Recent results of searches for BSM physics at CMS

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On behalf of the CMS Collaboration

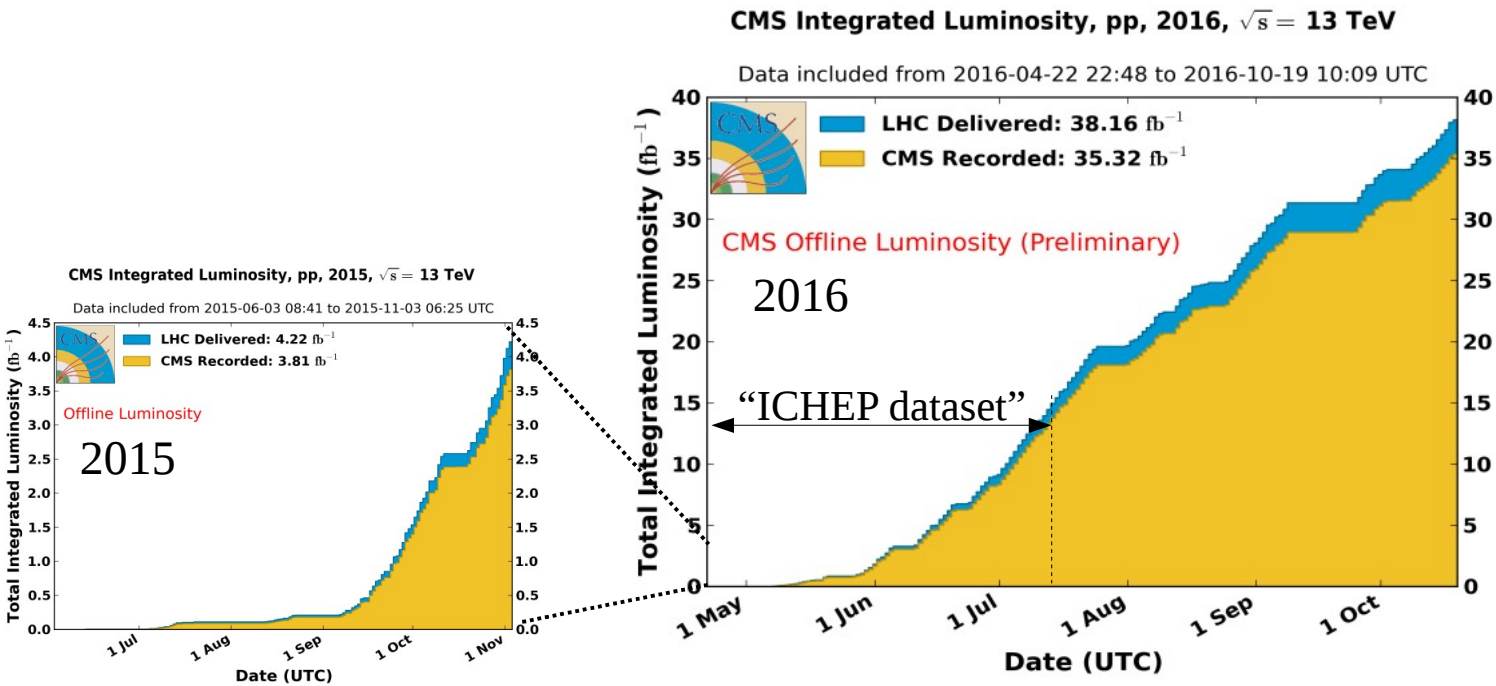
Introduction

- It's been a busy summer for CMS!
  - Culminating in multitude of results shown at ICHEP 2016 Conference
- I will present a subset of recent results from Exotica (EXO) and Beyond 2 Generations (B2G) physics groups in CMS
  - Resonances (i.e. bump hunts!)
  - Searches for long-lived particles
  - Dark matter seaches with MET signatures
  - Listing of public CMS EXO results: http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html
  - Listing of public CMS B2G results: http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html
- SUSY results outside the scope of this talk, but please check out listing of public CMS SUS results: http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/index.html

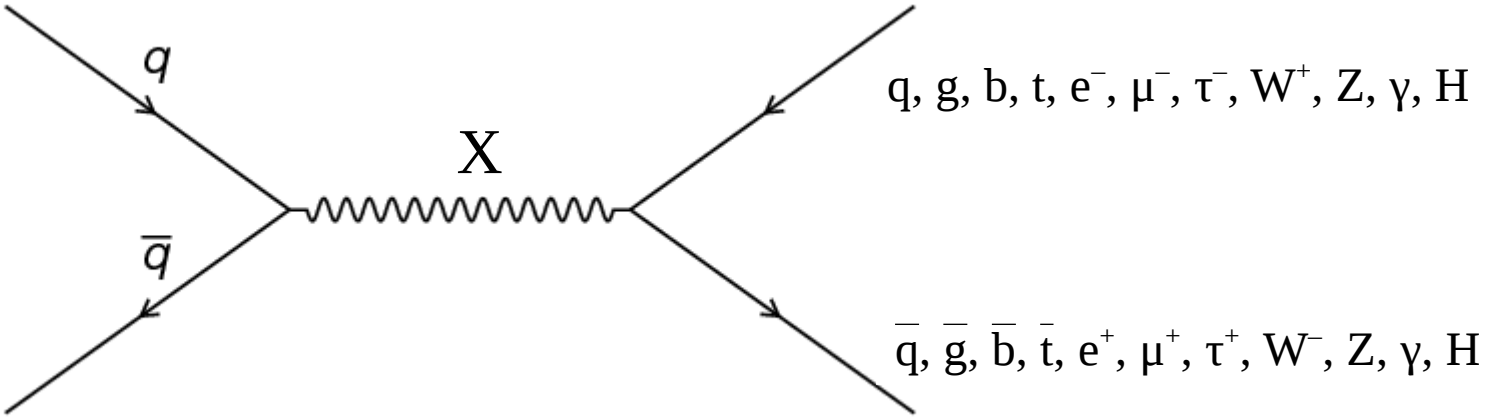
LHC Run-2

- LHC operations in 2016 delivered data at an impressive pace
- As 2016 proton-proton physics run comes to a close, we'll have about <u>ten</u> times more data in 2016 than in 2015!

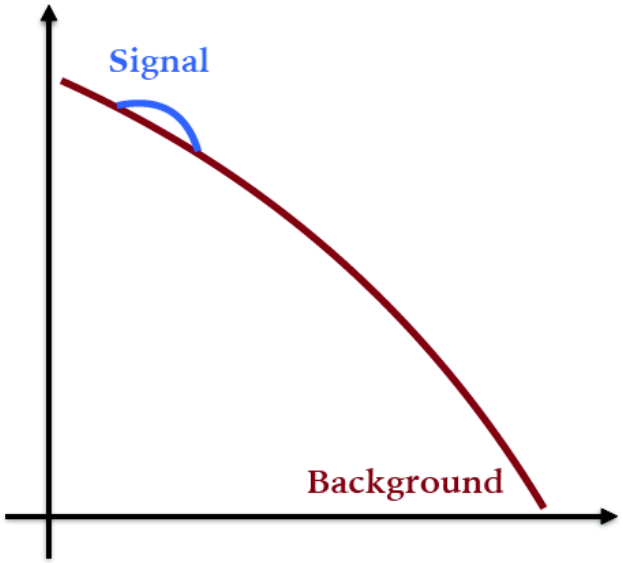
- Results to be presented cover the 2015 dataset (~2.5 fb^{-1}) and/or the 2016 "ICHEP dataset" (~13 fb^{-1})



Resonance Searches

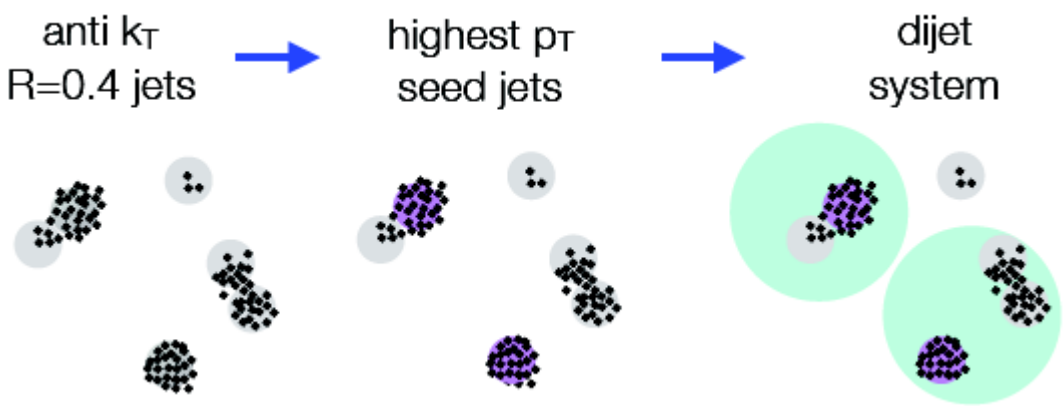


- Simple strategy: look for mass bump over falling bkgd spectrum



Dijet

- Consider the two leading jets
  - Combine all other jets within R<1.1 of either of the two leading jets
  - $|\Delta\eta_{jj}| < 1.3$ to suppress QCD background



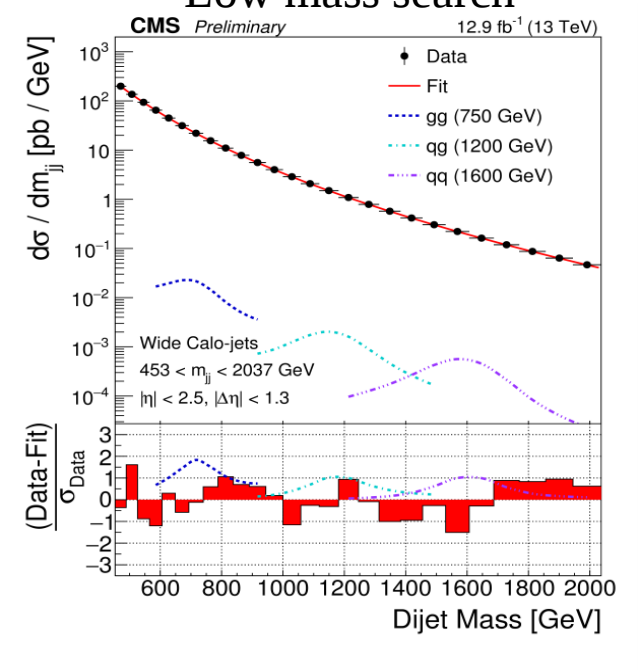
CMS-PAS-EXO-16-032

Dijet

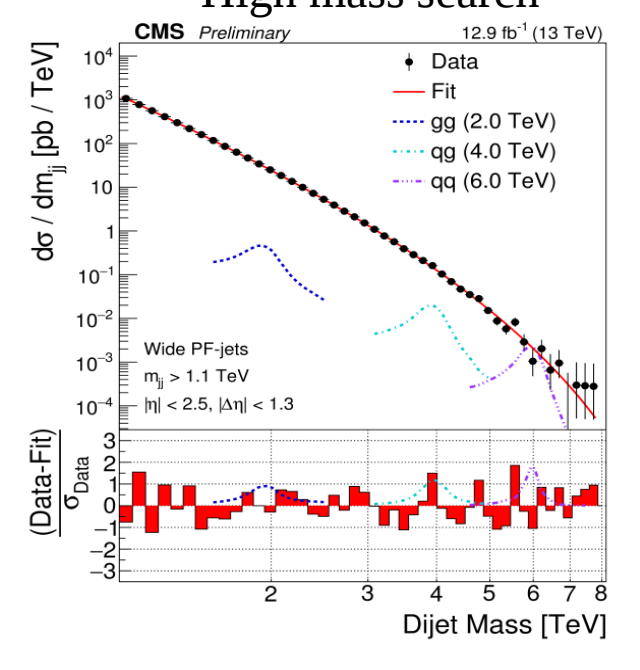
2016 data

- Fit mass spectra with parametric function for background and signal shape from simulation
- Increase search reach to lower mass range with *data scouting*
  - Reduced event data format to compensate for higher rate with less stringent trigger requirement (i.e. collect events with lower enegy jets)

Low mass search



High mass search



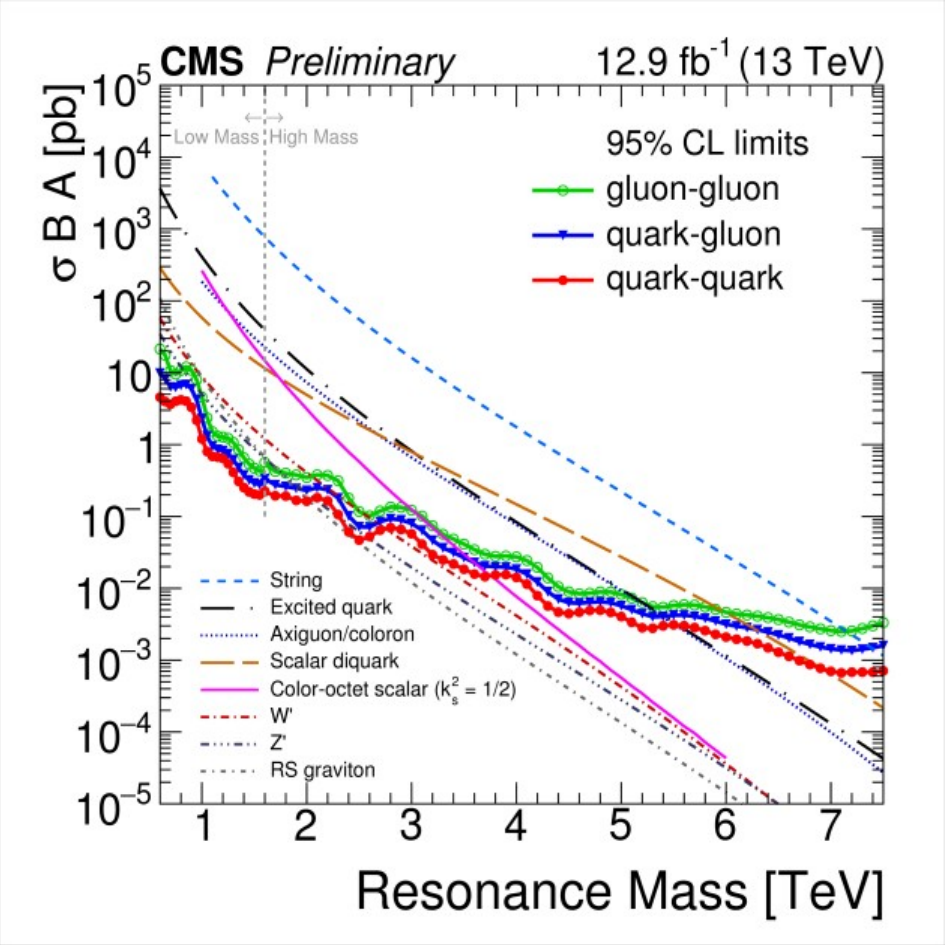
CMS-PAS-EXO-16-032

Dijet

2016 data

- Constraints placed on several models
- Exclusions were well beyond Run-1 results

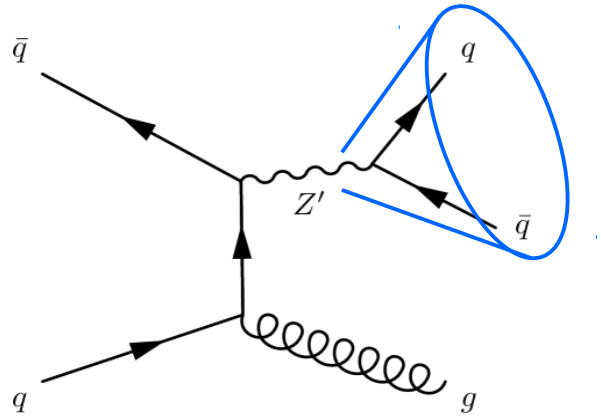
Model	Final State	Observed (expected) mass limit [TeV] 12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.0 (3.3)	—	—
W′	$q\bar{q}$	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$q\bar{q}$	2.1 (2.3)	—	1.7 (1.8)
RS Graviton	$q\bar{q}$, gg	1.9 (1.8)	—	1.6 (1.3)

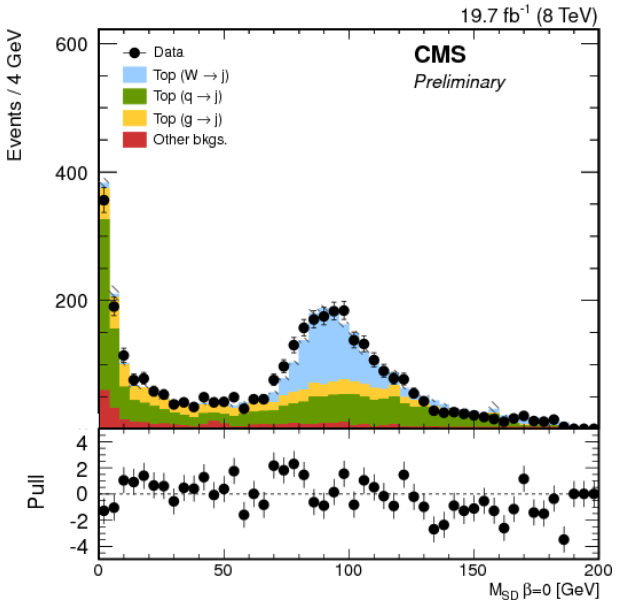


CMS-PAS-EXO-16-032

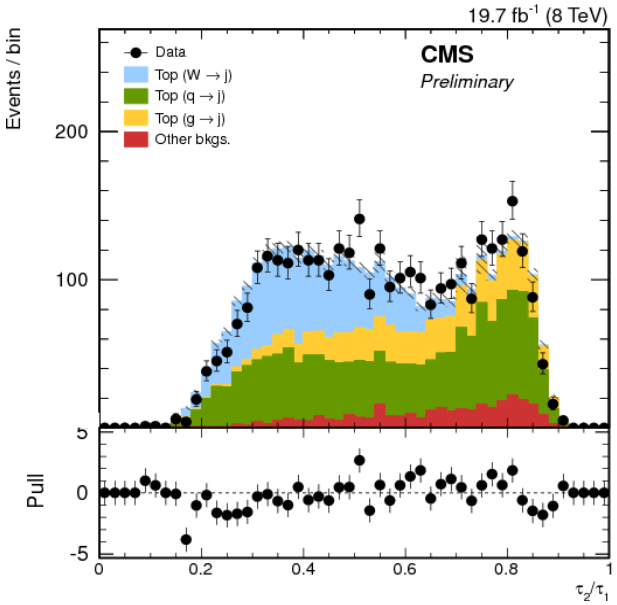
Boosted "Dijet"

2015 data





- Can reach lower dijet mass region by targetting decay of highly boosted Z'
  - Decay products merge to a single jet of R=0.8
    - Consider jet p_T > 500 GeV
    - Trigger rate manageable
  - Exploit jet substructure techniques to discriminate against q/g induced jets
    - *Grooming*: removes soft, wide-angle radiation
      - Several algorithms available: "soft drop" (arXiv:1402.2657), "pruning" (arXiv:0903.5081)
    - *N-subjettiness (arXiv:1011.2268)*: number of underlying "prongs"

