Status and prospects of dark matter search

Marco Cipriani

Università di Roma La Sapienza e INFN Roma

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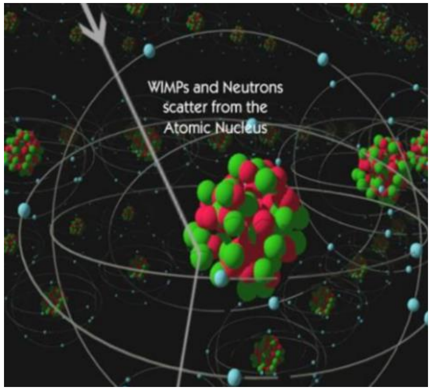
Searching for dark matter (DM)

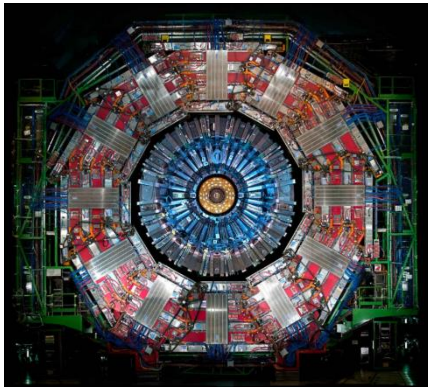
3 types of searches, with high degree of **complementarity**

indirect
- **DM annihilation** to SM particles
- constraints from cosmological parameters measurements

direct
- **DM scattering** on nuclei
- sensitive to $m_{DM} \gtrsim 10$ GeV

colliders
- **DM production** in pp collisions
- rich phenomenology

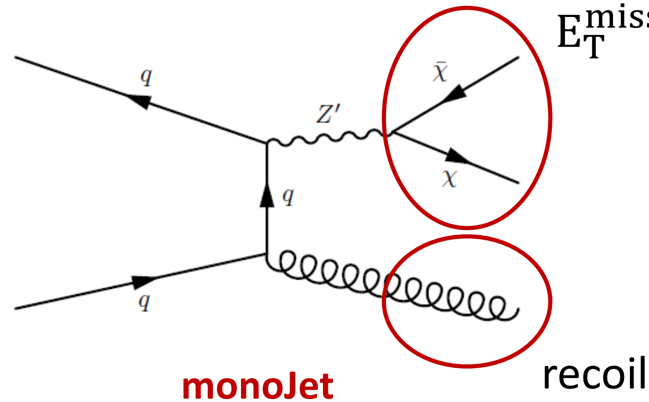




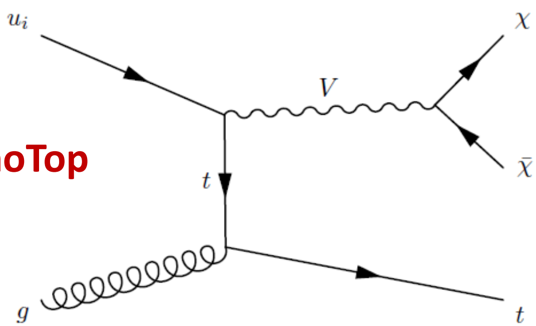
Dark Matter at colliders

MET+X searches:

- **DM** seen as missing transverse energy (**MET**)
- **X** is a Standard Model (SM) particle(s) from initial state radiation (**ISR**)
  → **trigger** on the event
- signal: **excess of events in the high MET region**

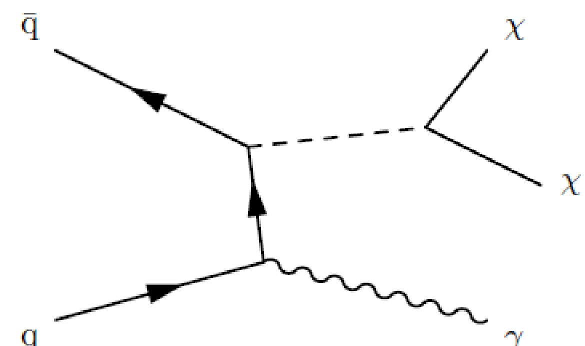


monoJet

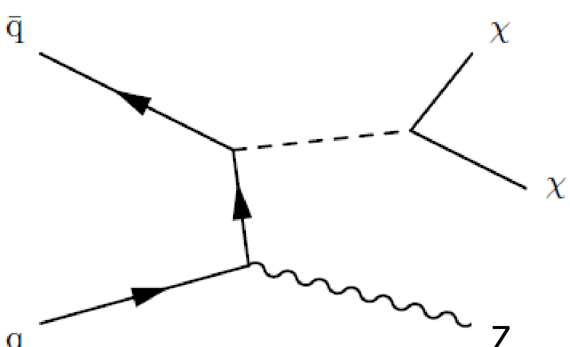


monoTop

mono-mania!



monoPhoton



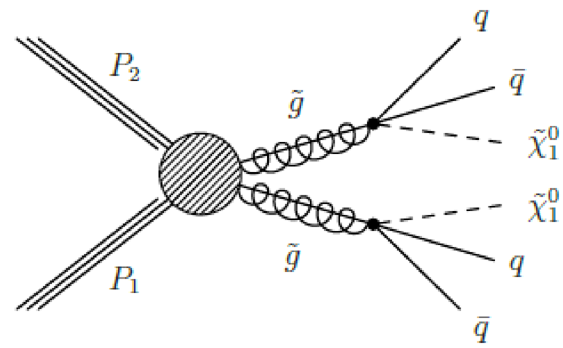
monoZ

one topology,
many final states

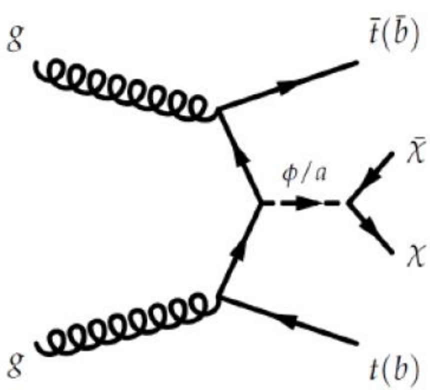
Dark Matter at colliders

Other interesting channels:

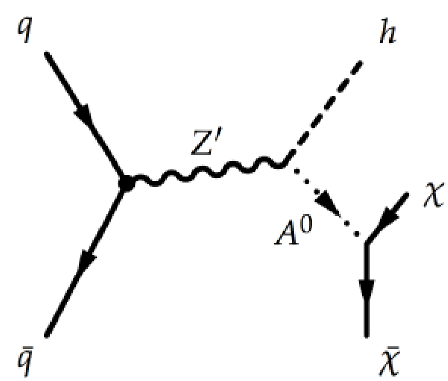
- **multijet + MET**
  - from Susy searches
  - gluinos/squarks decay to quarks and lightest supersymmetric particle
- **$t\bar{t}$ + MET, $b\bar{b}$ + MET**
- **Higgs + MET**
  - Higgs ISR suppressed
  - probe Higgs' coupling to DM
- **dijet**
  - MET-less, but provides DM interpretation



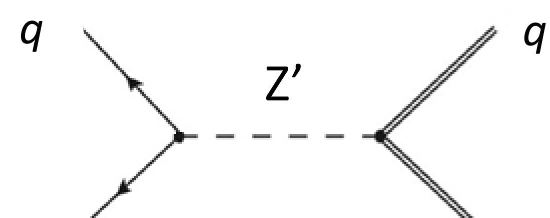
MET + (lots of) jets



MET + heavy quarks



monoHiggs

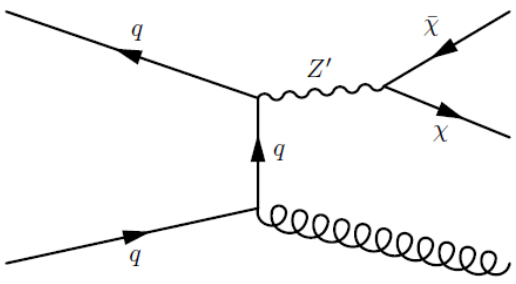


dijet

Dark Matter at colliders

Typical analysis strategy in Run2:

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

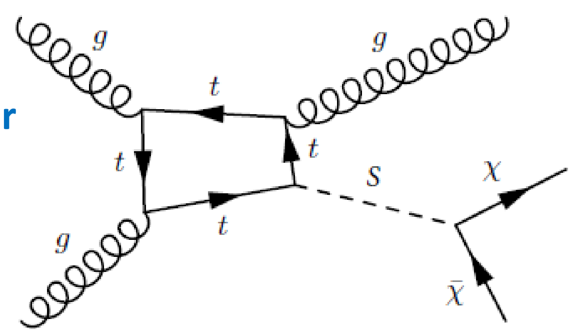


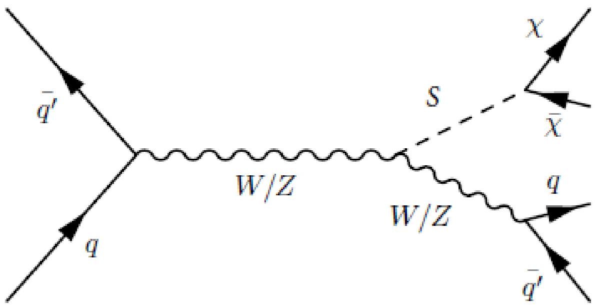
(axial)vector mediator

Potential:

- **collider searches sensitive to all possible mediator coupling structure**
  → vector, axial-vector, scalar, pseudoscalar
  → can **probe many theoretical scenarios**, unlike other searches

(pseudo)scalar mediator, monoJet



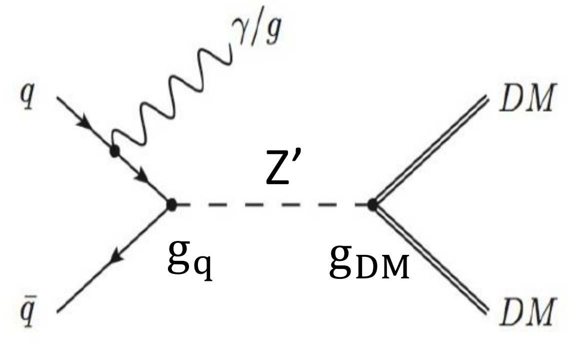


(pseudo)scalar mediator, monoV

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: $\mathbf{m_{DM}}$, $\mathbf{M_{med}}$, $\mathbf{g_{DM}}$, $\mathbf{g_q}$



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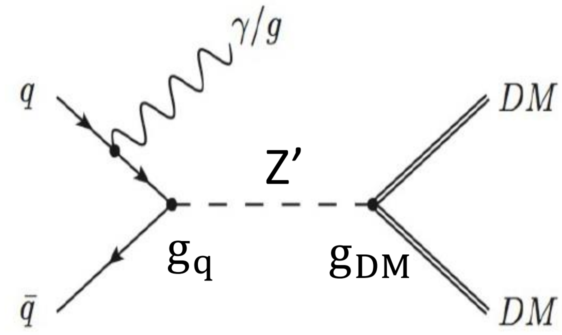
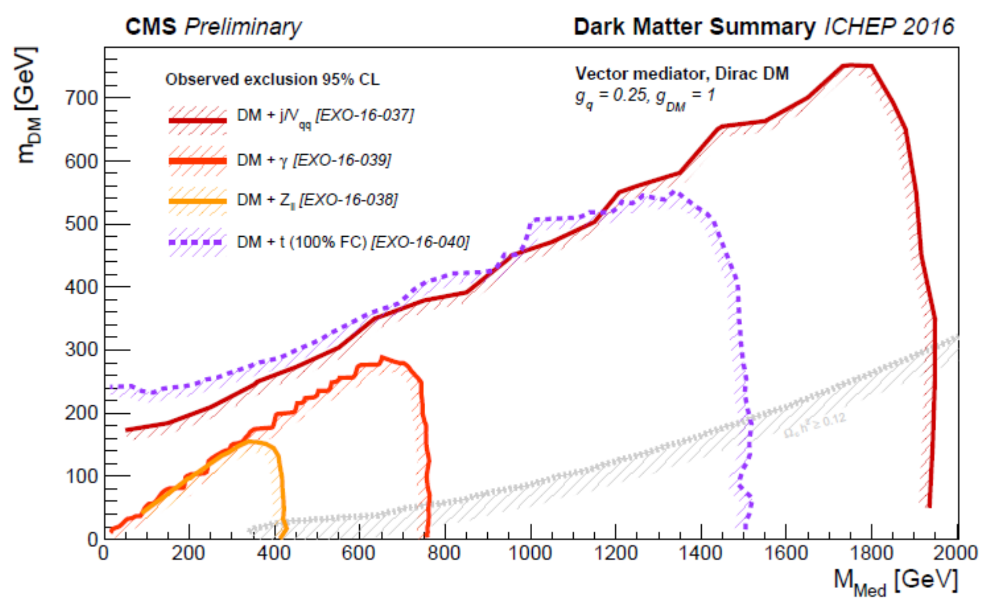


Assumptions:

- 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



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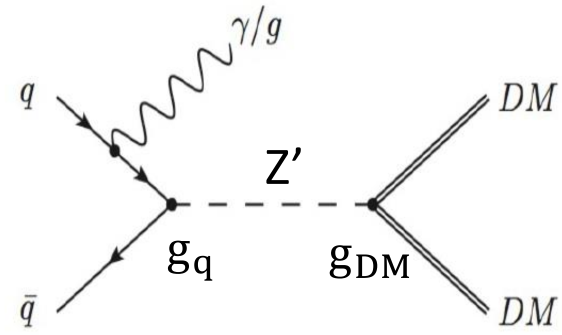

