New physics searches at ATLAS and CMS

Deborah Pinna

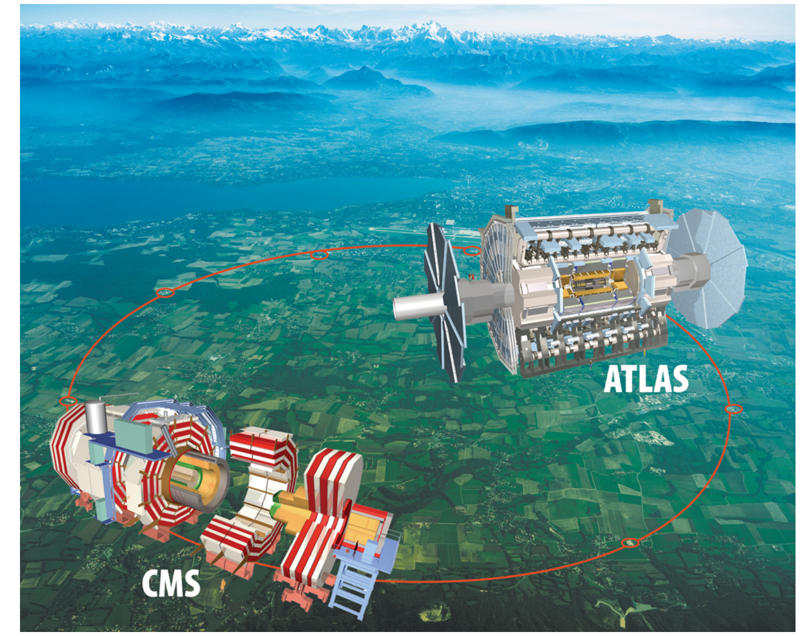
on behalf of the *ATLAS and CMS Collaborations*

PPNT19

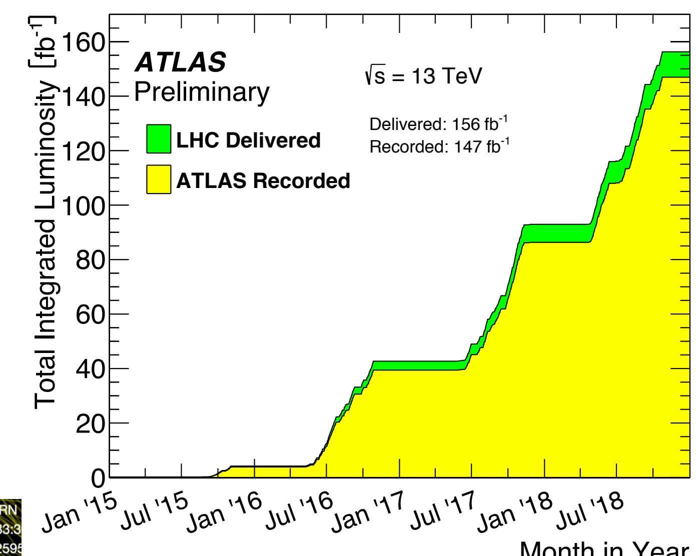
Uppsala, 7-9 October

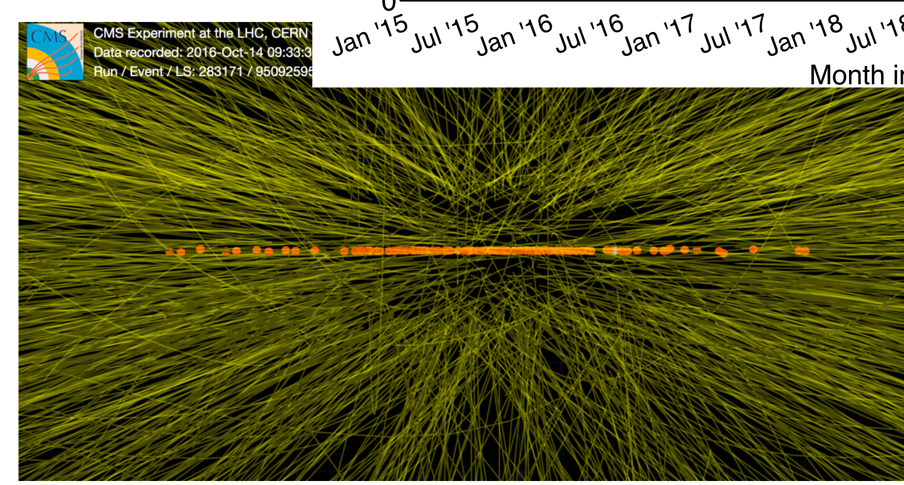
ATLAS, CMS and Run-2 data taking

- LHC accelerator designed to collide protons
- ATLAS and CMS multipurpose detector
  - particle identification, energy and momenta measurements
  - trigger system: select events interesting for physics analysis



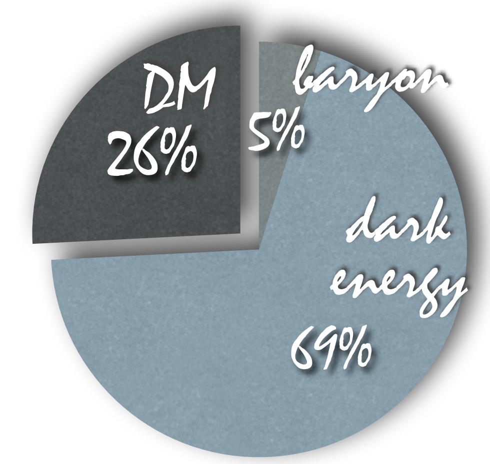
- Run-2: data taking period 2015-2018 at 13 TeV
- Excellent LHC (and ATLAS and CMS) performance:
  - ~140 fb^{-1} pp collision data good for analysis during Run 2
  - more than 8.5 million Higgs boson produced
- Mean number of additional pp interactions per crossing ~34
  - increasingly dense collision environment





Rich new physics program at ATLAS and CMS

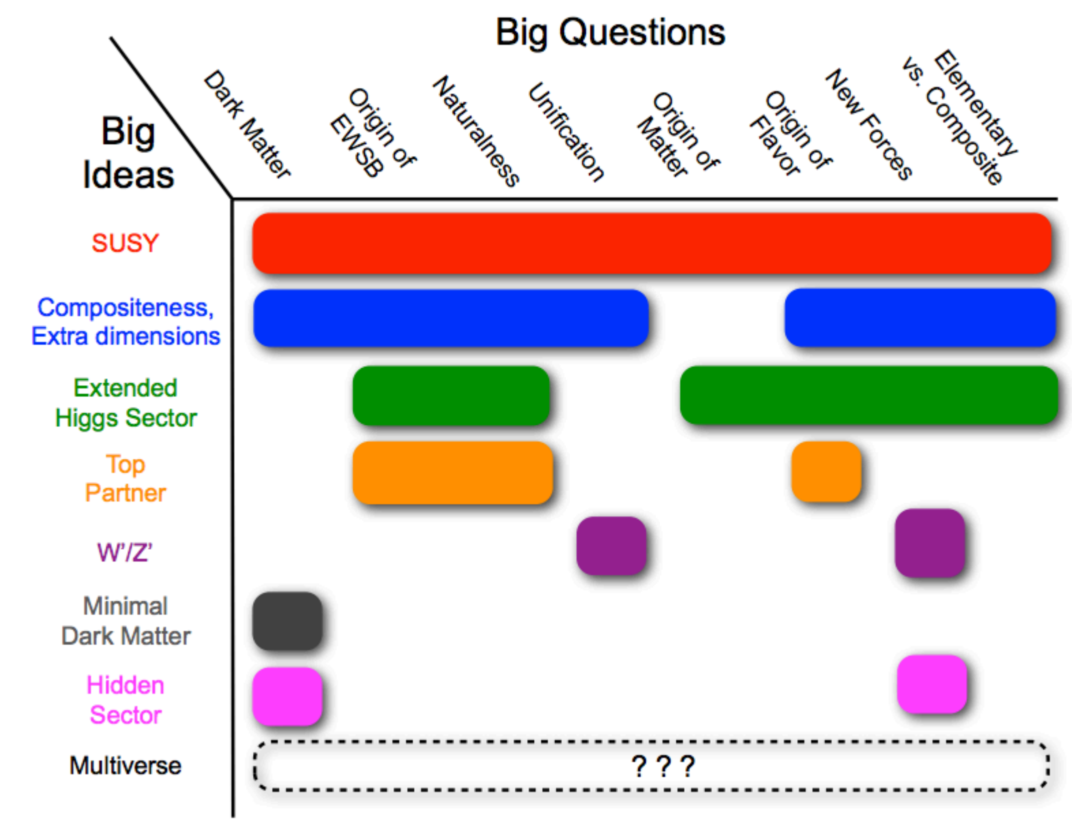
- *Despite the accuracy of the SM and its predictive power many open outstanding questions, eg.:*
  - matter-antimatter asymmetry
  - hierarchy problem
  - describes only ~5% of the universe, explanations for DM are not provided
  - gravitational force cannot be included in the current theoretical framework



- *LHC main goals: studying EWK symmetry breaking (Higgs), precision test of SM, search for new physics*
  - *direct production* of particles predicted by BSM theories
    - *direct coupling to the SM sector can estimated*
  - hints of new physics from *small deviations* between precision measurements and SM predictions
    - *allows to distinguish between possible SM extensions and to derive indirect constraints on their parameters*

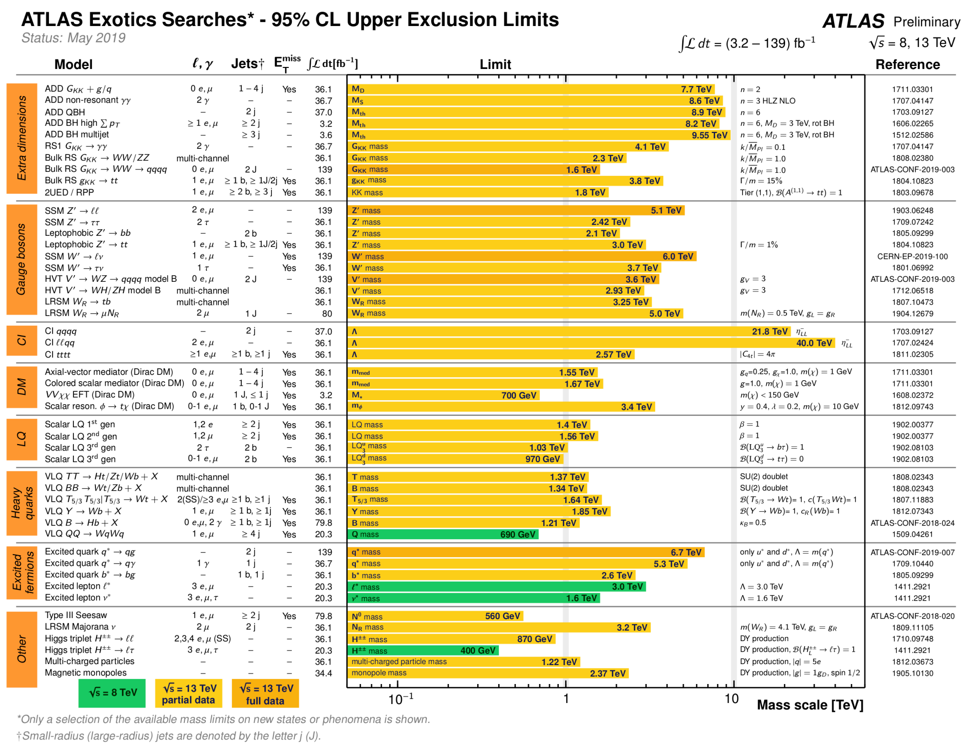
LHC Run-2 data

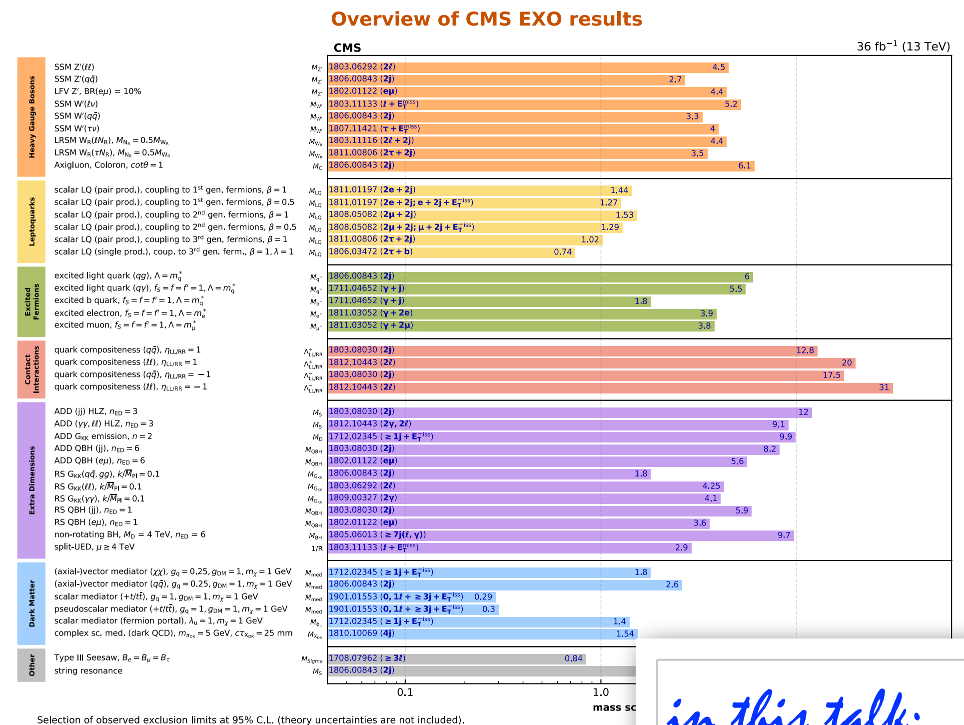
- ✱ detect rare processes
- ✱ use the Higgs as a discovery tool

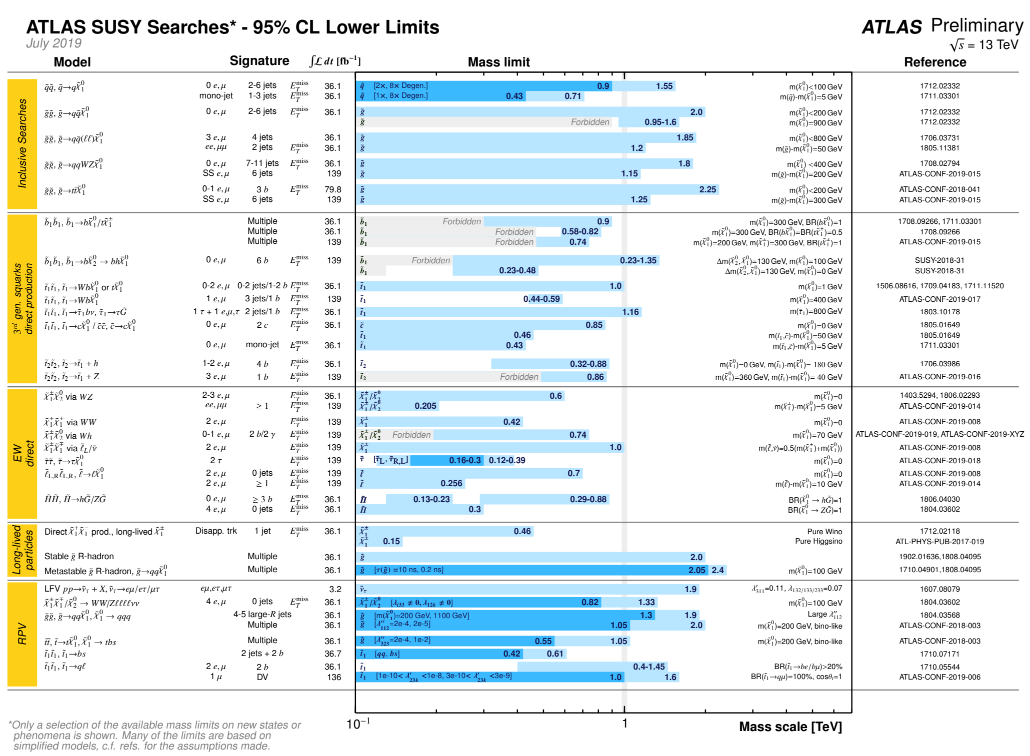


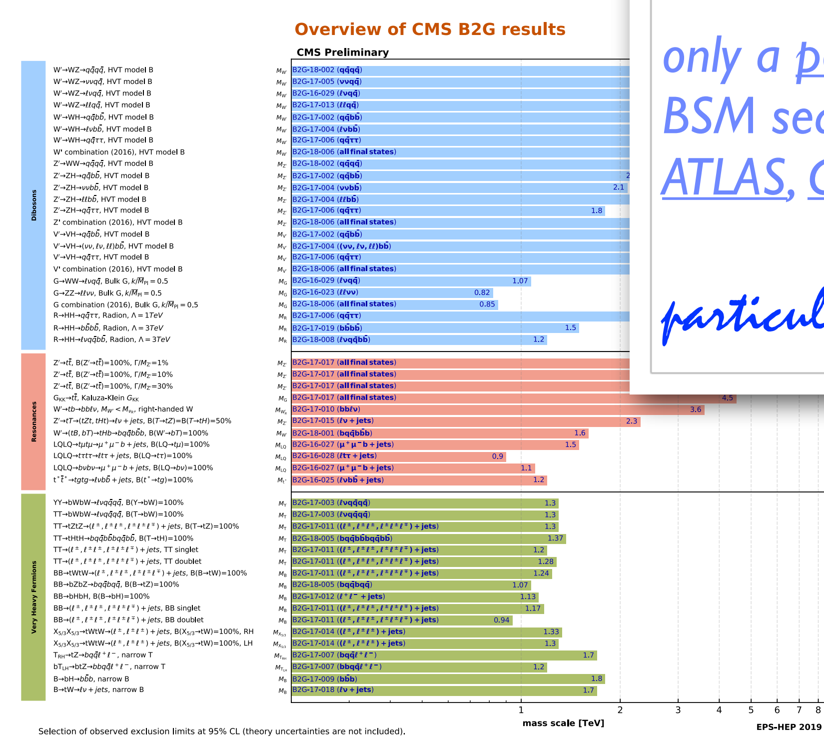
[arXiv:1311.0299]

Rich new physics program at ATLAS and CMS









in this talk:

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

particular focus on Dark Matter

Dark matter? *signature and phenomenology at collider*

DM evidence

- *Empirical evidence of DM from astrophysical observations at different scales*
  - interacts gravitationally, long lived and neutral
  - *no information about its nature*

✱ most studied class of theories: DM is a weakly interacting massive particle

assume weak interactions with SM

DM production

- *DM could be produced at colliders (rare process)*

✱ no direct trace in the detector, *but* could create a p_T imbalance (*MET*)

- parton initial p_T=0, conserved

$$\vec{E}_T^{miss} = -\sum \vec{p}_T$$

$|\vec{E}_T^{miss}|$ = *missing transverse energy (MET)*

✱ need *visible particle* to which DM particle recoils against

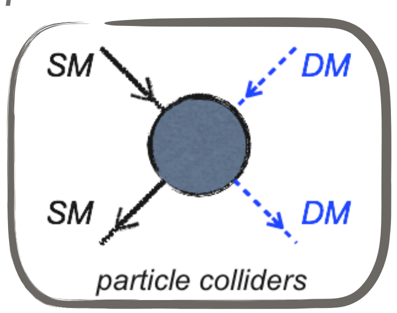
- "mono-*X* searches": *X* includes jets, vector bosons, top, …

Dark matter? signature and phenomenology at collider

DM evidence

assume weak interactions with SM

DM production



- *Empirical evidence of DM from astrophysical observations at different scales*
  - interacts gravitationally, long lived and neutral
  - *no information about its nature*

✱ most studied class of theories: DM is a weakly interacting massive particle

- *DM could be produced at colliders (rare process)*

✱ no direct trace in the detector, *but* could create a p_T imbalance (***MET***)

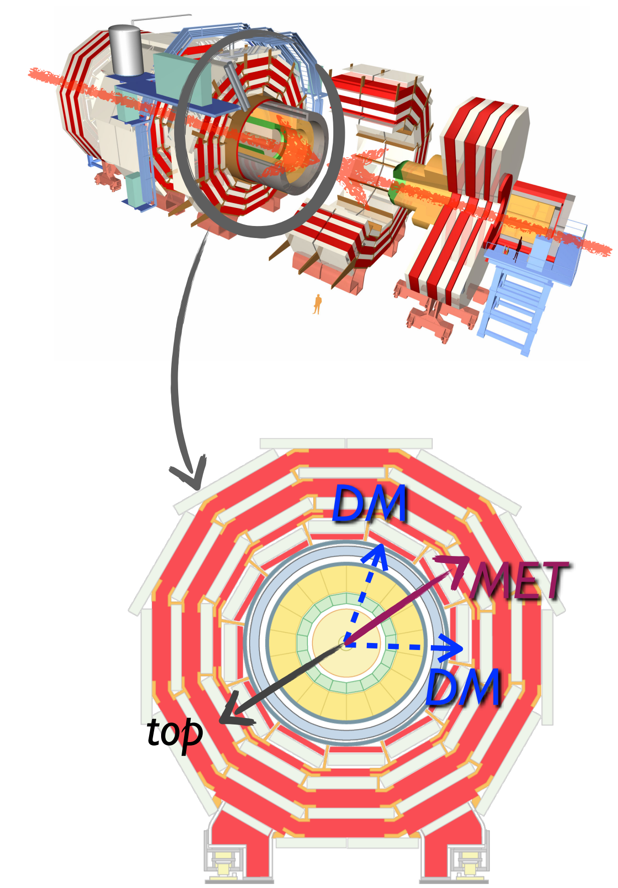
- parton initial p_T=0, conserved

$$\vec{E}_T^{miss} = -\sum \vec{p}_T$$

$|\vec{E}_T^{miss}|$ = *missing transverse energy (MET)*

✱ need *visible particle* to which DM particle recoils against

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

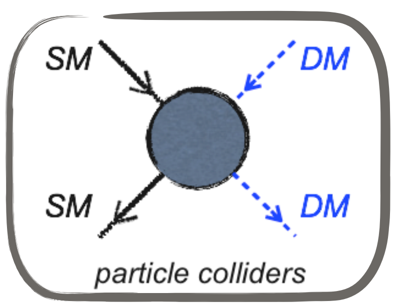


Dark matter? signature and phenomenology at collider

DM evidence

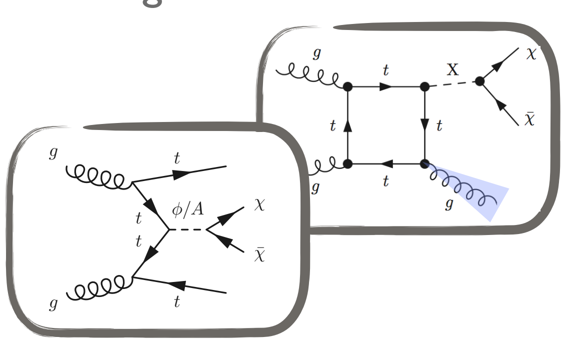
assume weak interactions with SM

DM production



investigate specific interactions/final states

DM signature



- **DM nature** (+m_{DM})
  - ☐ scalar (real or complex)
  - ☑ Dirac fermion (**assumption for LHC searches)*
  - ☐ …

- *Which type of events do we study at colliders?*
  can assume different interactions (med. couplings g_q, g_{DM})

	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	$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	$g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$

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

✱ benchmark models: 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

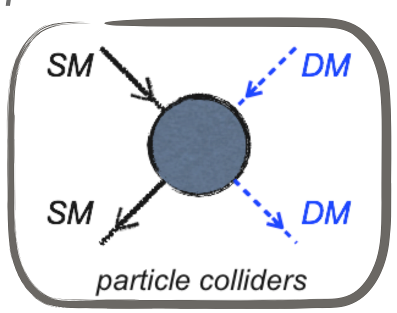
simpler (less parameters) → more (more parameters)

Dark matter? signature and phenomenology at collider

DM evidence

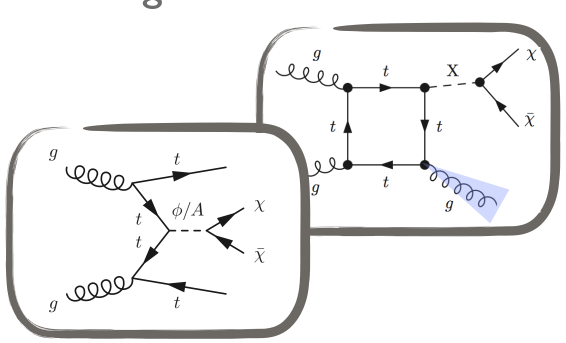
assume weak interactions with SM ↓

DM production



investigate specific interactions/final states ↓

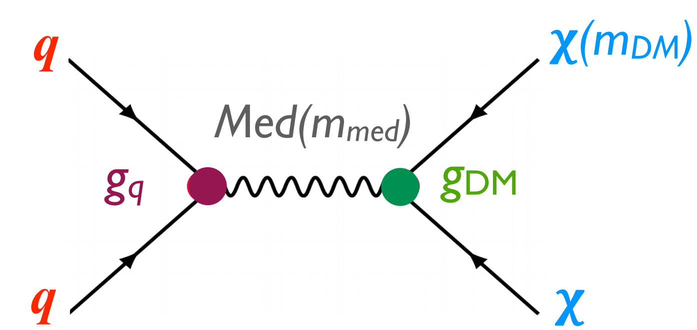
DM signature



- **DM nature** ($+m_{DM}$)
  - ☐ scalar (real or complex)
  - ☑ Dirac fermion (**assumption for LHC searches*)
  - ☐ …

- ***Which type of events do we study at colliders?***
  can assume different interactions (med. couplings g_q, g_{DM})

	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	$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	$g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$



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

✱ benchmark models: kinematically distinct set of model parameters

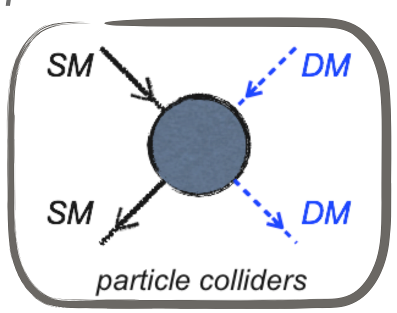
ATLAS/CMS DM forum [arXiv:1507.00966]

Dark matter? signature and phenomenology at collider

DM evidence

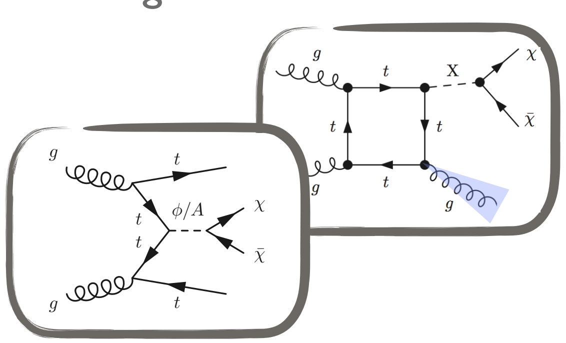
assume weak interactions with SM ↓

DM production



investigate specific interactions/final states ↓

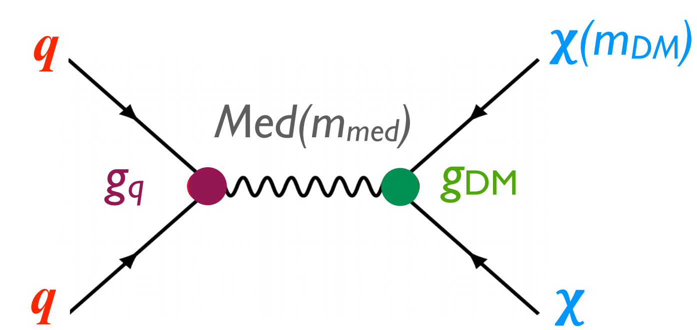
DM signature



- **DM nature** *(+m_{DM})*
  - ☐ scalar (real or complex)
  - ☑ Dirac fermion *(*assumption for LHC searches)*
  - ☐ …

- ***Which type of events do we study at colliders?***
  can assume different interactions (med. couplings g_q, g_{DM})

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



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

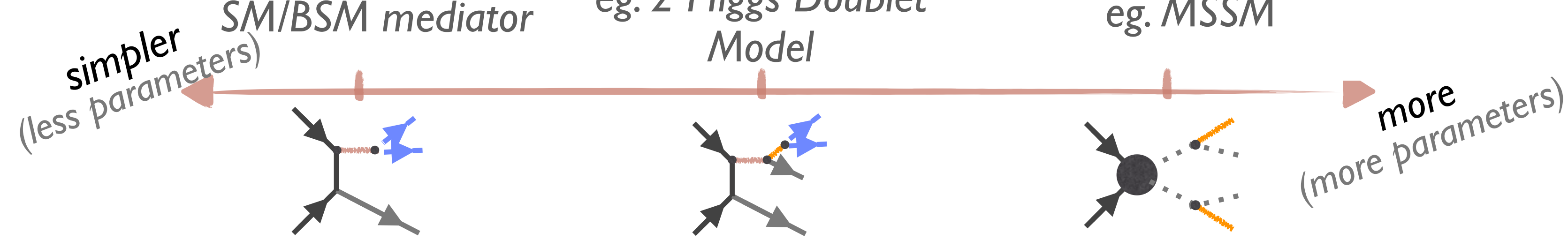
✱ benchmark models: *kinematically distinct set of model parameters*

ATLAS/CMS DM forum [arXiv:1507.00966]

Simplified models: SM/BSM mediator

Specific models: eg. 2 Higgs Doublet Model

Complete models: eg. MSSM



How do we search for DM at colliders?

1 - Selection: DM appears as excess of events in MET tail wrt SM

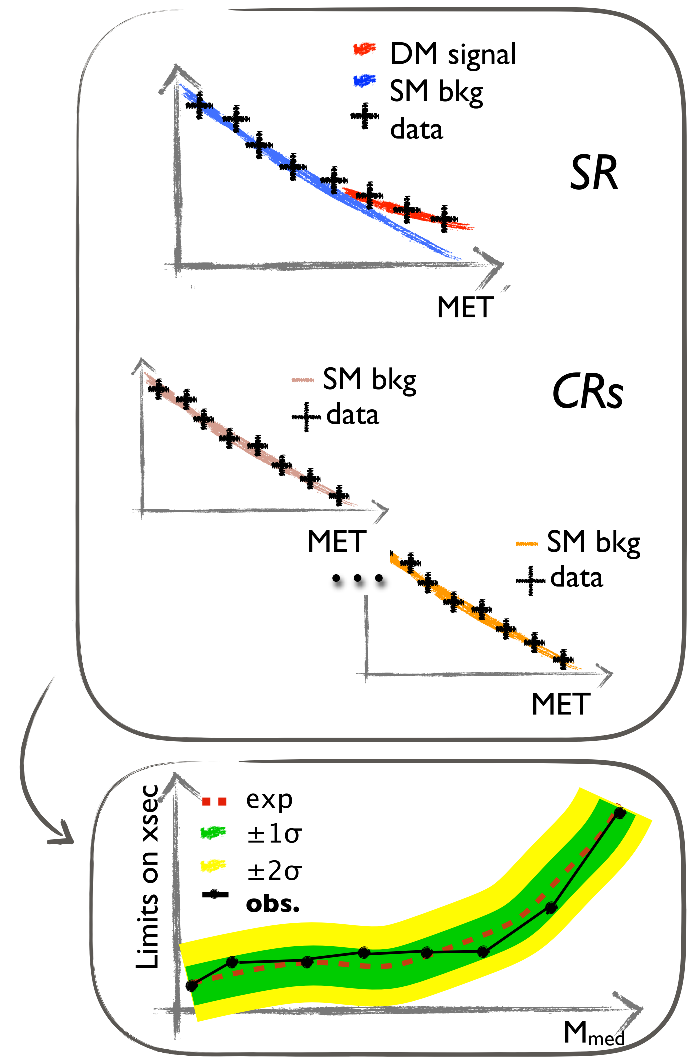
- no very striking signature, eg. mass peak, m_T kinematic endpoint
- look for excess in region enriched in signal *(signal region - SR)*

2 - Bkg: precise modeling and evaluation of other processes in SR essential

- achieved through use of multiple control regions *(CRs)*

3 - Results: Compare SM predictions with data

- *excess of events in data*. Did we find DM?
- *no excess*, interpret result in terms of theory model parameters



Experimental challenges

- accurate *E* calibration/resolution of visible objects *("fake" MET from mis-measured jets)*
- mitigate effects from additional *pp* collisions (pile-up)
- MET thresholds affected by trigger (very high collision rates)
- precise particle reconstruction and identification

How do we search for DM at colliders?

