CONSTRAINTS ON THE EXOTIC HIGGS WIDTH

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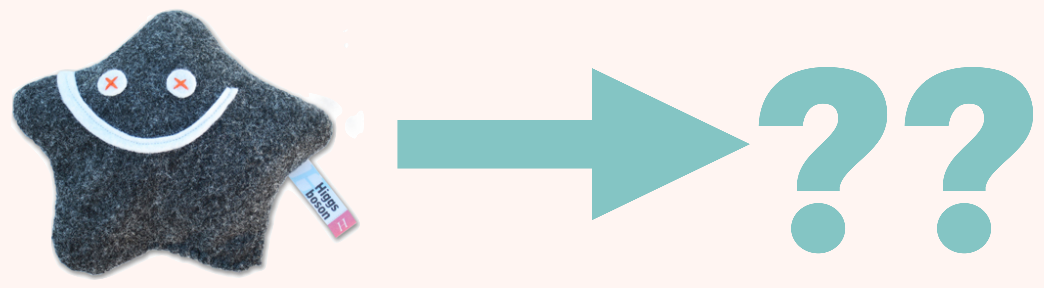
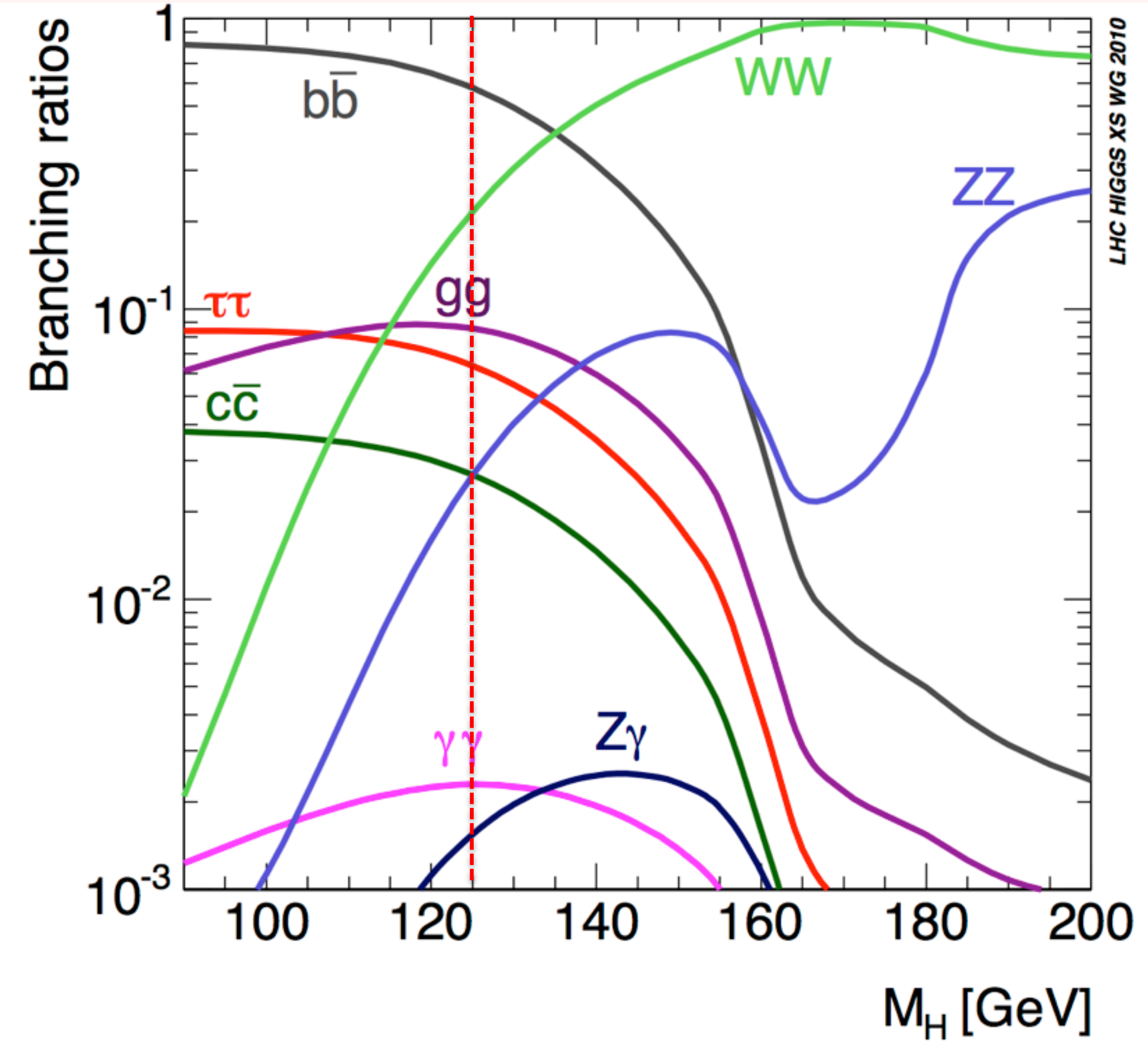
CMS
ATLAS EXPERIMENT

FIPS2020

EXOTIC WIDTH

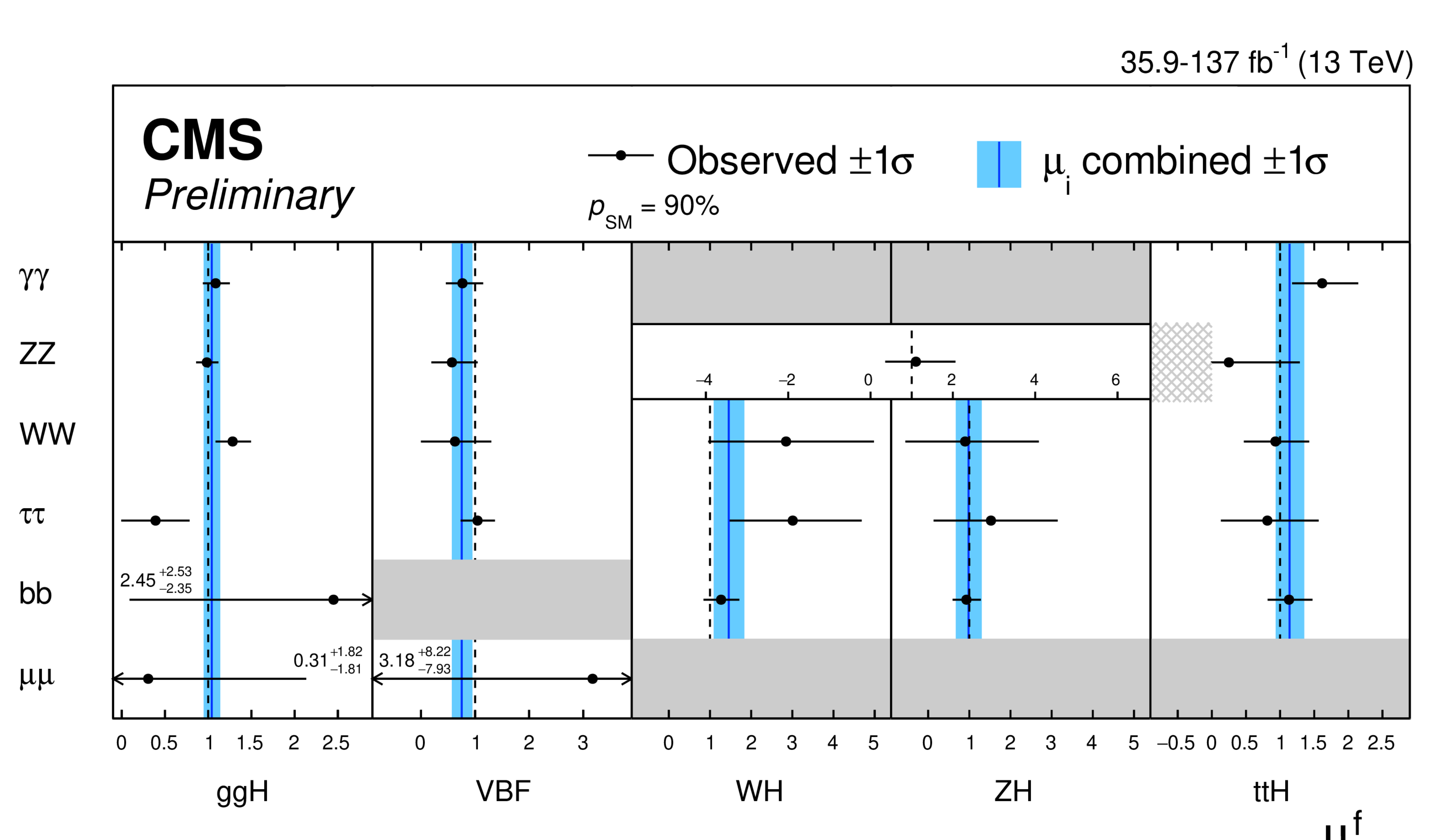




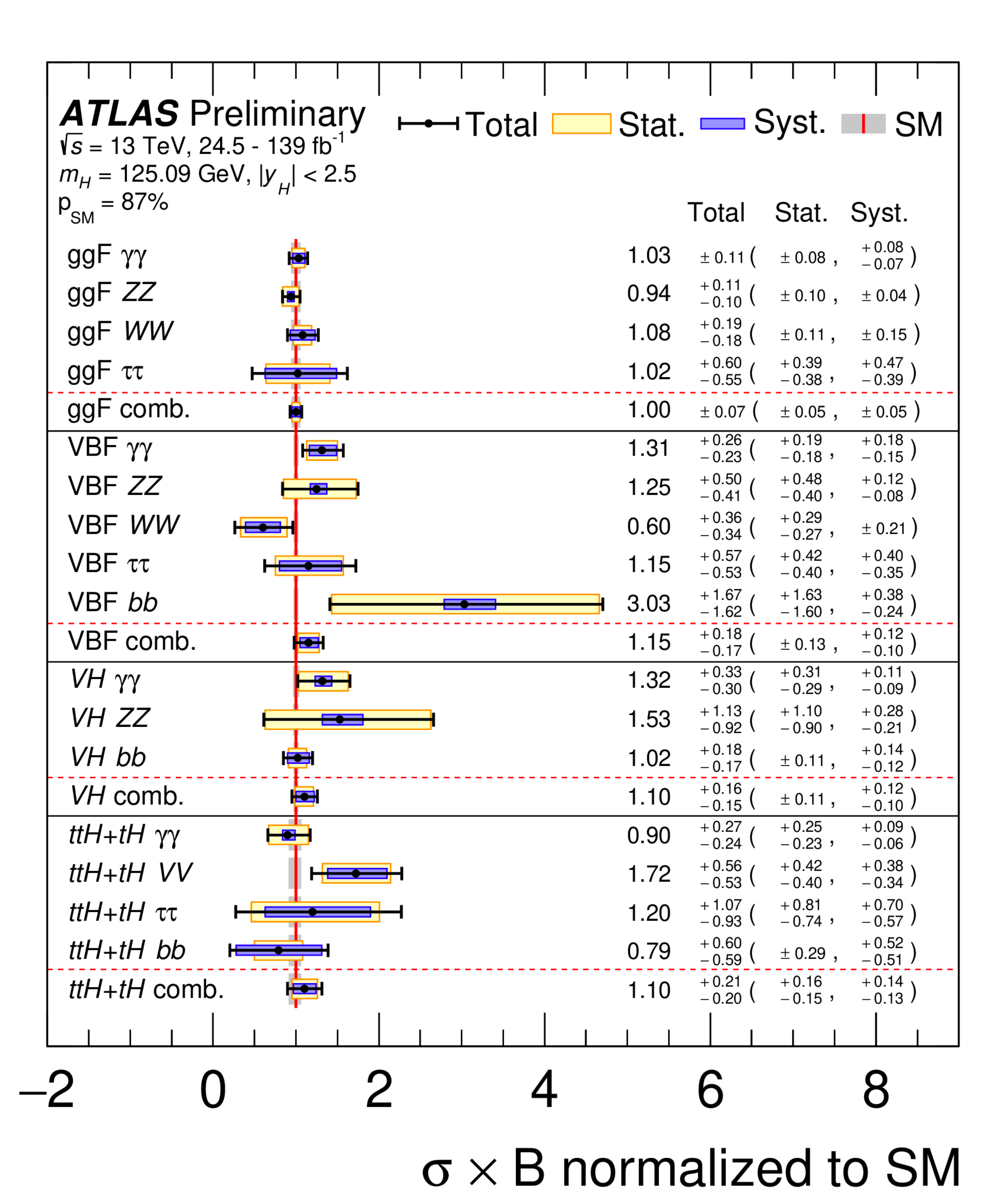
- **How much can we constrain the exotic Higgs width?**
- To answer, we first need to understand the status of the SM measurements of the Higgs boson: how much BR_{Inv} and B_{UNDET} remains allowed based on the current precision measurements?
- For BR_{Inv}, direct searches are also an input -> recap of the status of the ATLAS and CMS searches
- In parallel, direct searches for Higgs exotic decays —> see **Verena's** talk for the experimental searches and **Stefania's** for the theoretical background

HIGGS TODAY

- Main Higgs production & decay modes observed now
- So far, excellent agreement with the Standard Model prediction
- Similar performance in CMS and ATLAS: Single experiment partial Run2 results more precise already than Run1 ATLAS+CMS