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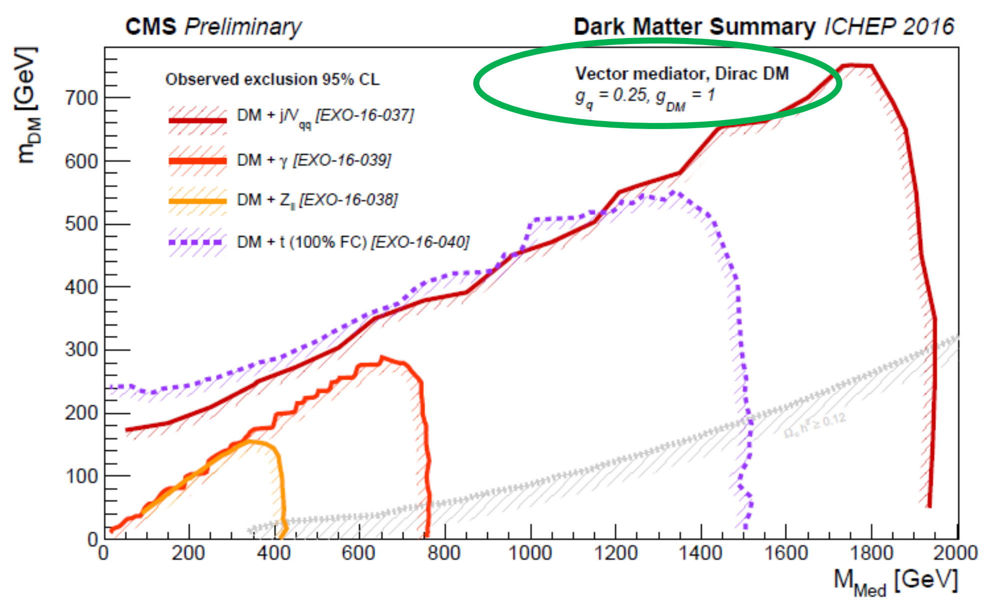
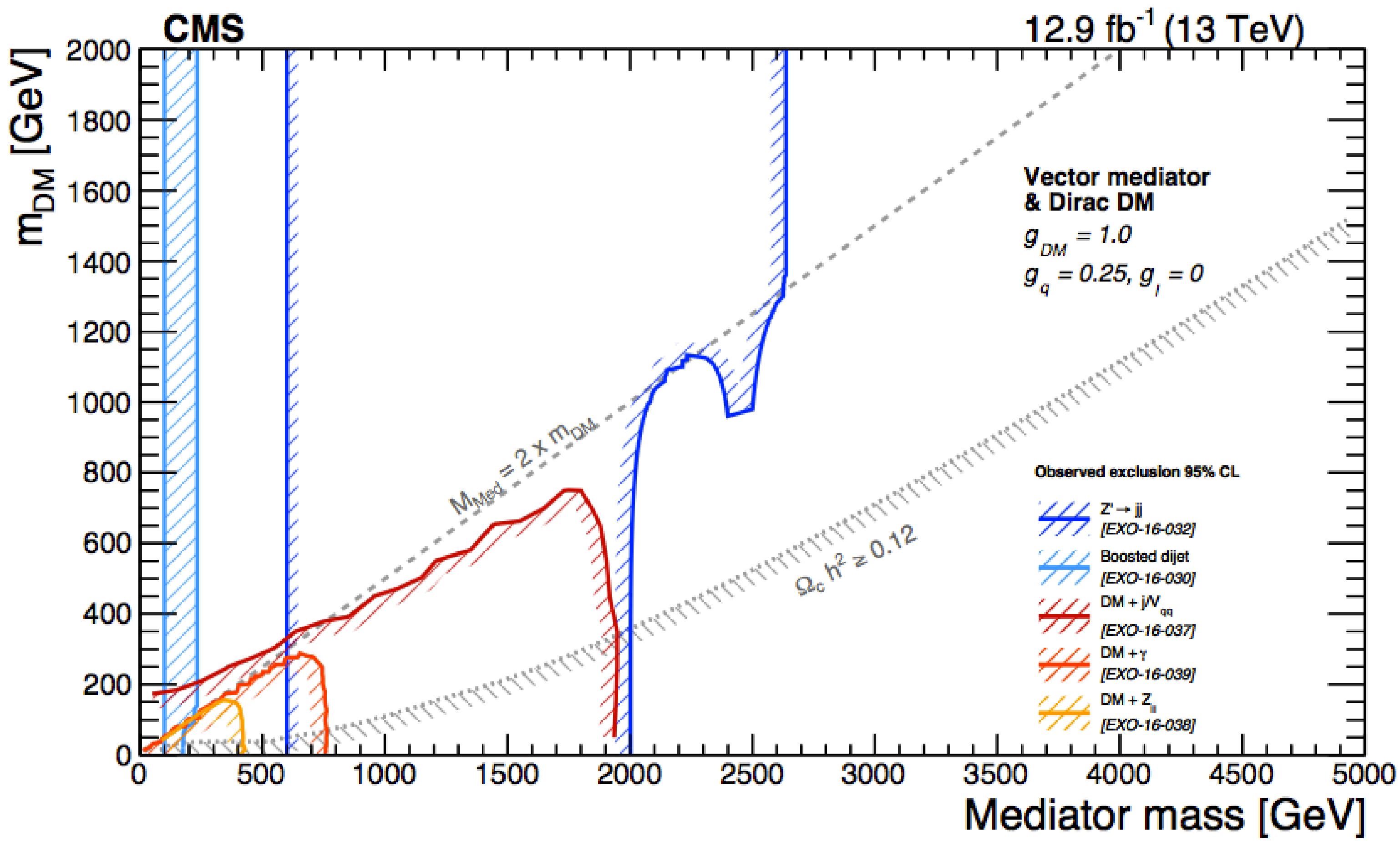


limits strongly depends on the couplings choice and model

→ change in couplings affects mediator's width

→ more details: arXiv:1603.04156v1

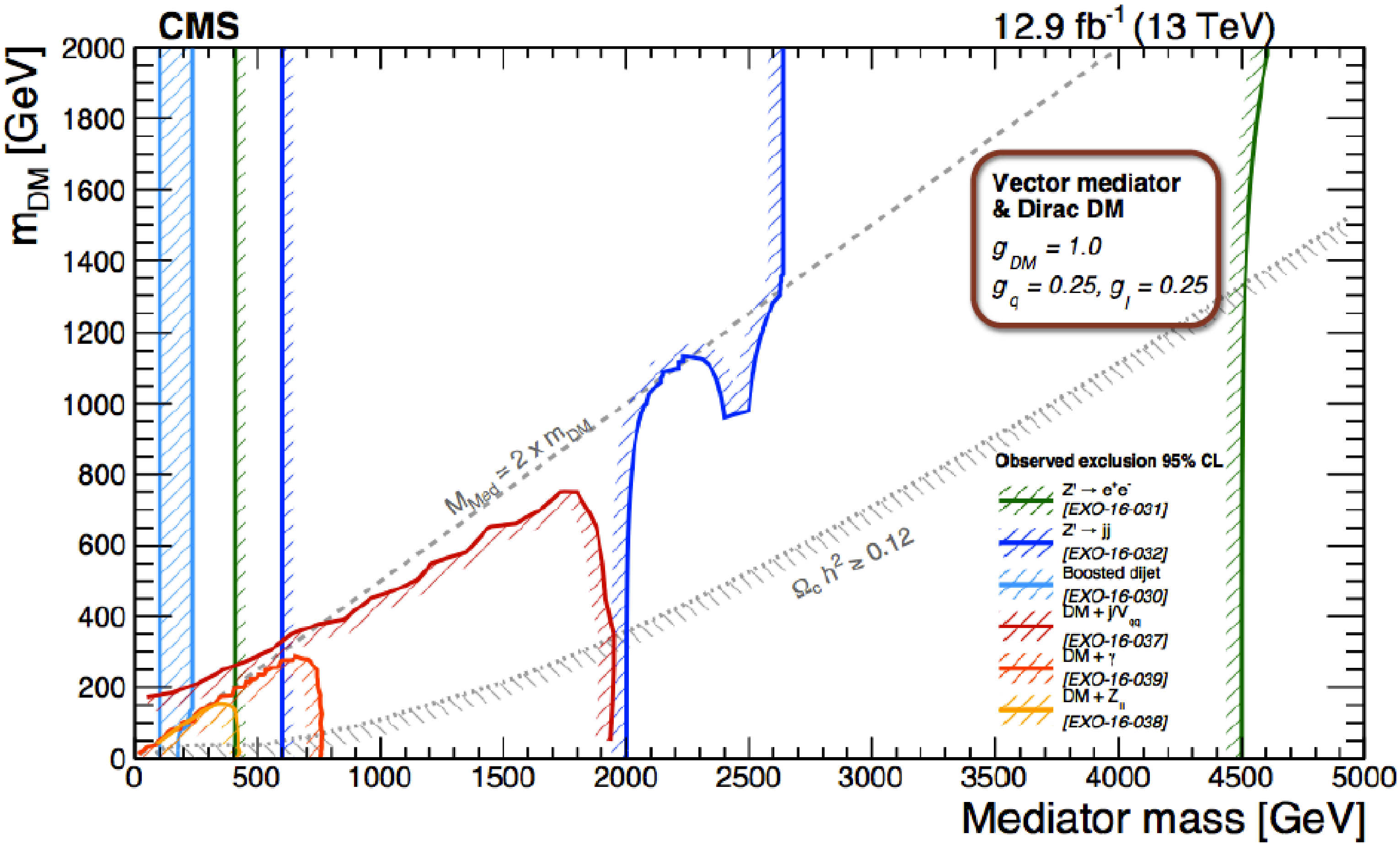
Comparison of some channels ($g_l = 0$)



dijet search dominates the picture (no DM production but limits on mediator mass)

plot from Tristan du Pree, EXO Workshop 2016

Comparison of some channels ($g_l = g_q$)

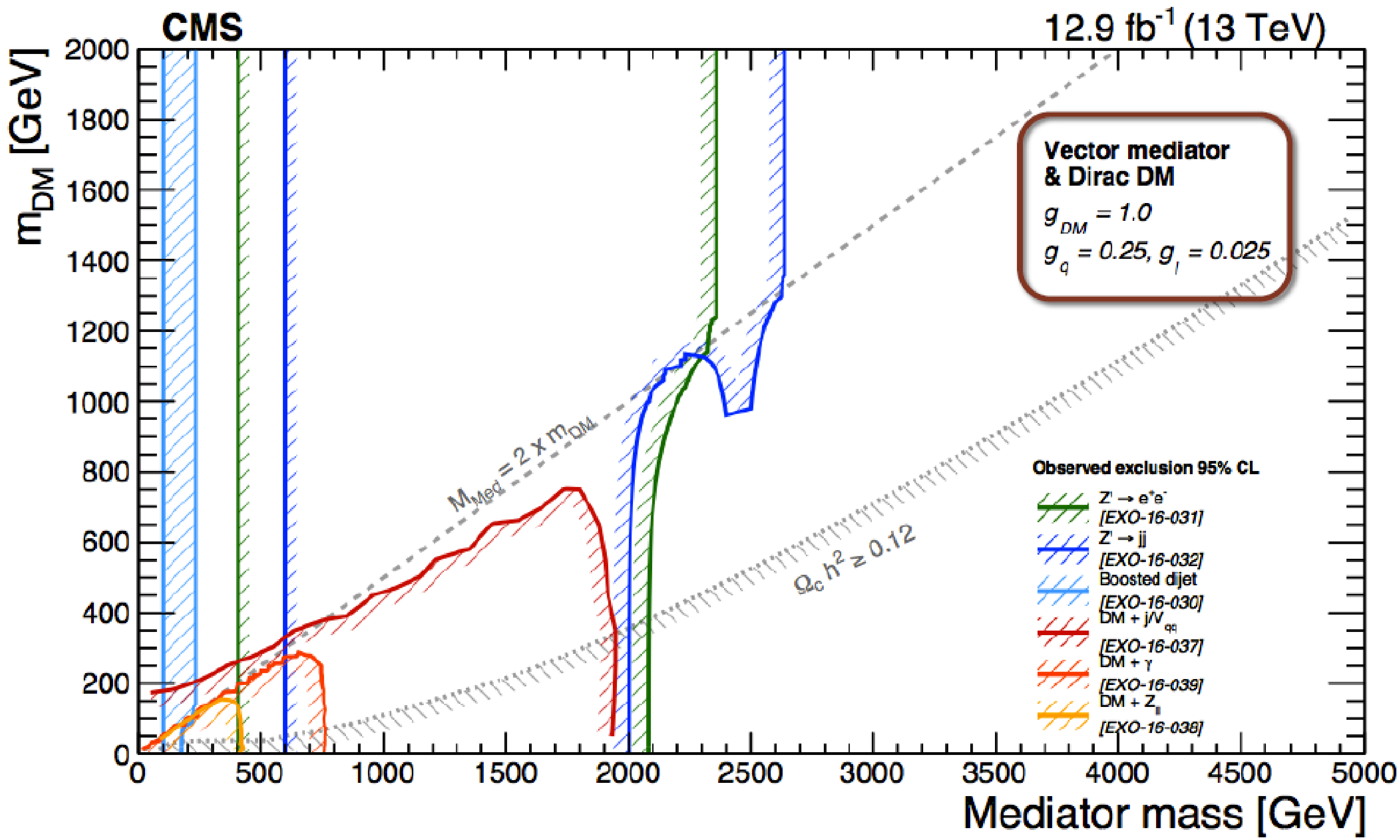


Z'(ee) most sensitive probe, if allowed.