1 - Selection: *DM appears as excess of events in MET tail wrt SM*

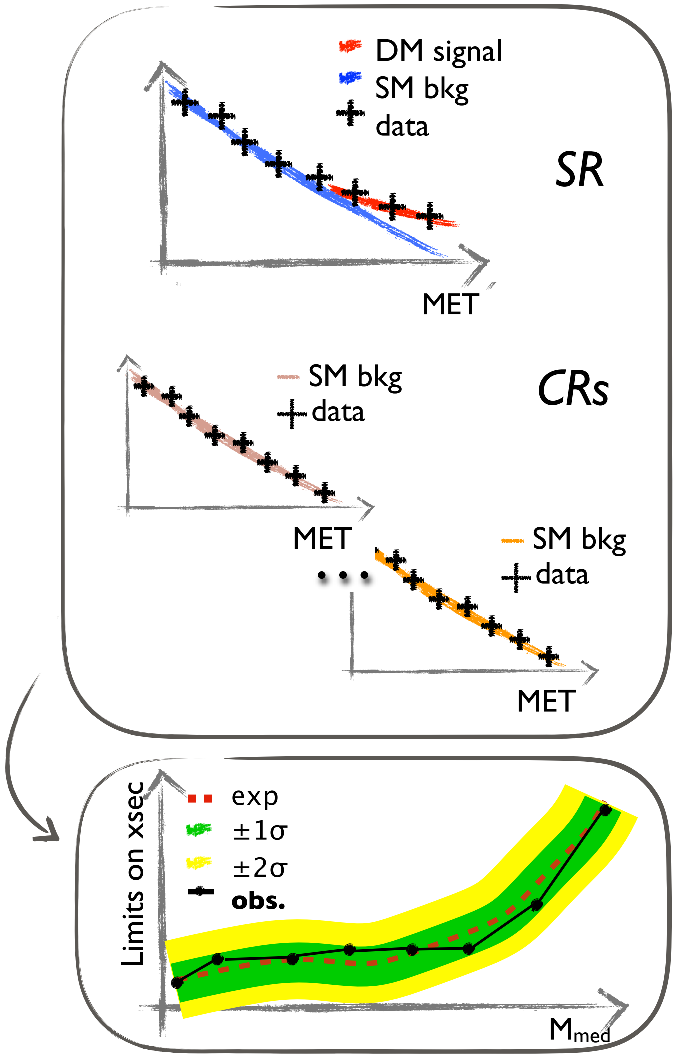
- no very striking signature, eg. mass peak, m_T kinematic endpoint
- look for excess in region enriched in signal *(signal region - SR)*

2 - Bkg: *precise modeling and evaluation of other processes in SR essential*

- achieved through use of multiple control regions *(CRs)*

3 - Results: *Compare SM predictions with data*

- *excess of events in data*. Did we find DM?
- *no excess*, interpret result in terms of theory model parameters



Experimental challenges

- ✱ accurate *E* calibration/resolution of visible objects *("fake" MET from mis-measured jets)*
- ✱ mitigate effects from additional *pp* collisions (pile-up)
- ✱ MET thresholds affected by trigger (very high collision rates)
- ✱ precise particle reconstruction and identification

Reminder:

vector

$$g_q \sum_q V_\mu \bar{q} \gamma^\mu q$$

axial-vector

$$g_q \sum_q A_\mu \bar{q} \gamma^\mu \gamma^5 q$$

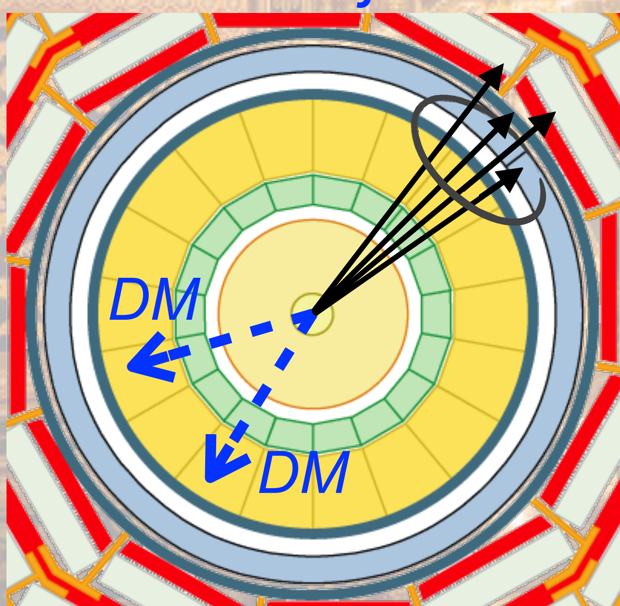
∗ choose X to increase xsec or bkg rejection

Spin-1 mediator:

simplified and extended sectors

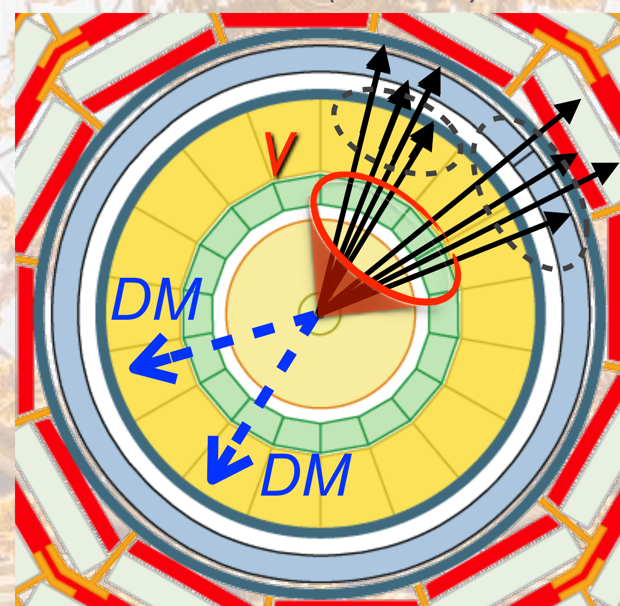
Signature: large MET and ≥1 high-p_T jet/vector boson/photon

mono-jet



✱ ATLAS: JHEP01(2018)126 (2015+2016)

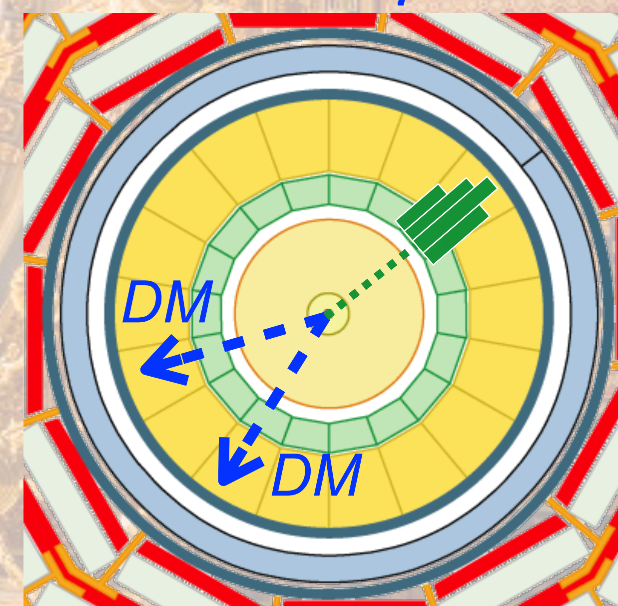
mono-V(=W,Z)/Z'



✱ ATLAS: JHEP10(2018)180 (2015+2016)

∗ CMS: PRD97,092005(2018) (2016)

mono-γ



∗ CMS: JHEP02(2019)074 (2016)

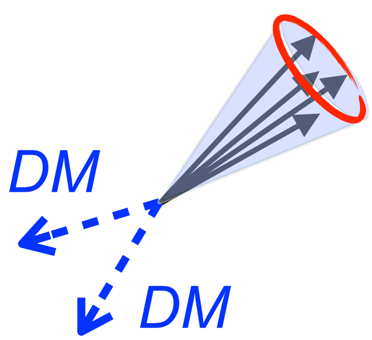
∗ ATLAS: EPJC77(2017)393 (2015+2016)

✱ selected most recent results

DM+jet search

ATLAS: JHEP01(2018)126

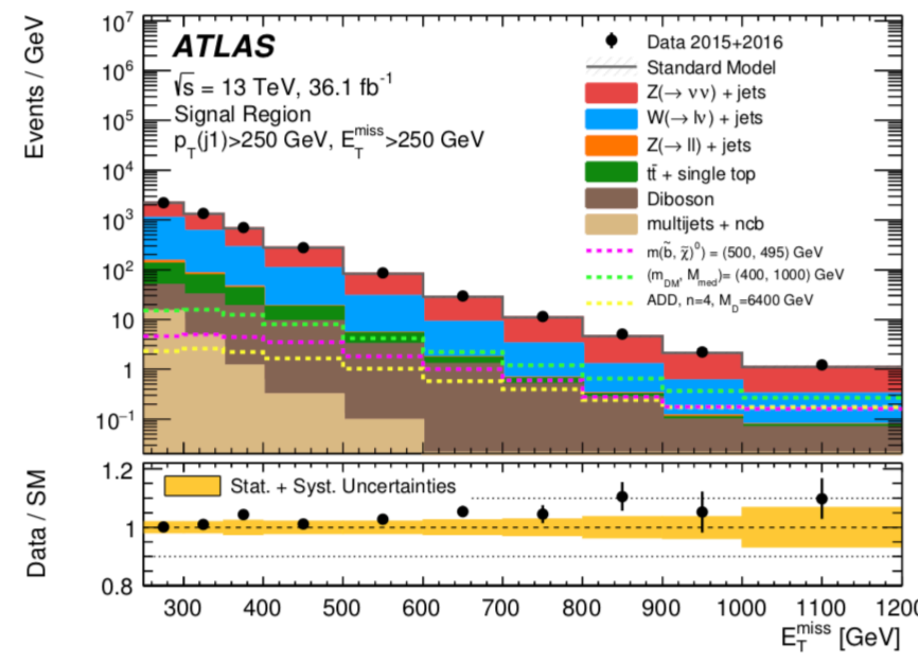
1 - Selection:



- ≥ 1 jets, $p_T(j_1) > 200$ GeV
- MET > 250 GeV
- lepton veto

2- Bkg:

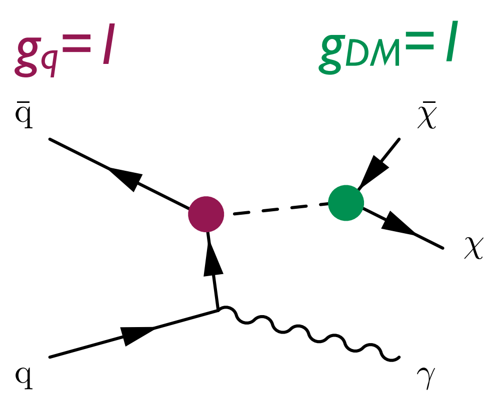
major:
Z(νν), tt, W(lν)+jets from CRs

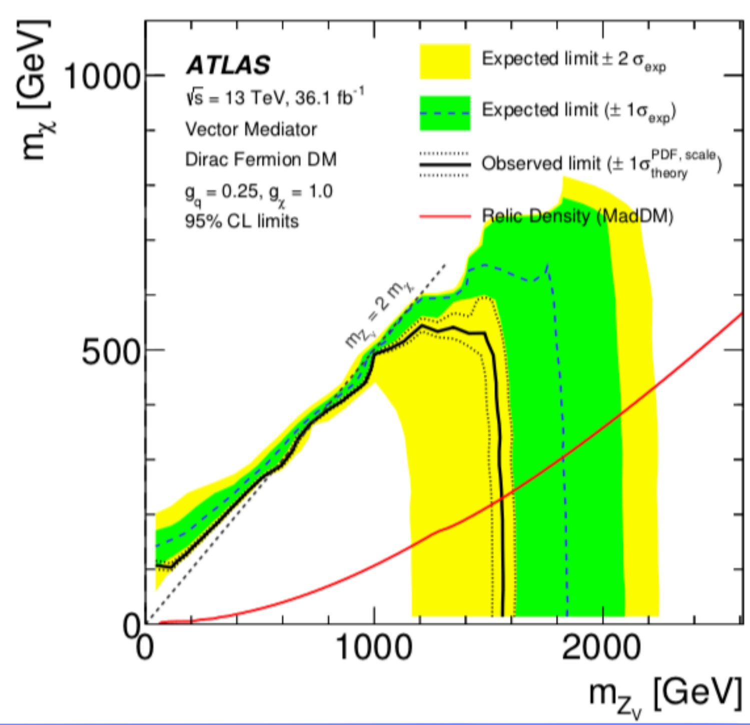


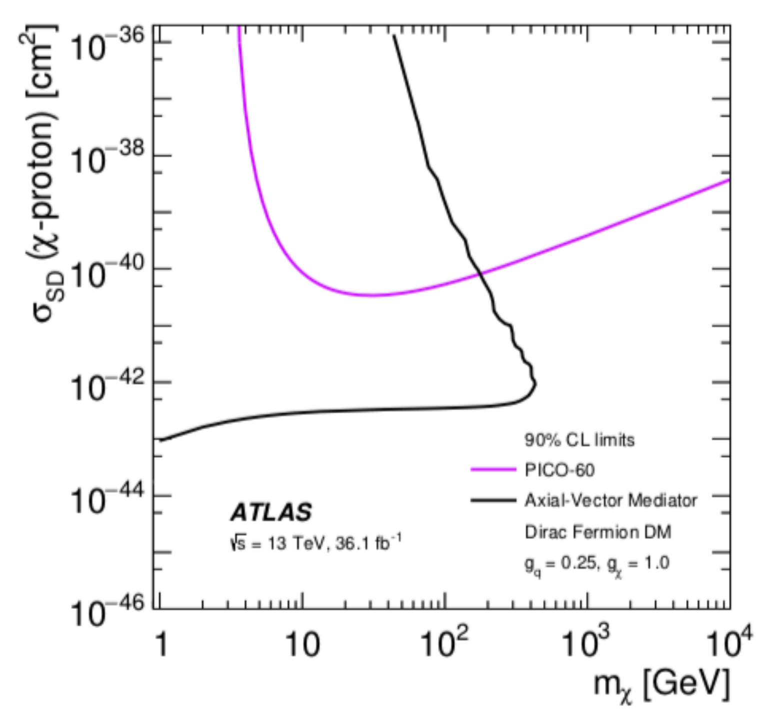
3- Results: signal extracted through combined fit of SRs and CRs (systematic unc. as nuisance parameters)

CMS: similar strategy, but targets mono-jet/V together

vector/axial-vector



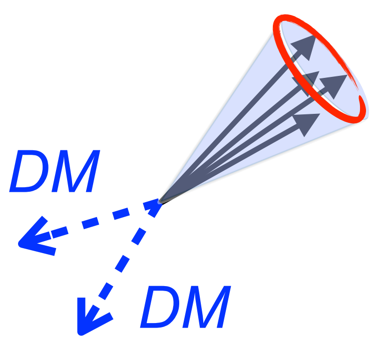




DM+jet search

ATLAS: JHEP01(2018)126

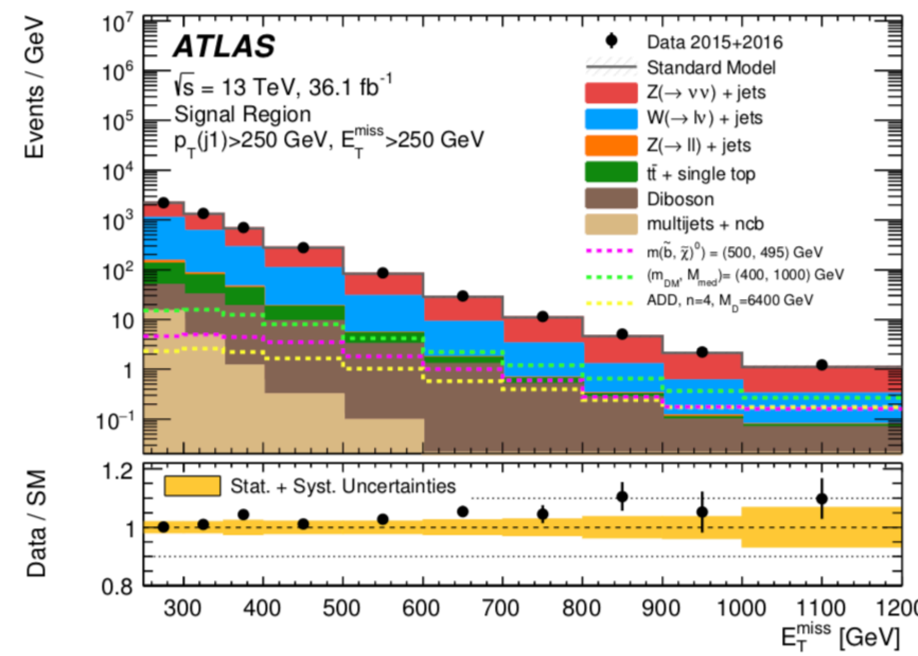
1 - Selection:



- ≥ 1 jets, $p_T(j_1) > 200$ GeV
- MET > 250 GeV
- lepton veto

2- Bkg:

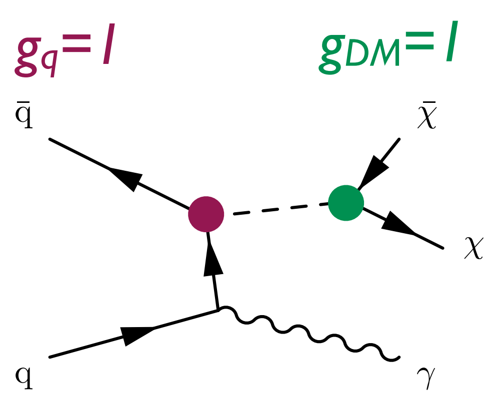
major:
Z(vv), tt, W(lv)+jets from CRs

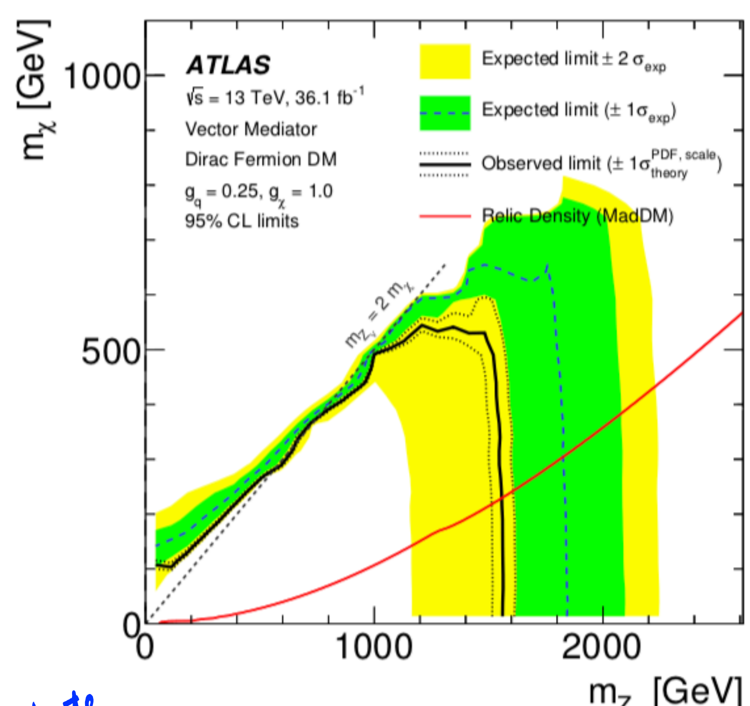


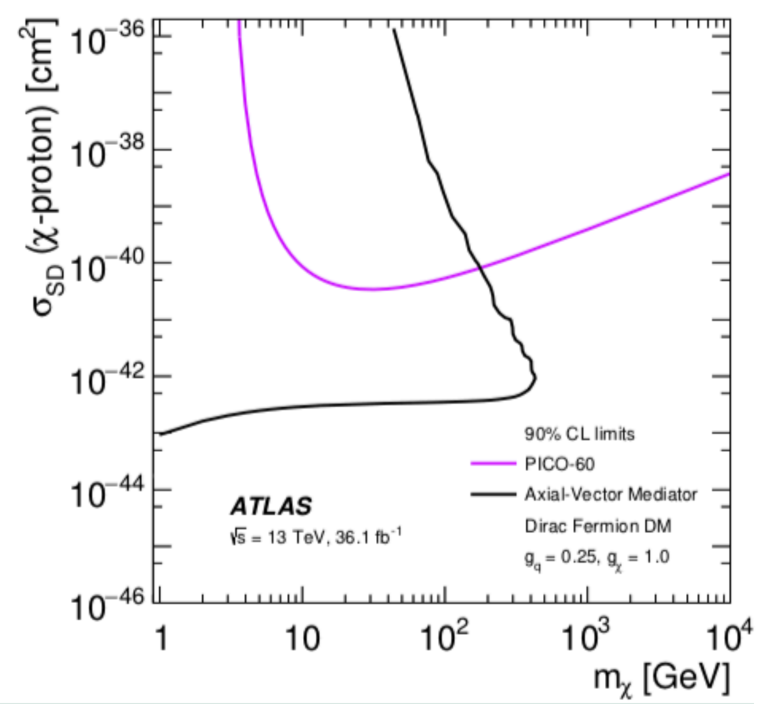
3- Results: *signal extracted through combined fit of SRs and CRs (systematic unc. as nuisance parameters)*

CMS: similar strategy, but targets mono-jet/V together

vector/axial-vector







LHC DM WG [arXiv:1603.04156]

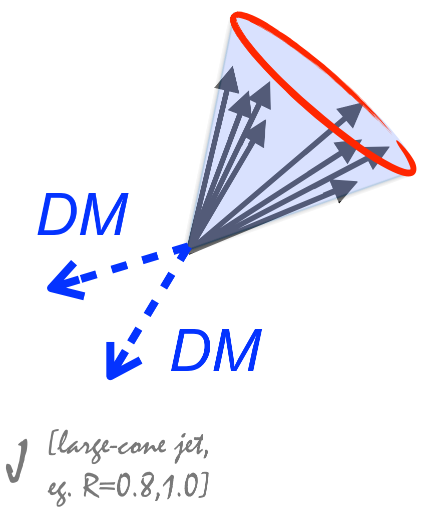
Note

- *comparisons possible only in the context of a benchmark model*
- *essential to fully specify model/parameters and be aware of limitation*

DM+V/Z' search

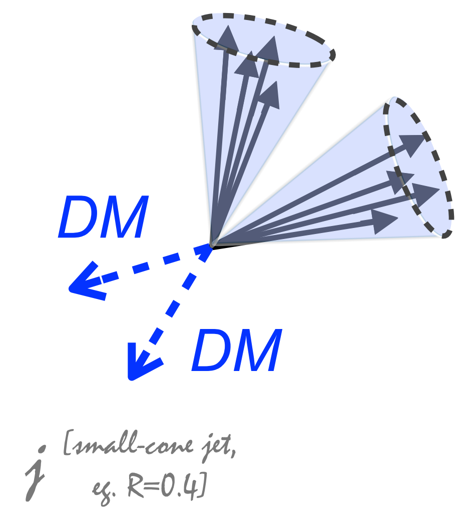
ATLAS: JHEP10(2018)180

▷ *1 - Selection:* *events categorized based on vector boson boost, b-jets multiplicity*



merged

- ≥ 1 jets, p_T (j) > 200 GeV
- MET > 250 GeV
- *invariant mass jet* consistent with V/Z'
- *2-prong structure* inside jet



resolved

- not selected as *merged*
- ≥ 2 jets, p_T (j) > 30 GeV
- MET > 150 GeV

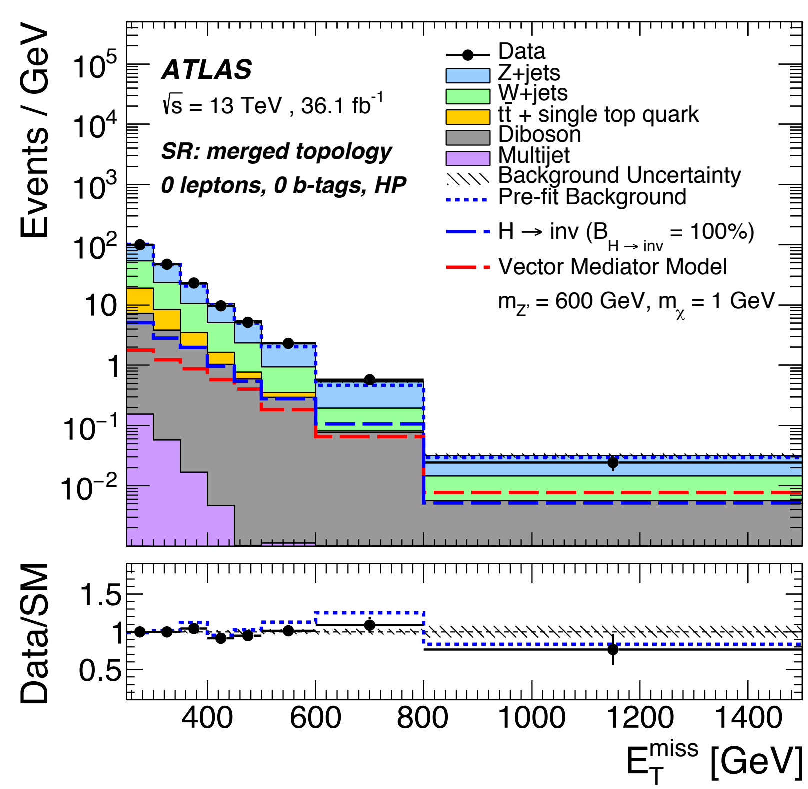
▷ *2- Bkg:*

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

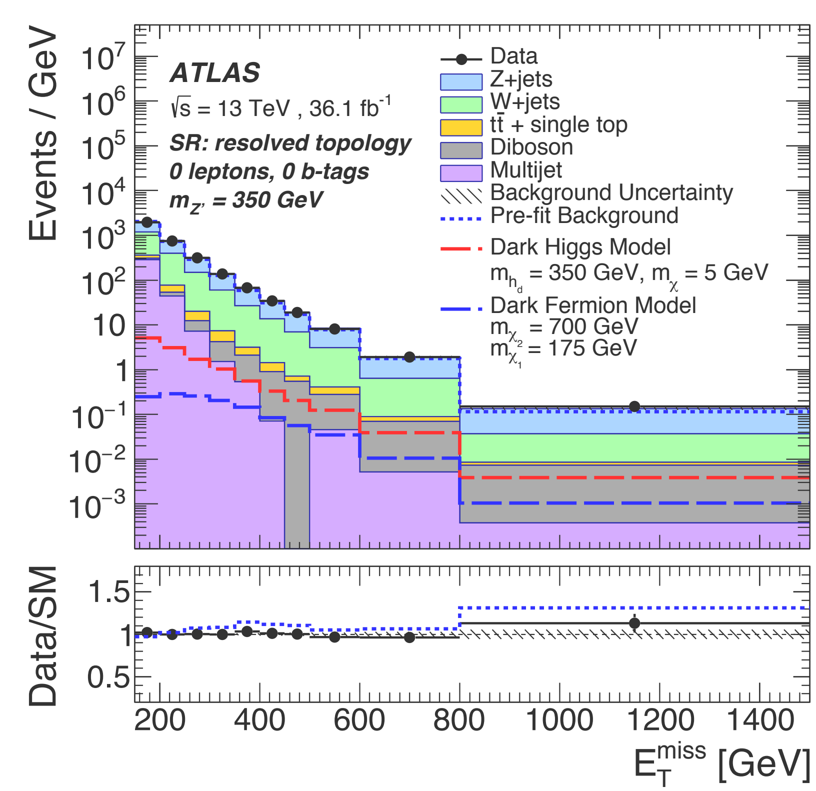
▷ *3- Results: combined fit of SRs and CRs*

- systematic unc. included as nuisance parameters

mono-V



mono-Z'

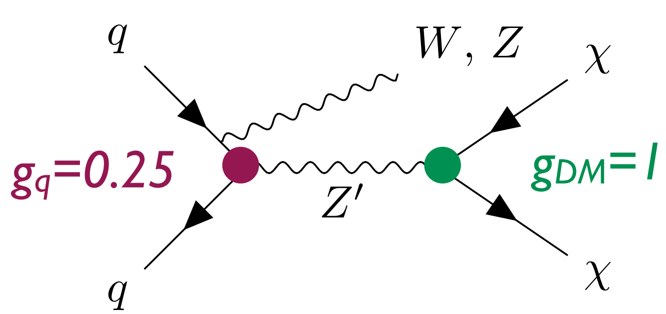


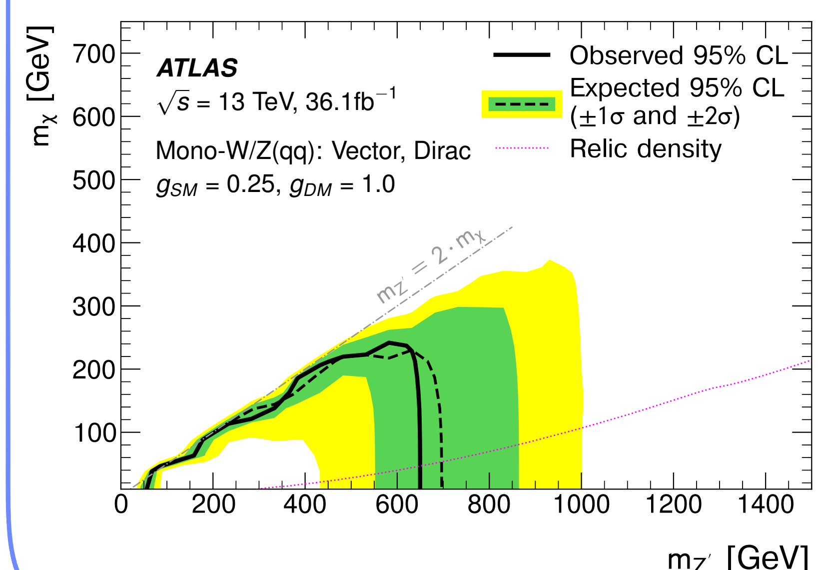
DM+V/Z' search

ATLAS: JHEP10(2018)180

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

Simplified vector model





CMS: similar strategy, but targets mono-jet/V together

Dark-fermion model

Z' couples to heavier dark-sector fermion χ_2 and DM χ_1

Dark-Higgs model

Z' radiates dark-sector Higgs ($h_D \to \chi\chi$)

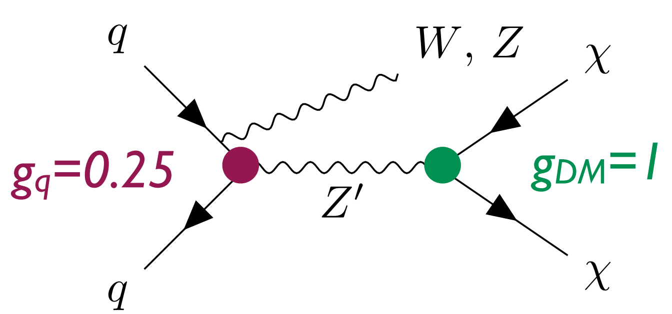
✱ First result for DM production in association with a new vector boson Z'

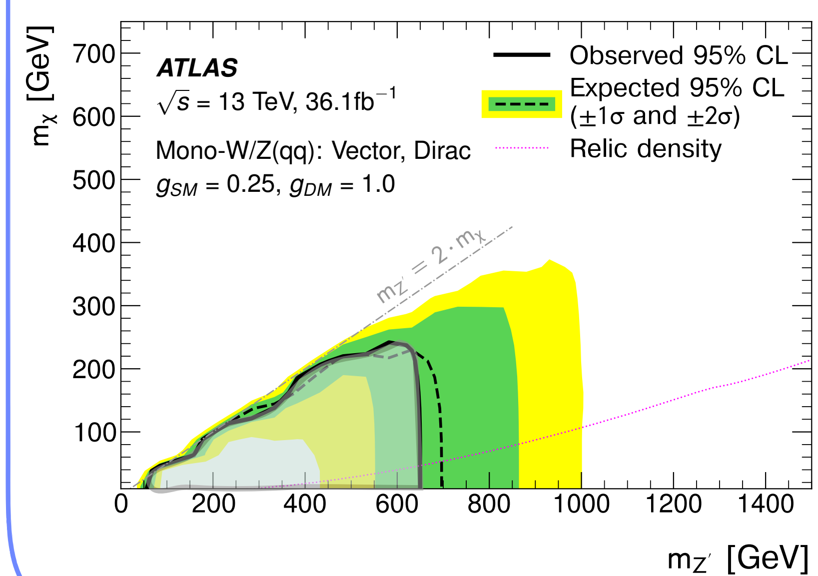
DM+V/Z' search

ATLAS: JHEP10(2018)180

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

Simplified vector model





Dark-fermion model

Z' couples to heavier dark-sector fermion χ_2 and DM χ_1

Dark-Higgs model

Z' radiates dark-sector Higgs ($h_D \to \chi\chi$)

CMS: similar strategy, but targets mono-jet/V together

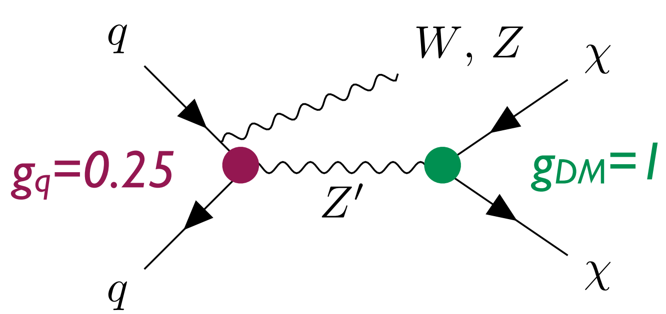
✱ First result for DM production in association with a new vector boson Z'

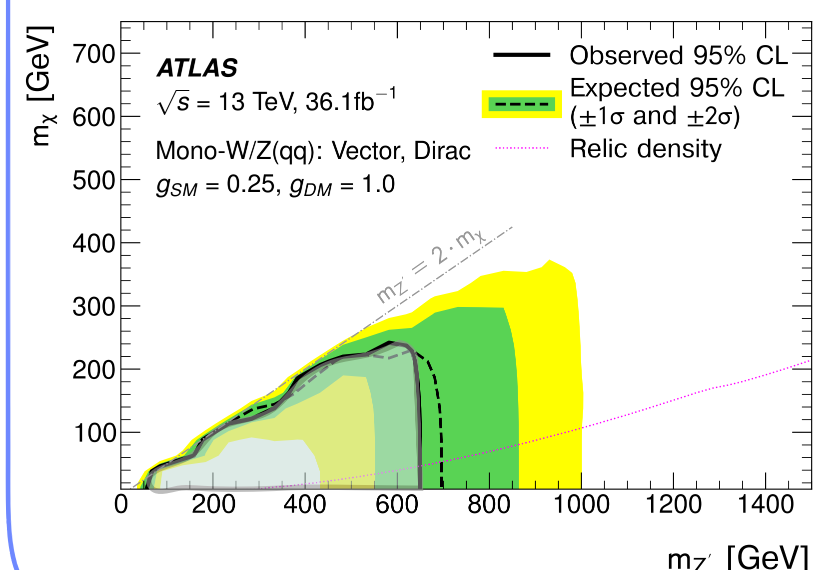
DM+V/Z' search

ATLAS: JHEP10(2018)180

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

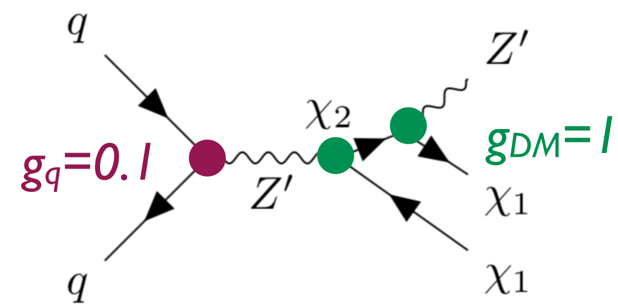
Simplified vector model

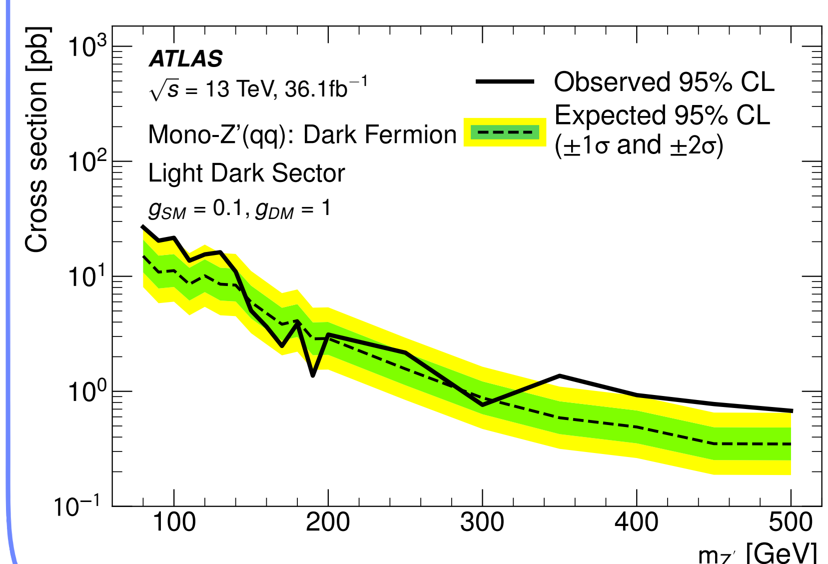




Dark-fermion model

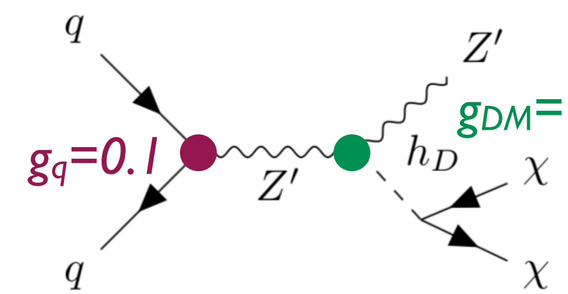
Z' couples to heavier dark-sector fermion χ_2 and DM χ_1

