Searches for Physics Beyond the Standard Model at CMS

Jamie Antonelli
for the CMS collaboration

La Thuile

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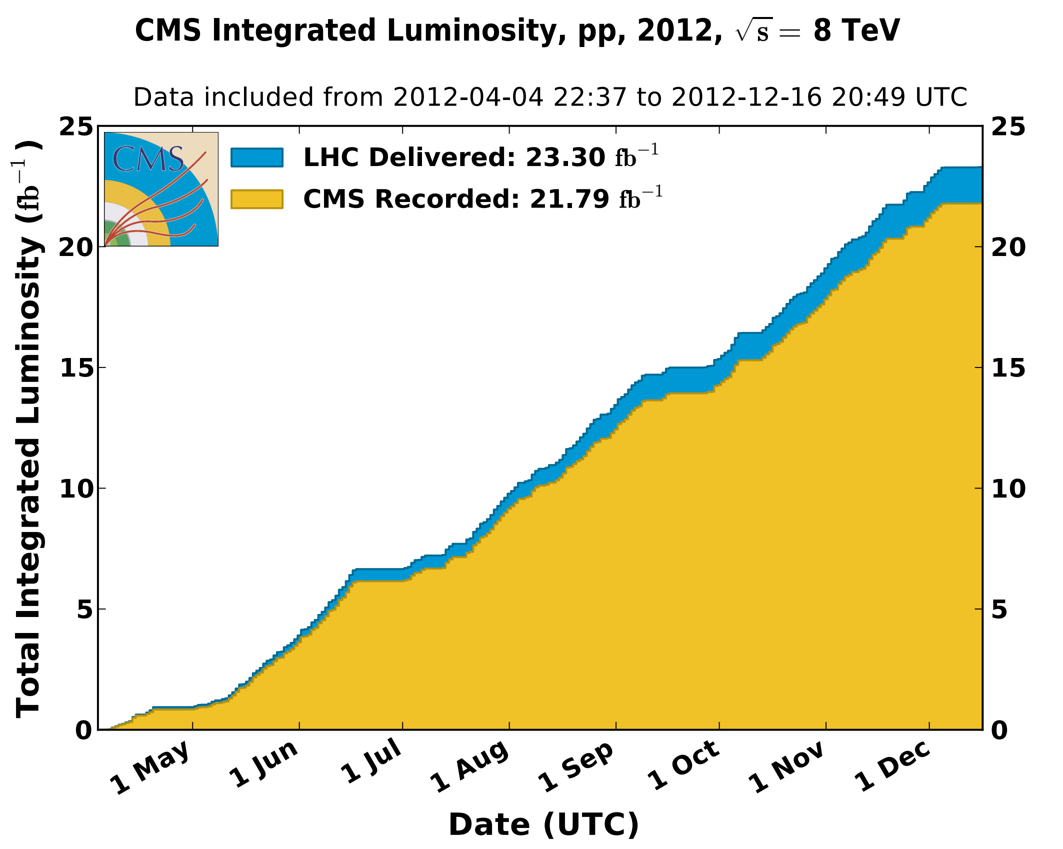
Introduction



- CMS has recorded ~20/fb of pp collision data at √s = 8 TeV
- There are many interesting phenomena that could be hiding in this dataset
- SUSY, dark matter, 4th generation, large extra dimensions, gravitons, hidden sectors, microscopic black holes - *or something completely unexpected*
- CMS has an extensive program of searches:

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

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

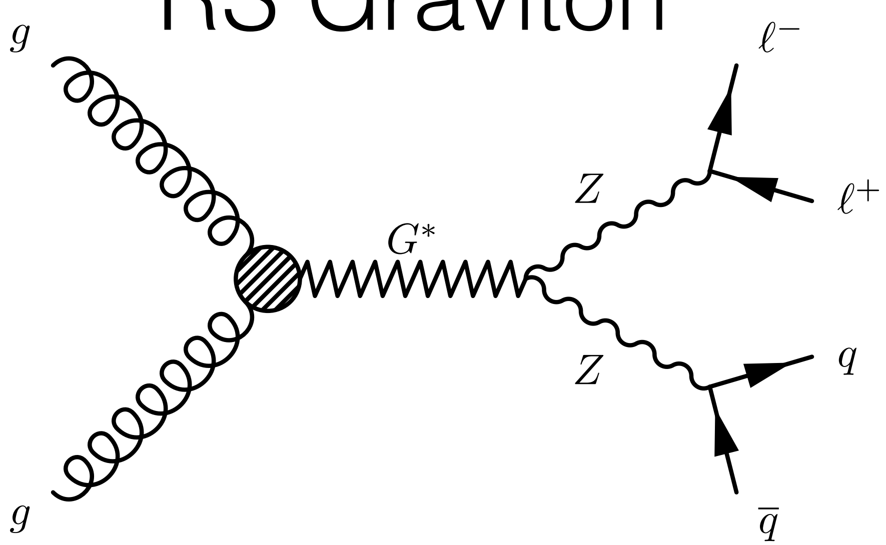
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

List of searches covered in this talk

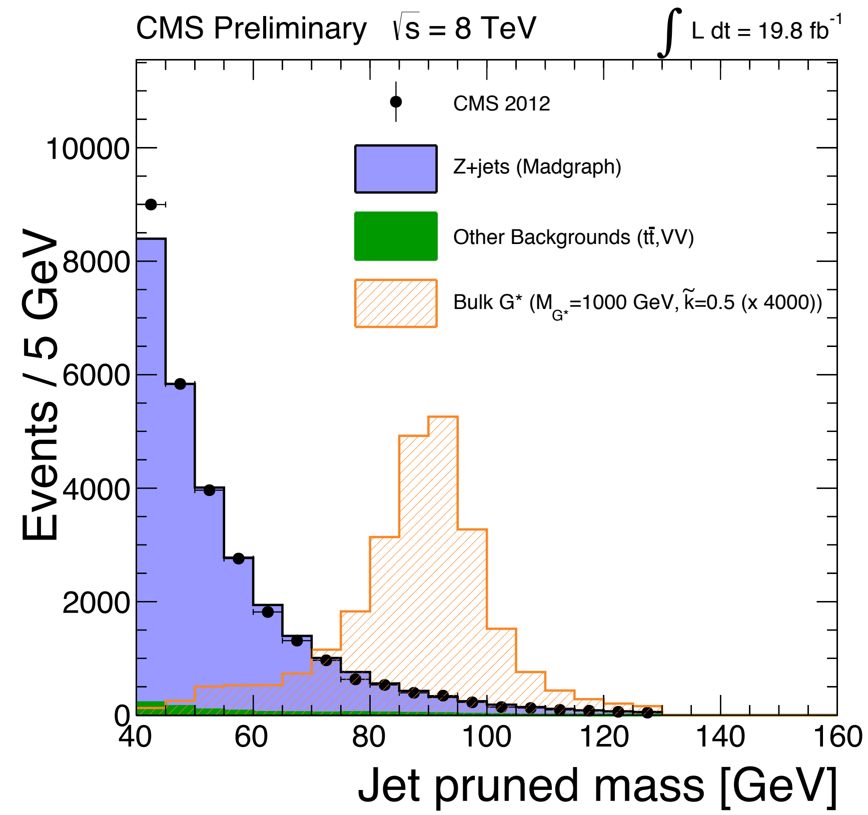
- ZZ resonance search EXO-12-022
- WW resonance search EXO-12-021
- Vector-like b′ search B2G-13-003
- Vector-like T search B2G-12-015
- Displaced dijet search EXO-12-038

ZZ resonances EXO-12-022

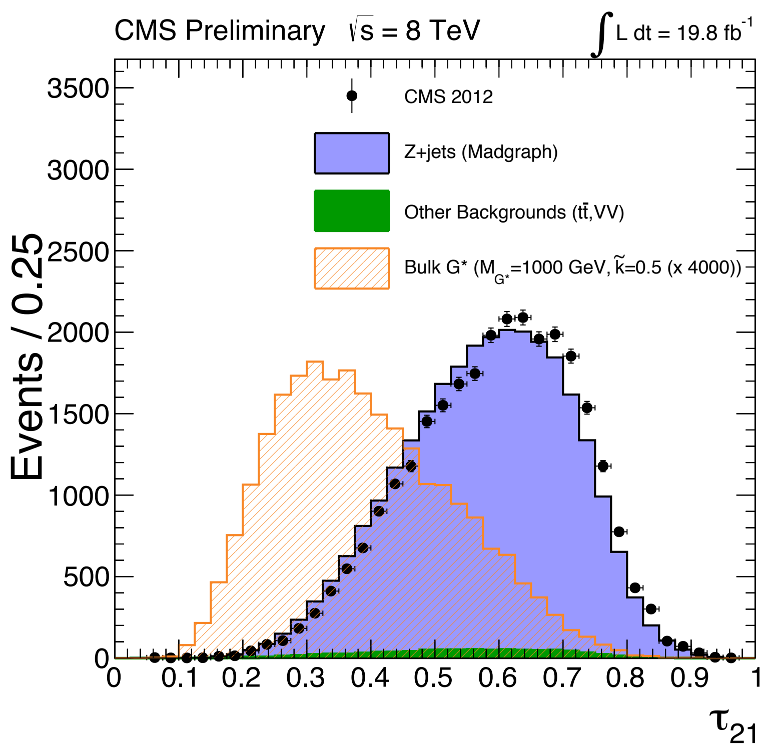
RS Graviton



heavy G* → boosted Z's
boosted Z's → collimated decays



jet pruning:
remove pileup,
UE, soft radiation

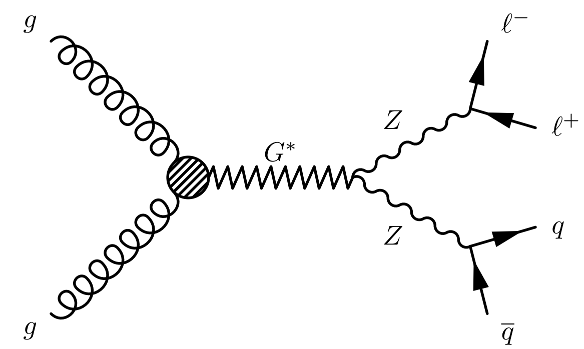


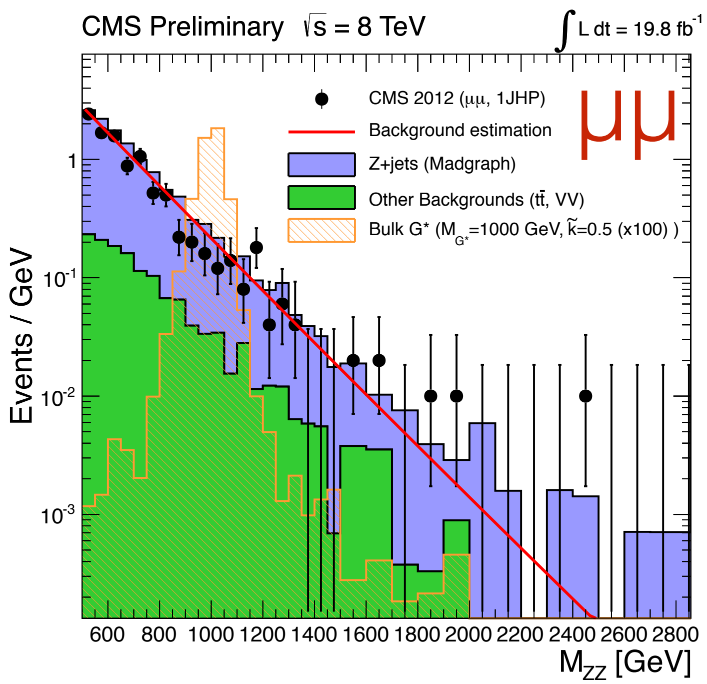
jet substructure:
classify jets by likelihood
to have *N* sub-jets

