CMS Dark Matter Results

Bhawna Gomber *(University of Hyderabad)*

Deborah Pinna *(University of Wisconsin)*

Spring 2020 LHC DM WG meeting

28 April 2020

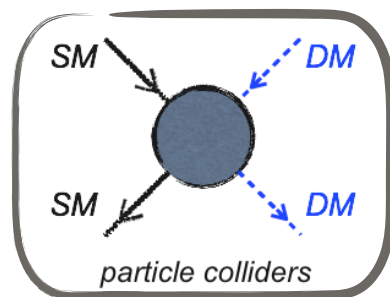# Dark matter? *signature and phenomenology at collider*
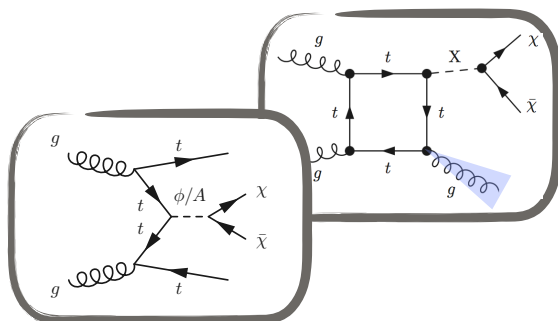
DM evidence

assume weak interactions with SM

DM production

SM → DM
SM → DM

particle colliders

investigate specific interactions/final states

DM signature

▷ **DM could be produced at colliders (rare process)**
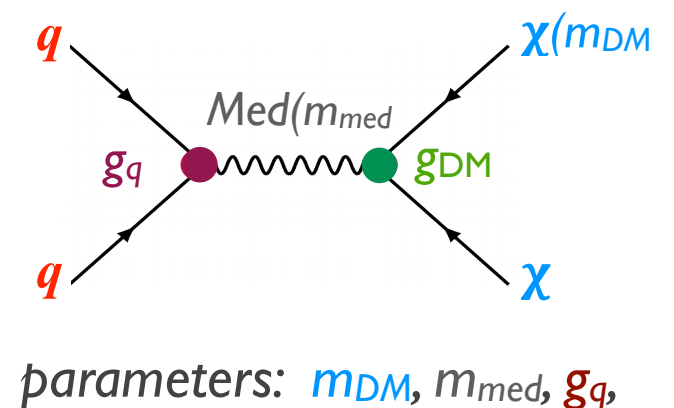
- no direct trace in the detector, need *visible particle* to which DM recoils against

 - "mono-X searches": X includes jets, vector bosons, top, …

 ✱ **DM nature** (m_{DM}): *scalar (real or complex), Dirac fermion* (*assumption for LHC searches), …

▷ **Which type of events do we study at colliders?** *(med. couplings g_q, g_{DM})*
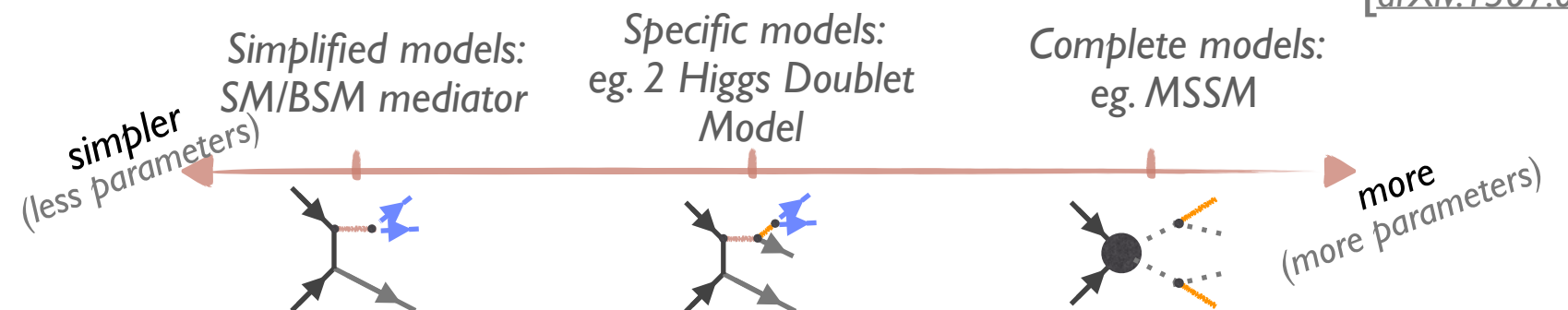
+ *s-channel mediators*

	vector	axial-vector
spin-1	$g_q \sum_q V_\mu \bar{q}\gamma^\mu q$	$g_q \sum_q A_\mu \bar{q}\gamma^\mu\gamma^5 q$
	scalar	**pseudoscalar**
spin-0	$g_q \dfrac{\phi}{\sqrt{2}} \sum_f y_f \bar{f}f$	$g_q \dfrac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$

q ⟶ $\chi(m_{DM}$
$Med(m_{med}$
g_q ⟿ g_{DM}
q ⟶ χ

parameters: m_{DM}, m_{med}, g_q,

+ *t-channel mediators*

✱ <u>benchmark models:</u> kinematically distinct set of model parameters   *ATLAS/CMS DM forum* [arXiv:1507.00966]

Simplified models: SM/BSM mediator

Specific models: eg. 2 Higgs Doublet Model

Complete models: eg. MSSM

simpler (less parameters) ⟵ ⟶ **more** (more parameters)

Rich dark matter program at CMS

MET+X signatures

Analysis	Dataset	Document
mono-jet	36 fb⁻¹	PRD97(2018)
mono-Z(ll)	36 fb⁻¹	EPJC78(2018)291
mono-photon	36 fb⁻¹	JHEP02(2019)074
mono-LQ	77 fb⁻¹	PLB795(2019)76
bb+DM	2.2 fb⁻¹	EPJC77(2017)845
mono-top (had)	36 fb⁻¹	JHEP06(2018)027
single top + DM	36 fb⁻¹	JHEP03(2019)141
tt+DM combination	36 fb⁻¹	PRL122,011803(2019)
mono-H(bb)	36 fb⁻¹	EPJC79(2019)280, JHEP11(2018)172
mono-H($\tau\tau$, $\gamma\gamma$)	36 fb⁻¹	JHEP09(2018)046
mono-H combination	36 fb⁻¹	JHEP03(2020)025
H to dark photons	137 fb⁻¹	JHEP10(2019)139

in this talk:

only a personal selection of recent DM searches, more results here CMS

particular focus on MET+X searches

Visible signatures (DM interpretation)

| Analysis	Dataset	Document
boosted dijet	77 fb⁻¹	PRD100,112007(2019)
dijet w/ btag	20 fb⁻¹ (8 TeV)	PRL120,201801(2018)
dijet w/ ISR	18 fb⁻¹(scouting)	arXiv:1911.03761
dijet	36 fb⁻¹ - 137 fb⁻¹	JHEP08(2018)130/arXiv:1911.03947
4 top quarks	137 fb⁻¹	EPJC80(2020)75

Spin-1 mediator:
simplified and extended sectors

Signature: large MET and ≥1 high-p_T jet/vector boson/photon

mono-jet   *mono-V* (=W,Z)   *mono-γ*
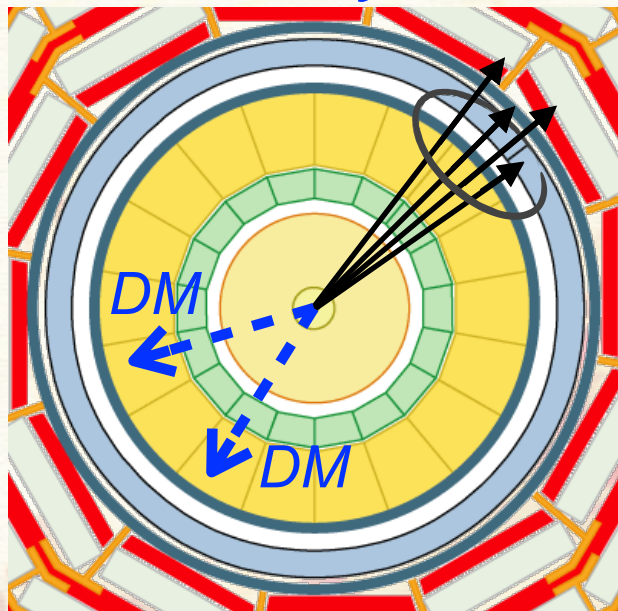
✳ CMS: <u>PRD97,092005(2018)</u>   ✳ CMS: <u>JHEP02(2019)074</u>
(2016)   (2016)

selected most recent results
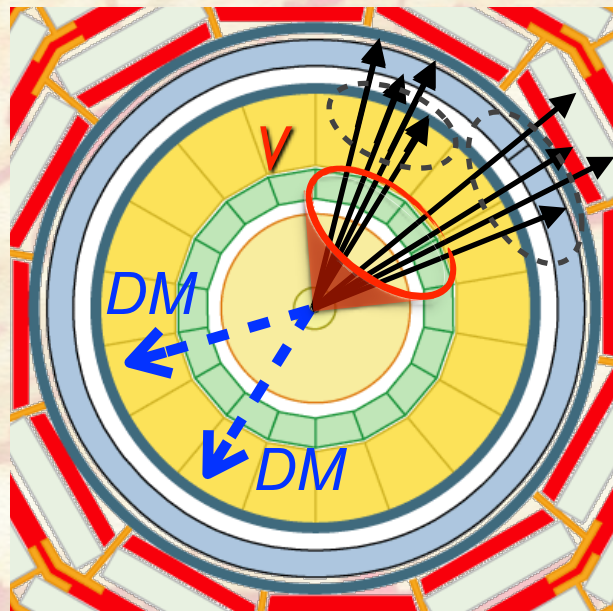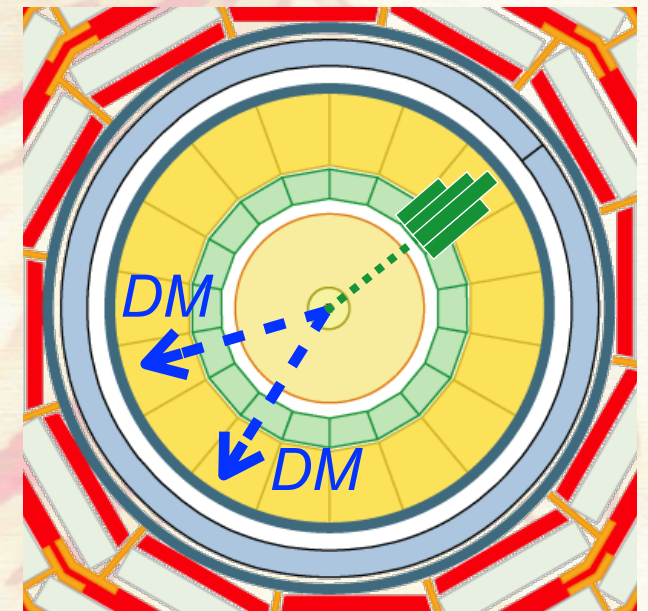
DM+jet/V search

▷ *1 - Selection:* events categorized based on *jet nature*

mono-V

[large-cone jet, R=0.8]
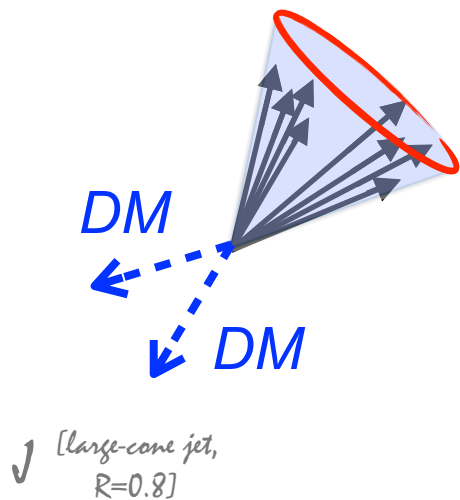
* ≥ 1 jets, $p_T (j)$ > 250 GeV
* MET > 250 GeV
* *invariant mass jet* consistent with W/Z
* *2-prong structure* inside jet

mono-jet

[small-cone jet, e.g. R=0.4]
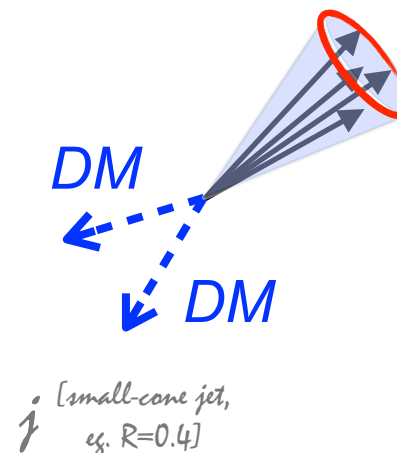
* not selected as *mono-V*
* $p_T (j)$ > 100 GeV

▷ *2- Bkg:*

- **Z(vv) and W(lv)+jets** *main bkg, from CRs*

▷ *3- Results:* combined fit of SRs and CRs

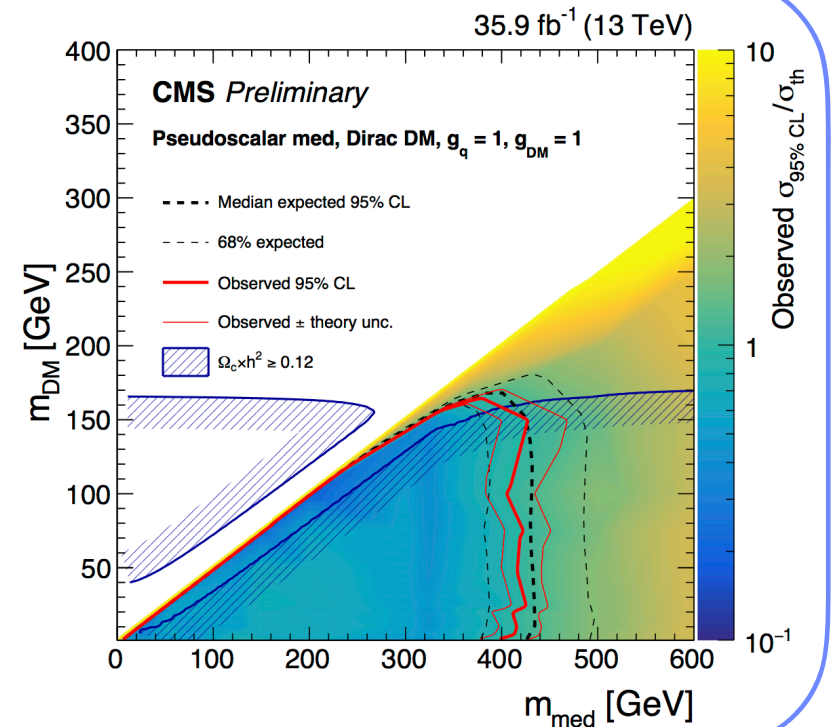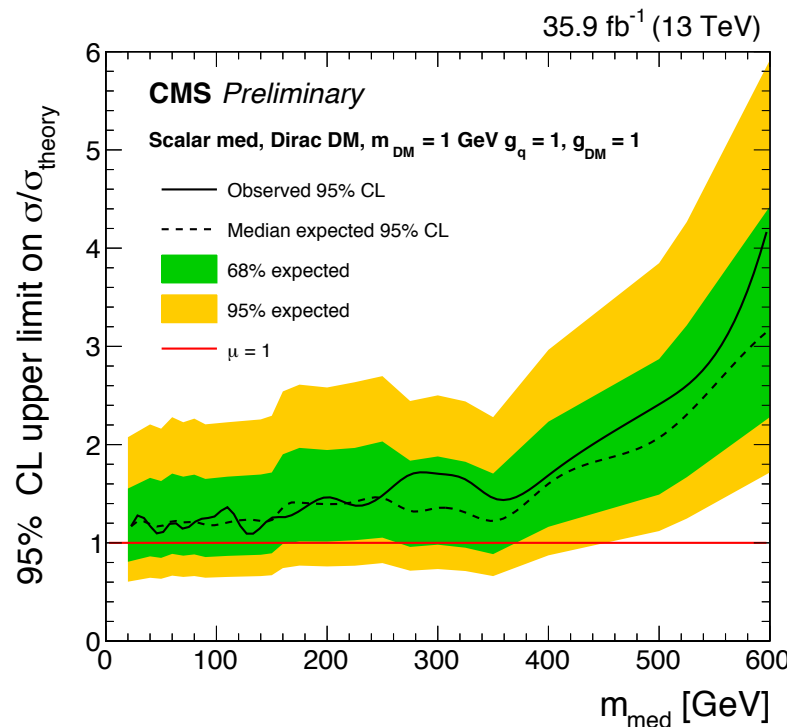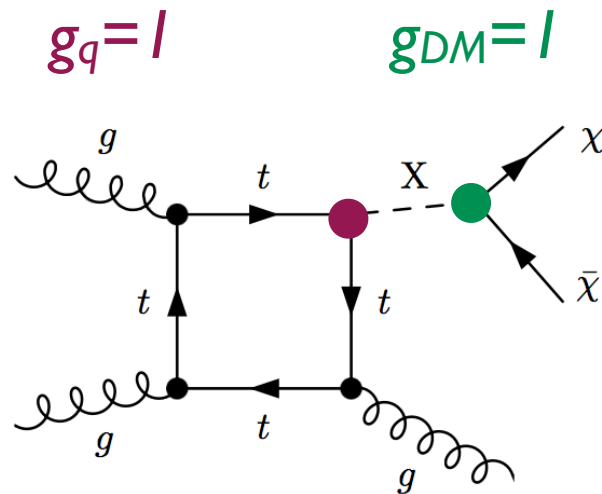- systematic unc. included as nuisance parameters