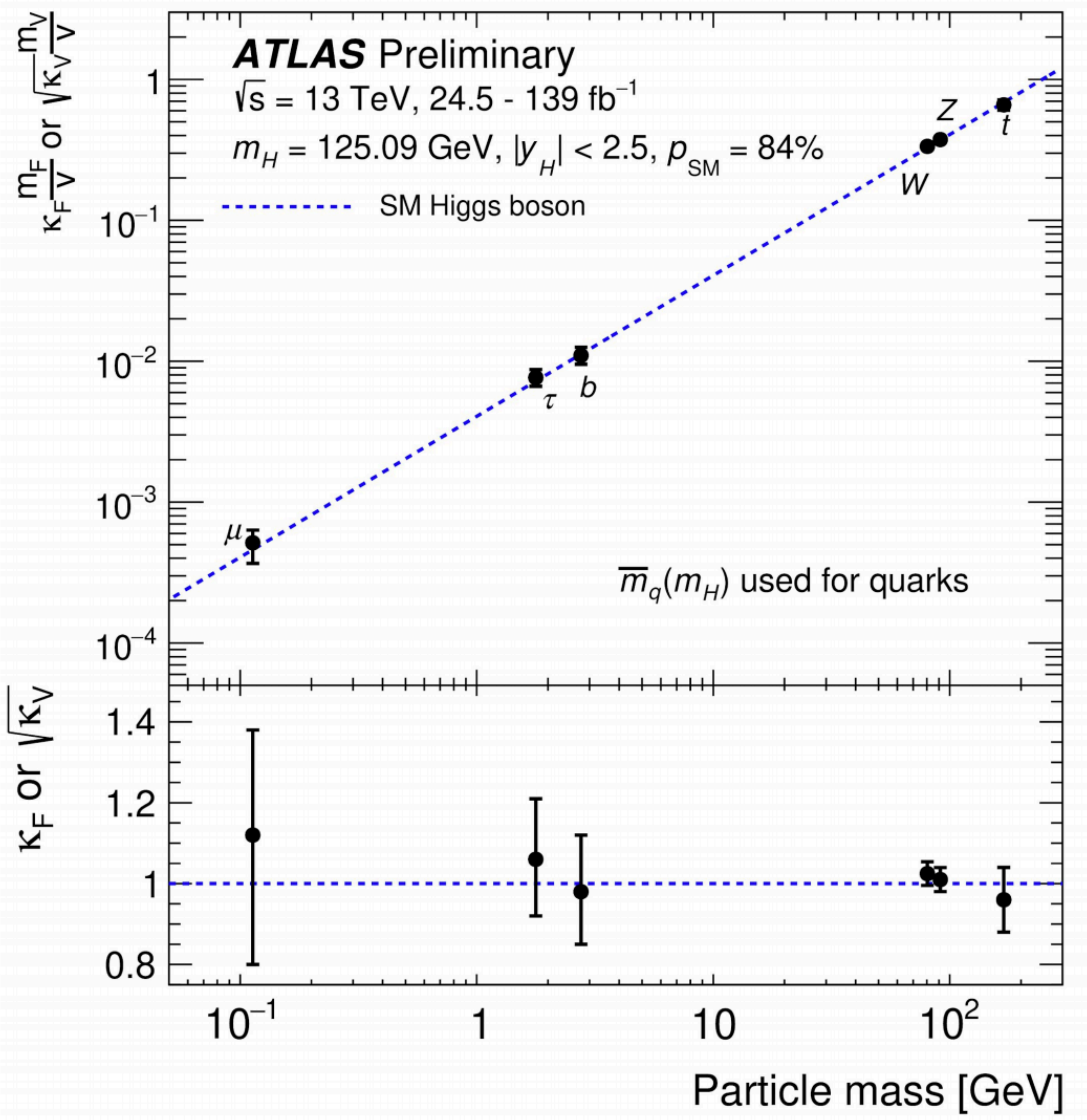


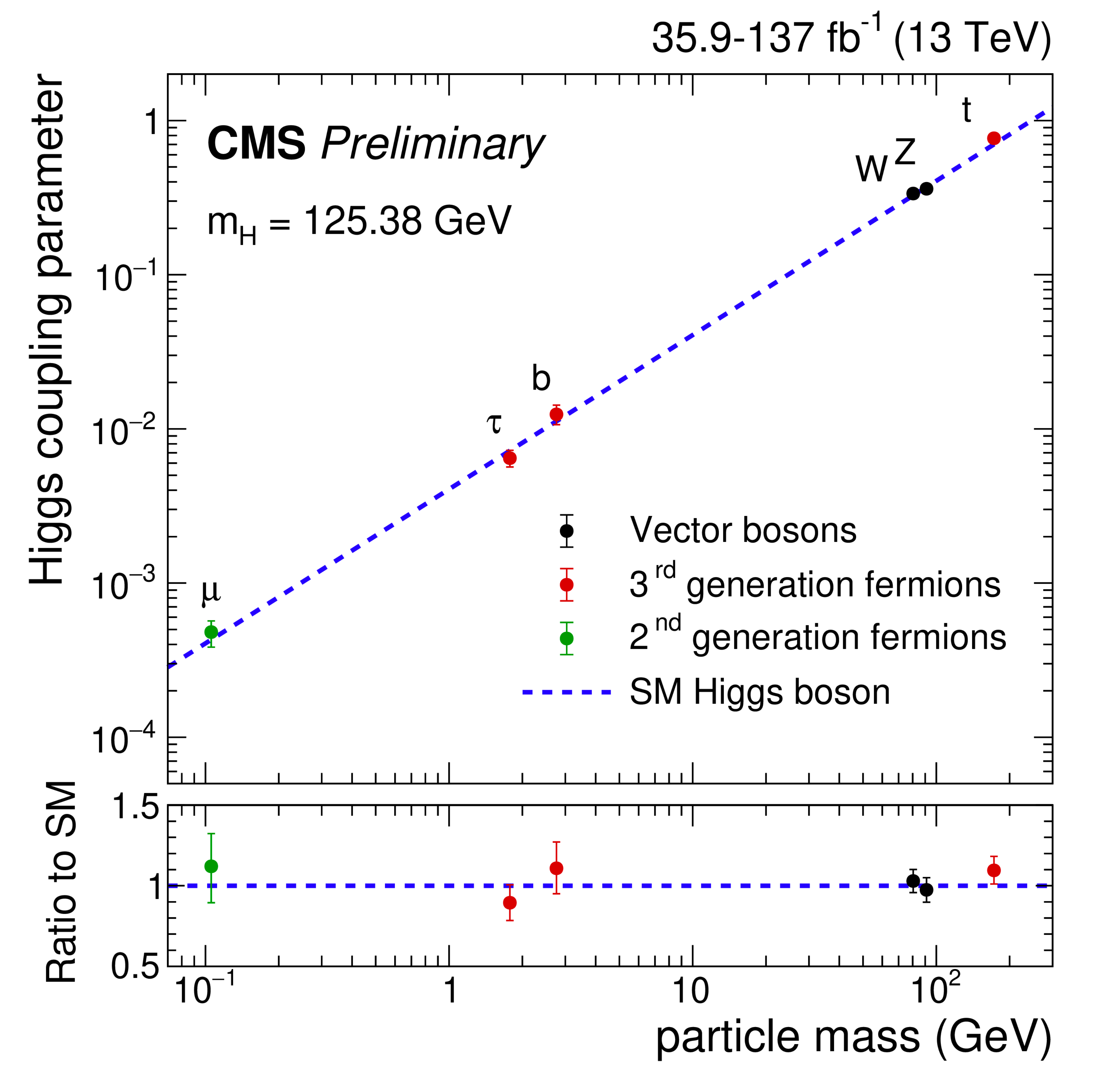
CMS-PAS-HIG-19-005



ATLAS-CONF-2020-027

HIGGS TODAY



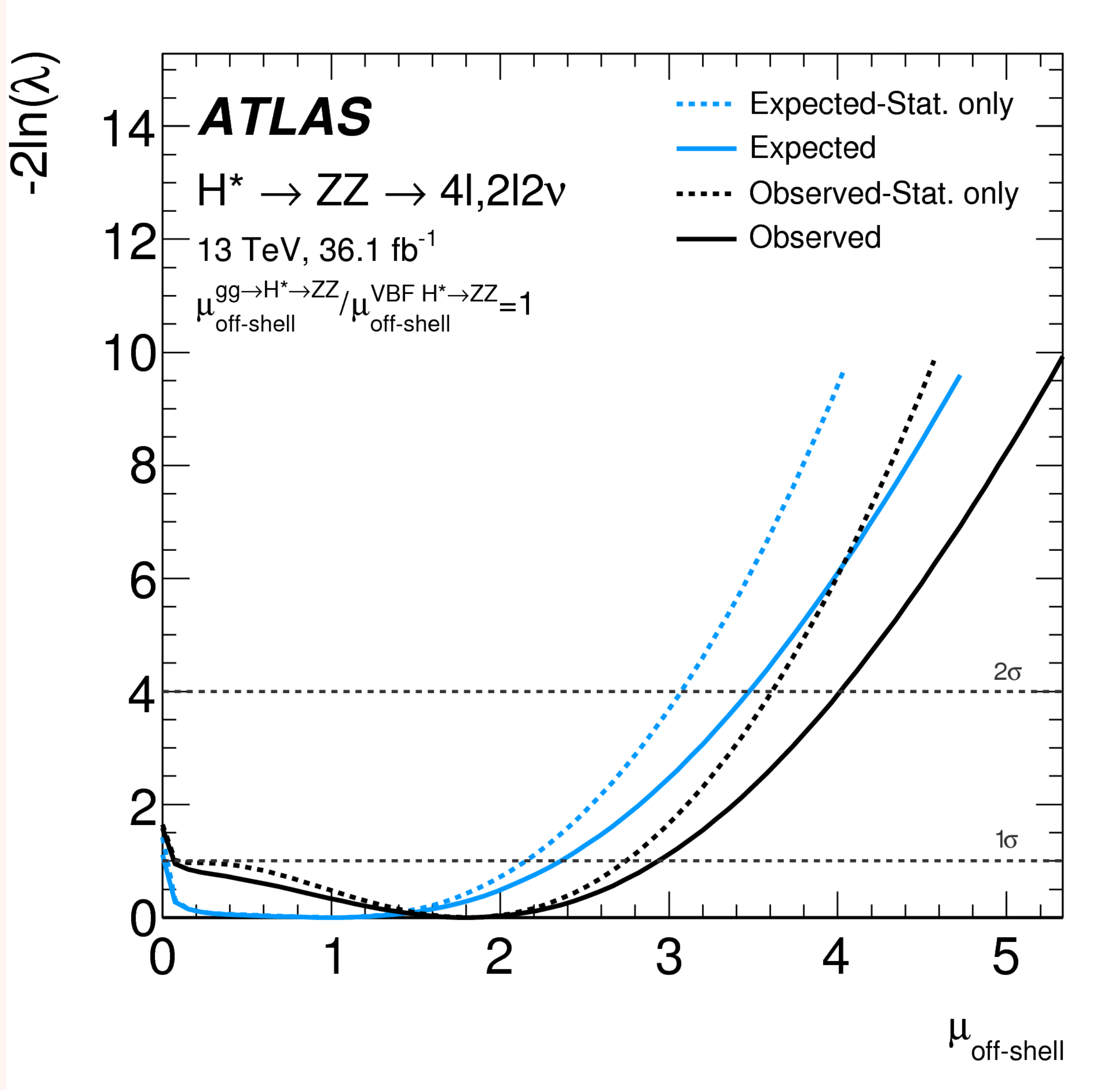


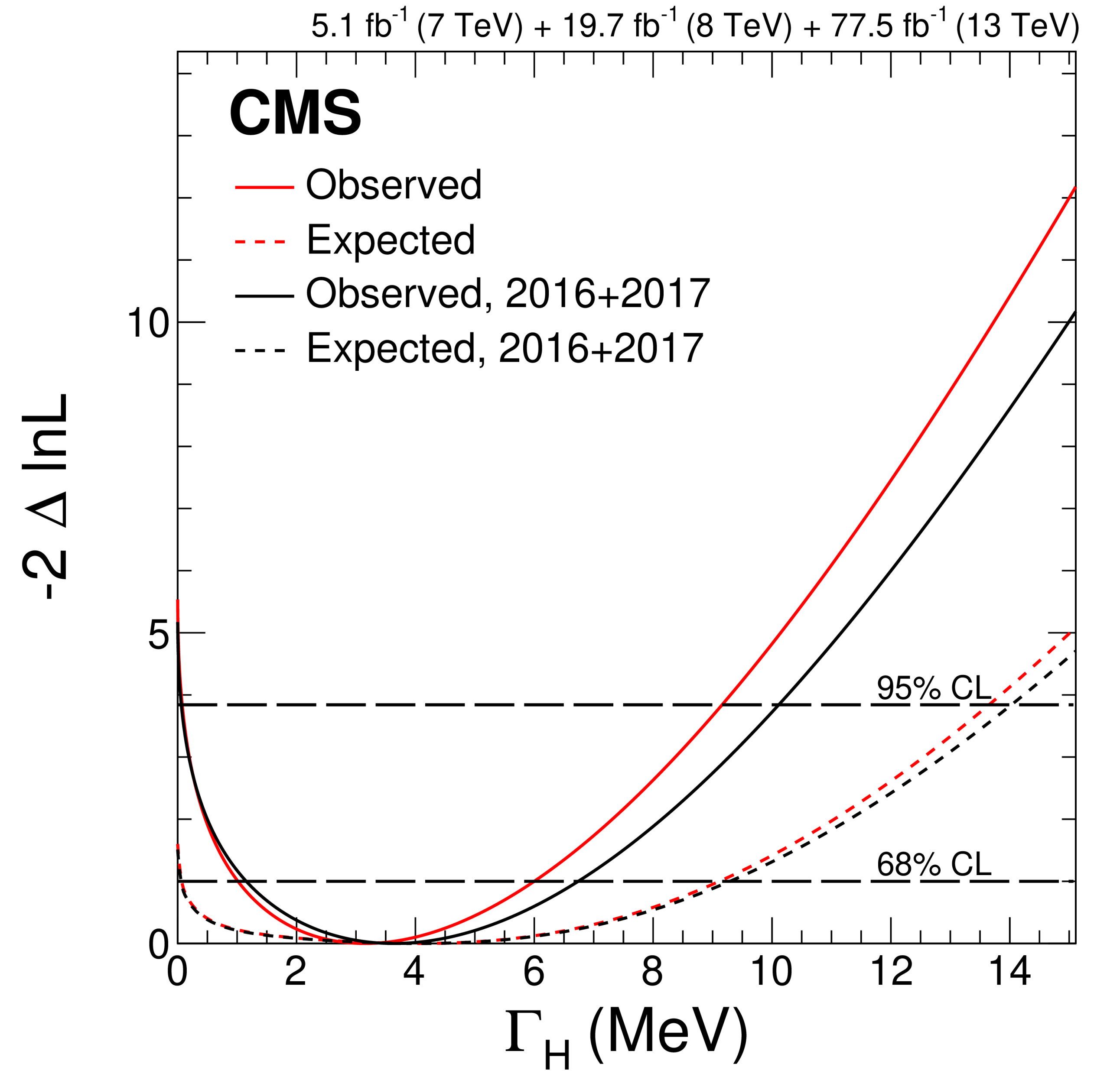
HIG-19-005

(*) kappa fit without additional BSM couplings

HIGGS WIDTH?

- Γ_H (SM)= 4 MeV
- Direct measurement: < 1.1 GeV (95% CL) (CMS)
- H→ZZ→4l: measure through the relative on-shell and off-shell production rates (model dependent)





$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H},$$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}.$$

$m_{ZZ} \sim m_H$
(On-shell production)

$m_{ZZ} > m_{ZZ}$
(Off-shell production)

	Lumi	Latest Result on Γ_H
CMS, Phys. Rev. D 99 (2019) 112003	Run1+ 77.5 fb^{-1}	$3.2^{+2.8}_{-2.2}\ (4.1^{+5.0}_{-4.0})\ MeV$ Γ_H < 9.16 (13.7) MeV (95% CL)
ATLAS, Phys. Lett. B 786 (2018) 223	36 fb^{-1}	Γ_H < 14.4 (15.2) MeV (95% CL)

HIGGS WIDTH: THE FUTURE?

- At HL-LHC, from offshell/onshell: +-1 MeV (25%)
- Measurements in Lepton colliders:
  - mass recoil: measure the inclusive cross-section of the ZH without assumption on the Higgs BR's
  - mild model dependence

$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [80]	2.6
CLIC_{1500}	2.6	κ-framework [80]	1.7
CLIC_{3000}	2.5	κ-framework [80]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, $\mathrm{BR}(H \to Z, b\bar{b}, WW)$ [85]	1.8
FCC-ee_{240}	2.7	κ-framework [1]	1.9
FCC-ee_{365}	1.3	κ-framework [1]	1.2

1-2%

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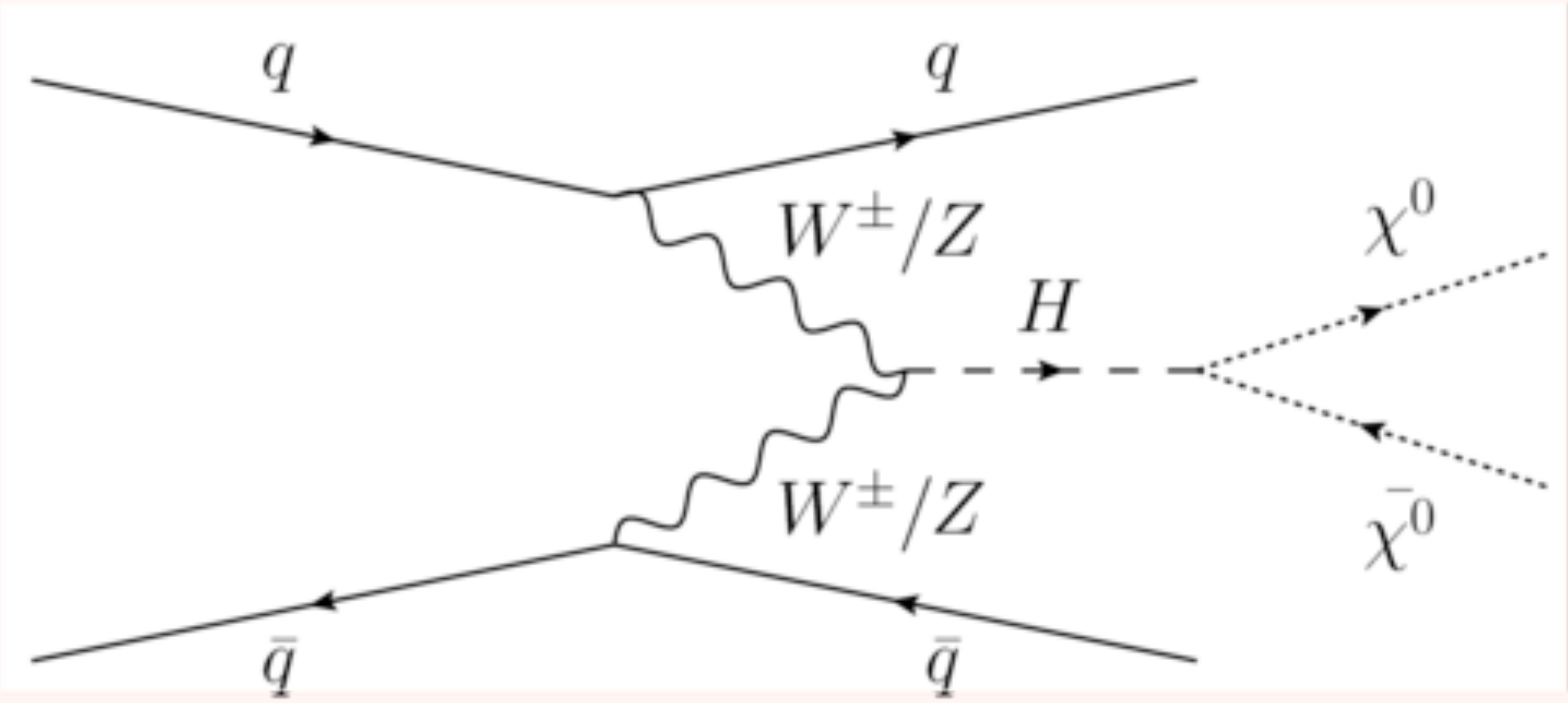
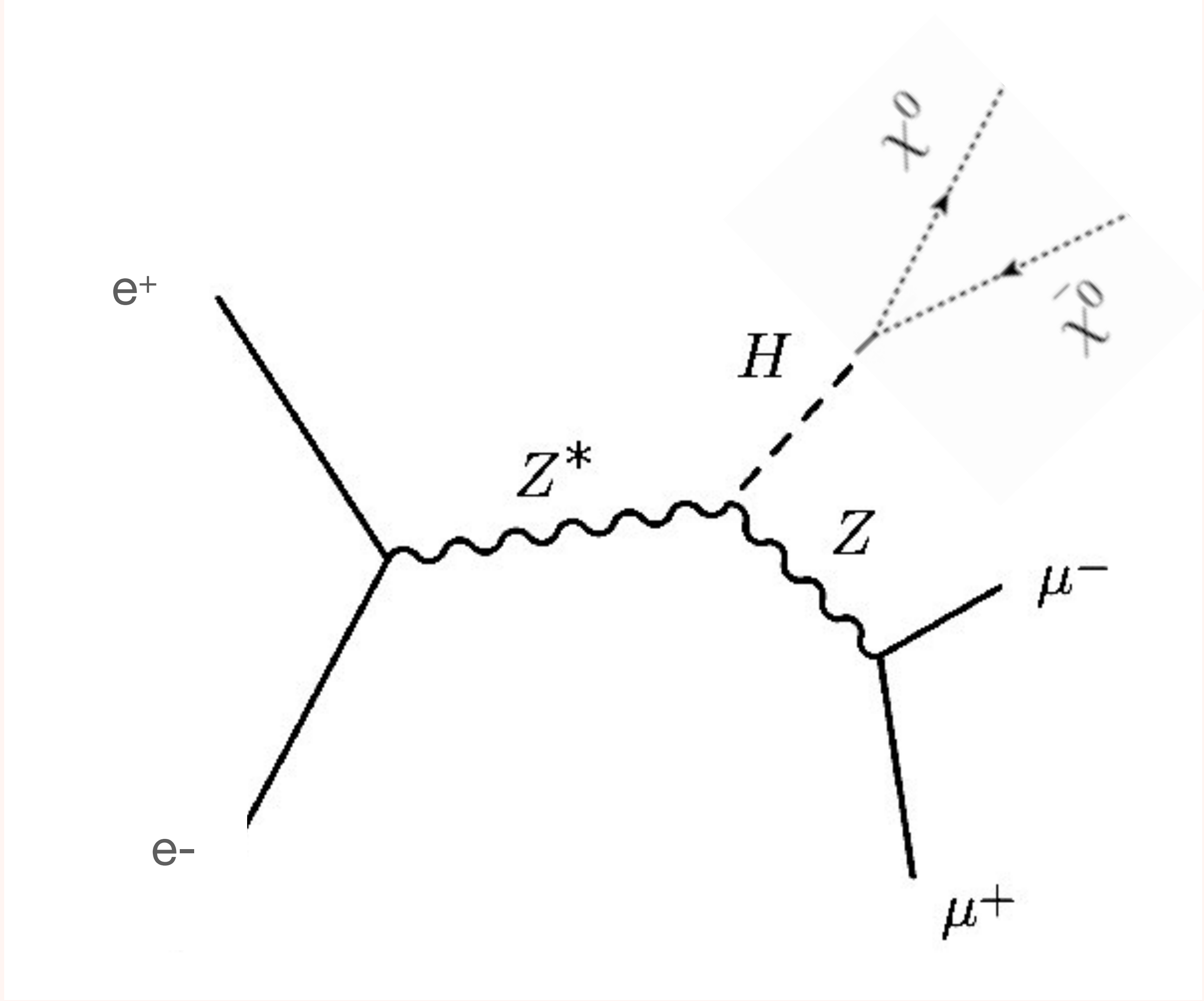
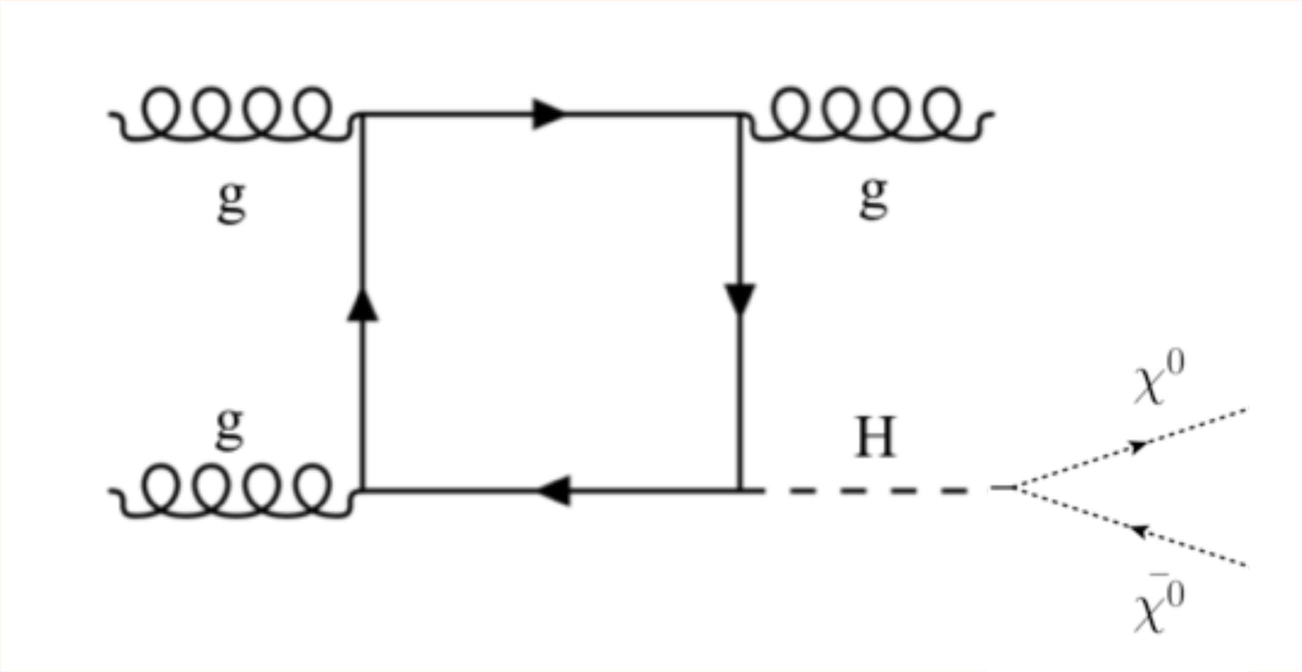
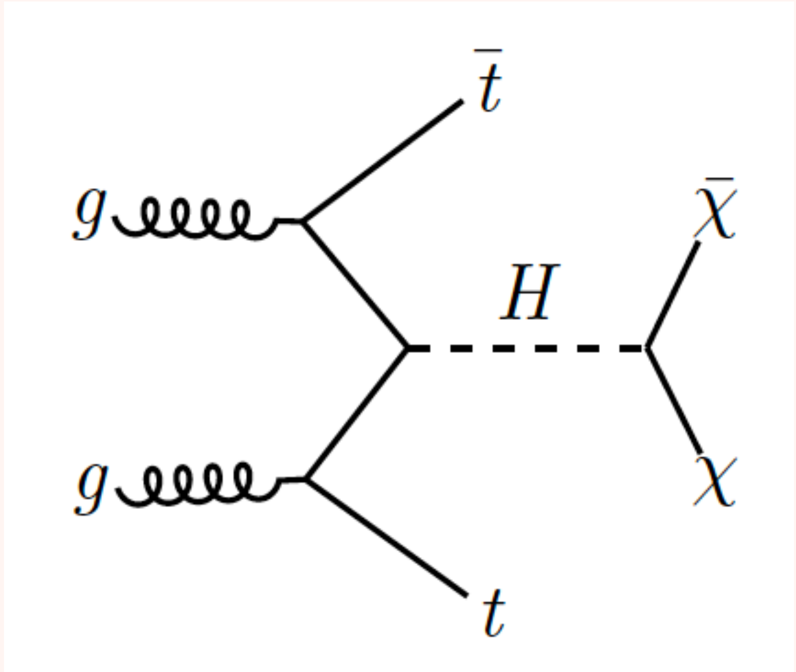
INVISIBLE HIGGS DECAYS

- **Higgs decays to undetected particles → connection to Dark Matter Searches**
- Challenging signature: E_T^{miss}
- Traditionally use associated production (WH and ZH) and especially weak vector boson fusion (VBF) to tag the events. But not only: V(jj)H, ttH, monoJet searches
- Background modelling (QCD/WJets/DY) is key



