# Dark Matter Searches with the CMS Experiment

Guillelmo Gómez-Ceballos
(on behalf of the CMS Collaboration)

Massachusetts Institute of Technology

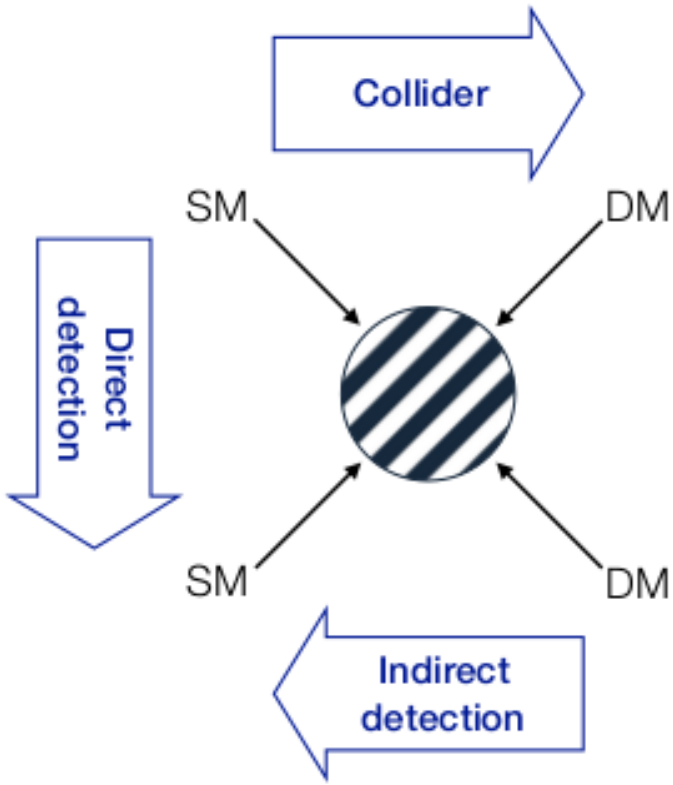
June 2018 Guadeloupe

# Probing Dark Matter (DM)

Underlying assumption: DM has also non-gravitational interactions with the Standard Model particles (SM)

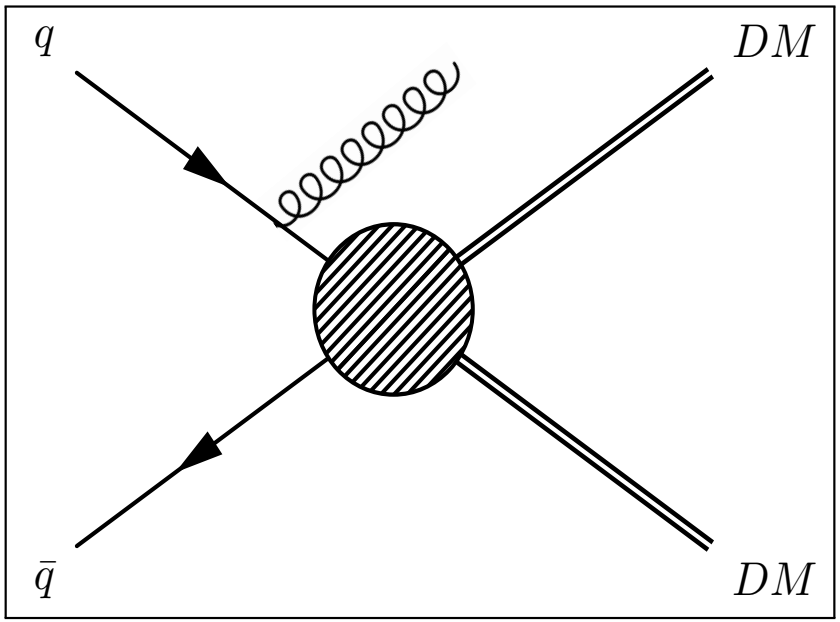
- *Direct detection*: scattering of DM particles on nuclei
- *Indirect detection*: annihilation products out of WIMP collisions
- *Collider search*: produce WIMPs through collision of SM particles

DM is assumed to be a *weakly interacting massive particle* (WIMP)

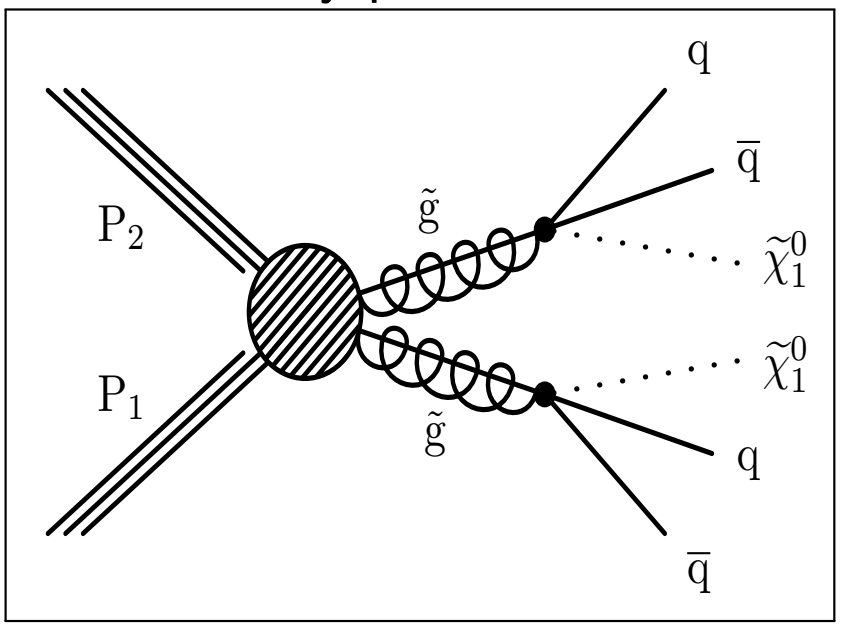


# DM Production at Colliders

Direct



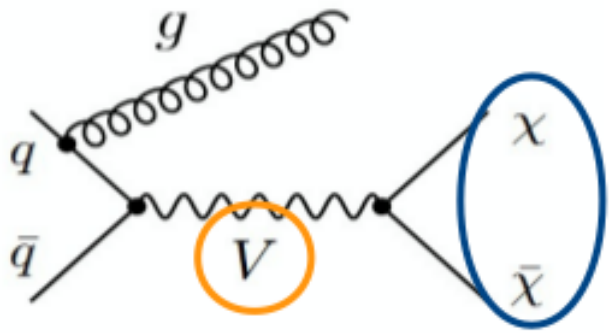

As decay product




- This talk will focus on "direct" production, not by-product of other searches
- A large number of SUSY searches can be re-interpreted as a DM search

# Simplified DM Models

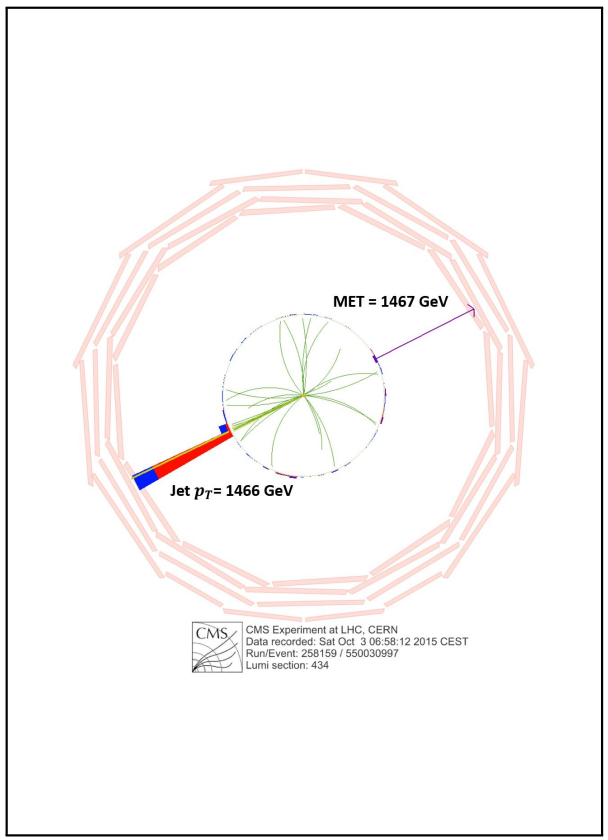
- idea:
  - restrict to relevant aspects aiming at maximal experimental coverage
- ingredients beyond SM:
  - mediator
  - DM particle
- free parameters:
  - masses, spins, coupling structure and strength
- recasting results in full models:
  - caveats may apply
  - parameter scans manageable



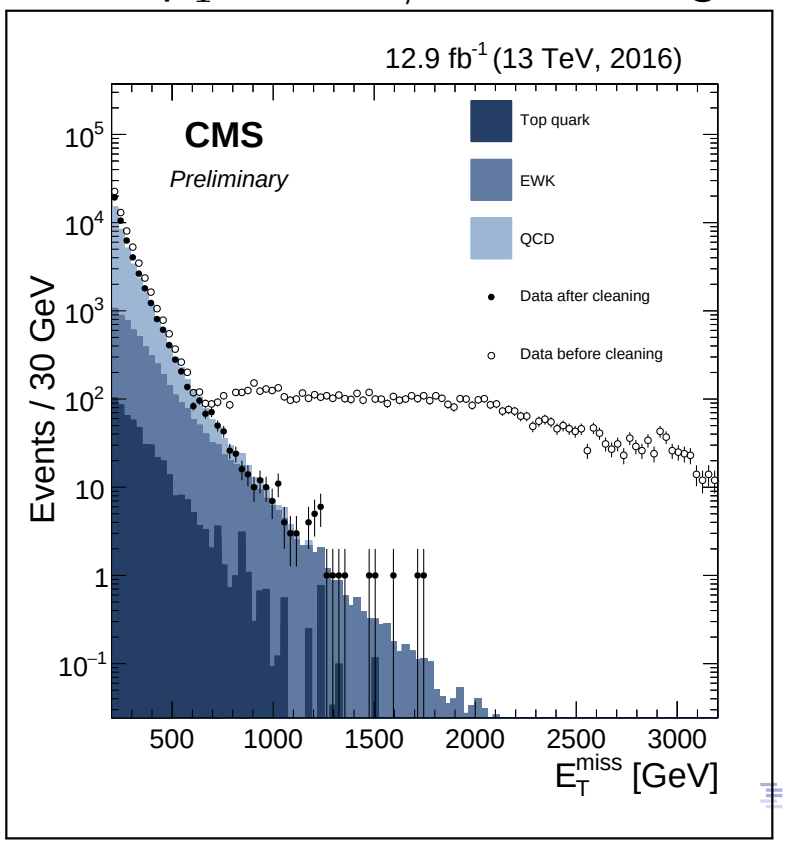
# Missing Transverse Energy ($p_{\mathrm{T}}^{\mathrm{miss}}$): The Name of the Game

- Most analyses rely on large $p_{\mathrm{T}}^{\mathrm{miss}}$ balancing against "visible" (X) objects (jets, boosted-jets, b-jets, photons, charged leptons)
  - $\Delta\phi_{p_{\mathrm{T}}^{\mathrm{miss}},X} \sim \pi$
  - $p_{\mathrm{T}}^{\mathrm{miss}} \sim p_{\mathrm{T}}^{X}$
- Understanding $p_{\mathrm{T}}^{\mathrm{miss}}$ is a critical component

