Mono-X searches for dark matter with the CMS detector

Siddharth Narayanan, on behalf of the CMS Collaboration

CIPANP, Palm Springs CA
30/05/2018

Seeing the invisible

- By definition, dark matter candidates couple weakly to a general-purpose LHC detector
- Not much point in producing DM if we can't see it!
- Introduce: the mono-**X** class of searches
  - DM produced in association with one or more SM particles (**X**)

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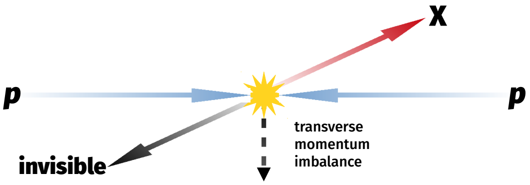
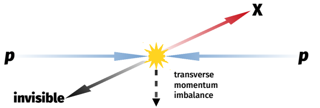


- **X** creates a transverse momentum imbalance ($p_{\mathrm{T}}^{\mathrm{miss}}$)
- Large $p_{\mathrm{T}}^{\mathrm{miss}}$ + conservation of momentum $\Rightarrow$ invisible particles!
- In certain cases, can trigger on **X**

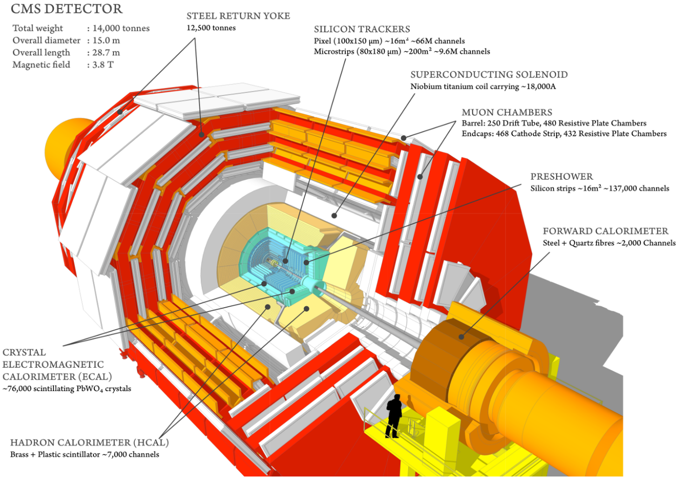
Compact Muon Solenoid

- CMS records proton collisions from the LHC
  - Today: $\sqrt{s} = 13\,\text{TeV}$ results
- pp events are messy, so replace:



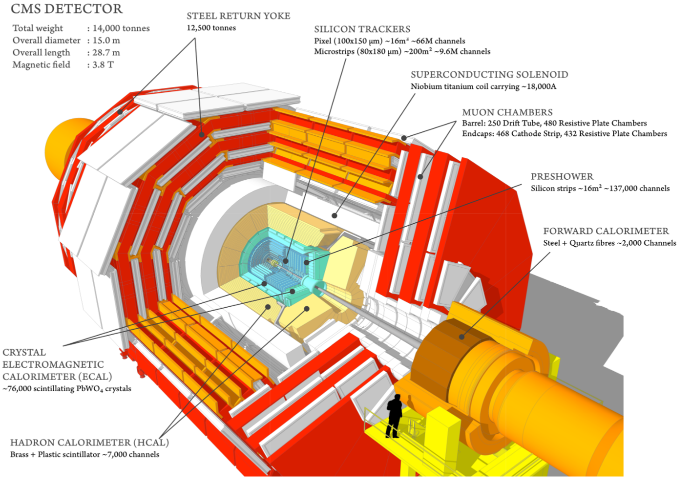
- with:

$$\vec{p}_{\mathrm{T}}^{\mathrm{miss}} = -\left(\sum_{i\in\text{particles}} \vec{p}_i\right)_{\mathrm{T}}$$



Compact Muon Solenoid

All particles in sum ⇒
all subdetectors help measure $p_{\mathrm{T}}^{\mathrm{miss}}$!



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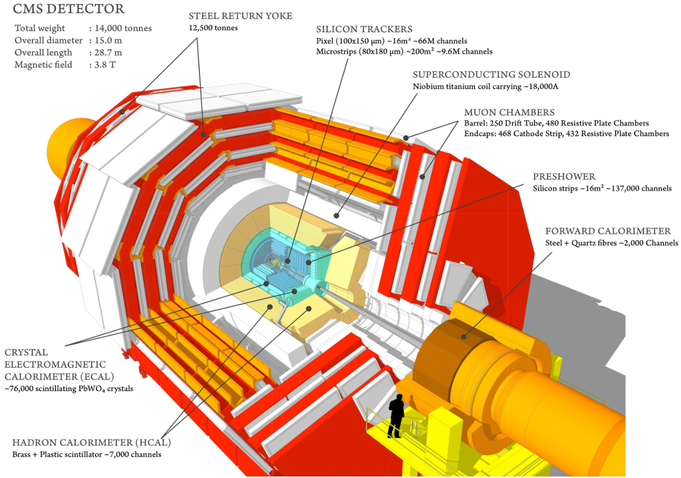
- Solenoidal magnet
  - 3.8 T B field
- Silicon tracker
  - Charged particles' $\vec{p}$
  - Track vertices



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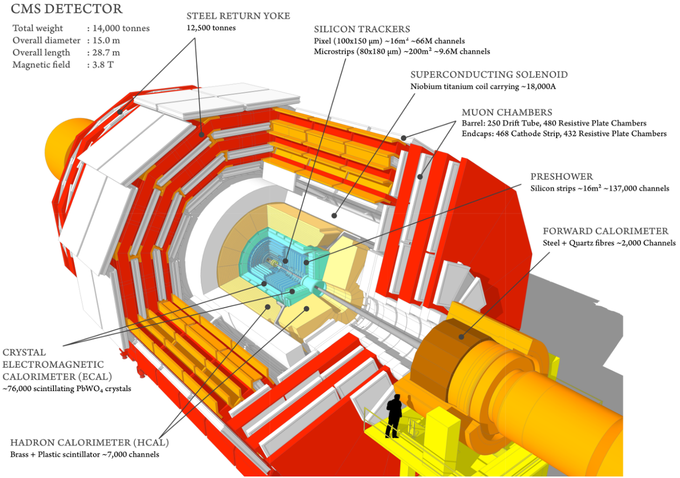
- Calorimeters
  - EM and hadronic
  - Good energy resolution
  - Large coverage



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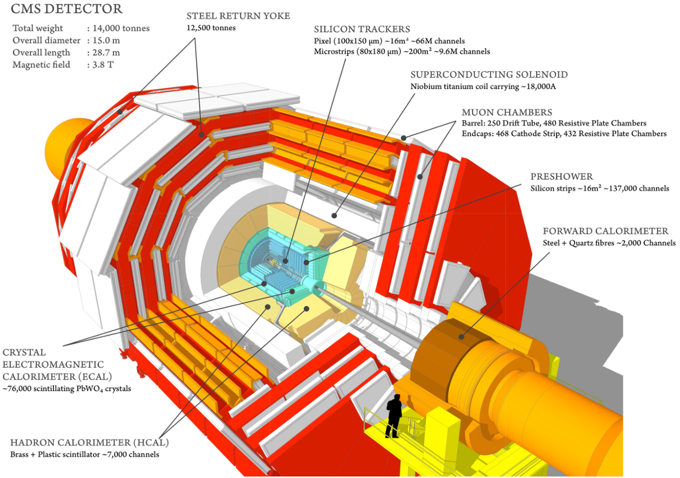
  - Large coverage
- Muon chambers
  - ID muons
  - Help measure $\vec{p}$