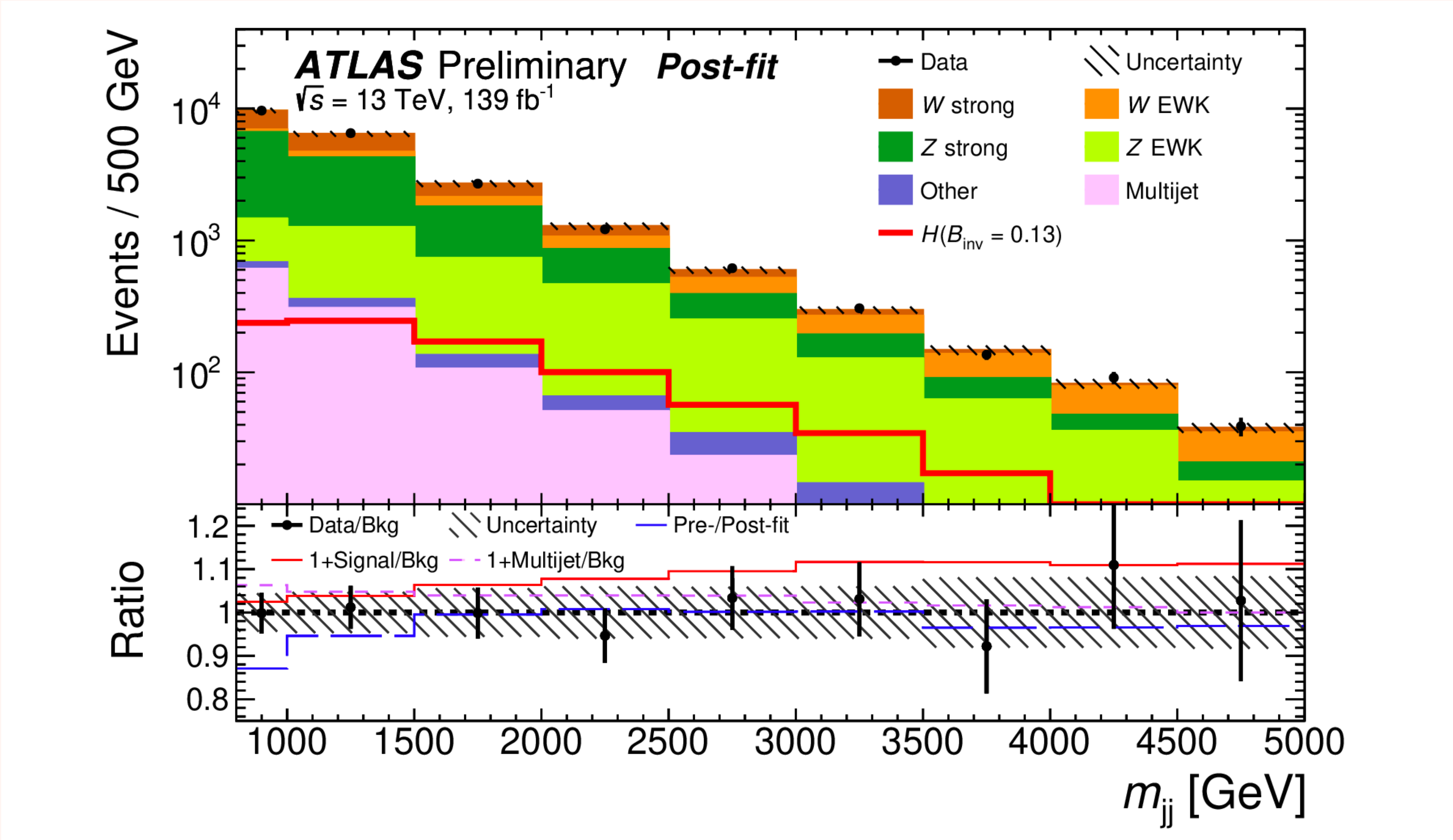


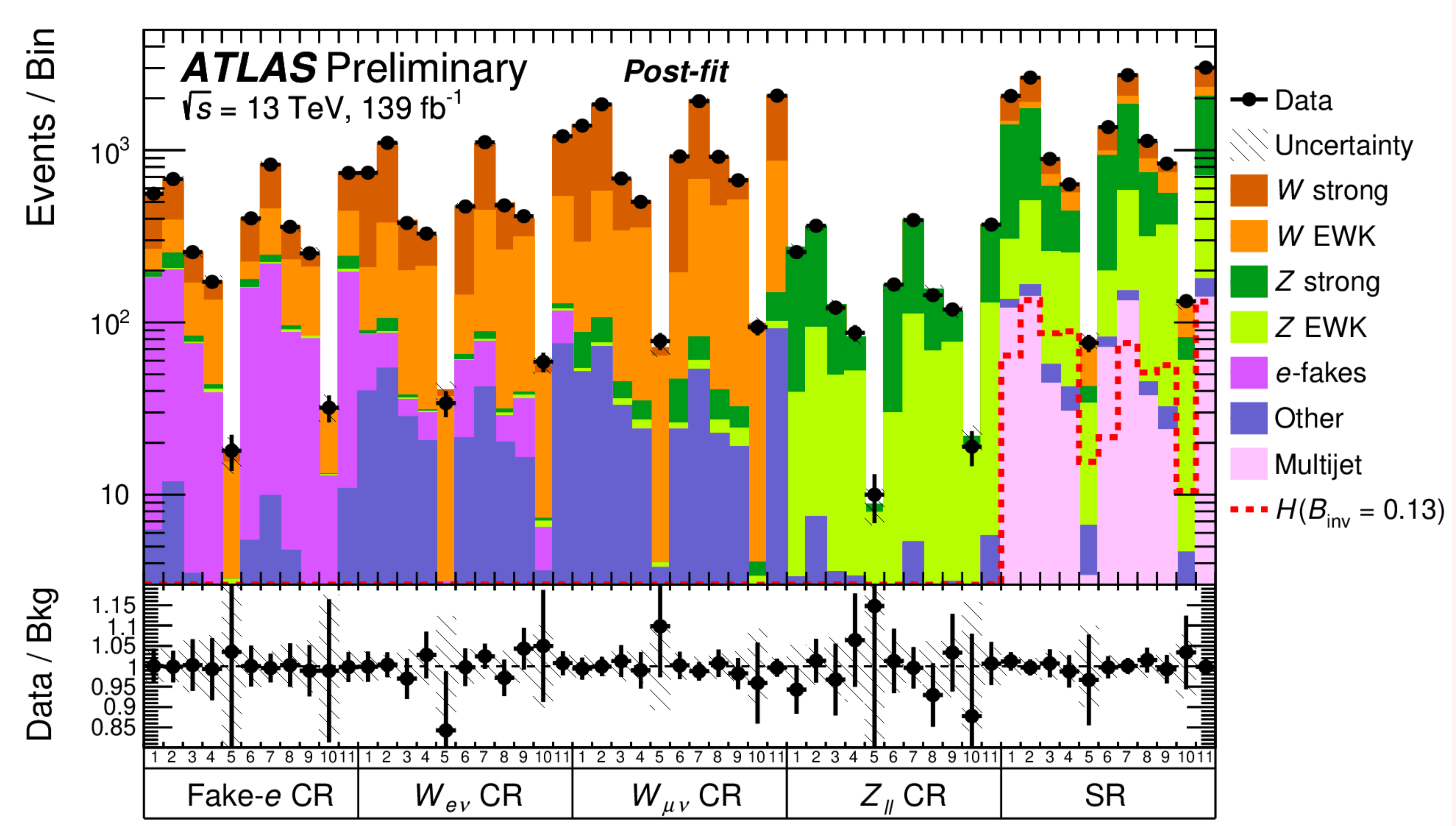




VBF PRODUCTION

- Most sensitive channel
- Profit from VBF Topology to identify the events and suppress QCD background: 2 forward jets + High M_{jj} and E_T^{miss} as signature
  - eg for ATLAS: M_{jj}>800 GeV and E_T^{miss}>200 GeV
- Background estimation/modelling key: Control regions for visible Z, W decays (single and double lepton) to control EWK W/Z backgrounds
- Full Run2 ATLAS result: improvement wrt to ATLAS 36fb^{-1} due not only to the increased luminosity but also to improvements of the analysis strategy, in particular an increase of the signal acceptance by 50%.



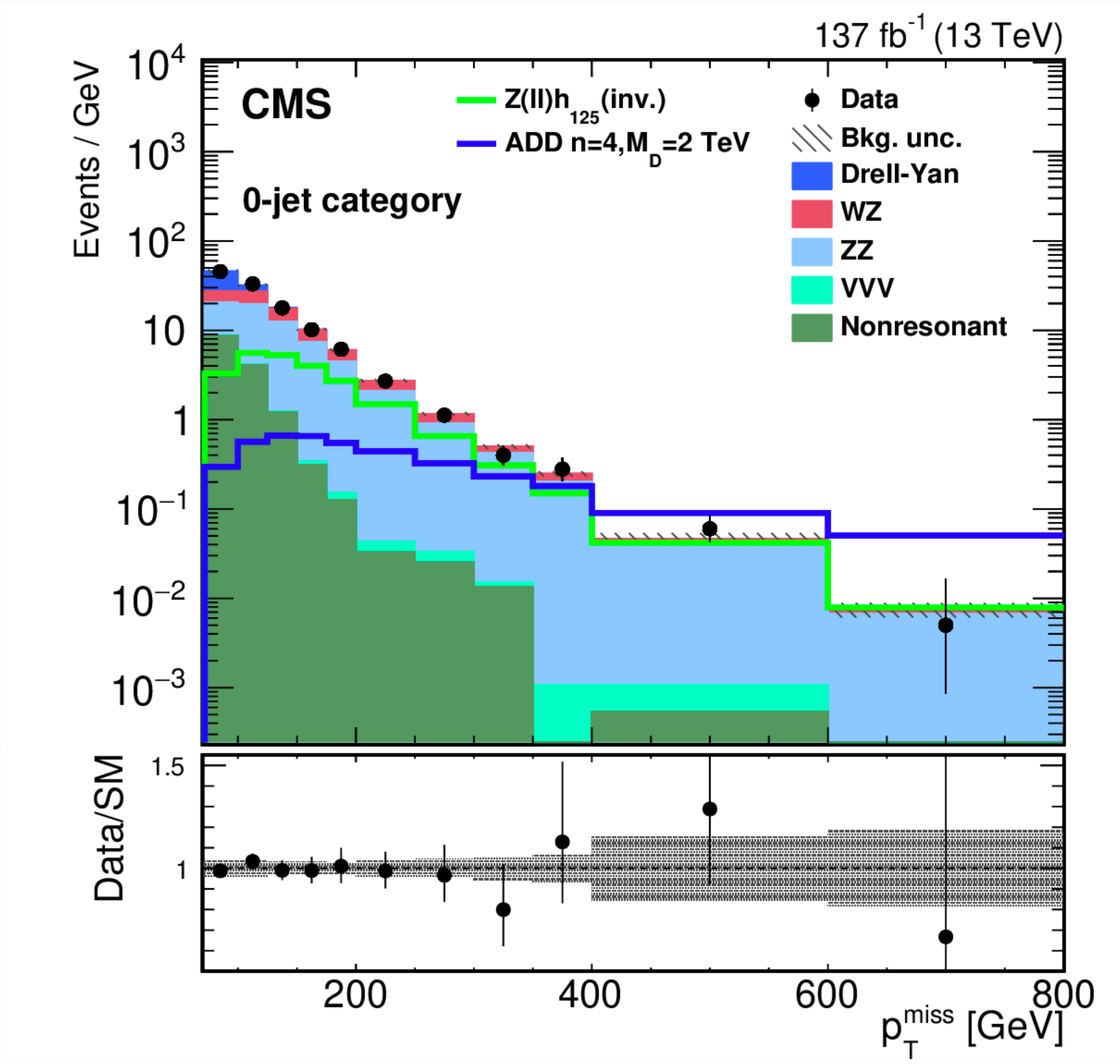


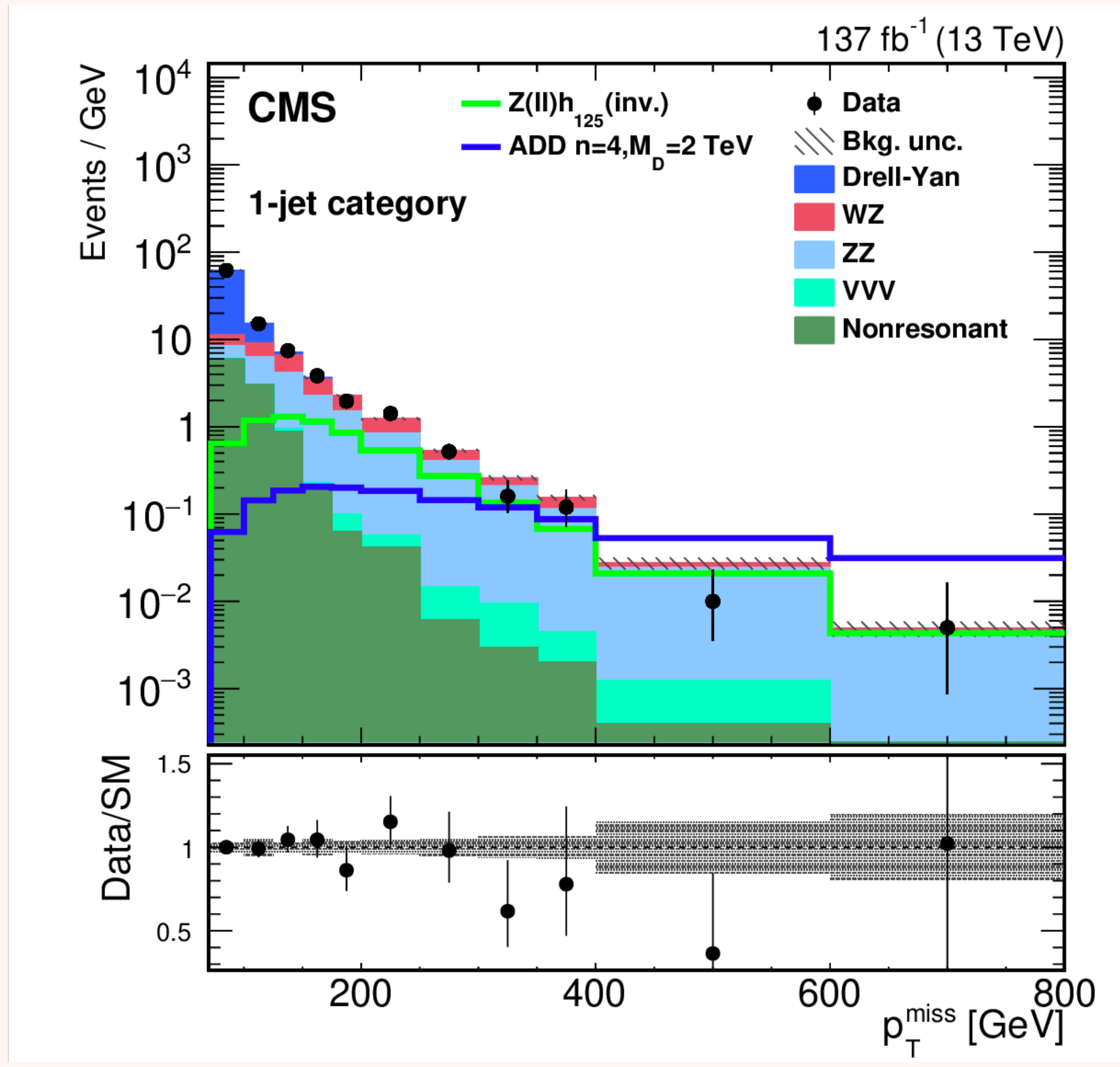
Latest Public Result	Lumi	95% CL Limit on $Br_{Inv\ (MH=125)}$
CMS Phys. Lett. B 793 (2019) 520	36 fb^{-1}	33% (25%)
ATLAS ATLAS-CONF-2020-008	139 fb^{-1}	13 % (13%)

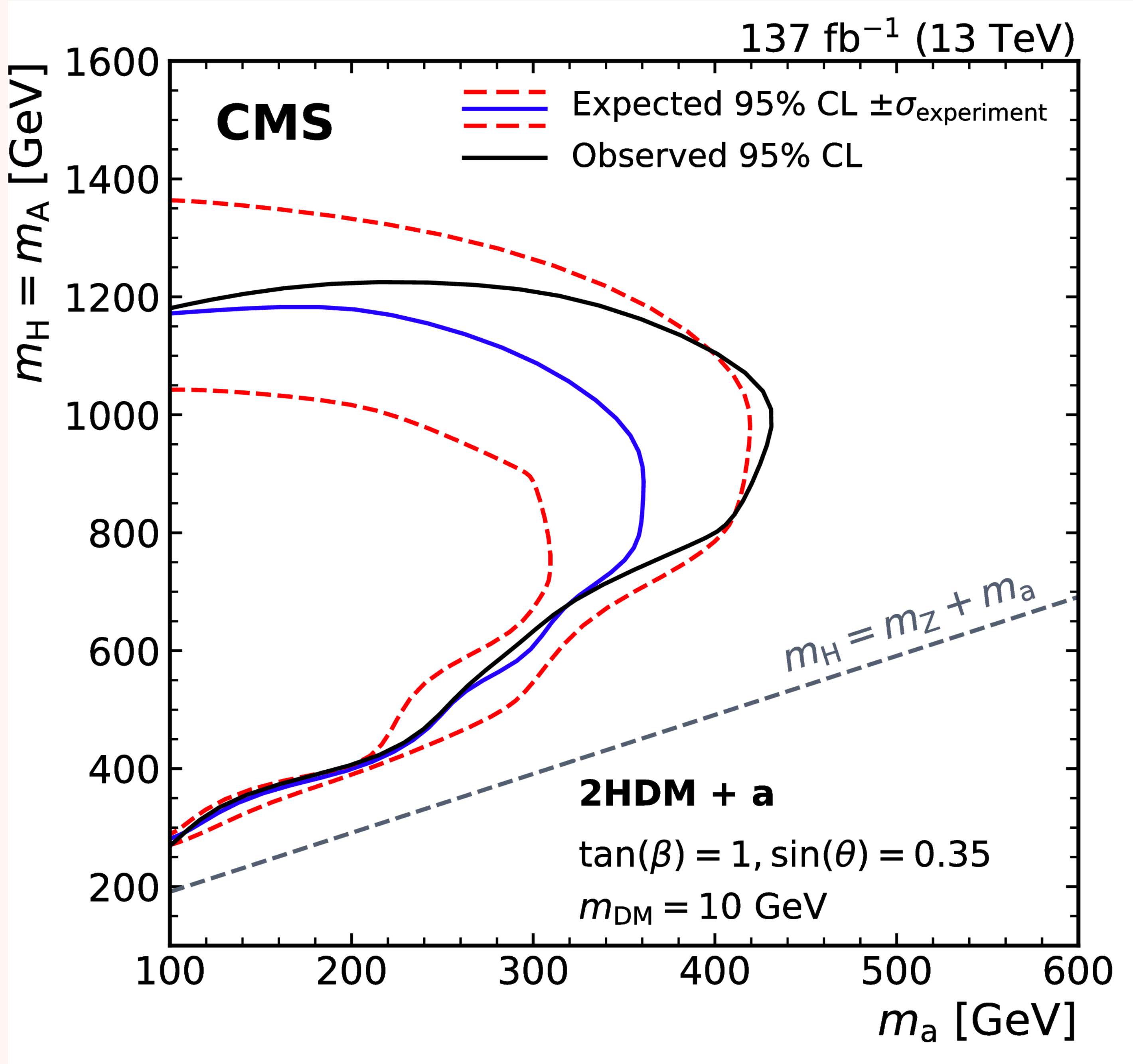
ZH PRODUCTION

- Tag Z decay: 2 opposite sign, same flavour (μμ, ee) leptons consistent with Z mass
- Cleaner, but much more statistically limited

Latest Public Result	Lumi	95% CL Limit on $Br_{Inv\ (MH=125)}$
CMS arXiv:2008.04735	137 fb^{-1}	29% (25%)
ATLAS PLB 776 (2017) 318	36 fb^{-1}	67 % (39%)

