80	4	4.75 ±0.70	3.70
Signal region			
> 1.80	0	0.64±0.10	6.90

Signal tends to reside in high invariant mass region

Exchange of Virtual Gravitons: Di-muon

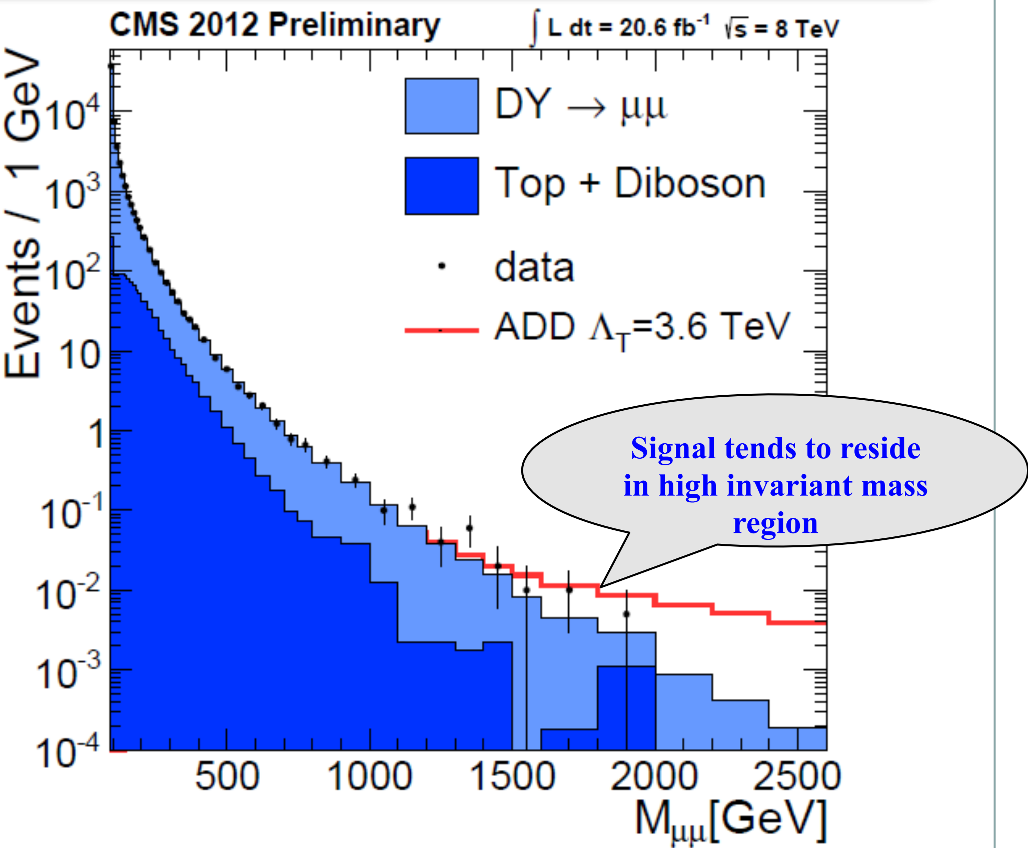
-Two isolated muons with:
P_T > 45 GeV and |eta| < 2.1

-Signal events above an invariant mass cut are used for the analysis.

-The optimal invariant mass cut is found to be 1.8 TeV

There are only contributions from DY above 1.8 TeV.

$\mu\mu$, $\mathcal{L} = 20.6$ fb^{-1}			
Mass region [TeV]	N_{obs}	Background expectation	Signal exp. $\Lambda_T = 3.6$ TeV
Control regions			
0.12–0.20	$8.20 \cdot 10^4$	$(7.96 \pm 0.64) \cdot 10^4$	
0.20–0.40	$1.92 \cdot 10^4$	$(1.87 \pm 0.15) \cdot 10^4$	
0.40–0.60	$1.42 \cdot 10^3$	$(1.45 \pm 0.14) \cdot 10^3$	
0.60–0.90	287	282 ± 32	
0.90–1.30	49	44.5 ± 6.6	
1.30–1.80	11	5.74 ± 1.16	3.38
Signal region			
> 1.80	1	0.73 ± 0.21	6.04



