Search for new massive resonances at CMS

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Introduction

- The Higgs boson discovery brought the last piece of the SM
- But many extensions of the SM could manifest at higher energies
- A myriad of models probed in CMS Exotica, in almost every channel
  - Essentially looking for a peak over the background in the invariant mass distribution.
  - Try to be as model independent as possible
  - Very specific reconstruction techniques and selection strategies due to boosted objects
- Not all searches covered here → `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO`
- Almost all analyses presented here use the Particle-Flow reconstruction algorithm
  - reconstruct and identify individually all stable particles in the event (e, μ, γ, charged and neutral hadrons)
  - uses a thorough combination of all sub-detectors
  - improves performance

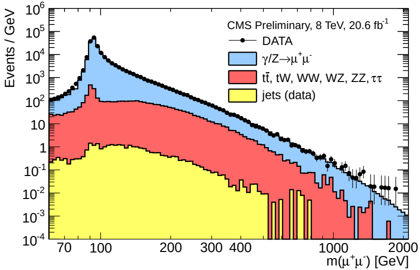
Outline

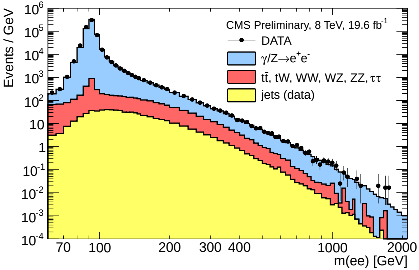
- Dilepton resonances
- Dijet resonances
- VV semileptonic resonances
- VV/qV hadronic resonances
- WZ resonances in leptonic channel
- Three jet resonances
- Run 2 prospects

Dilepton resonances

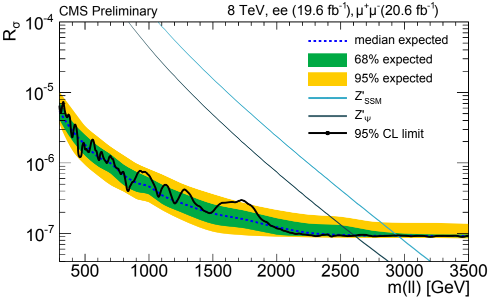
Dilepton resonances ($X \to ll$) — CMS EXO-12-061

- Models: Randall-Sundrum, Sequential Standard Model, Z'_ψ
- Main backgrounds: irreducible Drell-Yan, $t\bar{t}$, QCD
- Lepton selection: shower shape + isolation
- Background estimation
  - Drell-Yan: shape from MC normalized to number of events in data
  - $t\bar{t}$, tW, VV, $\tau\tau$ derived from Monte Carlo but cross-checks with $e\mu$ method $\to$ good agreement.
  - QCD multijets from double-differential fake rate method (E_t, η)





- Statistical interpretation
  - key point in this analysis is limit setting on $R_\sigma = \sigma_{Z'}/\sigma_Z \to$ cancel some systematic uncertainties.
  - Extended unbinnned likelihood (Bayesian) combining both channels

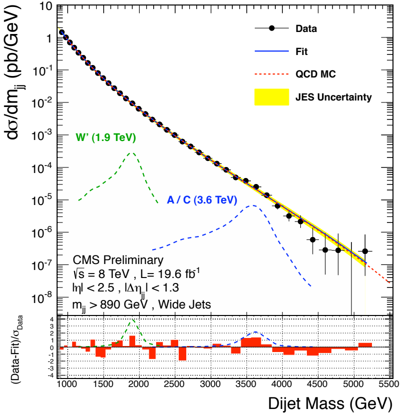


Model	Limit (GeV)
Z'_{SSM}	2960
Z'_ψ	2600
G_{RS} ($\tilde{k} = 0.1$)	2730
G_{RS} ($\tilde{k} = 0.05$)	2350

Dijet resonances

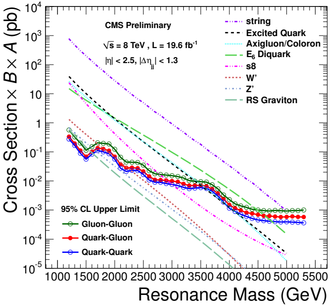
Dijet resonances ($X \to qq/gg/qg$) — CMS EXO-12-059