Exclusion (or discovery) potential driven by couplings choice and M_{med}

plot from Tristan du Pree, EXO Workshop 2016

Comparison of some channels (smaller g_l)



Exclusion (or discovery) potential driven by couplings choice and $\mathrm{M_{med}}$

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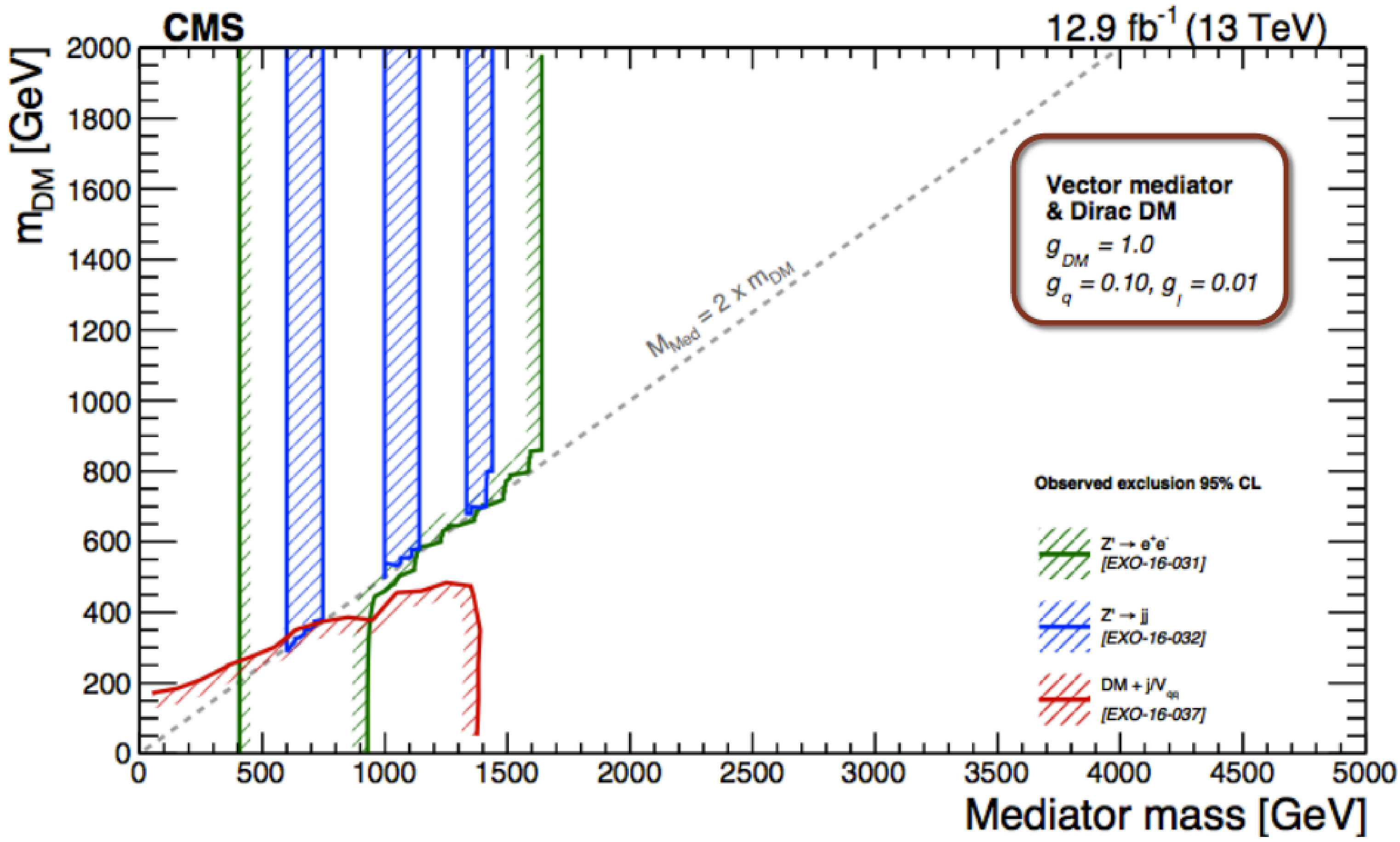
Comparison of some channels (smaller g_q and g_l)



Monojet dominates when coupling to DM bigger than that to quaks or leptons

plot from Tristan du Pree, EXO Workshop 2016

Publications up to ICHEP dataset

analyses status presented at the EXO Workshop in Zurich → https://indico.cern.ch/event/571620/

Mono-X channel	Dataset	Cadi line	Status
jet / V (hadr)	12.9 fb^{-1}, 2016	EXO-16-037	CWR
γ	12.9 fb^{-1}, 2016	EXO-16-039	PUB-Draft
dijet *	12.9 fb^{-1}, 2016	EXO-16-032	Submitted to PLB
Z(ll)	2.3 fb^{-1}, 2015	EXO-16-010	FR
Higgs($\gamma\gamma$)	2.3 fb^{-1}, 2015	EXO-15-011	CWR (combined for publication)
Higgs ($b\bar{b}$)	2.3 fb^{-1}, 2015	EXO-15-012	
Higgs (ZZ→4l)	2.3 fb^{-1}, 2015	not yet	AN
$t\bar{t}$ (dilepton)	2.2 fb^{-1}, 2015	EXO-15-028	PUB-Draft (combined with $b\bar{b}$+MET)
$t\bar{t}$ (semilep + hadr)	2.2 fb^{-1}, 2015	EXO-16-005	
jet / V (hadr)	19.7 fb^{-1}, 2012	EXO-12-055	Accepted by JHEP

* dijet not a MET+X search, but provides DM interpretation

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limited by systematics

limited by statistics

* dijet not a MET+X search, but provides DM interpretation

Next plans for publications

Sensitivity studies with 36.5 fb^{-1} and plans presented at MET+X workshop

→ https://indico.cern.ch/event/589460/

→ all analyses aim at **publishing with full dataset for Moriond**

→ **combine some channels** for publication, but separate PAS

- e.g.: monoH. **H→ $b\bar{b}$, $\tau\bar{\tau}$, $\gamma\gamma$, WW, ZZ**

Work in progress also toward combination of results from different analyses

Mediator:

(axial)vector → combine monojet, dijet , dilepton

(pseudo)scalar → combine monojet, MET+$t\bar{t}$, monoZ

Caveats

- nuisances correlations
- overlaps of signal and control regions
- cross-signal contributions

Closer look at monojet

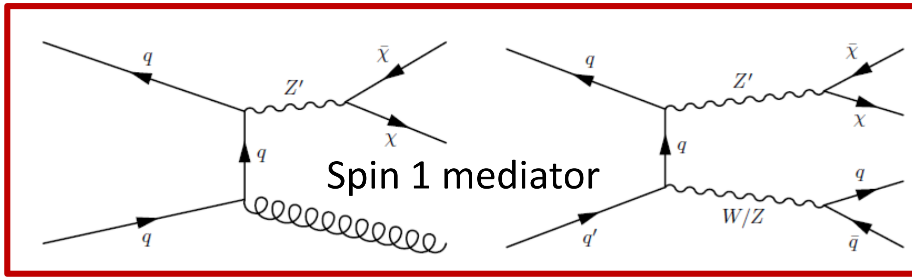
sensitive to wide range of processes

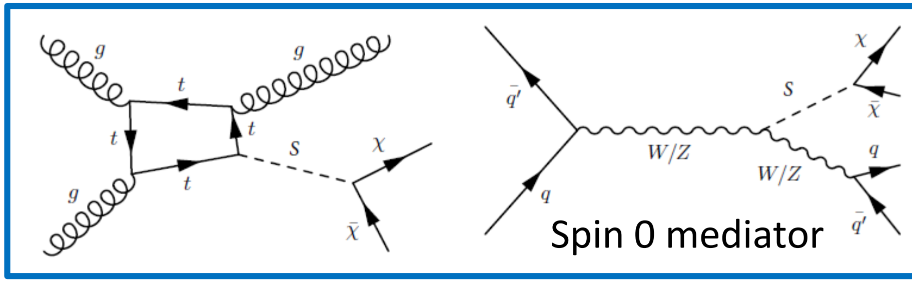
(axial)vector mediator:

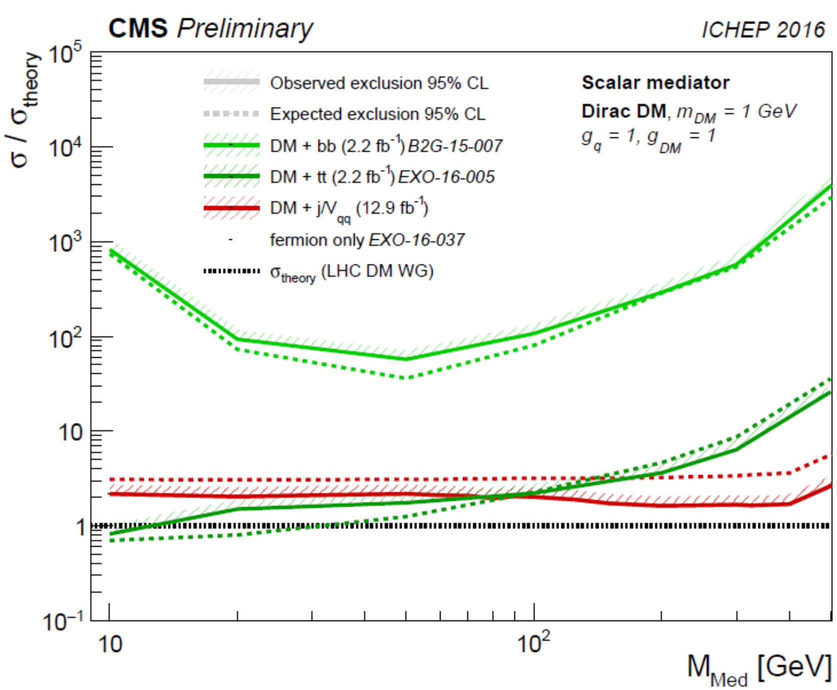
- monojet is the most sensitive channel

(pseudo)scalar mediator:

- $t\bar{t}$+MET has higher sensitivity







paper with ICHEP data seeking publication

2 event categories:

- **monojet**: jet from q/g hadronization
- **monoV** : jet from Z/W hadronic decay
  - → added in 2016

Moriond 2017 → add **more interpretations:**

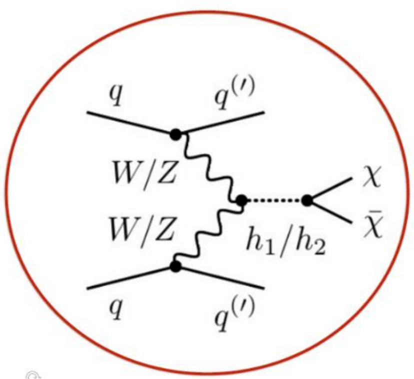
- ADD Extra Dimensions
- Non-Thermal Dark Matter
- Fermion Portal Model

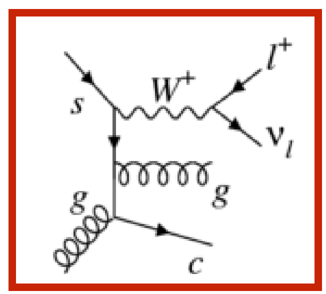
Recent monojet development: VBF H→inv

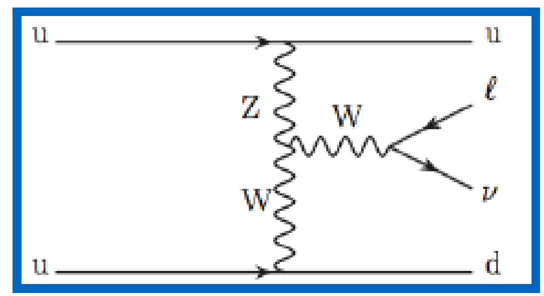
- ❑ **monojet** main focus on DM mediator **coupling only to fermions**
  - analysis already **limited by systematics**

- ❑ new models consider also possible **coupling to vector bosons**
  - **Scalar singlet model with mixing** (SMM) → arXiv:1607.06680v2
  - **H(inv) interpretation already explored by monojet:**
    - BR(H→inv) < 0.44 @ 95% CL (12.9 fb^{-1})
  - **VBF channel** expected to be the **most sensitive**