A broad spectrum of DM models and **X**

	Spin-1 mediated	Spin-0 mediated	Fermion portal DM	Non-thermal DM	ADD	2HDM	Baryonic Z'
X$=q,g$	■	■	■	■	■		
qq'		■					
$V(q\bar{q}')$	■	■					
γ	■				■		
$Z(\ell^+\ell^-)$	■	■			■		
$t\bar{t}$		■					
$b/b\bar{b}$		■					
t	■						
$H(x\bar{x})$[1]						■	■

All signatures characterized by high $p_{\mathrm{T}}^{\mathrm{miss}}$, but choice of **X** necessitates different reconstruction and background estimation strategies

[1] x refers to one of many fermion or gauge boson choices

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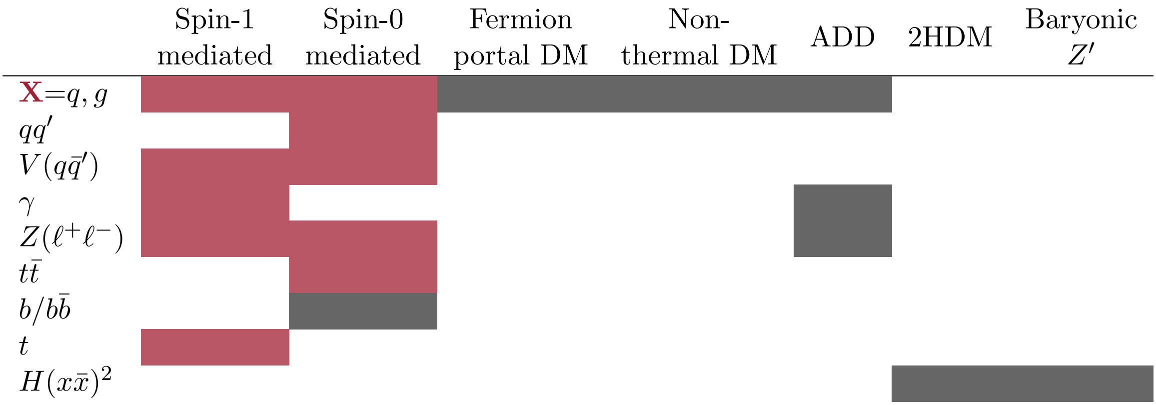

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A case study: mono-**jet**

- Why start here?
  - Sensitive to many models
  - In many cases, has the strongest collider limits
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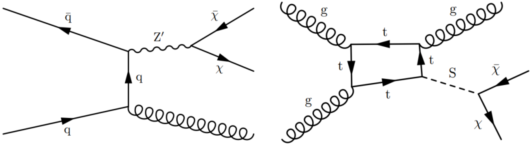
  - Spin-1 (0) mediator and DM fermion
  - 6 free parameters

Initial state radiation:



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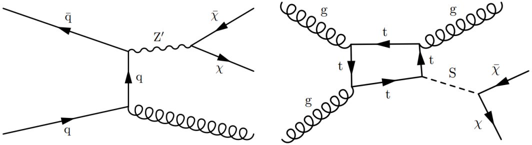
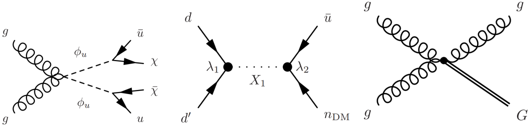
- ISR independent of specific BSM model $\Rightarrow$ simplified model
  - Spin-1 (0) mediator and DM fermion
  - 6 free parameters
- Jet(s) and DM from BSM vertex
  - Fermion-portal to DM
  - Non-thermal DM
  - ADD gravitons

Initial state radiation:

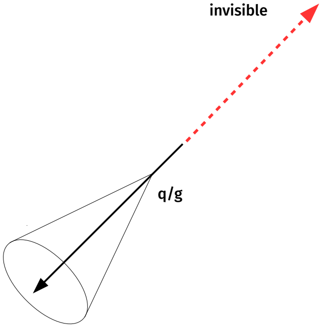


From BSM interaction:



Two experimental challenges

Reconstructed
mono-**jet** event



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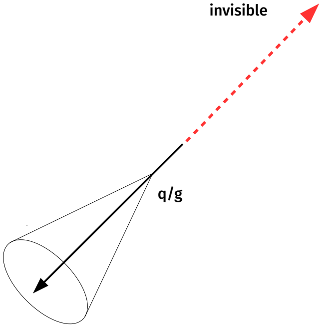

Challenge 1: Triggering

Online: particle flow $p_{\mathrm{T}}^{\mathrm{miss}}$ with threshold $\sim 100\,\mathrm{GeV}$.

Offline: threshold $\sim 250\,\mathrm{GeV}$

Challenges: maintain low threshold and rate with good $p_{\mathrm{T}}^{\mathrm{miss}}$ resolution

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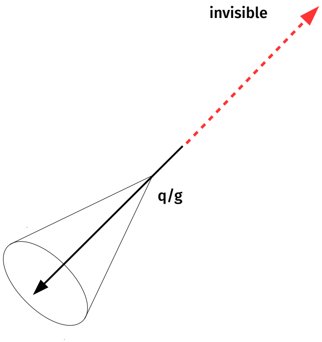

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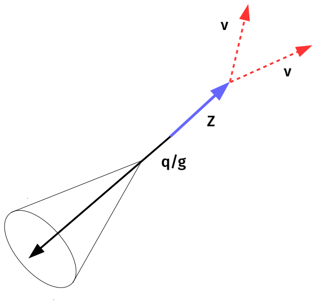
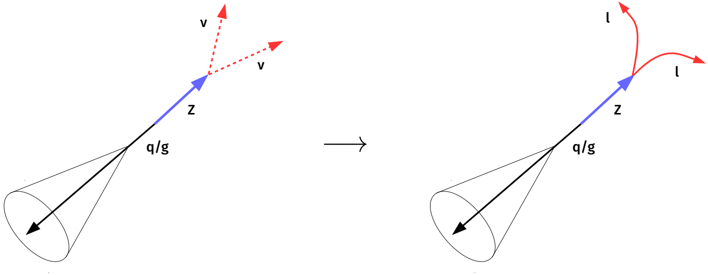
Challenge 2: SM backgrounds



Looks just like signal!

Estimating SM backgrounds

Estimate invisible backgrounds using visible processes in control data



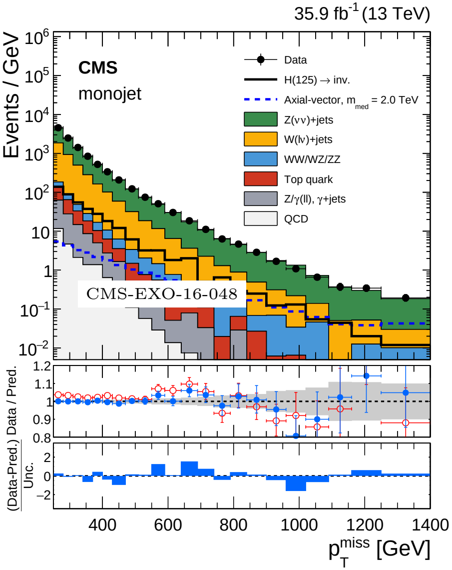
- $Z \to \nu\nu$ spectra are analogous to $Z \to \ell\ell$, modulo lepton ID
- $p_{\mathrm{T}}^{\mathrm{miss}} \approx p_{\mathrm{T}}^{Z\to\nu\nu}$