Mono-jet candidate

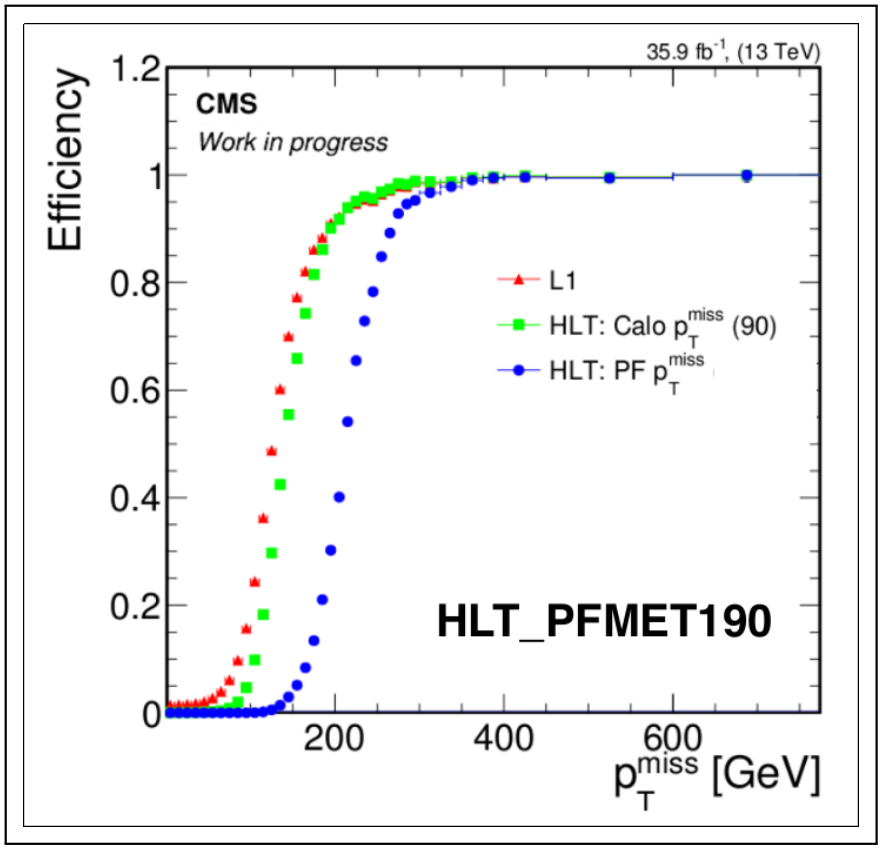



$p_{\mathrm{T}}^{\mathrm{miss}}$ before/after cleaning



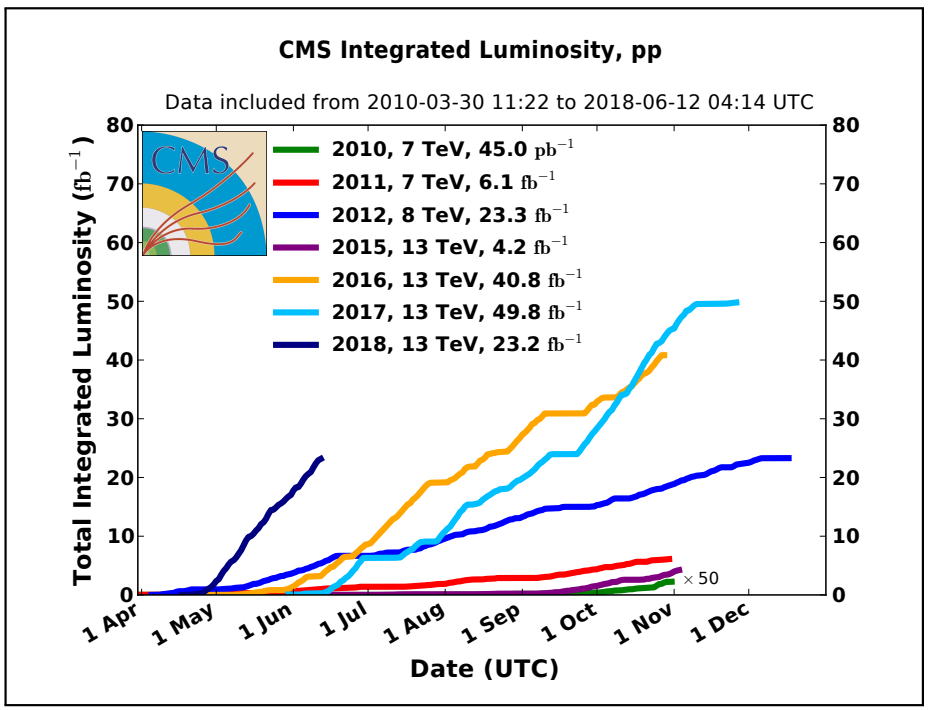
# How Are Interesting Events Selected?: Triggers

- Most multijet analyses rely on $p_{\mathrm{T}}^{\mathrm{miss}}$ triggers
- Triggers designed in similar way as offline with more basic/faster algorithms
- Efficiency turn-on reaches $\sim$100% at $p_{\mathrm{T}}^{\mathrm{miss}} \sim 250$ GeV
- Reconstruction differences in online/offline observables lead to broad turn-on curves
- Online thresholds are dictated by the rate of the trigger

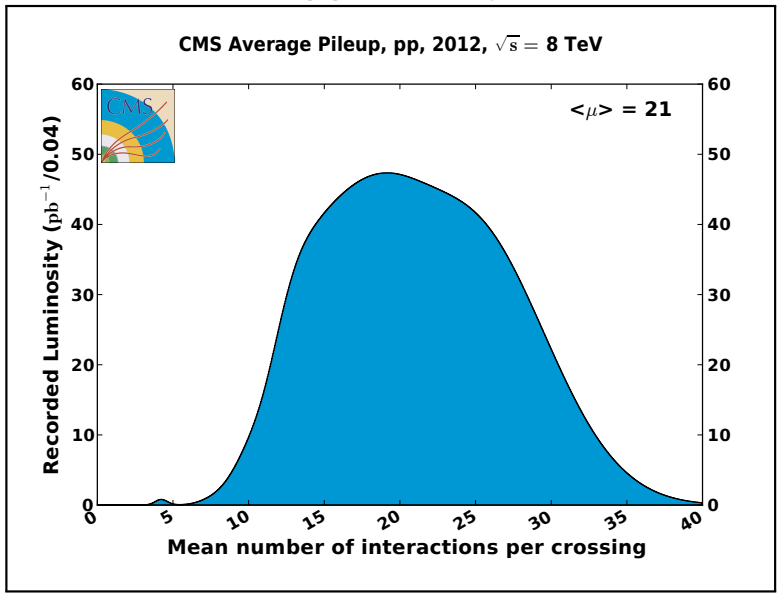


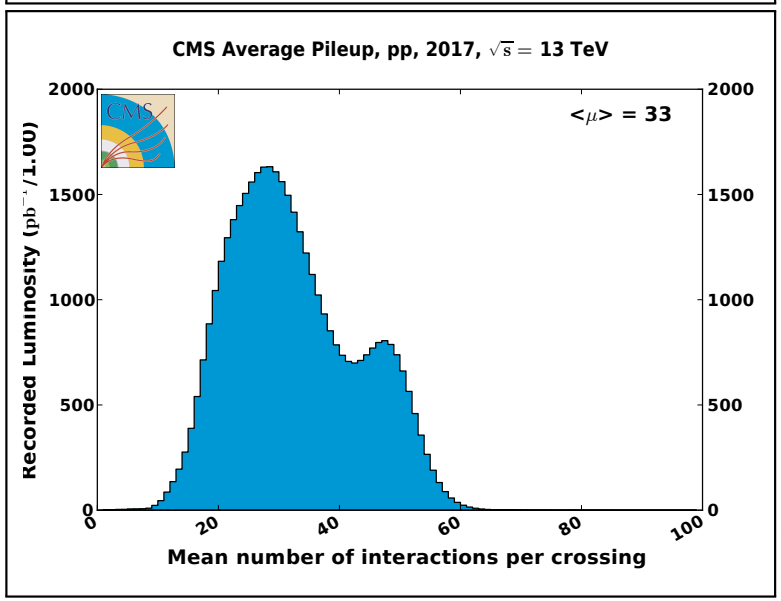
# Taking (Good) Data at $\sqrt{s} = 13$ TeV

- More than $20\text{fb}^{-1}$ of collected data in 2018
- More than $100\text{fb}^{-1}$ of collected data at $\sqrt{s} = 13$ TeV




- Larger datasets, but with larger pileup
- $p_{\text{T}}^{\text{miss}}$ and triggers very sensitive to this



# Analyses

Goal is to search for DM in all possible/feasible final states

- $p_{\mathrm{T}}^{\mathrm{miss}}$+X
  - mono-X
    - Mono-jet: one or more jets
    - Mono-$\mathrm{V}(qq)$: a single boosted jet compatible with an hadronic $\mathrm{W}/\mathrm{Z}$ boson decay
    - Mono-photon: a single energetic and isolated photon
    - Mono-$\mathrm{Z}(\ell\ell)$: a single $\mathrm{Z} \to \ell\ell$ boson decay
    - Mono-top: a single boosted top
    - VBF: a pair of jets compatible with Vector Boson Fusion production, mostly on $\mathrm{H} \to \mathrm{invisible}$ models
    - Mono-H: a SM Higgs boson decaying to $b\bar{b}$, $\gamma\gamma$, $\tau\tau$, WW...
  - DM+HF
    - $\mathrm{t\bar{t}}$: a top quark pair in all possible decaying final states
    - $b\bar{b}$: a b quark pair
- Di-jet
  - $\chi \to jj$ (bump hunting or angular analyses)
- Multijet + $p_{\mathrm{T}}^{\mathrm{miss}}$ SUSY reinterpretations

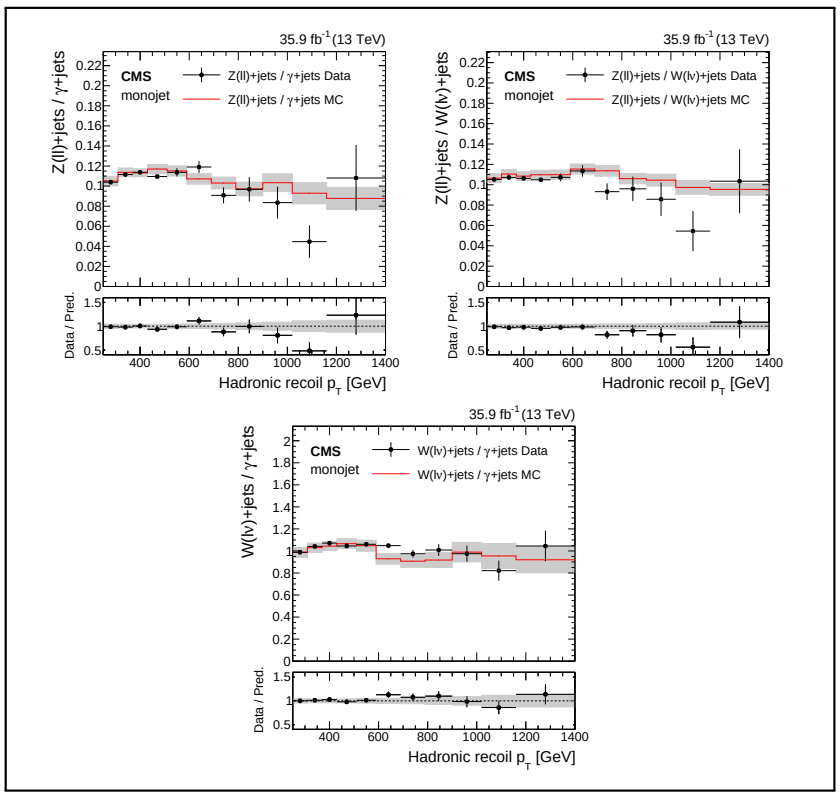
This talk focus on "mono-X" final states, see Tommaso's talk for DM+HF and di-jet related analyses

# Background Estimation (I)

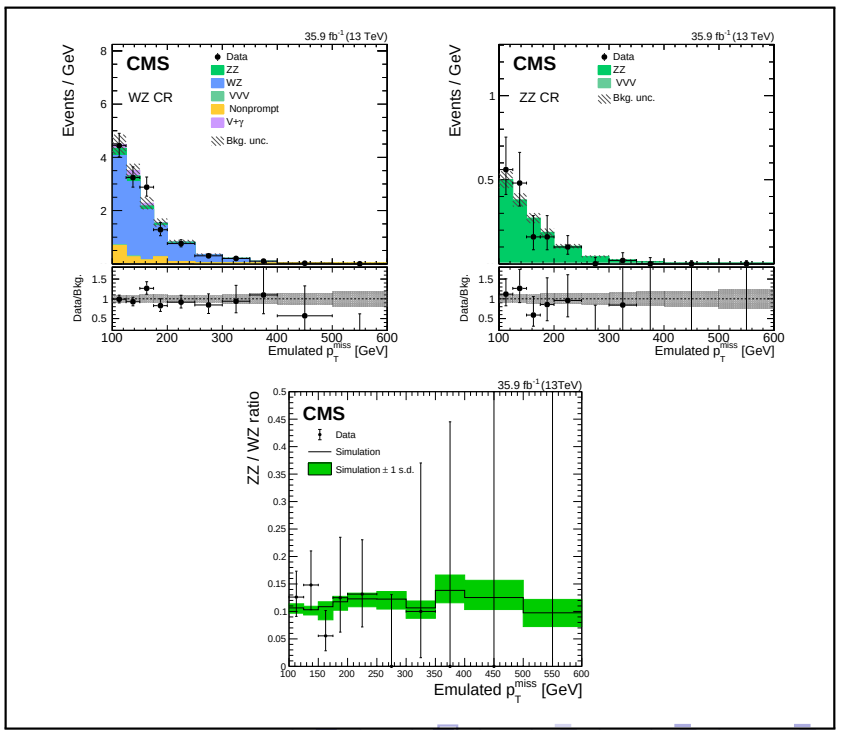
- Main backgrounds in fully hadronic modes come from $\mathrm{Z}(\nu\nu)$+jets, $\mathrm{W}(\rightarrow \ell\nu)$+jets, and $\mathrm{t\bar{t}}$+jets production, where possible leptons in the final state are not selected (either outside fiducial region or failure in the identification)
- Can not rely on purely simulated driven methods to their estimation
- Main estimation method uses events with identified leptons, and extrapolate to the zero identified leptons sample
  - $\mathrm{Z}(\rightarrow \ell\ell) \Rightarrow \mathrm{Z}(\rightarrow \nu\nu)$ or $\mathrm{W}(\rightarrow \ell\nu) \Rightarrow \mathrm{W}(\rightarrow X\nu)$
- Use of links among $\mathrm{Z}$+jets, $\mathrm{W}$+jets, and $\gamma$+jets to further constrain backgrounds
  - critical input from theory community to rely on $\mathrm{Z}/\mathrm{W}/\gamma$ ratios
- Simultaneous fit of control and signal regions to extract results
- Same technique is applied in mono-photon (mono-$\mathrm{Z}$) to estimate $\mathrm{Z}\gamma/\mathrm{W}\gamma$ ($\mathrm{ZZ}/\mathrm{WZ}$) backgrounds

# Background Estimation (II)

- Comparison between data and simulation for the $\mathrm{Z}(\ell\ell)/\gamma$+jets, $\mathrm{Z}(\ell\ell)/\mathrm{W}(\ell\nu)$, and $\mathrm{W}(\ell\nu)/\gamma$+jets ratios as a function of the hadronic recoil in the mono-jet analysis