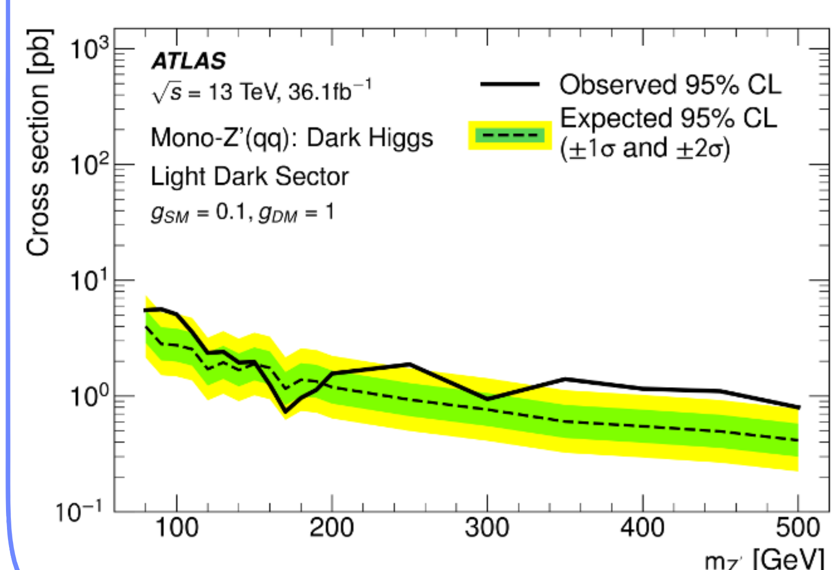




Dark-Higgs model

Z' radiates dark-sector Higgs ($h_D \to \chi\chi$)



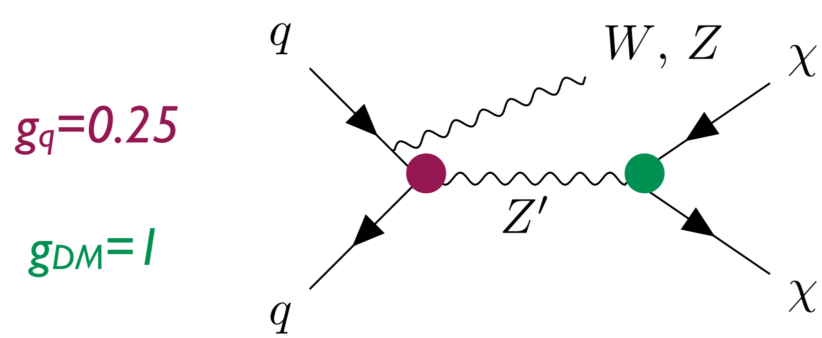


CMS: similar strategy, but targets mono-jet/V together

✱ First result for DM production in association with a new vector boson Z'

Spin-1 interactions

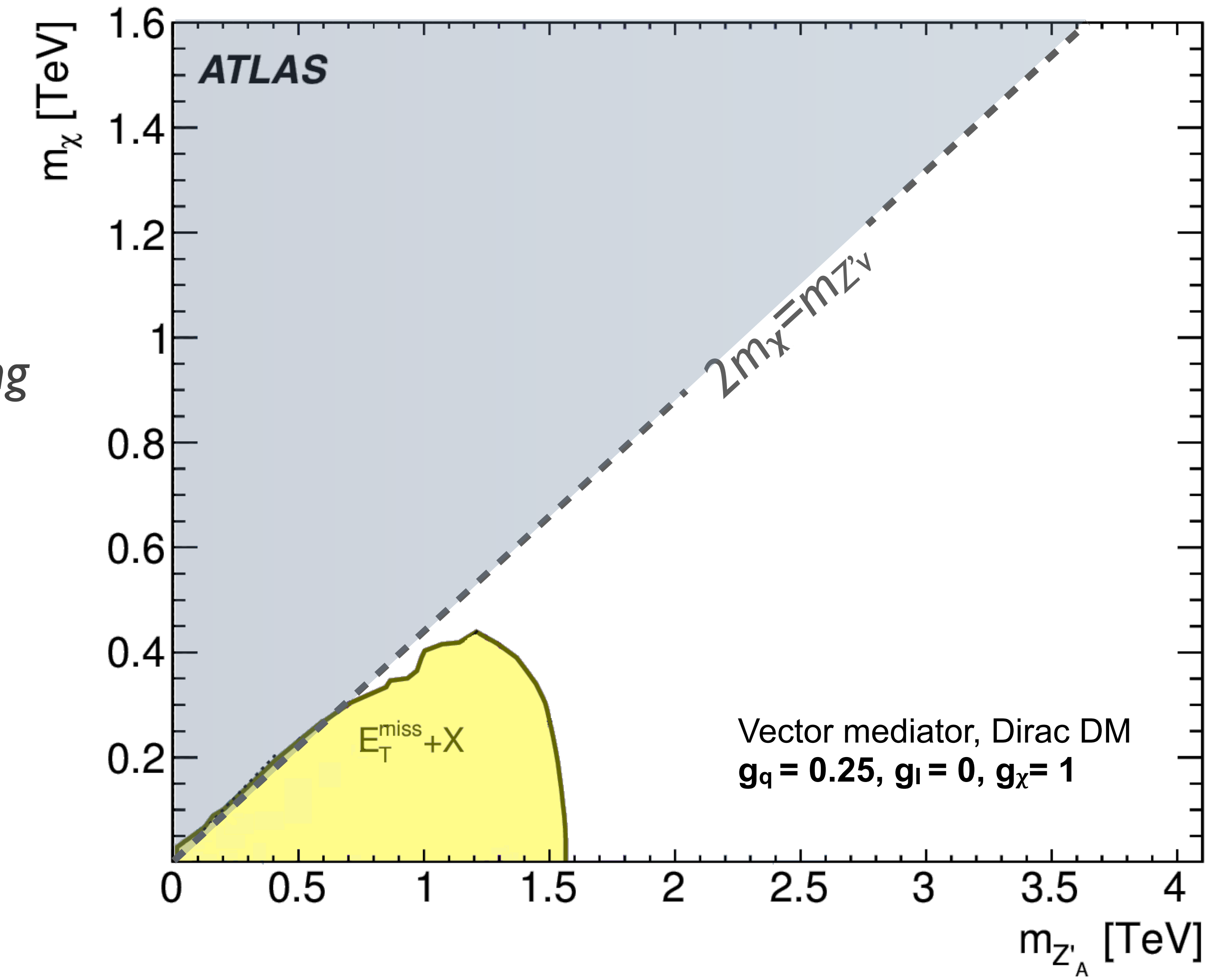
Simplified vector model



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

* *Can we recover the sensitivity?*

* *ATLAS: JHEP05(2019)142(2015+2016)*

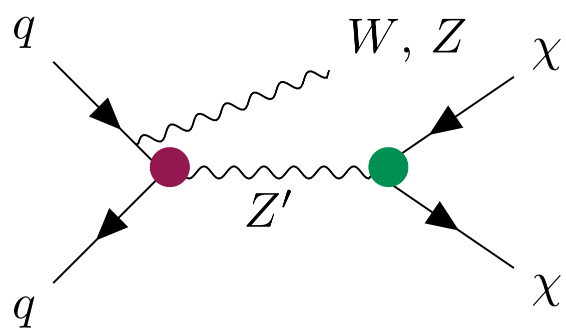


Spin-1 interactions: "the invisible through the visible"

Simplified vector model

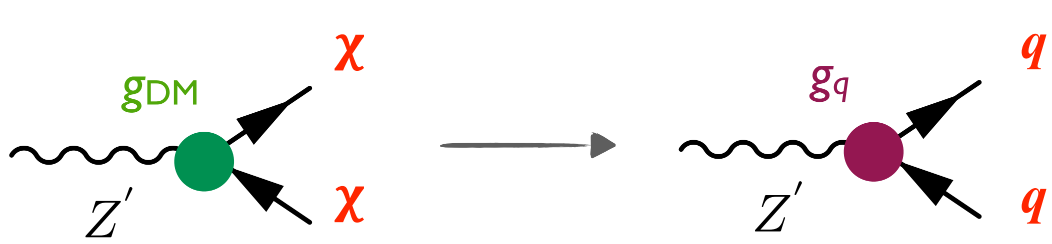
g_q=0.25

g_{DM}=1



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

✱ *Can we recover the sensitivity? visible decays*



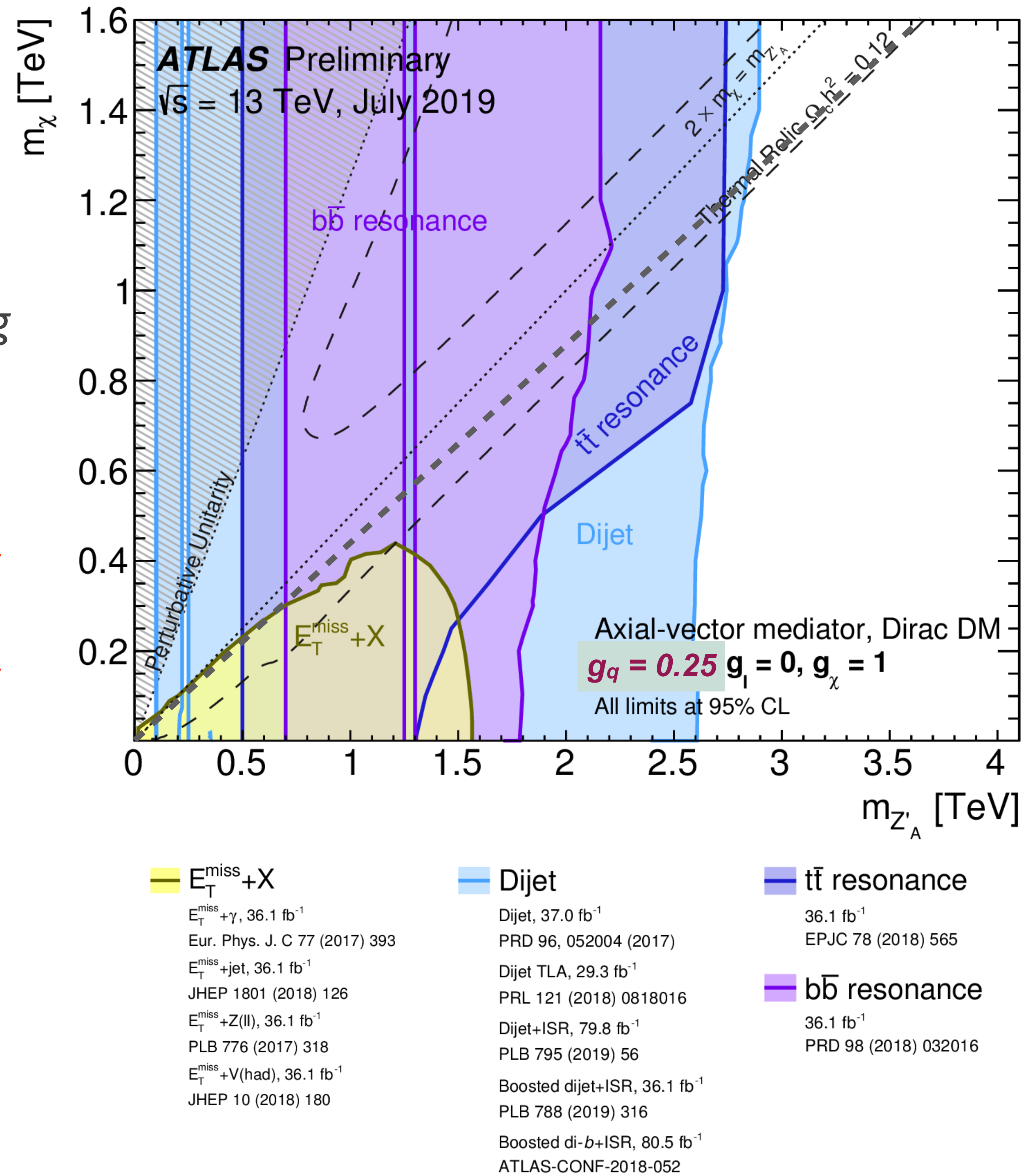
g_q=

▷ *mediator*

- *narrow resonance*
- *wide resonance*

▷ *interplay changes*

✱ *ATLAS: JHEP05(2019)142 (2015+2016)*

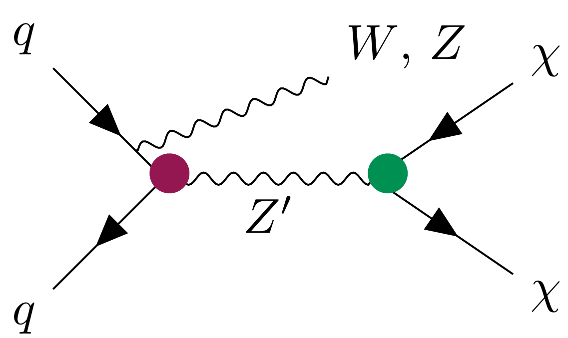


Spin-1 interactions: "the invisible through the visible"

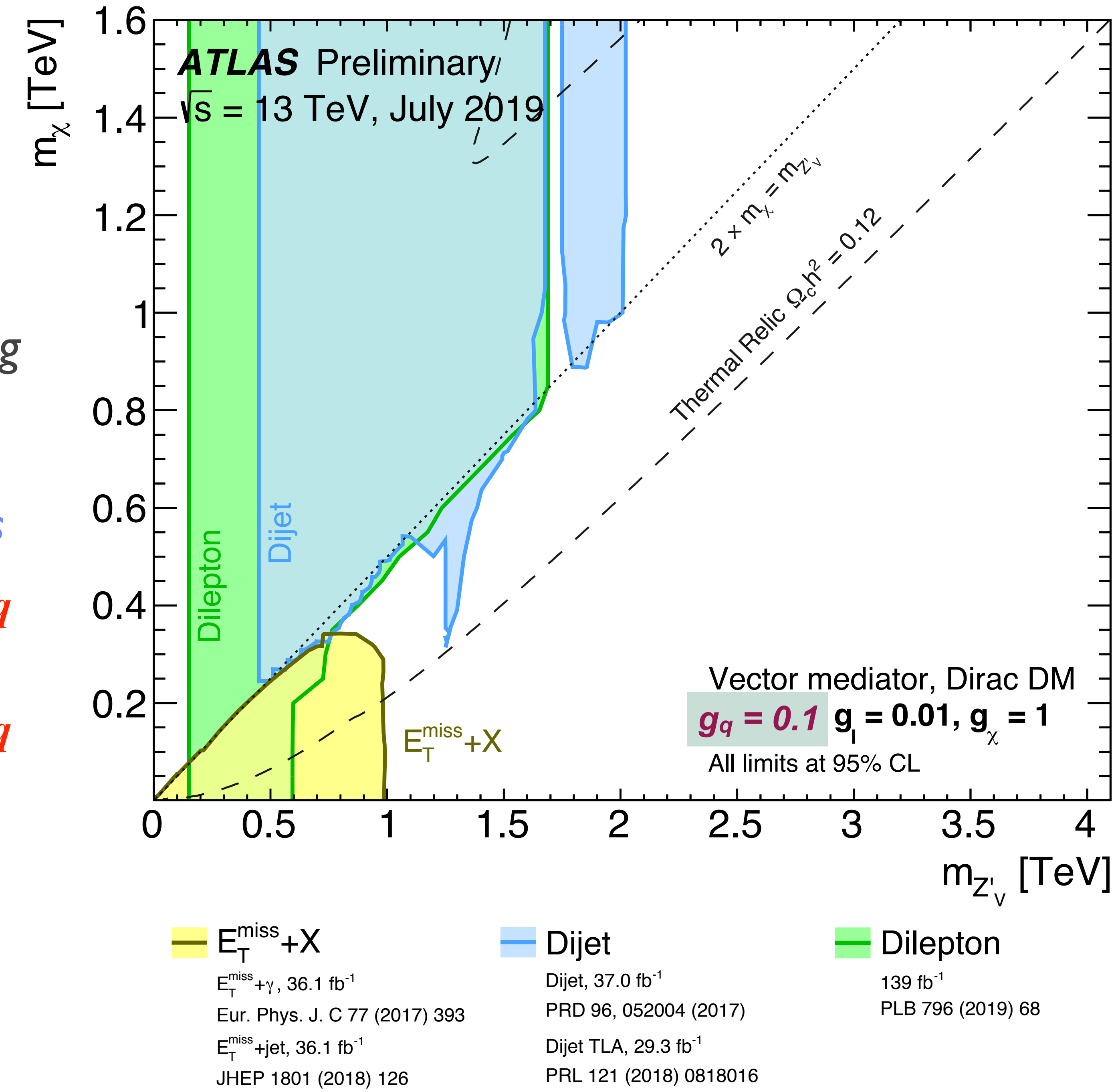
Simplified vector model

g_q=0.25

g_{DM}=1

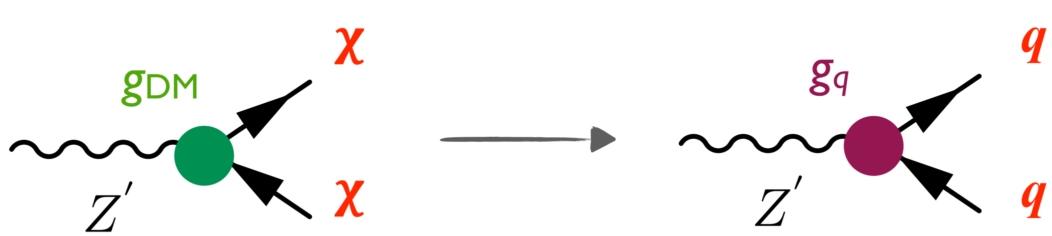


✱ ATLAS: JHEP05(2019)142(2015+2016)



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

✱ *Can we recover the sensitivity? visible decays*



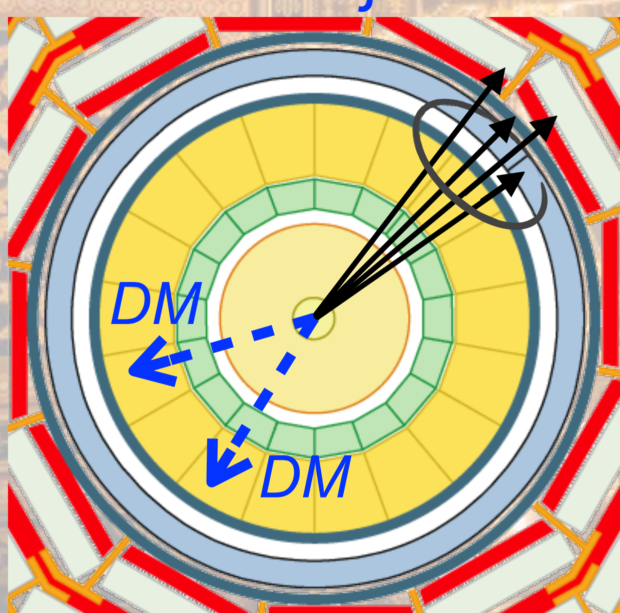
g_q=

- *mediator*
  - *narrow resonance*
  - *wide resonance*
- *interplay changes*

Can we infer more on new physics from this signature?

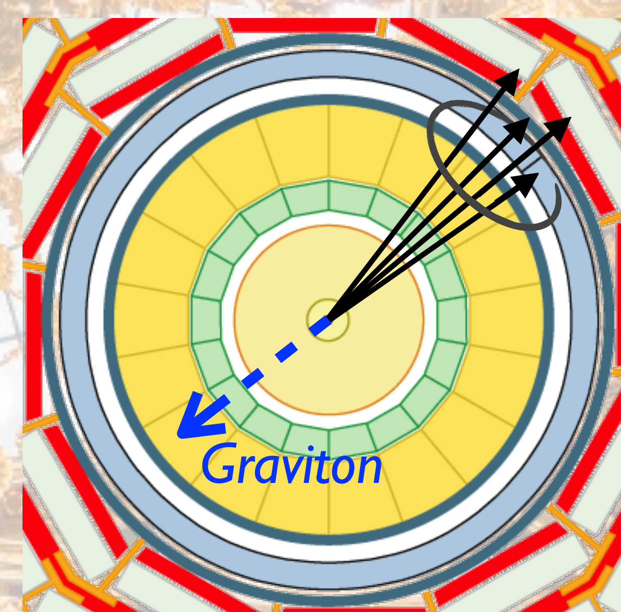
Signature: large MET and ≥1 high-p_T jet

mono-jet



- *ATLAS: JHEP01(2018)126 (2015+2016)*
- *CMS: PRD97,092005(2018) (2016)*

extra-dimension

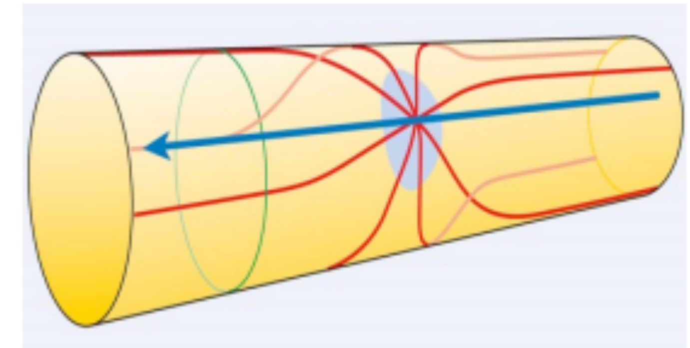


- *ATLAS: JHEP01(2018)126 (2015+2016)*
- *CMS: PRD97,092005(2018) (2016)*

✱ *selected most recent results*

Extra-dimensions: possible explanation to hierarchy problem

- *ADD model*
  - *n additional ED* compactified on a torus of radius R
    - SM particles and interactions confined to the 3+1 dim
    - gravity diluted in 4+n dim
  - *increased phase space available in EDs enhance gravitons (G) production*
  - ✱ *G produced in pp collisions escape undetected into EDs* *mono-jet signature*



$$M_D^{n+2} = \overline{M}_{Pl}^2 / R_C^n$$

M_D: fundamental Planck scale
M_{Pl}: apparent 4-dim Planck scale

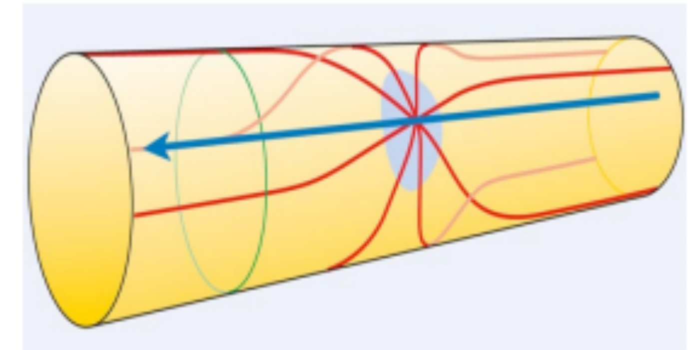
- *DM+jets interpretation in terms of ADD ED model: lower limits at 95% CL on M_D as a function of n*

ATLAS *M_D < 7.7 (4.8) TeV for n=2(6) excluded (obs.)*

CMS *M_D < 9.9 (5.3) TeV for n=2(6) excluded (obs.)*

Extra-dimensions: possible explanation to hierarchy problem

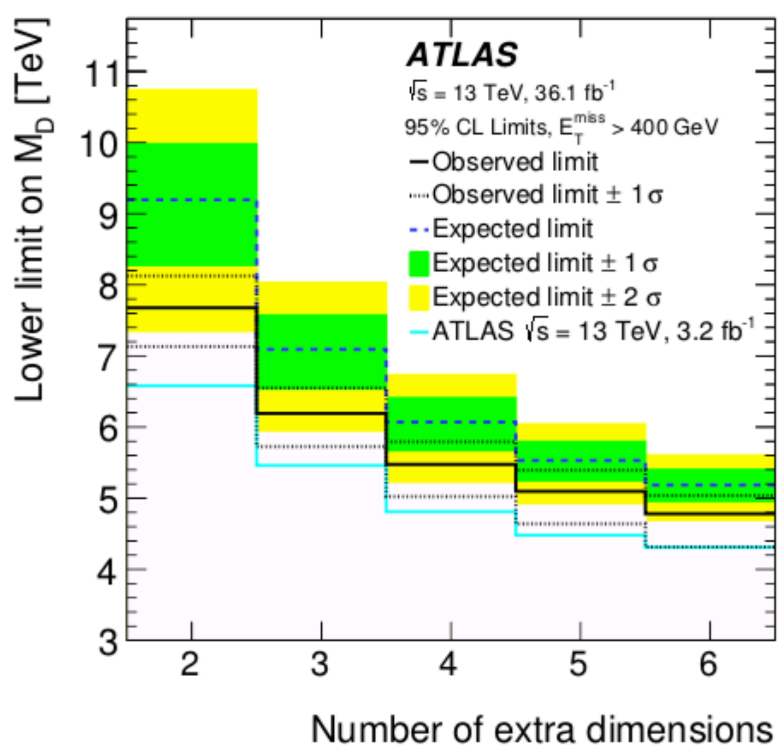
- *ADD model*
  - *n additional ED* compactified on a torus of radius R
    - SM particles and interactions confined to the 3+1 dim
    - gravity diluted in 4+n dim
  - *increased phase space available in EDs enhance gravitons (G) production*
  - ✱ *G produced in pp collisions escape undetected into EDs* **mono-jet signature**

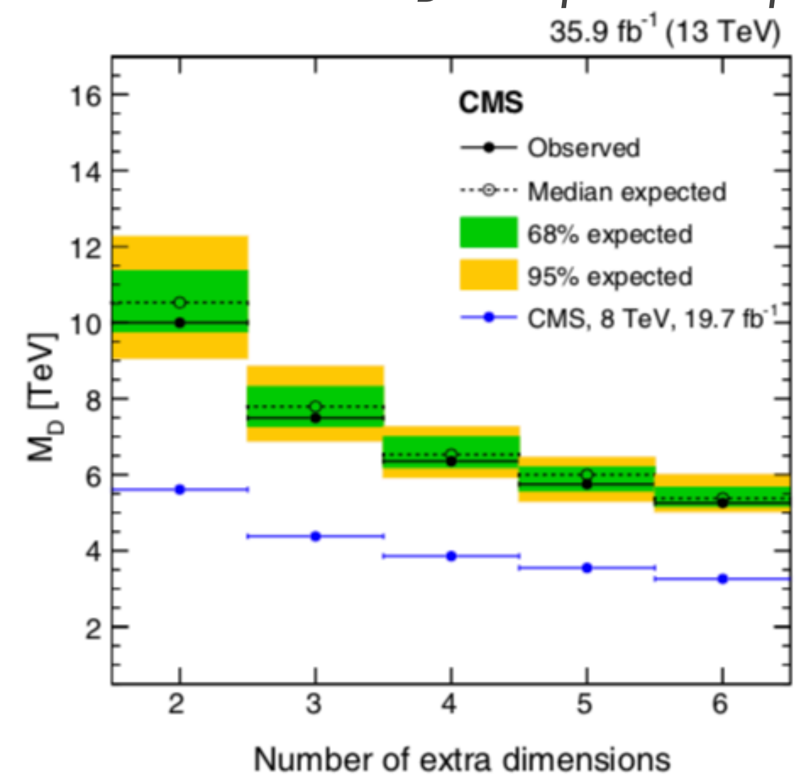


$$M_D^{n+2} = \overline{M}_{Pl}^2 / R_C^n$$

M_D: fundamental Planck scale
M_{Pl}: apparent 4-dim Planck scale

- *DM+jets interpretation in terms of ADD ED model:* *lower limits at 95% CL on M_D as a function of n*



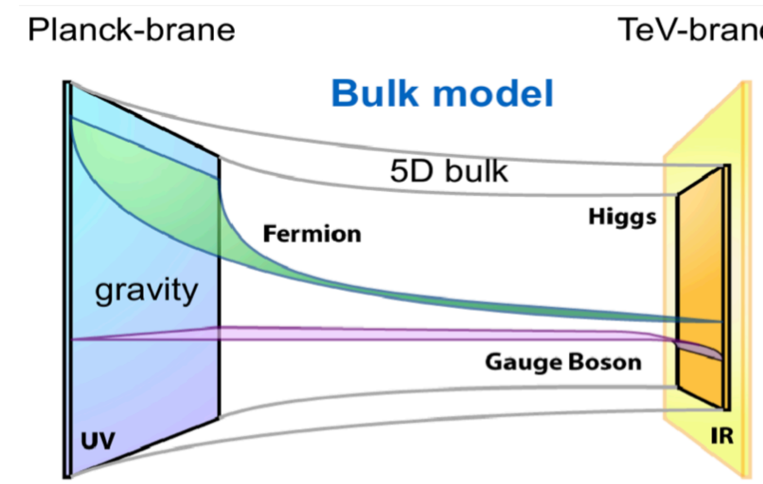


ATLAS: *M_D < 7.7 (4.8) TeV for n=2(6) excluded*

CMS: *M_D < 9.9 (5.3) TeV for n=2(6) excluded*

Extra-dimensions: possible explanation to hierarchy problem

- *Warped extra dimension model*
  - *one single compact extra dimension*
    - in which both gravity and all SM fields propagate
    - gravity exponentially suppressed from Planck to TeV brane
  - *massive spin-2 resonance*, first Kaluza–Klein excitation of graviton (G)
    - strength of the coupling depends on $\check{k}=k/M_{Pl}$ (k curvature of ED)
    - production through quark-antiquark annihilation and gluon-gluon fusion, *decay to WW, ZZ, HH* *visible signature*



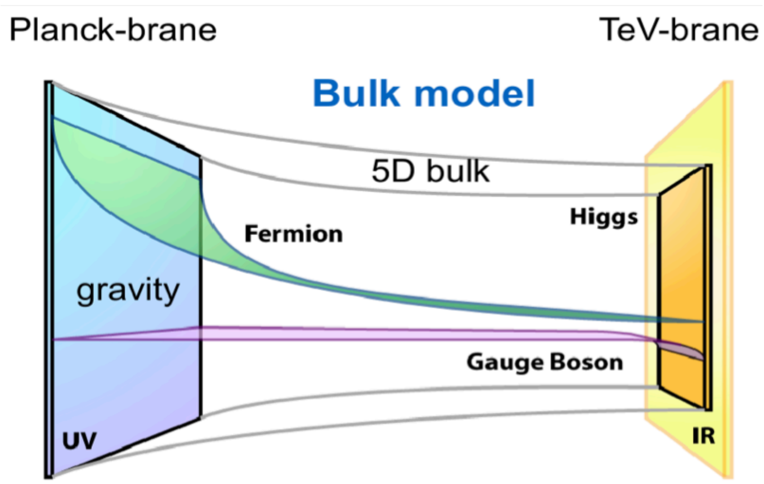
- *Plethora of final states considered based on VV decay: upper limits at 95% CL on prod. xsec as a function of m_G*

ATLAS $m_G < 2.3$ TeV, for $\check{k}=0.5$

CMS $m_G < 850$ GeV, for $\check{k}=0.5$

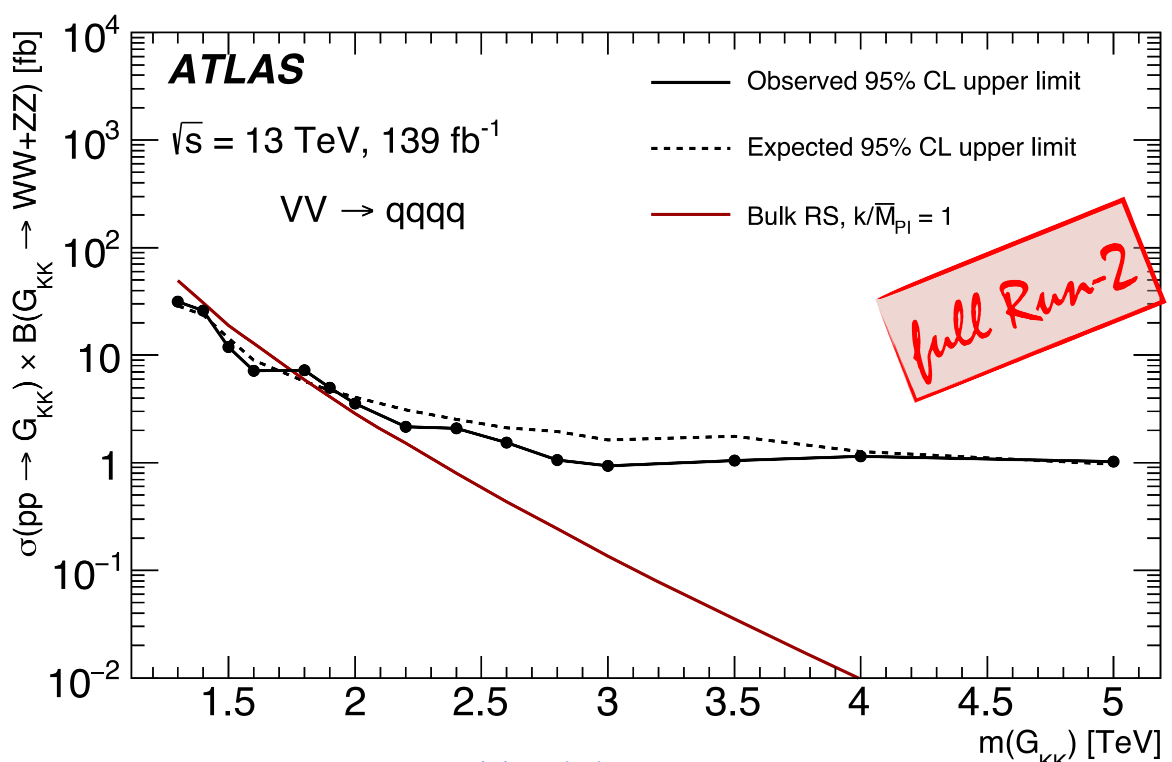
Extra-dimensions: possible explanation to hierarchy problem

