Searches for High Mass Resonances with the CMS Detector

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On behalf of the CMS Collaboration

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Introduction

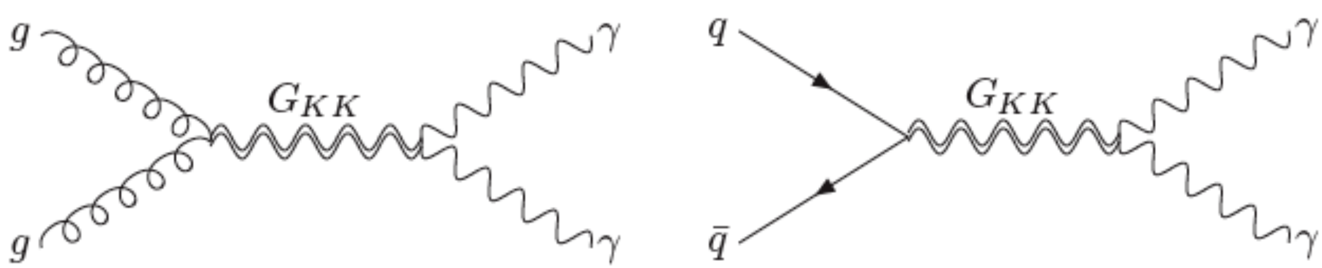
- Theoretical motivation: new resonances foreseen in many extensions of the SM (extra dimensions, GUT, compositeness, etc…)

- Benchmark models:
  - Diphotons, dileptons, dijets, $t\bar{t}$: Z'_{SSM}, GUT-inspired Z'_{ψ}, Randall-Sundrum gravitons, W', axigluons, colorons, excited quarks, E_6 diquark, string resonances
  - Focus on recent analyses with ~$1 fb^{-1}$
  - What's not discussed in this talk will be covered by B. Dahmes tomorrow

- General strategy:
  - Look for excess in data in the high mass region with respect to the SM expectations; no excess is observed → set exclusion limit

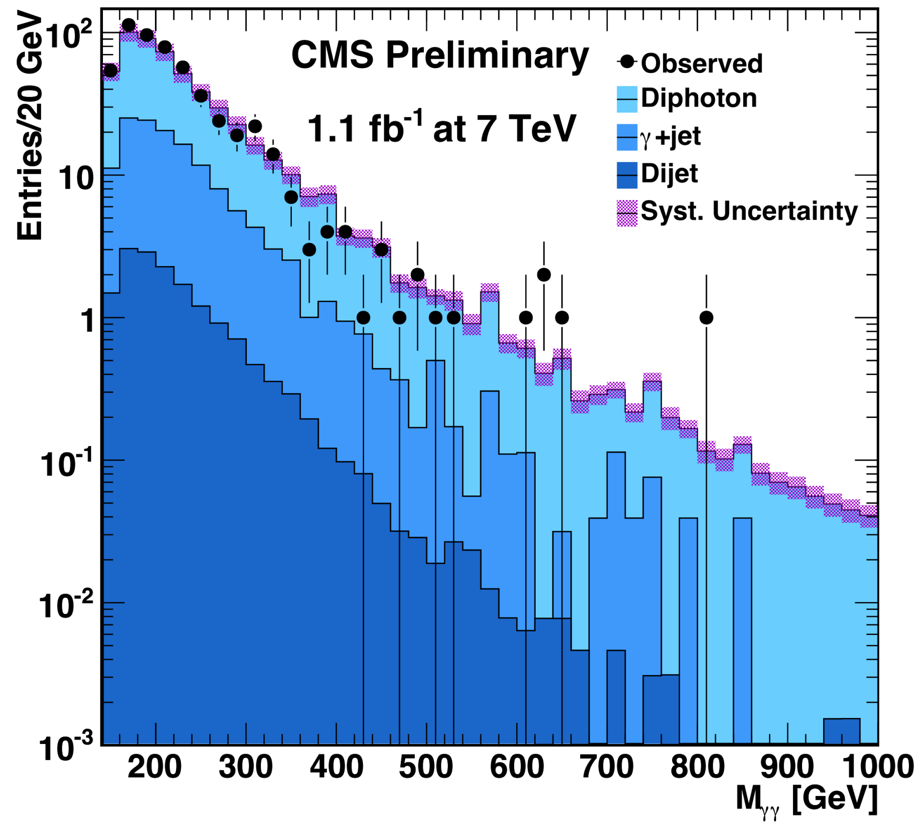
Diphoton Resonance

- Signal: RS Gravitons (qq/gg → G* → gg)
  - For diphotons, branching ratio for spin-2 RS G* is twice that to leptons
  - For RS gravitons, two parameters of interest: M_1 and k/M_{Pl}
- Analysis:
  - Straightforward: look for two isolated, high p_T photons
  - Counting experiment
- Offline: require 2 isolated photons with p_T > 70 GeV & $|\eta|<1.44$



Diphoton Results

- Backgrounds:
  - Irreducible SM diphoton production: from MC, scaling by NLO mass-dependent K-factors
  - γJet and dijets, where jets are misidentified as photons: measured in the data using fake rate method

