The invisible Higgs: newest results of CMS

Olivier Davignon
(**LLR** - CNRS-IN2P3 & École Polytechnique)
for the CMS Collaboration

Higgs Hunting
September 13th, 2022

Introduction

- **H(125) to invisible decays very small in the SM**

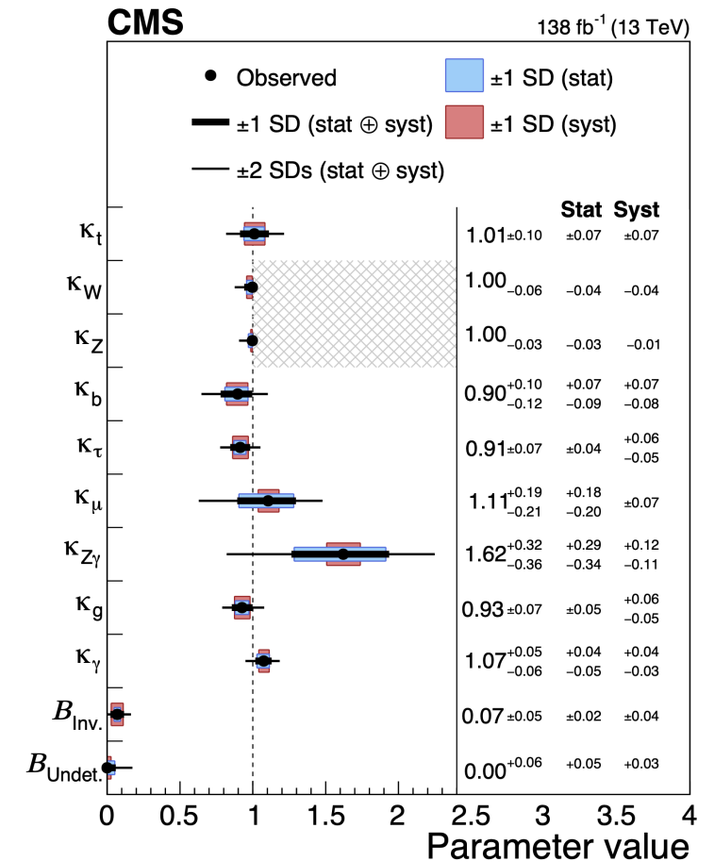
  SM $\mathcal{B}(H \to ZZ^* \to 4\nu) \sim 0.1\%$

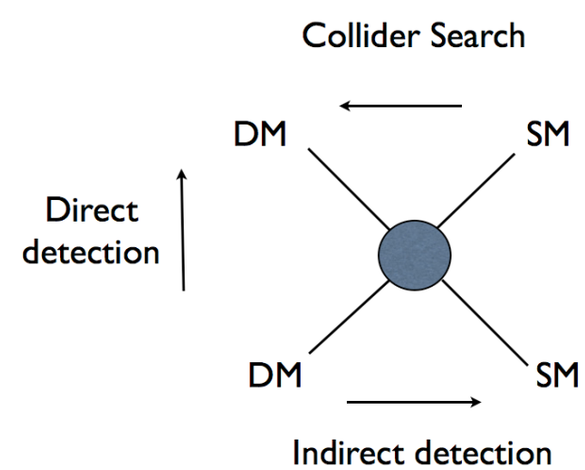
- **Direct searches + indirect constraints**: most recent result from CMS has a best fit $\mathcal{B}(H \to \text{inv.}) \sim 7\% \pm 5\%$ (compatible with 0)

- Several models predict an enhancement in invisible decays, e.g. if Higgs serving as/contributing to a **SM ↔ DM connection**
  - H(125) could decay to a pair of fermion/scalar/vector DM particles
  - There could be a Dark Higgs sector with mixing to the SM Higgs sector

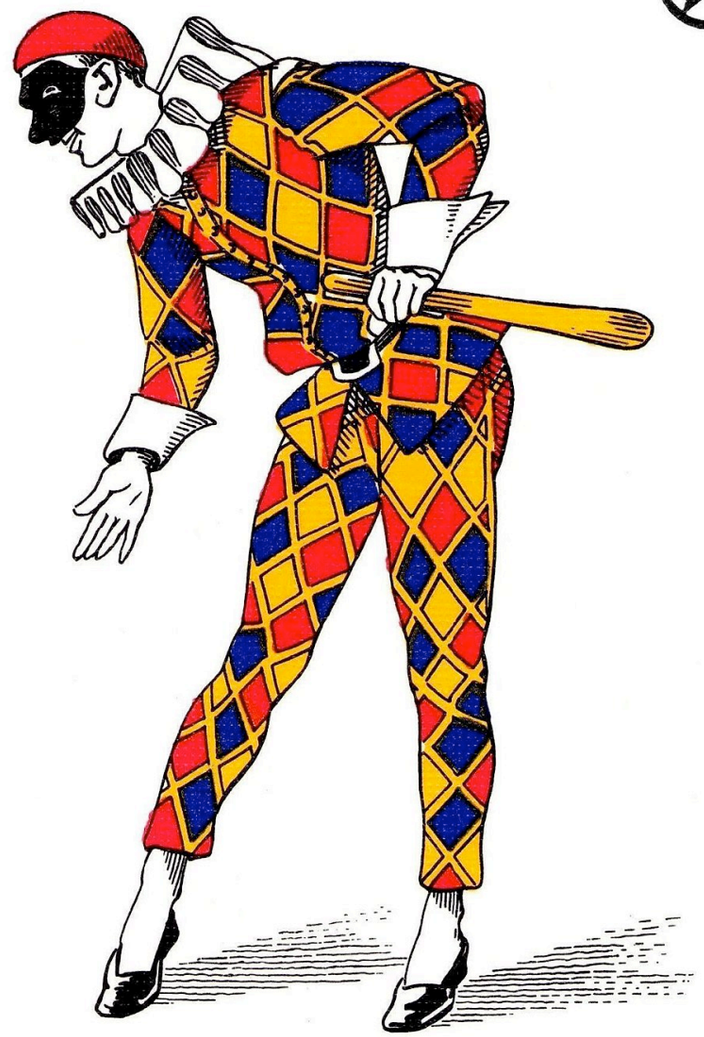
- **H→invisible searches at the LHC**
  - Complementary to direct DM searches
  - Observable production would be a very exciting sign of New Physics
  - Direct searches using MET+X signatures and their combination: subject of this talk