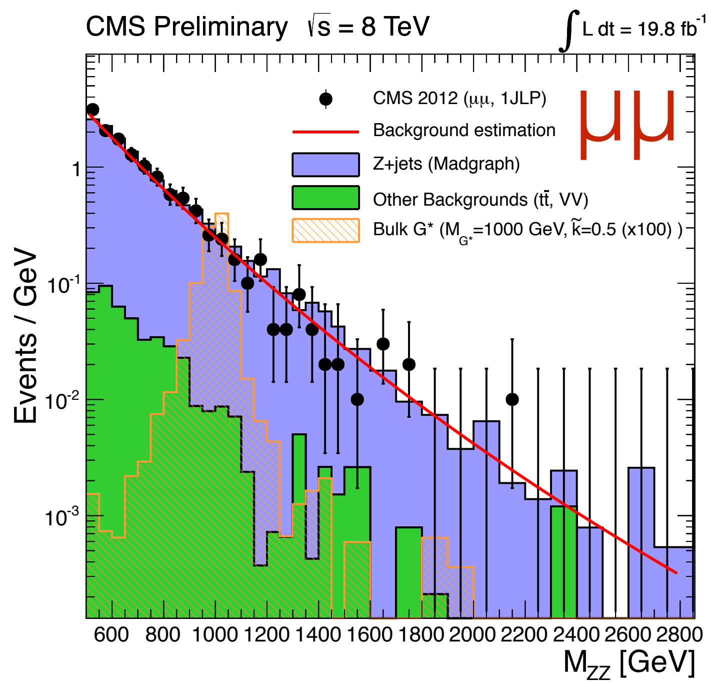
$$\tau_{21} = \tau_2 / \tau_1 \qquad \tau_N = \frac{1}{d_0}\sum_k p_{T,k}\min(\Delta R_{1,k}, \Delta R_{2,k} ... \Delta R_{N,k})$$

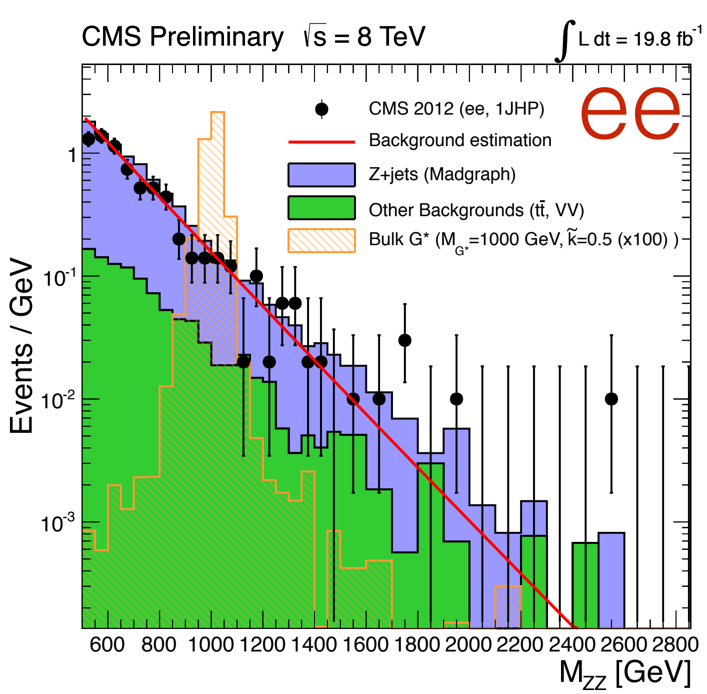
ZZ resonances EXO-12-022

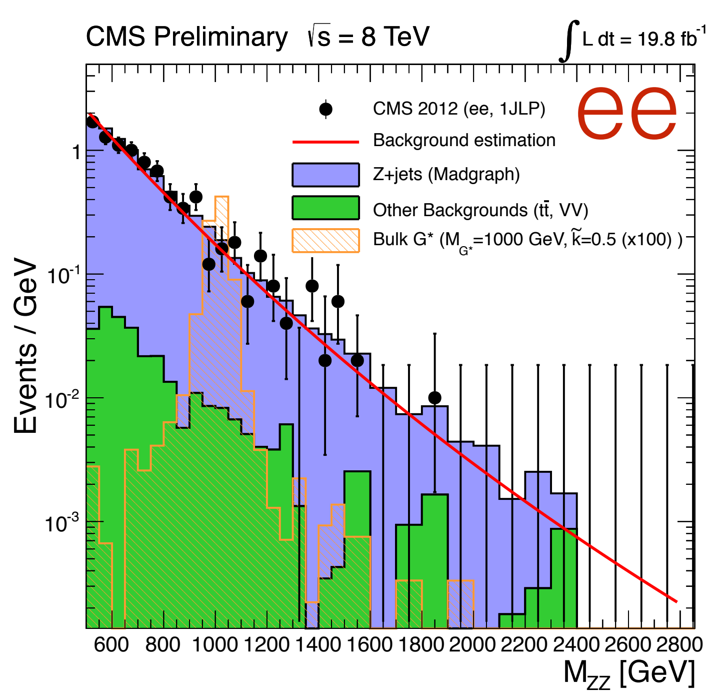
divide high purity (L) and low purity (R) regions in τ_{21}



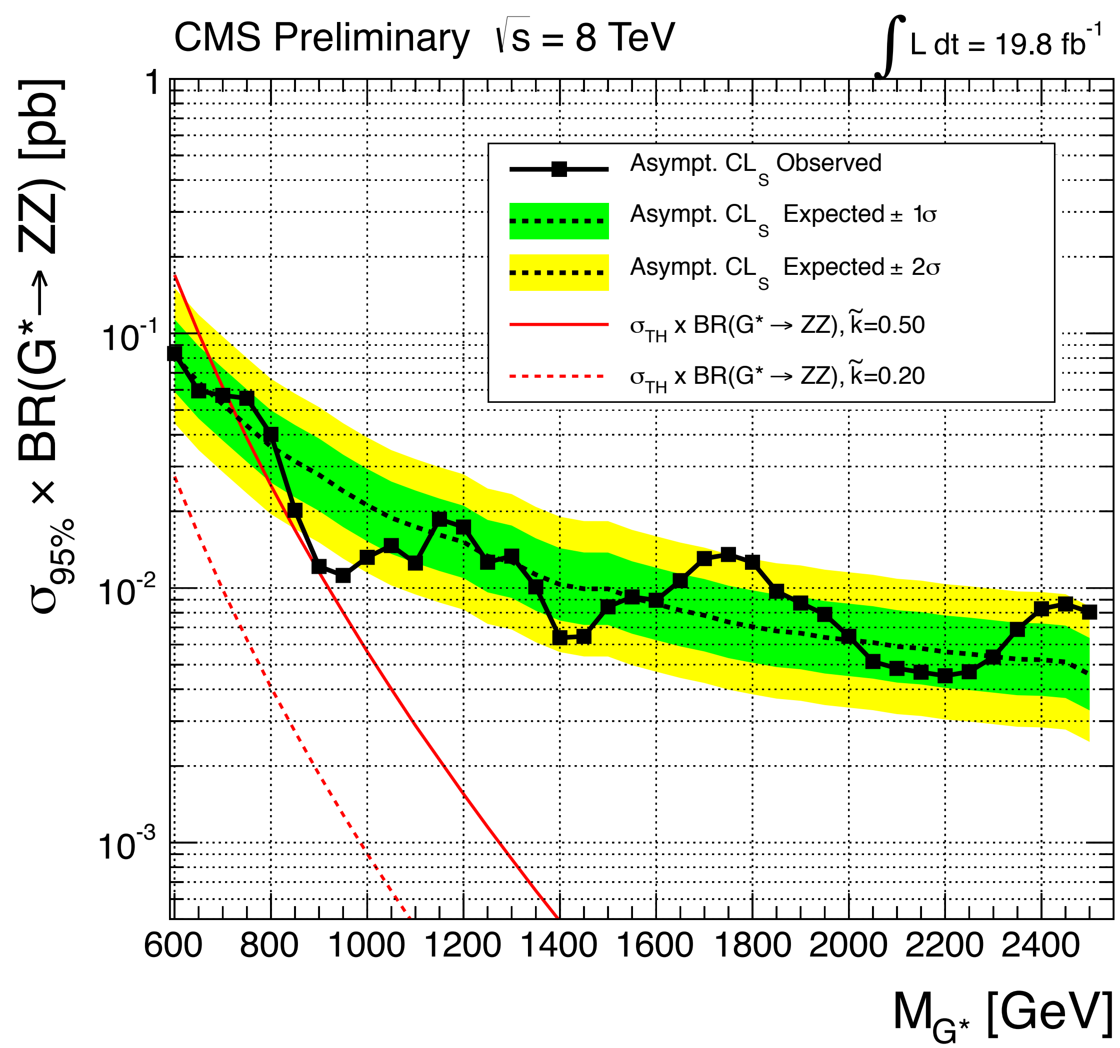








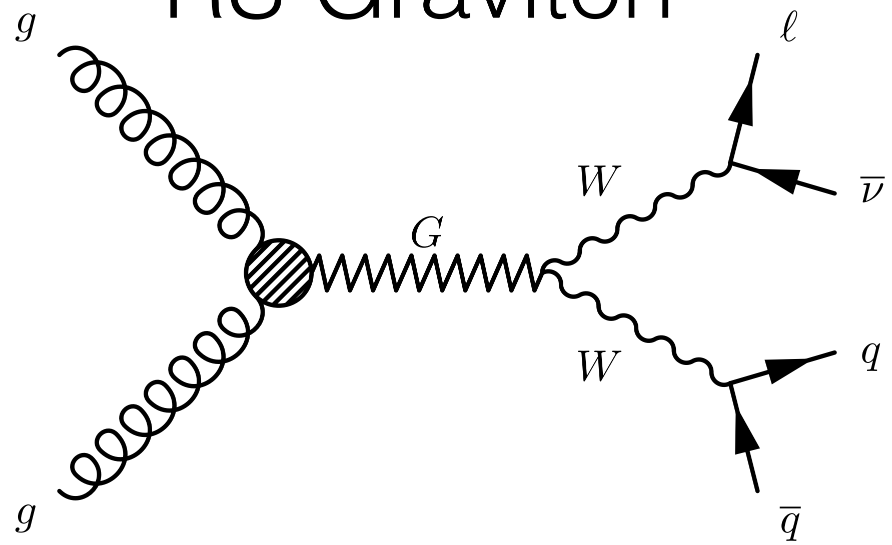
use low mass sideband of hadronic leg to estimate DY background



