Searches for dark matter at CMS

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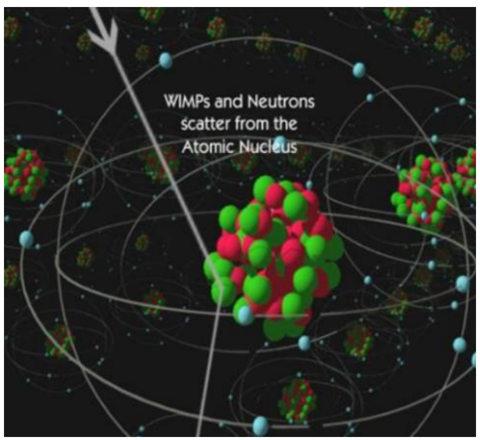
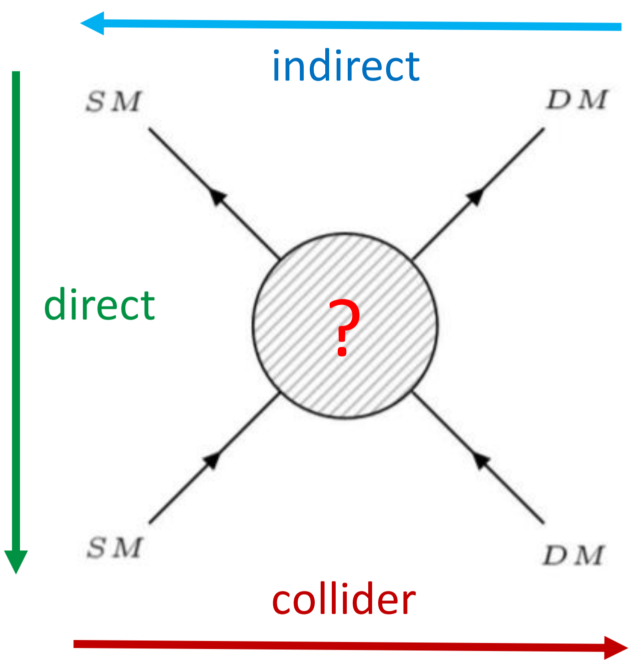
Searching for dark matter (DM)

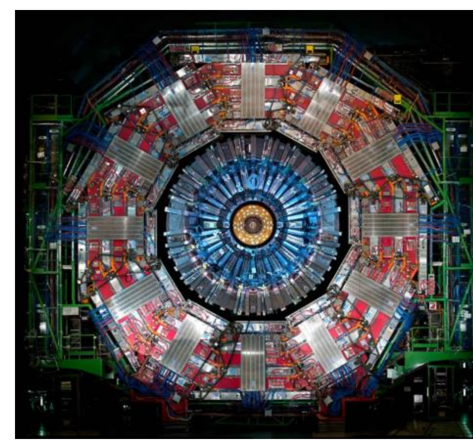
- DM probably made of **Weakly Interacting Massive Particles** (WIMPs)
- 3 types of searches, high degree of complementarity
- sensitivity depends on interaction details

DM annihilation to SM particles



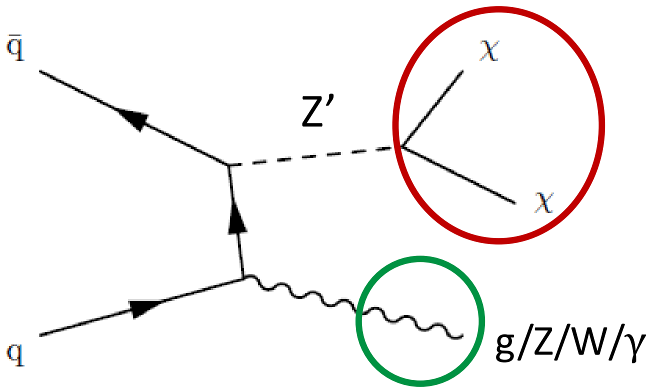
DM scattering on nuclei





DM production in pp collisions

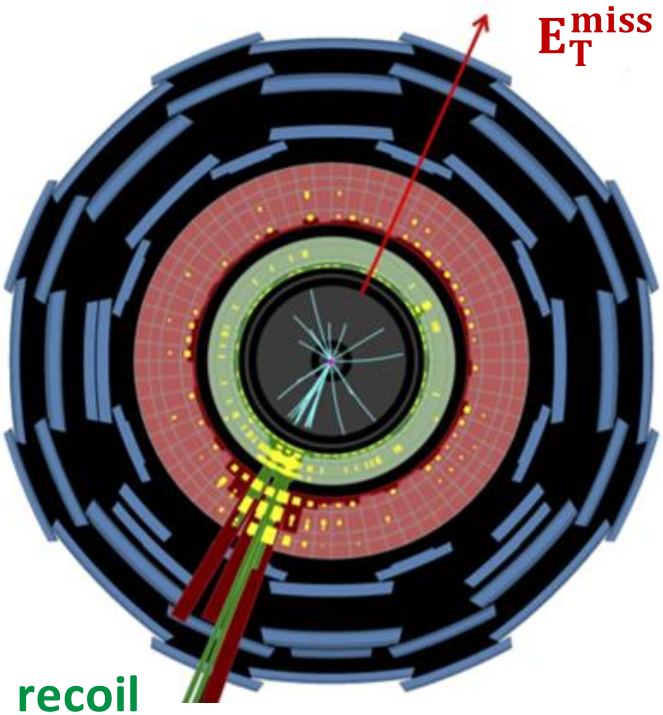
Dark Matter at colliders

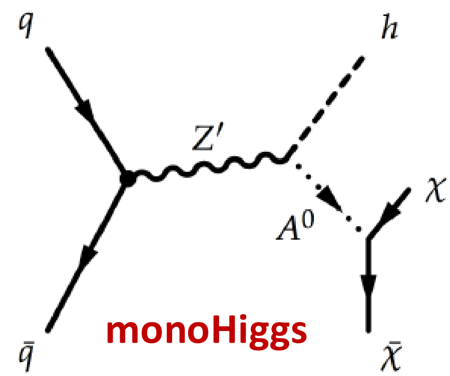


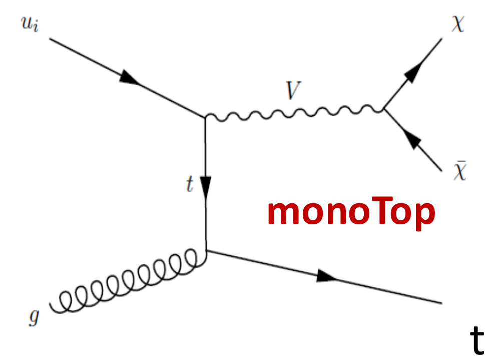
monoJet/Z/W/γ

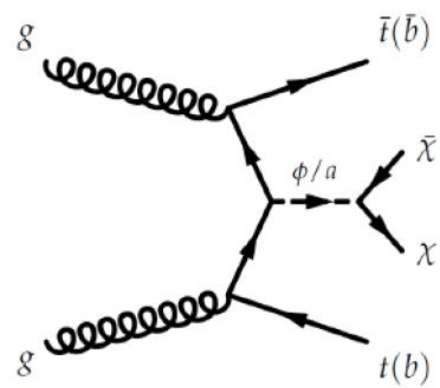
monoX searches:

- **DM**: missing transverse energy (E_T^{miss}, **MET**)
- **X**: **Standard Model** (SM) particles from initial state radiation (**ISR**) → **trigger** on the event
- **signal**: excess of events in the high MET region



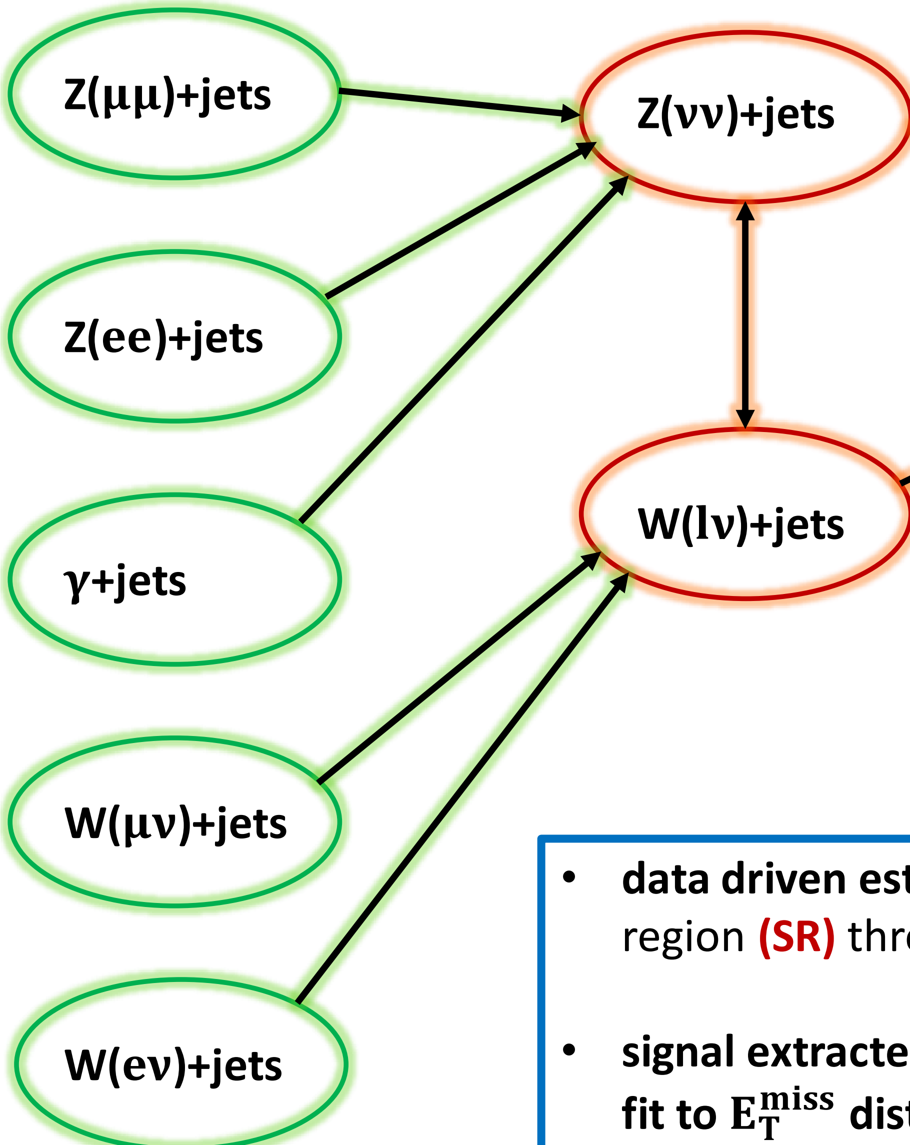


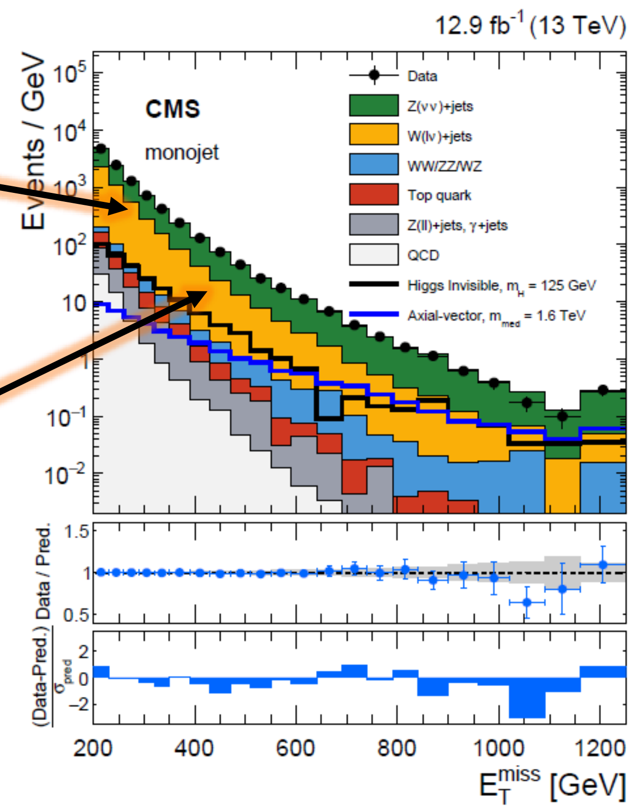




DM + heavy quarks

General analysis strategy





- **data driven estimate** of **irreducible backgrounds** in signal region **(SR)** through many **control regions (CR)**
- **signal extracted through** a combined maximum likelihood **fit to E_T^{miss} distribution** in SR and CR

MonoJet/V overview

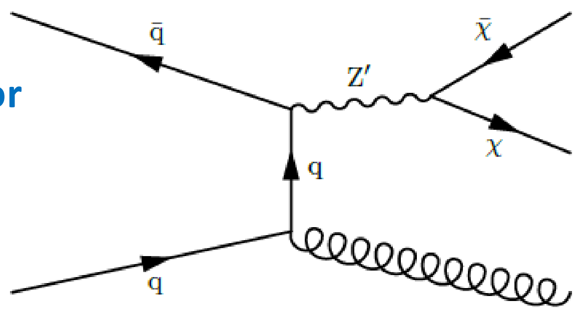
Greatest potential: sensitive to all possible mediator coupling structure

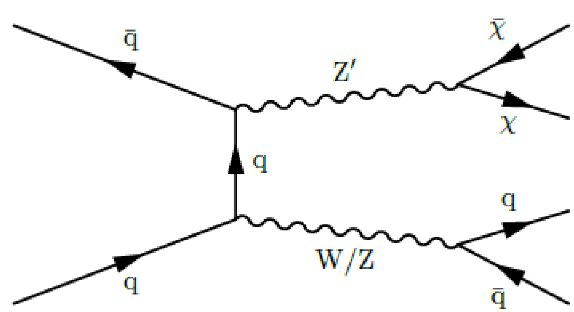
→ vector, axial-vector, scalar, pseudoscalar