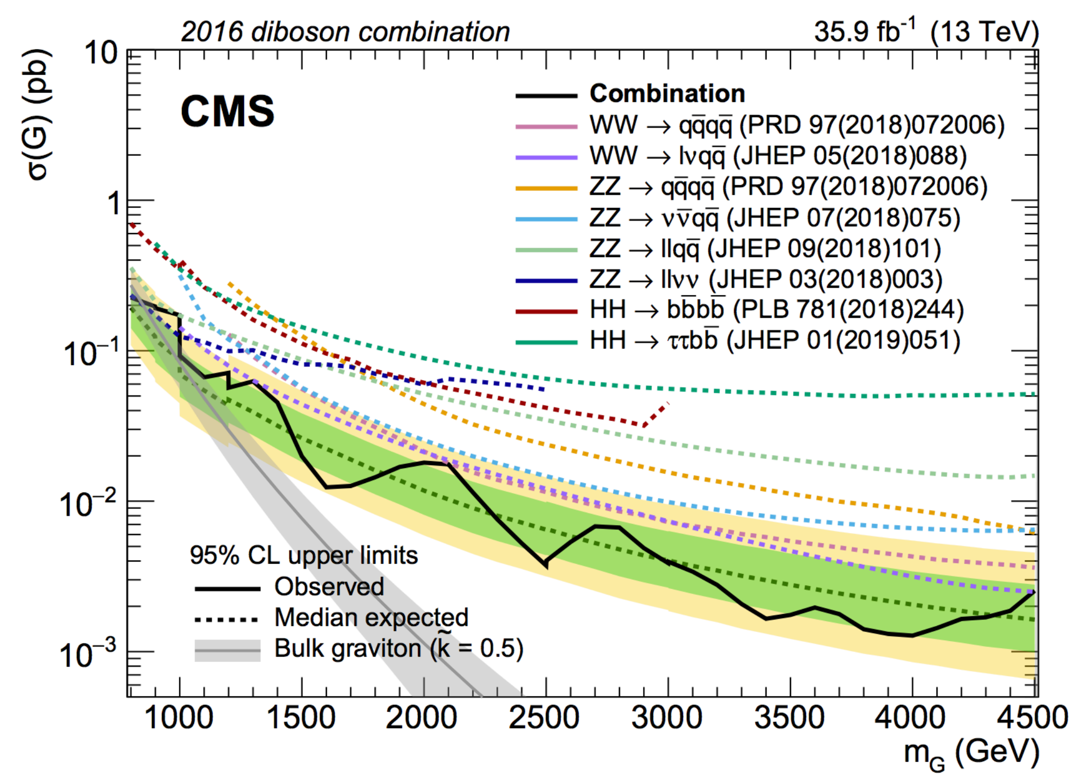
- *Warped extra dimension model*
  - *one single compact extra dimension*
    - in which both gravity and all SM fields propagate
    - gravity exponentially suppressed from Planck to TeV brane
  - *massive spin-2 resonance*, first Kaluza–Klein excitation of graviton (G)
    - strength of the coupling depends on $\check{k}=k/M_{Pl}$ (k curvature of ED)
    - production through quark-antiquark annihilation and gluon-gluon fusion, *decay to WW, ZZ, HH* *visible signature*



- CMS: arXiv:1906.00057
- ATLAS: arXiv:1906.08589

- *Plethora of final states considered based on VV decay: upper limits at 95% CL on prod. xsec as a function of m_G*





ATLAS: VV= WW, ZZ; $m_G < 1.8$ TeV, for $\check{k}=1.0$

CMS: VV= WW, ZZ, HH; $m_G < 850$ GeV, for $\check{k}=0.5$

Reminder:

scalar | pseudoscalar

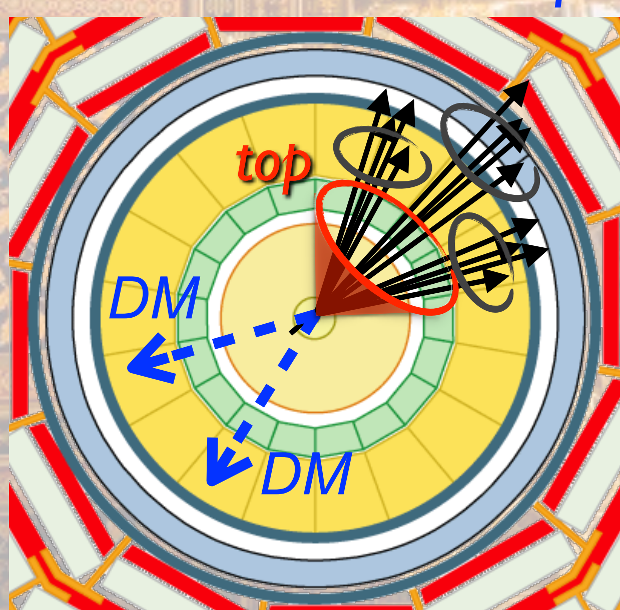
$$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f \quad \Big| \quad g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f} \gamma^5 f$$

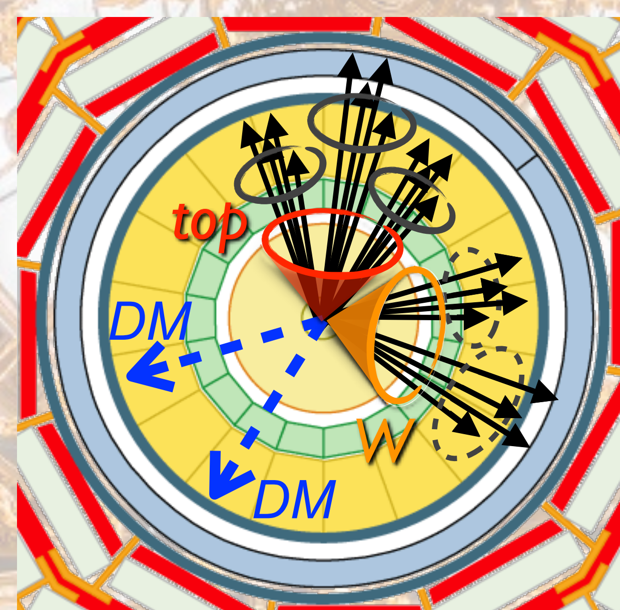
✻ choose X to exploit coupling ∝ to quark mass (or increase xsec)

Spin-0 mediator: simplified models

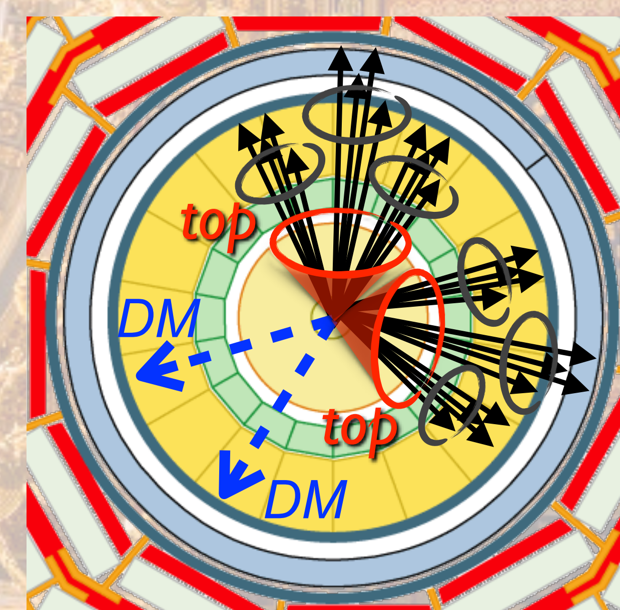
Signature: large MET and 1(2) top quarks

DM+top: t/tW-channel





DM+tt



- ✻ CMS: JHEP03(2019)141, (2016)
- ✻ ATLAS: JHEP05(2019)41 (2005+2016) [top+DM, different mediators: +2/3 charged, colored spin-0, or spin-1 with FCNC interactions]

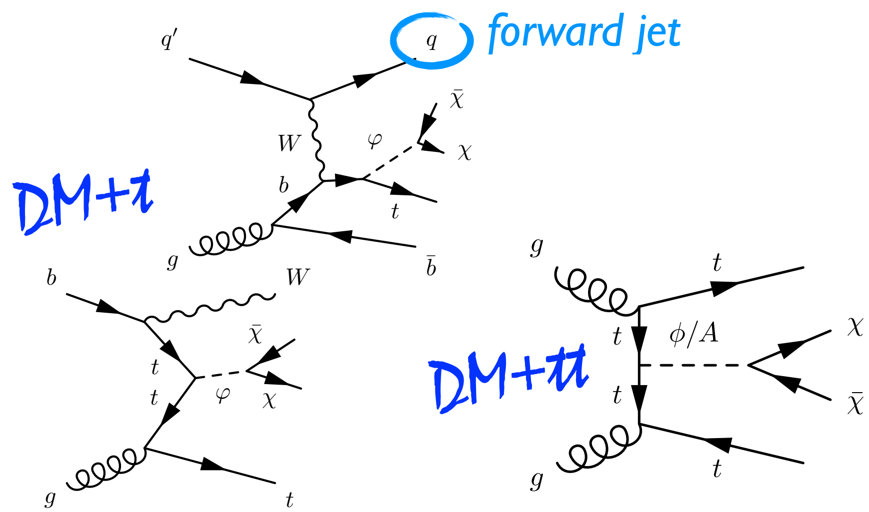
- ✻ CMS: PRL122,011803(2019) (2016)
- ✻ ATLAS: 0ℓ/2ℓ EPJC78(2018)18 1ℓ JHEP06(2018)108, (2015+2016)

✻ selected most recent results

DM+t(tt) search

CMS: JHEP03(2019)141

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



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)

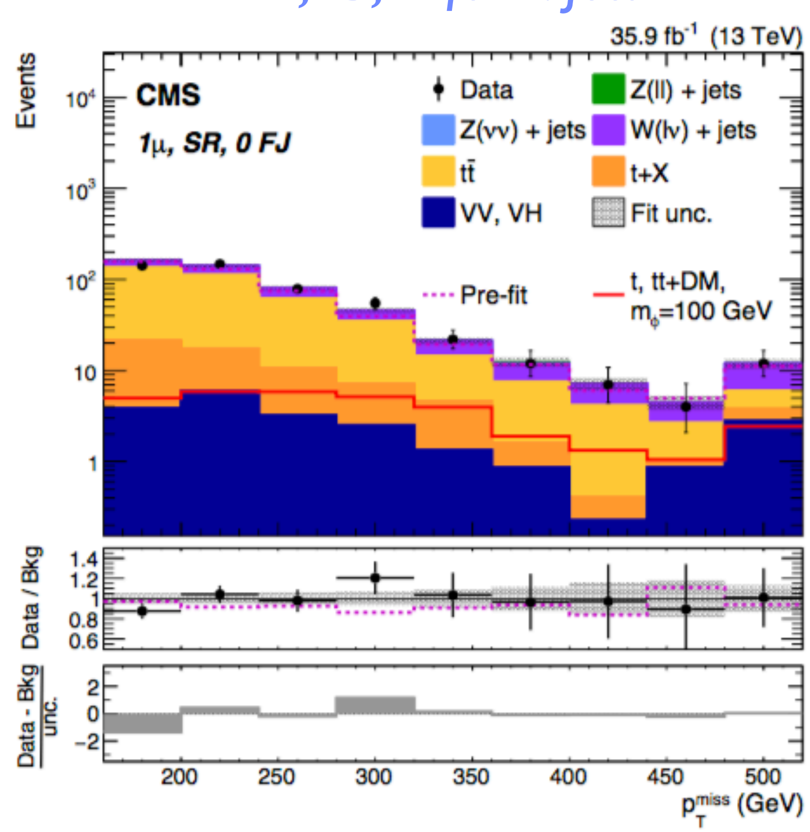
1ℓ
- 1 lepton: isolated e,μ
- ≥ 2 jets (j small-cone)
- =1, ≥ 2 b-tagged jets
- MET > 160 GeV

+0 or ≥1 forward jets (|η|>2.4)

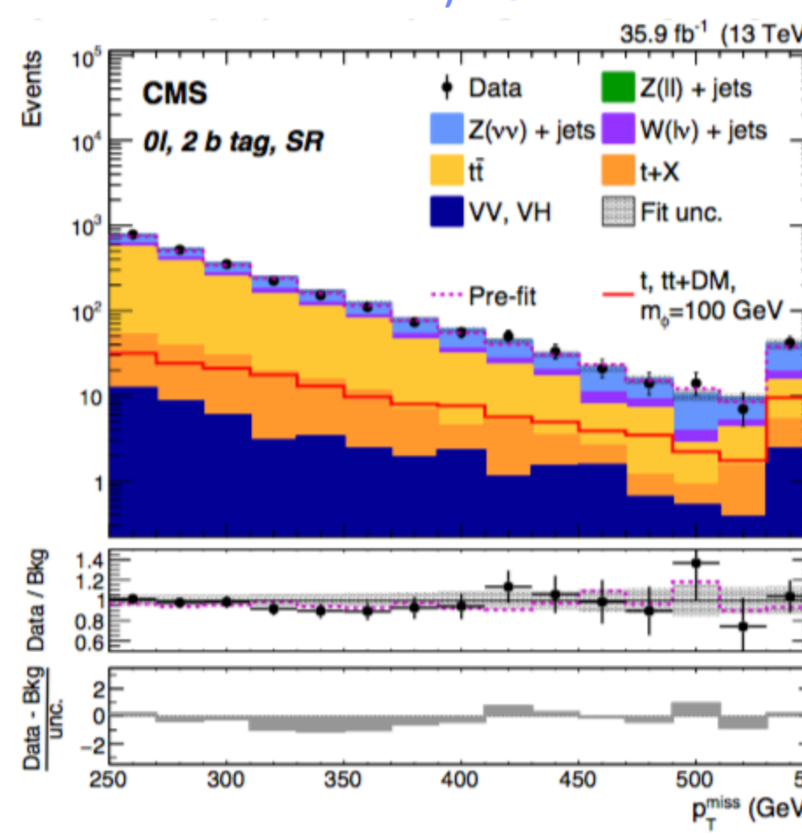
- **2- Bkg:**
  - **tt, V+jets** main bkg, from CRs

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

1ℓ,1b, 0 forw. jets



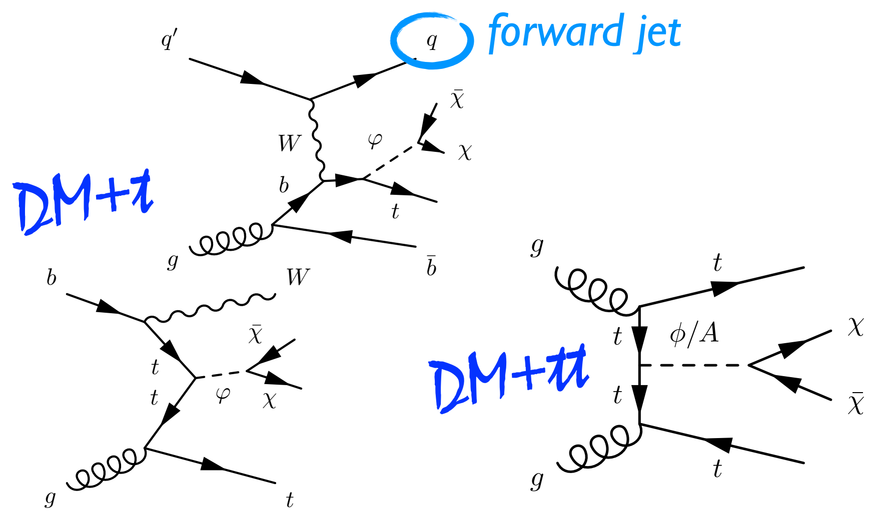
0ℓ, 2b



DM+t(tt) search

CMS: JHEP03(2019)141

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



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

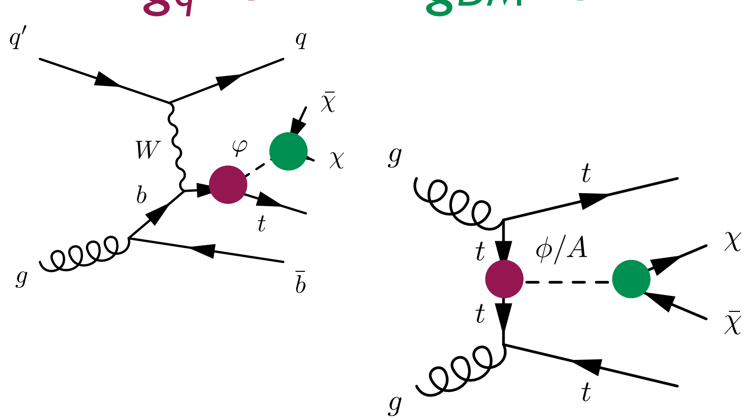
- 1 lepton: isolated e,μ
- ≥ 2 jets (j small-cone)
- =1, ≥ 2 b-tagged jets
- MET > 160 GeV

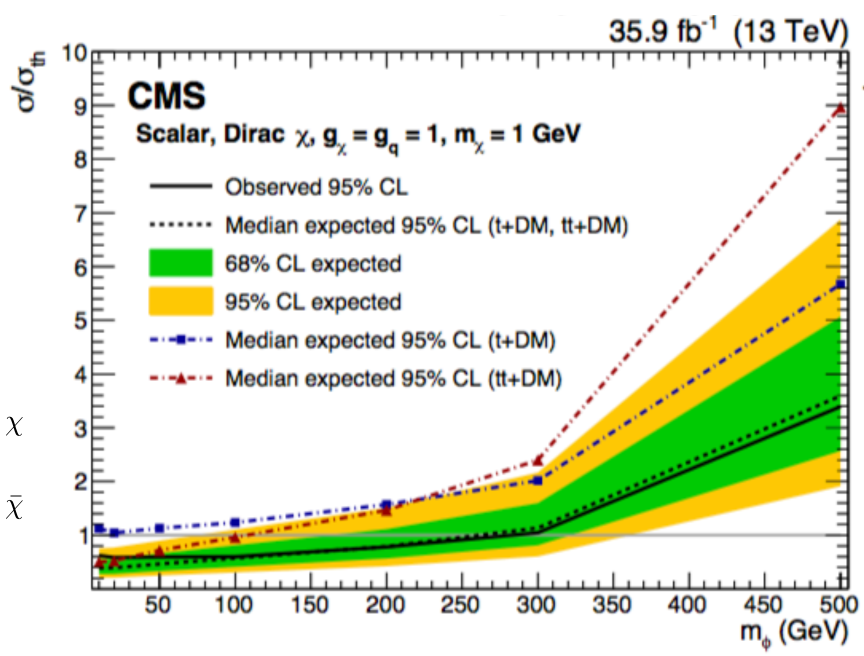
+0 or ≥ 1 forward jets (|η|>2.4)

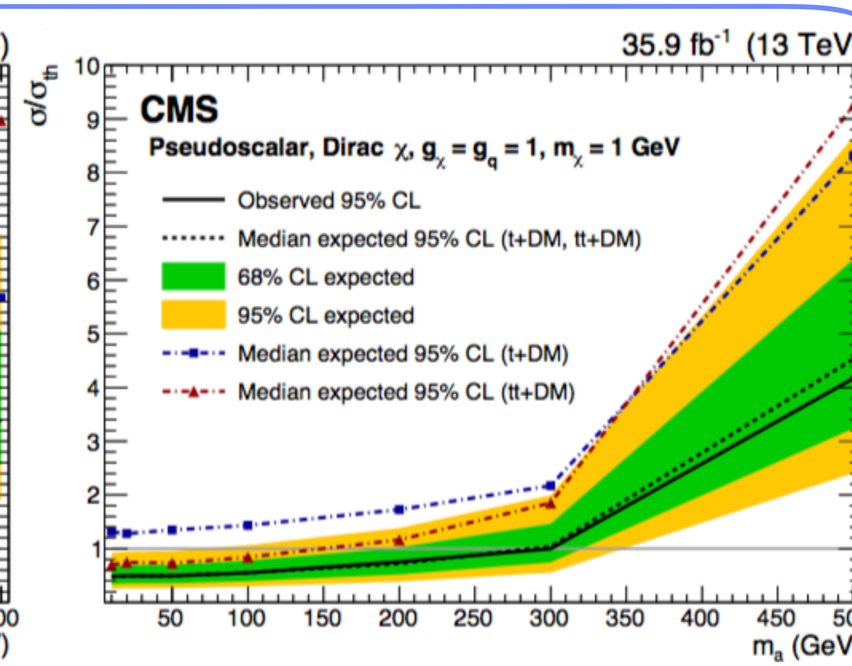
▷ *3- Results: interpretation in terms of DM model with Dirac DM upper limits at 95% CL on xsec*

scalar/pseudoscalar interaction

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







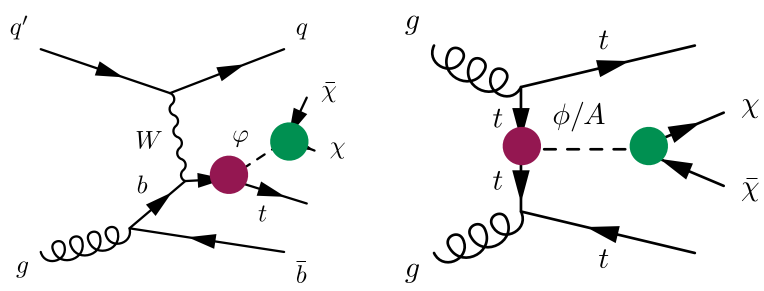
- **First search** *at LHC for DM+t or DM+tt in scalar/pseudoscalar interactions*
- *up to x2 limits improvement at high mediator masses wrt previous DM+tt results*

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

Simplified scalar/pseudoscalar model

$g_q = 1$

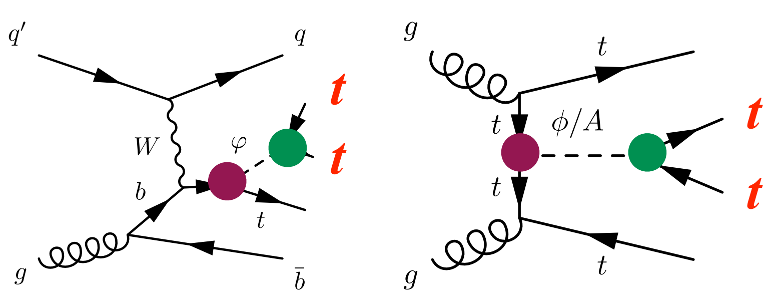
$g_{DM} = 1$



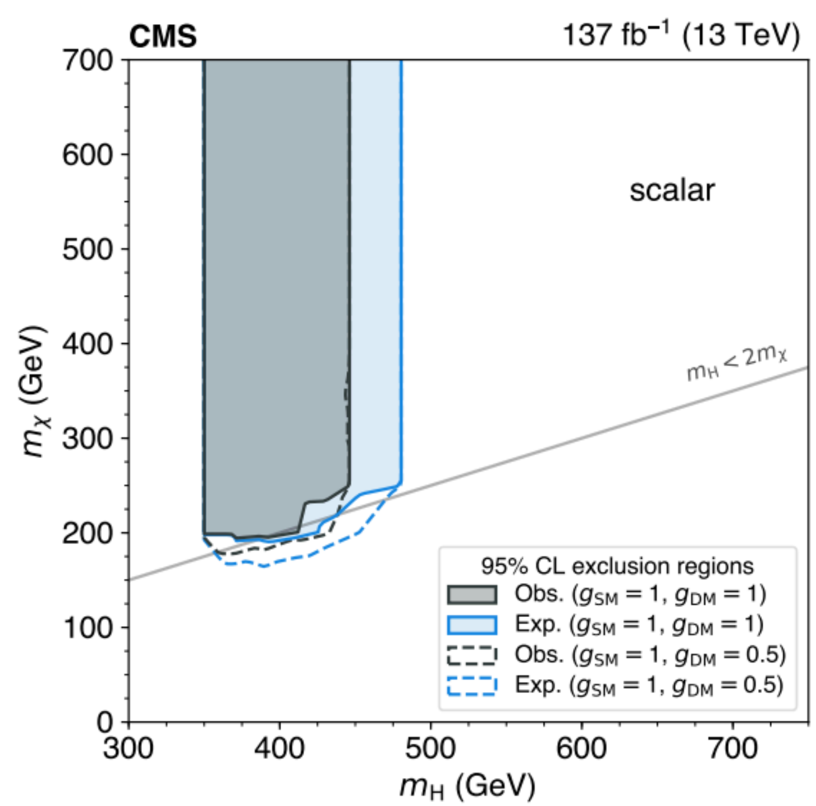
- *low sensitivity to off-shell region due to strong reduction of production cross-section*

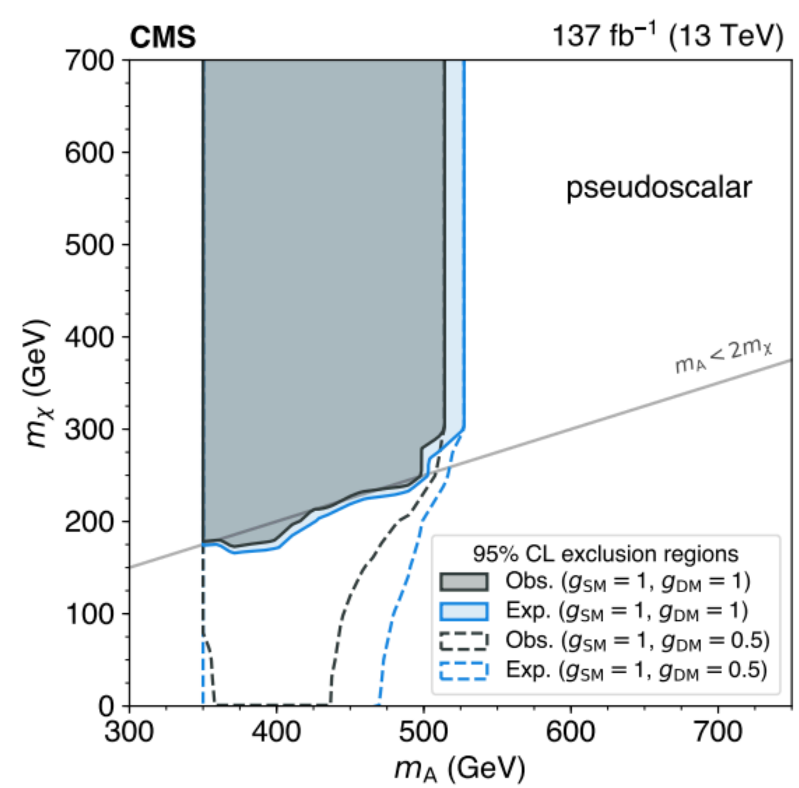
- *Can we recover the sensitivity? visible decay*

CMS: arXiv1908.06463



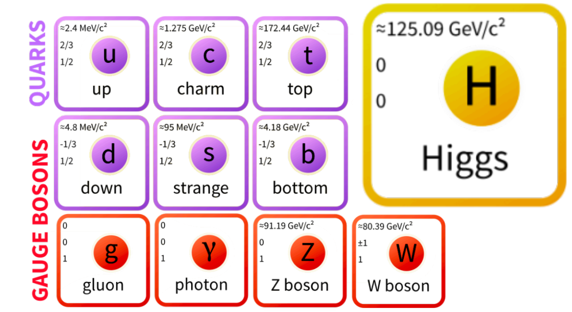
- *Selection:*
  2 same-sign leptons or at least three leptons, and jets
- $m_{MED} > 2\ m_t$





Higgs boson discovery

χ =

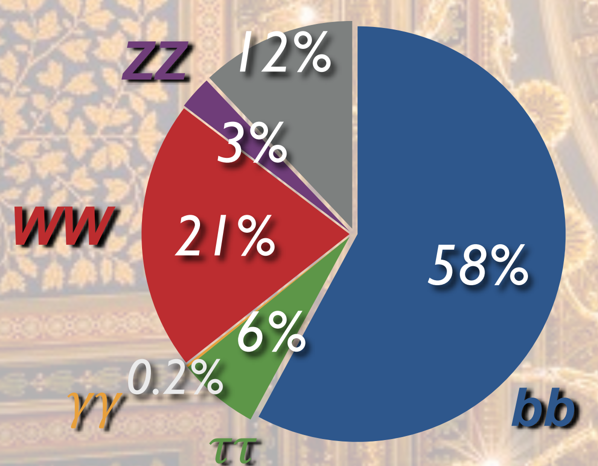


- mono-Higgs directly probe hard interaction (ISR Yukawa-suppressed)

Higgs boson:
extended sectors and invisible decays

Signature: large MET and one Higgs boson candidate

- *Various decay modes considered, H →*

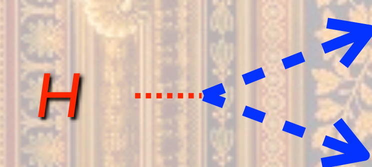


- CMS(ττ,γγ): JHEP 09 (2018) 046 (2016)
- ATLAS (γγ): PRD96(2017)112004 (2015+2016)
- CMS(WW,ZZ): arXiv:1908.01713, (2016)

mono-H(bb)

- ATLAS: CONF-2018-039 (2015+2016+ 2017)
- ATLAS: JHEP05(2019)142 (2015+2016)
- CMS:EPJC79(2019)280, (2016)
- CMS:JHEP11(2018)172, (2016)

H invisible decays



- ATLAS: PLB793(2019)499
- ATLAS: PLB793(2019)499
- CMS: PLB793(2019)520

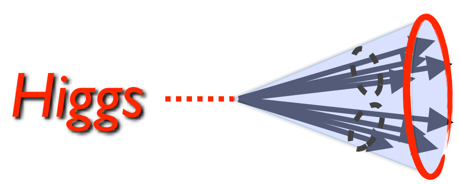
* selected most recent results

mono-Higgs: bb decay

- ATLAS: CONF-2018-039
- ATLAS: JHEP05(2019)142
- CMS:EPJC79(2019)280
- CMS:JHEP11(2018)172

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

large boost



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

ATLAS
- similar, with *jet radius(p_T)* for b-tagging *[MET>500 GeV, 2 b-jets]*

medium boost (CMS)

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

resolved (ATLAS)

- ≥ 2 jets, $p_T(j) > 20$ GeV *(j small-cone)*
- = 2 b-tagged jets
- 3 MET regions in range [150, 500] GeV

▷ 2- Bkg:
- *V+jets, tt main bkg, normalization (shape) from CRs*

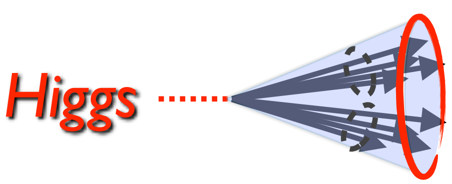
▷ 3- Results: *combined fit of SRs and CRs*
- *m_T(MET, H) for large boost (CMS)*
- *MET for medium boost*
- *m_H large boost+resolved (ATLAS)*

mono-Higgs: bb decay

- ATLAS: CONF-2018-039
- ATLAS: JHEP05(2019)142
- CMS:EPJC79(2019)280
- CMS:JHEP11(2018)172

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

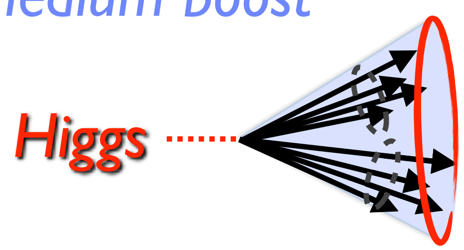
large boost



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

ATLAS
- similar, with *jet radius(p_T)* for b-tagging *[MET>500 GeV, 2 b-jets]*

medium boost CMS



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

resolved ATLAS

- ≥ 2 jets, p_T (j) > 20 GeV *(j small-cone)*
- = 2 b-tagged jets
- 3 MET regions in range [150, 500] GeV

▷ 2- Bkg:

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

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

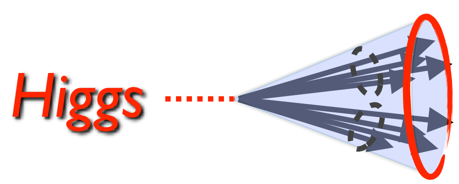
- *m_T(MET, H) for large boost (CMS)*
- *MET for medium boost*
- *m_H large boost+resolved (ATLAS)*

mono-Higgs: bb decay

ATLAS: CONF-2018-039
ATLAS: JHEP05(2019)142
CMS:EPJC79(2019)280
CMS:JHEP11(2018)172

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

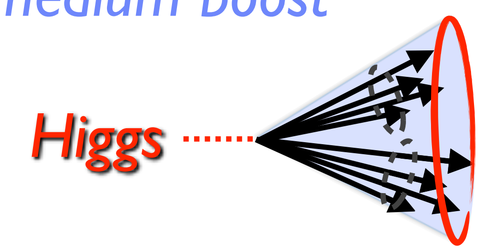
large boost



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

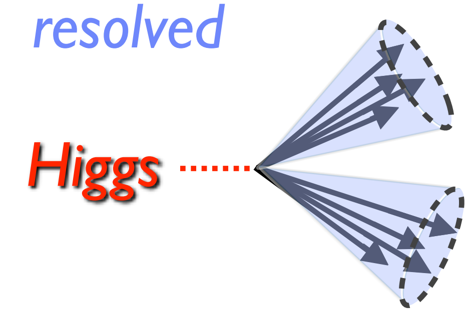
ATLAS
- similar, with *jet radius(p_T)* for b-tagging *[MET>500 GeV, 2 b-jets]*

medium boost CMS



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

resolved ATLAS



- ≥ 2 jets, p_T (j) > 20 GeV *(j small-cone)*
- = 2 b-tagged jets
- 3 MET regions in range [150, 500] GeV