mono-V
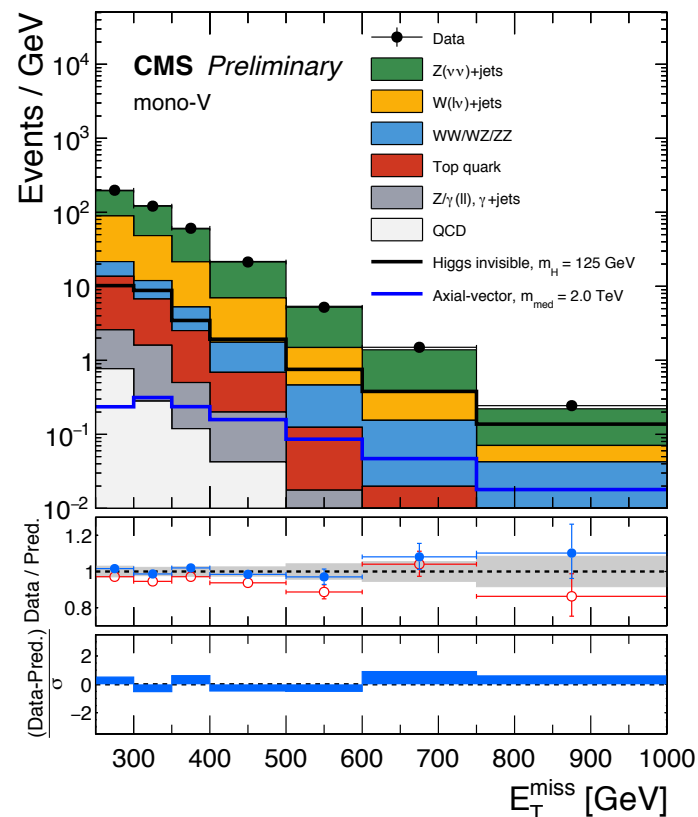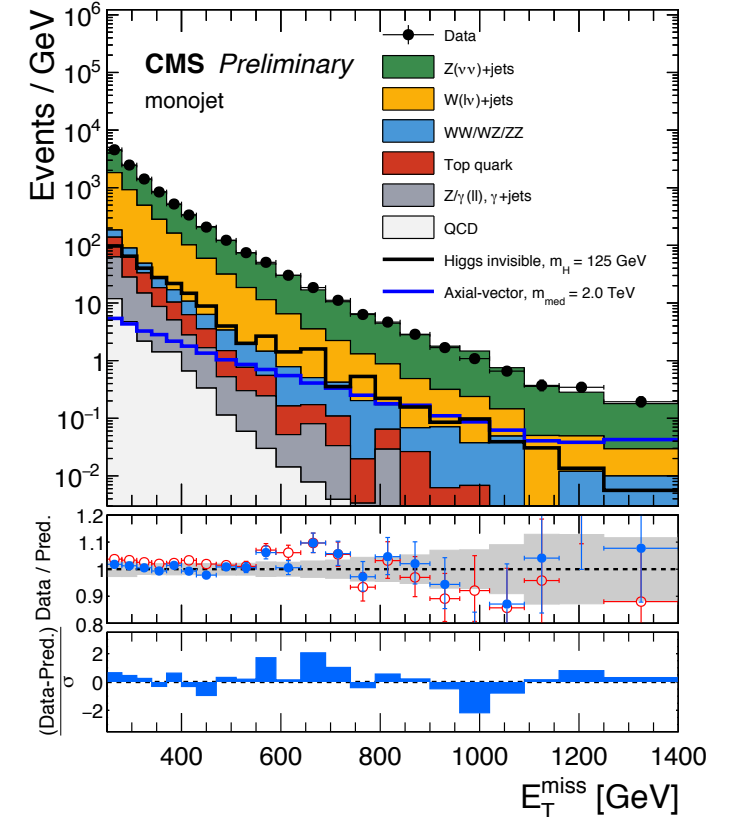
mono-jet

DM+jet/V search

▷ *Interpretation in terms of DM model with Dirac DM:* upper limits at **95% CL** on cross section
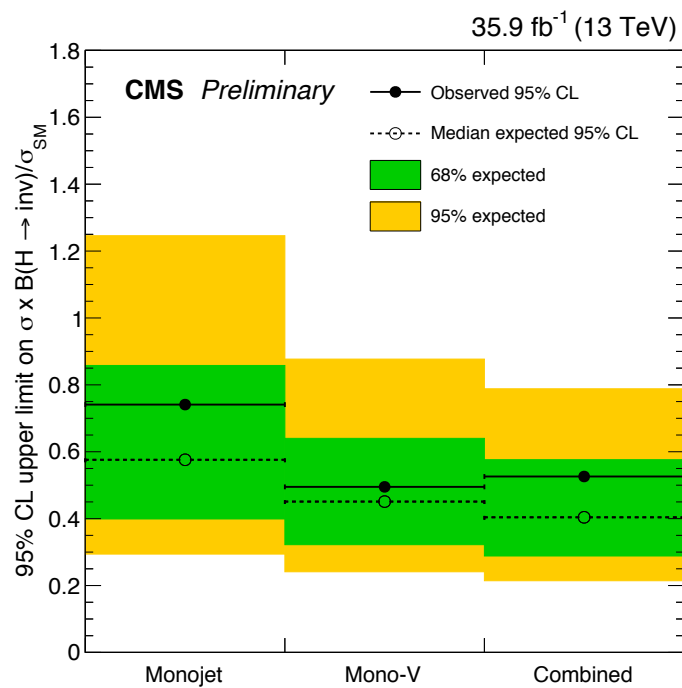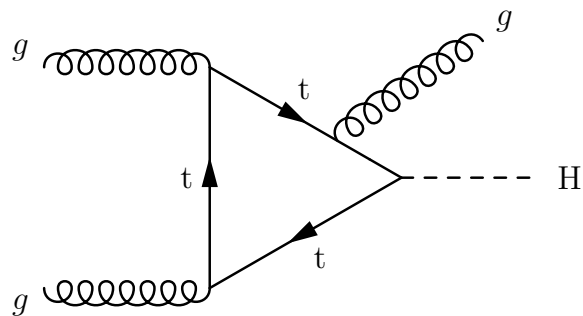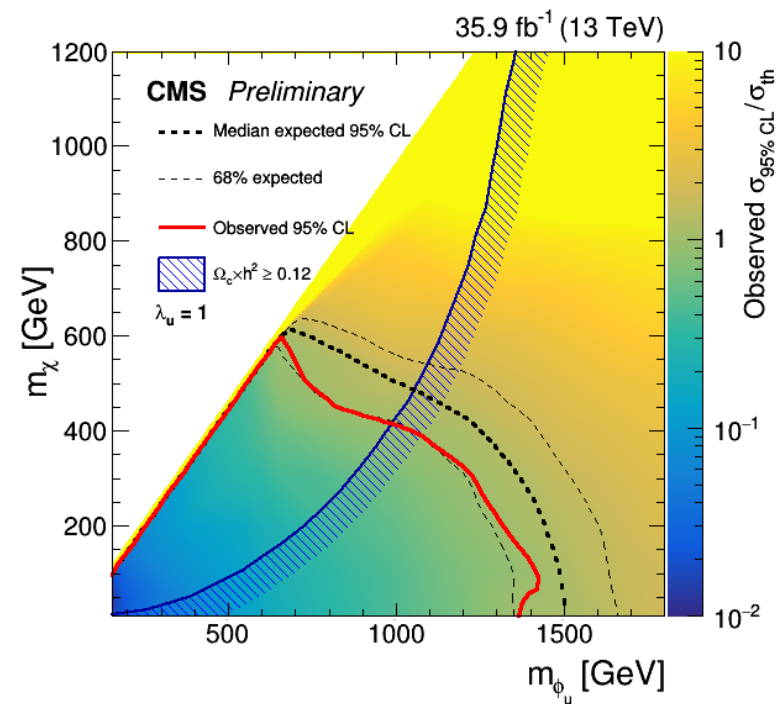
vector/axial-vector interaction
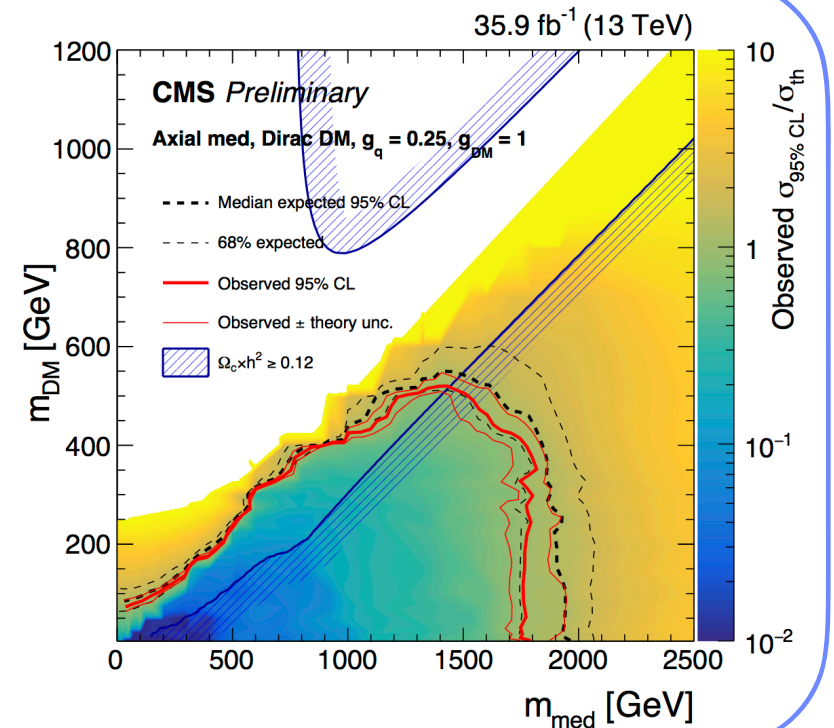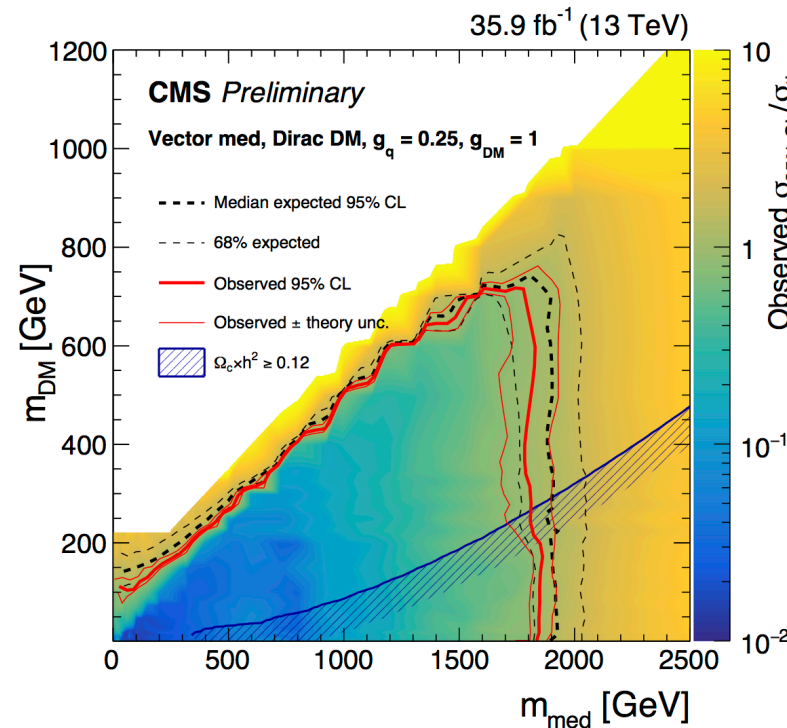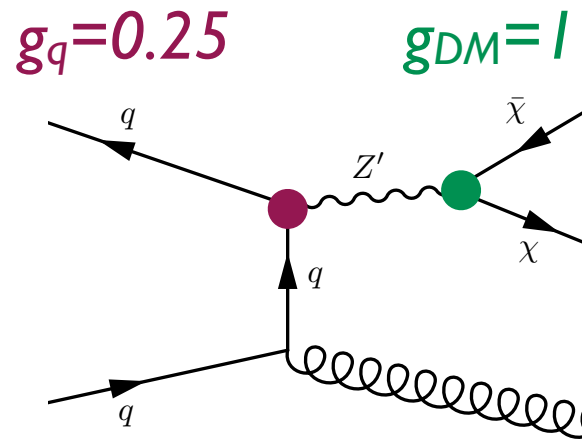
$g_q=0.25$ $g_{DM}=1$

scalar/pseudoscalar interaction

$g_q=1$ $g_{DM}=1$

DM+jet/V search

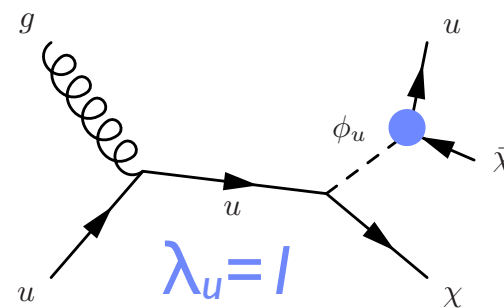▷ *Interpretation in terms of DM model with Dirac DM:* upper limits at **95% CL** on cross section