→ 2 exclusive category: jet from quark/gluon radiation or W/Z hadronic decay

→ can **probe many theoretical scenarios**, unlike other channels

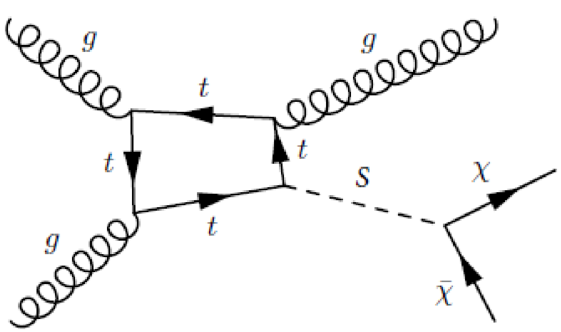
(axial)vector mediator, monoJet

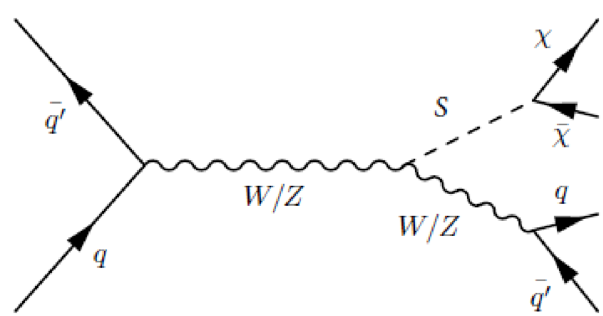




(axial)vector mediator, monoV

(pseudo)scalar mediator, monoJet





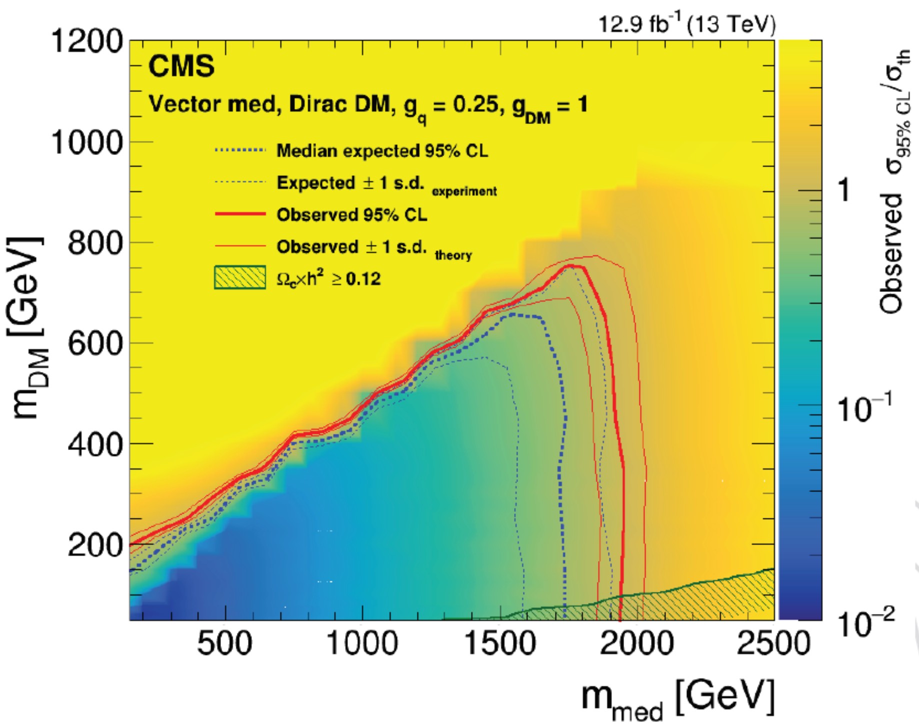
(pseudo)scalar mediator, monoV

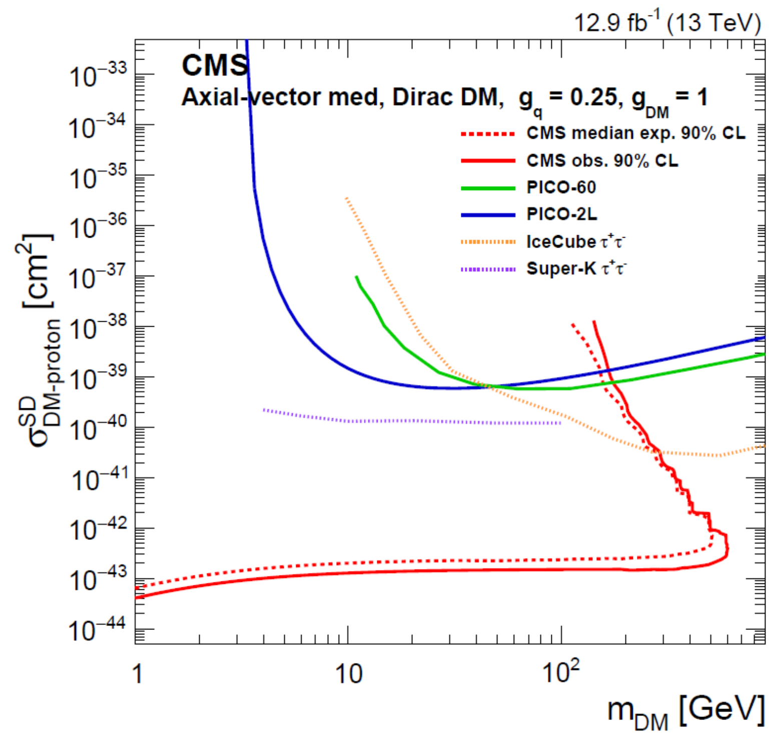
MonoJet/V results

Analysis on full 2016 dataset (36 fb^{-1}) under approval, showing ICHEP results (12.9 fb^{-1})

CMS paper (12.9 fb^{-1}) → arXiv:1703.01651 [hep-ex], submitted to JHEP

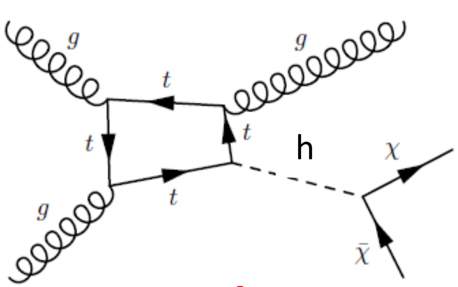
- interpretation with **simplified models: (axial)vector, (pseudo)scalar mediators**
- $\mathbf{m_{med}}$ **< 1.95 TeV** for (axial)vector, **< 100(430) GeV** for scalar(pseudoscalar) mediator
  - translated into DM-nuclei cross section plane and compared to direct searches



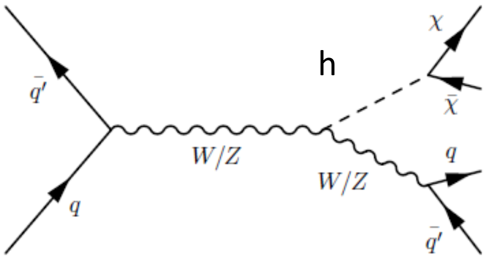


MonoJet Higgs→DM reinterpretation

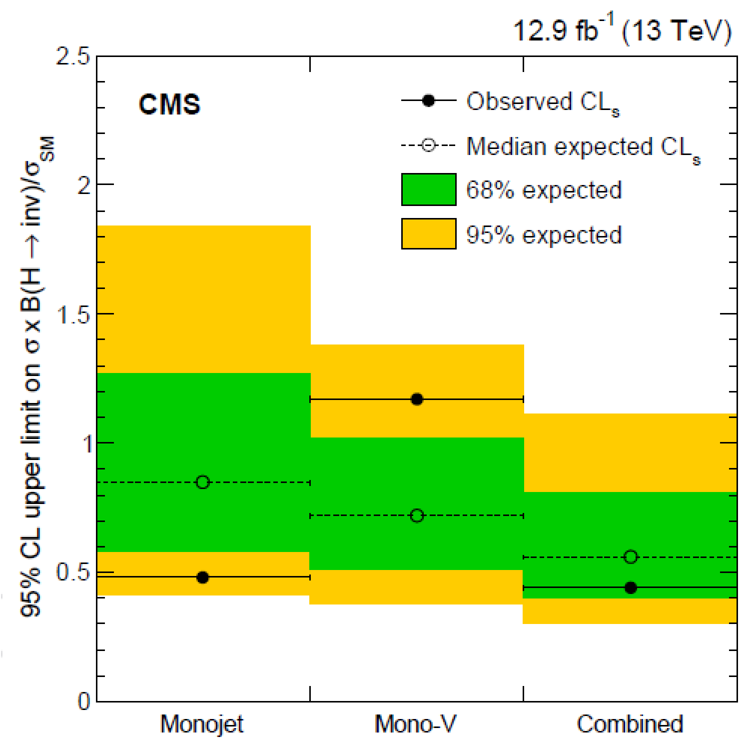
Category	Expected limit	Observed limit	±1 s.d.	Expected signal composition
Mono-V	0.72	1.17	[0.51–1.02]	39.6% ggH, 6.9% VBF, 32.4% WH, 21.1% ZH
Monojet	0.85	0.48	[0.58–1.27]	71.5% ggH, 20.3% VBF, 4.4% WH, 3.8% ZH
Combined	0.56	0.44	[0.40–0.81]	-



monoJet



monoV

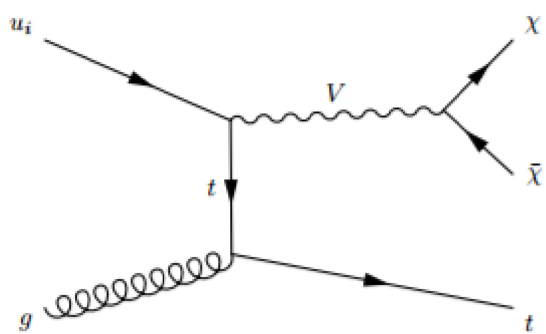


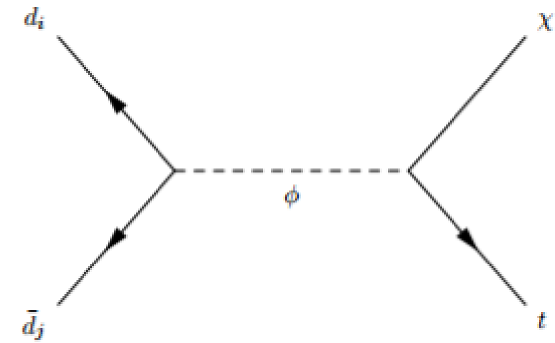
limits on SM Higgs→invisible branching ratio

- **monoJet/V** combined limit: **BR < 0.44**
- current observed limit is **0.24** from **Higgs→Inv direct searches**: arXiv:1610.09218v2 [hep-ex]

MonoTop

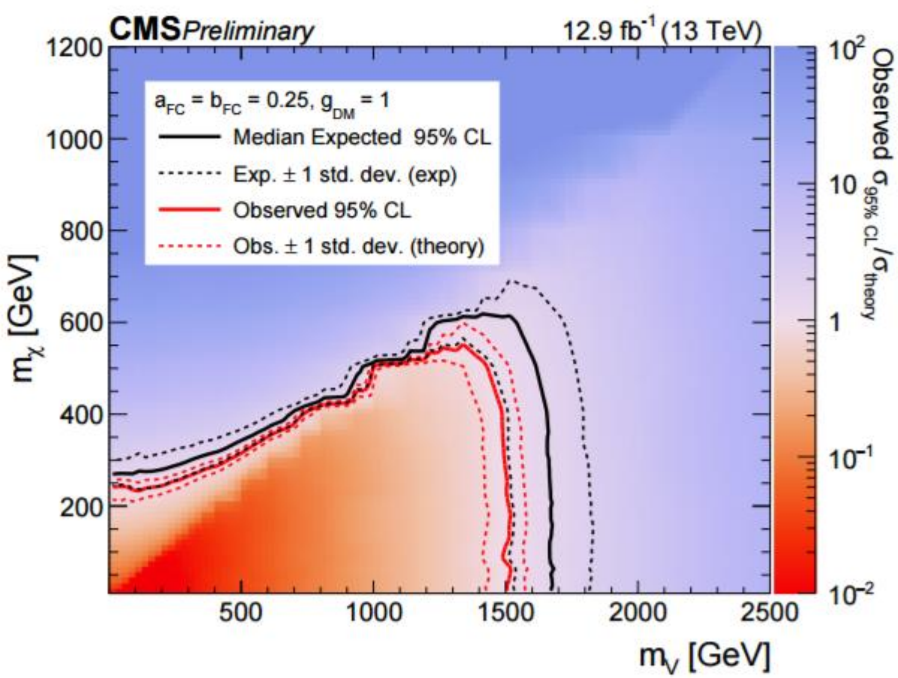
Search for MET and a single top quark decaying hadronically

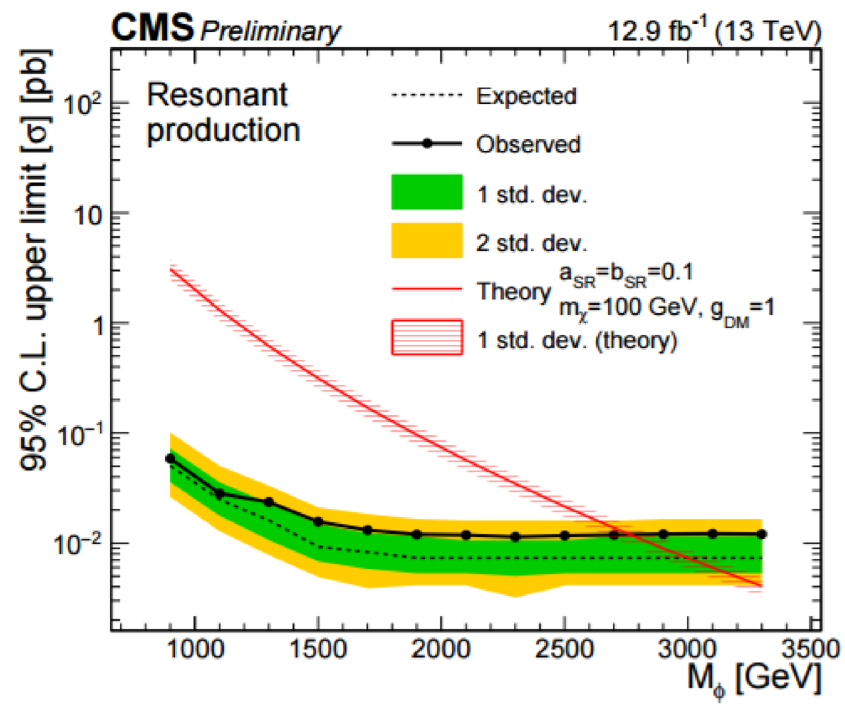




flavour changing neutral current

colored charged scalar ϕ

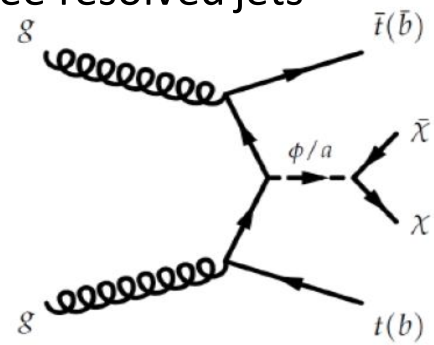


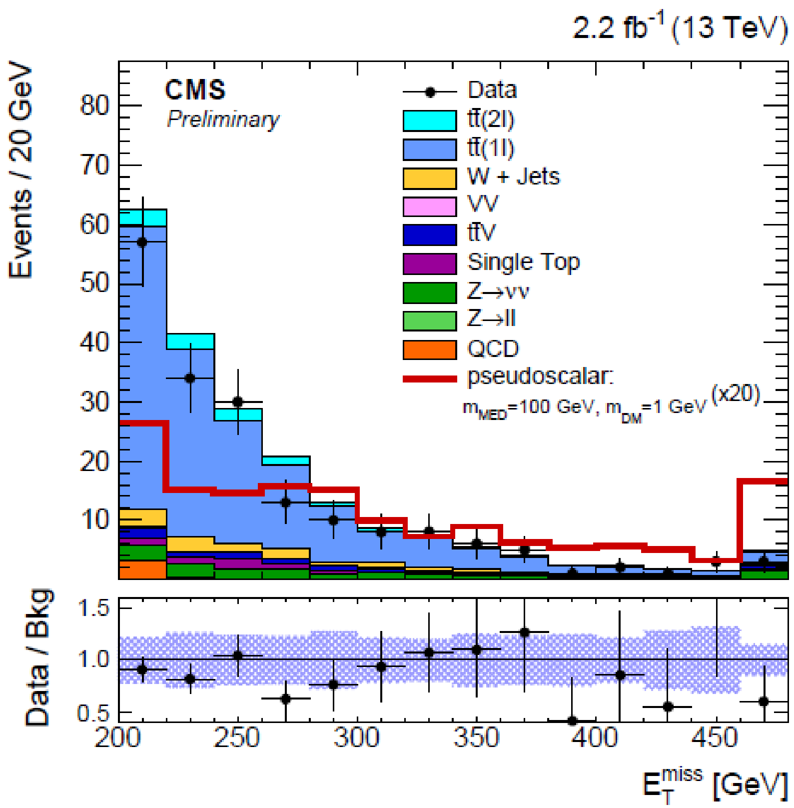


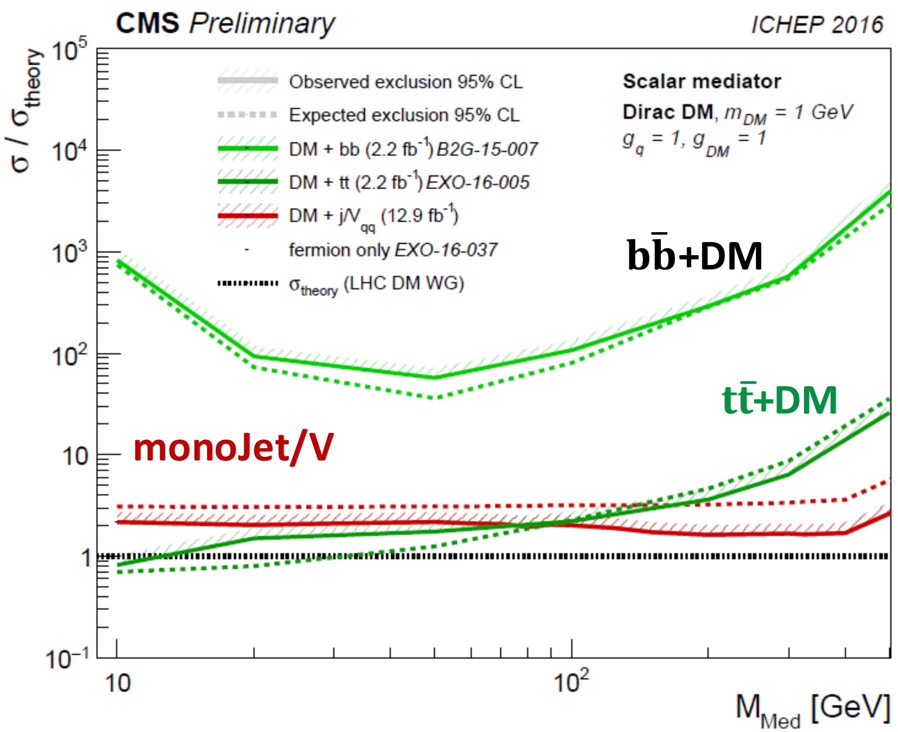
http://cds.cern.ch/record/2205286?ln=en

$t\bar{t}$ + Dark Matter

- **top tagging techiniques:** identify top quarks decaying into three resolved jets
- **hadronic or semileptonic top decays** considered
- data-driven estimate of **SM $t\bar{t}$ and W/Z+jets backgounds**
- sensitive to **(pseudo)scalar mediator**