p_T^{miss} and hadronic recoil

- Variable of interest in SR is p_T^{miss}
- For primary backgrounds:

$$p_T^{miss} = p_T^V \otimes \text{jet scale \& resolution}$$

- p_T^V in control events does not model jet effects



$p_{\mathrm{T}}^{\mathrm{miss}}$ and hadronic recoil

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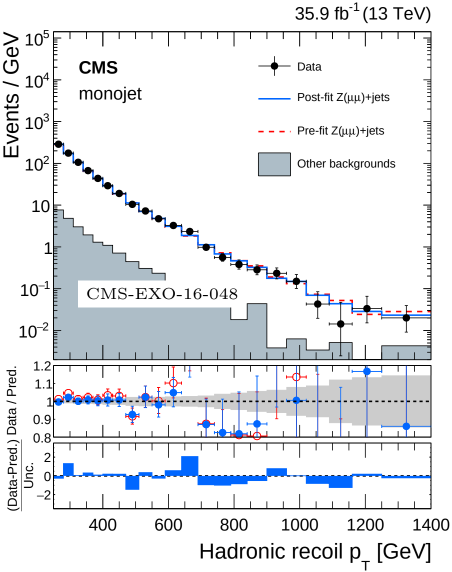
- For primary backgrounds:

$$p_{\mathrm{T}}^{\mathrm{miss}} = p_{\mathrm{T}}^{V} \otimes \text{jet scale \& resolution}$$

- p_{T}^{V} in control events does not model jet effects
- Solution: measure hadronic recoil U

$$\vec{U} = \vec{p_{\mathrm{T}}}^{\mathrm{miss}} + \sum_{i=\ell,\gamma} \vec{p_{\mathrm{T}}}^{i}$$

- U = "missing energy without leptons or photons"



Additional control regions

- Very few $Z \to \mu\mu$ events above $U > 1\,\text{TeV}$
- This is where signal sits $\Rightarrow$ need a good background estimate
- Additionally, non-negligible $W \to \ell\nu$ component in SR

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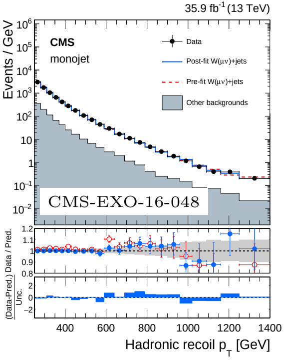
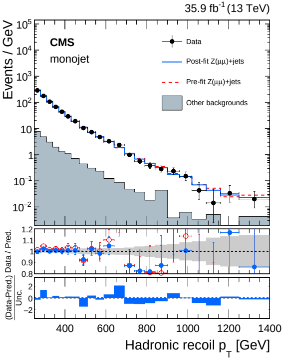
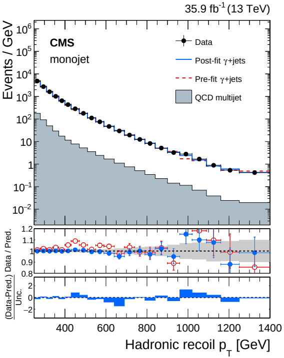
W CR to estimate W



Z CR (c.f. last slide)

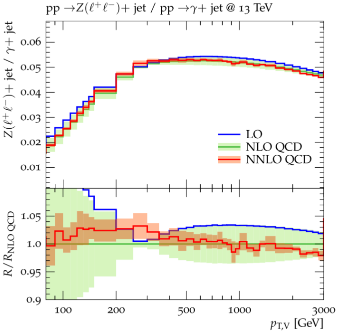


γ CR as proxy for Z



Theoretical uncertainties

- Extrapolation from W or γ to Z is not perfectly understood
- Prediction is corrected to NLO QCD+EWK [EPJC (2017) 77:829]
- Higher-order uncertainties modeled as variations on differential ratios γ/Z and W/Z



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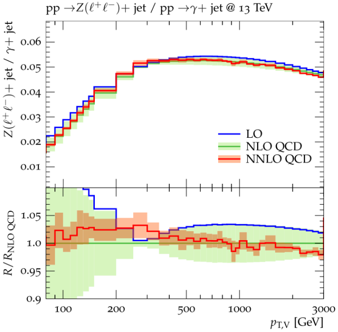
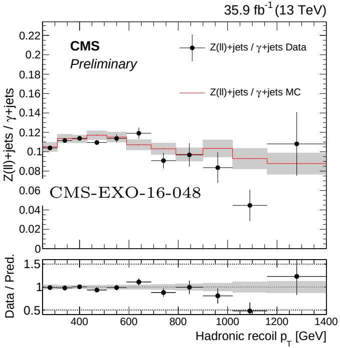
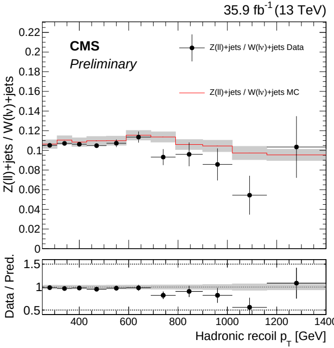
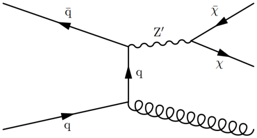
- Higher-order uncertainties modeled as variations on differential ratios γ/Z and W/Z
- Ratio prediction & uncertainties are validated using control data







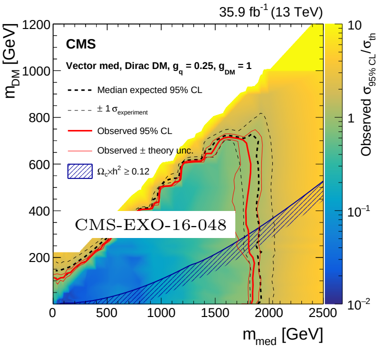
Mono-jet results: spin-1 simplified model



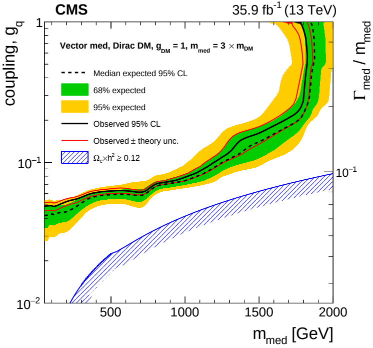
6 free parameters: $m_{Z'}$, m_χ, $g_q^{V,A}$, $g_\chi^{V,A}$

Showing vector-like results only here

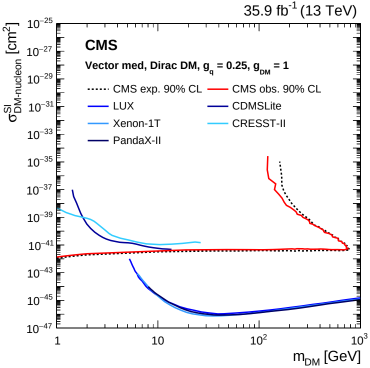
$m_{Z'}$ vs m_χ



m_χ vs g_q^{V}



m_χ vs $\sigma_{\chi\text{-}N}$



What you should remember about mono-**jet**

- Two themes arise in mono-**jet**
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- Theme 1: Key to sensitivity is differential estimation of Z+**X** and W+**X**
  - In some cases, these will be irreducible backgrounds
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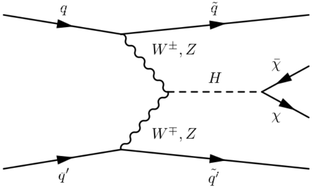
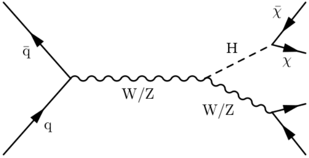
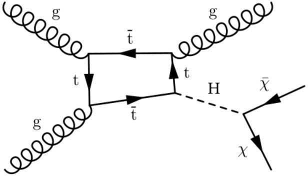
- Theme 1: Key to sensitivity is differential estimation of Z+**X** and W+**X**
  - In some cases, these will be irreducible backgrounds
  - Even when not irreducible, large σ means they dominate
- Theme 2: Estimate invisible Z+**X** (W+**X**) using visible Z+**X** (W+**X**)
  - $Z \to \ell\ell$ has small branching fraction, so correlate with other processes
  - Theoretical predictions of differential ratios are key

