Dark Matter searches with the **CMS experiment**

Annapaola de Cosa

on behalf of CMS collaboration

Universität Zürich[UZH]

ICNFP2017

Kolymvari, Crete, Greece

17th-29th August 2017

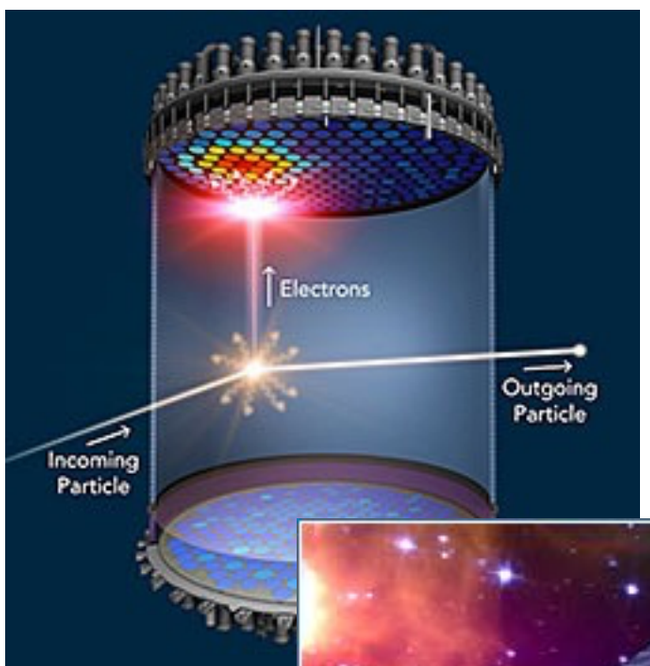
Outline

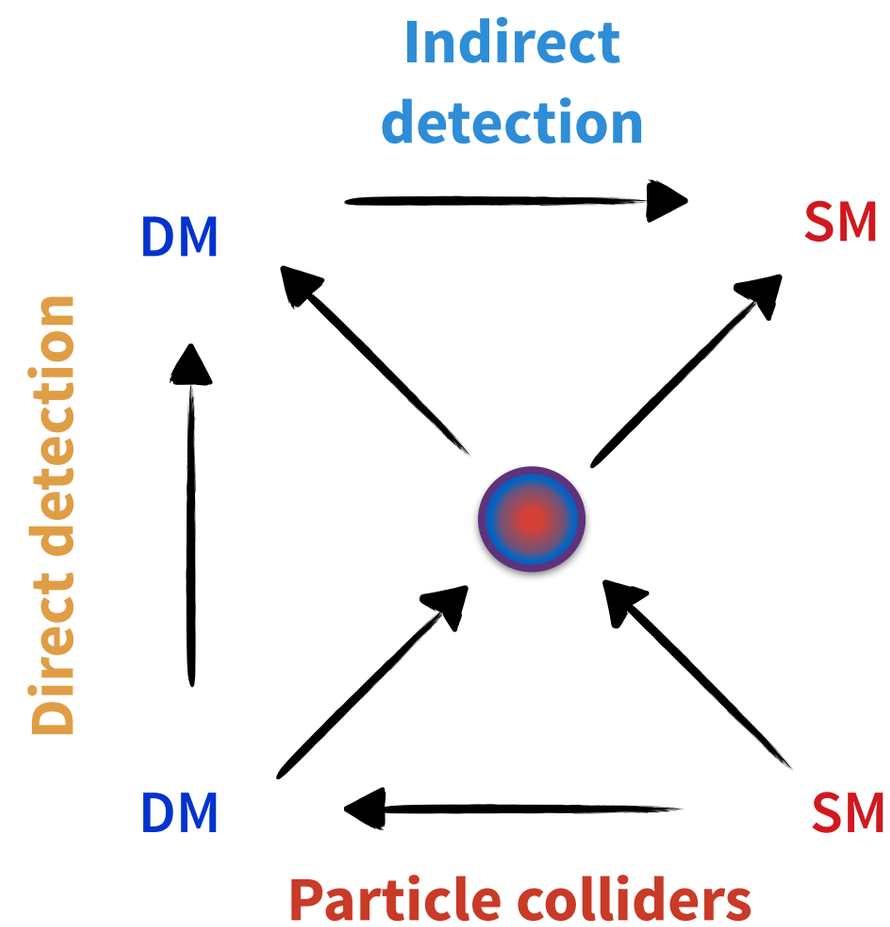
- **Overview of DM searches at CMS**
  - Direct production of DM at colliders
- **Evolution of the theoretical approach**
  - From effective field theory to simplified models
- **Experimental status**
  - Focus on the newest Run 2 results
  - Experimental techniques
  - Interpretation of results
- **Outlook**

Probing Dark Matter

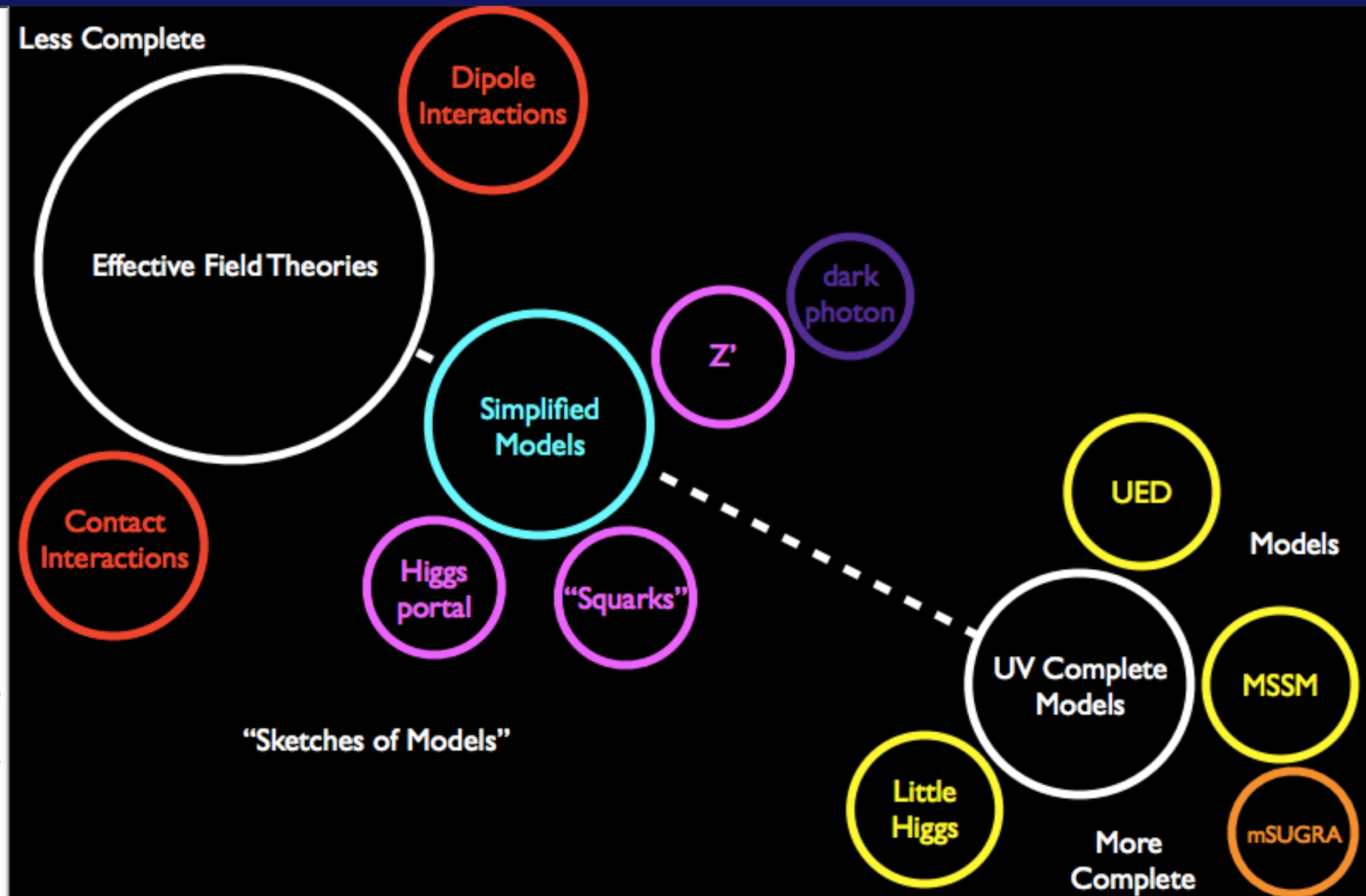
Three main strategies to search for weakly interacting DM

- Direct detection
- Indirect detection
- Production at particle colliders





Theoretical approach



Tim Tait, DM@LHC 2013

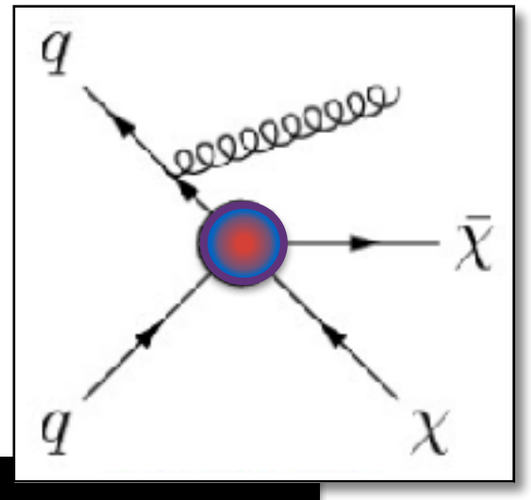
Towards more complete models

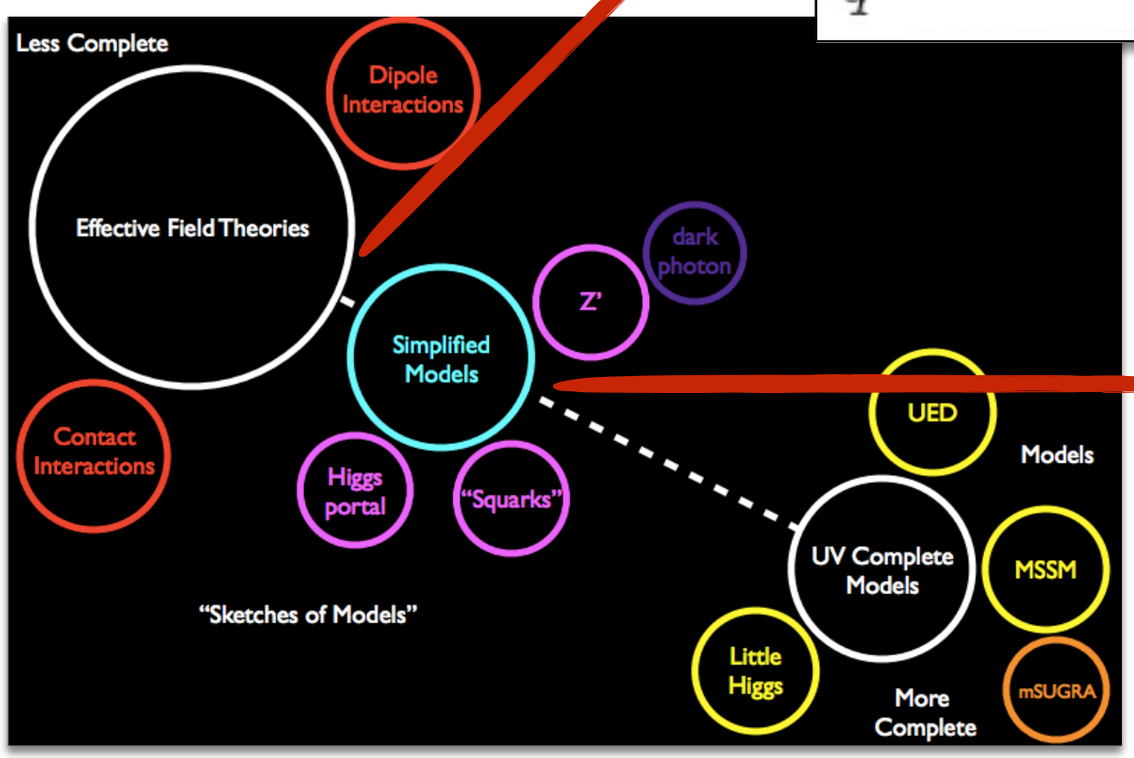
Effective Field Theory

- Simplest approach
- Critical at high energies [Q > M_{med}]
- Widely used in Run 1

$$\sigma \propto \frac{1}{M^{*4}}$$

[M*, m_X]





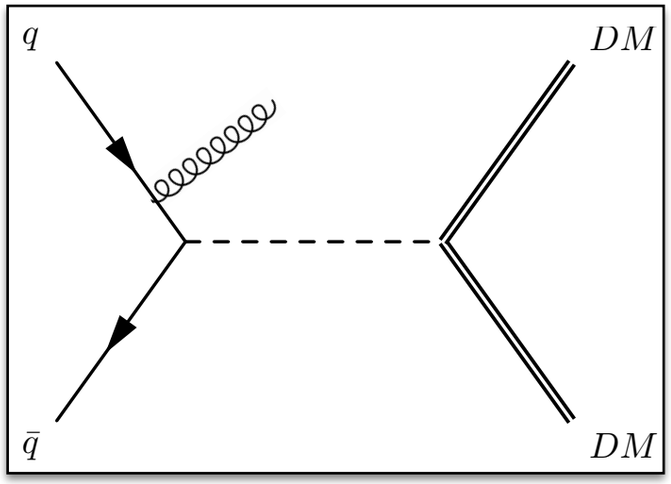
Tim Tait, DM@LHC 2013

Simplified Models

- Overcome EFT validity issue
- Direct access to the mediator
- Benchmark for Run 2 searches

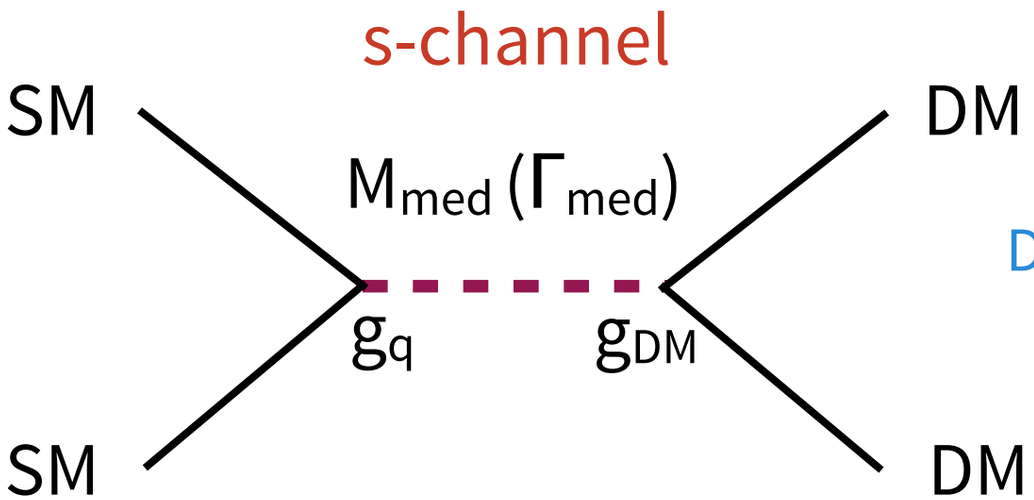
$$\sigma \propto \frac{g_{SM}^2 g_{DM}^2}{M_{med}^4}$$

[M_{med}, Γ_{min}, m_X, g_{SM}, g_{DM}]

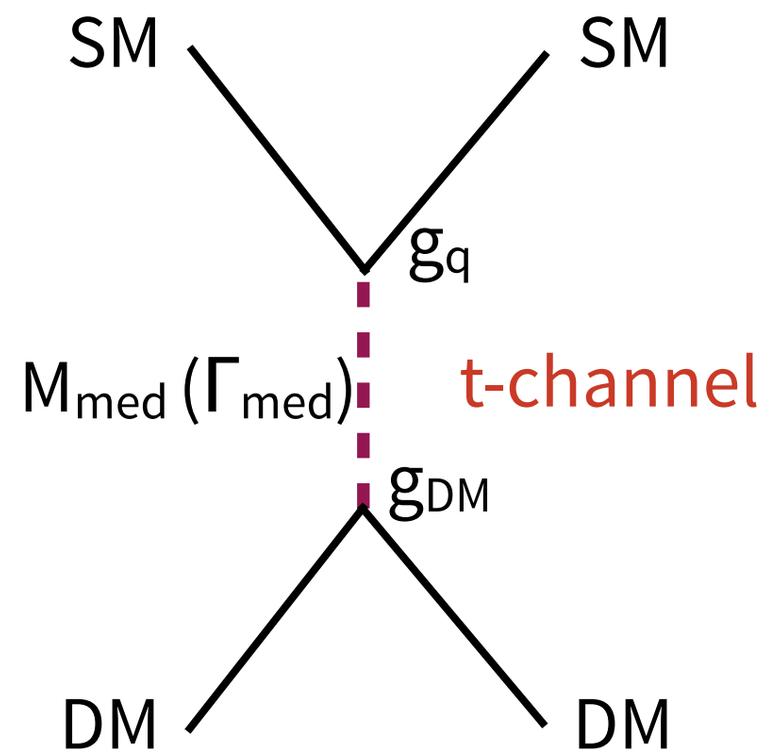


Simplified Models

DM production characterised by a small set of parameters



Dirac fermion
DM particle



4 parameters	
m_{DM}	M_{med}
g_q	g_{DM}

Mediators	
Vector	Axial-Vector
Scalar	Pseudo-Scalar

SM give direct access to the mediator

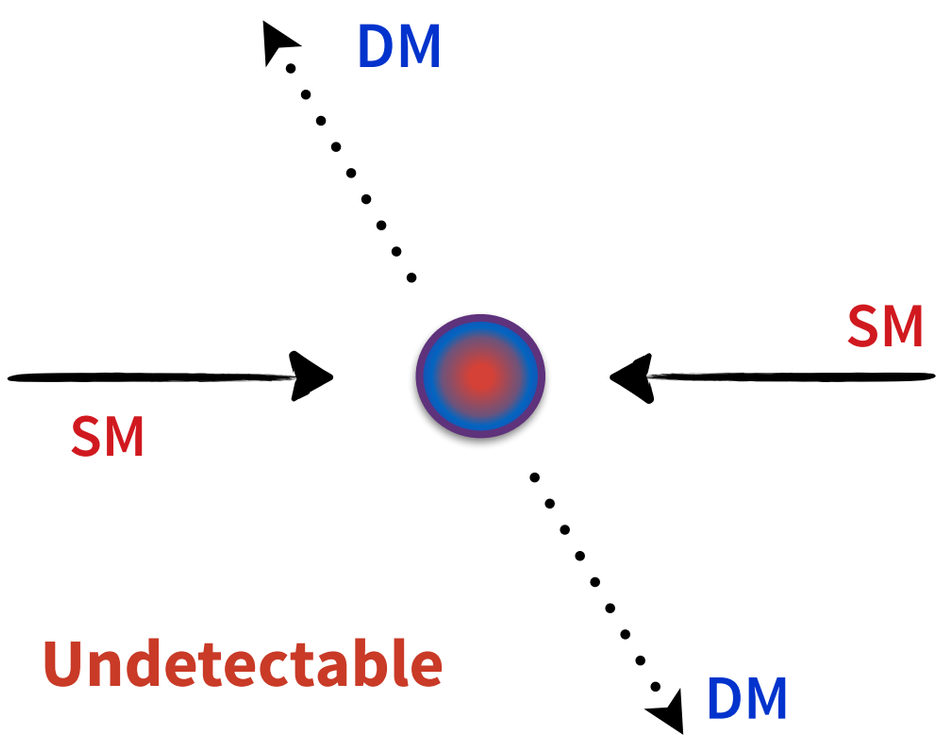
- **On-shell**: resonant enhancement
- **Off-shell**: limits suppression when $M_{med} < 2m_{DM}$
- **High mediator mass**: cross section drops, kinematics similar to EFT