HIG-22-001
Nature 607 (2022) 60



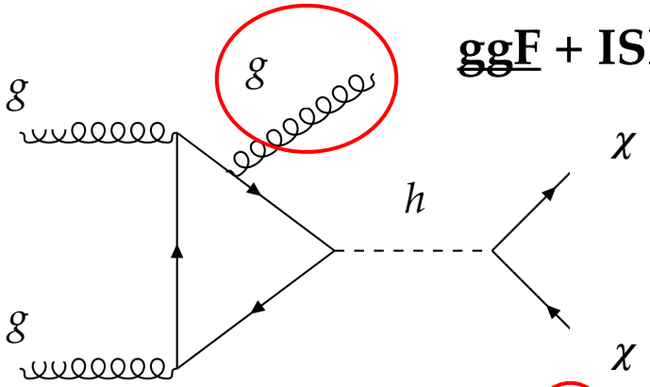


Olivier Davignon

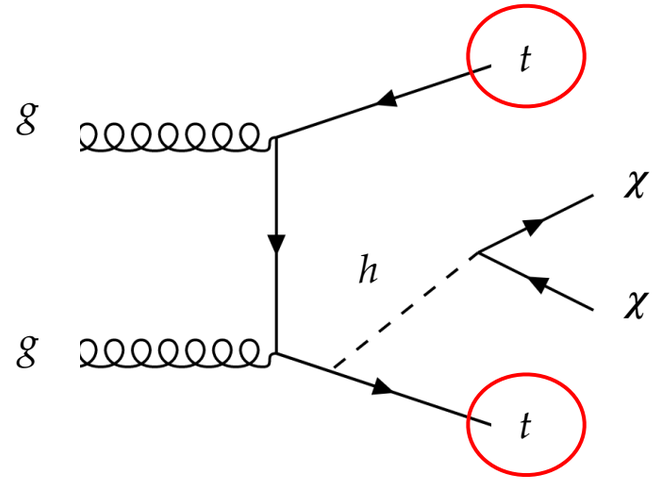


JOKER

The Higgs to invisible searches in CMS

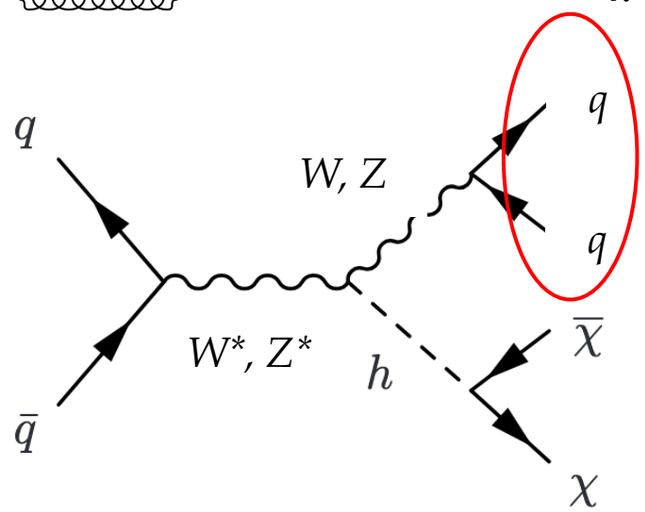


ggF + ISR → MonoJet



ttH

→ ttH semi leptonic
→ ttH fully leptonic
→ ttH hadronic

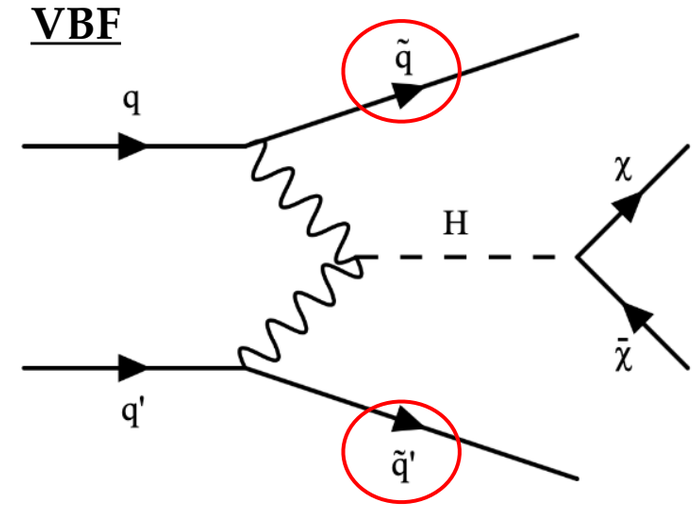


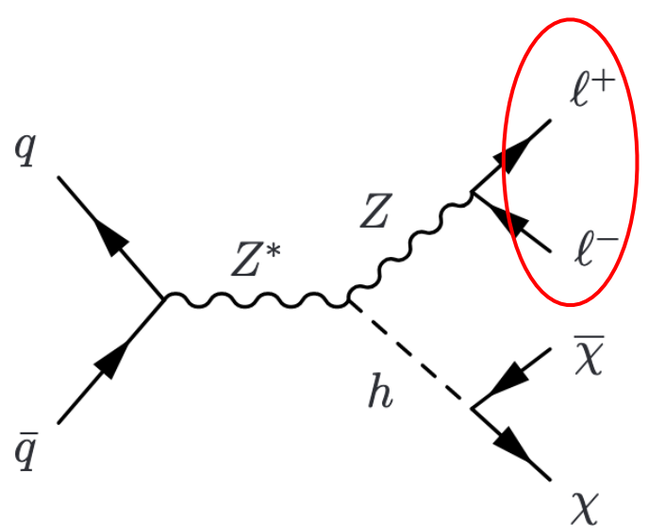
VH hadronic

Resolved qq pair → VH resolved

Unresolved qq pair → MonoV

VBF





ZH leptonic → (Z→ℓℓ)H

All major Higgs production modes and final states covered by CMS

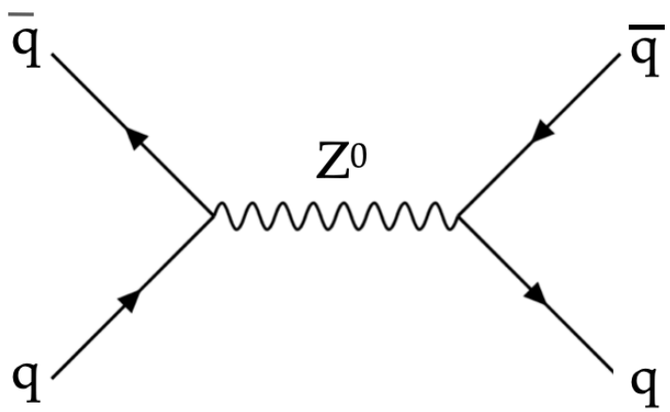
Olivier Davignon

The Higgs to invisible searches in CMS

Final state	Reference	Lumi
MonoJet	EXO-20-004 JHEP 11 (2021) 153	140 fb^{-1}
MonoV		
$(Z \to \ell\ell)H$	EXO-19-003 Eur. Phys. J. C 81, 1 (2021) pp.13	140 fb^{-1}
VBF	HIG-20-003 Phys. Rev. D 105 (2022) 092007	140 fb^{-1}
ttH semi leptonic	SUS-19-009 JHEP 05 (2020) 032	138 fb-1
ttH fully leptonic	SUS-19-011 Eur. Phys. J. C 81 (2021) 3	138 fb-1
ttH hadronic	NEW! **HIG-21-007**	138 fb^{-1}
VH hadronic resolved		
Combination of all channels		Up to 140 fb^{-1} @ 13 TeV Up to 24.6 fb^{-1} @ 7&8 TeV

Olivier Davignon

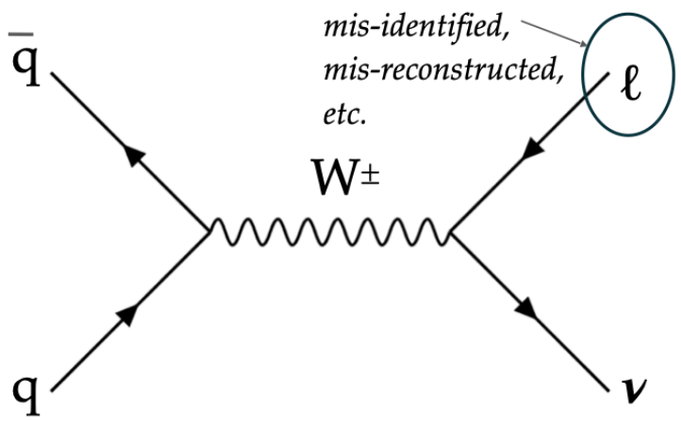
Background estimation



Z→ νν + jets → irreducible background

- Estimated along with VV and smaller bkgs using:
  - *Double-lepton control regions*, where the leptons are turned into sources of missing momentum
  - *Single-photon control region*, where the photon is turned into a source of missing momentum

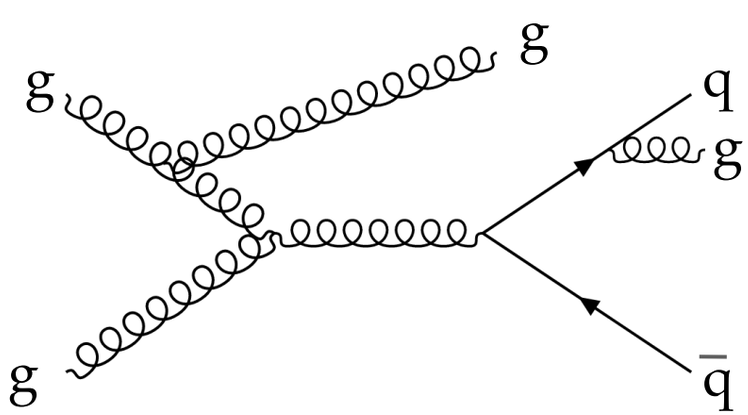
  + transfer factors used in simultaneous fit with the signal region



W→ ℓν + jets → "lost lepton" background

- Estimated along with leptonic top and smaller bkgs using:
  - *Single-lepton control regions*, where the lepton is turned into a source of missing momentum

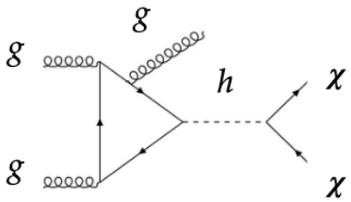
  + transfer factors used in simultaneous fit with the signal region



QCD multijet → reducible background

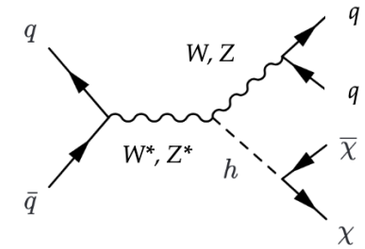
- Can be due to mismeasurements of jets energies, detector noise, etc. Reduced through dedicated selections & estimated using:
  - *QCD control regions*, and transfer factors

Olivier Davignon



MonoJet & MonoV search (1/2)

EXO-20-004 JHEP 11 (2021) 153



Experimental signature & selections

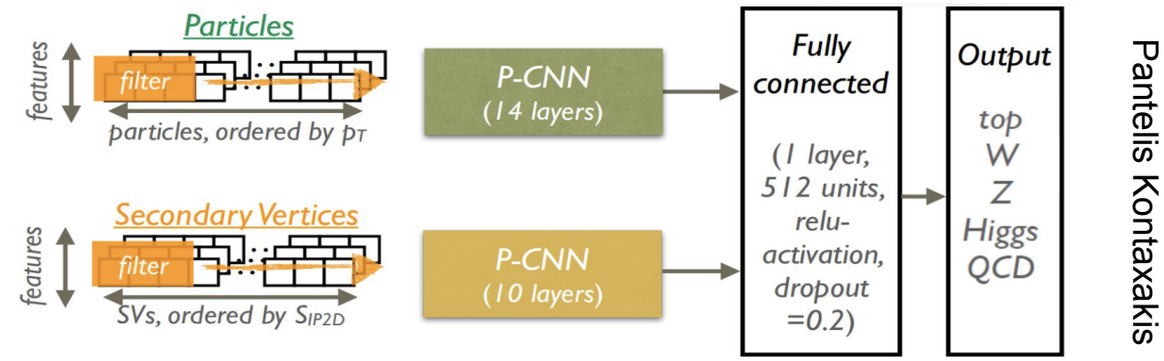
- Trigger on p_T^{miss} and H_T^{miss}
- High-p_T & central jet $|\eta| < 2.4$:
  - MonoV: AK8 $p_T > 250$ GeV
  - MonoJet: AK4 $p_T > 100$ GeV
- $p_T^{miss} > 250$ GeV
- Suppress QCD multijet background through $\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{j}) > 0.5$ cut
- Veto on leptons, photons, b-jets

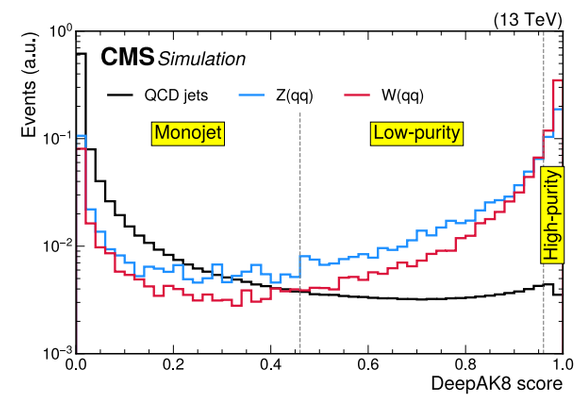
Jet tagging

- Events with an AK8 jet with $p_T > 250$ GeV that pass certain DeepAK8 score and m_{SD} cuts are assigned to one of the two MonoV categories (low or high purity)
- Events without such jet are assigned to MonoJet

Background estimation

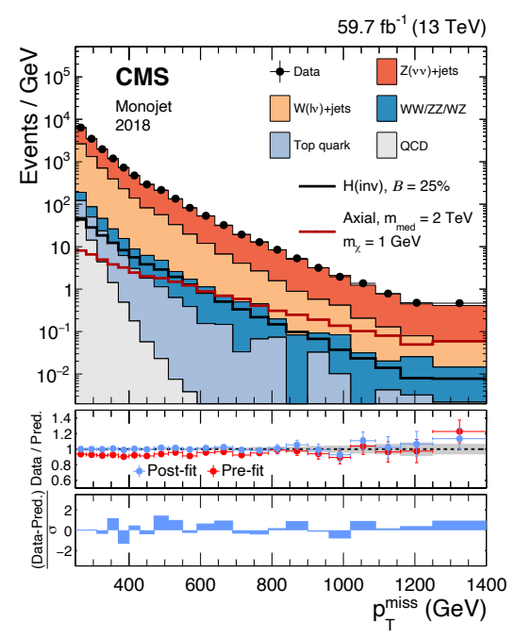
- Simultaneous fit to SR, ee, $\mu\mu$, e, μ and γ control regions to extract $Z\to\nu\nu$+jets and $W\to\ell\nu$+jets backgrounds
- QCD estimated in a dedicated CR where the $\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{j})$ cut is inverted

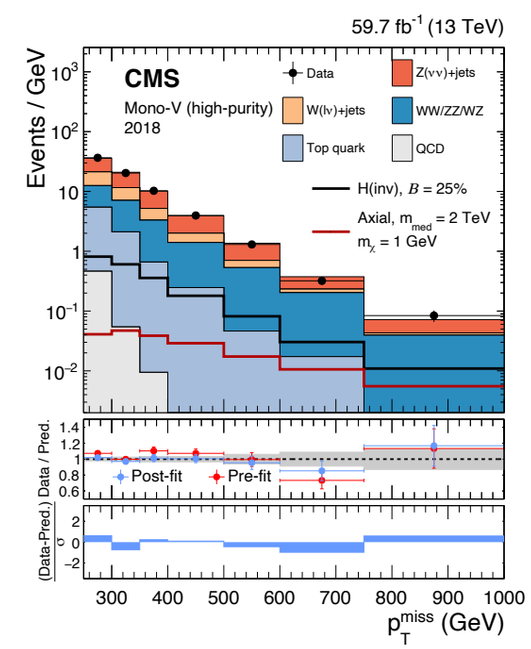




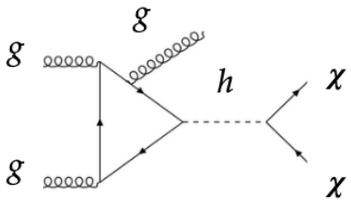
3 event categories:

- MonoJet
- MonoV low purity
- MonoV high purity



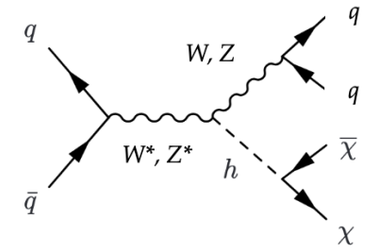


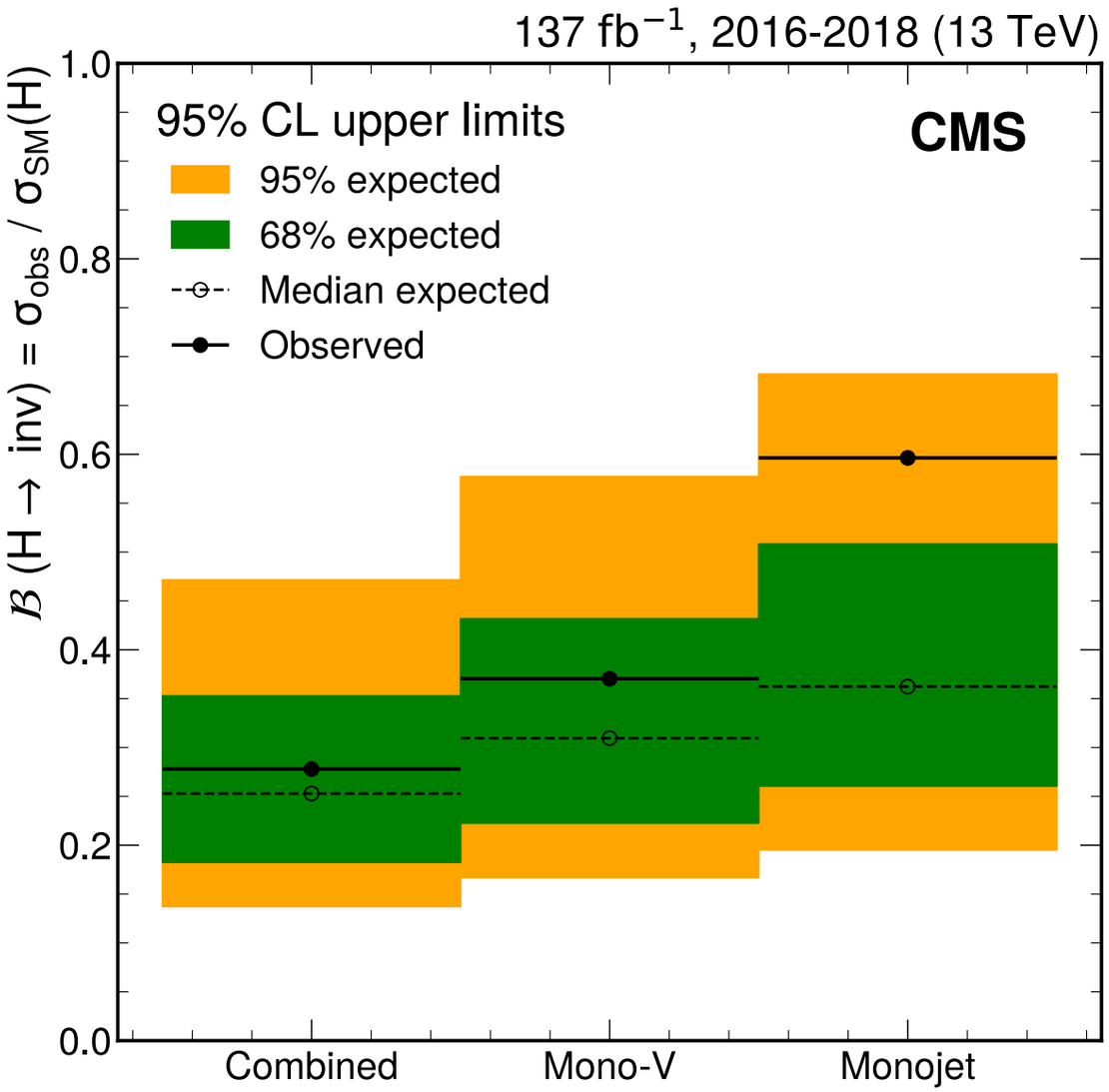
Olivier Davignon



MonoJet & MonoV search (2/2)

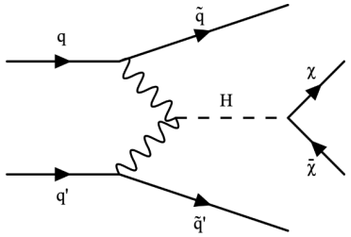
EXO-20-004 JHEP 11 (2021) 153





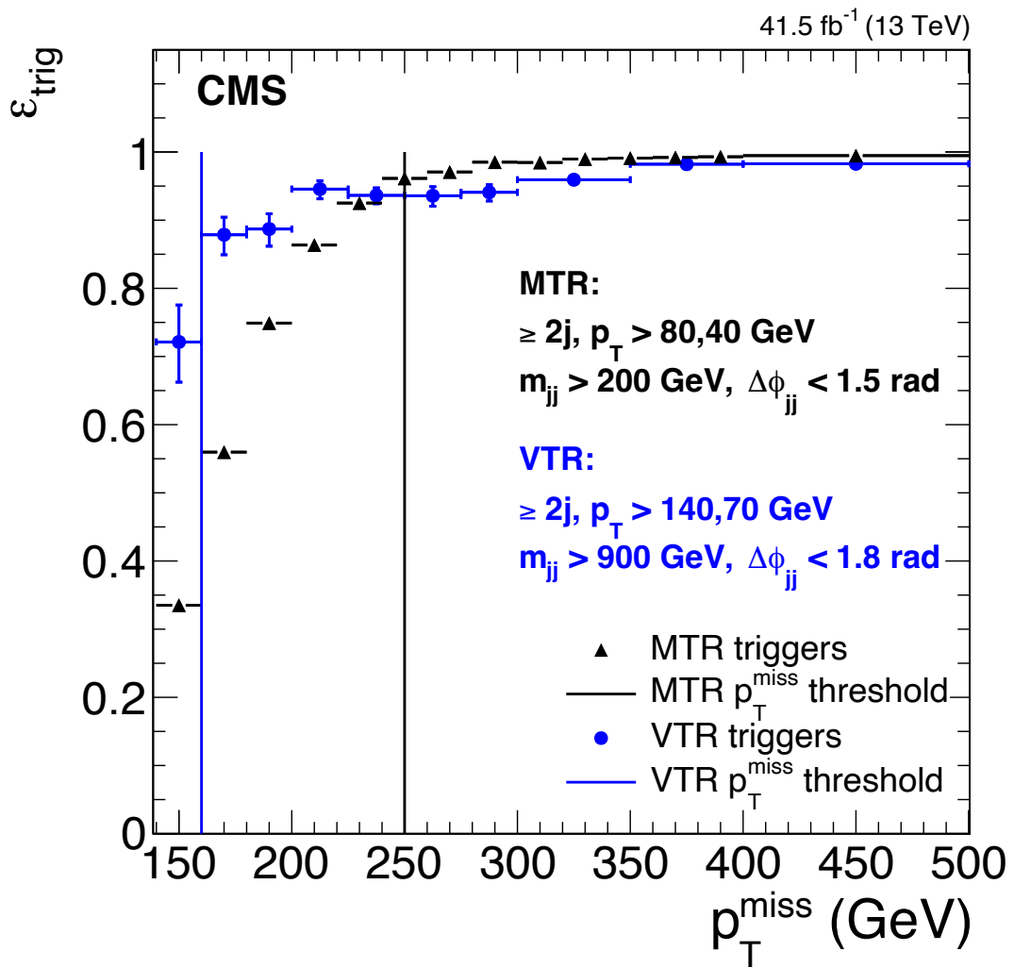
Analysis	95% C.L. upper limit on $\mathcal{B}$(H→inv.) observed (expected)
MonoJet	60% (36%)
MonoV	37% (31%)
Combination	28% (25%)

Olivier Davignon



VBF H→invisible (1/4)

HIG-20-003 Phys. Rev. D 105 (2022) 092007



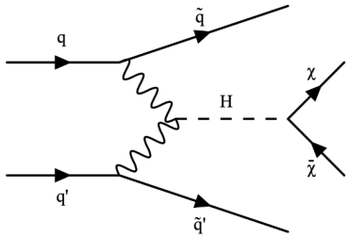
Triggers, categories & selections

2 event categories

- "MTR": based on standard p_T^{miss} and H_T^{miss} trigger, p_T^{miss} > 250 GeV cut offline
- "VTR": based on VBF 2-jet + MET trigger, p_T^{miss} > 160 GeV and tighter cuts on jets
  - Improvement of sensitivity ~ 8%

Selections

- Based on two forward / high p_T jets, close in $\Delta\phi$(jj), high p_T^{miss}, jets and p_T^{miss} well separated in $\Delta\phi$
  → fight against the main backgrounds from V+jets (in particular VBF/EWK) and QCD
- Mjj used as the fit variable

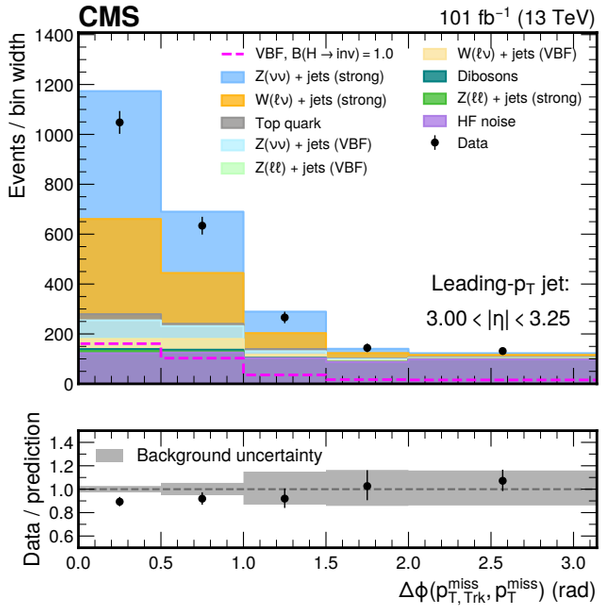


VBF H→invisible (2/4)

HIG-20-003 Phys. Rev. D 105 (2022) 092007

Instrumental backgrounds

Analysis affected by many instrumental backgrounds - mostly endcaps and forward calorimeters

