Invisible decay and constrains on BSM Higgs

Soshi Tsuno(KEK)

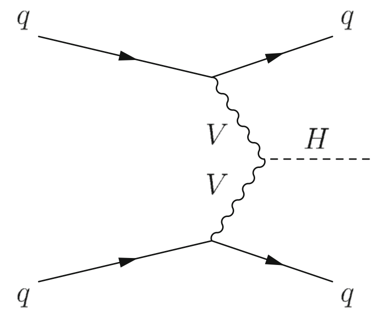
on behalf of the ATLAS and CMS Collaborations

Contents

VBF-production mode:

CMS : CMS-PAS-HIG-14-038

ATLAS : arXiv:1508.07869

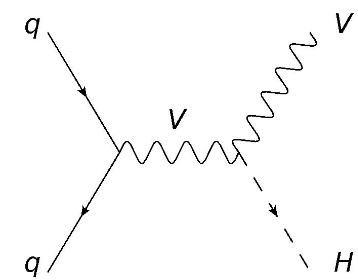


VBF-mode

VH-production mode:

CMS : Eur.Phys.J.C (2014) 74:2980

ATLAS : Eur.Phys.J.C (2015) 75:337

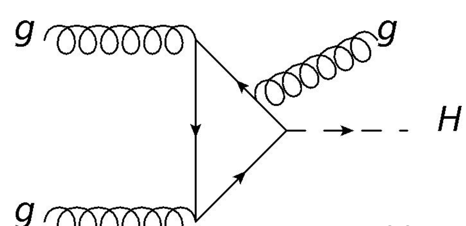


V(->jj/ll)H-mode

ggH (mono-jet)-mode:

CMS : CMS-PAS-EXO-12-055

ATLAS : Eur.Phys.J.C (2015) 75:299
Eur.Phys.J.C (2015) 75:408 (Erratum)



ggH-mode

Combination:

CMS : CMS-PAS-HIG-15-012

ATLAS : arXiv:1509.00672

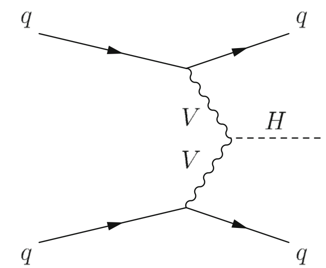
Upgrade physics:

CERN-LHCC-2015-020

ATL-PHYS-PUB-2014-007

Monte Carlo samples

VBF-mode



Signal modeling :

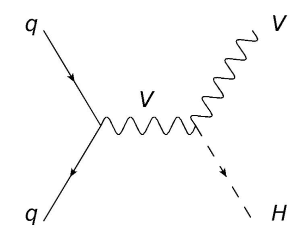
VBF-mode :

- CMS : Powheg (**LO**, CTEQ6L1)
- ATLAS : Powheg-Box (**NLO**, CT10, pT-reweight by HAWK2.0)

VH-mode :

- CMS : Pythia 6 (**LO**, CTEQ6L1)
- ATLAS : Powheg(Herwig++) (**NLO**, CT10)

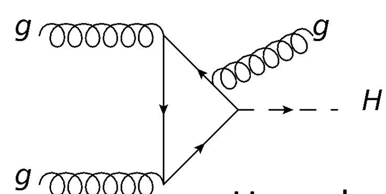
Z(->inv.)H->bb mode is treated as background



V(->jj/ll)H-mode

ggH (mono-jet) -mode :

- CMS : Powheg (p_T-rewighted to NLO)
- ATLAS : Powheg-Box (NLO, p_T-reweighted to NNLO+NNLL)



ggH-mode

Cross section (normalization) :

- LHC Higgs Cross Section Working Group (YR1/2)

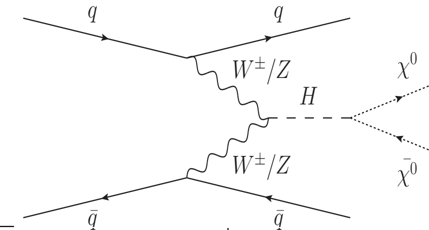
Backgrounds :

W/Z + jets : Sherpa (ATLAS) / MarGraph (CMS)

top : Powheg-Box (ATLAS) / MadGraph (CMS)

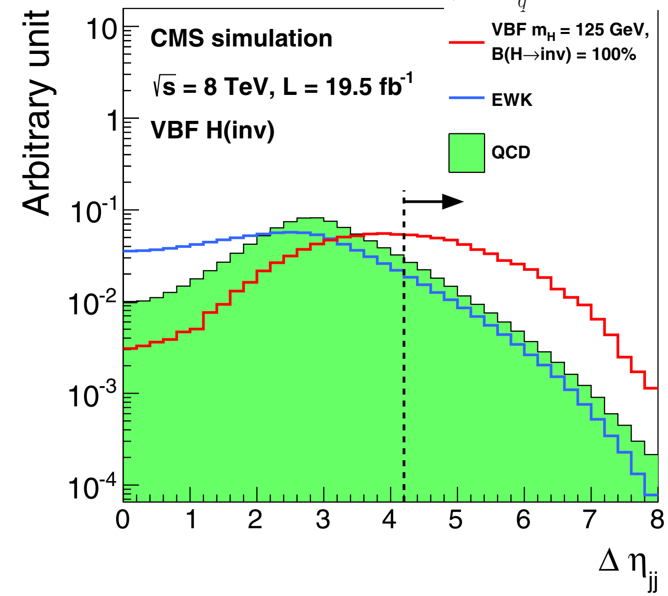
Use data-driven approach as much as possible.

Vector Boson Fusion mode



Unique topology : MET + VBF-jets

- Large Missing E_T (MET)
- Two jets in opposite direction with
  - large separation in eta
  - large di-jet mass.



Analysis strategy :

- CMS : **VBF-trigger**
  - MET > 65 GeV + 2 jets (> 40 GeV)
  - $\Delta\eta$ > 3.5 + M_{jj} > 800 GeV

loose MET but tight VBF selection
- higher yield for VBF production mode,
- lower for ggH mode.

- ATLAS : **MET trigger** > 80 GeV

tight MET but loose VBF selection
- relatively lower for VBF,
- but also save ggH mode.

Event selection

CMS :

- MET > 90 GeV
- $\Delta\eta > 3.6$, $M_{jj} > 1200$ GeV,
- $\Delta\phi$(MET,jet) > 2.3, METSig(*) > 4

(*) MET significance is defined as $\frac{\text{MET}}{\sqrt{\Sigma\,\text{E}_\text{T}}}$

Process	Event yields
$Z \to \nu\nu$	$158.1 \pm 37.3 \pm 21.2$
$W \to \mu\nu$	$102.5 \pm 6.2 \pm 11.7$
$W \to e\nu$	$57.9 \pm 7.4 \pm 7.7$
$W \to \tau\nu$	$94.6 \pm 13.1 \pm 23.8$
top	5.5 ± 1.8
VV	3.9 ± 0.7
QCD multijet	17 ± 14
Total Background	$439.4 \pm 40.7 \pm 43.5$
Signal(VBF)	273.1 ± 31.2
Signal(ggH)	23.1 ± 15.9
Observed data	508

ATLAS :

- MET > 150 GeV
- $\Delta\eta > 4.8$, $M_{jj} > 1000$ GeV,
- $\Delta\phi$(MET,jet) > 1.6 for j1, otherwise >1
- $\Delta\phi$(j,j) < 2.5, 3rd Jet Veto ($p_T > 30$ GeV)

enhance VBF mode

These categories are less sensitive.