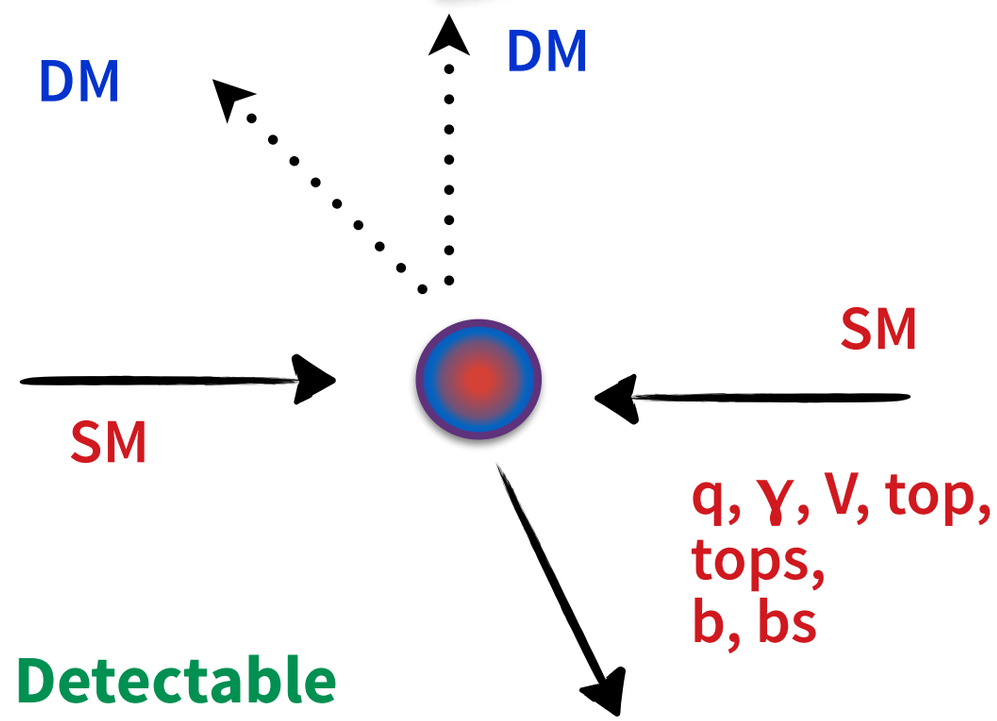
Experimental signature

Producing Dark Matter in a laboratory

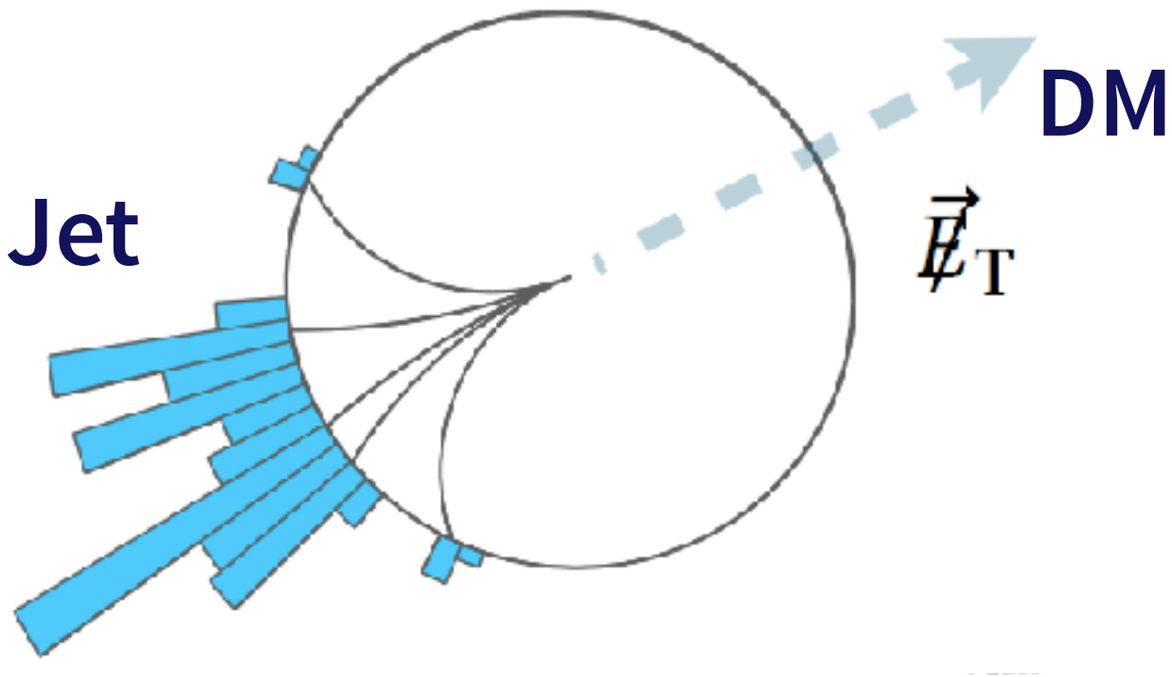
- **DM particles escape detectors** without interacting
- DM production inferred by measuring **energy imbalance** in the detector
  - Missing transverse energy (MET), $E_T^{miss} = \sqrt{\left(\sum_n E_x\right)^2 + \left(\sum_n E_y\right)^2}$
- **Visible objects used to flag DM production**

Search for DM in the tails of MET spectrum





Missing transverse momentum

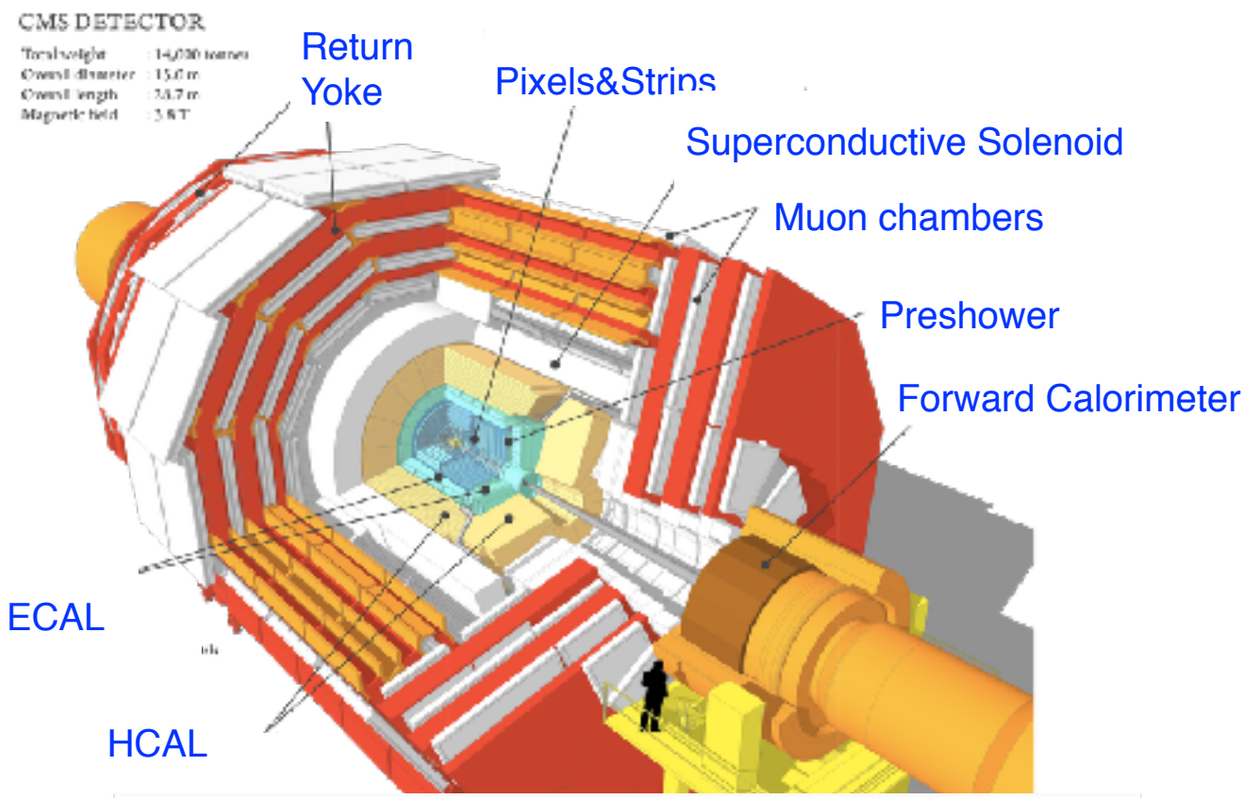


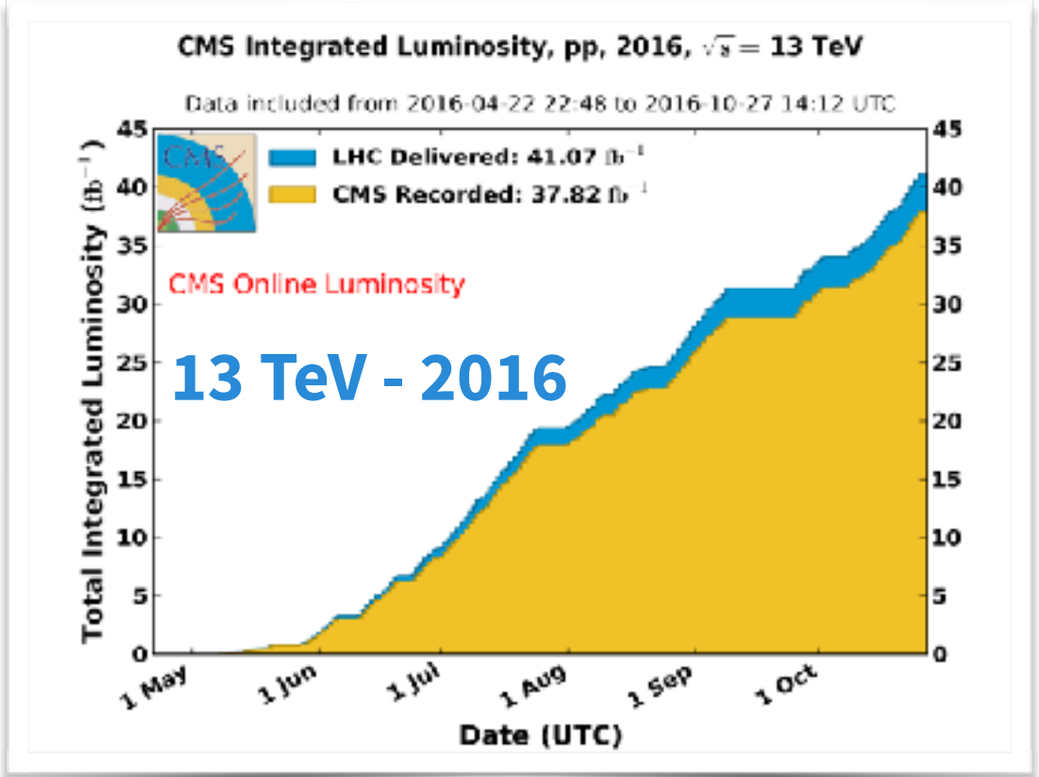
$$E_T^{miss} = -\sum_i p_T{}^i$$

- **Missing transverse momentum** (E_T^{miss}) is defined as ***the negative sum of the transverse momenta of all reconstructed particles***
- E_T^{miss} quantifies the energy imbalance due to **invisible particle production**

All DM searches at colliders rely on large amount of E_T^{miss}

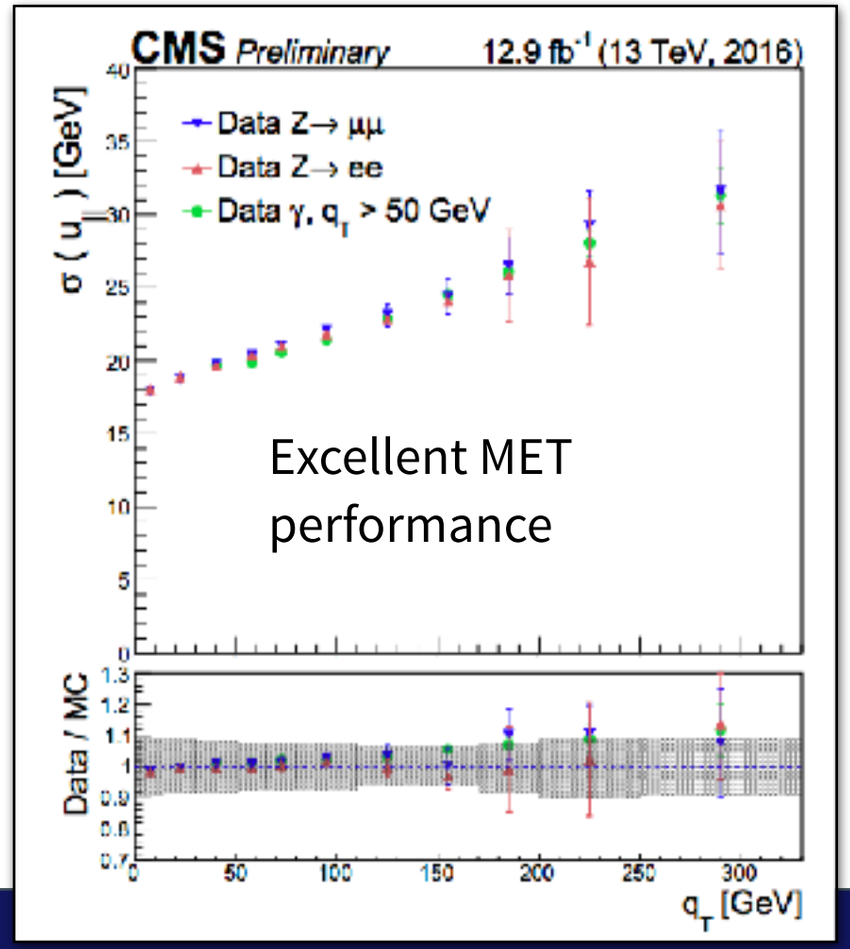
The CMS experiment





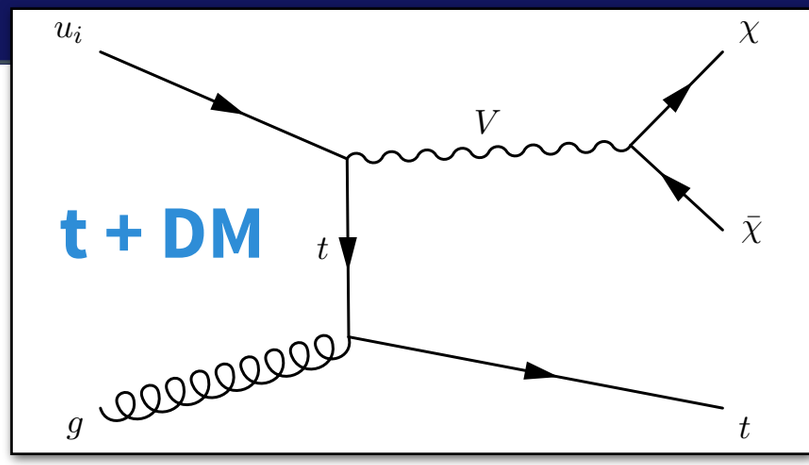
CMS

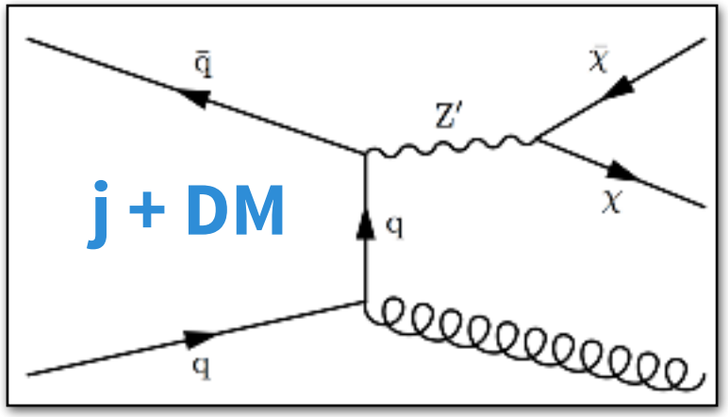
- Tracker: $\sigma(p_T)/p_T \sim 1.5 \cdot 10^{-4} p_T + 0.005$
- ECAL: $\sigma_E/E \sim 3\%/\sqrt{E}$ [GeV] $\oplus$ 0.5%
- HCAL: $\sigma_E/E \sim 100\%/\sqrt{E}$ [GeV] $\oplus$ 5%
- Trk+Mu: 1%÷10% [50 GeV-1 TeV]

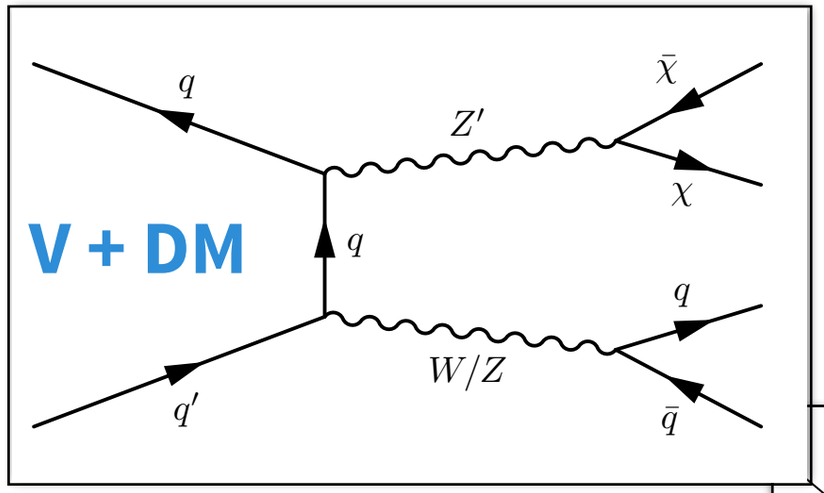


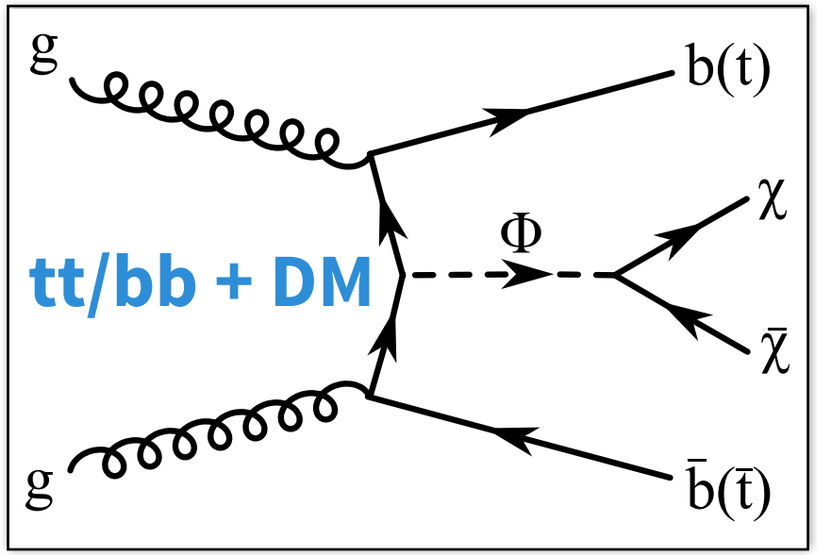
Experimental signatures

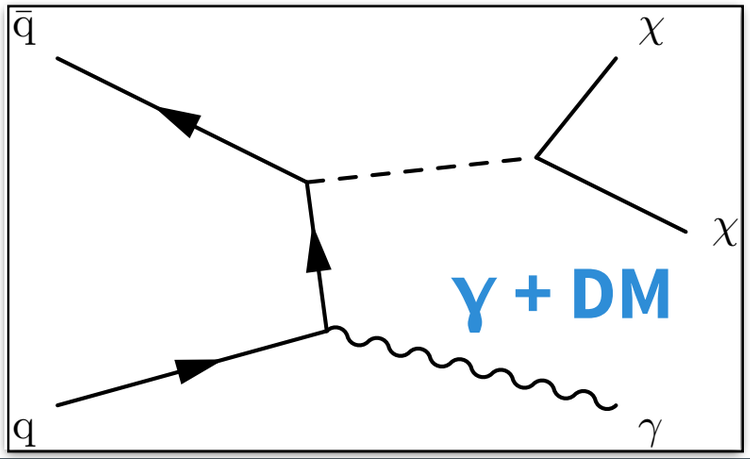
CMS experimental strategy to search for DM extends to a multitude of final states, including
j, W, Z, γ, Higgs boson, heavy flavour quarks



