Search for new particles in events with energetic jets and large MET with CMS Run-2 data (Monojet/Mono-V)

DPF 2021

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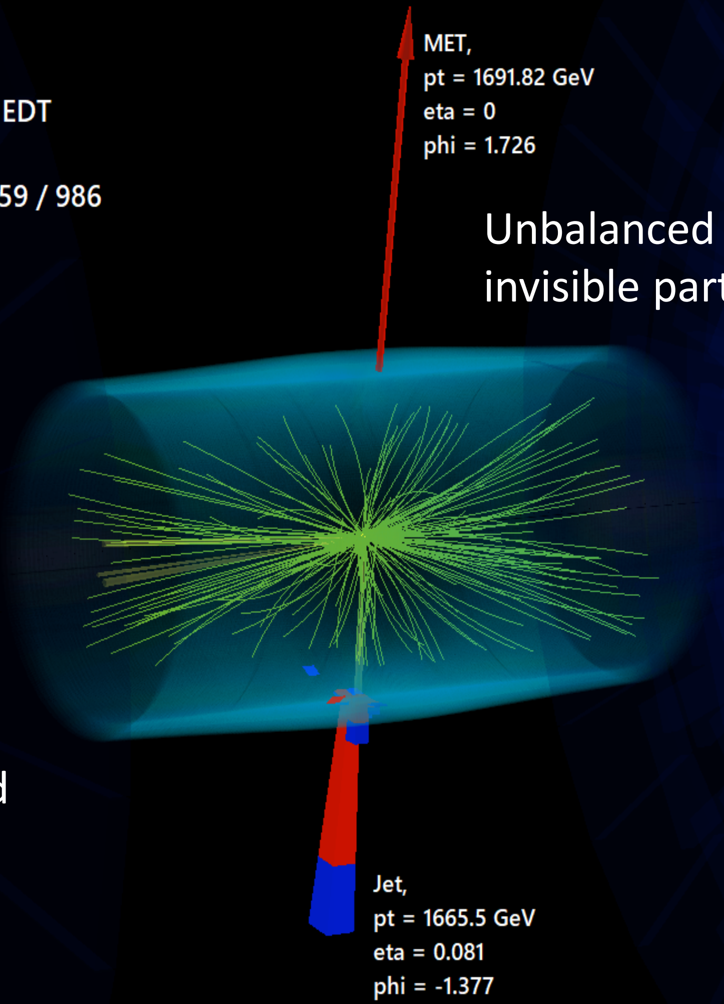
on behalf of the CMS collaboration

BOSTON UNIVERSITY

CMS Experiment at the LHC, CERN

Data recorded: 2018-Jul-14 21:03:24 EDT

Run / Event / LS: 319639 / 1418428259 / 986



Unbalanced transverse momentum indicates invisible particles produced in the event!

We use the word **Monojet** to refer to this kind of events

Analysis tag: CMS-EXO-20-004
Analyzed 2017-2018 data, combined with published 2016 result

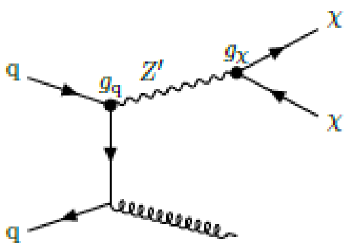
Physics Analysis summary (PAS) publicly available here

Signal model Interpretations

showing example diagram, more diagrams in backup

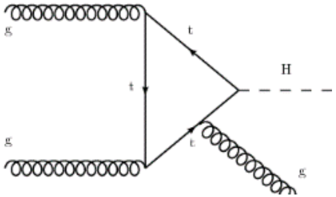
Dark matter simplified model with a color-neutral mediator

- **Simple generic dark model that produce dark matter through some mediators**
- mediator can be spin0 or spin1
- Fix couplings to benchmark values then scan in mass or,
- fix DM mass and scan in mediator mass and one of the coupling values



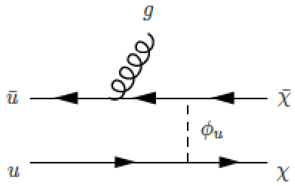
Higgs Portal:

- **SM-like Higgs decay into BSM invisible particles**
- Set limit on SM Higgs invisible branching fraction



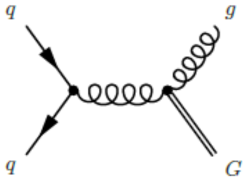
Fermion portal ("t-channel")

- **Mediator couples to quarks and DM**
- Assume all couplings=1 and scan in mediator mass and DM mass



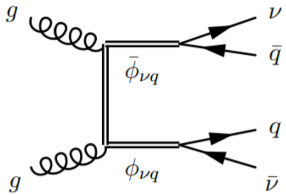
ADD

- **Produce gravitons that leaks into additional dimensions**
- Set limit on the reduced Planck scale as a function of number of additional dimensions

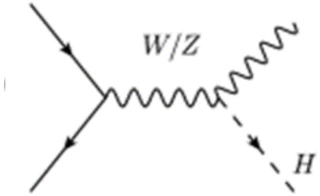


Leptoquark

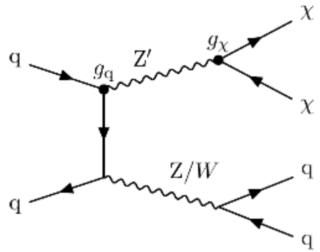
- **Couples to up quark and electron neutrinos**
- Scanning limit as function of leptoquark mass and coupling constant



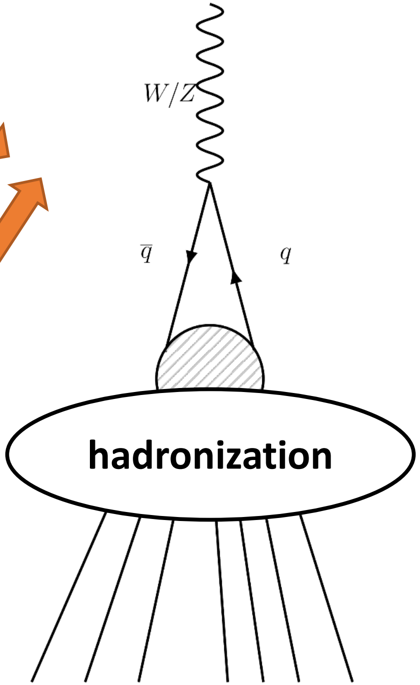
Special case – jets from V(qq) decays! (Mono-V)



W/Z produced in Higgs production through VH channel



W/Z produced in DMsimp model

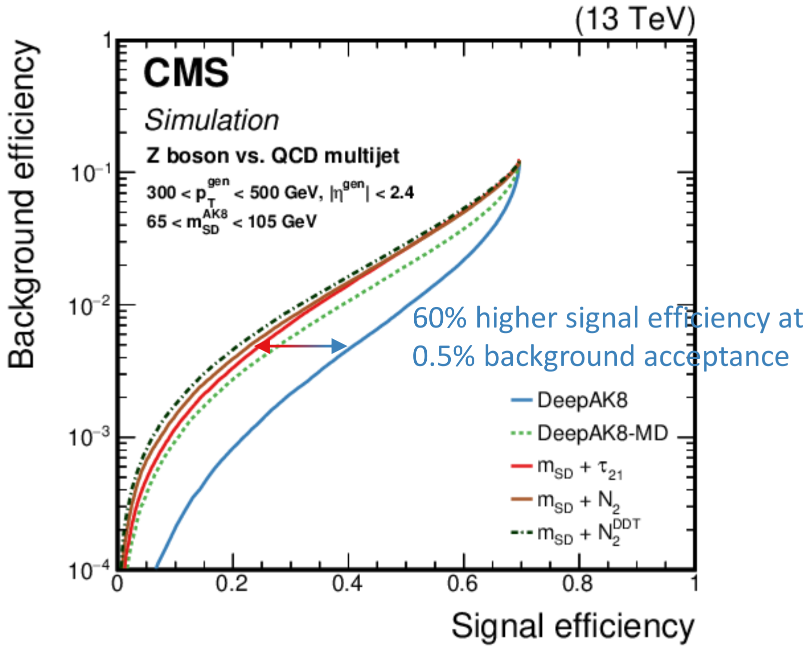


fat jet (AK8)
in **Lorentz-boosted frame**

Additional categories to capture these events based on V(qq) jet tagging:

- **Traditional**: N-subjetiness (used in 2016 analysis)
- **New**: DeepAK8 (Deep neural network)

comparison



Signal regions – define 3 categories!

Common Cuts

p_T^{miss} > 250 GeV
$\Delta\phi(j, recoil) > 0.5$ for 4 leading jets
(PF MET – Calo MET) / Recoil < 0.5
MET filters applied

} cleaning cuts

Mono-V

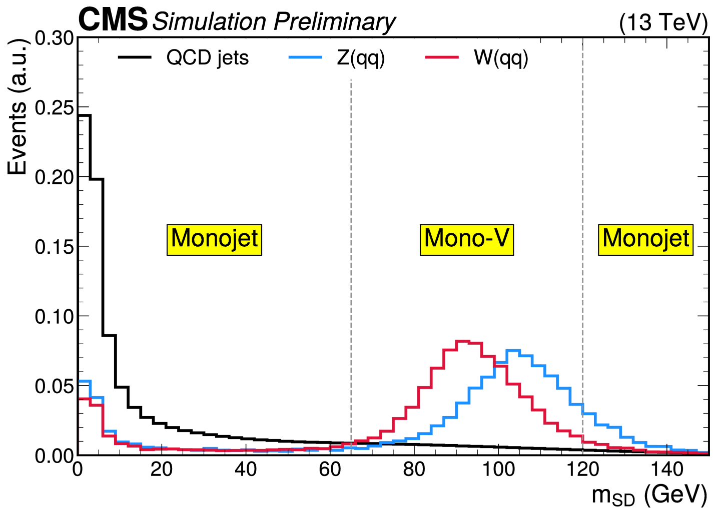
Leading AK8 jet:

- p_T>250 GeV, $|\eta|$<2.4
- Pruned mass in [65,120]
- Passing nominal deepAK8 WvsQCD tagger
- **Further split into high purity and low-purity**

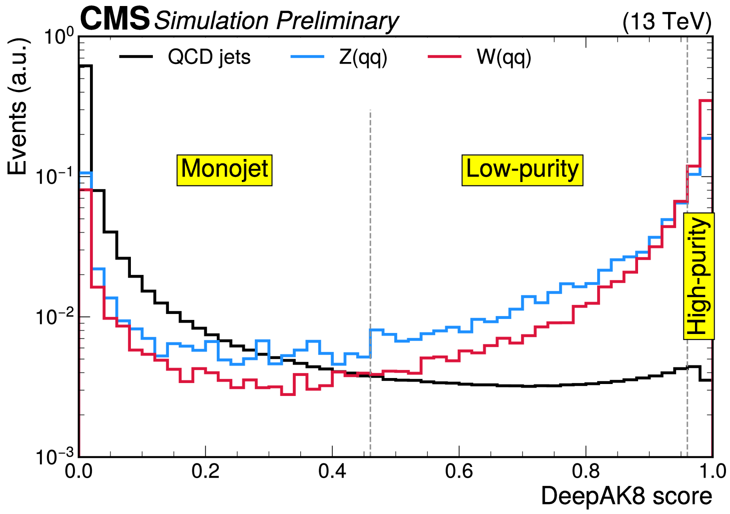
Monojet

No Mono-V event
Leading AK4 jet

- (CHS jet with tight jet ID and JES&JER applied)
- p_T>100 GeV, $|\eta|$<2.4, NHF<0.8 && CHF>0.1

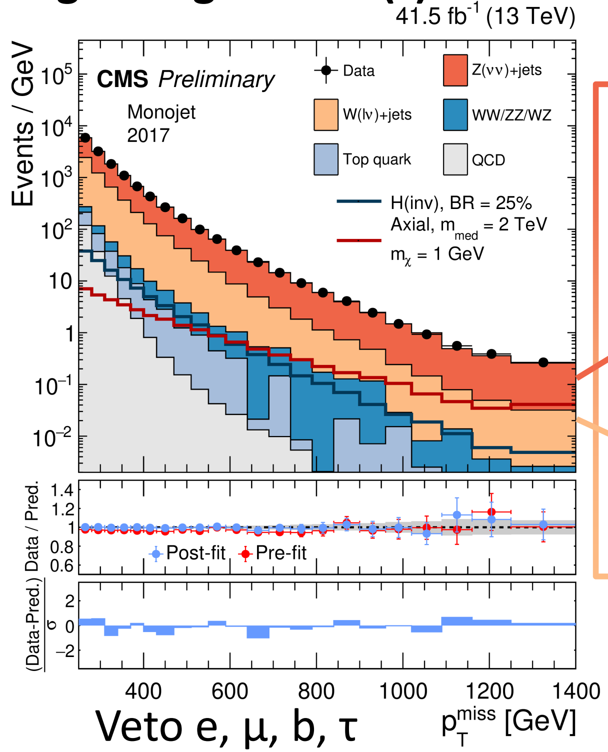


Soft-Drop pruned jet mass



Estimation of main background

Signal region = Jet(s) + MET



Veto e, μ, b, τ

detailed definition on next slide

Main background:

Z(νν)+jets

W(lν)+jets (missing lepton)

p_T^{miss} from Z/W p_T

Theoretically connected processes:

Z(ll)+jets

W(lν)+jets (detected lepton)

γ+jets

Define 5 Control Regions:

2e CR
2m CR

1e CR
1m CR

γ CR

All regions exist in the three categories defined on previous slide:
“Monojet”, “Mono-V high purity”, and “Mono-V low purity”

Control region event selections

- = Signal region selections
- + replace p_T^{miss} to **Recoil**
- + remove corresponding lepton/photon veto
- + region-dependent selections below:

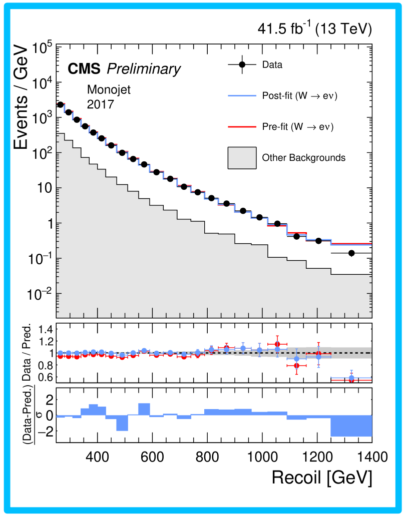
Recoil $:= p_T^{miss} + \sum p_T^{leptons/photons}$

$\approx p_T^{Z/W}$ in CR

mimics how Z/W p_T fakes p_T^{miss} in SR

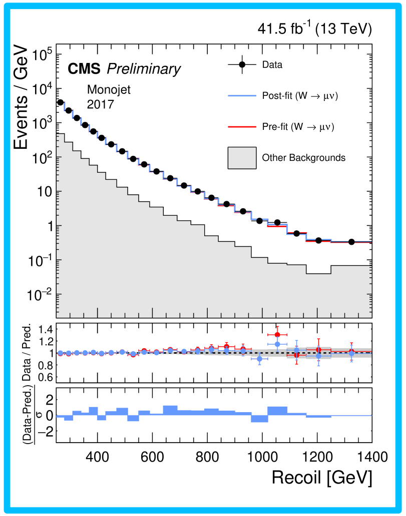
Single electron CR

- exactly 1 electron



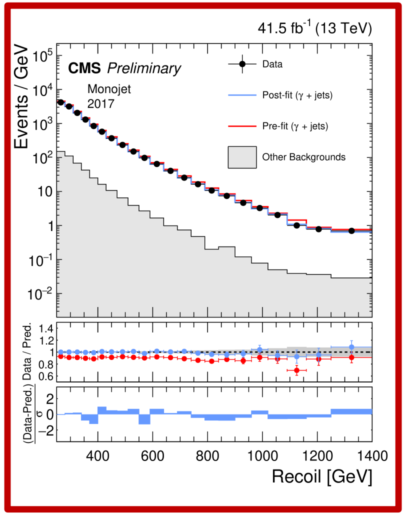
Single muon CR

- exactly 1 muon



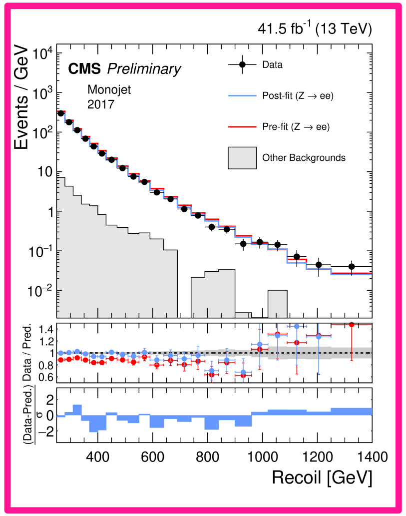
Photon CR

- Exactly 1 tight photon
- photon $p_T > 230\text{GeV}$



Double electron CR

- exactly 2 electrons
- 60<pair mass<120
- opposite charge



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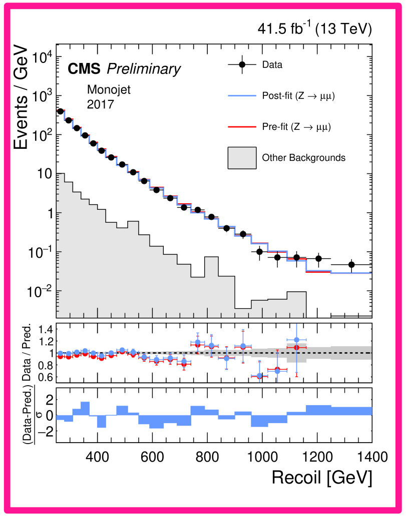
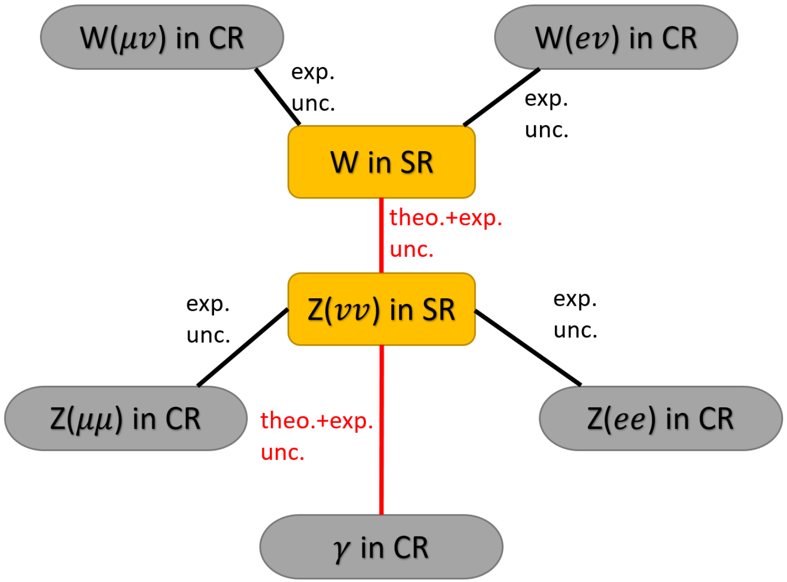


Signal Extraction Strategy: combined fit



× number of channels and years (6 in total)

- **Maximize likelihood between data and prediction,** likelihood function defined in backup
- **Unconstrained parameters**: per-bin (in Recoil) normalization of Z(νν) in SR, signal strength
- **Constrained parameters**: numerous nuisance parameters that allow the process ratios vary within syst./stat. uncertainties (each ratio represented by a link on the left diagram)
- **Uncertainties common between regions mostly cancel out!** Remaining uncertainties are e.g. lepton/photon ID. Summary of important uncertainties

p_T^{miss} distribution signal region year 2017

2018 result similar and in backup

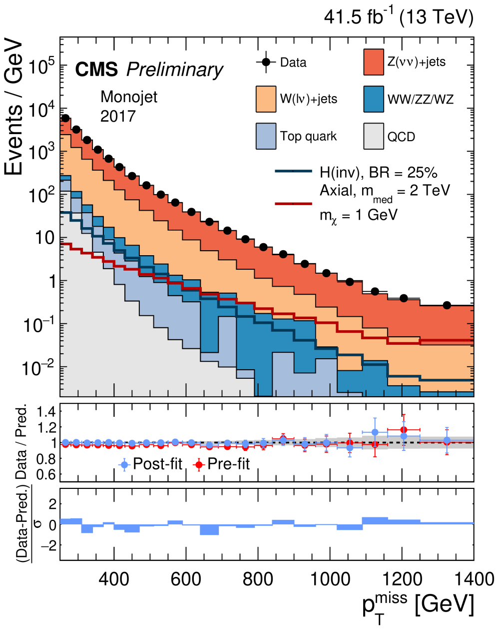
Background-only fit i.e. signal strength set to 0

Post-fit estimation has good agreement with data

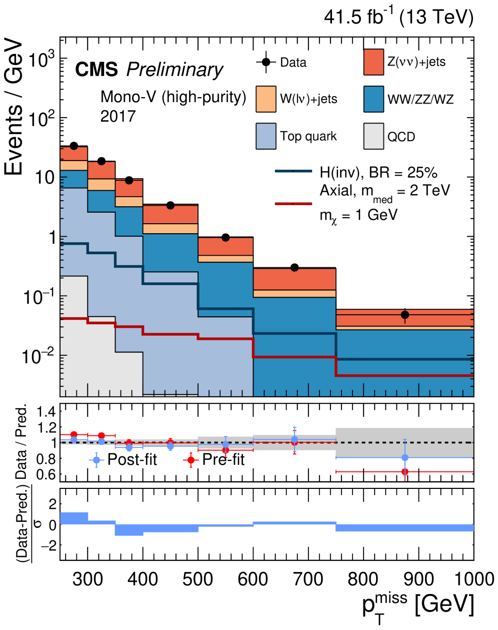
Pre-fit excess in mono-V low purity region consistent with trend in W CR → No post-fit excess

➔ **No significant excess**

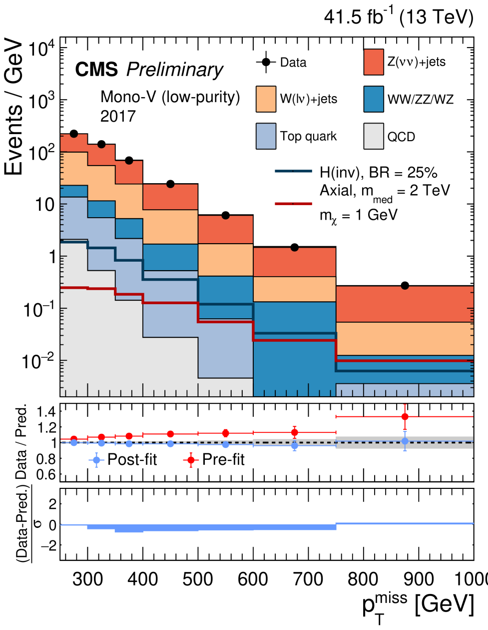
monojet



mono-V (high purity)

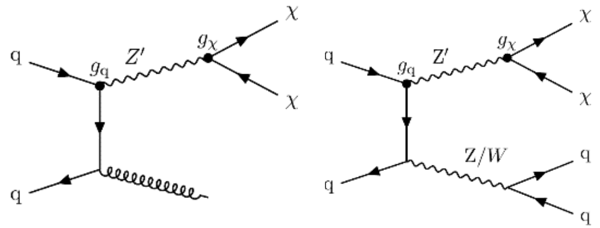


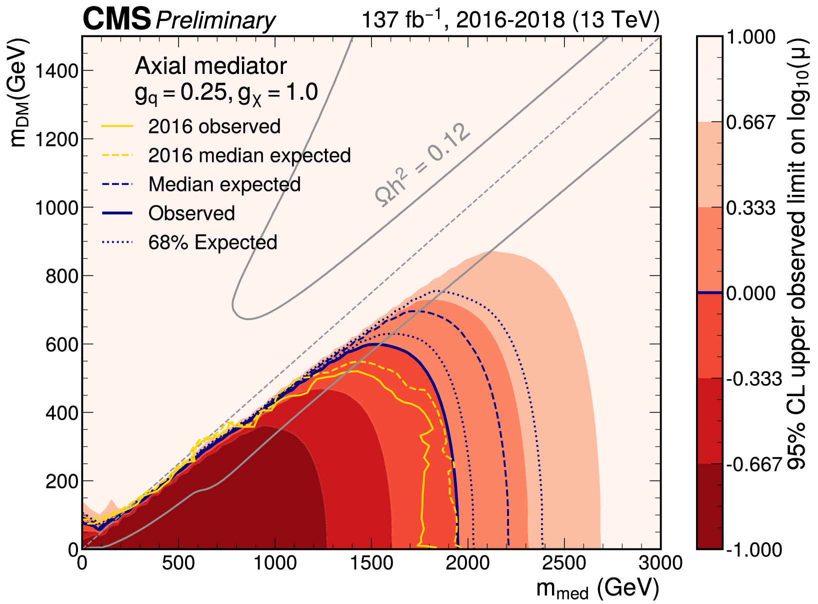
mono-V (low purity)