- ❑ introduce **VBF topology** as a 2-jets category **in the monojet analysis**







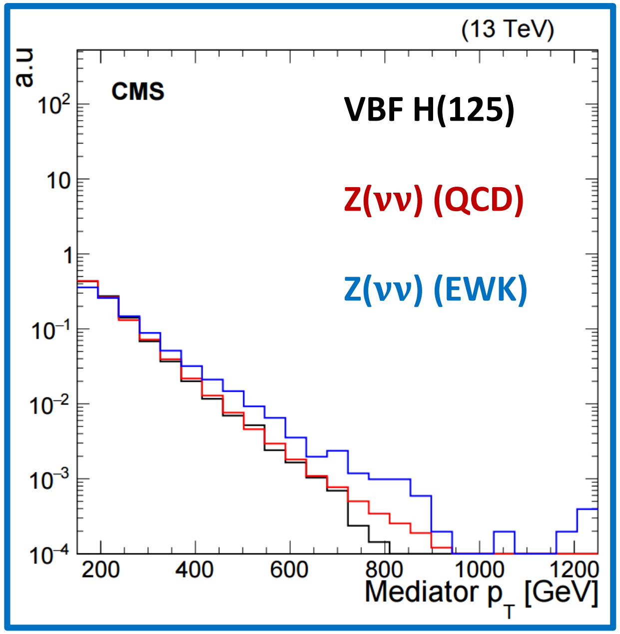
- ❑ **Benchmark: VBF H$_{125}$(inv)**
  - **distinctive topology**: two high pT forward jets and MET
  - **good S/B**

- ❑ **main backgrounds**: V+jets (V = Z,W)
  - V+jets QCD: jets from α_{QCD}
  - V+jets EWK: jets from α_{EWK}

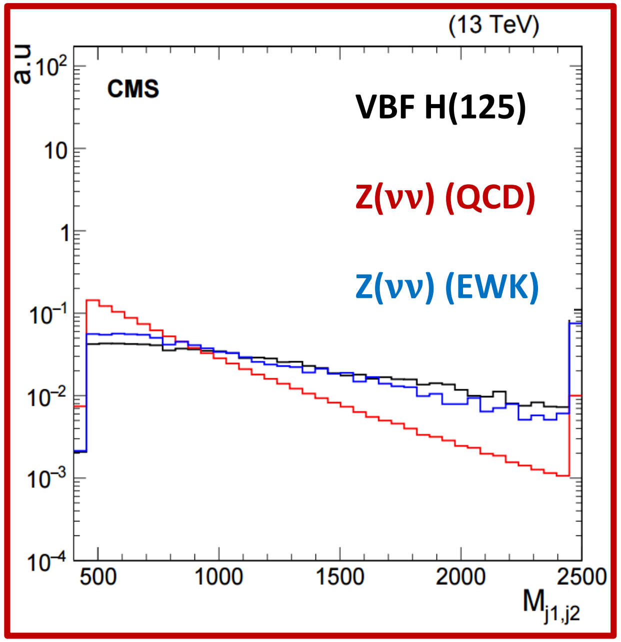
Recent monojet development: VBF H→inv

Discriminating variables:

- ❑ MET does not separate signal and background
- ❑ $\Delta\eta_{j1,j2}$ and $M_{j1,j2}$ are good variables (correlated)
- ❑ other variables are **Δφ(jets,MET)** and **Δφ(j1,j2)** (embed information on boson's spin)



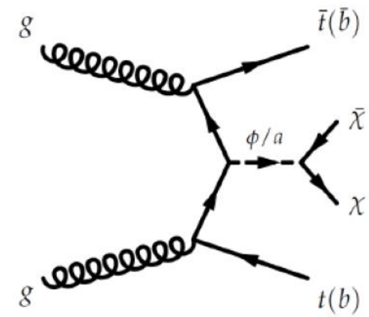
- ❑ **VBF H(inv)** analysis **already existing (HIG-PAG)**
  - expected limit: BR(H_{125}→inv) < 38.2 % (12.9 fb^{-1})
- ❑ **monojet group explored improvements to analysis**
  - different **selection**
  - **shape analysis** on $M_{j1,j2}$ or $\Delta\eta_{j1,j2}$
  - **more CRs** to constrain main backgrounds
  - preliminary results: **BR(H_{125}→inv) ≲ 20-25 %**
    - **still room for further improvements**



Other promising channels

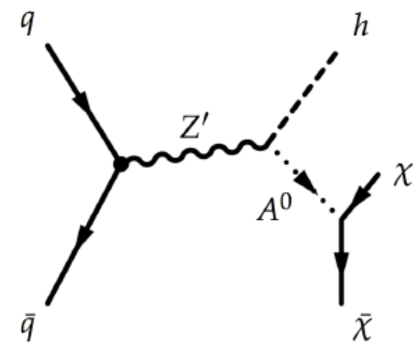
MET+$t\bar{t}$:

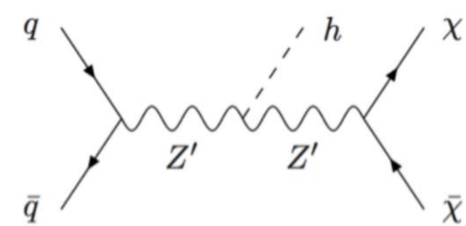
- ❑ top pair decays hadronically or (semi)leptonically
- ❑ currently separate analyses
  - work in progress toward combination for publication



MET+H

- ❑ probe **Higgs coupling to new physics**
  - **2 Higgs doublet model**: Z’ decays to H and a CP-odd A^0
  - **Z' Baryonic:** Z’ radiates a H and decays to DM
- ❑ **H($b\bar{b}$) and H($\gamma\gamma$)** combination done with **2015** data
- ❑ **$b\bar{b}$, $\tau\bar{\tau}$, $\gamma\gamma$, WW, ZZ** channels combination for **2016**
  - $b\bar{b}$, $\tau\bar{\tau}$ drive sensitivity





Great potential and much to gain from increasing dataset for both channels
→ **some of the main bets for the future**

What next …

Lots of improvements in Run2 with respect to Run1

No evident breakthrough foreseen for the near future

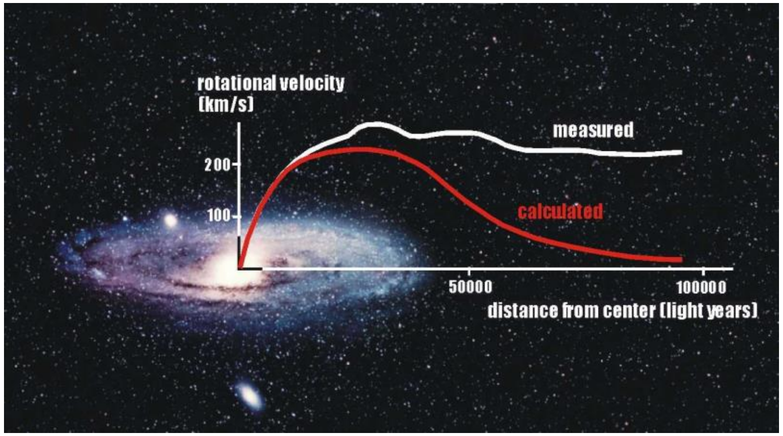
The bet is still open:

- ❑ **energy bound (almost) reached …**
- ❑ **… but still entering the high luminosity era**
  - **≈ 100 fb^{-1} expected to be collected in 2017-18**
- ❑ **with more data, analyses wil start being limited by systematics …**
- ❑ **… but will be able to target more complex diagrams and channels …**
- ❑ **… and possibly devise new smart analysis techniques**

Stay tuned !

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)

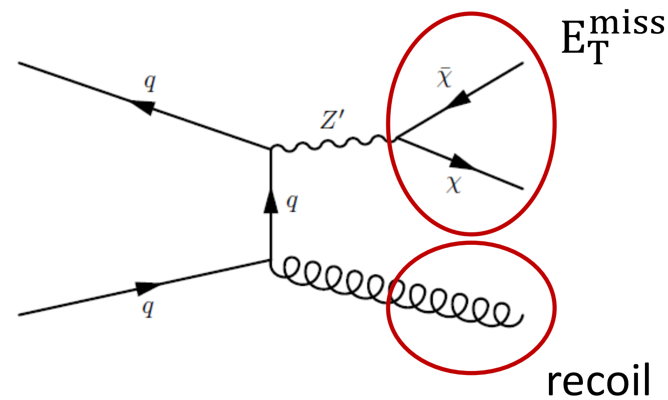
Dark Matter at colliders

MET+X searches:

- DM seen as missing transverse energy (MET)
- X is a SM particle(s) to trigger on the event
- signal: **excess of events in the high MET region**

Backgrounds:

- genuine E_T^{miss} from **Z(νν)/W(lν)** (irreducible)
- E_T^{miss} from **energy mismeasurement** (reducible)



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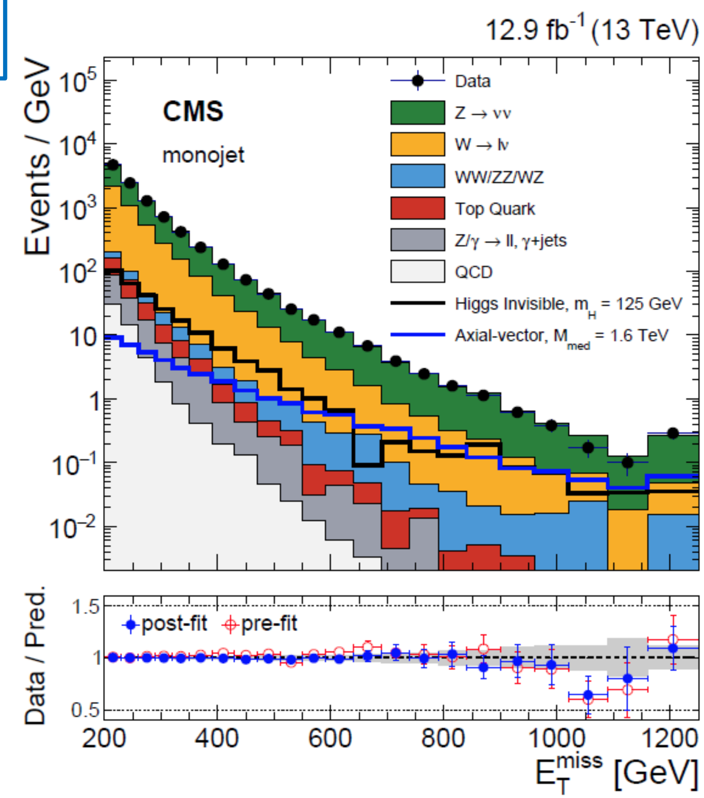
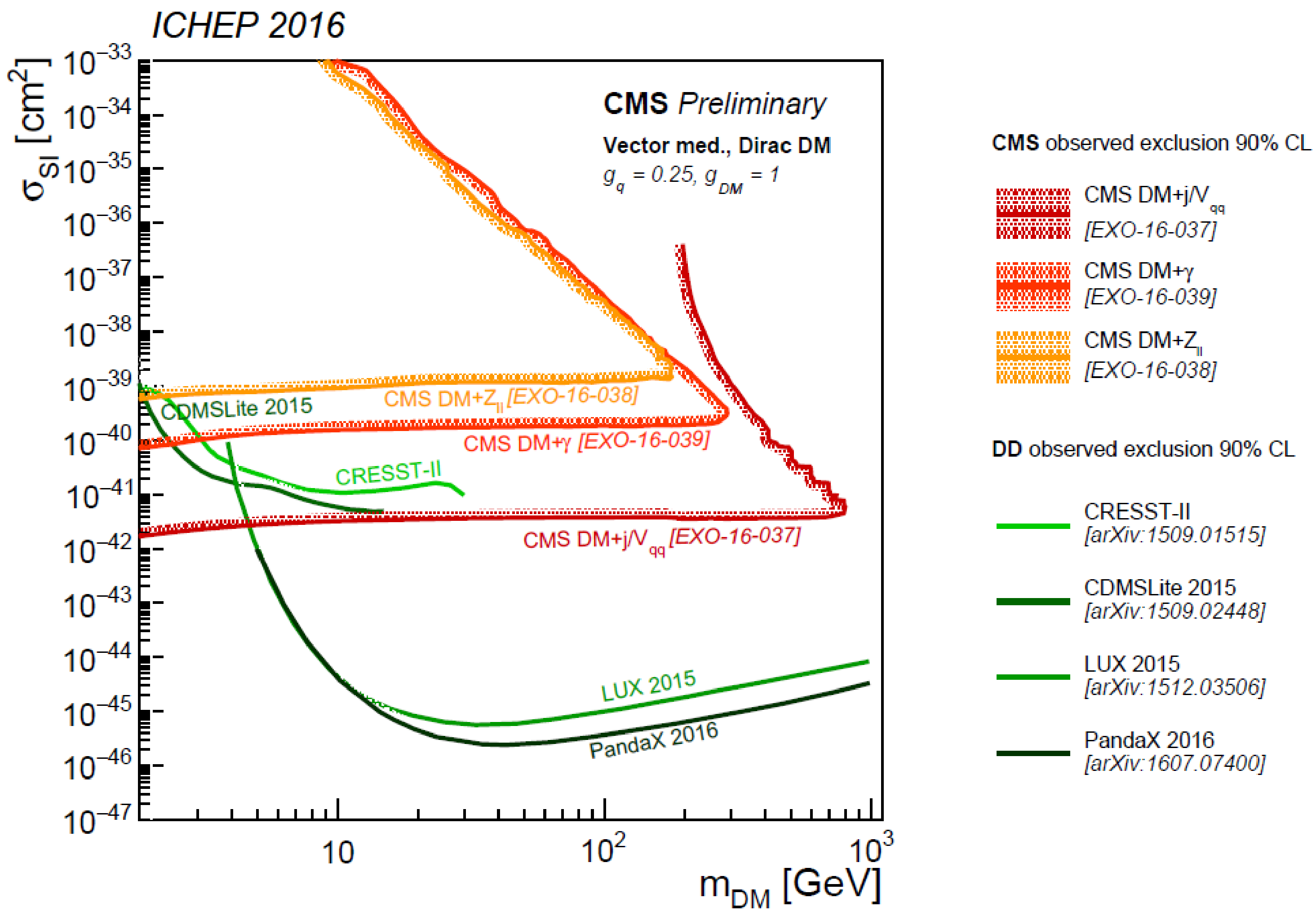