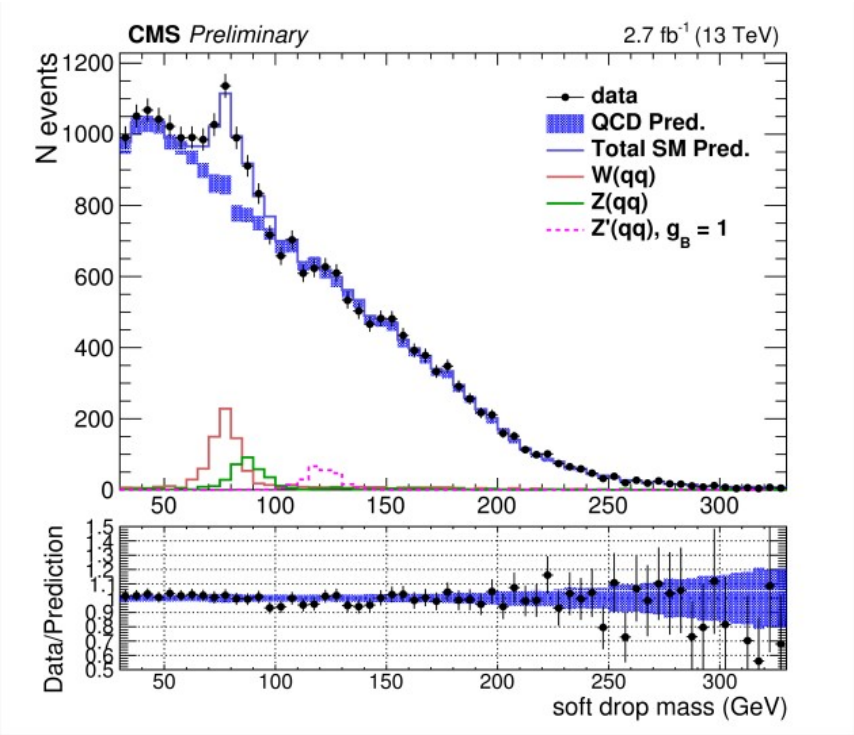


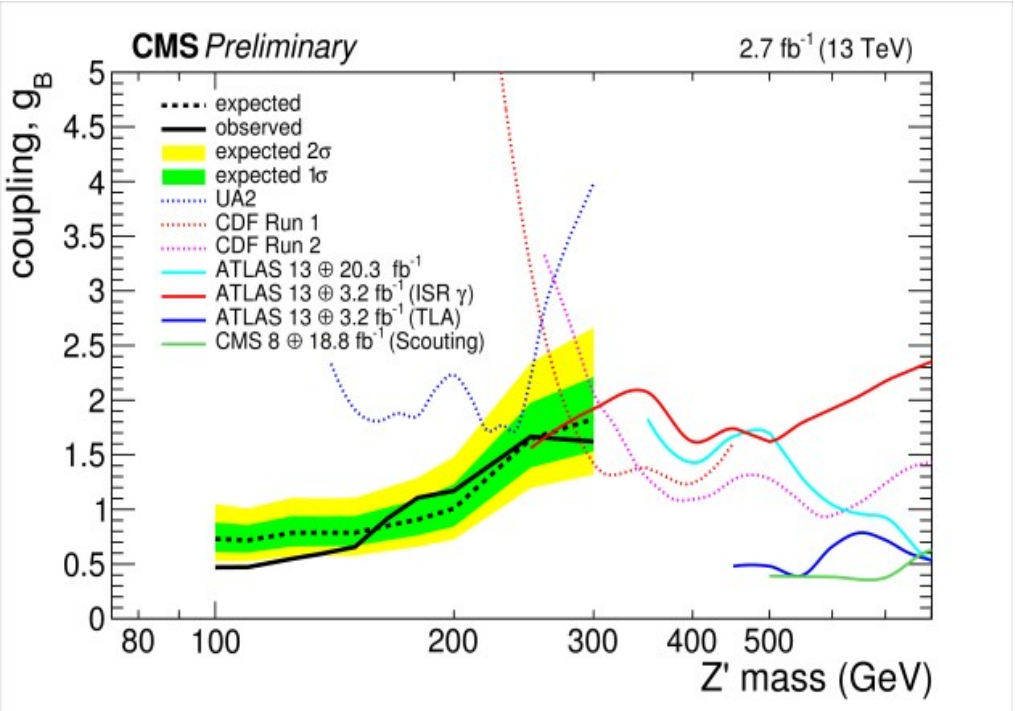
CMS-PAS-EXO-16-030

Boosted "Dijet"

2015 data

- Perform a search in the region 100 GeV < m_{SD} < 300 GeV
  - V(qq) bkg estimated from simulation (Note: V = W or Z)
  - QCD bkg estimated from data in sidebands
  - Most stringent contraint for $m_{Z'}$ < 300 GeV
    - **A new result for $m_{Z'}$ < 140 GeV !**





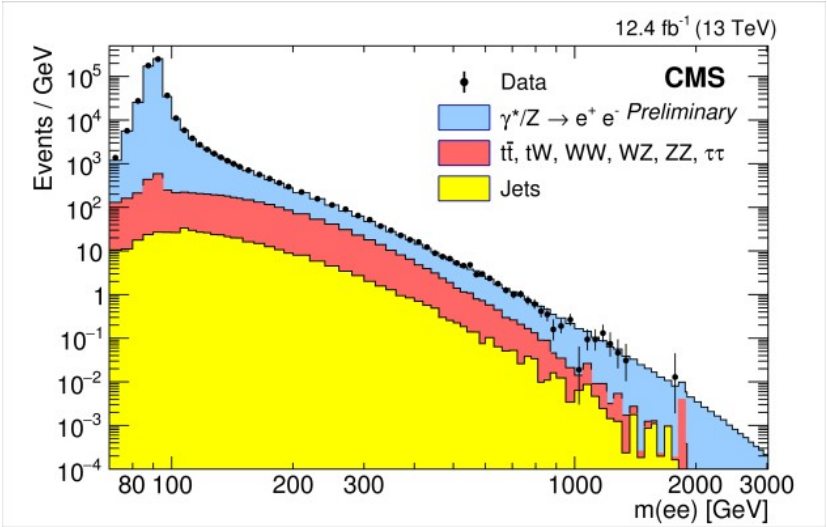
CMS-PAS-EXO-16-030

Z' to ee/μμ

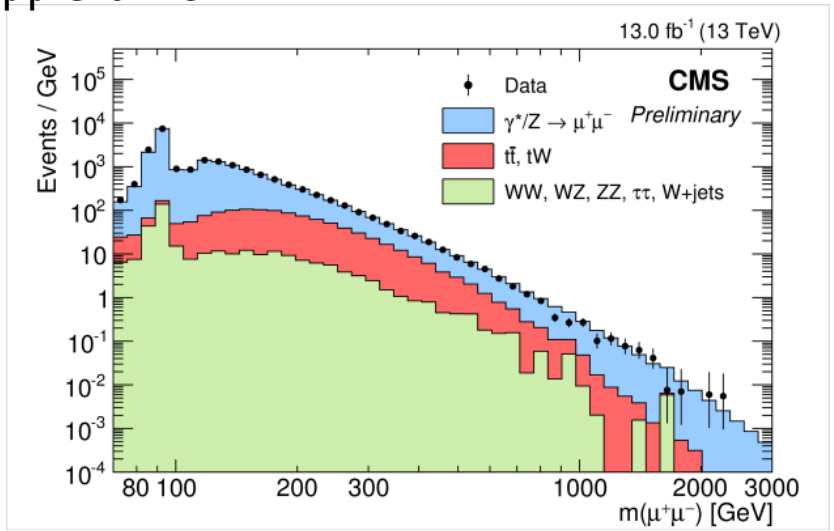
2016 data

- Search for narrow resonance in ee/μμ mass spectra
  - Fit with parametric functions for signal and background
- Exclude Z'_{ψ} < 3.5 TeV
- Exclude Z'_{SSM} < 4 TeV
- Exclusion reach with 2016 dataset extend significantly from search with 2015 dataset:
  - Excluded Z'_{ψ} < 2.6 TeV
  - Excluded Z'_{SSM} < 3.15 TeV

ee channel



μμ channel

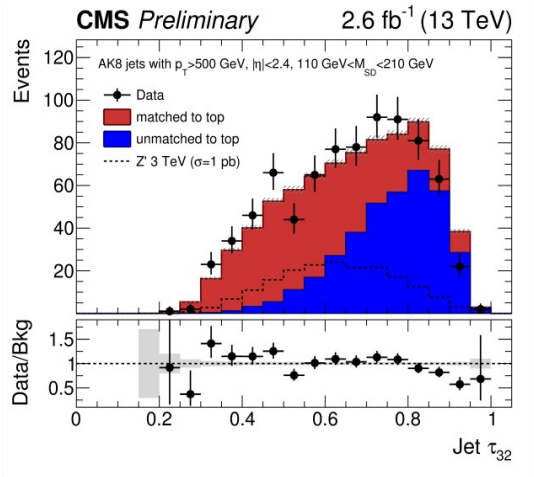


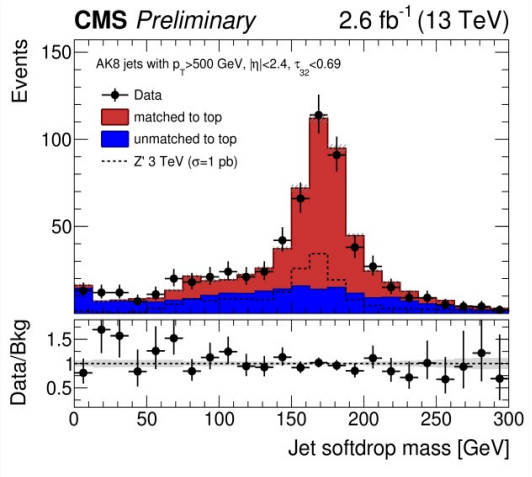
CMS-PAS-EXO-16-031

Z' to $t\bar{t}$

2015 data

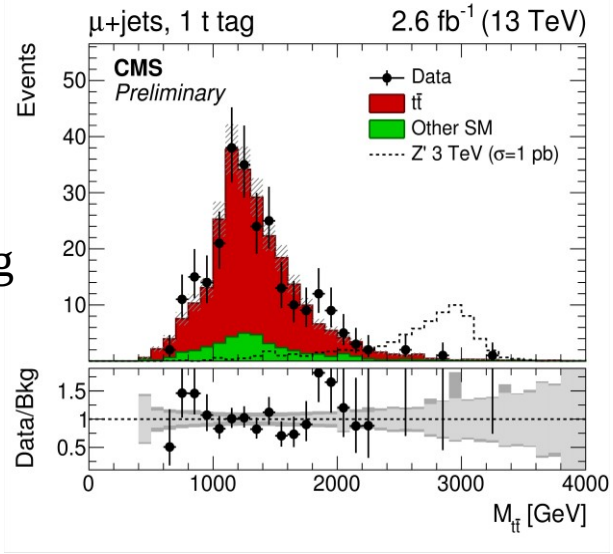
- Search for heavy resonance decay to pair of boosted top quarks
- Semileptonic channel:
  - Single e or μ and MET
    - Impose m_W constraint to get neutrino p_z
  - τ_3/τ_2 and m_{SD} for hadronic top with R=0.8 jets

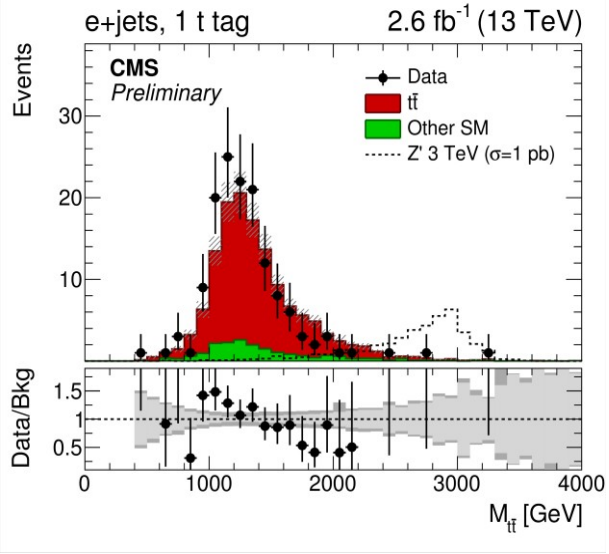




- Signal region categorized by number of b-tags and top tags

Muon + 1 top-tag





Electron + 1 top-tag

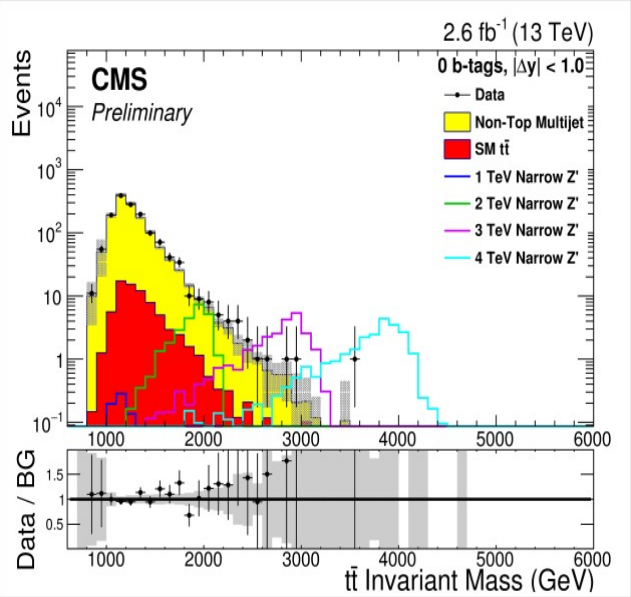
CMS-PAS-B2G-15-002

Z' to $t\bar{t}$

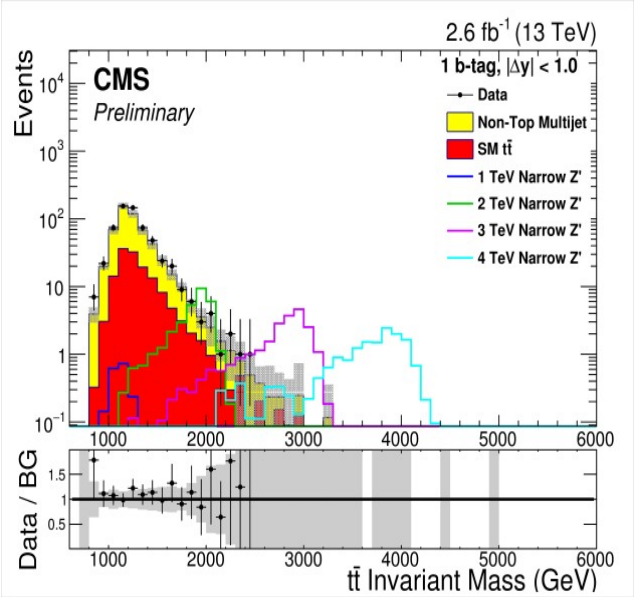
2015 data

- Search for heavy resonance decay to pair of boosted top quarks
- All hadronic channel
  - Require two boosted top tags using m_{SD}, τ_3/τ_2, and sub-jet b-tagging with R=0.8 jets
- Signal region categorized by number of b-tags (0,1,2) and rapidity difference of top pair (|Δy|<1 or |Δy|>1)

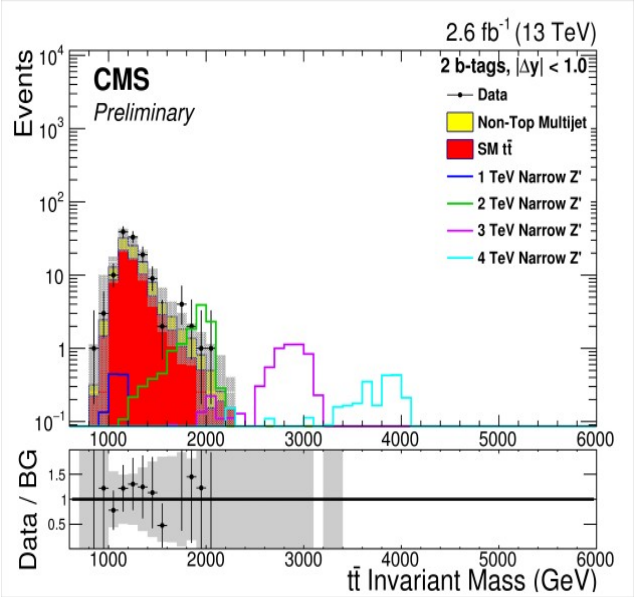
0 b-tags



1 b-tags



2 b-tags



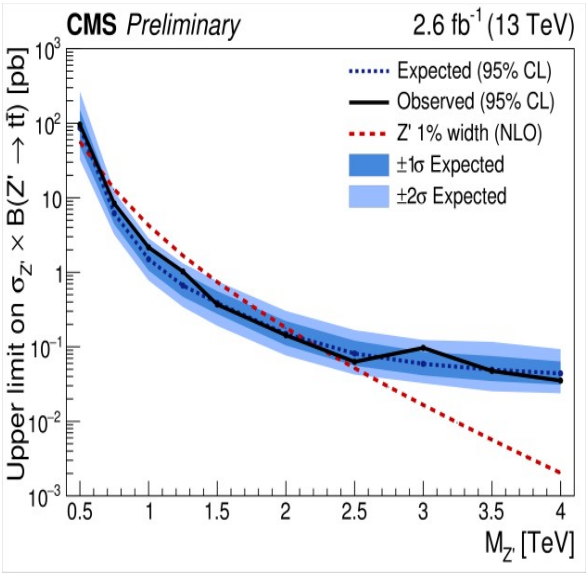
CMS-PAS-B2G-15-003

Z' to $t\bar{t}$

2015 data

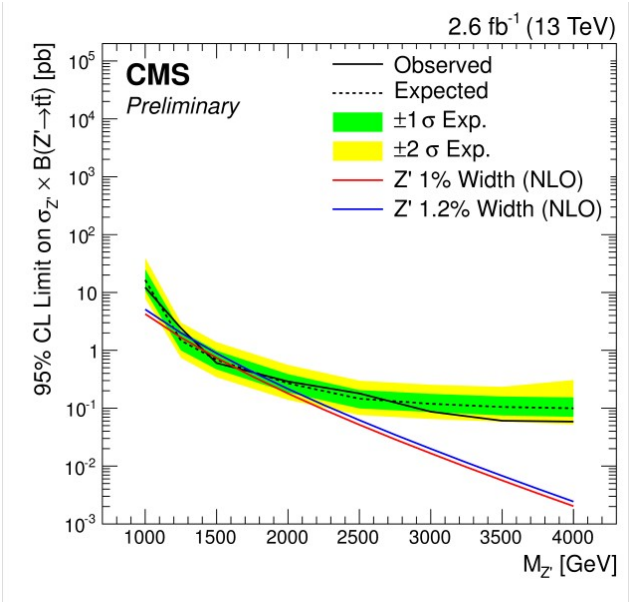
- Z' → $t\bar{t}$ searches performed in semileptonic and hadronic channels on the 2015 dataset
  - For Z' with 1% width:
    - Semileptonic channel excludes [0.6, 2.3] TeV
    - Hadronic channel excludes [1.4, 1.6] TeV