▶ *2- Bkg:*

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

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

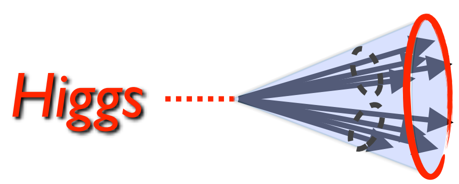
- m_T(MET, H) for large boost (CMS)
- MET for medium boost
- m_H large boost+resolved (ATLAS)

mono-Higgs: bb decay

ATLAS: CONF-2018-039
ATLAS: JHEP05(2019)142
CMS:EPJC79(2019)280
CMS:JHEP11(2018)172

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

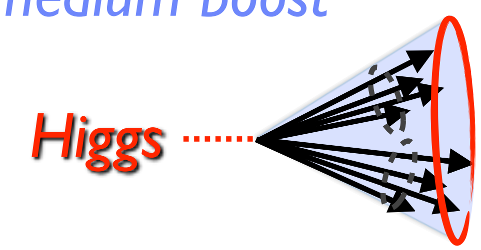
large boost



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

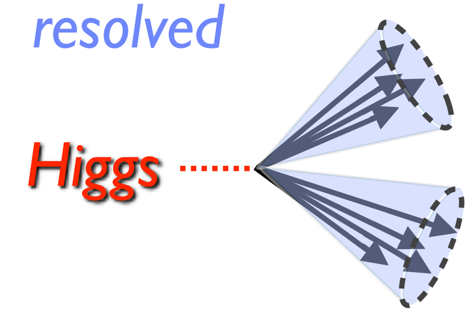
ATLAS
- similar, with *jet radius(p_T)* for b-tagging *[MET>500 GeV, 2 b-jets]*

medium boost CMS



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

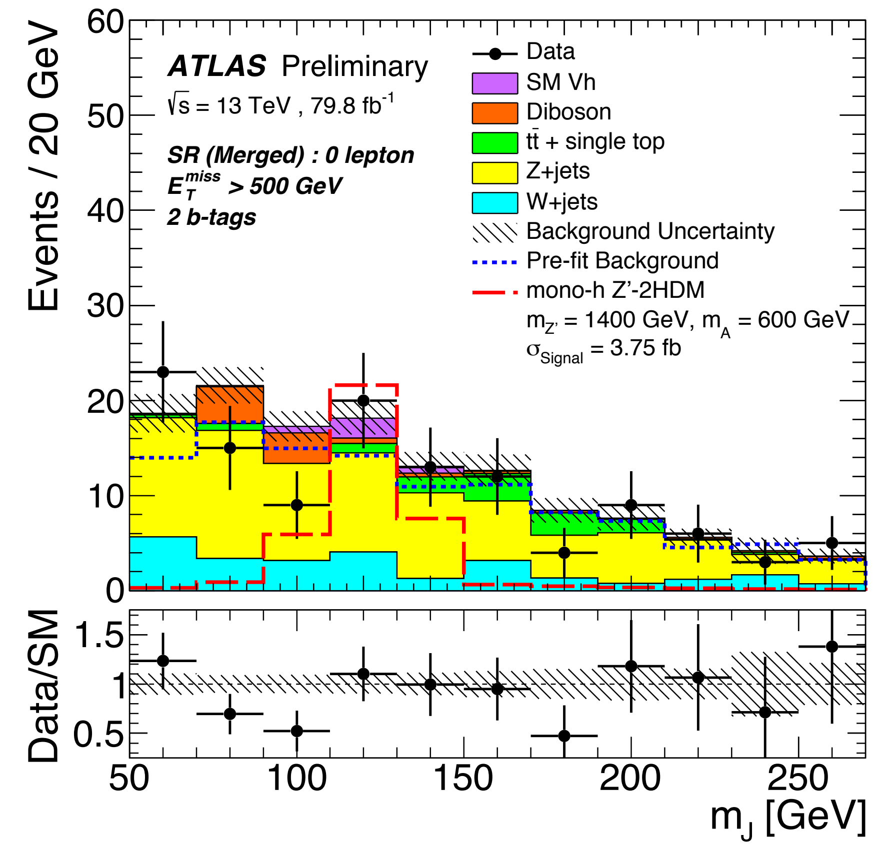
resolved ATLAS



- ≥ 2 jets, $p_T(j) > 20$ GeV *(j small-cone)*
- = 2 b-tagged jets
- 3 MET regions in range [150, 500] GeV

- 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 (CMS)*
  - *MET for medium boost*
  - *m_H in different MET ranges large boost+resolved (ATLAS)*

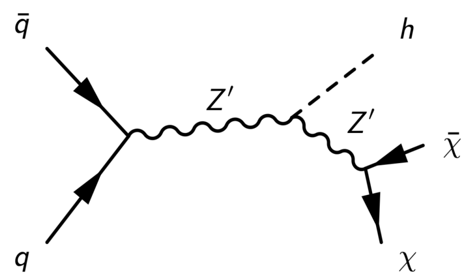


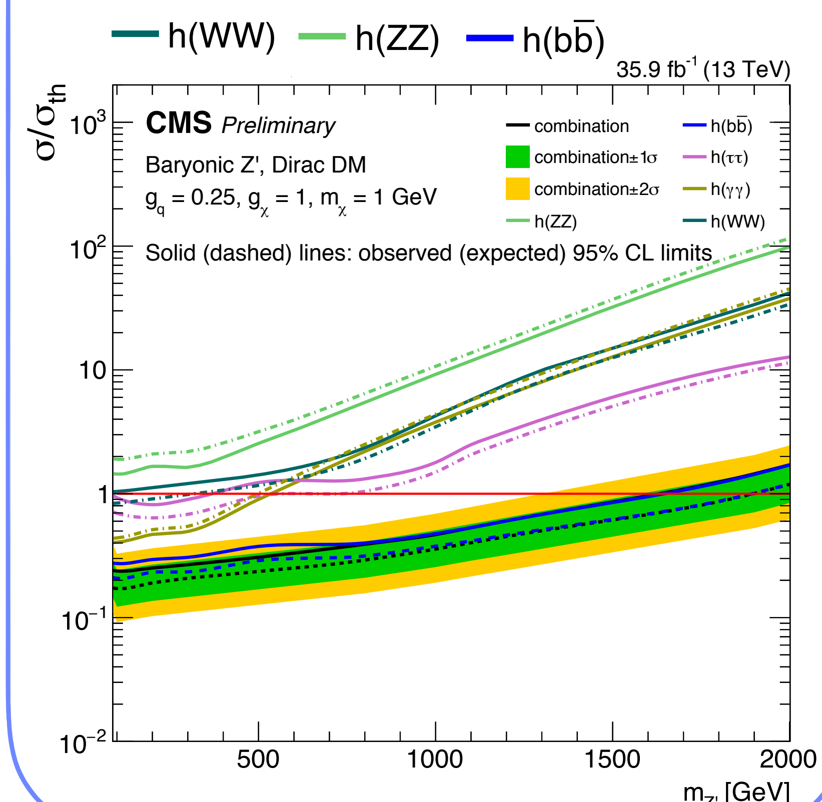
CMS: arXiv:1908.01713
ATLAS: JHEP05(2019)142
ATLAS: JHEP05(2019)142

mono-Higgs combination: rich phenomenology

- *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





CMS med. boost
ATLAS

ATLAS excl. up to 1.9 TeV, CMS up to 1.6 TeV in $m_{Z'}$

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

CMS med. boost
ATLAS

ATLAS excl. up to 2.8 TeV (79.8 fb^{-1}), CMS up 3.2 TeV (36 fb^{-1}) in $m_{Z'}$

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

CMS med. boost
ATLAS

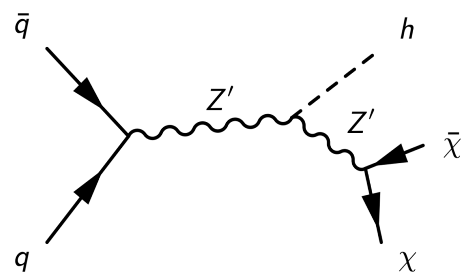
m_a=150 GeV, m_A excl. [350,1350]([500,900]) GeV for ATLAS (CMS)

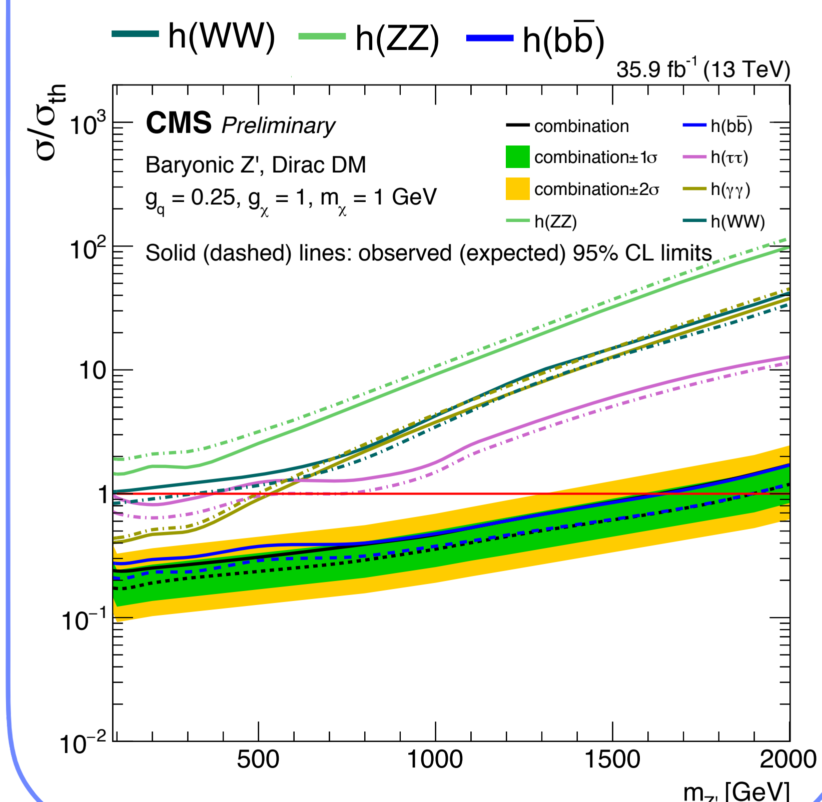
- CMS: arXiv:1908.01713
- ATLAS: JHEP05(2019)142
- ATLAS: JHEP05(2019)142

mono-Higgs combination: rich phenomenology

- *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



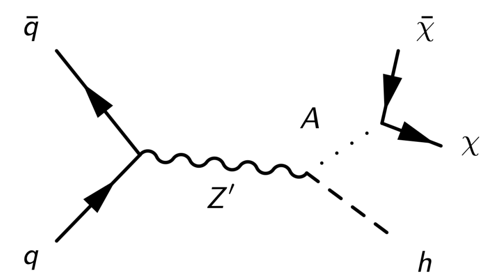


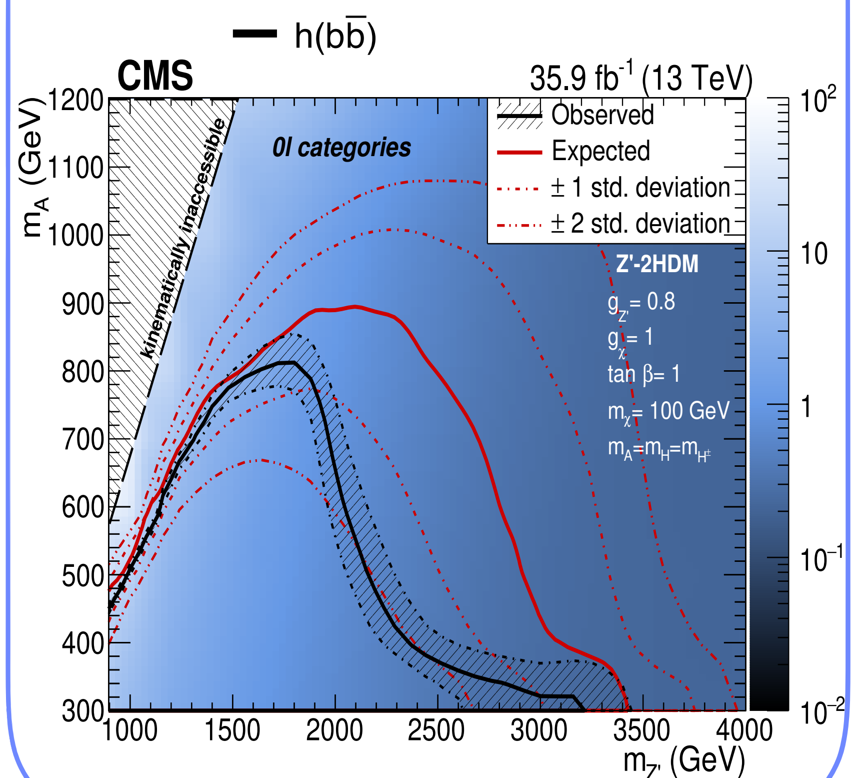
CMS med. boost

ATLAS

ATLAS excl. up to 1.9 TeV, CMS up to 1.6 TeV in $m_{Z'}$

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



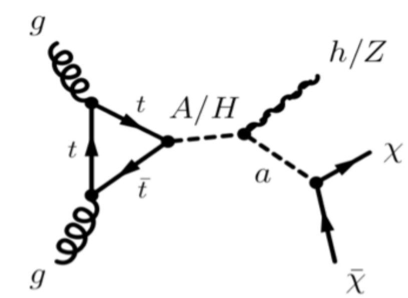


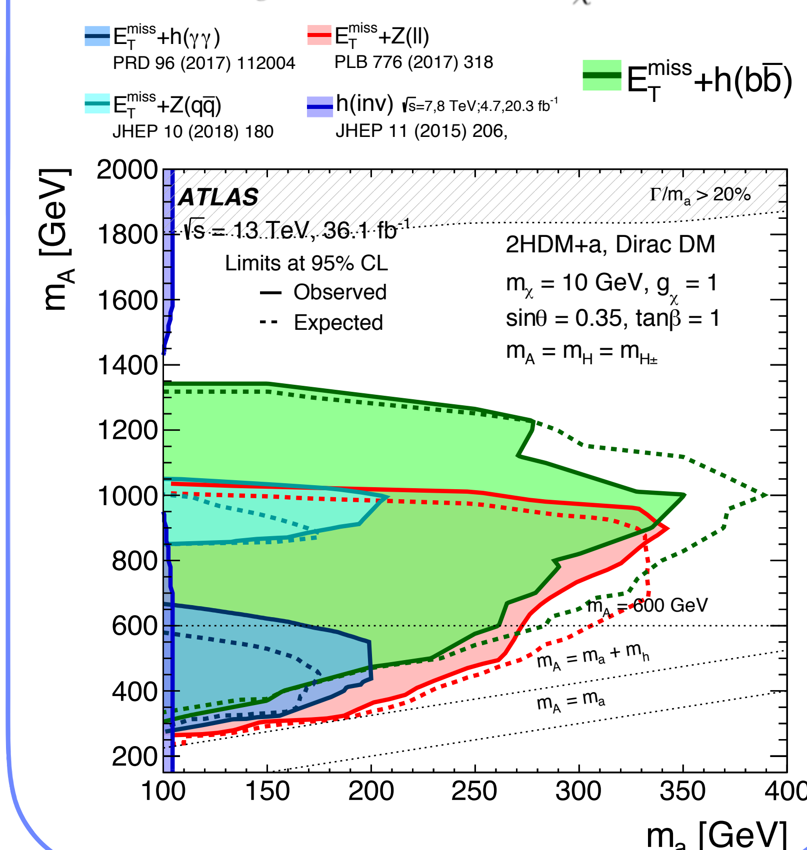
CMS med. boost

ATLAS

ATLAS excl. up to 2.8 TeV (79.8 fb⁻¹), CMS up 3.2 TeV (36 fb⁻¹) in $m_{Z'}$

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





CMS med. boost

ATLAS

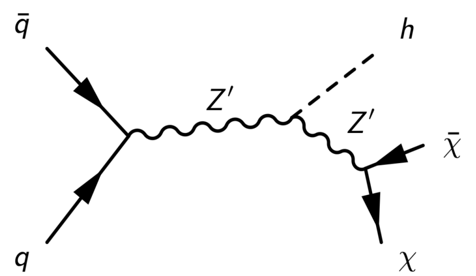
m_a=150 GeV, m_A excl. [350,1350]([500.900]) GeV for ATLAS (CMS)

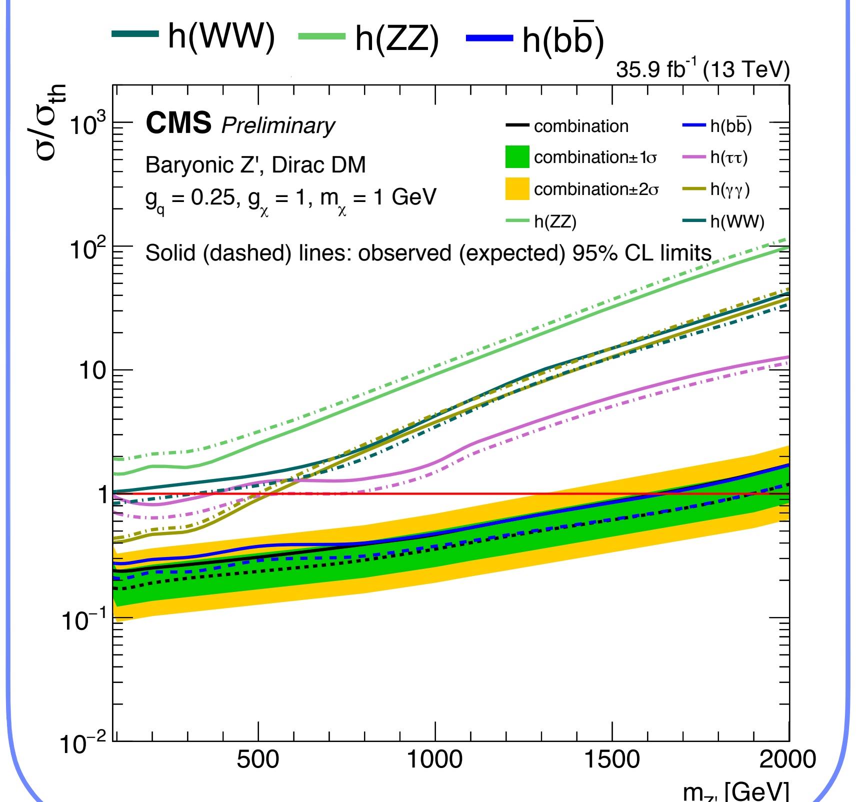
mono-Higgs combination: rich phenomenology

- CMS: arXiv:1908.01713
- ATLAS: JHEP05(2019)142
- ATLAS: JHEP05(2019)142

- *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



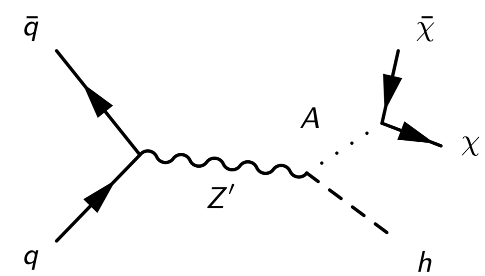


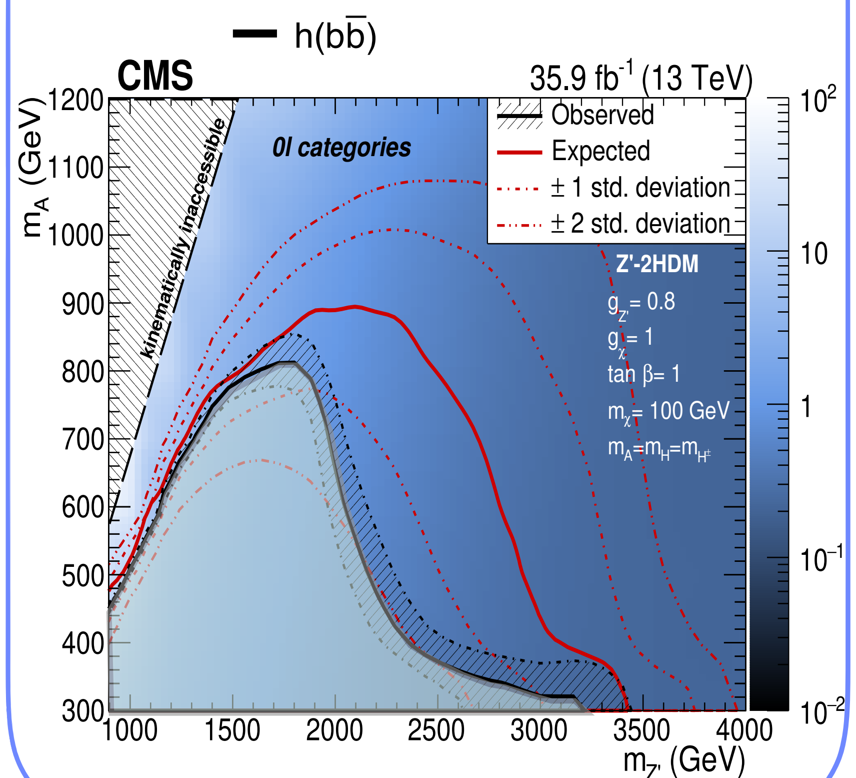
CMS med. boost

ATLAS

ATLAS excl. up to 1.9 TeV, CMS up to 1.6 TeV in $m_{Z'}$

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



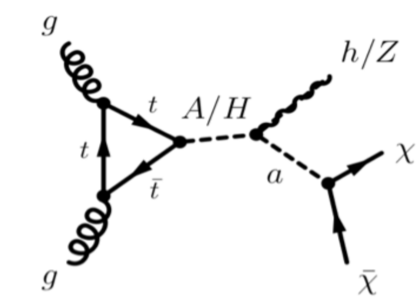


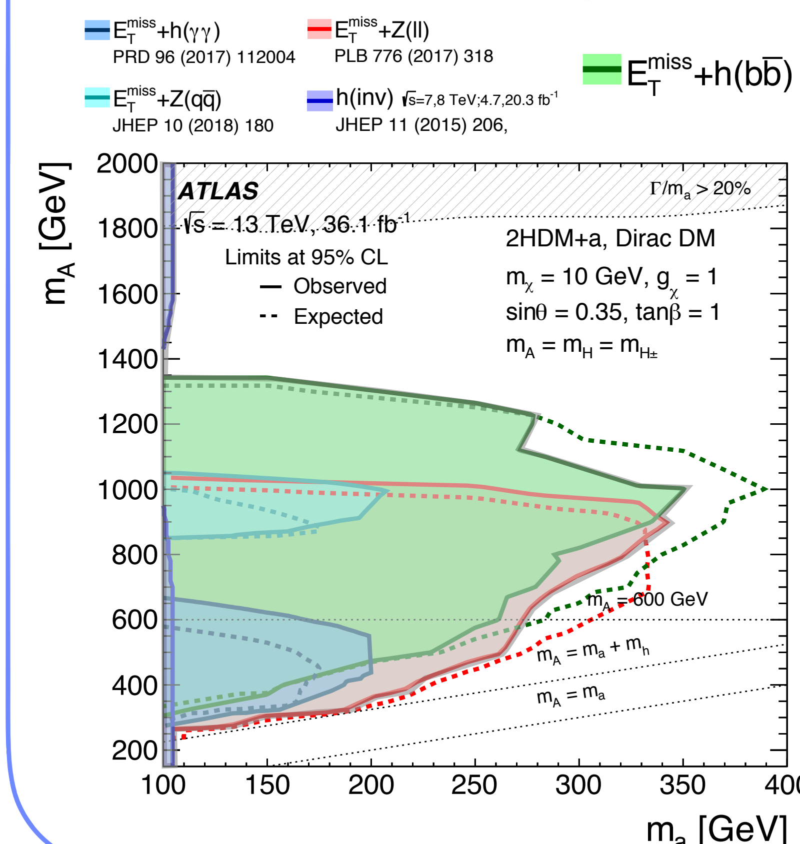
CMS med. boost

ATLAS

ATLAS excl. up to 2.8 TeV (79.8 fb^{-1}), CMS up 3.2 TeV (36 fb^{-1}) in $m_{Z'}$

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





CMS med. boost

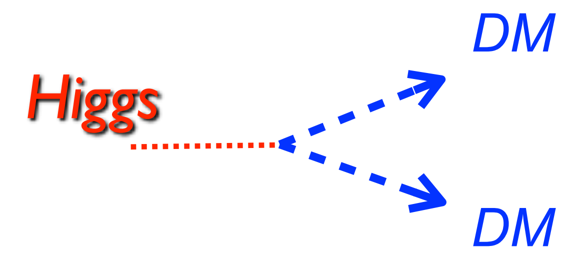
ATLAS

m_a=150 GeV, m_A excl. [350,1350]([500.900]) GeV for ATLAS (CMS)

Higgs: a portal to the invisible?

- CMS: PLB793(2019)520
- ATLAS: PLB793(2019)499
- ATLAS: PRL122,231801(2019)

- *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)*

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

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

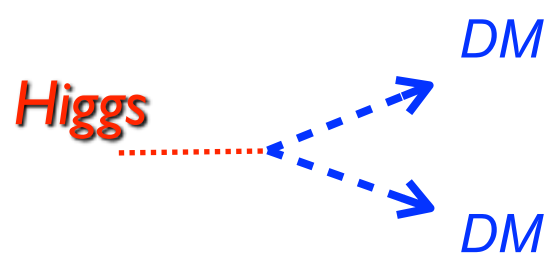
Experimental challenges

- ✱ 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

- CMS: PLB793(2019)520
- ATLAS: PLB793(2019)499
- ATLAS: PRL122,231801(2019)

Higgs: a portal to the invisible?

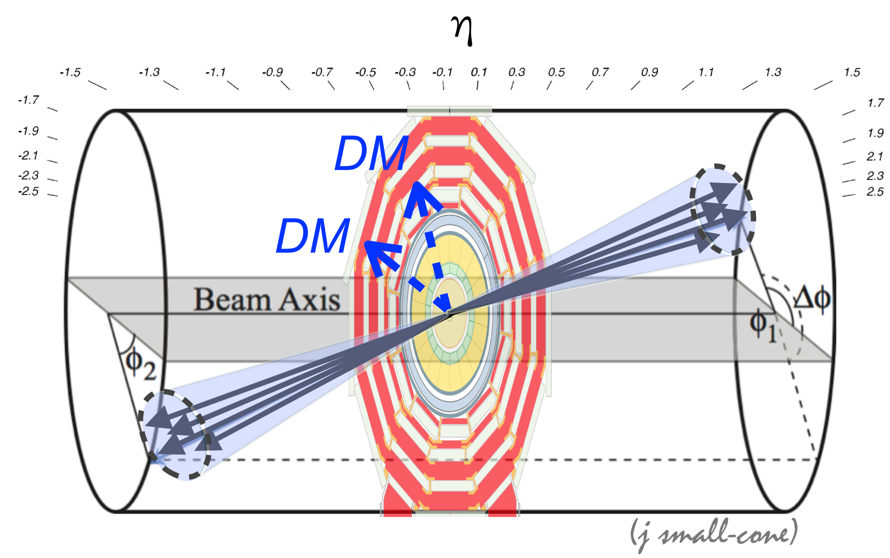
- *DM-SM interactions mediated by Higgs boson*
  - direct coupling to DM enhance H invisible decays (SM ~0.1%)



- *Higgs production as in SM*
  - gluon fusion *(MET+j)*
  - associated VH *(MET+V)*
  - ✱ *vector-boson fusion (MET+2jets)*

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

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

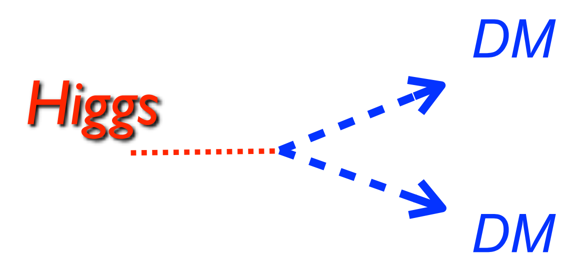


Experimental challenges

- ✱ 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

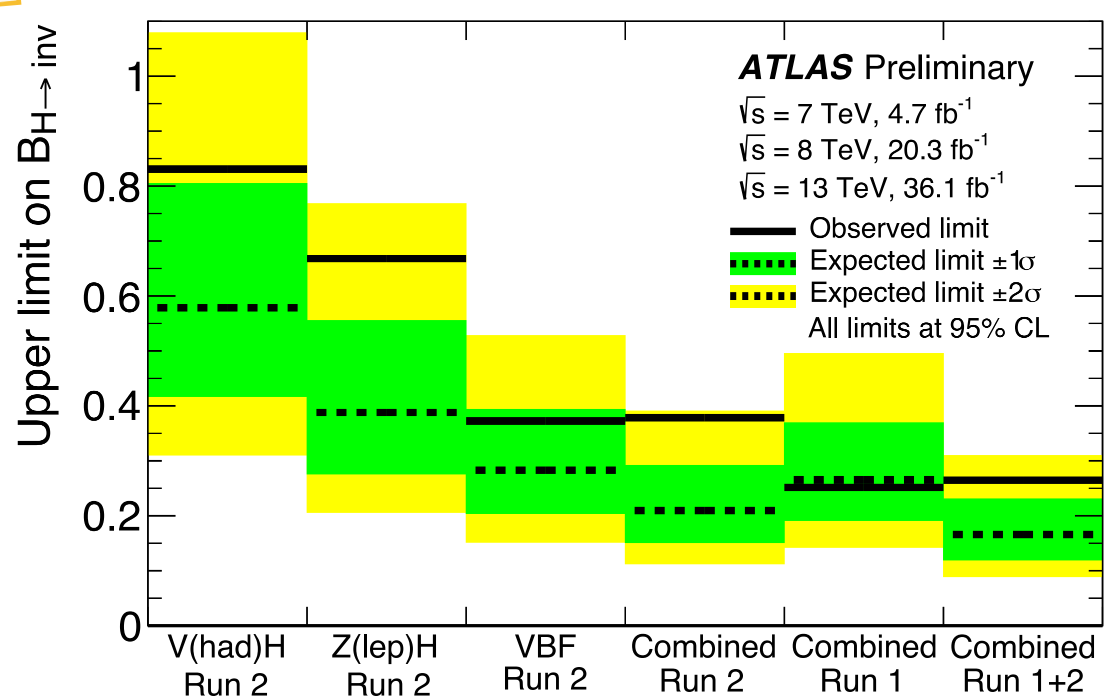
Higgs: a portal to the invisible?

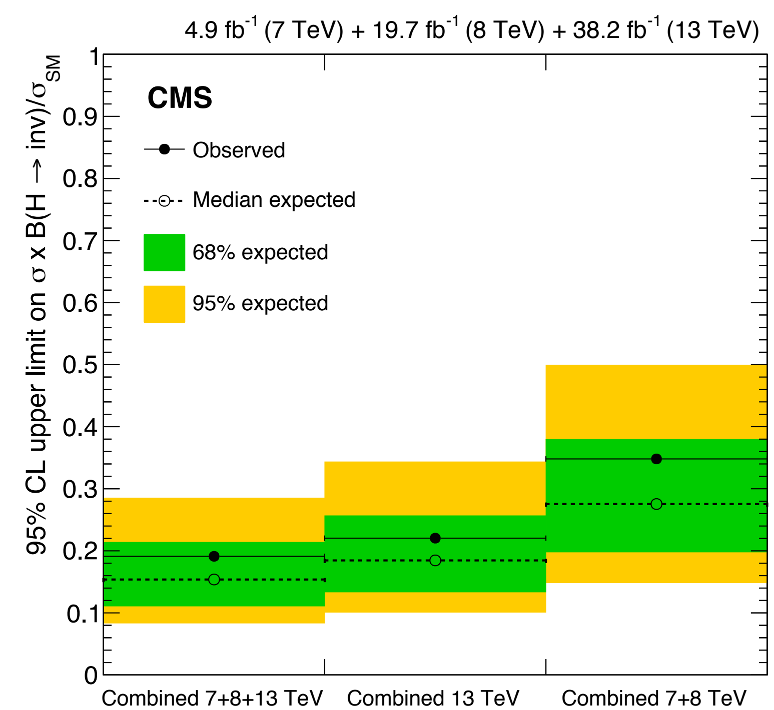
- *DM-SM interactions mediated by Higgs boson*
  - direct coupling to DM enhance H invisible decays (SM ~0.1%)



- *Higgs production as in SM*
  - gluon fusion *(MET+j)*
  - associated VH *(MET+V)*
  - ✱ *vector-boson fusion (MET+2jets)*

- *3- Results: combined fit of SRs and CRs to m_{jj}*
  - ATLAS - 3 bins
  - CMS - shape distribution





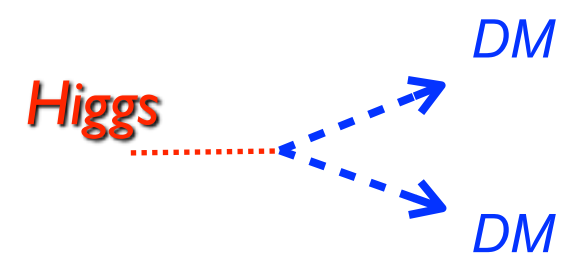
ATLAS BR(H→inv) <0.26(0.17) obs(exp.)

CMS BR(H→inv) <0.19(0.15) obs(exp.)

Higgs: a portal to the invisible?