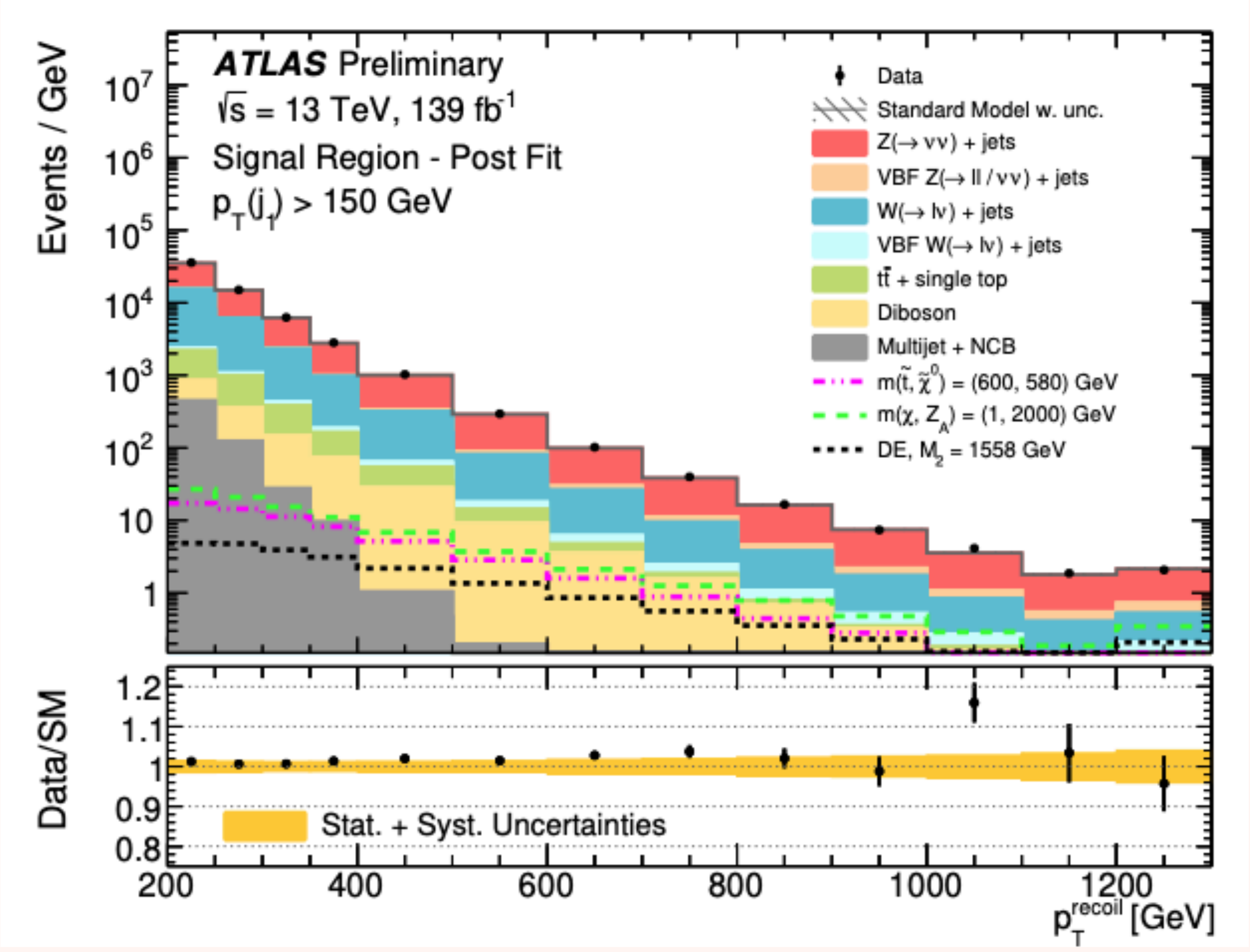


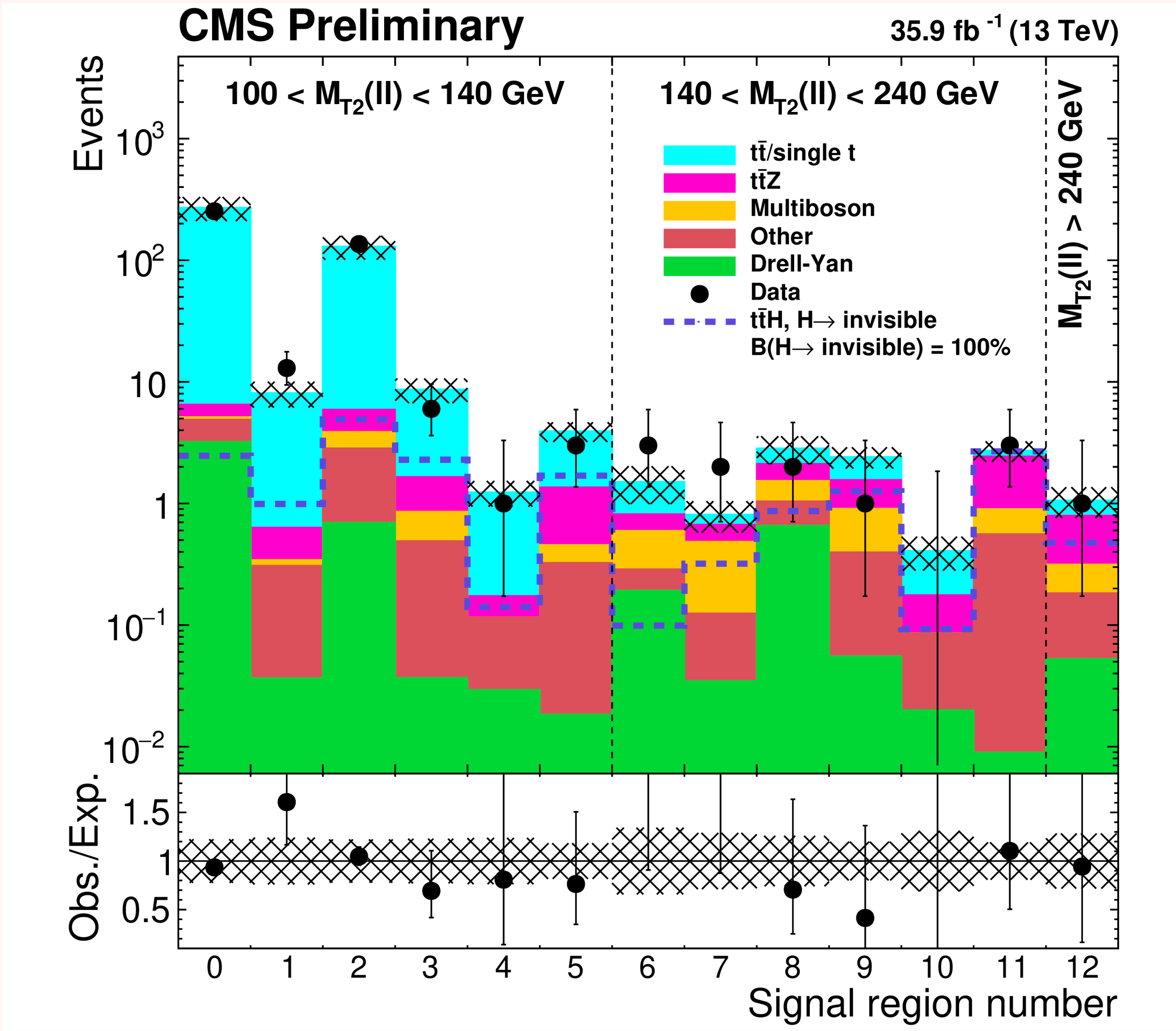




AND MORE…

		Lumi	95% CL Limit on $Br_{Inv\ (MH=125)}$
MonoJet	CMS Phys. Rev. D 97 (2018) 092005	36 fb^{-1}	66% (59%)
	ATLAS ATLAS-CONF-2020-048	139 fb^{-1}	63 % (57%)
TTH	CMS CMS-PAS-HIG-18-008	36 fb^{-1}	46% (48%)
VH Hadronic	CMS, Phys. Rev. D 97 (2018) 092005	36 fb^{-1}	50% (48%)
	ATLAS	36 fb^{-1}	83% (58%)

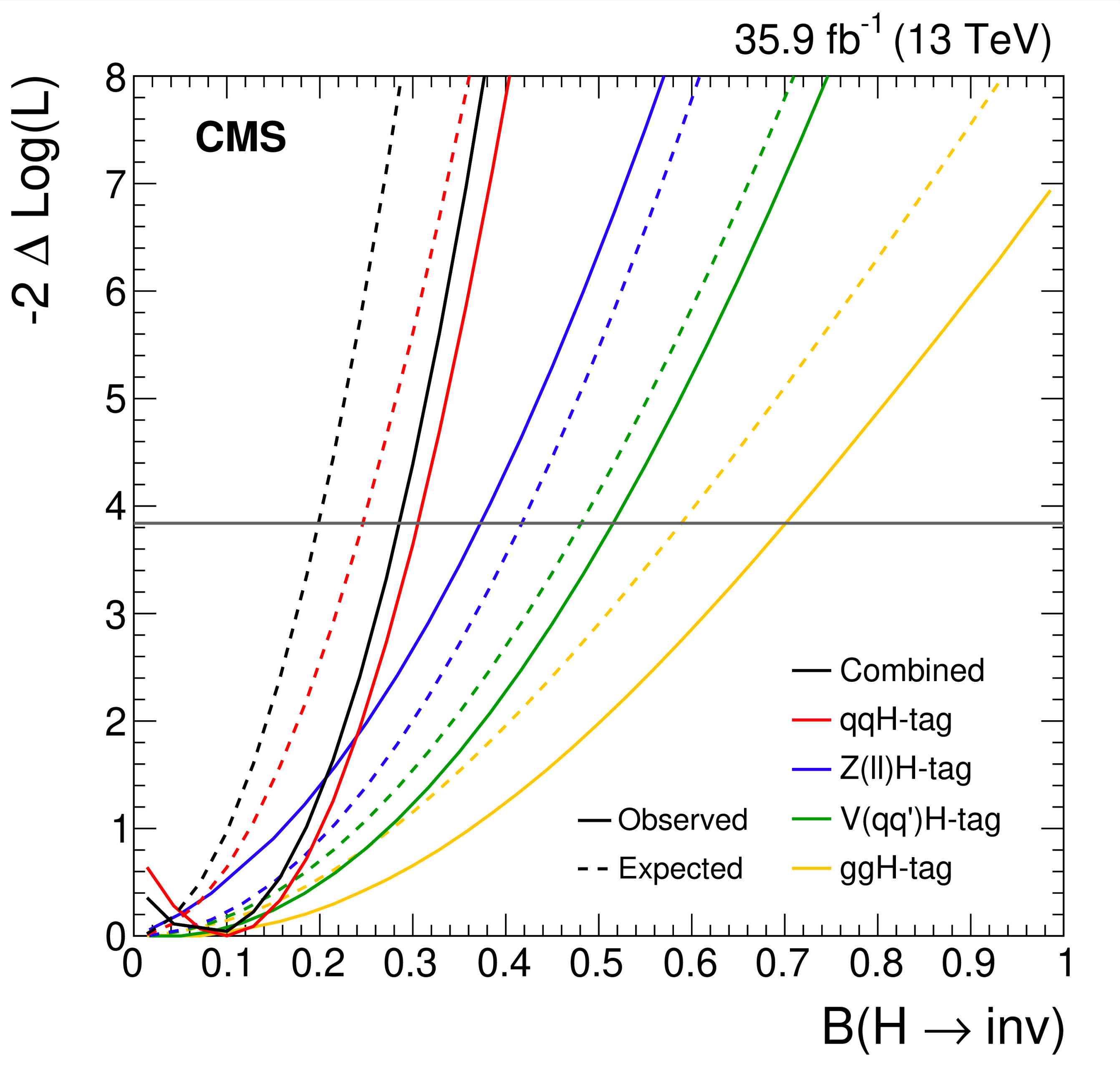


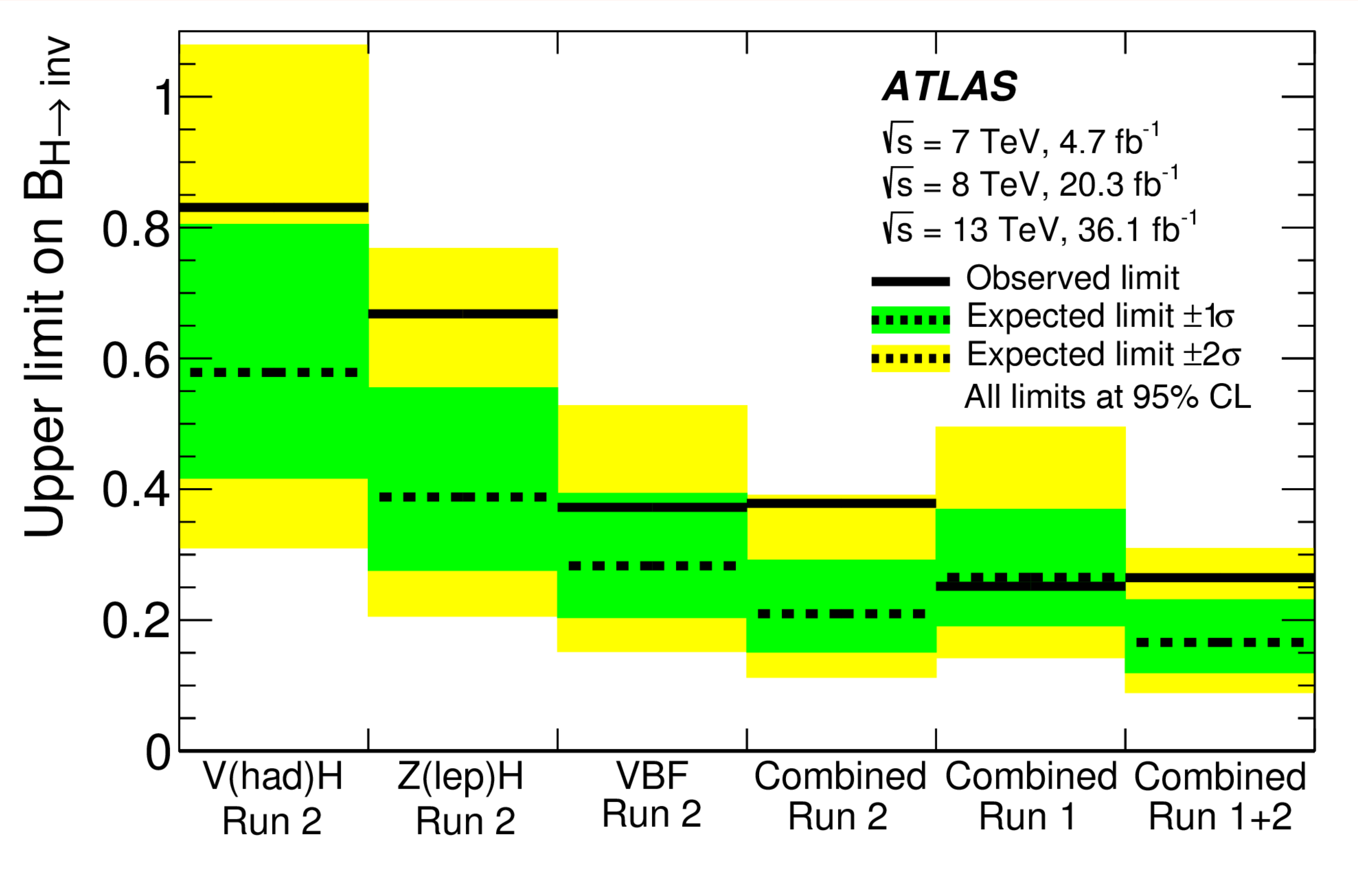


COMBINED RESULTS?

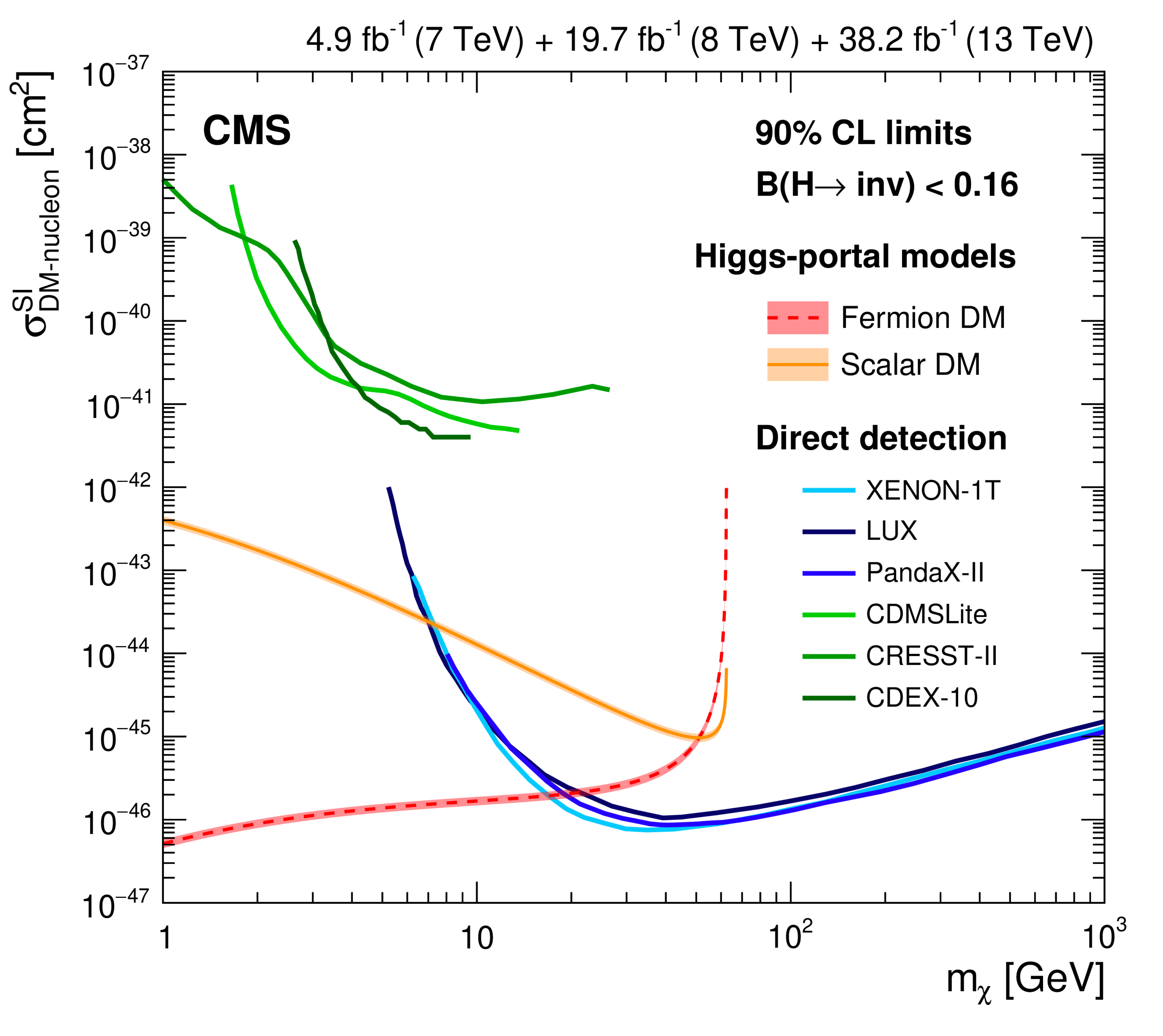
Latest Public Combination	Lumi	95% CL Limit on Br_{Inv} (MH=125)
CMS Phys. Lett. B 793 (2019) 520	Run1+36 fb^{-1}	19% (15%)
ATLAS Phys. Rev. Lett. 122 (2019) 231801	Run1+36 fb^{-1}	26% (17%)

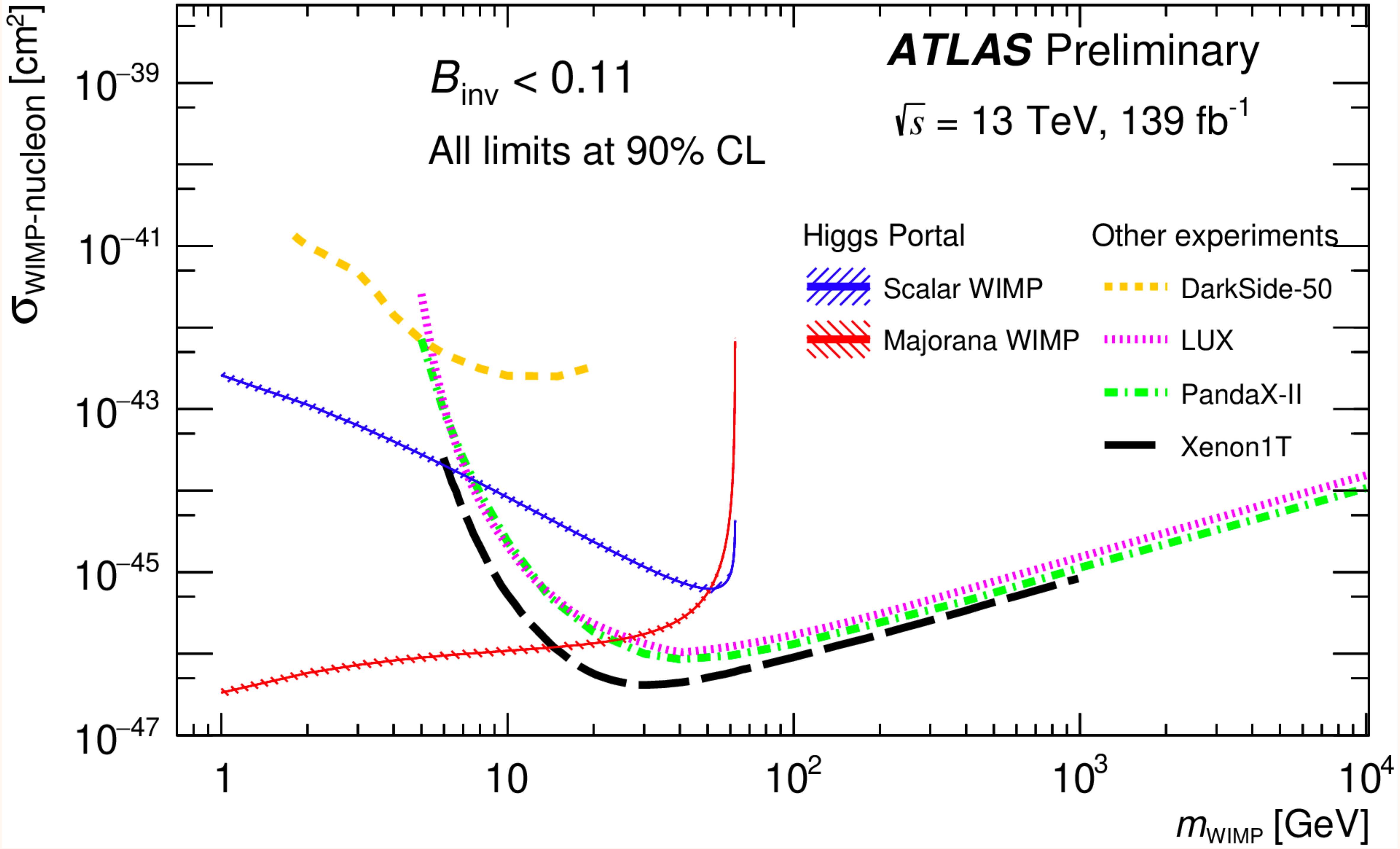
- To be updated to full Run2 results!
- Run2 VBF alone already at 13% (ATLAS)





HIGGS PORTAL





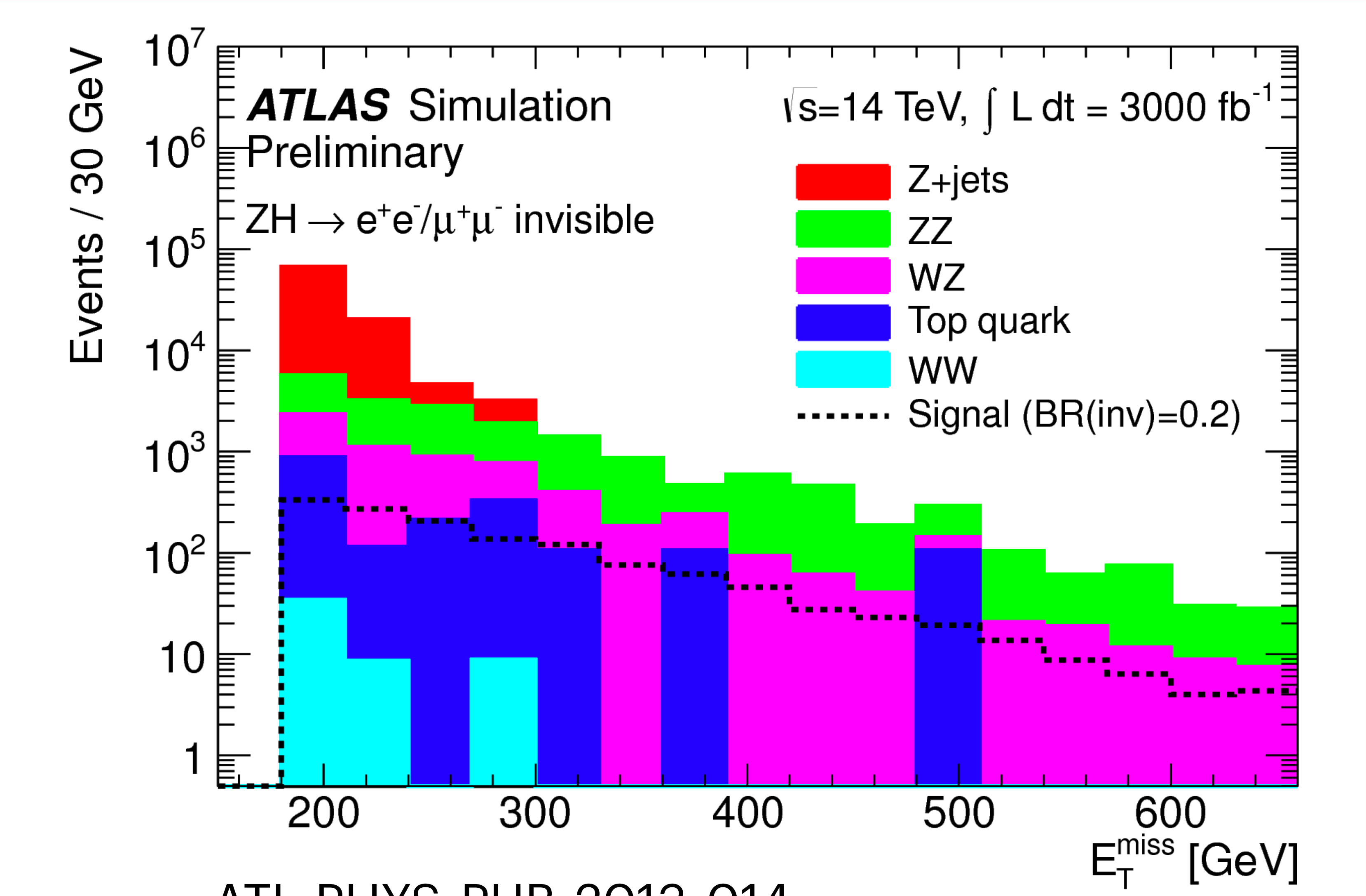
- Limits on WIMP-Nuclear cross section assuming that the dark matter interacts with the Higgs boson, with further assumptions on nuclear form factors
- Comparison to direct searches for dark matter

HL-LHC?