combined limit from 4 channels

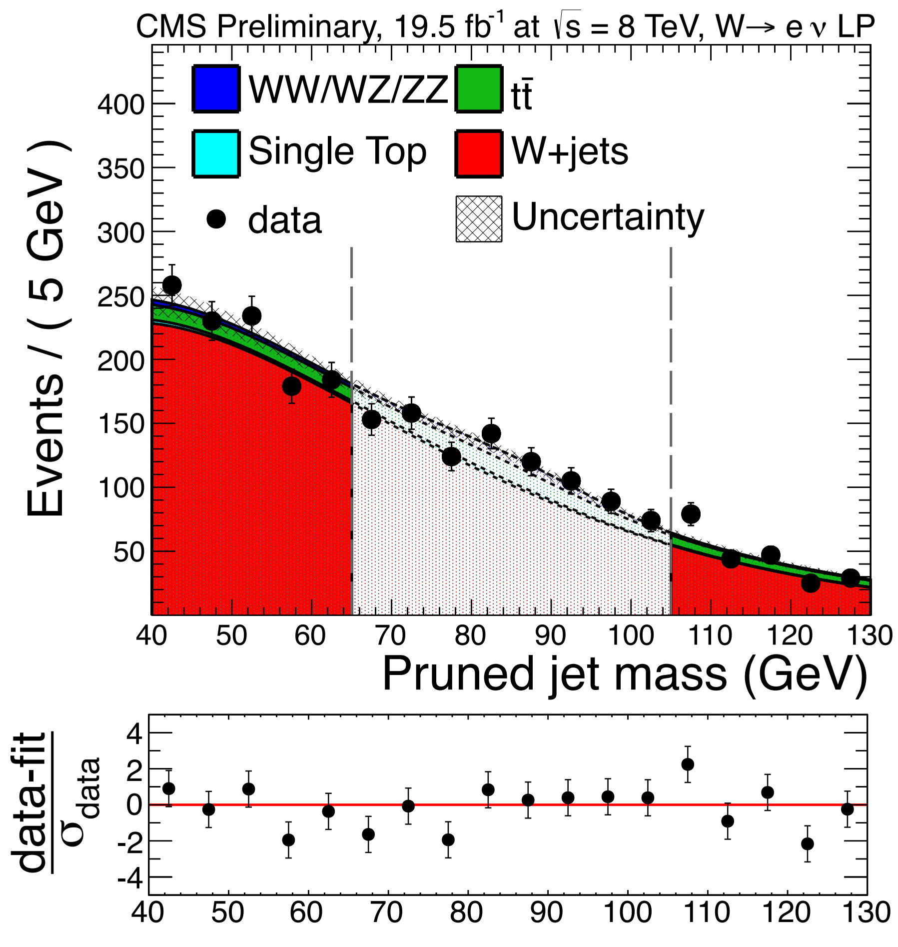
WW resonances EXO-12-021

RS Graviton

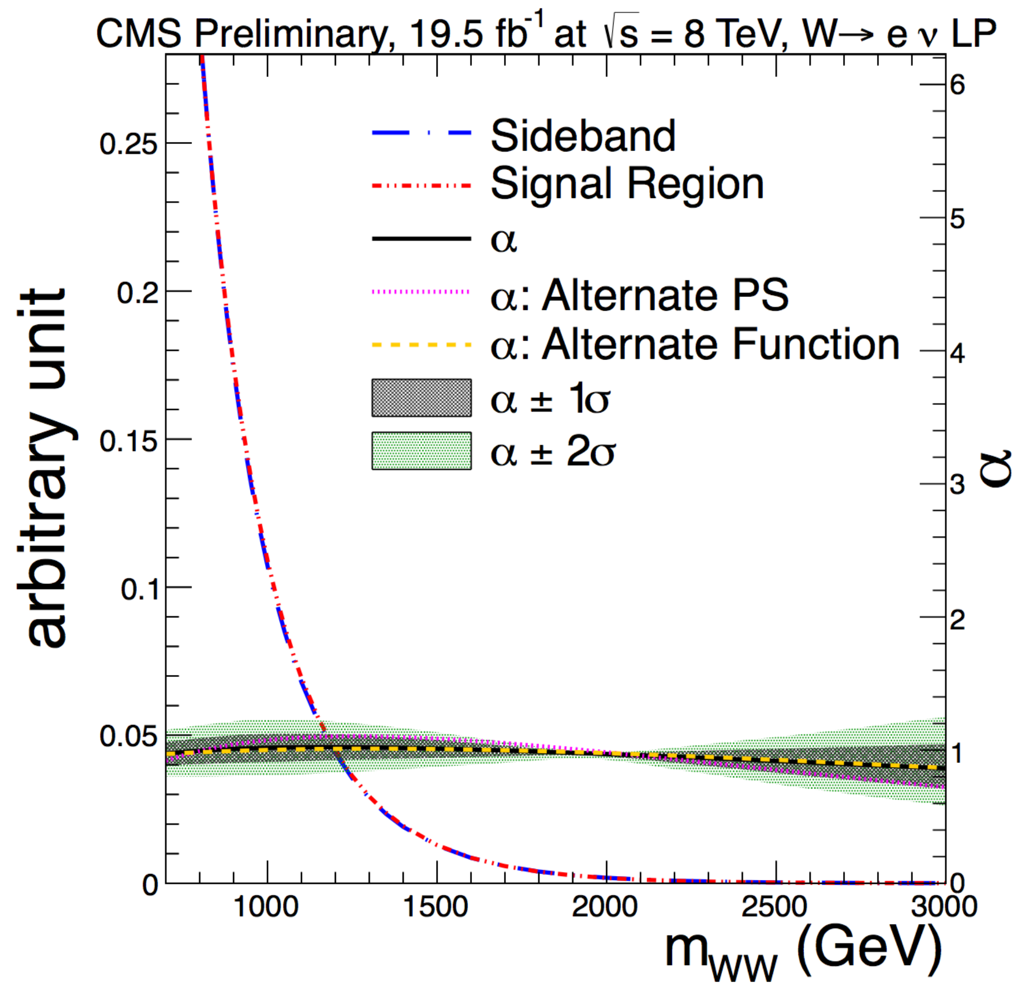


similar to ZZ search - high mass bump hunt

use similar jet pruning/substructure techniques

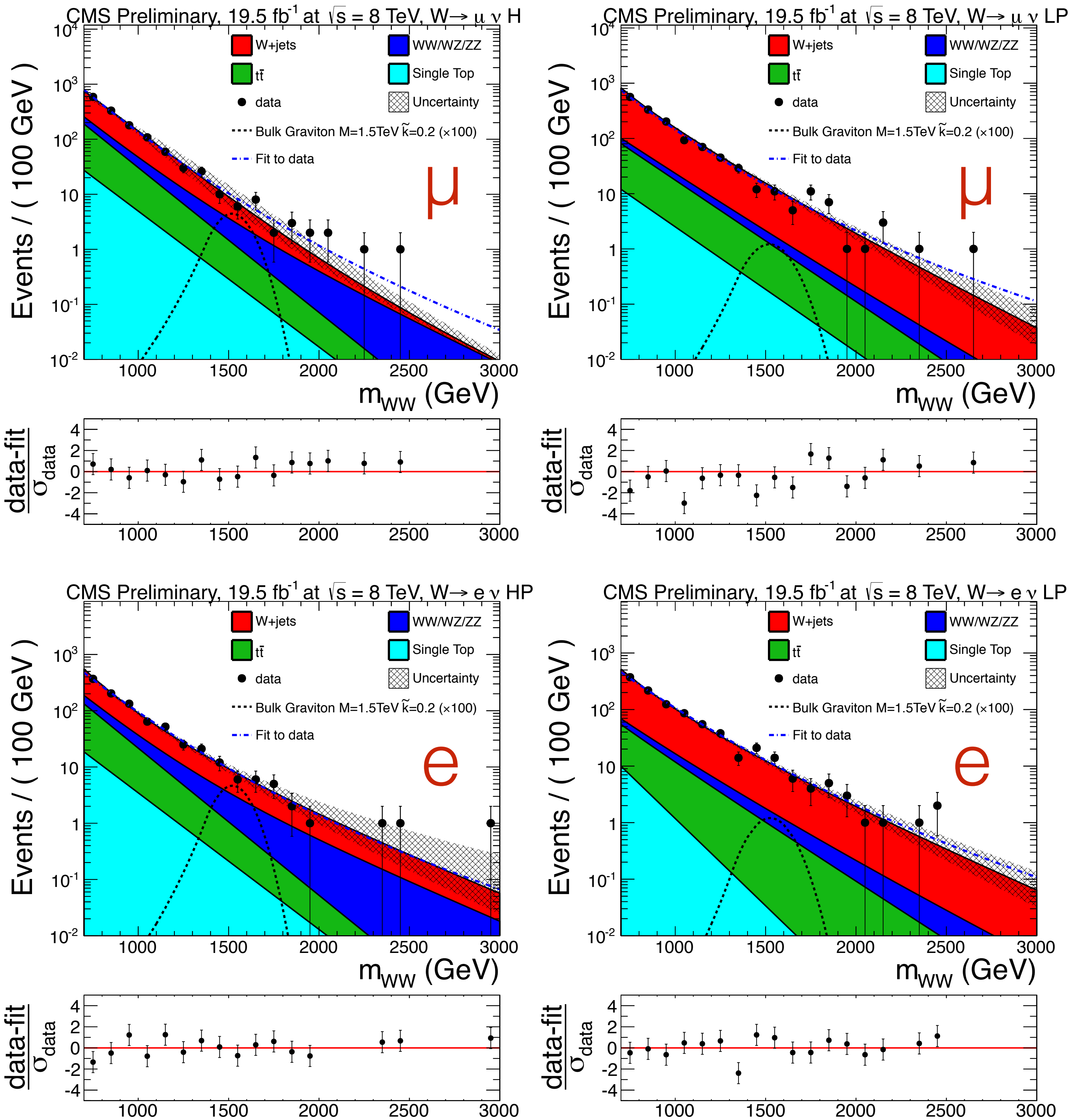


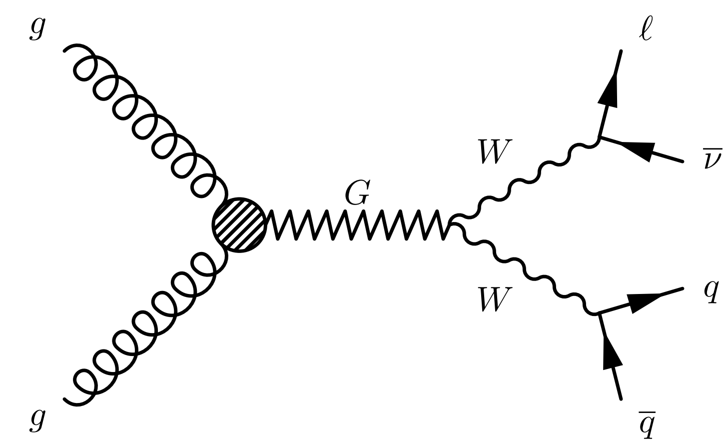
use low mass sidebands of hadronic leg to measure W background

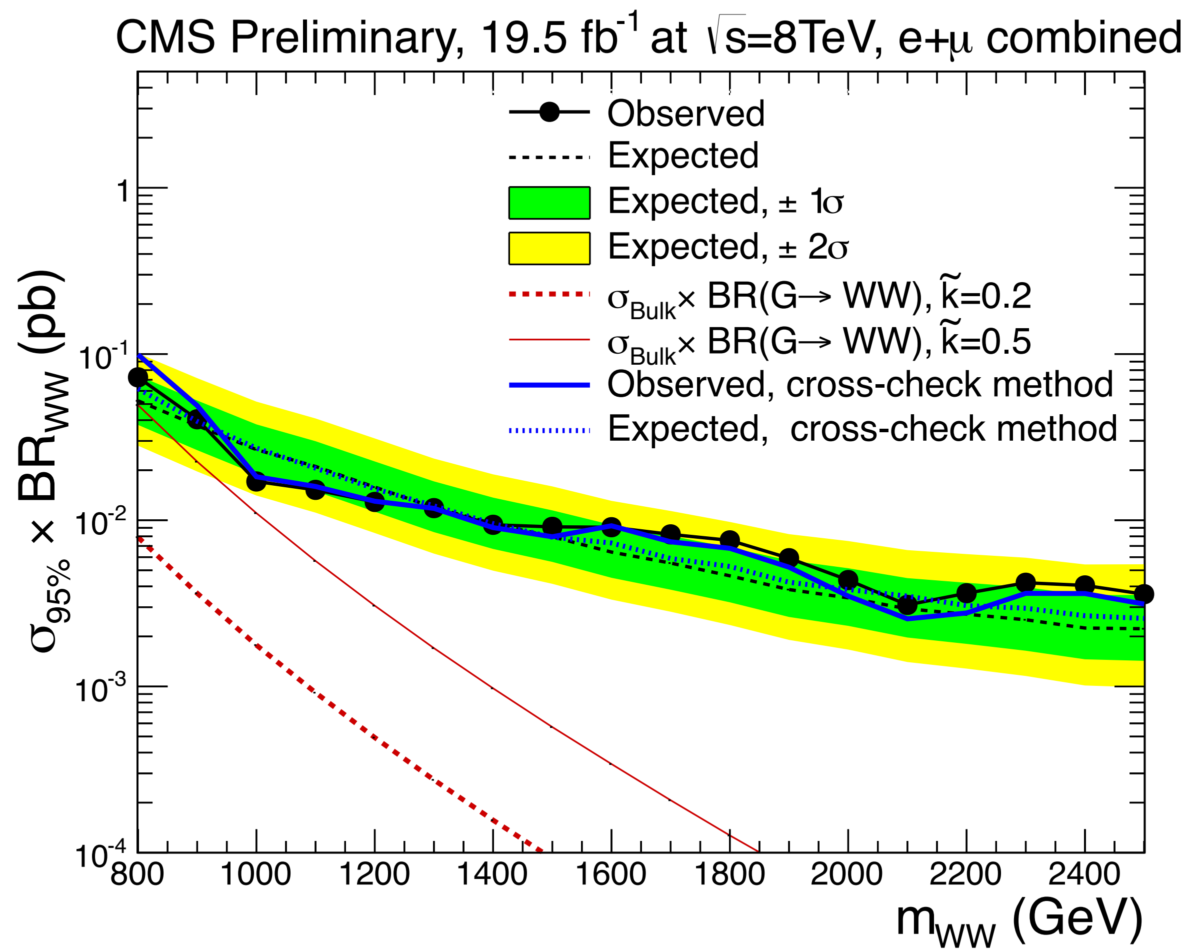


WW resonances EXO-12-021

low (L) and high (R) τ_{21}







combined limit from 4 channels

b′ searches B2G-13-003

b′ - vector-like 4th generation down-type quark

Little Higgs models use 4th generation to stabilize Higgs mass

Vector-like quark eludes limits on only 3 generations in SM

b′ decay chains:

- $b' \to tW$
- $b' \to bZ$
- $b' \to bH$

3,4-lepton final states

Categorize search sample by:

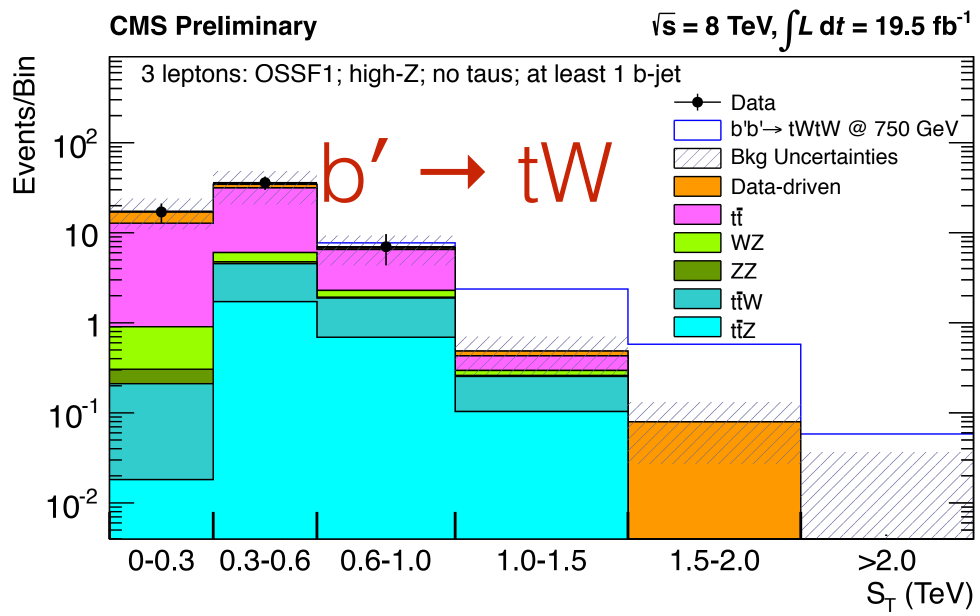
- # leptons
- # OS SF lepton pairs
- # Z candidates (using M_{ll})
- # hadronic tau decays
- # b-tagged jets
- Total activity (S_T):
  - $S_T = \Sigma p_T$ (leptons, jets, missing E_T)

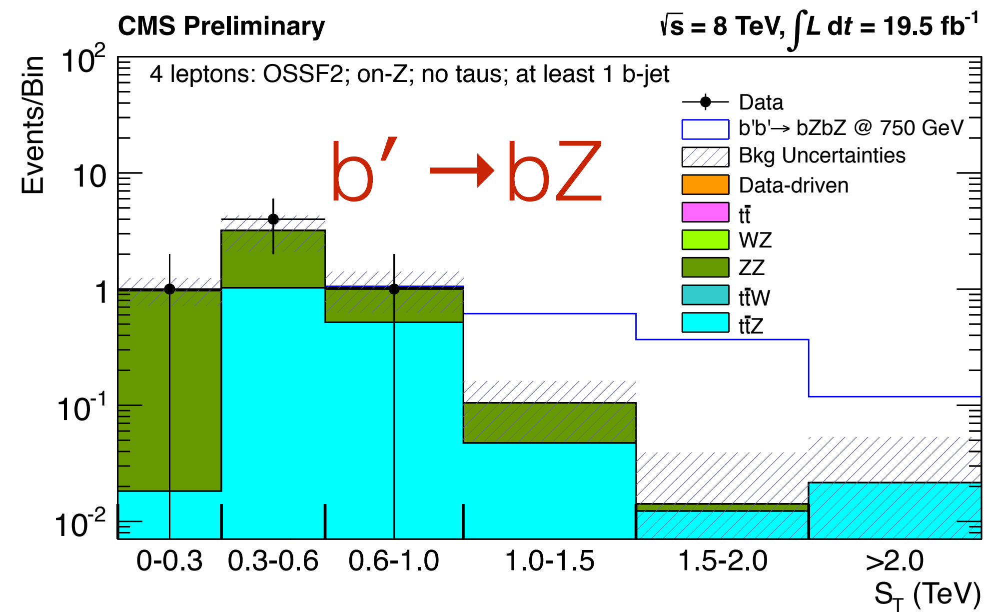
b′ searches

B2G-13-003

background estimate: data-driven for fake leptons, validated MC for irreducible

different channels for different decays

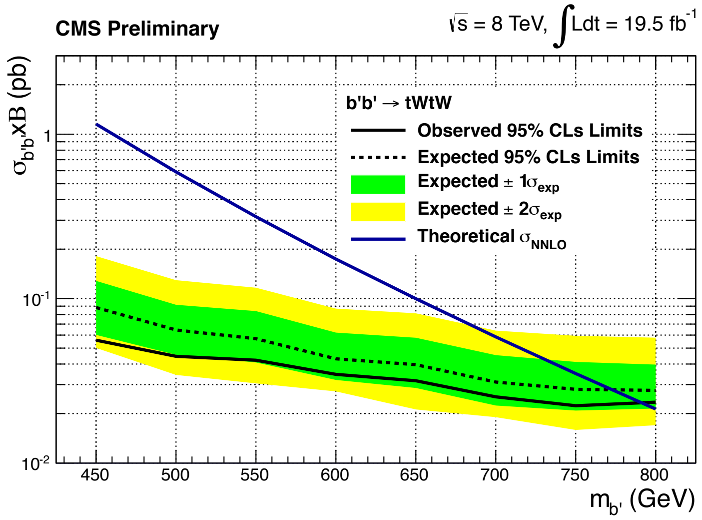




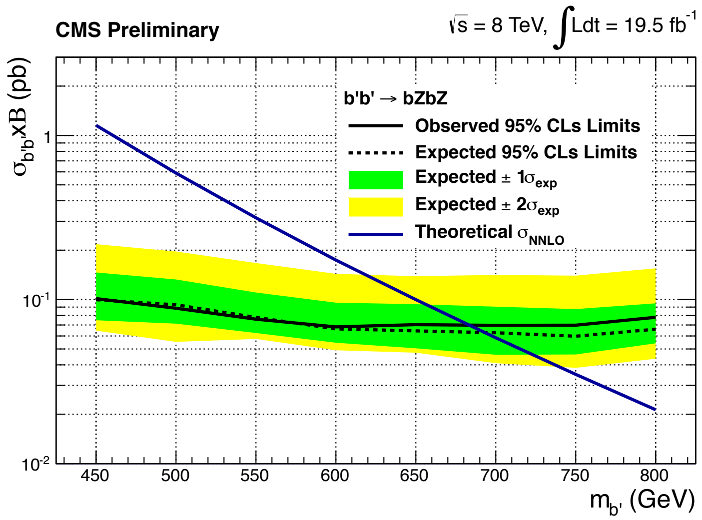
N_{OSSF}	$m(\ell^+\ell^-)$ (GeV)	S_T (TeV)	$N_{\tau_h}=0$, $N_{b\text{-jets}}=0$ obs	exp	$N_{\tau_h}=1$, $N_{b\text{-jets}}=0$ obs	exp	$N_{\tau_h}=0$, $N_{b\text{-jets}}\geq 1$ obs	exp	$N_{\tau_h}=1$, $N_{b\text{-jets}}\geq 1$ obs	exp
0	-	> 2.0	0	< 0.02	0	0.04 ± 0.05	0	0 ± 0.02	0	0 ± 0.22
0	-	1.5 − 2.0	0	0.07 ± 0.06	0	0.18 ± 0.19	0	0.05 ± 0.06	0	0.46 ± 0.28
0	-	1.0 − 1.5	0	0.21 ± 0.18	2	2.6 ± 1.2	0	0.36 ± 0.14	2	3.9 ± 2
0	-	0.6 − 1.0	†3	3.1 ± 1	†26	28 ± 12	2	4.9 ± 1.9	†46	58 ± 28
0	-	0.3 − 0.6	32	27 ± 10	289	290 ± 129	42	39 ± 17	410	480 ± 241
0	-	0 − 0.3	72	79 ± 22	1194	1324 ± 330	37	32 ± 15	316	331 ± 160
1	> 105	> 2.0	0	0.001 ± 0.02	0	0 ± 0.21	0	0 ± 0.03	0	0 ± 0.21
1	< 75	> 2.0	0	0.004 ± 0.02	0	0 ± 0.21	0	0.01 ± 0.04	0	0 ± 0.21
1	onZ	> 2.0	0	0.2 ± 0.12	0	0.009 ± 0.21	0	0.04 ± 0.06	0	0.04 ± 0.05
1	> 105	1.5 − 2.0	0	0.15 ± 0.09	0	0.22 ± 0.22	0	0.08 ± 0.05	0	0.2 ± 0.18
1	< 75	1.5 − 2.0	1	0.11 ± 0.08	0	0.03 ± 0.05	0	0.07 ± 0.05	0	0.06 ± 0.07
1	onZ	1.5 − 2.0	3	1.1 ± 0.6	0	0.31 ± 0.17	1	0.28 ± 0.18	0	0.25 ± 0.12
1	> 105	1.0 − 1.5	2	1 ± 0.4	1	1.3 ± 0.6	0	0.5 ± 0.22	1	2.1 ± 1.2
1	< 75	1.0 − 1.5	0	1.1 ± 0.38	1	0.9 ± 0.44	†1	0.6 ± 0.27	0	1 ± 0.7
1	onZ	1.0 − 1.5	11	15 ± 6.9	9	5.9 ± 1.6	2	3.3 ± 1.2	1	1.7 ± 0.6
1	> 105	0.6 − 1.0	13	10 ± 2.4	21	23 ± 7.2	†7	7.4 ± 2.4	23	28 ± 14
1	< 75	0.6 − 1.0	14	10 ± 3.6	21	11 ± 3.4	†4	8.3 ± 2.6	†14	12 ± 6
1	onZ	0.6 − 1.0	106	111 ± 40	108	70 ± 17	†16	24 ± 7	17	17 ± 4.7
1	> 105	0.3 − 0.6	63	65 ± 12	285	372 ± 96	36	35 ± 13	169	187 ± 94
1	< 75	0.3 − 0.6	84	86 ± 21	290	279 ± 71	52	56 ± 22	167	171 ± 87
1	onZ	0.3 − 0.6	*669	735 ± 166	*2099	2705 ± 772	122	108 ± 24	325	284 ± 73
1	> 105	0 − 0.3	180	195 ± 33	1620	1712 ± 482	17	17 ± 6.4	97	79 ± 35
1	< 75	0 − 0.3	617	644 ± 102	10173	9211 ± 2694	62	74 ± 28	297	288 ± 97
1	onZ	0 − 0.3	*4255	4439 ± 691	*49916	49192 ± 14670	*140	149 ± 24	795	826 ± 229
Total3	All	All	6125	6430 ± 916	66055	65233 ± 19038	541	564 ± 150	2680	2774 ± 903

b′ searches

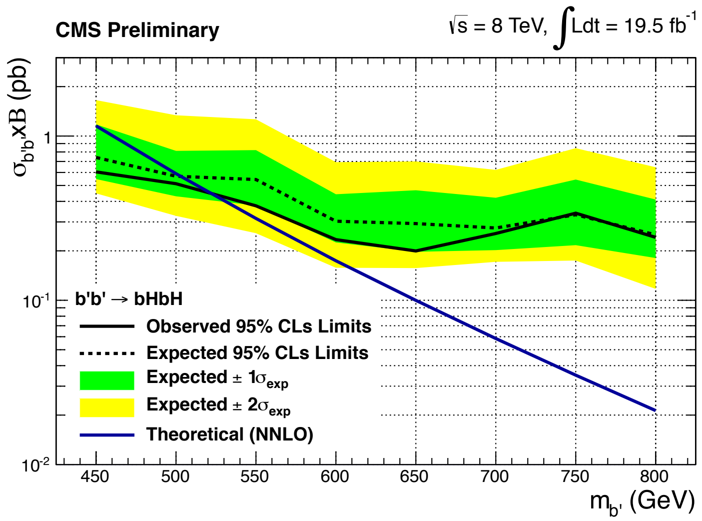
B2G-13-003



b′ → tW



b′ →bZ



b′ → bH

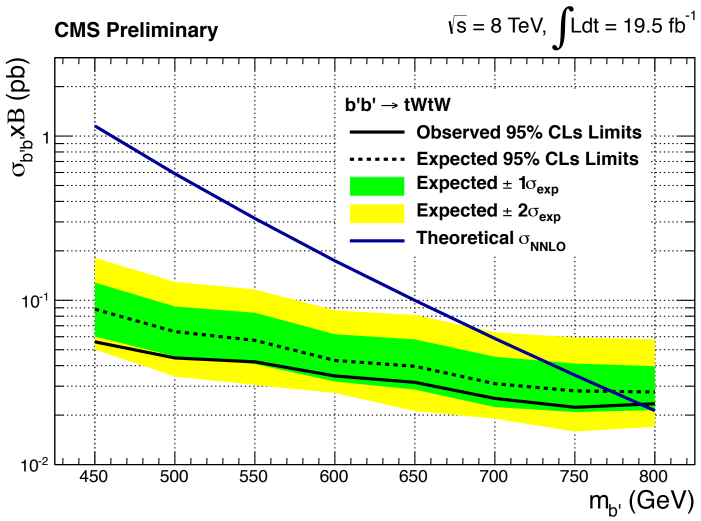
Limits derived from many bin counting experiment