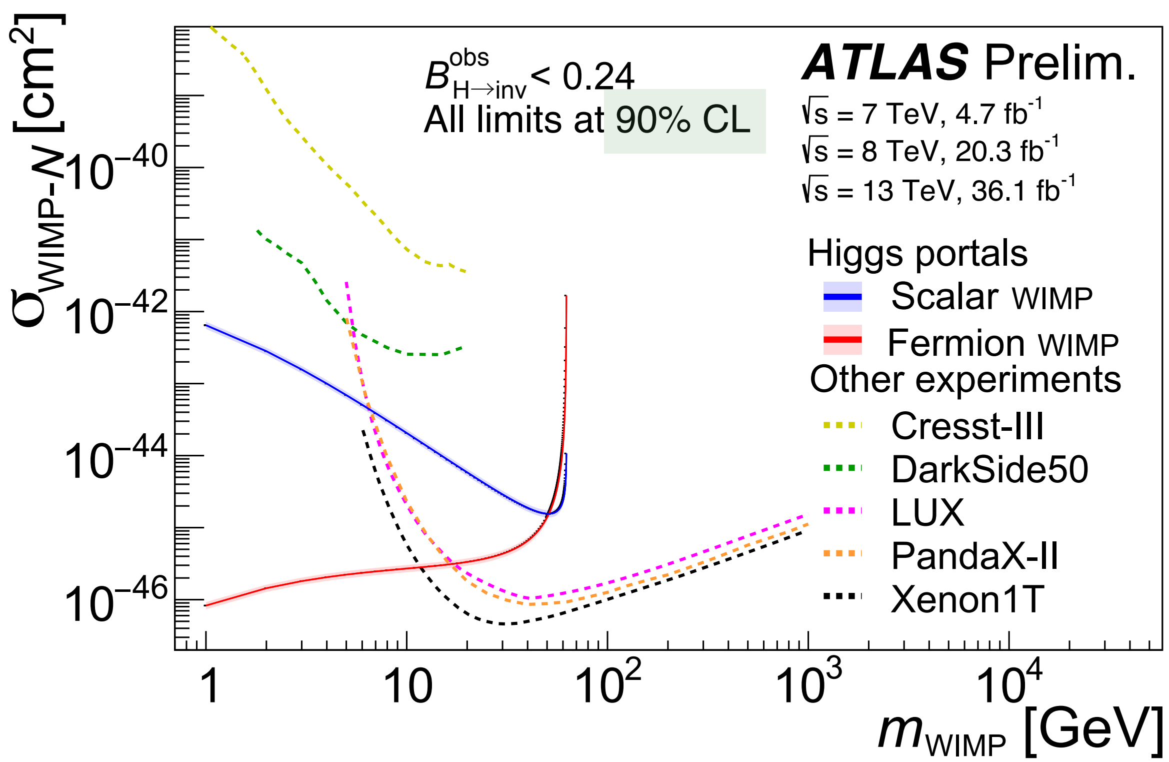
- *CMS: PLB793(2019)520*
- *ATLAS: PLB793(2019)499*
- *ATLAS: PRL122,231801(2019)*

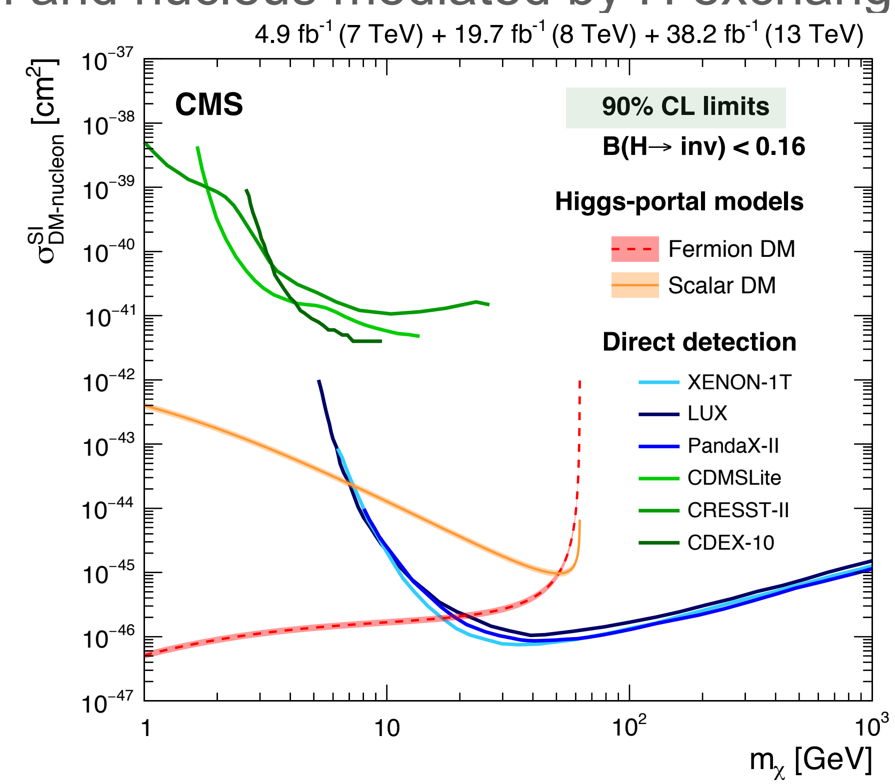
- *DM-SM interactions mediated by Higgs boson*
  - direct coupling to DM enhance H invisible decays (SM ~0.1%)



- *Higgs production as in SM*
  - gluon fusion *(MET+j)*
  - associated VH *(MET+V)*
  - ✱ *vector-boson fusion (MET+2jets)*

- *3- Results: translated into a spin-independent DM-nucleon elastic scattering xsec limit* [*PLB709(2012)65*]
  - ✱ m_{DM} smaller than half of m_H, interaction between DM and nucleus mediated by H exchange

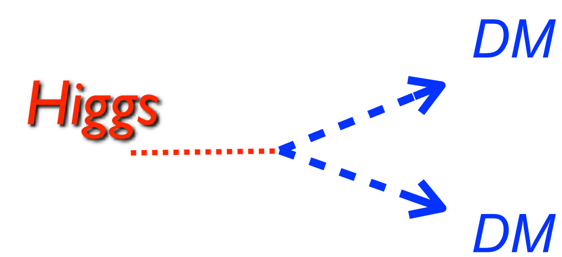




Higgs: a portal to the invisible?

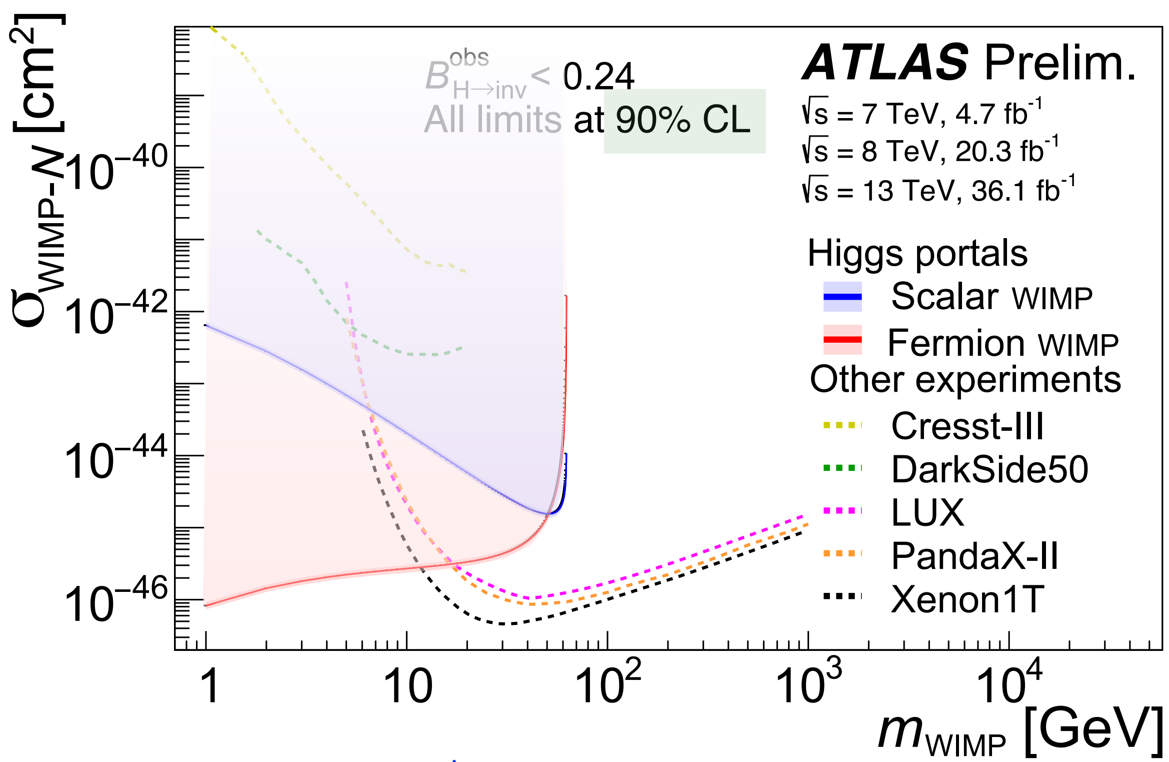
- CMS: [PLB793(2019)520]
- ATLAS: [PLB793(2019)499]
- ATLAS: [PRL122,231801(2019)]

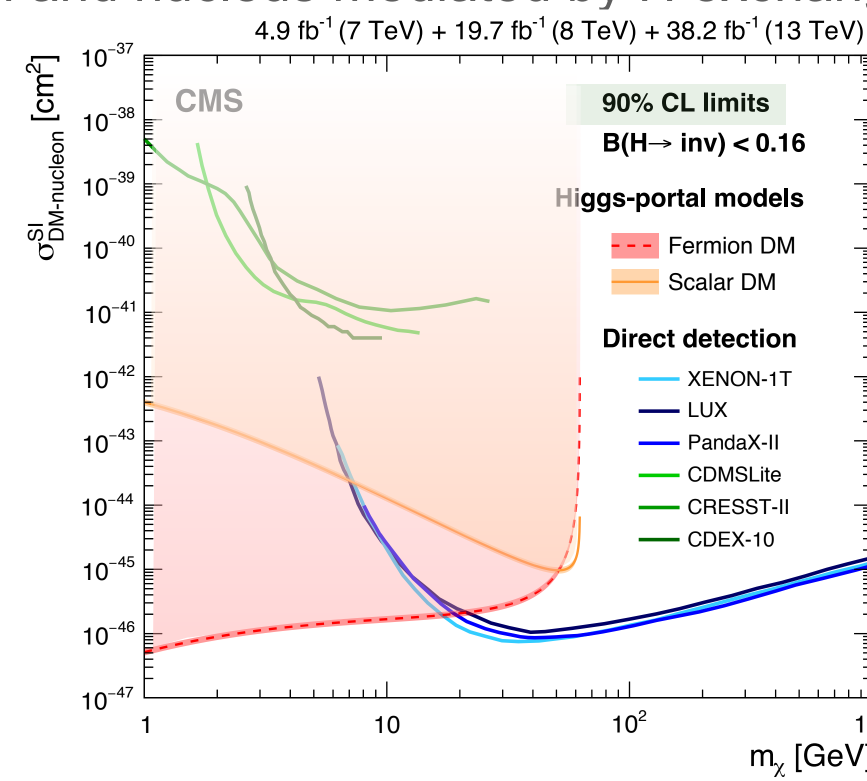
- *DM-SM interactions mediated by Higgs boson*
  - direct coupling to DM enhance H invisible decays (SM ~0.1%)



- *Higgs production as in SM*
  - gluon fusion *(MET+j)*
  - associated VH *(MET+V)*
  - ✱ *vector-boson fusion (MET+2jets)*

- ***3- Results:*** *translated into a spin-independent DM-nucleon elastic scattering xsec limit* [PLB709(2012)65]
  - ✱ m_{DM} smaller than half of m_H, interaction between DM and nucleus mediated by H exchange





Note

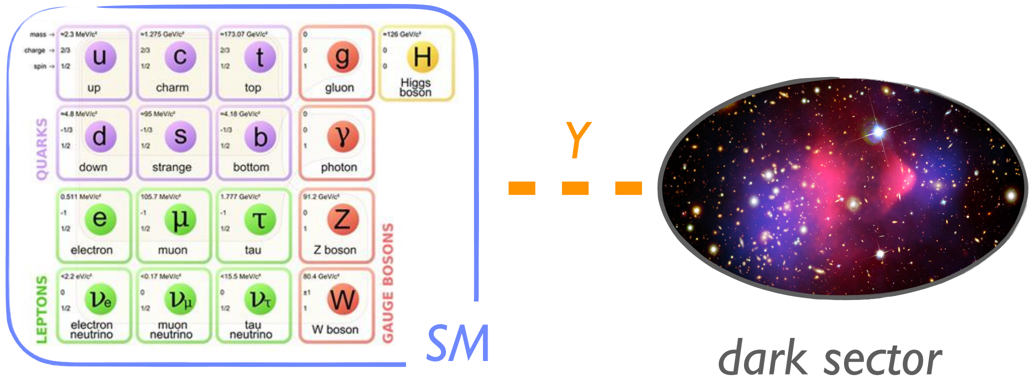
- ✱ *comparisons possible only in the context of a benchmark model*
- ✱ *essential to fully specify model/parameters and be aware of limitation*

LHC DM WG [arXiv:1603.04156]

Dark photon in Higgs decays

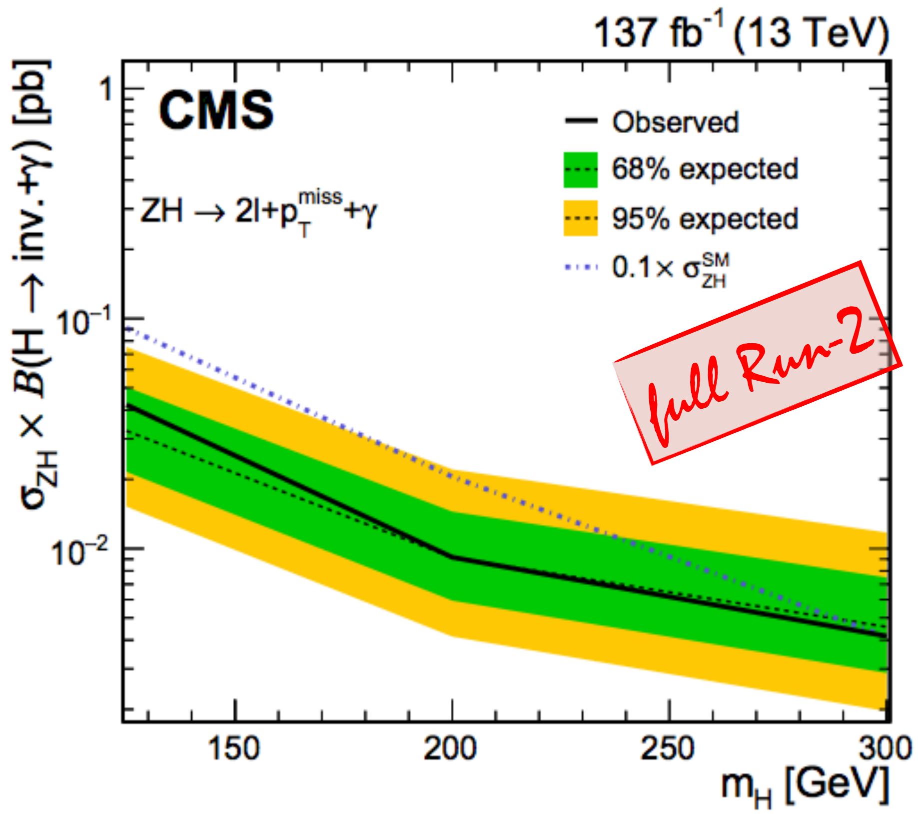
ATLAS: arXiv:1909.01246
CMS: arXiv1908.02699

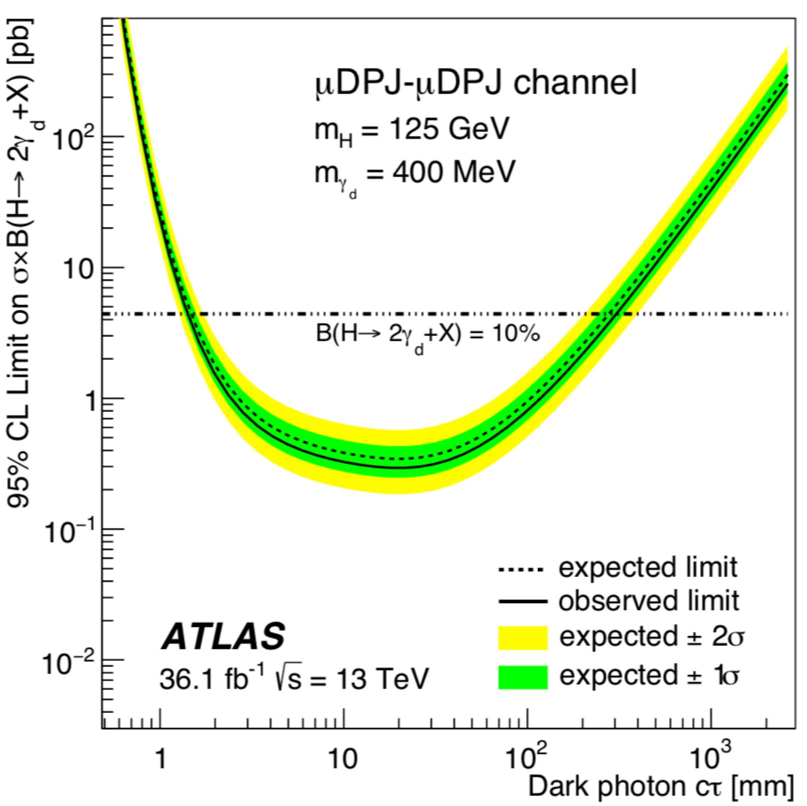
- Simplified models make minimal assumptions
- An extended dark sector might exist
  - contain DM candidate and a heavy resonance that couples dark sector to the SM
  - can lead to H exotic decays



- *Massless dark photon γ_D couples to H and escape undetected (MET signature)*
  - $BR(H \to \gamma\gamma_D)$ <5% not yet excluded
  - consider *associated Z(ℓℓ)H production* and heavy neutral H with masses [125, 300] GeV

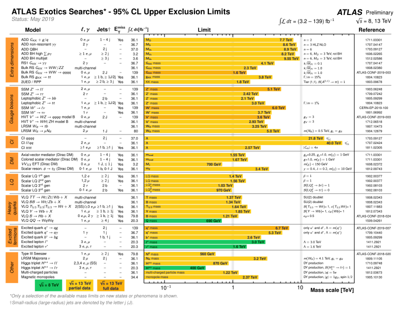
- *Massive γ_D mixes kinetically with SM γ and decays into SM leptons and light quarks*
  - kinetic mixing term (ε) determines γ_D lifetime
  - assume γ_D small mass leads to *large boosts*: *collimated leptons and light hadrons in jet-like structure*

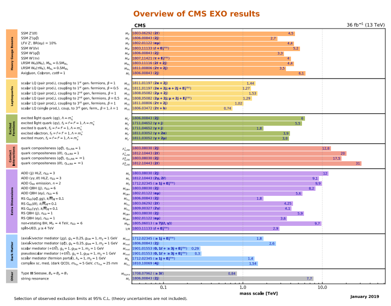




Summary

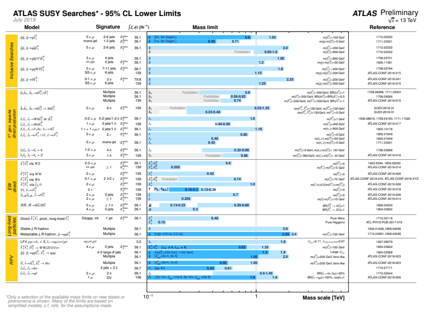
- *New physics is a main physics goal at the LHC*

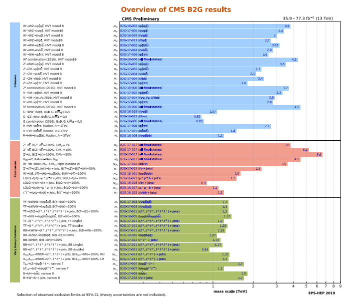




- *Rich new physics analyses program at ATLAS and CMS*
  - various interactions and signatures investigated
  - new experimental tools used to improve sensitivity

no signs of an excess yet so far

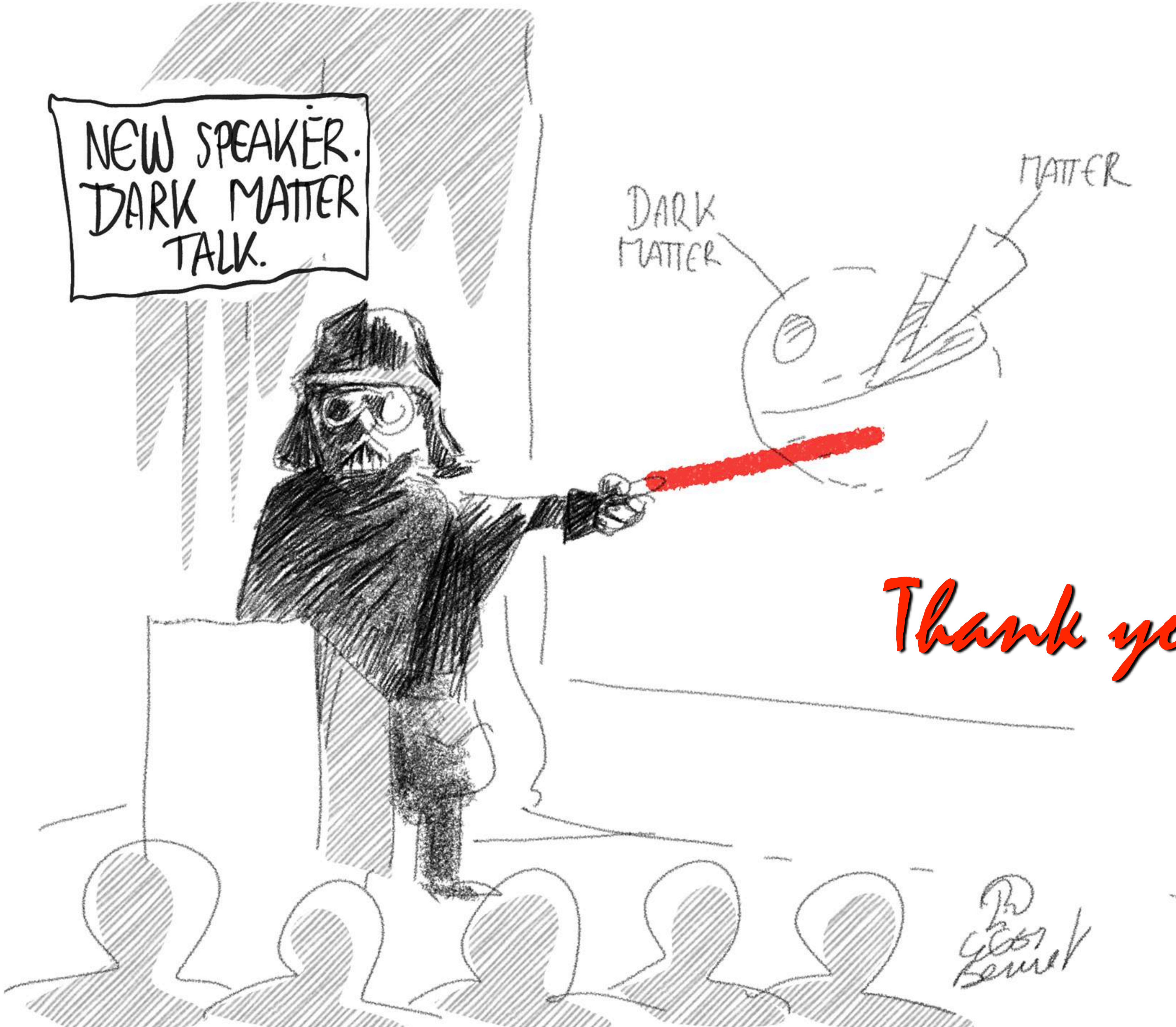




- *Essential complementarity with non-collider searches in the search for dark matter*
  - comparisons possible only in the context of a benchmark model
  - essential to fully specify model/parameters and be aware of limitation

- *Many new results expected with full 2016+2017+2018 data*
  - various analysis improvements foreseen

Stay tuned !



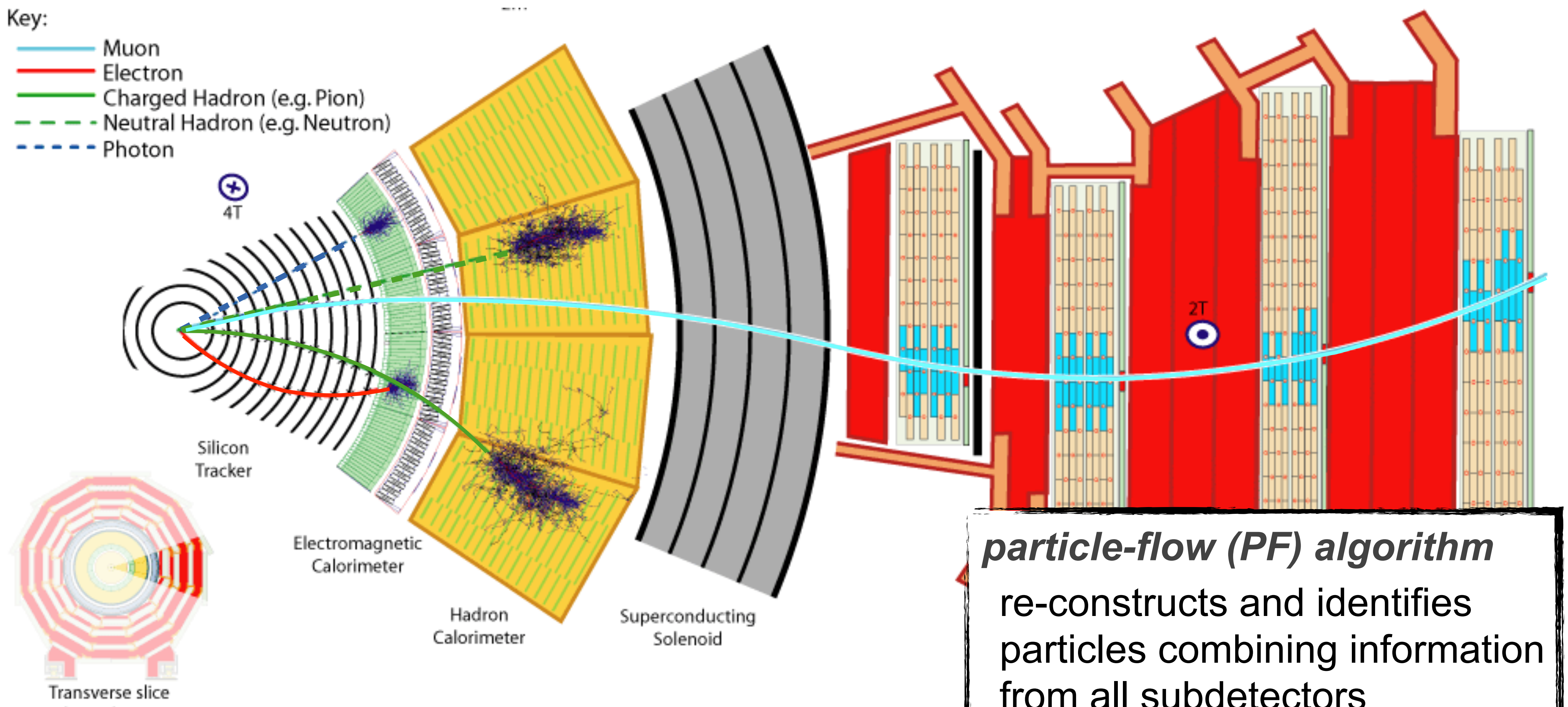
Thank you!

[credit Lison Bernet, EWK Moriond '19]

Backup

- mono-V
- t/tt+DM
- mono-H(WW/ZZ)
- mono-H(bb)
- dark photon

Particle reconstruction at CMS



particle-flow (PF) algorithm
re-constructs and identifies particles combining information from all subdetectors

Jet reconstruction

particle-flow candidates clustered using anti-k_T algorithm

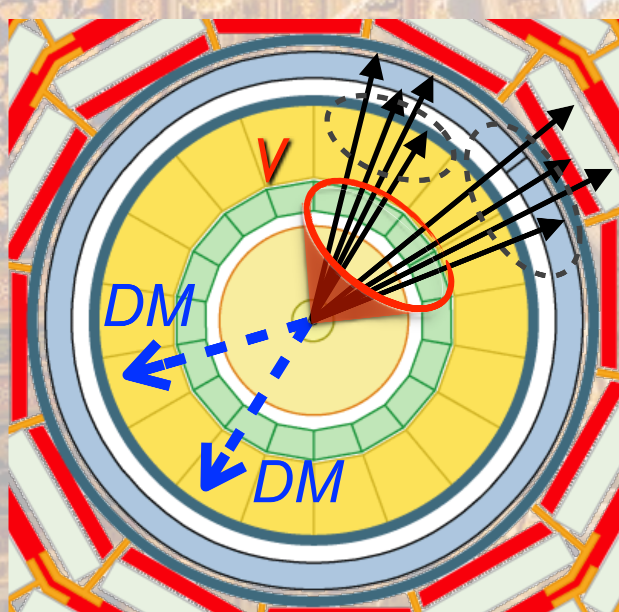
MET

$$MET = -\left|\sum \vec{p}_T\right|$$

used to indirectly detect non-interacting particles

sum over all PF candidates

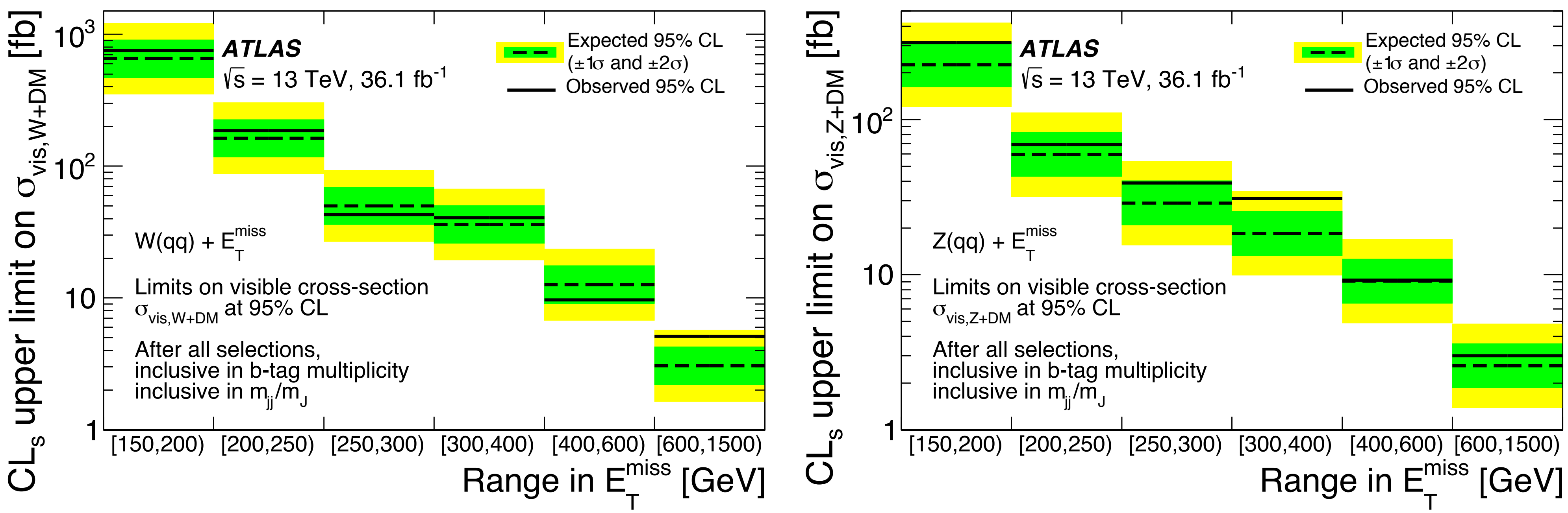
Mono-V



- *ATLAS: JHEP10(2018)180 (2015+2016)*
- *CMS: PRD97,092005(2018) (2016)*

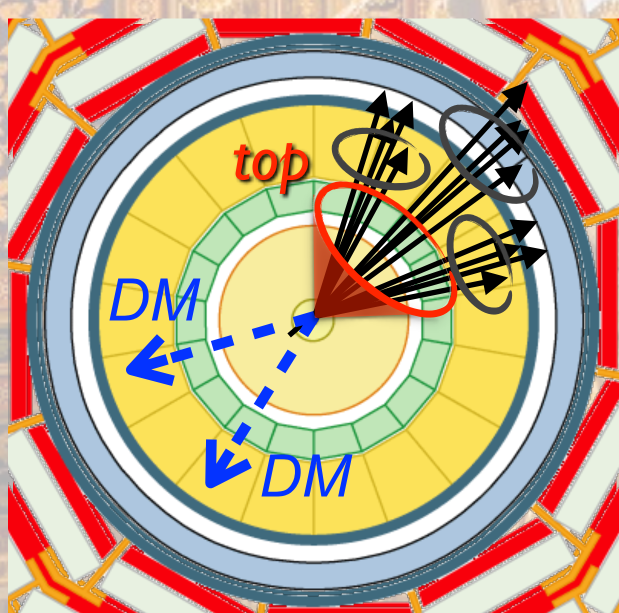
DM+V/Z' search: additional results

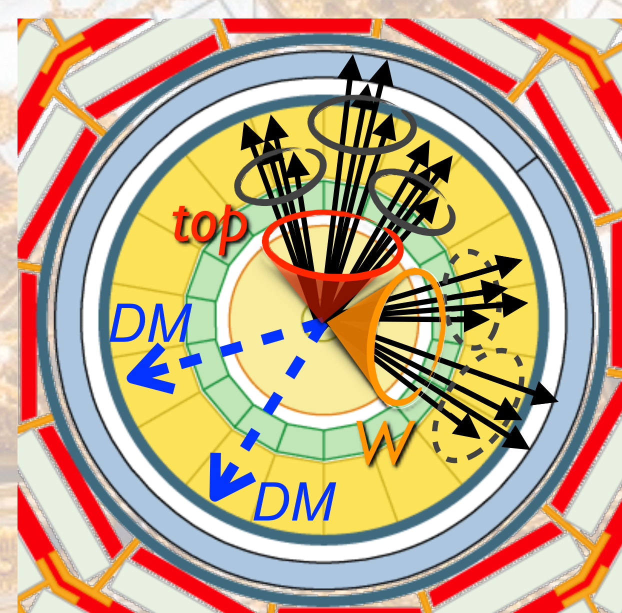
- *invisible Higgs boson decays:*
  - *observed (expected) upper limit on H BR(inv): <0.83 (0.58) at 95% CL*
    - *combining the contributions from VH, ggH and VBF production modes*
- *xsec of DM+W/Z*
  - *SR selection except m_{jet} requirements and the b-jet multiplicity*
    - *stronger limits for DM+Z wrt DM+W because in 2b cat (highest sensitivity/lowest bkg) mainly DM+Z events*



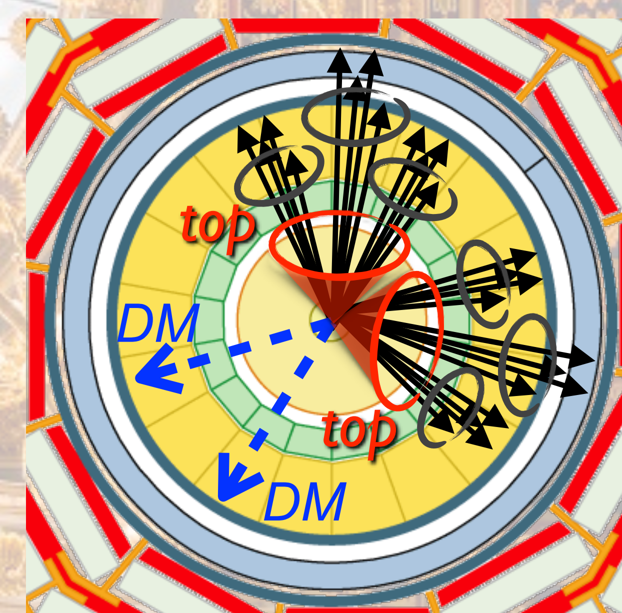
t/tt+DM

* CMS: arXiv1901.01553, (2016)