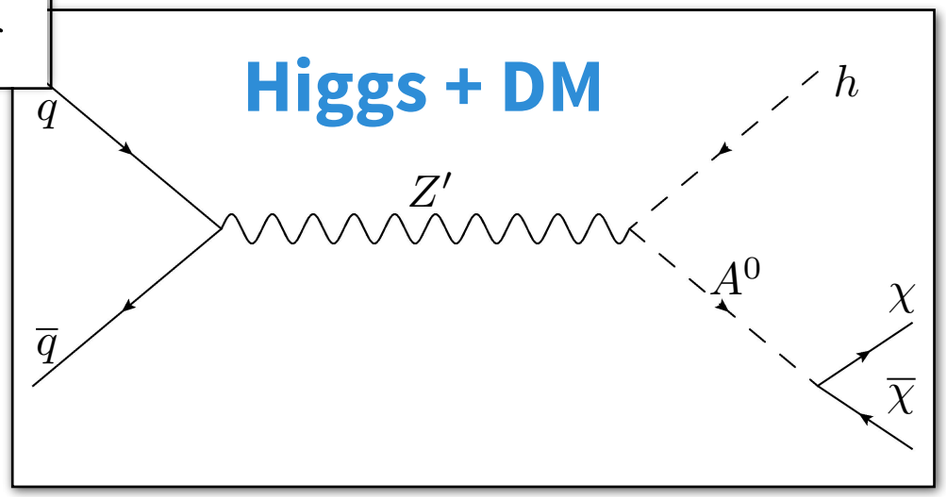




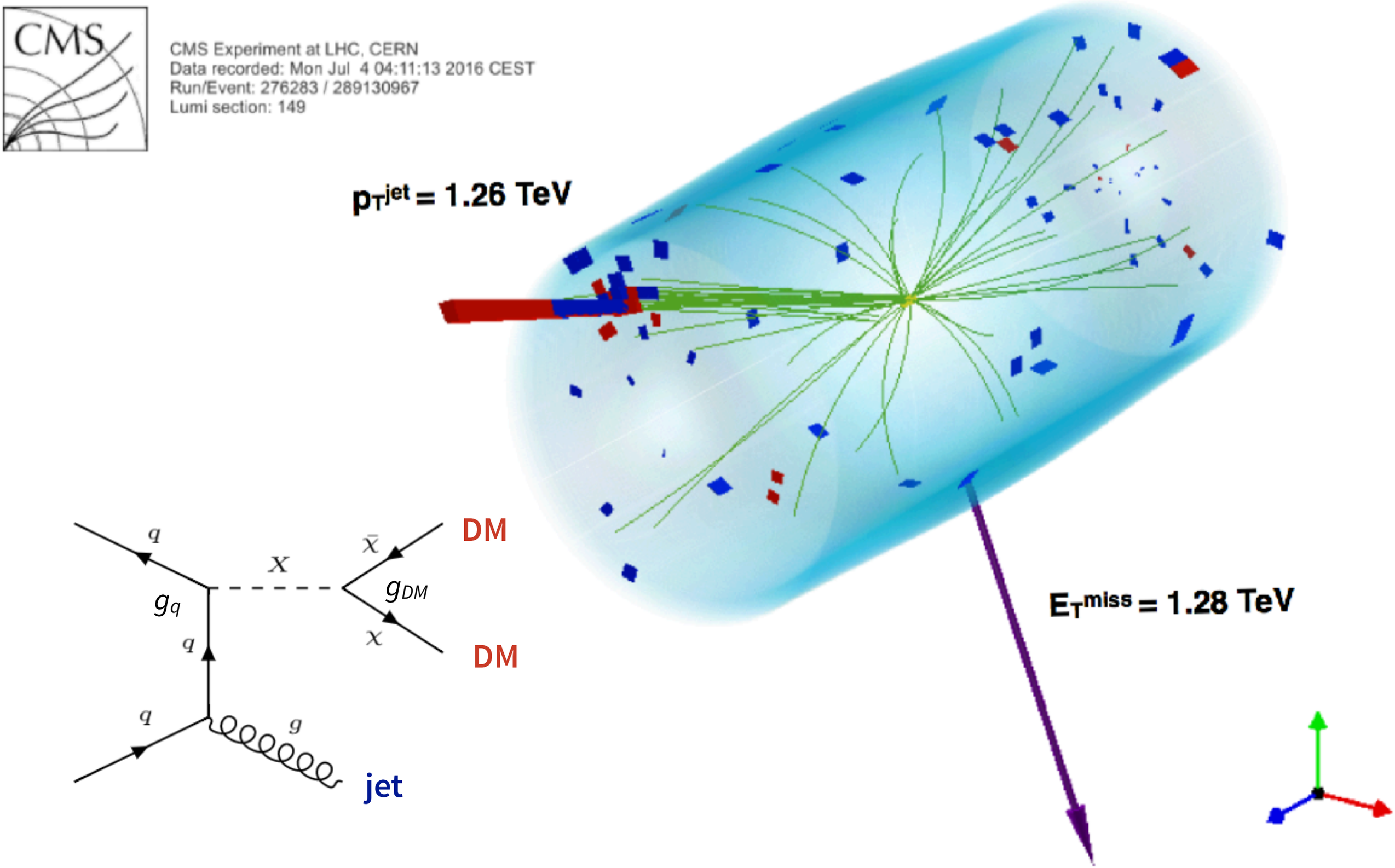




Plus more!



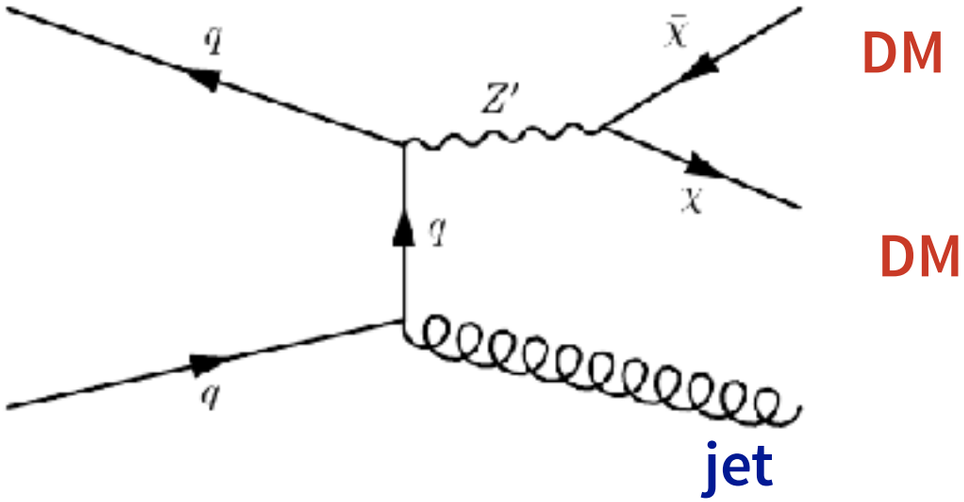
Striking signature: Mono-Jet

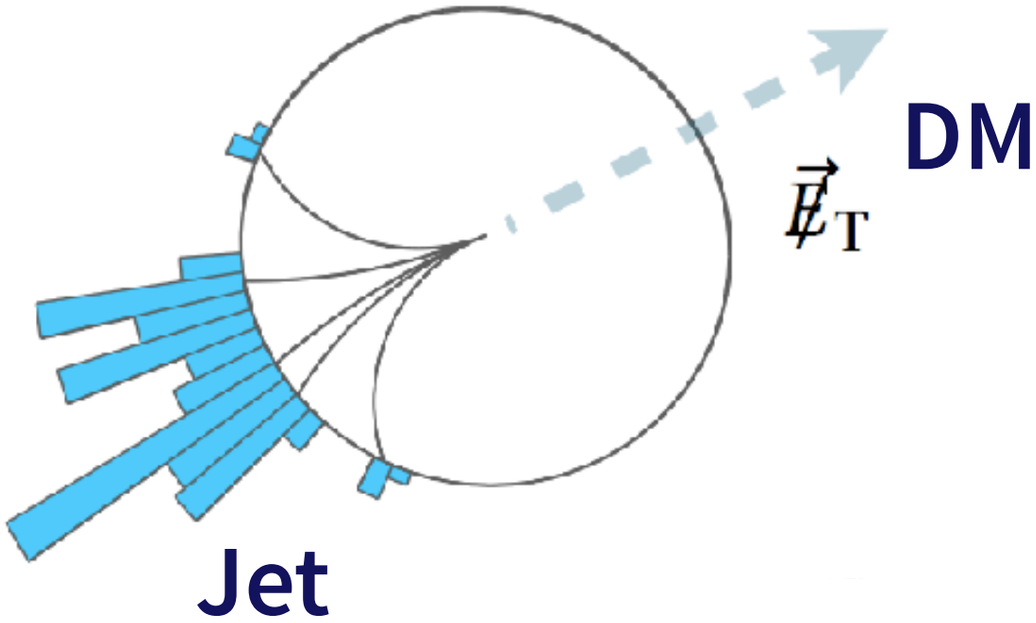


Mono Jet search

Hard jet/s from initial state radiation (ISR) recoiling against DM particles

- **Channel highly sensitive to DM production**
  - High gluon production cross-section
- **Selection highlights**
  - Large energy imbalance (E_T^{miss} > 200 GeV)
    - MET-based triggers
  - At least 1 central, high p_T jet (p_T > 100 GeV)
  - Veto on leptons/photons
  - **No veto on additional jets**
    - **targeting also multijet+MET signature**



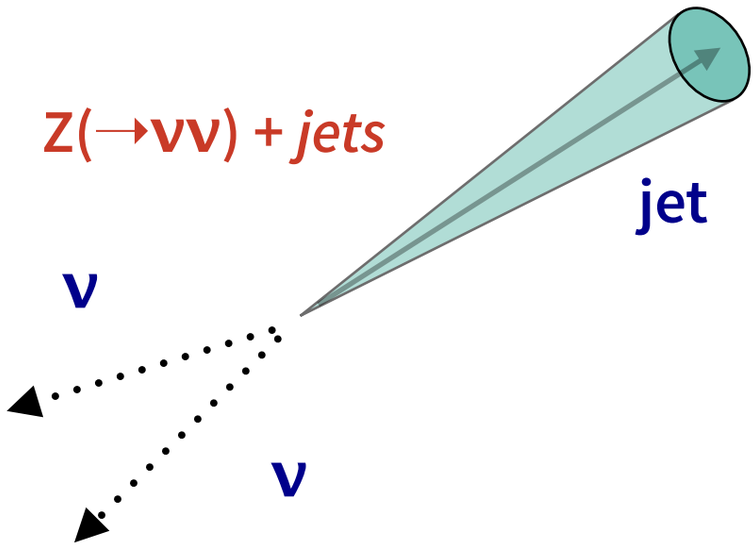


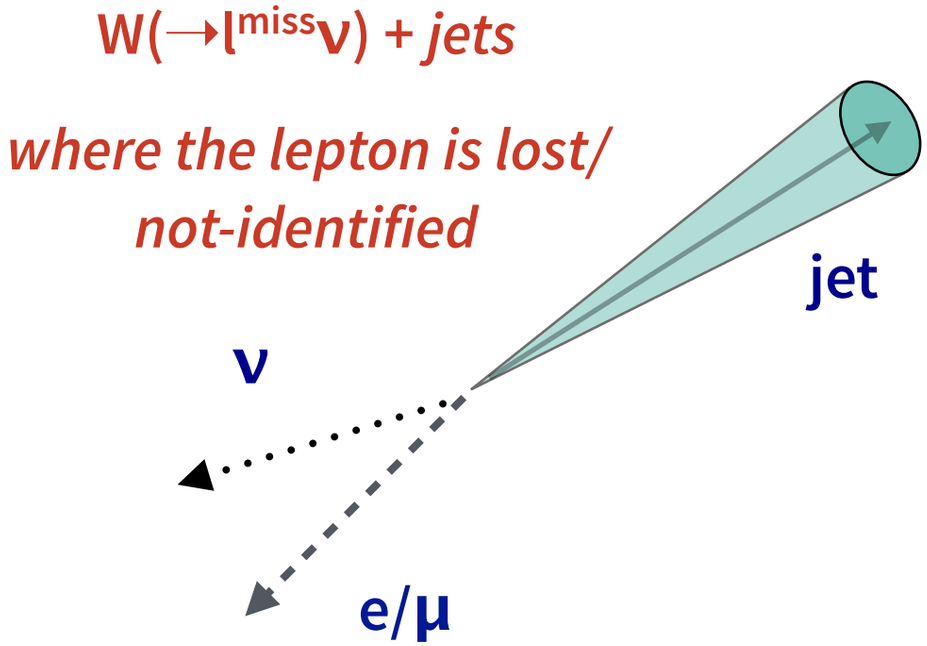
CMS PAS EXO-16-048

Mono Jet search: backgrounds

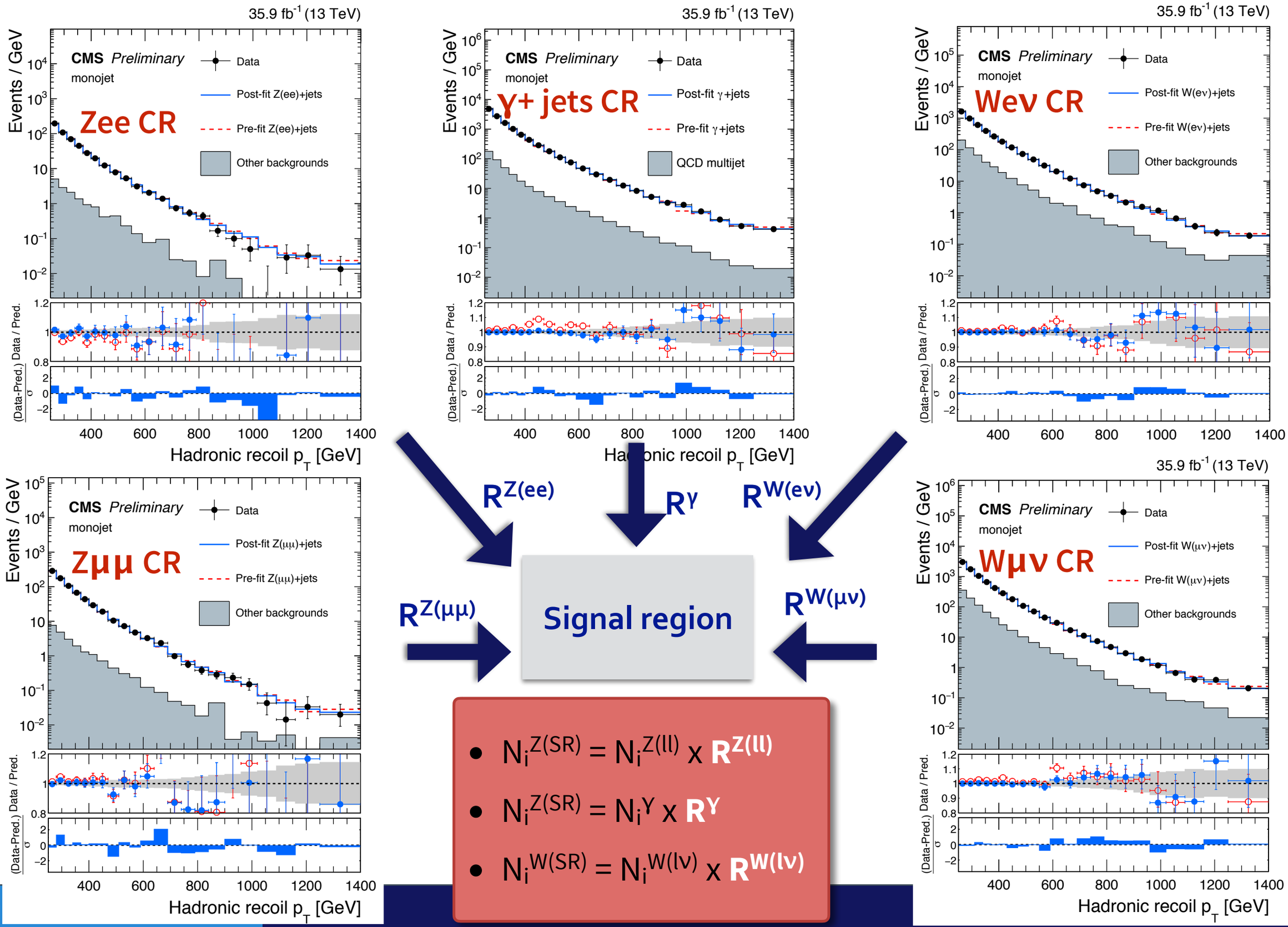
- **Major background from Z(→νν) + jets and W(l^{miss}ν) + jets**
- **Well controlled by fitting data in several control regions**
  - Z→νν inferred from Z→μμ/ee and γ+ jets events
  - W(→l^{miss}ν) + jets inferred from W(→lν) + jets events with a reconstructed lepton
  - Boson recoil (W/Z/γ p_T) used to mimic E_T^{miss} in SR
  - Simultaneous likelihood fit to E_T^{miss} spectrum in SR and CRs
- **Multi-jet background suppressed by requirement on Δφ(j,E_T^{miss})**

Relate CS and SR using bin-by-bin transfer factors "R" from simulation





Constraining backgrounds using data



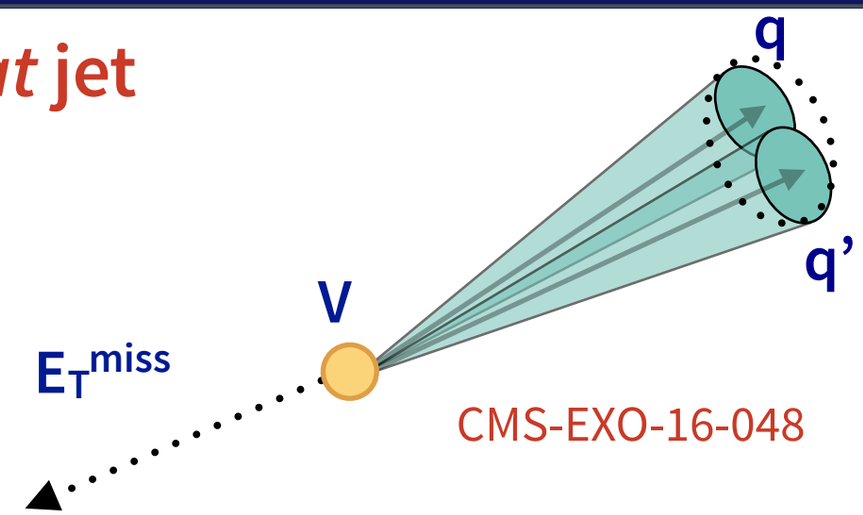
- $N_i^{Z(SR)} = N_i^{Z(ll)} \times R^{Z(ll)}$
- $N_i^{Z(SR)} = N_i^{\gamma} \times R^{\gamma}$
- $N_i^{W(SR)} = N_i^{W(l\nu)} \times R^{W(l\nu)}$

CMS PAS EXO-16-048

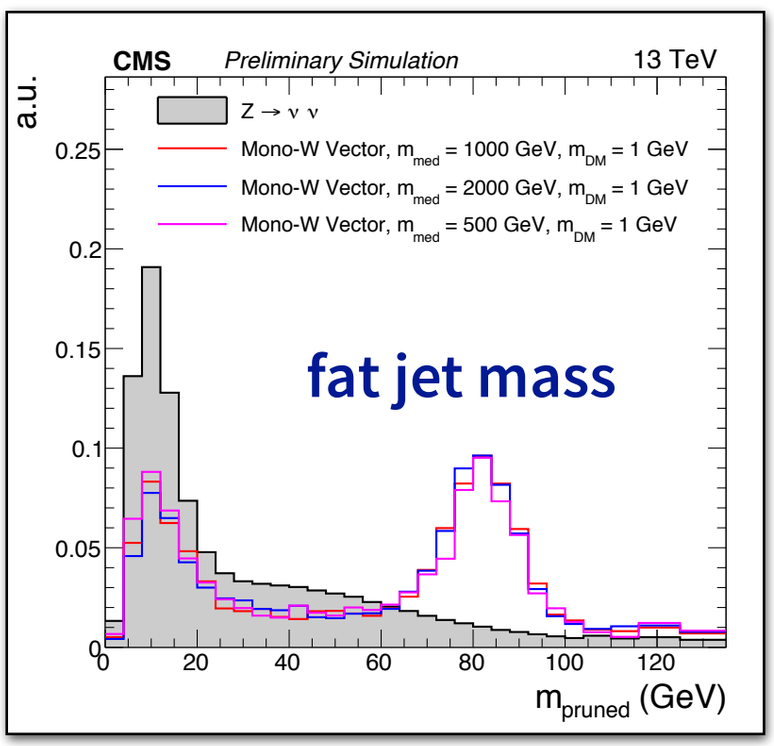
Adding Mono-V

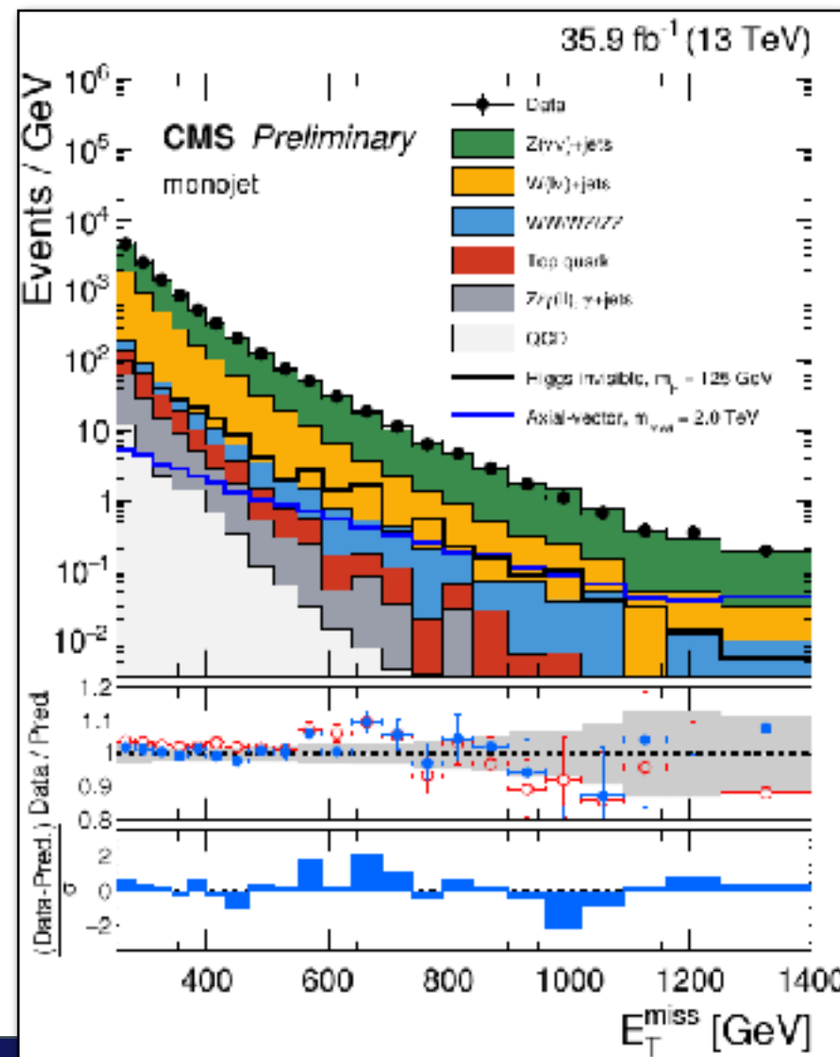
High V p_T: V→jj decay products merged in one *fat* jet