- Models: string resonances, scalar diquarks, excited quarks, axigluons, colorons, technicolor, Randall-Sundrum, KK
- Main background: QCD multijet
- "Wide" jets techniques
  - Take two leading jets and add all other jets to closest leading jet if within $\Delta R < R_{wide}$ ($R_{wide} = 1.1$)
  - Reduce sensitivity to gluon radiation
- Selection: $H_t = \sum p_{t,j} > 650$, $|\Delta\eta_{j_1 j_2}| < 1.3$, $M_{j_1 j_2} > 890$
- Background modeled through fit function: $f(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3 \ln x}}$, $x = \frac{M_{jj}}{\sqrt{s}}$



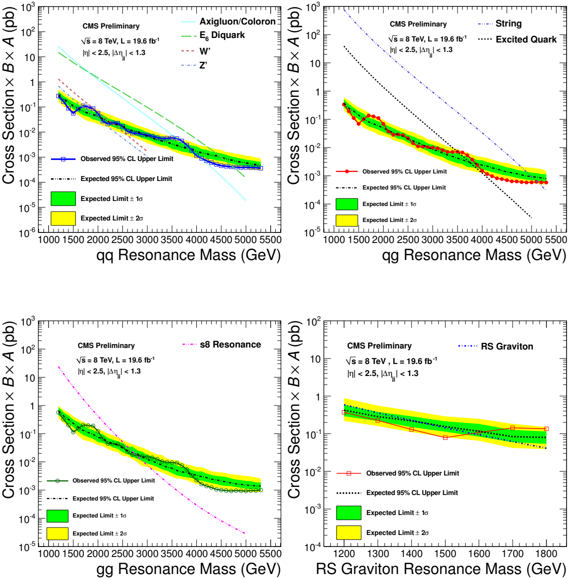
Dijet resonances ($X \to qq/gg/qg$) — CMS EXO-12-059

- Main systematic uncertainties
  - Jet energy scale $\to$ 1.25% on M_{jj}
  - Jet energy resolution $\to$ 10% on M_{jj}
  - Background parametrization
- Statistical interpretation
  - Bayesian formalism
  - Independenlty at each value of the resonance mass



Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q*)	qg	[1.20,3.50]	[1.20,3.75]
E_6 Diquark (D)	qq	[1.20,4.75]	[1.20,4.50]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]	[1.20,3.87]
Color Octet Scalar (s8)	gg	[1.20,2.79]	[1.20,2.74]
W′ Boson (W′)	$q\bar{q}$	[1.20,2.29]	[1.20,2.28]
Z′ Boson (Z′)	$q\bar{q}$	[1.20,1.68]	[1.20,1.87]
RS Graviton (G)	$q\bar{q}$+gg	[1.20,1.58]	[1.20,1.43]

Dijet resonances ($X \to qq/gg/qg$) — CMS EXO-12-059



VV resonances

VV resonances

- Characterized by two boosted bosons which can decay either leptonically or hadronically
- Hadronic decay: two jets merging into one due to boosting $\rightarrow$ jet substructure techniques
- Leptonic decay: lepton isolation cones overlap $\rightarrow$ Modified isolation cone
- V-tagging: tag V-jet $\rightarrow$ jet pruning algorithm
- Jet substructure techniques
  - Identify the subjets within the jet
  - Define a metric (N subjettiness) to quantify the capability of finding N subjets within a jet.

$$\tau_N = \frac{1}{d_0} \sum_k p_{t,k} min(\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k}), d_0 = R_0 \sum_k p_{t,k}$$

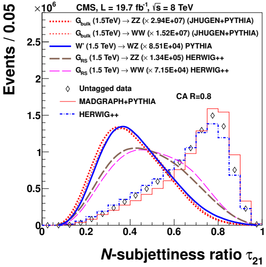
- N-subjettiness is smaller for jets effectively formed from N subjets.
- For V $\rightarrow$ qq, cut on $\tau_{21} = \tau_2 / \tau_1$ ratio