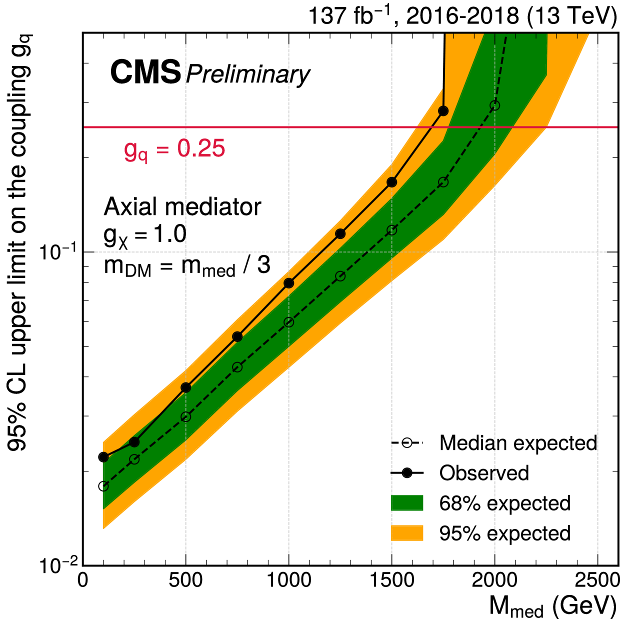
Model interpretation

Simplified DM model: Axial mediator





fix $m_{DM} = m_{med}/3$
and scan g_q

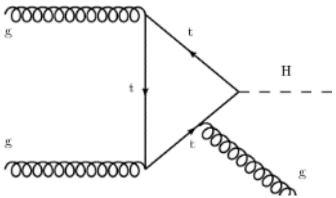


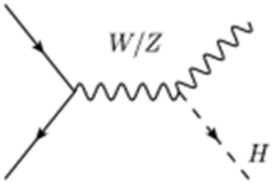
Full Run-2: Exclude m_{med} <≈ 2 TeV (≈2.2 TeV expected) for small m_{DM}

improvement relative to 2016 by ≈ 200 GeV in m_{med}

reached 1 order of magnitude lower than g_q bench mark value

Model interpretation
Higgs invisible model





ggH dominating in monojet

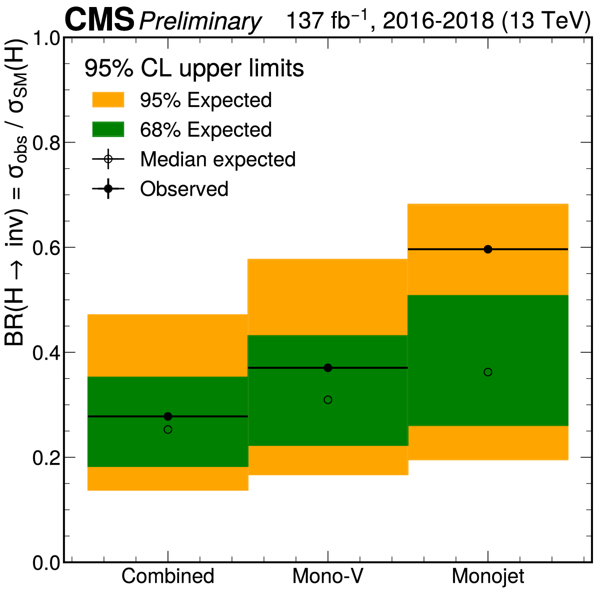
VH dominating in monoV

Expected signal composition

	ggH	VBF	WH	ZH	ggZH
Monojet	74%	21%	3%	2%	1%
MonoV low purity	52%	11%	22%	12%	3%
MonoV high purity	6%	3%	69%	19%	4%

40%-50% relative improvement in Higgs→invisible branching fraction limit

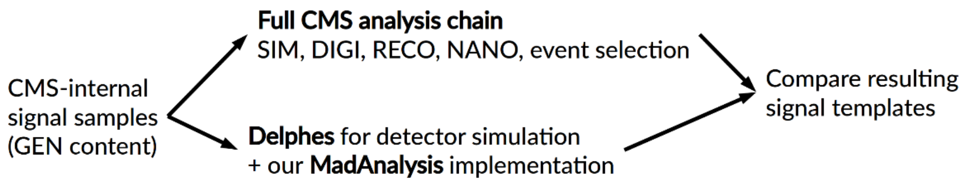
Set limit on standard-model Higgs invisible branching fraction



Both monojet and mono-V contribute, but more from mono-V

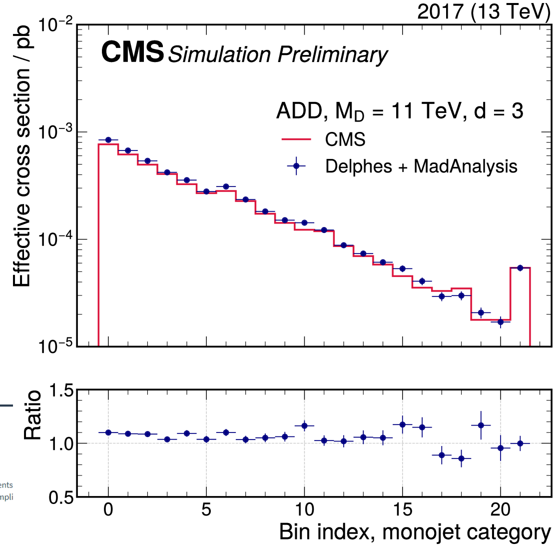
Channel	Expected	Observed
Mono-V	0.31	0.37
Monojet	0.36	0.60
Combined	0.25	0.28
2016-only	0.40	0.53

Analysis reinterpretation: MadAnalysis

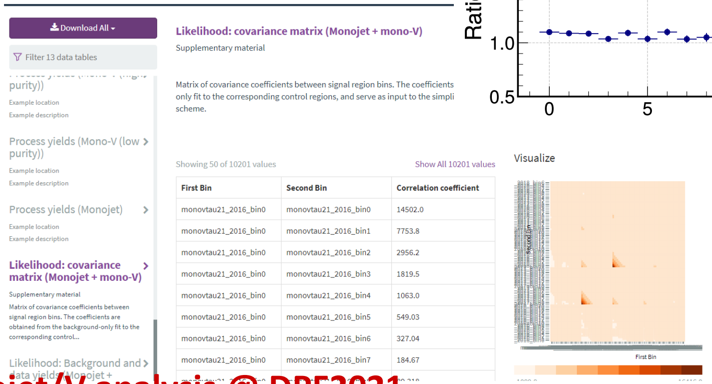


- **MadAnalysis** is a framework for the reinterpretation of existing analyses in terms of arbitrary new physics models
- Implemented monojet channel in MadAnalysis(**i.e. applies monojet selection on your model**), link to the implementation
- Validated the implementation by comparing with this analysis
- HEPData entry with **simplified likelihood**(yields and covariance matrix); signal cut-flows, signal generator cards, etc.

example on ADD model



screenshot



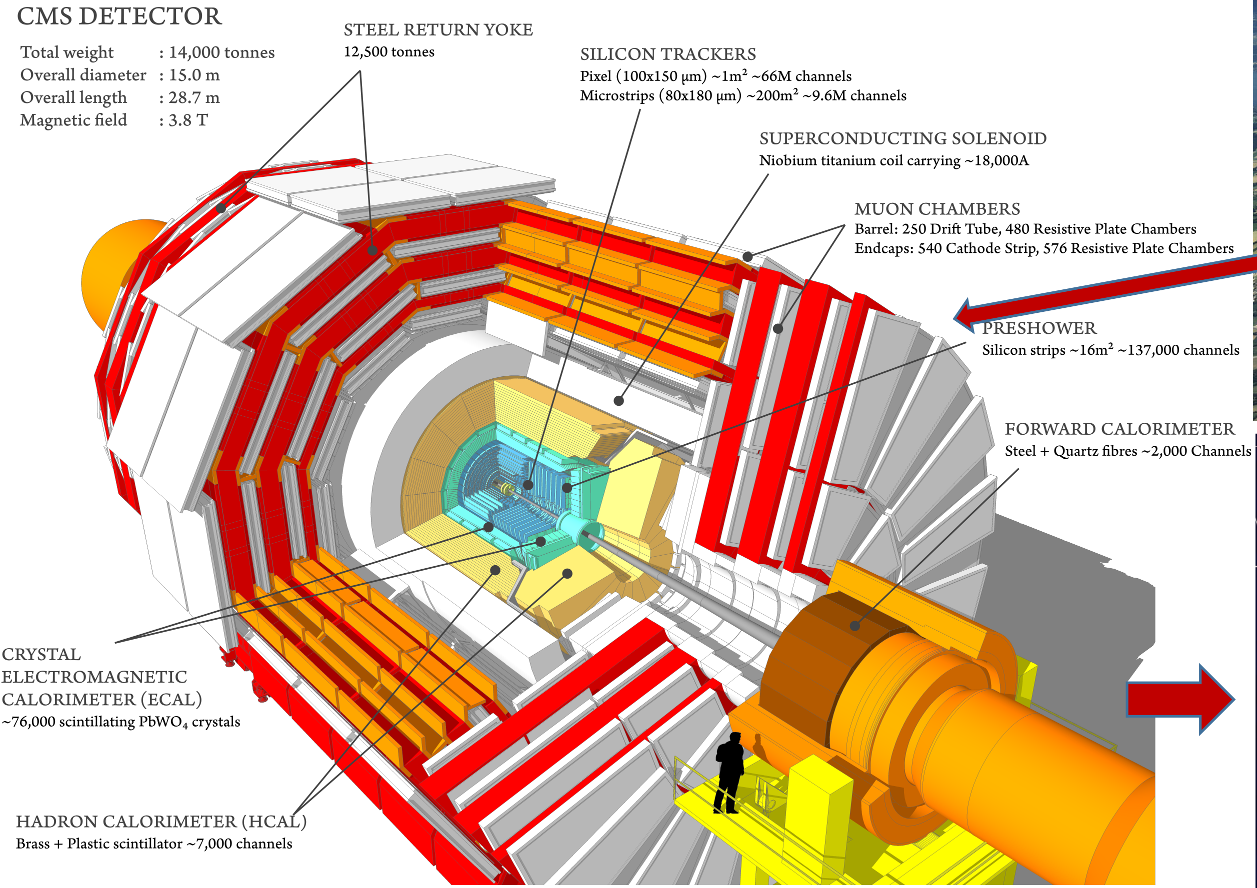
Summary

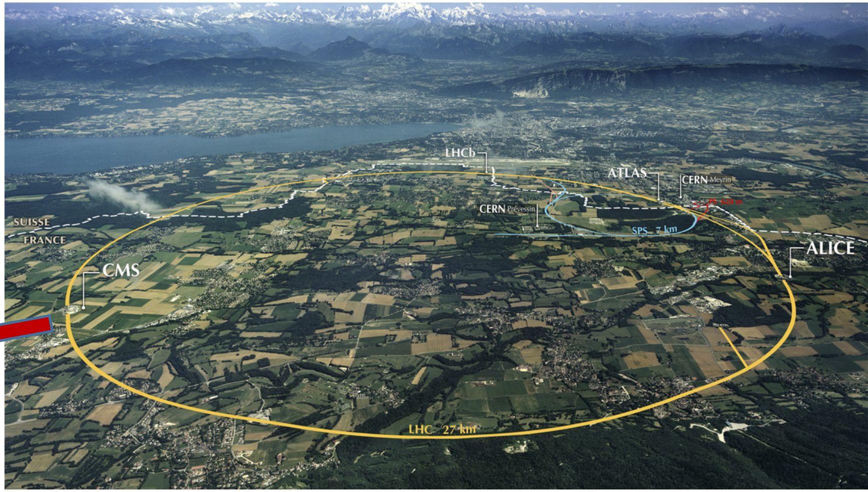
- **Presented the monojet + mono-V analysis** using full 2017 + 2018 data, and have combined with published 2016 result **for the full Run-2 result**
- **We do not see any significant deviation from SM expectations**, but instead we set:
  - upper limits on **Higgs boson to invisible** branching ratio
  - upper limits on the production of Dark Matter in the **simplified Dark Matter model** with vector/axial-vector/scalar/pseudo-scalar mediators
  - upper limits on the production of Dark Matter through **fermion portal mediator**
  - limits on the reduced Planck scale as a function of number of extra dimensions in the **ADD extra dimension model**
  - limits on the **leptoquark** coupling as a function of leptoquark mass
- **Better limits are observed in the above models compared to the published 2016-only result, some are among the most restrictive limits to date**
- **Implemented monojet category in MadAnalysis for re-interpretation**

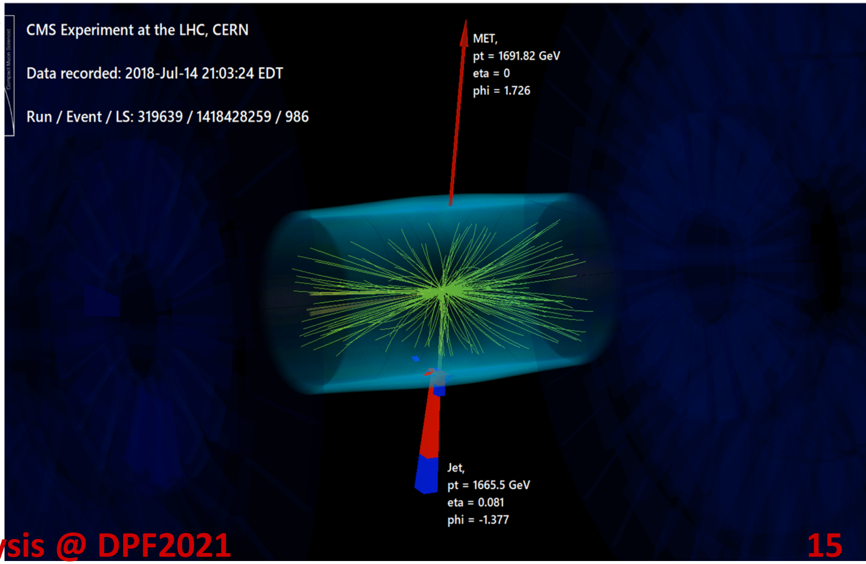
Thank you for your interest in this analysis!