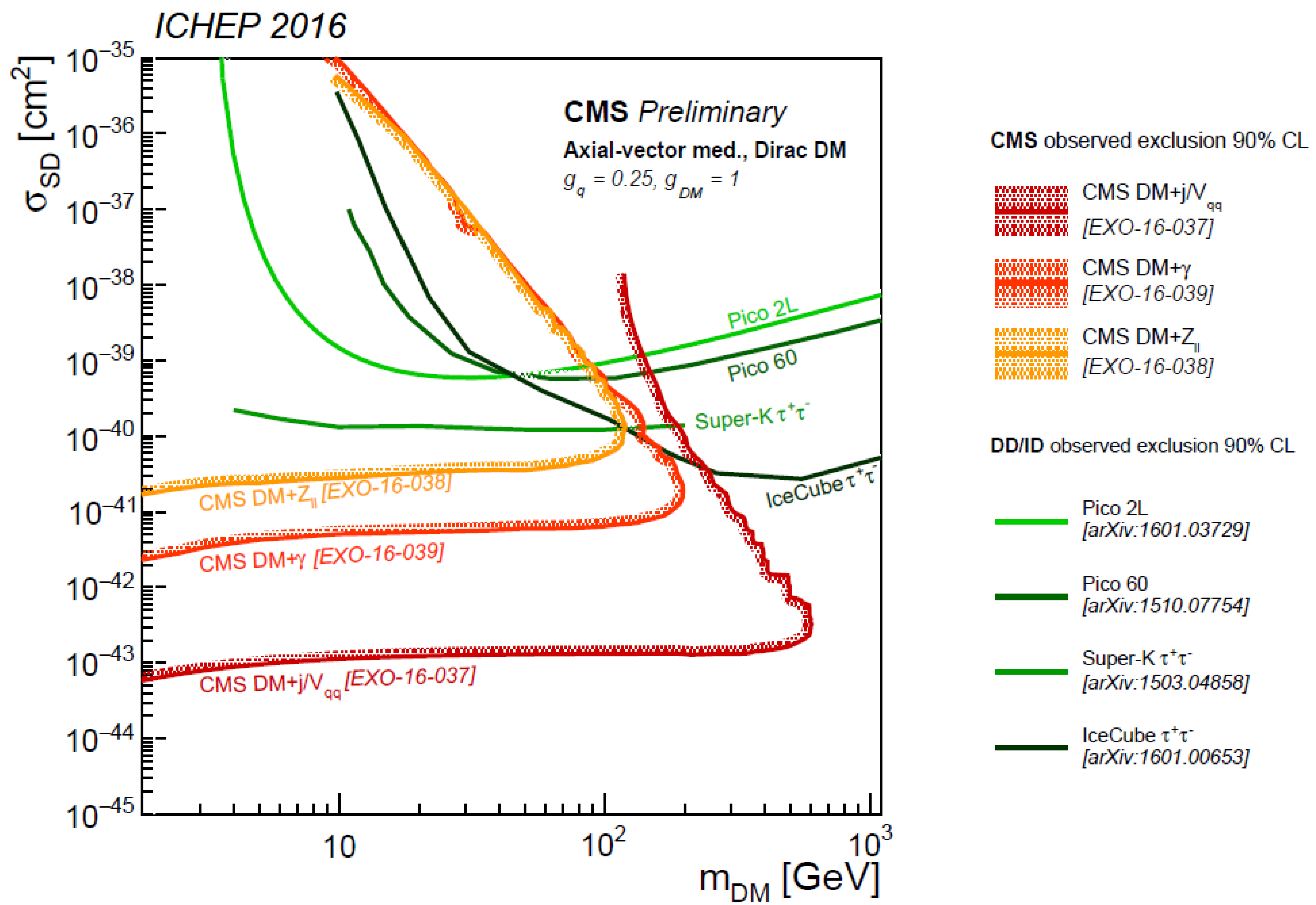
ICHEP summary plots



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*

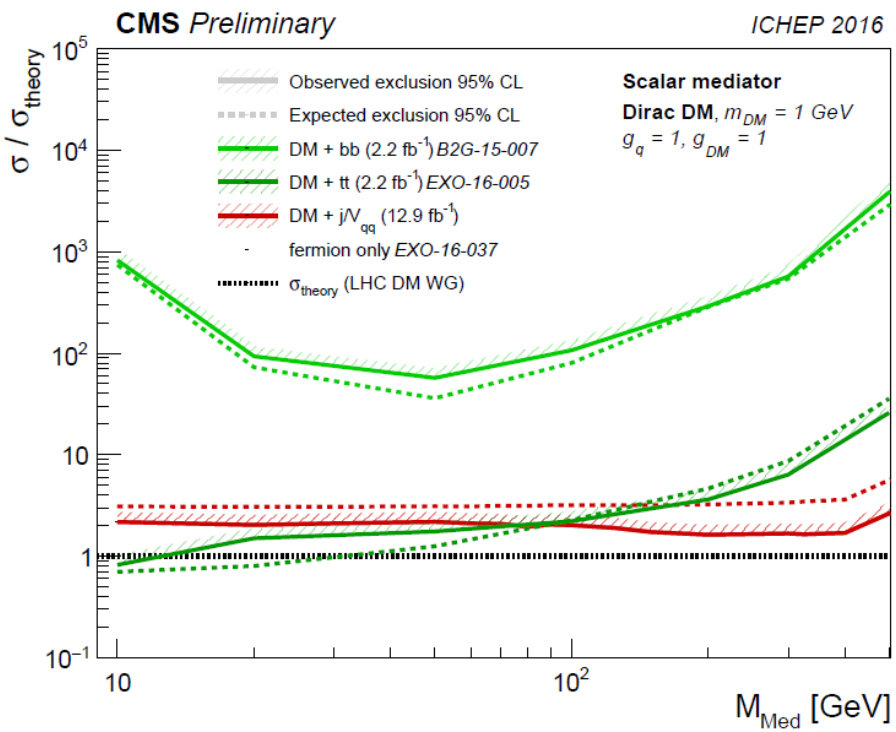
ICHEP summary plots

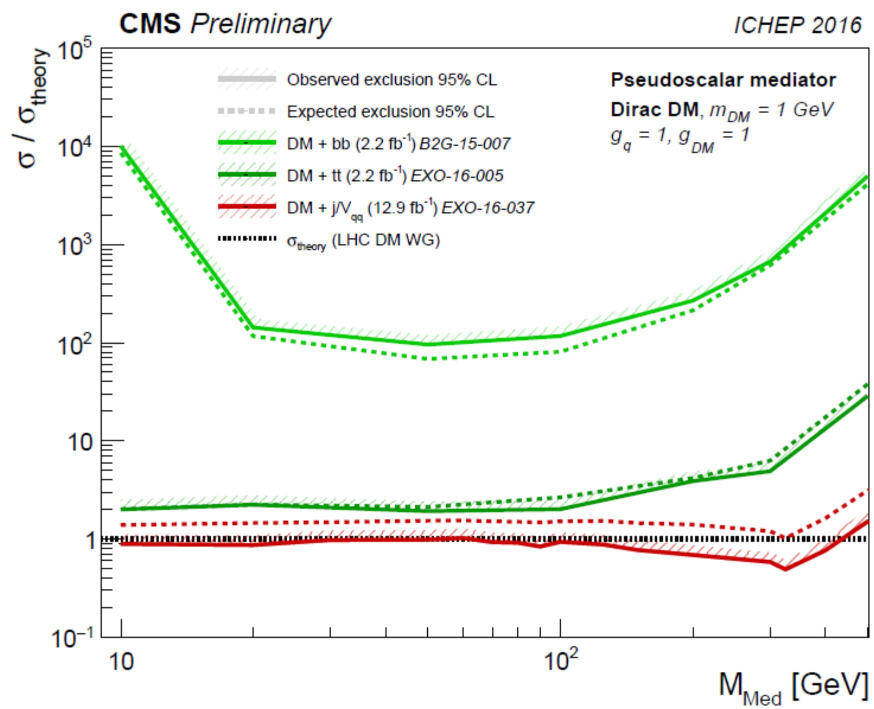


monojet most sensitive channel for axial-vector mediator
collider searches more sensitive than direct searches everywhere

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

ICHEP summary plots





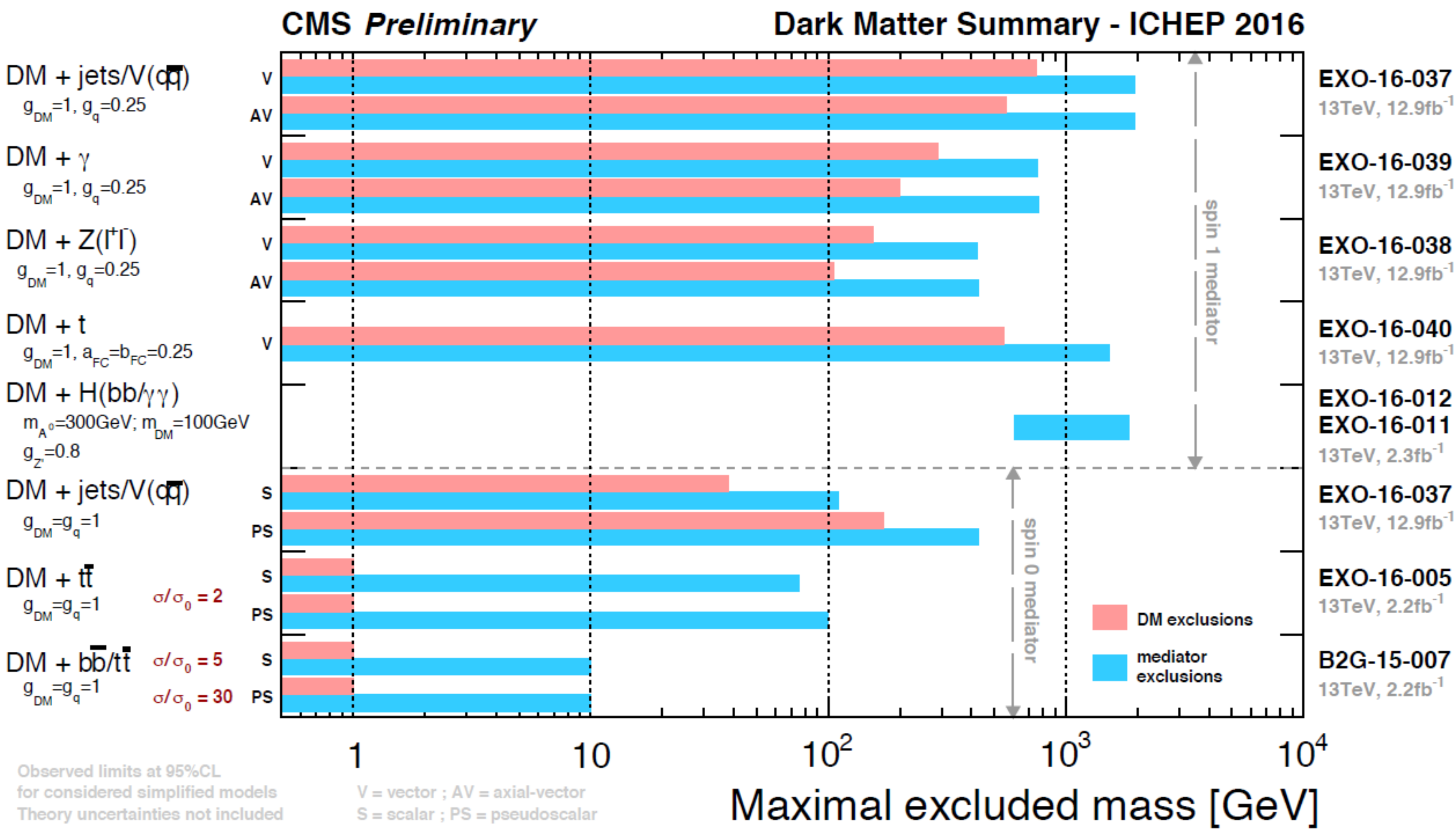
monojet and mono-$t\bar{t}$ most sensitive channels for (pseudo)scalar mediator