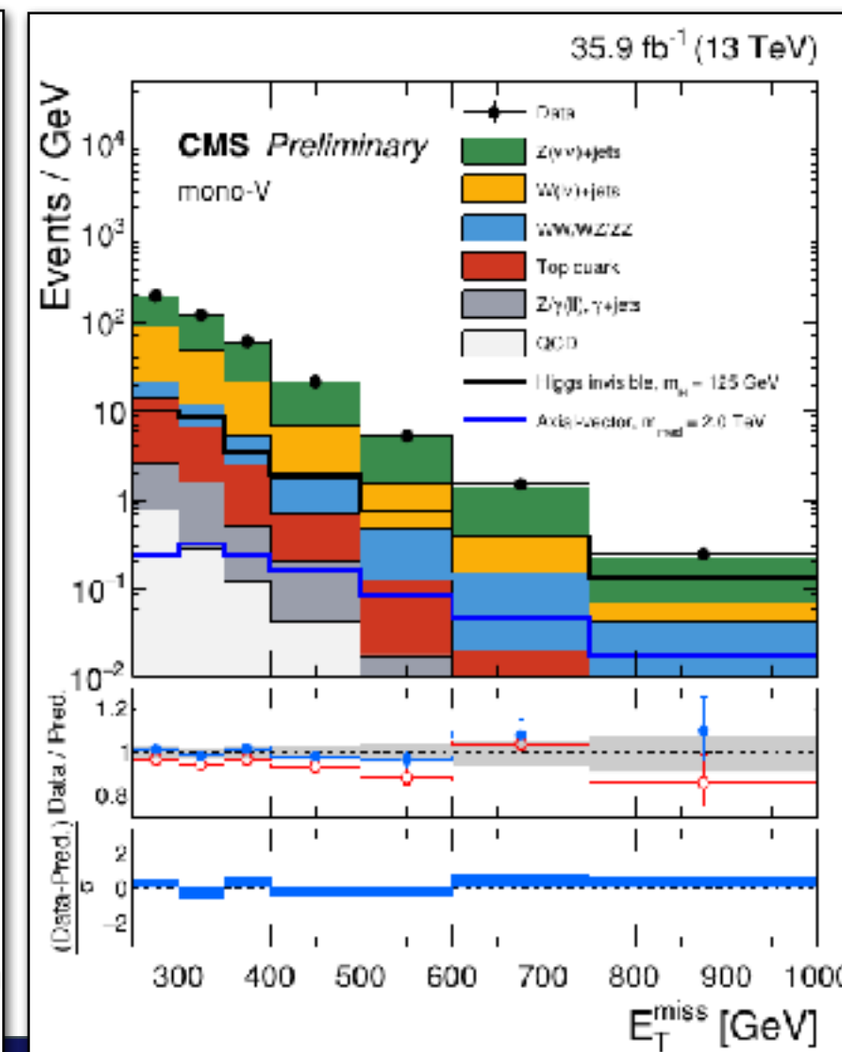
- **Analysis similar to Mono-jet except for boson reconstruction**
  - Exploiting boosted-jet reconstruction techniques
  - Jet mass, m_J, required to be compatible with V boson mass



CMS-EXO-16-048







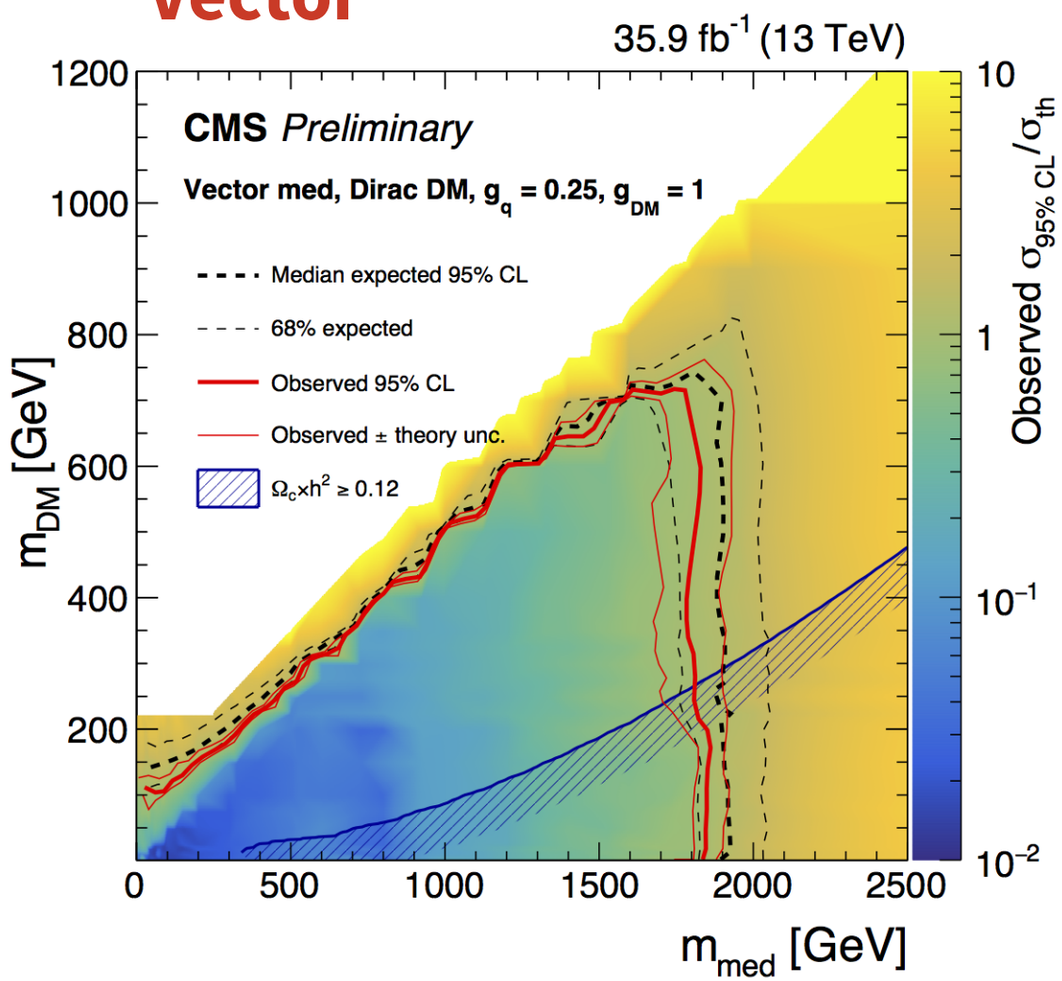
Interpretation of results

CMS-EXO-16-048

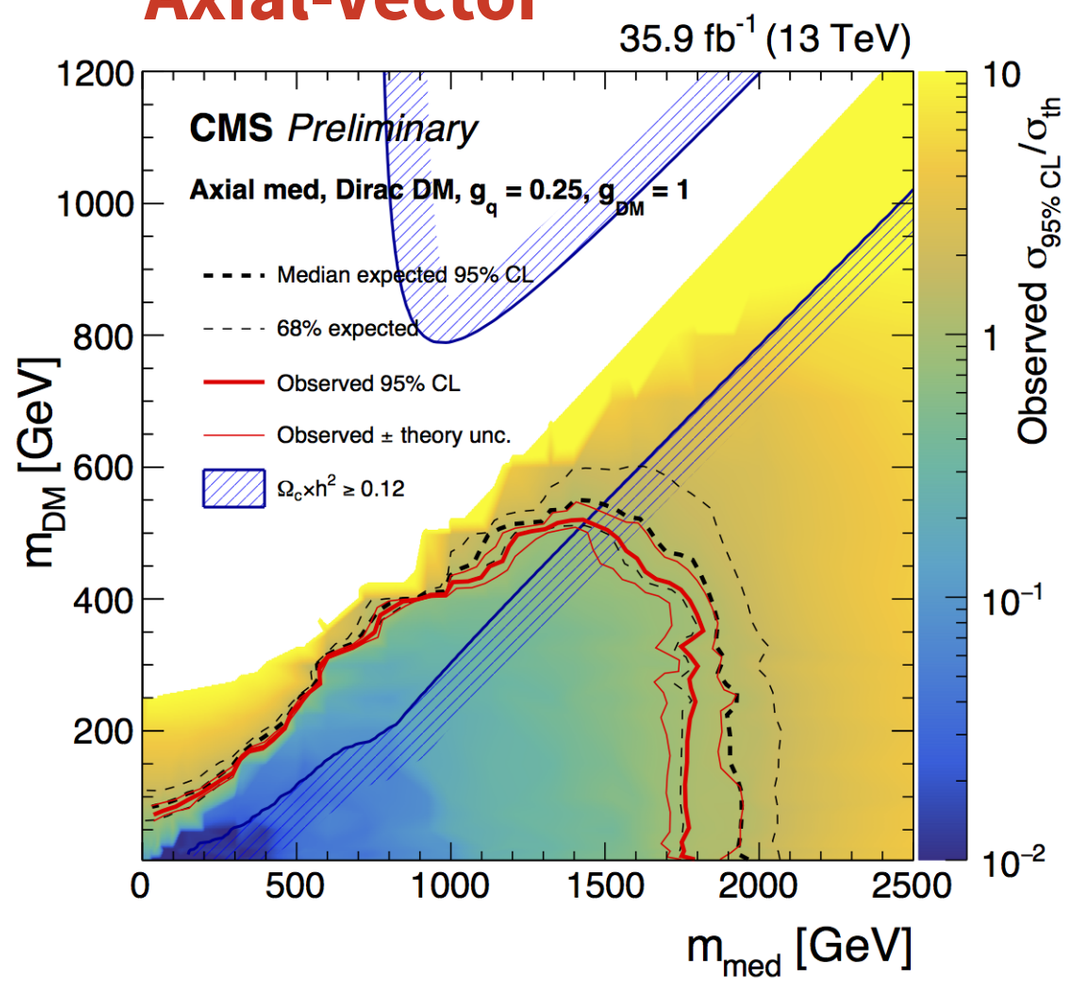
- **Given the observed lack of excess, upper limits are set on σ_{DM} assuming simplified models for signal**
  - As a function of M_{med} and m_{DM}

g_q=0.25, g_{DM} =1

Vector



Axial-Vector



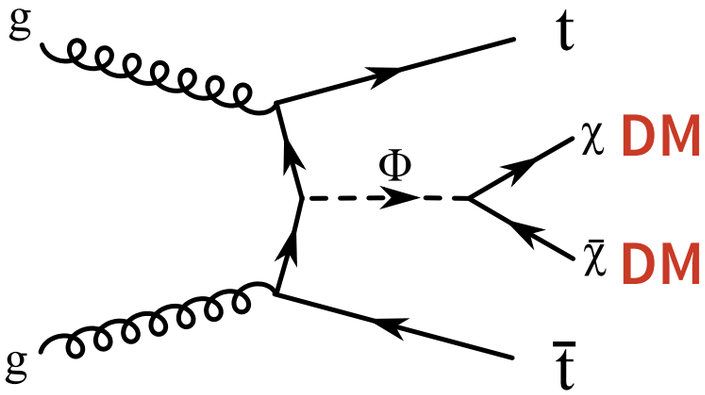
Under assumption of spin-1 mediator, MonoJet is certainly the most sensitive channel

DM + HF

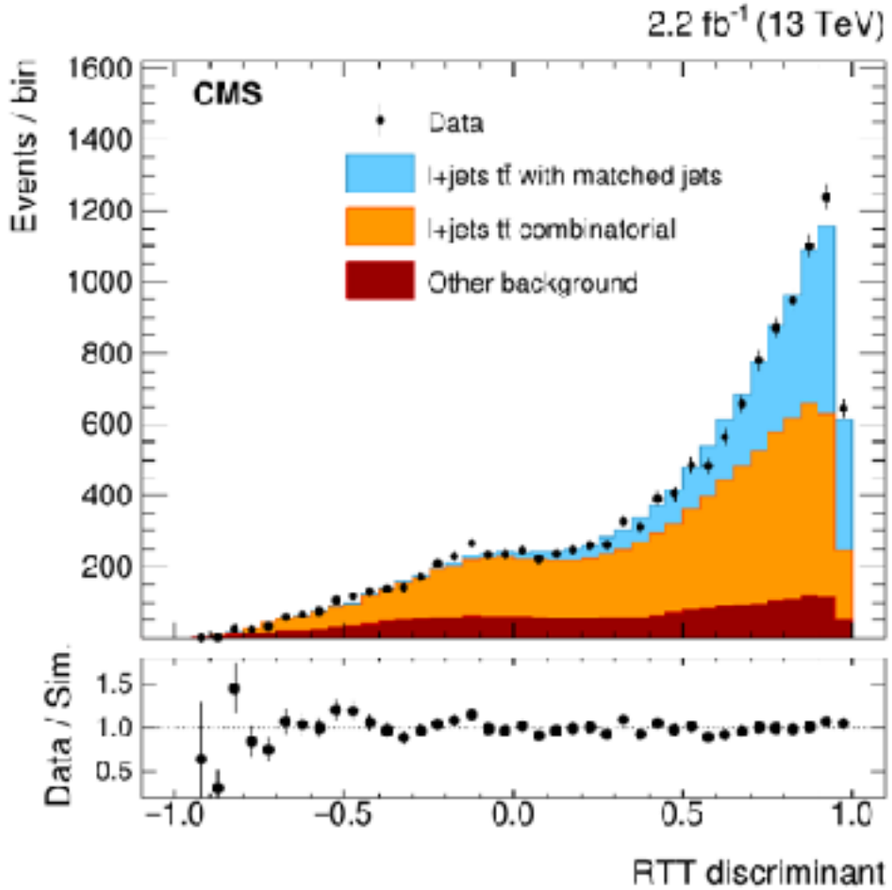
CMS-EXO-16-005 - arXiv:1706.02581

DM produced in association with heavy flavour quarks

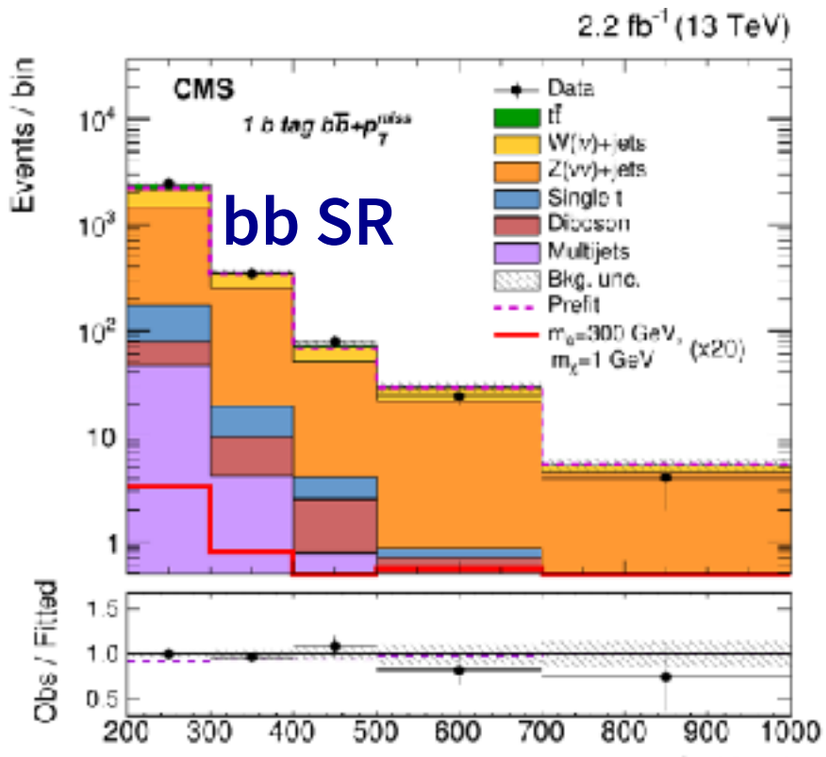
DM + tt

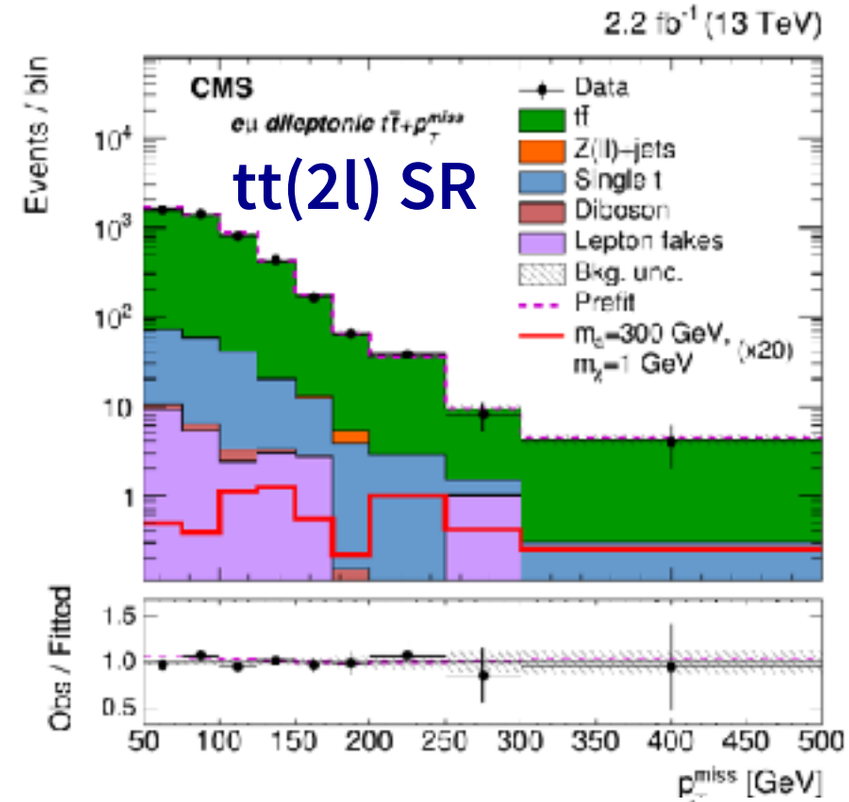


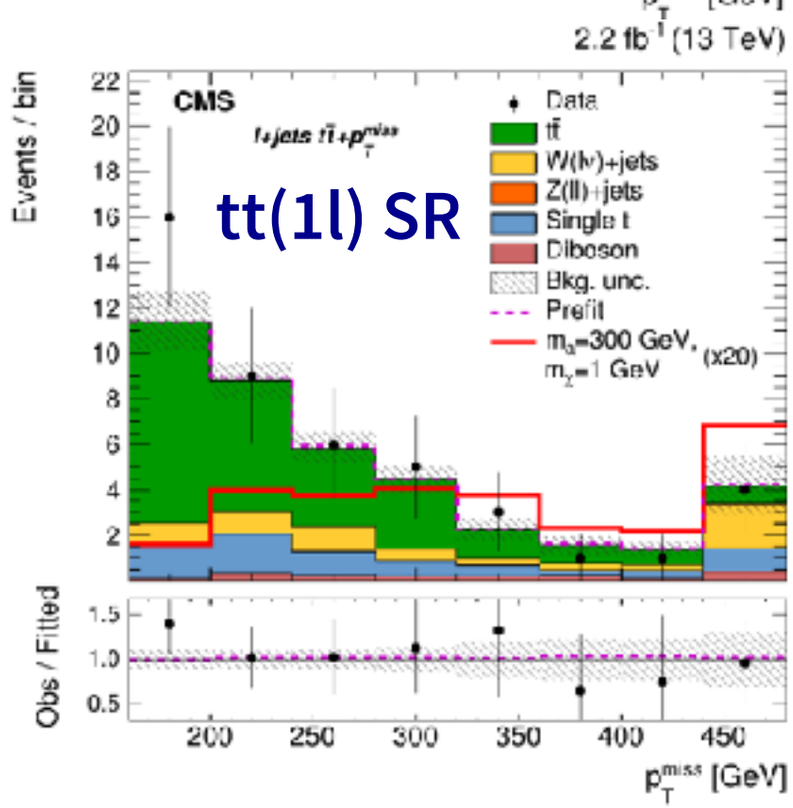
- **Favoured in case of scalar/pseudoscalar mediator models**
  - Mediator has Yukawa coupling ($\propto m_q$)
  - Mono-Jet through heavy quark loops
- **Top/bottom-quark pair recoiling against DM particles**
  - MET is the most sensitive variable
    - Currently best sensitivity to low MET
  - Search employs resolved top tagged to reconstruct low/medium p_T hadronic decays
- **Background mostly from SM ttbar**
  - Additional contribution from Z(νν)+jets and W(lν) +jets
  - Combined maximum likelihood fit to E_T^{miss} in SRs and CRs