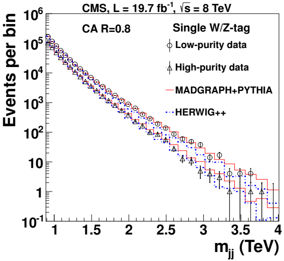
VV resonances

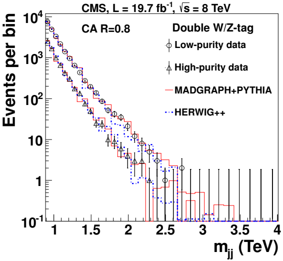
- Jet pruning algorithm (Cambridge-Aachen algorithm)
  - Remove soft radiation components
  - Recluster each jet starting from original constituents using the CA algorithm and discard soft recombinations at each step
    1. Start with two protojets i an j
    2. Define $p_t^\rho = p_t^i + p_t^j$
    3. $z = min(p_t^i/p_t^\rho, p_t^j/p_t^\rho)$
    4. $D_{cut} = m_{orig}/p_{t,orig}$
    5. if $z < 0.1$ or $\Delta R_{i,j} > D_{cut}$, then soft $\rightarrow$ discard protojet with min pt
- Usually, in addition, requirement on M_{jet} consistent with W/Z mass $\rightarrow$ V-tagging
- Allows to reduce QCD multijet contribution
- Leptonic isolation cones overlap
  - Mask off specific geometric region around leptons

VV/qV hadronic resonances — arXiv 1405.1994v2

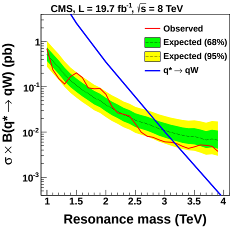
- $q^* \to qV$, $G_{RS} \to WW/ZZ$, $G_{bulk} \to WW/ZZ$, $W' \to WZ$
- Jet pruning, jet substructure, V-tagging
- Main background: QCD multijet
- Jet selection
  - $\Delta\eta_{j_1 j_2} < 1.3$, $M_{j_1 j_2} > 890$, HP-jet $\tau_{21} < 0.5$, LP-jet $0.5 < \tau_{21} < 0.75$
- Background estimation
  - Fitting data: $f(x) = p_0 x^{p_1} / x^{p_2}$, $x = M_{jj}/\sqrt{s}$, in each channel
  - Main systematics: V-tagging: 7.5% (HP), 54% (LP)

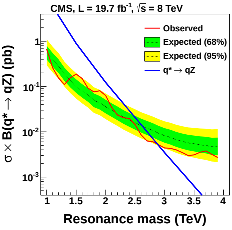


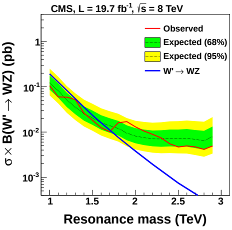


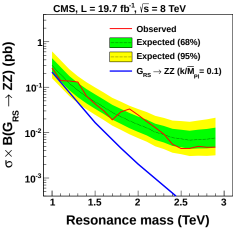


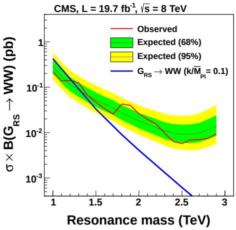
- Statistical interpretation: asymptotic frequentist (CLs method)
- Most stringent to date









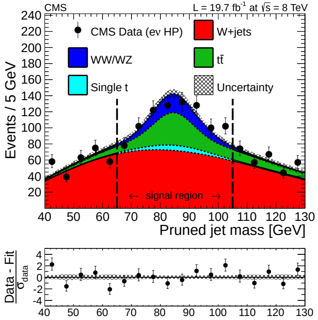


Process	Observed limit (TeV)	Expected limit (TeV)
$q^* \to qW$	3.2	3.0
$q^* \to qZ$	2.9	2.6
$W' \to WZ$	1.7	1.6
$G_{RS} \to WW$	1.2	1.3

VV semileptonic resonances: X $\rightarrow$ VV $\rightarrow$ $l\nu qq$ or $llqq$ — arXiv 1405.3447v2

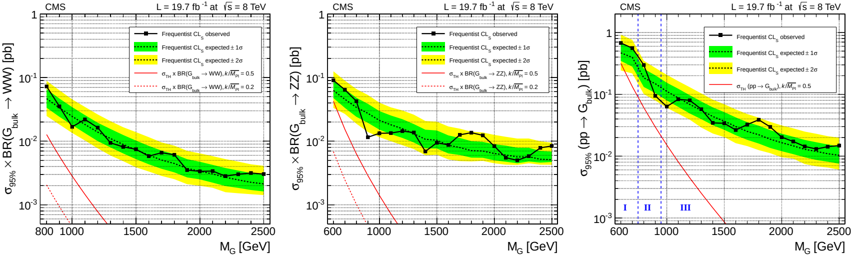
- Two main components: $l\nu$+V-jet and ll+V-jet
- Lepton selection: isolation + shower shape
- Jet selection
  - $p_t > 30$, $|\eta| < 2.4$ — HP-jet $\tau_{21} < 0.5$, LP-jet $0.5 < \tau_{21} < 0.75$
  - jet pruning, jet substructure
  - V-jet: $65 < M_j < 105$ for W-jet and $70 < M_j < 110$ for Z-jet
- Final event selection
  - V-boson p_t, $\not{E}_t$, back-to-back selection