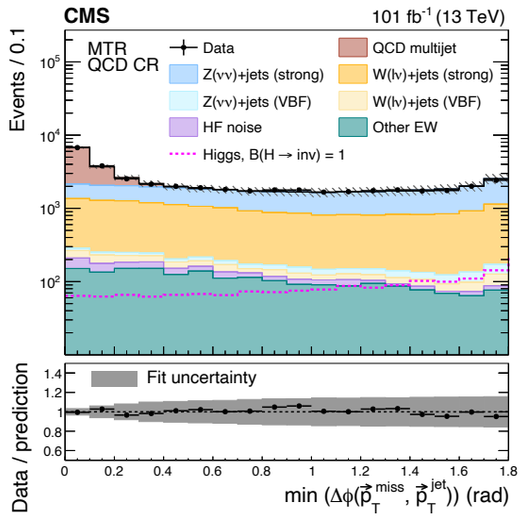


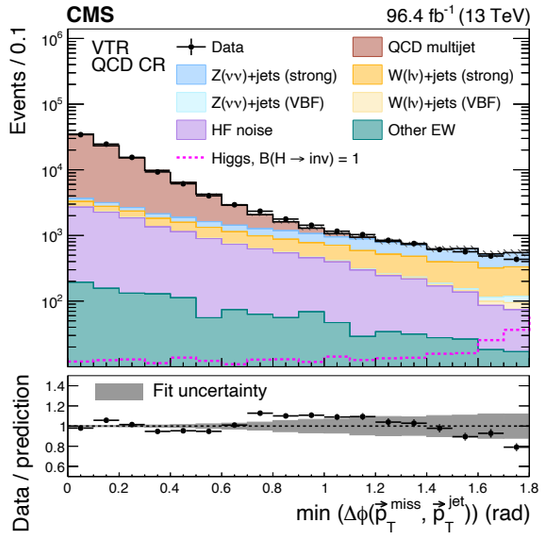
HF subdetector noise (p_T^{miss} aligned with jets)

- Suppressed using jet shape cuts
- Mjj shape of HF noise evaluated using dedicated control region with HF jet shape cuts inverted → closure test

QCD multijet (p_T^{miss} not aligned with jets)

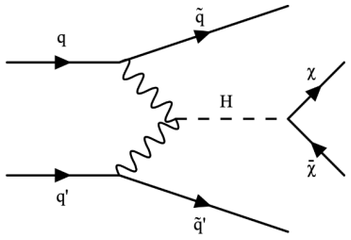
- Estimated using 2 dedicated control regions with min$\Delta\phi$(jet, p_T^{miss}) cut inverted; a fit is performed to the min$\Delta\phi$ distribution in order to extract the predicted yield in the SR (which is at high min$\Delta\phi$)





→ **Tremendous effort to suppress and estimate backgrounds coming from such effects**

Olivier Davignon

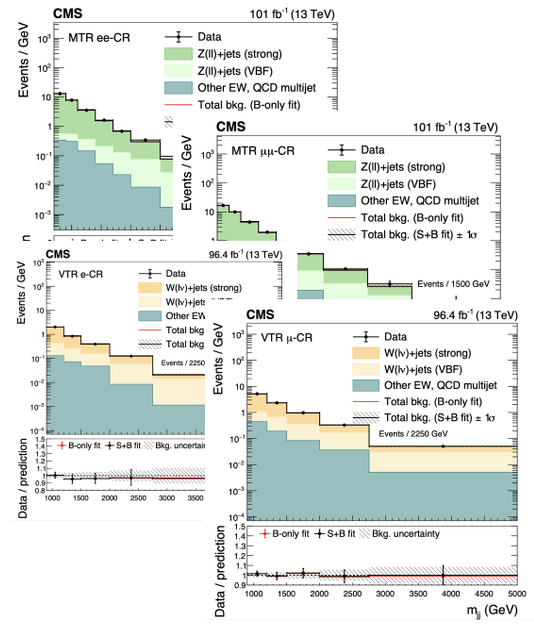


VBF H→invisible (3/4)

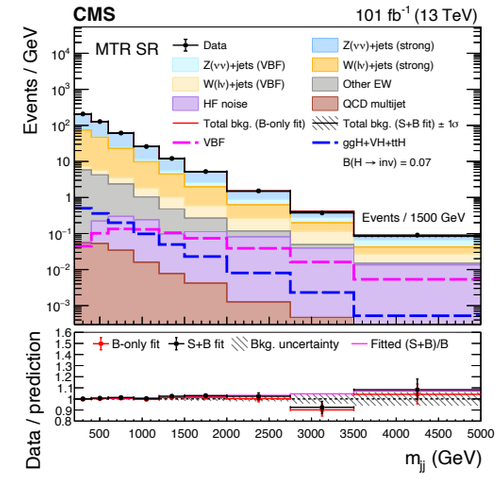
HIG-20-003 Phys. Rev. D 105 (2022) 092007

V+jets backgrounds

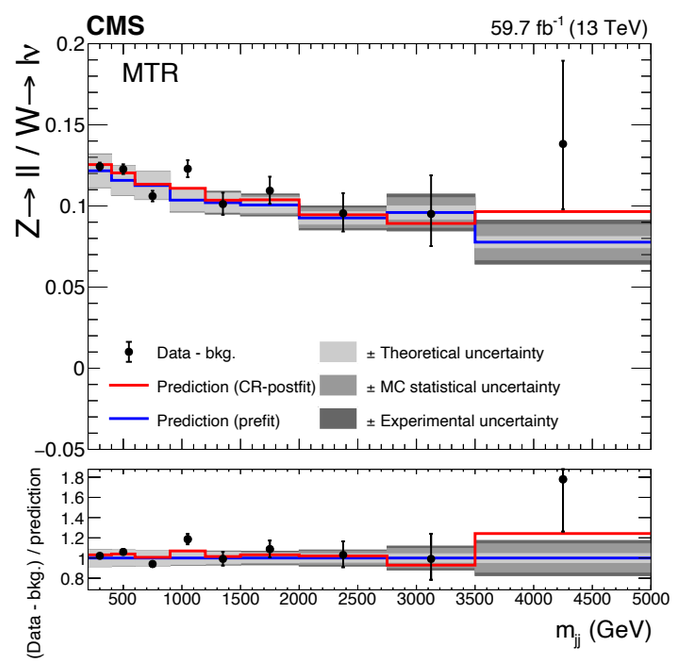
- Simultaneous fit to SR, ee, $\mu\mu$, e, μ and γ control regions to extract signal and $Z\to\nu\nu$+jets and $W\to\ell\nu$+jets backgrounds simultaneously
- Total of 18 such CRs for '17 & '18
- Transfer factors to predict W and Z backgrounds in the SR from the CR

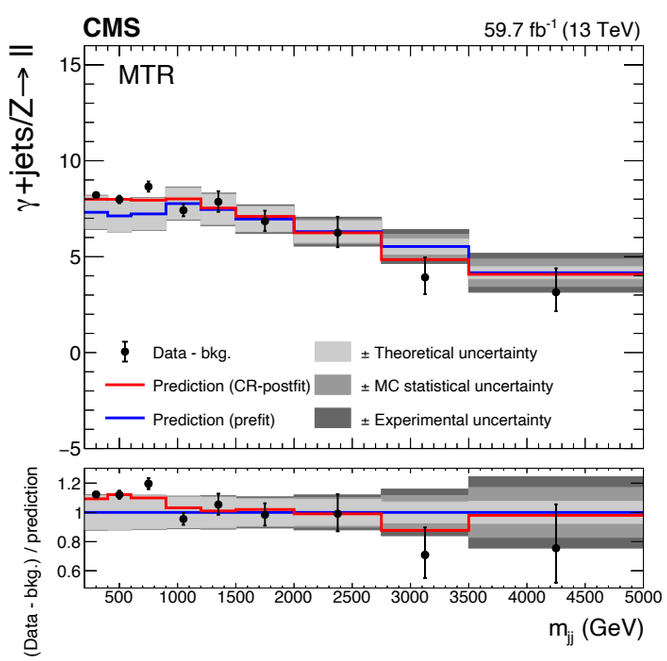


Transfer factors to the SR categories

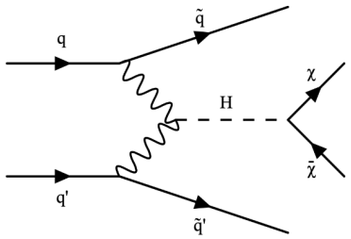


- Use W/Z and Z/γ ratios (separate for strong and ewk productions) to optimally use the information from the CRs





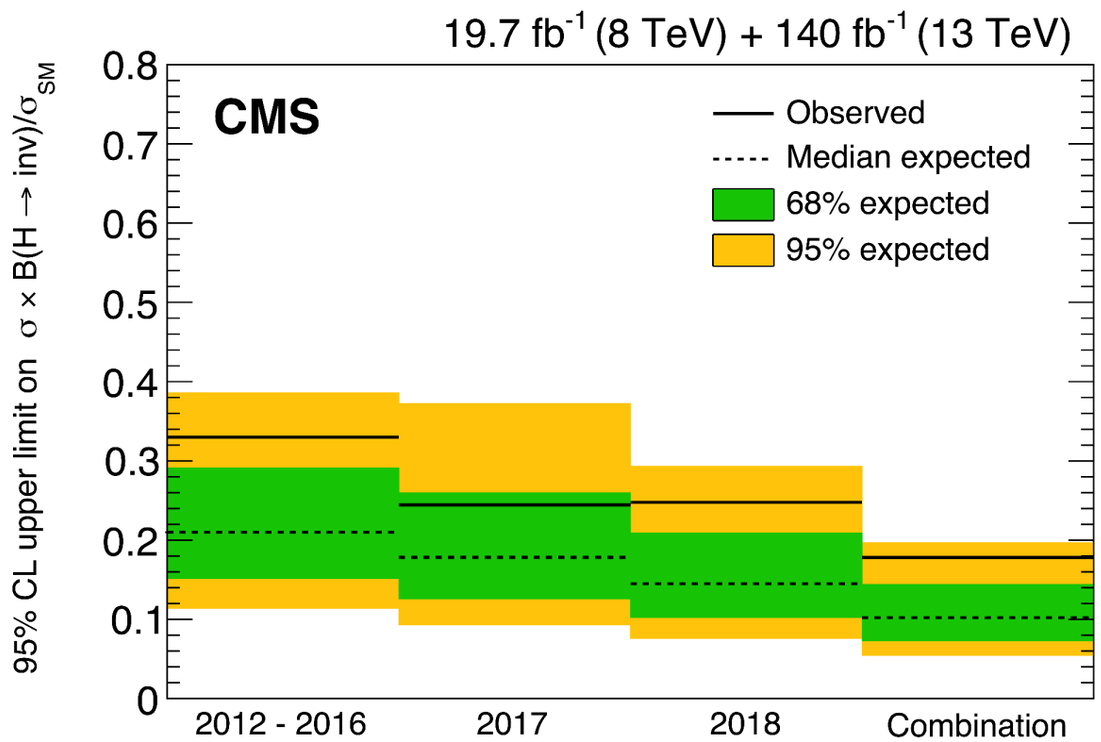
Olivier Davignon



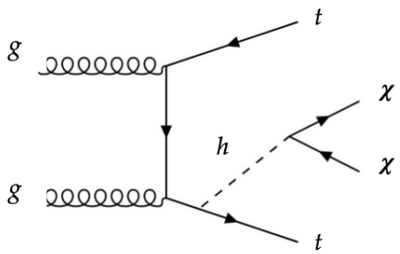
VBF H→invisible (4/4)

HIG-20-003 Phys. Rev. D 105 (2022) 092007

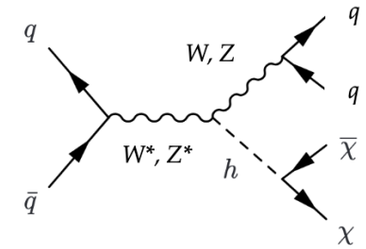
Combined with previous analyses from 2012 (8 TeV) and from 2015-2016



Analysis	95% C.L. upper limit on $\mathcal{B}$(H→inv.) observed (expected)
VBF	18% (10%)



ttH(hadronic)+VH(resolved)