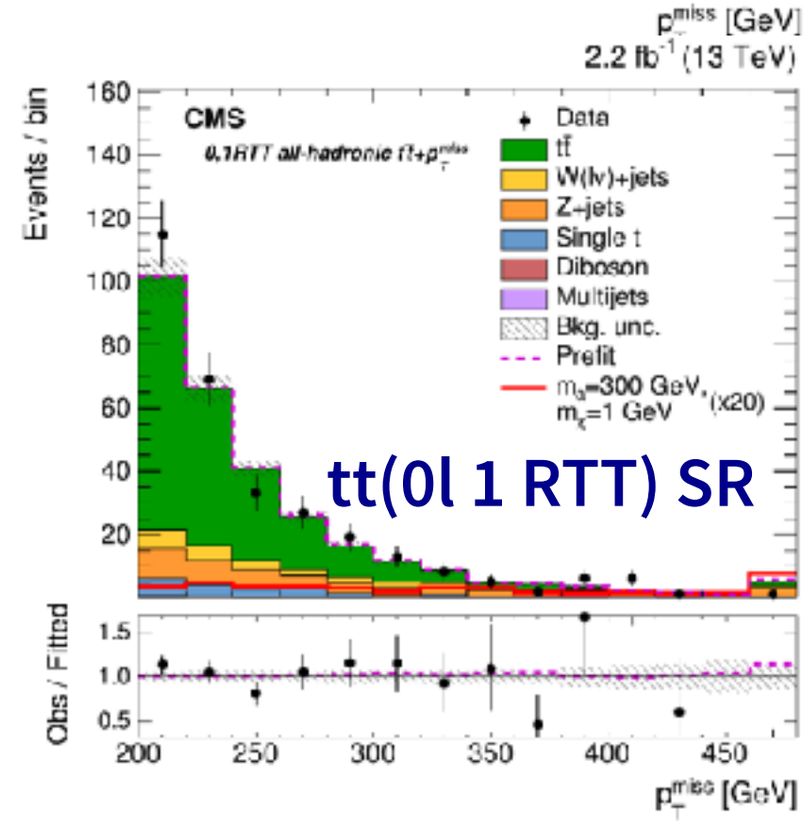


DM + HF







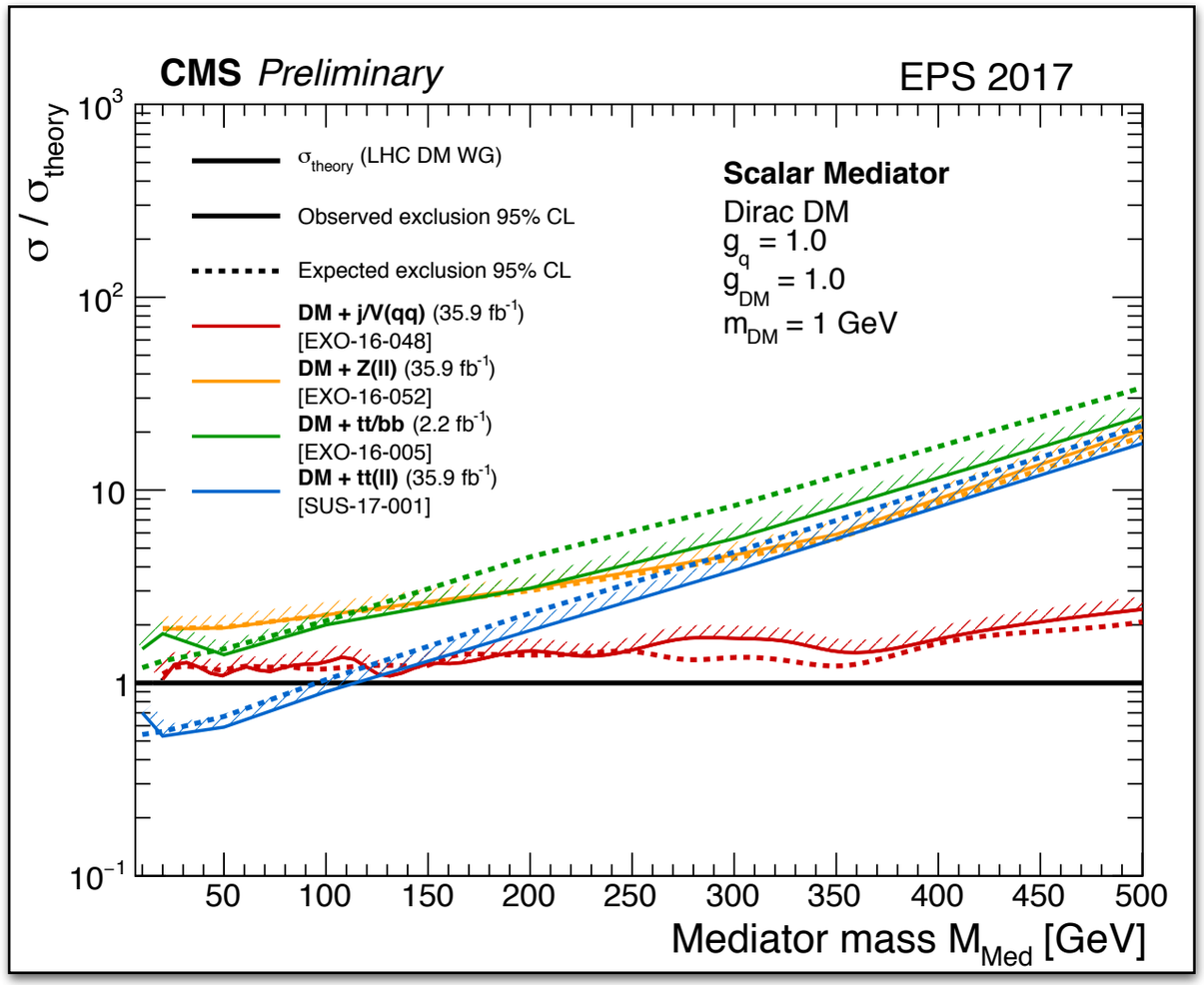


CMS-EXO-16-005 - arXiv:1706.02581

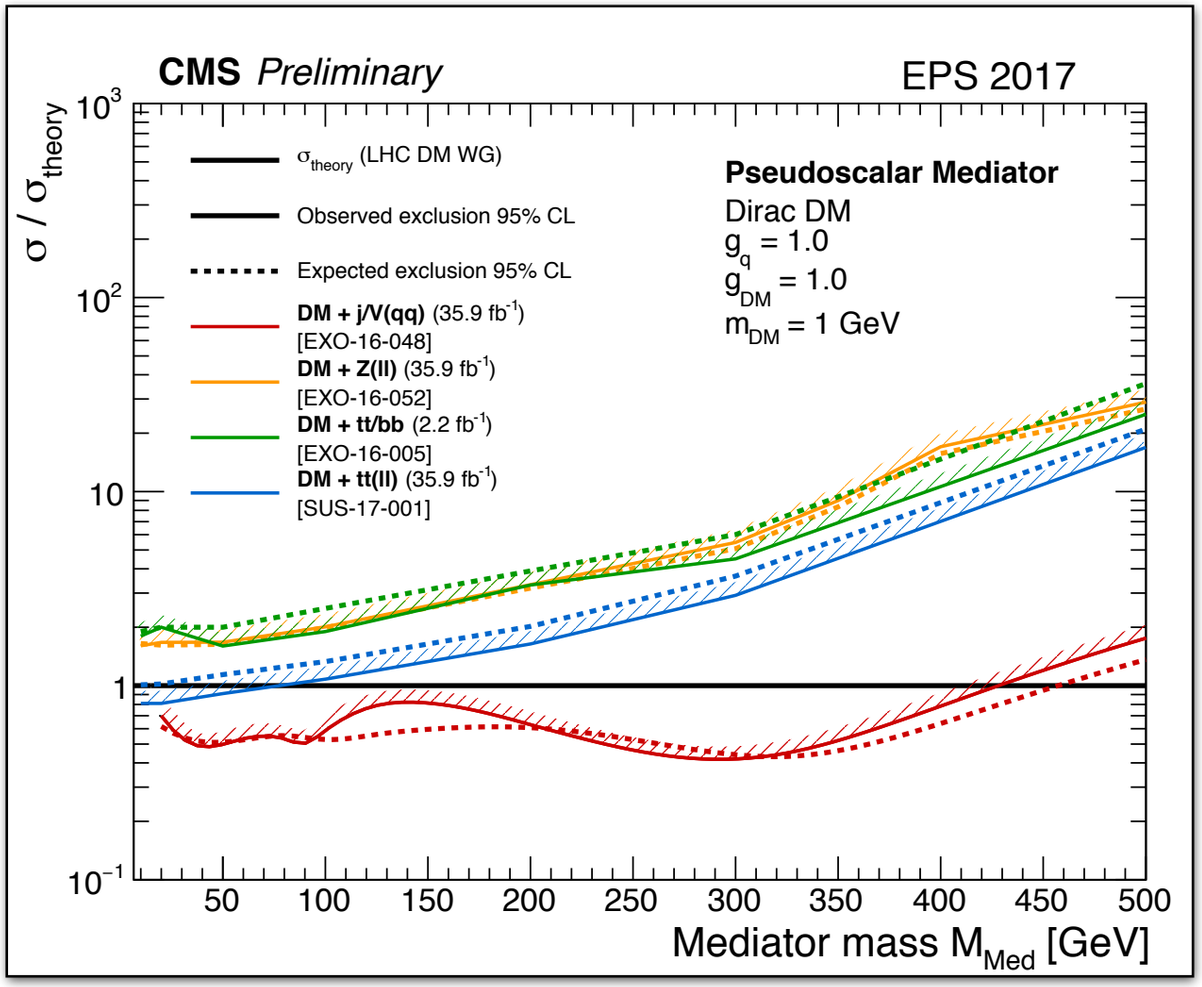
Scalar/Pseudoscalar mediators

- **Spin-0 mediator**
  - DM with heavy flavour can strongly constraint scalar/pseudoscalar DM mediators
  - Not fully luminosity exploited for DM + HF channels
  - Lots of progress expected in 2017

Scalar

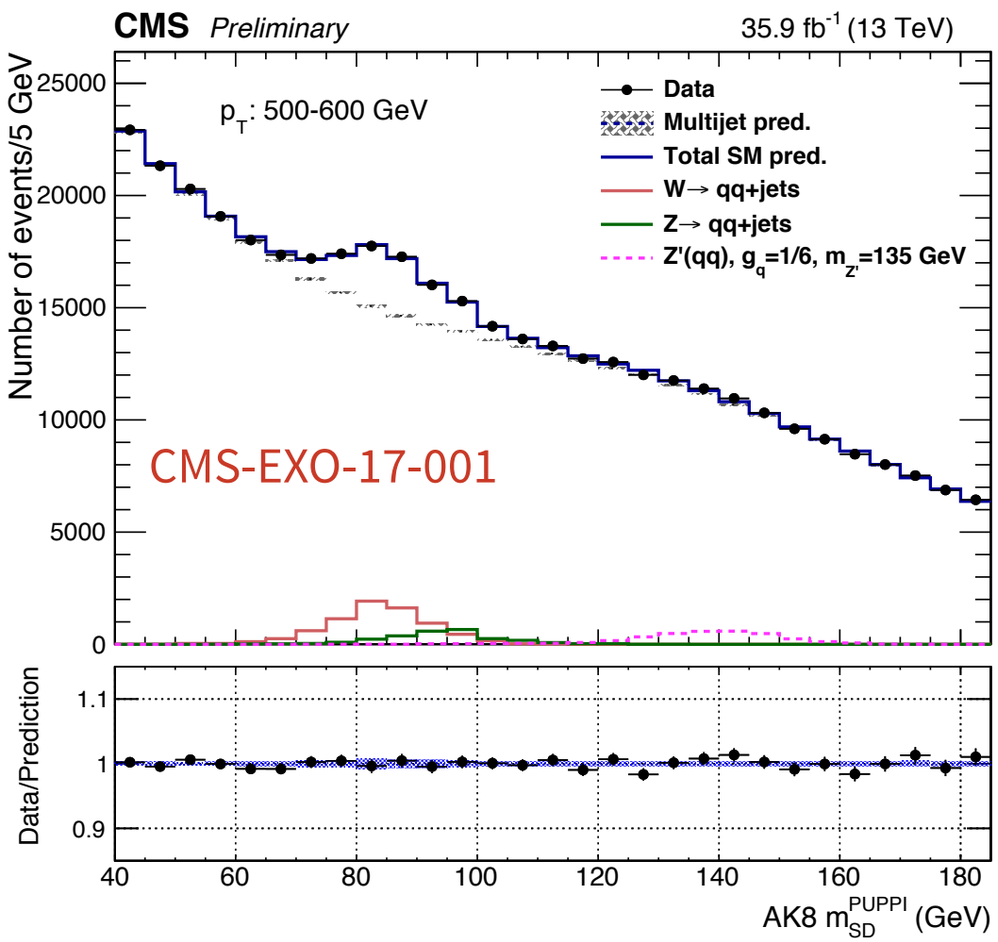


Pseudo-Scalar

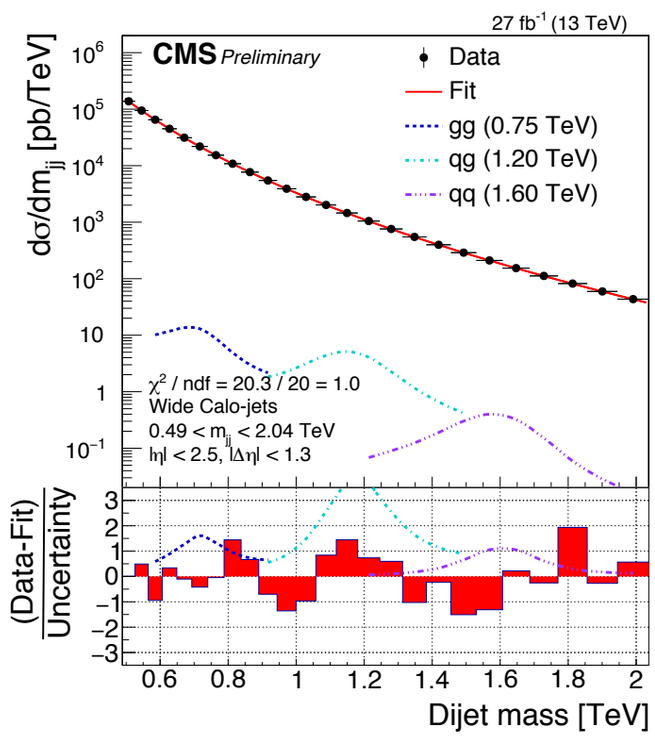


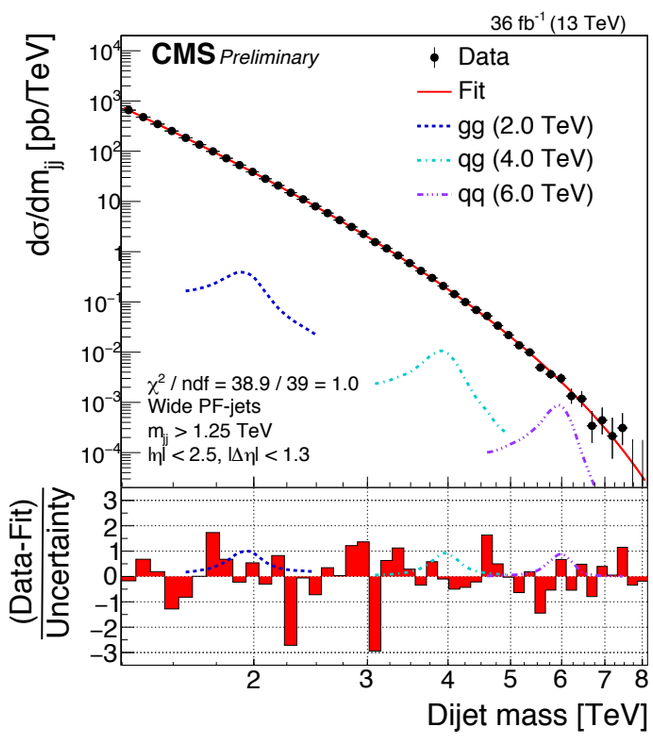
Visible mediator searches

- **Complementary information from visible decays of the mediator**
  - If mediator couples to quarks, it can also decay to SM particles
  - Look for a bump in dijet invariant mass spectrum
    - New techniques employed to further extend the reach (data-scounting, using data with only trigger-level objects to get small m_{jj})