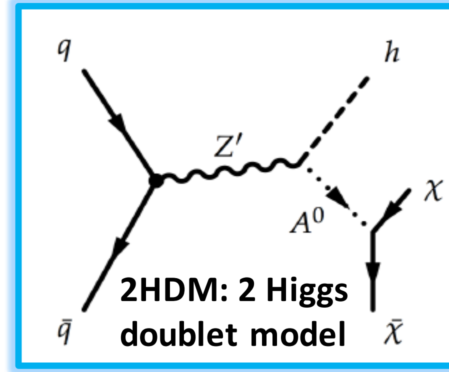


https://cds.cern.ch/record/2204933

https://cds.cern.ch/record/2208044

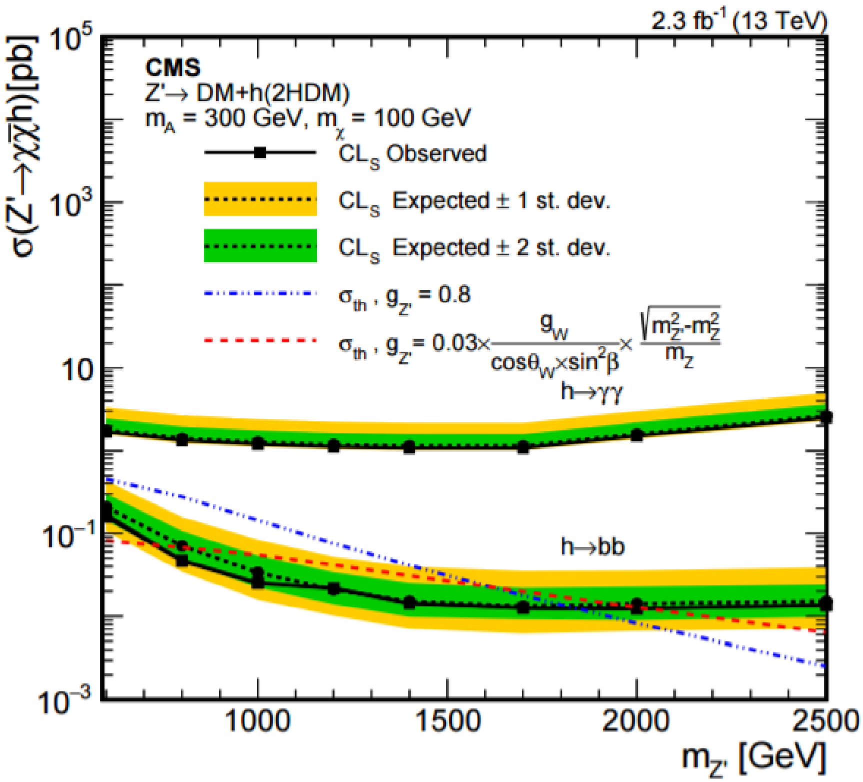
Probing Dark Matter with MonoHiggs

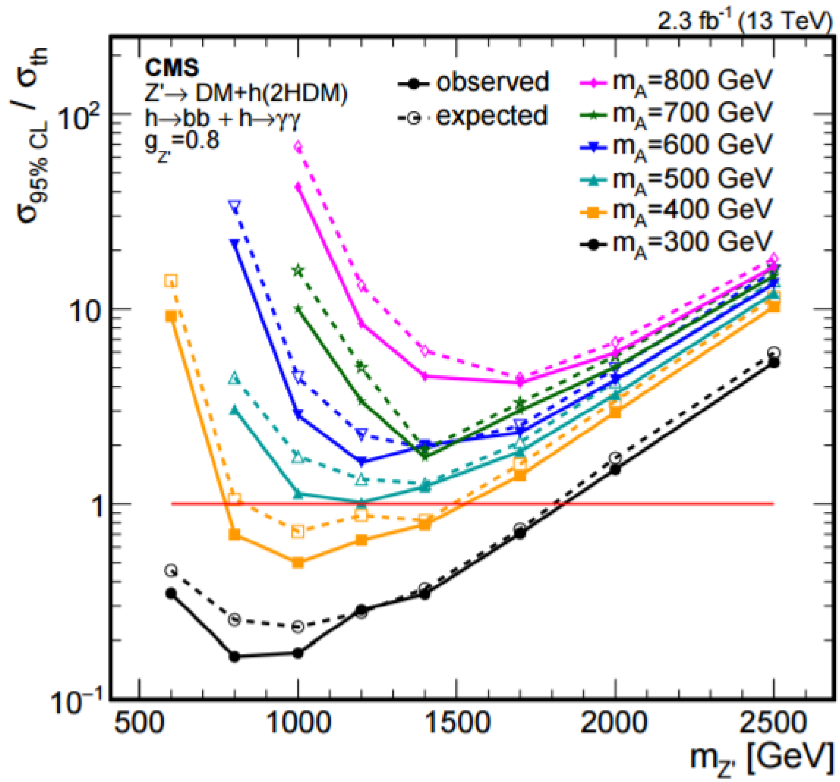
- Higgs ISR suppressed: **probe direct Higgs-DM coupling**
- search for MET+ SM **Higgs**→ $\mathbf{b\bar{b}}$, **γγ, ZZ,** $\boldsymbol{\tau\bar{\tau}}$ …



combination of $\mathbf{b\bar{b}}$**, γγ** (**2.3 fb**$^{-1}$ @ 13TeV) submitted to JHEP

- **Z'-2HDM** interpretation
- $\mathbf{m_{Z'}}$ **< 1860** GeV for $\mathbf{g_{Z'}}$ **= 0.8** and $\mathbf{m_A}$ **= 300** GeV



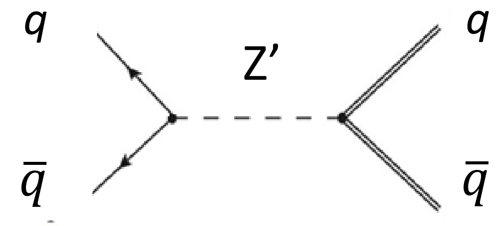


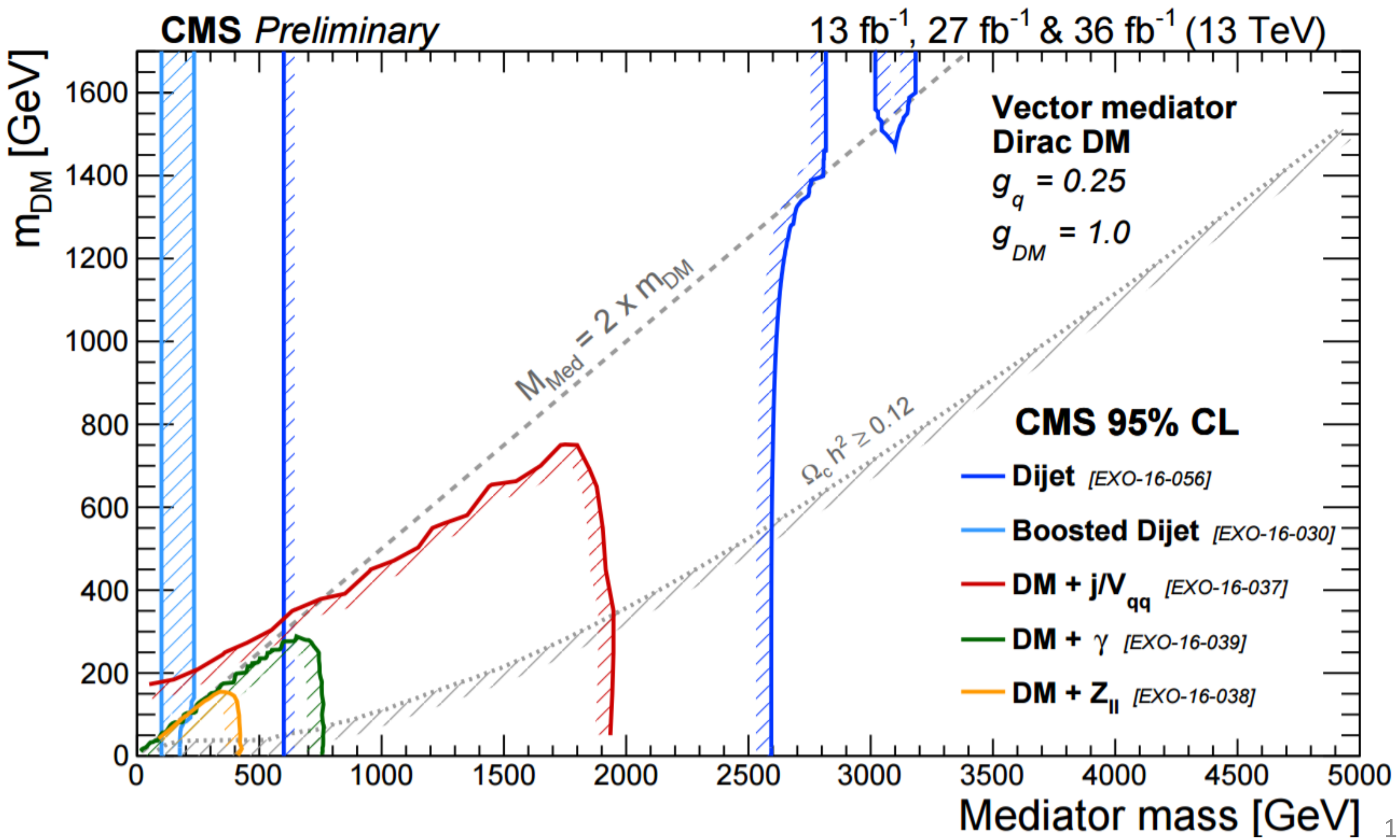
https://arxiv.org/pdf/1703.05236.pdf

https://arxiv.org/pdf/1507.00966.pdf

Constraints on DM from dijet search

- **most powerful search at a hadron collider**
- search for a bump over falling dijet mass spectrum
- **limits on mediator mass**





http://cds.cern.ch/record/2256873?ln=en

What next?

Many **analysis on full 2016 dataset (36 fb^{-1}) being approved**: signal region still blinded

Not just a bare recast of lower luminosity analyses

- treatment of theoretical uncertainties
- better constraints from control regions with more available data
- additional interpretations

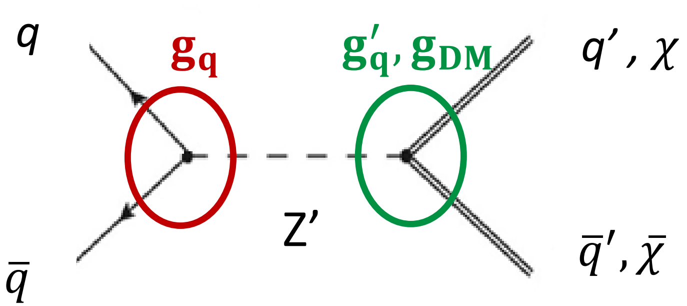
Still entering the high luminosity era

- other 100 fb^{-1} expected in 2017-18

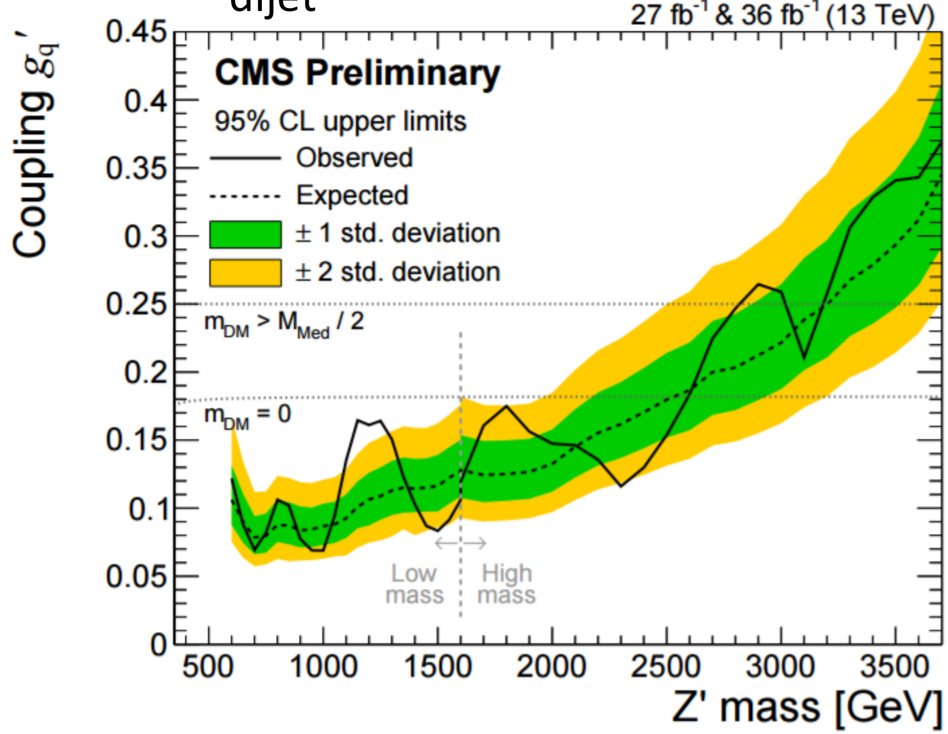
Limits scaling with couplings not trivial