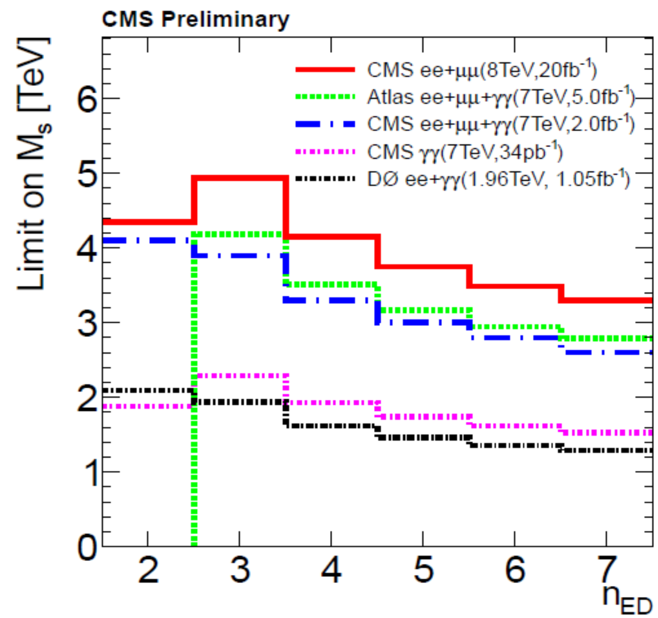
CMS-PAS-EXO-12-027

Exchange of Virtual Gravitons: Results

ADD k-factor	Λ_T [TeV] (GRW)	M_s [TeV] (HLZ) $n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
ee, $\sigma_{s,ee} < 0.19$ fb (0.19 fb expected) at 95% CL							
1.0 (observed)	3.90	3.72	4.64	3.90	3.52	3.28	3.10
1.0 (expected)	3.89	3.70	4.62	3.89	3.51	3.27	3.09
1.3 (observed)	4.01	3.99	4.77	4.01	3.63	3.37	3.19
1.3 (expected)	4.00	3.95	4.76	4.00	3.61	3.36	3.18
$\mu\mu$, $\sigma_{s,\mu\mu} < 0.25$ fb (0.25 fb expected) at 95% CL							
1.0 (observed)	3.64	3.48	4.33	3.64	3.29	3.06	2.89
1.0 (expected)	3.65	3.50	4.34	3.65	3.30	3.07	2.90
1.3 (observed)	3.77	3.69	4.49	3.77	3.41	3.17	3.00
1.3 (expected)	3.78	3.70	4.50	3.78	3.42	3.18	3.01
ee and $\mu\mu$, per channel $\sigma_s < 0.12$ fb (0.12 fb expected) at 95% CL							
1.0 (observed)	4.01	4.14	4.77	4.01	3.63	3.37	3.19
1.0 (expected)	4.00	4.13	4.76	4.00	3.62	3.37	3.18
1.3 (observed)	4.15	4.35	4.94	4.15	3.75	3.49	3.30
1.3 (expected)	4.14	4.37	4.93	4.14	3.74	3.48	3.30

The numberical resluts of obsereved(expected) limits for the dielectron, dimuon and combination respectively in the GRW and HLZ convention with the k_f=1 and k_f=1.3

The improvement of ADD limits as a function of number of extra dimensions up to now which are compare with the other experiment results.