Signal region Process	SR1	SR2a	SR2b
ggF signal	20± 15	58± 22	19± 8
VBF signal	286± 57	182± 19	105±15
$Z(\to \nu\nu)$+jets	339± 37	1580± 90	335±23
$W(\to \ell\nu)$+jets	235± 42	1010± 50	225±16
Multijet	2± 2	20± 20	4± 4
Other backgrounds	1±0.4	64± 9	19± 6
Total background	577± 62	2680±130	583±34
Data	539	2654	636

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(*) MET significance is defined as MET

Signal fraction (VBF v.s. ggH) is similar.

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This cut provides further QCD reduction.

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Multi-jet background is very different.

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VBF mode

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Background estimation

Dominant background:

Z(νν)+jet, W(lν)+jets

Background estimation:

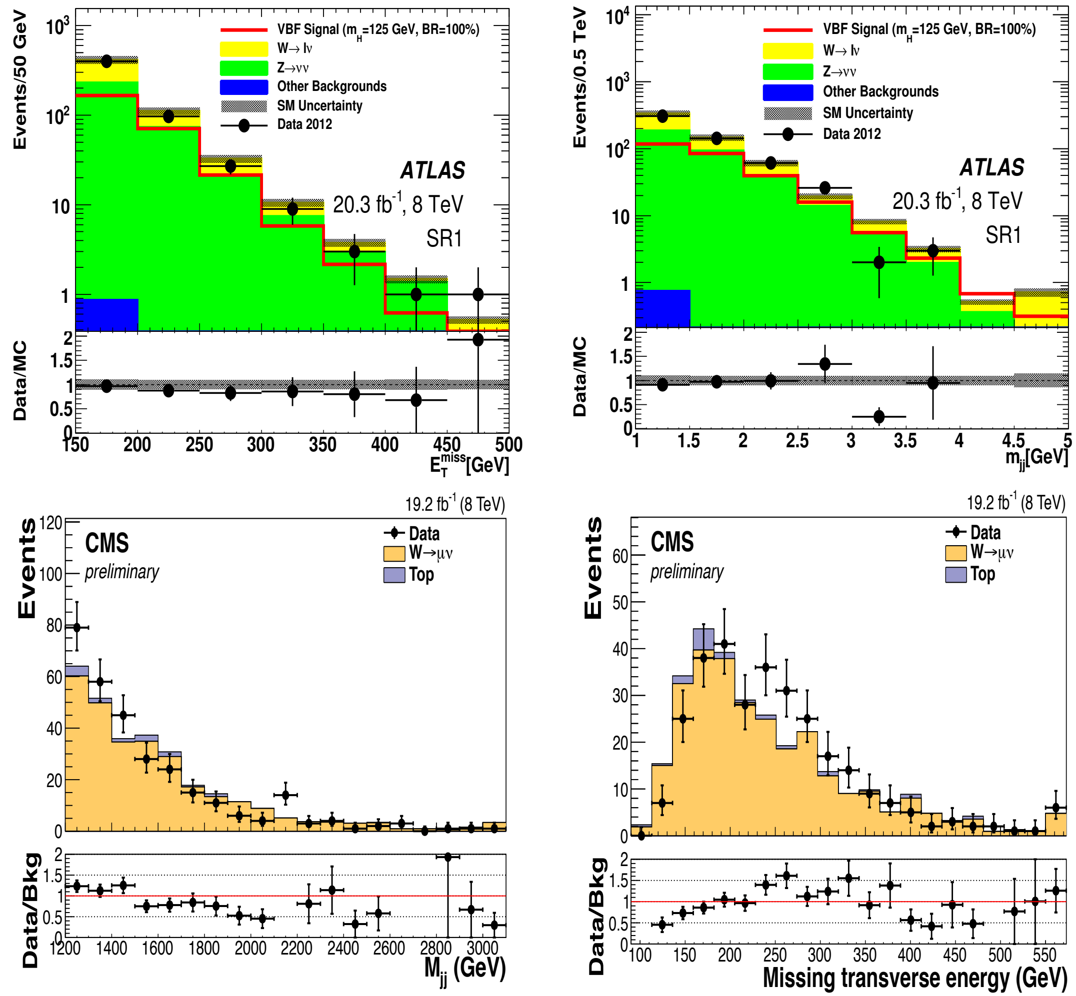
W/Z + jets :

- construct W/Z+jets control region. (tag leptons, M_T)
- normalization from BR ratio.
- use shape from MC.

Multi-jets :

- so-called Matrix or ABCD method
  (shape) : MET v.s 3rd jet
  (normalization) : MET v.s. Δϕ

Others (top/WW) : simulation



Final discriminant : MET and M_{jj}

Systematics

ATLAS uncertainties due to JET energy scale / theory prediction (3rd jet) are larger.

(3rd jet veto)

CMS uncertainty

Source	Total background	Signal
Control region data stat.	9.3	-
MC stat.	5.4	3.8
Jet energy scale	4.6	11
$W \to \tau\nu$ control region extrapolation	4.3	-
QCD normalisation (ATLAS:QCD100%)	3.2	-
Jet energy resolution	3.0	1.8
Lepton ID efficiency	2.4	-
Unclustered energy scale	1.9	1.6
Pileup weight	1.1	1.5
Top MC scale factor unc.	0.25	-
Luminosity	0.02	2.6
QCD scale, PDF and cross section uncertainties	0.01	5.2

ATLAS signal uncertainty

Uncertainty	VBF	ggF
Jet energy scale	16 9	43 12
Jet energy resolution	Negligible 3.1	Negligible 3.2
Luminosity	2.8	2.8
QCD scale	0.2	7.8
PDF	2.3 2.8	7.5
Parton shower Veto on third jet	4.4	41 29
Higgs boson p_T	Negligible	9.7
MC statistics	2 0.6	46 13

Systematics

ATLAS uncertainties due to JET energy scale / theory prediction (3rd jet) are larger.

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CMS uncertainty

Source	Total background	Signal
Control region data stat.	9.3	-
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PDF	2.3 2.8	7.5
Part[illegible]	4.4	41
V[illegible]on third jet		29
Higgs boson p_T	Negligible	9.7
MC statistics	2 0.6	46 13