Invisible Higgs

- DM fermion could be given mass through Higgs mechanism
- If $2m_\chi < m_H$, should observe $H \to \chi\bar{\chi}$
- Mono-**jet** targets $gg \to H$ + ISR
- Production mode $\Rightarrow$ mono-**X** channels
- $VH \Rightarrow$ mono-$\boldsymbol{V(qq')}$ and mono-$\boldsymbol{Z(\ell\ell)}$
- VBF $\Rightarrow$ VBF+$p_{\mathrm{T}}^{\mathrm{miss}}$







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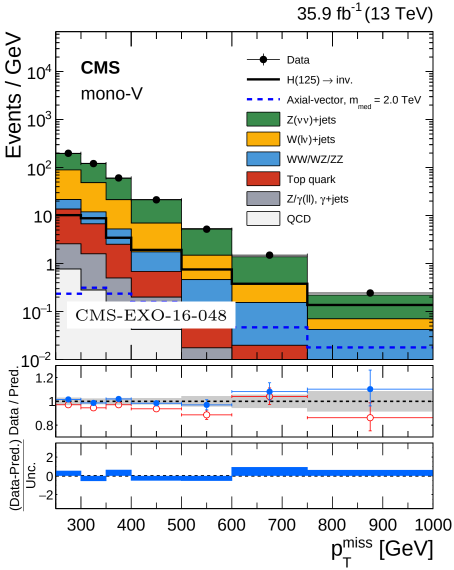
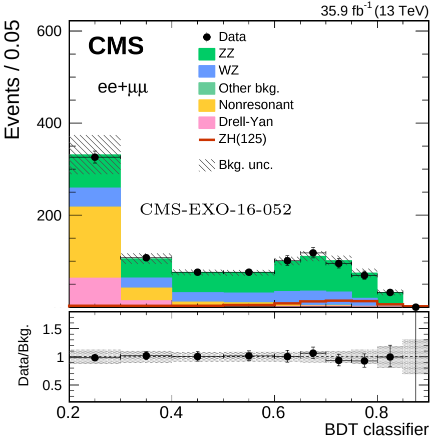
- Production mode ⇒ mono-**X** channels
- VH ⇒ mono-$\boldsymbol{V(qq')}$ and mono-$\boldsymbol{Z(\ell\ell)}$
- VBF ⇒ VBF+p_T^{miss}
- Mono-**V** is a category of mono-**jet**
  - Look for **V** as single large-cone jet
  - Jet substructure (N-subjettiness and soft-drop mass) to reject backgrounds
  - Background estimation as described before



Mono-$Z(\ell\ell)$

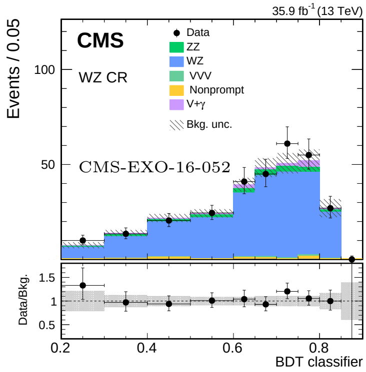
- Basic selection:
  - High $p_{\mathrm{T}}^{\mathrm{miss}}$
  - e^+e^- or $\mu^+\mu^-$ consistent with Z mass
- BDT classifier for Higgs-specific topology
  - Also provided is a $p_{\mathrm{T}}^{\mathrm{miss}}$-based analysis for other signals
- BDT uses kinematics of leptons and $p_{\mathrm{T}}^{\mathrm{miss}}$ system
  - e.g. $|m_{\ell\ell} - m_Z|$, $m_{\mathrm{T}}(p_{\mathrm{T}}^{\ell_1}, p_{\mathrm{T}}^{\mathrm{miss}})$, $\cos\theta_{l_1}^{\mathrm{CS}}$, ...
- Primary backgrounds are $Z(\nu\nu)Z(\ell\ell)$ and $W(\ell\nu)Z(\ell\ell)$



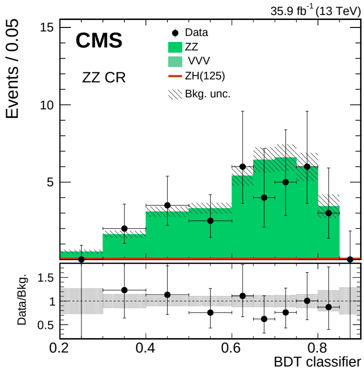
Mono-$Z(\ell\ell)$ background estimation

- As with mono-**jet**, estimate invisible processes with visible analogues
- 3ℓ (WZ) and 4ℓ (ZZ) control regions to estimate 2ℓ WZ and ZZ
- p_T^{miss} is an input to the BDT observables
  - Emulated in CRs by adding lepton(s) back into p_T^{miss}

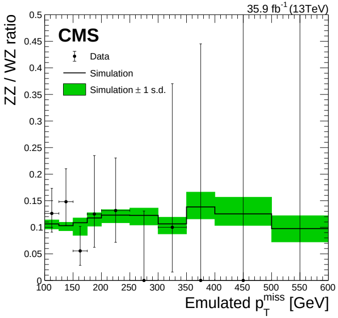
WZ



ZZ

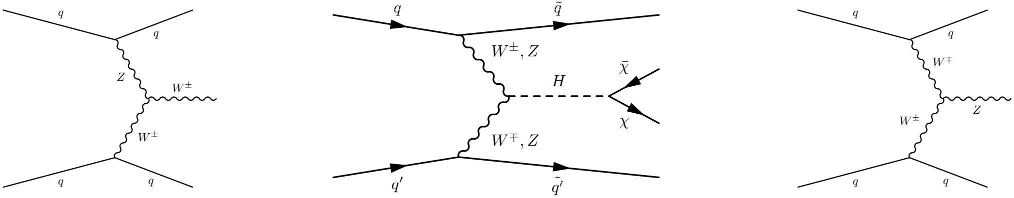


ZZ/WZ



VBF+$p_{\mathrm{T}}^{\mathrm{miss}}$

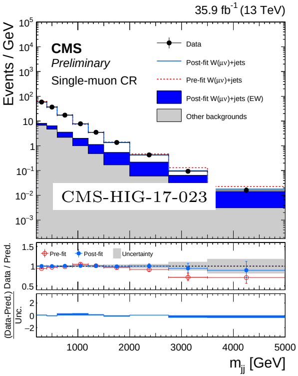
- Two forward, energetic jets with large $p_{\mathrm{T}}^{\mathrm{miss}}$
- Backgrounds are similar to inclusive $p_{\mathrm{T}}^{\mathrm{miss}}$+jets search, but also sensitive to EW V+jets diagrams