The limit on M_s varies from 4.77 to 3.2 TeV with k-factor

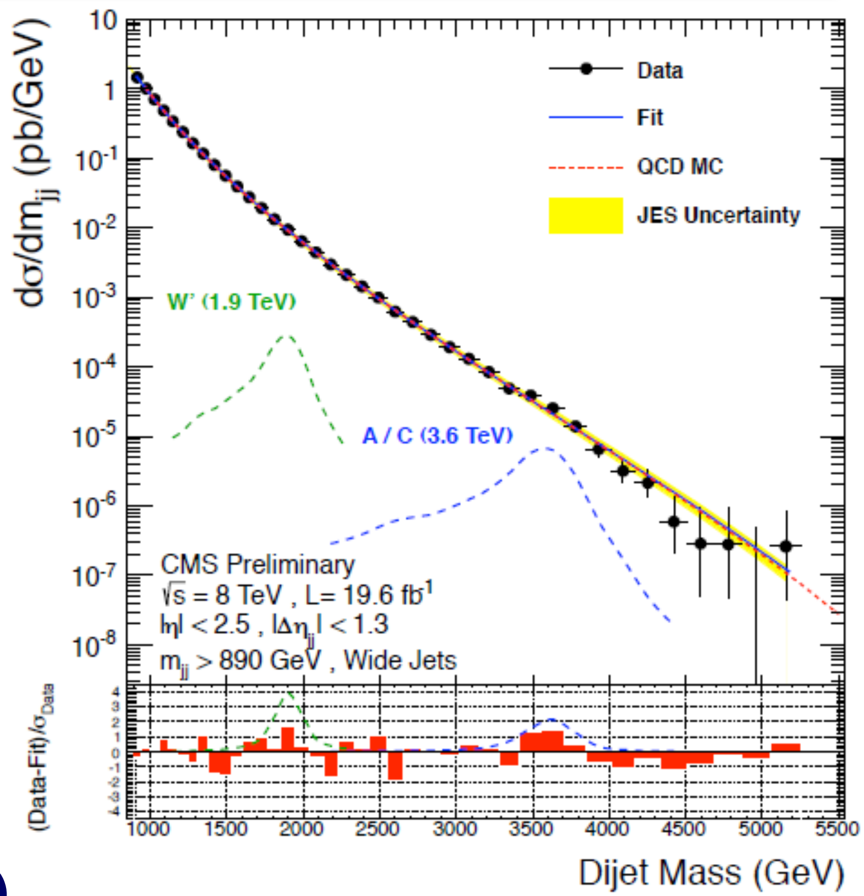
Search for RS Gravitons

In the RS scenario, gravitons appear as a well-separated tower of Kaluza-Klein (KK) Excitations with masses and widths determined by the parameters of the RS1 model.

The excited gravitons can decay into two jets

No deviations that are statistically significant are observed between the distribution of the data points and the SM prediction is observed.

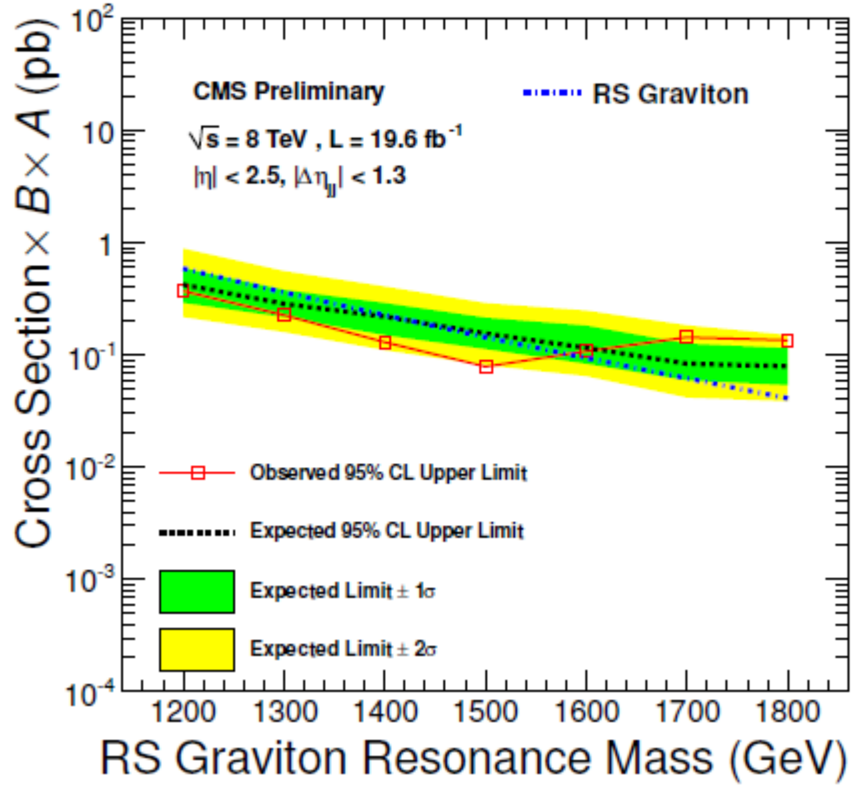
The highest mass event (5.15 TeV) is shown in Figure. We proceed to set upper limits on the cross section of new physics processes.



CMS-PAS-EXO-12-16
Accepted for publication in PRD

Search for RS Gravitons

The observed 95% CL upper limits on cross section times BR*Acc. for resonances decaying into dijet final state are compared to the expected limits.