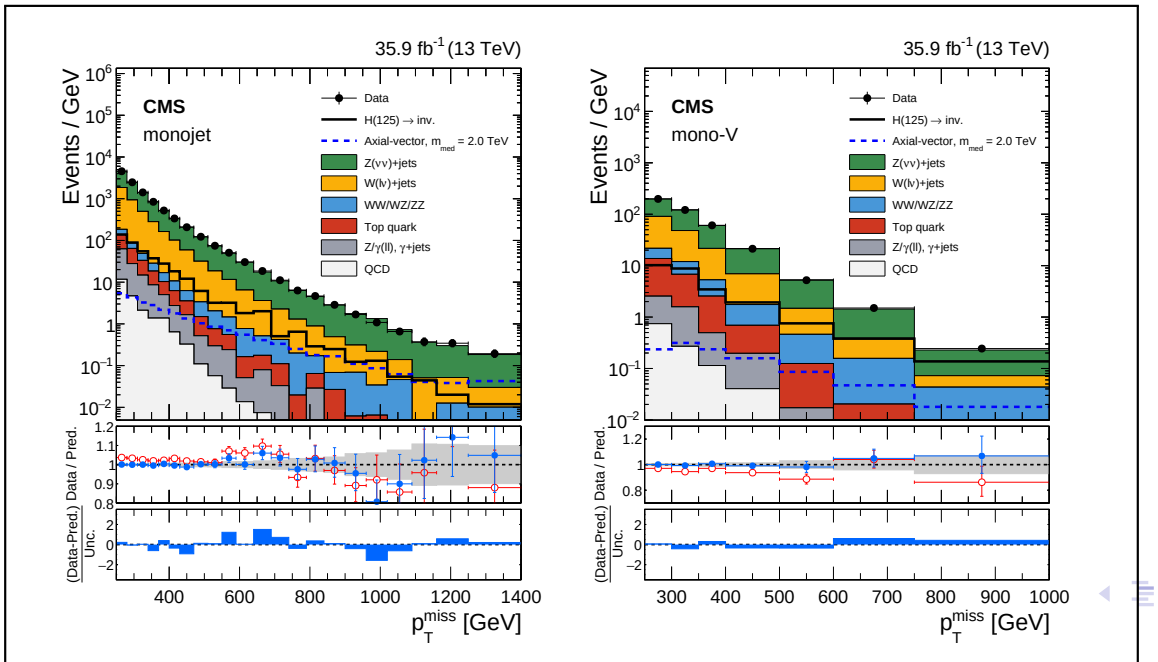

- Emulated $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution in data and simulation for the $\mathrm{WZ}(\rightarrow 3\ell\nu)$ and $\mathrm{ZZ} \rightarrow 4\ell$ control regions, and the ratio between both distributions in the mono-Z analysis



# Mono-jet/Mono-V($qq$) Analysis

- Either a hard ISR jet or a boosted-jet compatible with an hadronic W/Z boson decay recoiling against DM
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV, $p_{\mathrm{T}}^{j} > 100$ GeV
  - $\Delta\phi_{jet_{=1\ldots4},p_{\mathrm{T}}^{\mathrm{miss}}} > 0.5$
  - vetoing b-jets, charged leptons, and isolated photons in the signal region
- Preference to boosted category, both analyses non-overlapping by construction
- Major backgrounds are Z+jets (60%) and W+jets (30%)

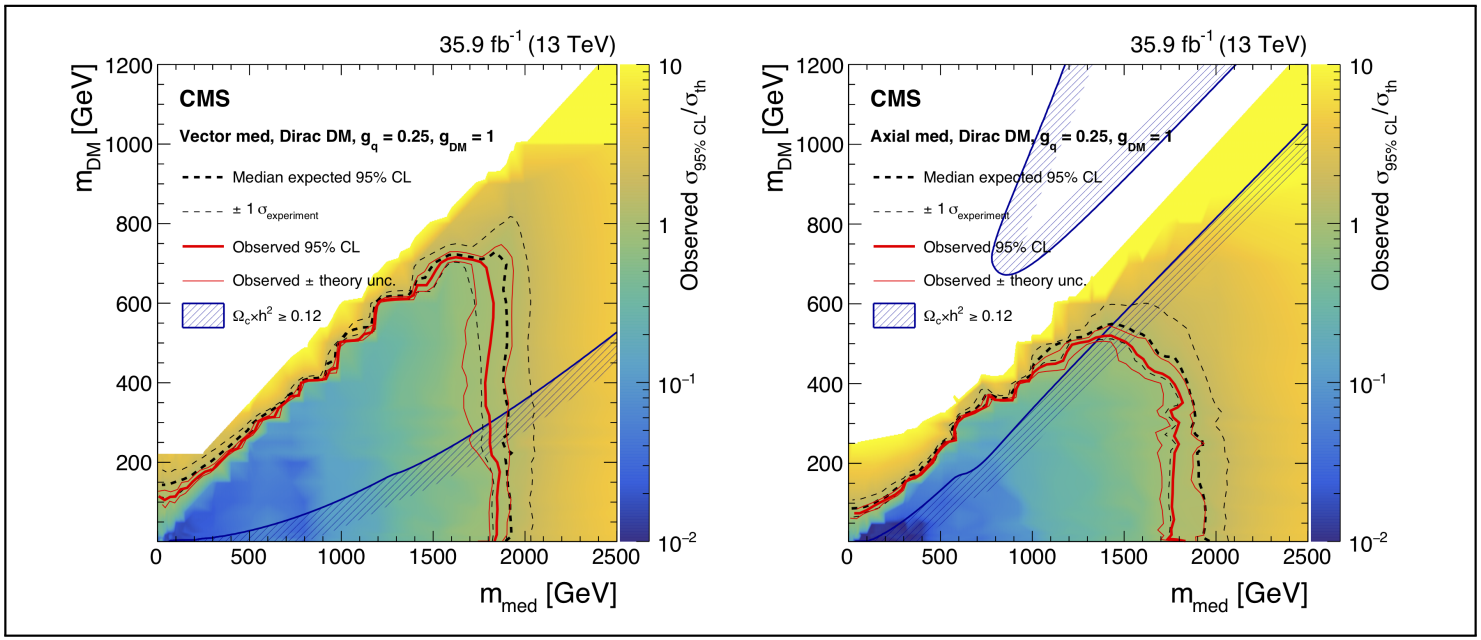
Mono-jet

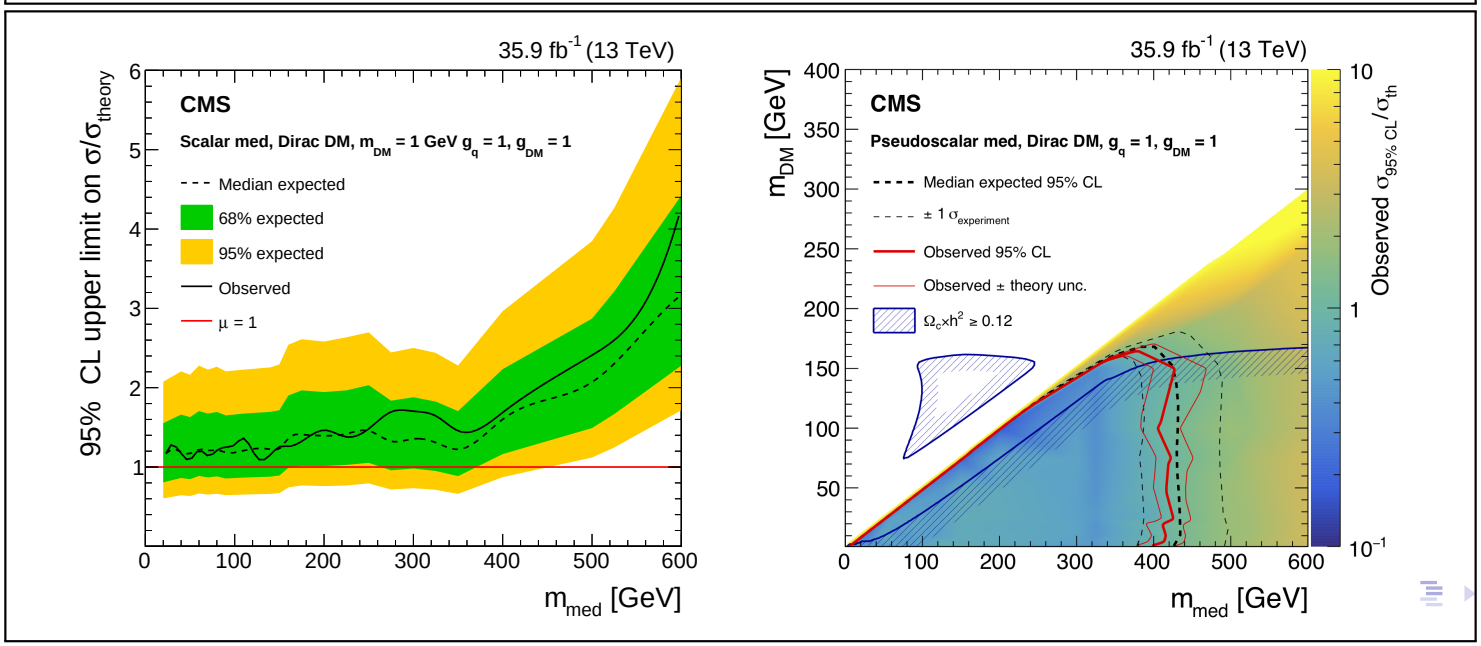



Mono-V($qq$)

# Mono-jet/Mono-V($qq$) Analysis: 95% CL Limits

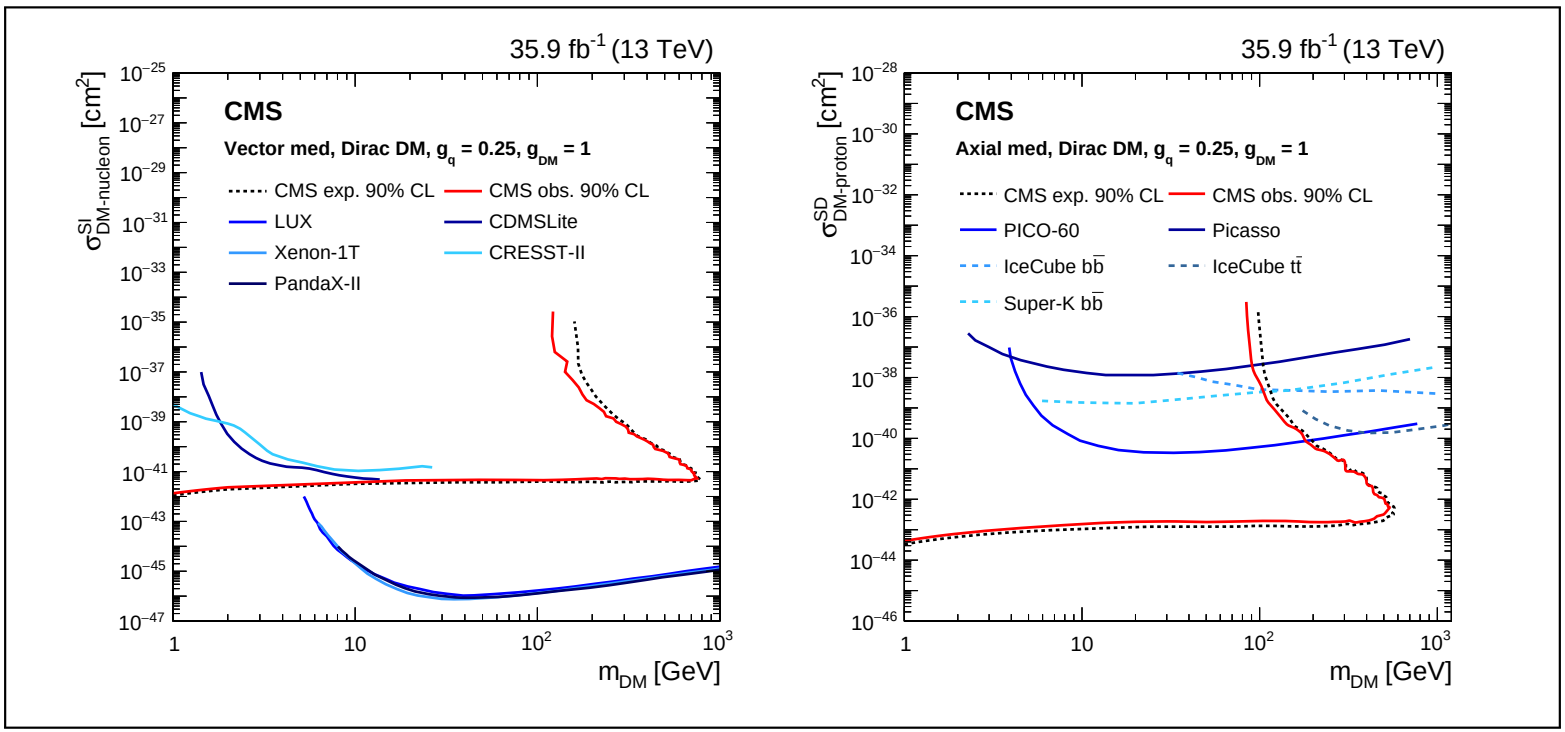
Limits for different mediator types and for different coupling strengths