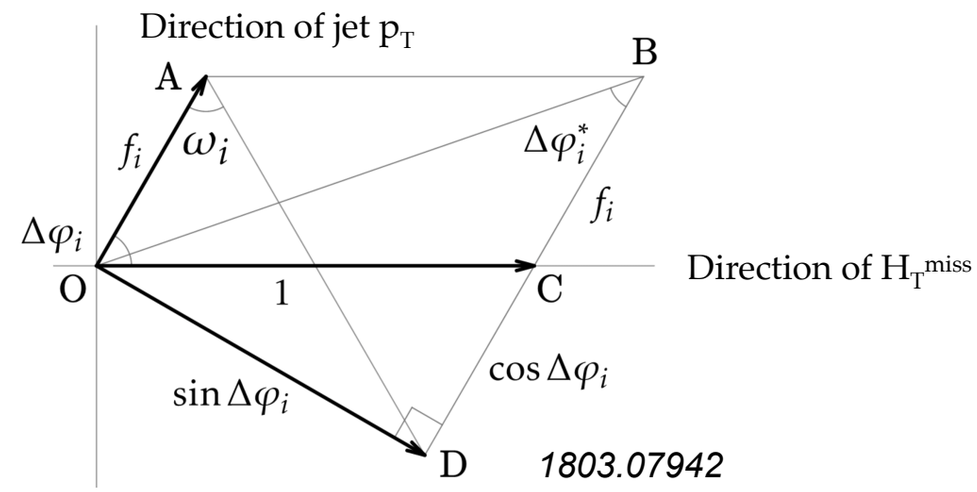


NEW! HIG-21-007

Selections & categories

Selections are targeting >=2 jets final states, where the jets are rather central $|\eta| < 2.4$

- Cuts are mainly aimed at improving signal purity: p_T^{miss}, H_T^{miss} and jet p_T
- Cuts ensuring event quality on $p_T^{miss}/H_T^{miss} < 1.2$, $\min\Delta\phi(\text{jet}, p_T^{miss}) > 0.5$, $\tilde{\omega}_{min} > 0.3$



Categories

- Count the number of jets and b-jets
- Use of DeepAK8 taggers to tag top's and W's in boosted ttH decays: "**ttH Boosted**" categories
- Also target resolved ttH decays with high jet multiplicity: "**ttH Resolved**" categories
- 2 well resolved jets (+0/1/2 b-jets) with mjj compatible with m_W or m_Z make up the "**VH resolved**" categories

Category	Subcategory	n_j	n_b	n_t	n_V	p_{T,j_2} (GeV)	Other
ttH Boosted	2Boosted1b	≥ 5	1		2	≥ 80	-
	2Boosted2b	≥ 5	≥ 2		2		
	1t1b	≥ 5	1	1	0		
	1t2b	> 5	> 2	1	0		
	1W1b	≥ 5	1	0	1		
	1W2b	≥ 5	≥ 2	0	1		
ttH Resolved	5j1b	5	1	0	0	≥ 80	$\Delta\phi(b_1, \vec{p}_T^{miss}) > 1.0$ & $\Delta\phi(j_1, \vec{p}_T^{miss}) > \pi/2$
	6j1b	≥ 6	1	0	0		
	5j2b	5	≥ 2	0	0		$\Delta\phi(b_1, \vec{p}_T^{miss}) > 1.0$ & $\Delta\phi(b_2, \vec{p}_T^{miss}) > \pi/2$
	6j2b	≥ 6	≥ 2	0	0		
VH	2j0b	2	0	0	0	≥ 30	$m_{jj} \in [65, 120)$ GeV
	2j1b	2	1	0	0		
	2j2b	2	2	0	0		

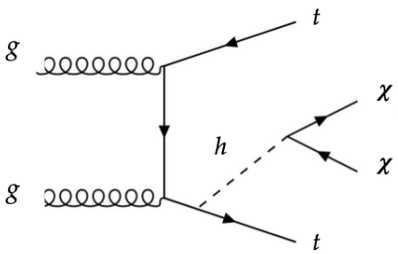
QCD estimation

Relies on dedicated CR with $\min\Delta\phi(\text{jet}, p_T^{miss})$ and $\tilde{\omega}_{min}$ cuts inverted → used to normalize MC in SR using transfer factors

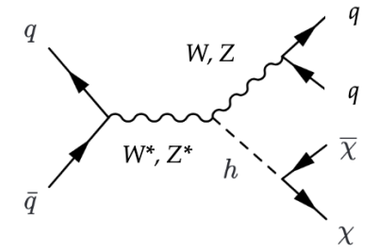
Ewk background estimation

- Use dedicated ee, $\mu\mu$, e, μ and γ (VH-only) control regions simultaneously in the fit with the SR

Olivier Davignon



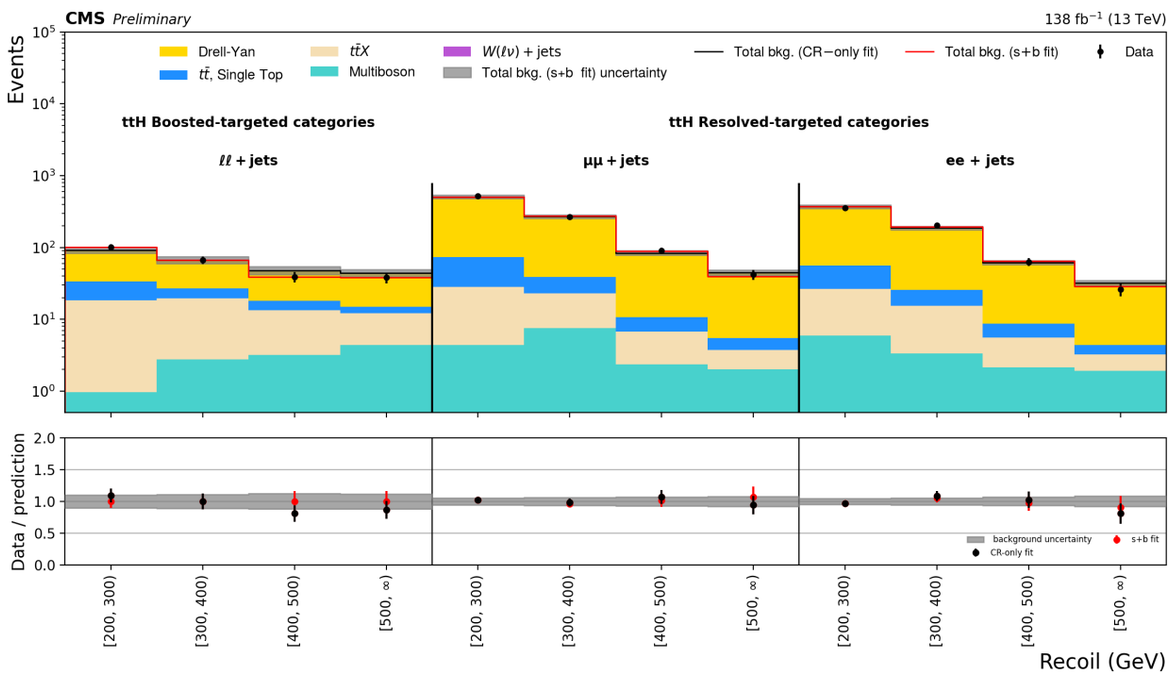
ttH+VH: control regions (1/2)



NEW! HIG-21-007

- p_T^{miss} used as discriminant variable
  - fine binning when allowed by statistics

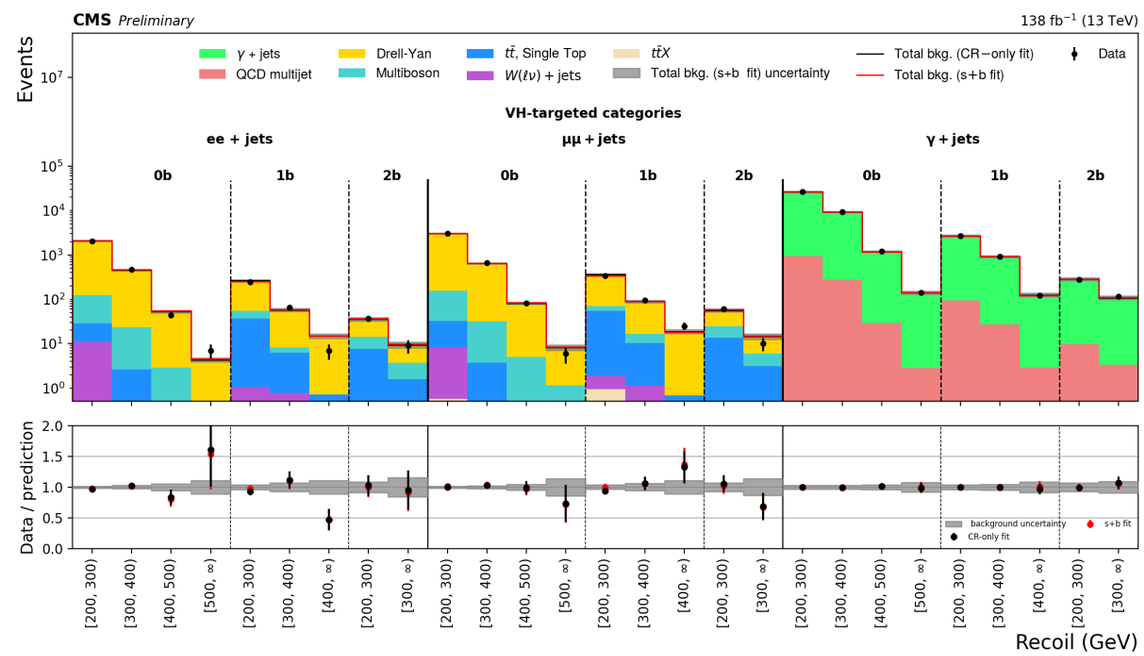
ttH



In ttH, for statistical reasons:

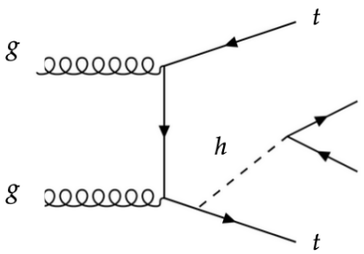
- Di-lepton CRs shared across categories
- Boosted ttH: $\ell\ell$ = ee+$\mu\mu$ CR

VH resolved

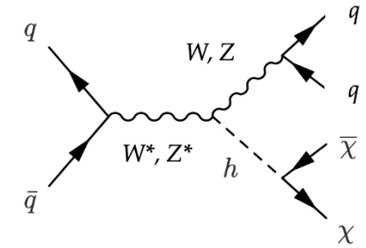


Photon CR only used in VH

Olivier Davignon



ttH+VH: control regions (2/2)