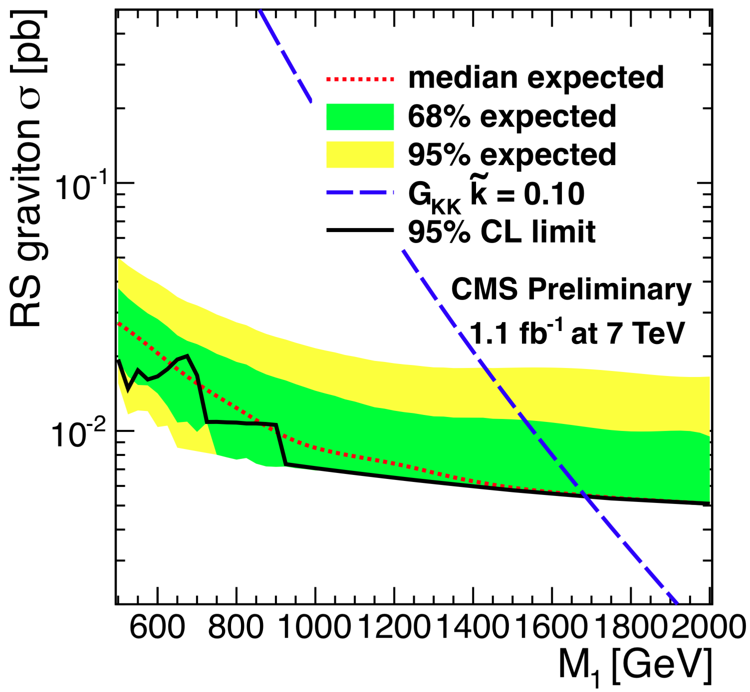


Process	Diphoton Invariant Mass Range [TeV]			
	[0.14,0.2]	[0.2,0.5]	[0.5,0.8]	[0.8, ∞)
Multijet	7 ± 3	9 ± 3	0.1 ± 0.1	0.003 ± 0.001
$\gamma+$jet	53 ± 8	67 ± 10	1.5 ± 0.2	0.19 ± 0.04
Diphoton	185 ± 33	205 ± 37	7.6 ± 1.4	1.1 ± 0.2
Total Backgrounds	245 ± 35	283 ± 39	9.2 ± 1.4	1.3 ± 0.2
Observed	263	276	6	1

EXO-11-038

Diphoton Limits

- Set 95% CL limits with counting experiment in sliding mass window, with CL_S method



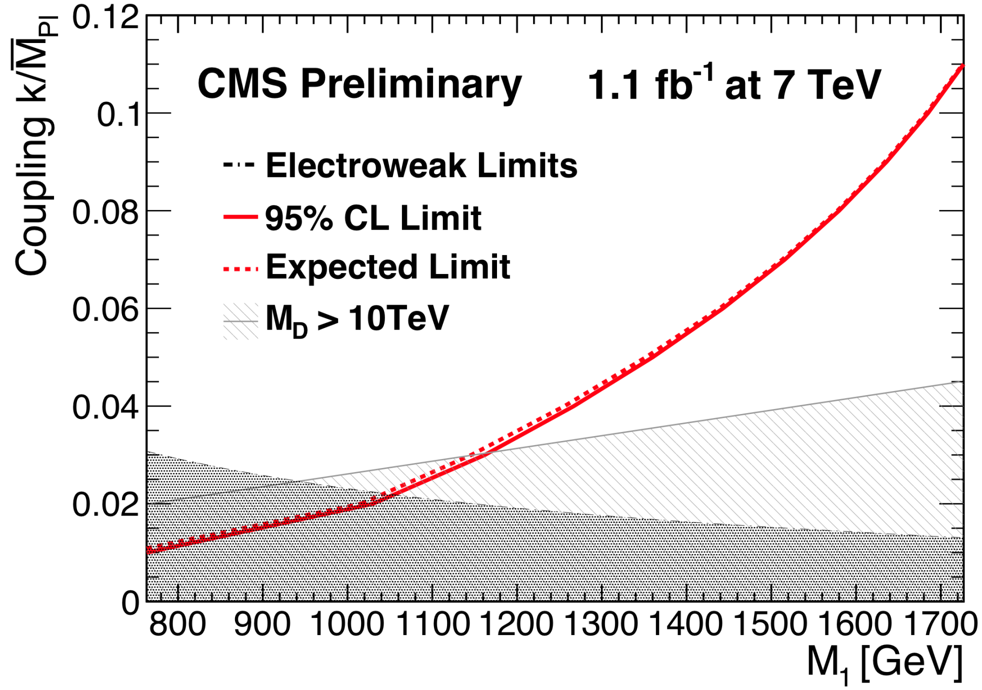


Table 3: Table of 95% CL lower limits on M_1 for given values of the coupling parameter, $\tilde{k}$.

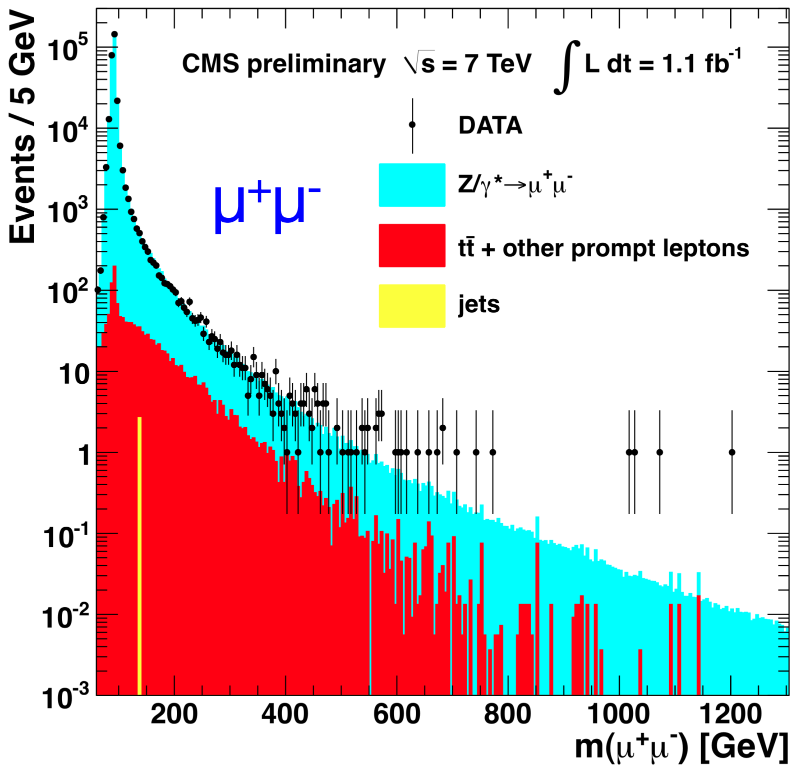
$\tilde{k}$	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
M_1 [TeV]	0.77	1.05	1.20	1.31	1.41	1.49	1.57	1.63	1.69	1.74	1.78