# Mono-jet/Mono-V($qq$) Analysis: 90% CL Limits

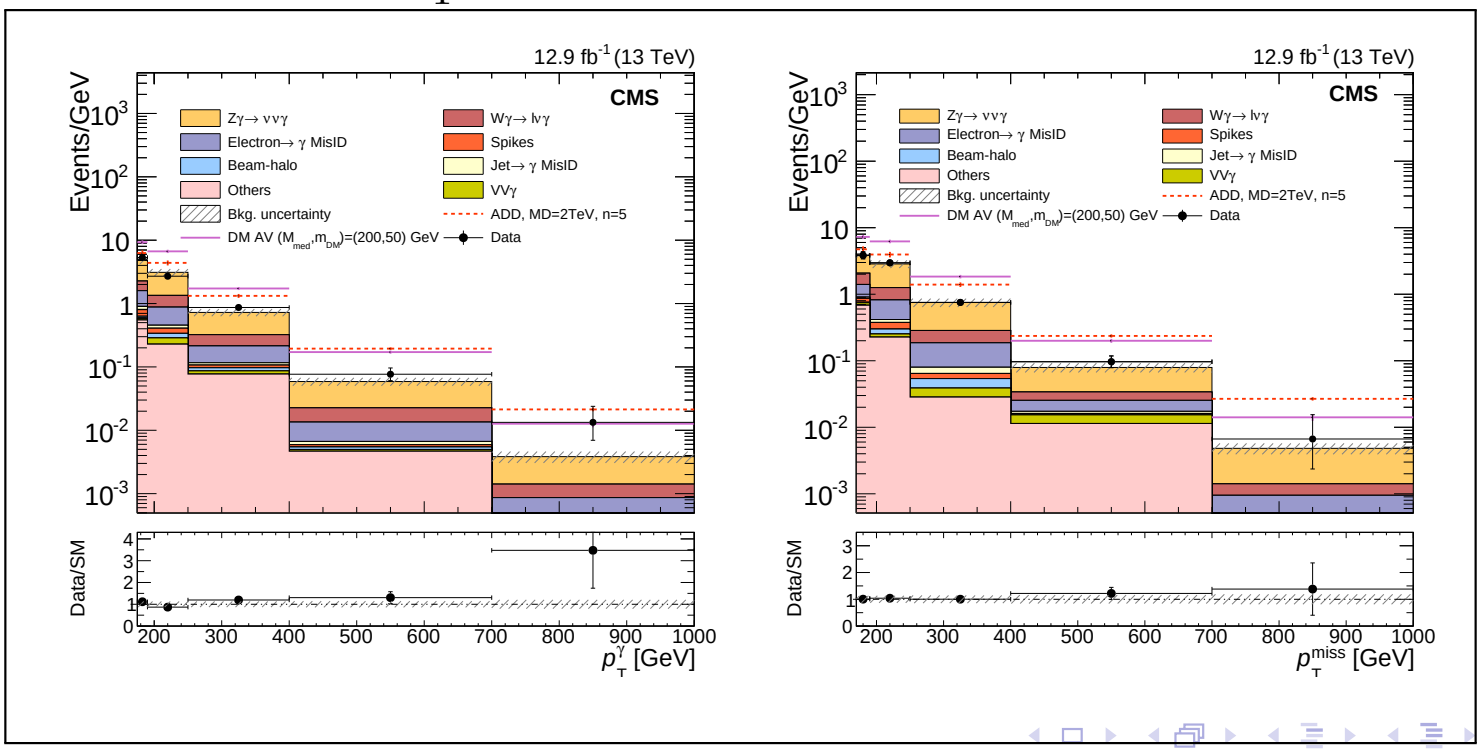
Exclusion limits at 90% CL in the $m_{DM}$ vs. SI/SD plane for vector (left) and axial-vector (right) mediator models



# Mono-photon Analysis

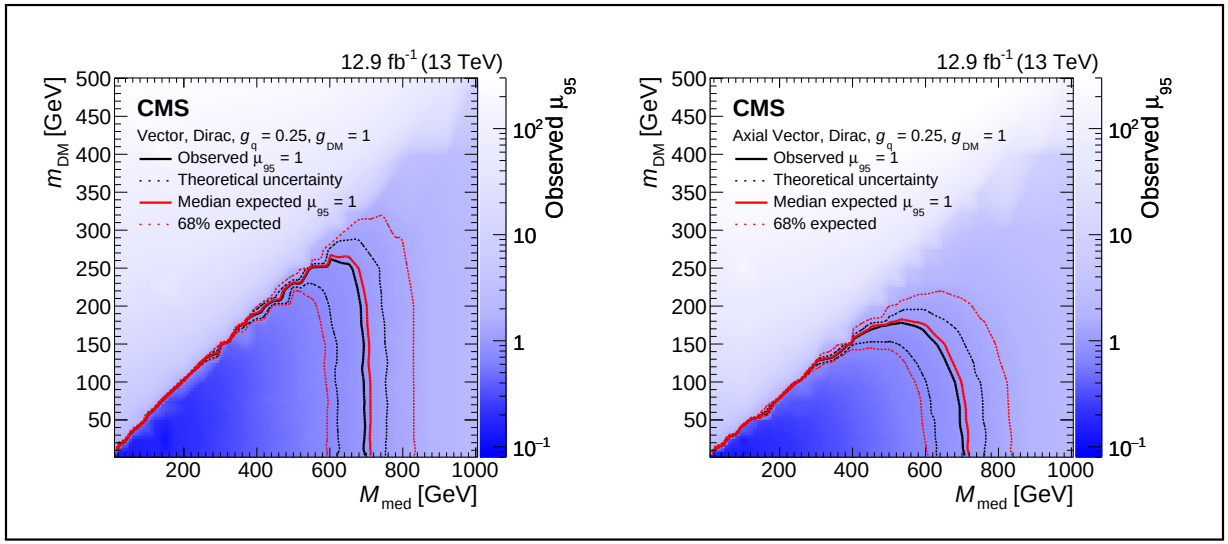
- Hard ISR photon recoiling against DM
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 170$ GeV, $p_{\mathrm{T}}^{j} > 175$ GeV
  - $\Delta\phi_{jet_{=1\ldots4},p_{\mathrm{T}}^{\mathrm{miss}}} > 0.5$
  - vetoing charged leptons in the signal region
- Major backgrounds are Z+jets (55%) and W+jets (25%)
- Understanding (subdominant) instrumental backgrounds is a very important point

$p_{\mathrm{T}}^{\gamma}$ $p_{\mathrm{T}}^{\mathrm{miss}}$

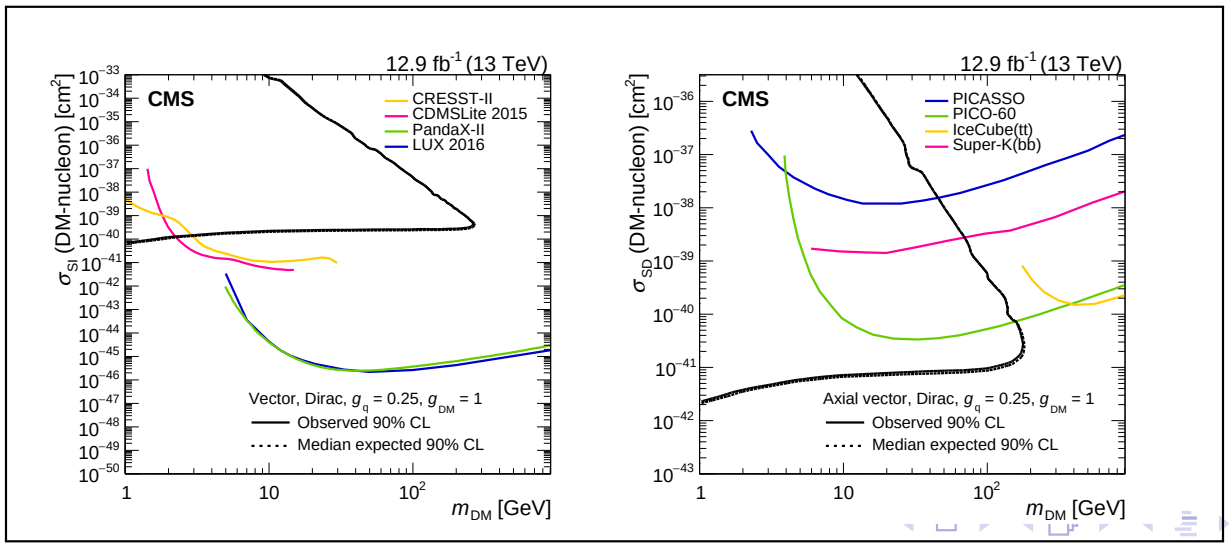


# Mono-photon Analysis: Limits

95% CL cross section upper limits to theoretical cross section for DM simplified models

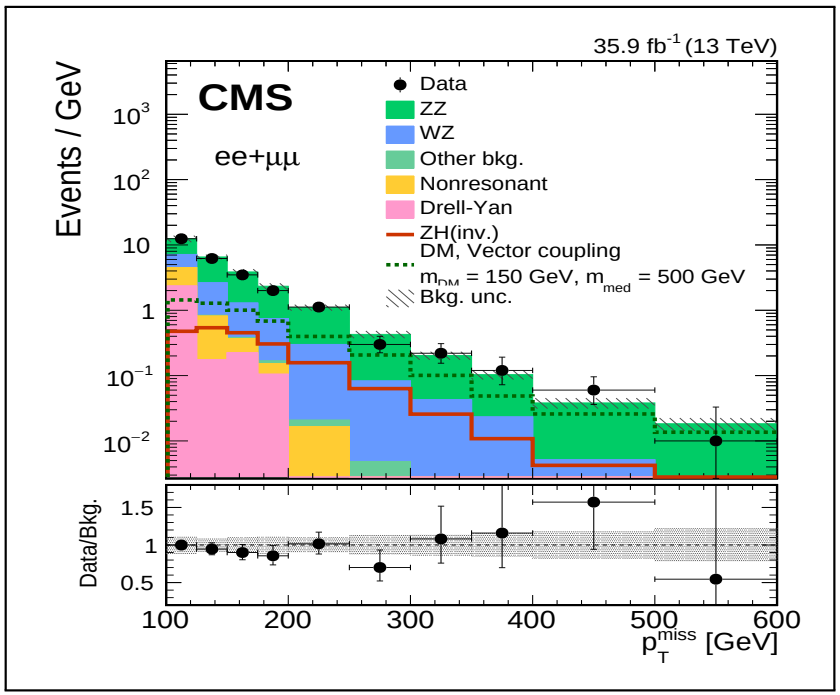


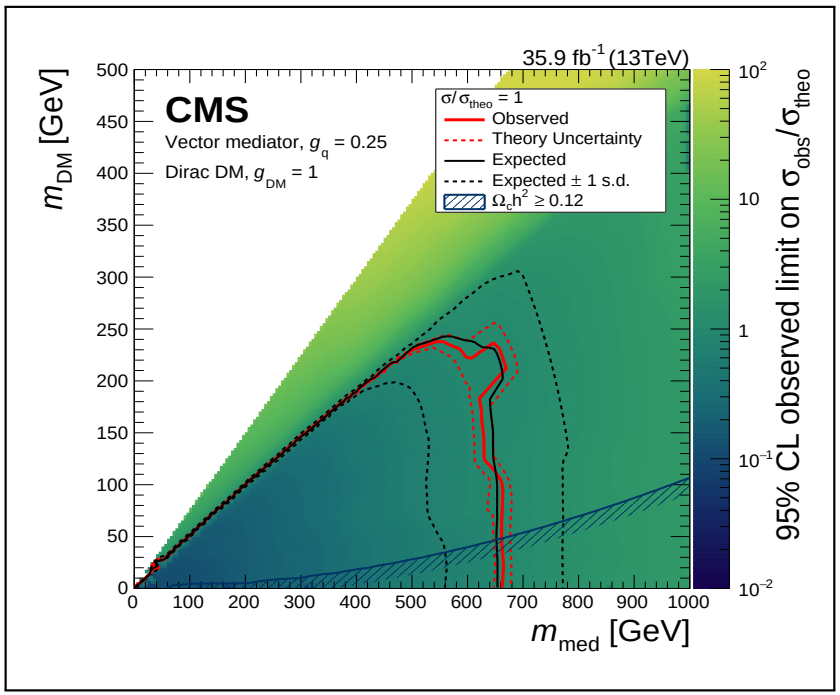

90% CL exclusion limits on the $\chi$-nucleon spin-dependent scattering cross sections