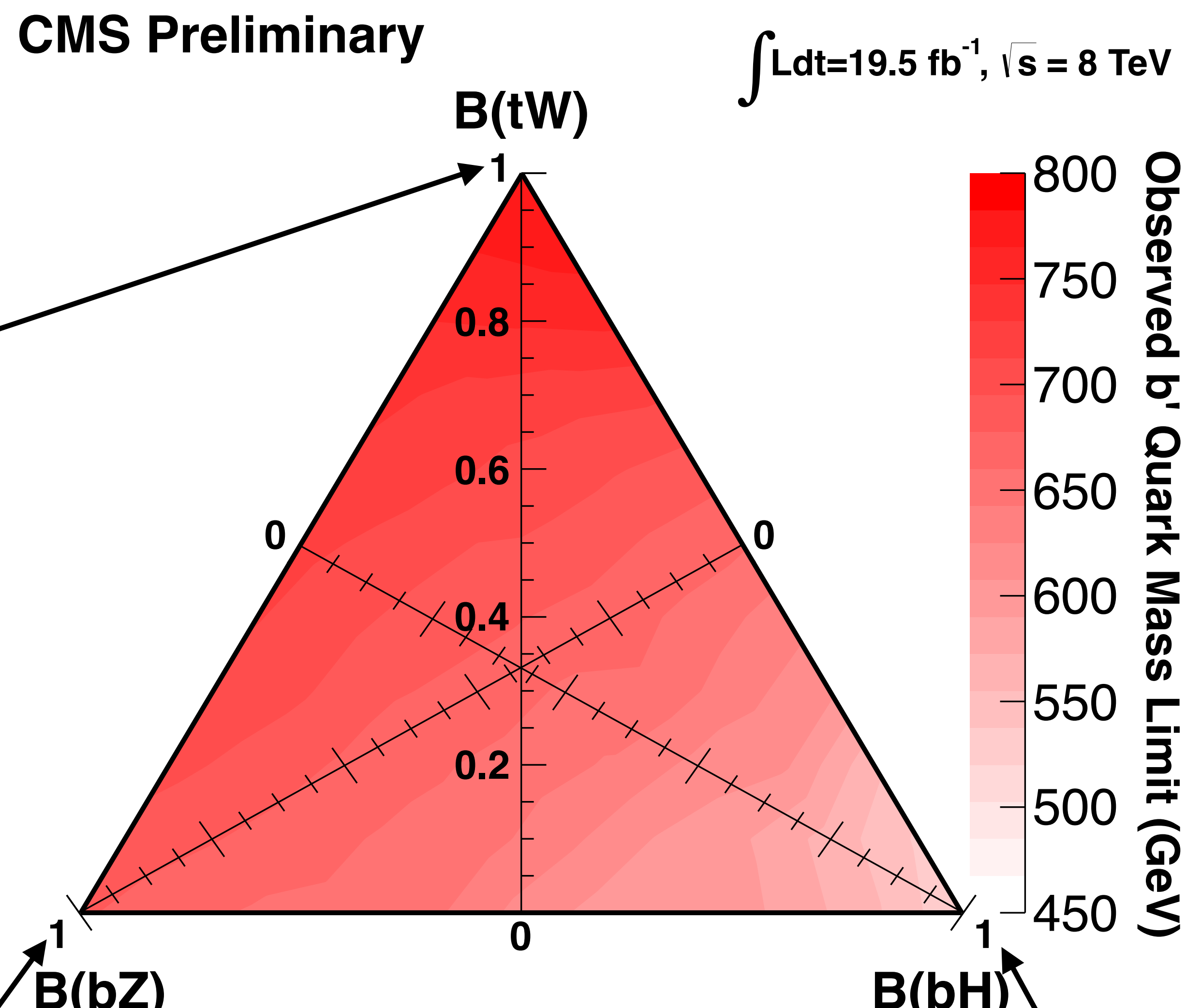
1D limits set for each decay mode independently

limits are also calculated for mixtures of the 3 decays - displayed as equilateral triangle

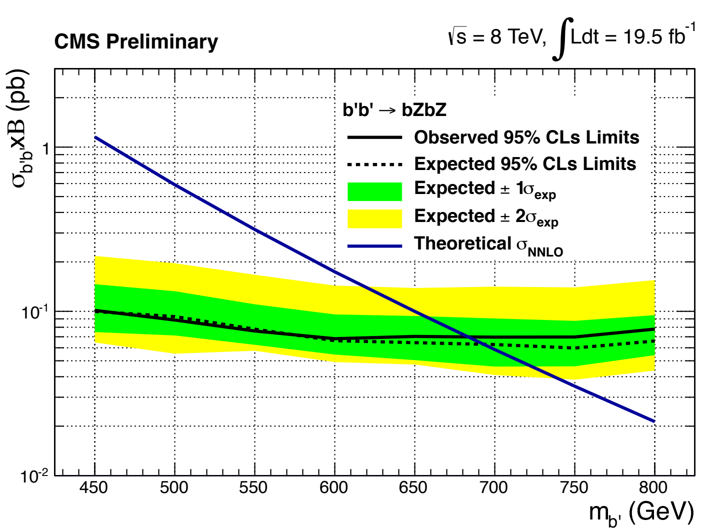
b′ searches B2G-13-003

b′ → tW

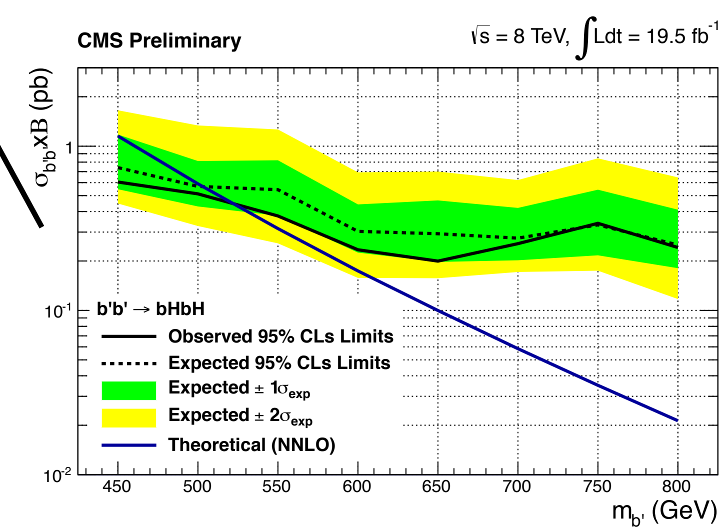




b′ →bZ



b′ → bH



reduces model dependence

T searches B2G-12-015

T - vector-like 4th generation up-type quark

T decay chains:

$T \rightarrow bW$
$T \rightarrow tZ$
$T \rightarrow tH$

Similar final states to b′, but different analysis strategy

Target single and multilepton final states
- multilepton channel split into OS1, OS2, SS, trileptons
    - targeting different T decay modes

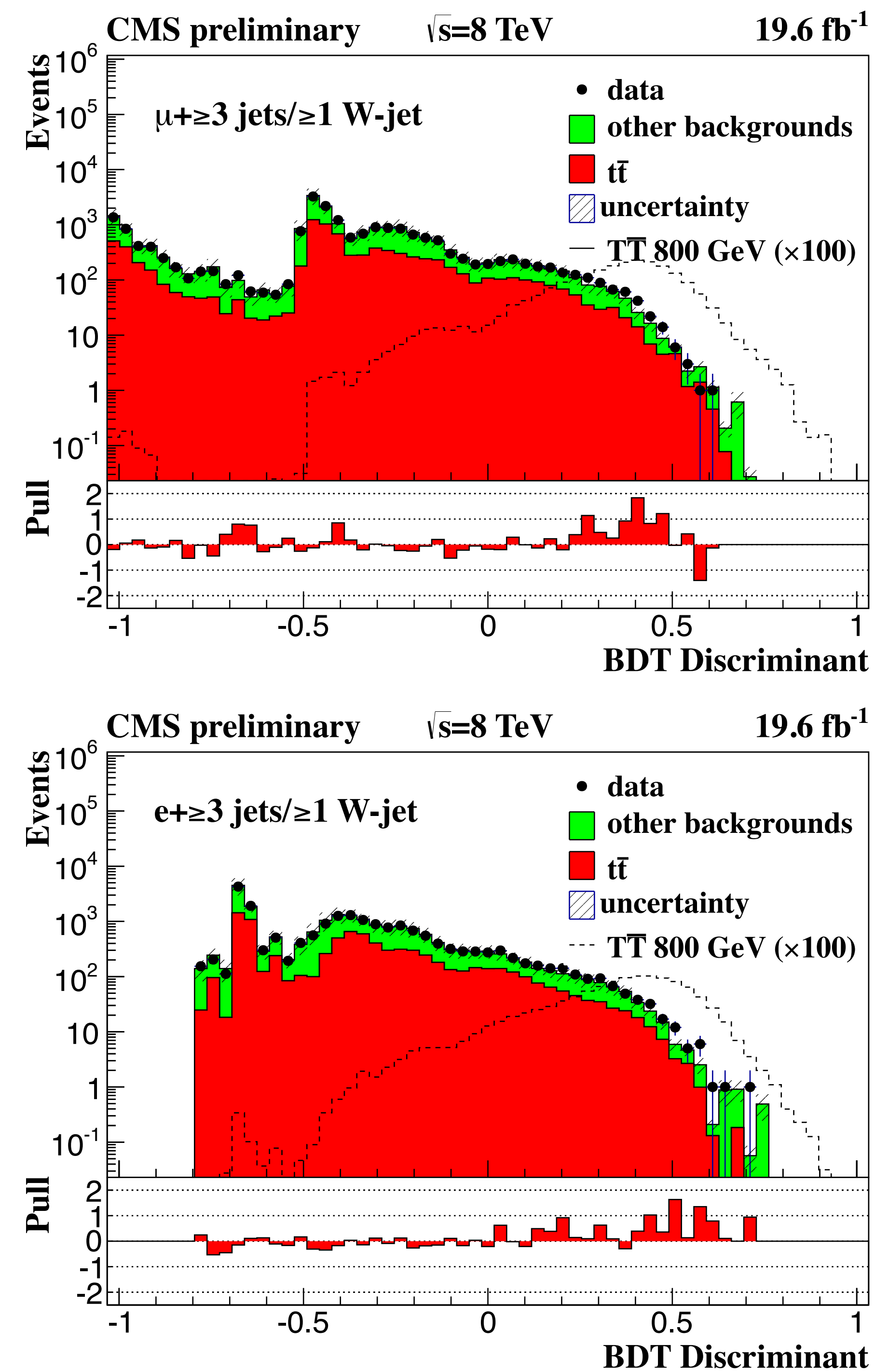
Single lepton channel

Selection:

- exactly 1 muon or electron
- ≥ 3 jets, > 0 tagged as Z or W
- missing E_T > 20 GeV

Input event quantities into boosted decision tree (BDT):

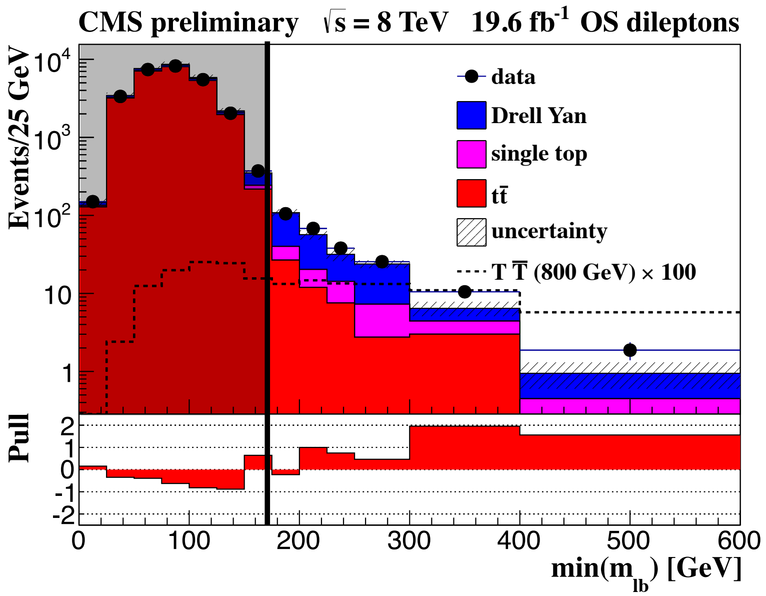
- # jets
- # b-tagged jets
- lepton p_T
- jet p_T
- H_T (Σp_T jets)