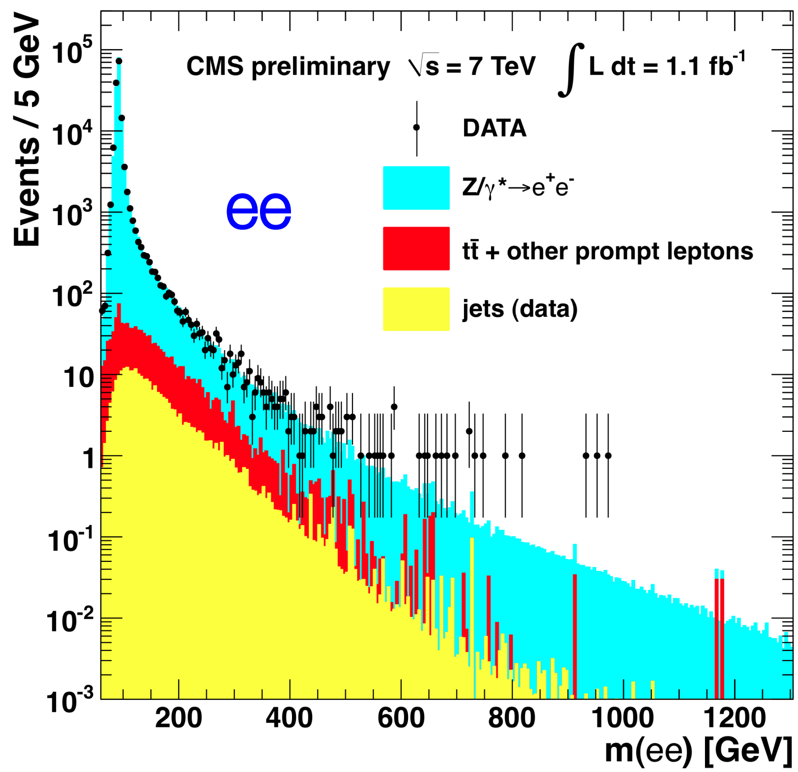
EXO-11-038

Dilepton Resonances

- Signal: Z' and RS G* ($q\bar{q} \rightarrow Z'/G^* \rightarrow l^+l^-$; $gg \rightarrow G^* \rightarrow l^+l^-$)
- Analysis:
  - Generic model-independent shape-based search; no assumptions on the absolute background rate
  - Results are normalized to the Z^0 peak
- Offline: require 2 isolated leptons with p_T > 35 GeV (40 GeV for endcap electrons), opposite-sign for dimuons, + further quality cuts
- Backgrounds:
  - SM Drell-Yan (irreducible): MC normalized to data at the Z peak
  - Prompt leptons (tt, tW, dibosons): $e\mu$ Method
  - Jets faking leptons (W+jet, di-jet, QCD): fake rate from jets-enriched data
  - Cosmic muons: Reject with impact parameter and opening angle between the two muons

Dileptons in Data





Source	Number of events			
	Dimuon sample		Dielectron sample	
	(120 – 200) GeV	>200 GeV	(120 – 200) GeV	>200 GeV
CMS data	5216	1095	3410	809
Total background	5537 ± 250	1100 ± 48	3375 ± 161	787 ± 67
Z/γ^*	5131 ± 246	922 ± 44	2992 ± 149	622 ± 62
$t\bar{t}$ + other prompt leptons	404 ± 46	178 ± 20	275 ± 20	118 ± 8
Multi-jet events	3 ± 3	0	107 ± 43	46 ± 18

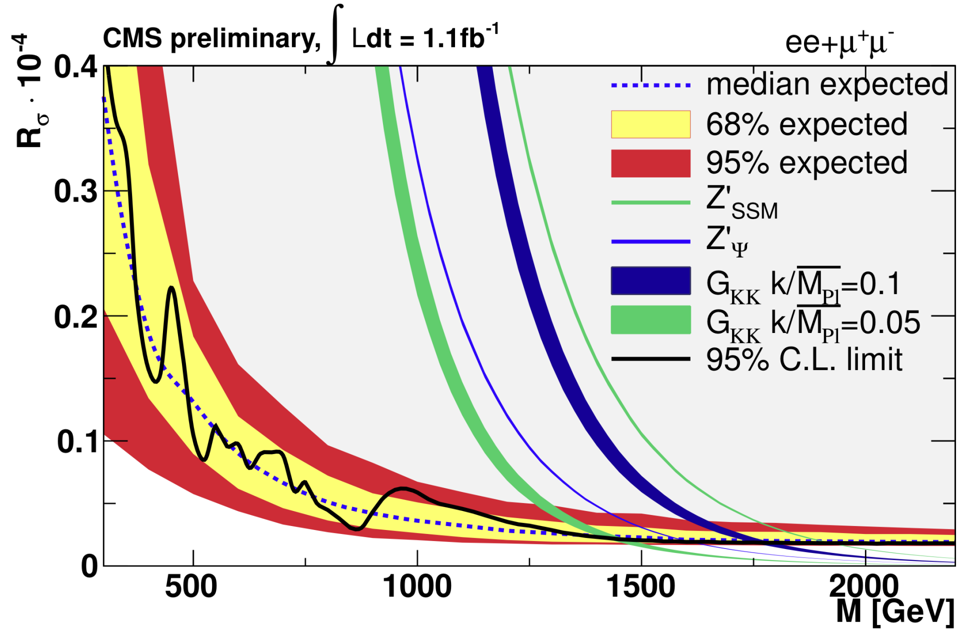
EXO-11-019

Dilepton Limits

- Signal and background shape parameters from MC
- Limit on ratio wrt Z

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}$$

- Use different methods: CL_{SB}, Feldman-Cousins, and a fully Bayesian technique