# Mono-Z($\to \ell\ell$) Analysis

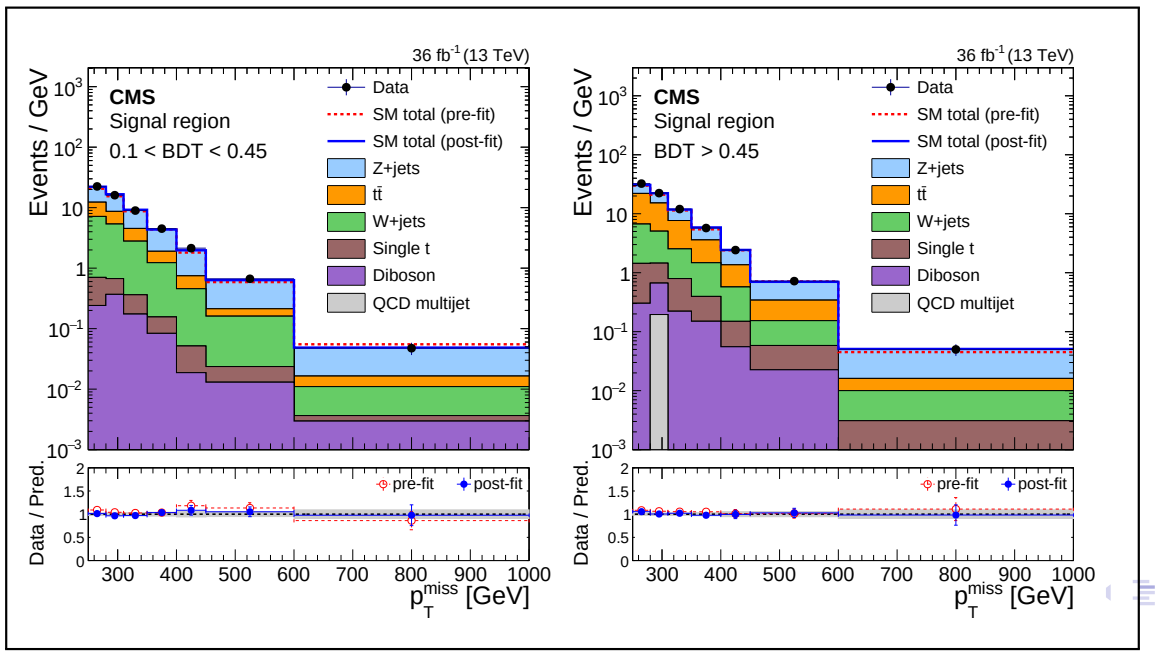
- DM recoiling against a Z $\to\to \ell\ell$ boson decay
  - The easiest channel to trigger due to the presence of leptons in the final state
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV, $p_{\mathrm{T}}^{\ell\ell} > 60$ GeV
  - $p_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}^{\ell\ell}$ consistent with each other
  - vetoing b-jets and additional charged leptons in the signal region
- Major backgrounds are ZZ (60%) and WZ (25%)
- ZZ, WZ, non-resonant, and Z+jets backgrounds estimated from data



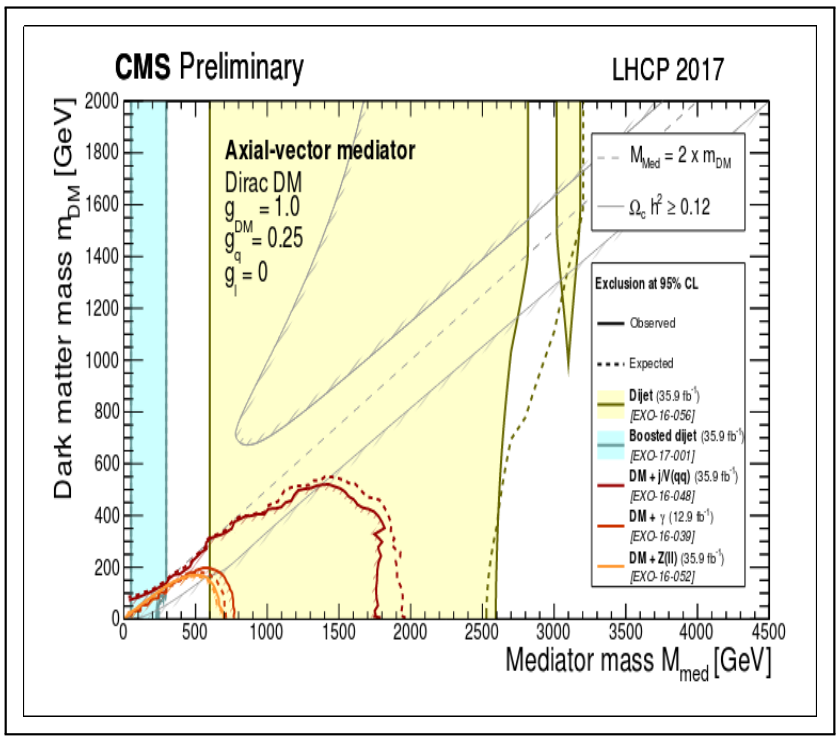
# Mono-Top Analysis

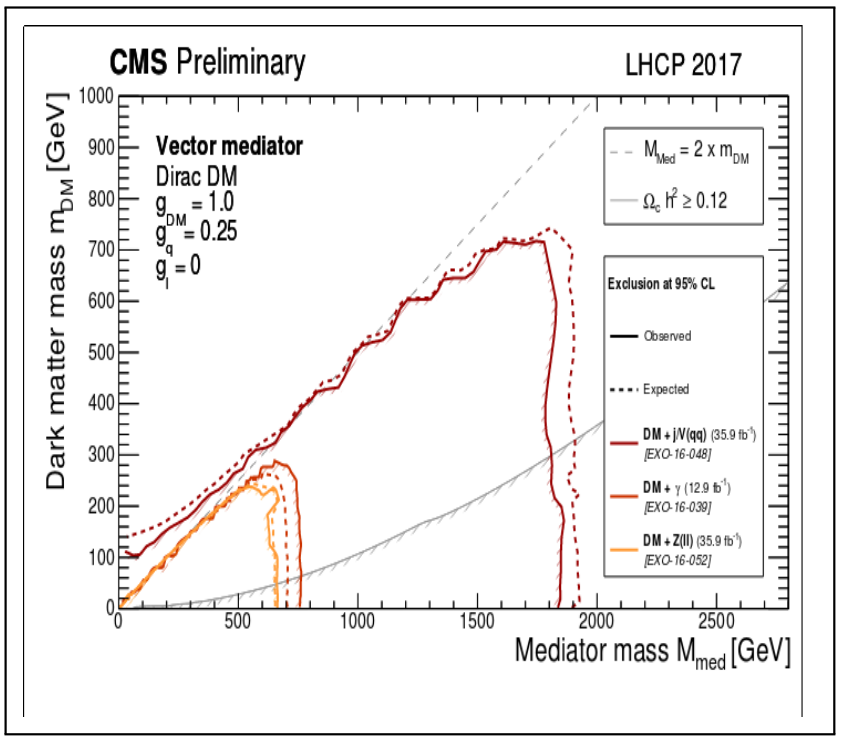
- DM recoiling against a boosted hadronically decaying top quark
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 250\ \mathrm{GeV}$, $p_{\mathrm{T}}^{j} > 250\ \mathrm{GeV}$
  - CA15 b-tagged jet with a mass compatible with a top quark decay
  - BDT to separate top and gluon/jets to split events in categories
  - using $p_{\mathrm{T}}^{\mathrm{miss}}$ as final discriminant variable
- $\mathrm{Z}$+jets, $\mathrm{W}$+jets, and $\mathrm{t\bar{t}}$ similarly important backgrounds
- No excess of events observed, 95% CL limits on a large variety of models considered



# Putting All Together (I)

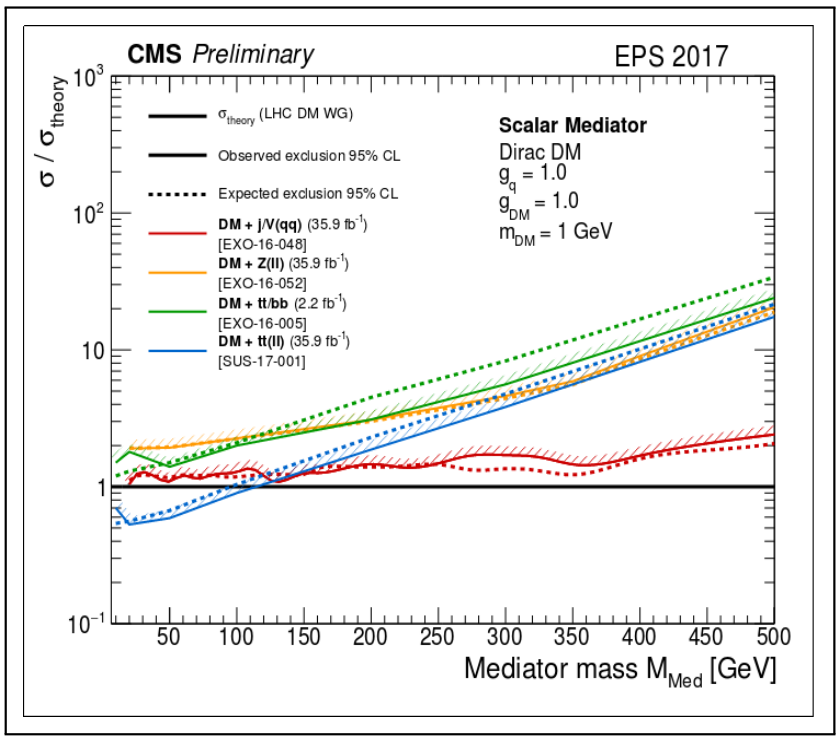
- Dijet searches (discussed by Tommaso) dominate under some assumptions
- Results updated rapidly due to the increase in the integrated luminosity

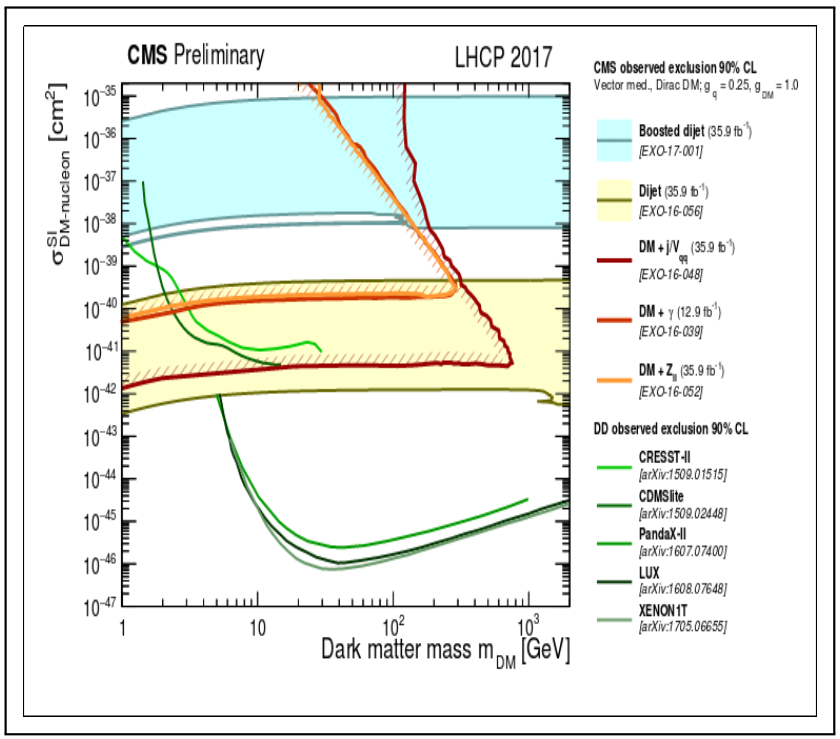


# Putting All Together (II)

- Heavy flavor searches (also discussed by Tommaso) allow for excluding scalar mediators
- Good complementarity between LHC and direct detection experiments



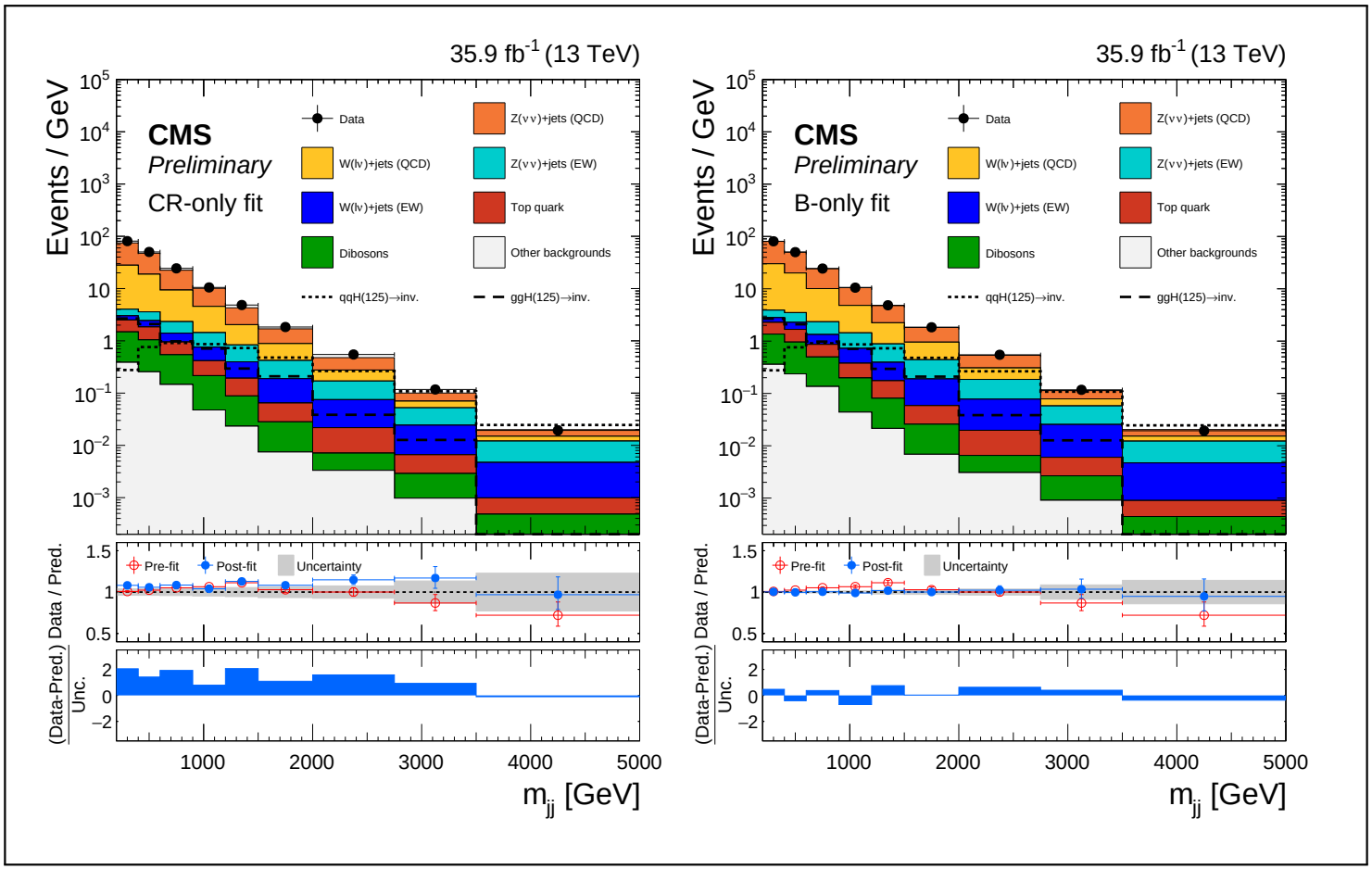



# Invisible Higgs Decays

- The most extensive set of rare decays searches by far
- It exists in the SM, but extremely rare: $BR(\mathrm{H} \to \mathrm{ZZ} \to 4\nu) \sim 0.1\%$
- Observation of a large rate would be a sign of BSM:
  - LSPs in SUSY (neutralinos, gravitinos)
  - Graviscalars (large extra-dimensions)
  - Dark Matter (DM) $\rightarrow$ limits competitive with other DM searches
- Several production modes can be studied:
  - $qq\mathrm{H}$ (VBF): two forward/backward jets with high $\Delta\eta_{jj}$ & $m_{jj}$
  - $\mathrm{Z}(\ell\ell/b\bar{b})\mathrm{H}$: two leptons/two b-jets compatible with a Z boson
  - $\mathrm{Z/W}(q\bar{q}')\mathrm{H}$: two jets compatible with a Z/W boson
  - $gg \to \mathrm{H} +$ jet: one high $p_{\mathrm{T}}$ jet
  - $\mathrm{t\bar{t}H}$: two top-quarks
- DM searches can directly be re-used for these studies