t-channel interpretation

Higgs boson as mediator

Color-triplet mediator

$\lambda_u = 1$
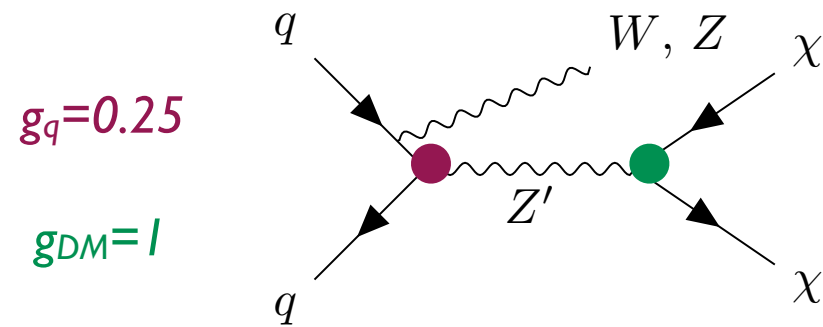
Colored mediator, Majorana DM
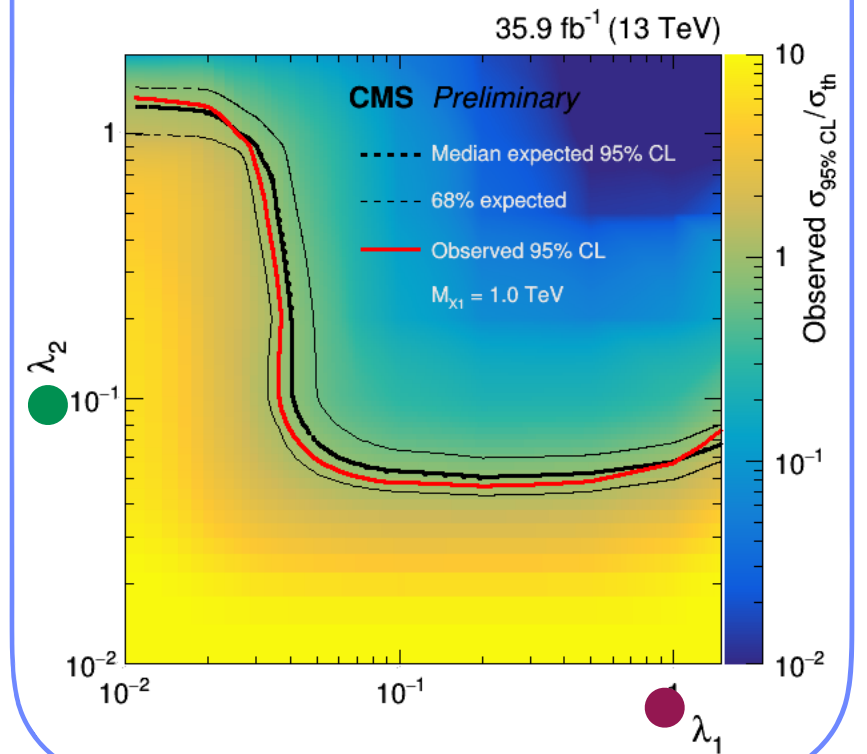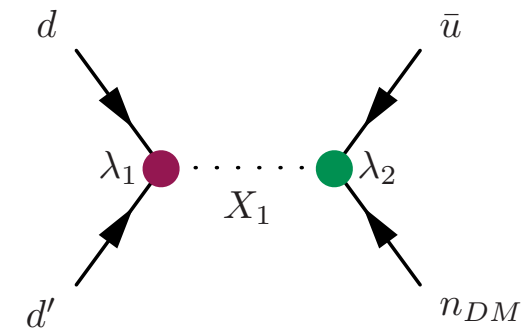
Spin-1 interactions

Simplified vector model

g_q=0.25

g_{DM}=1

✳ *low sensitivity to off-shell region due to strong reduction of production cross-section*

✳ **Can we recover the sensitivity?**

Spin-1 interactions

Simplified vector model

$g_q = 0.25$

$g_{DM} = 1$
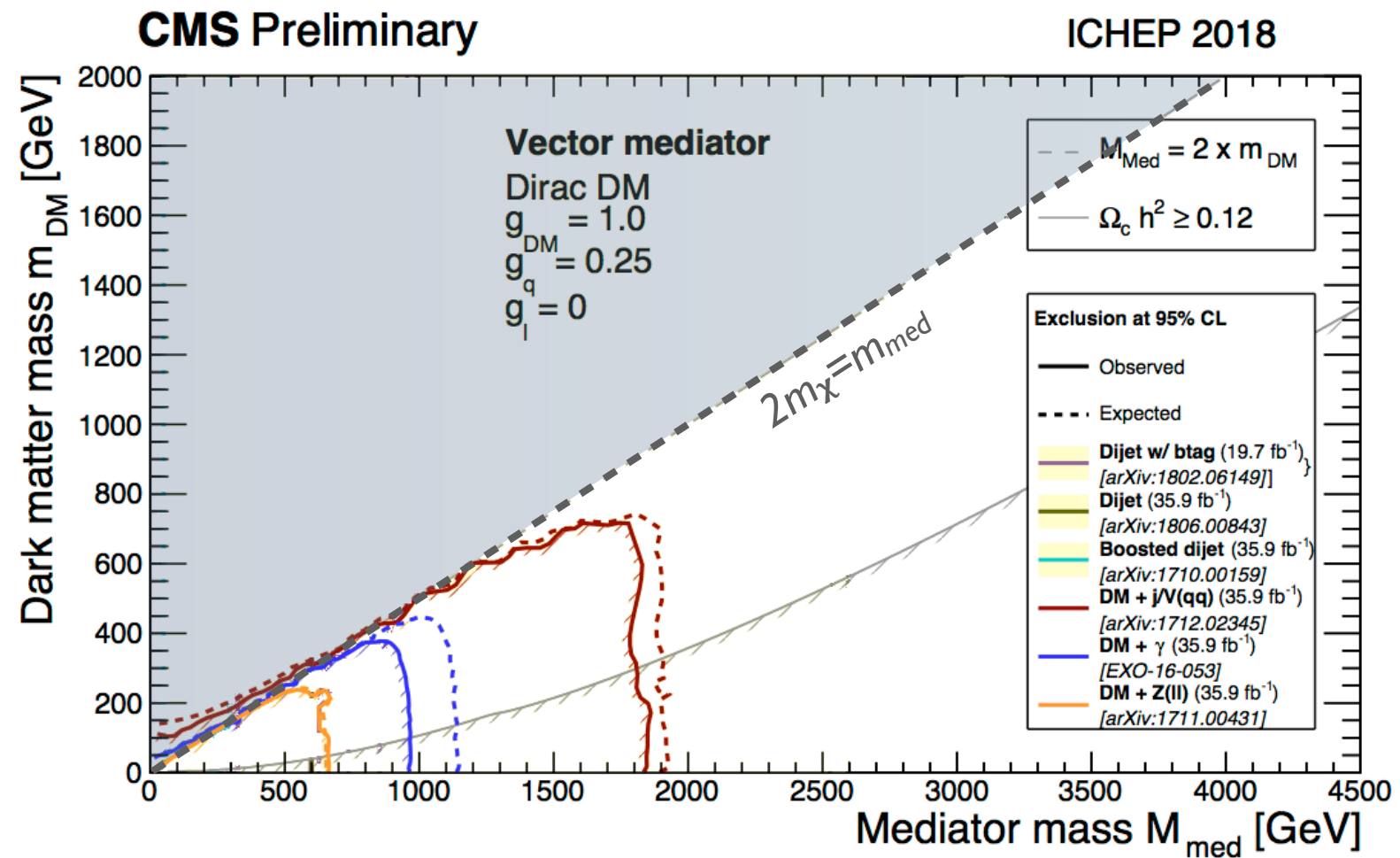
✱ *low sensitivity to off-shell region due to strong reduction of production cross-section*

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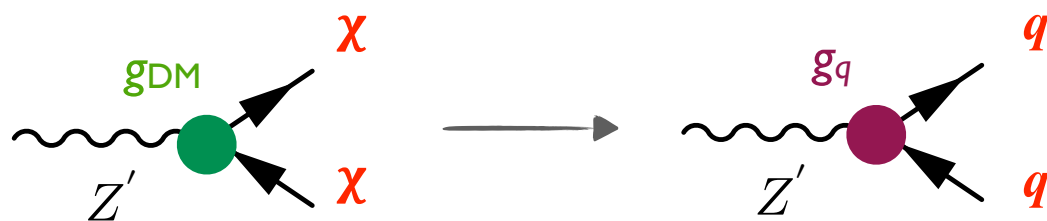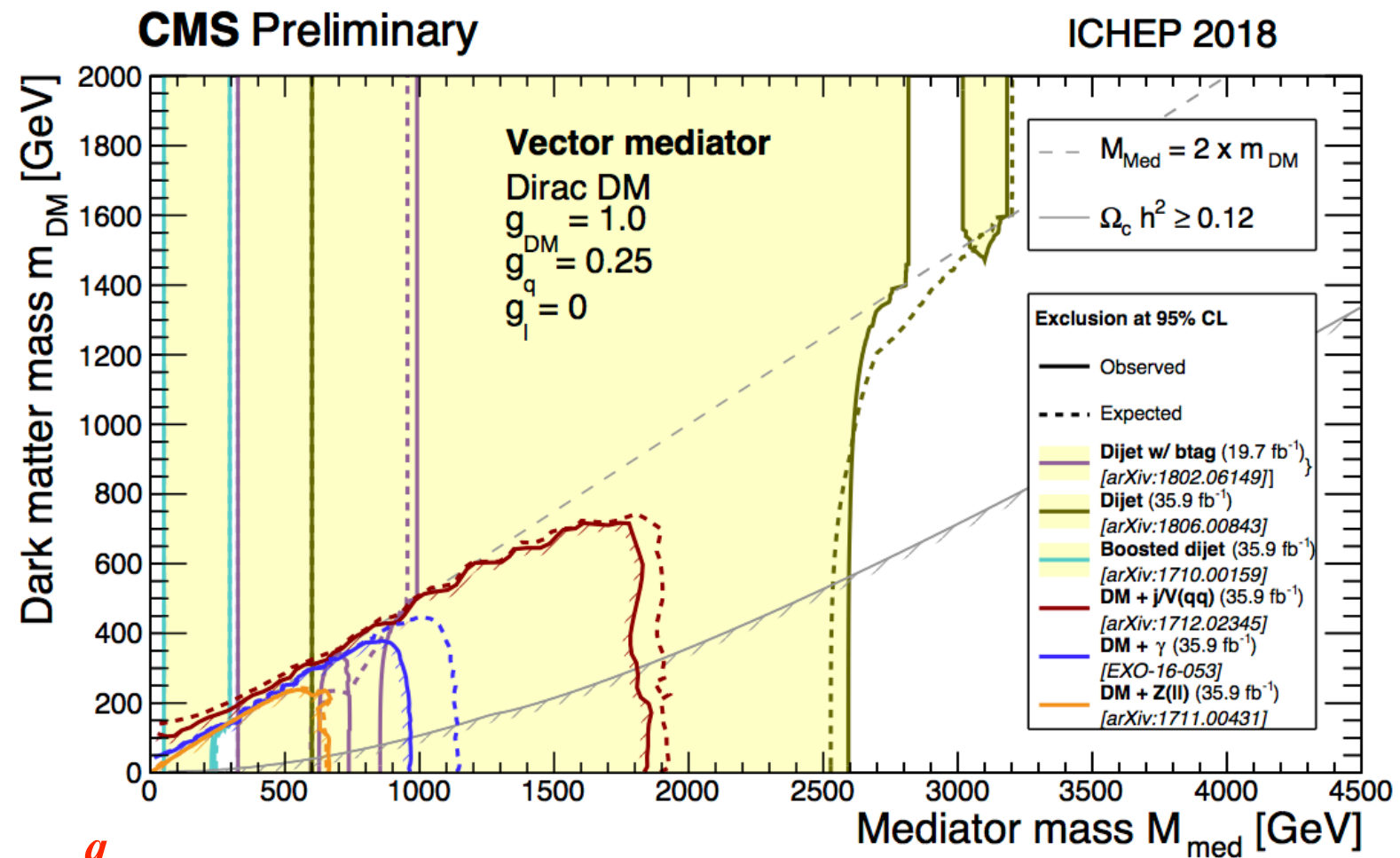g_{DM} · χ / χ · Z' → g_q · q / q · Z'

CMS Preliminary — ICHEP 2018

Vector mediator
Dirac DM
$g_{DM} = 1.0$
$g_q = 0.25$
$g_l = 0$

$M_{Med} = 2 \times m_{DM}$

$\Omega_c h^2 \geq 0.12$

Exclusion at 95% CL
— Observed
···· Expected

Dijet w/ btag (19.7 fb^{-1}) [arXiv:1802.06149]]
Dijet (35.9 fb^{-1}) [arXiv:1806.00843]
Boosted dijet (35.9 fb^{-1}) [arXiv:1710.00159]
DM + j/V(qq) (35.9 fb^{-1}) [arXiv:1712.02345]
DM + γ (35.9 fb^{-1}) [EXO-16-053]
DM + Z(ll) (35.9 fb^{-1}) [arXiv:1711.00431]

Dark matter mass m_{DM} [GeV]
Mediator mass M_{med} [GeV]

$g_q =$

▷ *mediator*
  - *narrow resonance*
  - *wide resonance*

▷ *interplay changes*

Reminder:

scalar   *pseudoscalar*

$$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f \quad \Big| \quad g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f} \gamma^5 f$$
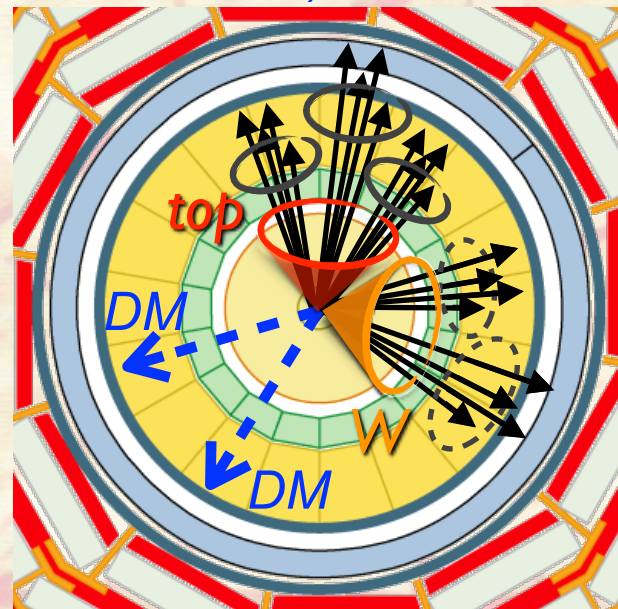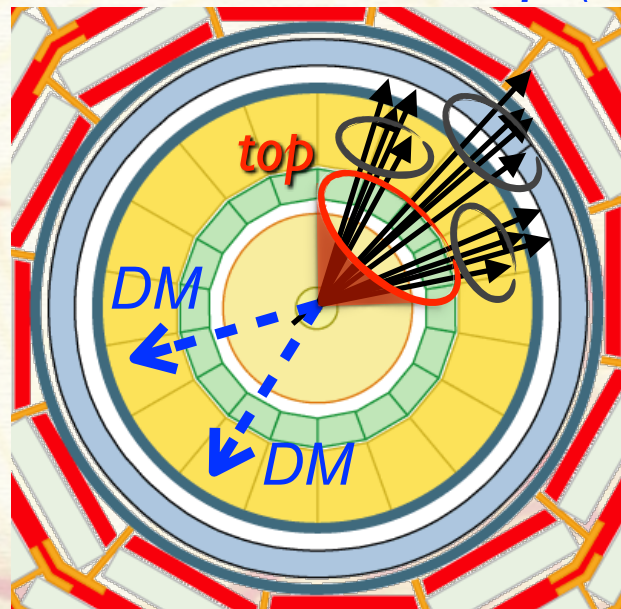
✳ *choose X to exploit coupling* ∝ *to quark mass (or increase xsec)*
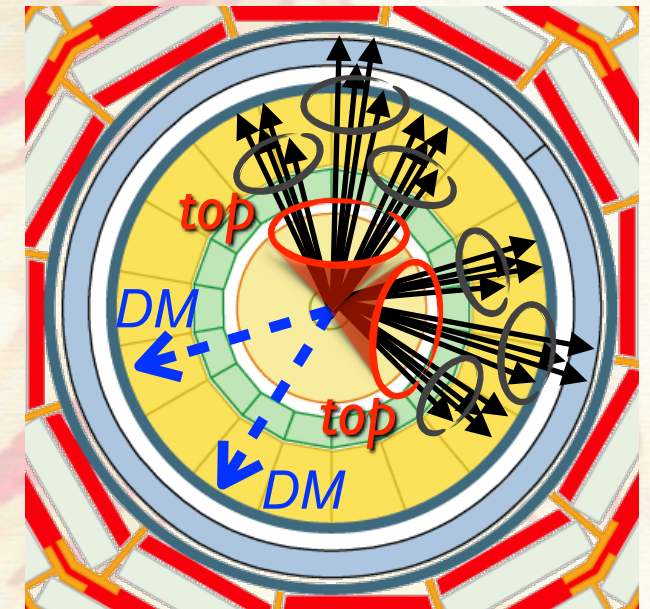
Spin-0 mediator: *simplified models*