Backup

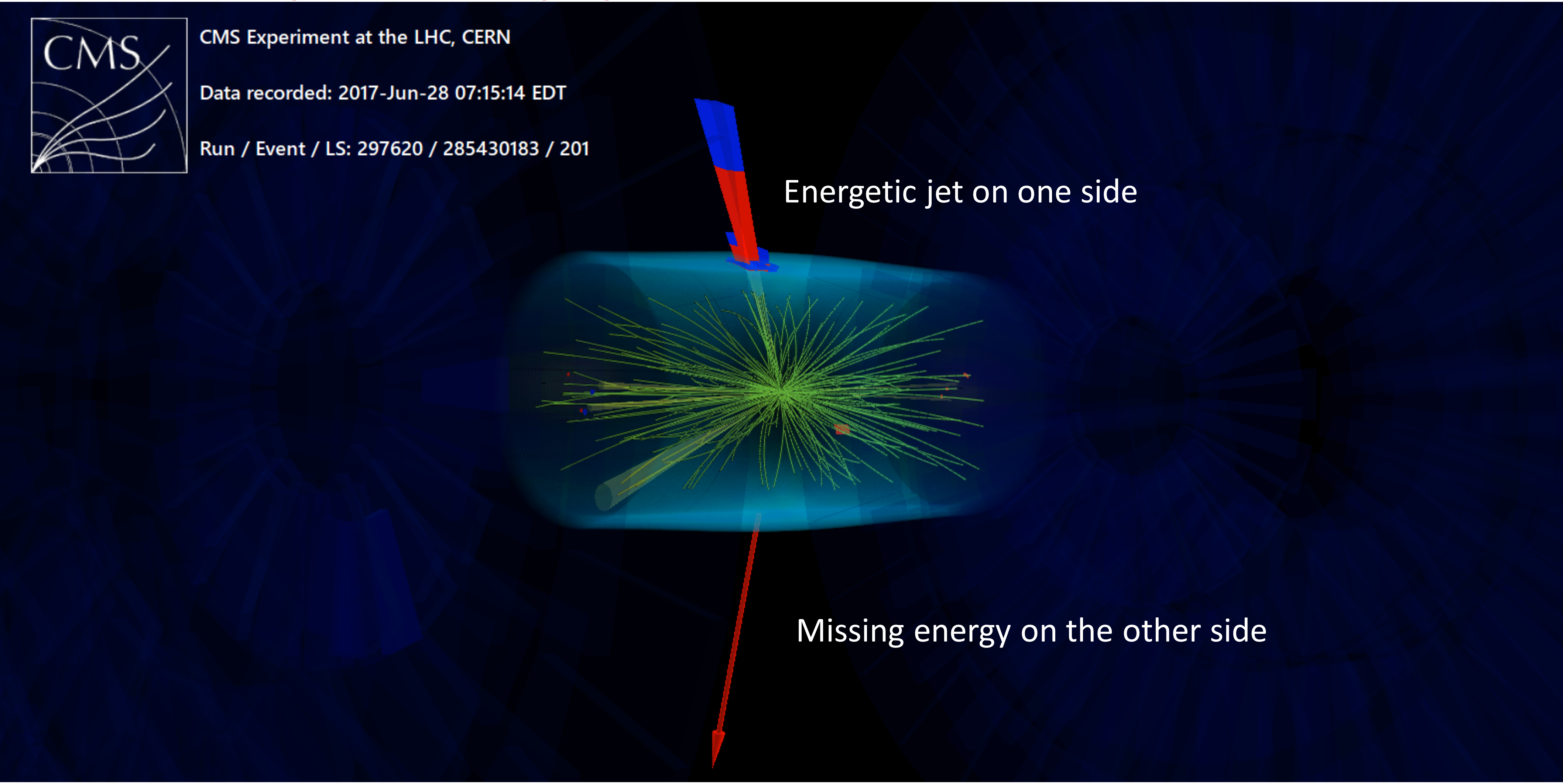
The CMS detector – where we take data





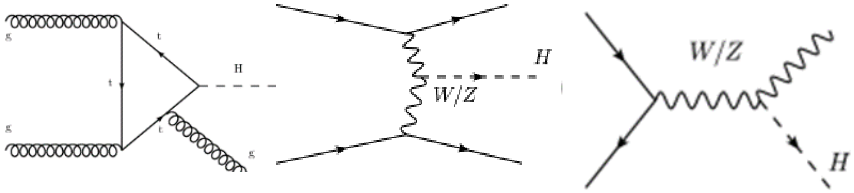


Another example event display

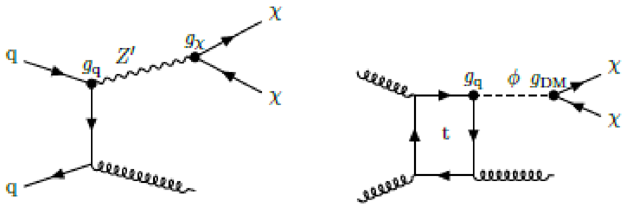


Signal model Interpretations (more diagrams)

Higgs Portal:

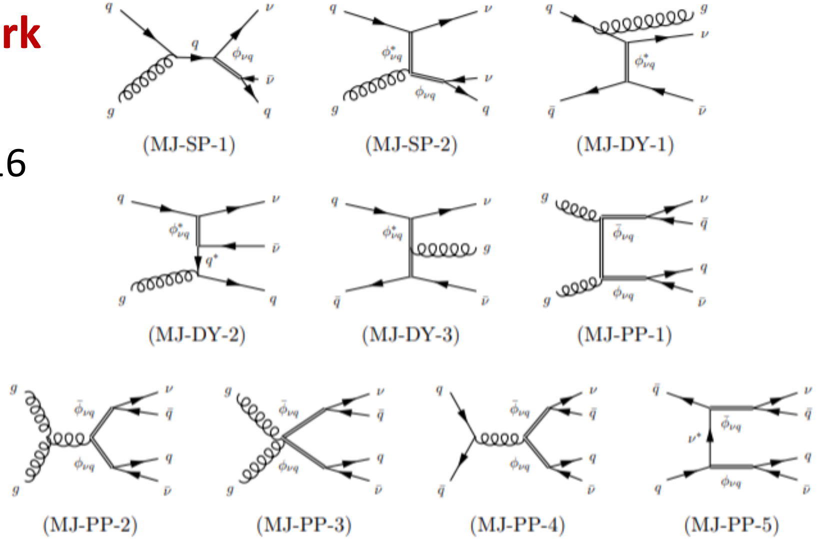


Dark matter simplified model with a color-neutral mediator

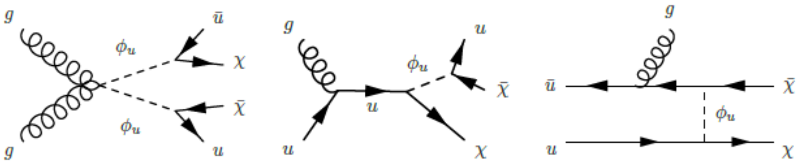


Leptoquark

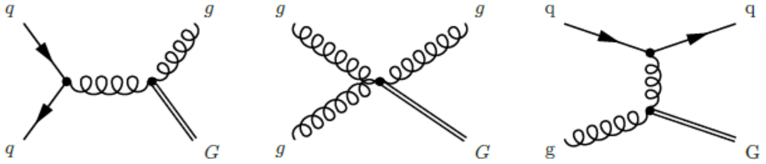
not in 2016 analysis



Fermion portal (t-channel)



ADD



Object definitions

Electrons:

- Tight = POG cut-based tight WP
  - $p_T > 40GeV, |\eta| < 2.5$
- Loose = POG cut-based
  - $p_T > 10GeV, |\eta| < 2.5$

Photons:

- Tight = POG cut-based tight WP
  - $p_{\mathrm{T}} > 230\mathrm{GeV}, |\eta| < 1.4442$
- Loose = POG cut-based veto WP
  - $p_{\mathrm{T}} > 15\mathrm{GeV}, |\eta| < 2.5$

Muons:

- Tight = POG cut-based tight WP
  - $p_{\mathrm{T}} > 20\mathrm{GeV}, |\eta| < 2.4$
- Loose = POG cut-based veto WP
  - $p_{\mathrm{T}} > 10\mathrm{GeV}, |\eta| < 2.4$

At least one tight electron/photon/muon is required in the corresponding CRs
Loose electrons/photons/muons are also used in vetoing events in SR (see region definitions)
Taus and B-tagged jets are only used for veto

Taus:

- $p_{\mathrm{T}} > 18\mathrm{GeV}, |\eta| < 2.3$
- Old DM ID + VLoose MVA ISO

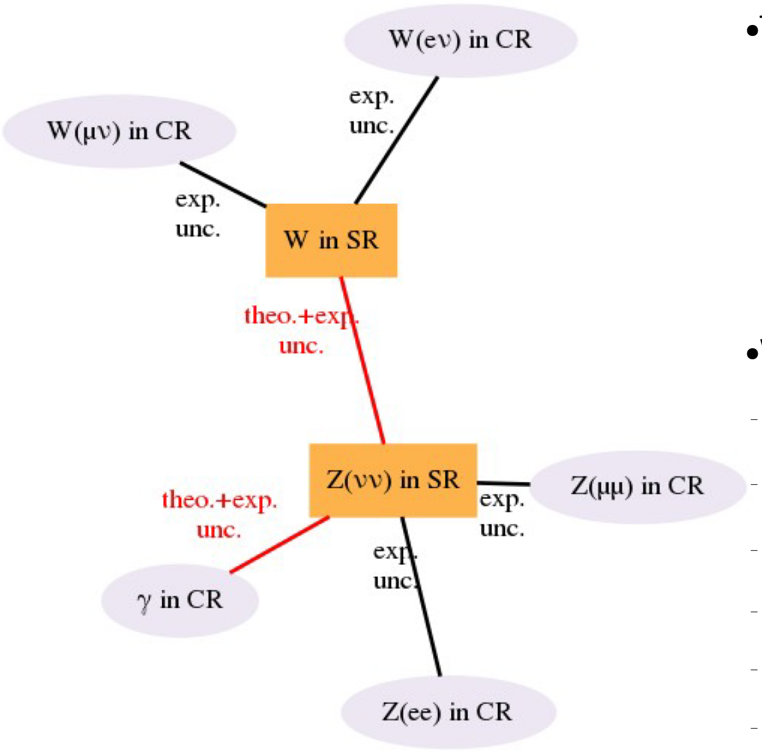
B-tagged jets:

- $p_{\mathrm{T}} > 20\mathrm{GeV}, |\eta| < 2.4$
- DeepCSV medium

Event selection summary table

Category	Variable / Description	Selection
All	Muon (electron) veto	$p_T > 10\,\text{GeV}$ and $\|\eta\| < 2.4(2.5)$
	τ lepton veto	$p_T > 18\,\text{GeV}$ and $\|\eta\| < 2.3$
	Photon veto	$p_T > 15\,\text{GeV}$ and $\|\eta\| < 2.5$
	Bottom jet veto	DeepCSV "medium", $p_T > 20\,\text{GeV}$, $\|\eta\| < 2.4$
	p_T^{miss}	$> 250\,\text{GeV}$
	Δp_T^{miss}(PF–Calorimeter)	< 0.5
	$\Delta\phi$(PF, Charged)	$< 2\,\text{rad}$
	$\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{j})$	$> 0.5\,\text{rad}$
	$\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{j})$	$> 0.5\,\text{rad}$
All (2018)	Calorimeter failure mitigation	no AK4 jet with $p_T > 30\,\text{GeV}$, $-1.57 < \phi < -0.87$, $-3.0 < \eta < -1.3$. $\phi(\vec{p}_T^{miss}) \notin [-1.62, -0.62]$ if $p_T^{miss} < 470\,\text{GeV}$.
Monojet	Leading AK4 jet	$p_T > 100\,\text{GeV}$ and $\|\eta\| < 2.4$
Mono-V	Leading AK8 jet	$p_T > 250\,\text{GeV}$, $\|\eta\| < 2.4, 65 < m_{SD} < 120\,\text{GeV}$ Subcategorization based on DeepAK8 score