- coupling → mediator width → kinematics

Perform scan in both mass and couplings phase space



dijet



https://cds.cern.ch/record/2256873

Summary and outlook

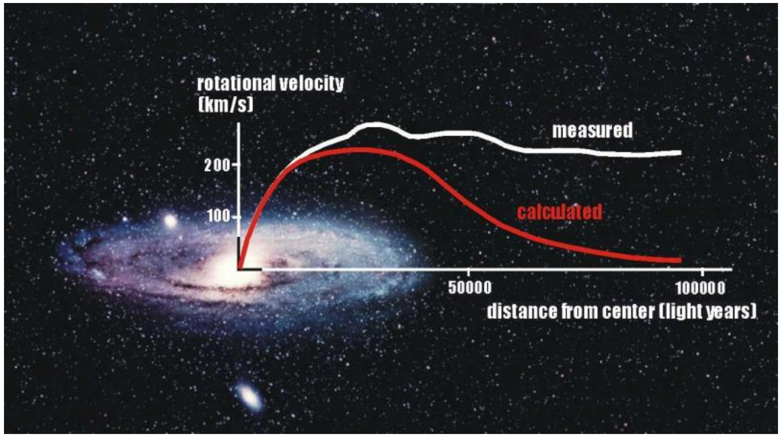
- **CMS has an extensive physics program focused on dark matter**
- **searches performed in all possible final states**
  - monoJet/V, monoHiggs, SingleTop/$t\bar{t}$+DM presented
  - probe many theoretical scenarios
  - **no evidence for DM production yet**
- **current public results mainly based on 2015 or ICHEP 2016 datasets**
- **many analyses (top,Higgs) still limited by low statistics**
  - a lot to gain from an always larger datasets

➢ **generally speaking, LHC DM physics program still has a lot of potential**

- energy bound (almost) reached, but **high luminosity era approaching**
- possibility to perform an unprecedented **scan in mass-coupling phase space**
- opportunity to **probe unexplored physics scenarios**

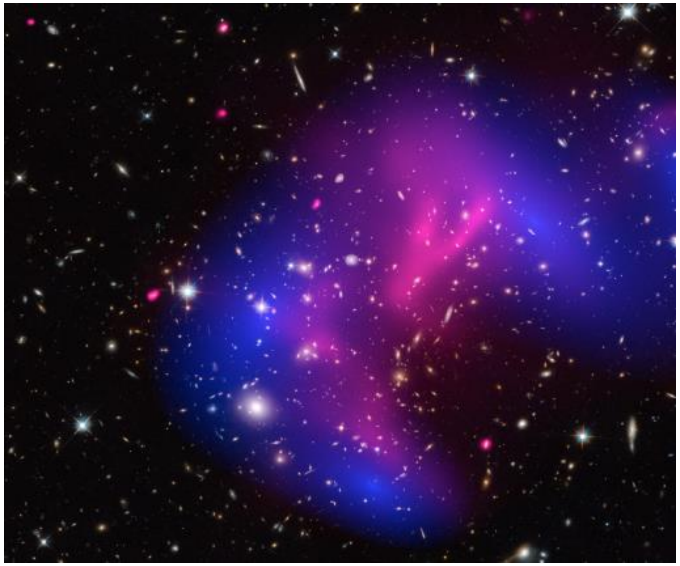
BACKUP

What do we know about dark matter?



- many evidences of dark matter (DM) from **astrophysical observations**

- **particle nature of DM** a **big assumption,** though very natural

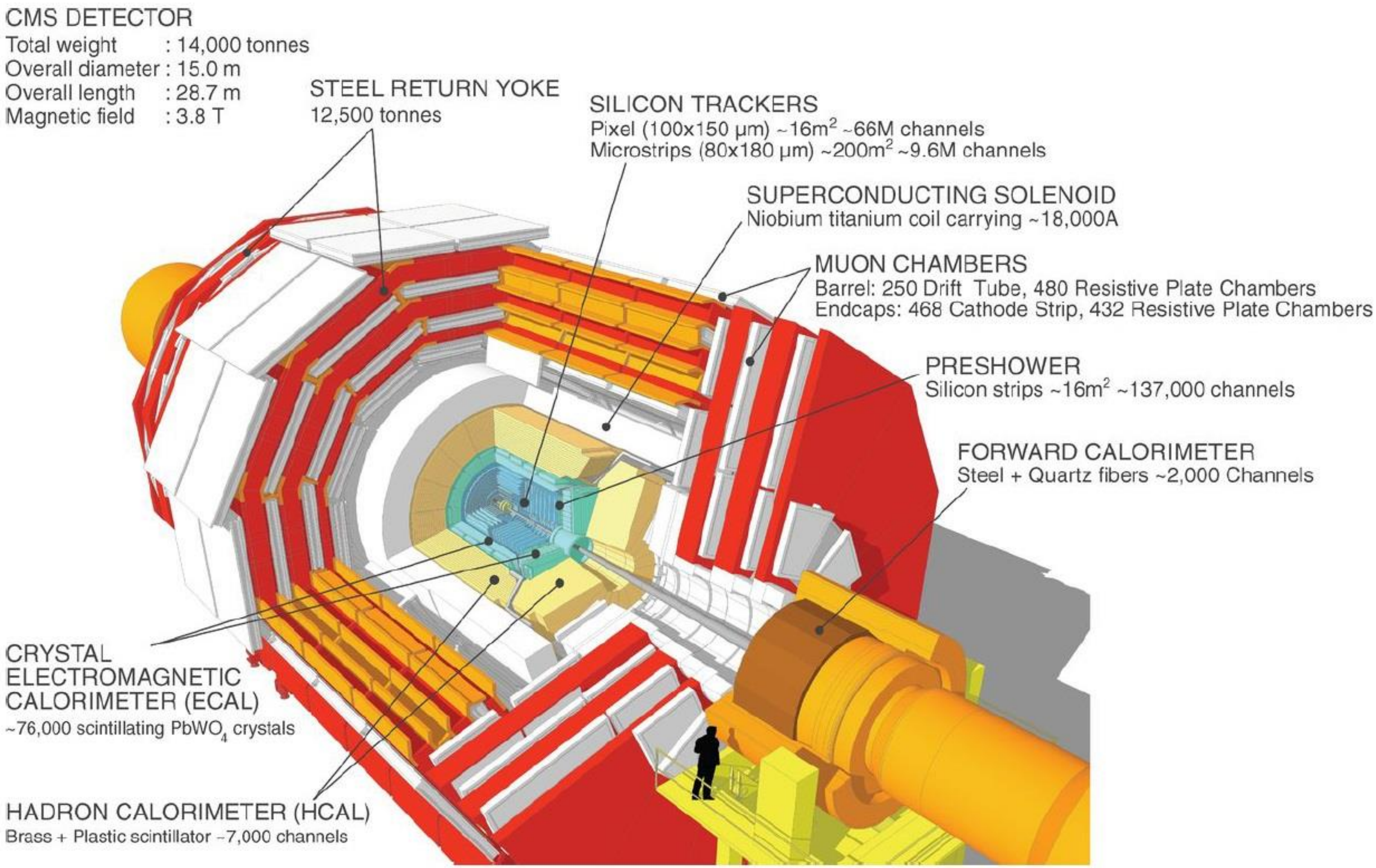


- properties of DM:
  - **gravitational influence** on ordinary matter
  - **neutral** under electromagnetic or strong interaction
  - **stable** on universe lifetime scale

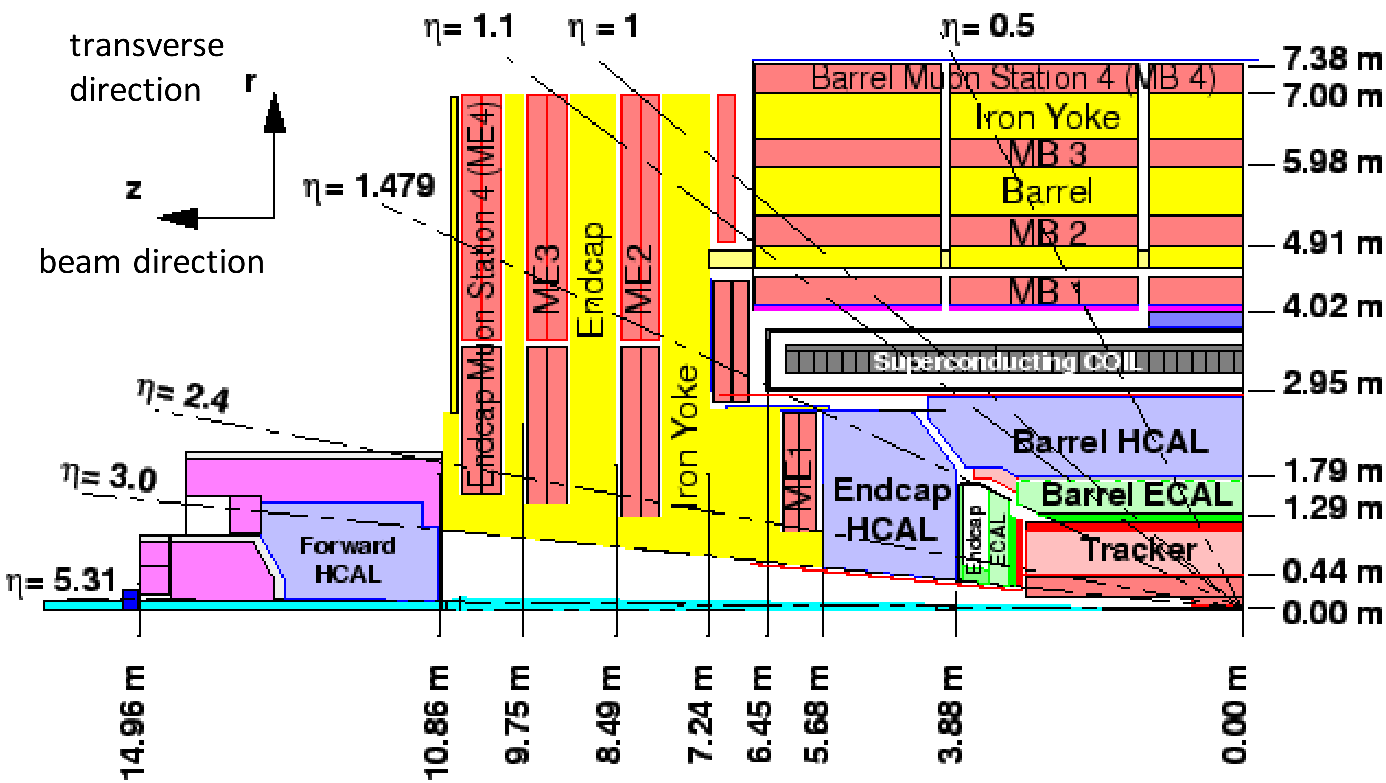
- assume **DM interacts weakly with Standard Model** (SM) particles

  → Weakly Interacting Massive Particle (WIMP)

COMPACT **M**UON **S**OLENOID



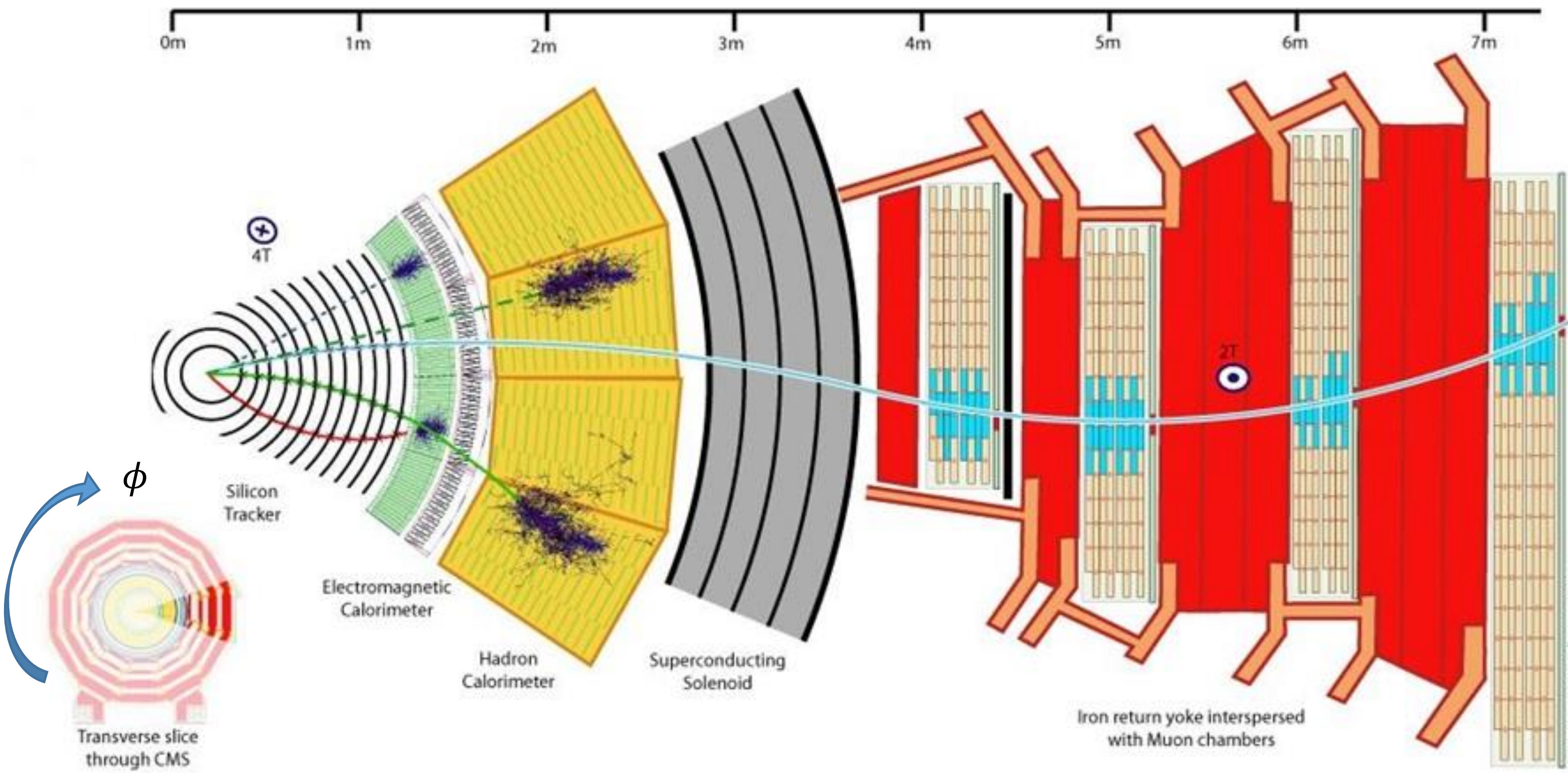
CMS longitudinal view



$$\eta = -\ln tg\frac{\theta}{2}$$

η differences are Lorentz invariant for high energy particles

Particles reconstruction in CMS



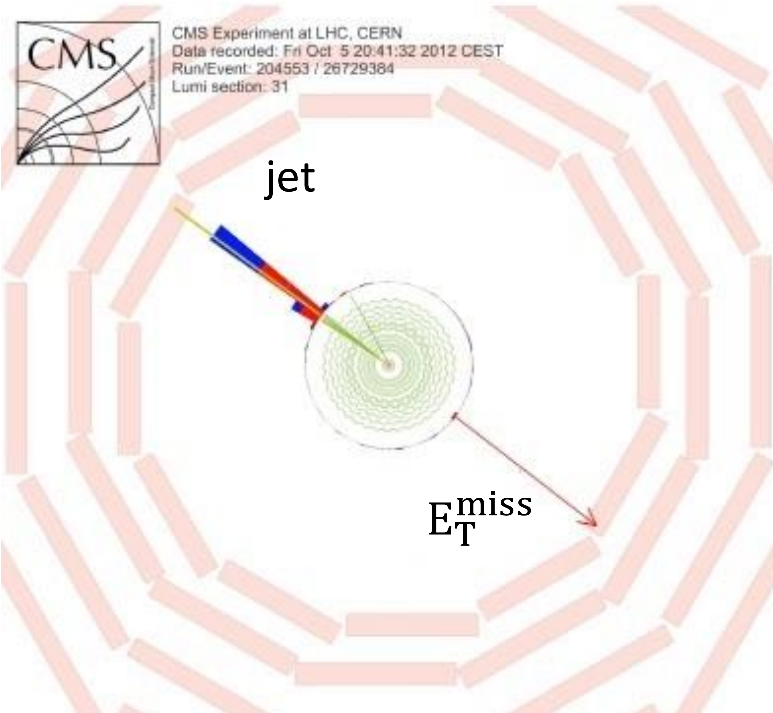
- muon
- electron
- charged hadron (e.g. π^+)
- neutral hadron (e.g. neutron)
- photon