Semileptonic



CMS-PAS-B2G-15-002

Hadronic



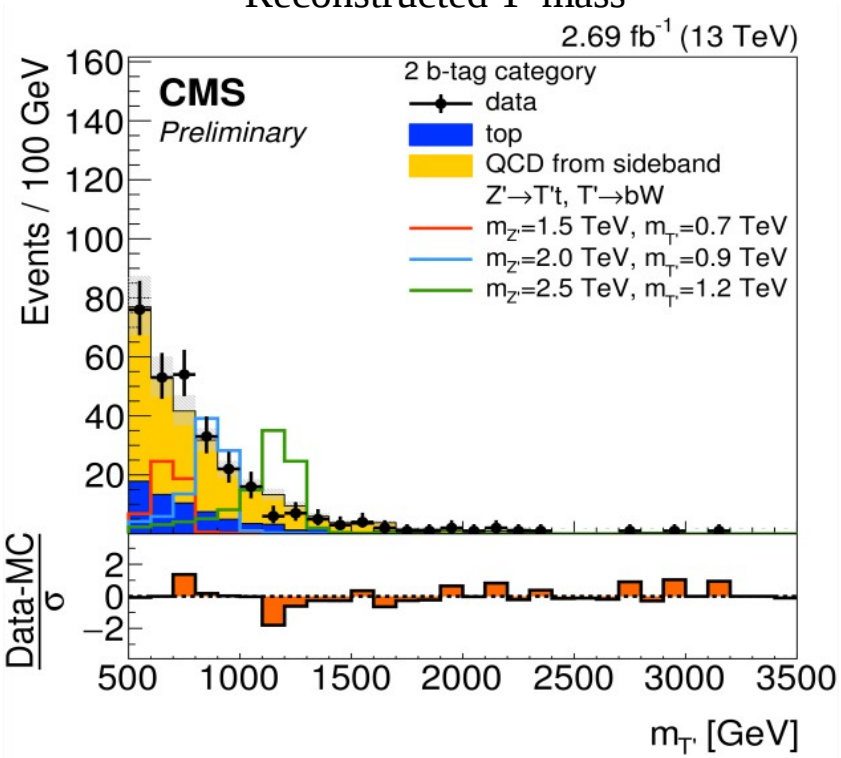
CMS-PAS-B2G-15-003

Z' → T't

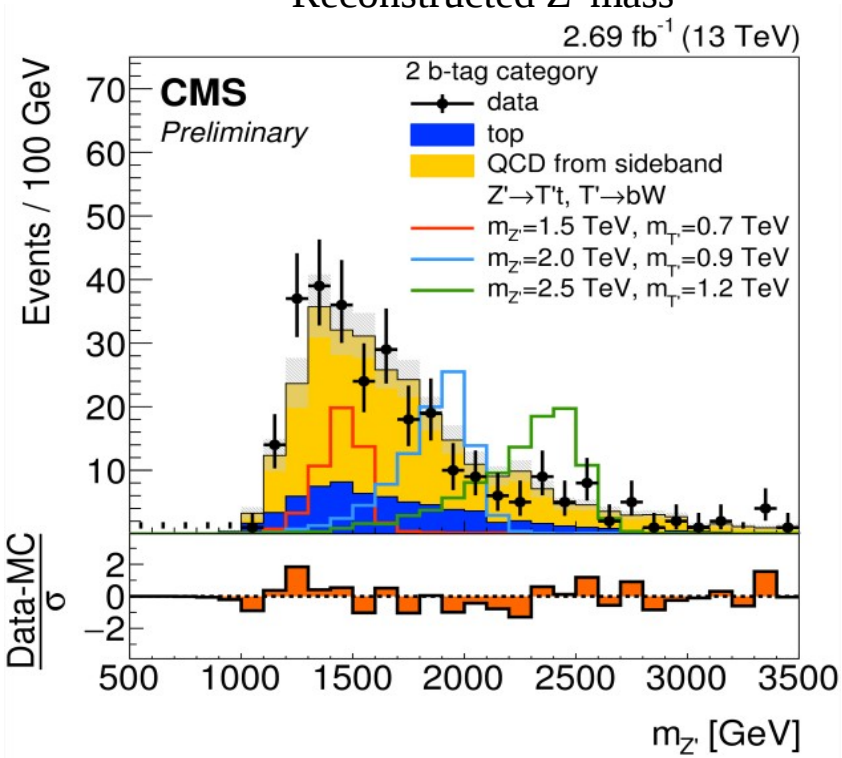
2015 data

- First search for Spin-1 resonance decaying to top and vector-like top partner (T') in Run-2
  - T' → Wb, W decays hadronically
    - Use substructure methods to tag W and t
  - $t\bar{t}$ bkgd from simulation, QCD bkgd from sideband data

Reconstructed T' mass



Reconstructed Z' mass

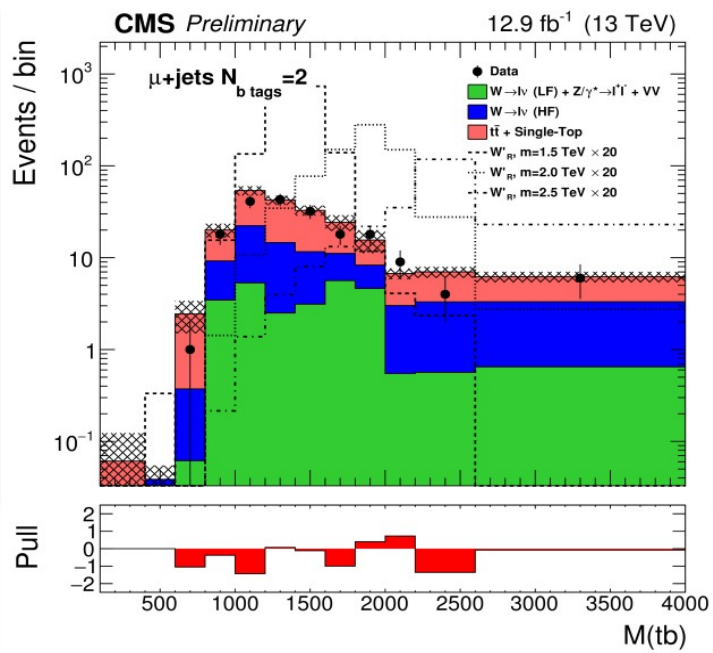


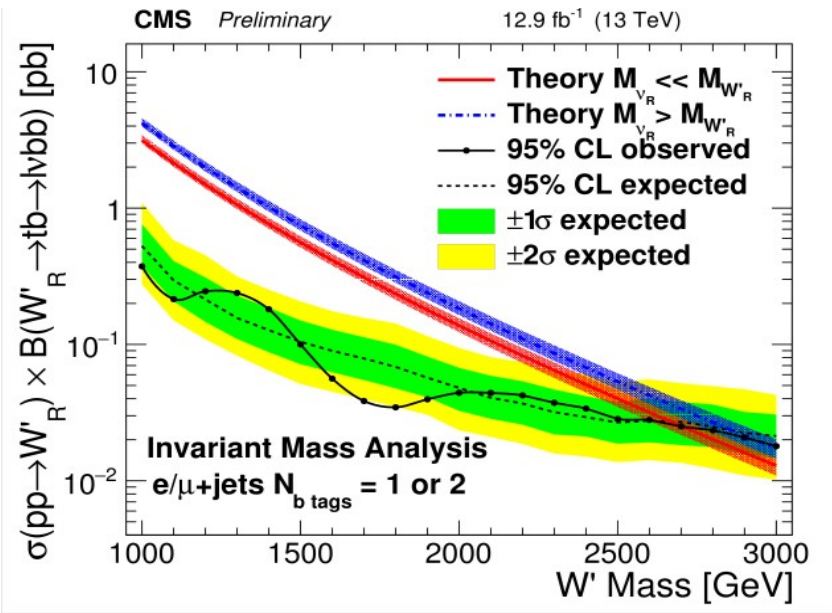
CMS-PAS-B2G-16-013

W' to tb

2016 data

- W' → tb where W from top quark decays leptonically
  - M_W constraint used to solve neutrino p_z, then reconstruct M(tb)
- Interpretation for right-handed W'
  - Exclude masses up to 2.67 TeV



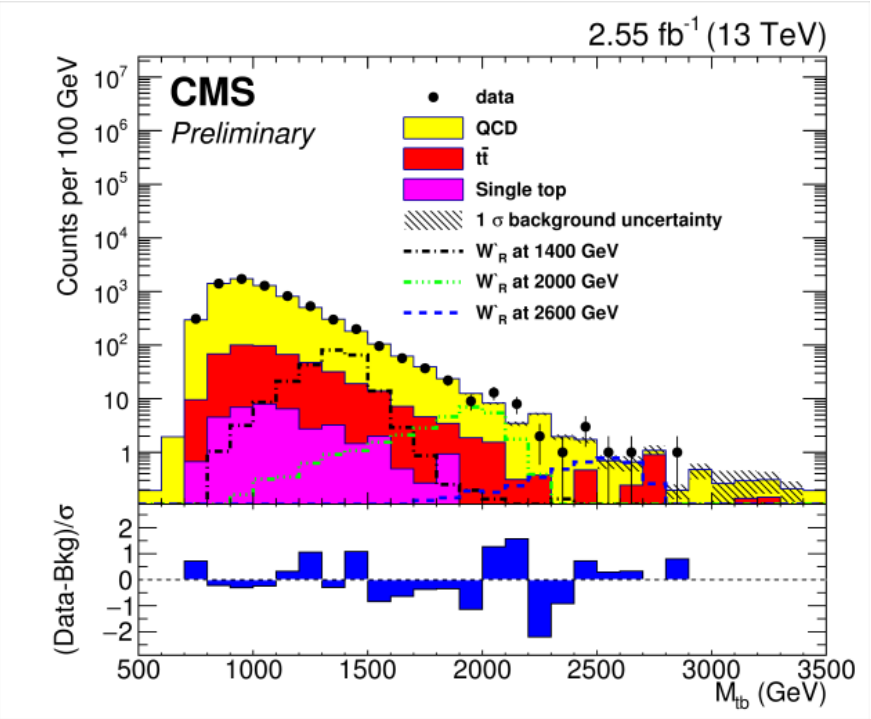


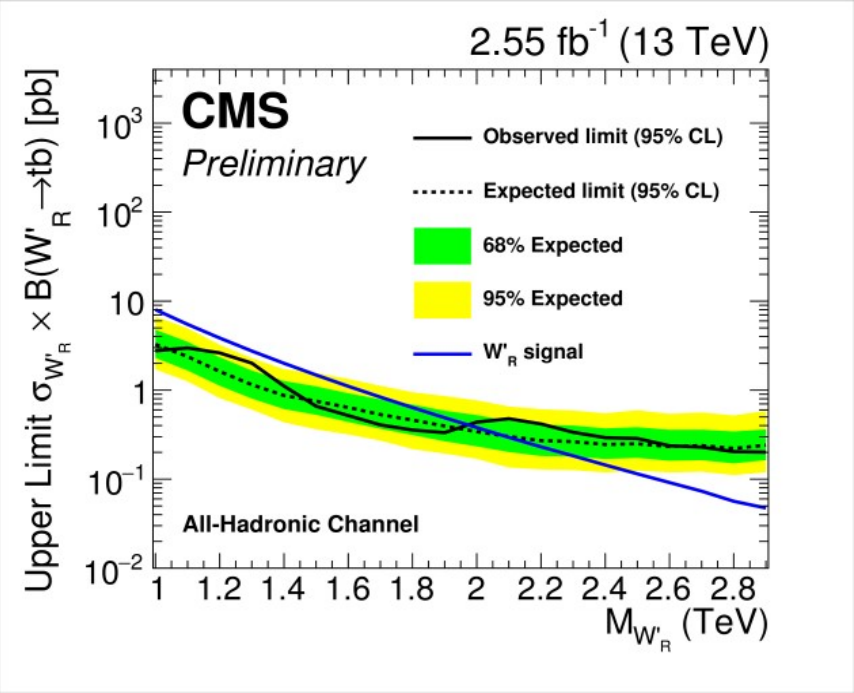
CMS-PAS-B2G-16-017

W' to tb

2015 data

- W' → tb where W from top quark decays hadronically
  - M(tb) directly reconstructed
  - Substructure used to tag boosted hadronic tops
- Interpretation for right-handed W'
  - Exclude masses up to 2 TeV



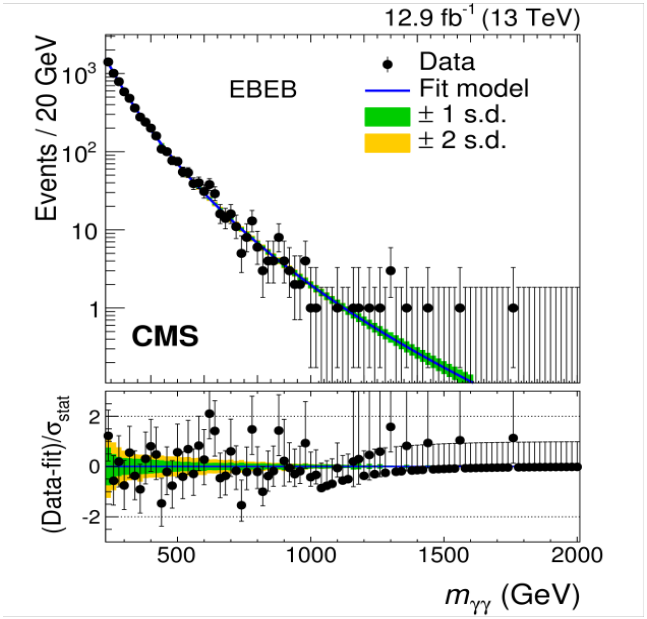


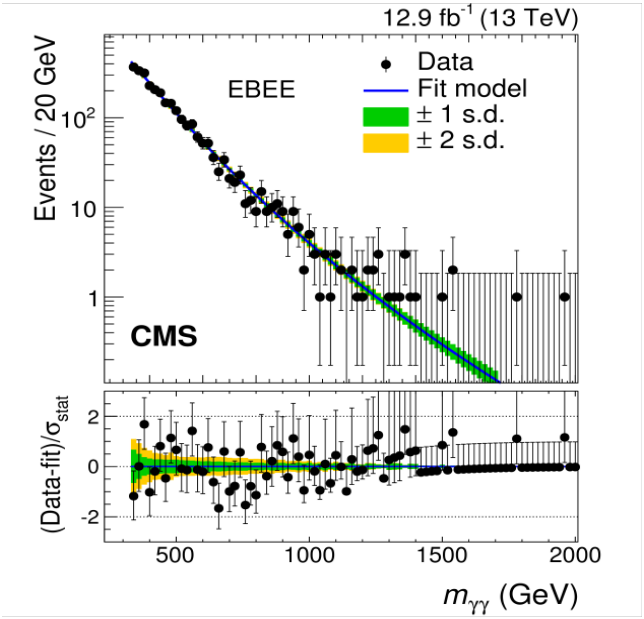
CMS-PAS-B2G-16-009

Diphoton

2016 data

- Search for resonances with mass above 500 GeV decaying to γγ
  - Select pair of photons with p_T>75 GeV
  - 2 categories: barrel-barrel (EBEB), barrel-endcap (EBEE)
- Fit $m_{\gamma\gamma}$ spectra with parametric functions for signal and background
  - Parameters of signal model are polynomial functions of m_X hypothesis
- No hint of excess ~750 GeV in 2016 data
  - Local significance 0.8σ with combined 2015+2016 dataset