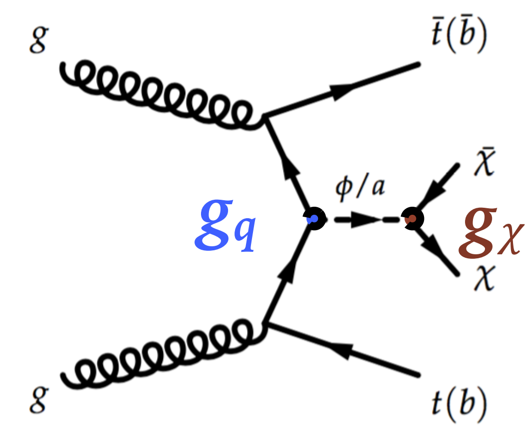
DM+top: t/tW-channel

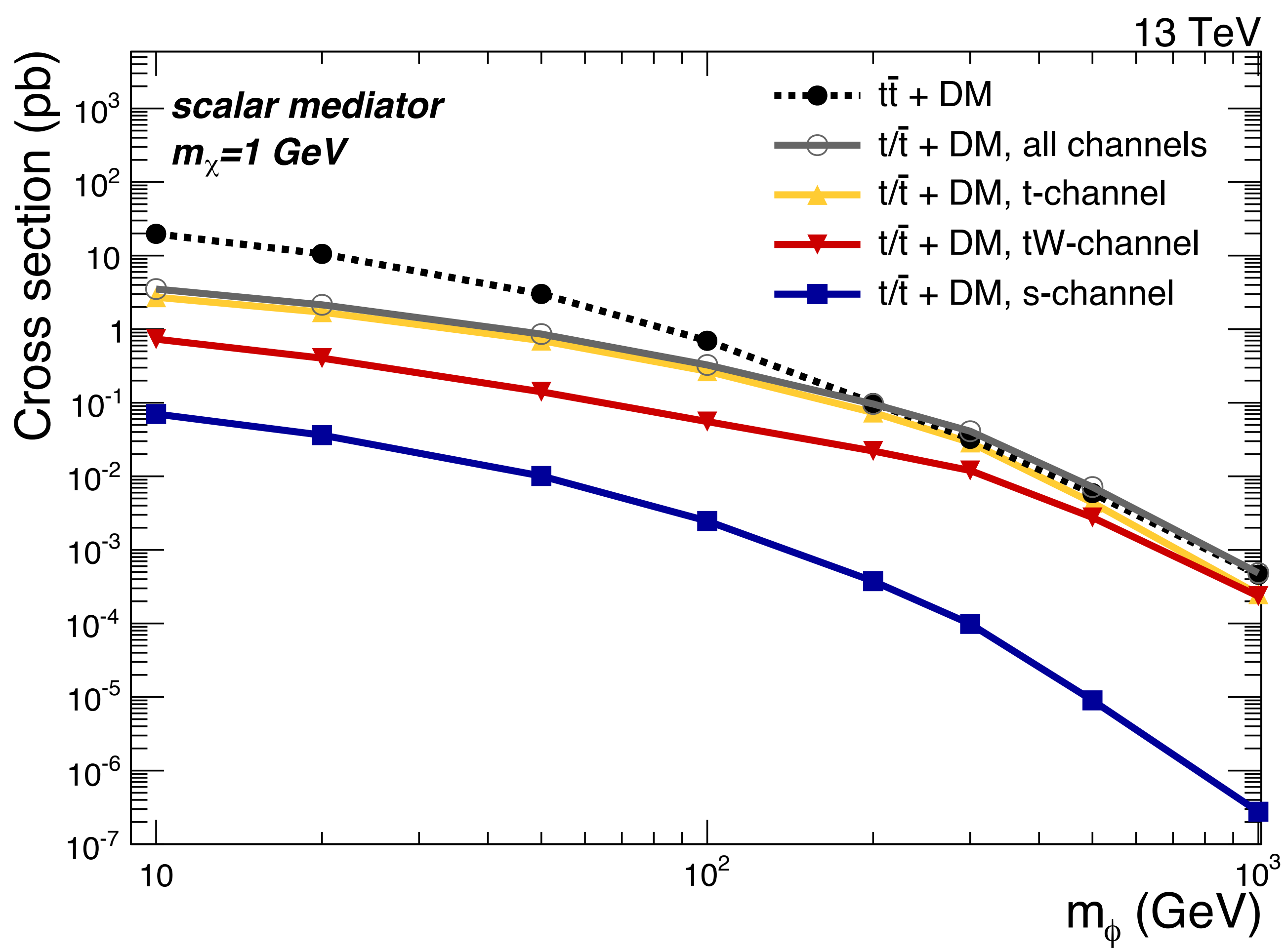


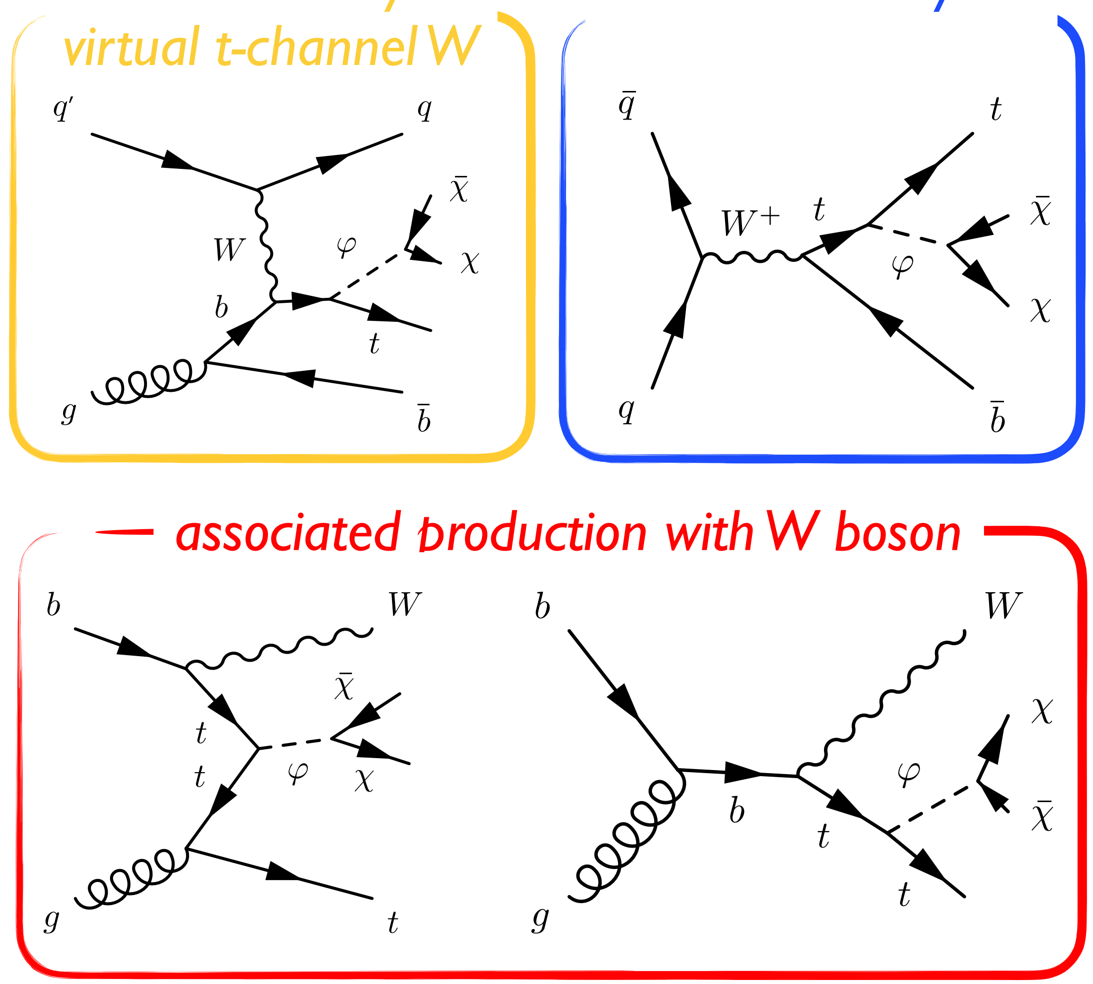
DM+tt

DM+t(tt) search: phenomenology

- *Two is not always better than one …* (Phys. Rev. D 96, 035031)
  - *DM+t previously overlooked production predicted from same spin-0 model*
    - *minimal flavour violation*, couplings proportional to SM fermions masses
    - motivated various collider searches for *DM+tt* and *DM+bb*
  - *sizable contribution to DM searches with HF quarks (up to factor of 2)*
  - *up to now only FCNC processes (mono-top)*

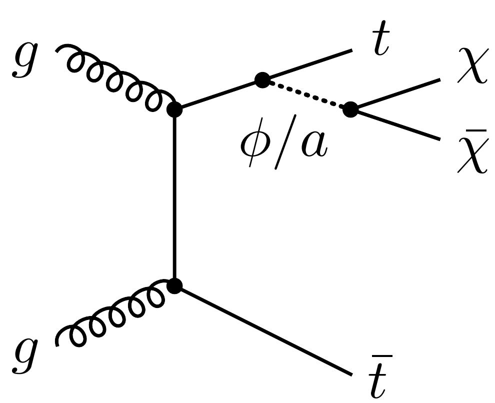


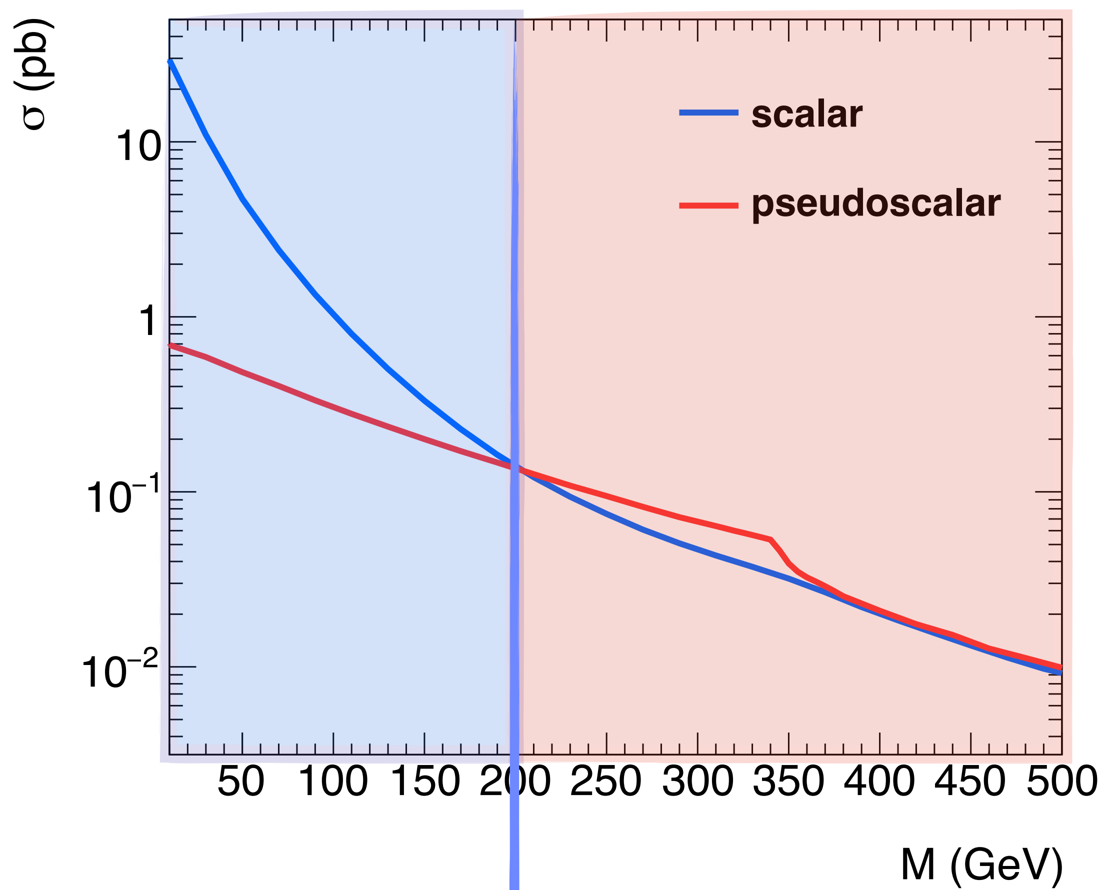


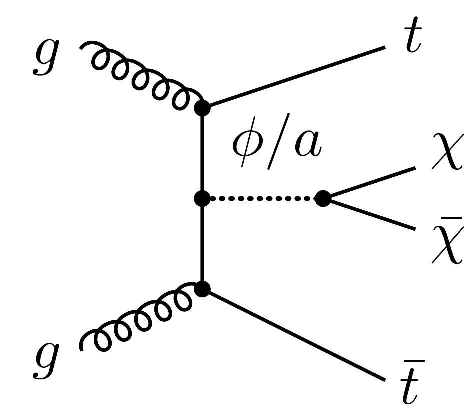


DM+t(tt) search: phenomenology

U. Haisch, P. Pani, G. Polesello







Fragmentation function

sc $$f_{t\to\phi}(x) = \frac{g_t^2}{(4\pi)^2}\left[\frac{4\,(1-x)}{x} + x\ln\left(\frac{s}{m_t^2}\right)\right],$$

ps $$f_{t\to a}(x) = \frac{g_t^2}{(4\pi)^2}\left[x\ln\left(\frac{s}{m_t^2}\right)\right],$$

Squared matrix elements

$$\overline{\sum}|\mathcal{M}(t\bar{t}\to\phi)|^2 = \frac{g_t^2 s}{12}\beta^2$$

$$\overline{\sum}|\mathcal{M}(t\bar{t}\to a)|^2 = \frac{g_t^2 s}{12}$$

Scalar xsec: dominated by gluon-fusion diagram with a mediator fragmentation

Pseudo xsec: both mediator-fragmentation and top-fusion diagrams in gluon-fusion are relevant

DM+t(tt) search: phenomenology

tt+DM

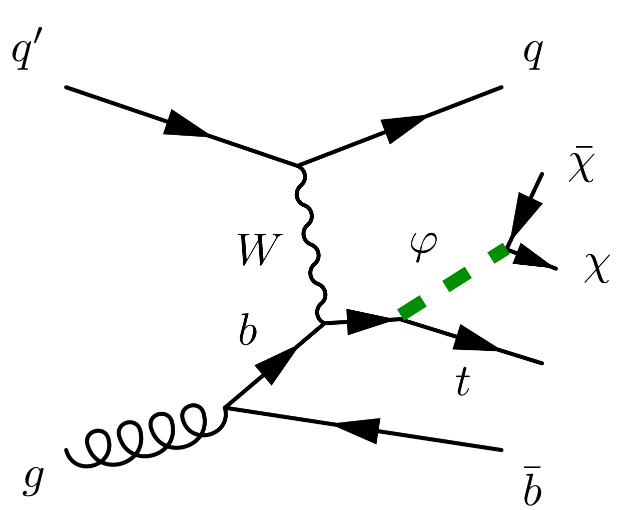
Scalar xsec: dominated by gluon-fusion diagram with a mediator fragmentation

Pseudo xsec: both mediator-fragmentation and top-fusion diagrams in gluon-fusion are relevant

t+DM

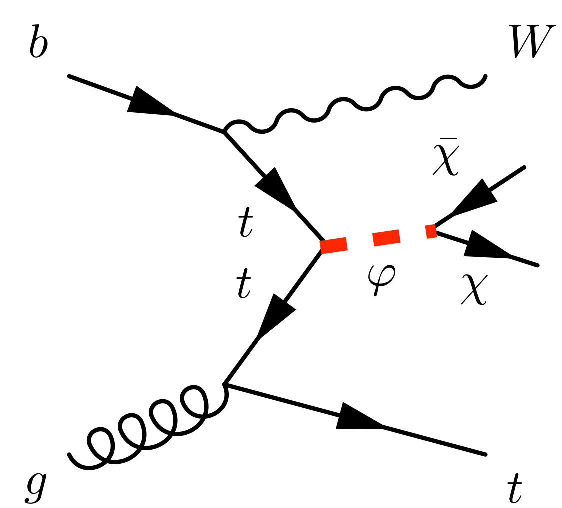
- *t-channel: has contributions only from diagrams with mediator fragmentation*
- *tW-channel has contributions from both mediator-fragmentation and top-fusion diagrams*

mediated by virtual t-channel W

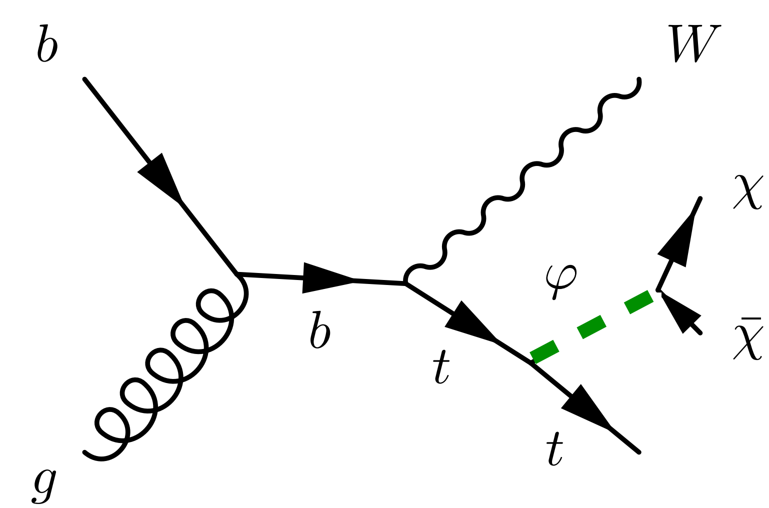


med. fragmentation

associated production with W boson



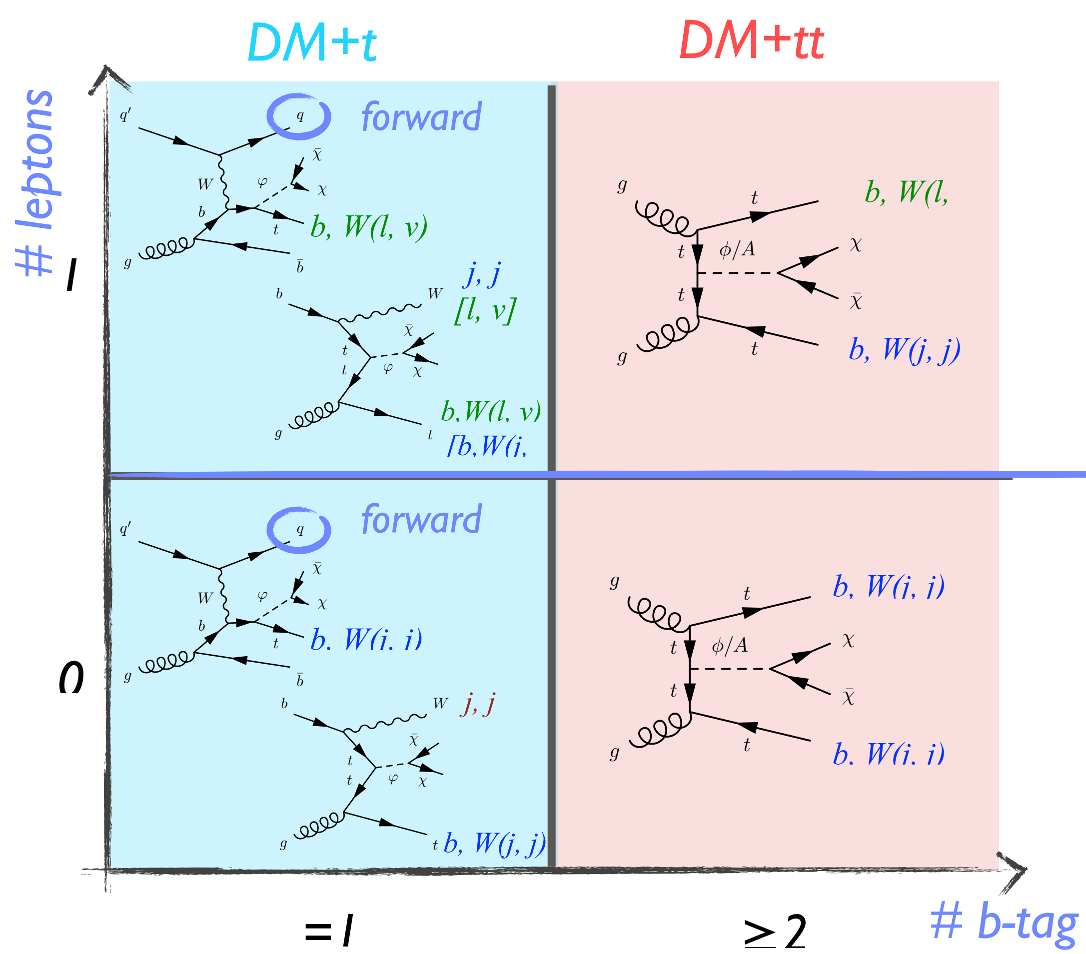
top fusion



med. fragmentation

DM+t(tt) search: selection

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



0
- ✱ leptons veto: e,μ
- ✱ ≥ 3 jets (j small-cone)
- ✱ =1, ≥ 2 b-tagged jets
- ✱ MET > 250 GeV

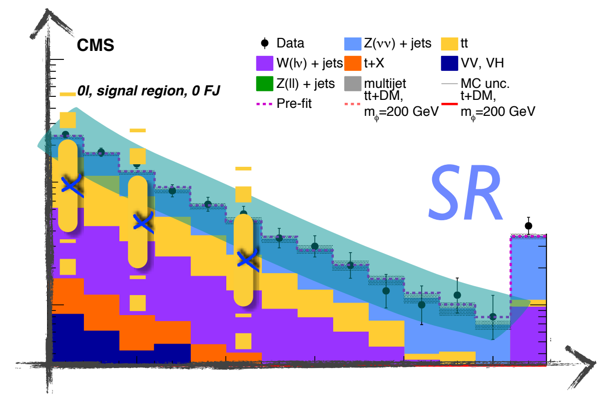
1
- ✱ 1 lepton: isolated e,μ
- ✱ ≥ 2 jets (j small-cone)
- ✱ =1, ≥ 2 b-tagged jets
- ✱ MET > 160 GeV

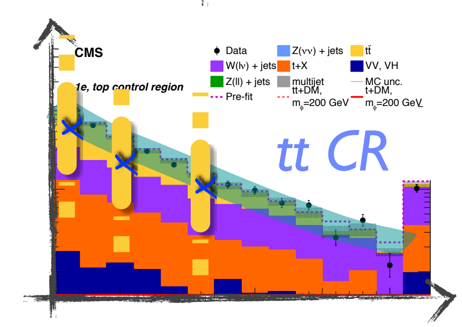
	Single-lepton SRs			All-hadronic SRs		
	1ℓ, 1 b-tag, 0 FJ	1ℓ, 1 b-tag, 1FJ	1ℓ, 2 b-tag	0ℓ, 1 b-tag, 0 FJ	0ℓ,1 b-tag, 1 FJ	0ℓ, 2 b-tag
Forward jets	=0	≥1	—	= 0	≥1	—
n_b	=1	=1	≥2	= 1	=1	≥2
n_{lep}	=1	=1	=1	= 0	=0	=0
$p_T(j_1)/H_T$		—		—		<0.5
n_{jet}		≥2			≥3	
p_T^{miss}		>160 GeV			>250 GeV	
m_T		>160 GeV			—	
m_{T2}^W		>200 GeV			—	
$\min\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$		>1.2 rad.			>1.0 rad.	
m_T^b		>180 GeV			>180 GeV	

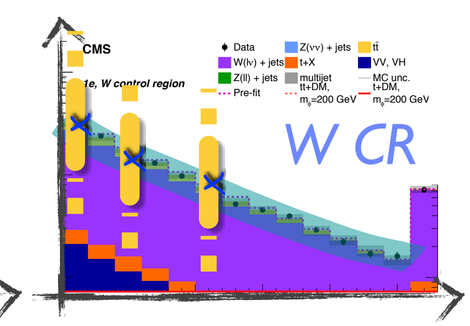
DM+t(tt) search: background estimation

- **2- Bkg:**
  - **tt, V+jets** main bkg contributions
    - **CRs**: similar selection to SR except #leptons and hadronic recoil as proxy for Z(ℓℓ) CR
    - no b-jets/forward jets categories
  - **remaining contributions** from simulation

- **3- Results:**
  - ✱ bin-by-bin maximum likelihood fit to MET distributions in SR and CR, fitted simultaneously
    - constrained nuisance parameters: effect of syst. unc. constrained by magnitude of corresponding source of unc.
    - unconstrained parameter: rate parameters, connect separately each main bkg across CRs and SRs for each bin of MET spectrum
    - expected signal included in fit of SRs and CRs to account for CR contaminations





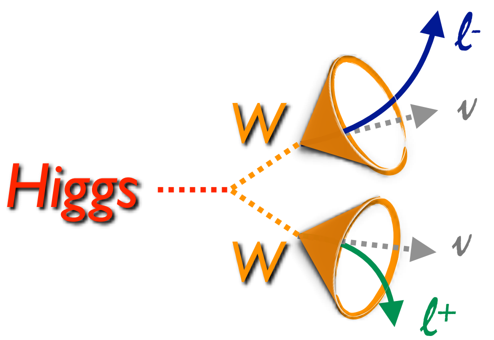


  - ✱ DM production cross section: expressed in terms of ratio between excluded xsec and theory prediction
    - computed with modified frequentist approach (CLs), profile-likelihood ratio as test-statistic in the asymptotic approximation
  - ✱ syst. unc. included as nuisance parameters
    - dominant unc from b-tagging eff data/MC scale factors, theoretical unc on backgrounds

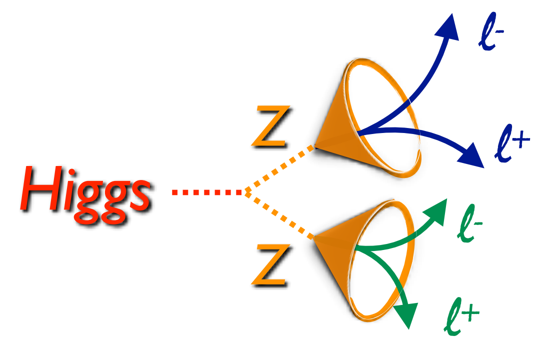
mono-H: WW and ZZ decays

mono-Higgs: WW and ZZ decays

▷ *1 - Selection:* *MET and identification of Higgs boson candidate*



- 1 opposite-sign eμ pair
- MET > 20 GeV
- ν prevent full kinematic Higgs reconstruction
  - MVA techniques to recover sensitivity



- = 4 leptons
- Z candidates from same flavour $\ell^+\ell^-$
- $m_{4\ell}$ consistent with SM Higgs

▷ *2- Bkg:*

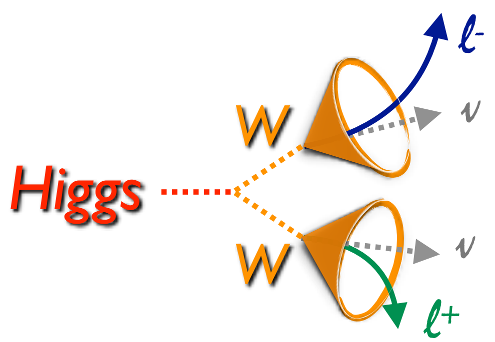
major: WW, tt, Z(ll) from CRs

major: ZH and WH and non-resonant ZZ from MC

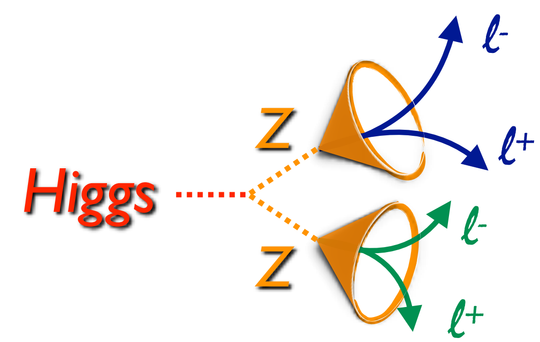
▷ *3- Results:* *fit to MVA in CRs and SRs* *from fit to MET*

mono-Higgs: WW and ZZ decays

▷ *1 - Selection: MET and identification of Higgs boson candidate*



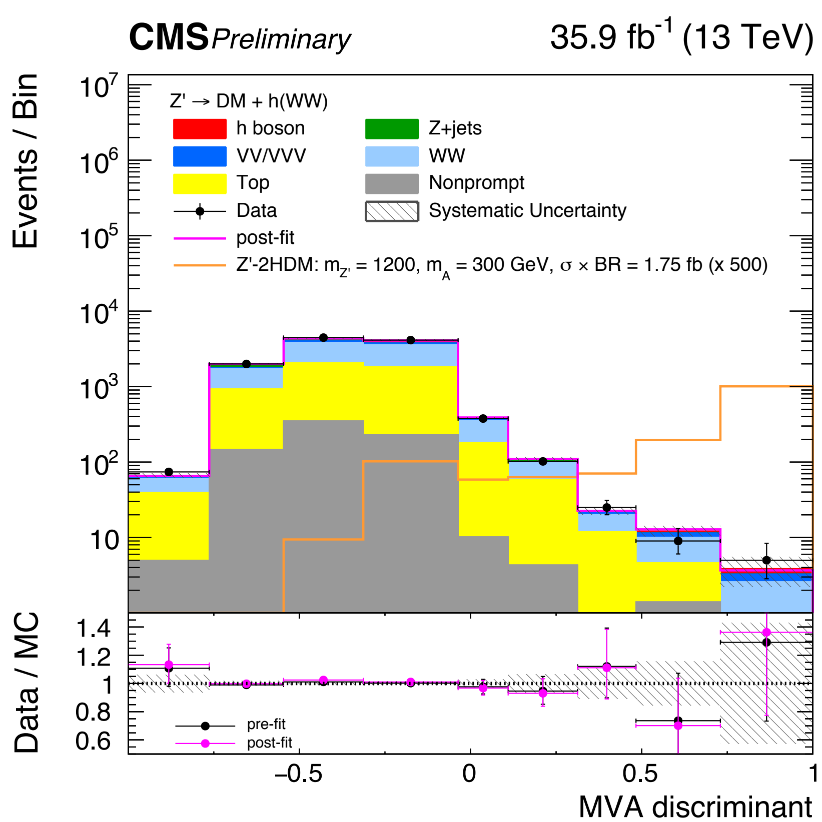
- 1 opposite-sign eμ pair
- MET > 20 GeV
- *ν* prevent full kinematic Higgs reconstruction
  - MVA techniques to recover sensitivity



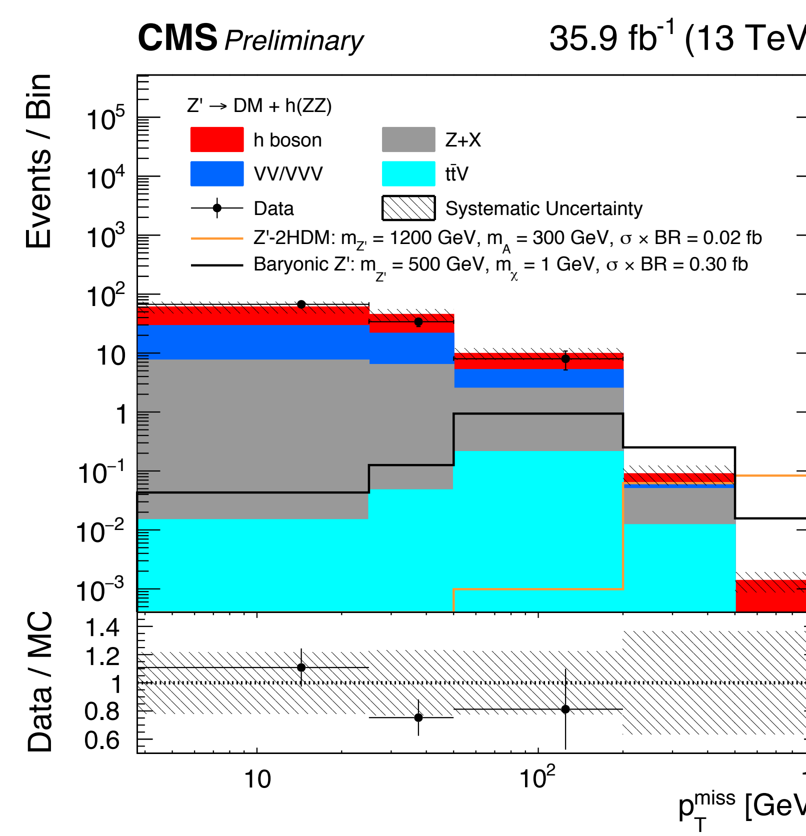
- = 4 leptons
- Z candidates from same flavour ℓ+ℓ-
- $m_{4\ell}$ consistent with SM Higgs

▷ *2- Bkg:*

major:
WW, tt, Z(ll) from CRs



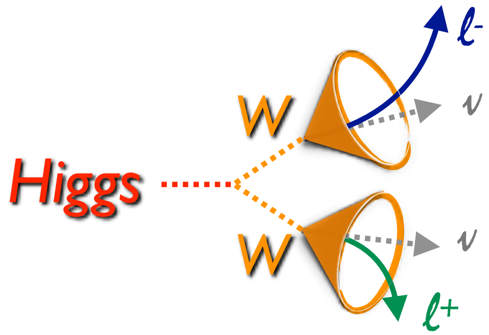
major:
ZH and WH and non-resonant ZZ from MC