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

direct searches have much less or no sensitivity to this case

Summary table

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

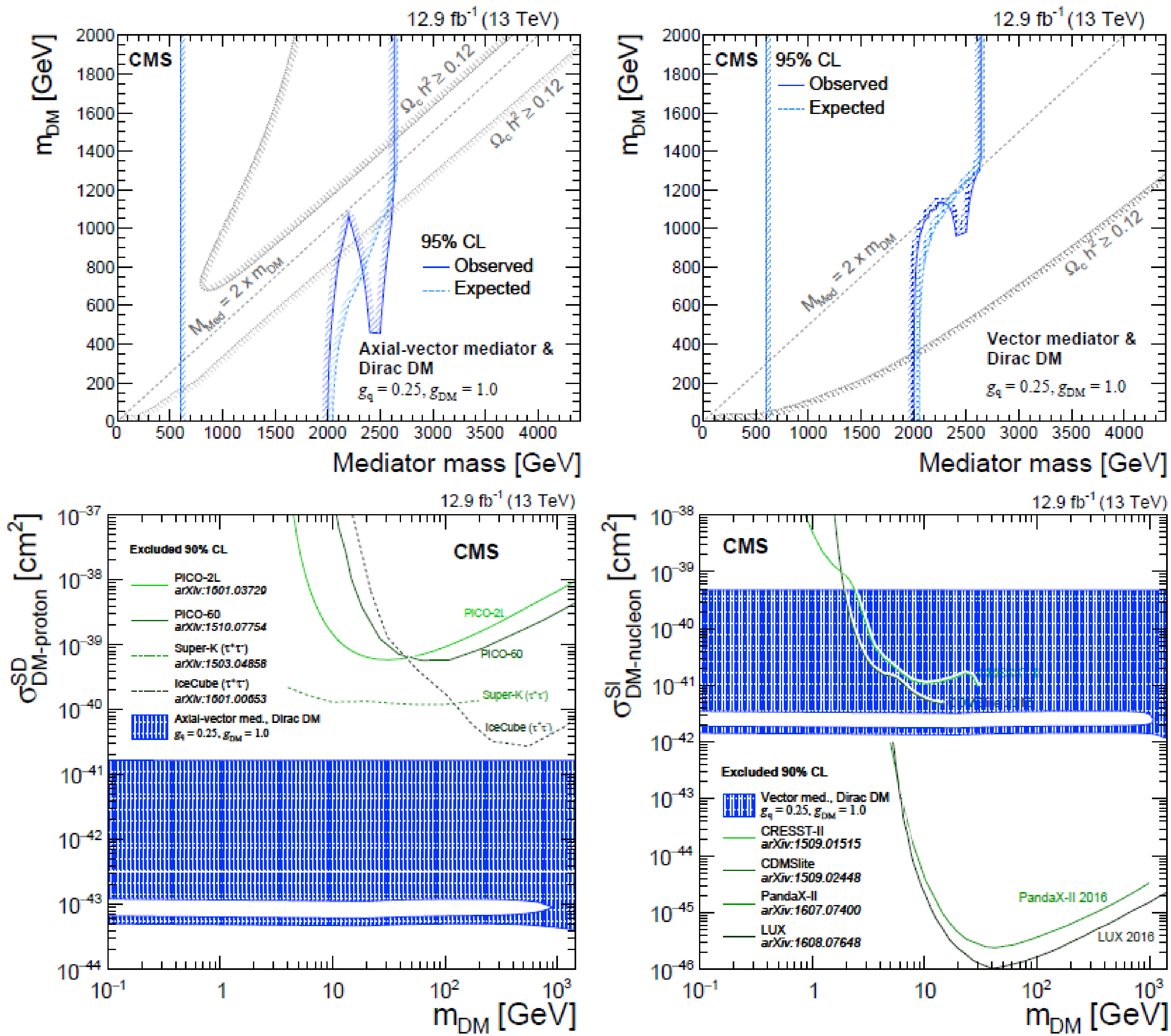


Limits at 95% CL for considered simplified model (theory uncertainties not included)

V = vector; A = axial-vector; S = scalar; PS = pseudoscalar

Dijet limits

arXiv:1611.03568v1



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

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

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

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

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

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

Theory

Lagrangian for spin 0 mediator

arXiv:1603.04156v1

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

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

Partial widths

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

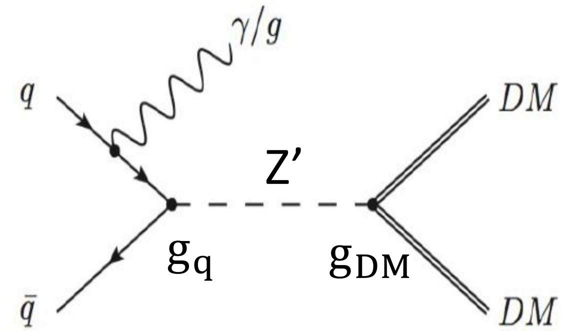
pseudoscalar: highly suppressed

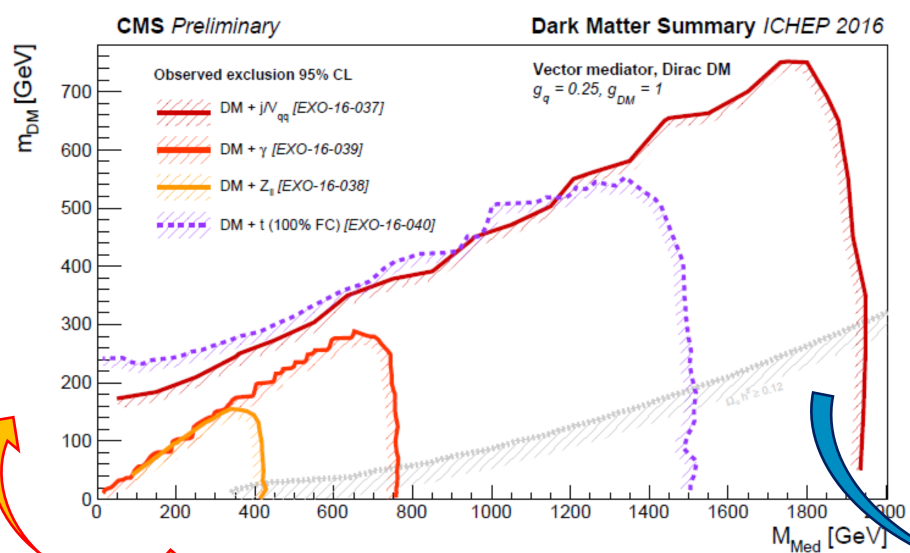
arXiv:1603.04156v1

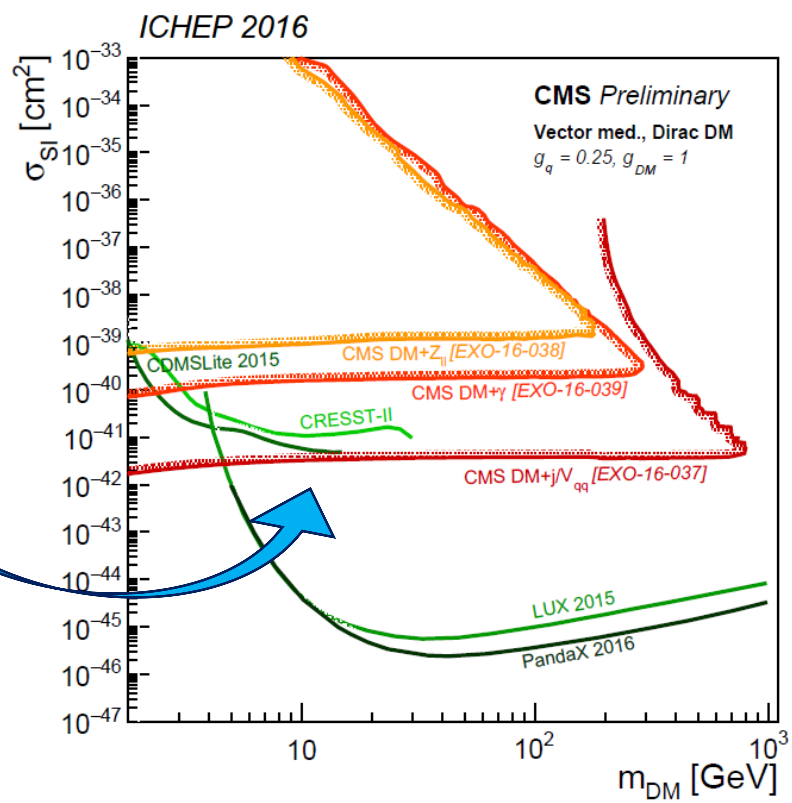
Theoretical overview

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



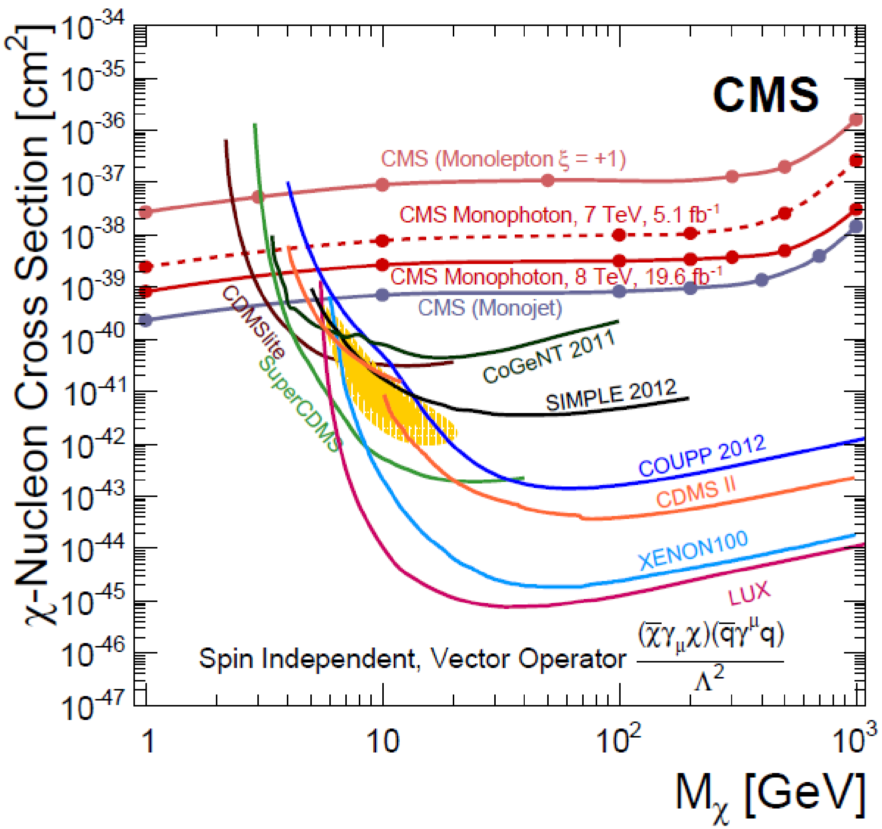




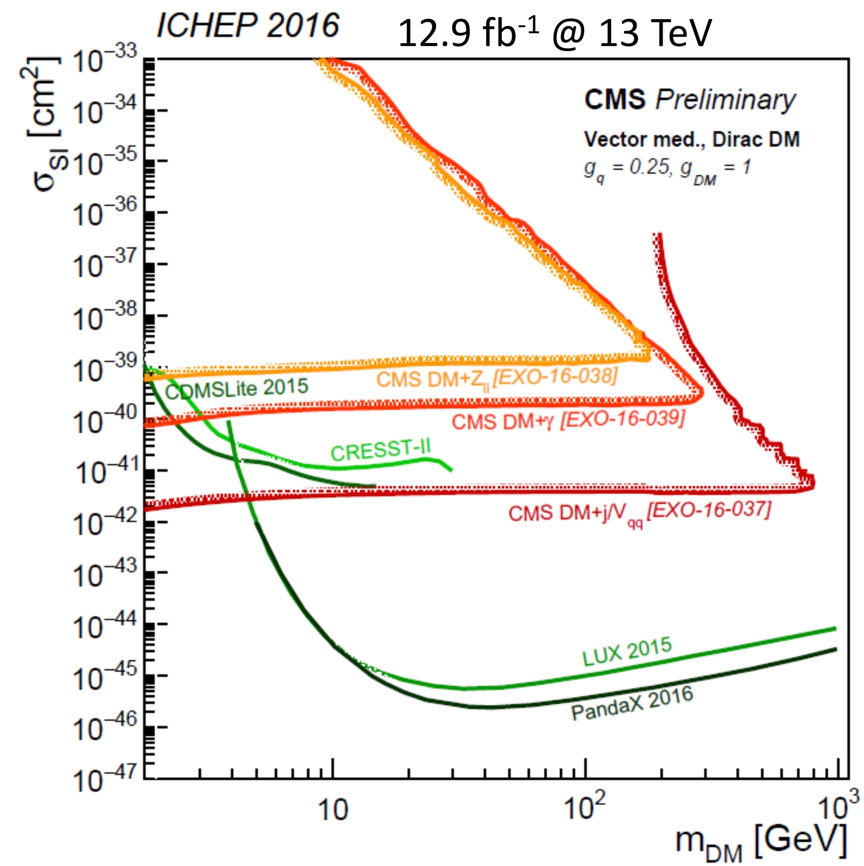
collider searches **limits flat with respect to m_{DM}** and **sensitive also to low m_{DM}**