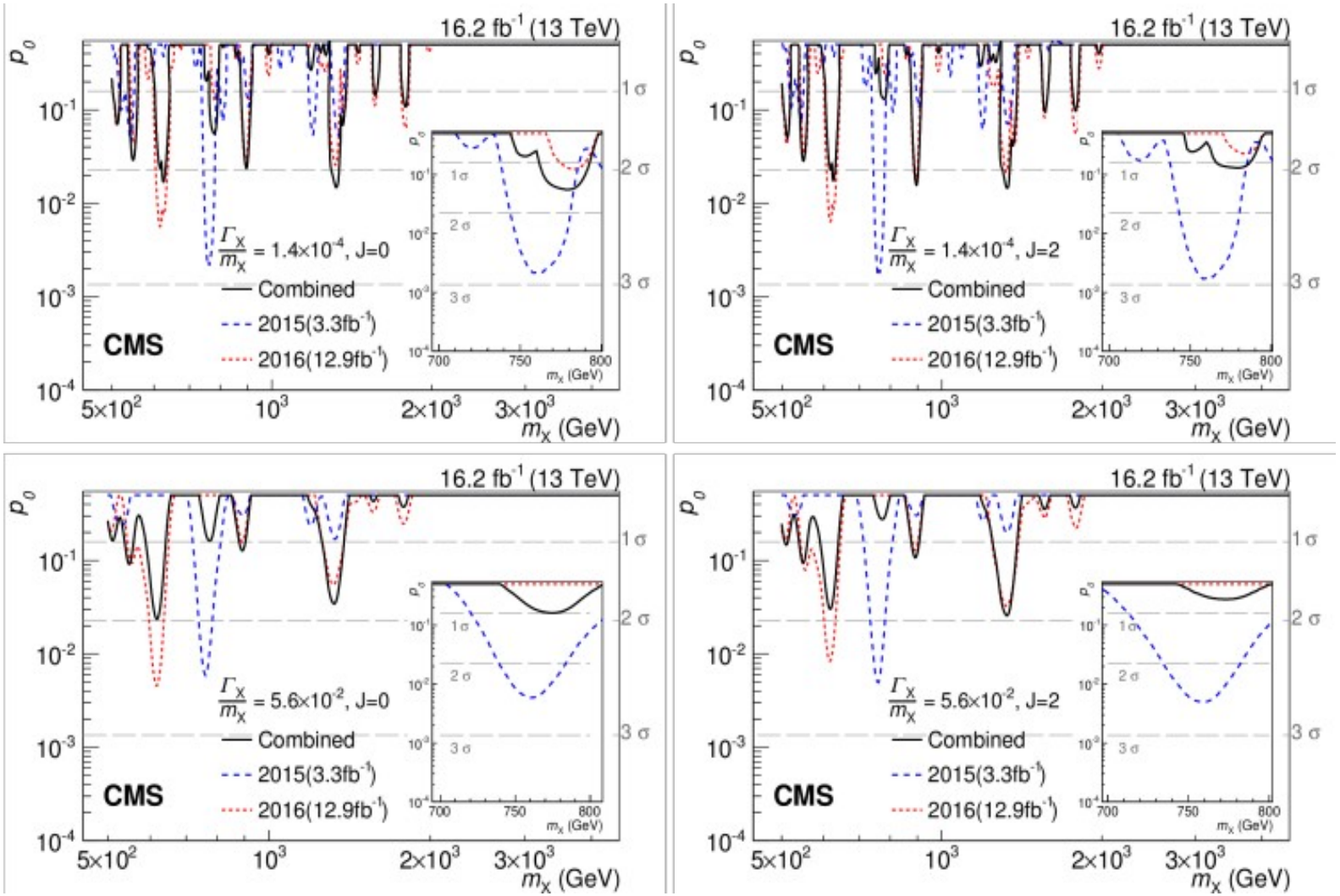




CMS-EXO-16-027

Diphoton

- Local p-values around 750 GeV for 2015 data, 2016 data, and 2015+2016 data



CMS-EXO-16-027

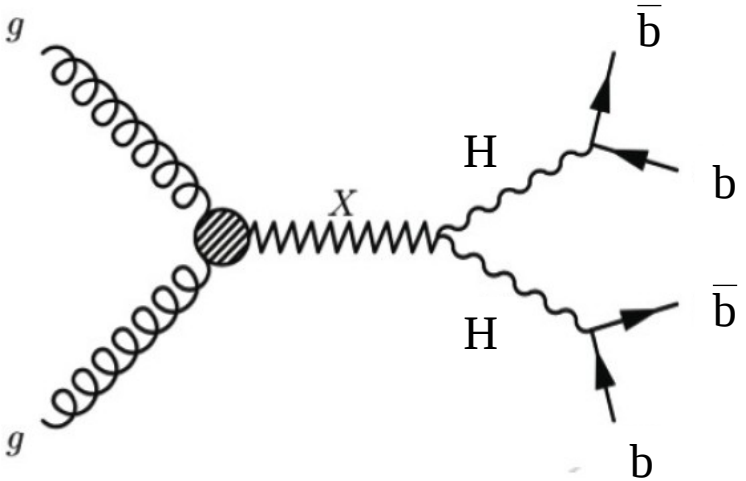
HH

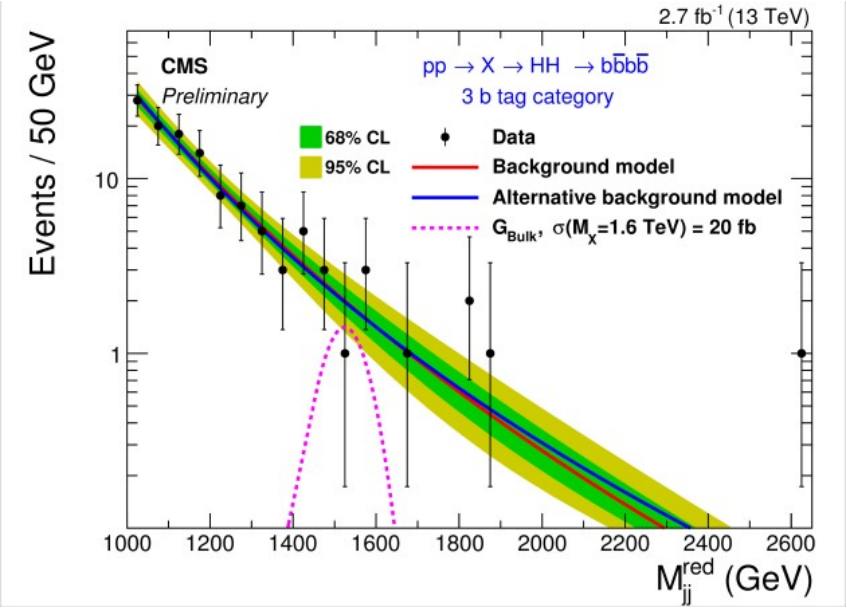
2015 data

- Search in the HH → 4b final state
  - Select pair of Higgs-tagged R=0.8 jets
- Consider the reduced mass:

$$M_{jj}^{red} = M_{jj} - (M_1 - m_H) - (M_2 - m_H)$$

  - Better resolution than M_{jj}
- Constraints on Radion and Bulk graviton models

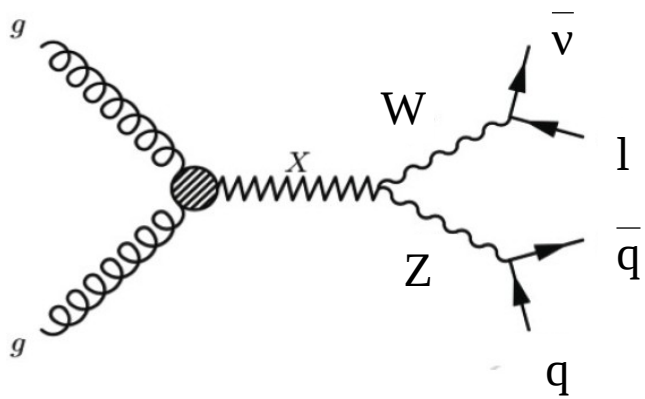


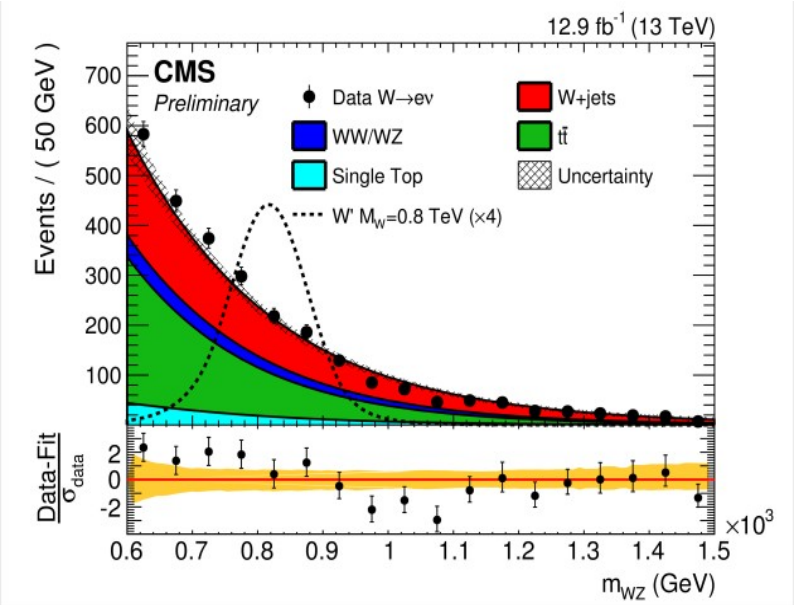


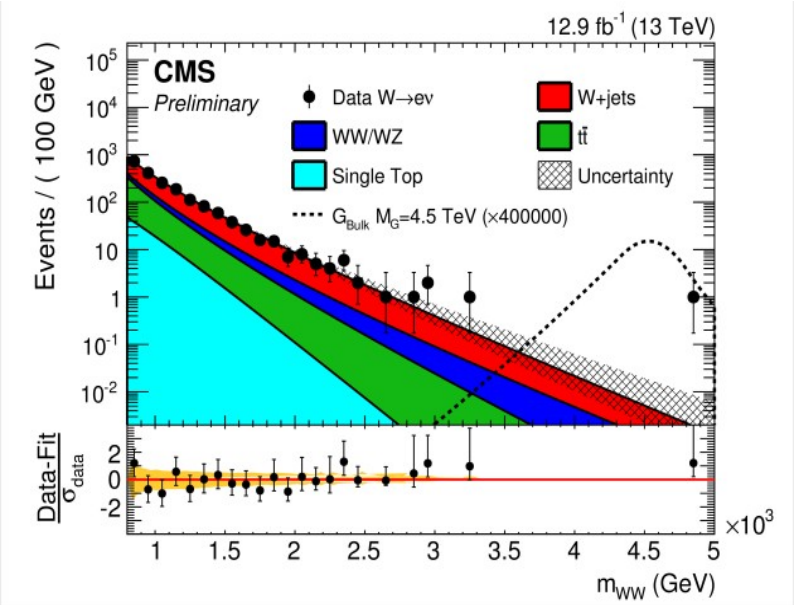
CMS-PAS-B2G-16-008

WW/WZ

2016 data







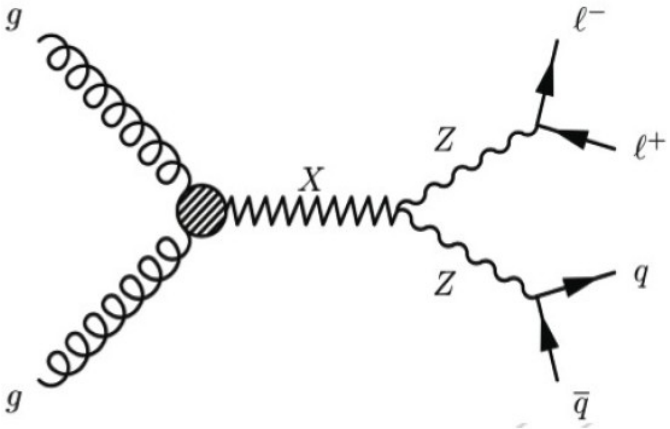
- Search in the W(lν)V(qq) mass spectrum
  - Boosted V-tagging used
  - M_W constraint to solve for neutrino p_z
  - Parametric function for signal
  - W+jets bkg normalization from sideband
- Interpretations:
  - Bulk graviton → WW
  - HVT W' → WZ

CMS-PAS-B2G-16-020

ZV

2015 data

- Search in the Z(ll)V(qq) mass spectrum
  - Z(ll)+jets is dominant background, estimated with data in sidebands
  - Low mass analysis (550 GeV < M_{ZV} < 800 GeV)
    - Consider boosted and resolved decays of V → qq
    - Further categorize according to b-tagging
    - Correction to Z(ll)+jets MC from sidebands
  - High mass analysis (M_{ZV} > 800 GeV)
    - Boosted selection only
    - Categorized according to τ_2/τ_1
    - Parametric function for Z(ll)+jets

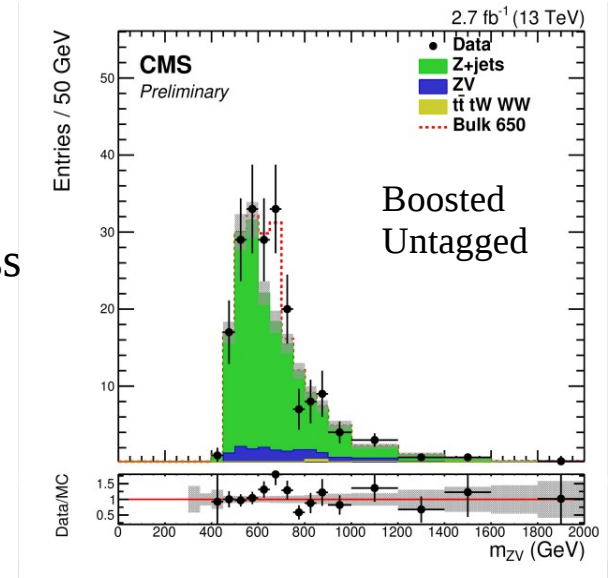


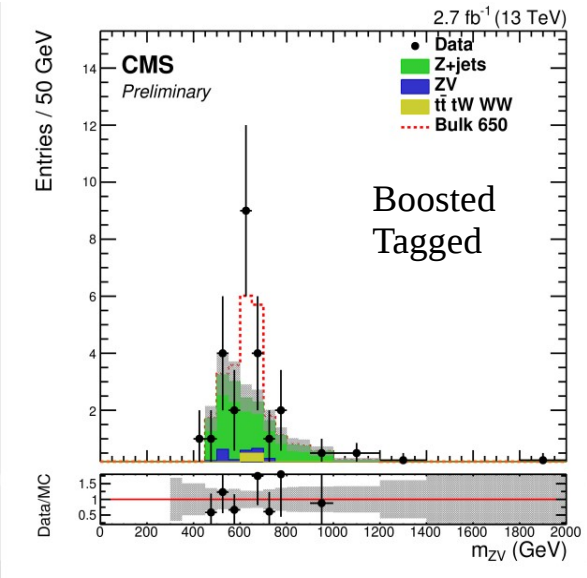
CMS-PAS-B2G-16-010

ZV

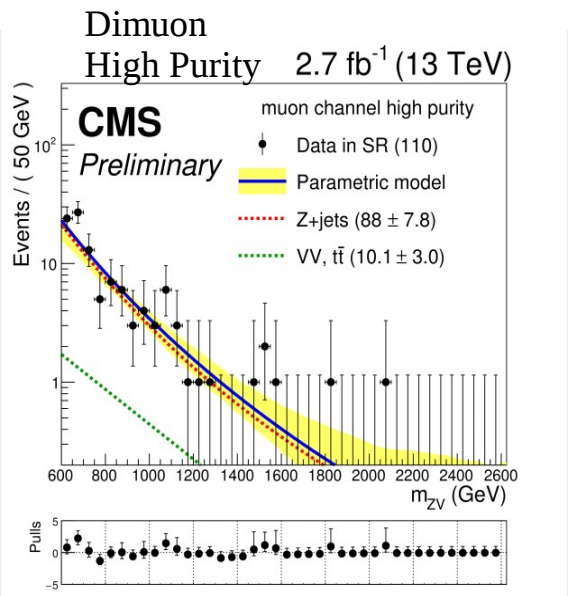
2015 data

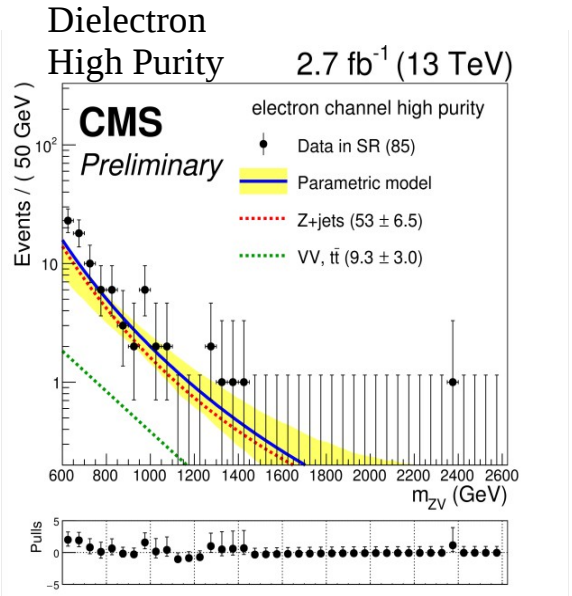
Low mass Search





High mass Search



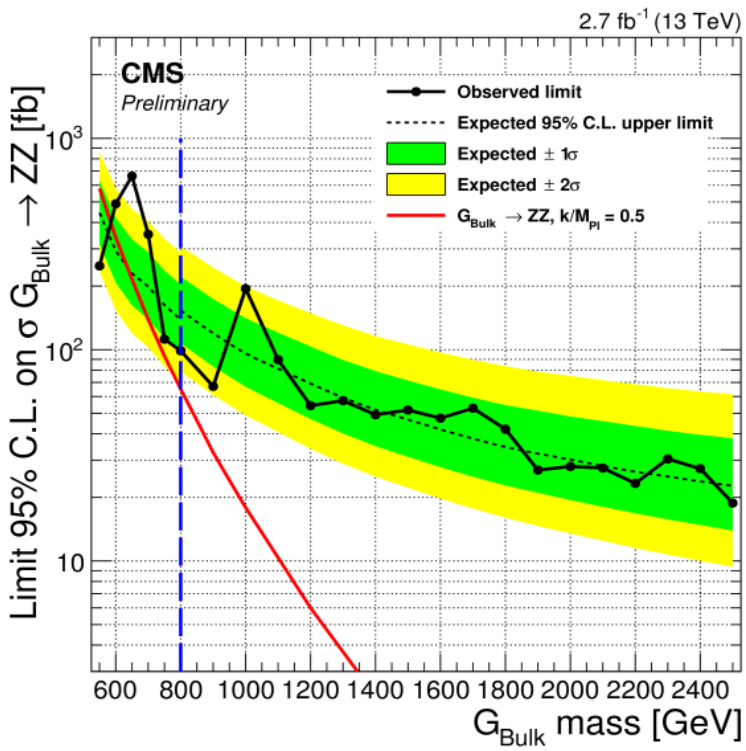


CMS-PAS-B2G-16-010

ZV

2015 data

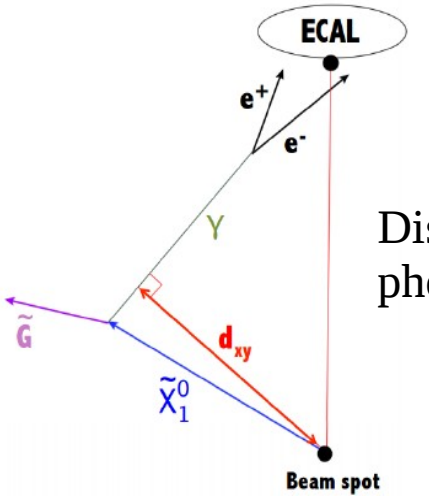
- Interpretation with RS graviton and Bulk graviton
- Hint of excess at 650 GeV:
  - RS intepretation: 3.4σ (local), 2.9σ (global over [550, 1400] GeV)
  - Bulk interpretation: 3.9σ (local), 3.5σ (global over [550, 1400] GeV)
- Result from 2015 dataset, analysis on 2016 dataset in progress



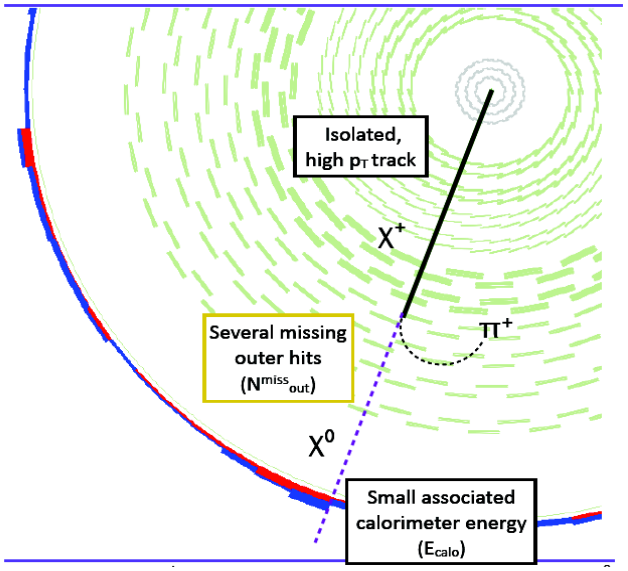
CMS-PAS-B2G-16-010

Long-lived Particles

- Interesting signatures where BSM particle decays in the detector or not at all
- Can be challenging: standard techniques typically optimzed for prompt decays
- Past publications include:
  - Displaced photons *[JHEP 11 (2012) 172]*
  - Disappearing tracks *[JHEP 01 (2015) 096]*
- Two recent searches for long-lived particles:
  - Displaced leptons (eμ)
  - Heavy stable charged particles