Fit likelihood function



- The likelihood is a product of the Poisson likelihood in each ***Recoil*** bin in each region:

$$\mathcal{L}_c(\mu^{Z\to\nu\nu}, \boldsymbol{\mu}, \boldsymbol{\theta}) = \prod_i \text{Poisson}\left(d_i^{\gamma} \middle| B_i^{\gamma}(\boldsymbol{\theta}) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^{\gamma}(\boldsymbol{\theta})}\right) \times$$ photon CR

$$\prod_i \text{Poisson}\left(d_i^{Z} \middle| B_i^{Z}(\boldsymbol{\theta}) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^{Z}(\boldsymbol{\theta})}\right) \times$$ di-lepton CR

$$\prod_i \text{Poisson}\left(d_i^{W} \middle| B_i^{W}(\boldsymbol{\theta}) + \frac{f_i(\boldsymbol{\theta})\mu_i^{Z\to\nu\nu}}{R_i^{W}(\boldsymbol{\theta})}\right) \times$$ single lepton CR

$$\prod_i \text{Poisson}\left(d_i \middle| B_i(\boldsymbol{\theta}) + (1 + f_i(\boldsymbol{\theta}))\mu_i^{Z\to\nu\nu} + \mu S_i(\boldsymbol{\theta})\right)$$ SR

- Where

- $d_i^{\gamma/W/Z}$ are the observed number of events in the i^{th} ***Recoil*** bin of the photon, single lepton, or di-lepton regions.
- $B_i^{\gamma/W/Z}$ are the background in the corresponding CRs.
- $R_i^{\gamma/W/Z}$ are the transfer factor of $Z \to \nu\nu$ yields between SR and CRs.
- $\mu_i^{Z\to\nu\nu}$ is the $Z \to \nu\nu$ yield in the SR.
- μ is the signal strength.
- f_i is the ratio of W→ $l\nu$ and $Z \to \nu\nu$ background in SR.

go back to main text

List of most important experiment uncertainties

Source	Process	Uncertainty
Electron trigger	$W_{SR}/W_{e\nu}$, Z_{SR}/Z_{ee}	1%
E_T^{miss} trigger	$W_{SR}/W_{e(\mu)\nu}$	1-2% (shape)
	$Z_{SR}/Z_{\mu\mu}$	2-3% (shape)
Photon trigger	Z_{SR}/γ_{CR}	2%
Photon p_T scale	Z_{SR}/γ_{CR}	$<$ 4% (shape)
Muon-reco efficiency per muon	$W_{SR}/W_{\mu\nu}$, $Z_{SR}/Z_{\mu\mu}$	1%
Muon-ID efficiency per muon	$W_{SR}/W_{\mu\nu}$, $Z_{SR}/Z_{\mu\mu}$	1%
Muon-iso. efficiency per muon	$W_{SR}/W_{\mu\nu}$, $Z_{SR}/Z_{\mu\mu}$	1%
Electron-reco efficiency per ele.	$W_{SR}/W_{e\nu}$, Z_{SR}/Z_{ee}	1%
Electron-ID efficiency per ele.	$W_{SR}/W_{e\nu}$, Z_{SR}/Z_{ee}	3%
Photon-ID efficiency	Z_{SR}/γ_{CR}	$4-13\%$ (shape)
Muon veto	$W_{SR}/W_{e(\mu)\nu}$ Z_{SR}/W_{SR}	$<$ 1% (shape)
Electron veto	$W_{SR}/W_{e(\mu)\nu}$ Z_{SR}/W_{SR}	2% (shape)
Tau veto	$W_{SR}/W_{e(\mu)\nu}$,Z_{SR}/W_{SR}	1–2% (shape)
Prefiring	Z_{SR}/Z_{CR},W_{SR}/W_{CR}	$<$ 1% (shape)

- Important uncertainties that have effect on Transfer Factors
- Correlated between bins of recoil and categories
- Uncorrelated between years
- Uncertainties e.g. on luminosity, jes and jer, affect both numerator and denominator in TF, and thus cancel out partially or fully

Summary of uncertainties for other small background in backup

Summary of uncertainties on small background

Source	Process	Uncertainty
Luminosity	All	2.5 %/ 2.3%
Electron trigger	All in 1e CR	1%
$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	All in SR and 1μ CR	2%
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ energy calibration	All	5% (shape)
Muon-reco efficiency per muon	All in muon CRs	1%
Muon-ID efficiency per muon	All in muon CRs	1%
Muon-iso efficiency per muon	All in muon CRs	1%
Electron-reco efficiency per ele.	All in electron CRs	1%
Electron-ID efficiency per ele.	All in electron CRs	3%
b-jet veto	Top in SR and all CRs	6%
	All remaining in SR and all CRs	2%
Top p_{T} reweight	Top	10%
Top norm	Top	10%
Diboson mixed EWK-QCD corr.	Diboson	up to 10% (shape)
Diboson normalization	Diboson	10%
$\mathrm{Z}(\ell\ell)+$jets norm	$\mathrm{Z}(\ell\ell)+$jets (SR)	20%
QCD	QCD in SR	from 20% up to $>$ 100% (shape)
Fake muons	QCD in $W_{\mu\nu}$	50%
Jet-to-electron fakes	QCD in $W_{e\nu}$	75%
Photon-to-electron fakes	$\gamma+$jets in $W_{e\nu}$	20%

uncertainties on transfer factors

Data Validation: Pre-fit control region ratios (year 2017)

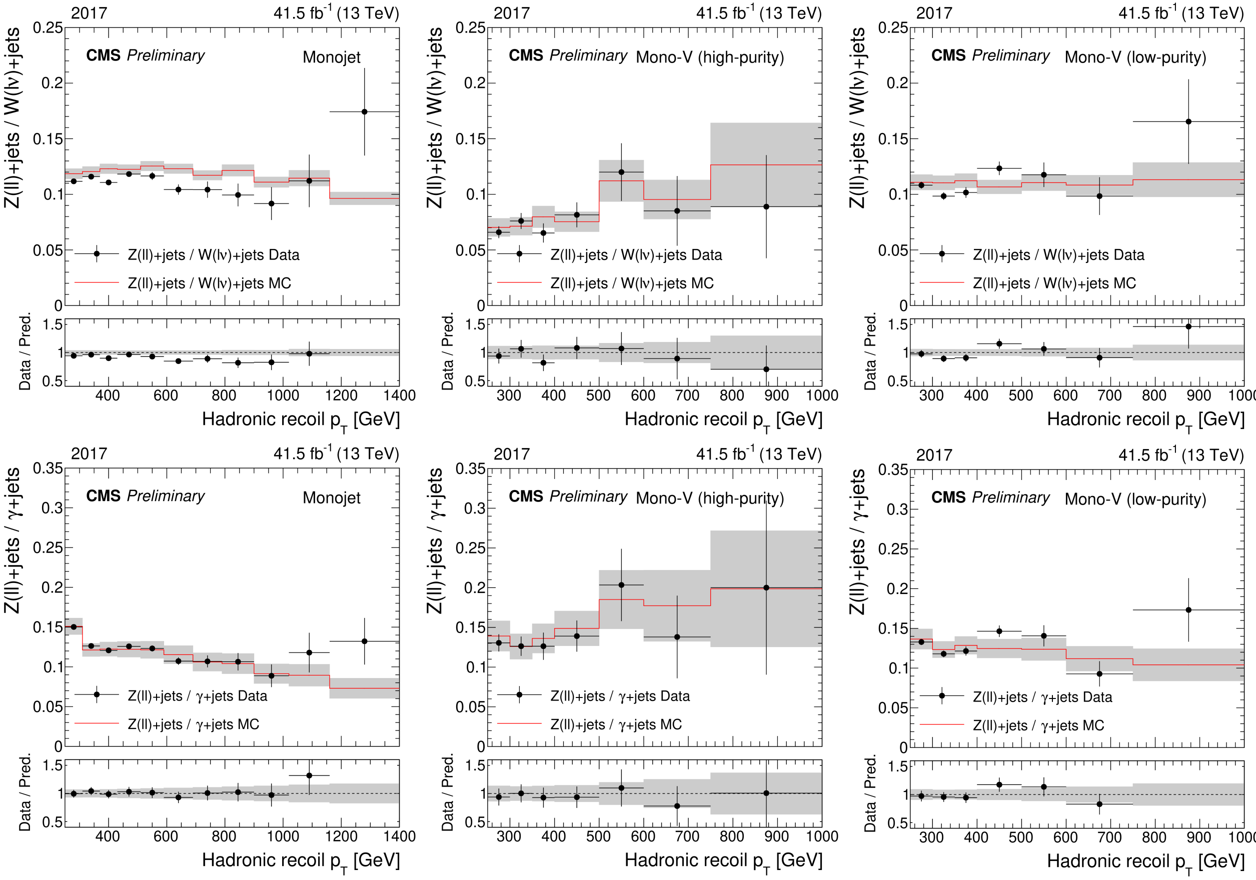
Ratios between the control regions
A proxy for validating transfer factors

- **Overall good agreement with data**
- 2017 ratios hint at need to pull W relative to others (accomplished mainly by lepton ID + theory pulls, see backup)

monojet | mono-V (high purity) | mono-V (low purity)

Z/W

Z/Photon



Data Validation: Pre-fit control region ratios (year 2018)

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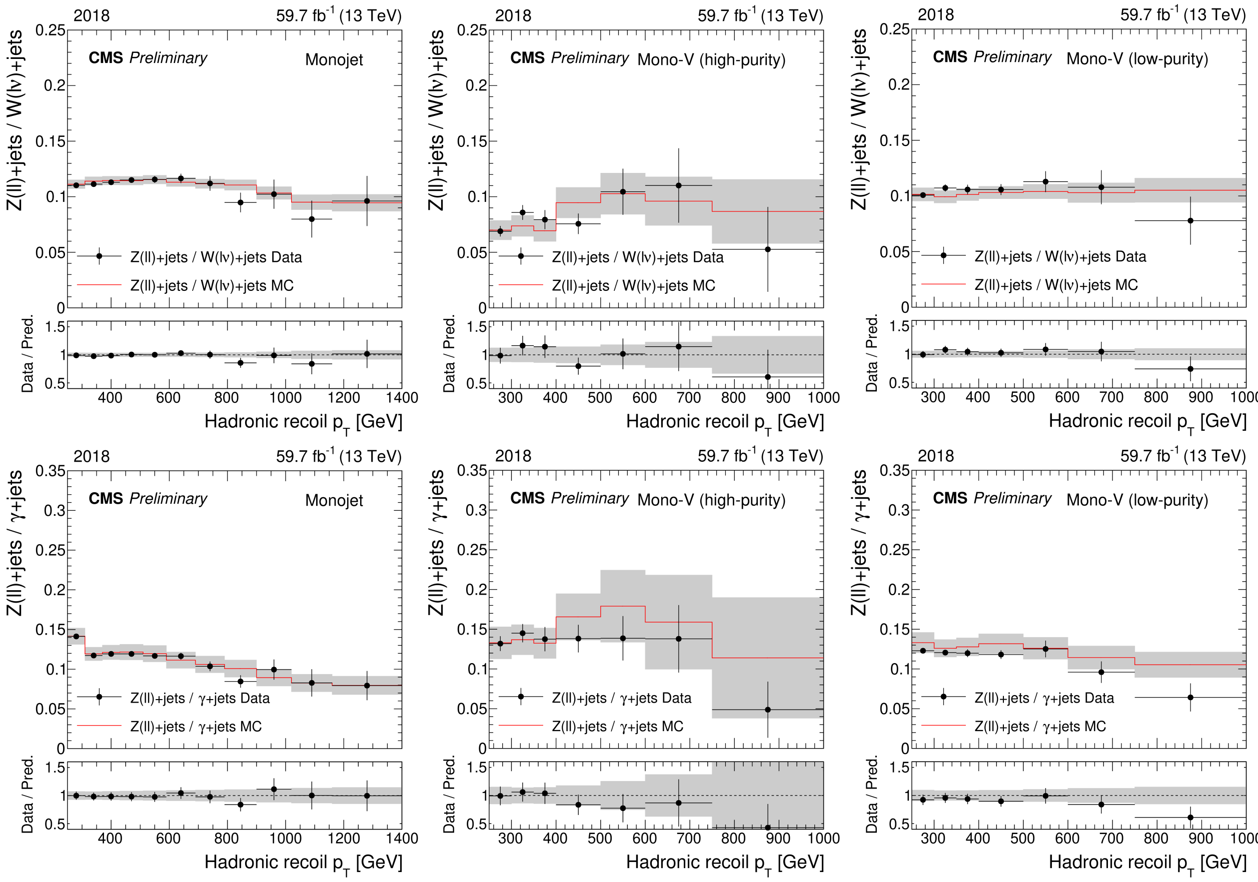
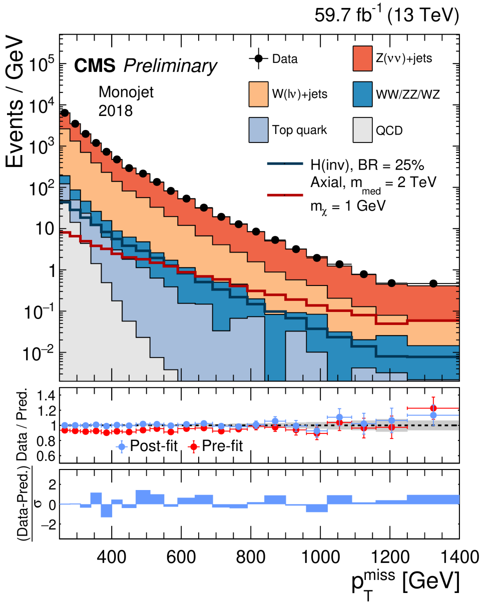