LO v.s. NLO

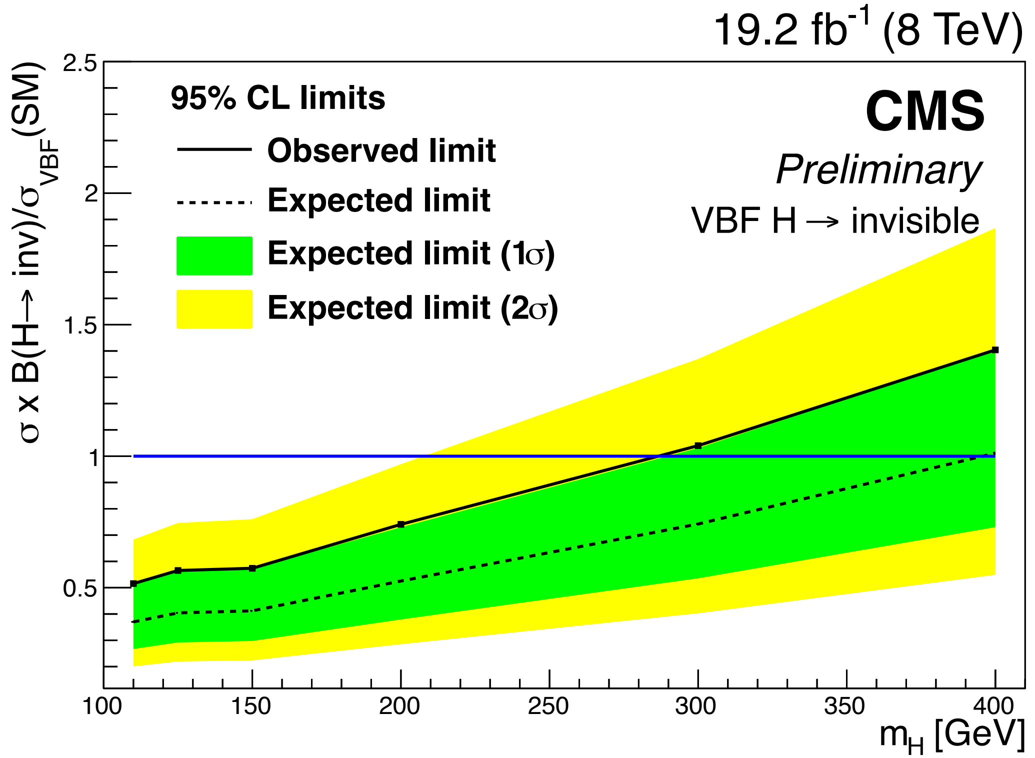
Limit on BR(H->invisible)

Assuming SM cross section (VBF) at m_H = 125 GeV,

CMS : BR(95%CL) < 0.57 (exp. 0.40)

ATLAS : BR(95%) < 0.30 (exp. 0.35)

Note: coupling strength k_V = 1 is assumed.



ATLAS limit

Results	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ	Observed
SR1 (VBF)	0.35	0.49	0.25	0.67	0.19	0.30
SR2 (ggH)	0.60	0.85	0.43	1.18	0.32	0.83
Combined Results	0.31	0.44	0.23	0.60	0.17	0.28

ggH category is not so sensitive.

No deviation seen from SM expectation.

Associated production mode (VH)

Categorize by Z-decay mode :

- Z -> ll (lepton triggers)
- Z -> jet jet (incl. b-jet) (MET triggers)

Dominant background :

- W/Z + jets (similar technique as VBF-analysis)
- ZZ / WZ (simulation)

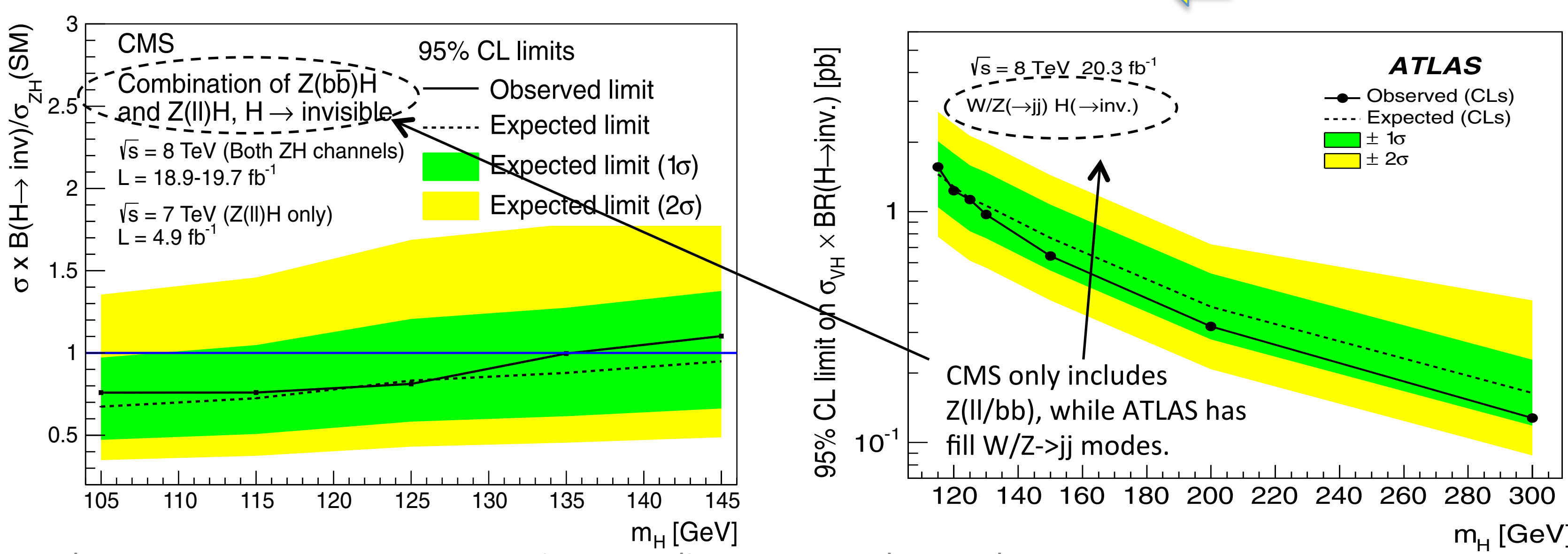
Event selection :

- optimize $\Delta\phi$(MET, jet)
- categorize by # of b-jets and MET

Final discriminant :

- CMS : BDT score
- ATLAS : MET and $p_T(V)$

Limit of BR(H->invisible) : CMS:0.81(0.83) ATLAS : 0.78 (0.86) ⇦ weaker than VBF-mode



ggH (mono-jet)-mode

Trigger :

- CMS : MET (>120) and Mono-jet (p_T > 80GeV)
- ATLAS : MET > 80 GeV

Event selection:

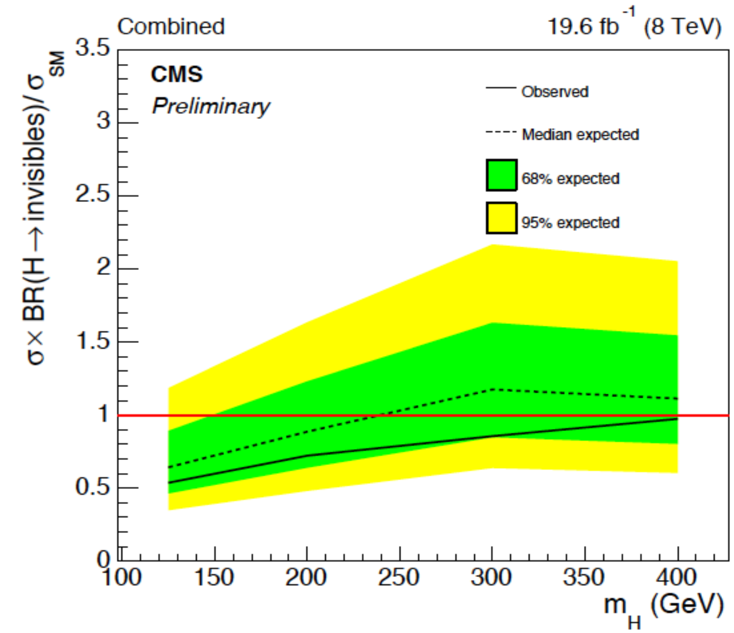
- CMS : MET > 200 GeV, jet p_T > 150 GeV,
  veto event if >2 jets (p_T > 30GeV, $|\eta|$<2.5)
- ATLAS : MET > 250 GeV, $\Delta\phi$(MET,jet) > 1.0,
  leading jet p_T > 120 GeV, p_T/MET > 0.5