Particle flow algorithm:

- combine information from all subdetectors to build particles

Seeing the invisible

event candidate for monoJet



$$\vec{E}_T^{miss} = - \sum_{\substack{\text{visible} \\ \text{particles}}} \vec{p}_T$$

$\vec{p}_T$: momentum in transverse plane

- **DM does not interact** with the detector
- observed through **momentum imbalance** in transverse plane
- **single DM particle kinematics not accessible**, only the pair total transverse momentum (i.e. the mediator $\vec{p}_T$)
- **irreducible backgrounds** due to SM processes involving **neutrinos**

Theory

Lagrangian for spin 1 mediator

arXiv:1603.04156v1

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q \,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q$$

Partial widths

$$\Gamma^{\chi\bar{\chi}}_{\text{vector}} = \frac{g^2_{\text{DM}} M_{\text{med}}}{12\pi} \left(1 - 4\, z_{\text{DM}}\right)^{1/2} \left(1 + 2\, z_{\text{DM}}\right) \,,$$

$$\Gamma^{q\bar{q}}_{\text{vector}} = \frac{g^2_q M_{\text{med}}}{4\pi} \left(1 - 4\, z_q\right)^{1/2} \left(1 + 2\, z_q\right) \,,$$

$$\Gamma^{\chi\bar{\chi}}_{\text{axial-vector}} = \frac{g^2_{\text{DM}} M_{\text{med}}}{12\pi} \left(1 - 4\, z_{\text{DM}}\right)^{3/2} \,,$$

$$\Gamma^{q\bar{q}}_{\text{axial-vector}} = \frac{g^2_q M_{\text{med}}}{4\pi} \left(1 - 4\, z_q\right)^{3/2} \,.$$

$$z_{\text{DM},q} = m^2_{\text{DM},q} / M^2_{\text{med}}$$

Theory

Lagrangian for spin 0 mediator

arXiv:1603.04156v1

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\,\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q \,,$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -i g_{\text{DM}}\,\phi\bar{\chi}\gamma_5\chi - i g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q \,,$$

Partial widths

$$\Gamma^{\chi\bar{\chi}}_{\text{scalar}} = \frac{g_{\text{DM}}^2 M_{\text{med}}}{8\pi}\left(1 - 4 z_{\text{DM}}^2\right)^{3/2} ,$$

$$\Gamma^{q\bar{q}}_{\text{scalar}} = \frac{3 g_q^2 y_q^2 M_{\text{med}}}{16\pi}\left(1 - 4 z_q^2\right)^{3/2} ,$$

$$\Gamma^{gg}_{\text{scalar}} = \frac{\alpha_s^2 g_q^2 M_{\text{med}}^3}{32\pi^3 v^2}\left|f_{\text{scalar}}(4 z_t)\right|^2 ,$$

$$\Gamma^{\chi\bar{\chi}}_{\text{pseudo-scalar}} = \frac{g_{\text{DM}}^2 M_{\text{med}}}{8\pi}\left(1 - 4 z_{\text{DM}}^2\right)^{1/2} ,$$

$$\Gamma^{q\bar{q}}_{\text{pseudo-scalar}} = \frac{3 g_q^2 y_q^2 M_{\text{med}}}{16\pi}\left(1 - 4 z_q^2\right)^{1/2} ,$$

$$\Gamma^{gg}_{\text{pseudo-scalar}} = \frac{\alpha_s^2 g_q^2 M_{\text{med}}^3}{32\pi^3 v^2}\left|f_{\text{pseudo-scalar}}(4 z_t)\right|^2 .$$

$$z_{\text{DM},q} = m_{\text{DM},q}^2 / M_{\text{med}}^2$$

$$y_q = \sqrt{2} m_q / v$$

$$v \simeq 246 \text{ GeV}$$

$$f_{\text{scalar}}(\tau) = \tau\left[1 + (1-\tau)\arctan^2\left(\frac{1}{\sqrt{\tau - 1}}\right)\right] ,$$

$$f_{\text{pseudo-scalar}}(\tau) = \tau \arctan^2\left(\frac{1}{\sqrt{\tau - 1}}\right) .$$

Comparison to indirect searches

- **vector, scalar** mediator → **spin independent** (SI) cross section
- **axial-vector, pseudoscalar** mediator → **spin dependent** (SI) cross section

DM-nucleon scattering cross section

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}, \qquad \mu_{n\chi} = m_n m_{\rm DM}/(m_n + m_{\rm DM}) \qquad m_n \simeq 0.939\,\text{GeV}$$

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

scalar: $\sigma_{\rm SI} \simeq 6.9 \times 10^{-43}\ \text{cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\,\text{GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\text{GeV}}\right)^2$

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

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

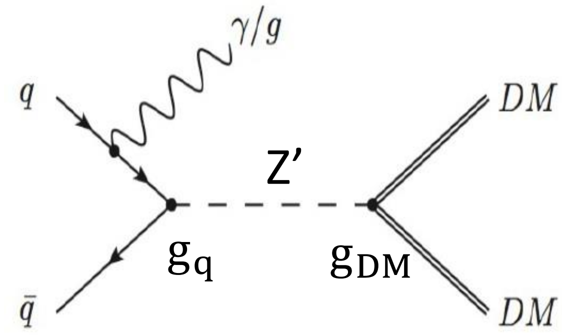
pseudoscalar: highly suppressed

arXiv:1603.04156v1

Theoretical overview

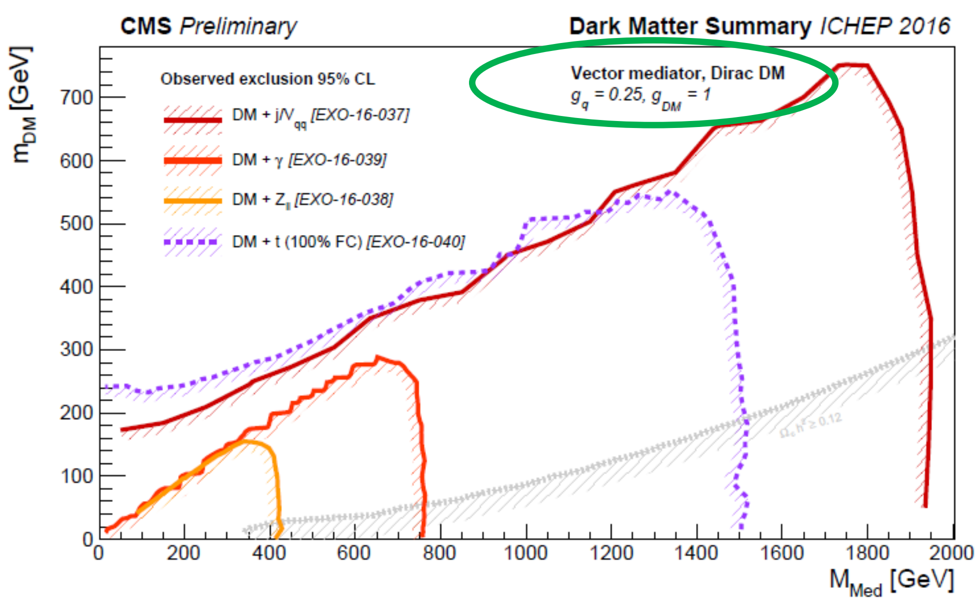
Interpretation with simplified models

- ❑ Dark Matter Forum prescriptions → arXiv:1507.00966
- ❑ benchmark of Run2 interpretation
- ❑ new mediator connecting SM and DM
- ❑ free parameters: $\mathbf{m_{DM}}$, $\mathbf{M_{med}}$, $\mathbf{g_{DM}}$, $\mathbf{g_q}$



Assumptions:

- DM is a Dirac fermion
- DM produced on-shell in pairs
- minimal decay width for mediator
- minimal flavour violation
- $g_{DM} = 1$ and $g_q = 0.25$



limits strongly depends on the couplings choice and model

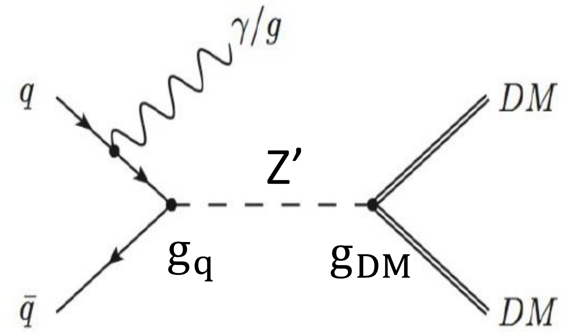
→ change in couplings affects mediator's width

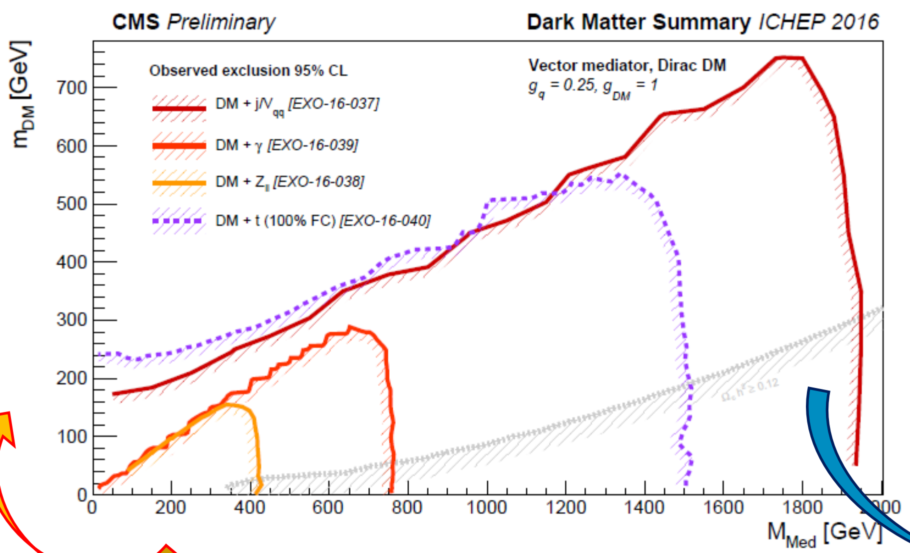
→ more details: arXiv:1603.04156v1

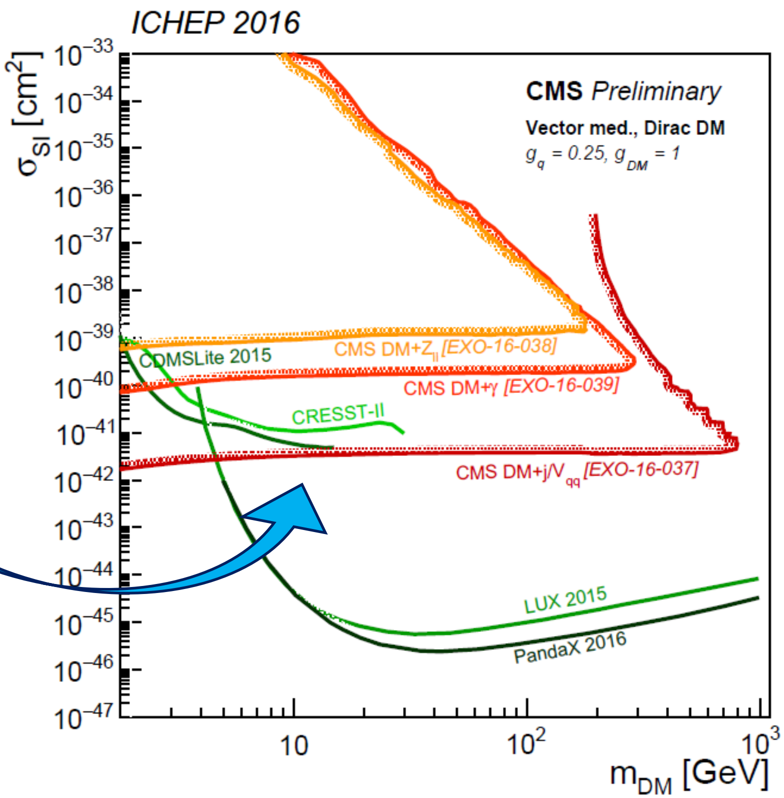
Theoretical overview

Limits tipically @ 95% CL in the m_{DM}, M_{med} plane

- switch to limits on cross section as a function of m_{DM}
- 90% CL used to compare with direct searches

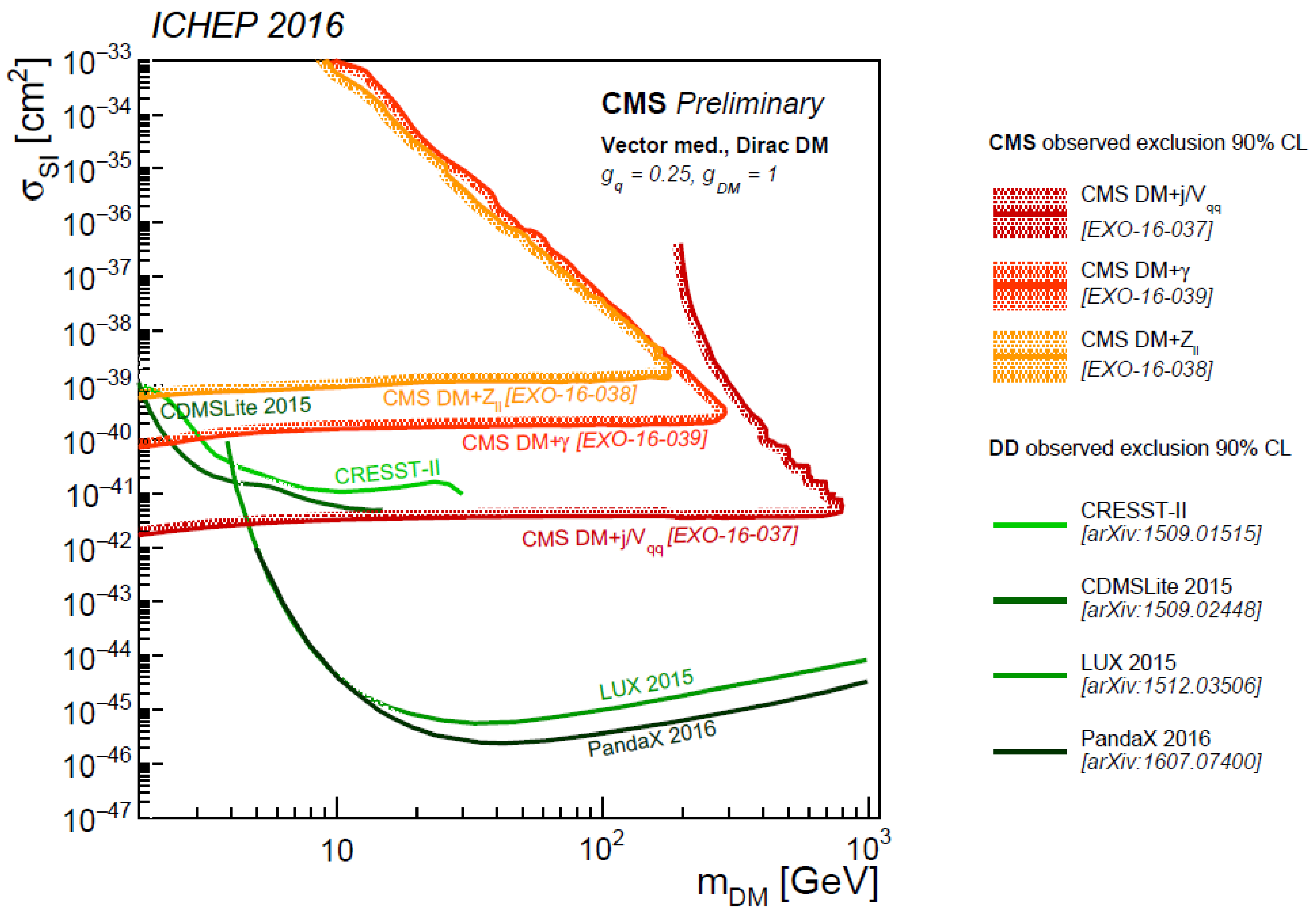






collider searches **limits flat with respect to m_{DM}** and **sensitive also to low m_{DM}**