p_T^{miss} distribution signal region year 2018

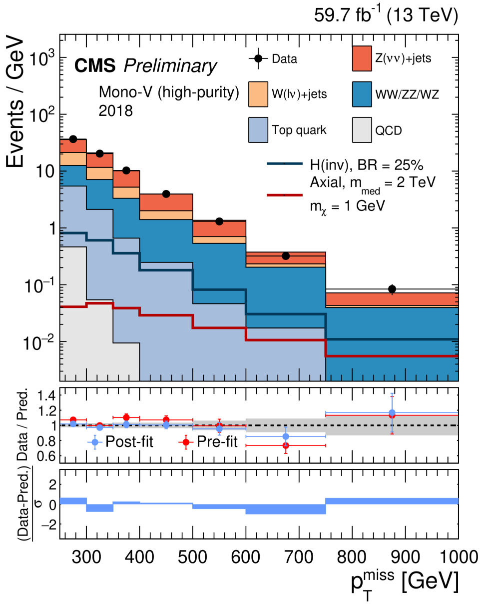
Same conclusion as 2017

➔ **No significant excess**

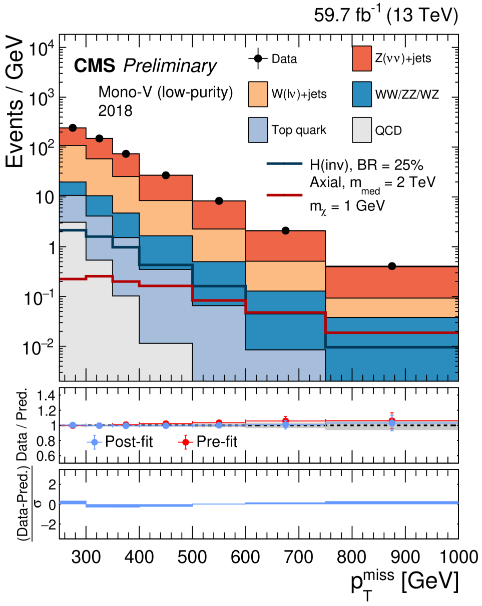
monojet



mono-V (high purity)



mono-V (low purity)

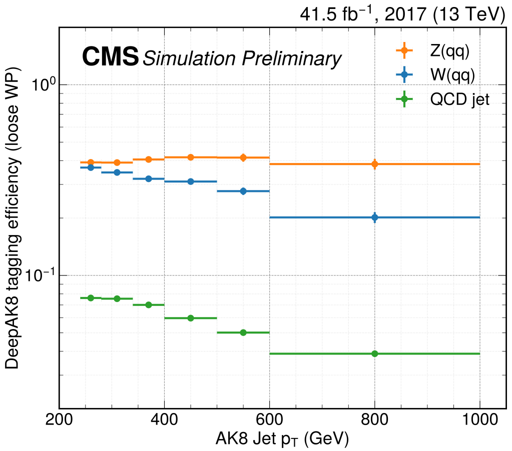


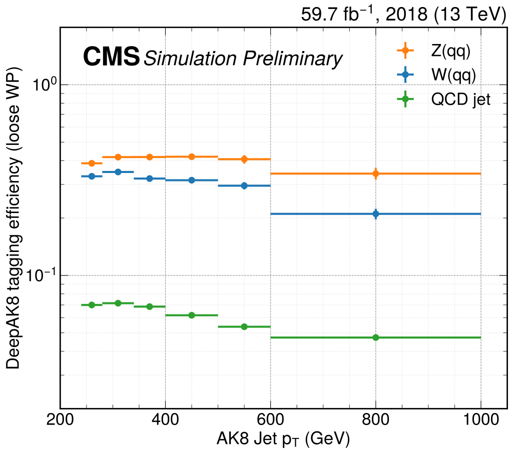
Wide jet tagging efficiencies for reinterpretation

2017

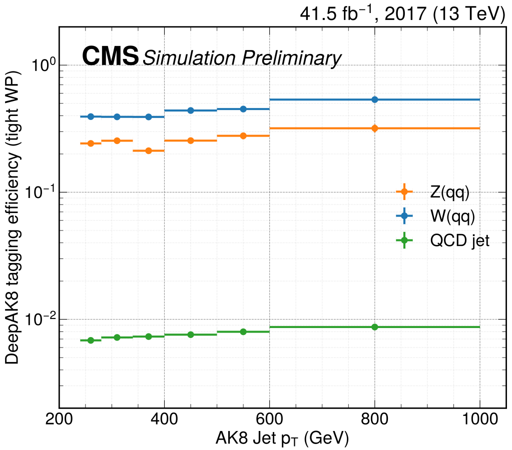
2018

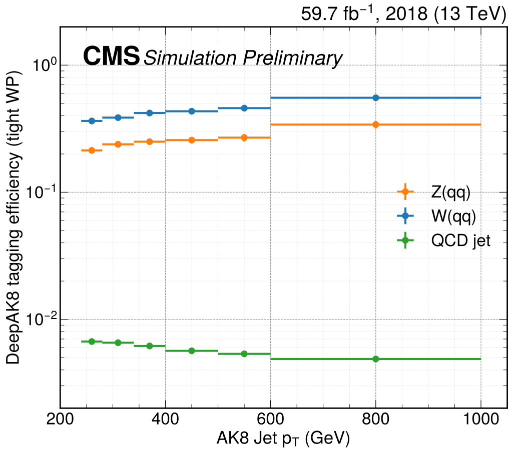
loose WP





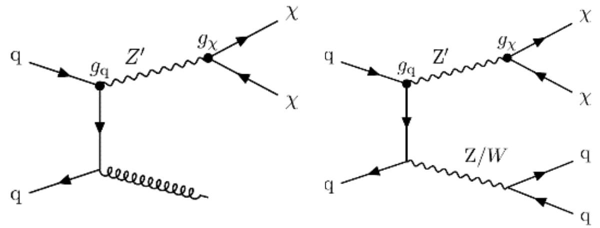
tight WP

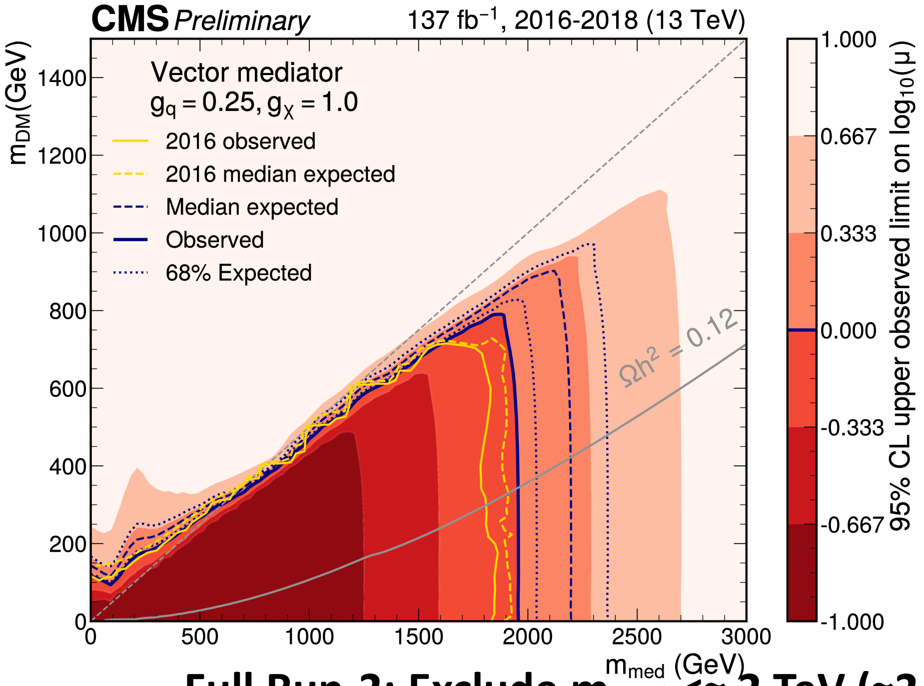


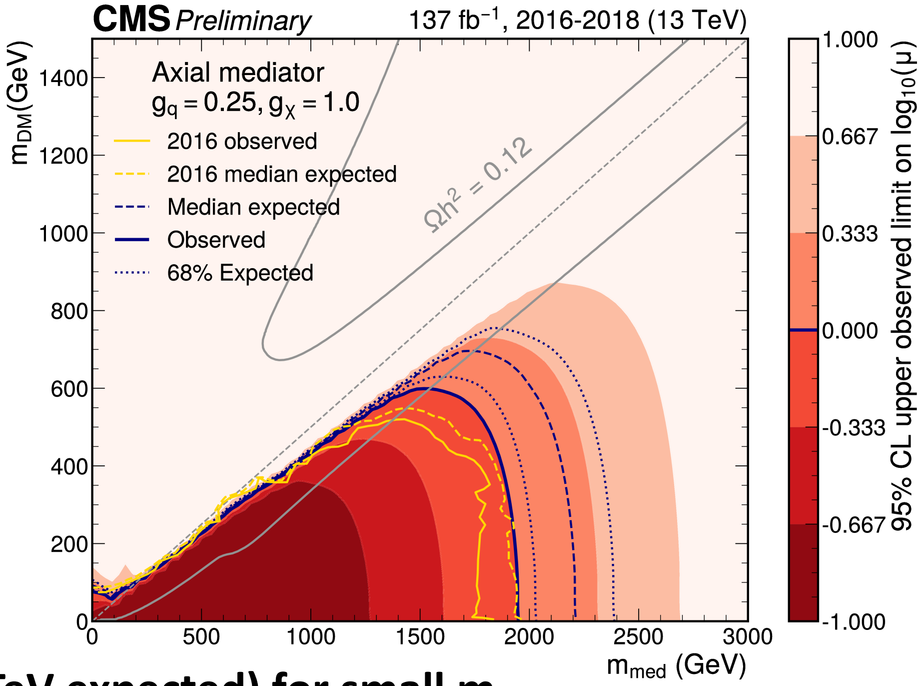


Model interpretation

Simplified DM model: Spin-1 mediator



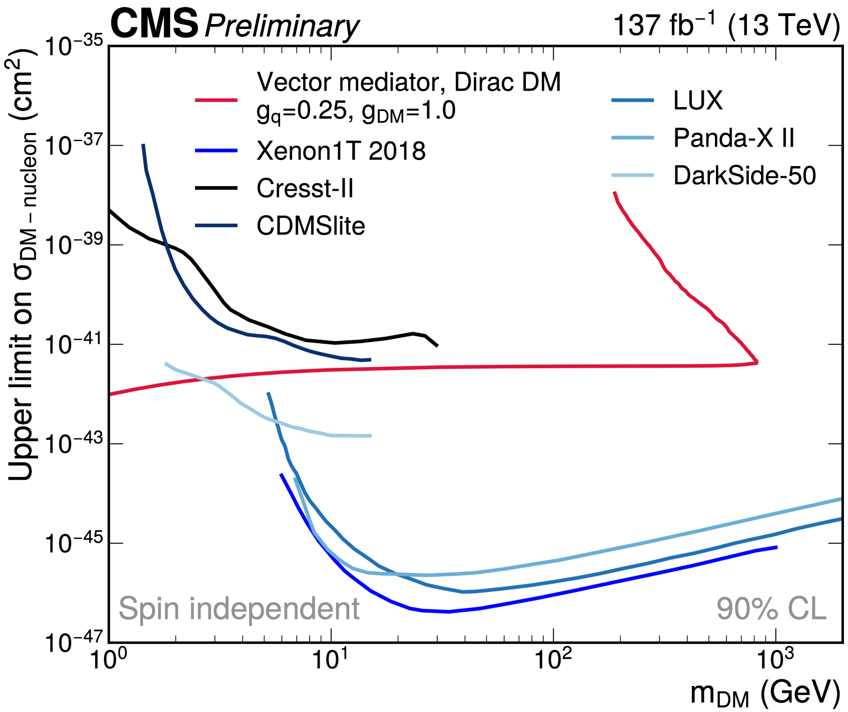


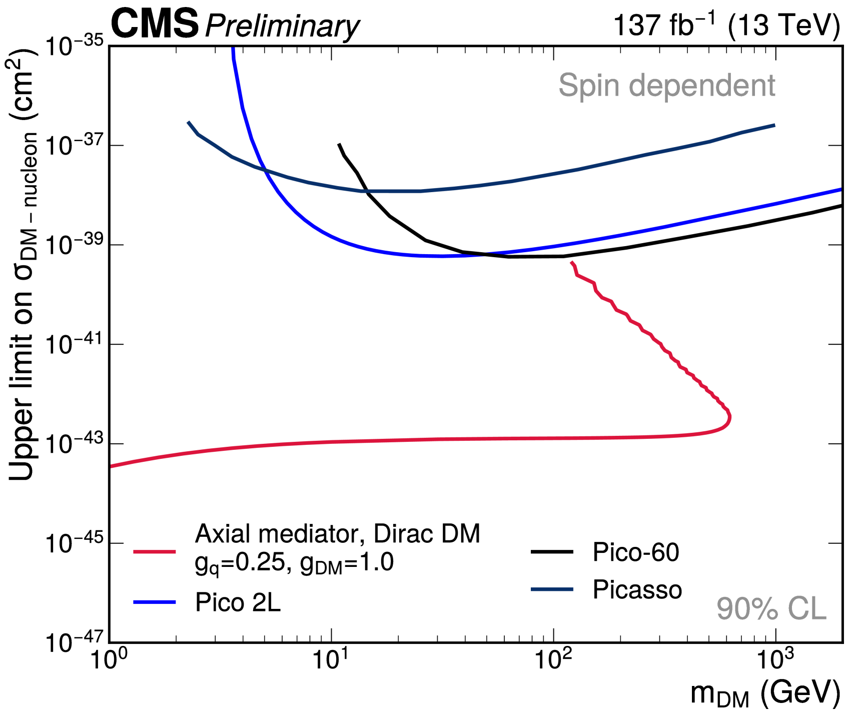


Full Run-2: Exclude m_{med} <≈ 2 TeV (≈2.2 TeV expected) for small m_{DM}

improvement relative to 2016 by ≈ 200 GeV in m_{med} (≈ 300 GeV expected)