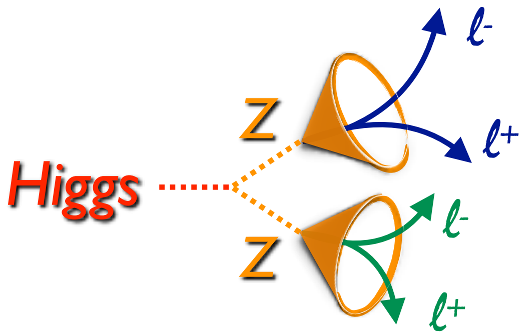


▷ *3- Results:* *fit to MVA in CRs and SRs* *from fit to MET*

mono-Higgs: WW and ZZ decays

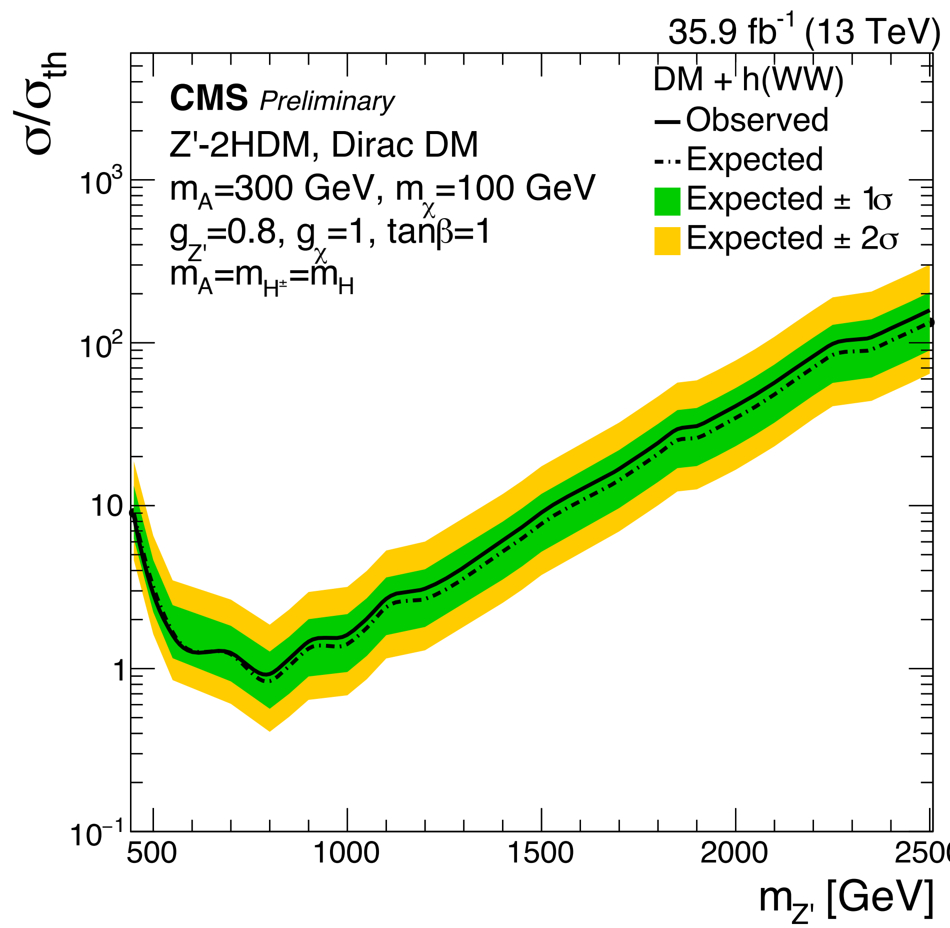
▷ 3 - Results:

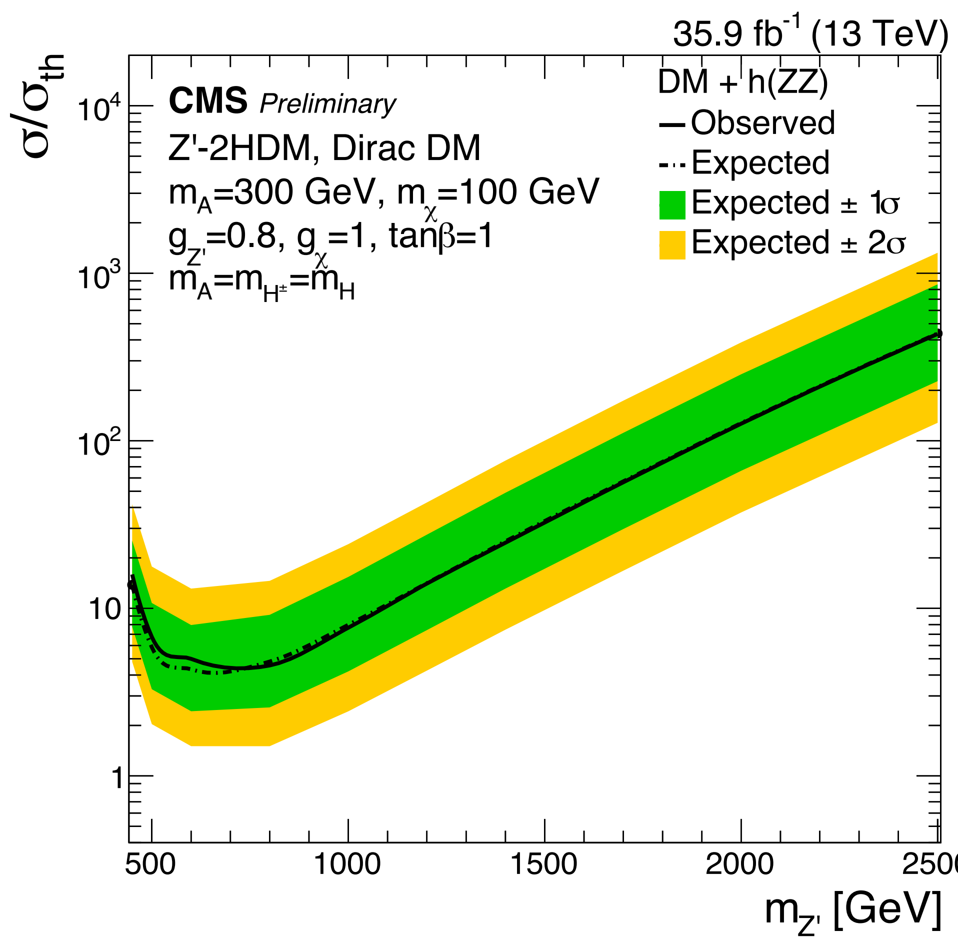




- syst. unc. included as nuisance parameters
  - dominating unc from statistics, bkg estimation/ normalization

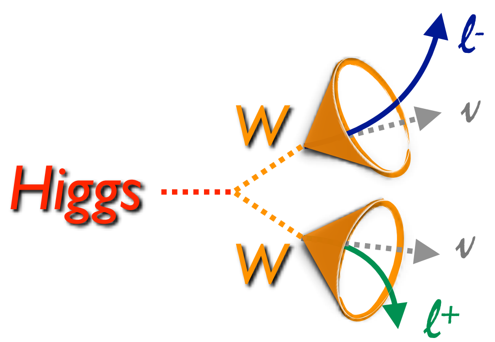
- syst. unc. included as nuisance parameters
  - dominating unc from statistics, bkg estimation/ normalization





mono-Higgs: WW and ZZ decays

1 - Selection: MET and identification of Higgs boson candidate



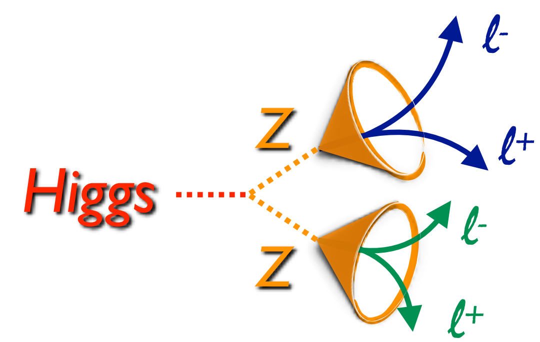
- 1 opposite-sign eμ pair
- MET > 20 GeV
- ν prevent full kinematic Higgs reconstruction
  - MVA techniques to recover sensitivity

2- Bkg:

- ***tt, single top***
  - **CRs**: *similar selection to SR except #b-jets (=1) and hadronic recoil as proxy*
- ***remaining contributions*** *from data driven methods or from simulation*

Note:

- *easily reducible backgrounds*



- = 4 leptons
- Z candidates from same flavour $\ell^+\ell^-$
- $m_{4\ell}$ consistent with SM Higgs

2- Bkg:

- ***SM Higgs boson and non-resonant ZZ production*** *from simulation*
- ***remaining contributions*** *from data driven methods or from simulation*

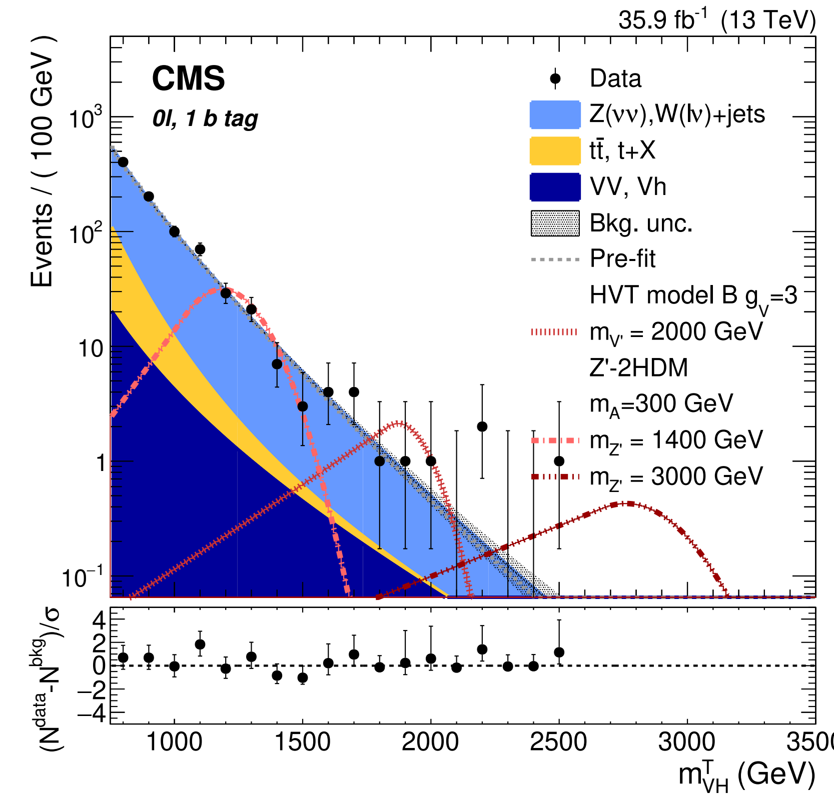
Note:

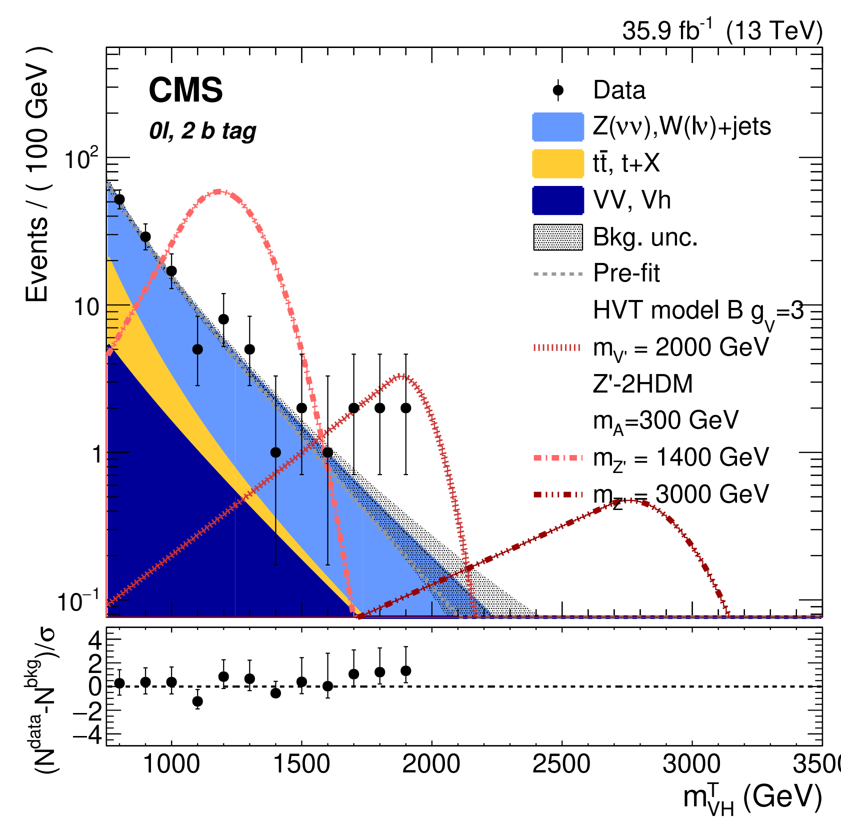
- *easily reducible backgrounds*
- *fully reconstructable Higgs boson candidate, with excellent mass resolution*

mono-H: bb and combination

mono-Higgs: bb (high-boost), CMS

- signal will appear as localized excess in the m_T (A(inv),H(bb)) distribution above SM backgrounds
  - resonance masses [0.8, 4] TeV considered to have a sufficiently boosted Higgs boson
- b-jet categorization:
  - 2 b-tagged category most sensitive at low m_X
  - 1 b-tagged category most sensitive at high m_X
    - track-reconstruction efficiency decreases + overlap between the two subjets at very large jet p_T
- V+jets main bkg contributions
  - tt estimated from CR
  - V+jet: m_T distribution in SR derived from data in the m_{jet} SB + a transfer function determined from simulation

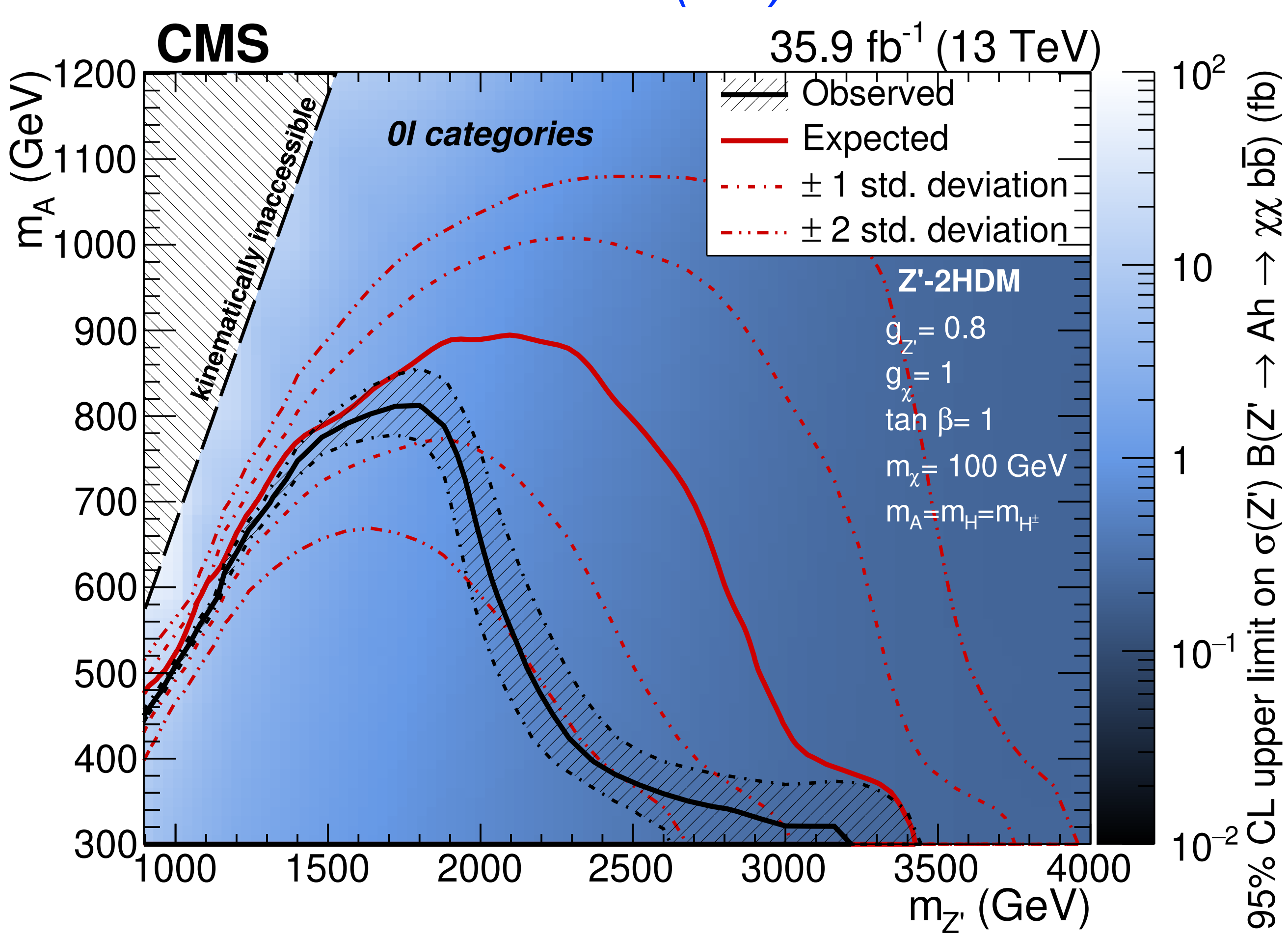




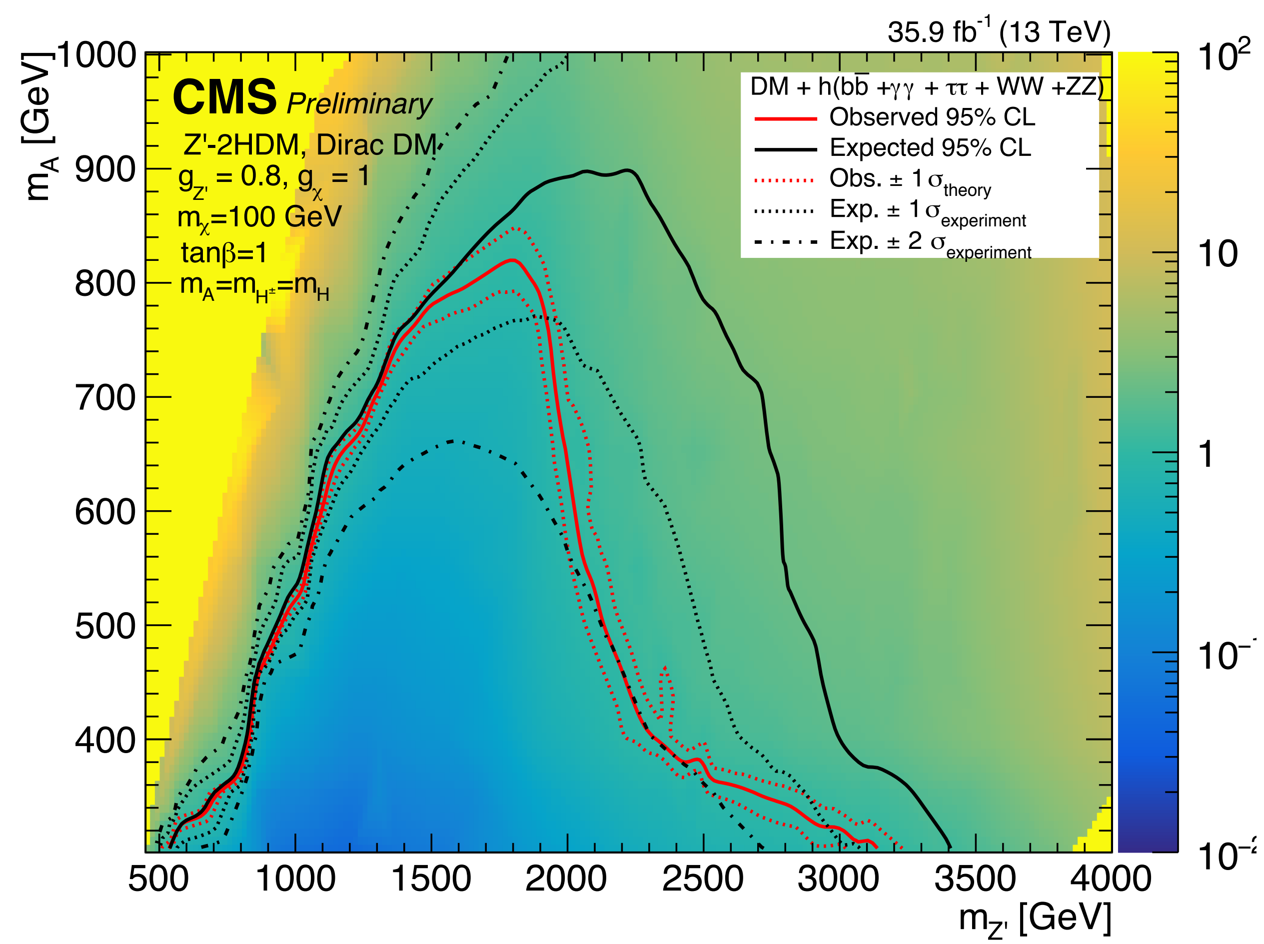
mono-Higgs: bb (high-boost), CMS

- *3 - Results:*
  - *results extracted from m_T(A(inv),H(bb)) distribution*
  - *syst. unc. included as nuisance parameters*
    - *dominating unc from bkg estimation/normalization*

mono-H(bb)

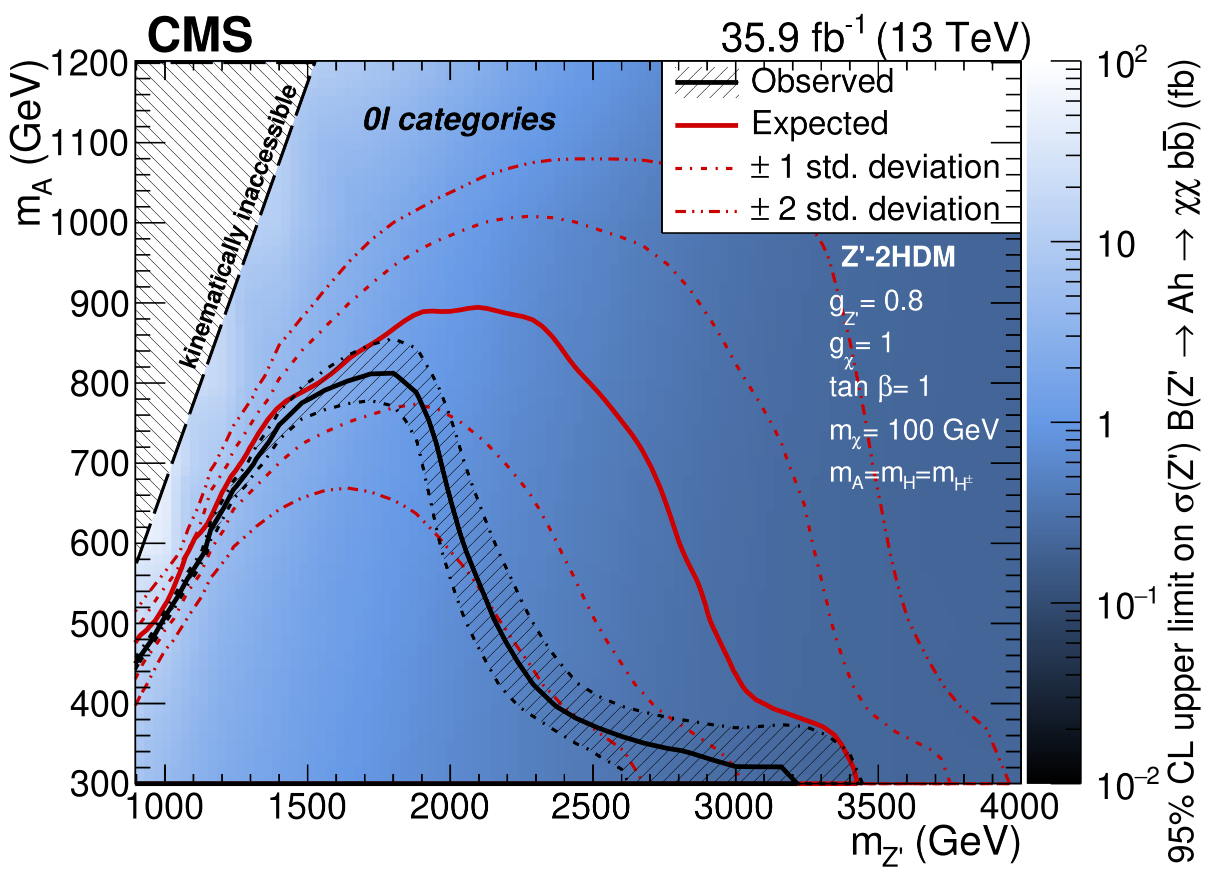


combination

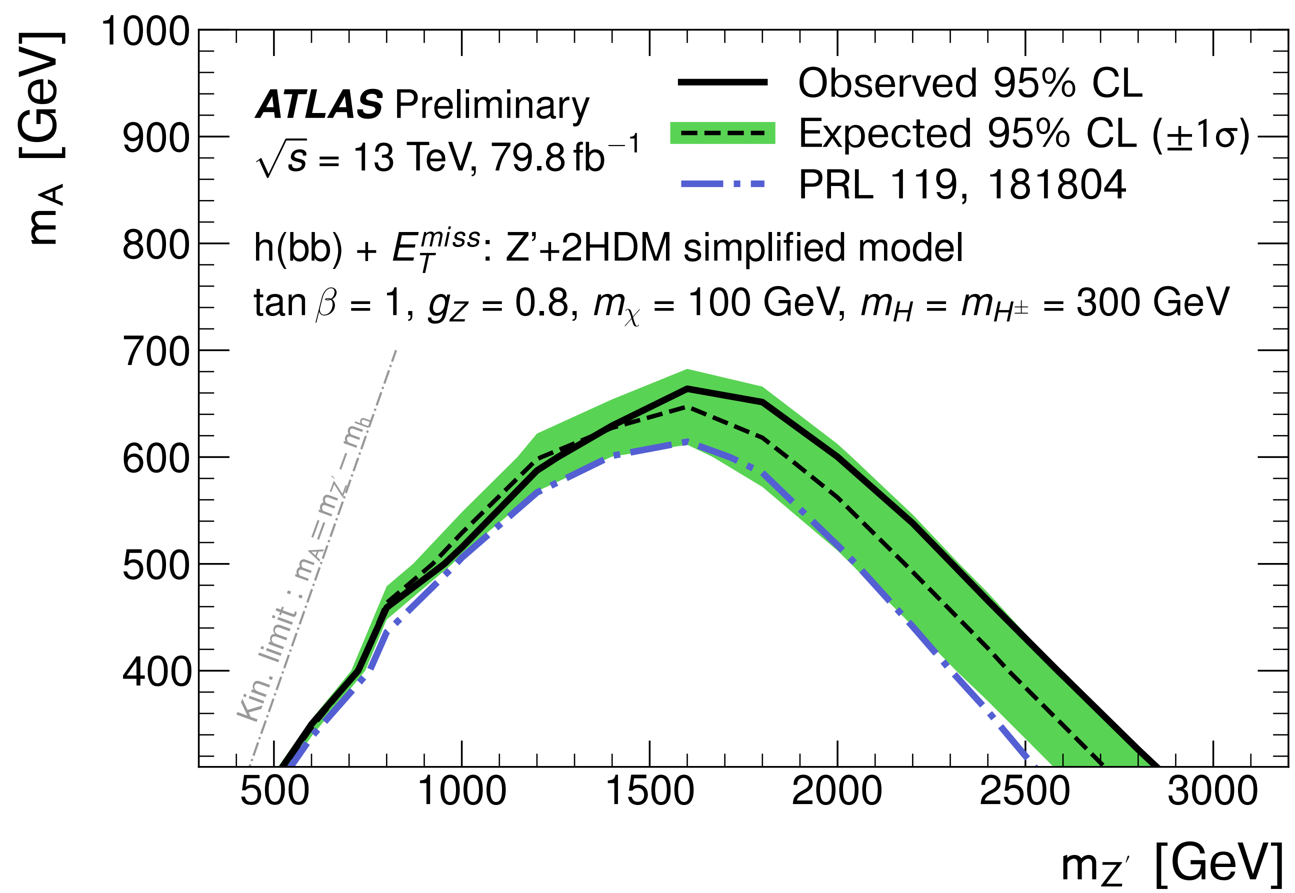


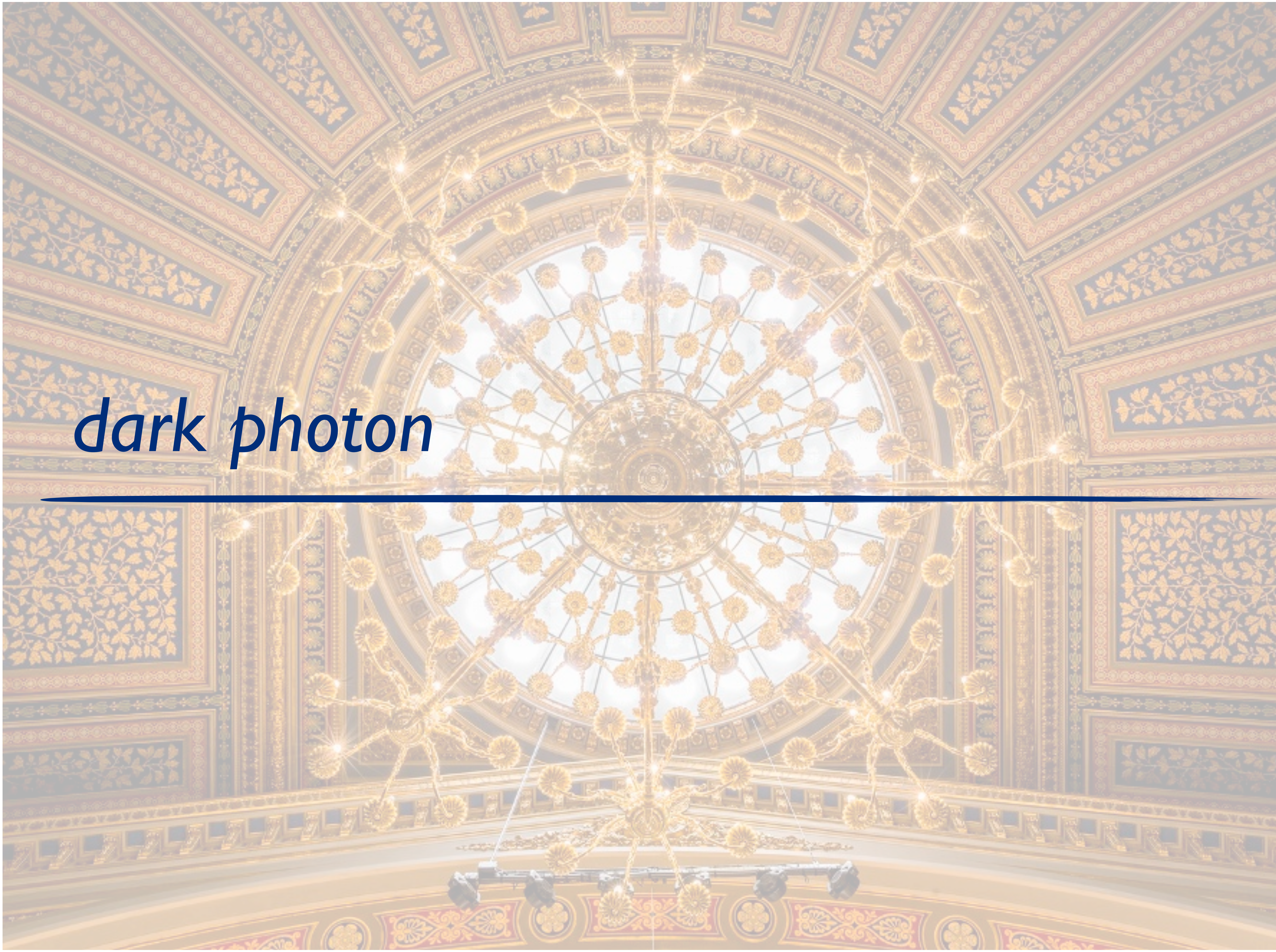
mono-Higgs: bb (Z'-2HDM)

CMS: high boost



ATLAS: resolved+high boost

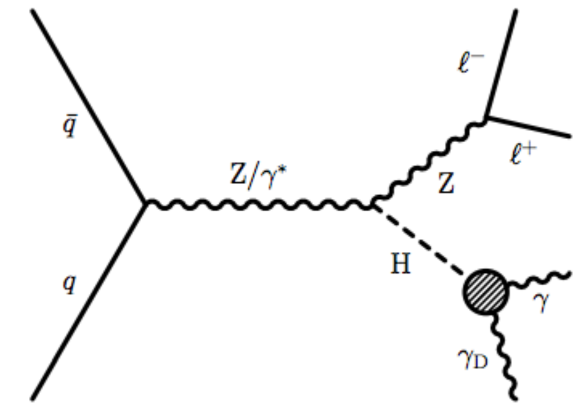




dark photon

Dark photon in Higgs decays

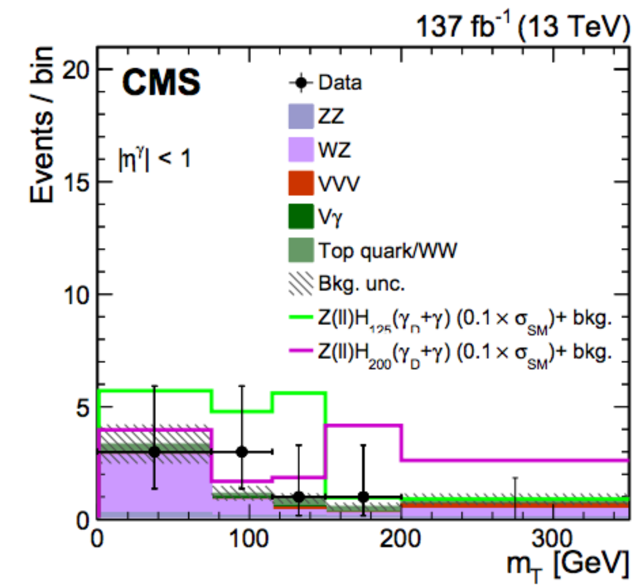
- *Several BSM models predict H decays to undetected particles and photons*
  - consider associated ZH production



- *Massless dark photon γ_D couples to H through a charged dark sector and escape undetected (MET signature)*
  - BR($H \rightarrow \gamma\gamma_D$) <5% consistent with all model parameters and LHC constraints
  - also heavy neutral H with masses [125, 300] GeV considered

- *1 - Selection:*
  - 2 opposite charge leptons same-flavor (ee,μμ), consistent with Z boson decay
  - ≥ 1 γ
  - MET > 110 GeV

- *2- Bkg:*
  - ***WZ, ZZ*** *main bkg from CRs*



- *3- Results: signal extracted fitting $m_T(\gamma,MET)$ in bins of $|\eta(\gamma)|$ using in SRs and CRs (systematic unc. as nuisance parameters)*