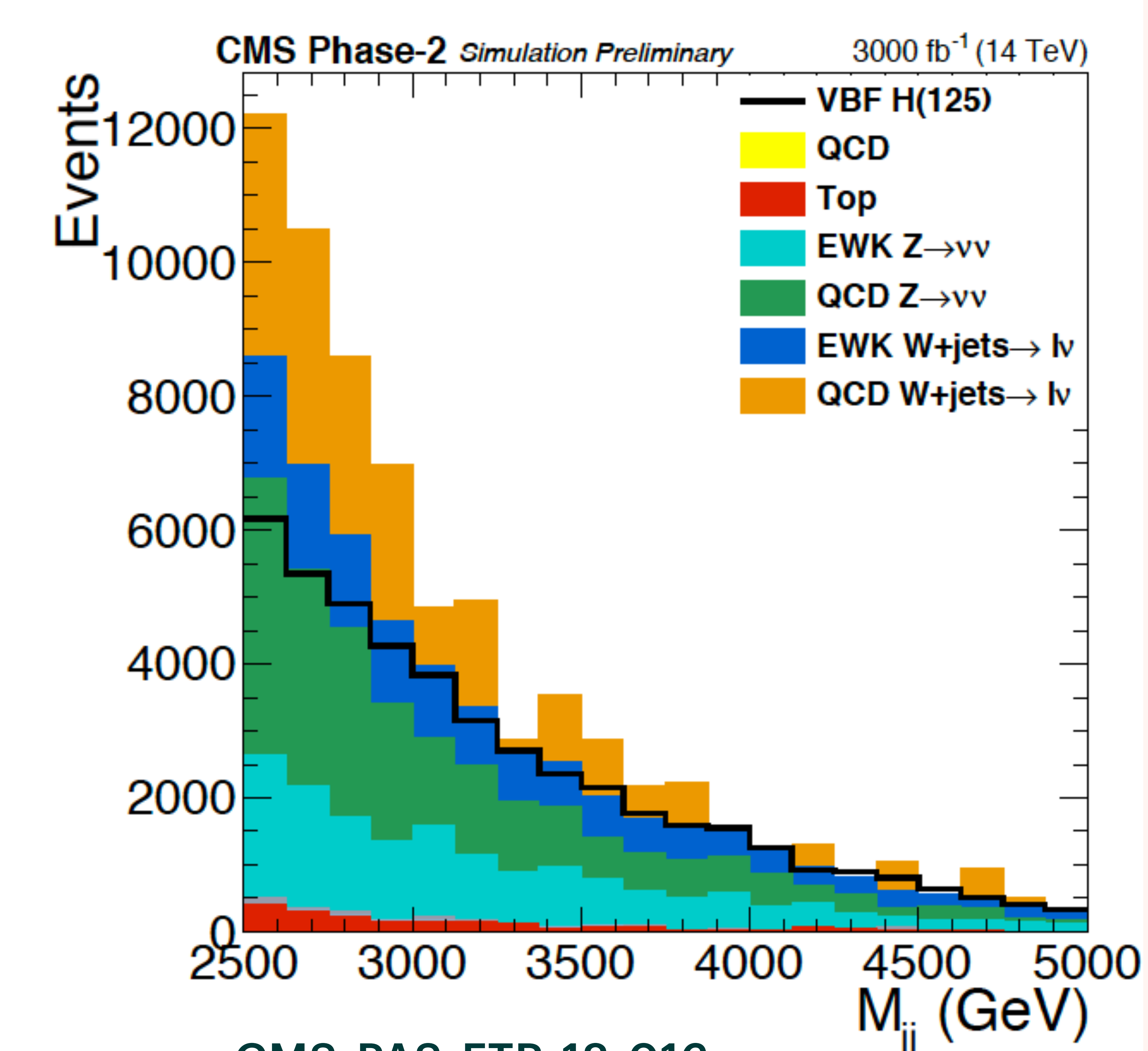
- Prospects based on VBF and ZH leptonic 36 fb^{-1} direct searches
- In the VBF case: Delphes based, full reoptimization of the analysis at 200PU to handle the impact of PU in MET

VH: ATLAS, 2013: <8% @ 95%CL
VBF: CMS, 2018: <3.8% @ 95%CL
HL-LHC: <2.5% @ 95% CL

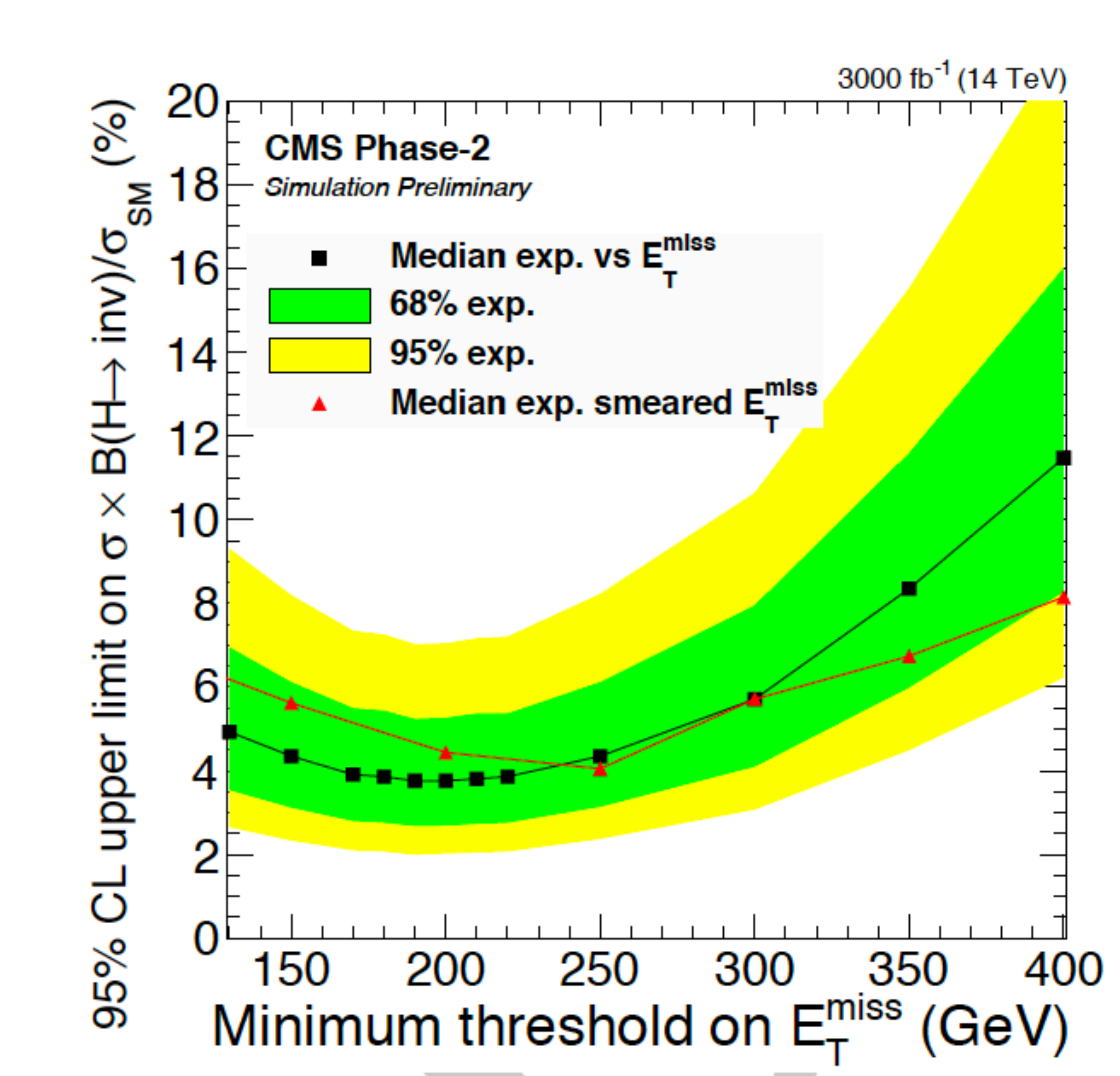
HL-LHC CERN Yellow Report 2018



ATL-PHYS-PUB-2013-014



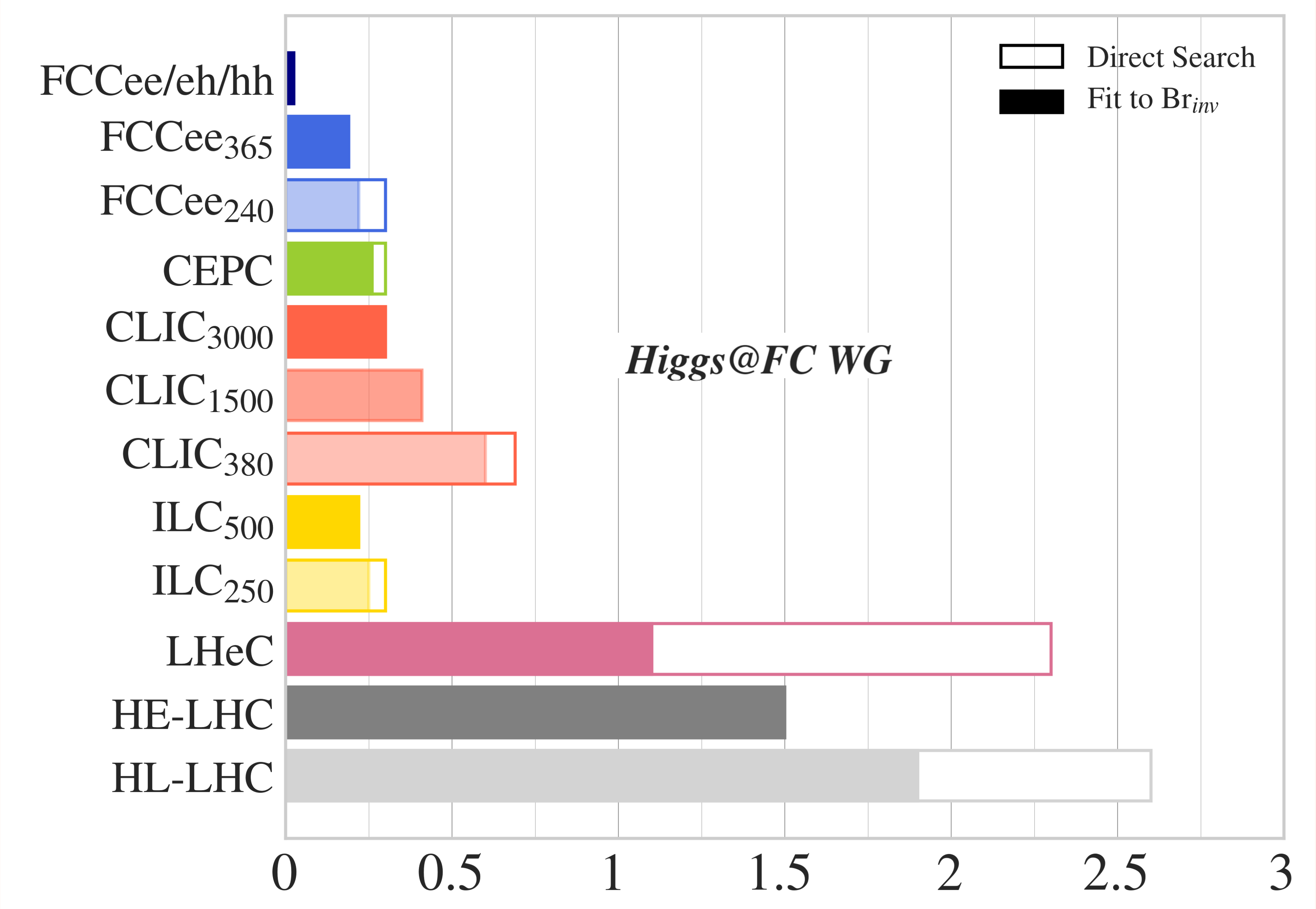
CMS-PAS-FTR-18-016



THE FAR FUTURE?

- Direct searches for Invisible width: fundamentally different in a hadron collider (MET uncertainties) and a lepton collider (Z recoil)
  - Lepton colliders would improve upon HL-LHC limits by an order of magnitude
  - FCC-hh : another order of magnitude: values below the SM

Collider	95% CL upper bound on BR_{inv} [%]		
	Direct searches	kappa-3 fit	Fit to BR_{inv} only
HL-LHC	2.6	1.9	1.9
HL-LHC & HE-LHC		1.5	1.5
FCC-hh	0.025	0.024	0.024
HL-LHC & LHeC	2.3	1.1	1.1
CEPC	0.3	0.27	0.26
$FCC\text{-}ee_{240}$	0.3	0.22	0.22
$FCC\text{-}ee_{365}$		0.19	0.19
ILC_{250}	0.3	0.26	0.25
ILC_{500}		0.22	0.22
$CLIC_{380}$	0.69	0.63	0.60
$CLIC_{1500}$		0.62	0.41
$CLIC_{3000}$		0.61	0.30



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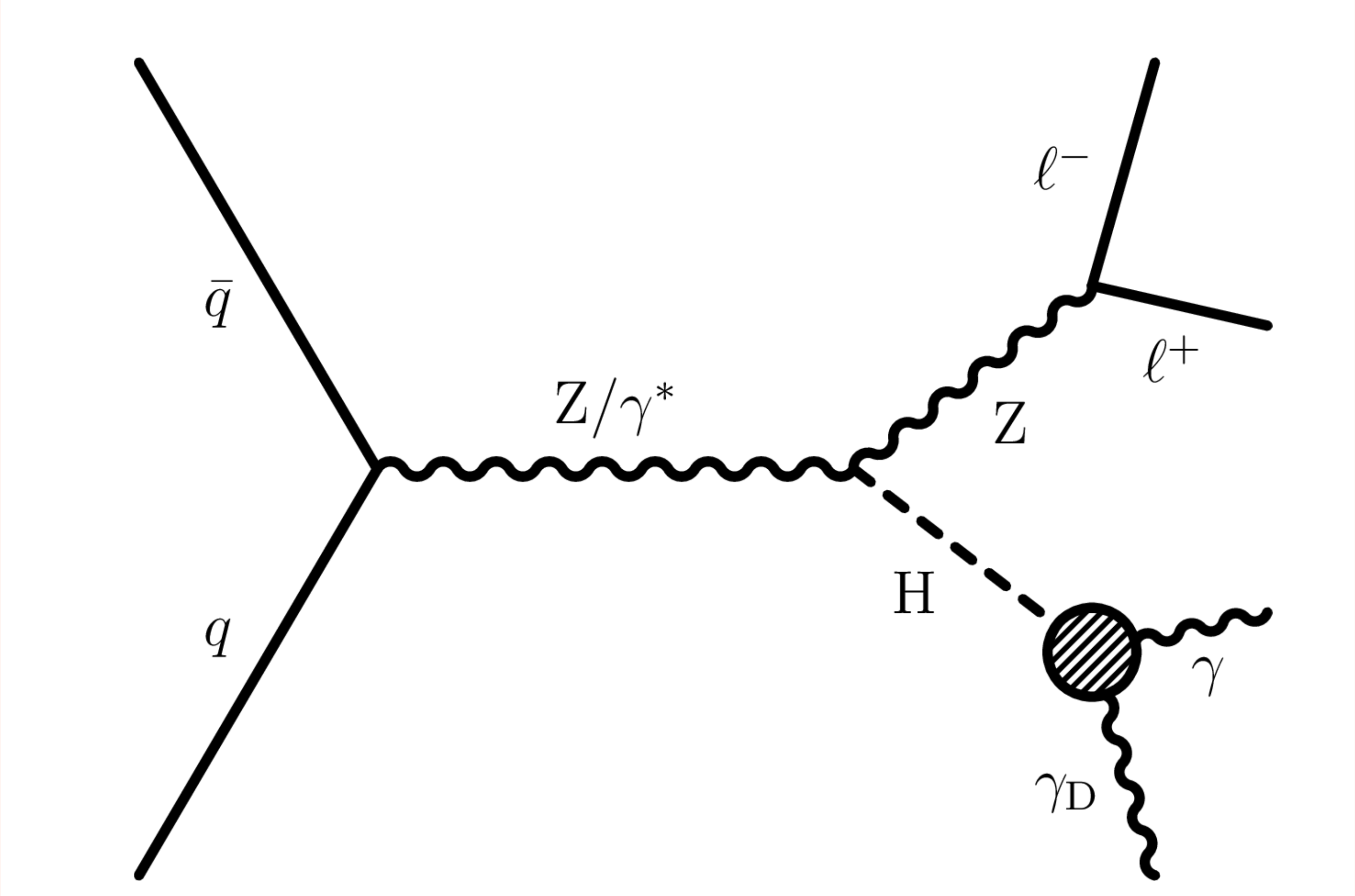
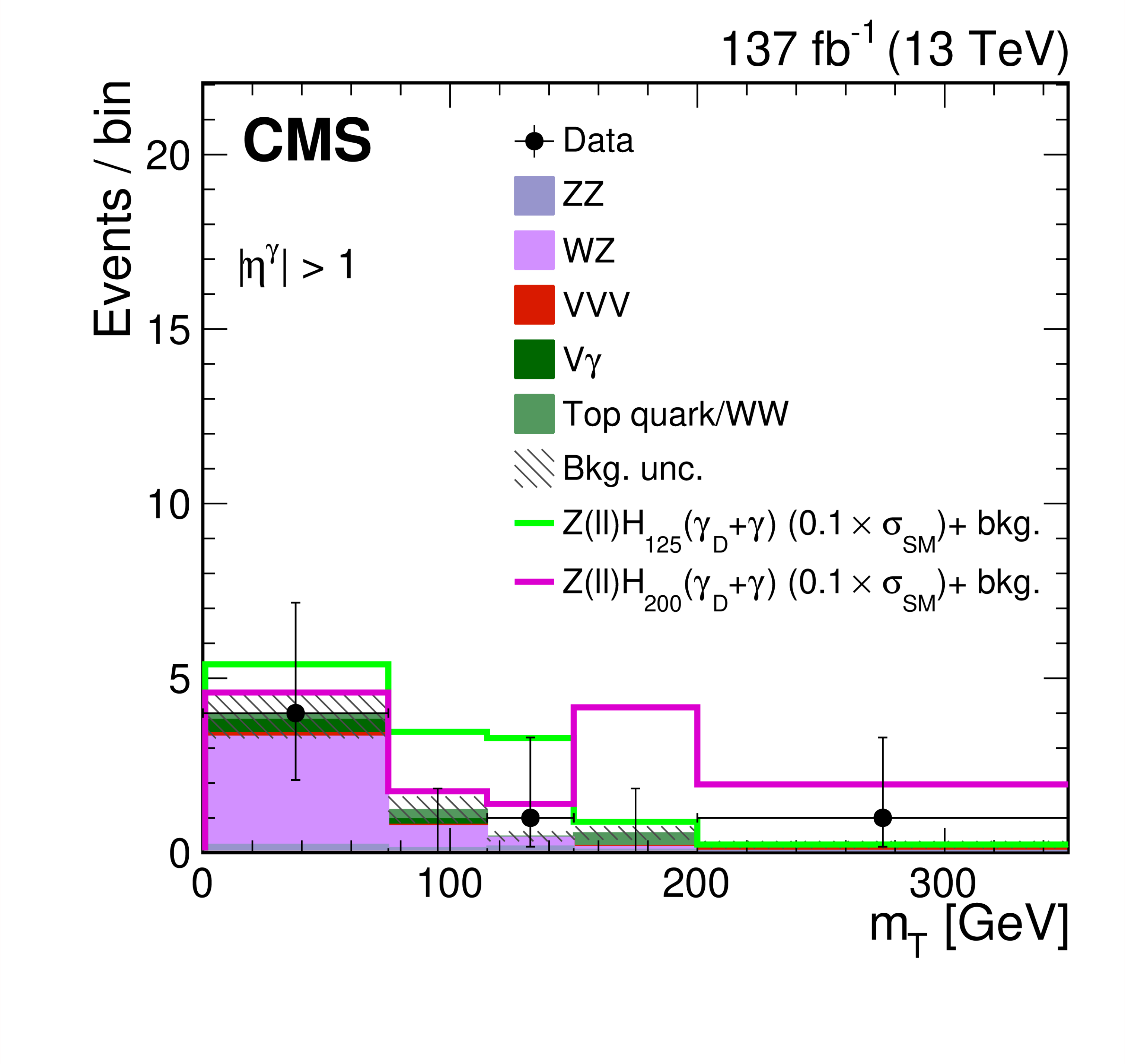
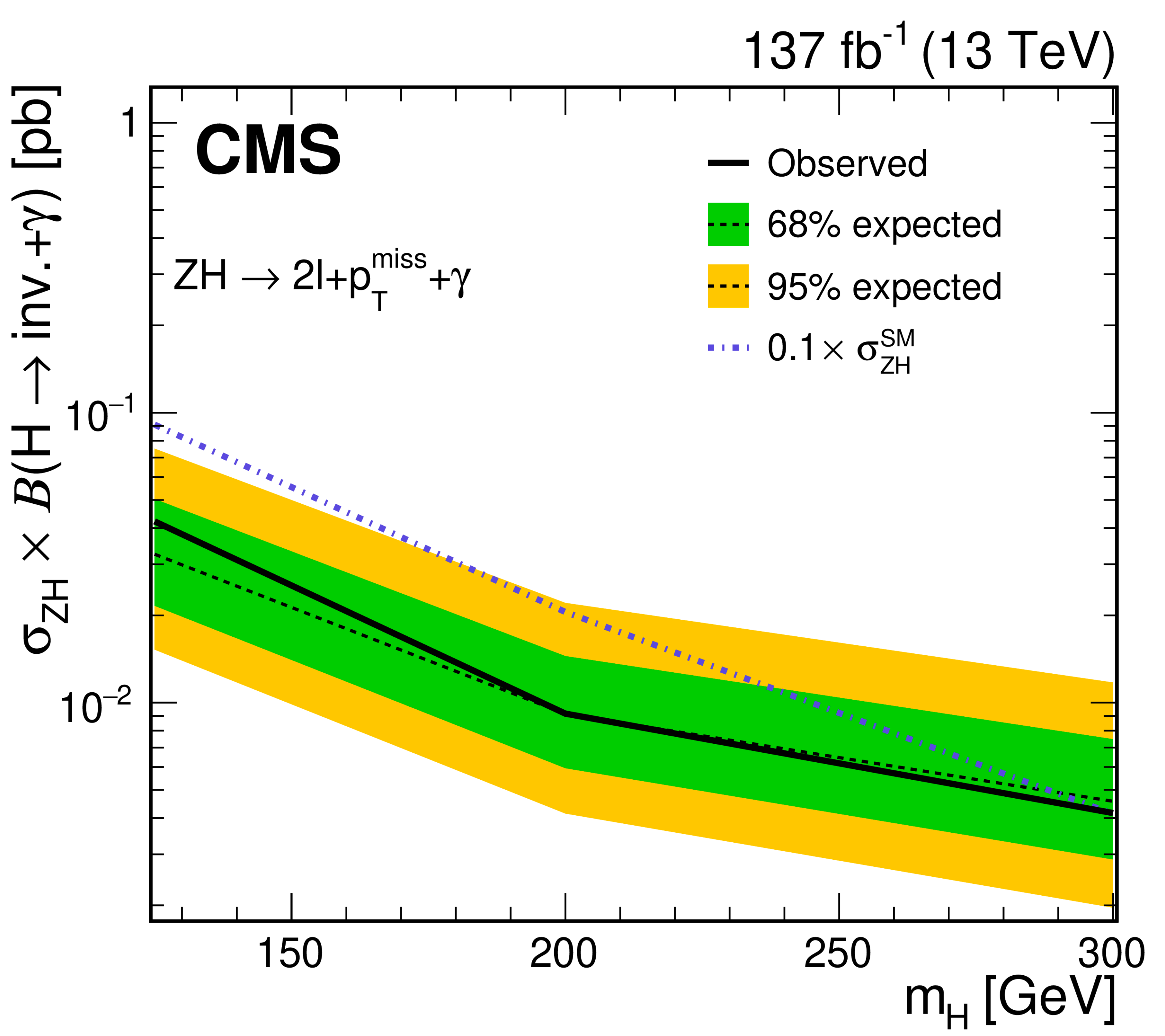
SEMI VISIBLE DECAYS