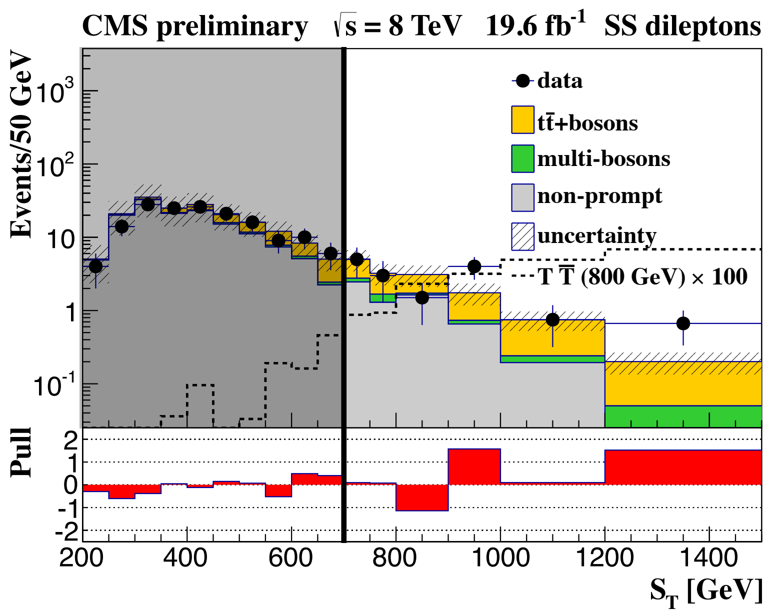


BDT output shapes for signal, background, and data used in limit-setting

T searches B2G-12-015

Multilepton channels





All channels require large H_T,S_T

OS 1: low # jets, Z veto T → bW

OS 2: high # jets T → tZ,tH

SS: lower background than OS

trileptons: lowest background

channel	OS1	OS2	SS	trileptons
$t\bar{t}$	5.2±1.9	80 ±12	-	-
single top	2.5±1.3	2.0±1.0	-	-
Z	9.7±2.9	2.5±1.9	-	-
$t\bar{t}W$	-	-	5.8 ±1.9	0.25±0.11
$t\bar{t}Z$	-	-	1.83±0.93	1.84±0.94
WW	-	-	0.53±0.29	-
WZ	-	-	0.34±0.08	0.40±0.21
ZZ	-	-	0.03±0.00	0.07±0.01
WWW/WWZ/ZZZ/WZZ	-	-	0.13±0.07	0.08±0.04
$t\bar{t}WW$	-	-	-	0.05±0.03
charge mis-ID	-	-	0.01±0.00	-
non-prompt	-	-	7.9 ±4.3	0.99±0.90
total background	17.4±3.7	84 ±12	16.5 ±4.8	3.7 ±1.3
data	20	86	18	2

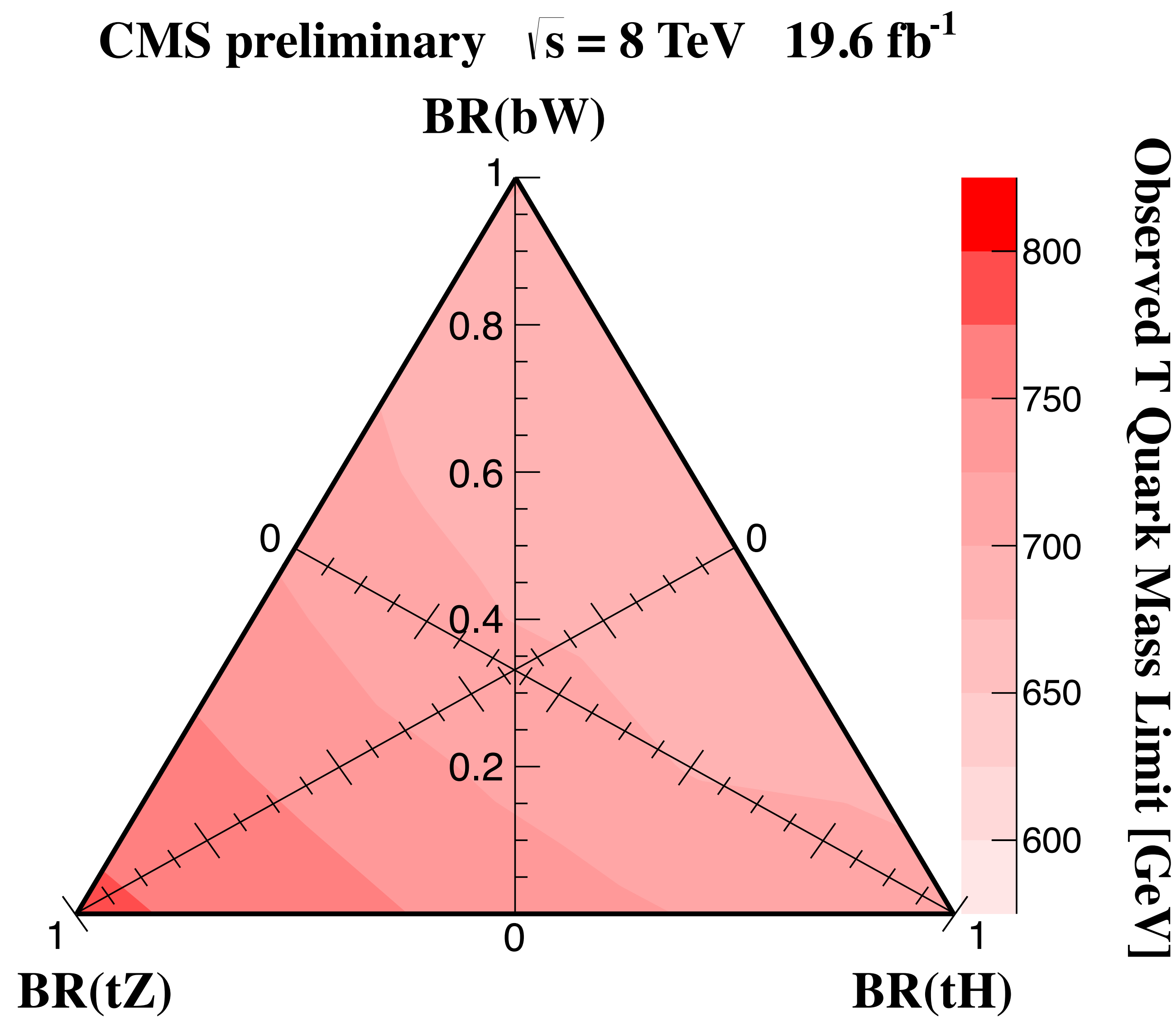
T searches

B2G-12-015

Combined results

BDT shapes from single lepton channels

Event counts from multilepton channels



Displaced jets EXO-12-038

Model independent search

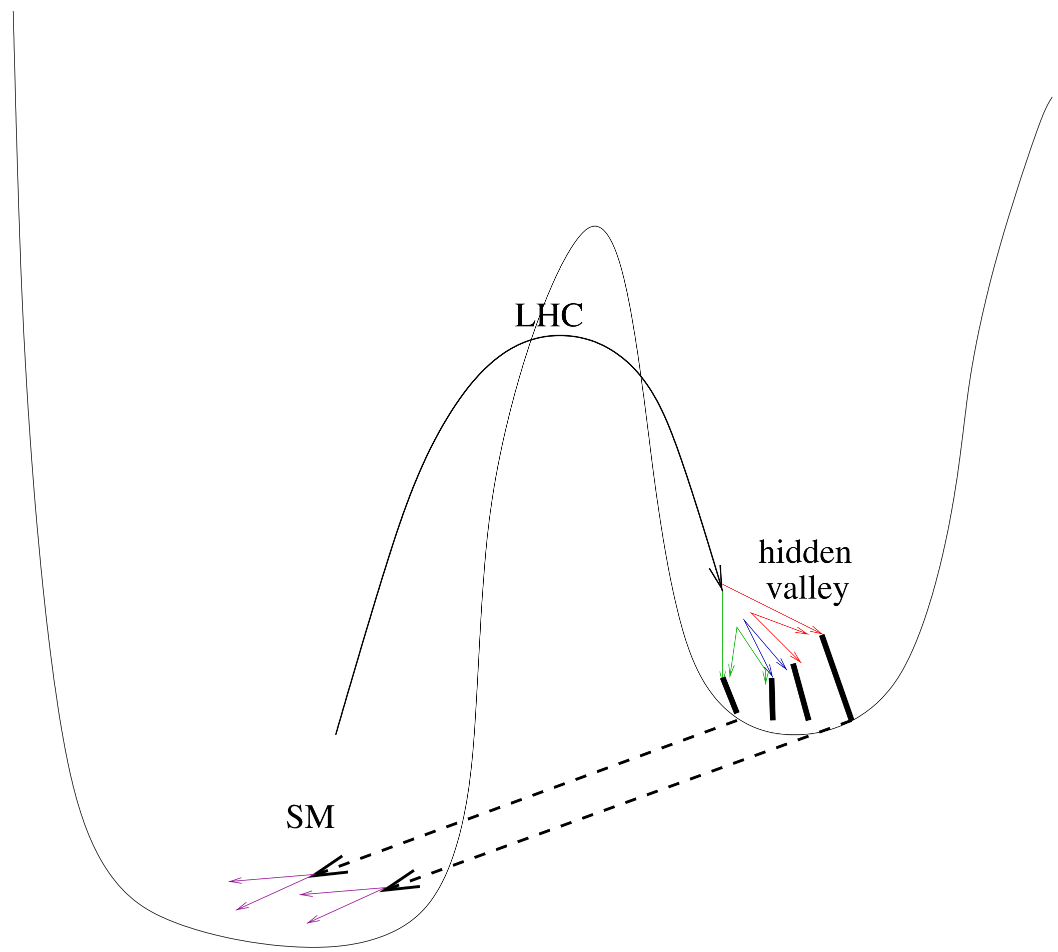
- any neutral long-lived particle decaying to quark pairs

Benchmark model used to set exclusions

- hidden valley (HV) decays: $pp \to H^0 \to 2X^0$, $X^0 \to$ q-qbar
- H^0 is BSM higgs
- X^0 is long-lived hidden sector particle
    - $\langle c\tau \rangle \sim$ 0.1-200 cm

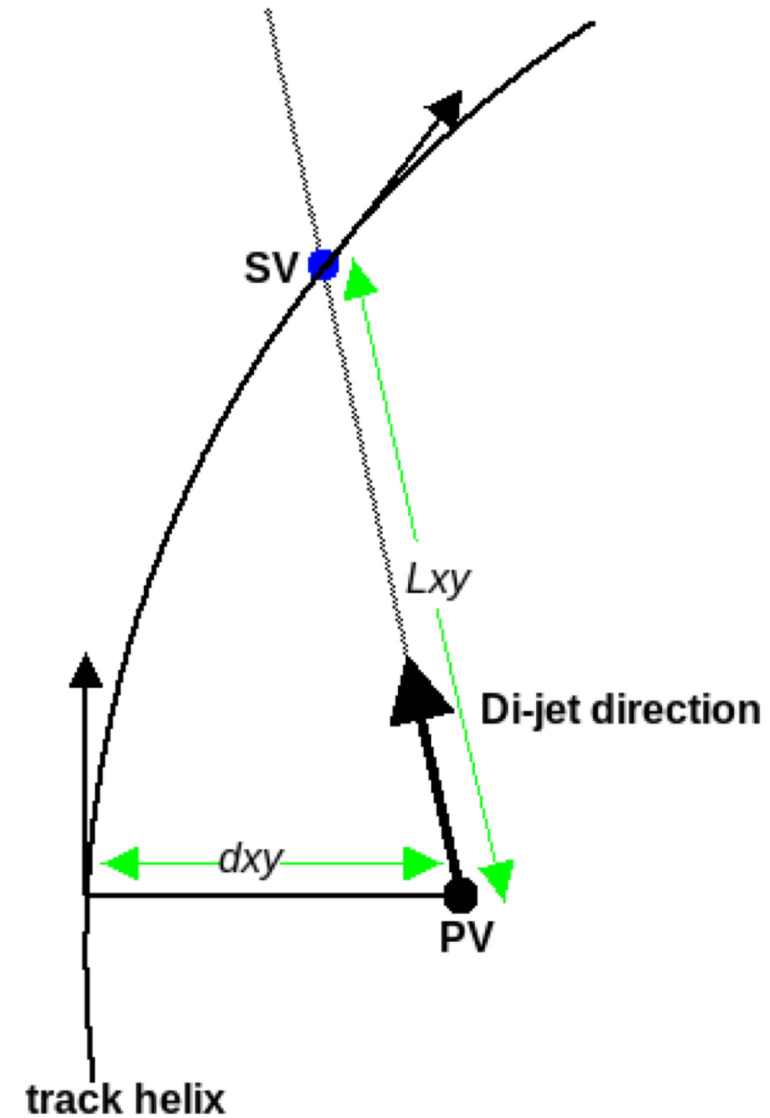
Striking signature of new physics

- very low SM background



Displaced jets EXO-12-038

Object definitions



Tracks:

- tagged as prompt or displaced
- displaced ⇒ d_{xy} > 500 μm

Jets:

- standard anti-k_T algorithm

Dijets:

- vertex fit to all *displaced* tracks from jet pair
- track clusters made using L_{xy} wrt SV

Event selection variables

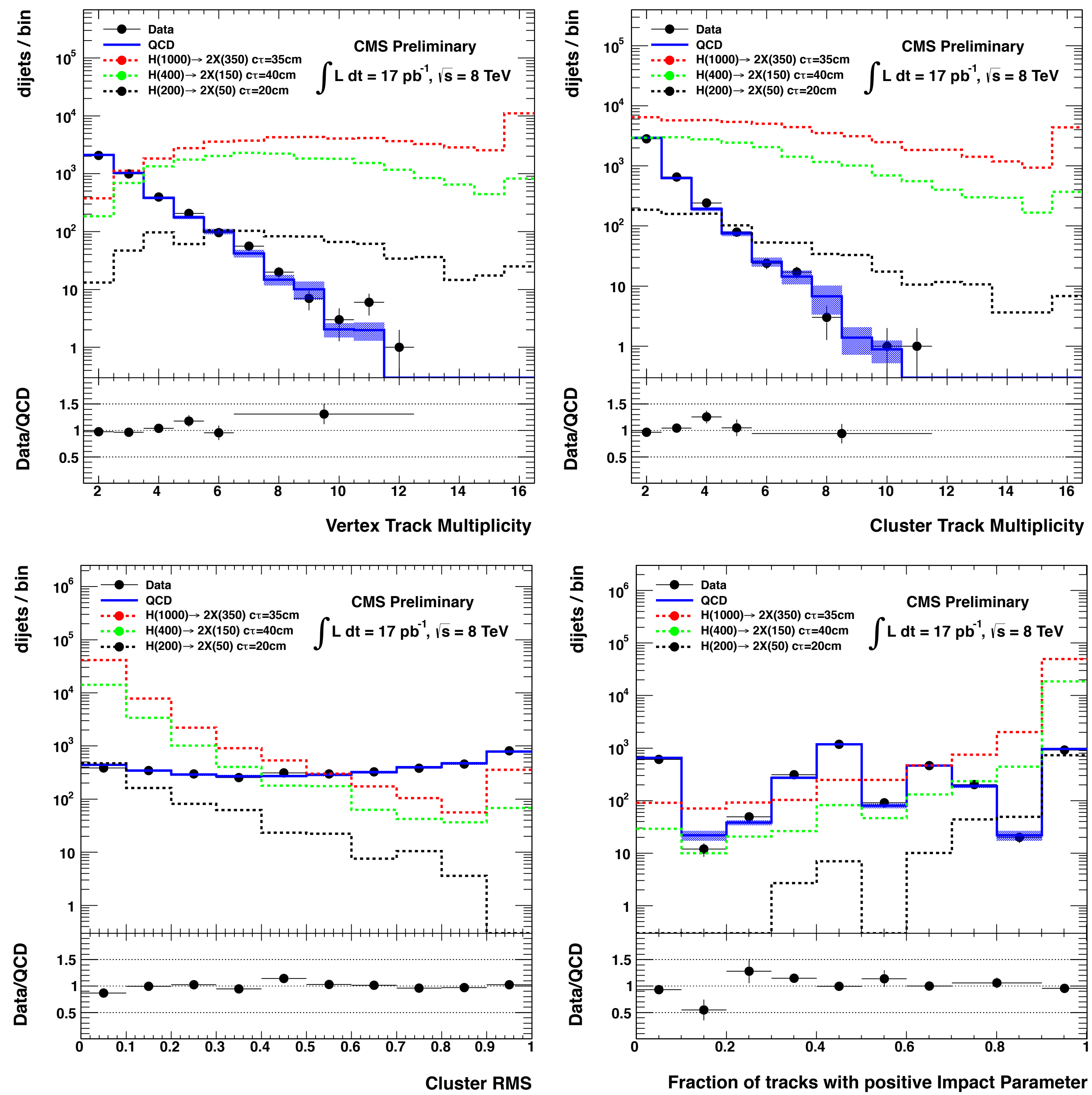
number of prompt tracks

energy fraction of prompt tracks

likelihood discriminant using:

- vertex track multiplicity
- cluster track multiplicity
- cluster RMS
- fraction of “downstream” tracks