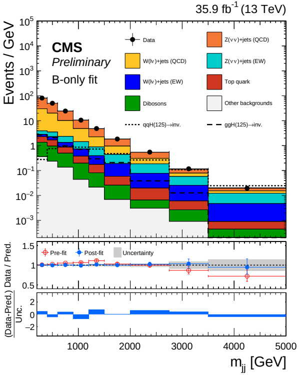
- Use dijet kinematics to focus phase space
  - $m_{jj}, \Delta\eta_{jj}$ - suppress QCD V+jets
  - $\Delta\phi_{jj}$ - sensitive to spin of boson

VBF+p_T^{miss} signal extraction

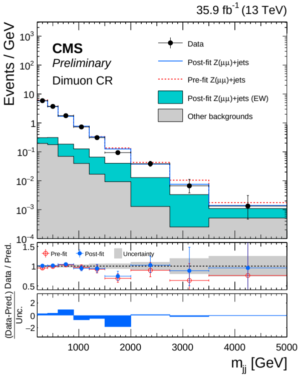
W



Signal

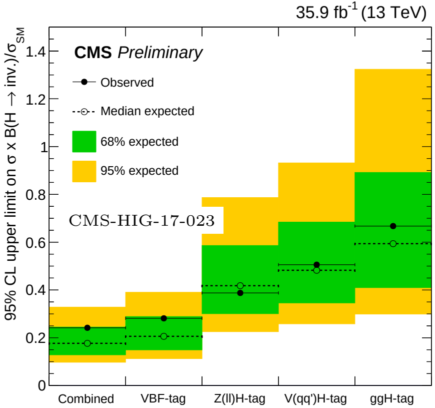


Z

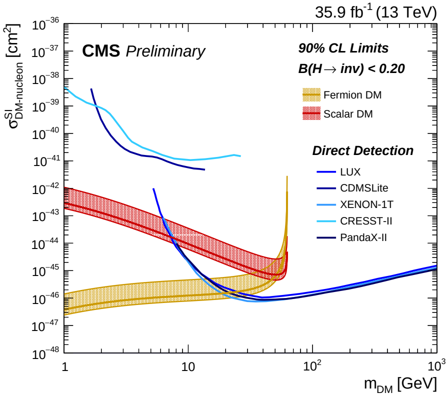


- Fit the m_{jj} spectra
- Control regions estimate both QCD and EW contributions to V+jets background

Upper limits on $\mathcal{B}(H \to \text{inv})$



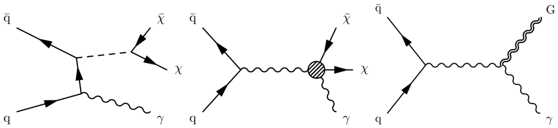
Combination of channels has observed (expected) limit at $\mathcal{B} < 0.24$ (0.18)

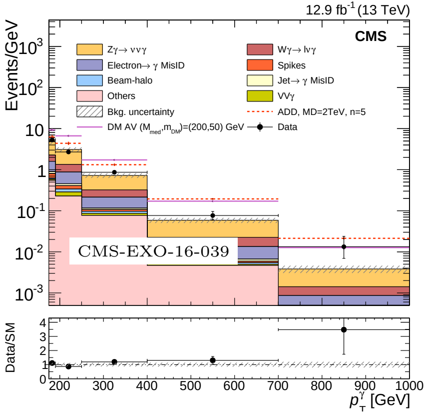


Also re-cast the result as a limit on $\sigma_{\mathrm{DM}-N}$. Best sensitivity at low masses.

Mono-photon

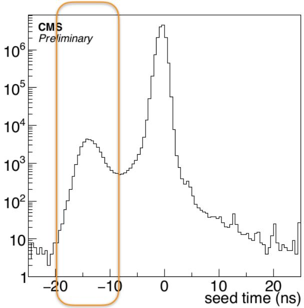
- Signal models and production mechanism similar to those already discussed
- Primary SM backgrounds are $Z/W + \gamma$
  - Measured with 2/1 lepton events, respectively
- Jet/e mis-ID'd as γ
  - Data-driven estimate of fake rate
- Non-collision backgrounds
  - Beam halo
  - Detector noise spikes

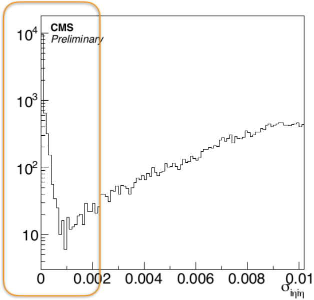




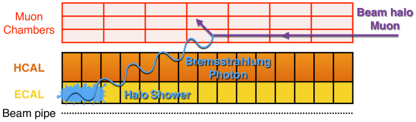
Non-collision backgrounds

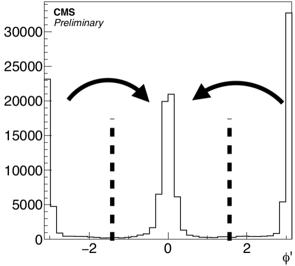
- Spikes: single APD has a fake signal, resulting in anomalous response and very narrow "shower"





- Beam halo: particles travelling parallel to beam, hit ECAL from side

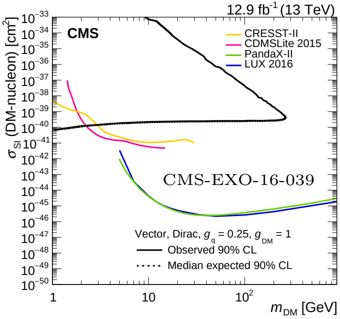




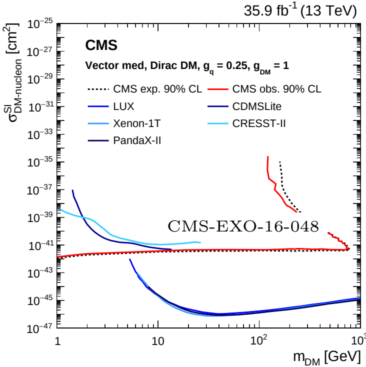
Summary of vector-mediated DM results

vector couplings ⇔ spin-independent DM-nucleon interaction

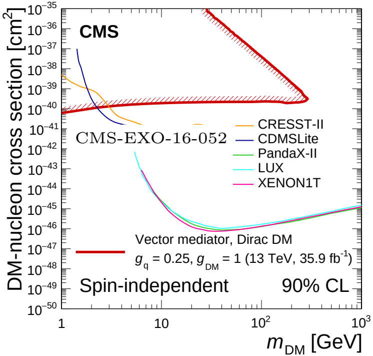
mono-**photon**



mono-**jet**



mono-$Z(\ell\ell)$

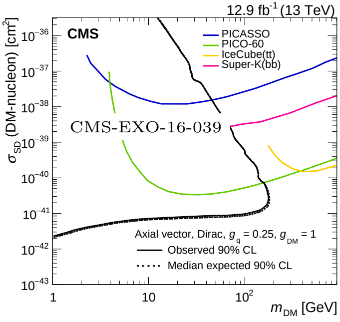


Collider searches contribute at low m_{DM}

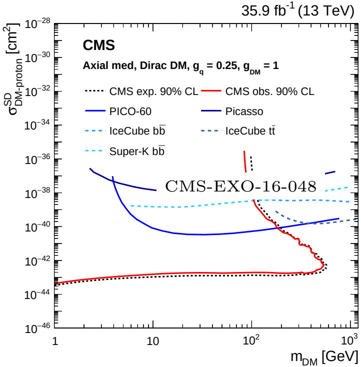
Summary of axial vector-mediated DM results