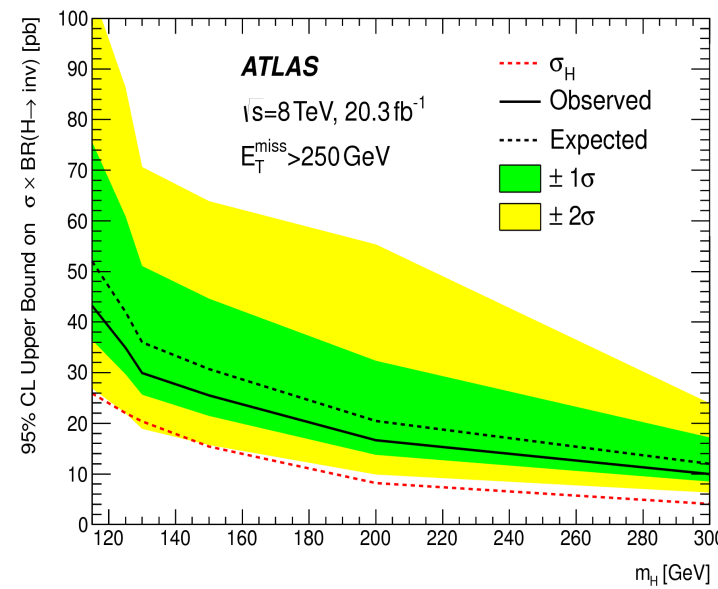
Dominant background :

- Z($\nu\nu$) + jet (similar technique as VBF-analysis)

Limits at m_H = 125 GeV :

- CMS : BR(H->inv.) < 0.53 (0.62)
- ATLAS : σ x BR(H->inv.) < 1.59 (1.91)



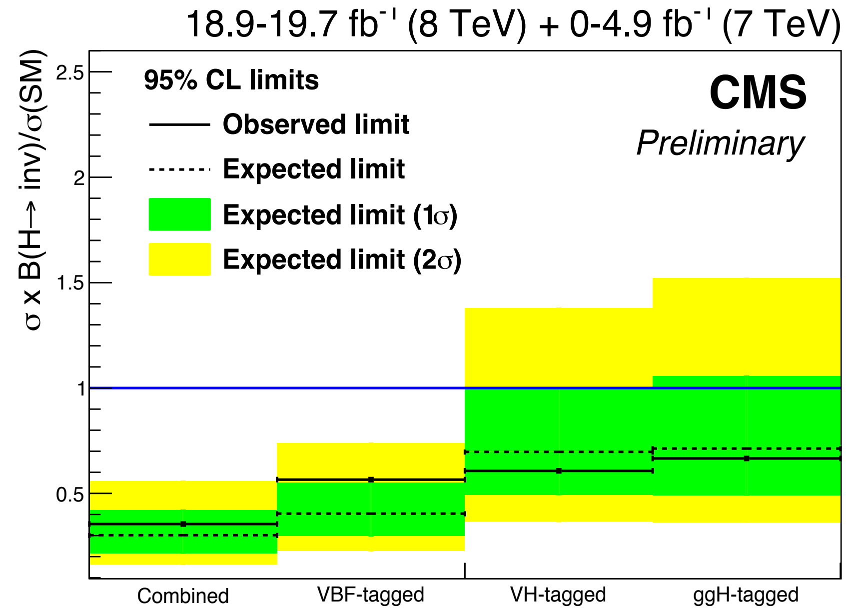


Rather sensitive to higher mass Higgs.

Summary of BR(H->inv.) limit

BR(H->inv.) Limit @m_H = 125 GeV

	ATLAS	CMS
VBF-mode	0.30 (0.35)	0.57 (0.40)
ggH-mode	0.83 (0.60)	0.67 (0.71)
VH-mode	0.78 (0.86)	0.60 (0.69)
Combined	0.25 (0.27)	0.36 (0.30)



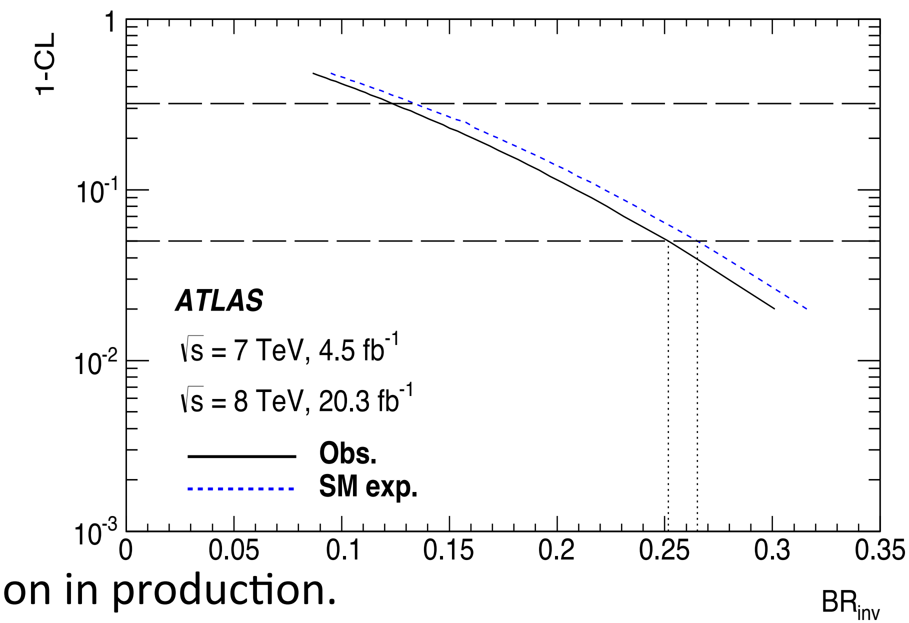
Constraint from visible analyses :

Combined with BR(H->visible; i:[k_W, k_Z , k_f …])

$$\kappa_h^2 = \Gamma_h/\Gamma_{h,\mathrm{SM}} = \sum_j \kappa_j^2 \mathrm{BR}_j/(1-\mathrm{BR}_{\mathrm{inv}})$$

ATLAS:

	Inv. + vis.
k_W , k_Z < 1	0.23 (0.23)
None	0.23 (0.24)



Visible decays allow to remove k_V = 1 assumption in production.