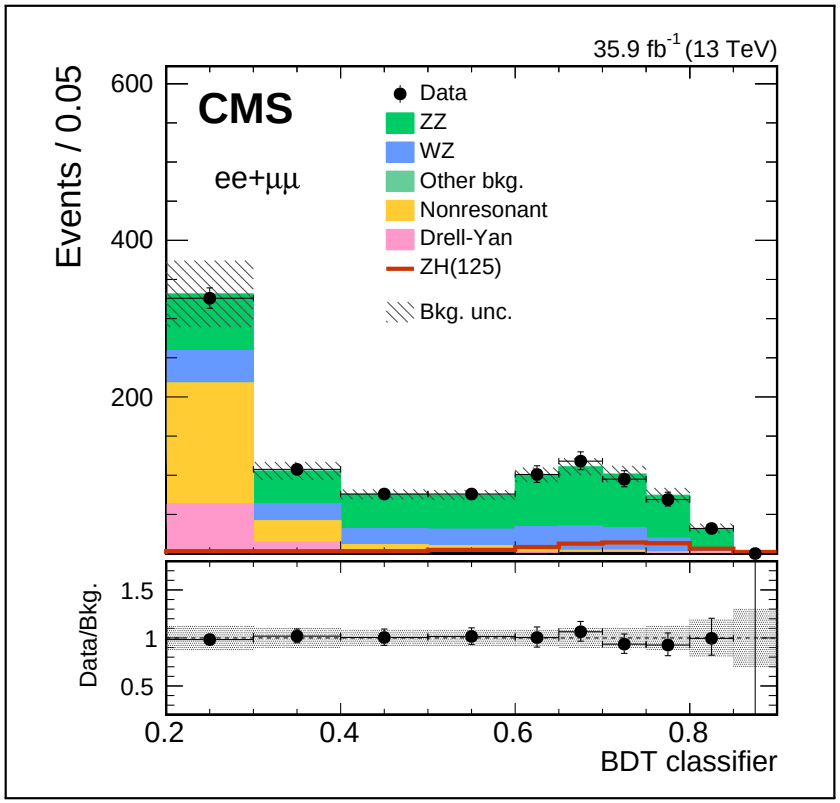
# VBF Searches

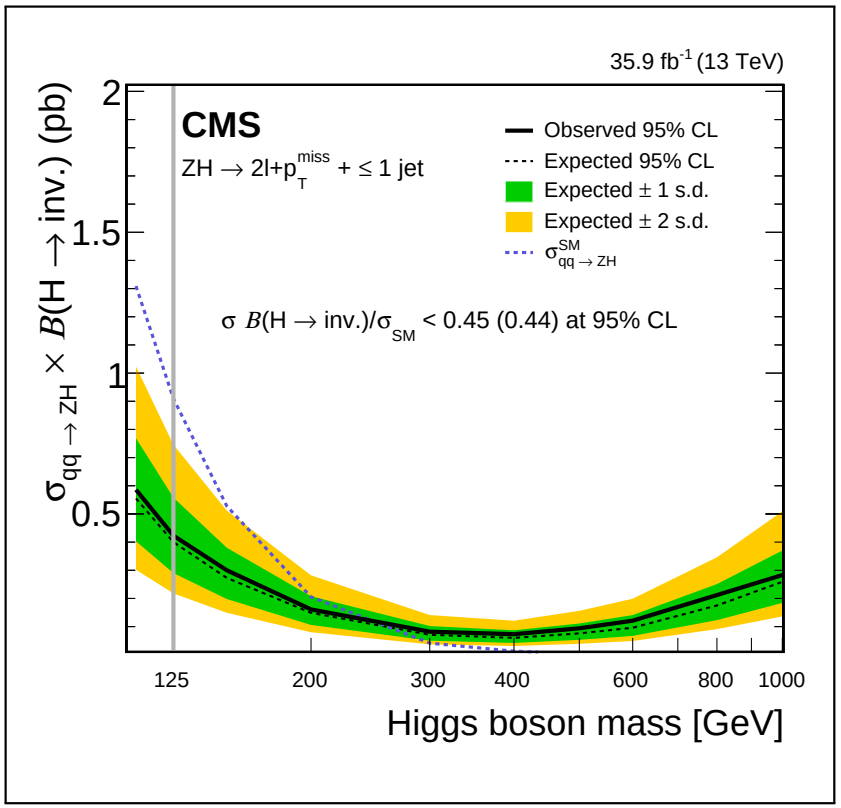
- Two forward/backward jets with high $\Delta\eta_{jj}$ & $m_{jj}$
- Most sensitive channel at this point
- Fitting for first time a distribution ($m_{jj}$) as a final discriminant variable, instead of a simple cut-and-count analysis



# Mono-Z($\to \ell\ell$) for Invisible Higgs Searches

- To further squeeze the sensitivity a BDT analysis is performed for this search
- Observed (expected) 95% CL limits for $BR(\mathrm{H} \to \mathrm{invisible})$ at $m_{\mathrm{H}} = 125\ \mathrm{GeV}$ assuming SM rates:
  - BDT approach: 0.40 (0.42)
  - $p_{\mathrm{T}}^{\mathrm{miss}}$ approach: 0.45 (0.44)

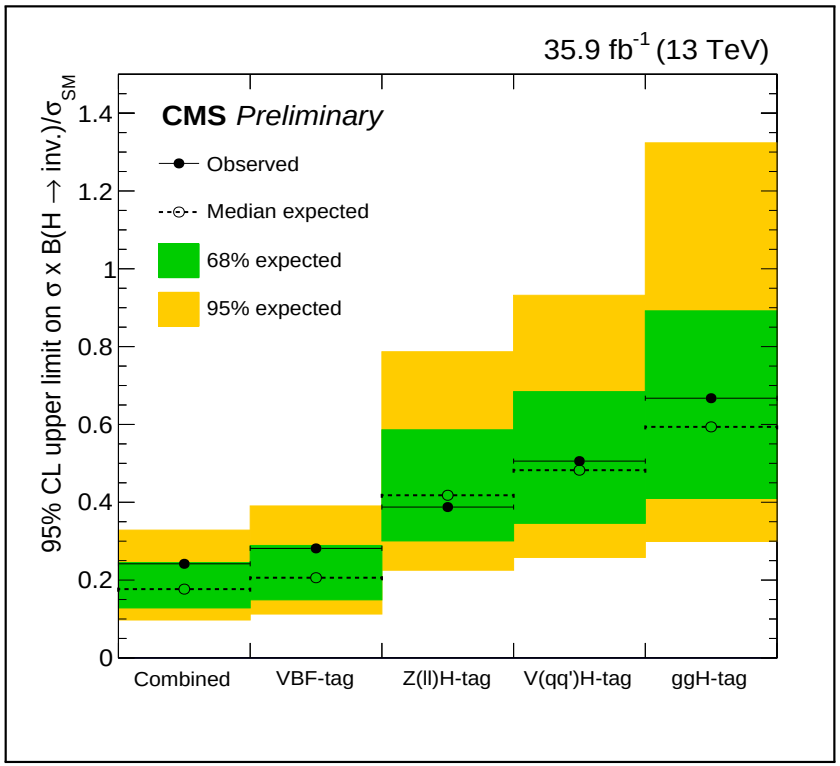


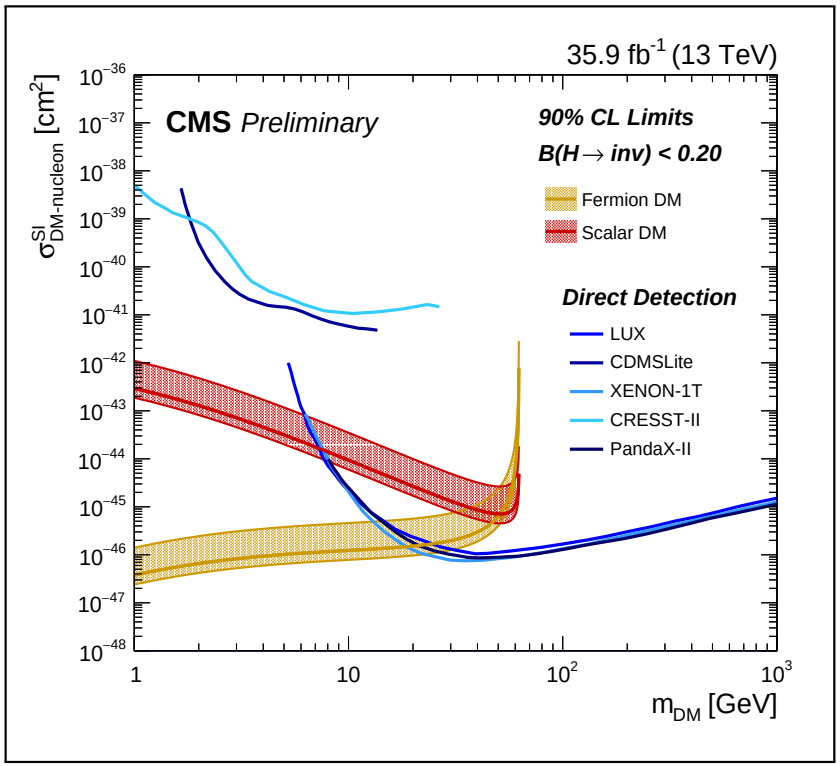
# Invisible Higgs Decays: Combination

- A large set of analyses coming up
- More complex techniques exploited by having a single fit combining signal and background regions
- For $m_{\mathrm{H}} = 125\ \mathrm{GeV}$ will profit from a larger dataset