Signature: large MET and 1(2) top quarks

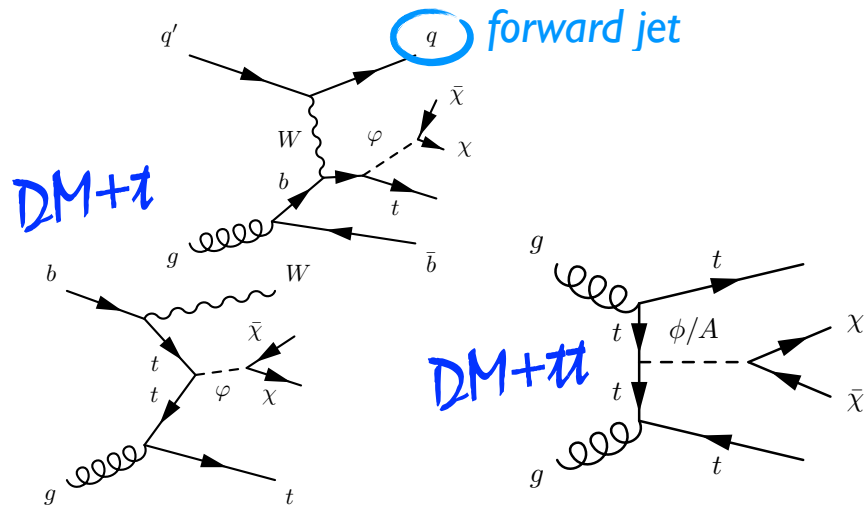### DM+*top (eg. t/tW-channel)*   DM+tt

✳   CMS: *JHEP03(2019)141, (2016)*

✳   CMS: *JHEP06(2018)027 (2016)*

✳   CMS: *PRL122,011803(2019)*
       (2016)

selected most recent results

✳

DM+t(tt) search

▷ **1 - Selection:** *events categorized based on #leptons, # b-jets and #forward jets*

forward jet

DM+t

DM+tt

0ℓ

* leptons veto: e,μ
* ≥ 3 jets (*j small-cone*)
* =1, ≥ 2 b-tagged jets
* MET > 250 GeV

+0 or ≥1 forward jets (|η|>2.4)

1ℓ

* 1 lepton: isolated e,μ
* ≥ 2 jets (*j small-cone*)
* =1, ≥ 2 b-tagged jets
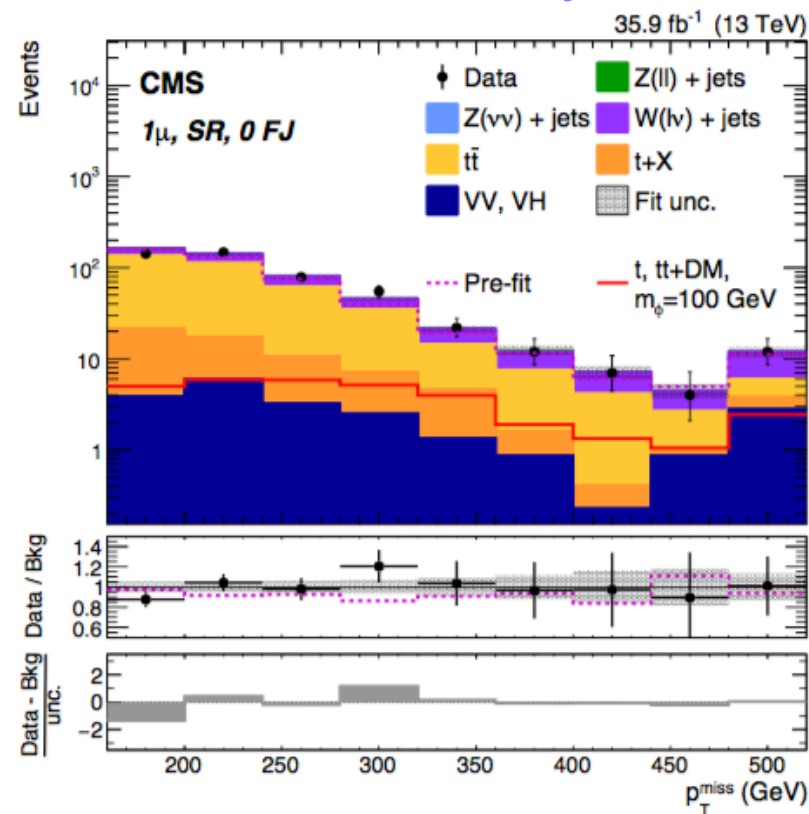* MET > 160 GeV

+0 or ≥1 forward jets (|η|>2.4)

▷ **2- Bkg:**
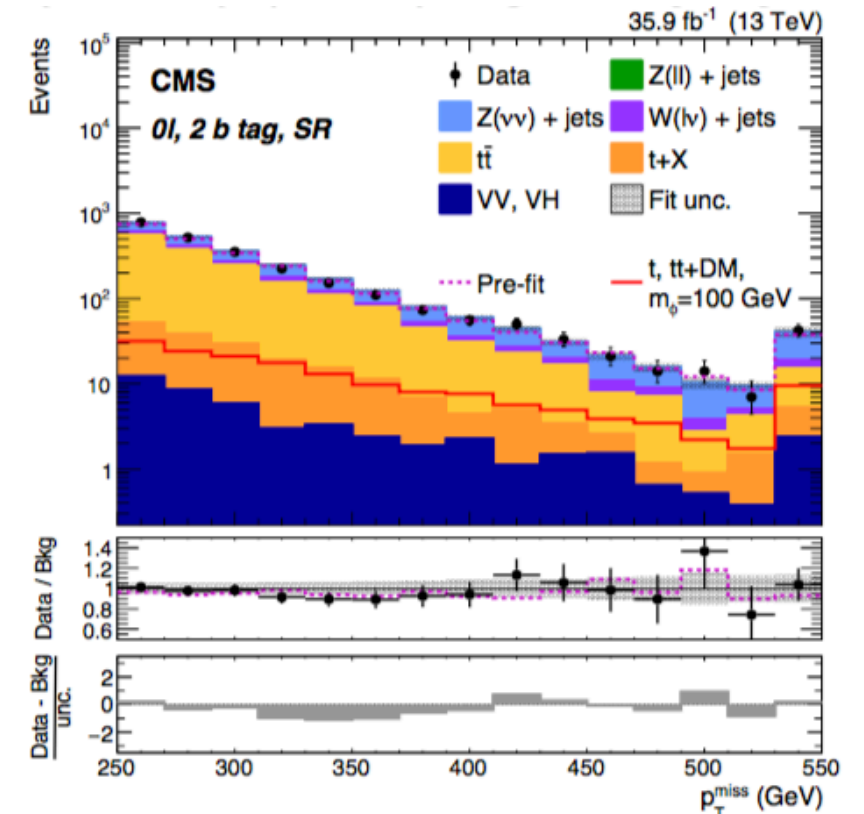- **tt, V+jets** *main bkg, from CRs*

▷ **3- Results:** *combined fit of SRs and CRs*
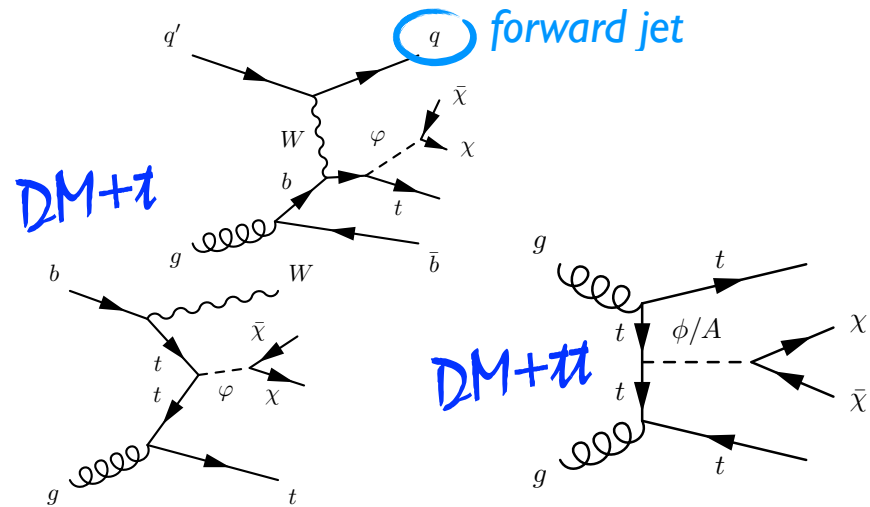- systematic unc. included as nuisance parameters

1ℓ, 1b, 0 forw. jets

0ℓ, 2b

DM+t(tt) search

▷ **1 - Selection:** *events categorized based on #leptons, # b-jets and #forward jets*

forward jet

DM+t

DM+tt

0ℓ
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▷ **3- Results:** *interpretation in terms of DM model with Dirac DM* upper limits at **95% CL** *on xsec*

scalar/pseudoscalar interaction

$g_q = 1$ $g_{DM} = 1$
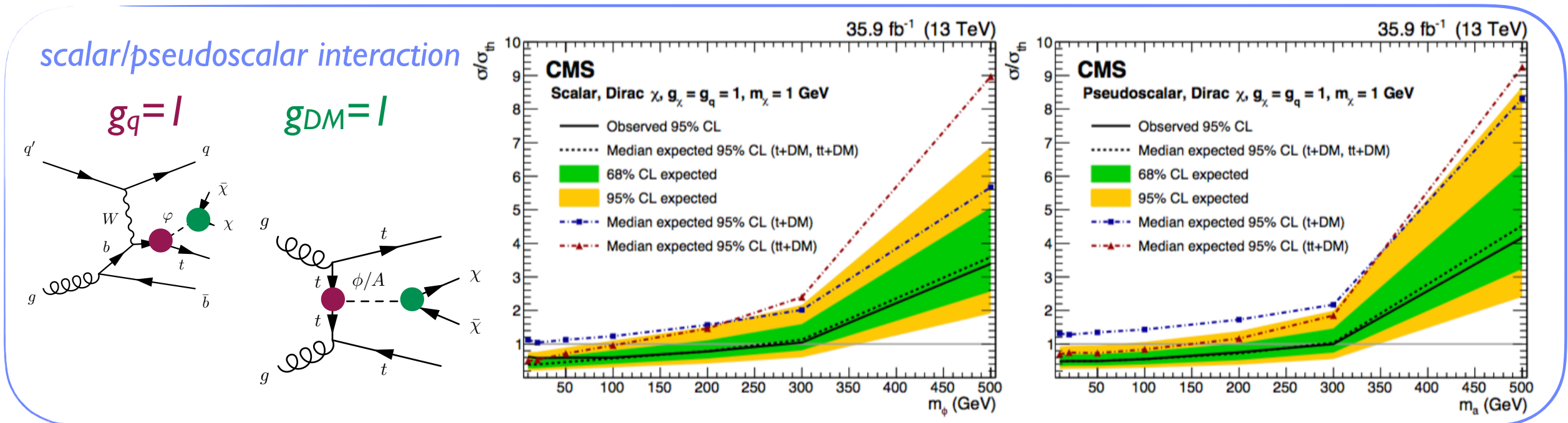
* **First search** *at LHC for DM+t or DM+tt in scalar/pseudoscalar interactions*
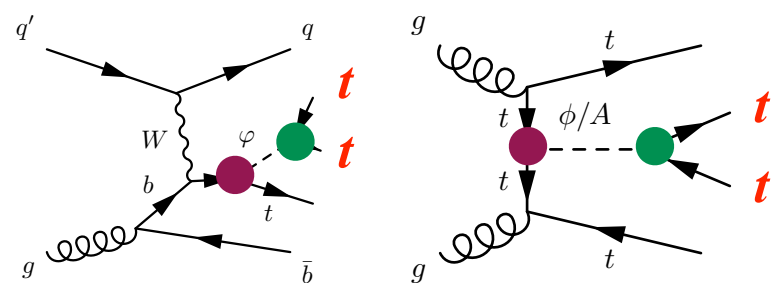* *up to x2 limits improvement at high mediator masses wrt previous DM+tt results*

Spin-0 interactions: "the invisible through the visible"

Simplified scalar/pseudoscalar model
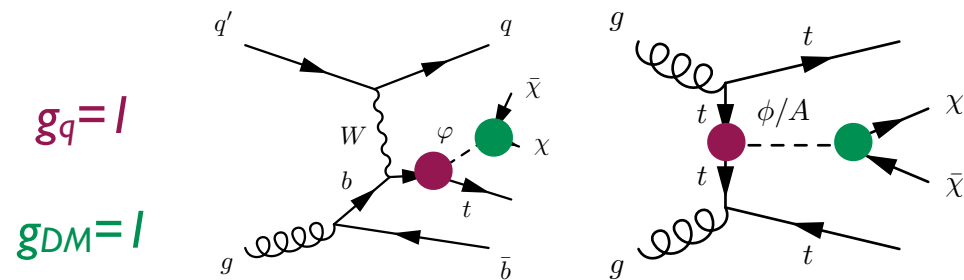
$g_q = 1$