Displaced photon

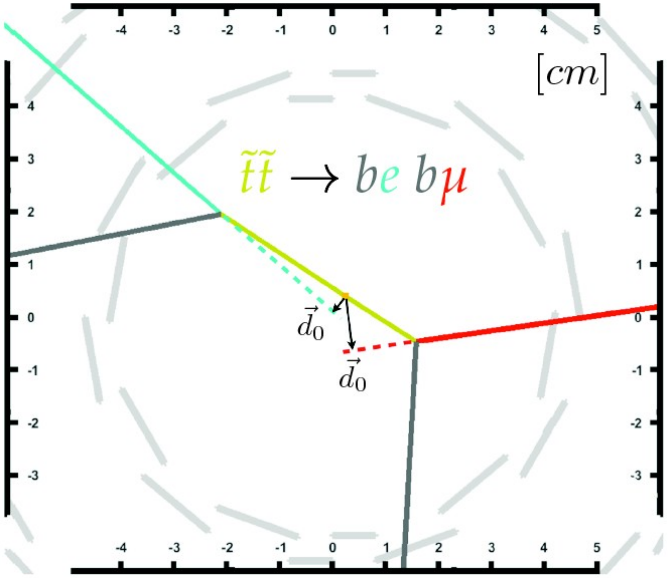


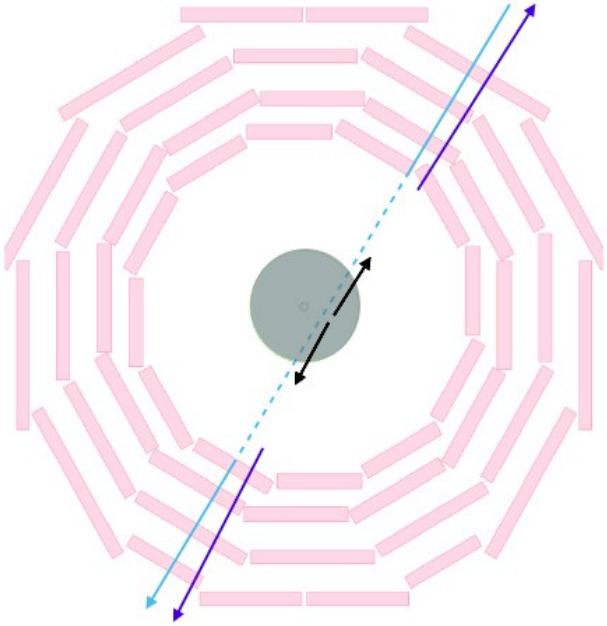
Disappearing track

Displaced eμ

2015 data

- Target lifetimes of cτ ~ 100 μm – 10 cm
  - Benchmark: Displaced SUSY
    - Long-lived $\tilde{t} \rightarrow bl$
- Select eμ events where each lepton is isolated and have large d_0
- Dedicated trigger select “muon”+”photon”
  - No vtx and IP constraints on muon
  - No electron track constraint
- Performance of displaced tracking efficiency measured in data with cosmics
  - Data taken “parasitically” between BX
  - Cosmic muon identified by muon chamber, look for corresponding tracker track



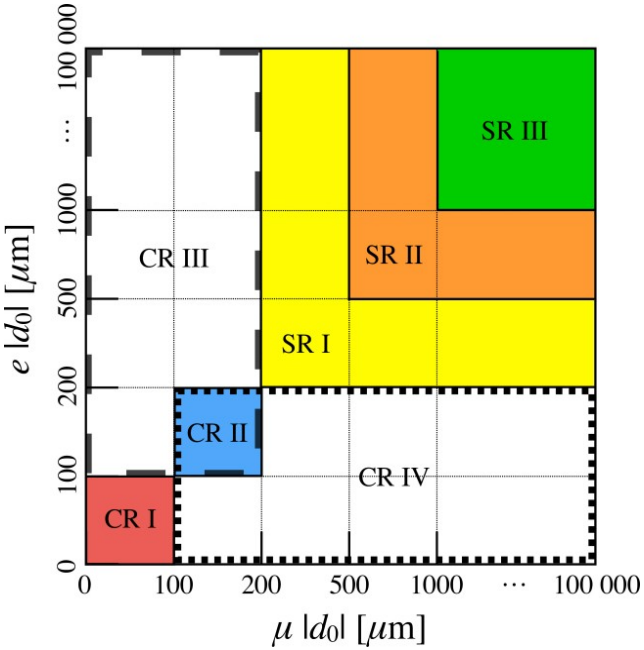


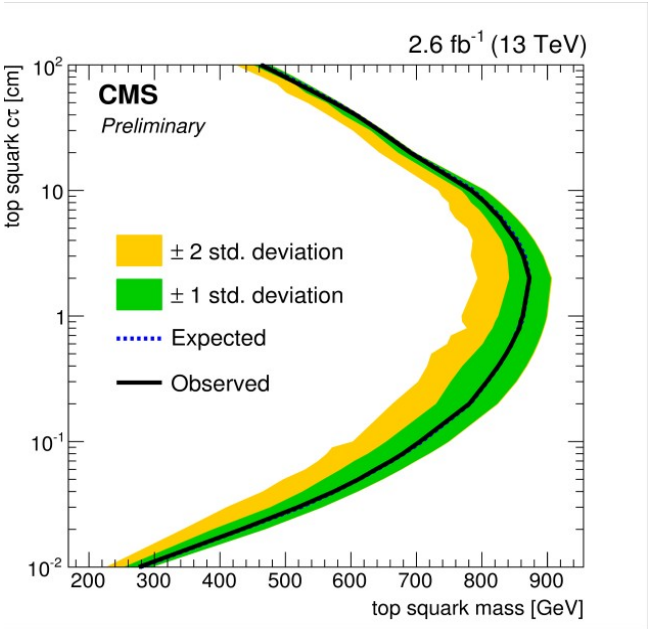
CMS-PAS-EXO-16-022

Displaced eμ

2015 data

- Signal regions defined in different ranges of d_0 of e and μ
  - Probe BSM particles of different lifetimes
- Limits placed in mass vs cτ plane of $\tilde{t}$
  - Sensitivity with 2015 dataset (2.6 fb^{-1}) already exceeds Run-1 (19.7 fb^{-1}), e.g. for cτ = 2 cm:
    - Run-1: $m_{\tilde{t}}$ > 790 GeV *(Phys. Rev. Lett. 114, 061801)*
    - 2015 dataset: $m_{\tilde{t}}$ > 870 GeV



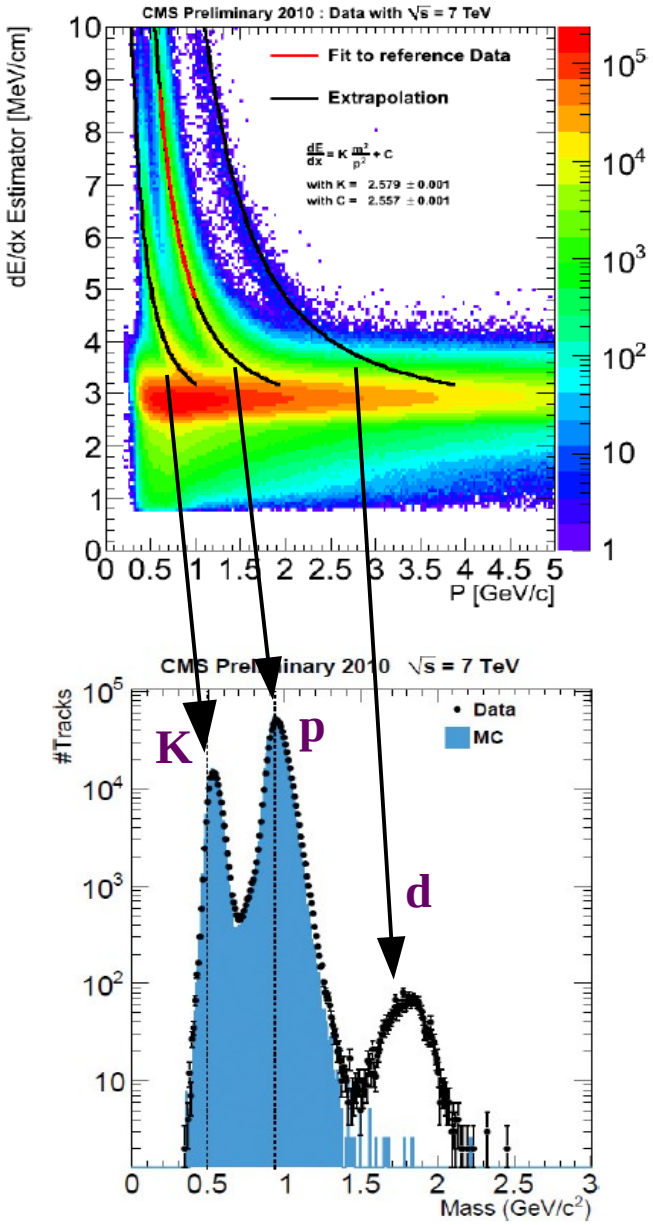


CMS-PAS-EXO-16-022

Heavy Stable Charged Particles

2016 data

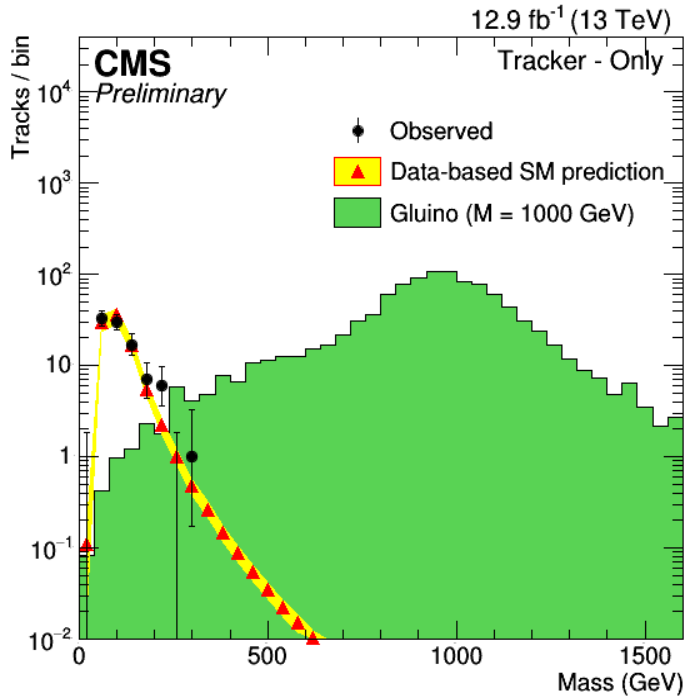
- Heavy Stable Charged Particles
  - Typical lifetimes cτ ~ O(1 m)
- Signatures of HSCP:
  - Anomalous ionization energy loss (dE/dx) in tracker
  - Large time-of-flight (TOF) measured with muon system
- Two search strategies:
  - ***Tracker-only*** – consider only dE/dx, for scenario where R-hadron becomes neutral in flight due to charge exchange with detector material
  - ***Tracker + TOF*** – use dE/dx and require large TOF

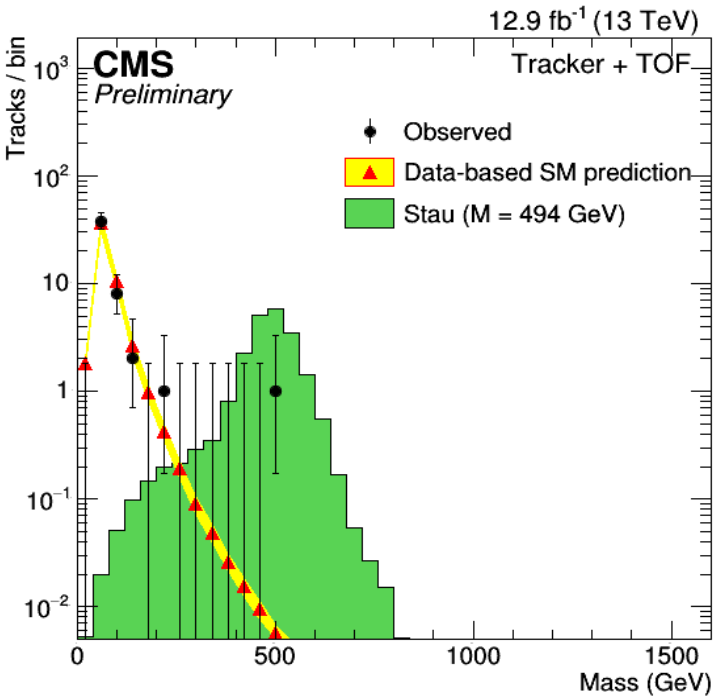


CMS-PAS-EXO-16-036

Heavy Stable Charged Particles

2016 data





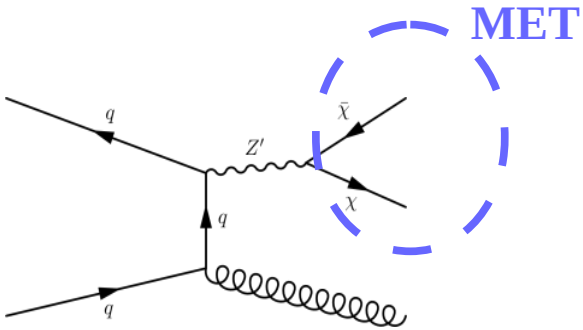
- Constraints on several benchmark models predicting HSCP
  - $\tilde{g}$ and $\tilde{t}_1$ pair production from Split SUSY
  - $\tilde{\tau}_1$ from mGMSB model
  - Drell-Yan production of exotic fermions

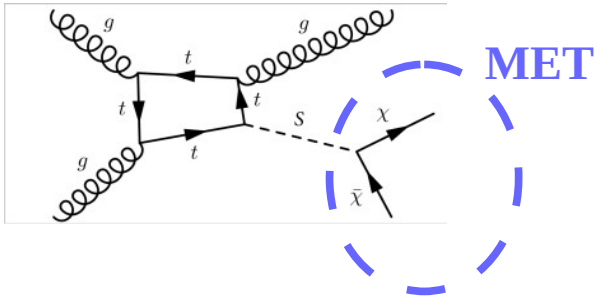
CMS-PAS-EXO-16-036

Dark Matter Searches with MET

- If produced at colliders, DM particles escape leaving MET
- Benchmarks for DM: simplified models with 4 types of mediators
  - m_{DM}, m_{MED}, g_q, g_{DM} are "free" parameters of these models
  - Different MET+X channels are more/less sensitive to different mediator types (X = jets, photons, Z, W, t, etc.)

Spin-1	Vector $g_{DM} Z'_\mu \bar{\chi} \gamma^\mu \chi$ EWK style coupling (equal to all leptons)	Axial $g_{DM} Z''_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$ EWK style coupling (equal to all leptons)
Spin-0	Scalar $g_{DM} S \bar{\chi} \chi$ Yukawa style coupling (Mass based coupling)	Pseudoscalar $g_{DM} P \bar{\chi} \gamma^5 \chi$ Yukawa style coupling (Mass based coupling)

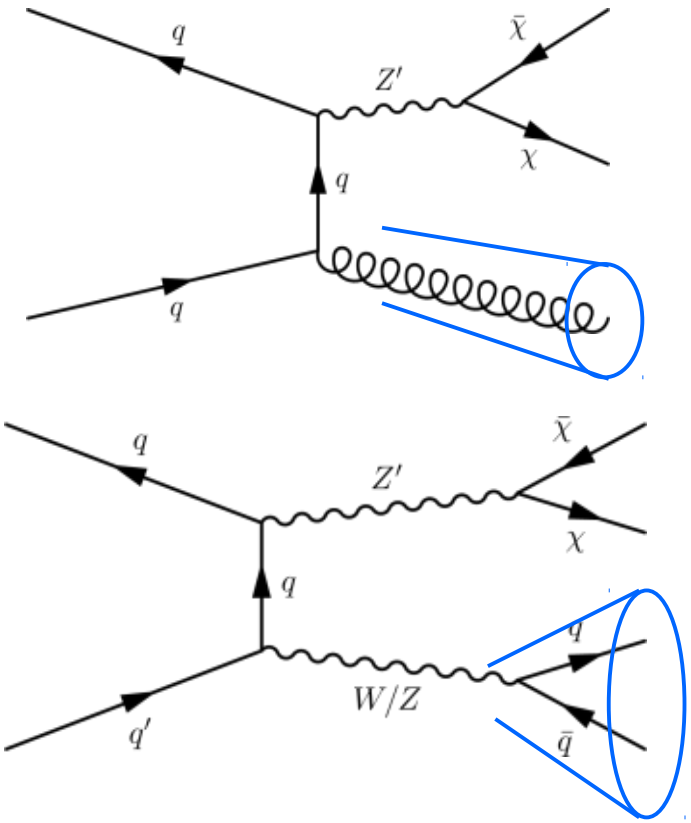


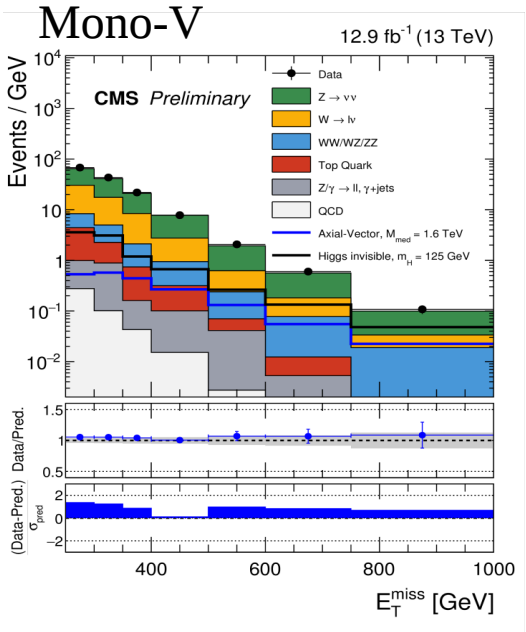


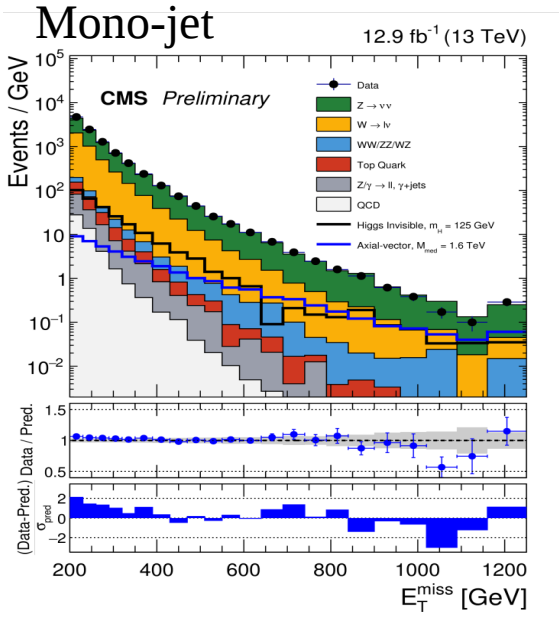
Mono-jet/V(had)

2016 data

- MET+jet(s)
  - MET > 200 GeV
  - A high energy jet carries (most of) the recoil against the DM particles:
    - R=0.8 jet p_T > 250 GeV, V-tagged
    - Light jet (R=0.4) p_T > 100 GeV
  - MET shape analysis