axial couplings ⇔ spin-dependent DM-nucleon interaction

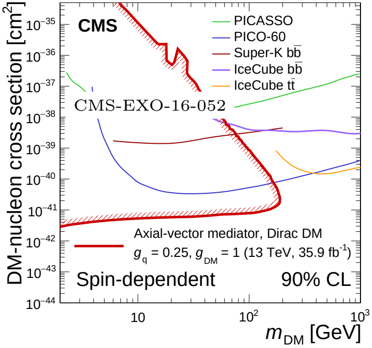
mono-**photon**



mono-**jet**



mono-$Z(\ell\ell)$

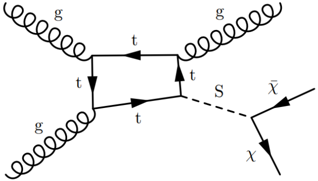


DD searches are much less sensitive to SD DM ⇒ CMS results are complementary

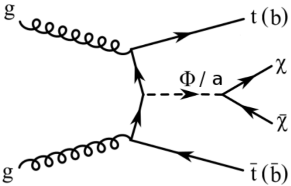
$t\bar{t}$ +DM

- Assume we have a spin-0 mediator with Yukawa-like couplings to fermions only
- Then, we should see two signatures:

$gg \to g\phi$



$gg \to t\bar{t}\ \phi$

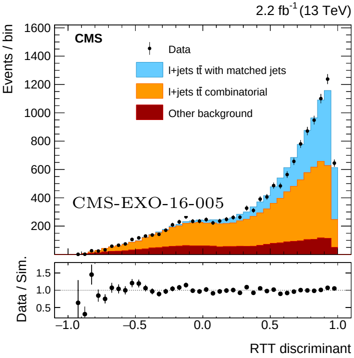


- Natural to complement mono-**jet** search with search for top quark pairs plus DM

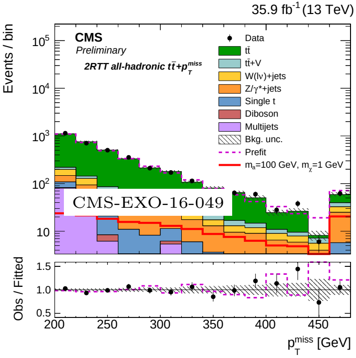
$t\bar{t}$ +DM signal extraction

- Three channels, categorized by t decay: all-hadronic, semi-leptonic, and all-leptonic
- BDT classifier to identify trijet systems consistent with top quark decay

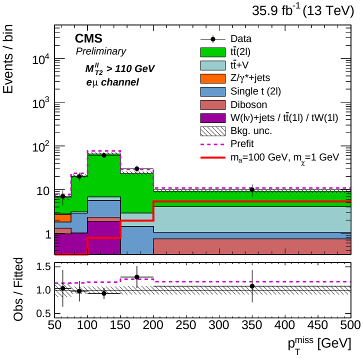
Resolved top tagger



All-hadronic

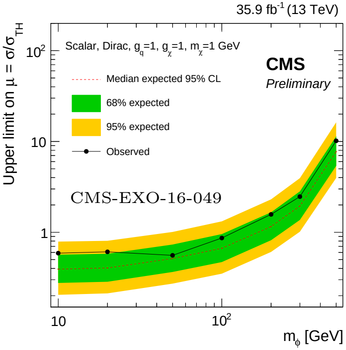


All-leptonic

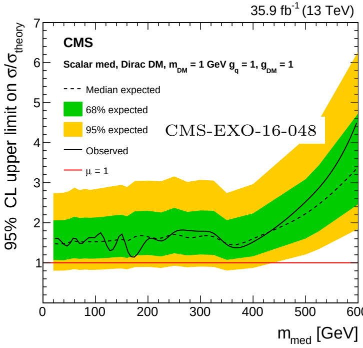


Summary of scalar-mediated DM results

$t\bar{t}$ +DM



mono-jet



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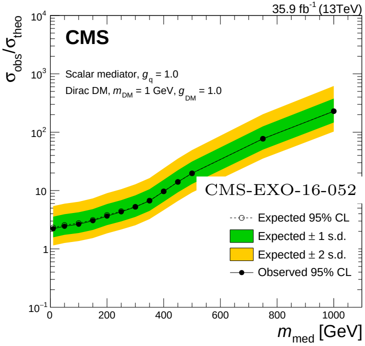
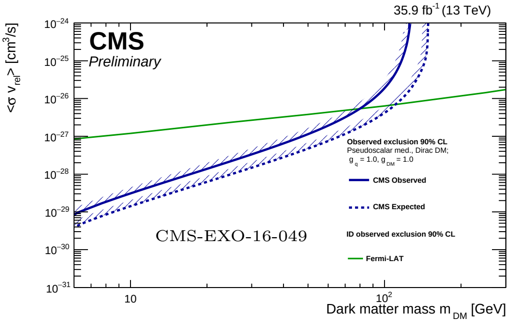


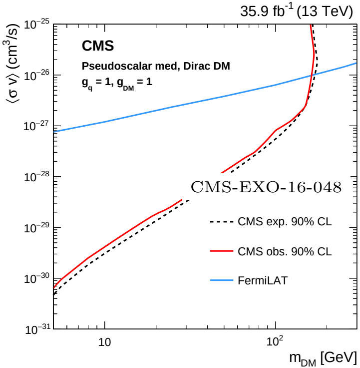
Only $t\bar{t}$ +DM is able exclude scalars with $m_\phi \lesssim 100\,\text{GeV}$.
Mono-**jet** is more sensitive than $t\bar{t}$ +DM at high m_ϕ.

Summary of pseudoscalar-mediated DM results

$t\bar{t}$ +DM



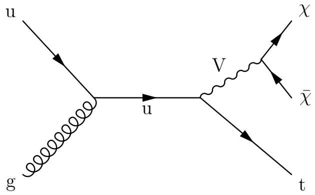
mono-jet



Presented as upper limits on velocity-averaged DM annihilation cross section.
Significantly extend limits from FermiLAT.

Mono-**top**

- $t + p_{\mathrm{T}}^{\mathrm{miss}}$ heavily suppressed in SM
  - $\sigma(tZ(\to \nu\nu)q) = 0.14$ pb
- Enhanced mono-**top** implies:
  - DM candidate
  - Flavor-violating new physics
- Benchmark model: spin-1 simplified model with FCNC



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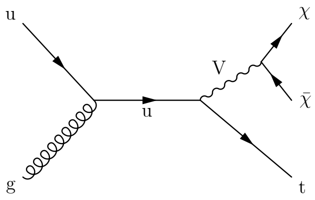

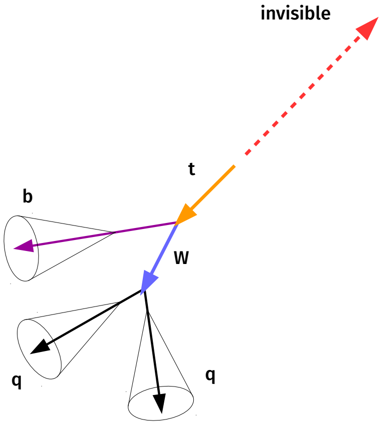

Hadronic decay $\Rightarrow$ larger BR, no $p_{\mathrm{T}}^{\mathrm{miss}}$

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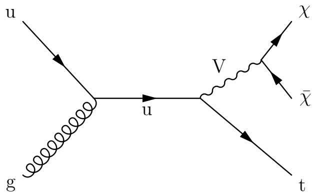
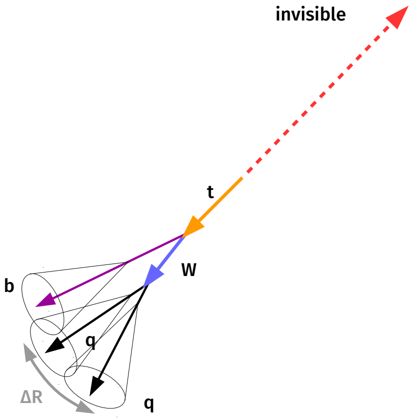
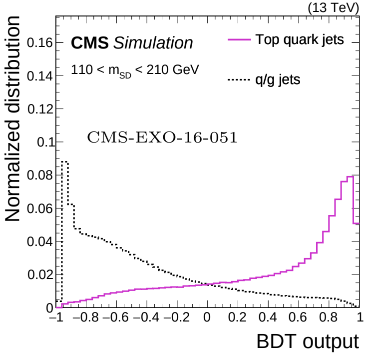