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✳ *low sensitivity to off-shell region due to strong reduction of production cross-section*
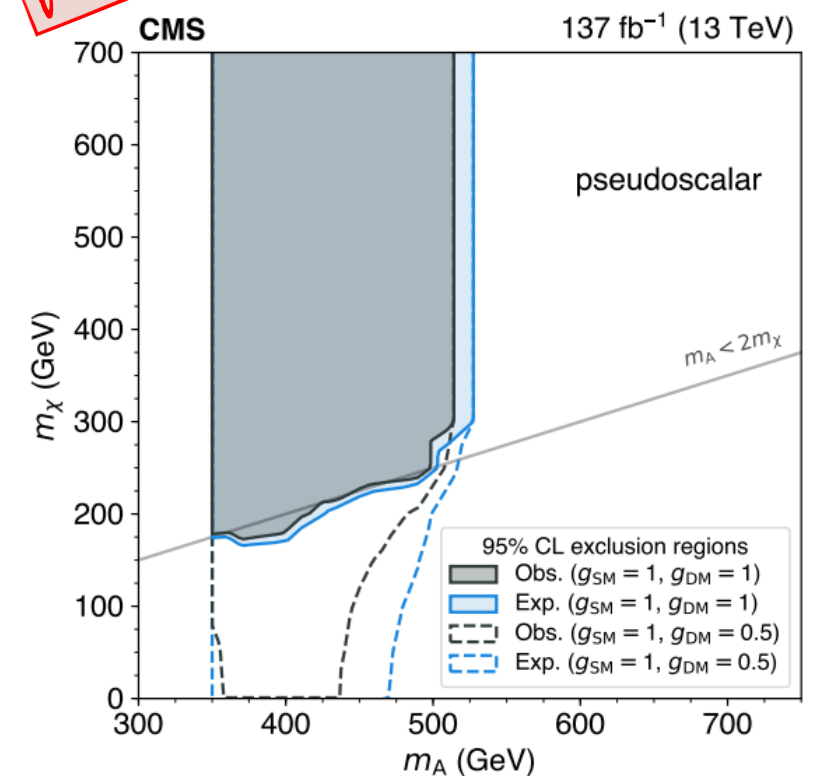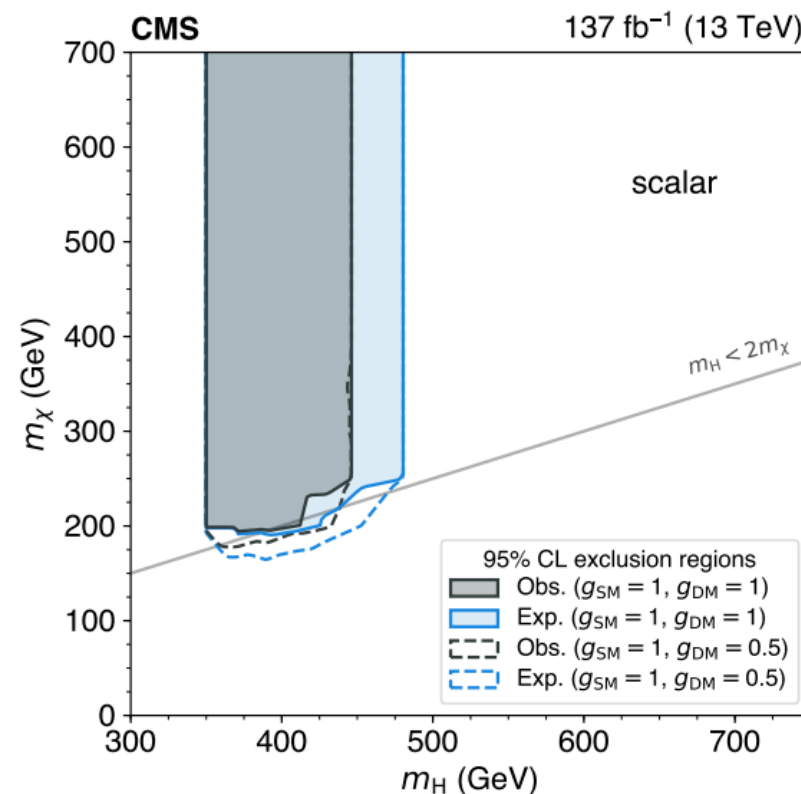
✳ **Can we recover the sensitivity?** *visible decay*

full Run-2   📌 *CMS: EPJC80(2020)75*

✳ *Selection:*
  2 same-sign leptons or at least three leptons, and jets

✳ $m_{MED} > 2\, m_t$

DM+top (mono-top)

▷ **1 - Selection:**

DM

DM

[large-cone jet, R=1.5]
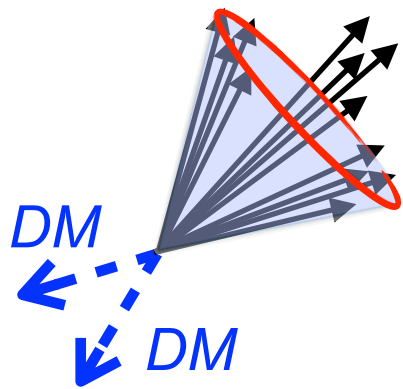
✳ =1 jets, p_T (jet) > 250 GeV

✳ MET > 250 GeV

✳ *invariant mass jet* consistent with top quark

✳ *3-prong structure* inside jet

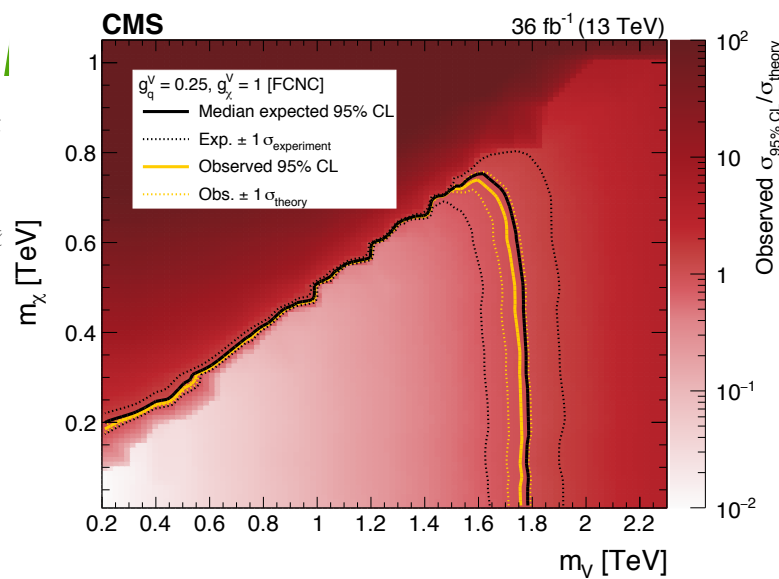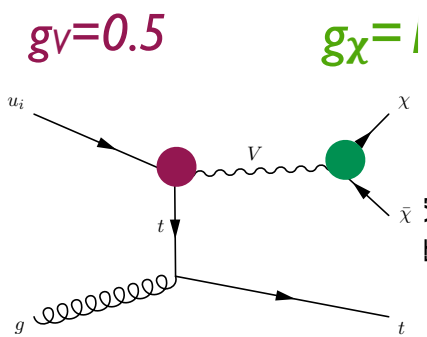✳ *BDT discriminant from substructure variables*

▷ **2- Bkg:**

major: tt, Z(νν), W(lν) +jets from CRs

tight category
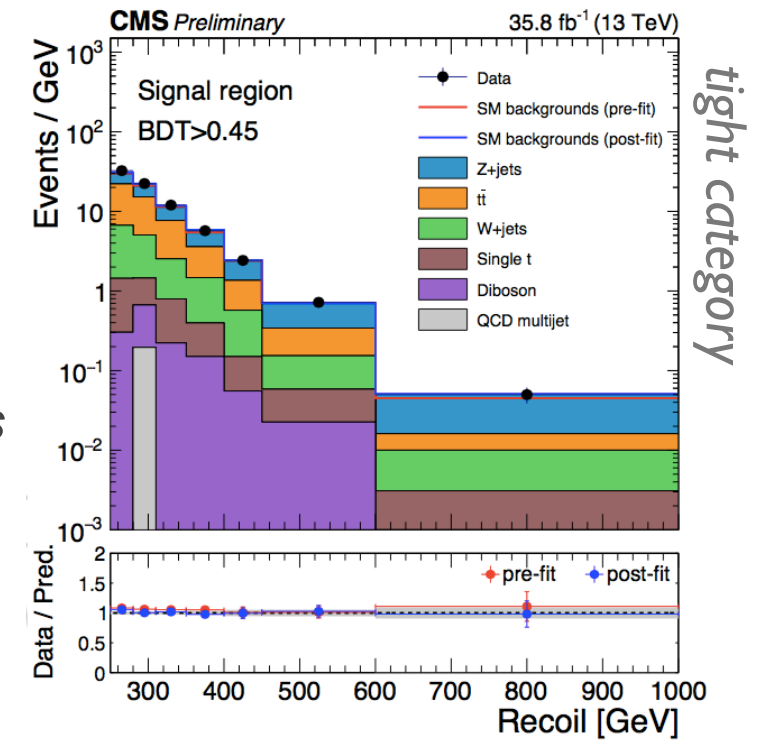
▷ **3- Results:** signal extracted through *combined fit of SRs and CRs* (systematic unc. as nuisance parameters)

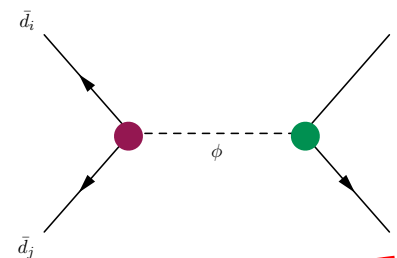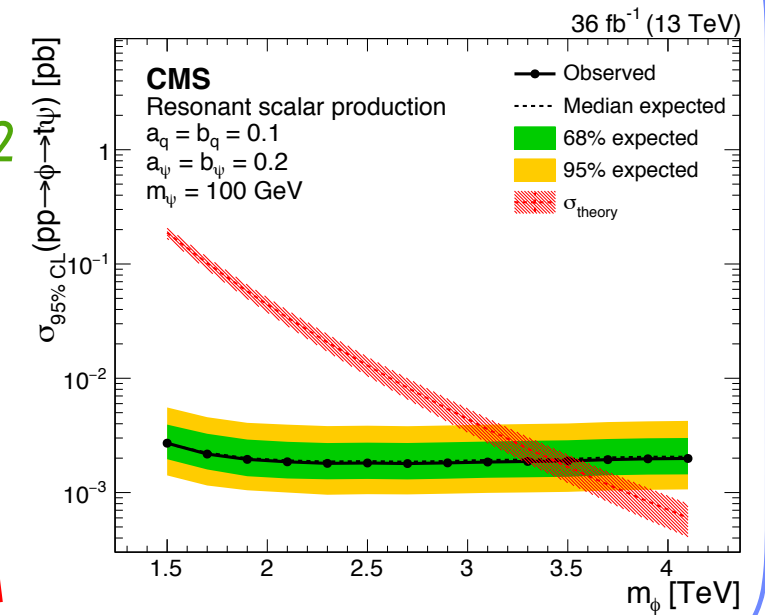**non-resonant model** *spin-1 with FCNC interactions*

g_V=0.5 g_χ=1

resonant model *2/3 charged, colored spin-0*

a_q=b_q=0.1

$a_{1/2}$=$b_{1/2}$=0.2

t-channel interpretation

Higgs boson:
extended sectors and invisible decays

* mono-Higgs directly probe hard interaction (ISR Yukawa-suppressed)

Signature: large MET and one Higgs boson candidate

▷ *Various decay modes considered, H →*

mono-H(bb)
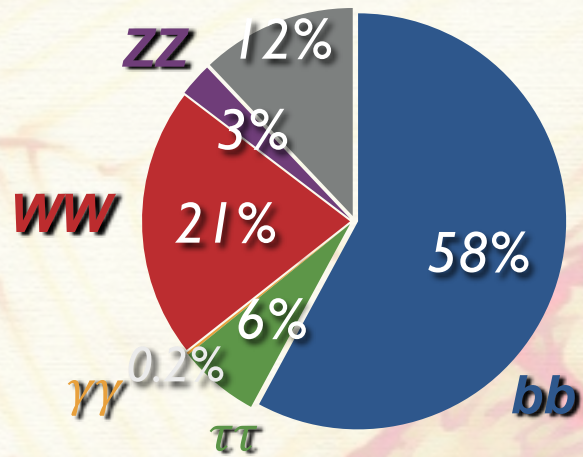
mono-H(inv)

* *CMS(ττ,γγ):* JHEP 09 (2018) 046 (2016)

* *CMS(WW,ZZ):* JHEP03(2020)025 (2016)
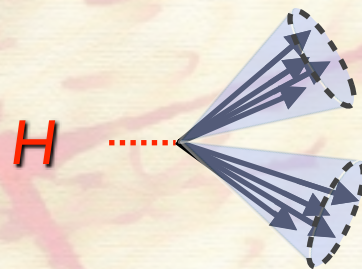
* *CMS:* EPJC79(2019)280, (2016)

* *CMS:* JHEP11(2018)172, (2016)

* *CMS:* PLB793(2019)520

selected most recent results

*

mono-Higgs: *bb decay*

▷ **1 - Selection:** *different approach based on Higgs boson boost*

large boost

Higgs

* 1 jet, p_T (j) > 200 GeV
* [1,2] b-tagged jets categories
* *jet invariant mass* in m_H range

medium boost

Higgs

* similar approach as *large boost*, but with "*larger cone*" to reconstruct the jet

▷ **2- Bkg:**

- **V+jets, tt** *main bkg, normalization (shape) from CRs*

▷ **3- Results:** *combined fit of SRs and CRs*

- $m_T(MET, H)$ *for large boost*
- *MET for medium boost*

mono-Higgs: bb decay

▷ *1 - Selection:* different approach based on Higgs boson boost

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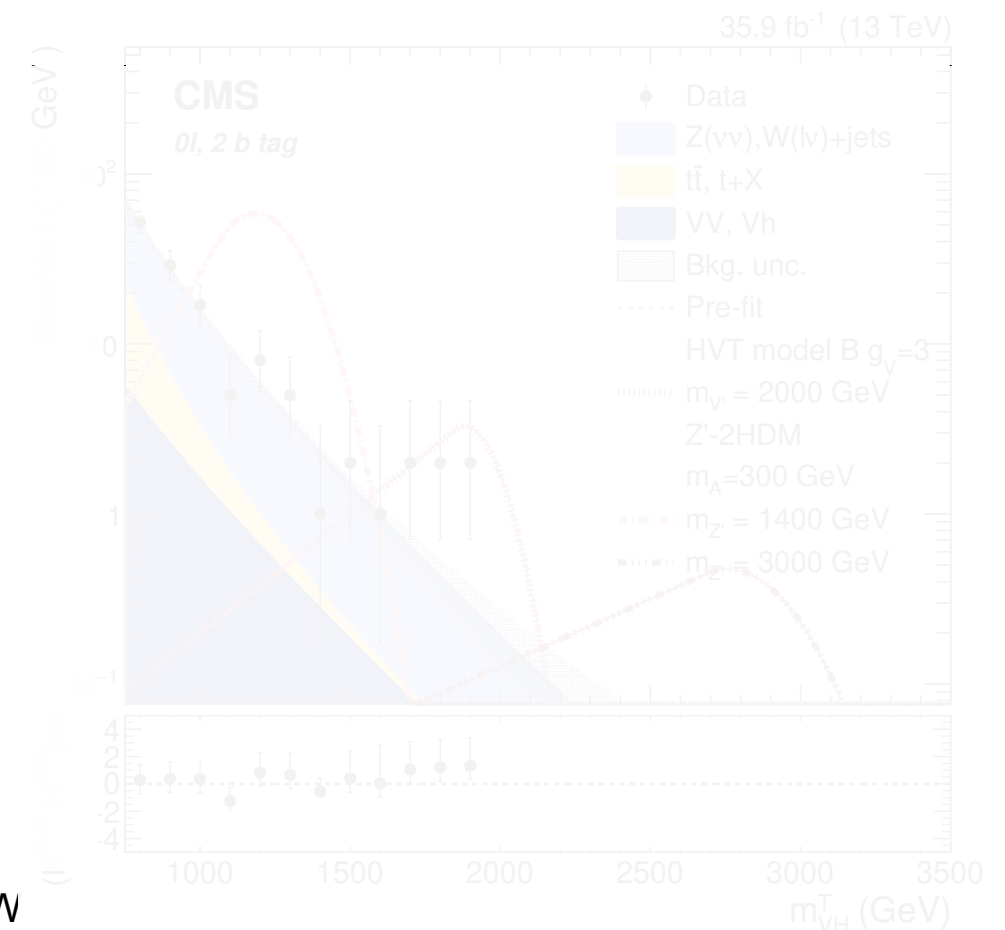* *jet invariant mass* in m_H range