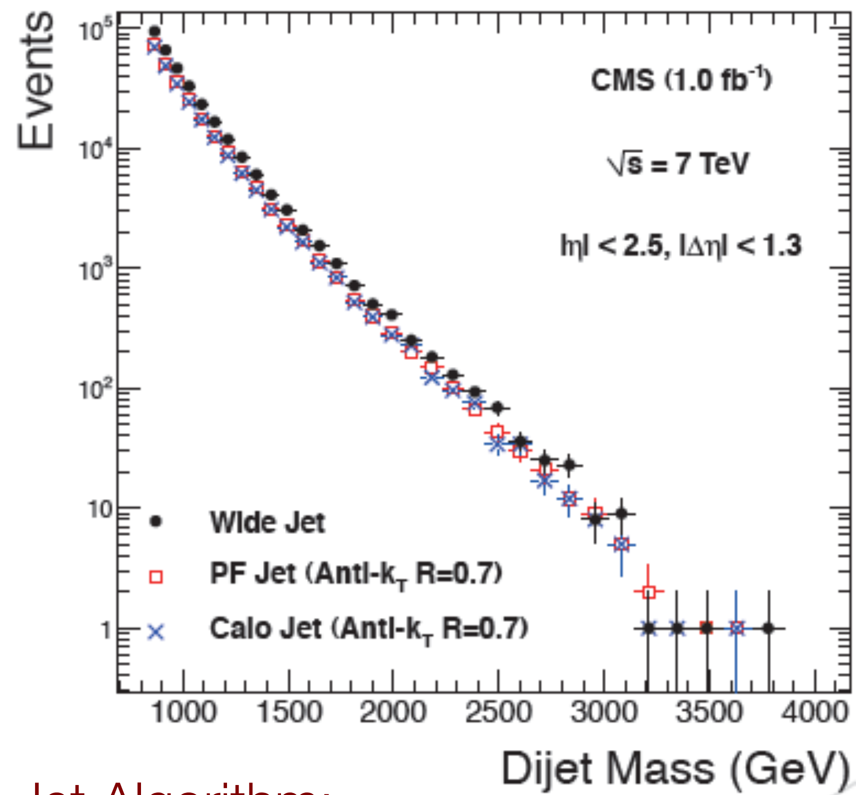


Model	$\mu^+\mu^-$+ee (GeV)
Z'_{SSM}	1940
Z'_{ψ}	1620
G*, k/M_{Pl}=0.05	1450
G*, k/M_{Pl}=0.1	1780

EXO-11-019

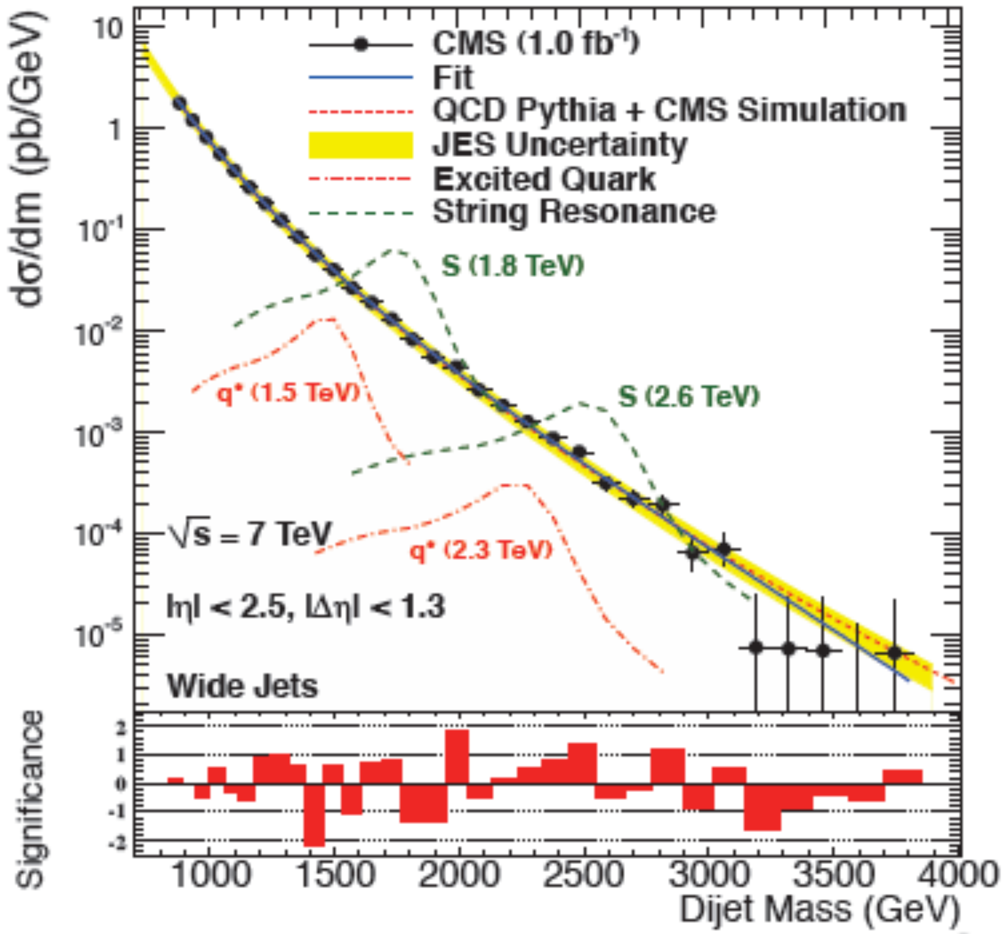
Dijet Resonances

- Signal: String resonance, excited quarks, axigluons, colorons, E_6 diquark, Z', W', RS gravitons
- Backgrounds:
  - QCD multijets (smoothly falling distribution predicted by SM)
- Analysis:
  - General model independent shape-based approach for 3 types of narrow resonances: qq, qg, gg
  - Differences mainly from FSR
- Offline: require 2 leading jets with $|\eta|$ <2.5 and $|\Delta\eta|$<1.3 and dijet mass > 838 GeV