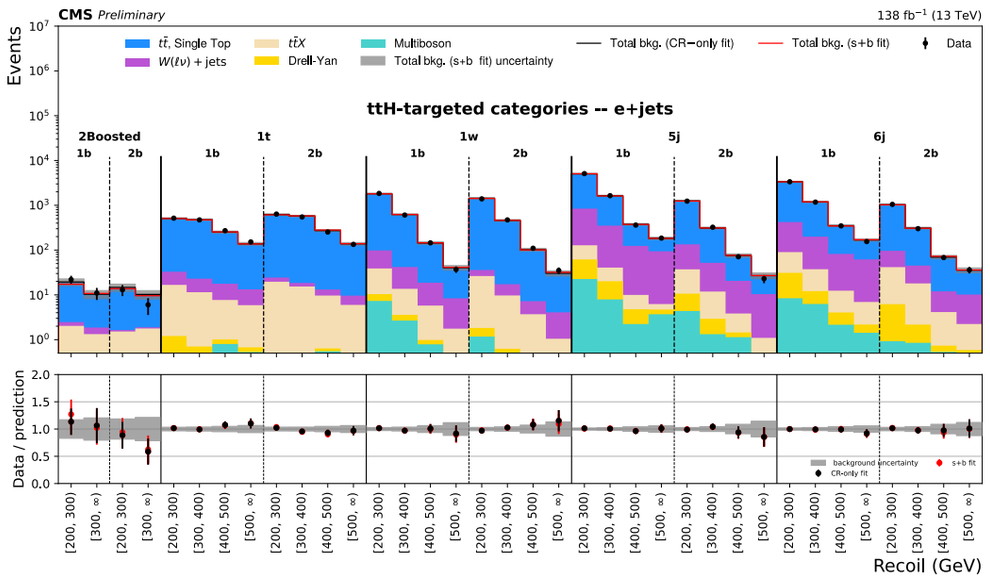


NEW! HIG-21-007

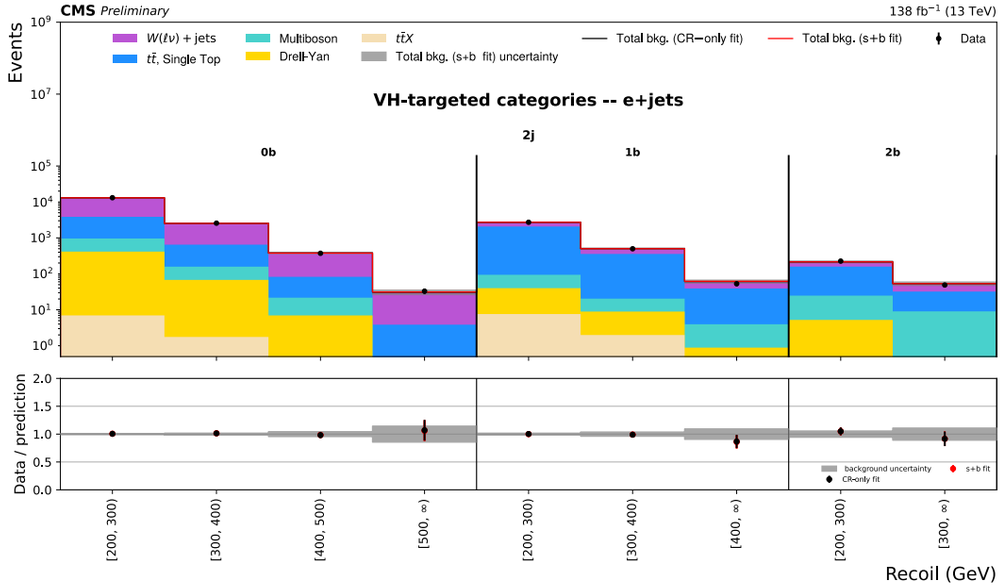
e+jets CR

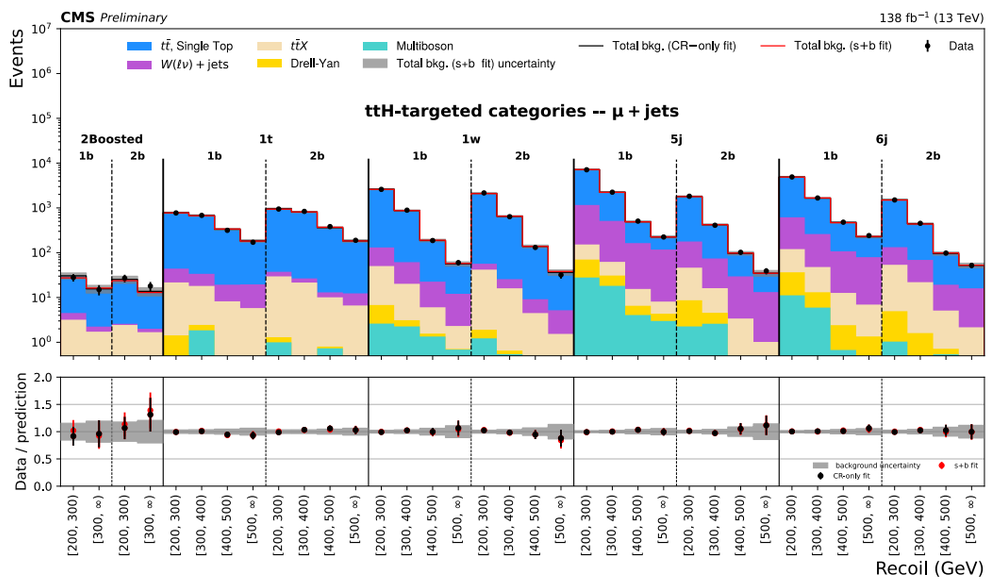
μ+jets CR

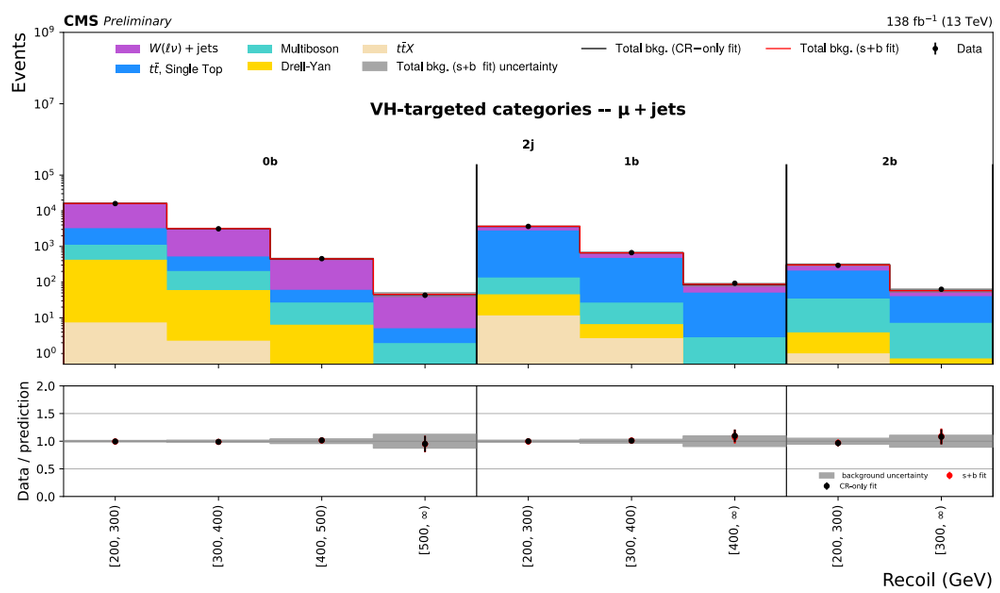
ttH



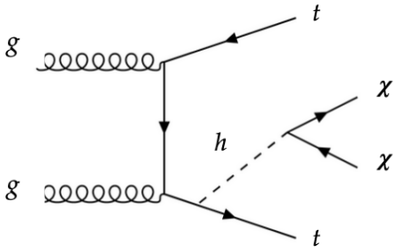
VH resolved





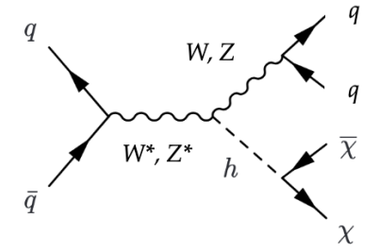


Olivier Davignon

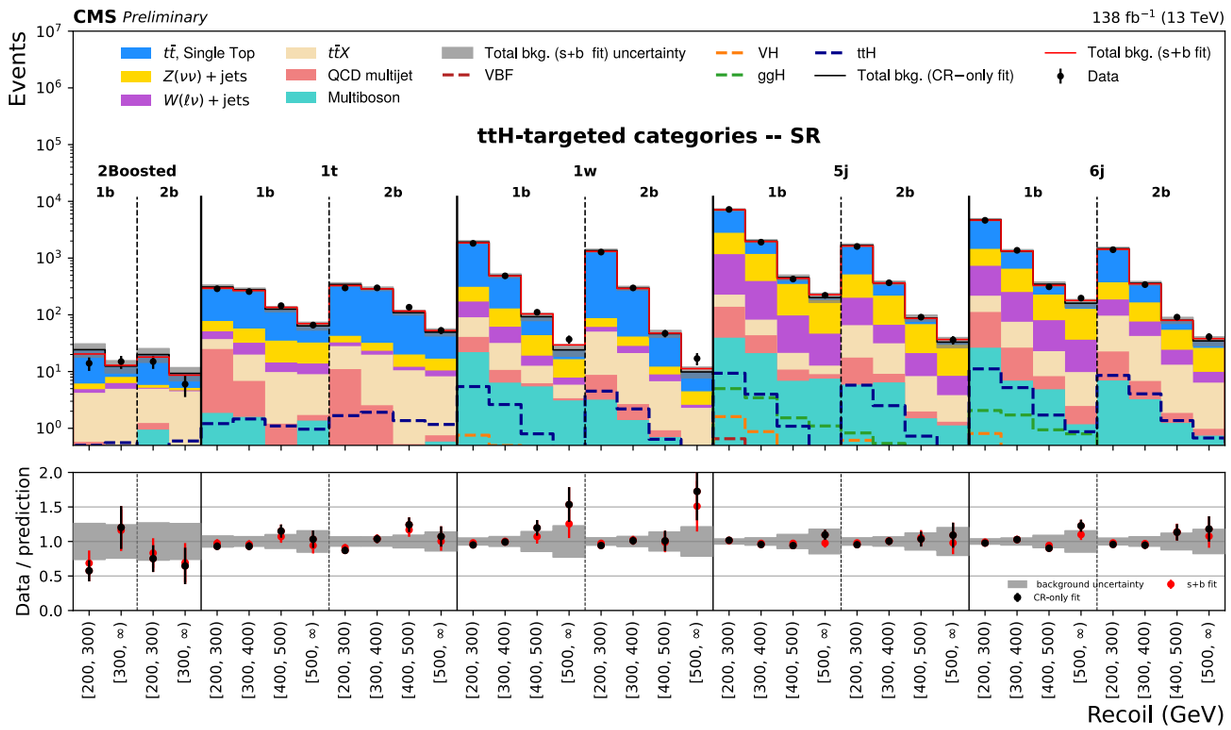


ttH+VH: signal regions

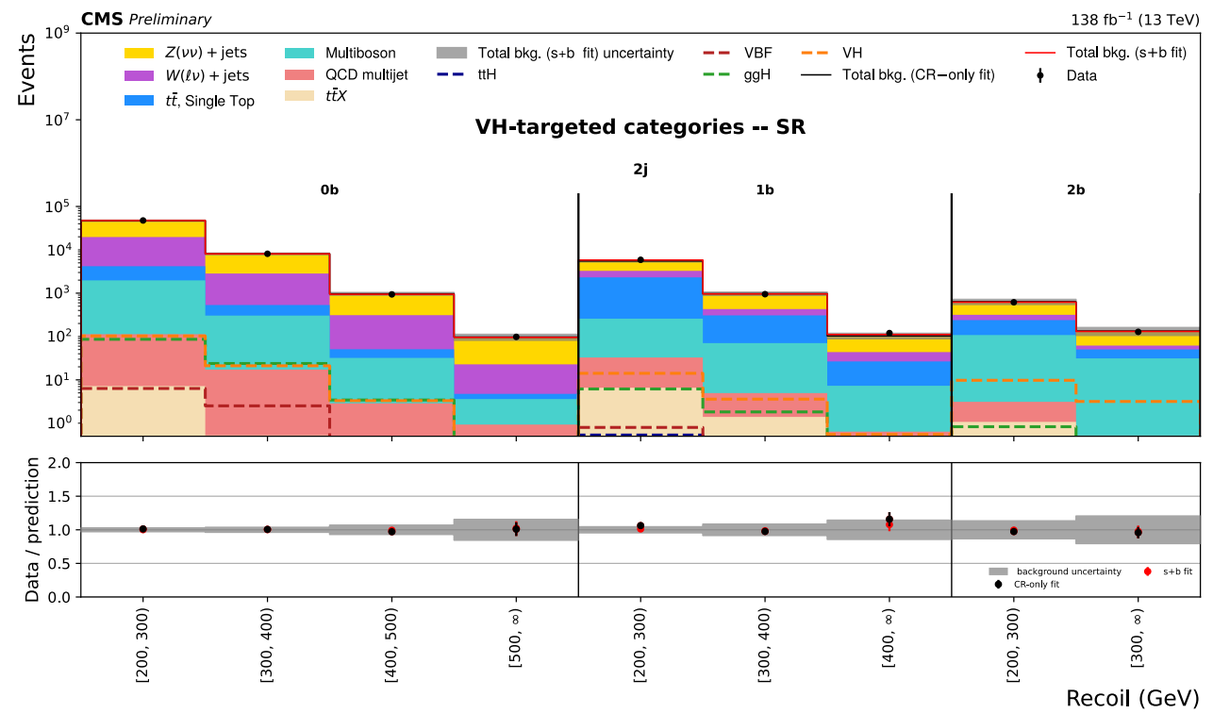
NEW! HIG-21-007



ttH



VH resolved

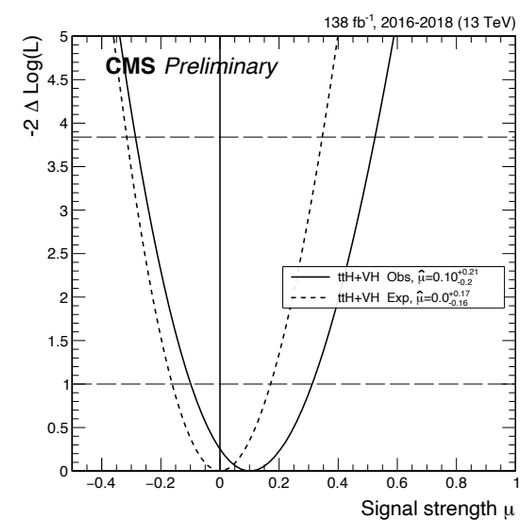


Dominant backgrounds

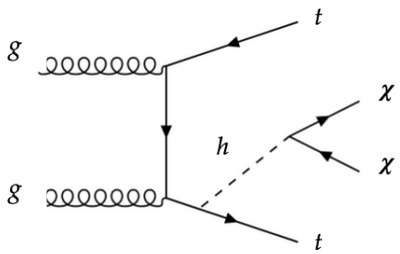
- ttH: ttbar
- VH: Z→$\nu\nu$+jets

QCD is a small background after selection cuts

Good data/MC agreement post-fit, no significant excess

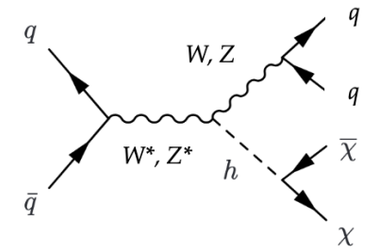


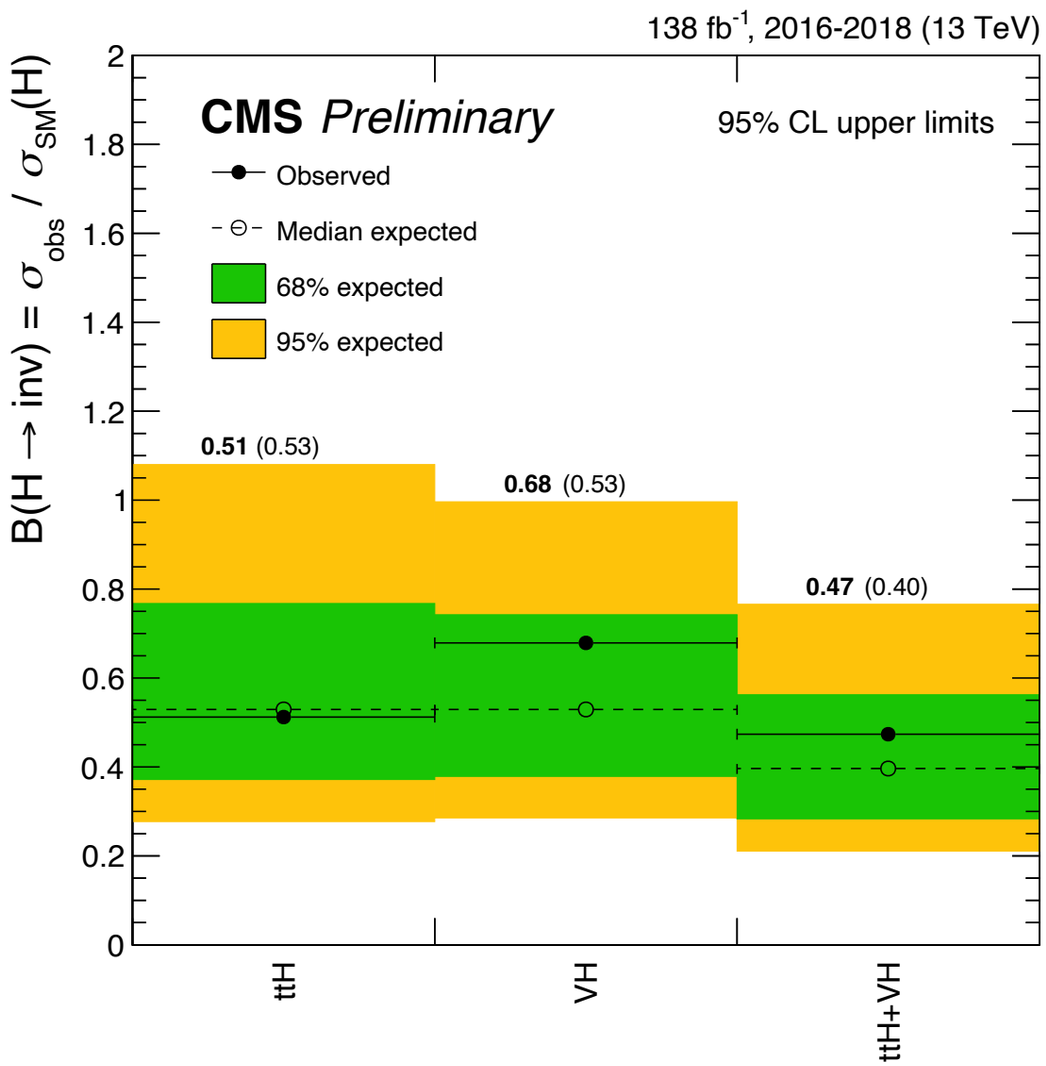
Olivier Davignon



ttH+VH: limits

NEW! HIG-21-007





Analysis	95% C.L. upper limit on $\mathcal{B}$(H→inv.) observed (expected)
ttH hadronic	51% (53%)
VH resolved	68% (53%)