- Background estimation
  - After full selection, main background is V+jets
  - Overall normalization is done through fit in sidebands in M_j
  - Shape is taken from low M_j sideband using extrapolation function



VV semileptonic resonances: X $\rightarrow$ VV $\rightarrow$ $l\nu qq$ or $llqq$ — arXiv 1405.3447v2

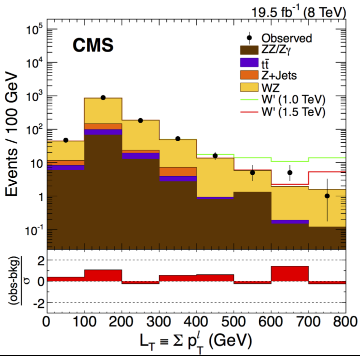
- Statistical interpretation
  - Asymptotic frequentist method (CLs), unbinned shape analysis
  - Combine all categories and further with all hadronic channel $\rightarrow$ 15-20% more stringent

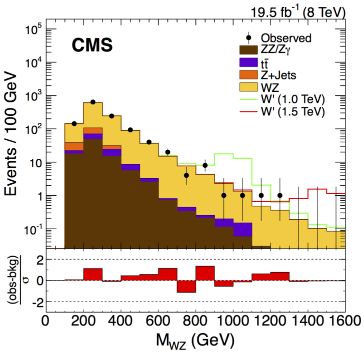


WZ resonances in leptonic channel

WZ resonances in leptonic channel ($X \to WZ \to l\nu ll$) — arXiv 1407.3476v1

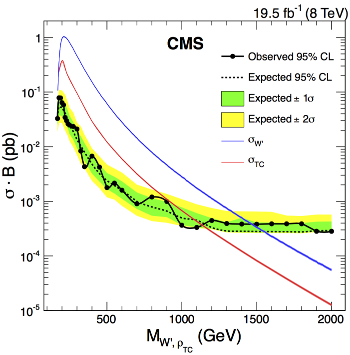
- Lepton selection: isolation + shower shape
- Cone isolation overlap $\to$ mask off specific region
- Event selection
  - Opposite charge, $71 < M_{l^+l^-} < 111$ GeV, $\not{E}_t > 30$ GeV, $M_{3l} > 120$ GeV, $\Delta R(l_Z, l_W) > 0.3$
  - Additional criteria on $L_t = \sum p_{t,l}$ and M_{WZ} optimized for best expected limit

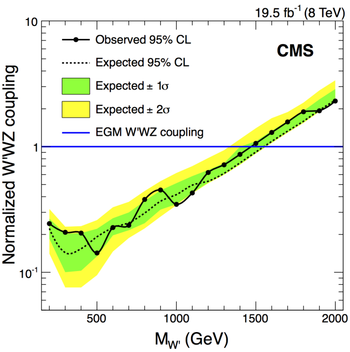




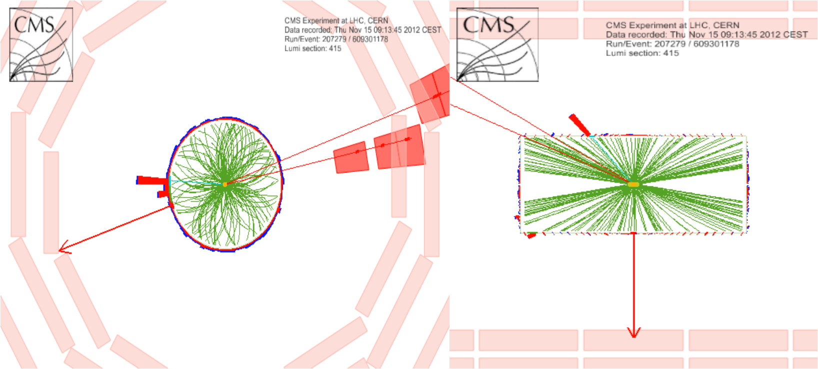
WZ resonances in leptonic channel ($X \to WZ \to l\nu ll$) — arXiv 1407.3476v1

- Statistical interpretation
  - counting experiment (Bayesian formalism)
  - W'_{SSM} limit: 1470 GeV, $\rho_{TC}(LSTC)$ limit: 1140 GeV
  - Possibility to modify $g_{W'WZ}$ and put limits on coupling.