CMS-EXO-16-056

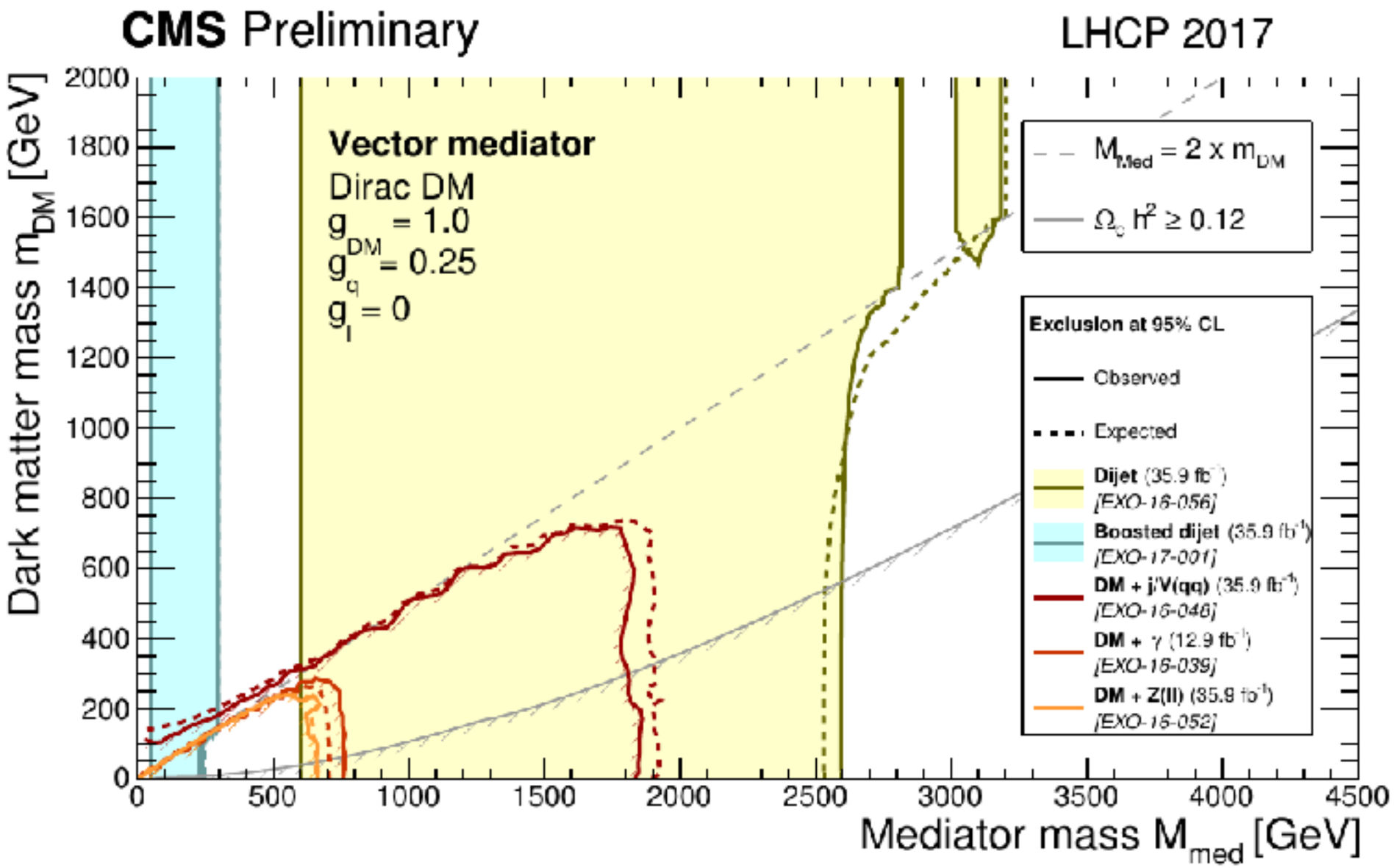




Visible mediator searches

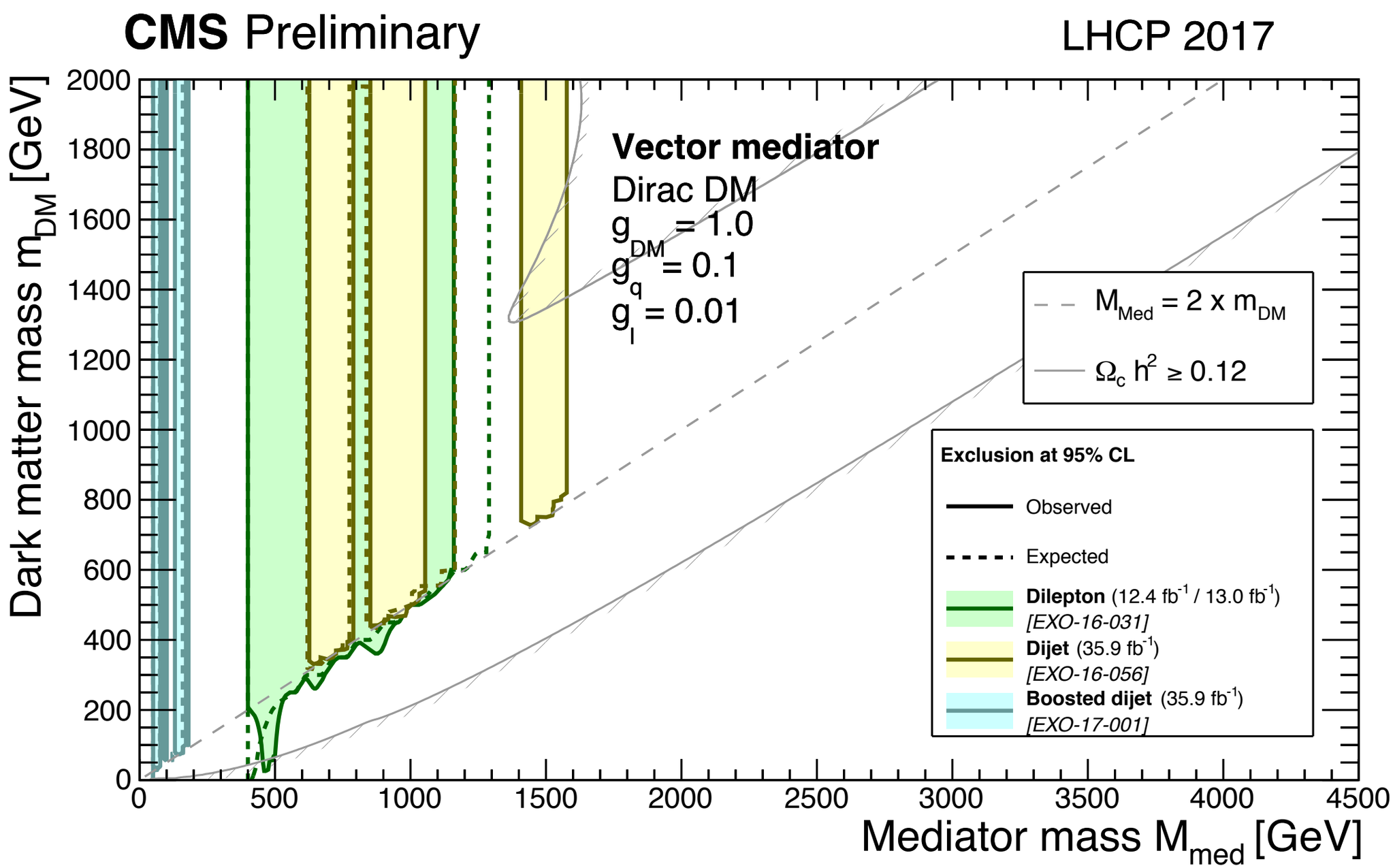
Searches for visibly decaying mediators can constrain DM

Provides complementary information to searches for invisible decay



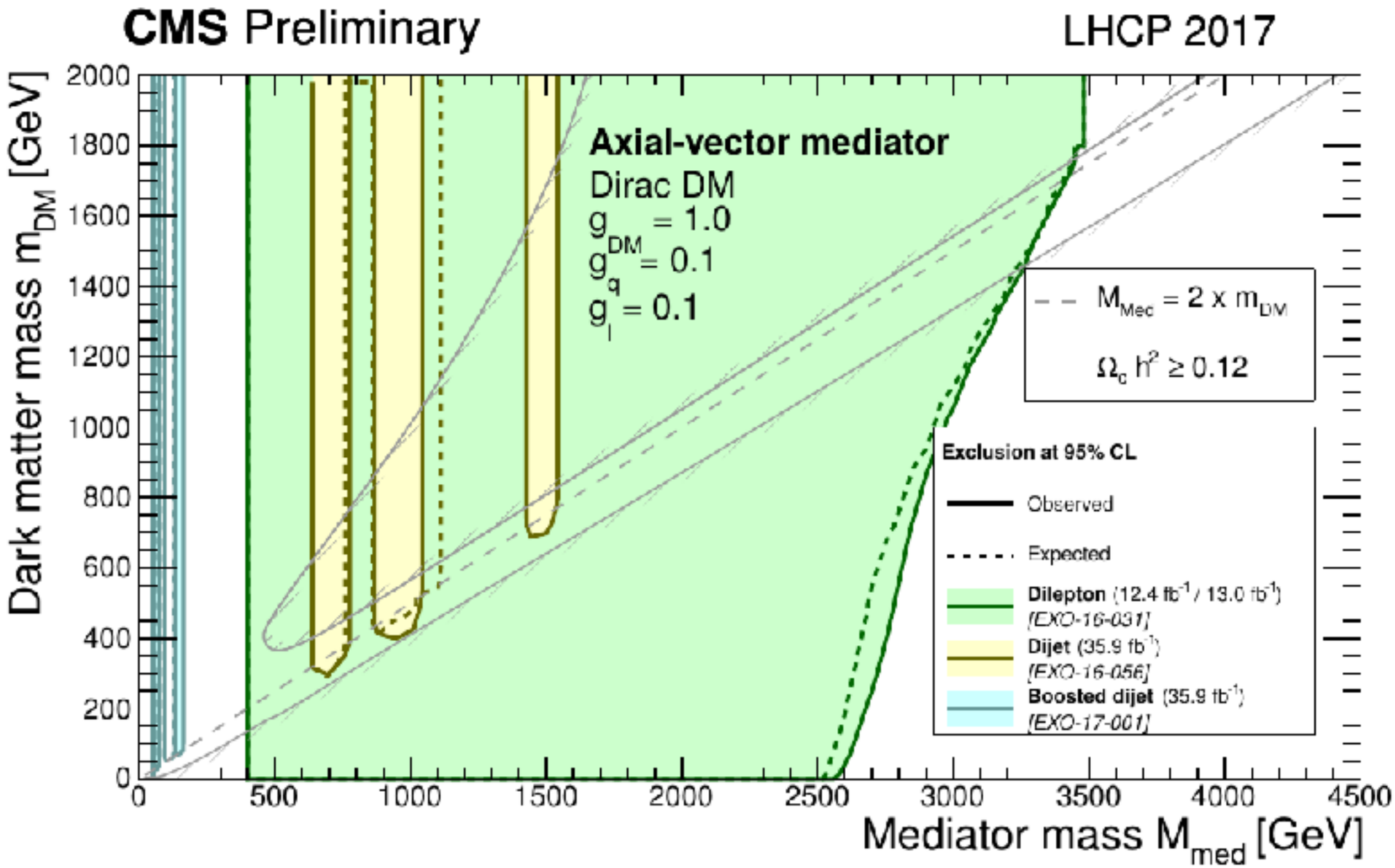
Visible mediator searches

Strong dependence on coupling choice



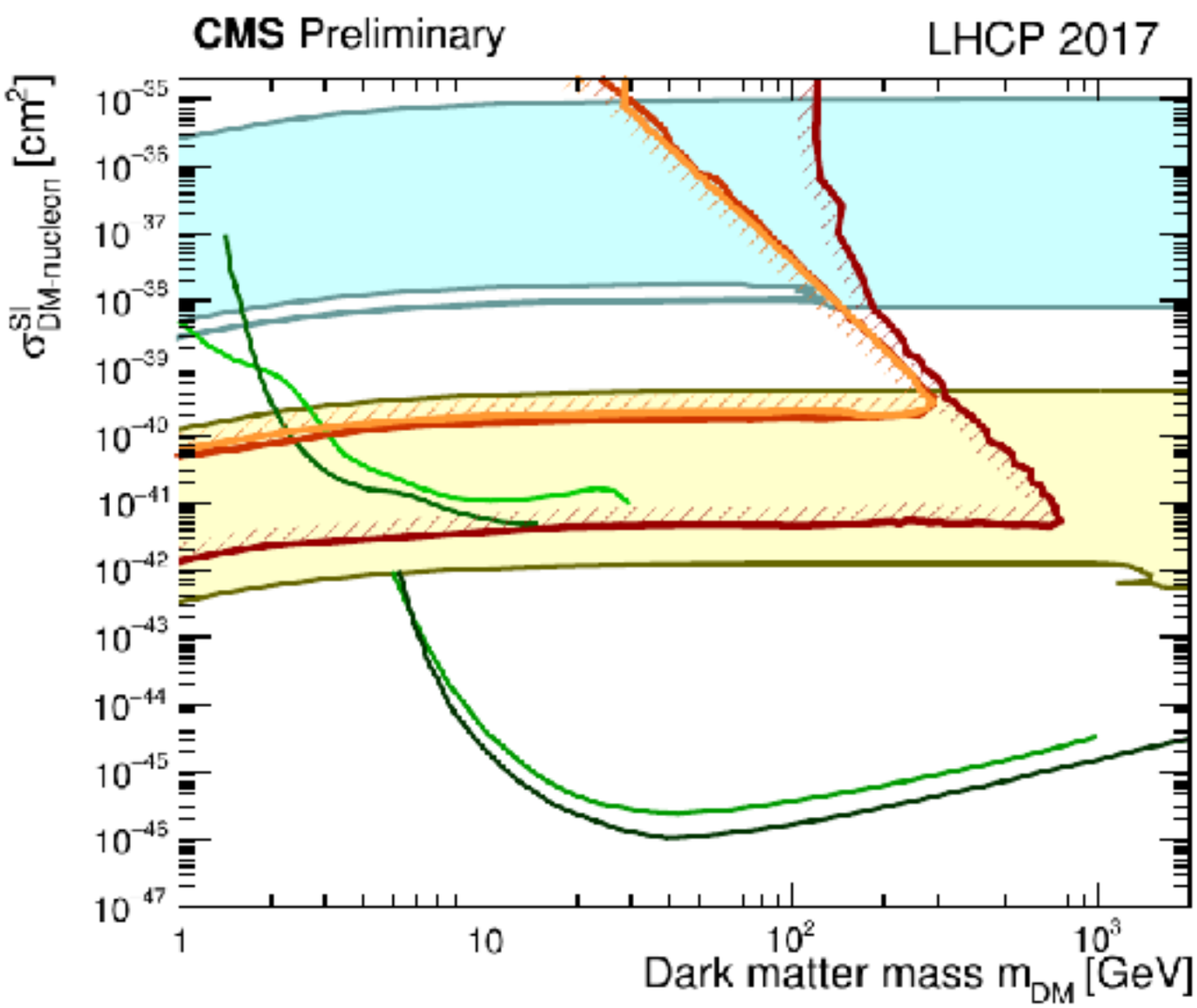
Visible mediator searches

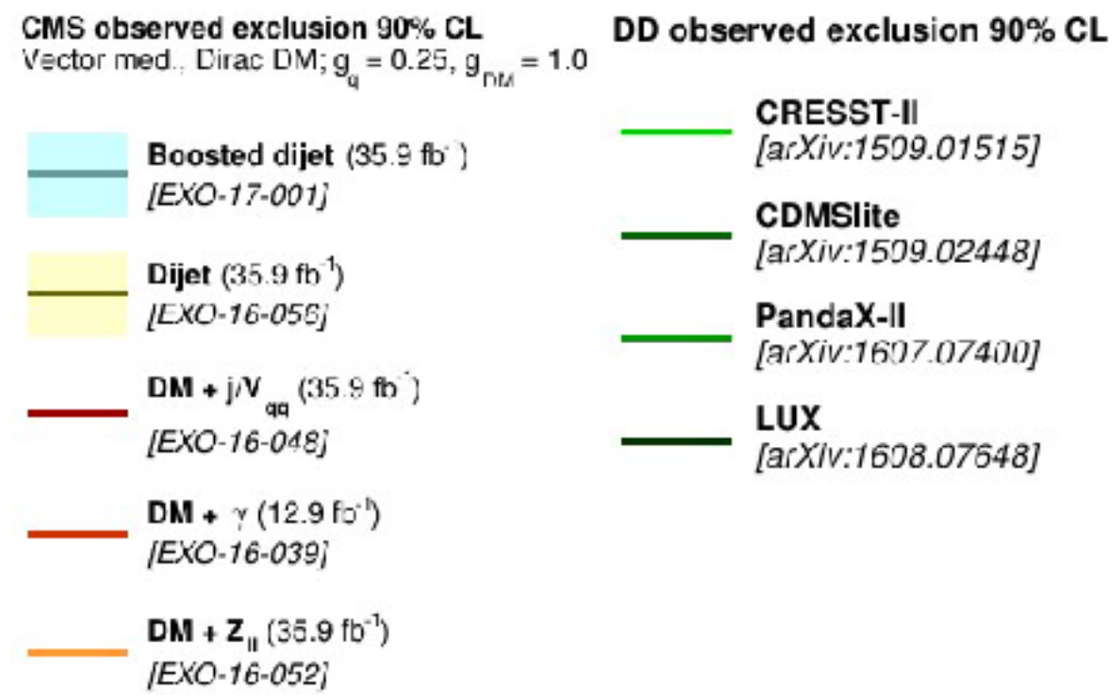
Strong dependence on coupling choice



Comparison with Direct Detection

- **Translation into direct-detection plane (Spin Independent)**
  - From m_{DM}—M_{med} to $\sigma_{DM\text{-}nucleon}$ —m_{DM} plane



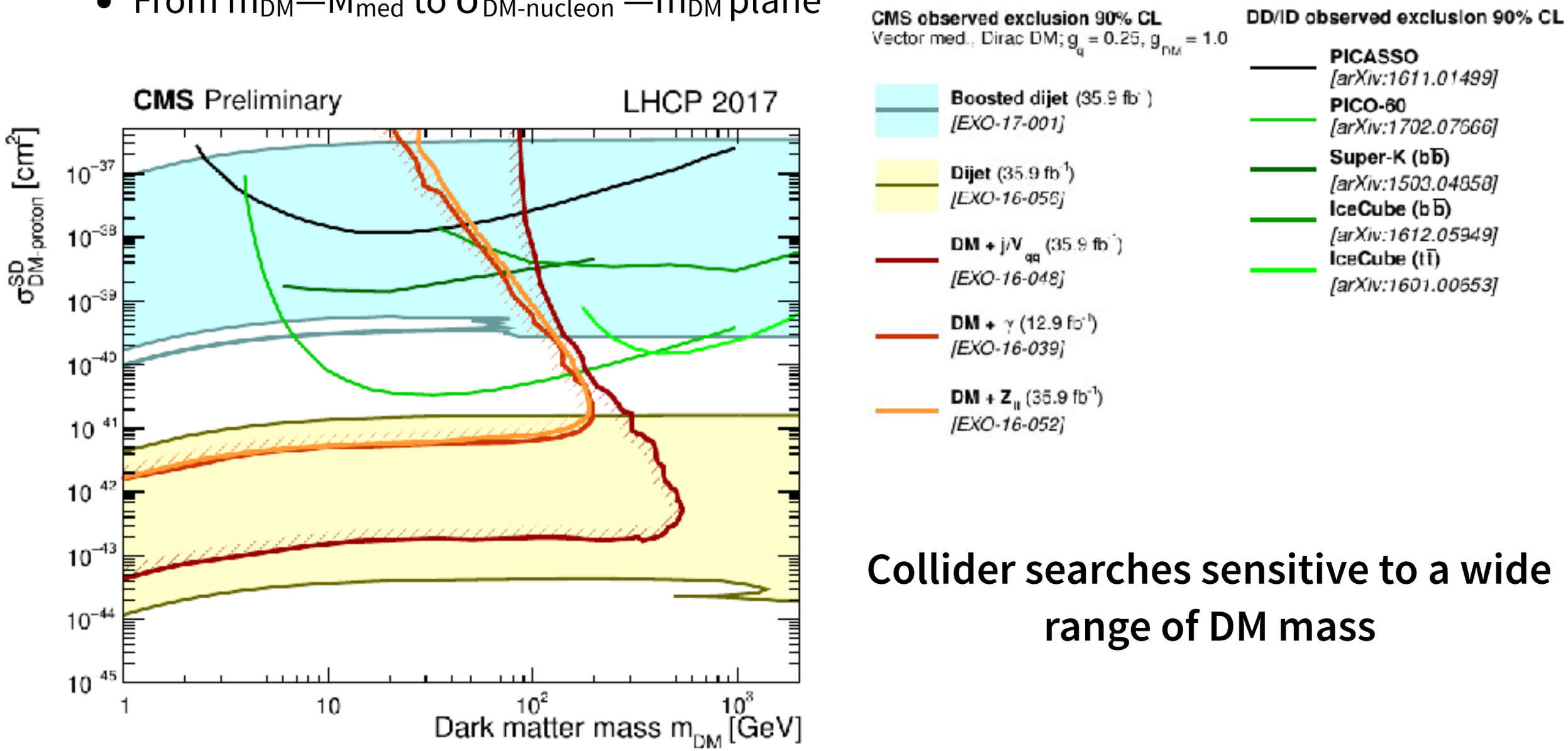


Collider searches sensitive to low DM mass region

Complementarity to DD experiments

Comparison with Direct detection

- **Translation into direct-detection plane (Spin Dependent)**
  - From m_{DM}—M_{med} to $\sigma_{DM\text{-}nucleon}$ —m_{DM} plane



Collider searches sensitive to a wide range of DM mass

Conclusions and Outlook

- **The Dark Matter problem stands out as one of the major challenges for modern physics**
  - LHC can probe DM at the frontiers of high energy physics
  - Providing complementarity to direct and indirect searches
- **Run II searches enable probing WIMP DM models**
  - Employing more accurate models
  - Exploiting advanced analysis techniques and background estimation methods
- **Moving towards interpretation with more complex models**
  - Working closely with theorists to develop new models: LHC DM working group
- **Great expectations for 2017: ~ 45 fb^{-1} of data expected by the end of the year**