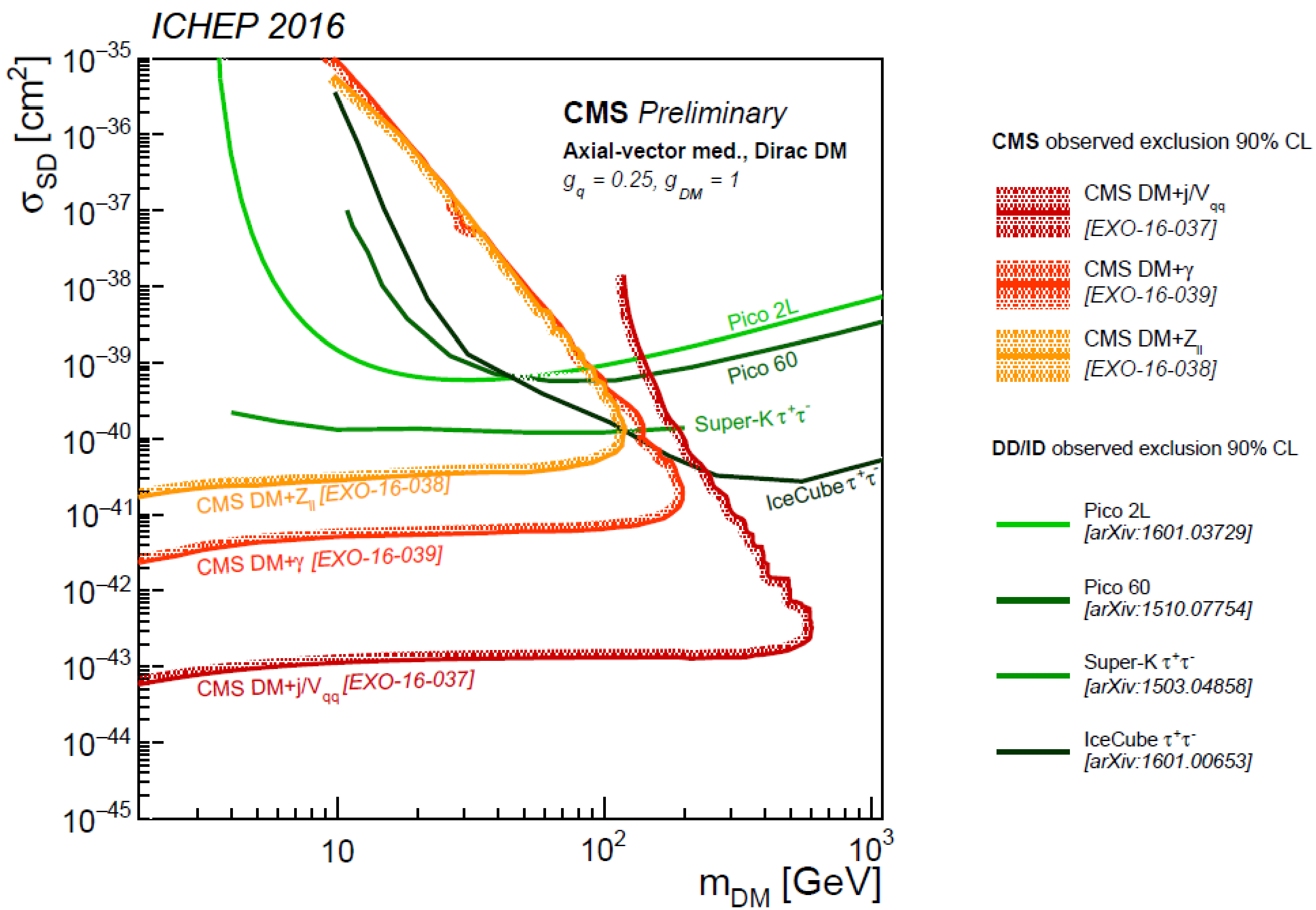
ICHEP summary plots



monojet most sensitive channel for vector mediator
direct searches more sensitive than collider searches for m_{DM} > few GeV

CERN-CMS-DP-2016-057 *https://cds.cern.ch/record/2208044*

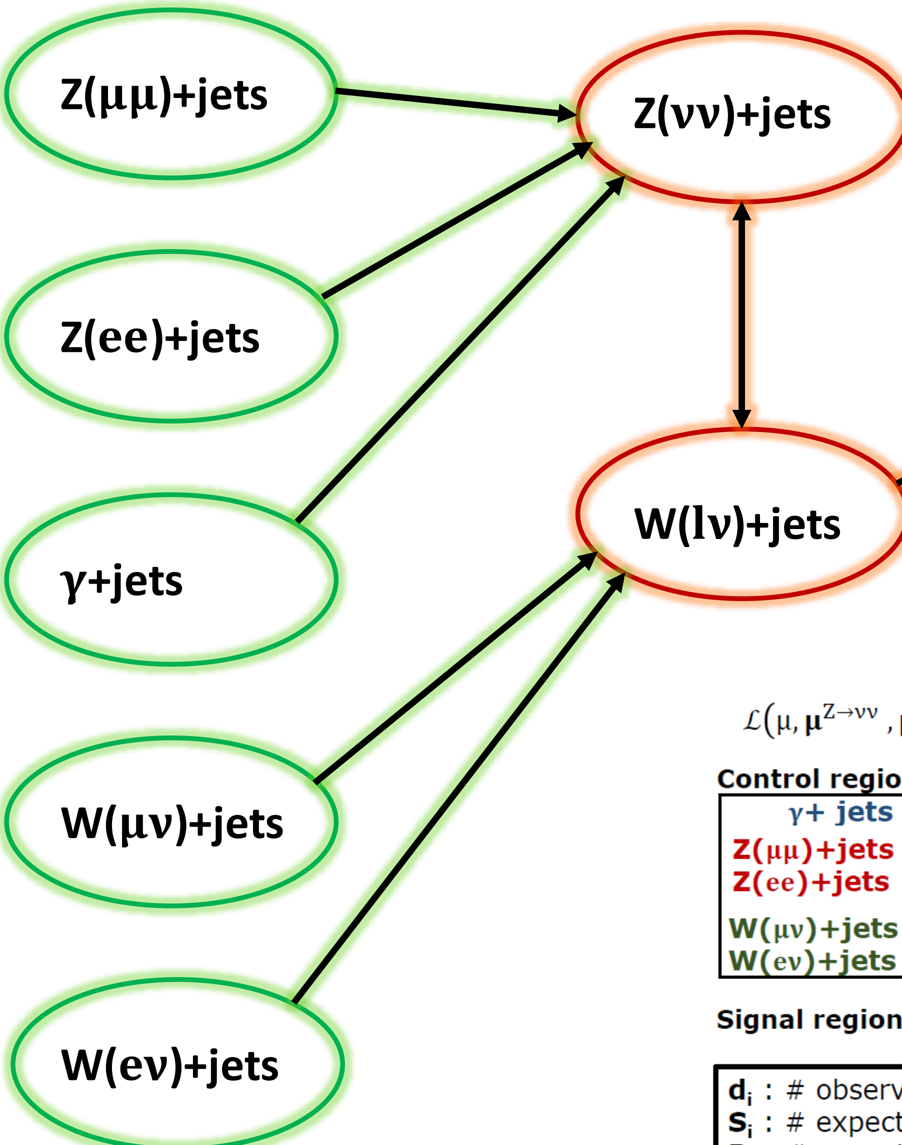
ICHEP summary plots

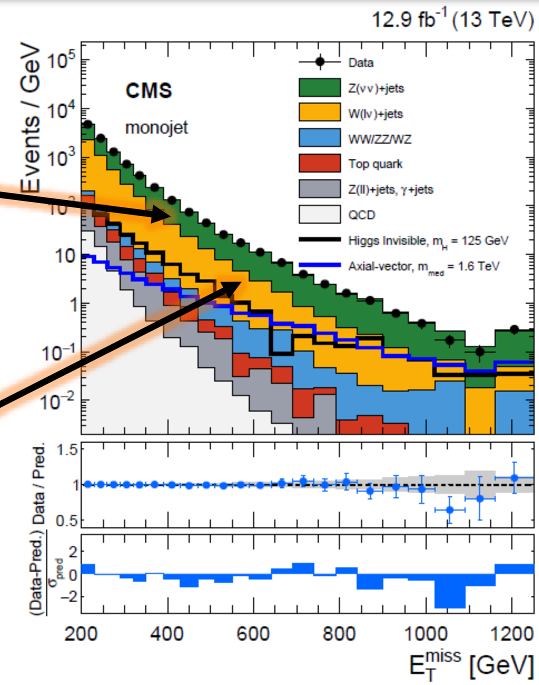


monojet most sensitive channel for axial-vector mediator
collider searches more sensitive than direct searches everywhere

CERN-CMS-DP-2016-057 *https://cds.cern.ch/record/2208044*

MonoJet background estimate





$$\mathcal{L}(\mu, \boldsymbol{\mu}^{Z\to\nu\nu}, \boldsymbol{\mu}^{W\to l\nu}, \boldsymbol{\theta}) = \prod_i \mathrm{Poisson}\left(d_i^{\gamma} \middle| B_i^{\gamma}(\boldsymbol{\theta}) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^{\gamma}(\boldsymbol{\theta})}\right) \times \prod_i \mathrm{Poisson}\left(d_i^{Z} \middle| B_i^{Z}(\boldsymbol{\theta}) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^{Z}(\boldsymbol{\theta})}\right) \times \prod_i \mathrm{Poisson}\left(d_i^{W} \middle| B_i^{W}(\boldsymbol{\theta}) + \frac{\mu_i^{W\to l\nu}}{R_i^{W}(\boldsymbol{\theta})}\right) \times \prod_i \mathrm{Poisson}\left(d_i \middle| B_i(\boldsymbol{\theta}) + \mu_i^{W\to l\nu} + \mu_i^{Z\to\nu\nu} + \mu S_i(\boldsymbol{\theta})\right)$$

exp. events for Z(νν): $\mu_i^{Z\to\nu\nu}$

exp. events for W(lν): $\mu_i^{W\to l\nu}$

Control regions

- γ+ jets
- Z(μμ)+jets
- Z(ee)+jets
- W(μν)+jets
- W(eν)+jets

Signal region

- **d_i** : # observed events in i-th bin
- **S_i** : # expected signal events
- **B_i** : # expected background events (MC)
- **R_i** : scale factors from CR to SR

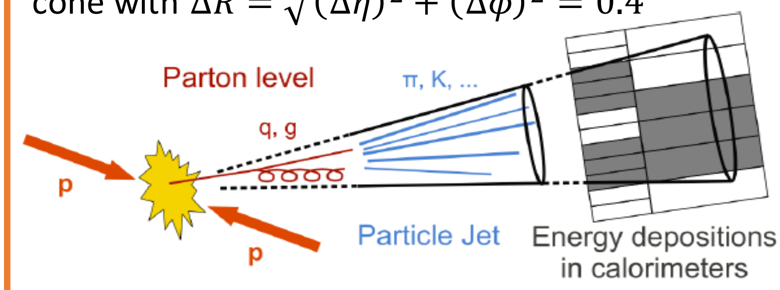
μ: signal strength

θ: nuisance parameters (systematic uncertainties)

MonoJet event selection

Common selection (both monoJet/V)

- ✓ MET > 200 GeV (recoil)
- ✓ leading **AK4 jet**: p_T > 100 GeV, $|\eta|$< 2.5



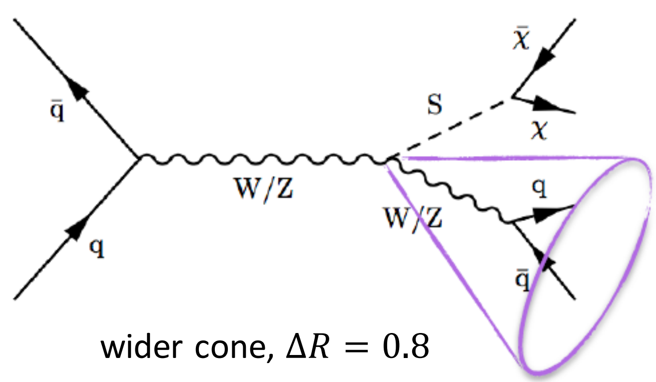
Background suppression

- ✓ leading jet noise cleaning → beam backgrounds
- ✓ $\Delta\phi(\text{jets}, \text{MET}) > 0.5$ → QCD
- ✓ veto on photons and charged leptons → EWK backgrounds
- ✓ veto on b-jets → top

< 10 % of total bkgs after selection

Specific selection for monoV (boosted topology)

- ✓ leading **AK8 jet**: p_T > 250 GeV, $|\eta|$< 2.4
- ✓ MET > 250 GeV
- ✓ **V-tagging** techniques
  - boson pruned mass in [65,105] GeV
  - N-subjettines $\tau_2/\tau_1 < 0.6$



N-subjettiness

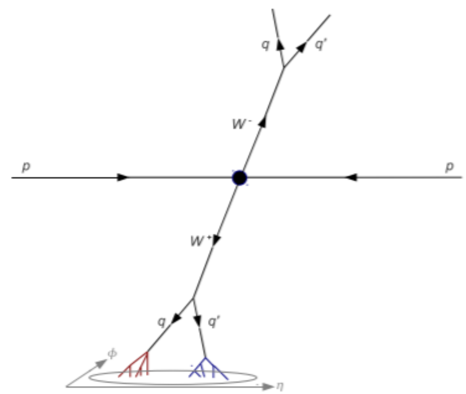
k runs over the constituent particles in a given jet, $p_{T,k}$ are their transverse momenta and $\Delta R_{J,k}$ is the distance in rapidity-azimuth plane between a candidate subjet J and a constituent particle k

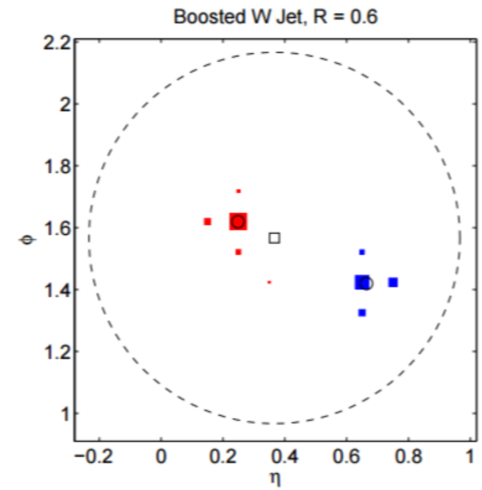
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

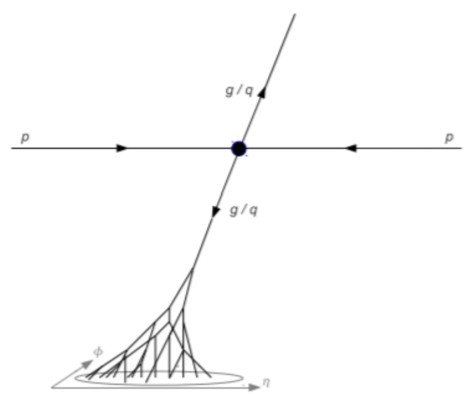
$$\Delta R_{J,k} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