Constraint of Higgs portal to dark matter interactions

WIMP dark matter interacts through Nuclei recoil by Higgs :

$$\sigma^{\rm SI}_{\rm S-N} = \frac{4\Gamma_{\rm inv}}{m_{\rm H}^3 v^2 \beta} \frac{m_{\rm N}^4 f_{\rm N}^2}{(M_\chi + m_{\rm N})^2}$$

$$\sigma^{\rm SI}_{\rm V-N} = \frac{16\Gamma_{\rm inv} M_\chi^4}{m_{\rm H}^3 v^2 \beta (m_{\rm H}^4 - 4M_\chi^2 m_{\rm H}^2 + 12 M_\chi^4)} \frac{m_{\rm N}^4 f_{\rm N}^2}{(M_\chi + m_N)^2}$$

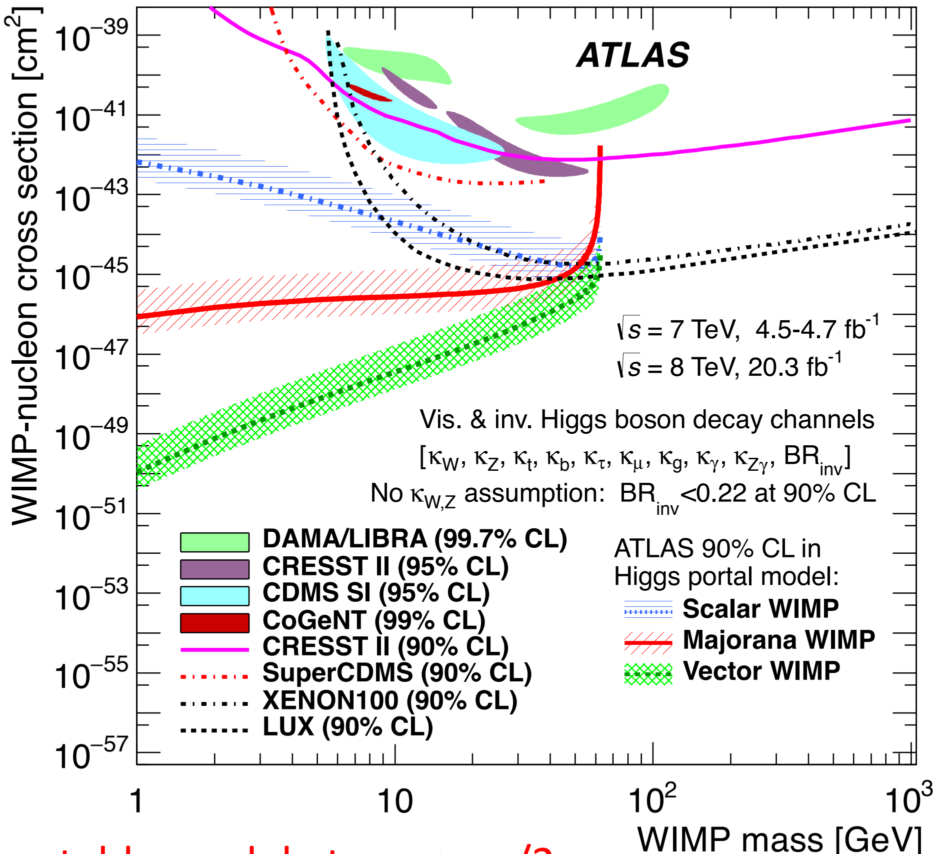
$$\sigma^{\rm SI}_{\rm f-N} = \frac{8\Gamma_{\rm inv} M_\chi^2}{m_{\rm H}^5 v^2 \beta^3} \frac{m_{\rm N}^4 f_{\rm N}^2}{(M_\chi + m_{\rm N})^2}$$

where

VEV: $\sqrt{2}v = 246\mathrm{GeV}$ $\beta_\chi = \sqrt{1 - 4m_\chi^2/m_h^2}$

m_N (proton mass) = 0.939GeV,

f_N (H-nucleon coupling) = 0.33+0.30-0.07



LHC is the most sensitive search for the Higgs portable model at $m_\chi < m_H/2$.

Prospect for low mass region

For "vector WIMP",

Current limit : λ_{hVV} = 0.013 @ BR = 0.2

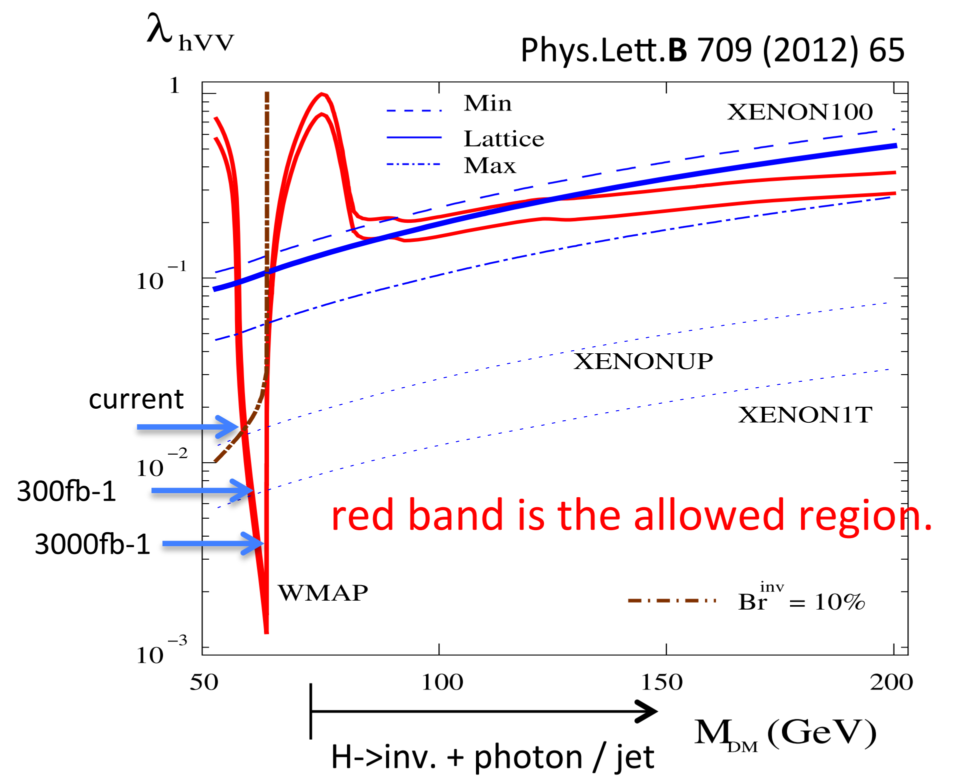
Simple scaling by the statistics :

λ_{hVV} = 0.0065 @ L = 300 fb^{-1}

0.0037 @ L = 3000 fb^{-1}

With 3000 fb^{-1} by simple scaling, "vector WIMP" can be excluded if $m_\chi < m_H/2$.

The scalar is most severe case…



Critical path :

requires to improve MET resolution

RMS ~ 10 GeV @ Run1 ⇨ 40 GeV @Run4 (2026, 3000fb^{-1}, μ=200) (Ref. ATLAS)

Single photon / (mono-)jet can explore high mass (> 60 GeV) region.