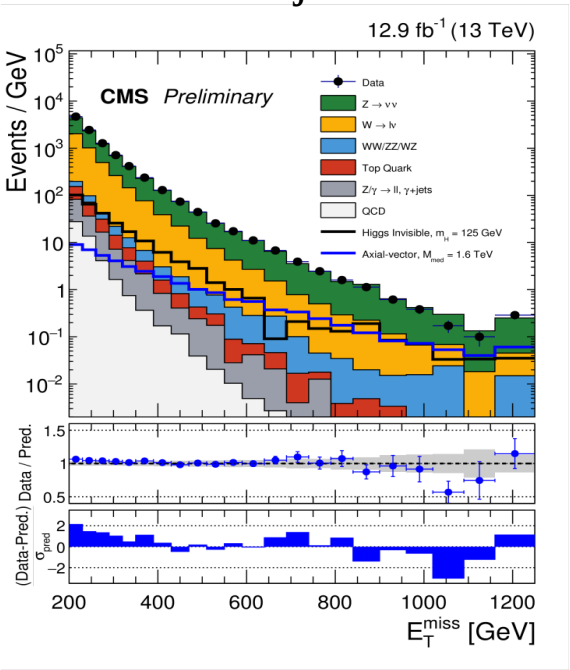
CMS-PAS-EXO-16-037

Mono-jet/V(had)

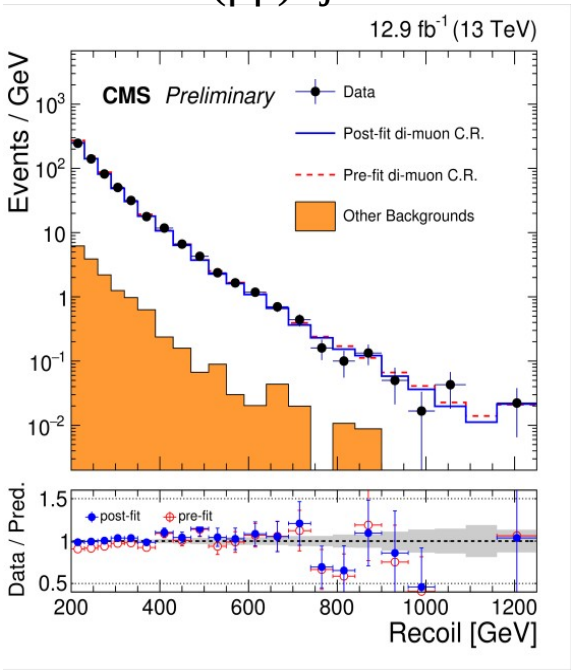
2016 data

- Dominant backgrounds are Z(νν)+jets and W(lν)+jets
  - Z(νν)+jets constrained with data from Z(ll)+jets, W(lν)+jets, γ+jets CRs
  - W(lν)+jets constrained with data from W(lν)+jets CRs
  - CR → SR "transfer factors" relies on accurate simulation of V+jets processes and understanding of how theoretical uncertainties correlate between Z/W/γ and across boson p_T spectrum

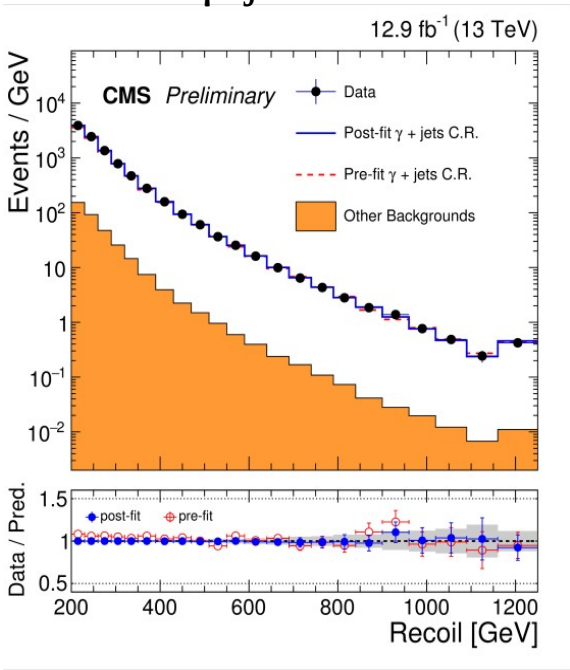
Mono-jet SR



Z(μμ)+jets CR



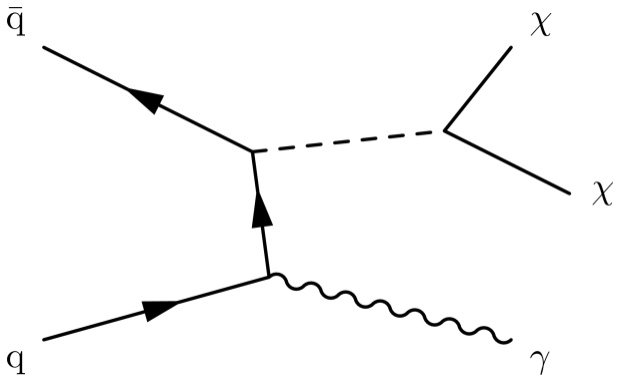
γ+jets CR



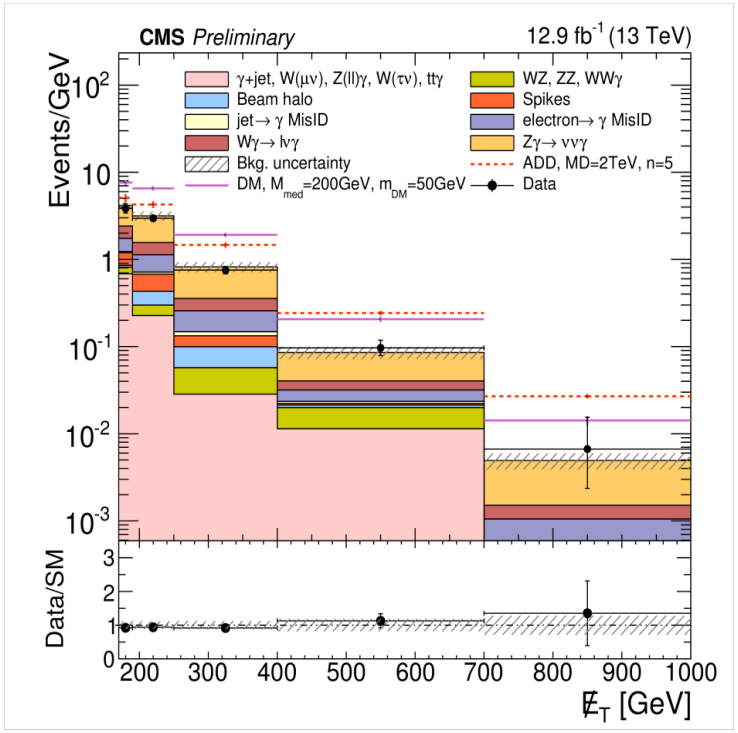
CMS-PAS-EXO-16-037

Mono-photon

2016 data



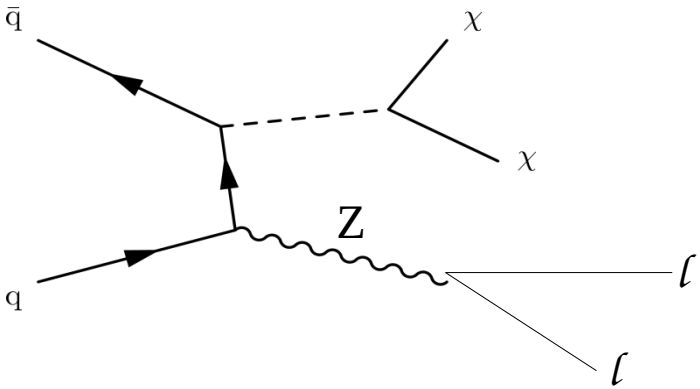
- MET+photon signature
  - Photon E_T > 175 GeV
  - MET > 170 GeV
- Dominant backgrounds are Z(νν)+γ and W(lν)+γ
- Must contend with non-collision backgrounds from beam halo or ECAL spikes producing spurious photon+MET signature
  - ~10% of bkg, difficult to estimate precisely



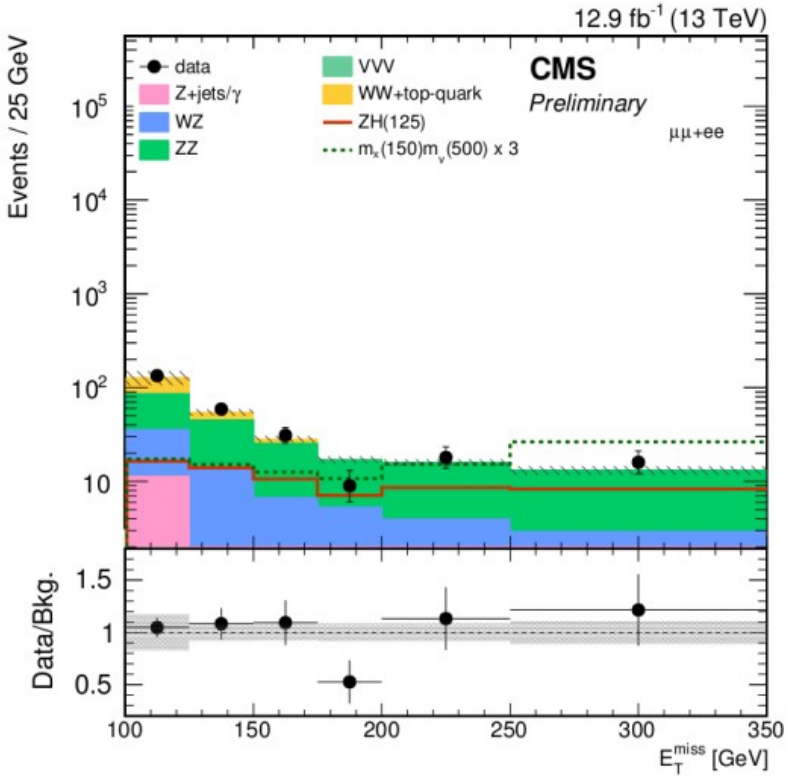
CMS-PAS-EXO-16-039

Mono-Z(ll)

2016 data



- MET+Z(ll) signature
  - ee/μμ with in Z mass window
  - MET > 100 GeV
- Dominant backgrounds are Z(ll)Z(vv) and Z(ll)W(lv)
- MET shape analysis

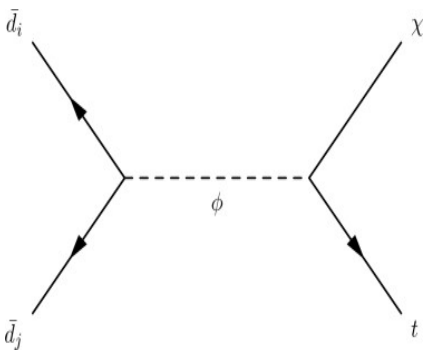


CMS-PAS-EXO-16-038

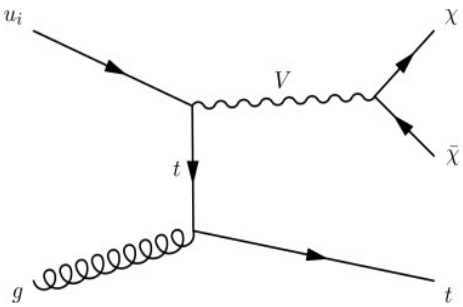
Mono-top

2016 data

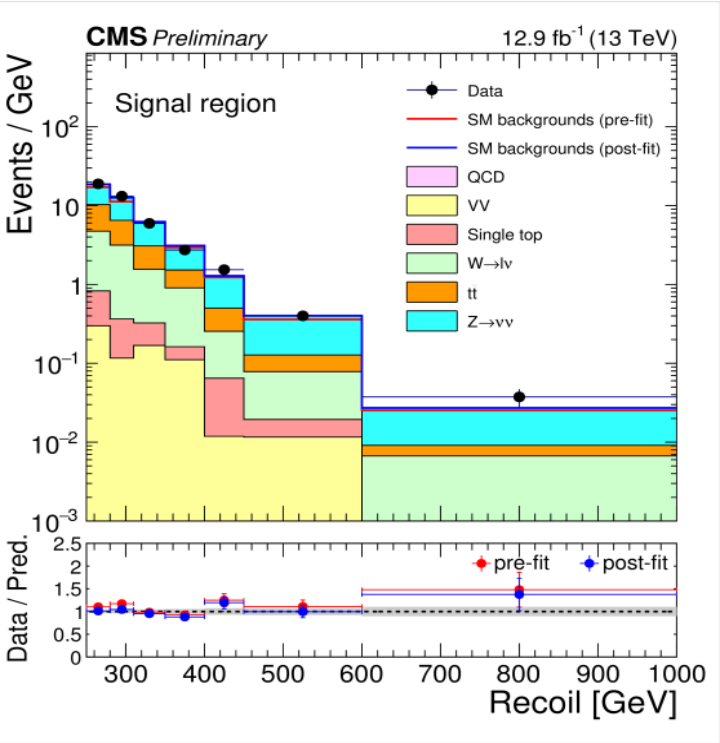
- MET+top (boosted)
  - MET > 250 GeV
  - R=1.5 jet with top-tagging
    - Larger jet cone to cover broader range of top p_T spectra
  - Main bkgds are $t\bar{t}$, Z(νν)+jets, and W(lν)+jets
    - Constrain with data from CRs similar to mono-jet/V
  - MET shape analysis
- Mono-top DM models involve BNV or FCNC



Resonant scalar



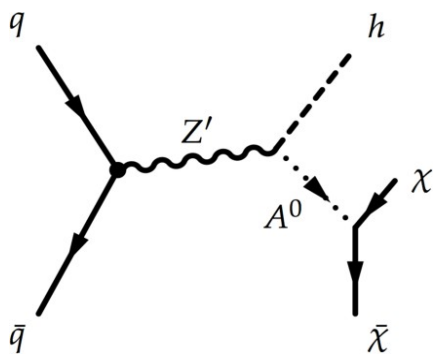
Flavor-changing Vector



CMS-PAS-EXO-16-040

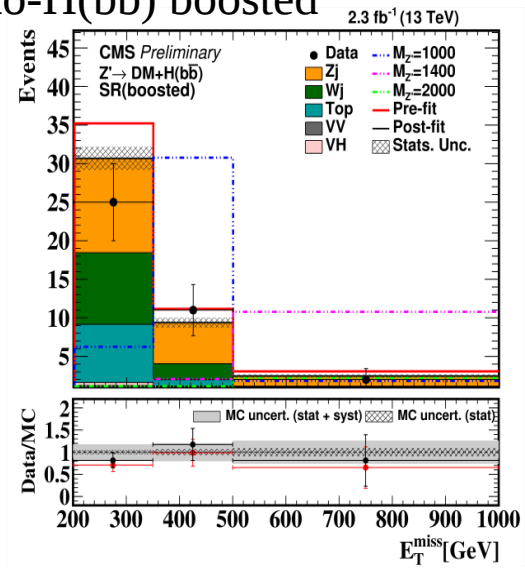
Mono-Higgs

2015 data

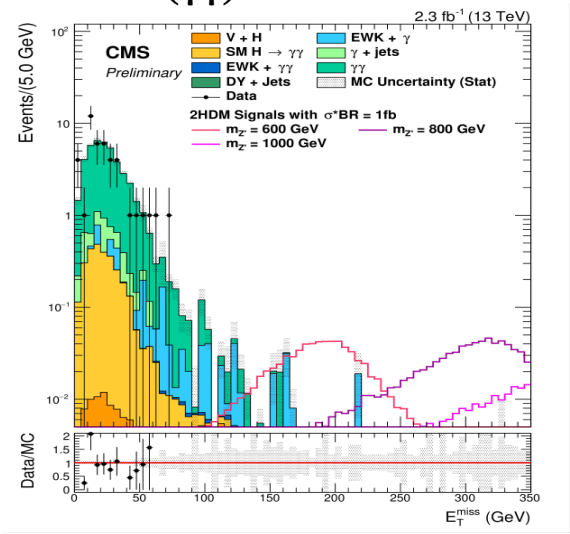


- MET+H(bb)
  - MET > 170 GeV
  - Boosted and resolved tagging of H→bb decay
  - Dominant bkgs Z(νν)+bb, W(lν)+bb, $t\bar{t}$; normalizations constrained by CRs
- MET+H(γγ)
  - MET > 105 GeV
  - 120 < M < 130
  - Dominant bkgs γγ, QCD, γ+jets estimated in mass sidebands
- Interpretation in the context of 2HDM

Mono-H(bb) boosted



Mono-H(γγ)

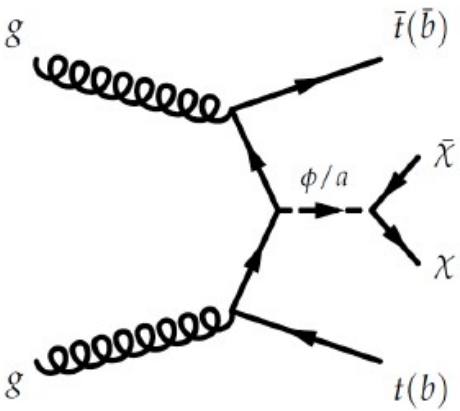


CMS-PAS-EXO-16-011
CMS-PAS-EXO-16-012

$t\bar{t}$+DM

2015 data

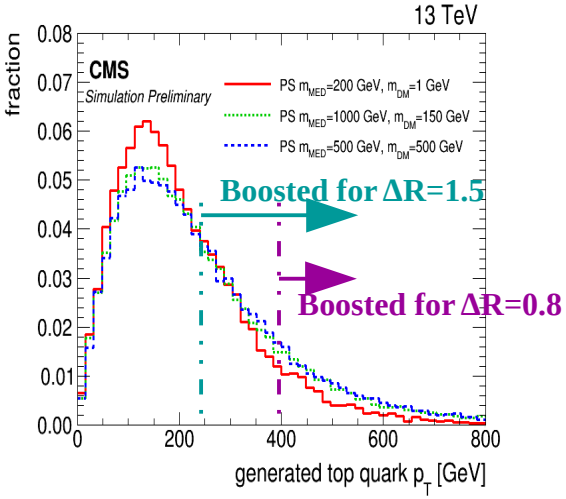
- MET + $t\bar{t}$
  - **Relevant to spin-0 mediators (Yukawa coupling)**
- 3 final states analyzed
  - Hadronic
  - Semileptonic
  - Dileptonic