- Jet Algorithm:
  - Combines Particle Flow jets with the anti-k_T (R=0.5) into "wide jets"
  - Radiation recovery: collect more FSR and improve mass resolution

Dijet Results

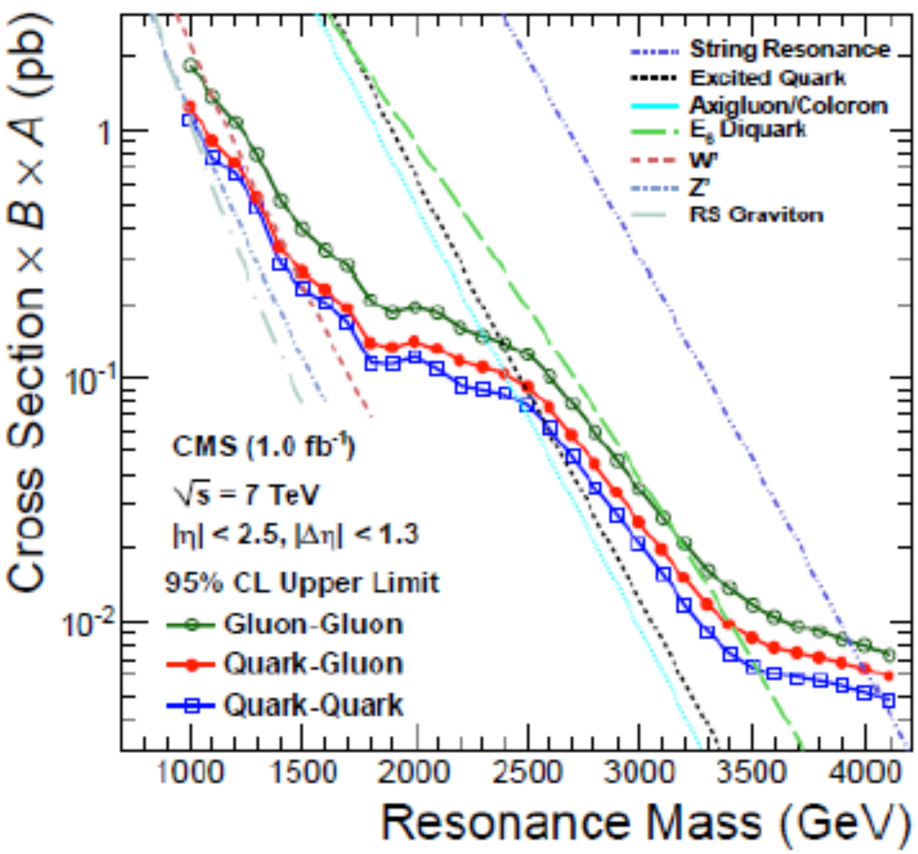


$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}}$$

- Systematic Uncertainties:
  - Jet Energy Scale: 2.2%
  - Jet Energy Resolution: 10%

EXO-11-015

Dijet Resonance Search Limits



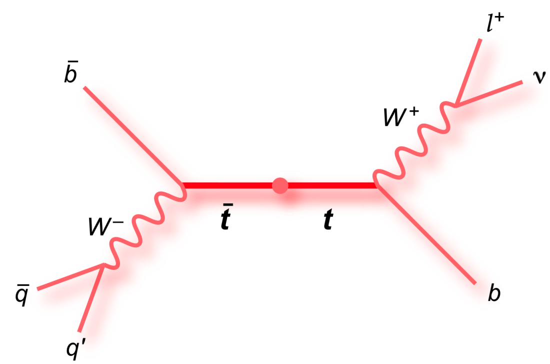
- Limits are set using Bayesian approach with constant prior and binned likelihood
- Benchmark models written as function of qq, qg, gg
- The use of wide-jets improves the limits by 20% for gg, 10% for qg, and 5% for qq

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

EXO-11-015

$t\bar{t}$ Resonances: Semileptonic Decay

- New bosons with enhanced coupling to top appear in many SM extensions (dynamical symmetry breaking, little higgs, extra-dim, etc)
- Signal: Z' (qq → Z' → $t\bar{t}$ → $W^+b\ W^-b$ → (qq'b)($\mu\nu$b) (or c.c.)
  - BR(t→Wb) ≈ 0.99; $t\bar{t}$ semileptonic (e, μ) BR ≈ 0.3
  - For benchmark Z', assume width is 1% of m_Z
  - Focus here on the updated μ analysis with 1.1fb^{-1}