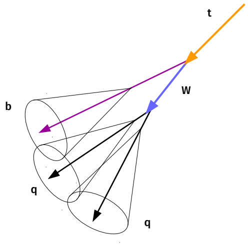


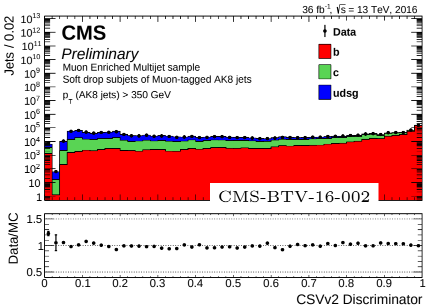
Trigger requirements ⇒ large $p_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{t}$
Large p_{T}^{t} ⇒ decay products collimate

Boosted hadronic top quark identification

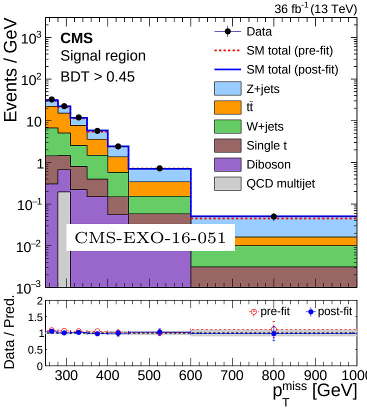
- Large cone jets have many combinatorial backgrounds
- Reject using jet substructure and flavor-tagging
- Novel experimental use of energy correlation function basis [JHEP (2016) 153]

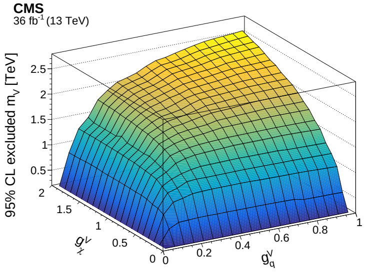




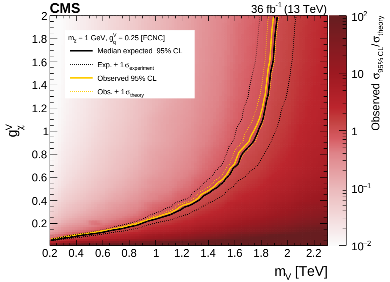


- Constrain large range of FCNC masses and coupling strengths
  - As low as $g \sim 0.05$, as high as $m_V \sim 2.5\,\text{TeV}$
- $m_V \lesssim 200\,\text{GeV}$ excluded from measurements of Γ_t





g_χ vs g_q vs m_V



m_χ vs m_V

Summary and outlook

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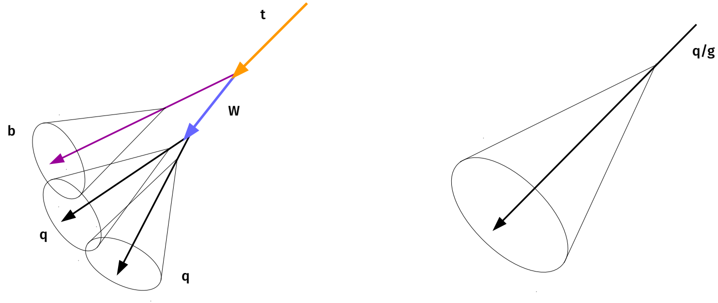
    - Among limiting factors for **VBF**+$p_{\mathrm{T}}^{\mathrm{miss}}$, mono-**top**, mono-**Higgs**
  - VV ratios $\Rightarrow$ mono-$\boldsymbol{Z(\ell\ell)}$ and mono-$\boldsymbol{\gamma}$
  - $t\bar{t}\,V$ prediction $\Rightarrow$ dileptonic $\boldsymbol{t\bar{t}}$ +DM

BACKUP

Jet substructure

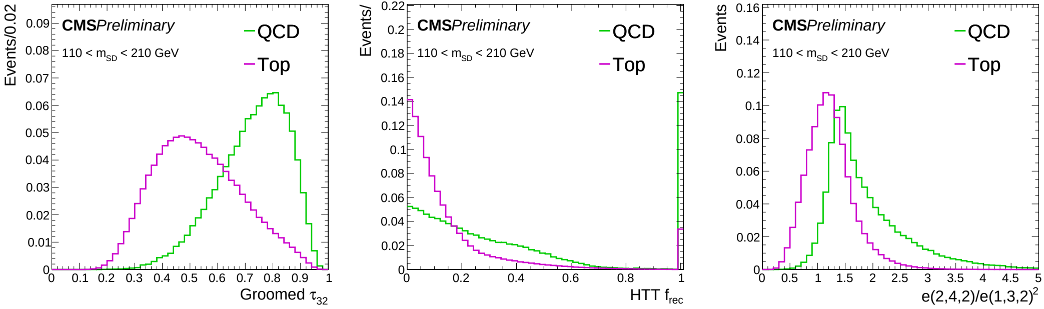
- Top quark $\rightarrow$ 3q $\Rightarrow$ top jet has 3 “prongs”



- **Substructure** observables are sensitive to such features

Useful substructure observables

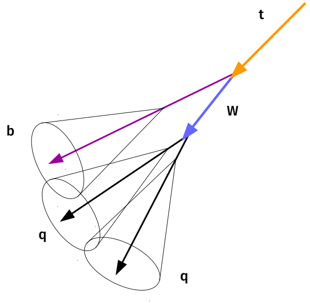
- N-subjettiness [Thaler *et al*, arXiv:1011.2268]
  - $\tau_{\mathbf{N}}$: compatibility of jet with **N**-axis hypothesis
- HEPTopTagger [Anders *et al*, arXiv:1312.1504]
  - Reconstruct W and t decay products inside jet
- Energy correlation functions [Moult *et al*, arXiv:1609.07473]
  - $e(\alpha, \mathbf{N}, a)$ sensitive to **N**-point correlations in the jet



ECF ratios

ECFs are **N**-point distance-weighted correlation functions among particles of the jet

$$e(a, \mathbf{N}, \alpha) \sim \sum_{\mathbf{N} \text{ particles } \in J} \left[\prod_{p \in \text{particles}} \frac{E_p}{E_J} \right] \times \min \left\{ \prod_{p,q \in \text{particles}}^{a} \theta(p, q) \right\}^{\alpha}$$