- Extended dark sector with DM candidate and a heavy resonance that couples the dark sector to the SM —> massless dark photon couples to the Higgs —> MET + photon signature associated to the Higgs decay
- Profit from ZH production to identify events: search for Z + MET + 1 Photon
- 95% CL limit : BR(h_{125}->$\gamma\gamma_D$) < 4.6 (3.6)% (CMS, 137 fb^{-1})

OTHER DARK PHOTON SEARCHES (VISIBLE) COVERED BY VERENA







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COMBINED COUPLING FIT

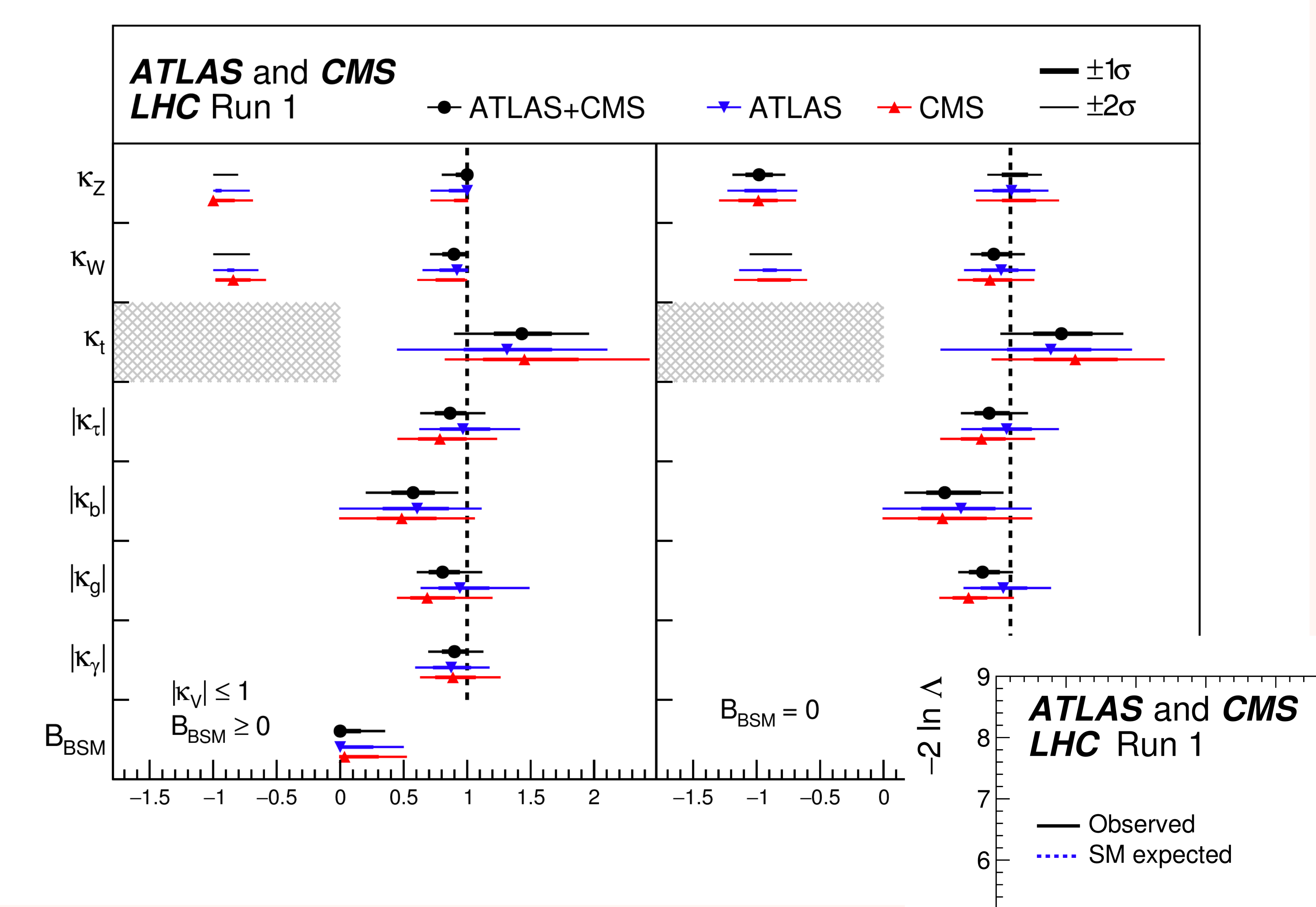
- We can derive constraints on the Exotic Higgs Branching ratio from the Higgs couplings measurements in the kappa framework, combining the information from all measured Higgs decay channels

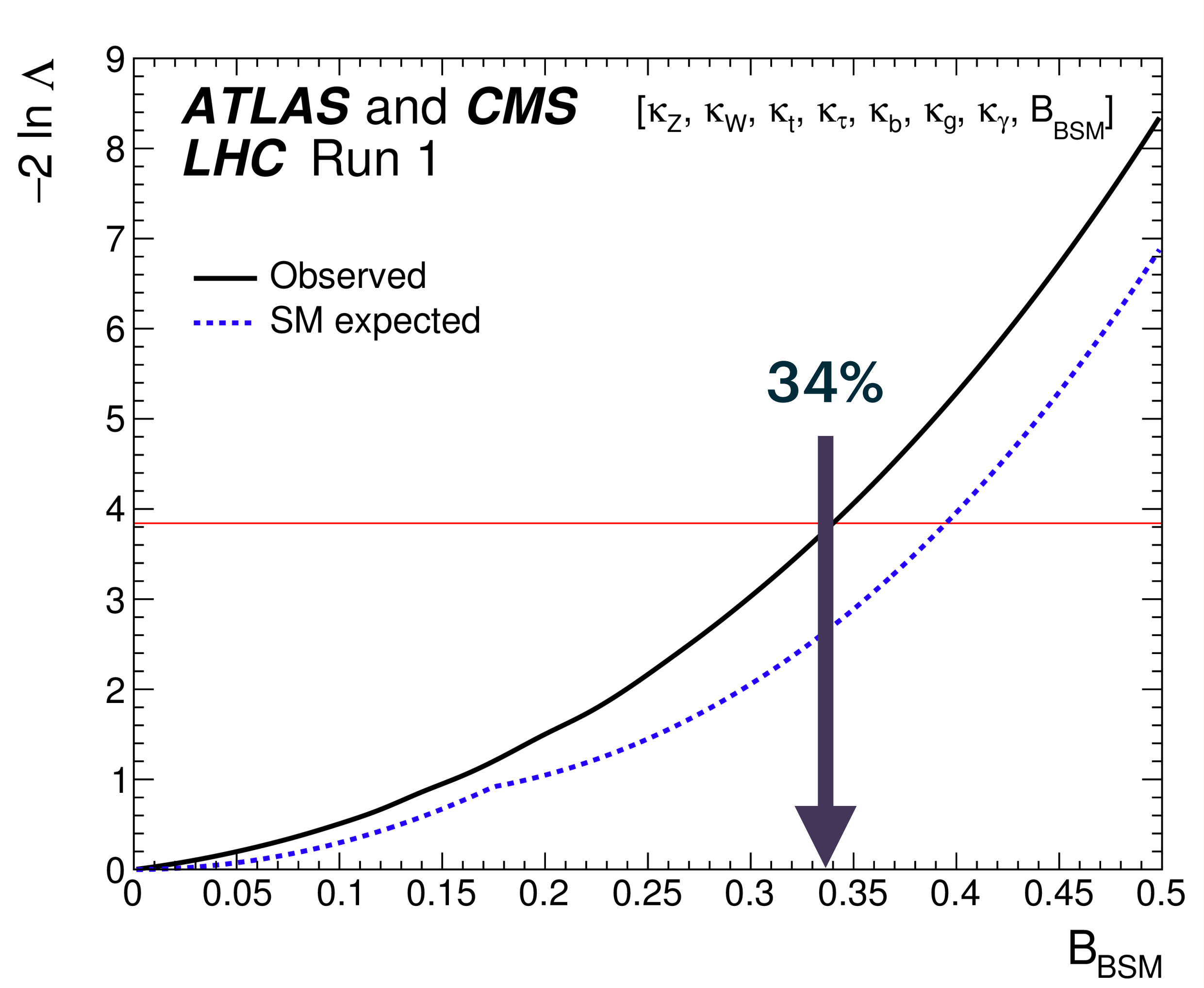
$$\Gamma_H = \frac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - BR_{BSM}}$$

- Warning: no direct measurement of the width. To probe the BSM BR an additional constrain needs to be imposed. Usually, $\kappa_{W,Z} \leq 1$.

- Higgs couplings in terms of kappas known to 10-20% precision

- Older coupling fits (eg the ATLAS+CMS Run1 combination) fitted together the Invisible and Untagged/BSM branching ratio





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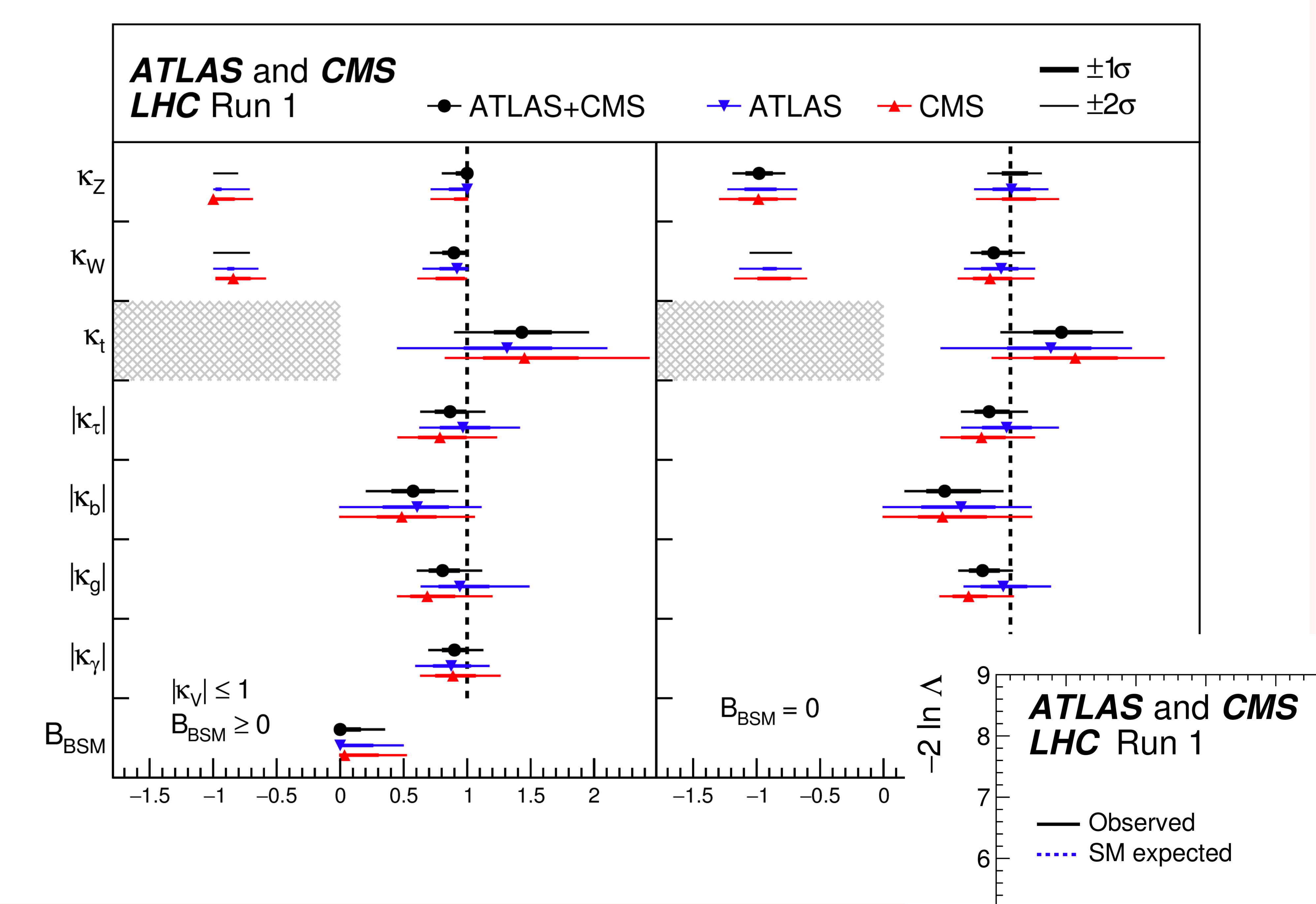
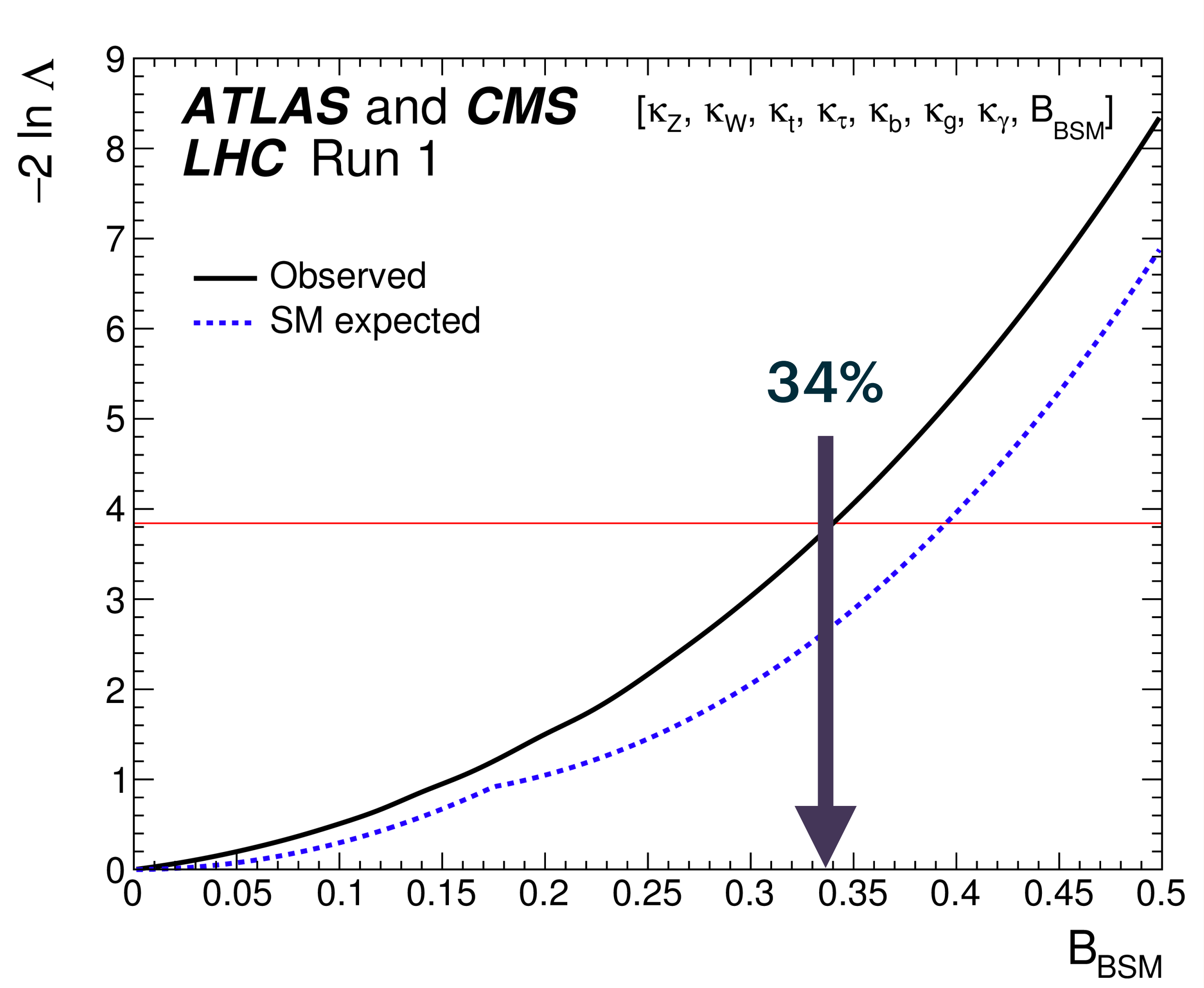
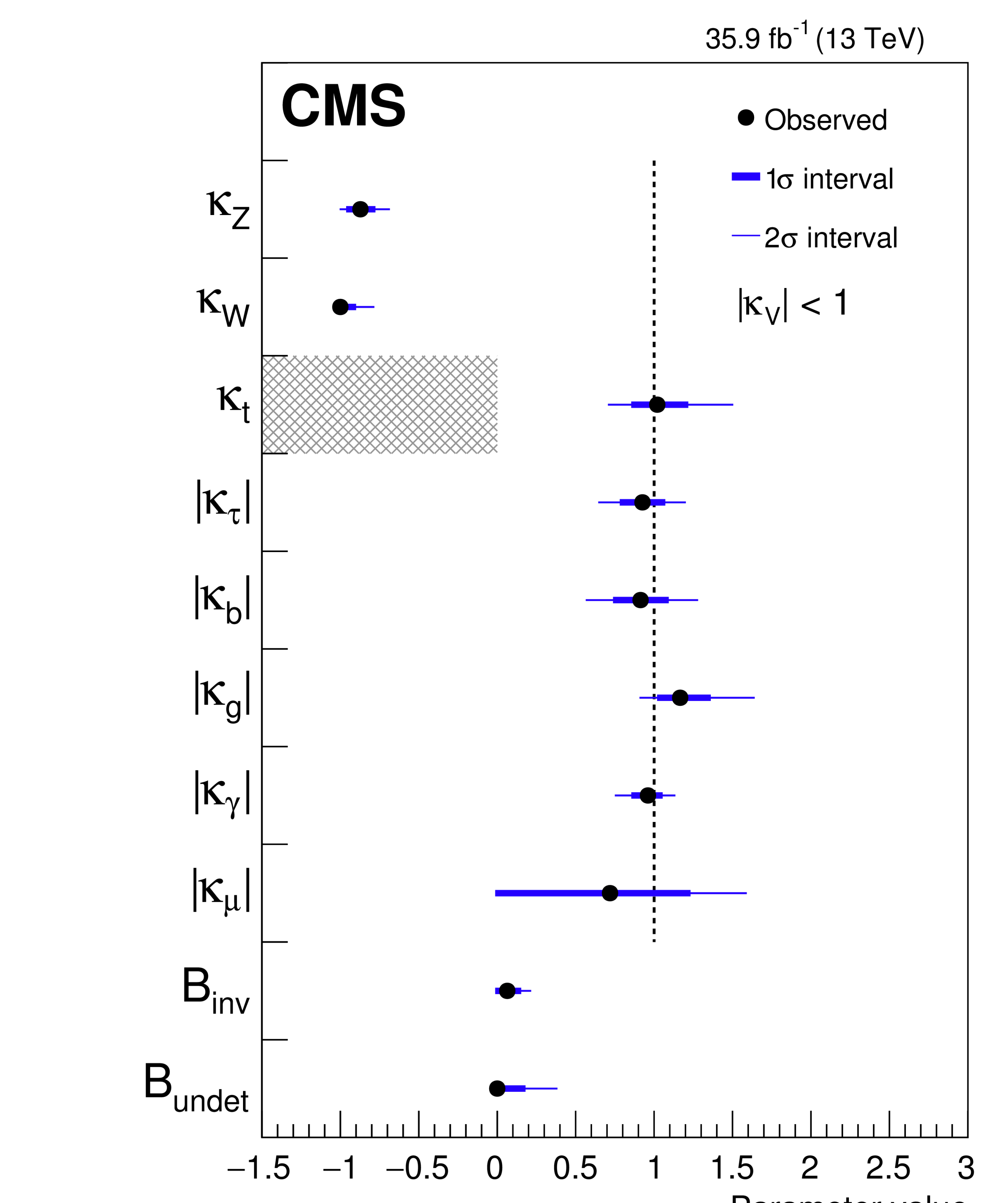




Individual Run2 results by ATLAS and CMS already more precise than the Run1 combination !