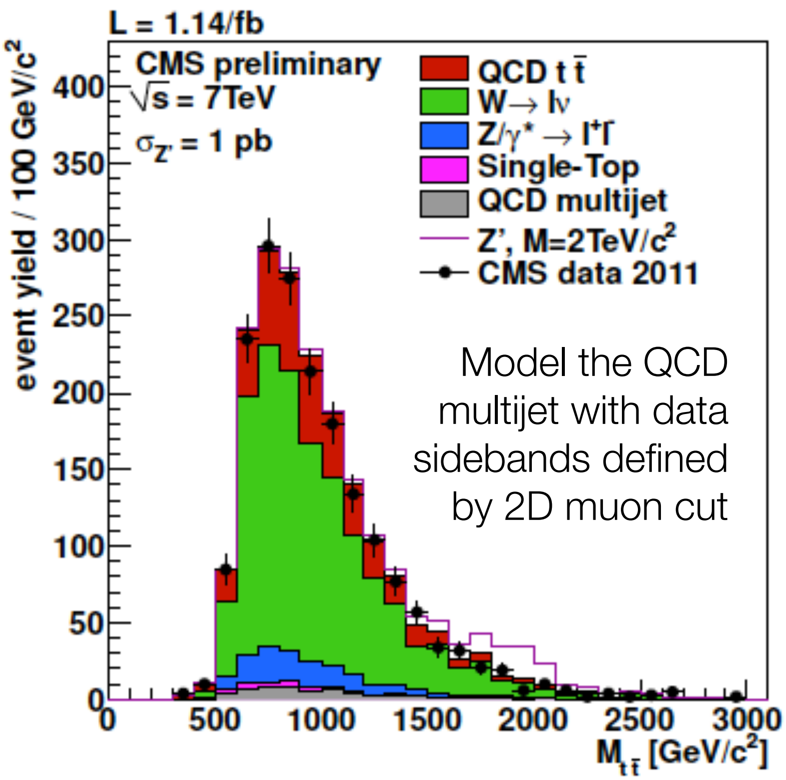
- Backgrounds:
  - SM $t\bar{t}$, W/Z + jets, single top, QCD multijets
- Analysis:
  - Search focuses on using $t\bar{t}$ with decay products narrowly collimated along the direction of the top
  - Assignment of jets to top quarks during mass reconstruction is based on topological criteria favoring back-to-back highly boosted top pairs

EXO-11-055

Semileptonic $t\bar{t}$: Selection

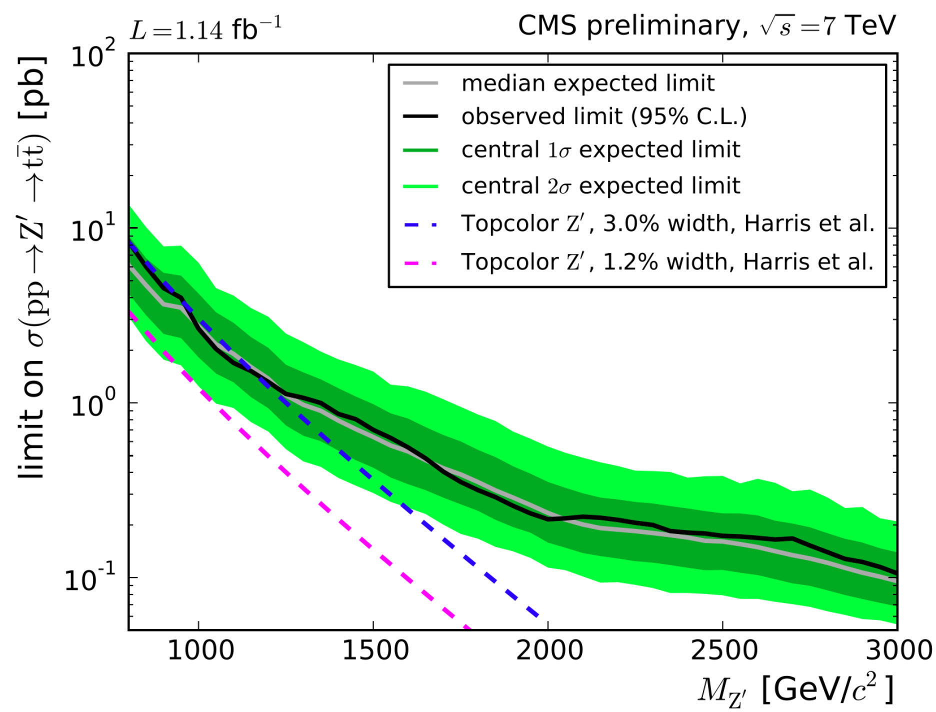
- Jets:
  - For high mass tt, the decay products of the hadronic decaying top can have small opening angles in the detector frame
  - Instead, rather than 4 jets: require two Particle Flow jets, p_T>50 GeV & $|\eta|$<2.4 with leading jet p_T>250 GeV
  - Jet Algorithm: Anti-k_T with R=0.5
- Muons:
  - p_T>35 GeV & $|\eta|$<2.1
  - Likewise, high top p_T results in low ΔR between μ and b, making it non-optimal to require the muon to be well-isolated
  - 2D cut: $\Delta R > 0.5$ or $p_{T,rel} > 25$ GeV to fight QCD multijets
- Lepton cut: veto events with additional μ/e to fight tt dilepton and Z
- $H_{T,lep} > 150$ GeV: scalar sum of muon p_T and MET

Semileptonic $t\bar{t}$: Limits



Model the QCD multijet with data sidebands defined by 2D muon cut

- Bayesian 95% CL upper limit on σ



- Systematic Uncertainties:
  - Jet Energy Scale 2-3%
  - Jet Energy Res 10-20%

Process	Expected limit $\pm 1\sigma$ band [pb]	Observed limit [pb]
$Z', M = 1\ \mathrm{TeV}/c^2$	$2.7^{+1.5}_{-0.9}$	2.7
$Z', M = 1.5\ \mathrm{TeV}/c^2$	$0.64^{+0.34}_{-0.21}$	0.70
$Z', M = 2\ \mathrm{TeV}/c^2$	$0.23^{+0.12}_{-0.07}$	0.22
$Z', M = 3\ \mathrm{TeV}/c^2$	$0.10^{+0.04}_{-0.03}$	0.11