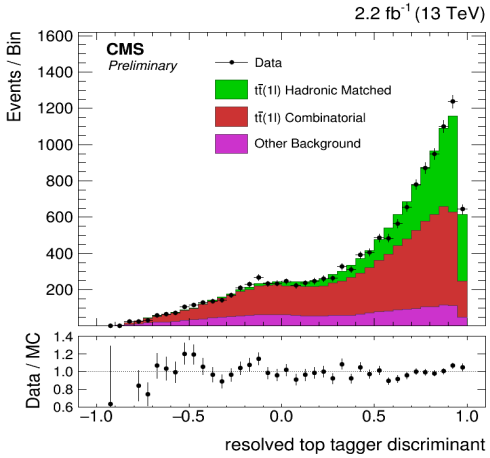


$t\bar{t}$+DM

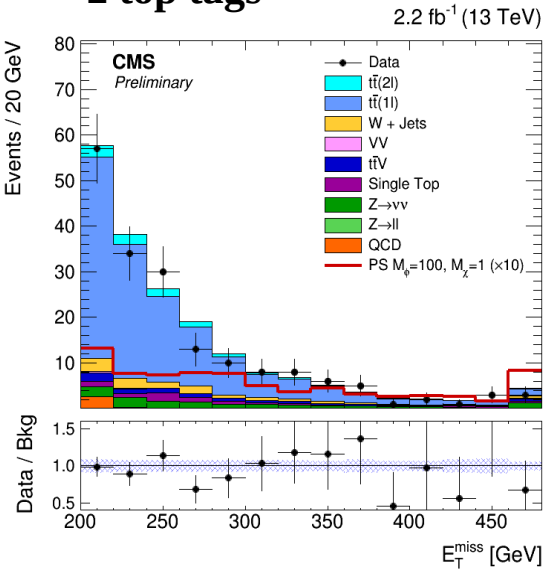
2015 data

- MET + $t\bar{t}$
- 3 final states analyzed
  - **Hadronic**
    - **MET > 200 GeV**
    - **Developed MVA to identify top decays to 3 jets**
    - **Categorize by number of resolved top tags**
    - **$t\bar{t}$(1l) is dominant bkgd**
  - Semileptonic
  - Dileptonic

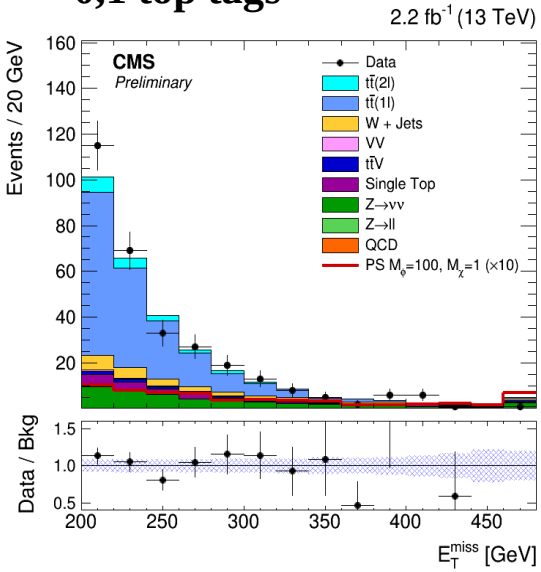




2 top tags



0,1 top tags



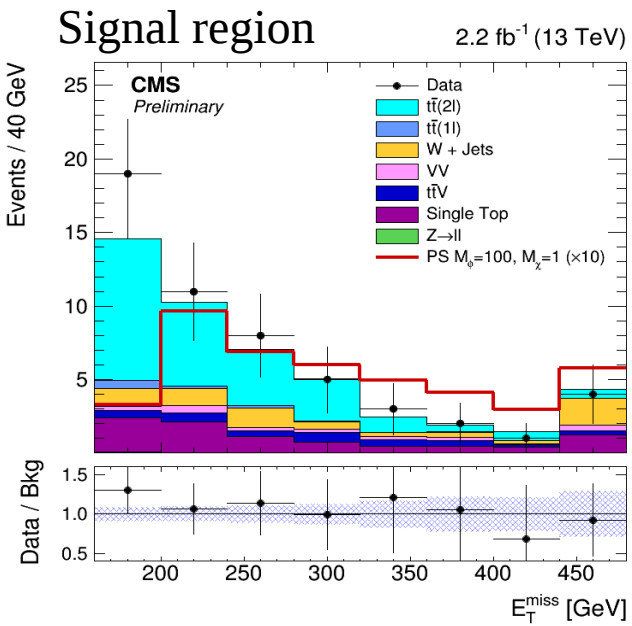
CMS-PAS-EXO-16-005

$t\bar{t}$+DM

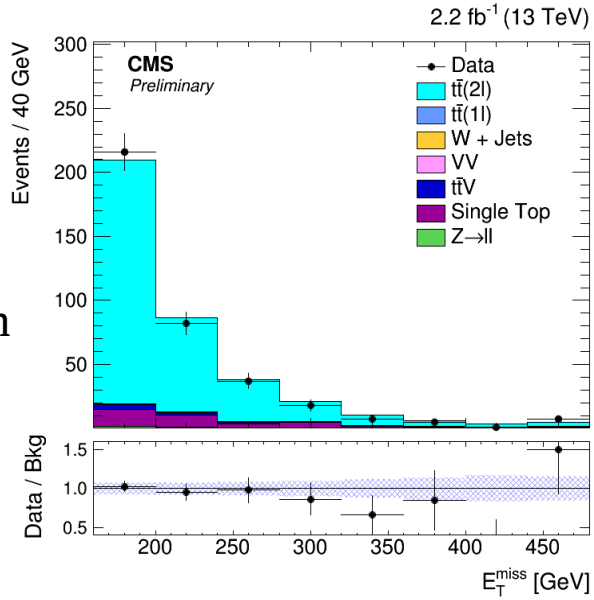
2015 data

- MET + $t\bar{t}$
- 3 final states analyzed
  - Hadronic
  - **Semileptonic**
    - **MET > 160 GeV**
    - **Single e/μ with m_T>160 GeV to reduce $t\bar{t}$(1l) bkgd**
    - **Dominant bkgd is $t\bar{t}$(2l)**
  - Dileptonic

Signal region



$t\bar{t}$(2l) control region by selection dilepton events

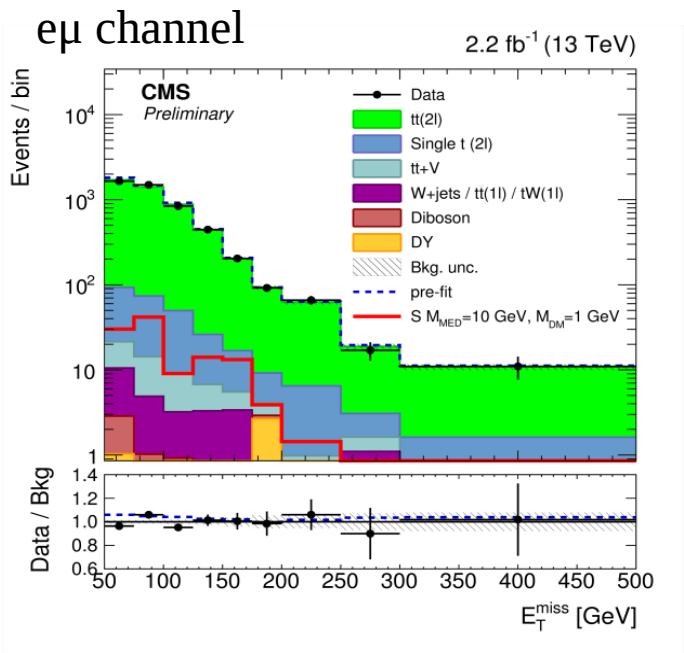


CMS-PAS-EXO-16-005

$t\bar{t}$+DM

2015 data

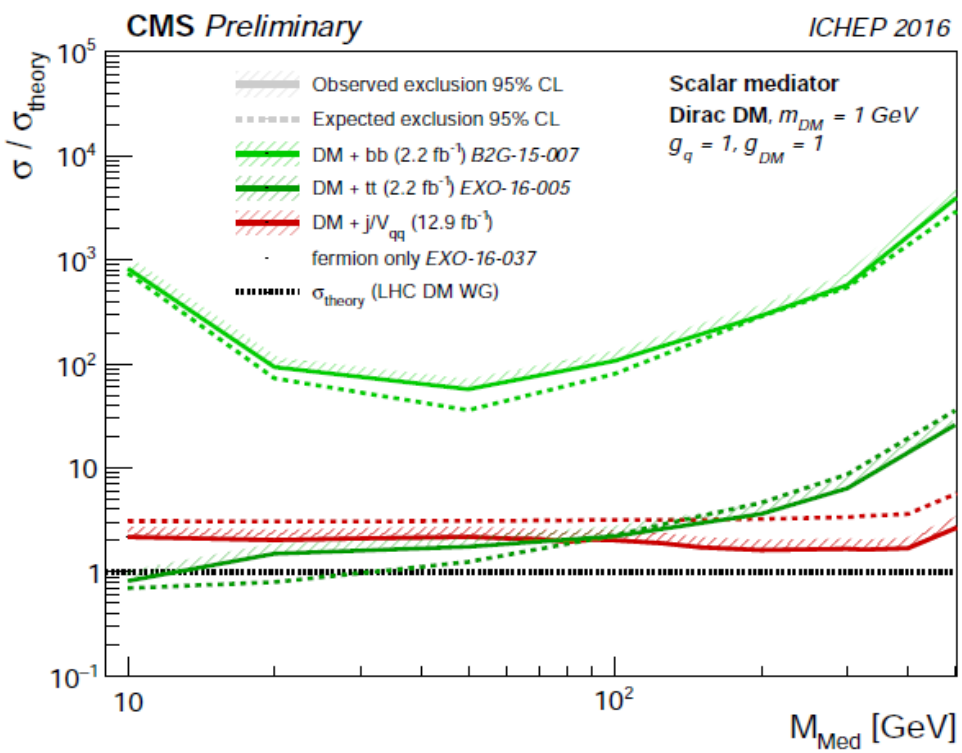
- MET + $t\bar{t}$
- 3 final states analyzed
  - Hadronic
  - Semileptonic
  - **Dileptonic**
    - **ee/eμ/μμ with MET>50 GeV for higher signal acceptance of low mass scalar models**
    - **$t\bar{t}$(2l) is dominant bkgd**

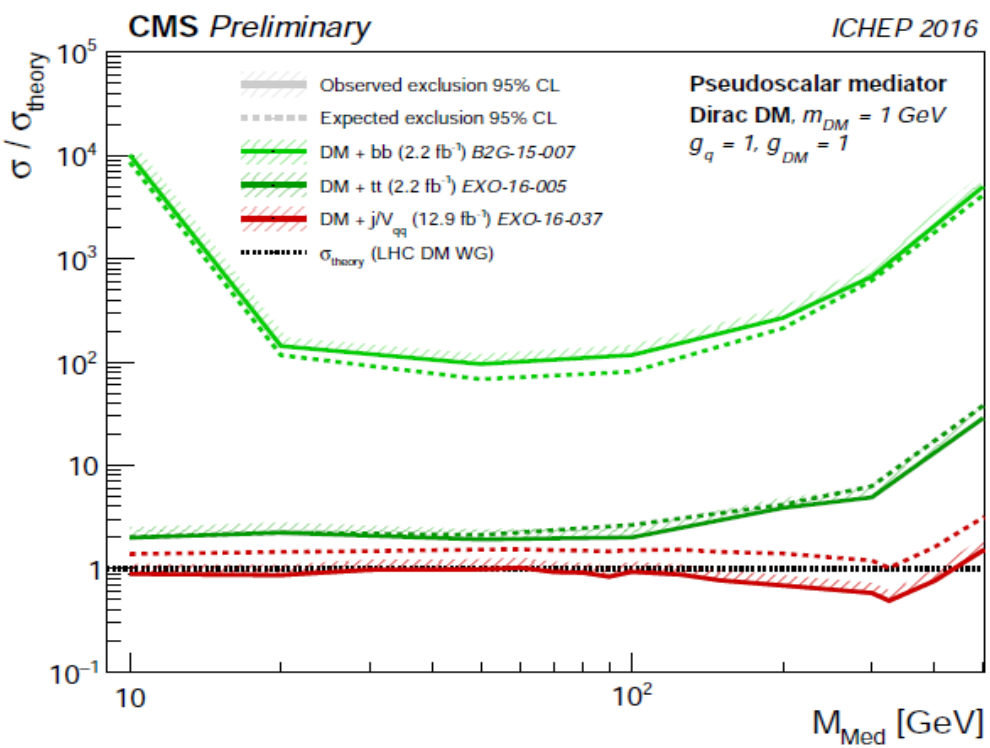


CMS-PAS-EXO-16-028

DM Summary

- $t\bar{t}$+DM search is competitive with mono-jet/V for spin-0 mediators at low mass
  - Interpretation with $g_q=g_{DM}=1$
  - Suggest a statistical combination of searches is useful

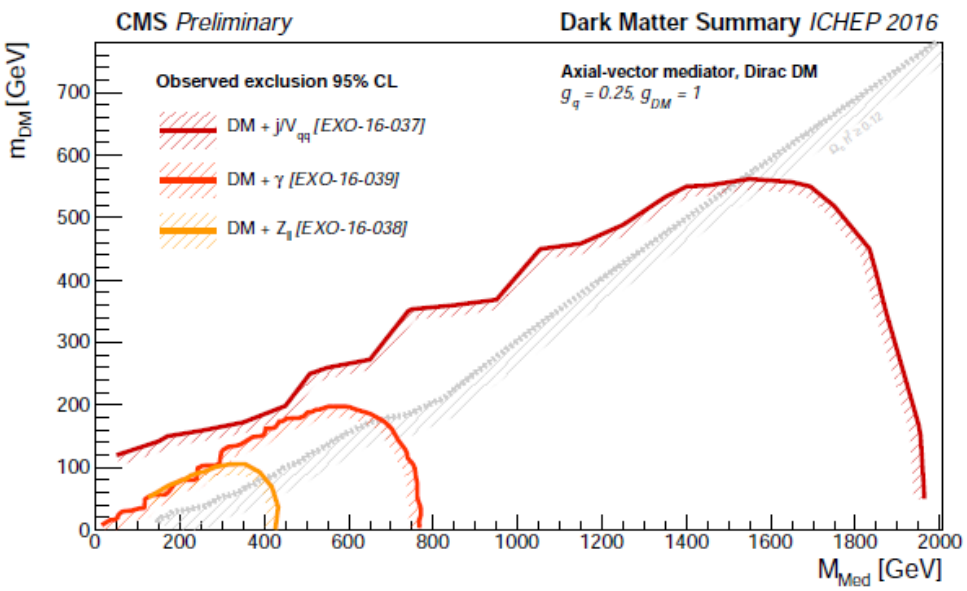


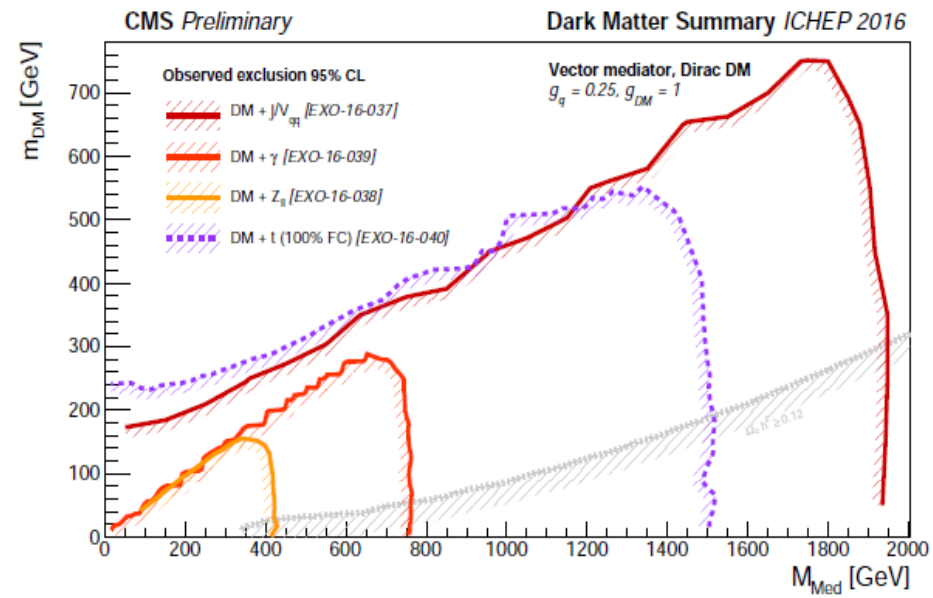


CMS-DP-2016-057

DM Summary

- Comparison of Mono-* channels for spin-1 mediators
  - Interpretation with g_q=0.25, g_{DM}=1

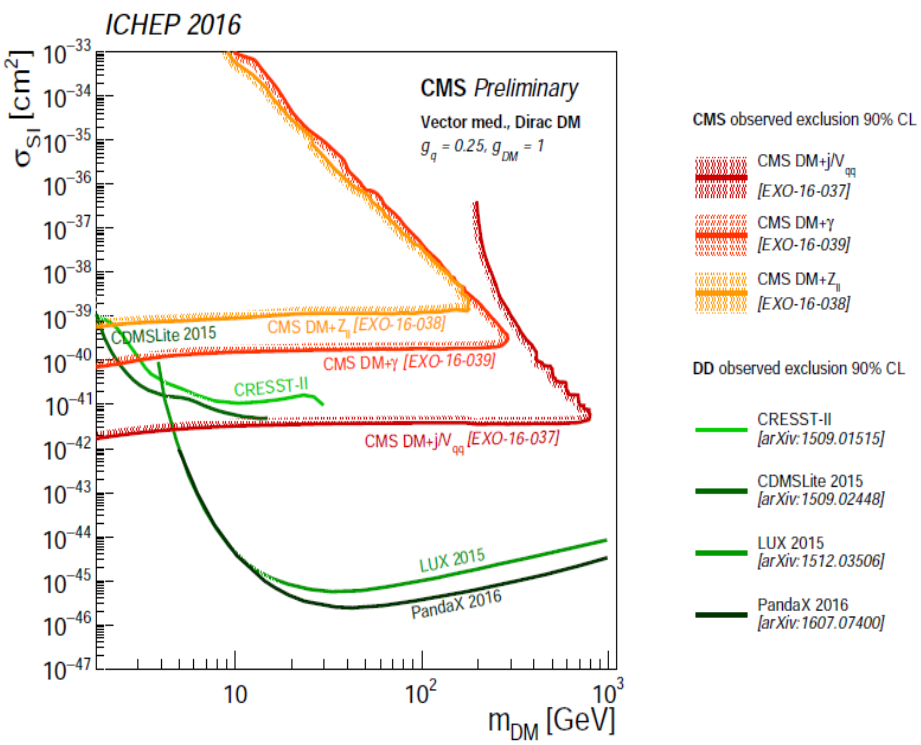


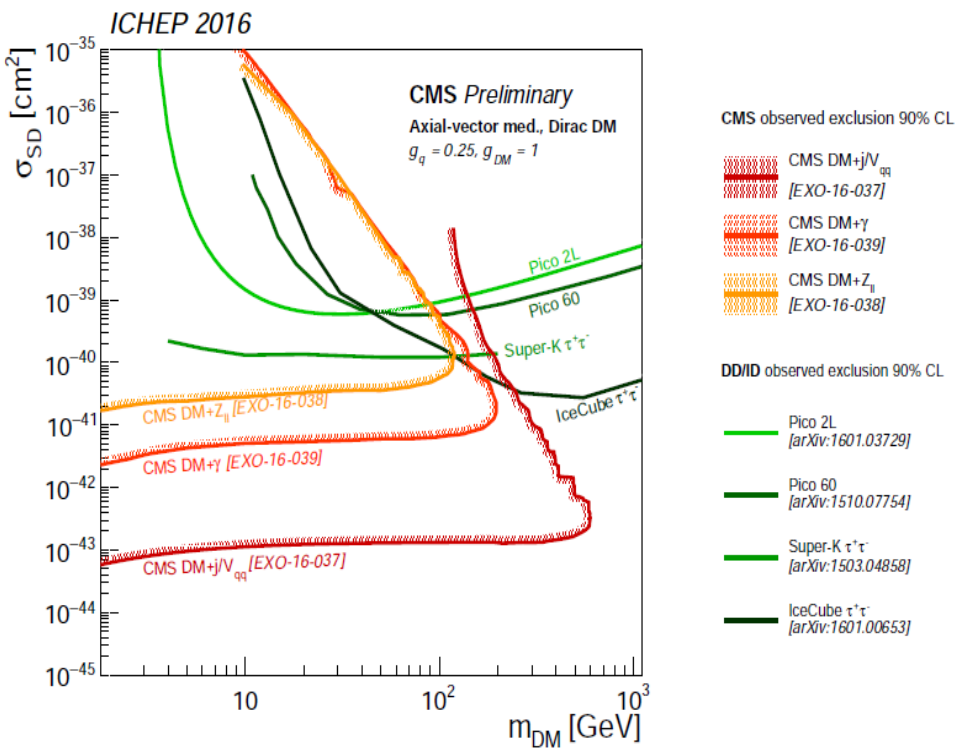


CMS-DP-2016-057

DM Summary

- Comparison with direct detection experiments
- Convert collider limits on mediators to a limit on DM-nucleon scattering cross section
- Collider constraints most stringent at lowest m_{DM} and for σ_{SD}