BRINV VS BRUNT



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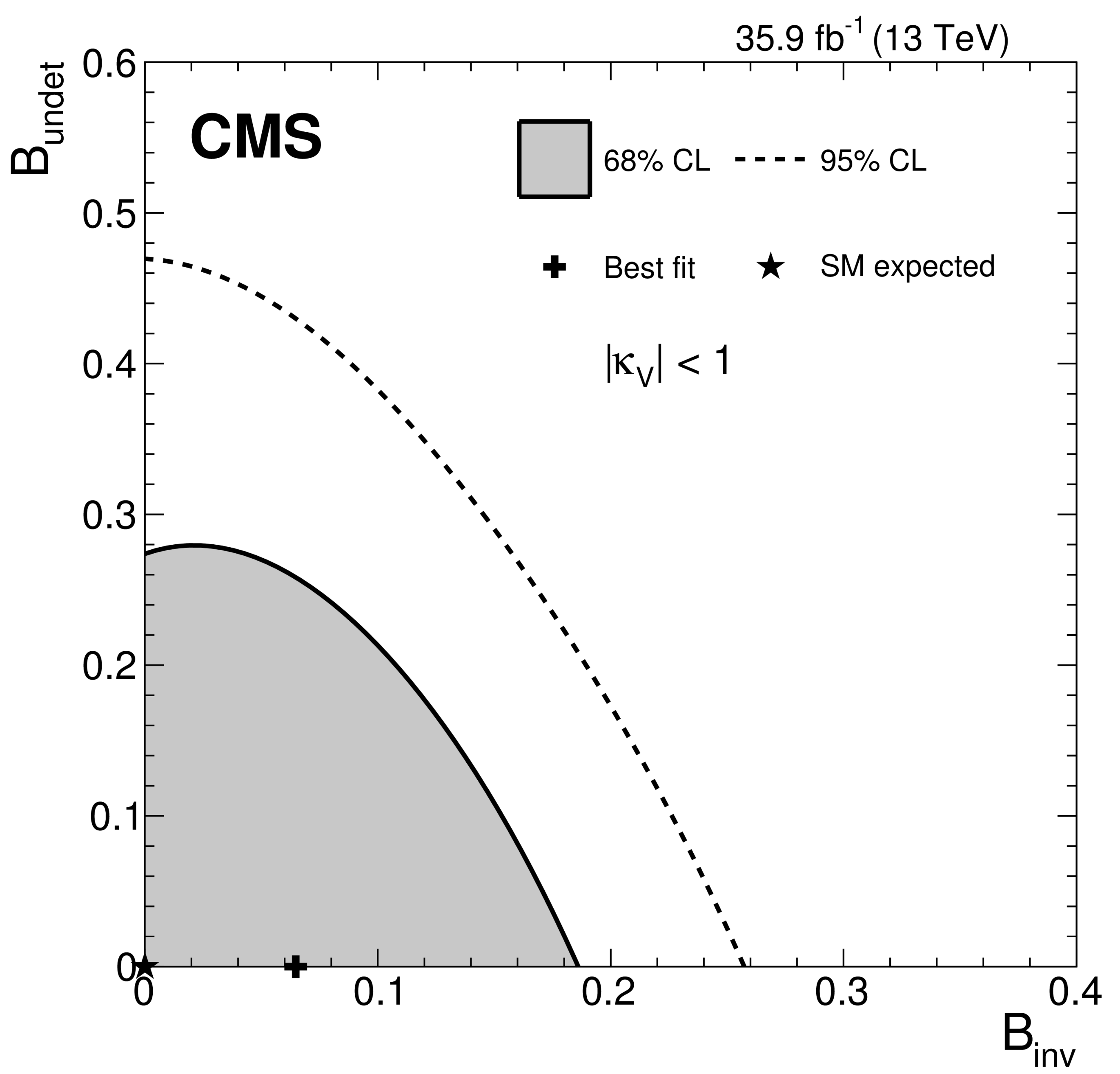
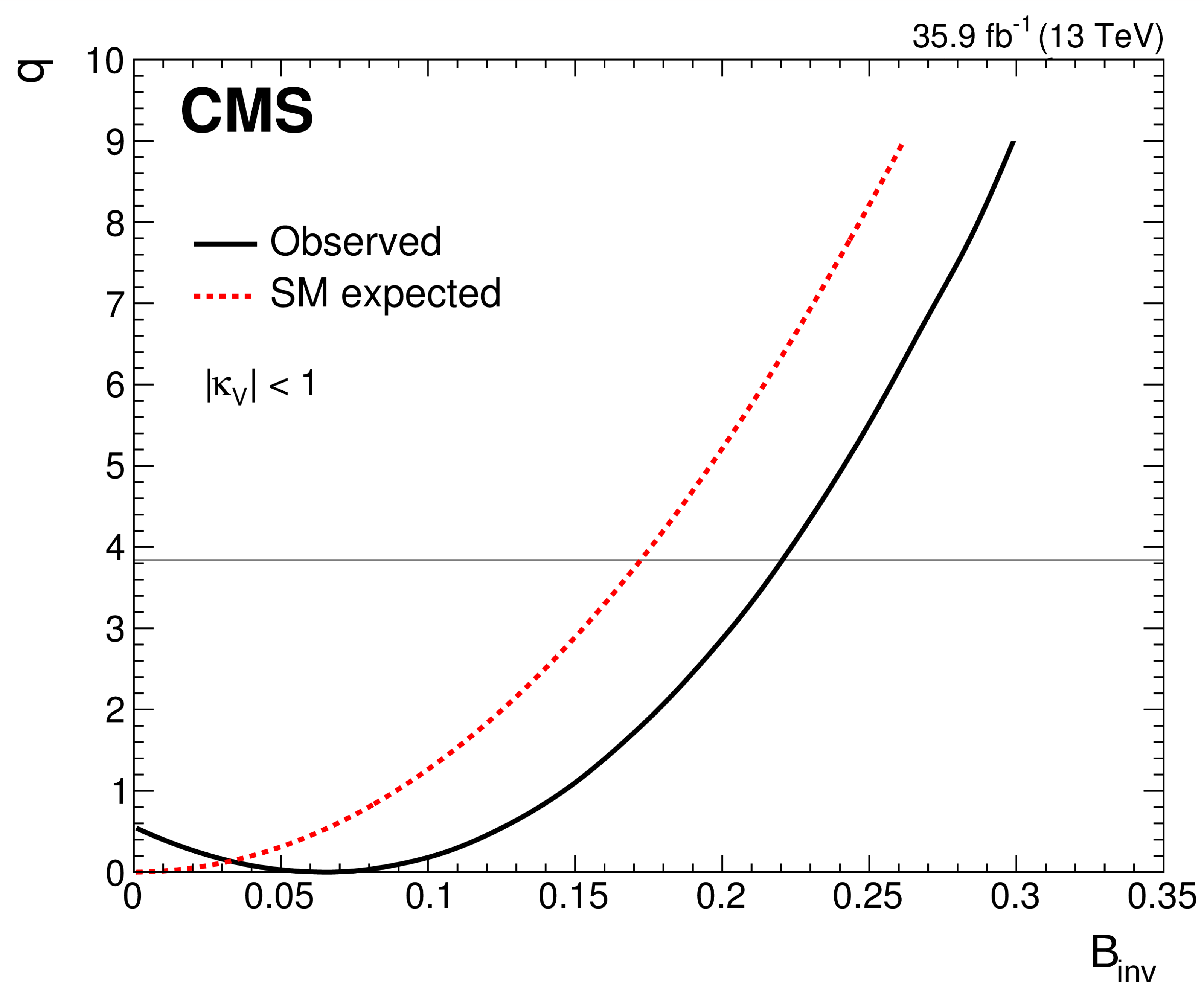


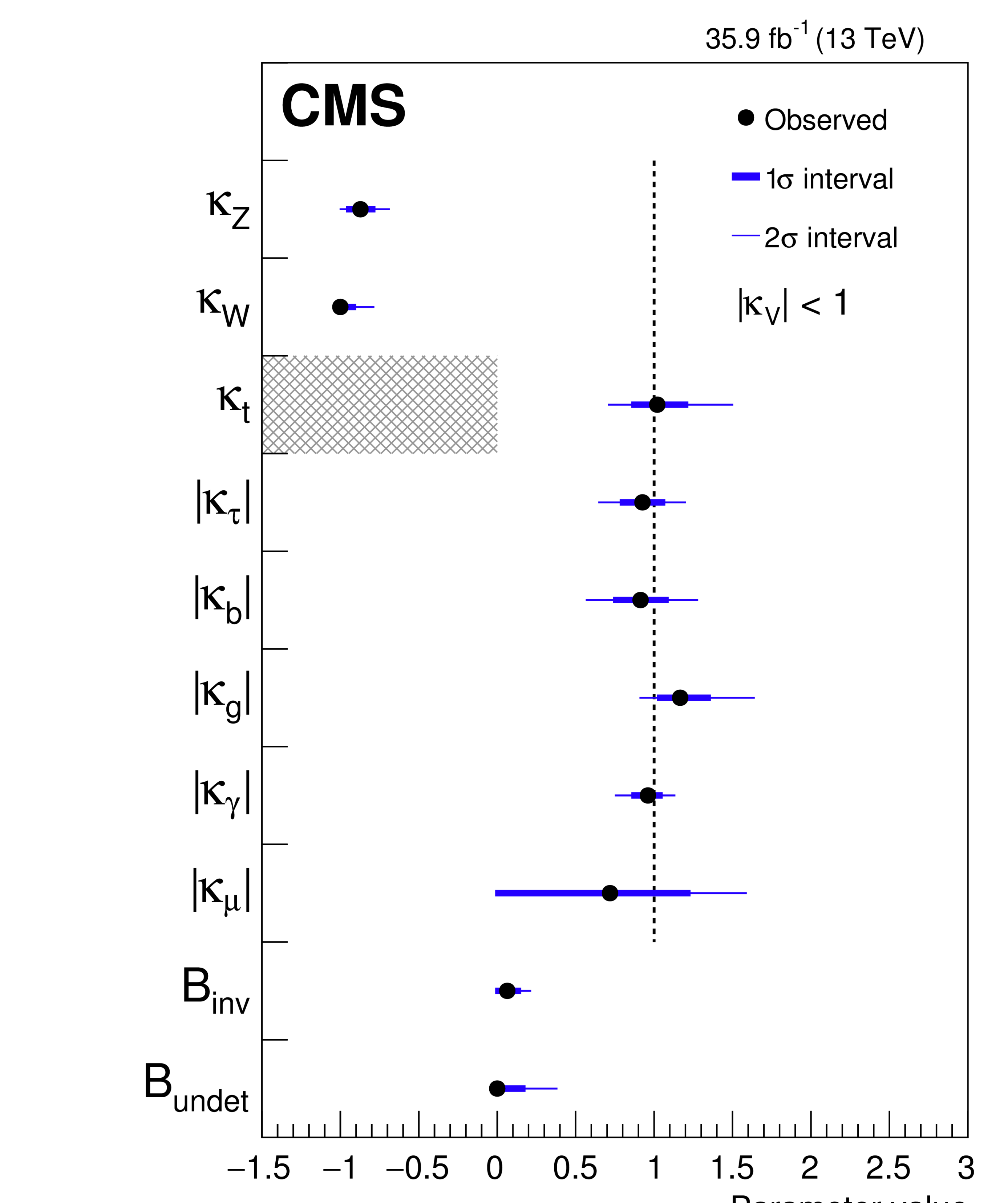


(Note: 36fb^{-1}. Not the latest CMS Higgs couplings combination - that is HIG-19-005 - but the latest to explore B_{BSM})

$$\Gamma_H = \frac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{undet})}$$

- Invisible width: experimentally directly constrained (ZH, VBF H→invisible) -> invisible direct searches are also an input to the combination
- Undetermined / Untagged width: h(125)->??. BSM, but also rare SM decays not directly probed by searches (eg to light quarks)

BR$_{INV}$ VS BR$_{UNT}$



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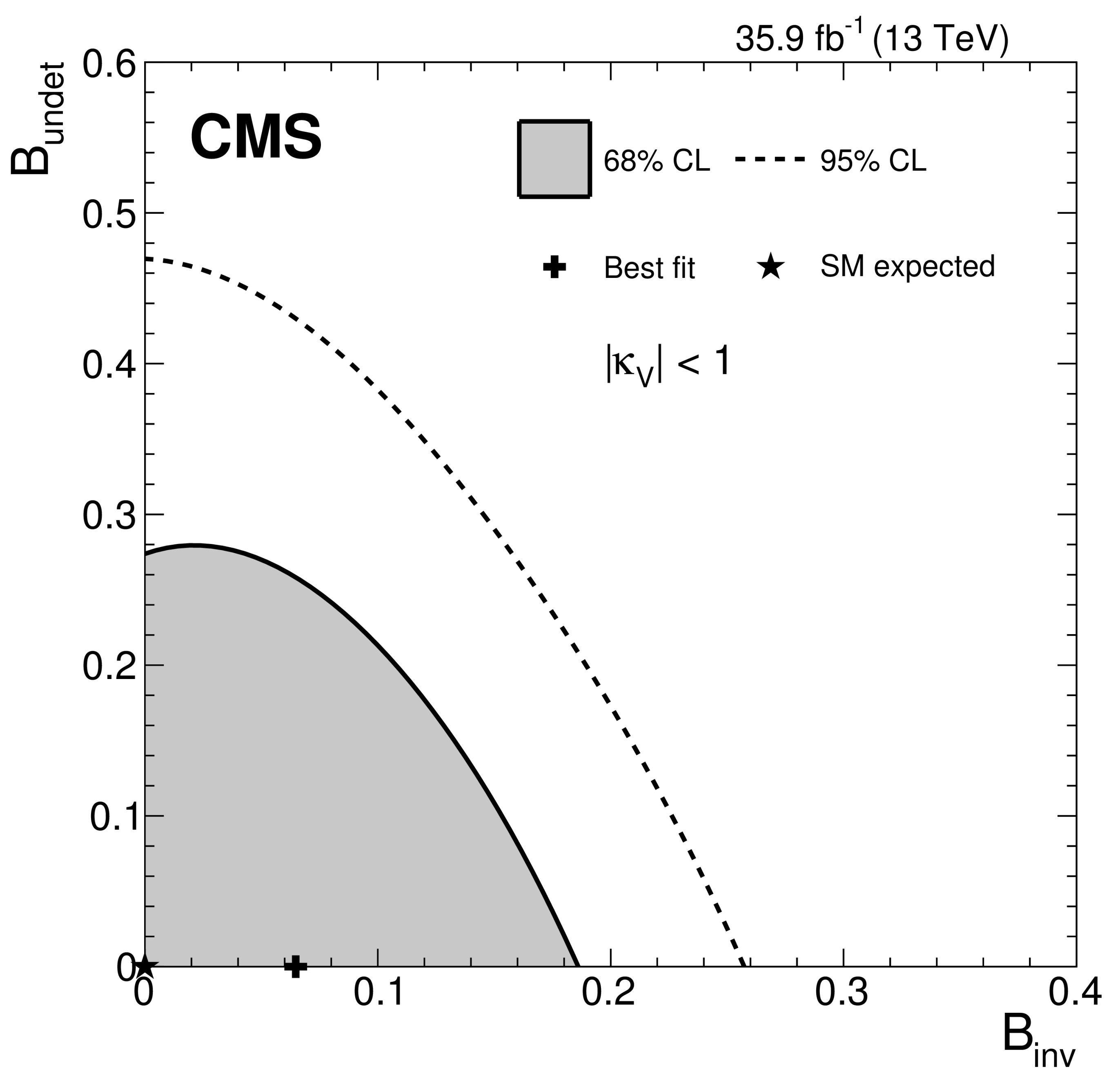
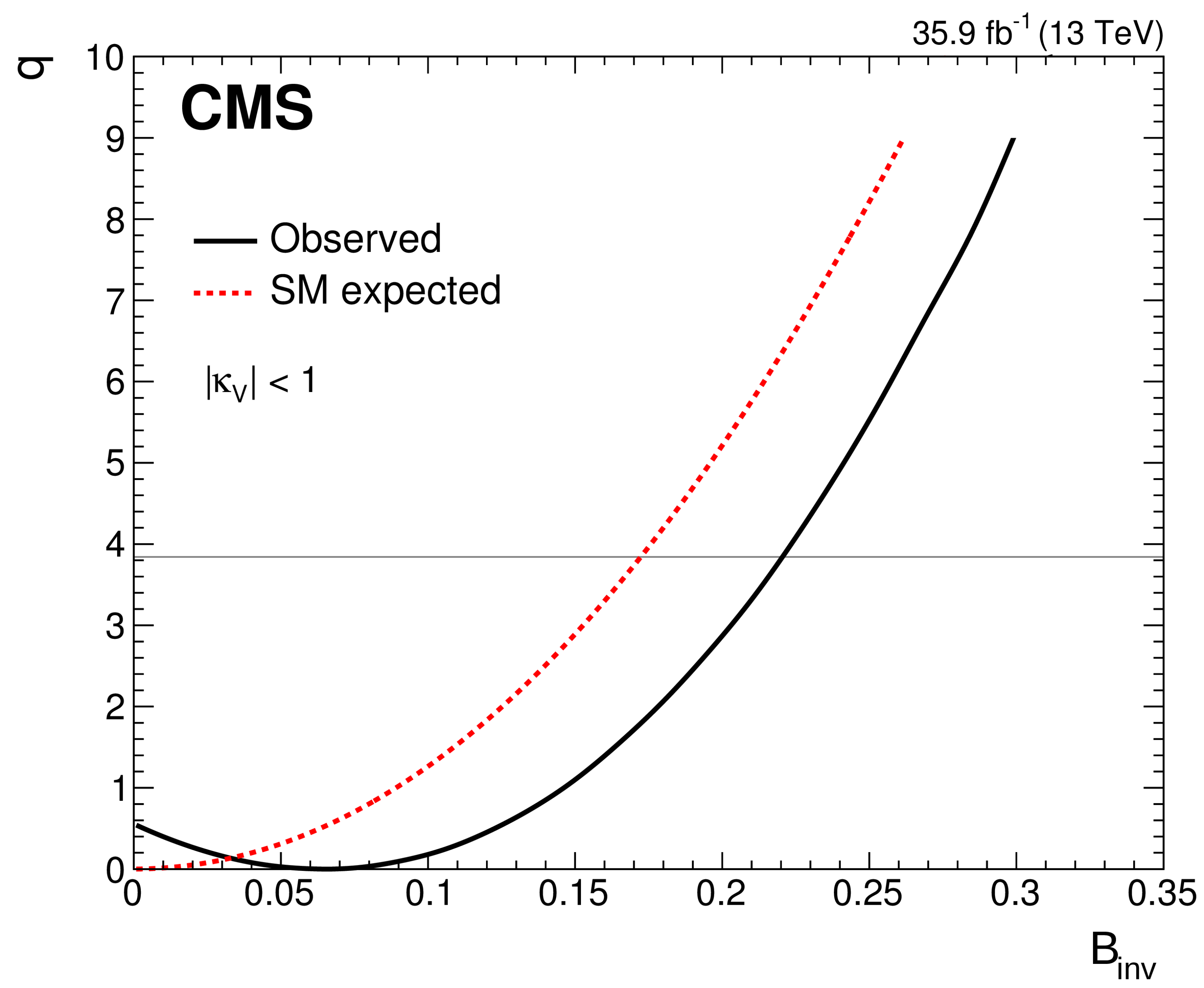