Comparison of simplified model constrains to direct detection experiments



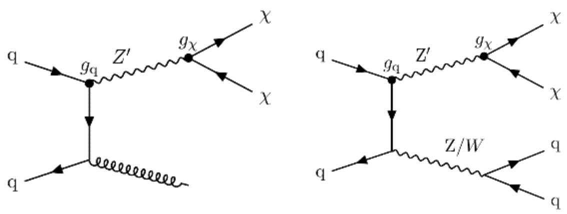


Point-to-point conversion from $m_{\text{med}} - m_{\text{DM}}$ countour to $\sigma_{\text{DM-nucleon}} - m_{\text{DM}}$ plane

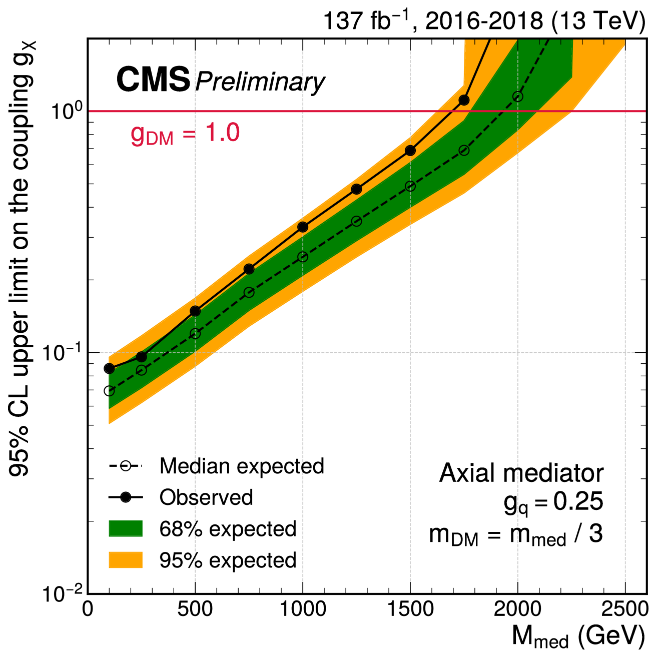
Show stronger limit at small m_{DM} for $\sigma_{\text{spin independent}}$ up to $m_{\text{DM}} = 1\text{TeV}$ for $\sigma_{\text{spin dependent}}$

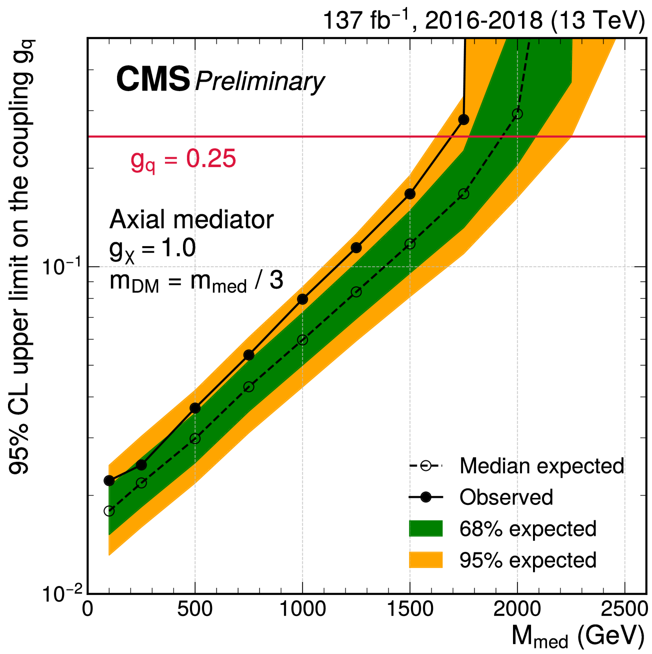
Note that the **red lines** are subject to specific choice of couplings

Simplified DM model: Spin-1 mediator coupling limit



1D scan of mediator mass with $m_{DM} = \frac{m_{med}}{3}$

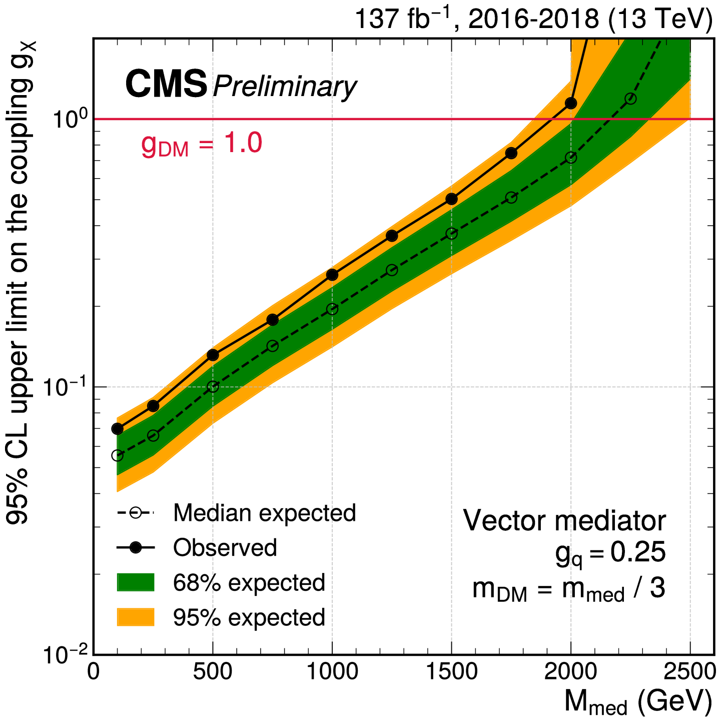


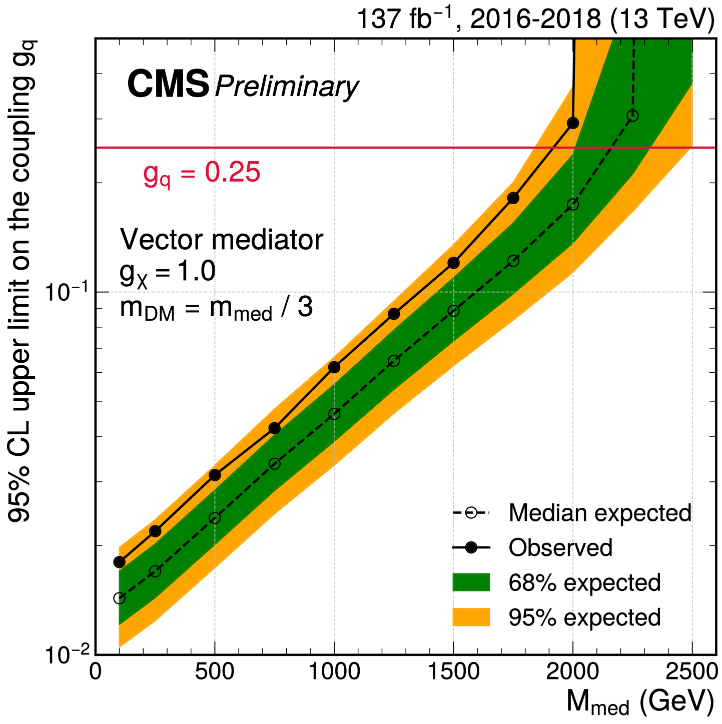


More than one additional order of magnitude in coupling limit approached compared to the nominal limit with 2D contour

Same plots with vector mediators in backup

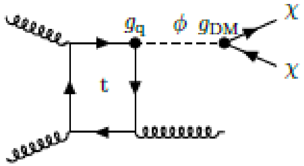
Simplified DM model: Spin-1 mediator coupling limit for vector mediators

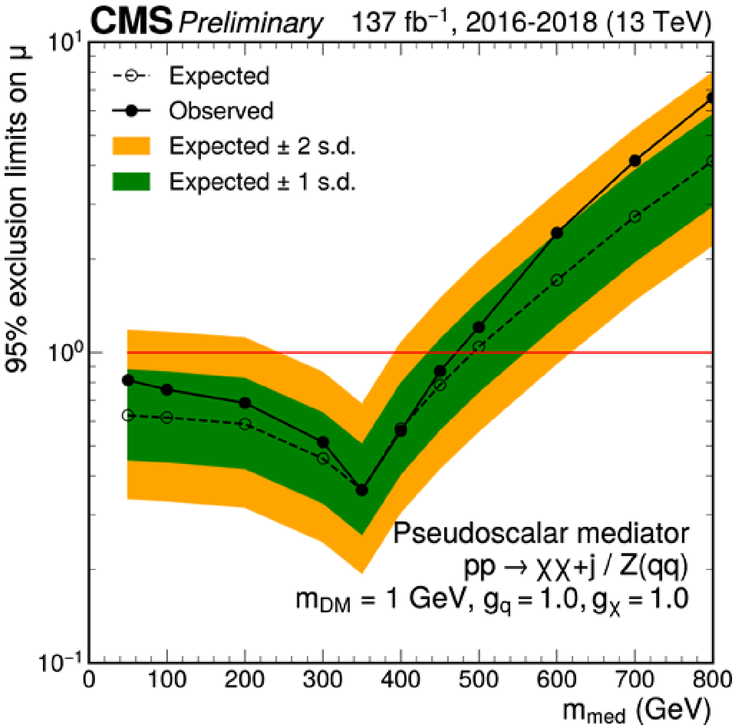


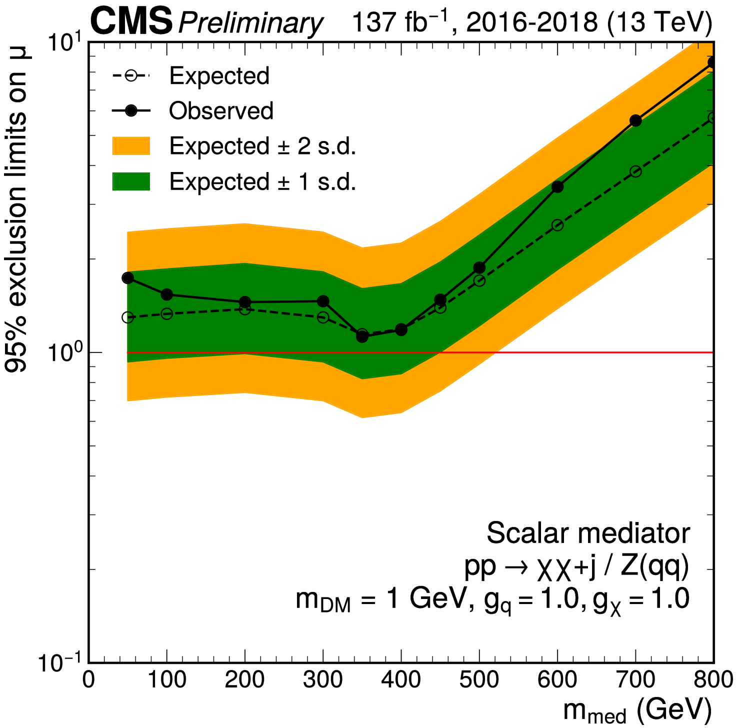


[same plots with axial vector mediators]