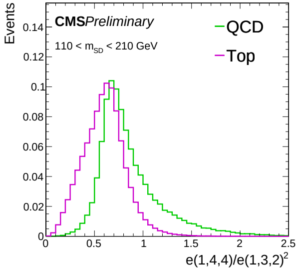
- Top jet: **N** $= 3$ correlations are strong, **N** $= 4$ are weak
  - Can't pick 4 **energetic** particles that are **far apart**
  - $e(\mathbf{N} = 4)/e(\mathbf{N} = 3) \to 0$
- q/g jets: **N** $= 3$ and **N** $= 4$ are both weak
  - $e(\mathbf{N} = 4)/e(\mathbf{N} = 3) > 0$

Non-trivial ECF ratios

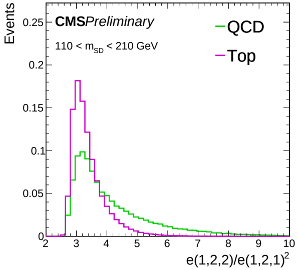
- Interesting ratios do not depend on jet's momentum:

$$\frac{e(a, \mathbf{N}, \alpha)}{e(b, \mathbf{M}, \beta)^x}, \text{ where } M \leq N \text{ and } x = \frac{a\alpha}{b\beta}$$

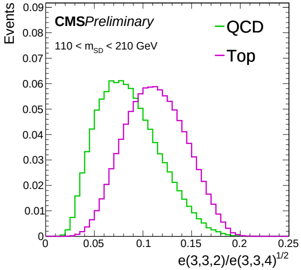
- Turns out many correlation function ratios can separate signal and background



$e(\mathbf{N} = 4)/e(\mathbf{N} = 3)$



$e(\mathbf{N} = 2)/e(\mathbf{N} = 2)$



$e(\mathbf{N} = 3)/e(\mathbf{N} = 3)$

Generalized ECFs

- Extension of original ECFs to allow for different angular orders:

$$e(o,N,\beta) \equiv {}_o e_N^\beta = \sum_{i_1<i_2<\cdots<i_N\in J} \left[\prod_{1\le k\le j} z_{i_k} \right] \times \min \left\{ \prod_{k,l\in\text{pairs}\{i_1,\ldots,i_N\}}^{o} \Delta R_{kl}^\beta \right\}$$

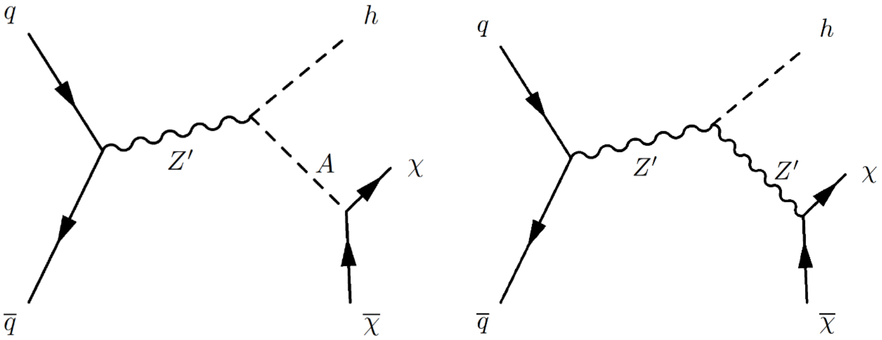
- e.g.

$${}_2e_3^1 = \sum_{a<b<c\in J} z_a z_b z_c \times \min\{\Delta R_{ab}\Delta R_{ac}, \Delta R_{ab}\Delta R_{bc}, \Delta R_{bc}\Delta R_{ac}\}$$

- Summary of parameters:
  - N = order of the correlation function. An N-pronged jet should have $e_N \gg e_M$, for $N < M$
  - o = order of the angular factor.
  - β = angular power

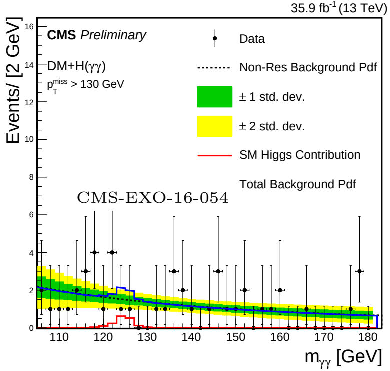
Mono-**Higgs**

- Signature arises from a more specific set of models
  - Cannot rely on simplified models for interpretation
- Still, can focus on "minimal" extensions to SM:
  - Two-Higgs doublet models
  - Addition of baryonic Z' to SM

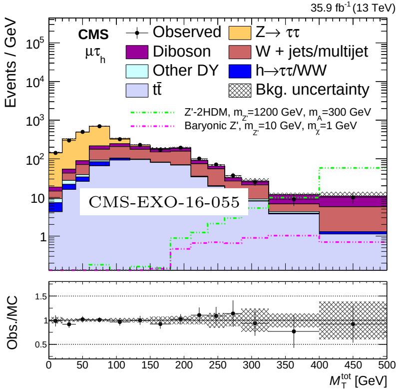


Mono-Higgs($\gamma\gamma/\tau\tau$)

- $m_{\gamma\gamma}$ fit using smooth power law
- SM H included as background
- Events are categorized by $p_{\mathrm{T}}^{\mathrm{miss}}$

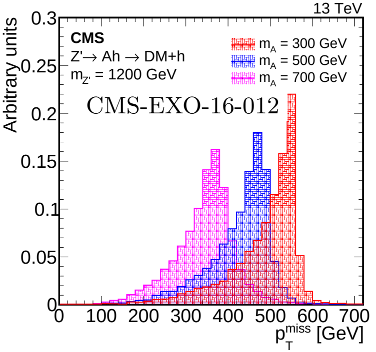


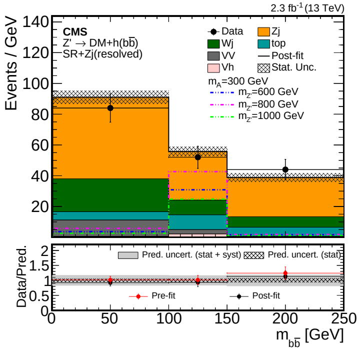
- $M_{\mathrm{T}}^{\mathrm{t}}$ used as proxy for m_H
- Events are categorized by τ decay mode

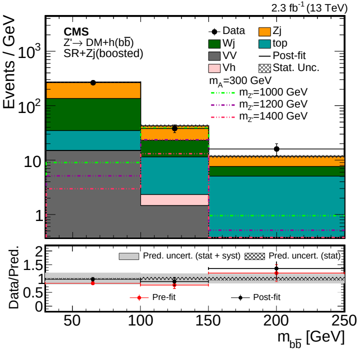


Mono-Higgs(*bb*)

- Different reconstruction used based on $m_{Z'}$ hypothesis
- Low $m_{Z'} \Rightarrow$ low p_{T}^{H}
  - Resolve the H decay as dijet system
- High $m_{Z'} \Rightarrow$ high p_{T}^{H}
  - Reconstruct H has a single large jet

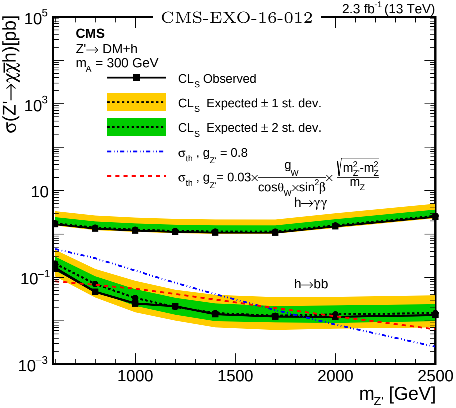






Combination of channels

$\gamma\gamma + bb$ (2.3/fb)



$\gamma\gamma + \tau\tau$ (36/fb)