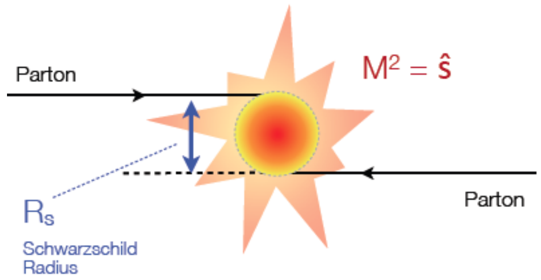


The signal shape for the RS model is obtained weighting the shapes for qq and gg final states according to LO calculations of the relative branching fractions.

Any Randall-Sundrum Graviton with the coupling k/M_{Pl}= 0.1 with a mass below 1.33 TeV has been excluded.

Search for Mini Black Holes

Main idea: Within the ED frameworks if c.m.s energy of the collision is above Planck scale a black hole can be formed ...
For TeV scale Planck mass the Cross Section is typically large.

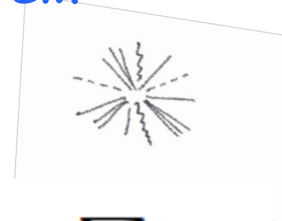


- Democratic decay into SM particles
- High multiplicity e.g. M_{BH} = 10 TeV: 50 part. with E ~ 200 GeV
- Spheric Events, production at high x without Boost
- A characteristic signature of evaporating semiclassical black holes or string balls is a large number of energetic final-state particles of various types while quantum black holes typically decay into a pair of energetic jets.

Search for Mini Black Holes

The search for black holes is based on a search for a deviation from the SM background predictions in the S_T spectra observed in data.

The S_T variable is defined as the scalar sum of transverse momenta of all the final-state objects in the event with p_T in excess of 50 GeV.



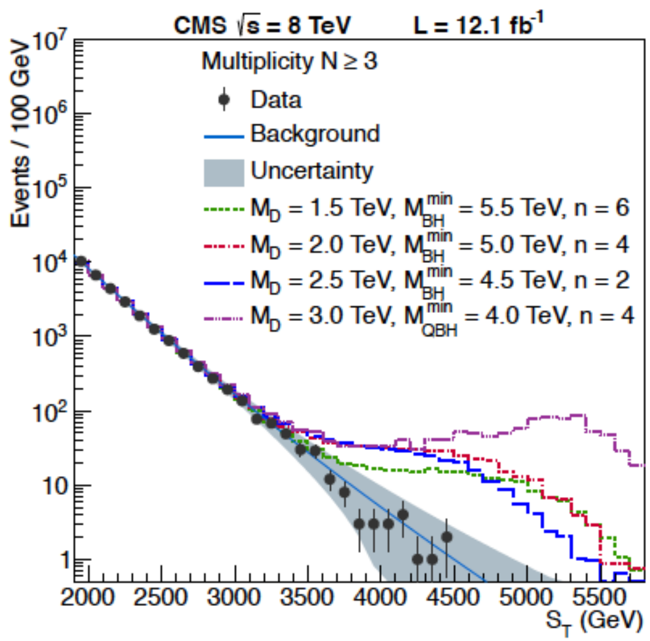
$$S_T = \sum_{\text{Objects}} E_T$$

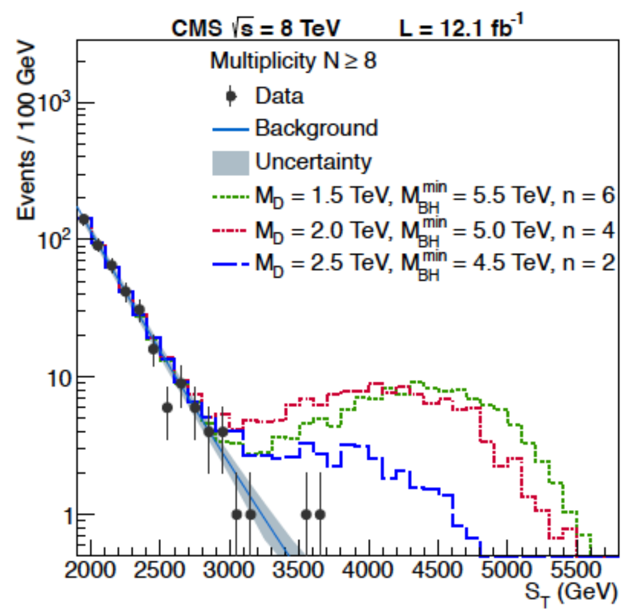
The SM background is completely dominated by QCD multijet production and is directly from data.