Prospect for high mass region

Accessible to high mass region using mono-jet search

Three scenario :

- MET > 400, 600, 800 GeV
  with leading jet p_T > 300 GeV

Suppose dominant background :

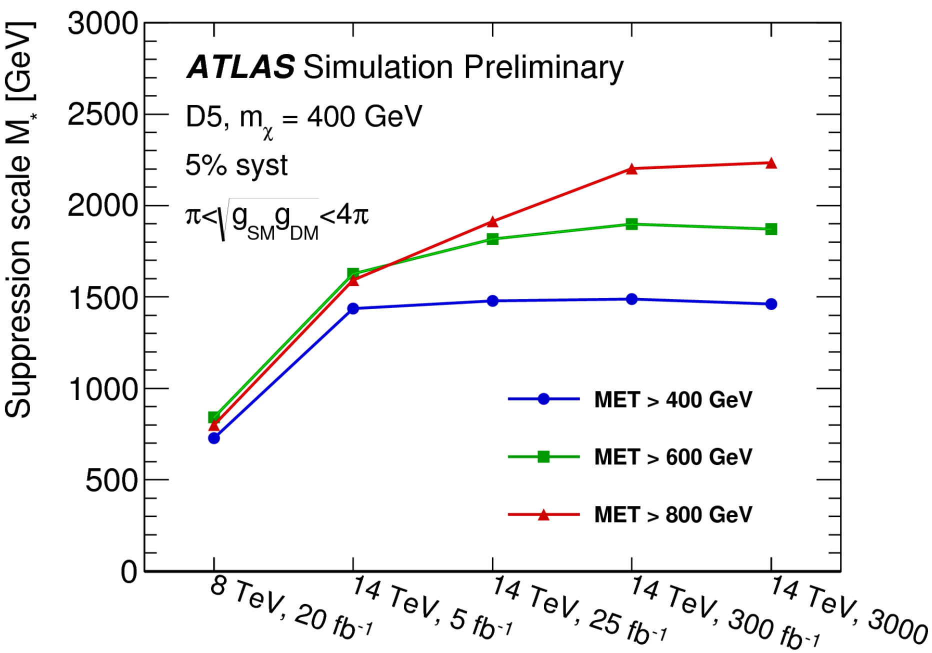
- <u>Z -> νν controlled under 5%</u>

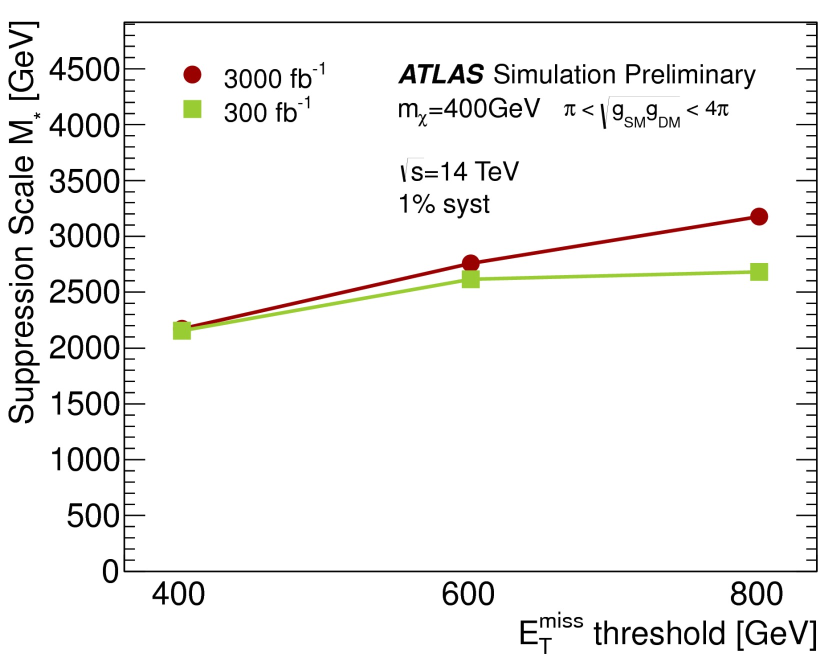
Suppression scale M* by EFT:

$$M^* = \frac{M_{med}}{\sqrt{g_{SM} g_{DM}}}$$

where, EFT is valid under

$$\pi < \sqrt{g_{SM} g_{DM}} < 4\pi$$ (checked stability of M*)





Prospect for high mass region

Accessible to high mass region using mono-jet search

Three scenario :

- MET > 400, 600, 800 GeV with leading jet p_T > 300 GeV

Suppose dominant background :

- Z -> νν controlled under 1%

Suppression scale M* by EFT:

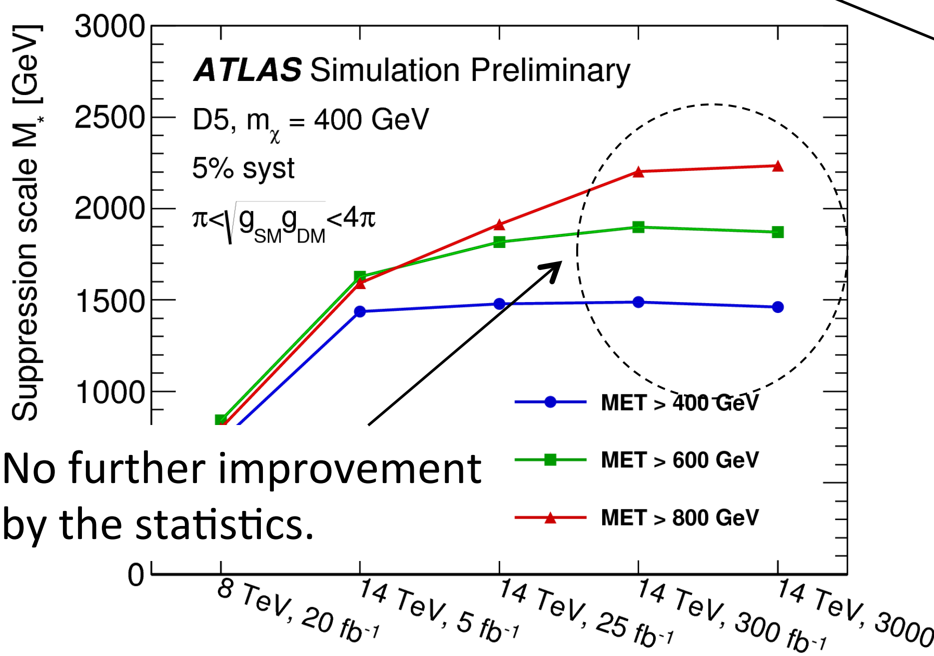
$$M^* = \frac{M_{med}}{\sqrt{g_{SM} g_{DM}}}$$

(This is not Higgs-portal scenario, but brings same experimental message.)

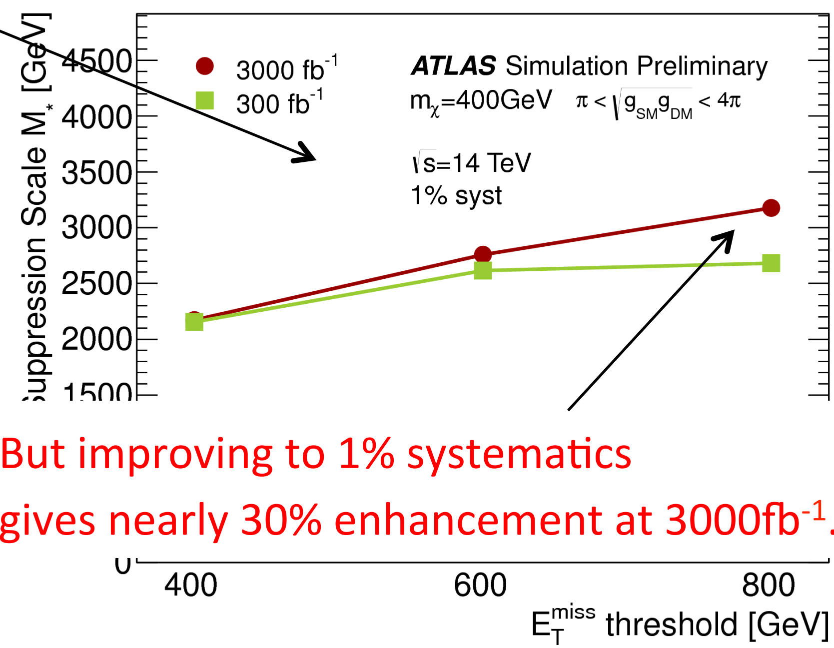
where, EFT is valid under

$$\pi < \sqrt{g_{SM} g_{DM}} < 4\pi$$

(checked stability of M*)



No further improvement by the statistics.