Simplified DM model: Spin-0 mediator







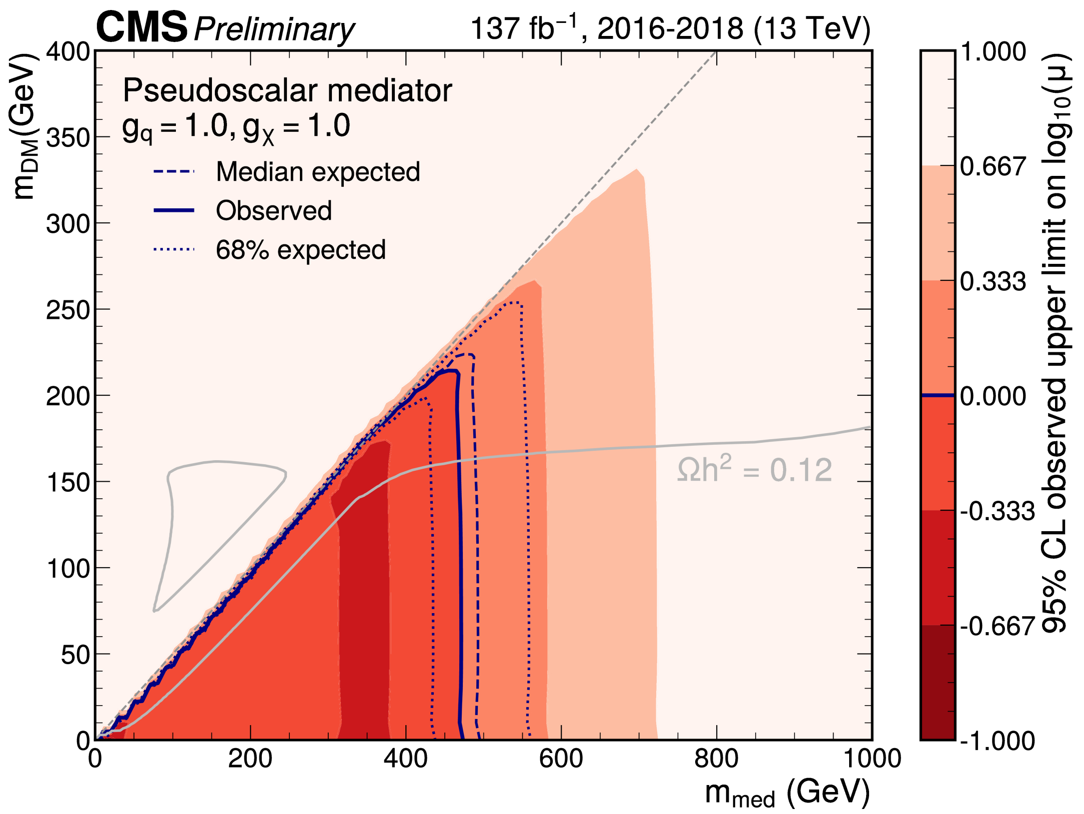
Exclude m_{med} < 480 GeV (460 exp)

(60 GeV improvement (20 exp))

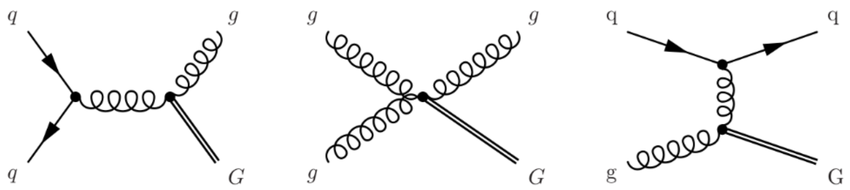
Exclusion around μ≈1.15-1.2 (1.0-1.1)

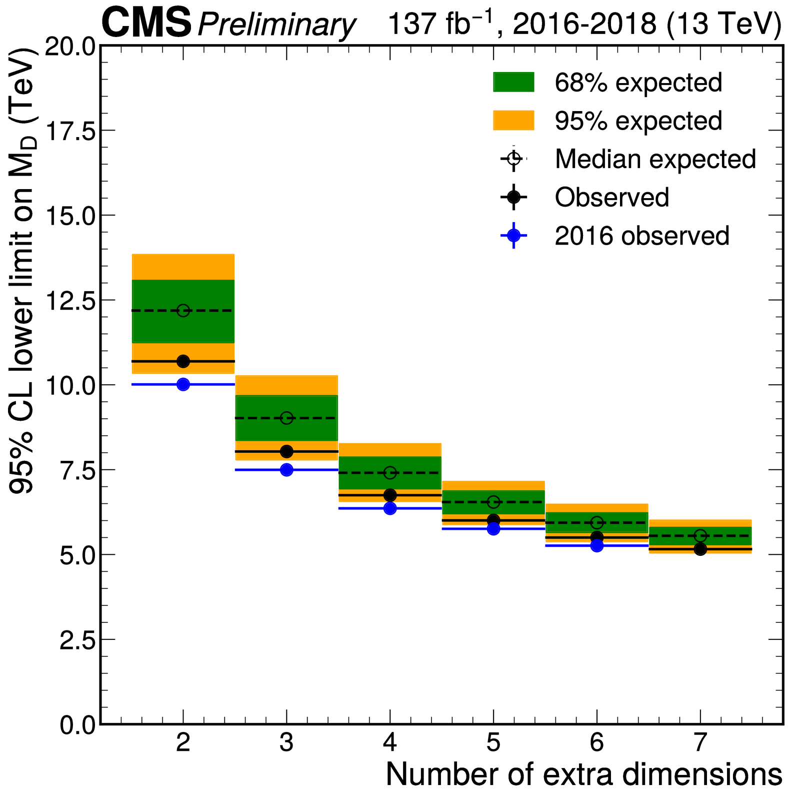
There is also 2D limit contour on the m_{med}-m_{DM} plane in backup

Two-dimensional exclusion in the simplified DM model with pseudoscalar mediator

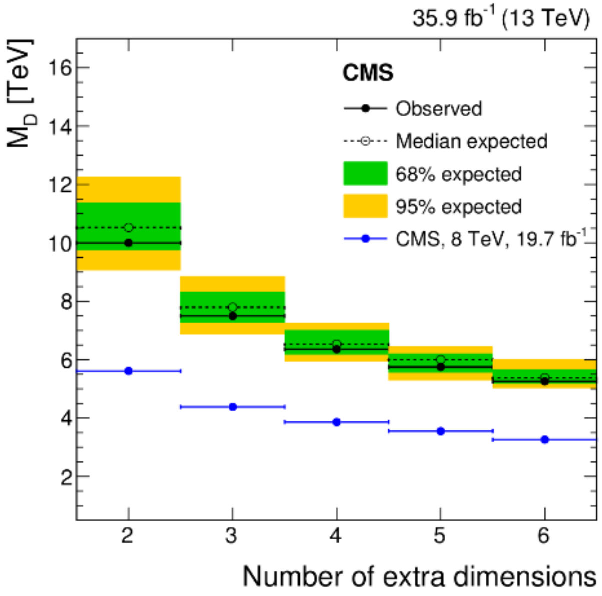


ADD extra dimensions





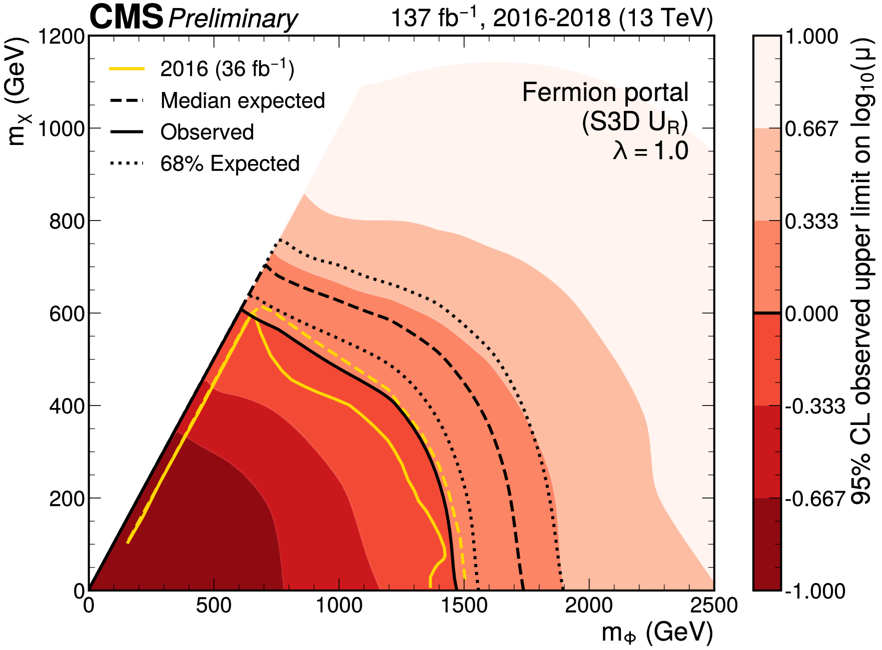
Exclude MD < 5.4 – 10.8 TeV
(6-12 expected)

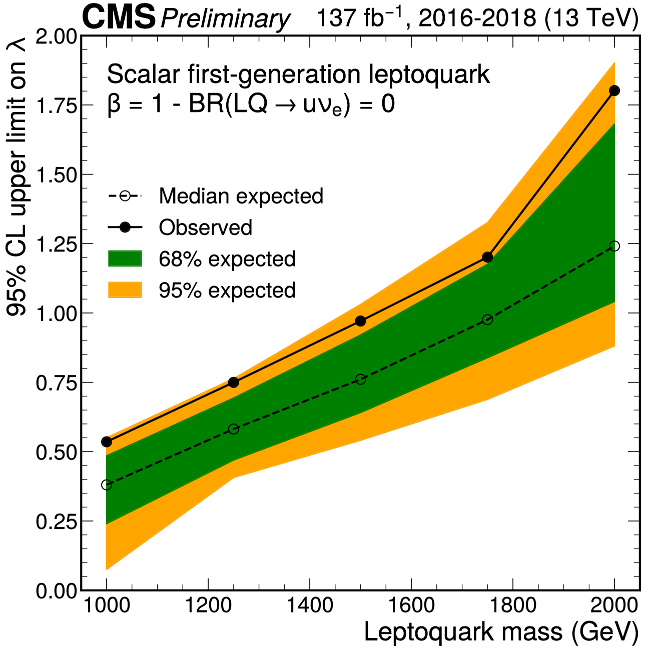


2016 result

Fermion portal DM and LQ(qv)

Both cases: Single, pair and t channel production





Max exclusion around 1.5 TeV for m_Φ

New interpretation, not done in '16

low MLQ: λ → 0, pair prod alone is excluded

higher MLQ: single prod. dominates, exclude λ=1

Higgs invisible model (fine-binned information)

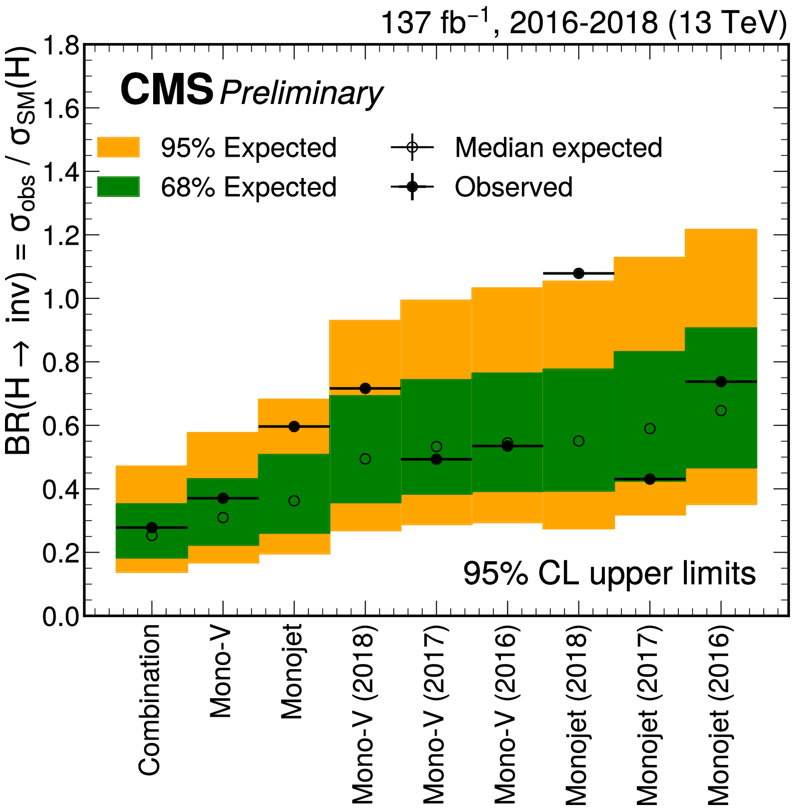


Table of exclusion limits in ADD model

d	Lower limit on M_D	
	Expected	Observed
2	12.2	10.7
3	9.0	8.0
4	7.4	6.7
5	6.5	6.0
6	5.9	5.5
7	5.6	5.2