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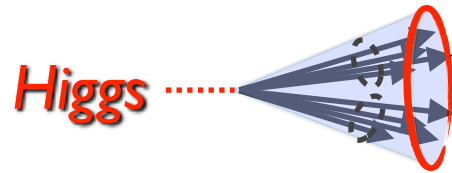
  – m_T(MET, H) for large boost
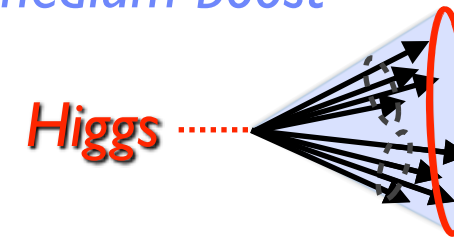
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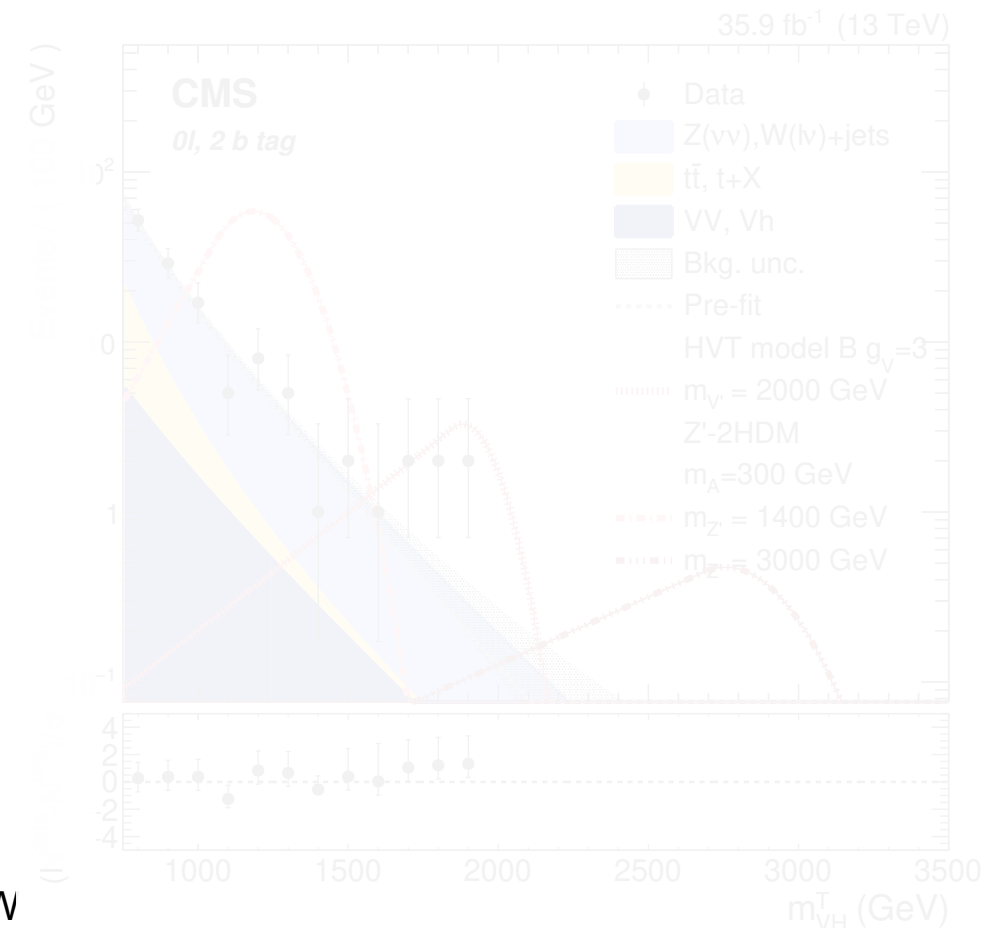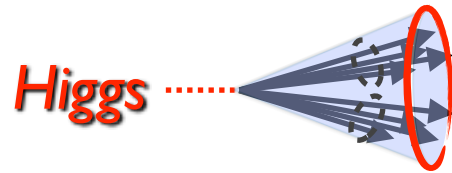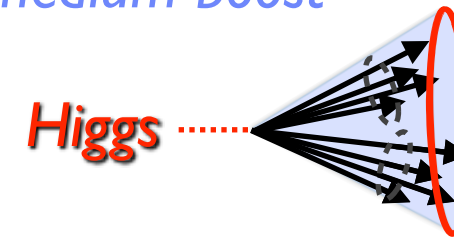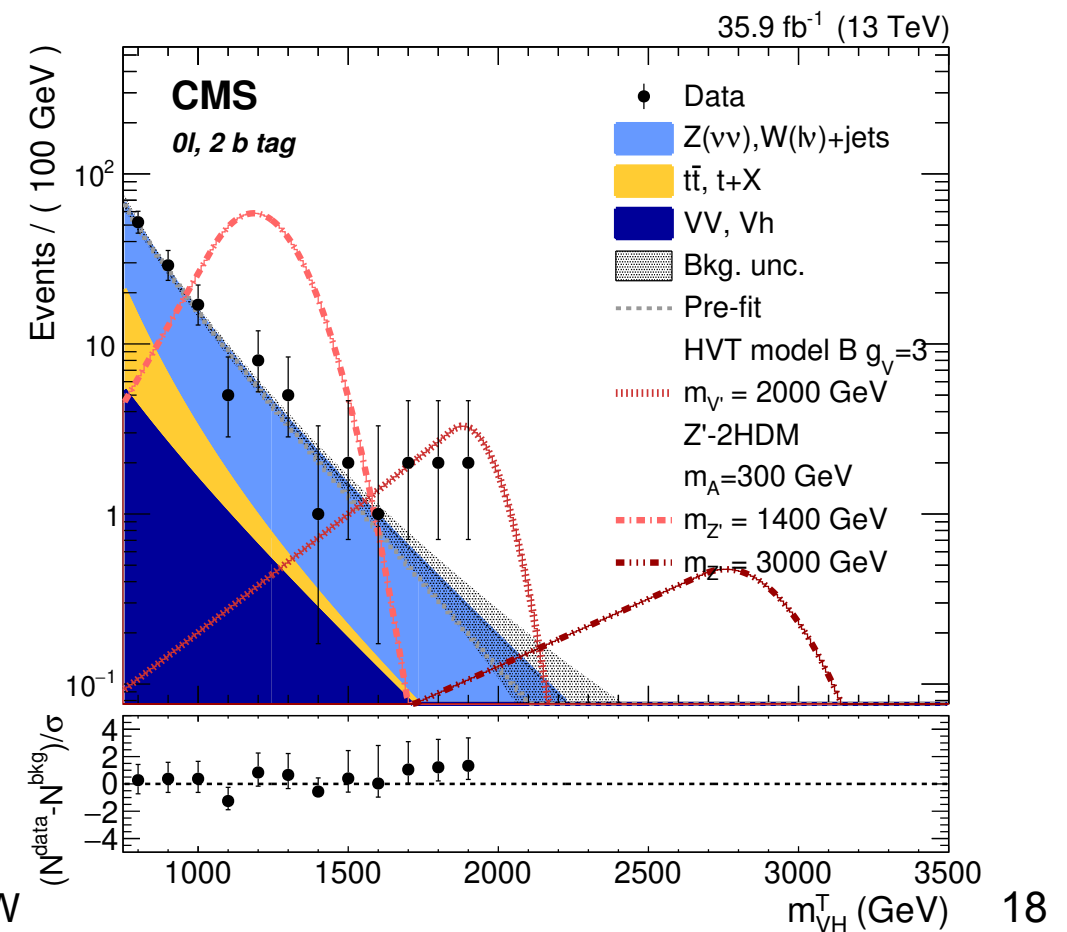* *jet invariant mass* in m_H range

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▷ *3- Results:* combined fit of SRs and CRs

- $m_T(MET, H)$ *for large boost*

- MET *for medium boost*

35.9 fb⁻¹ (13 TeV)

CMS
0l, 2 b tag

- Data
- $Z(\nu\nu), W(l\nu)$+jets
- $t\bar{t}$, t+X
- VV, Vh
- Bkg. unc.
- Pre-fit
- HVT model B $g_V=3$
- $m_{V'}$ = 2000 GeV
- Z'-2HDM
- m_A=300 GeV
- $m_{Z'}$ = 1400 GeV
- $m_{Z'}$ = 3000 GeV

$(N^{data}-N^{bkg})/\sigma$

m_{VH}^T (GeV)

▷ *Interpretation in terms of DM model with Dirac DM:* upper limits at **95% CL** on cross section

Z' baryonic: *Z' radiates a Higgs and decays to DM, non-resonant*

— h(WW)   — h(ZZ)   — h(b$\bar{b}$)

CMS
Baryonic Z', Dirac DM
$g_q = 0.25$, $g_\chi = 1$
$m_\chi = 1$ GeV

Solid (dashed) lines:
observed (expected) 95% CL limits

35.9 fb^{-1} (13 TeV)

— Combination — h(ZZ)
  ± 1 s.d.   — h(WW)
  ± 2 s.d.   — h($\gamma\gamma$)
— h(b$\bar{b}$) — h($\tau\tau$)

Z'-2HDM: *2HDM + Z' → h A, "resonant" to the Z' mass*

2HDM+a: *2HDM+light pseudo a, a couples DM to SM, mixes with A*

CMS
med. boost

excl. up to 1.6 TeV in m$_{Z'}$

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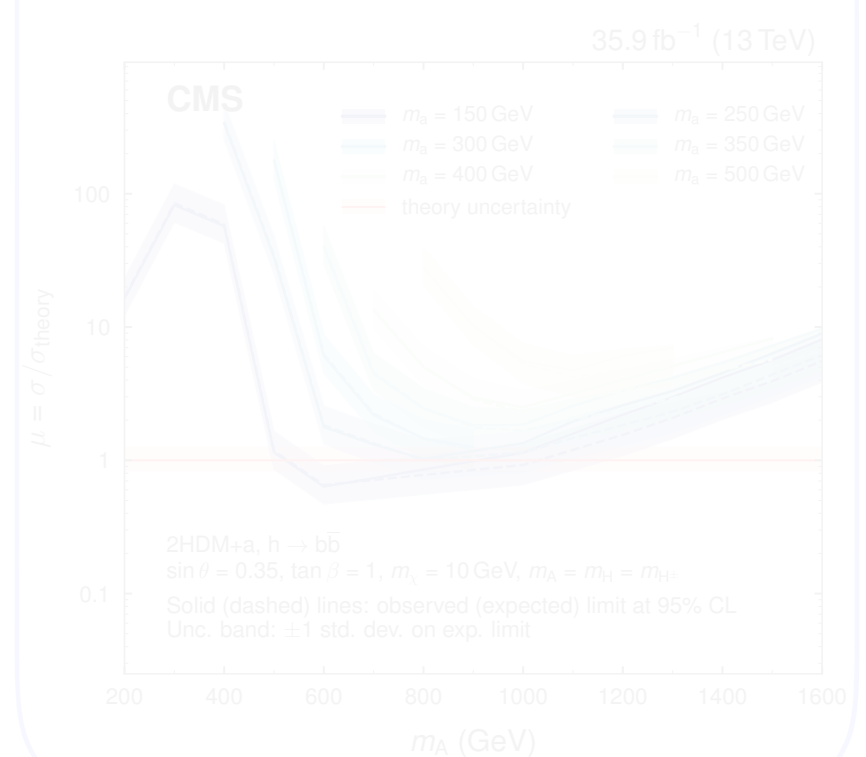
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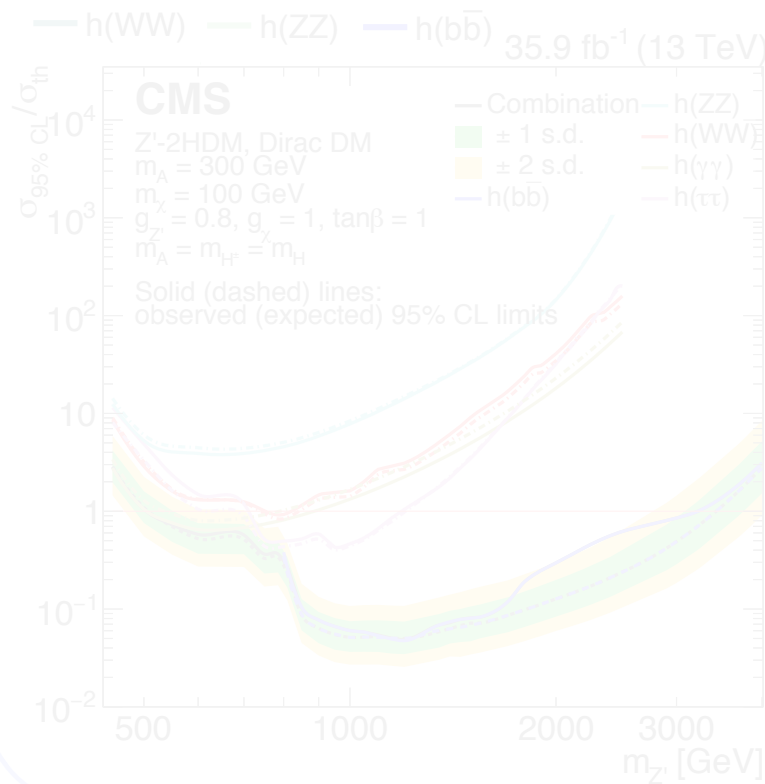
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CMS med. boost — *excl. up to 1.6 TeV in $m_{Z'}$*