Combination	47% (40%)

ttH hadronic and VH resolved yielding similar performance in terms of H→invisible exclusion limits

H→invisible combination

NEW! HIG-21-007

Analysis Tag	Production Mode	Integrated Luminosity (fb^{-1})		
		7 TeV	8 TeV	13 TeV (Run 2)
VBF-tagged [20]	VBF	-	19.2	140
VH-tagged [24][22]	Z(ll)H	4.9	19.7	140
	Z(bb)H	-	18.9	138
	V(jj)H	-	19.7	140
ttH-tagged [68, 69]	ttH (had)	-	-	138
	ttH (lep)			138
ggH-tagged [24]	MonoJet	-	19.7	140

Combination of all channels presented today
+ tt(leptonic)H→ invisible re-interpretation from SUS-19-009 and SUS-19-011
+ (Z→ℓℓ)H→invisible from EXO-19-003

Overlap between analyses

Canceled/made negligible through specific cuts, e.g.:

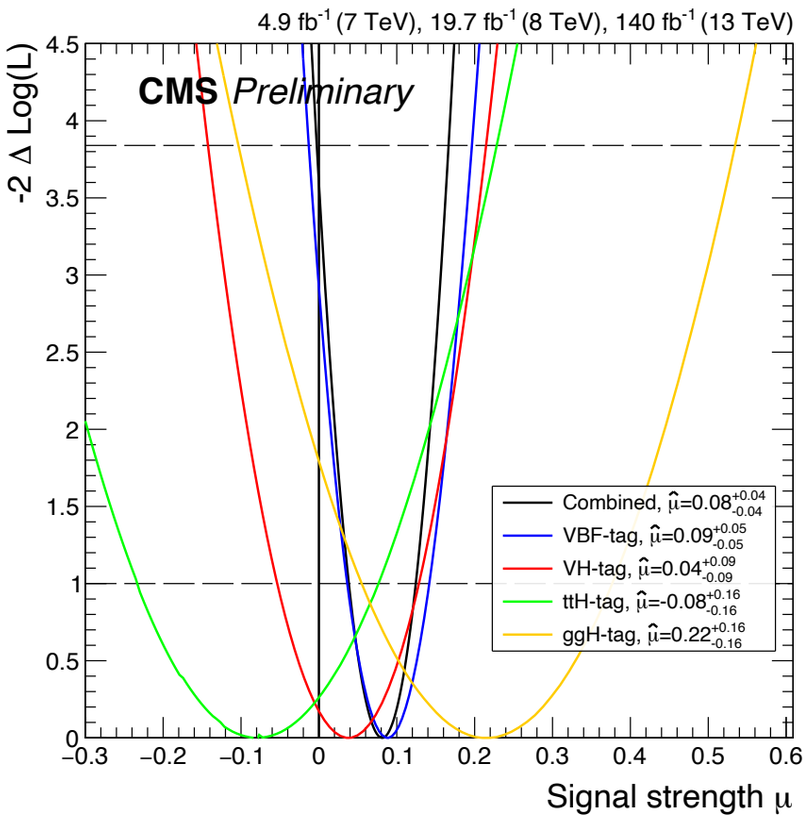
- Overlap with VBF: in other analyses, veto events with 2 jets with $p_T > 80$, 40 GeV, in opposite hemispheres, with $m_{jj} > 200$ GeV
- Overlap with MonoJet/MonoV: in VH resolved analysis, remove events that have $65 < m_{jj} < 120$ GeV