WZ resonances in leptonic channel ($X \to WZ \to l\nu ll$) — arXiv 1407.3476v1



$\mu\mu e$: $M_{WZ} = 1250$ GeV, $L_t = 733$ GeV, $\not{E}_t = 458$ GeV

Three jet resonances

Light/heavy flavour three jet resonances $XX \to qqqqqq$ — arXiv 1311.1799v3

- Models: Heavy coloured fermions or RPV gluinos
- Topology: events with at least 6 jets
- Jet ensemble technique: recombine jets to find correct triplets
- First analysis of its kind to include heavy flavour

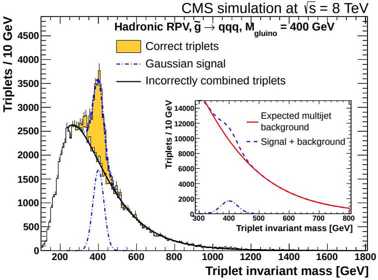
- Two main components:
  - Light flavour inclusive mass search
  - Heavy flavour high and low mass searches

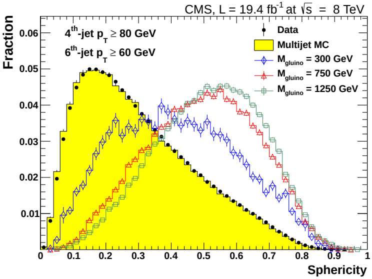
- Optimized 6_{th} jet p_t cut (inclusive and high mass heavy search)
- Optimized 4_{th} jet p_t cut and b-tagging (low mass heavy search)

- Triplet invariant mass: $M_{jjj} < \sum_{i=1}^{3} p_t^i - \Delta$
  - Observed correlation between M_{jjj} and $\sum p_t^i$ for background and incorrectly recombined signal triplets
  - Δ chosen so as to have as broad a range as possible for $M_X \to \Delta =$ 110 GeV

Light/heavy flavour three jet resonances $XX \to qqqqqq$ — arXiv 1311.1799v3

- Sphericity: $S = (3/2) \times (\lambda_2 + \lambda_3)$, λ_i eigenvalues of $S^{\alpha\beta} = \frac{\sum p^\alpha p^\beta}{\sum |p|^2}$
  - Signal events are more spherical than background events
  - No significant difference in the low mass heavy flavour search

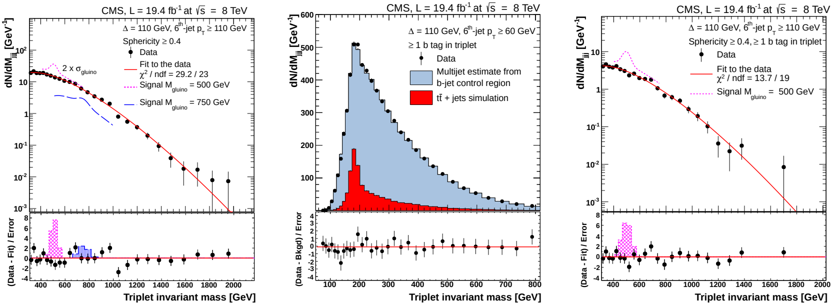




Selection criteria	Inclusive search	Heavy-flavour search low mass	Heavy-flavour search high mass
Mass range	400–1500 GeV	200–600 GeV	600–1500 GeV
Δ	110 GeV	110 GeV	110 GeV
Min. fourth-jet p_T	110 GeV	80 GeV	110 GeV
Min. sixth-jet p_T	110 GeV	60 GeV	110 GeV
Min. sphericity	0.4	—	0.4

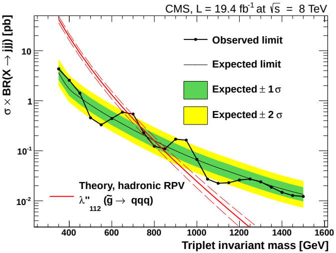
Light/heavy flavour three jet resonances $XX \to qqqqqq$ — arXiv 1311.1799v3