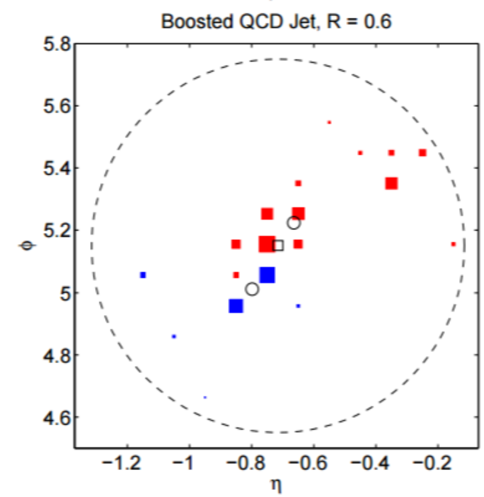
$$d_0 = \sum_k p_{T,k} R_0$$

R_0: the jet radius used in the original jet clustering algorithm





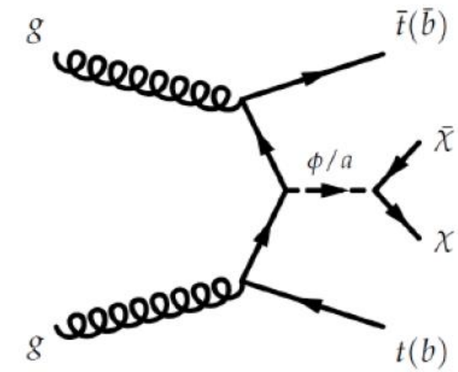


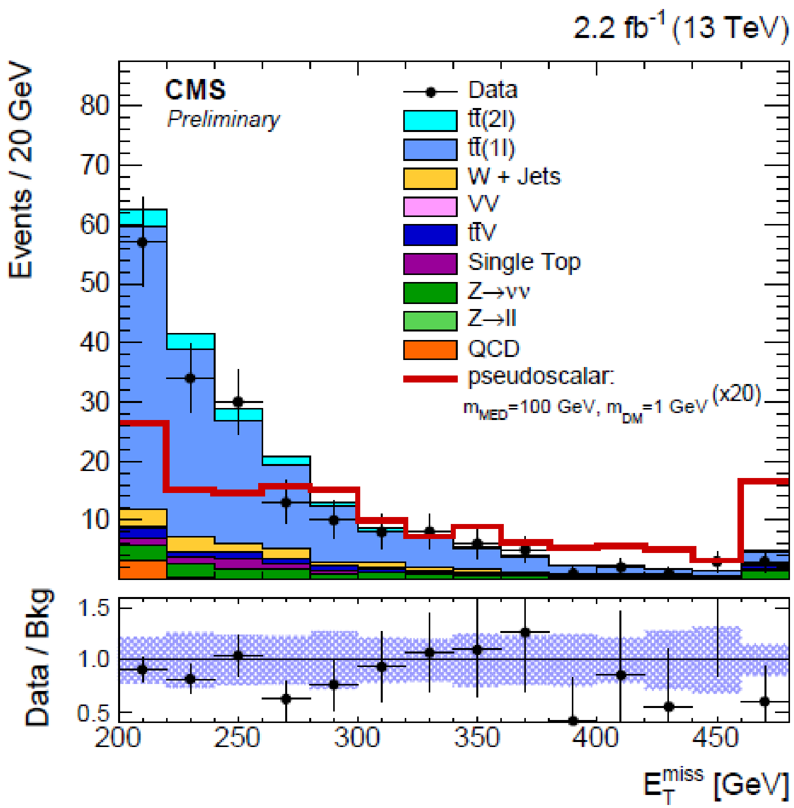


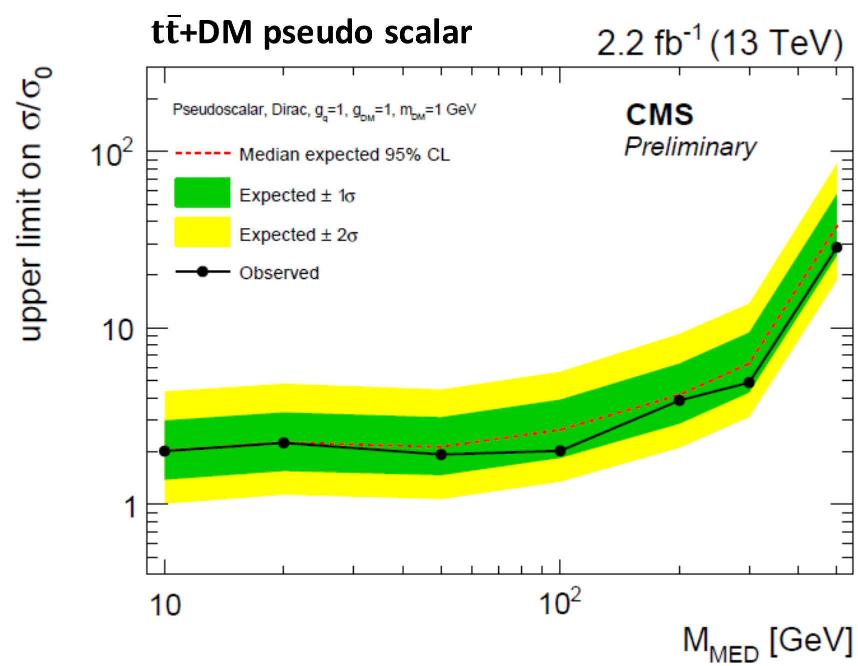
https://arxiv.org/pdf/1011.2268.pdf

$t\bar{t}$ + Dark Matter

- **top tagging techiniques:** identify top quarks decaying into three resolved jets
- **hadronic or semileptonic top decays** considered
- data-driven estimate of **SM $t\bar{t}$ and W/Z+jets backgounds**

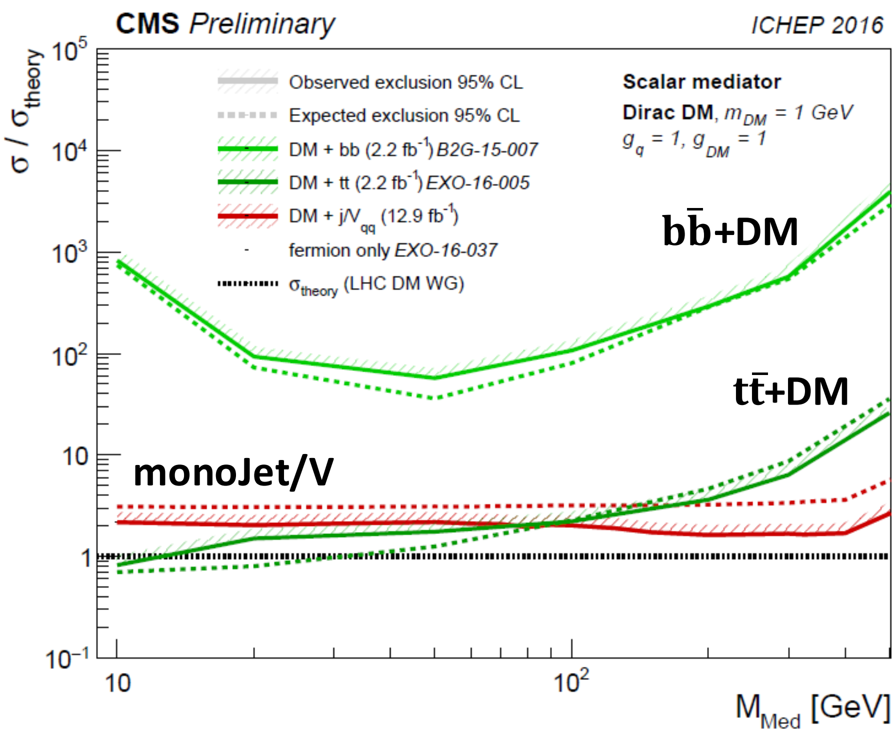


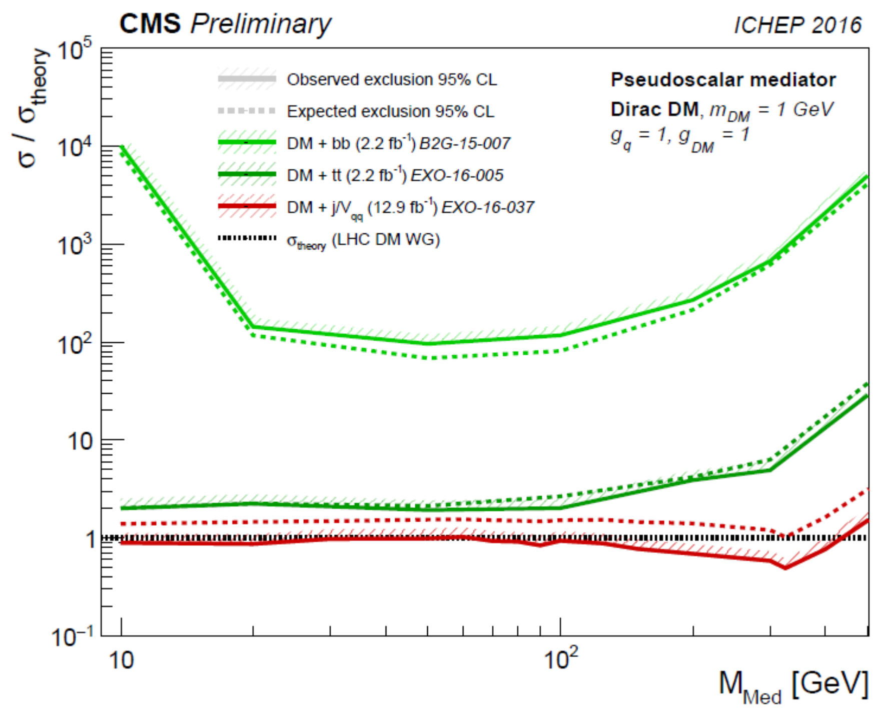




https://cds.cern.ch/record/2204933

Comparison of Monojet and $t\bar{t}$+DM





monoJet and **$t\bar{t}$+DM** **most sensitive** channels for (pseudo)scalar mediator

$t\bar{t}$+DM has a better S/B ratio (note the different luminosity in the plot)

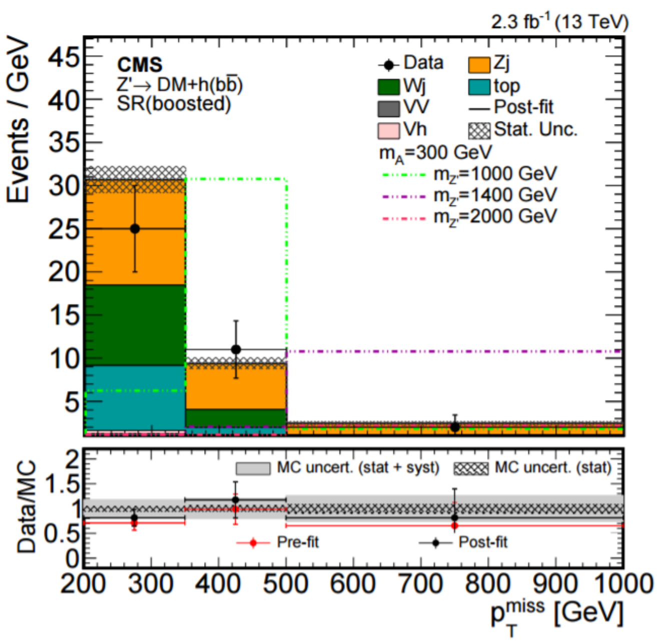
direct searches have much less or no sensitivity to this case

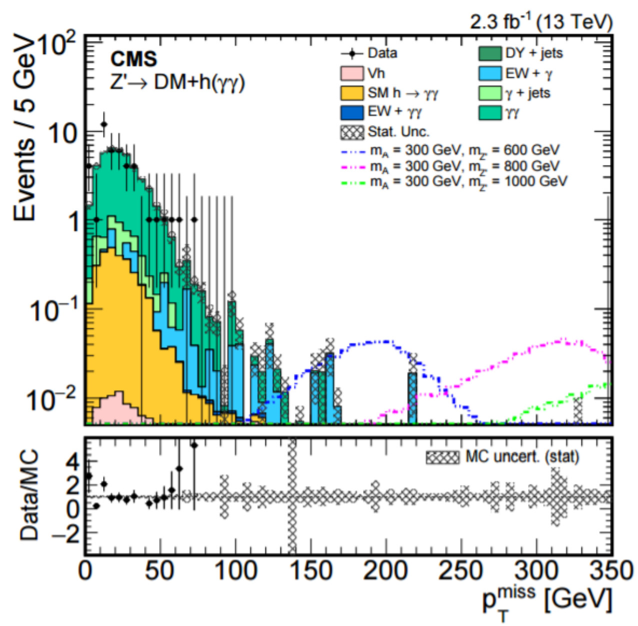
CERN-CMS-DP-2016-057 *https://cds.cern.ch/record/2208044*

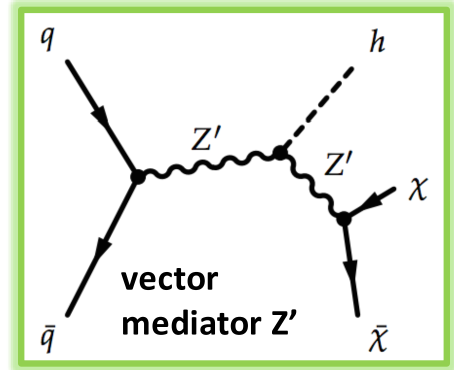
Probing Dark Matter with MonoHiggs

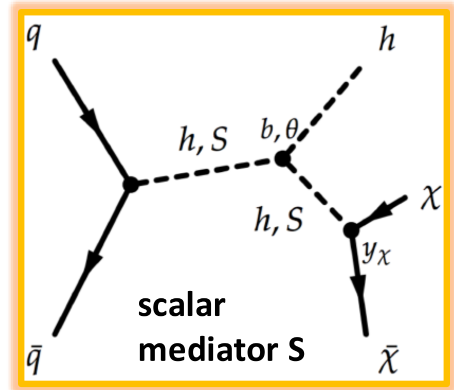
- **Higgs ISR suppressed** (coupling ∝ mass)
- search for MET+ SM **Higgs**→ $\mathbf{b\bar{b}}$**, γγ, ZZ,** $\boldsymbol{\tau\bar{\tau}}$ …

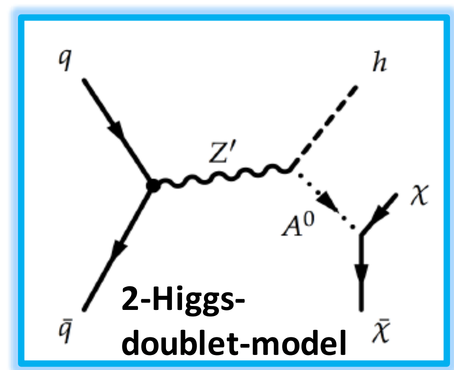
- **H**→ $\mathbf{b\bar{b}}$
  - **b-tagging** (resolved and boosted category)
- **H**→ **γγ**
  - **SM Higgs** included as **resonant background**
  - non resonant bkg from fit to $m_{\gamma\gamma}$ in low-p_T^{miss} CR