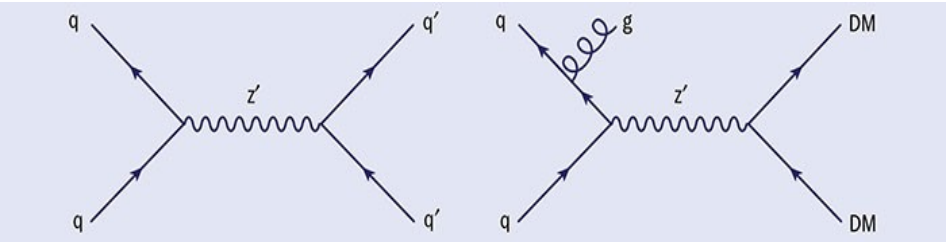


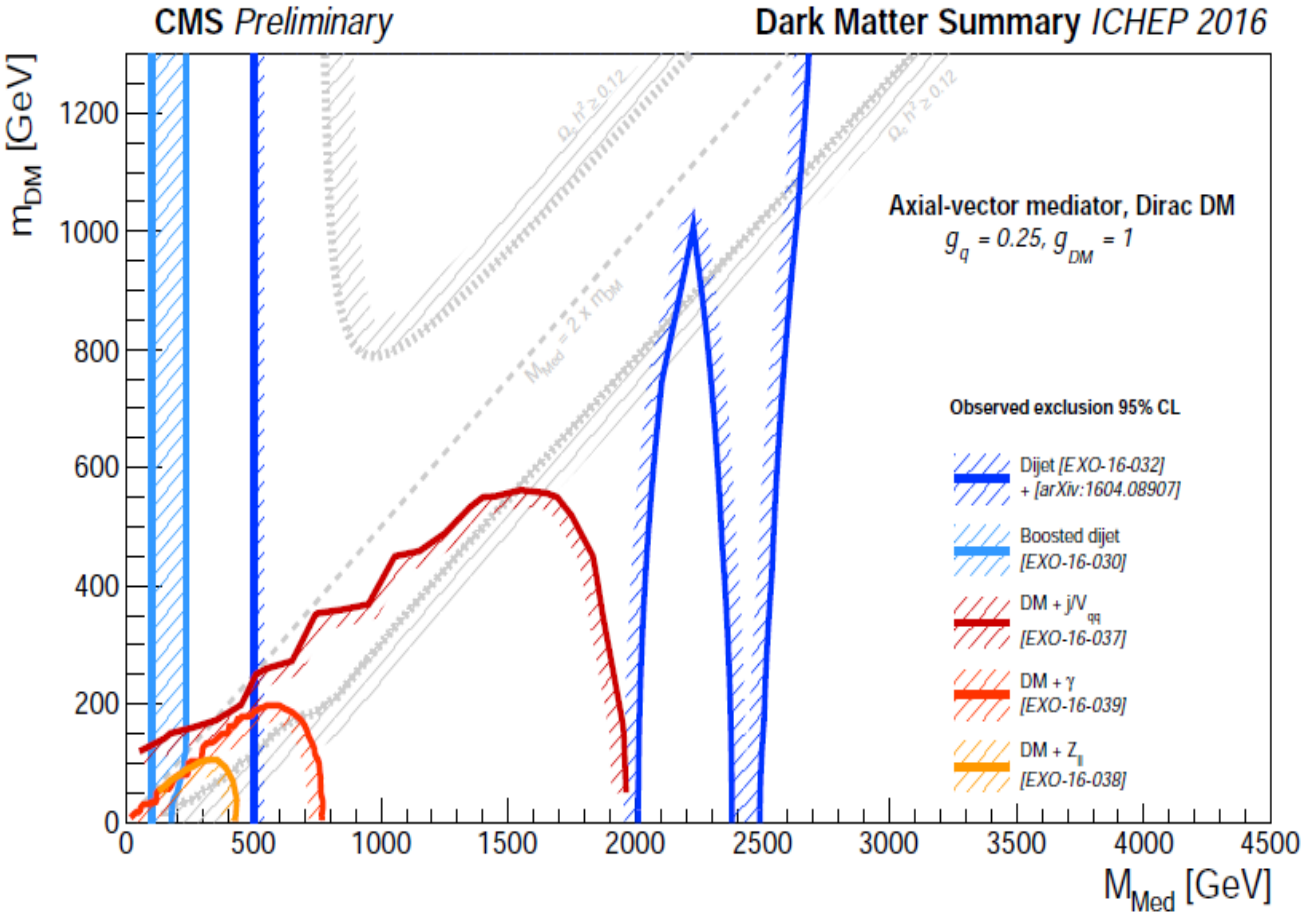


CMS-DP-2016-057

DM Summary

- Get input from resonance searches
  - Dijets provide stringent constraints for certain couplings





CMS-DP-2016-057

Conclusion

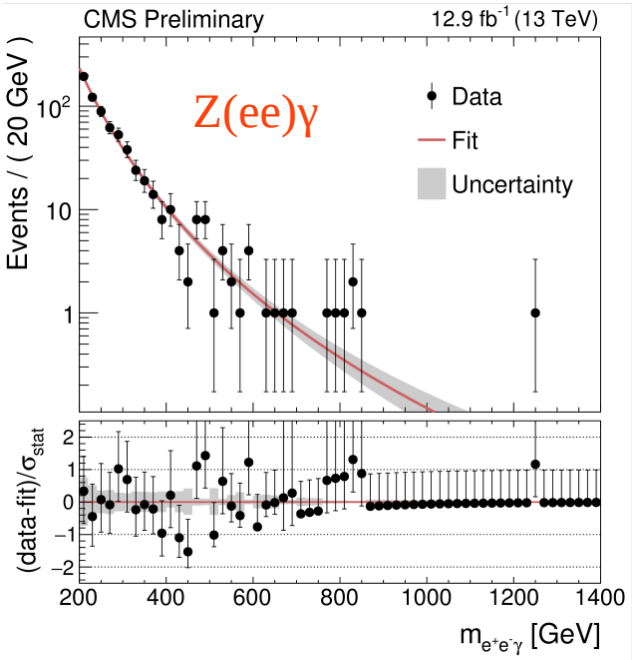
- Lots of recent results in CMS on searches for resonances, long-lived particles, and dark matter covering wide range of channels
  - Entertain as many coupling scenarios as possible
  - “Cross referencing” different channels should help determine the structure of any new physics
  - Recent results also on topics including: compositeness, leptoquarks, VLQ,...
    - Please take a look at EXO and B2G public pages if you're interested!

- Much more data still to be analyzed, the coming months should be exciting!

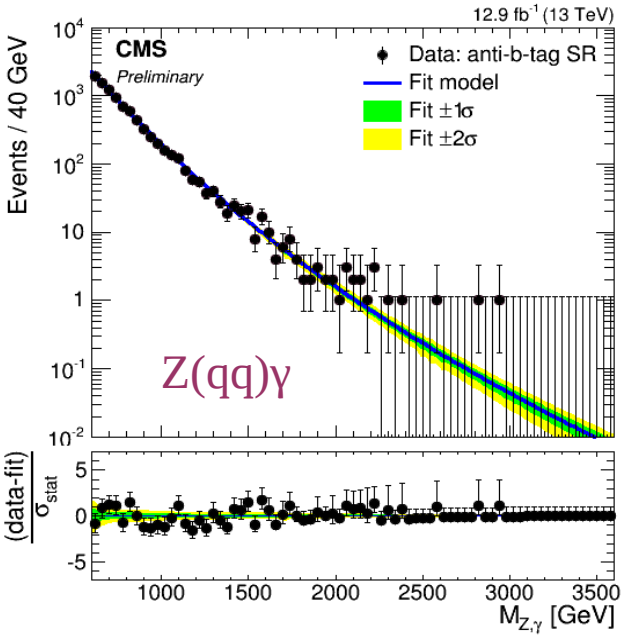
Backup Slides

Zγ

- Complementary search channel to γγ
- Identifying the Z boson:
  - Z(ll): ee or μμ in the Z mass window
  - Z(qq): boosted Z-tag with M_{prune} in the Z mass window; also categorize via sub-jet b-tagging
- Parametric functions for signal and background



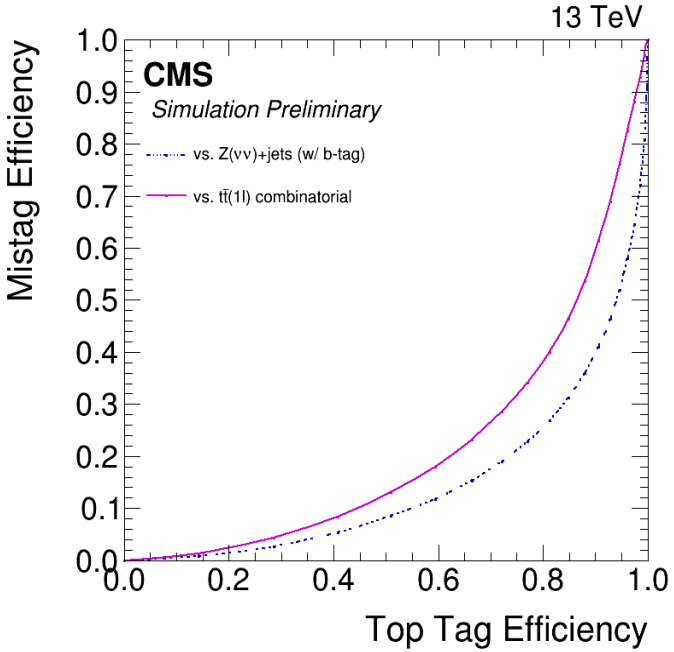
CMS-PAS-EXO-16-034

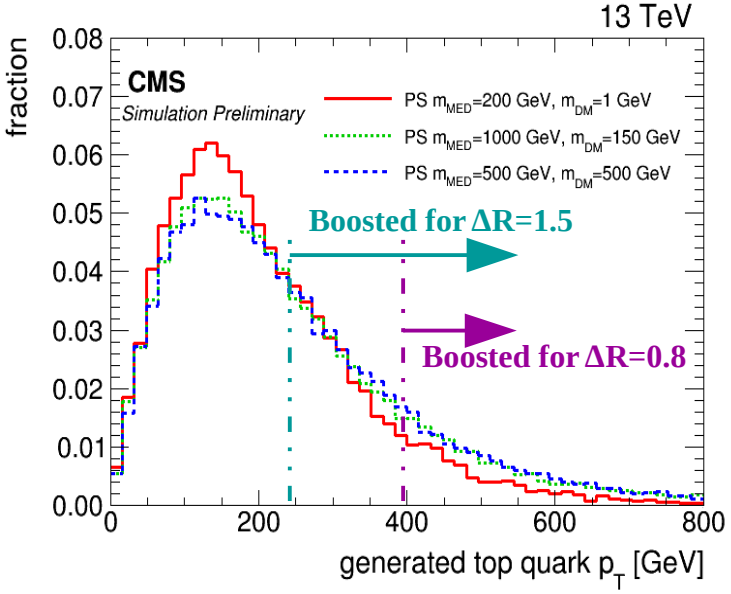


CMS-PAS-EXO-16-035

Resolved Top Tagger

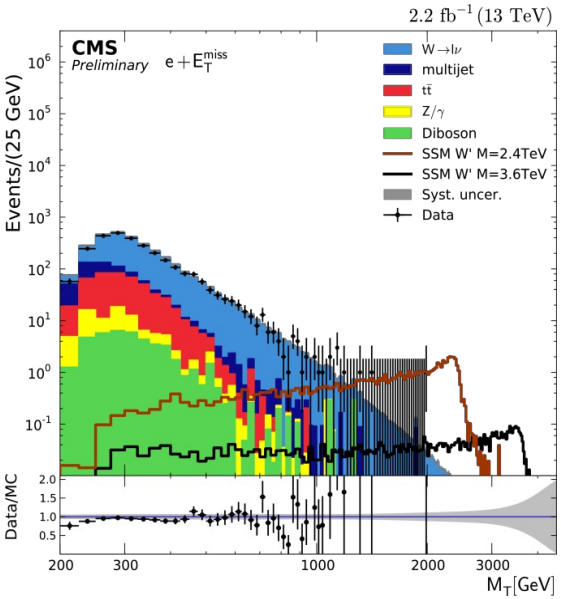
- MVA discriminant to identify tri-jet combinations from top quark decays
- Training a BDT with simulated $t\bar{t}$ events
- Input variables:
  - Kinematic fit probability
  - b-tag discriminant
  - Quark/gluon likelihood
  - $\Delta R(j_1,b)$, $\Delta R(j_2,b)$
  - $\Delta\varphi(j_1,b)$, $\Delta\varphi(j_2,b)$
- Efficiencies in MC calibrated with $t\bar{t}$ events in data
- Tops in $t\bar{t}$+DM production generally have moderate p_T

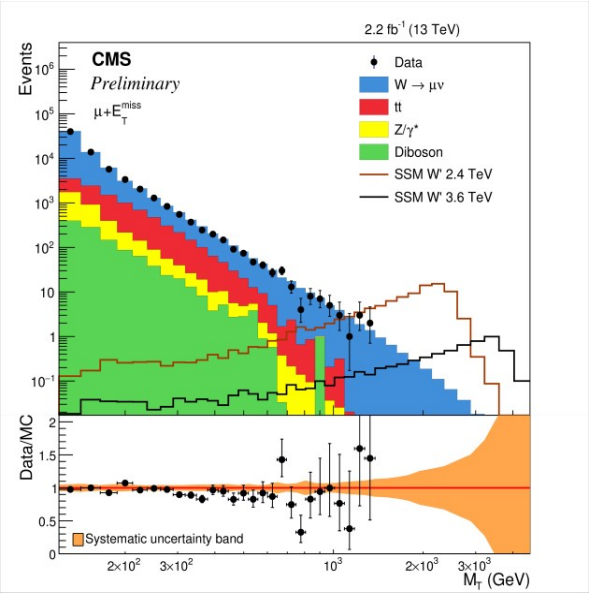


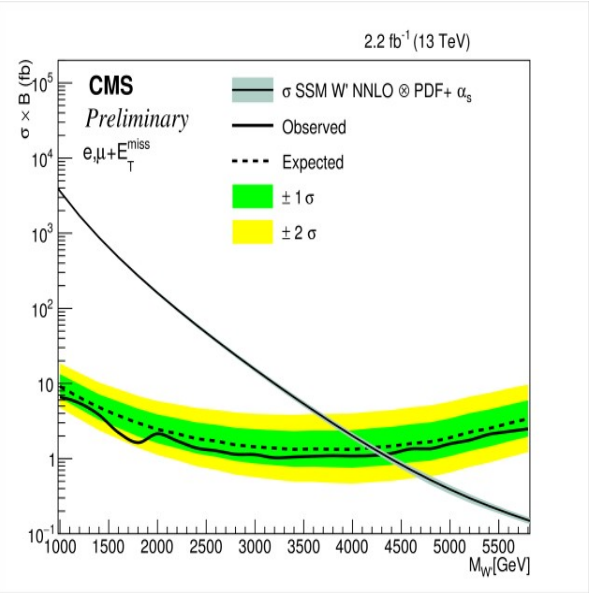


CMS-PAS-EXO-16-005

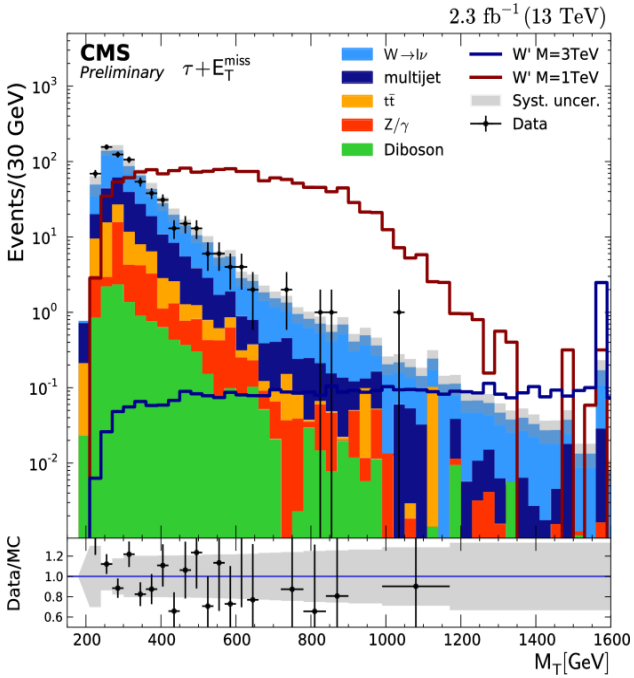
W' → lν

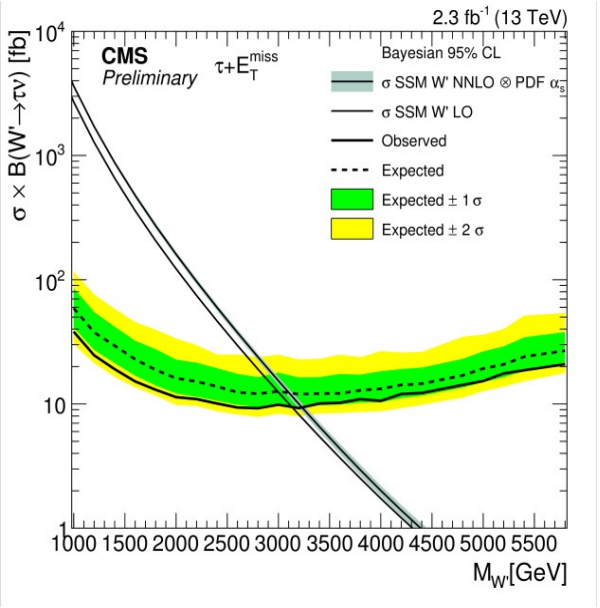






CMS-PAS-EXO-15-006





CMS-PAS-EXO-16-006