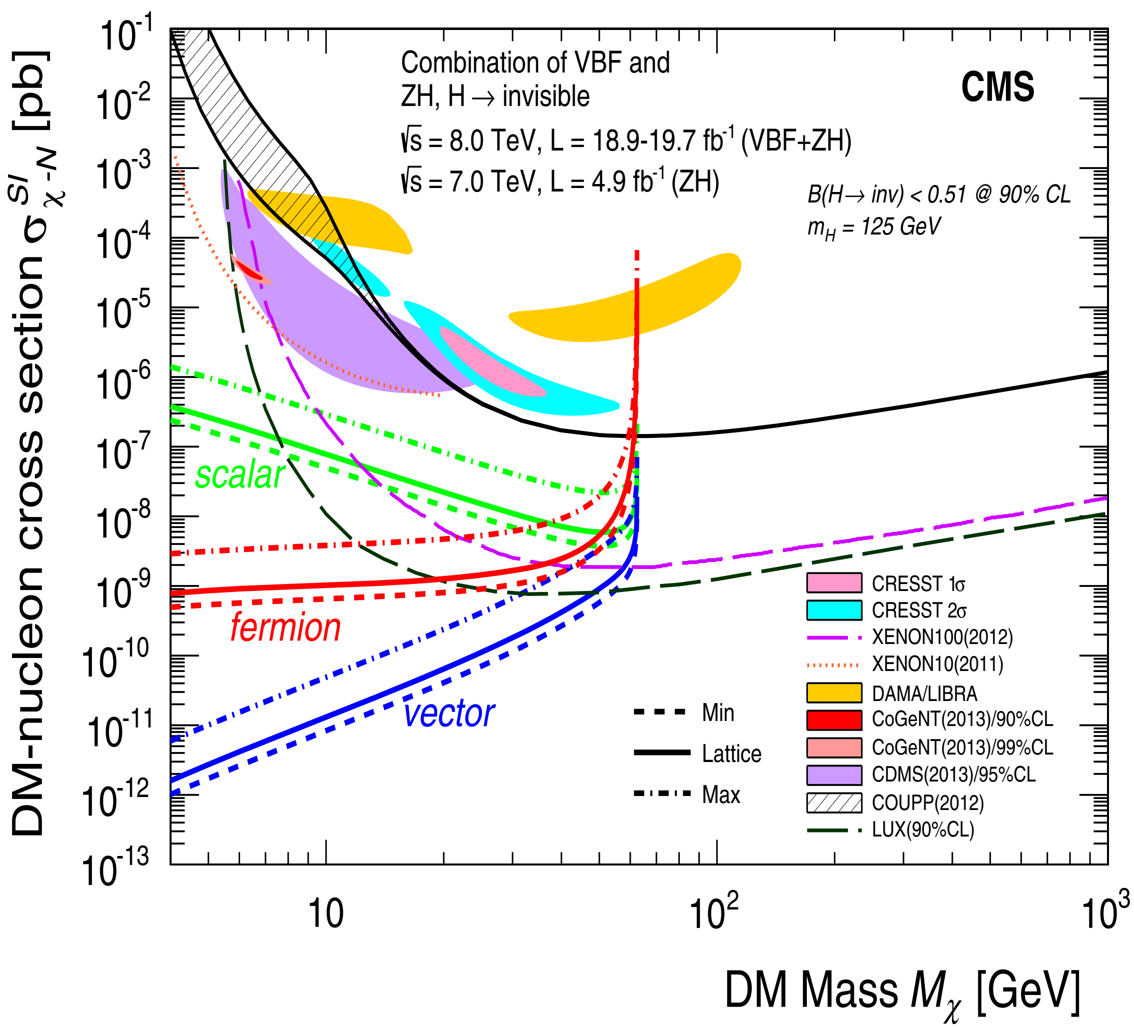
But improving to 1% systematics gives nearly 30% enhancement at 3000fb^{-1}.

Summary

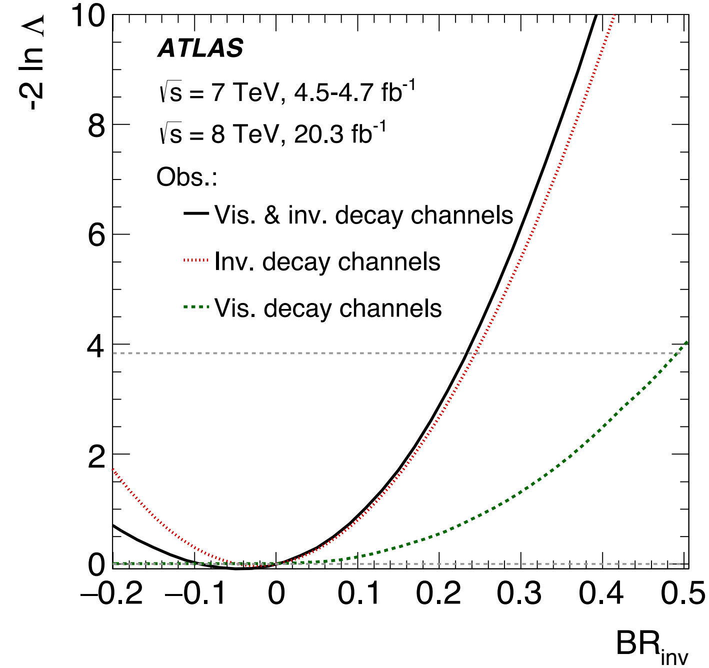
- VBF H->inv. is the most sensitive channel.
  - MET or VBF trigger is good.
  - Z H channel is significantly less sensitive.
  - Should improve MET resolution.
- "3rd jet veto" looks very powerful to reject QCD multi-jet events.
  - Theory uncertainty ?
  - Modeling systematics especially at higher pileup.
- LHC is the most powerful machine to search for DM if $m\chi < m_H /2$.
  - Supposing WMAP constraint, almost entire region is covered for vector WIMP scenario at $m\chi < m_H /2$.
  - MET should be improved for further extension to access higher mass region.