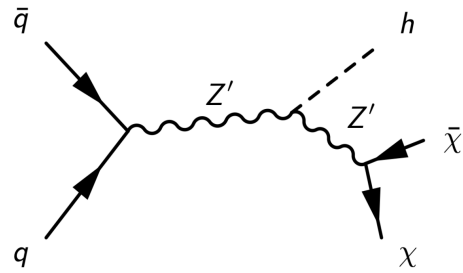CMS large boost — *excl. up to 3.2 TeV (36 fb⁻¹) in $m_{Z'}$*
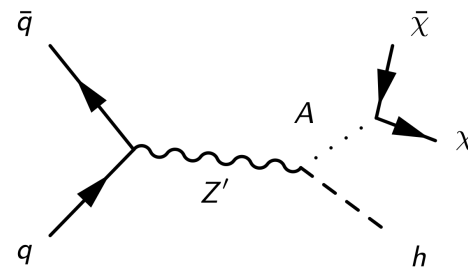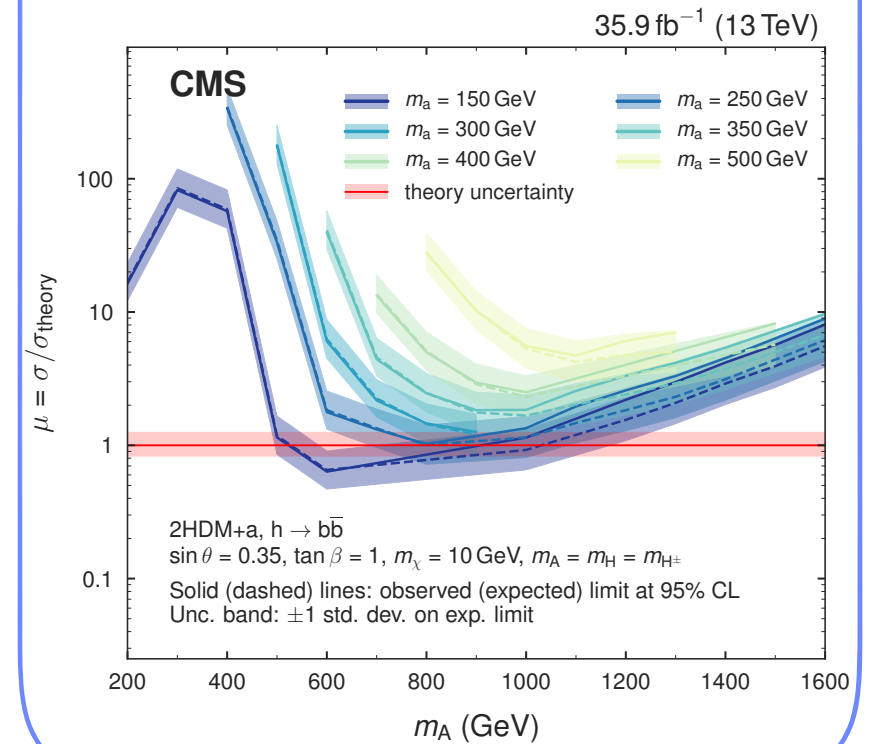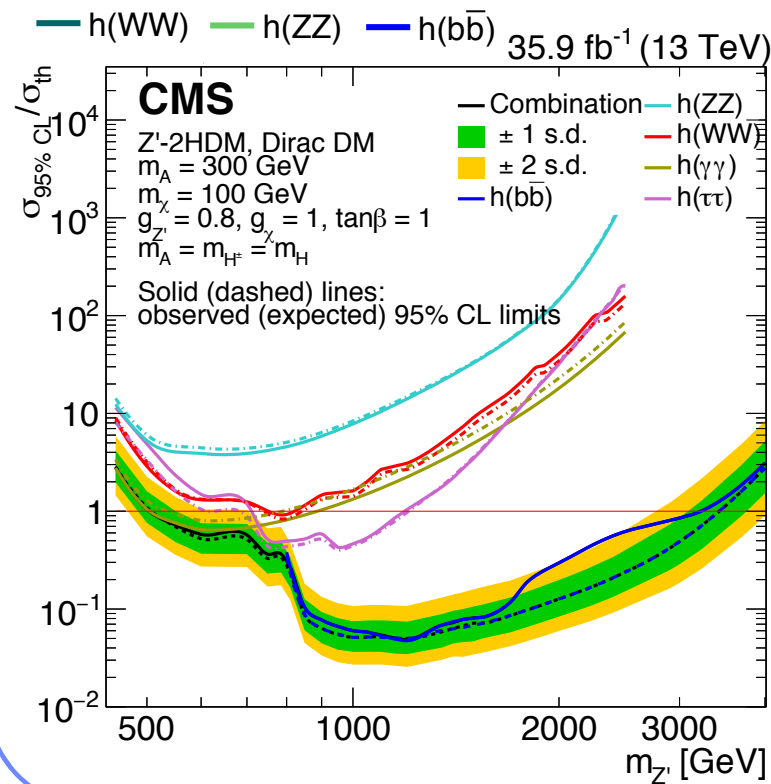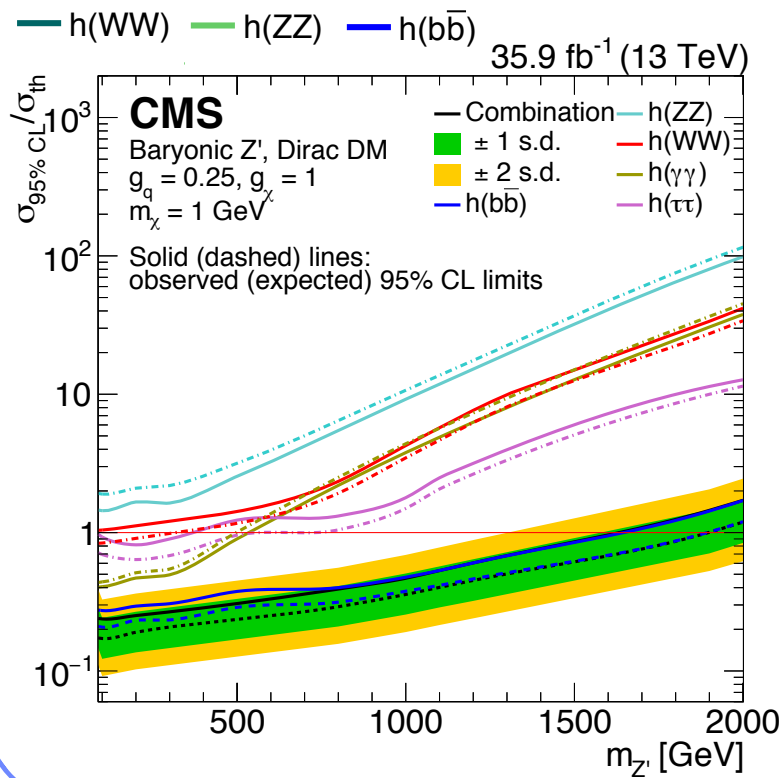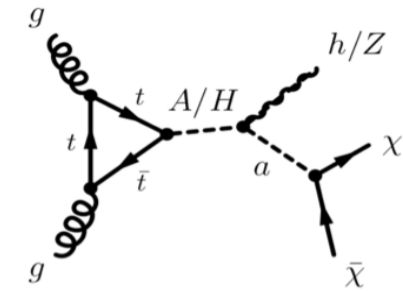
CMS med. boost — *m_a=150 GeV, m_A excl. [500.900] GeV*

Higgs: a portal to the invisible?

▷ *DM-SM interactions mediated by Higgs boson*

 - direct coupling to DM enhance H invisible decays (SM ~0.1%)

▷ *Higgs production as in SM*

 - gluon fusion *(MET+j)*

 - associated VH *(MET+V)*

✱ *vector-boson fusion (MET+2jets)*

Higgs DM DM

▷ 1 - Selection:

 - 2 jets (large $|\Delta\eta_{jj}|$, small $|\Delta\Phi_{jj}|$), MET > 180-250 GeV

▷ 2- Bkg:

 - V+jets main bkg from CRs

Experimental challenges

✱ precise estimation of bkg m_{jj} shape distribution, signal as excess of events at large m_{jj}

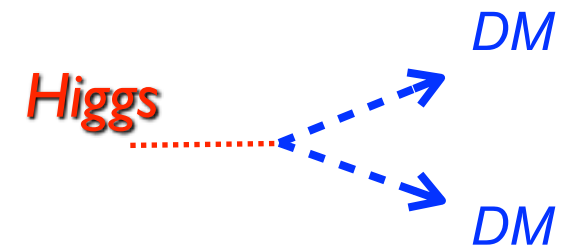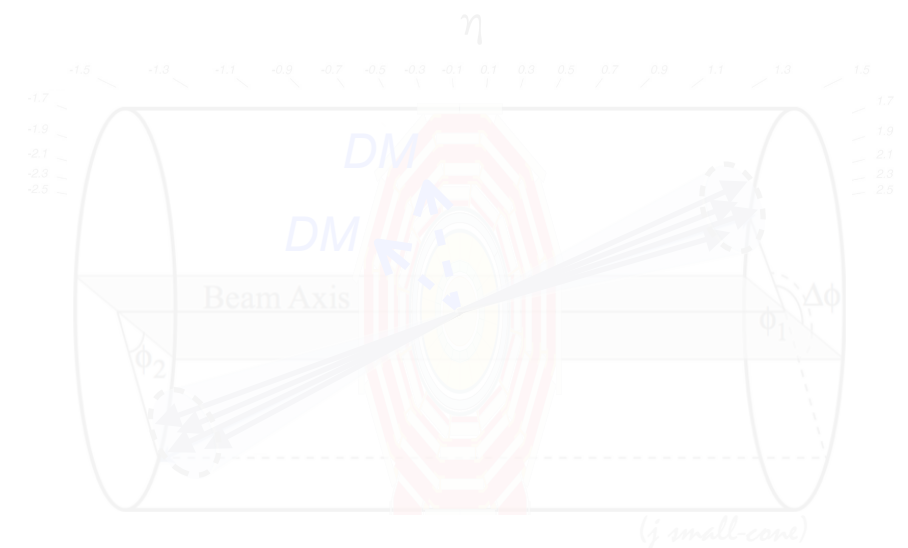✱ excellent calorimetry in forward region to measure jets

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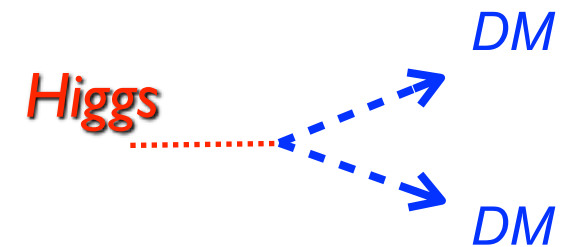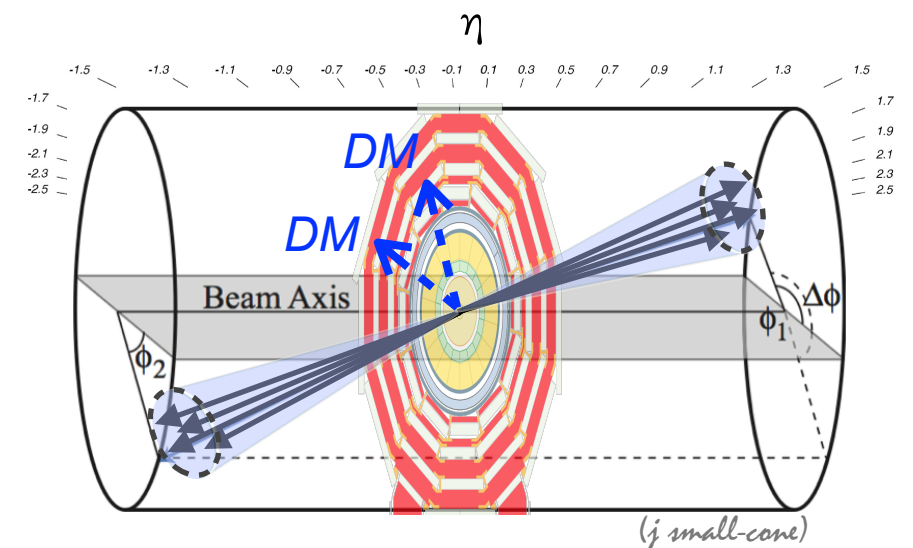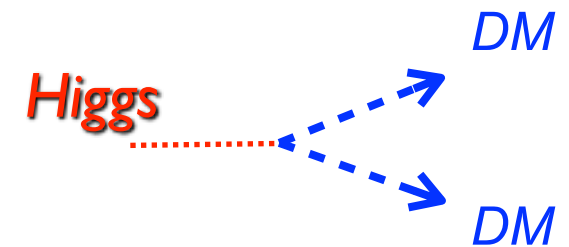✱ excellent calorimetry in forward region to measure jets

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$BR(H\rightarrow inv)$
$<0.19(0.15)$
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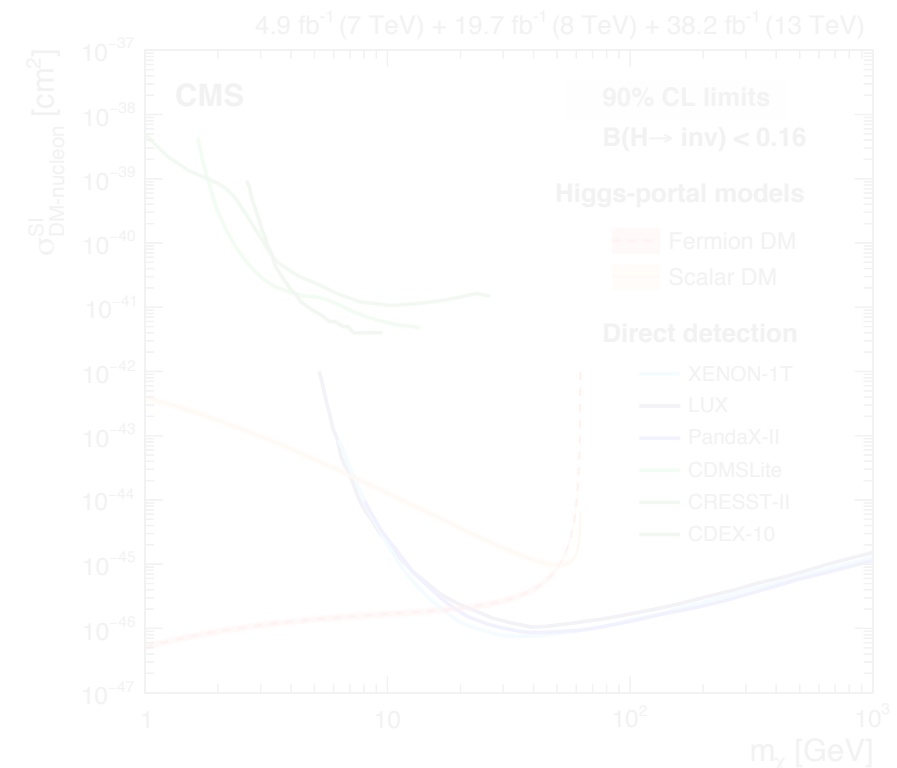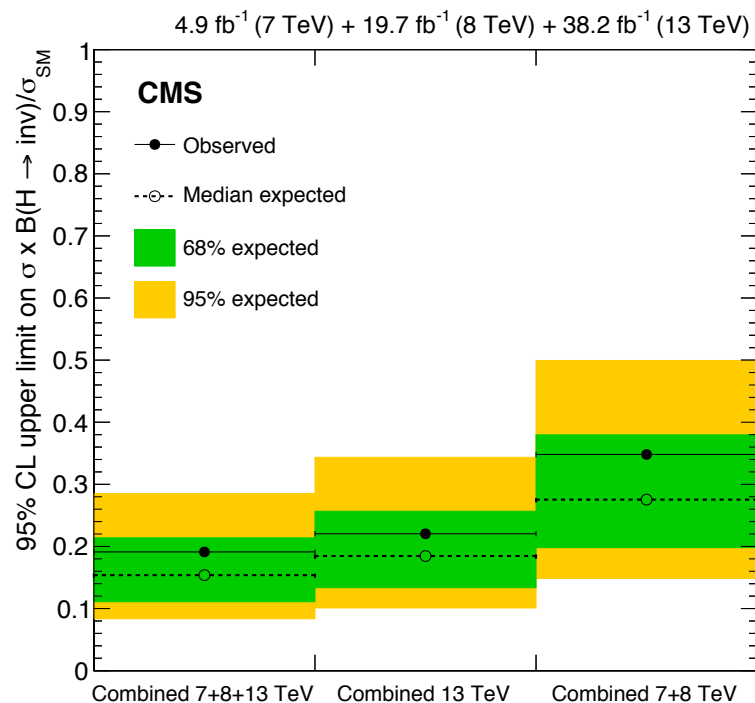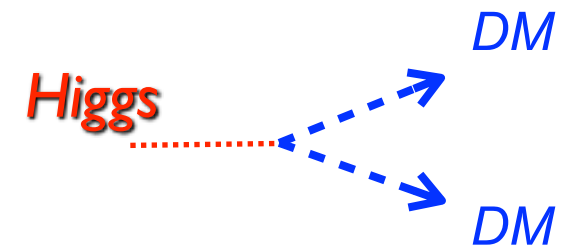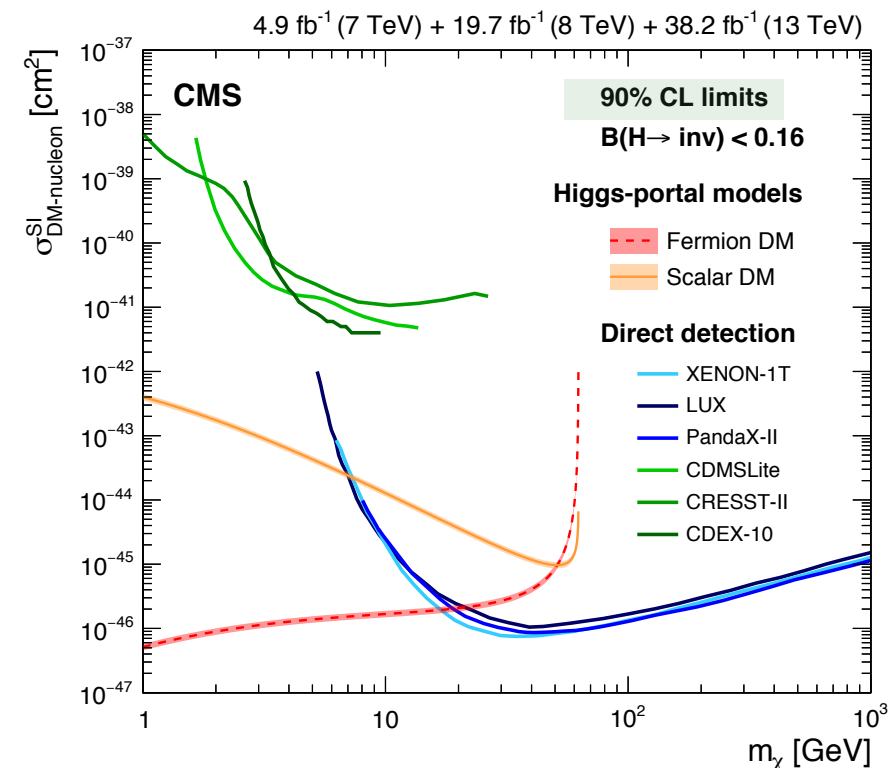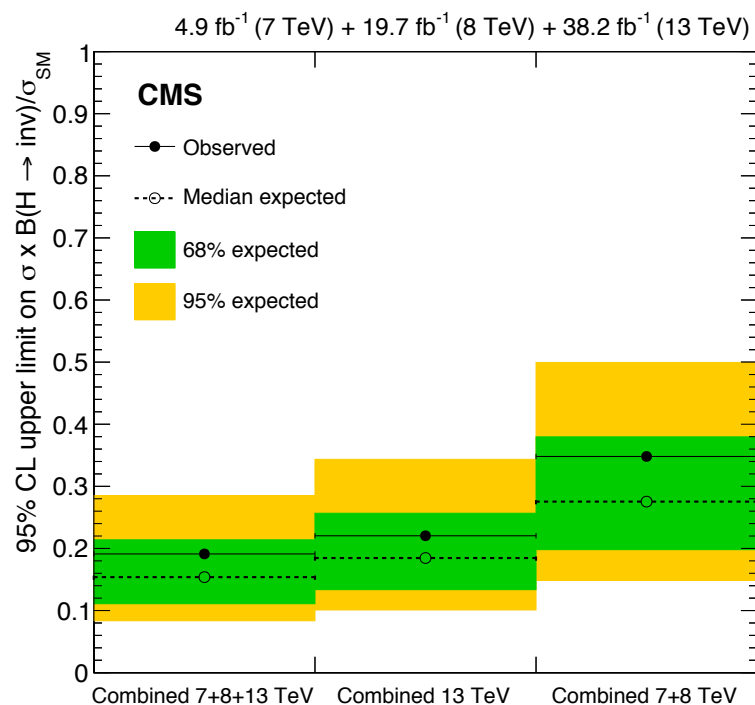
DM