95% CL $BR(\mathrm{H} \to \mathrm{invisible})$ limits



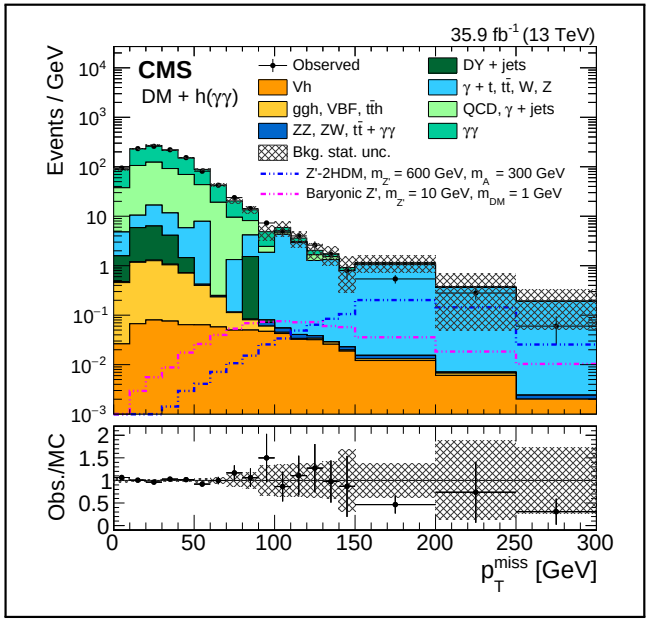

90% CL DM limits

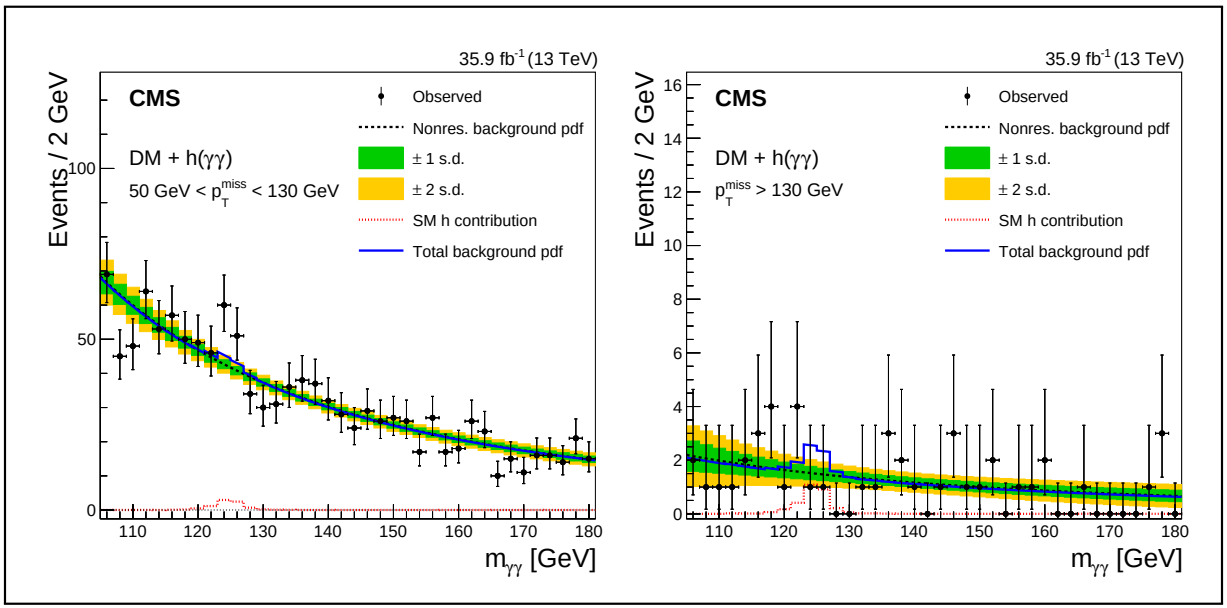


# Mono-H $\rightarrow \gamma\gamma$ Analysis

- $H \rightarrow \gamma\gamma$ events recoiling against $p_T^{miss}$

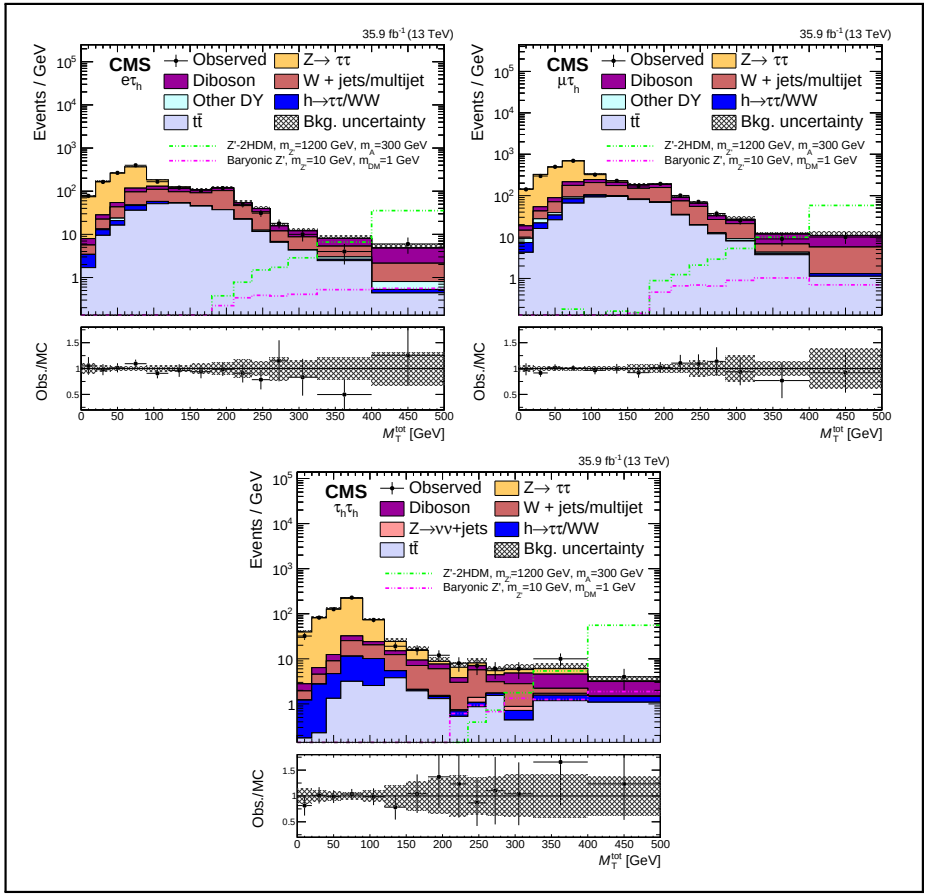
| Variable | Low-$p_T^{miss}$ category | High-$p_T^{miss}$ category |
|---|---|---|
| $p_T^{miss}$ | $>50$ GeV, $<130$ GeV | $>130$ GeV |
| $p_{T1}/m_{\gamma\gamma}$ | $>0.45$ | $>0.5$ |
| $p_{T2}/m_{\gamma\gamma}$ | $>0.25$ | $>0.25$ |
| $p_{T\gamma\gamma}$ | $>75$ GeV | $>90$ GeV |



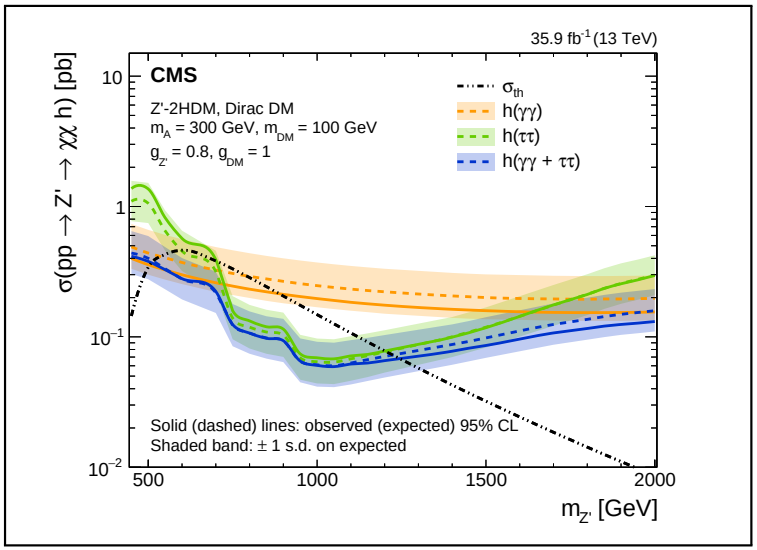
# Mono-H $\rightarrow \tau\tau$ Analysis

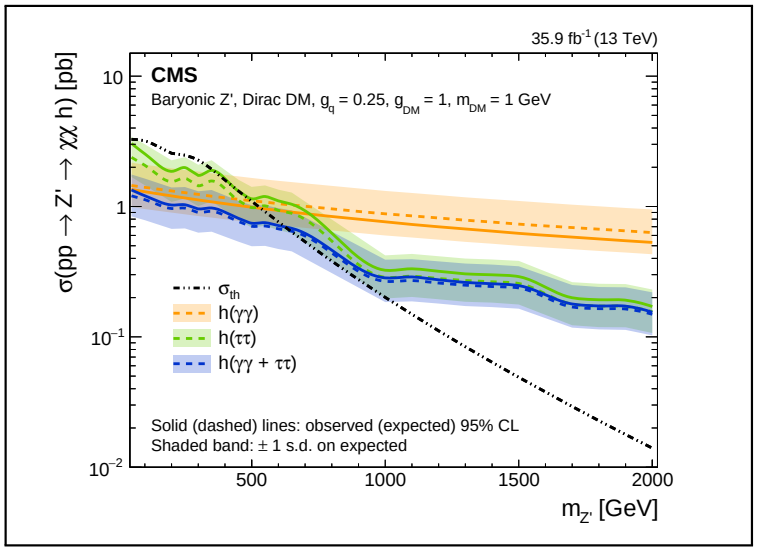
- Selecting $\mathrm{H} \rightarrow \tau\tau$ event candidates recoiling against $p_{\mathrm{T}}^{\mathrm{miss}}$
- Using $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$ categories
- Making use of transverse mass using $p_{\mathrm{T}}^{\mathrm{miss}}$ and visible objects as a final discriminant variable



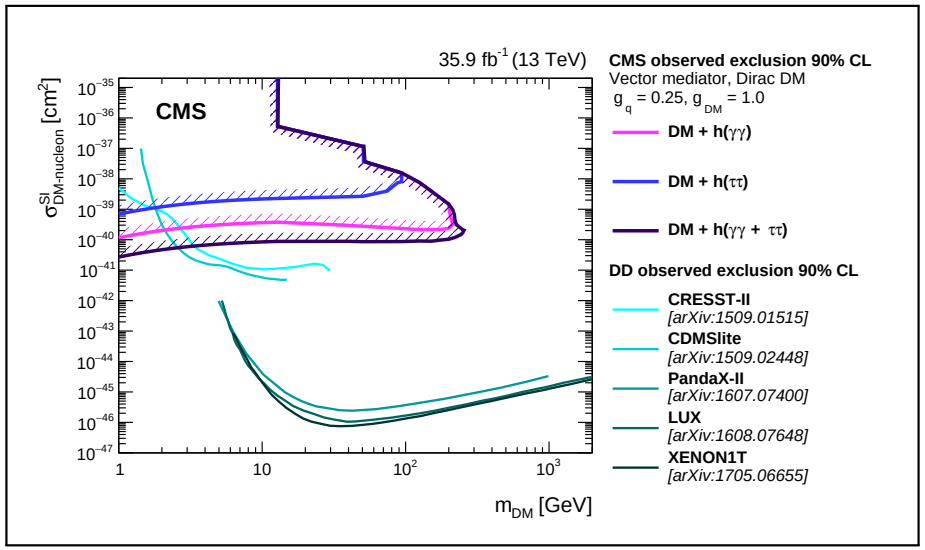
# Mono-H $\rightarrow \gamma\gamma/\tau\tau$ Combination

95% CL upper limits on Z'-2HDM DM and on baryonic Z' production cross sections



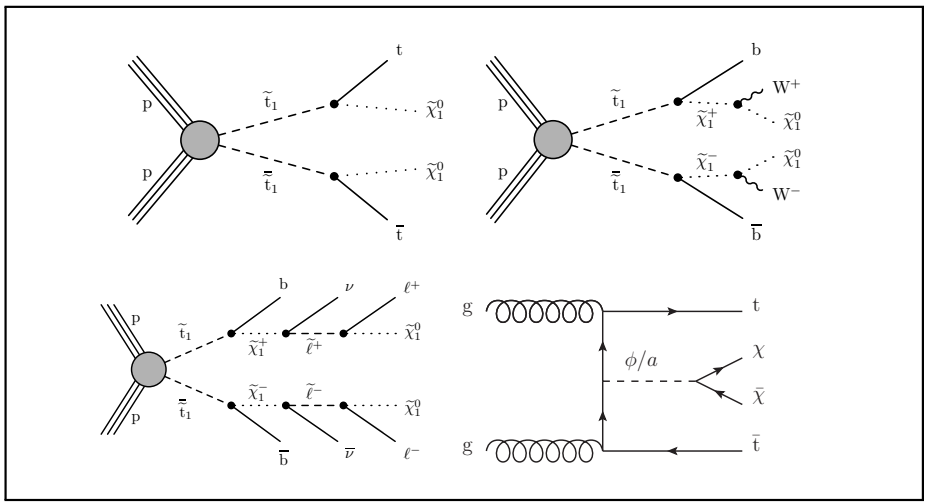

90% CL exclusion limits on the DM-nucleon SI scattering cross section as a function of $m_{DM}$

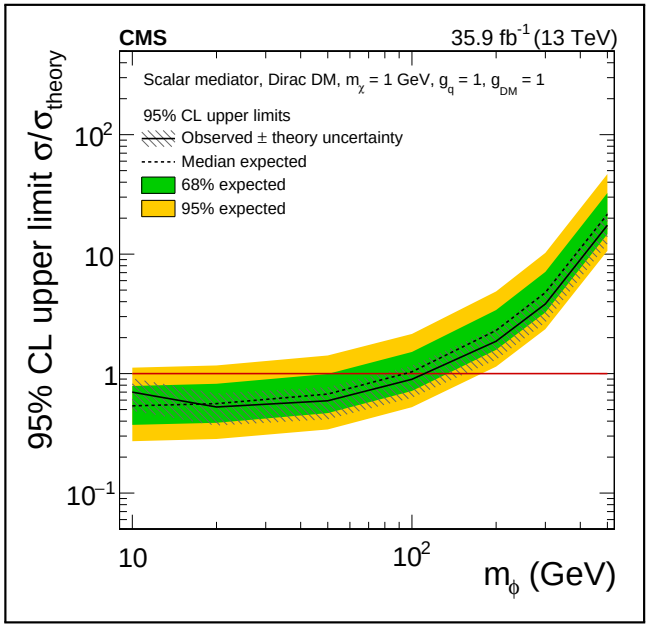


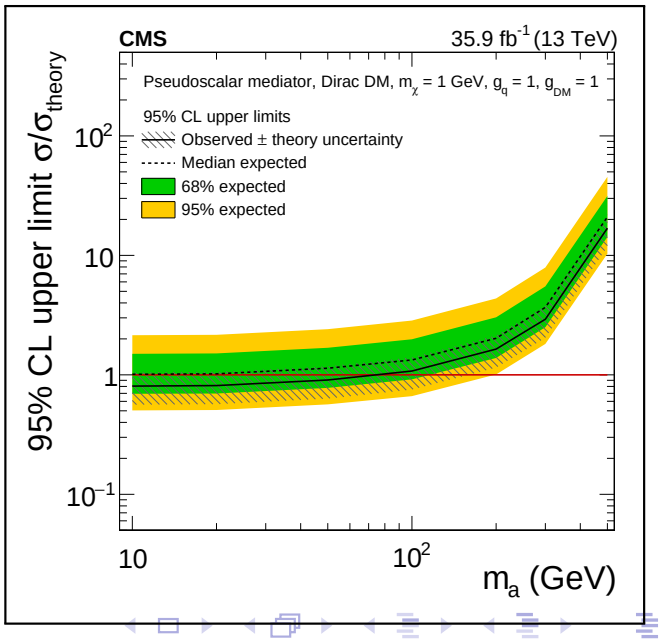

Additional Mono-H analyses coming up, stay tuned...