Additional Material

EFT limitations

EFT doesn't correctly accounts for kinematics and is not valid for $Q > m_{MED}$

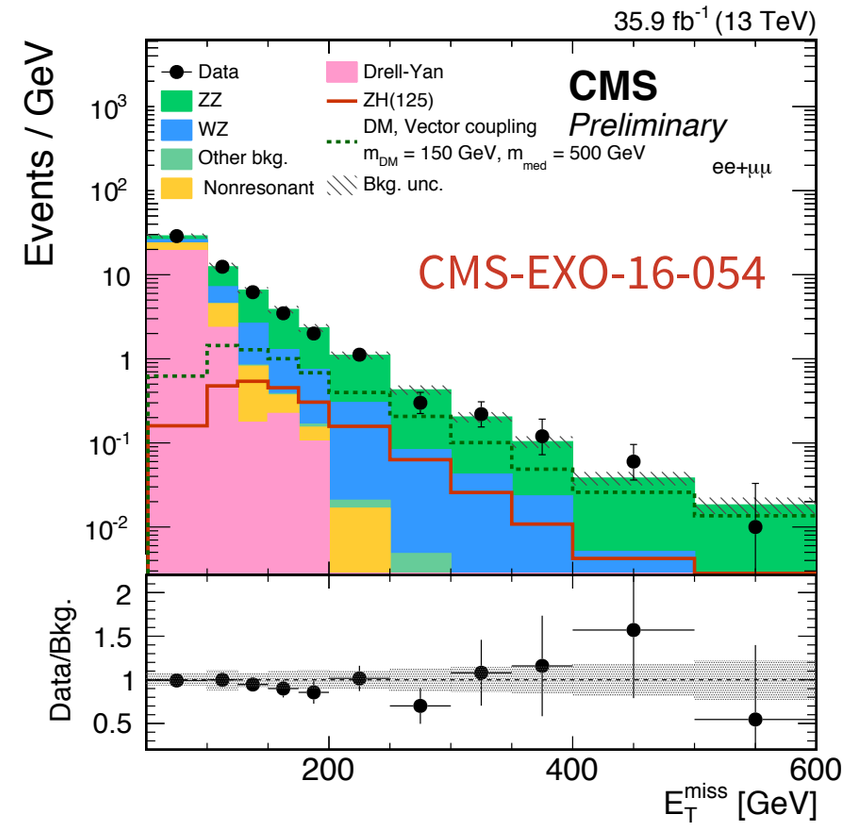
- **High m_{Med}:**
  - EFT consistent with SM
- **Intermediate m_{Med}:**
  - On-shell production increases σ
  - EFT limits too weak
- **Low m_{Med}:**
  - Off-shell production $\rightarrow \sigma$ decreases
  - Events are softer
  - EFT limits too strong

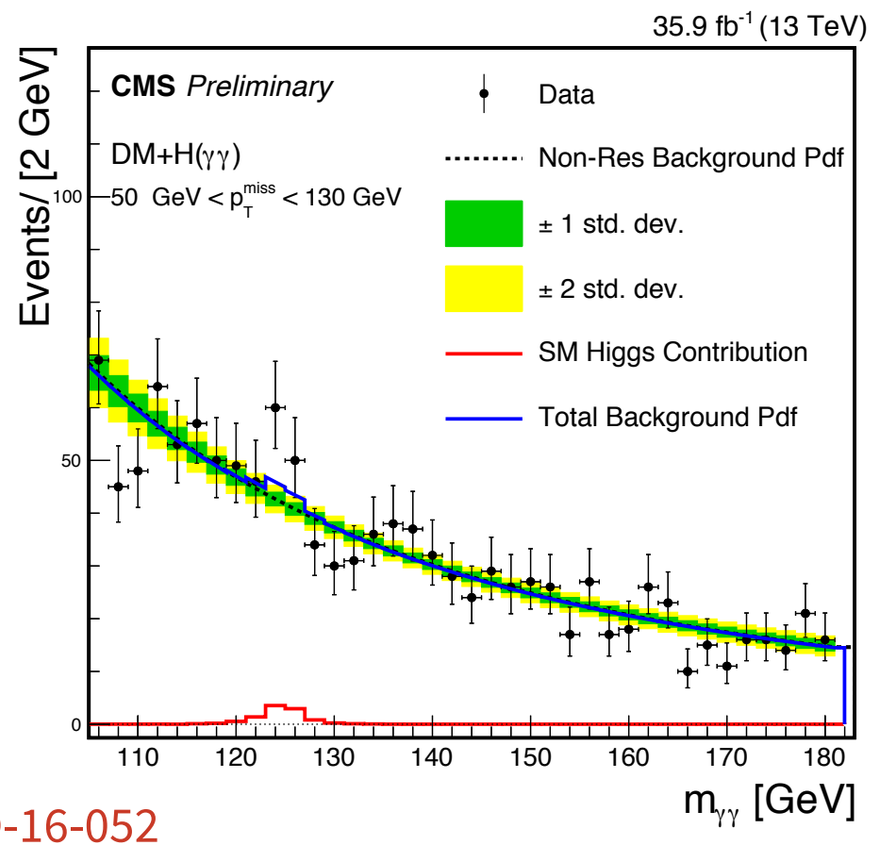
EFT not an appropriate approach to reach a comprehensive interpretation of DM searches

Higgs boson: a bridge to DM

Higgs boson may work as SM-DM mediator or produced in association to DM particles

- **Mono-Z(ll)**
  - Lepton triggers can probe lower MET spectrum
  - Dominant background from VV production estimated from a binned maximum likelihood fit to MET in SR and CRs





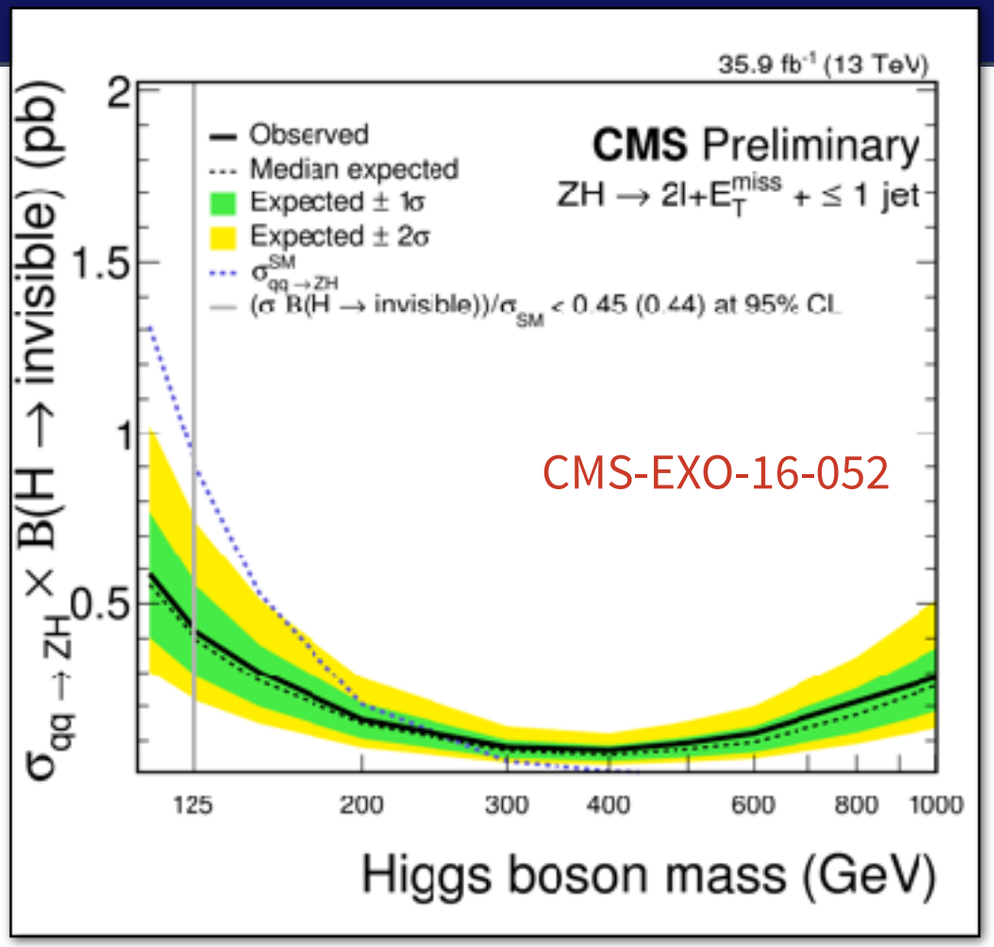
CMS-EXO-16-052

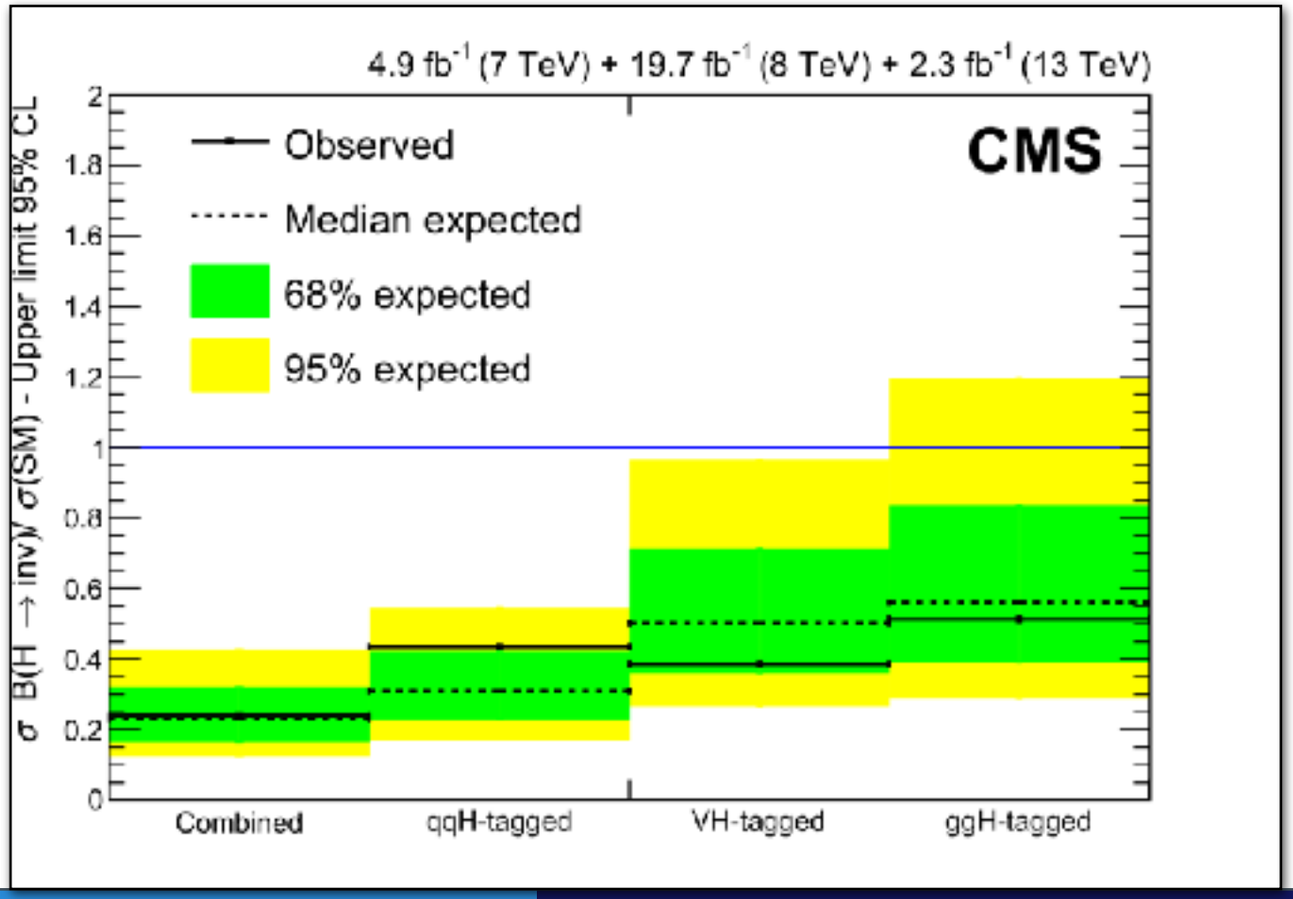
- **Mono-h(in γγ)**
  - Very small background and excellent diphoton mass resolution
    - Fit to $m_{\gamma\gamma}$
  - Background estimation includes resonant and non-resonant contributions

Higgs invisible

Mono-Z search with a Z boson decaying leptonically

- **reinterpreted in terms of ZH with H invisible**





No significant excess observed over SM prediction in all the channel investigates

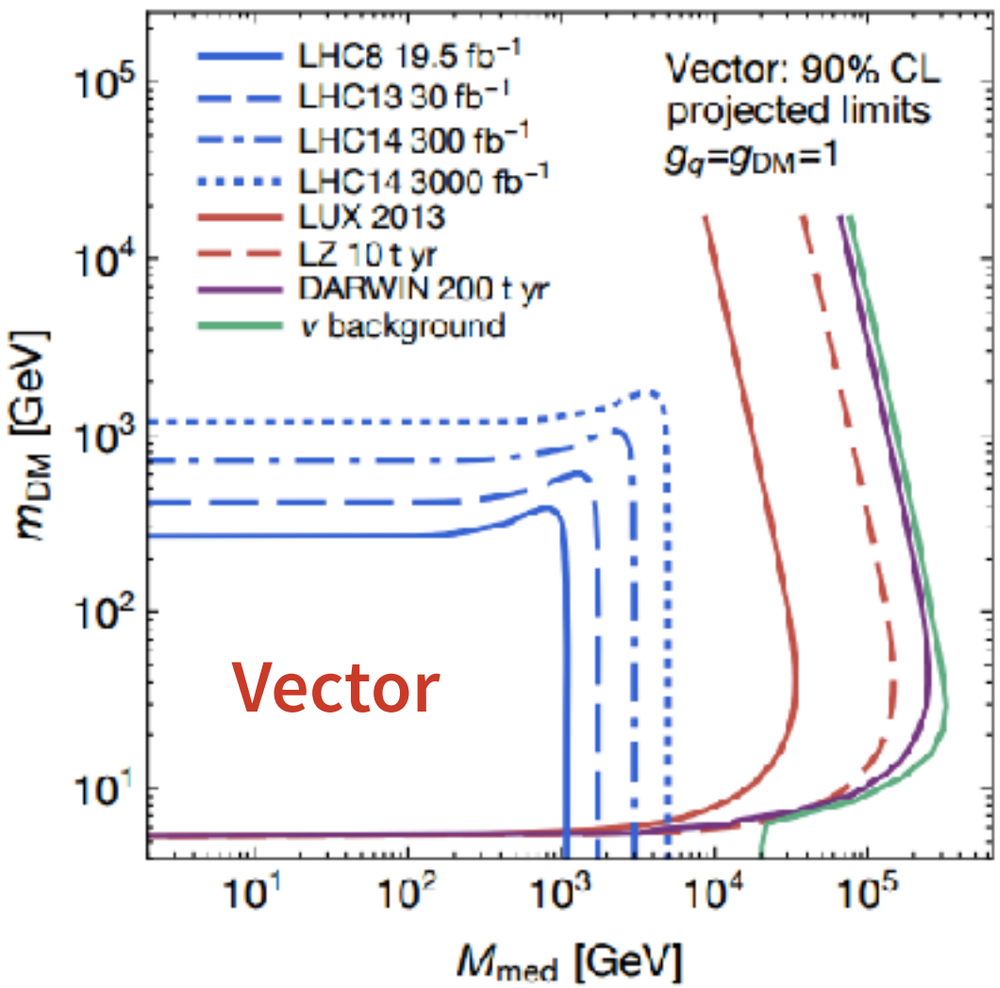
Results still dominated by 8 TeV

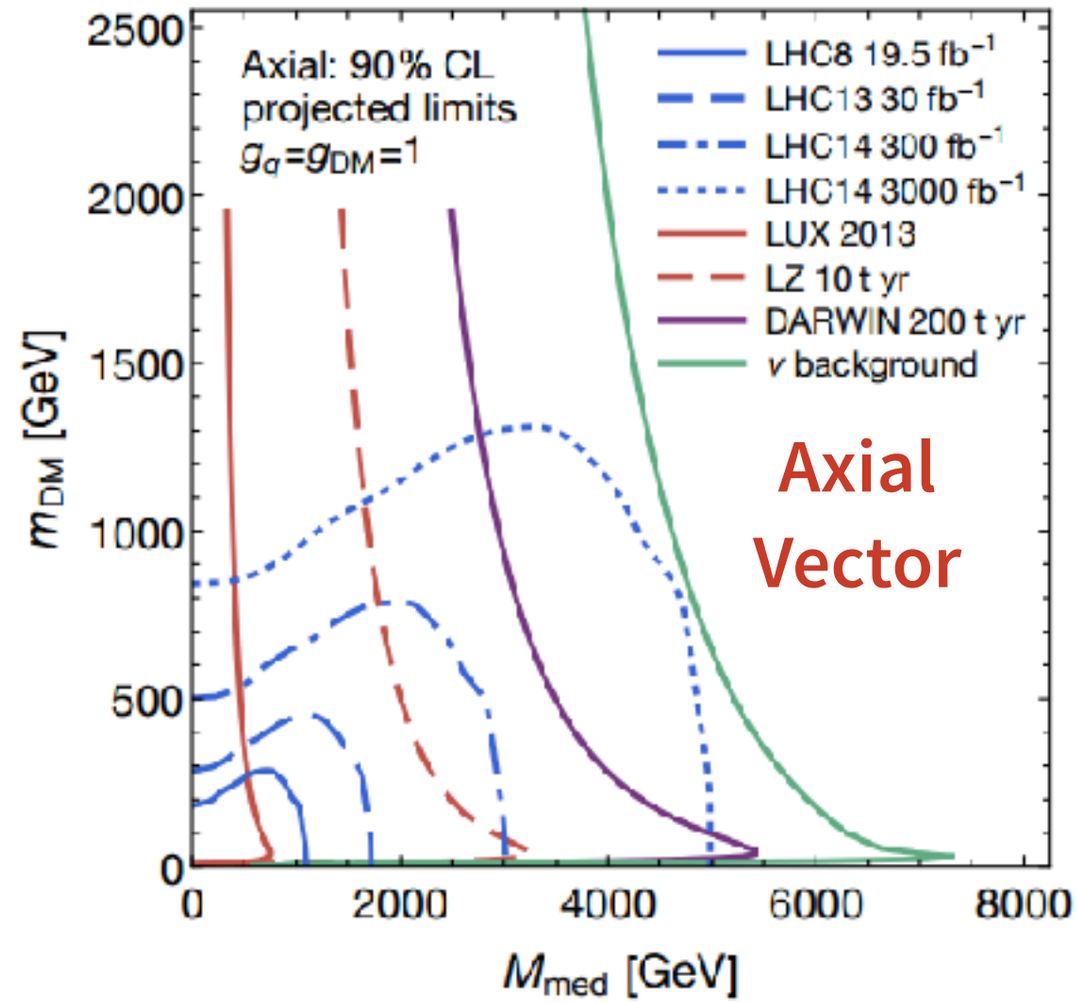
CMS-EXO-16-009

A look to the future

Projections for

- **Run-II: 30 fb^{-1} @ 13 TeV**
- **Run-III: 300 fb^{-1} @ 14 TeV**
- **HL-LHC: 3000 fb^{-1} @ 14 TeV**





Expected limits for

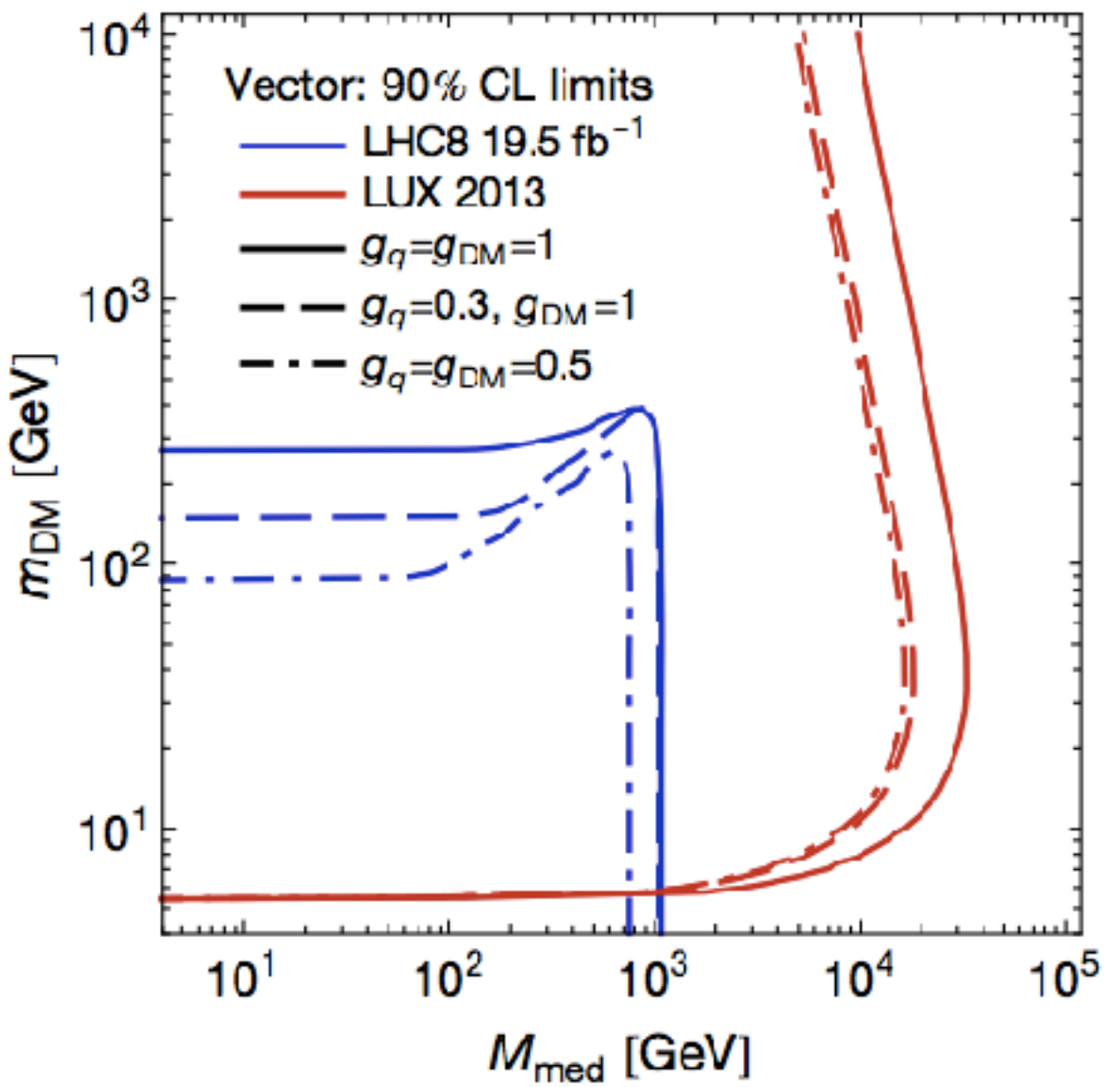
- **LUX-ZEPLIN: 10 tonne years exposure**
- **DARWIN 200 tonne years exposure**