Higgs

DM

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Dark photon in Higgs decays

▷ **Simplified models make minimal assumptions**

▷ *An extended dark sector might exist*

- contain DM candidate and a heavy resonance that couples dark sector to the SM

- can lead to H exotic decays

SM

Y

dark sector
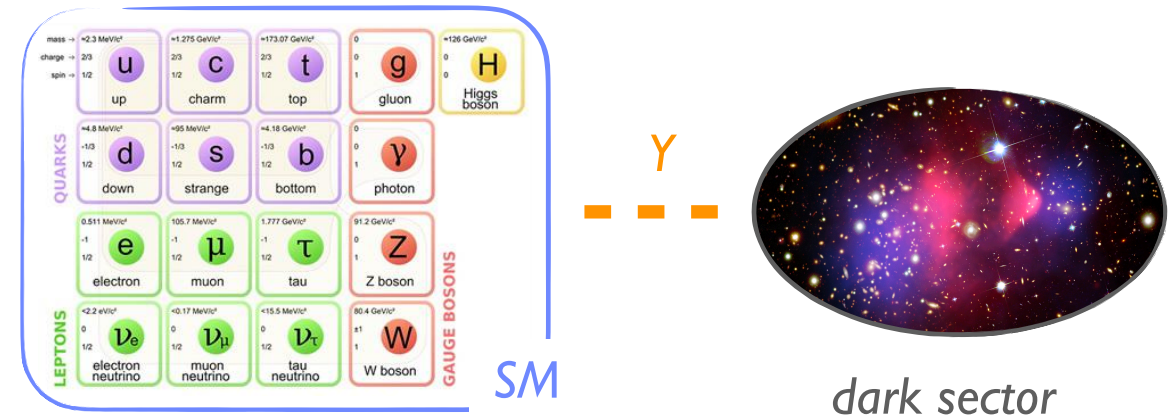
▷ *Massless dark photon γ_D couples to H and escape undetected (MET signature)*

- $BR(H \rightarrow \gamma\gamma_D)$ <5% not yet excluded

- consider *associated Z(ℓℓ)H production* and heavy neutral H with masses [125, 300] GeV

full Run-2

Summary
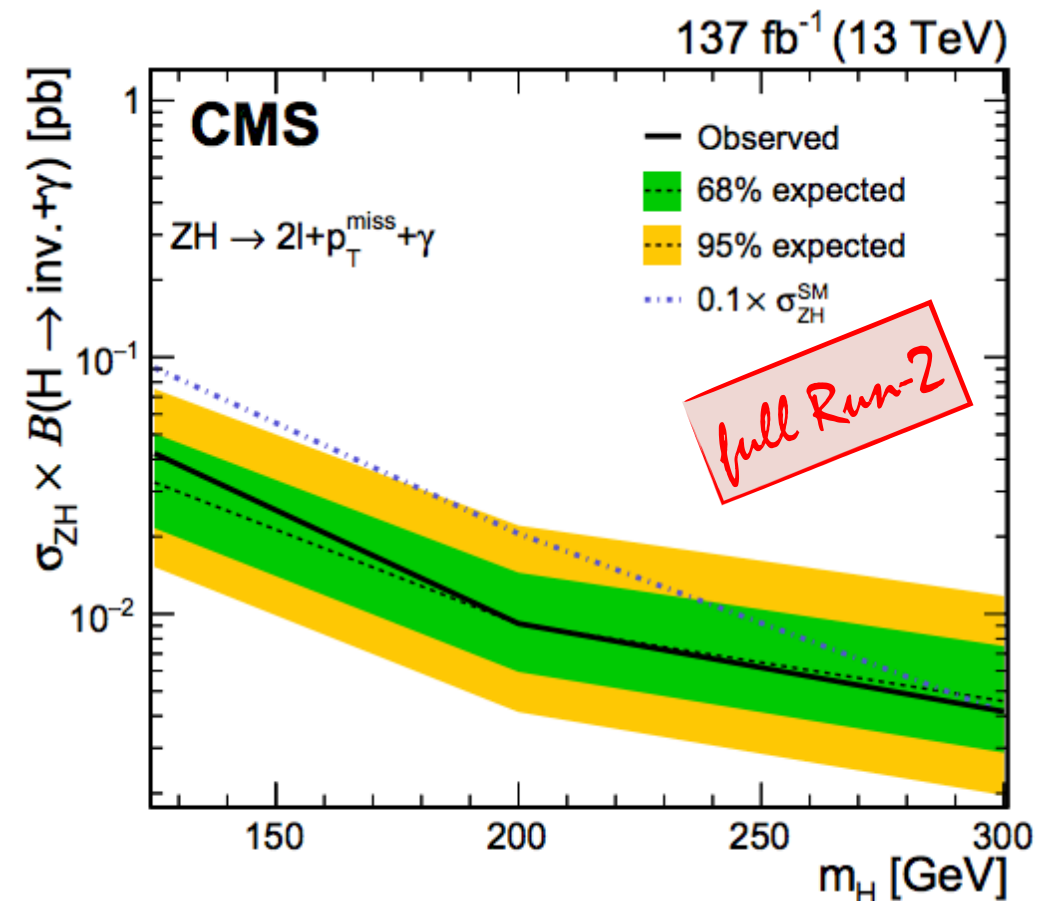
▷ *New physics is a main physics goal at the LHC*

▷ *Rich MET+X analyses program at CMS*

- various interactions and signatures investigated

- new experimental tools used to improve sensitivity

- essential complementarity with visible searches to investigate larger regions of parameter space of DM models

no signs of an excess yet so far

MET signatures

| Analysis	Dataset	Document
mono-jet	36 fb-1	PRD97(2018)
mono-Z(ll)	36 fb-1	EPJC78(2018)291
mono-photon	36 fb-1	JHEP02(2019)074
mono-LQ	77 fb-1	PLB795(2019)76
bb+DM	2.2 fb-1	EPJC77(2017)845
mono-top (had)	36 fb-1	JHEP06(2018)027
single top + DM	36 fb-1	JHEP03(2019)141
tt+DM combination	36 fb-1	PRL122,011803(2019)
mono-H(bb)	36 fb-1	EPJC79(2019)280, JHEP11(2018)172
mono-H($\tau\tau$, $\gamma\gamma$)	36 fb-1	JHEP09(2018)046
mono-H combination	36 fb-1	JHEP03(2020)025
H to dark photons	137 fb-1	JHEP10(2019)139

Visible signatures (DM interpretation)

boosted dijet	77 fb-1	PRD100.112007(2019)
dijet w/ btag		
dijet w/ ISR		
dijet		
4 top quarks		
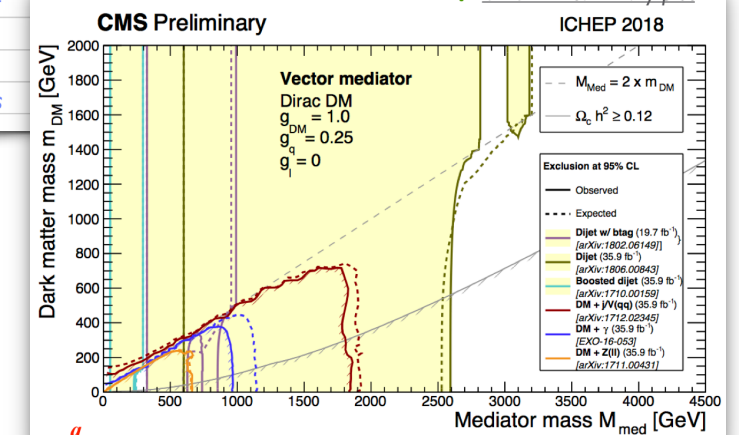
✳ *Many new results expected with full 2016+2017+2018 data*

- *various analysis improvements foreseen*

- *new signatures investigated*

Stay tuned !
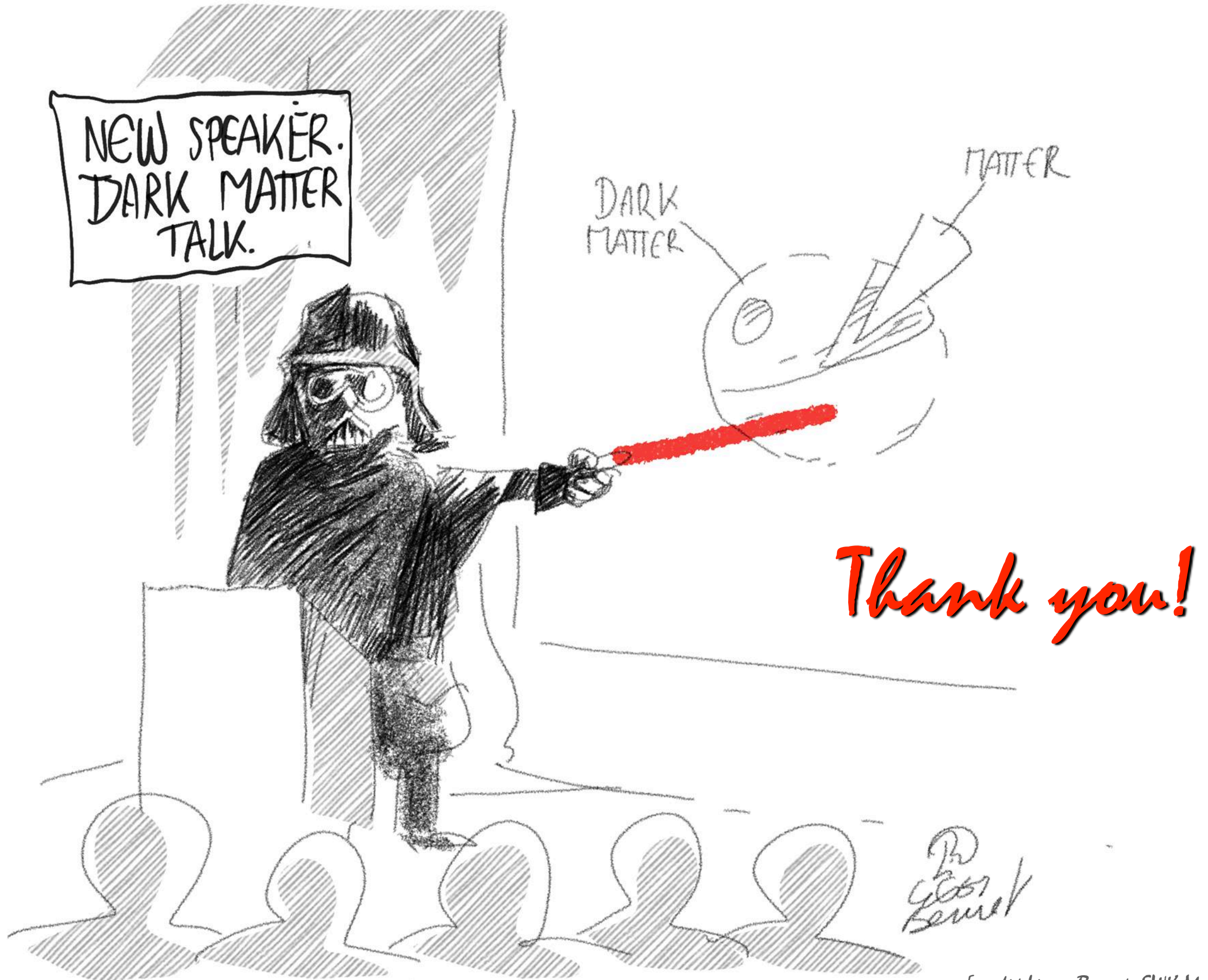
[credit Lison Bernet, EWK Moriond '19]

Backup