Distribution of the total transverse energy, S_T, for events with various final state multiplicities:

The expected Semiclassical black hole signals for three parameter sets of the nonrotating black hole model are also shown

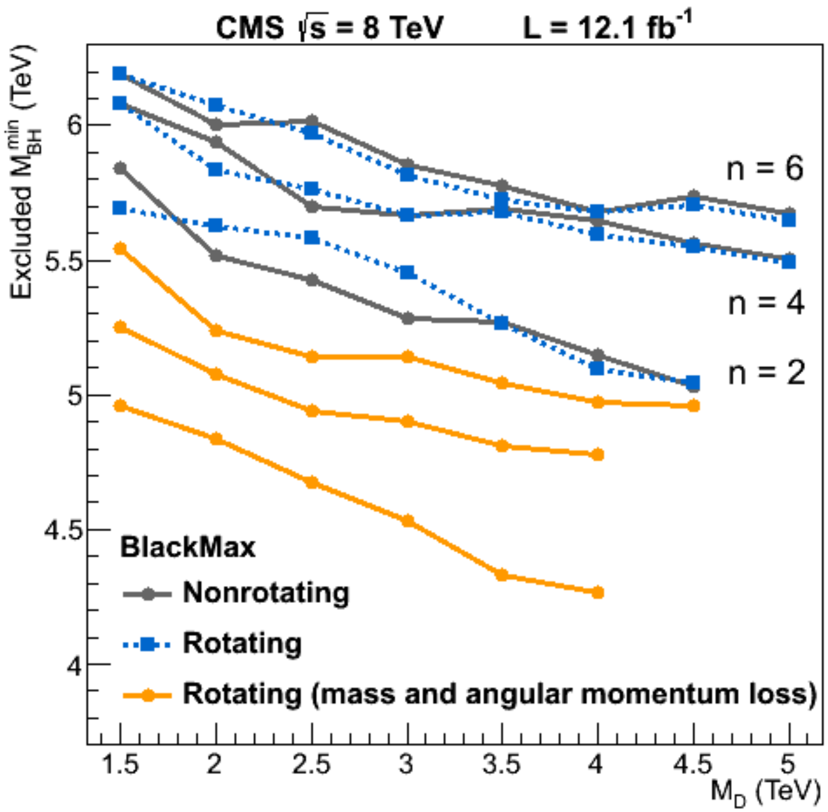
CMS-PAS-EXO-12-009

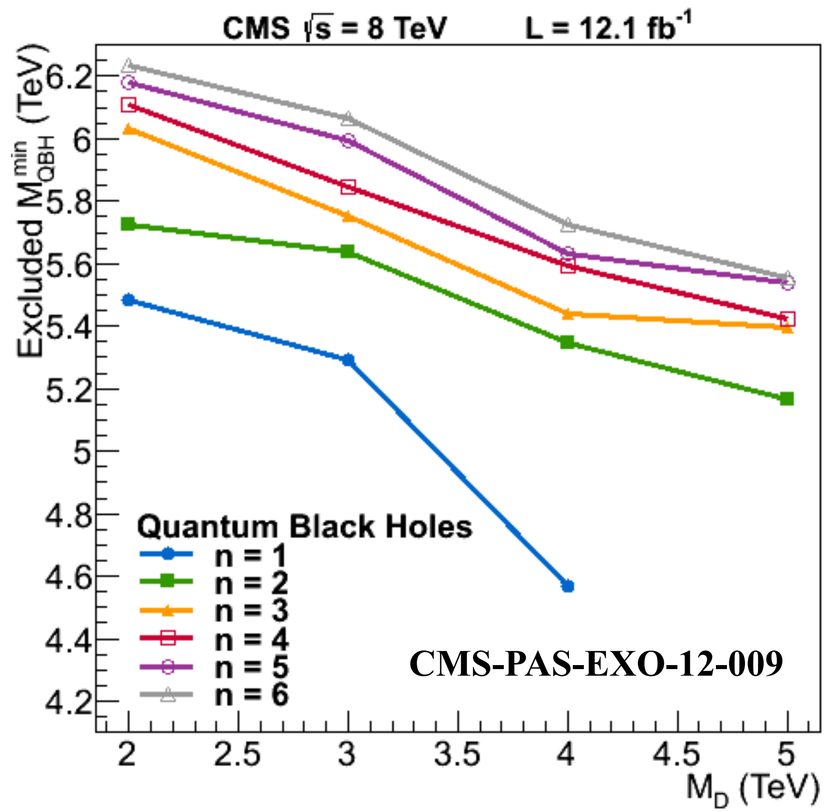




Search for Mini Black Holes

In the absence of an excess of data over the background prediction, we set limits on black hole production rates.





With this search, semiclassical and quantum black holes with masses below 4.3–6.2 TeV are excluded.

Jet Extinction

- It has been shown that if the fundamental Planck scale is not too far above the EW scale, it leads to a suppression of perturbative hard scattering processes that give low multiplicity final states.