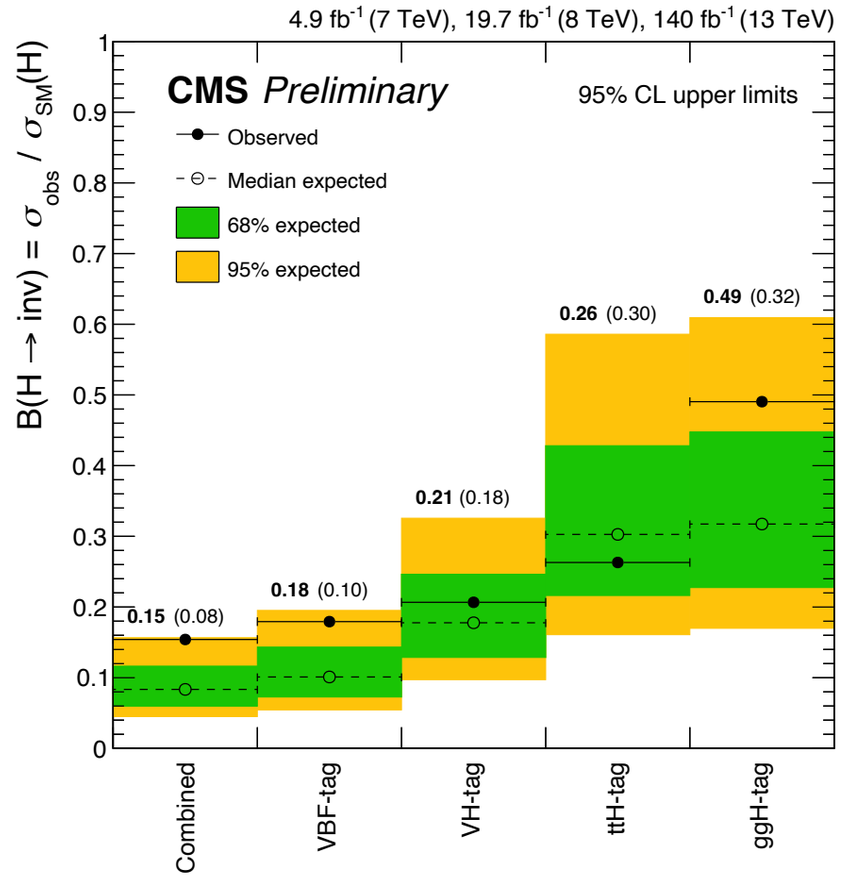
Treatment of systematics

- Theo. signal systematics → correlated
- Theo. background systematics → uncorrelated (≠ phase space)
- Luminosity → correlated
- Trigger → correlated if same paths / datasets
- Lepton efficiencies → correlated if identical
- JES & JER → correlated between VBF/MonoJet/MonoV
- Everything else → uncorrelated

H→invisible combination: results (1/2)

NEW! HIG-21-007





Channels grouped by production mode

- Measurement dominated by VBF
- Other channels improve VBF-standalone by about 20%

Analysis	95% C.L. upper limit observed (expected)
Combination	$\mathcal{B}$(H→inv.) < 15% (8%)

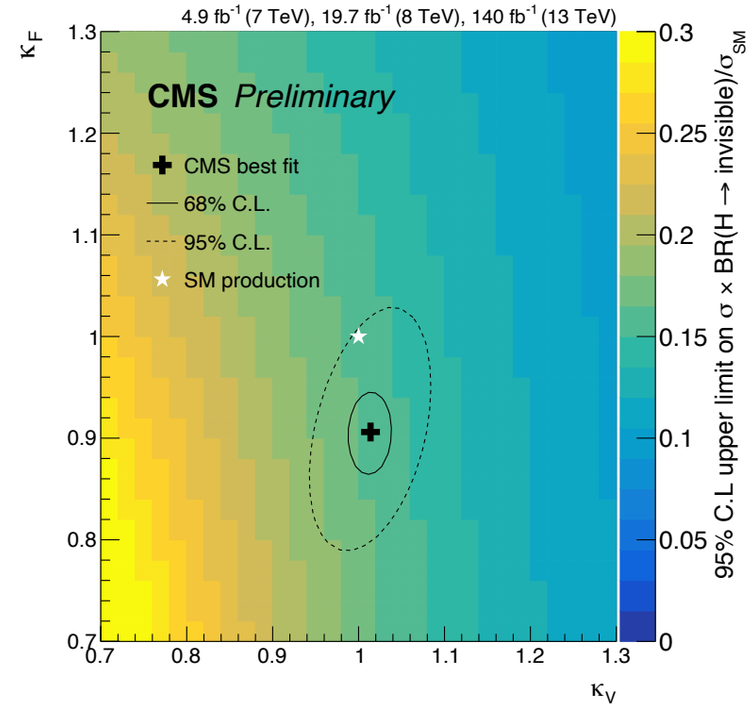
Strongest expected exclusion limit to date from direct searches

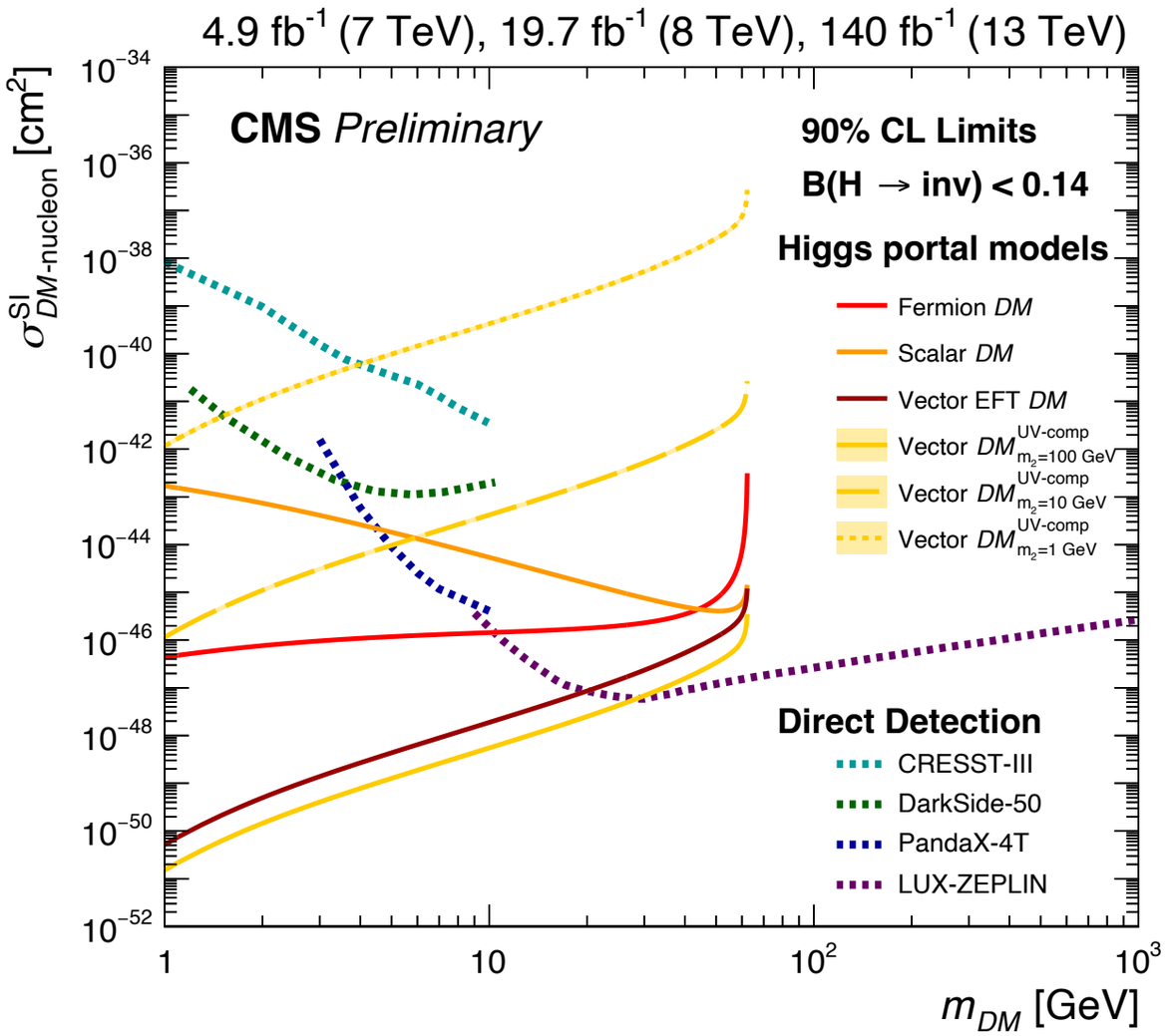
H→invisible combination: results (2/2)

NEW! HIG-21-007

Observed limit on $\mathcal{B}$(H→inv.) also set as a function of the k_V and k_F coupling modifiers

- Best fit / contours from CMS Higgs10 paper [Nature 607 (2022) 60]
- In the 95% C.L. ellipse, observed limit on $\mathcal{B}$(H→inv.) ranges between 14 and 17%





Result also interpreted in the context of Higgs portal models (i.e. where there is a substantial coupling of DM to the Higgs)**, setting 90% C.L. limits on the DM-nucleon cross section for:**

- Fermion / scalar DM
- Vector DM using the "historical" EFT
- Vector DM using new EFT approach: UV-complete model at dark Higgs masses of m_2 =1,10,100 GeV, mixing angle θ=0.2 [LHEP 2022 (2022) 270]

Result competitive/complementary with direct DM detection

≲ 10 GeV for fermion DM

≲ 6 GeV for scalar DM

≲ 20 GeV for vector DM in the most favorable case shown here (with m_2=100 GeV)

Olivier Davignon

Summary

- **Two new results presented today**
  - Analysis of ttH + VH resolved hadronic modes → $\mathcal{B}$(H→inv.) < 47% (exp. 40%) @ 95% C.L.
  - Combination of all CMS H → invisible searches → $\mathcal{B}$(H→inv.) < 15% (exp. 8%) @ 95% C.L.

    → Improvement of ~ 20% relative on top of standalone VBF result

- Small < 2σ excess in both ATLAS* and CMS H → invisible results

?

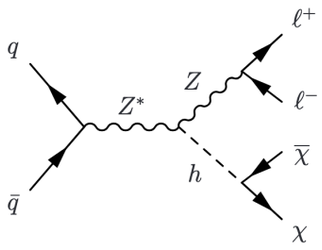
  → To be followed up with more data

*From ATLAS Higgs10 paper combining direct+indirect constraints:
$\mathcal{B}$(H→inv.) < 13% (exp. 8%)
[Nature volume 607, pages 52–59 (2022)]

- **Limits also set in the context of Higgs-portal models of dark matter interactions**
  - Complementary to direct searches for low masses

- **Run-3 has just started:** LHC will provide more data and we can expect more improvements in data collection and analysis techniques from experiments

BACKUP



(Z→ℓℓ)H→invisible

EXO-19-003 Eur. Phys. J. C 81, 1 (2021) pp.13

Experimental signature & selections

- Single/double electron and muon triggers
- Two same flavour opposite sign leptons, with $|m_{\ell\ell}-m_Z| < 15$ GeV, $p_{T,\ell\ell} > 60$ GeV
- b-jet, tau, > 1 jet, additional leptons vetoes
- Additional (mostly angular) selections to reject DY, WZ and top backgrounds

Background estimation

- 3ℓ control region: estimation of the WZ→ℓ′νℓℓ background
- 4ℓ control region: estimation of the ZZ→ℓ′ℓ′ℓℓ background
- eμ control region: estimation of the non-resonant background WW→ℓνℓν, fully leptonic tt, etc.
- Low p_T^{miss} control region: estimation of the DY background

Final state	95% upper limit on $\mathcal{B}$(H→inv.) observed (expected)
(Z→ℓℓ)H	29% (25%)