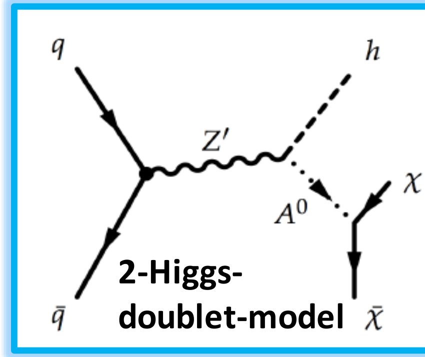


https://arxiv.org/pdf/1507.00966.pdf

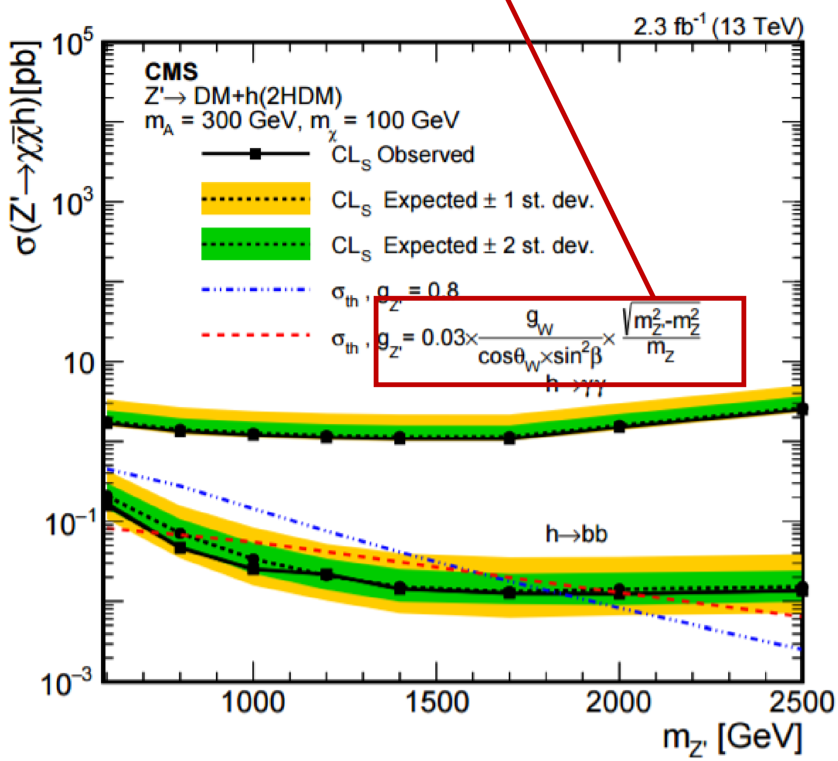
Mono-Higgs search results

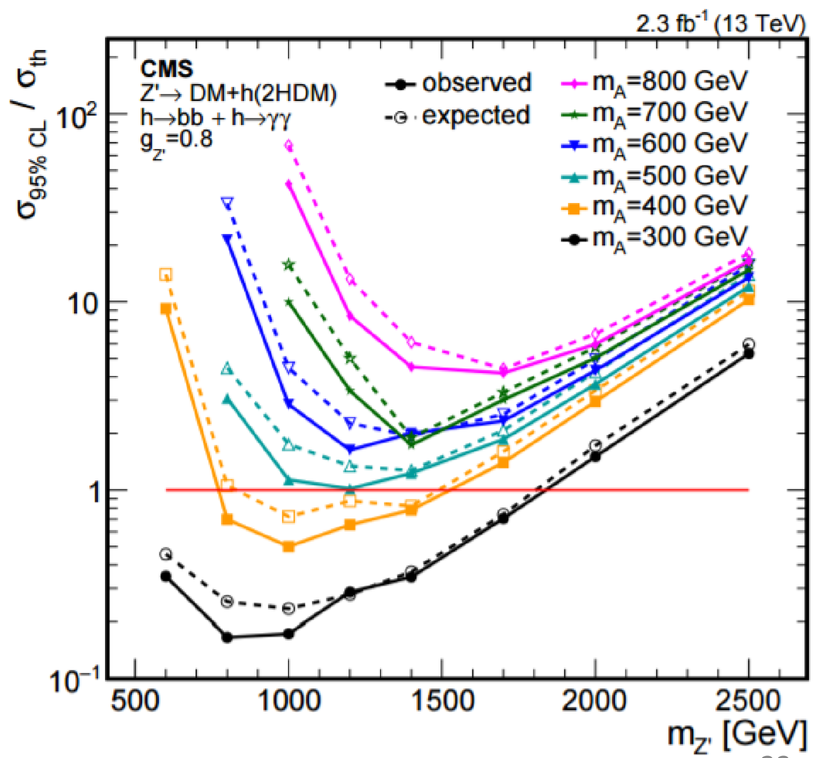
combination of $b\bar{b}$, $\gamma\gamma$ (2.3 fb^{-1} @ 13TeV) submitted to JHEP

- **Z'-2HDM** interpretation
- $\mathbf{m_{Z'}}$ **< 1860** GeV for $\mathbf{g_{Z'}}$ **= 0.8** and $\mathbf{m_A}$ **= 300** GeV
- $\mathbf{m_{Z'}}$ **< 2040** GeV for constrained $\mathbf{g_{Z'}}$ and $\mathbf{m_A}$ **= 300** GeV



g'_Z constrained from global EWK fit and dijet searches

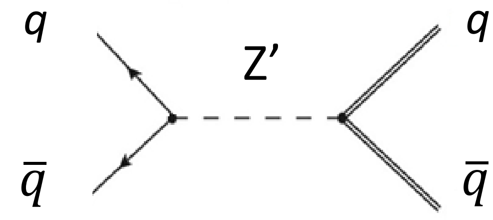


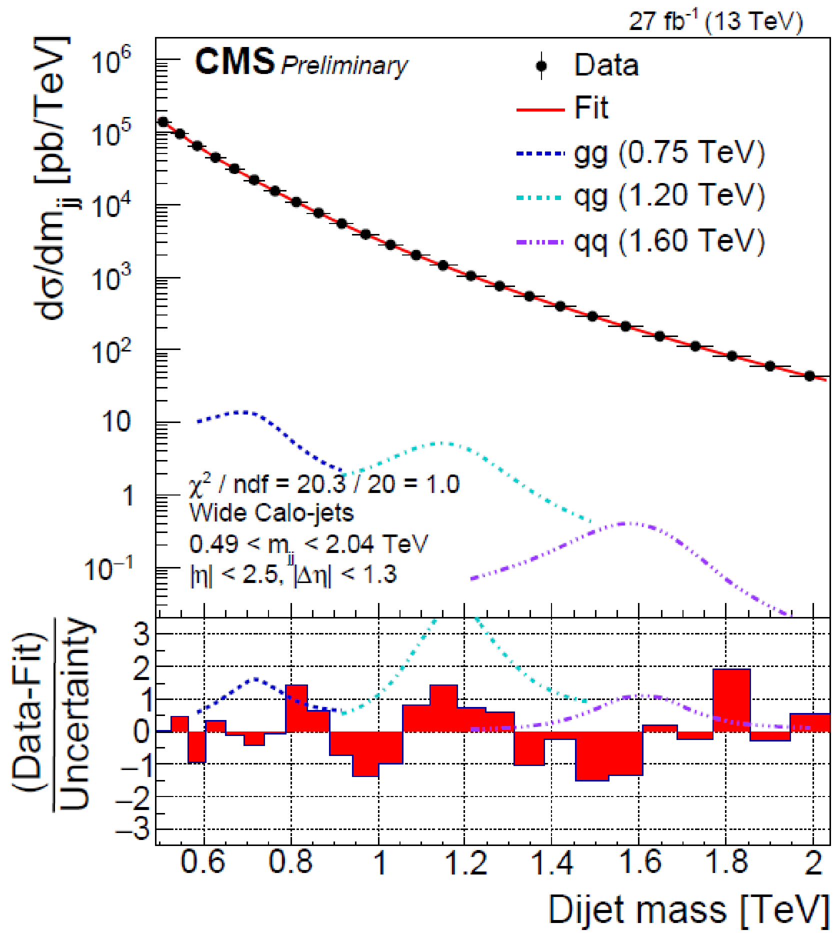


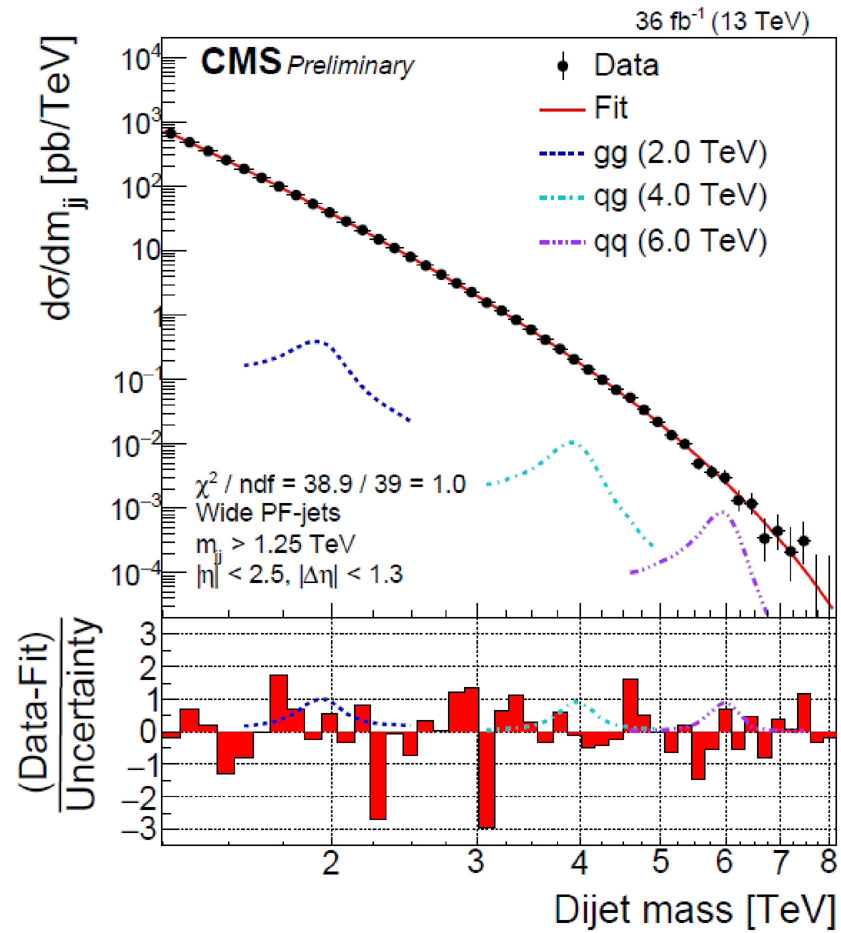
https://arxiv.org/pdf/1703.05236.pdf

Dijet search

- **most powerful search at a hadron collider**
- search for a bump over falling dijet mass spectrum
- low mass and high mass search



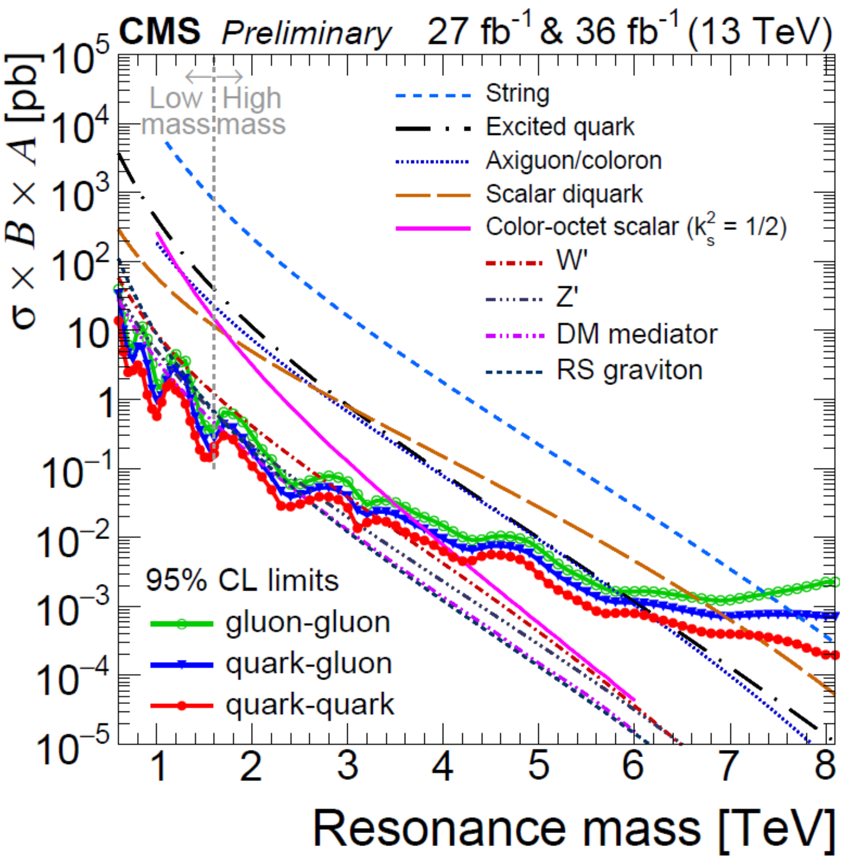


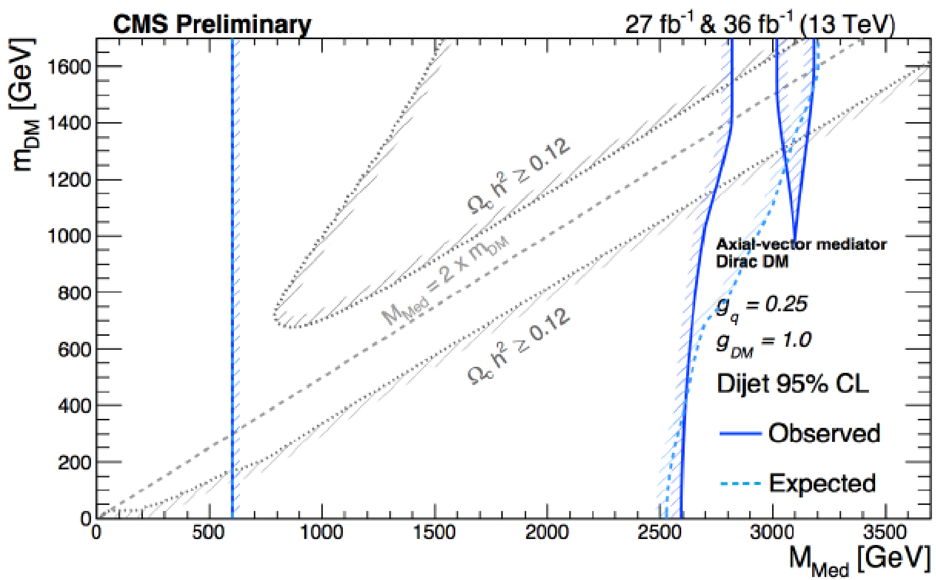


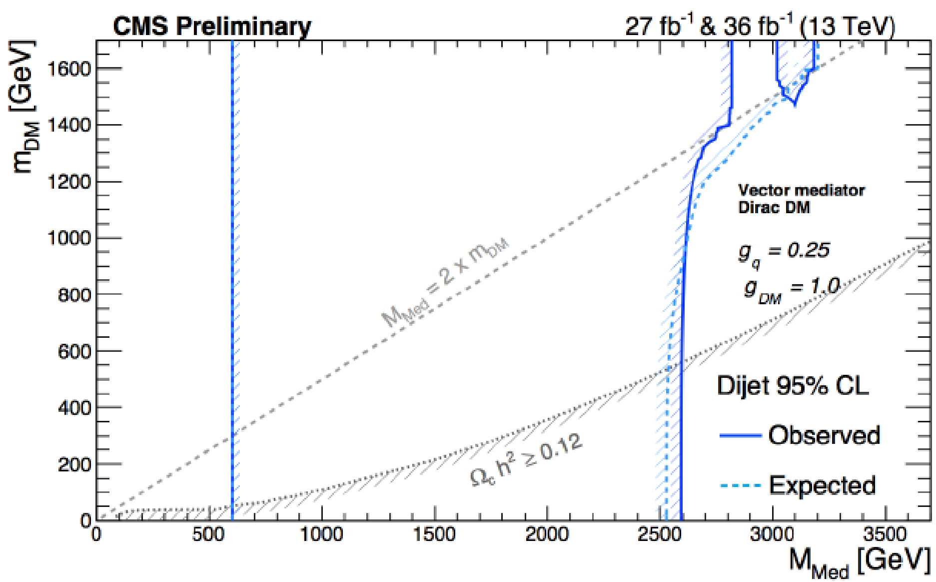
https://cds.cern.ch/record/2256873

Dijet search

- constrain on many models predicting resonances decaying into two jets
- constrain also simplified models with **(axial) vector mediator coupling only to quarks and DM**







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