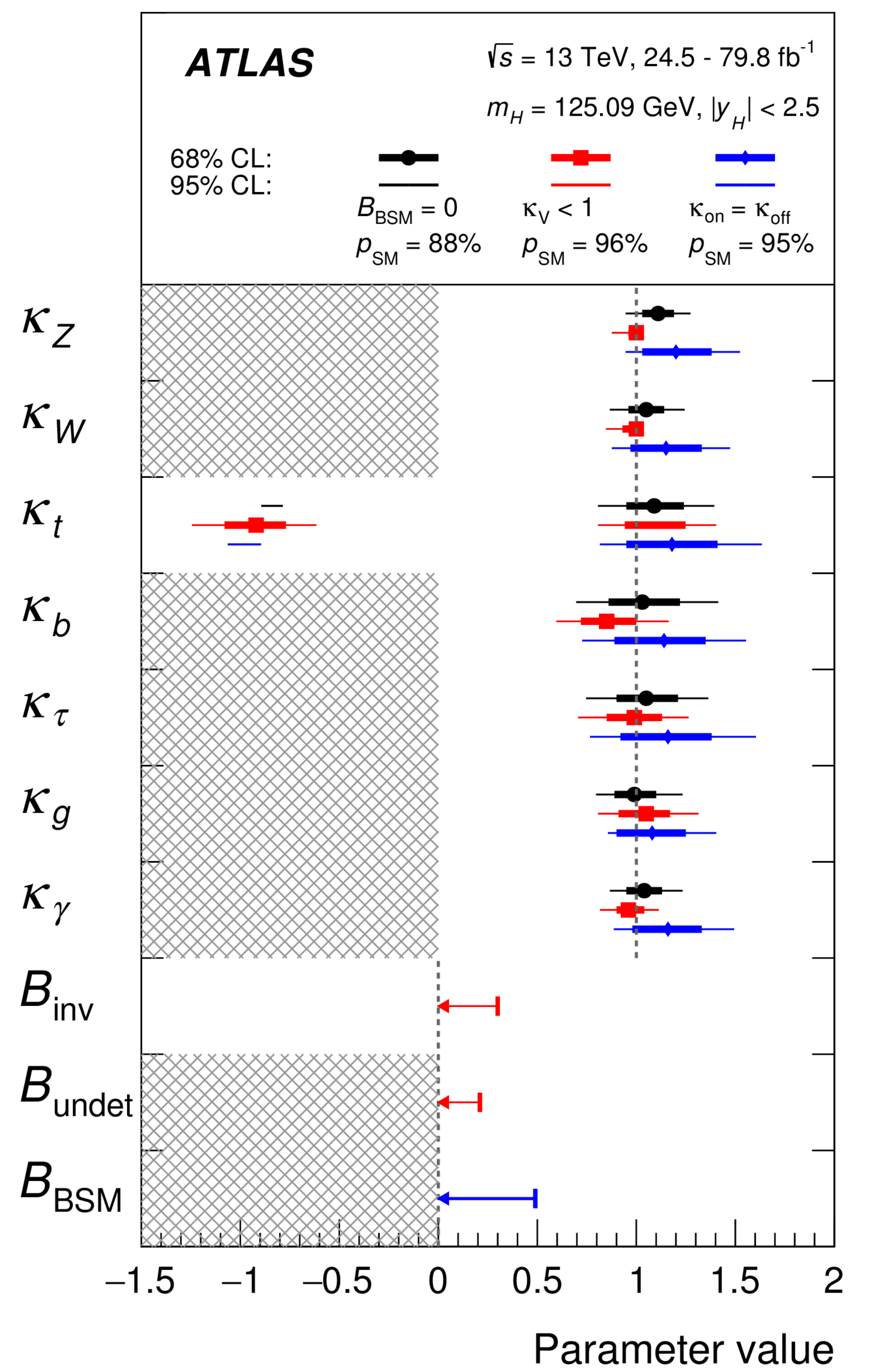


(Note: 36fb^{-1}. Not the latest CMS Higgs couplings combination - that is HIG-19-005 - but the latest to explore B$_{BSM}$)

$$\Gamma_H = \frac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{undet})}$$

- Still 36 fb^{-1} . Includes HInv combination.
- **Invisible: BR$_{inv}$ < 22% at 95% CL**
- **Undet: BR$_{undet}$< 38% at 95% CL**

|κV|≤1 VS OFFSHELL



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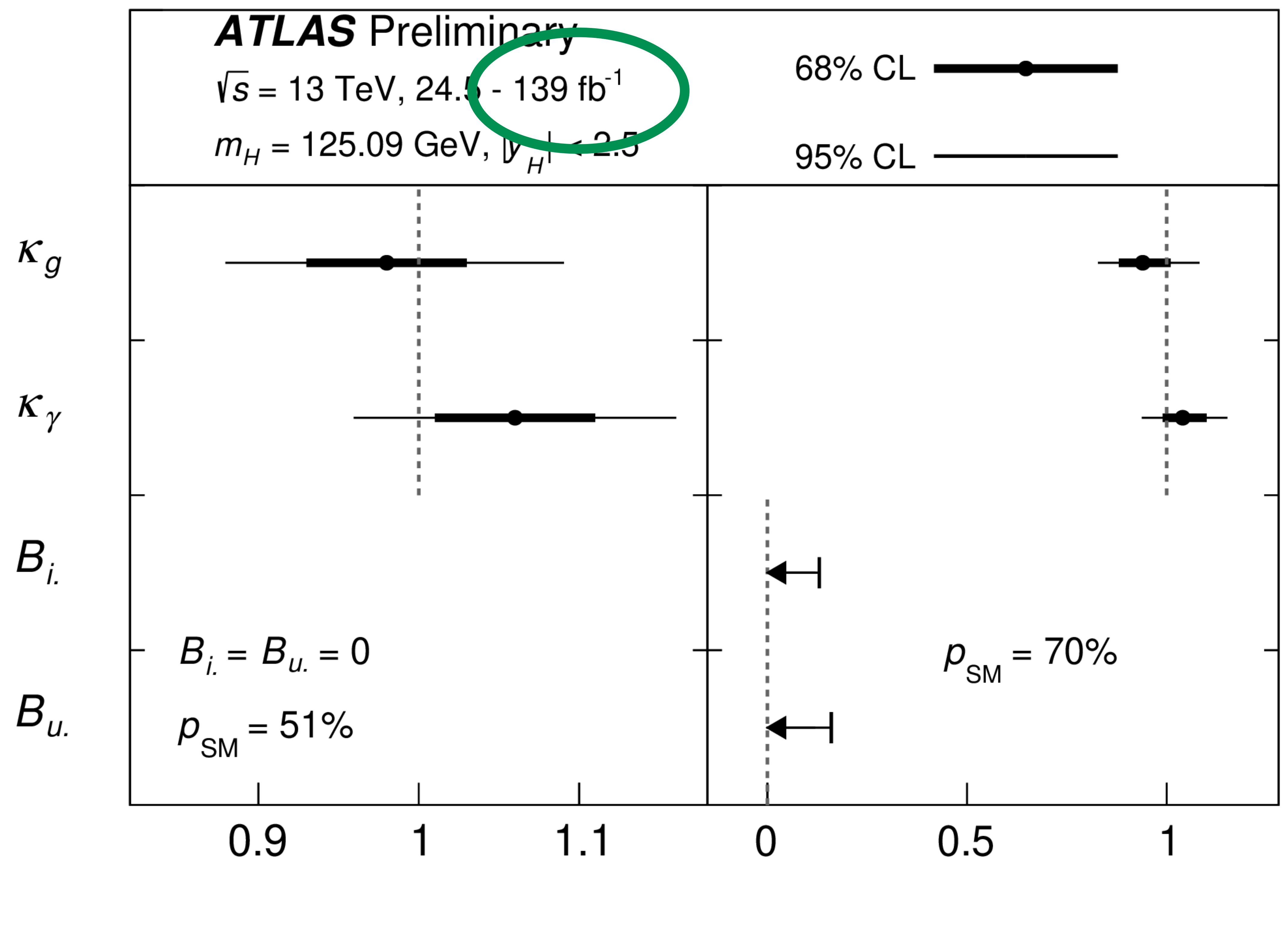
- Coming back to the warning: since it is not possible to directly measure the Higgs width at the LHC, to probe the BSM BR an additional constrain needs to be imposed.
- Usually, $|\kappa_{W,Z}| \leq 1$, but not the only option. An alternative (probed by ATLAS) is to include the measurement of off-shell Higgs boson production in the combination (assuming $\kappa_{offshell} = \kappa_{onshell}$)

Parameter	(a) $B_{inv} = B_{undet} = 0$	(b) B_{inv} free, $B_{undet} \geq 0$, $\kappa_{W,Z} \leq 1$	(c) $B_{BSM} \geq 0$, $\kappa_{off} = \kappa_{on}$
B_{inv}	-	< 0.30 at 95% CL	-
B_{undet}	-	< 0.21 at 95% CL	-
B_{BSM}	-	-	< 0.49 at 95% CL

(Note: This is also not the latest ATLAS Higgs couplings combination, and uses $36 fb^{-1}$ both for the offshell and for HInv)

UPDATED FIT - INCLUDING FULL RUN2 VBF HINV

- Float effective couplings (g, γ) , fix others to SM
- **B_{inv} < 13% and B_{undet} < 16% at 95% CL**



ATLAS-CONF-2020-027

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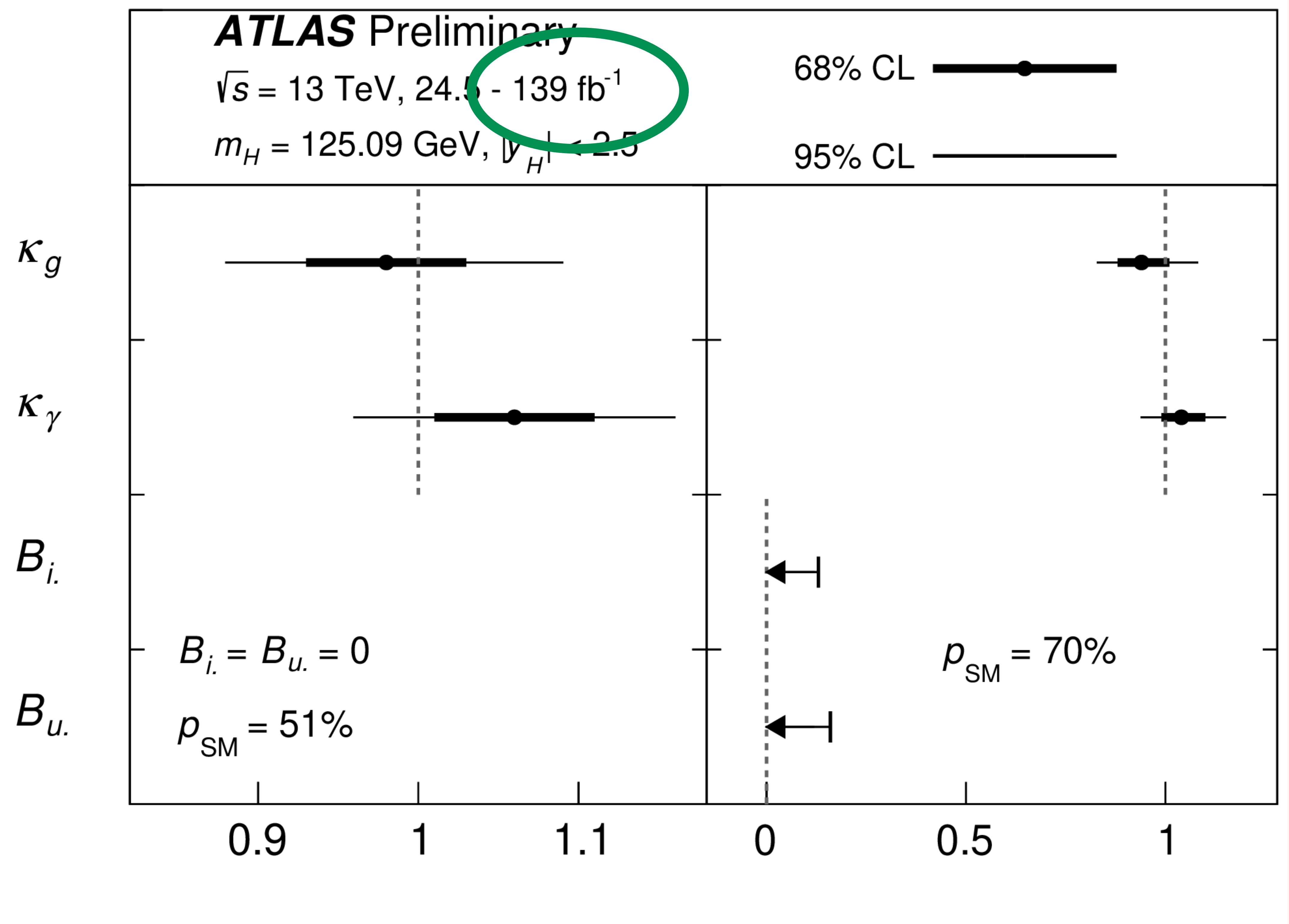
- **B_{inv} < 13% and B_{undet} < 16% at 95% CL**



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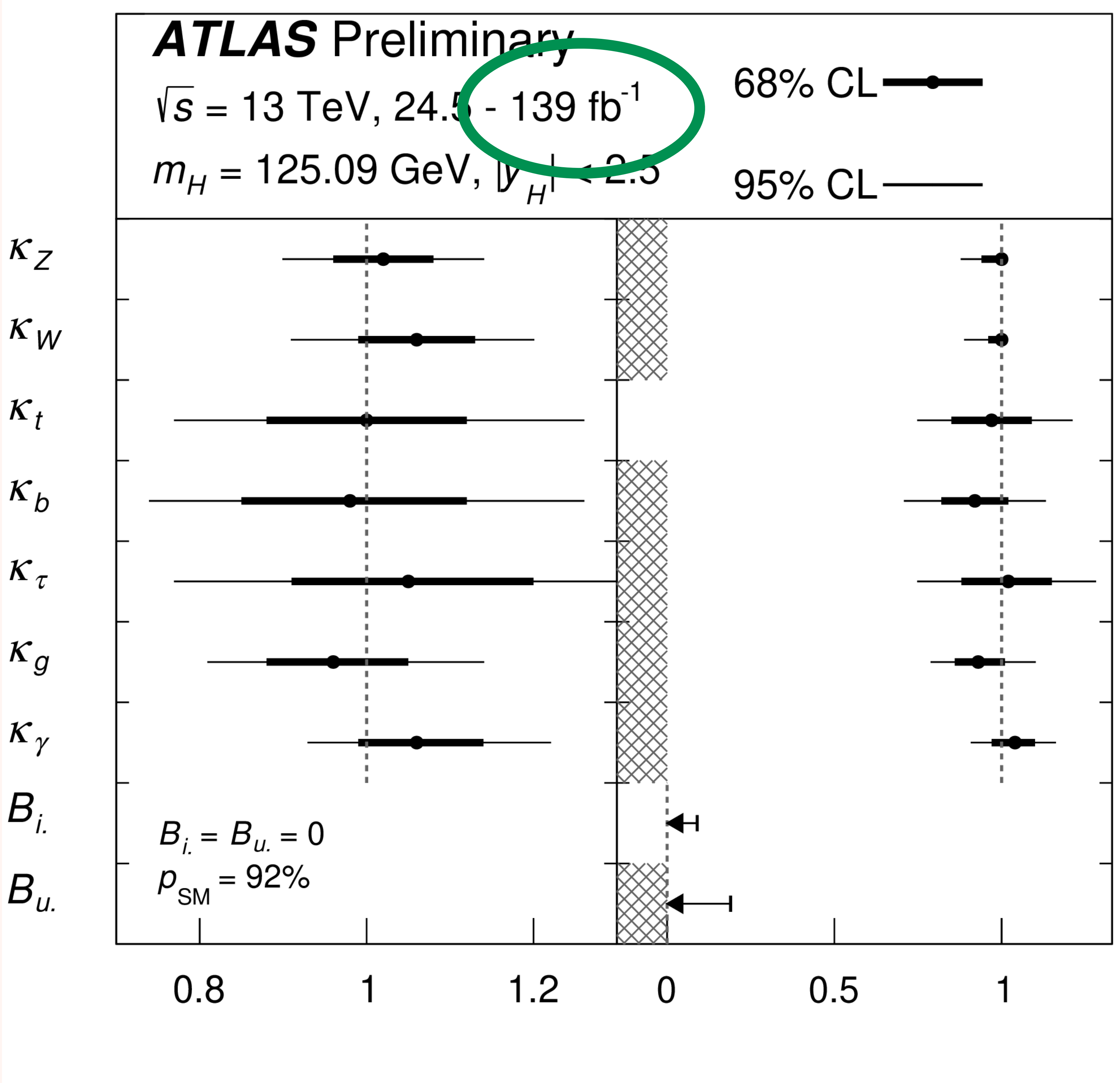
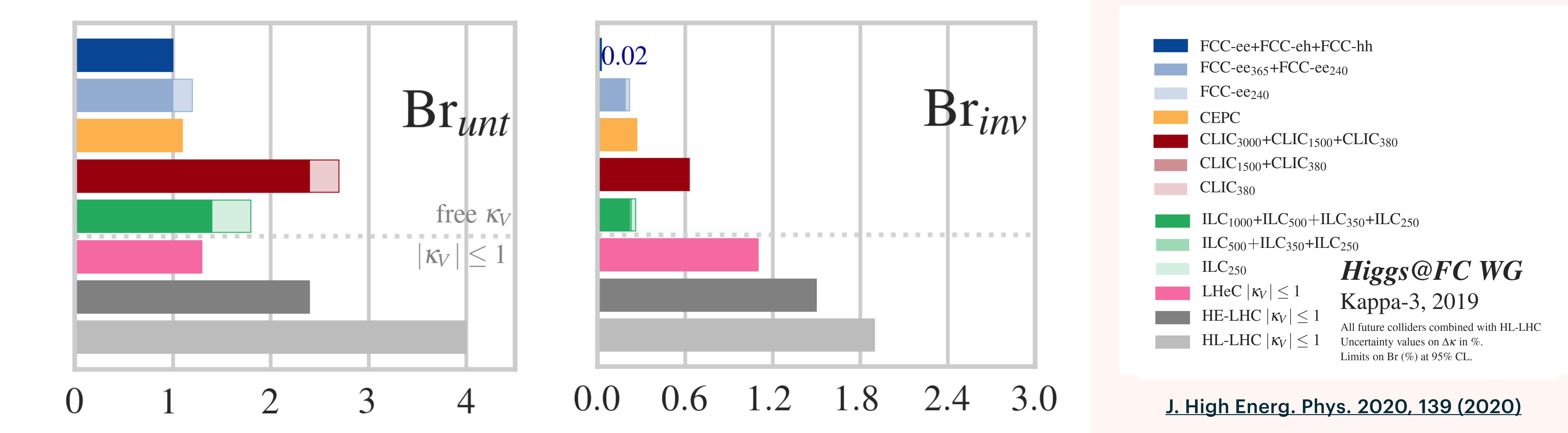
- General fit including effective couplings -> to allow probing for BSM decays, constrain $\kappa_{W,Z} \leq 1$
- **B_{inv} < 9% and B_{undet} < 19% at 95% CL**



BEYOND THE LHC

- At the HL-LHC, from the ATLAS+CMS global coupling fit, if $B_{BSM} \geq 0$ (any invisible or undetected states): $B_{BSM} < 2.5\%$ @ 95% CL (Yellow Report)
- Lepton colliders: recoil method to probe the width, no need to impose $\kappa_{W,Z} \leq 1$
- More than an order of magnitude improvement for Invisible, and large (~4x) improvement for Untagged



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SUMMARY

- How well can we constrain today the Exotic Higgs width?
  - Run1 ATLAS+CMS combination yielded BRBSM<34% at 94% CL -> this is now very outdated!
  - Higgs Invisible: 36 fb^{-1} 13 TeV combinations reached <19/26% at 95% CL. Full Run2 VBF results alone already at 13% (ATLAS)
    - Full Higgs Invisible combination to come soon
  - Constraints on B_{Inv} and B_{unt} from couplings fits, incorporating Higgs Invisible: most up to date result already $B_{inv} < 9\%$ and $B_{undet} < 19\%$ at 95% CL (ATLAS).
    - This is not yet the full Run2 combination either!
- And what do we know about the future?
  - HL-LHC Prospects: $B_{inv} < 1.9\%$ and $B_{undet} < 4\%$ at 95% CL
  - Future machines will be able to greatly improve the sensitivity to invisible and exotic decays of the Higgs (more than an order of magnitude for invisible)

THANKS!

HINV ANALYSES: COMPOSITION

Analysis	Final state	Signal composition	Observed limit	Expected limit
VBF-tag	VBF-jet + $p_{\mathrm{T}}^{\mathrm{miss}}$	52% VBF, 48% ggH	0.33	0.25
VH-tag	$\mathrm{Z}(\ell\ell) + p_{\mathrm{T}}^{\mathrm{miss}}$ [72]	79% qqZH, 21% ggZH	0.40	0.42
	V(qq') + $p_{\mathrm{T}}^{\mathrm{miss}}$ [73]	39% ggH, 6% VBF, 33% WH, 22% ZH	0.50	0.48
ggH-tag	jets + $p_{\mathrm{T}}^{\mathrm{miss}}$ [73]	80% ggH, 12% VBF, 5% WH, 3% ZH	0.66	0.59

HIGGS WIDTH AT HL-LHC

- **4L Offshell: 25% precision at 68% CL (20% assuming CMS+ATLAS: +-0.8 MeV)**
- GammaGamma interference study: <40-50 Γ_{SM} (ATLAS), reduction of the on-shell rate by 2% (Campbell, Carena, Harnik, Liu, 2018 Yellow Report)