Complementarity of DM search strategies

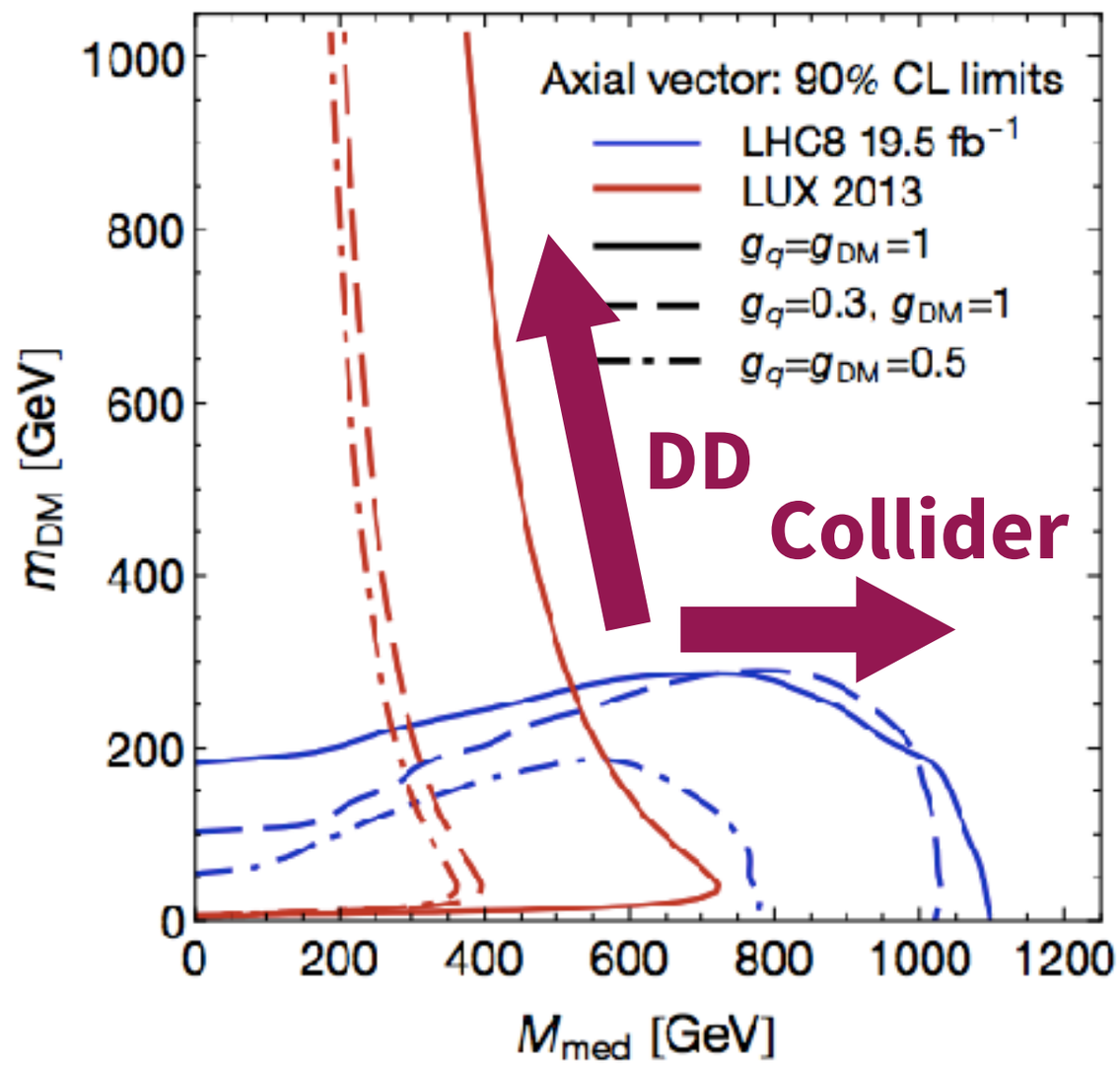
All these search channels are highly complementary to one another

- Access to different regions of DM masses

Vector



Axial-Vector



Direct detection limited at m_{DM} ~ 6 GeV

Translating results on DD plane

Vector

$$\sigma^V_{\chi p} = \frac{9}{\pi}\frac{g^2_{\rm DM} g^2_{\rm SM} \rho^2}{m^4_{\rm MED}}$$

Scalar

$$\sigma^S_{\chi p} = \frac{\rho^2}{\pi}\left|\frac{m_p}{m_t}\frac{g_t y_t \; g_\chi y_\chi}{m^2_{\rm MED}}\frac{2}{27} f_{\rm TG}\right|^2$$

Axial-Vector

$$\sigma^A_{\chi p} = \frac{3}{\pi}\frac{g^2_{\rm DM} g^2_{\rm SM} a^2 \rho^2}{m^4_{\rm MED}}$$

Pseudoscalar

$$\langle \sigma v \rangle^P_{\bar{b}b} = \frac{N_C}{2\pi}\frac{(y_b g_b)^2 (y_\chi g_\chi)^2 \, m^2_{\rm DM}}{(m^2_{\rm MED} - 4m^2_{\rm DM})^2 + m^2_{\rm MED}\Gamma^2_{\rm MED}}\sqrt{1 - \frac{m^2_b}{m^2_{DM}}}$$

hep-ph/1411.0535v2

hep-ph/1407.8257v2

Fit to signal and control regions

Combined maximum likelihood fit to CRs and SR to estimate E_T^{miss} shape and normalisation of EWK backgrounds

signal

$$\mathcal{L}(\mu, \mu^{Z\to\nu\nu}, \mu^{W\to l\nu}, \theta) = \prod_i \text{Poisson}\Big(d_i | B_i(\theta) + \mu_i^{W\to l\nu} + \mu_i^{Z\to\nu\nu} + \mu S_i(\theta)\Big)$$

$$\times \prod_i \text{Poisson}\Big(d_i^Z | B_i^Z(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^Z(\theta)}\Big)$$ ***dilepton***

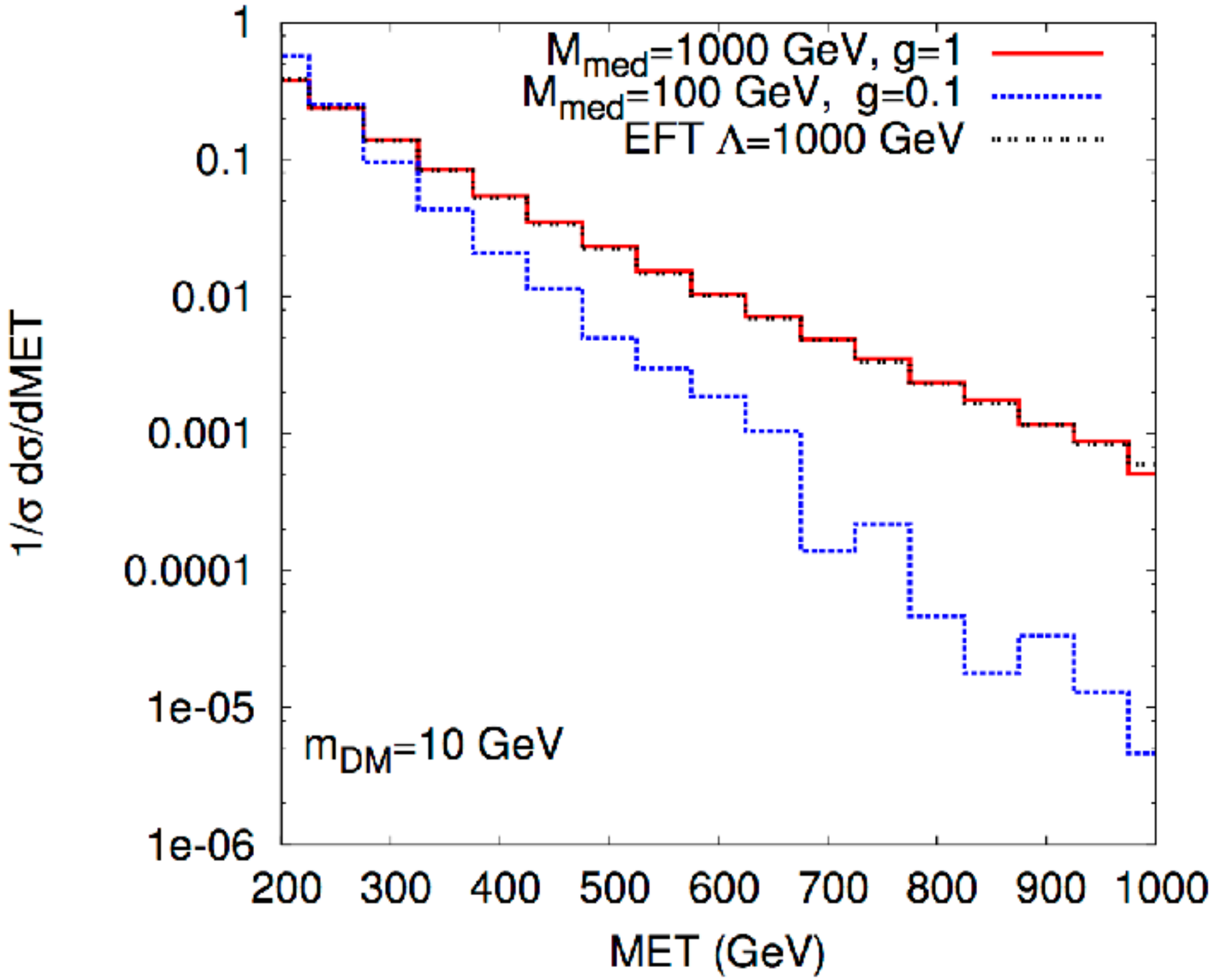
$$\times \prod_i \text{Poisson}\Big(d_i^\gamma | B_i^\gamma(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^\gamma(\theta)}\Big)$$ ***photon***

$$\times \prod_i \text{Poisson}\Big(d_i^W | B_i^W(\theta) + \frac{\mu_i^{W\to l\nu}}{R_i^W(\theta)}\Big)$$ ***single lepton***

Z(→νν) + jets and W(→μ/e ν) + jets estimates further constrained by Z/W cross-section ratio

$$\mu^{W\to l\nu} \to f_i(\theta) \cdot \mu^{Z\to\nu\nu}$$

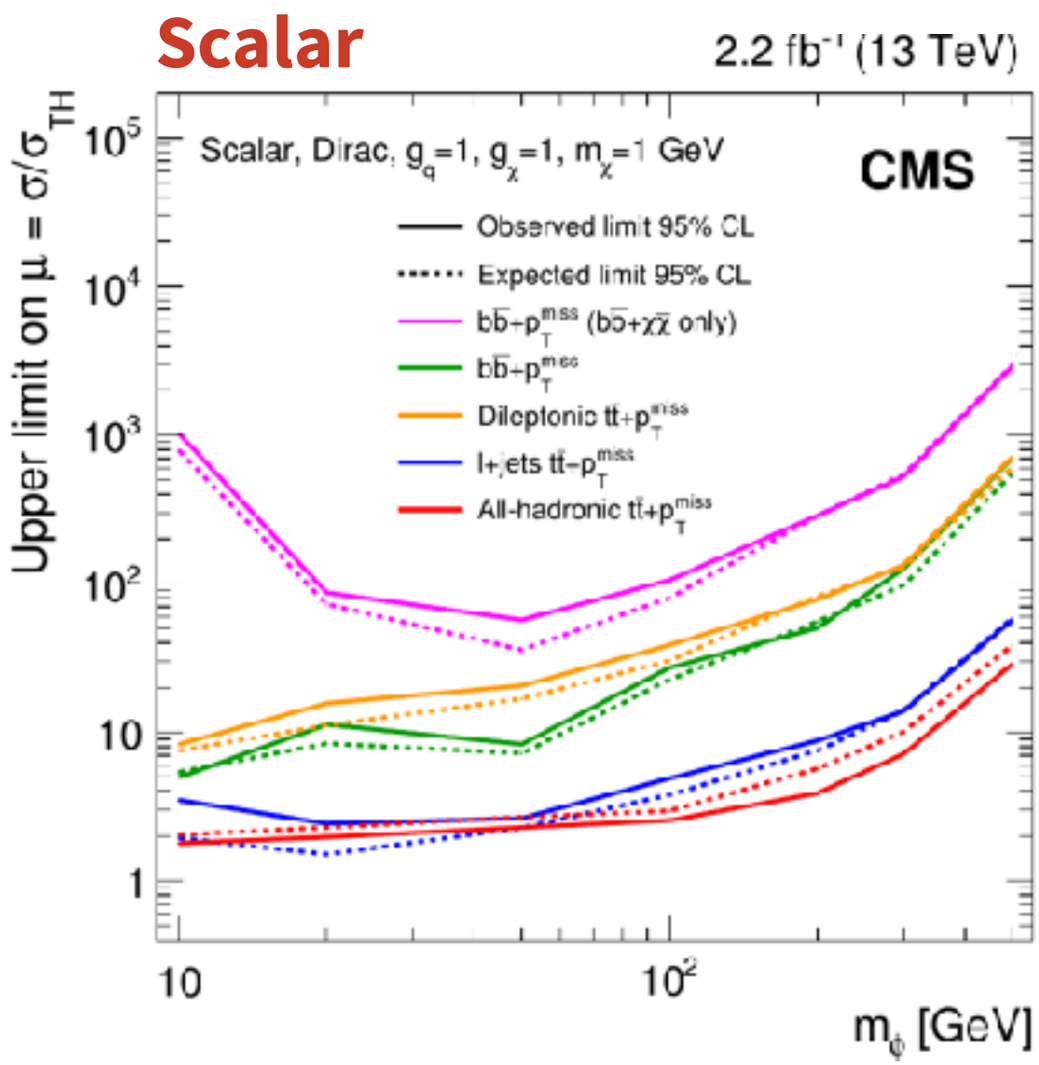
DM Kinematics

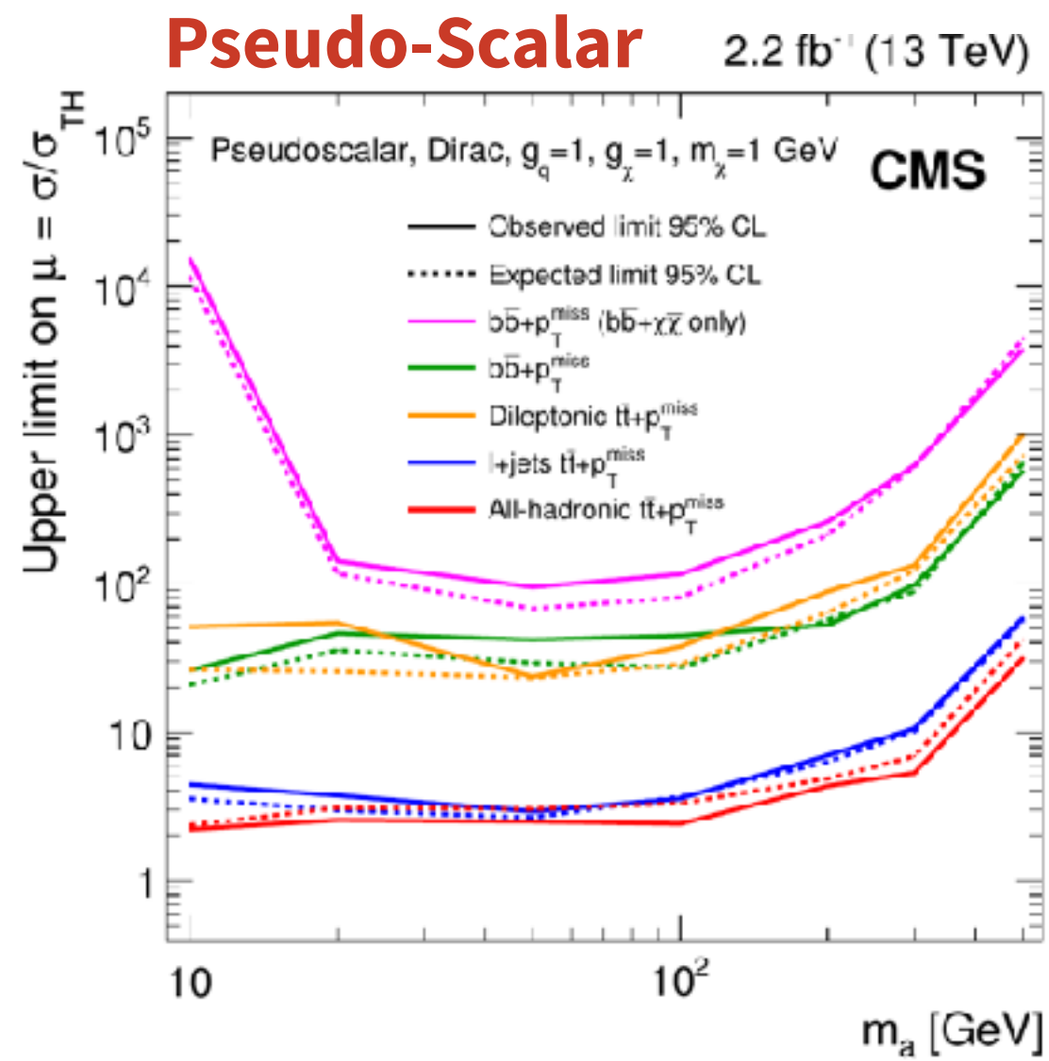


Scalar/Pseudoscalar mediators

CMS-EXO-16-005 - arXiv:1706.02581

- **Spin-0 mediator**
  - DM with heavy flavour can strongly constraint scalar/pseudoscalar DM mediators
  - Not fully luminosity exploited for DM + HF channels
  - Lots of progress expected in 2017





Bounds on $\sigma_{\chi\text{-}N}$

- **Upper limits on σ_χ in mDM—Mmed plane translated to $\sigma_{\chi\text{-}N}$ – mDM plane in lower (arXiv:1603.04156)**

In general, the SI DM-nucleon scattering cross section takes the form

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}\,, \tag{4.1}$$

where $\mu_{n\chi} = m_n m_{\rm DM}/(m_n + m_{\rm DM})$ is the DM-nucleon reduced mass with $m_n \simeq 0.939\,\text{GeV}$ the nucleon mass. The mediator-nucleon coupling is $f(g_q)$ and depends on the mediator-quark couplings. For the interactions mediated by vector and scalar particles and for the recommended coupling choices, the difference between the proton and neutron cross section is negligible.

For the vector mediator,

$$f(g_q) = 3 g_q\,, \tag{4.2}$$

and hence

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-41}\ \text{cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,\text{TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\text{GeV}}\right)^2 . \tag{4.3}$$

Bounds on $\sigma_{\chi\text{-}N}$

- **Upper limits on σ_χ in mDM—Mmed plane translated to $\sigma_{\chi\text{-}N}$ – mDM plane in lower (arXiv:1603.04156)**

For the axial-vector mediator, the scattering is SD and the corresponding cross section can be written as

$$\sigma_{\rm SD} = \frac{3 f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4} \,. \tag{4.7}$$

In general $f^{p,n}(g_q)$ differs for protons and neutrons and is given by

$$f^{p,n}(g_q) = \Delta_u^{(p,n)}\, g_u + \Delta_d^{(p,n)}\, g_d + \Delta_s^{(p,n)}\, g_s \,, \tag{4.8}$$

Under the assumption that the coupling g_q is equal for all quarks, one finds

$$f(g_q) = 0.32 g_q \,, \tag{4.9}$$

and thus

$$\sigma^{\rm SD} \simeq 2.4 \times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2 . \tag{4.10}$$