# SUSY Re-interpretation Example

- Search for top squarks and DM particles in opposite-charge dilepton final states
- Select events with two electrons or muons, b-jets, and large $p_{\mathrm{T}}^{\mathrm{miss}}$
- Signal and backgrounds separated using $p_{\mathrm{T}}^{\mathrm{miss}}$ and transverse mass variables



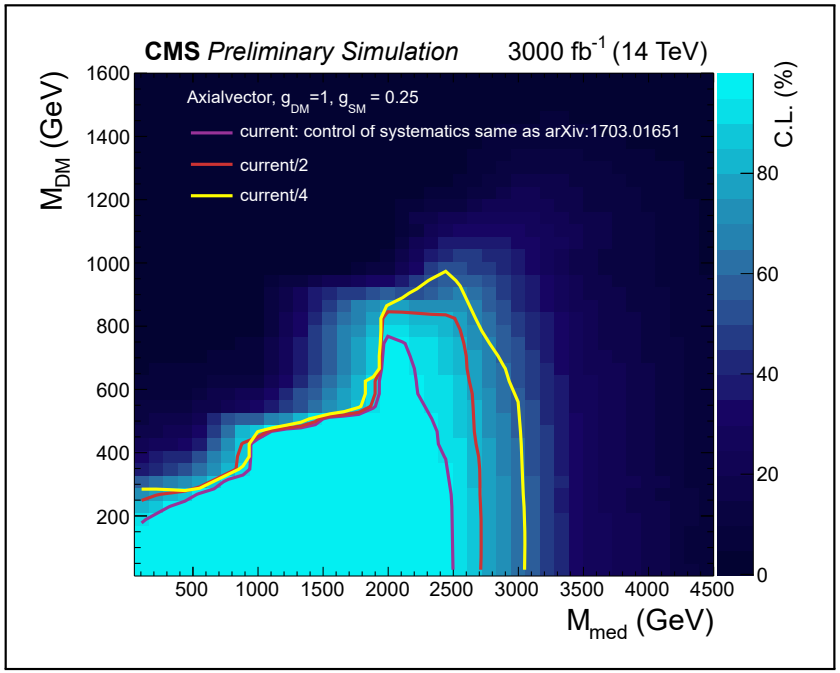



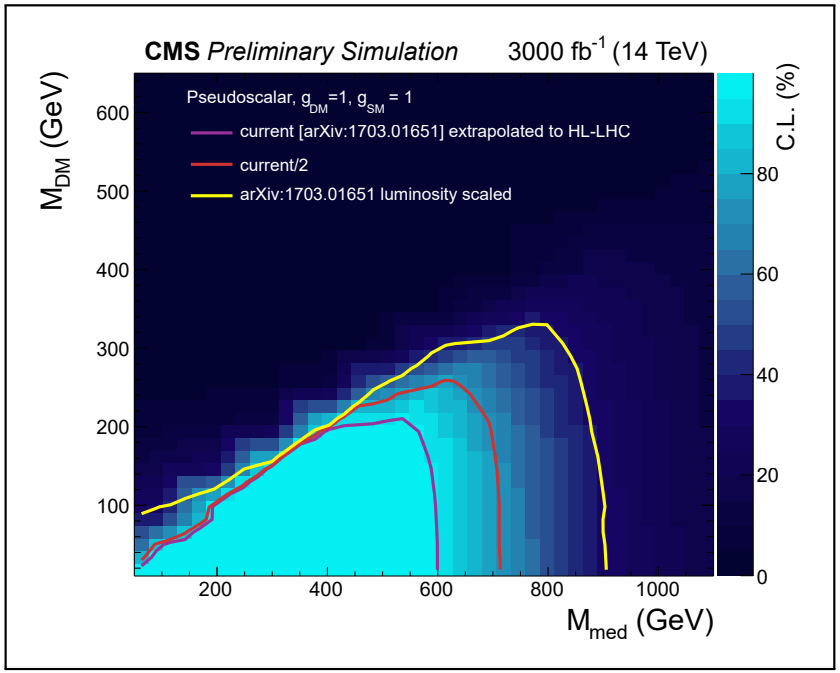



# New Directions & Prospects

- Entering era of "precision" searches in multi-jet analyses:
  - Vector & Axial-vector models: tails of the distributions
    - more statistically limited
    - extended binning $\Rightarrow$ theory uncertainties will be getting important (again)
  - Scalar & Pseudo-scalar models: bulk of the distributions
    - experimental uncertainties in the lepton / photon identification are very important
    - trigger thresholds need to be kept under control for maximum sensitivity
- $\mathrm{H} \rightarrow$ *invisible* searches will improve again and again with larger datasets
  - $\mathrm{Z} \rightarrow \ell\ell$ and VBF channels not systematic limited yet
- Long-lived + DM decays
  - very reach phenomenology, not much explored experimentally
  - need to make sure this possible signal events are triggered!

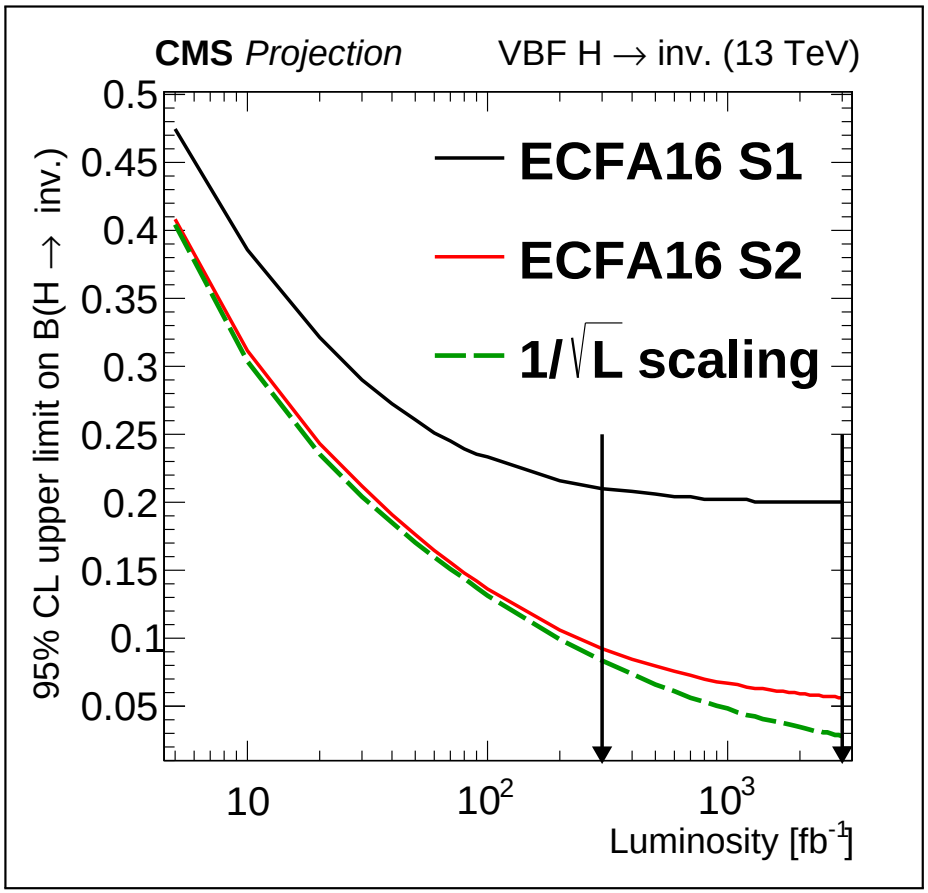
# HL-LHC DM Projections with Mono-Jet




- Current 95% CL limits:
  - on axial-vector mediators, $m_{med} \sim 2000$ GeV
  - on pseudoscalar mediators, $m_{med} \sim 450$ GeV
- Systematic uncertainties matter a lot

# HL-LHC Projections for Invisible Higgs Searches

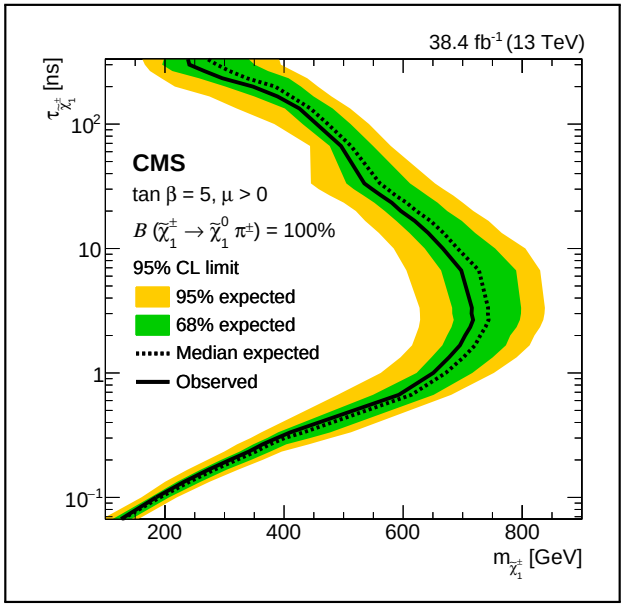



| | ECFA2016 (S1) | ECFA2016 (S2+) | ECFA2016 (S2) |
|---|---|---|---|
| 300 $fb^{-1}$ | 0.210 | 0.092 | 0.084 |
| 3000 $fb^{-1}$ | 0.200 | 0.056 | 0.028 |

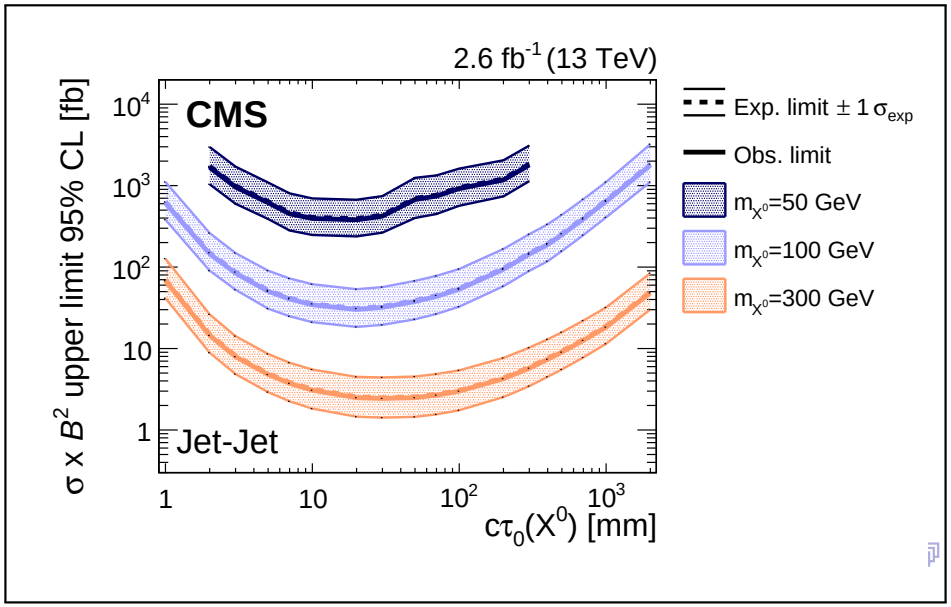
- Current 95% limits:
  - HIG-16-016 (run-I + 2015): 0.23
  - HIG-17-023 (2016): 0.18
- An unofficial naive combination gives ∼0.15
- Better than existing projections with much less data!

# Long-Lived Searches (Examples)

## Search for disappearing tracks




## Search for displaced jets



# Summary

- Manifold DM program at CMS
  - missing transverse momentum signatures and visible mediator searches
  - complementarity to direct and indirect searches
- LHC Run-II going full speed
  - factor 3 more collisions to analyze
- Several developments to come
  - more realism/complexity in scalar sector
  - include scenarios with long-lived particles

# References

- Mono-jet: EXO-16-048 (arXiv:1712.02345)
- Mono-$\mathrm{V}(qq)$: EXO-16-048 (arXiv:1712.02345)
- Mono-photon: EXO-16-039 (arXiv:1706.03794)
- Mono-$\mathrm{Z}(\ell\ell)$: EXO-16-052 (arXiv:1711.00431)
- Mono-top: EXO-16-051 (arXiv:1801.08427)
- $\mathrm{H} \rightarrow \mathrm{invisible}$: HIG-17-023 (paper submission in progress)
- Mono-$\mathrm{H}$: EXO-16-055 (arXiv:1806.04771)
- SUSY search: SUS-17-001 (arXiv: 1711.00752)
- Long-lived analyses: EXO-16-044 (arXiv:1804.07321) & EXO-16-004 (arXiv:1801.00359)
- Projections: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

You can find all EXO and HIG results on:

http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html