Backup

CMS dark matter result



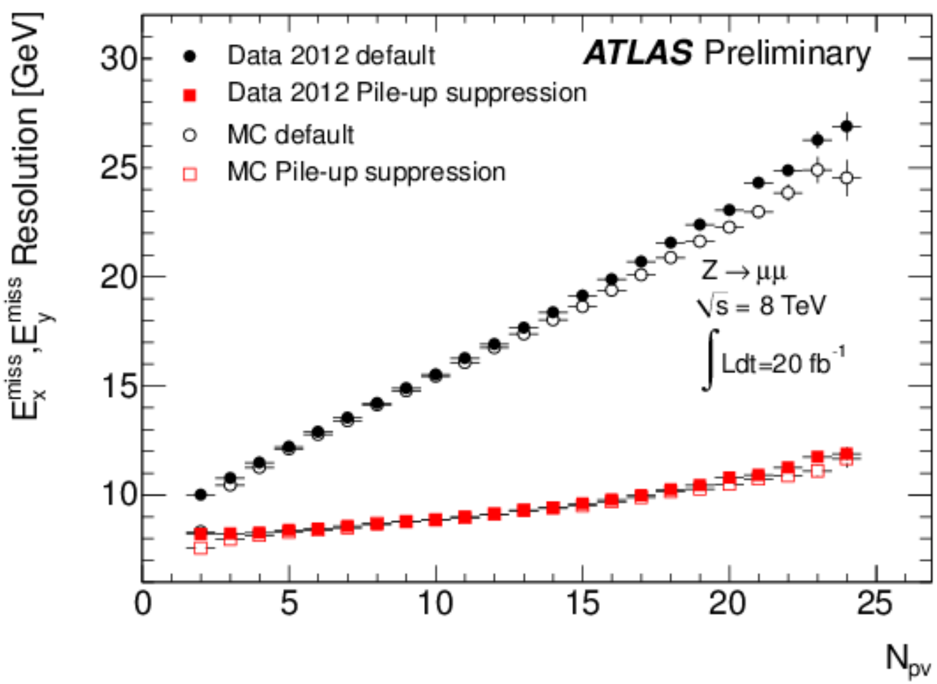
ATLAS Constraint from visible decay



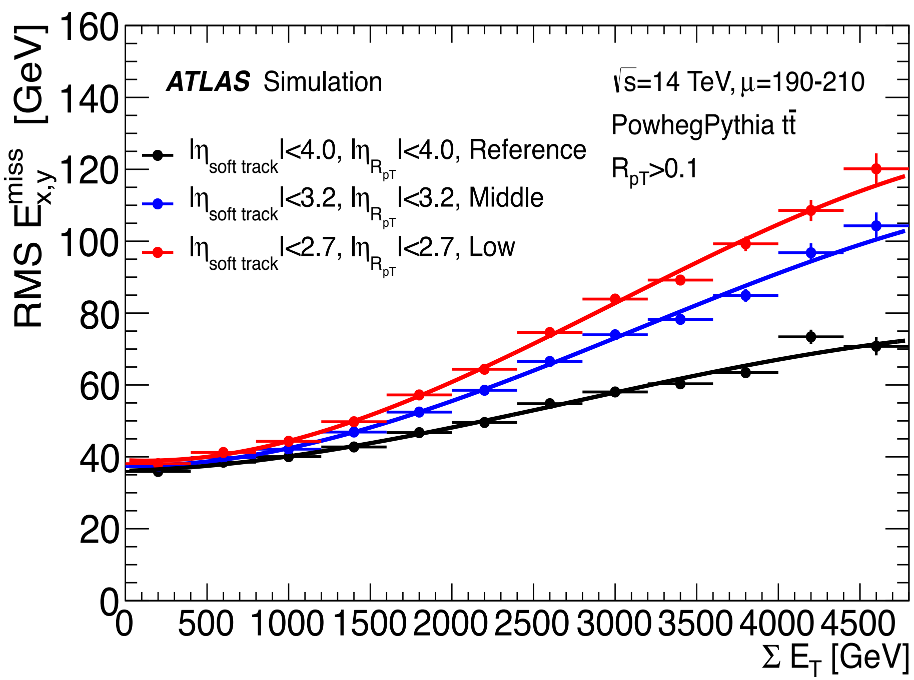
Higgs portal (Baseline config. of vis. & inv. Higgs boson decay channels: general coupling param., no assumption about $\kappa_{W,Z}$)	κ_Z	Z boson coupling s.f.	0.99 ± 0.15
	κ_W	W boson coupling s.f.	0.92 ± 0.14
	κ_t	t-quark coupling s.f.	$1.26^{+0.32}_{-0.34}$
	κ_b	b-quark coupling s.f.	0.61 ± 0.28
	κ_τ	Tau lepton coupling s.f.	$0.98^{+0.20}_{-0.18}$
	κ_μ	Muon coupling s.f.	< 2.25 at 95% CL
	κ_g	Gluon coupling s.f.	$0.92^{+0.18}_{-0.15}$
	κ_γ	Photon coupling s.f.	$0.90^{+0.16}_{-0.14}$
	$\kappa_{Z\gamma}$	$Z\gamma$ coupling s.f.	< 3.15 at 95% CL
	$\mathrm{BR}_{\mathrm{inv}}$	Invisible branching ratio	< 0.23 at 95% CL

ATLAS MET resolution

Run-1



Run-4



EFT validity test

Suppression scale M* by EFT:

$$M^* = \frac{M_{\mathrm{med}}}{\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}}}$$

where, EFT is valid under

$$\pi < \sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} < 4\pi$$

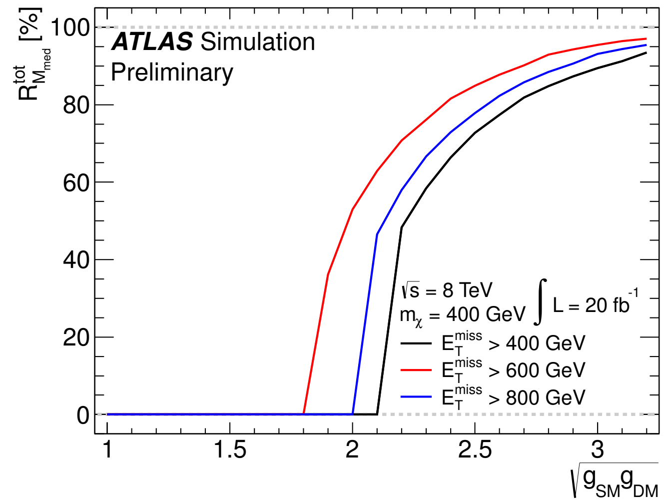
$Q_{\mathrm{tr}} < M_{\mathrm{med}}$ is typical scale of the production.

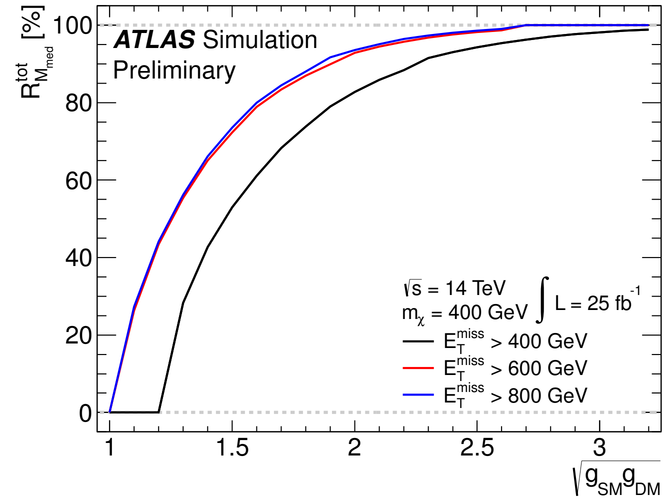
In this case, Q_{tr} is mass of $\chi\chi$ system that satisfies:

$$Q_{\mathrm{tr}} < \sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} M^*$$

Validity is tested how often event fails above formula given fraction of

$$\sigma_{\mathrm{valid}}(M^*) = \sigma_{\mathrm{full}}(M^*) \cdot R^{\mathrm{tot}}_{M_{\mathrm{med}}}(M^*)$$





For given range: $\pi < \sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} < 4\pi$

R = 100%.