Comparison of Run1 and Run2

19.6 fb^{-1} @ 8 TeV



12.9 fb^{-1} @ 13 TeV



CAVEAT: simplified model interpretation and different analysis strategy in Run2

Improvements in Run2

Almost doubled energy wrt Run1

- ❑ **enhanced cross section** (parton luminosities)
- ❑ no large gain from 13 to 14 TeV

Better background estimate

- ❑ **more control regions** to constrain backgrounds

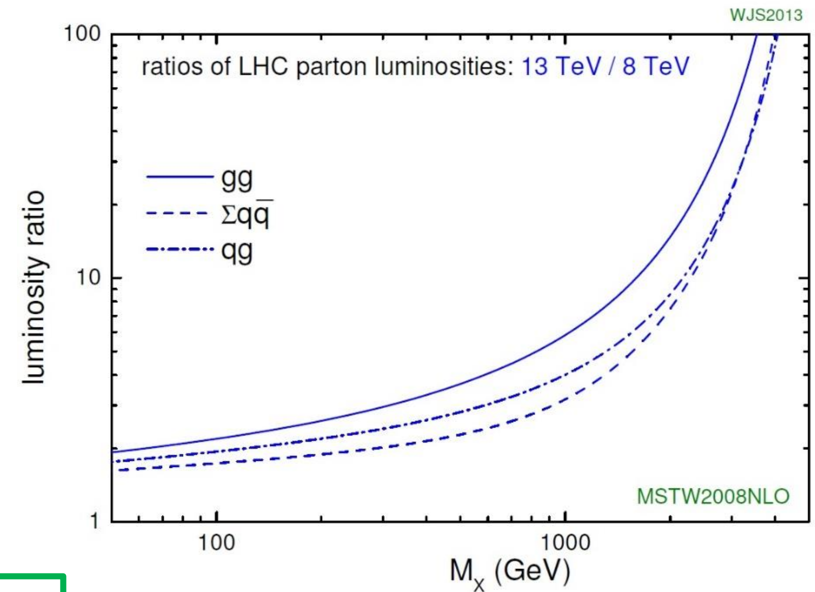
New analysis strategy

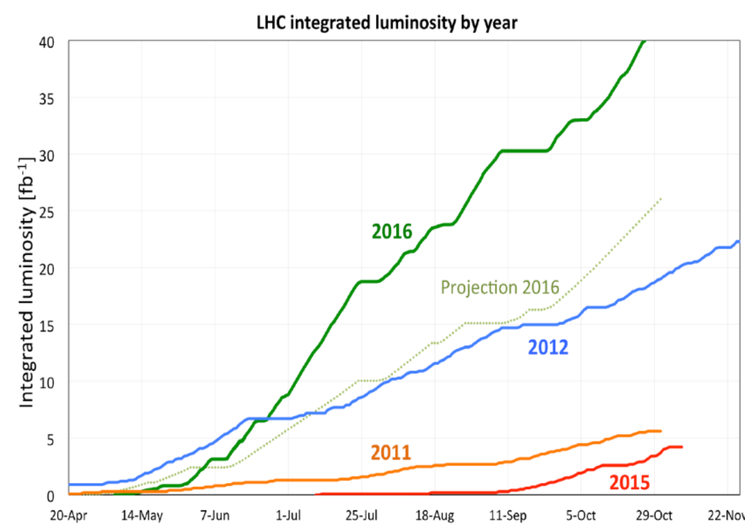
- ❑ switch from cut&count to **shape analysis**
- ❑ signal from combined fit in signal and control regions

Last but not least …

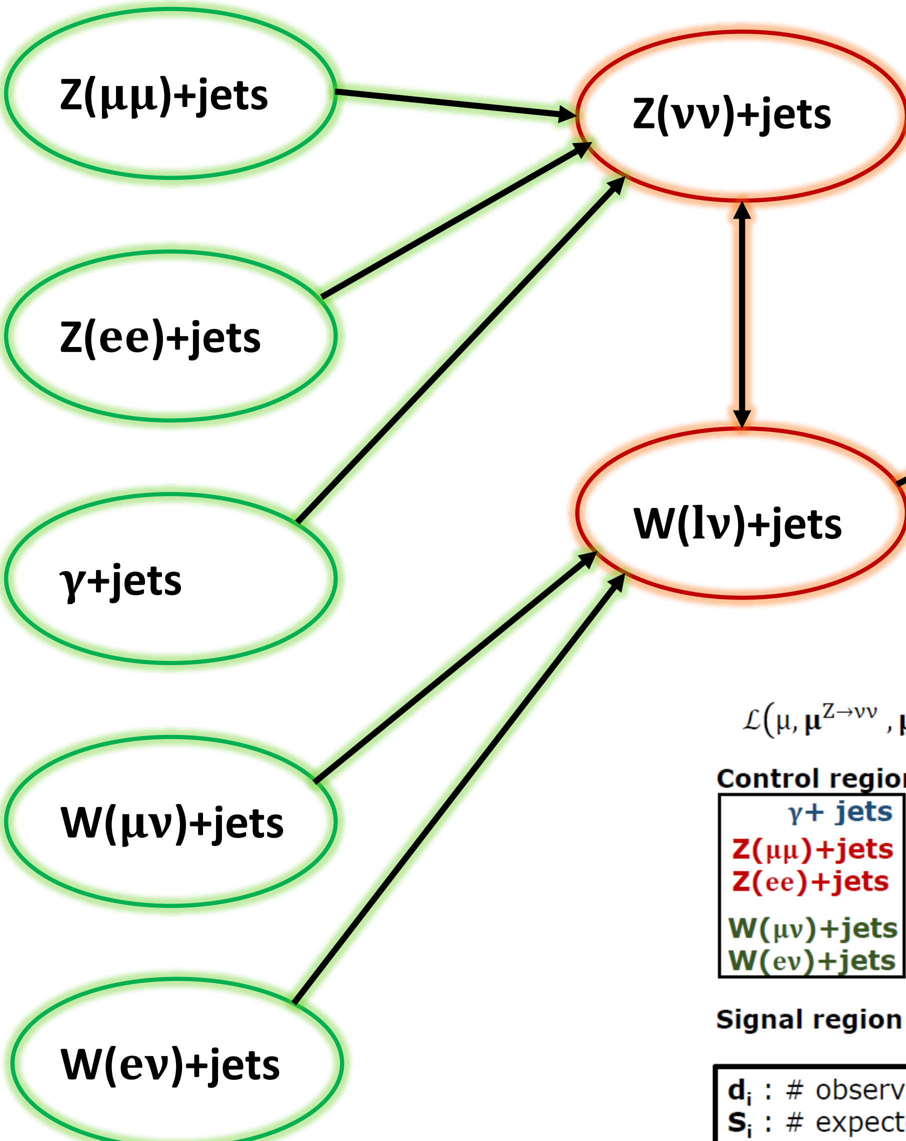
- ❑ **lots of new data**, excellent detector performance

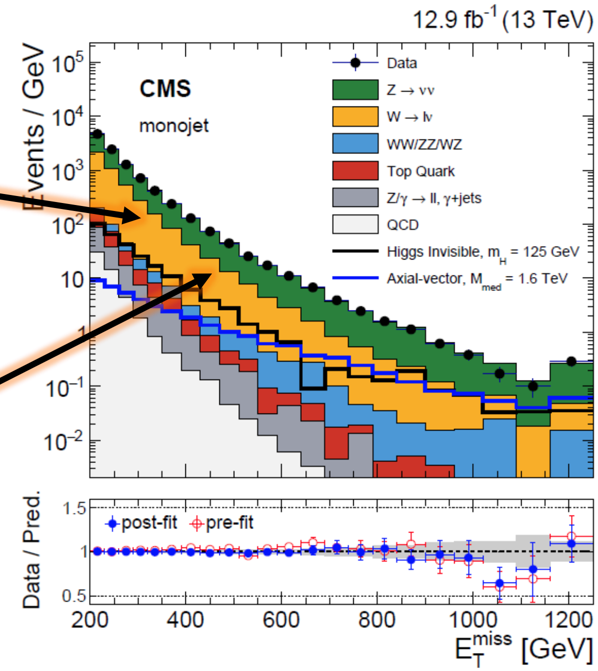
→ now can **target rare processes** outside Run1 sensitivity





Background estimate





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

exp. events for Z(νν):

exp. events for W(lν)

Control regions

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

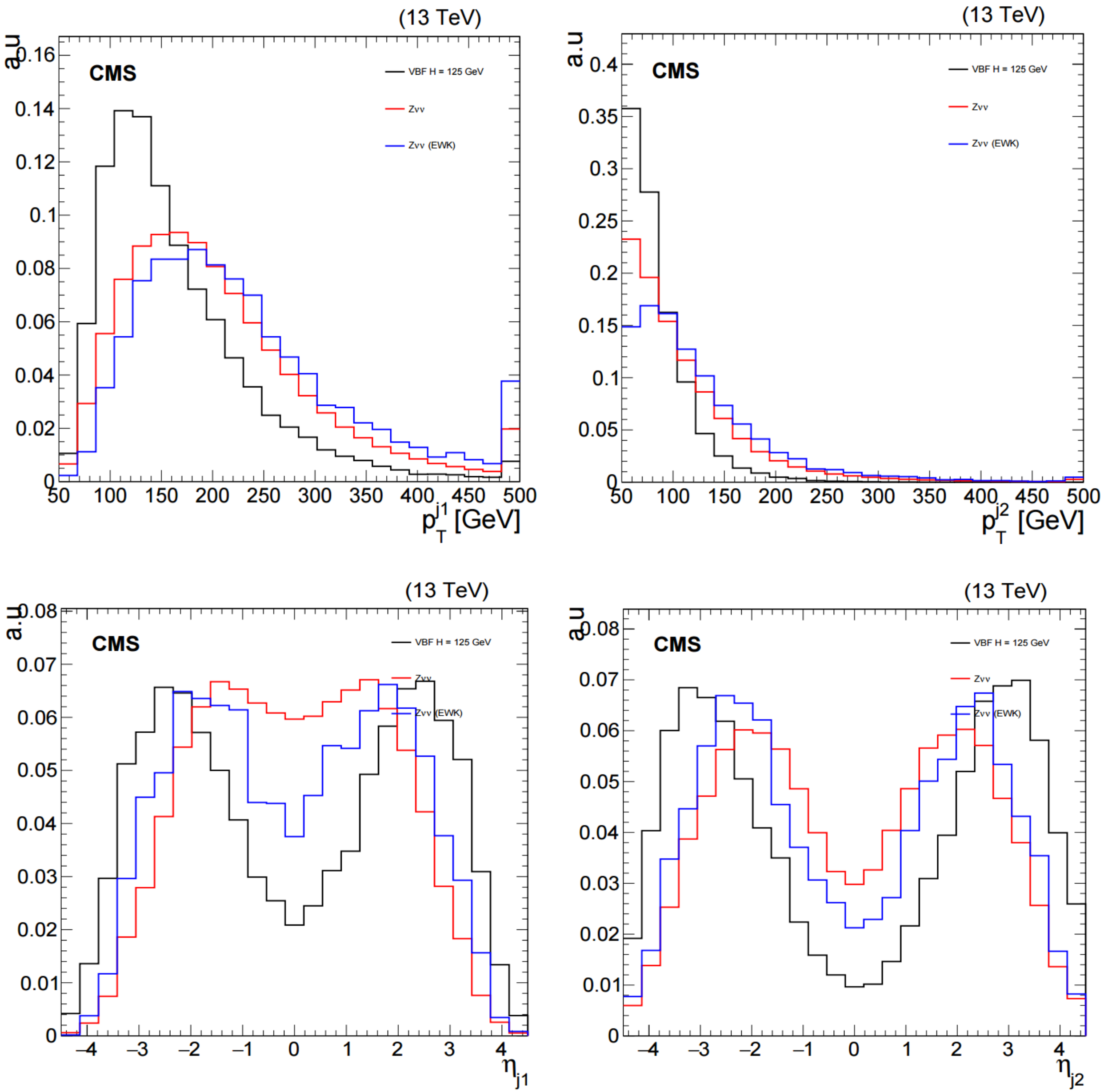
Signal region

- **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)

Exploring VBF signal properties



VBF H(125)