- At the LHC the leading hard scattering process at high energies is jet production from QCD interactions. Extinction from non-perturbative quantum gravity effects should therefore be most apparent as a suppression of large invariant mass scattering processes involving jets, or equivalently a suppression of large transverse momentum in the inclusive jet spectrum.

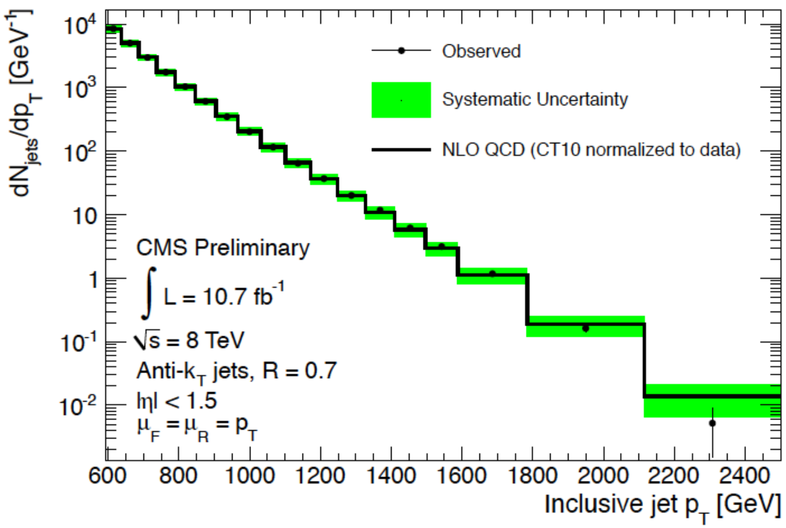
- The specific model that has been utilized to quantify the extinction of hard scattering is a Veneziano form factor modification of QCD processes with a large damping component.

For more information about the theoretical and phenomenological aspects, please see:

-arXiv:1207.3525
-arXiv:hep-ph/9906038

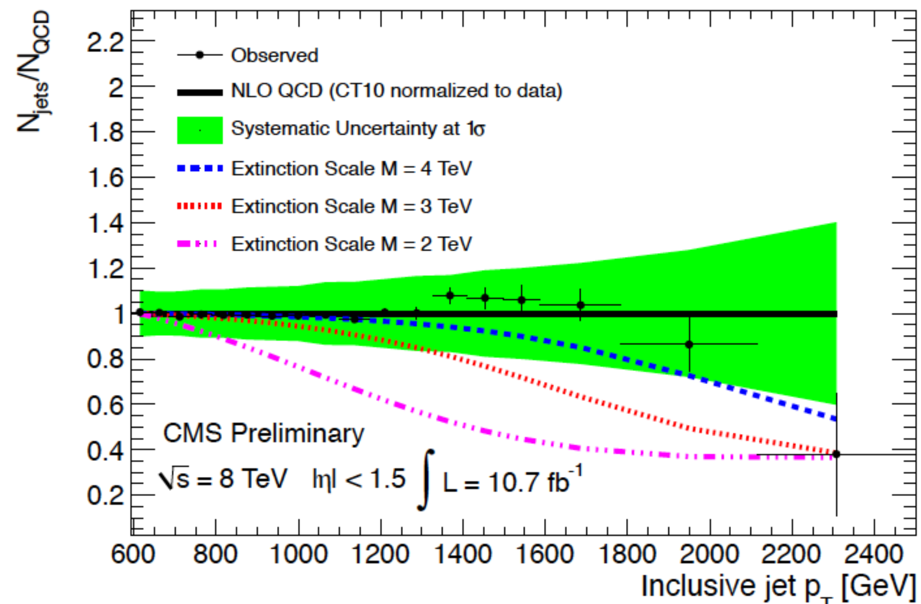
Jet Extinction

The ratio of the inclusive jet-**p**T spectrum to the NLO QCD prediction with nonperturbative corrections and convolved with the detector resolution. The colored band shows the magnitude of all sources of systematic uncertainty. Dashed lines indicate the effects of extinction at three different values of the extinction scale, **M** = 2, 3, and 4 TeV.



Inclusive jet $\mathbf{p}_T$ spectrum (points) for |eta| < 1.5, as observed in 10.7/fb of data.

CMS-PAS-EXO-12-051

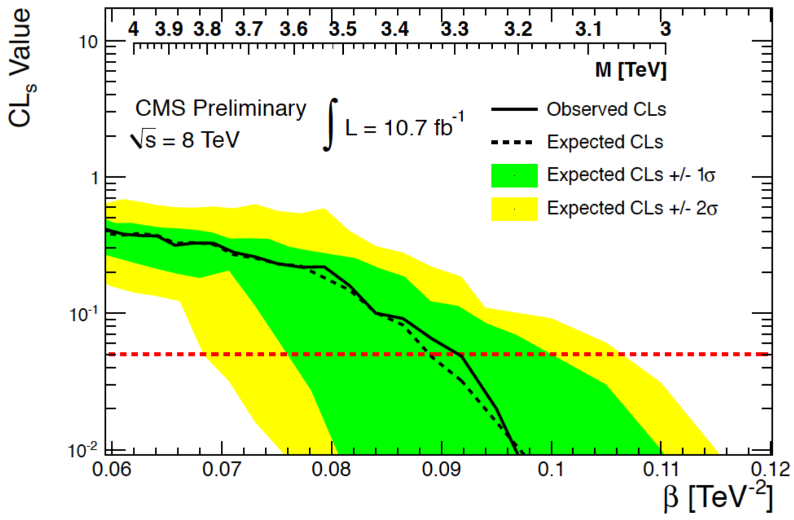


For finite values of **M**, the predicted jet $\mathbf{p}_T$ spectrum by SM is suppressed above **M**. At very large values of **M**, the SM and extinction spectra become identical.

Jet Extinction

- Detailed comparison between the measured Jet p_T spectrum and the theoretical prediction is performed.
- The main sources of systematic uncertainties are the JES, JER, PDFs, and luminosity
- No significant deviation of events is found at high transverse momentum.
- Using CLs method, 95% CL lower limit of 3.3 TeV is set on the extinction parameter M.

Results of a CLs scan in the extinction scale.
Any value of M for which CLs < 0.05 is regarded as excluded at 95% confidence level (CL).



CMS-PAS-EXO-12-051

Conclusions

- Several searches for TeV scale gravity performed with the CMS detector.
- No evidence of any deviations from the Standard Model expectations observed.
- Limits were set on the model parameters using mono-jet, dilepton, dijet,… events.
- Quantum gravity effects, or others, can lead to cross sections to be lower. Limit set on the extinction scale.

References

-Search for large extra dimensions in dimuon events in pp collisions at sqrt (s) = 8 TeV, CMS PAS EXO-12-027.

-Search for large extra dimensions in dielectron production with the CMS detector, CMS PAS EXO-12-031.

-Search for narrow resonances using dijet mass spectrum with 19.6 fb-1 of pp collisions at sqrt(s) = 8 TeV, CMS PAS EXO-12-059.

-Search for new physics in monojet events in pp collisions at sqrt(s) = 8 TeV, CMS PAS EXO-12-048.

-Search for microscopic black holes at sqrt(s) = 8 TeV with the CMS detector, CMS PAS EXO-12-009.

-Search for Jet Extinction in the Inclusive Jet pT spectrum at sqrt(s) =8~TeV, CMS-PAS-EXO-12-051

Thanks to CMS colleagues for the nice analyses and providing me the materials.