EXO-11-055

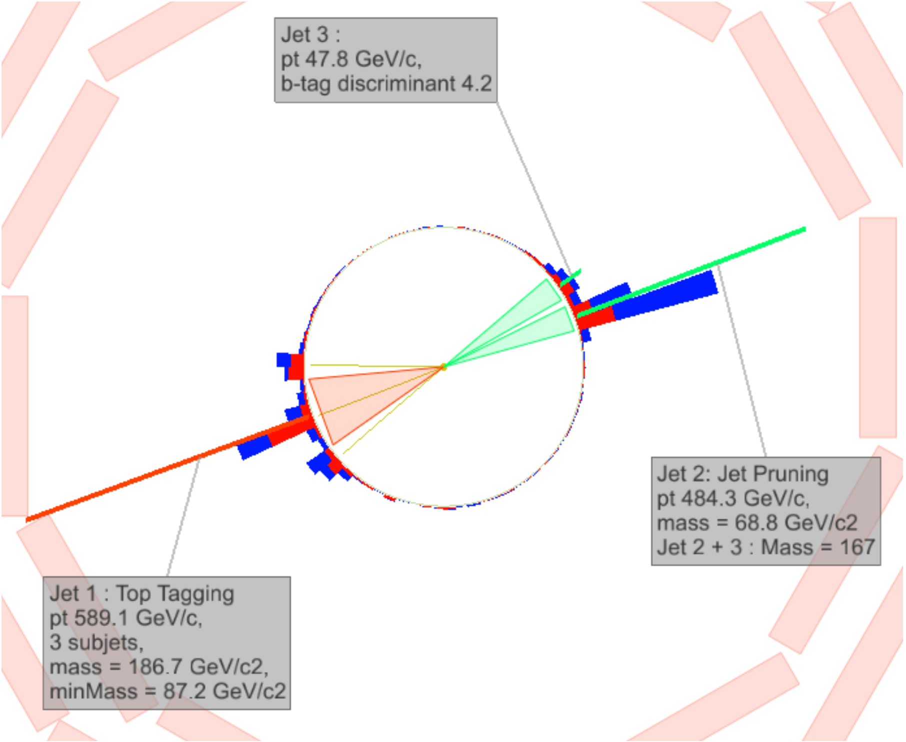
$t\bar{t}$ Resonances: All Hadronic Decay

- Signal: Z' (qq → Z' → tt → Wb Wb → (qq'b)(qq'b))
  - Motivations similar to previous analysis EXO-11-055, but BR 46%
  - Again, the benchmark is a generic Z' with narrow width (1%)
- Backgrounds:
  - QCD multijet production (dominant, use data-driven methods)
  - SM tt production (significantly smaller, estimated from MC)
- Analysis:
  - Focus on > 1 TeV
  - Exploits highly-boosted nature of top quarks from the high mass resonances (decay products falling inside single jet)
- Jet tagging algorithms:
  - Top tagging: identify merged top jets by analyzing their substructure
  - Jet pruning: Performs less well, but more generic for arbitrary topologies

EXO-11-006

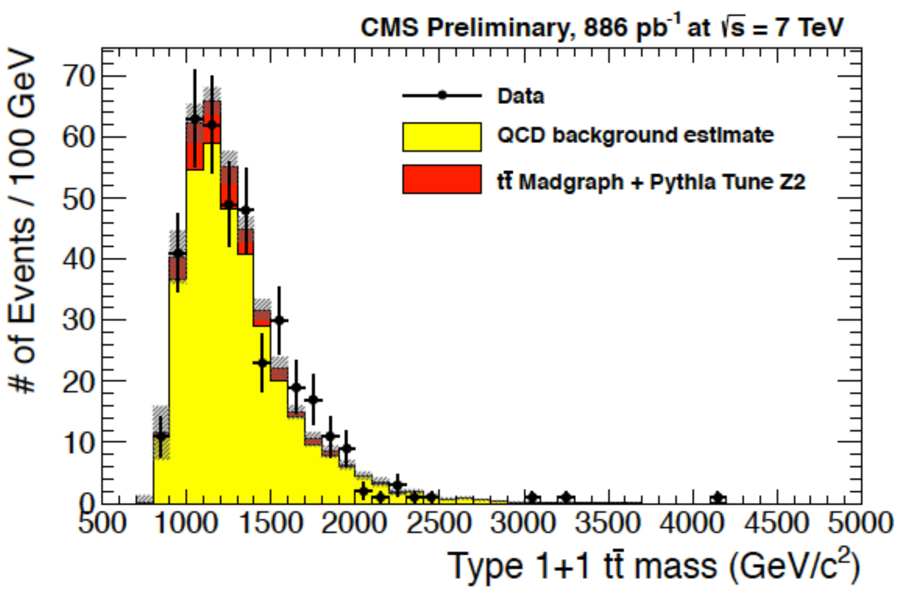
Hadronic $t\bar{t}$: Categories

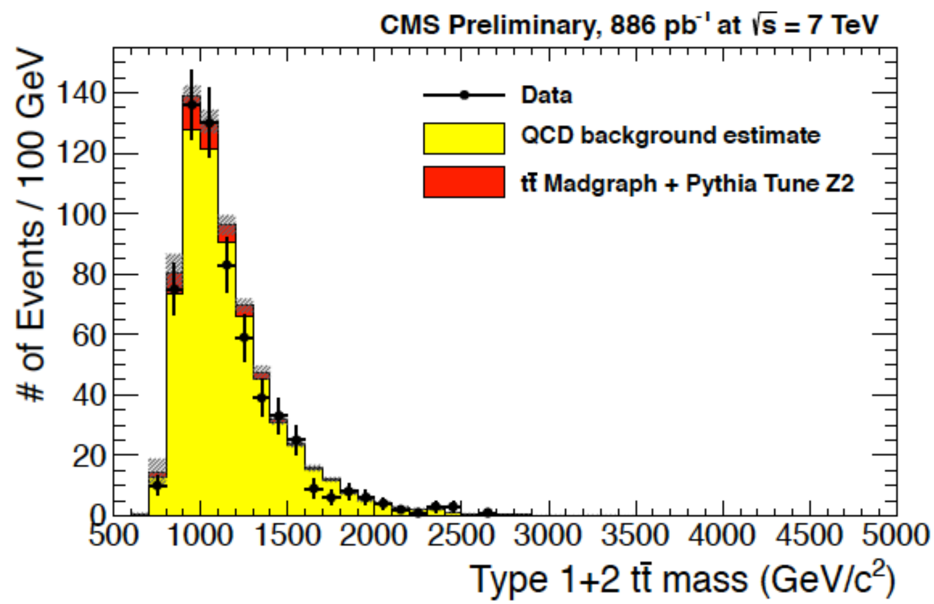
- Events are classified into categories, depending on boost
- Event is divided into hemispheres, so each hemisphere contains the final products of each top
  1. High boost: all 3 jets in one hemisphere are merged into one “top jet”
  2. Moderate boost: only 2 out of 3 of the jets are merged