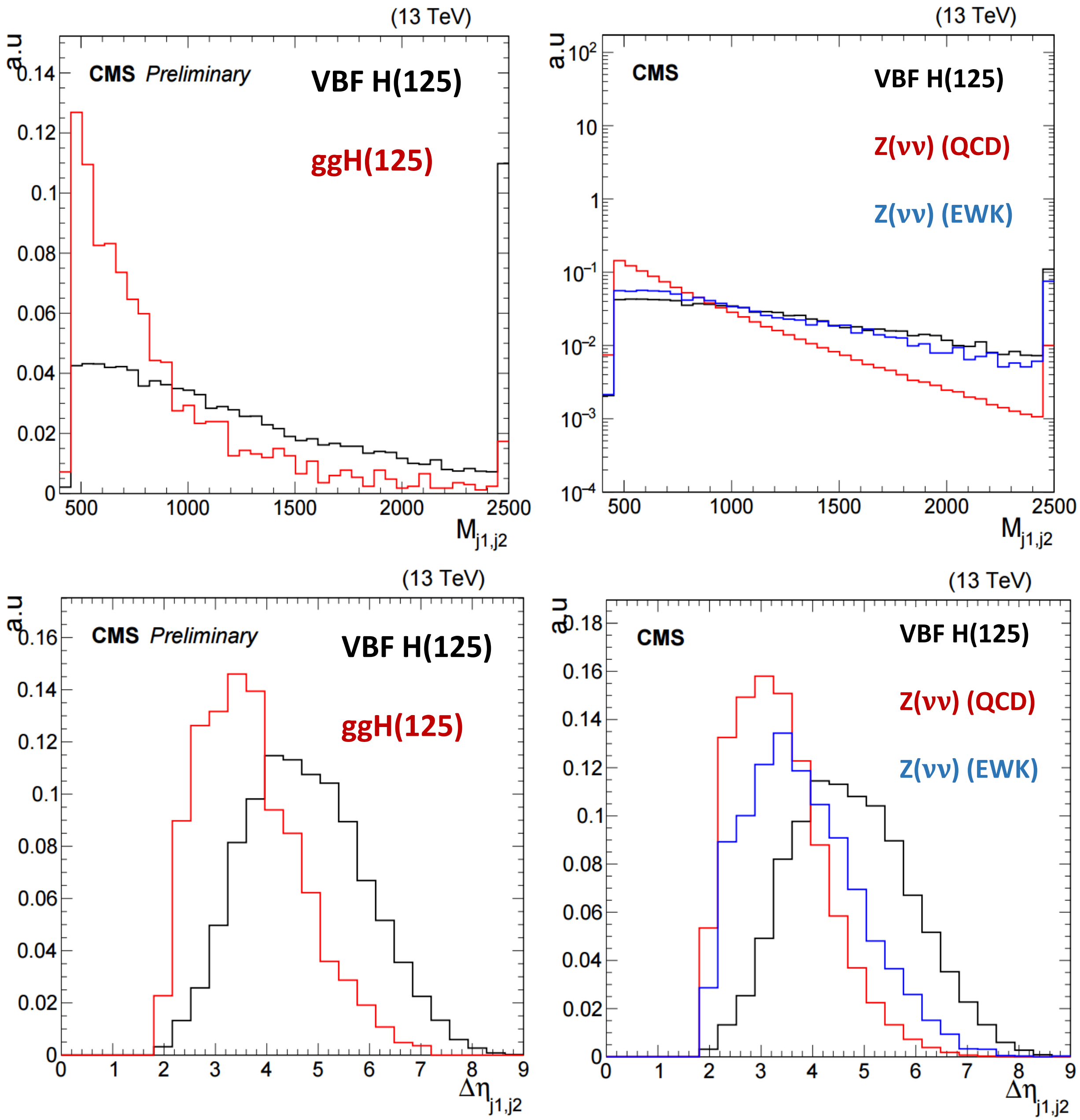
Z(νν) (QCD)

Z(νν) (EWK)

❑ Outcome:

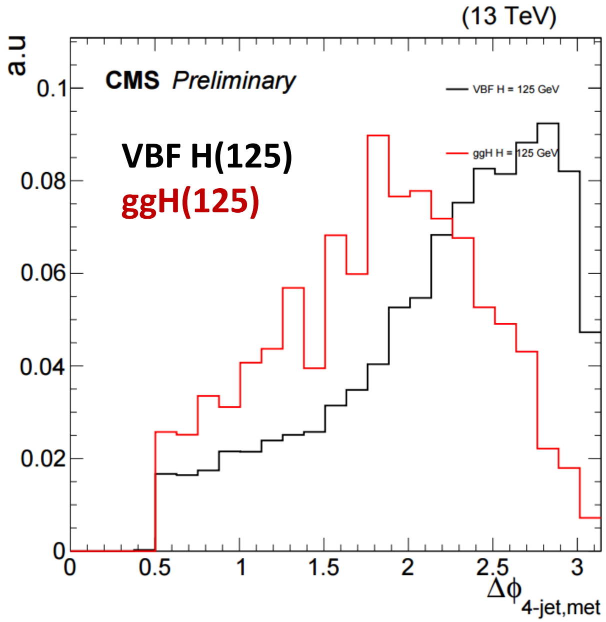
- **VBF jets softer**: should be as loose as possible (monojet triggers allow it, they are based on MET and MHT)
- **leading jets more forward** due to $\Delta\eta_{j1,j2}$ and $M_{j1,j2}$ selections

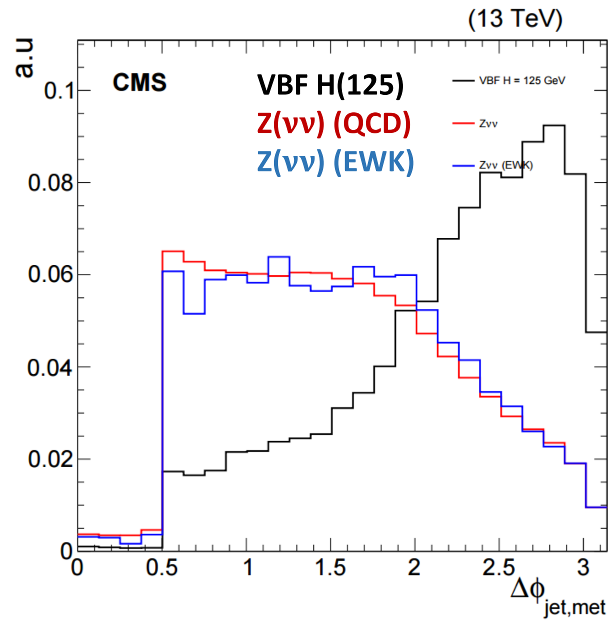
Exploring VBF signal properties



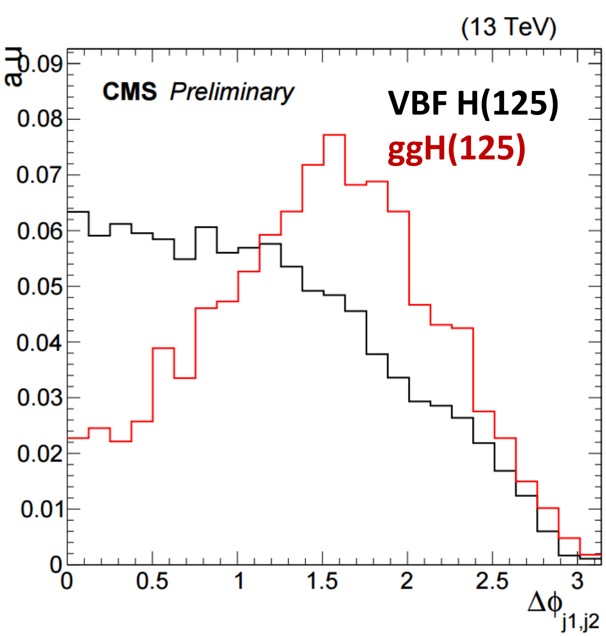
- **Outcome:**
  - $\mathbf{M_{j1,j2}}$ **discriminates** between **VBF and ggH**, **VBF and QCD** Z but not VBF and EWK Z
  - $\boldsymbol{\Delta\eta_{j1,j2}}$ discriminates all modes → good **candidate for a shape analysis**
  - **VBF selection should reduce the ggH contamination** (high purity category of monojet analysis dedicated to VBF)

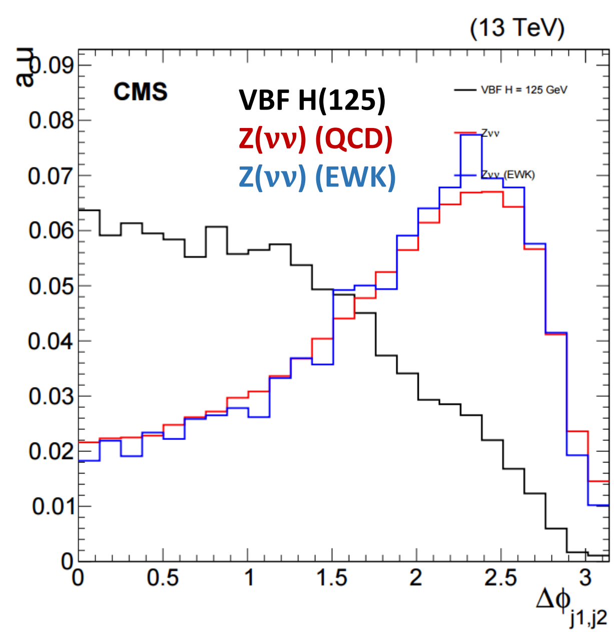
Exploring VBF signal properties





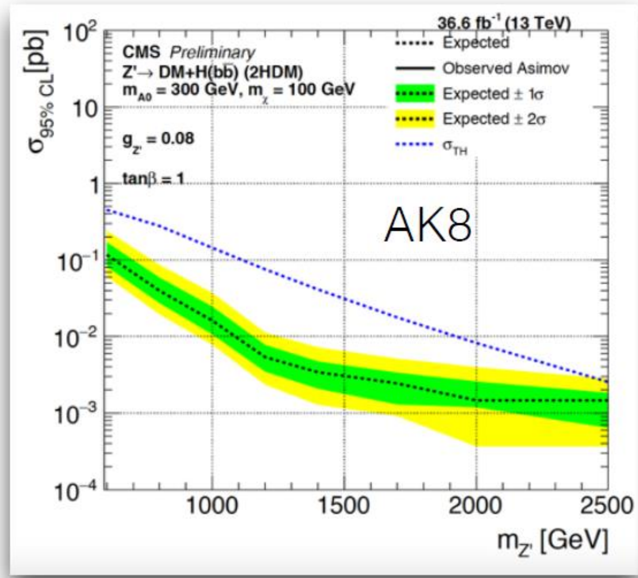
- **Outcome**:
  - **Δϕ(jets,MET)** able to discriminate VBF from both ggH and backgrounds
  - same for **Δϕ(j1,j2)**

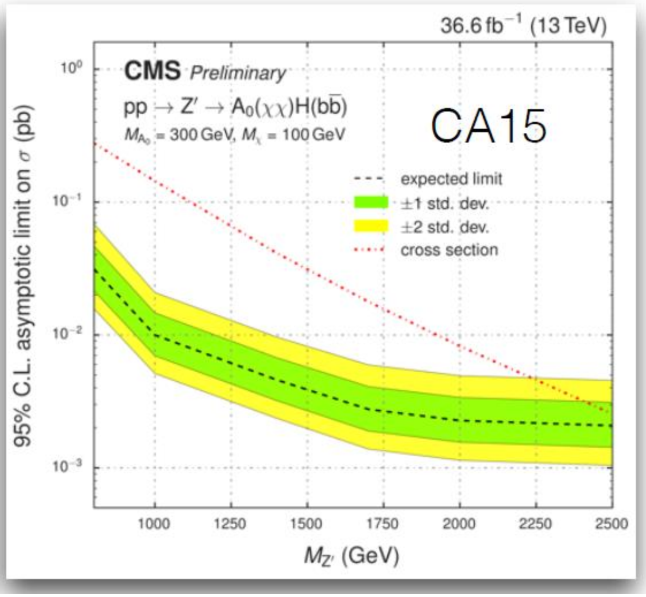


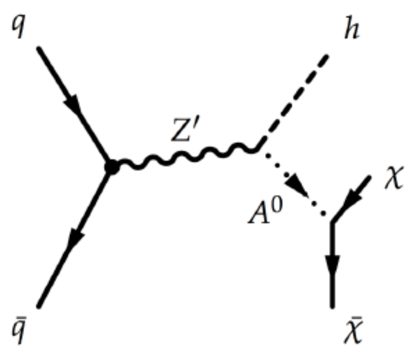


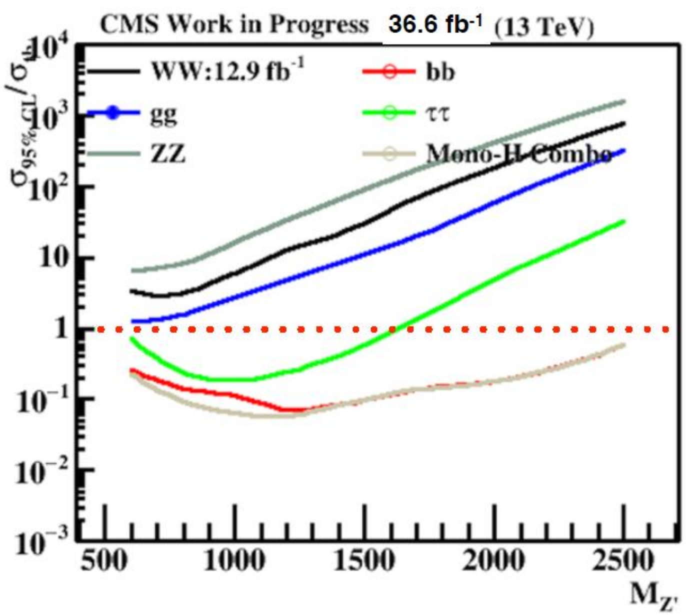
- **Caveat**:
  - such a good separating power for **Δϕ(jets,MET)** is tricky: it embeds information on the number of jets in the events (most likely two for signal, more for backgrounds)

MonoH combination









2HDM interpretation

H($b\bar{b}$) most sensitive channel for MET+H

- $\mathbf{b\bar{b}}$ reconstructed as AK4, AK8 or CA15 jets

← Combination of $b\bar{b}$ and $\tau\bar{\tau}$ shown in plot