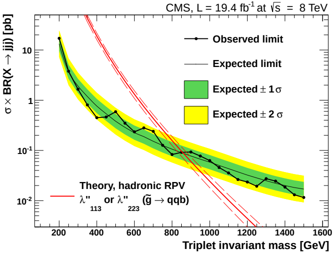
- Background estimation
  - Light and high mass heavy flavour: modeled with a dijet function
  - Low mass heavy flavour: $t\bar{t}$ from MC, SM multi jet shape from b-jet control region
  - $t\bar{t}$ estimation technique validation



Light/heavy flavour three jet resonances $XX \rightarrow qqqqqq$ — arXiv 1311.1799v3

- Statistical interpretation
  - Asymptotic frequentist approach (CLs)
  - Profile likelihood





$RPV \tilde{g}$	-1 σ limit (GeV)	Central limit (GeV)
Light flavour	650	670
Heavy flavour	200-835	200-855

Run 2 prospects

Run2 prospects

- LHC is expected to restart around May 2015 with increased luminosity and $\sqrt{s}$
- Programme up to now is to collect 1 fb^{-1} of 50 ns data ($\sim$ 3 weeks)
- Goal is to reach $\sim$ 10 fb^{-1} by end of 2015

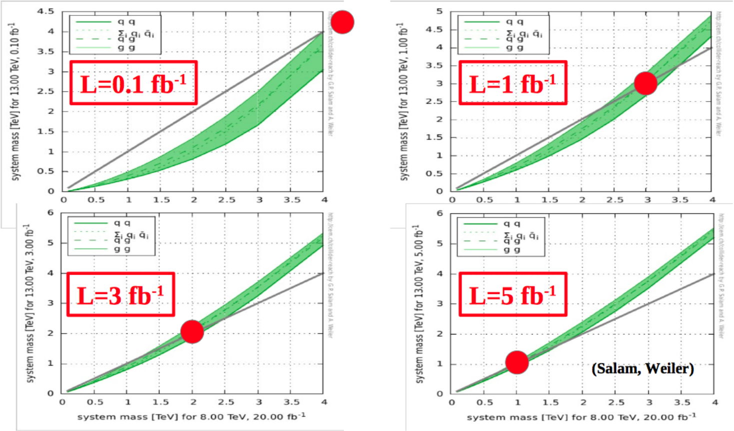
Period	N_{bunch} [10^{11}]	ε* [μm]	k	β* [cm]	L [$cm^{-2}s^{-1}$]	<μ>	Days(*)	∫L [fb^{-1}]
50 ns	1.2	2.2	≈1370	80	5.3×10^{33}	30	21	≈1
25 ns / 1	1.2	2.5	≈2500	80	8.1×10^{33}	26	44	≈4
25 ns / 2	1.2	2.5	≈2500	**40**	14.7×10^{33}	45	46	≈13

- What we can reach with X fb^{-1} of data in terms of limits ?
- `http://collider-reach.web.cern.ch/collider-reach/`

$$\text{(20 fb}^{-1}\text{)} \; \text{(PartonLuminosity(}M_X(8\,TeV)\text{))} \simeq \text{(13 TeV luminosity)} \; \text{(PartonLuminosity(}M_X(13\,TeV)\text{))}$$

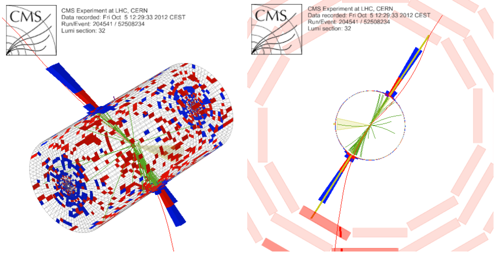
Run2 prospects

- Sensitive to around 3 TeV with $\sim 1\ fb^{-1}$
- But with higher σ model, could push the limit further



Conclusions

- Many searches in almost every decay channel
- Stringent limits (many most stringent to date)
- Novel techniques for analyses involving jets
- Dedicated isolation techniques for analyses involving leptons
- Standard Model is still holding up...



$$M_{jj} = 5.15 \text{ TeV}$$

- ...but discovery could be around the corner in 2015


Thank You