Background estimate from data using ABCD method



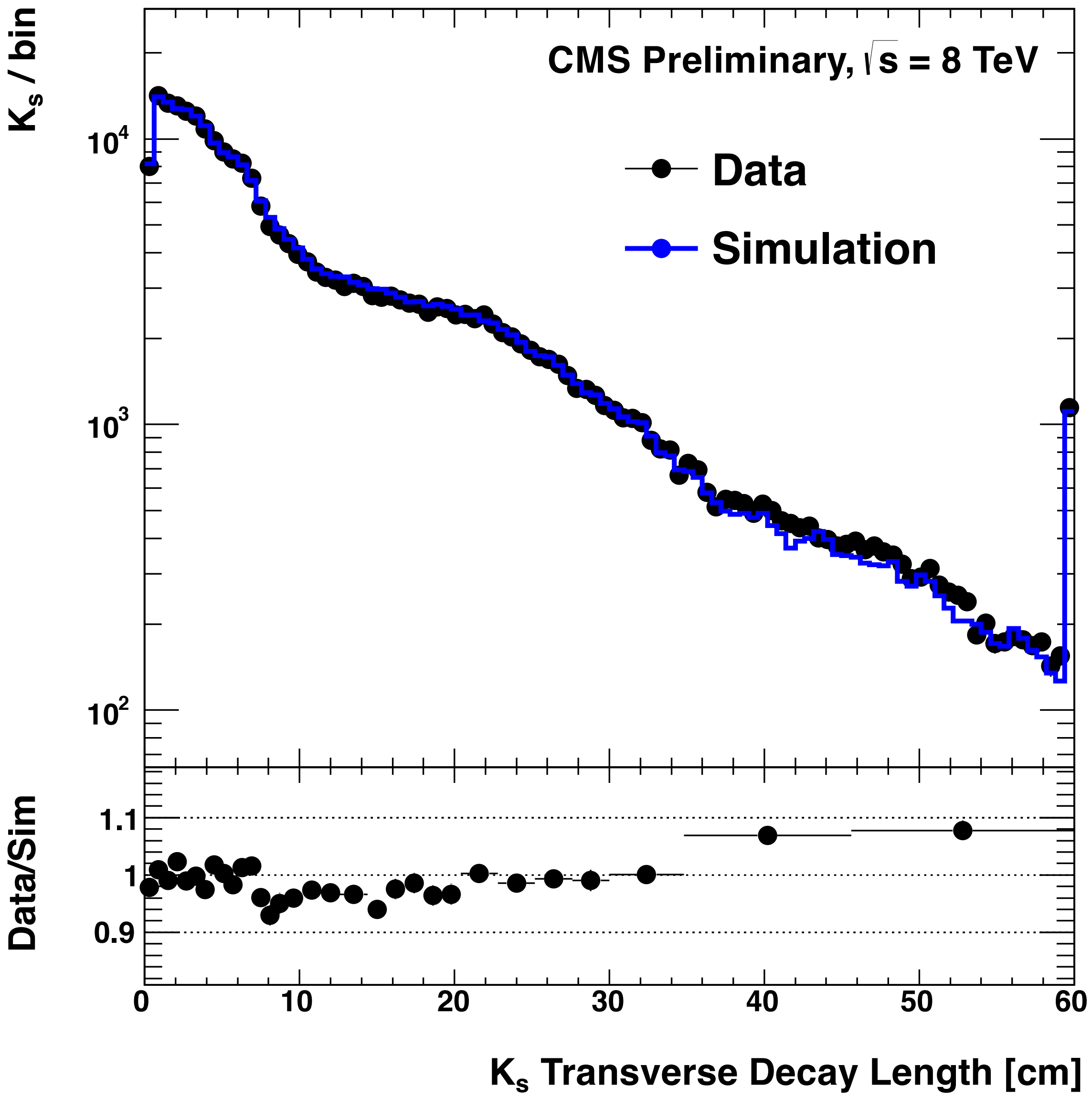
Displaced jets EXO-12-038

Tracking efficiency measurement

Dominant systematic effect

Measured in data:
- $K_S \rightarrow \pi^+\pi^-$ decays

Simulation accurate to 10% even far from the center of the detector



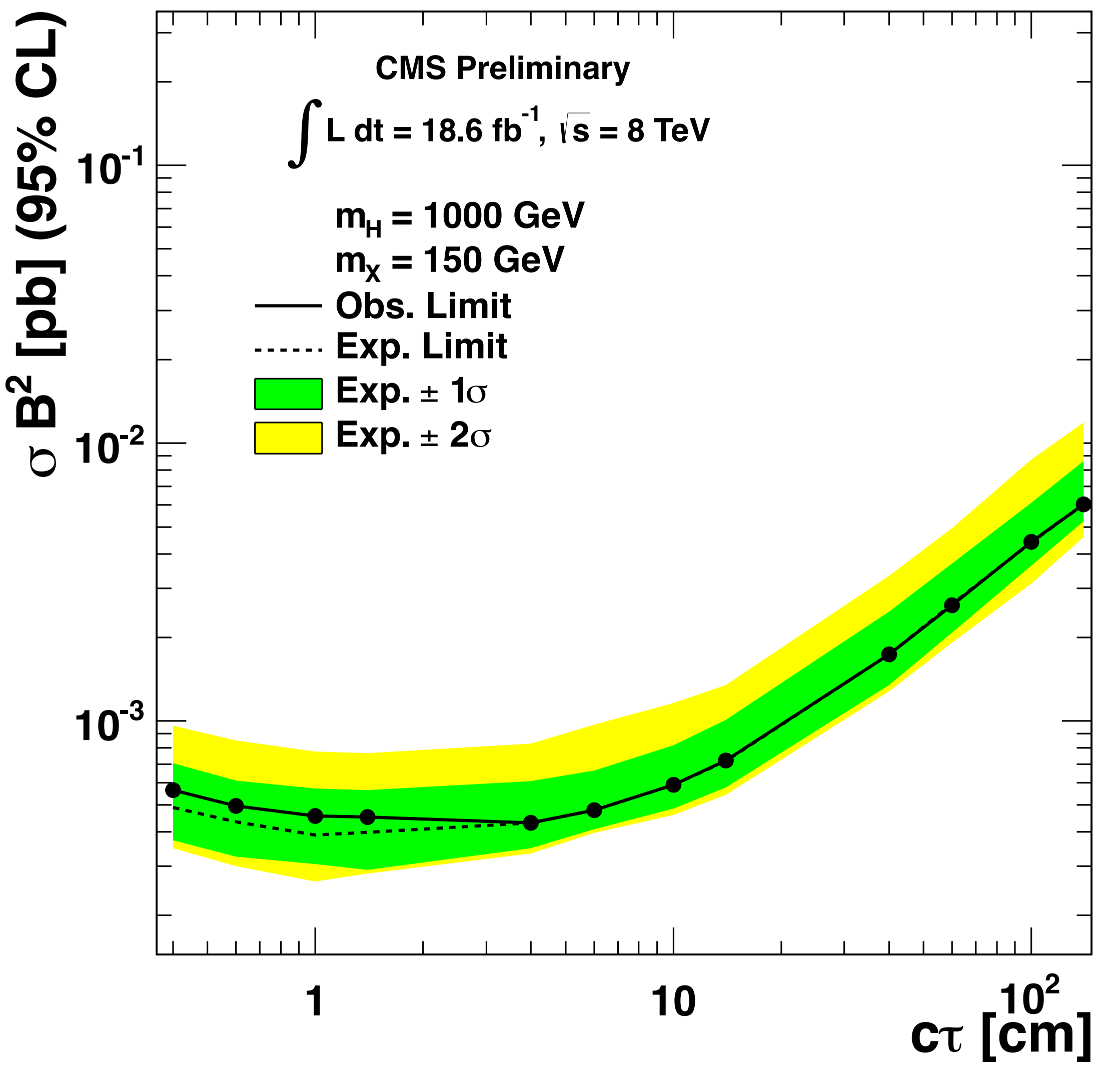
Displaced jets

EXO-12-038

Two signal regions defined:
- optimized to low and high L_{xy}

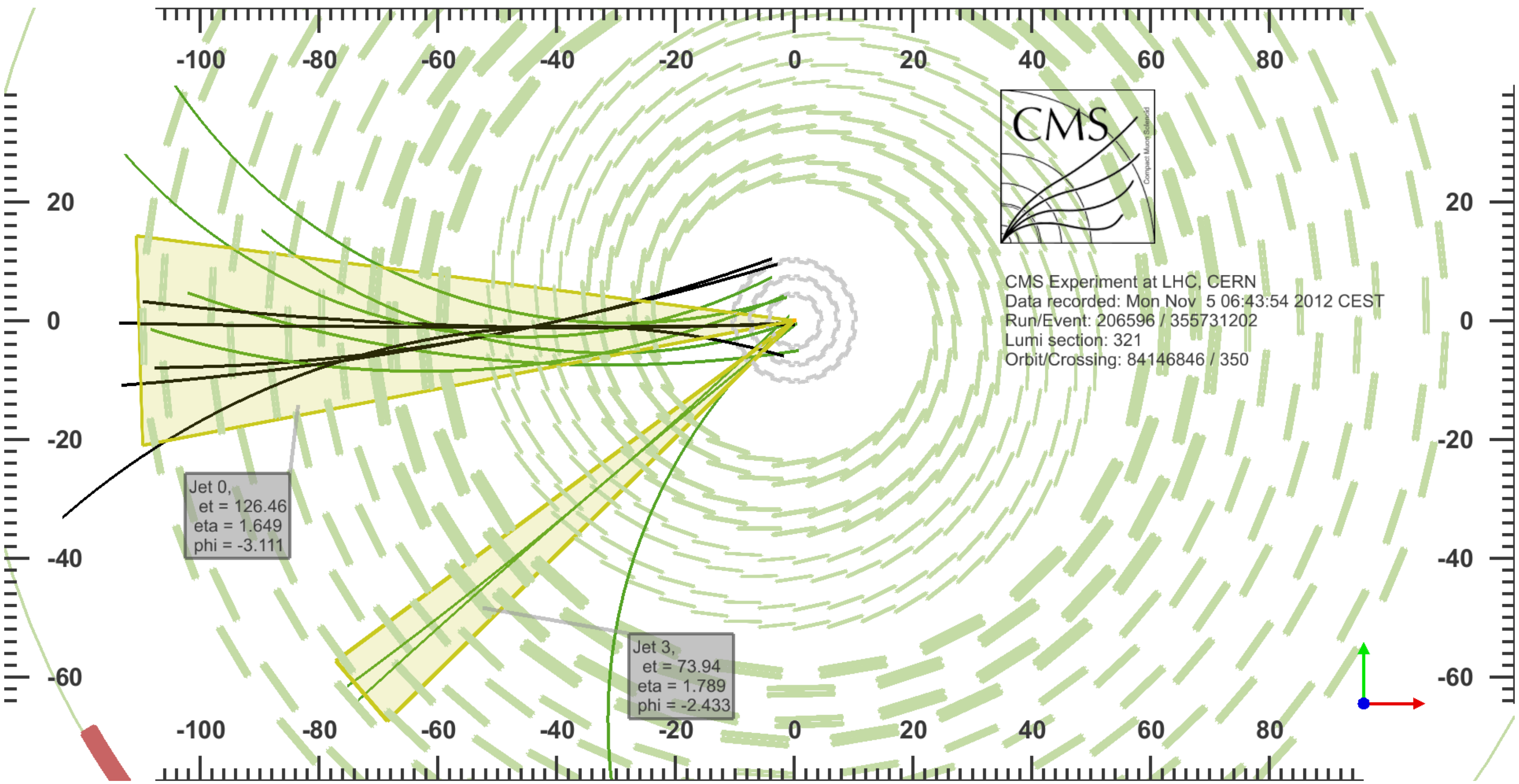
For each signal hypothesis, choose region with best expected sensitivity

Set limits on 3 orders of magnitude in lifetime



$\mathbf{L_{xy}}$	$< \mathbf{20\ cm(low)}$	$> \mathbf{20\ cm(high)}$
prompt tracks	≤ 1	≤ 1
prompt energy fraction	< 0.15	< 0.09
vertex/cluster disc.	> 0.9	> 0.8
expected background	$1.60 \pm 0.26(stat.) \pm 0.51(syst.)$	$1.14 \pm 0.15(stat.) \pm 0.52(syst.)$
observed	**2**	**1**

Data event in *high* signal region



cones/tracks:
selected jets

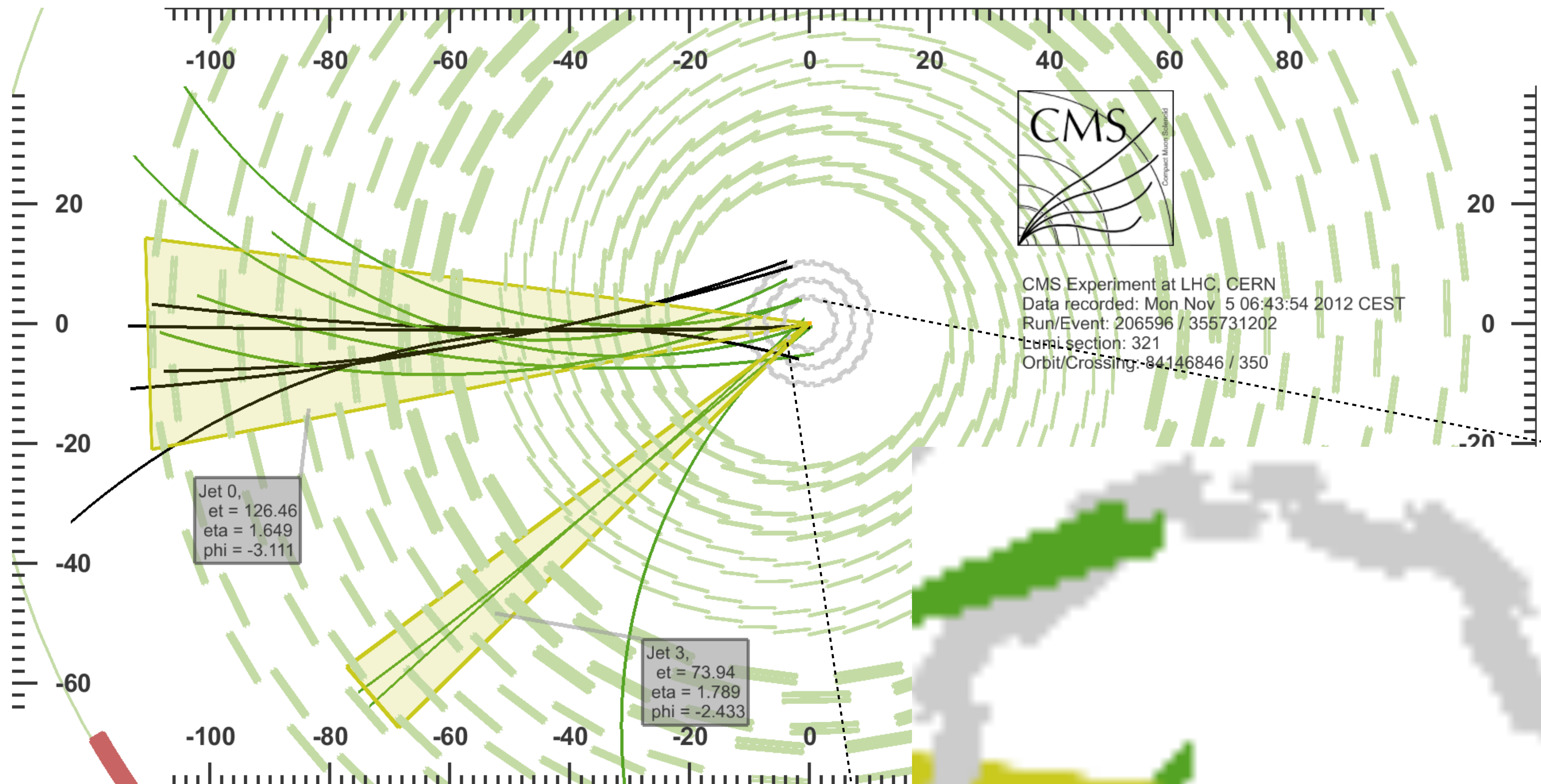
black tracks:
matched to SV

secondary vertex (SV) with 5 tracks, located within a tracking layer

consistent with a nuclear interaction in the tracking material

Displaced jets EXO-12-038

Data event in *high* signal region



cones/tracks:
selected jets

black tracks:
matched to SV

secondary vertex (SV) with 5 t acking layer

consistent with a nuclear inter erial

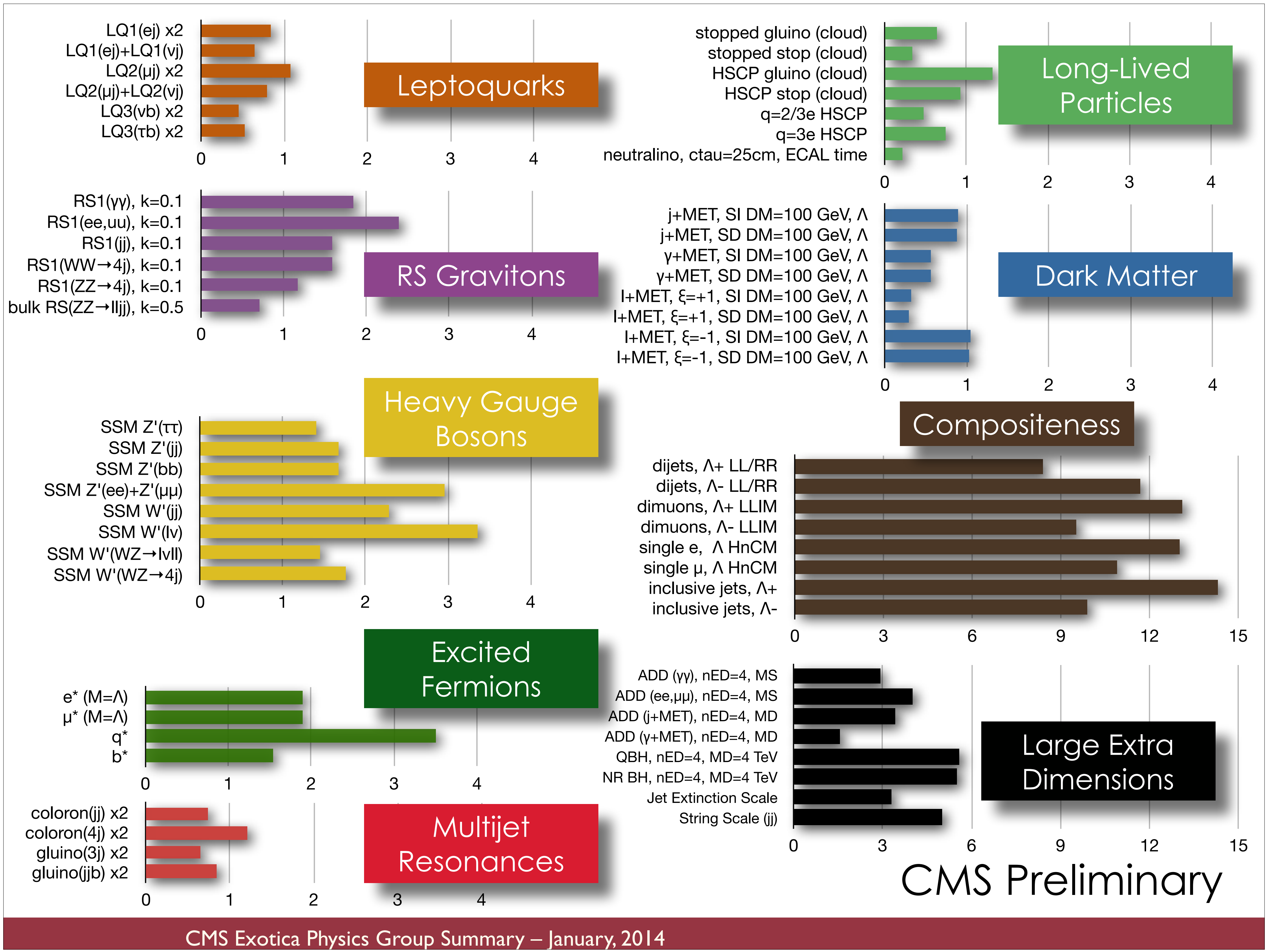
Summary

- New phenomena at $\sqrt{s}$ = 8 TeV could very well be in the current CMS dataset
  - CMS has conducted a broad program of searches for new physics
  - Using a wide variety of novel analysis strategies
    - *See upcoming Young Scientist talk by Thomas Reis*

- 13 TeV data is coming in 2015
  - Most exotic searches are statistically limited
  - Sensitivity of high mass searches will greatly improve at higher LHC energy

Backup

(EXO)tica Results



Beyond Two Generations (B2G) Results