- Search in two categories:
  - “Type 1+1”: two highly boosted jets
  - “Type 1+2”: three-jet event

Hadronic $t\bar{t}$: Results

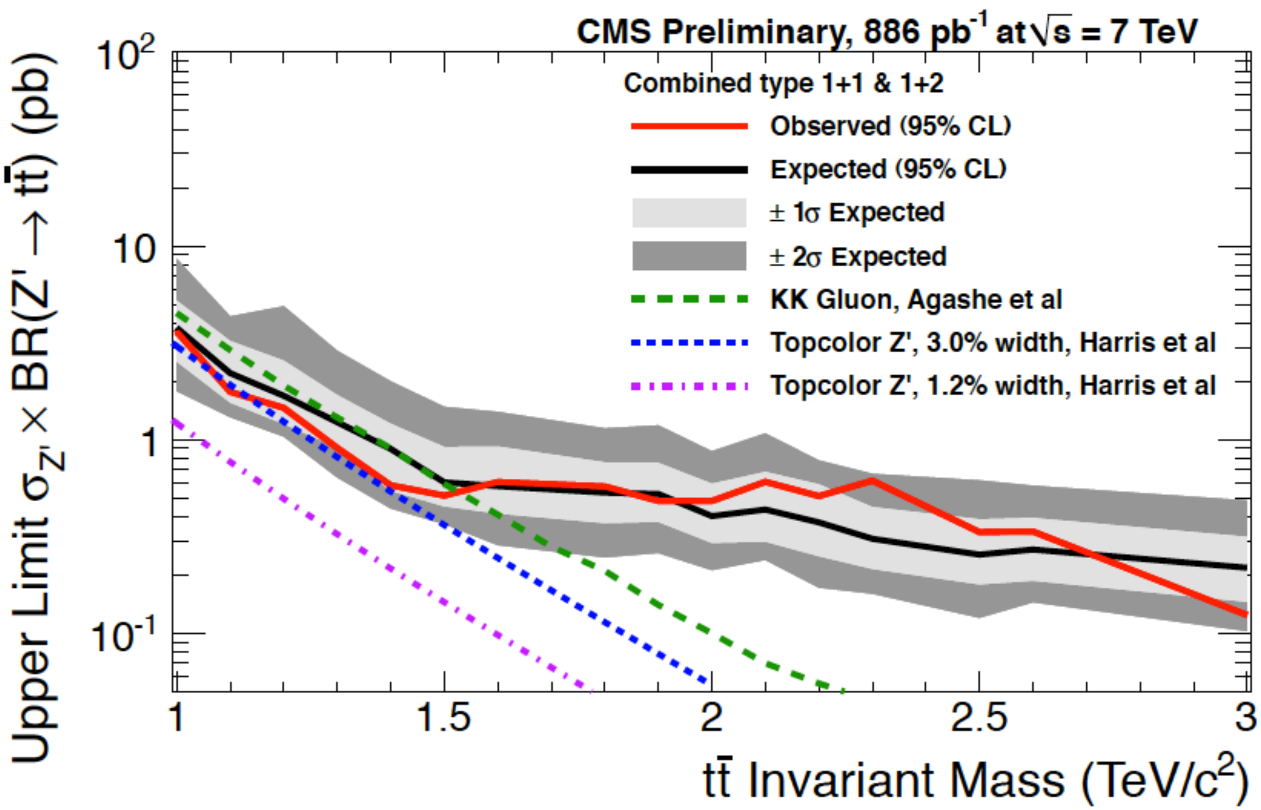




- High Mass Search: Type 1+1 events
- Intermediate Mass Search: Type 1+2 events
- Continuum tt contribution is small and is estimated from MC
- QCD estimated with top tagging mistag rate measured from data

Hadronic $t\bar{t}$: Results

- Systematic uncertainties:
  - Subjet eff scale factor (28%)
  - Jet energy scale (2-19%)
  - Trigger (13-20%)
  - Mistag (1-25%)



- Limits:
  - Counting Experiment
  - Set sub-pb limits on σ x BR for $m_{Z'}$>1.1 TeV
  - Exclude KK gluon model with 1.0<m<1.5 TeV

Conclusions

Analysis	Dataset (fb^{-1})	Signal	95% CL Limits (TeV)
Diphoton	1.1	RS G* k/MPl=0.01, 0.05, 0.1	0.77, 1.41, 1.74
Dilepton	1.1	RS G* k/MPl=0.05, 0.1 Z'_{SSM} Z'_{Ψ}	1.45, 1.78 1.94 1.62
Dijet	1.0	String Resonances E6 Diquarks Excited Quarks Axigluons/Colorons W'	4 3.52 2.49 2.47 1.51
$t\bar{t}$ semileptonic	1.1	Topcolor Z' with width 3% $\sigma(pp \rightarrow Z' \rightarrow tt) < 1\ (0.2)$ pb for $m_{Z'}>1.35\ (2.3)$ TeV	Exclude $0.805<m_{Z'}<0.935$ and $0.960<m_{Z'}<1.060$
$t\bar{t}$ all hadronic	0.886	RS KK gluon $\sigma(pp \rightarrow Z' \rightarrow tt) < 1$pb for $m_{Z'}>1.1$TeV	Excluded for $1.0<m<1.5$

Thank you!

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

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