Higgs boson physics at CMS: combination and recent highlights

Julie Malclès (CEA-Saclay IRFU)

on behalf of the CMS Collaboration

3rd October 2022, LHC Days at Split

Introduction & overview

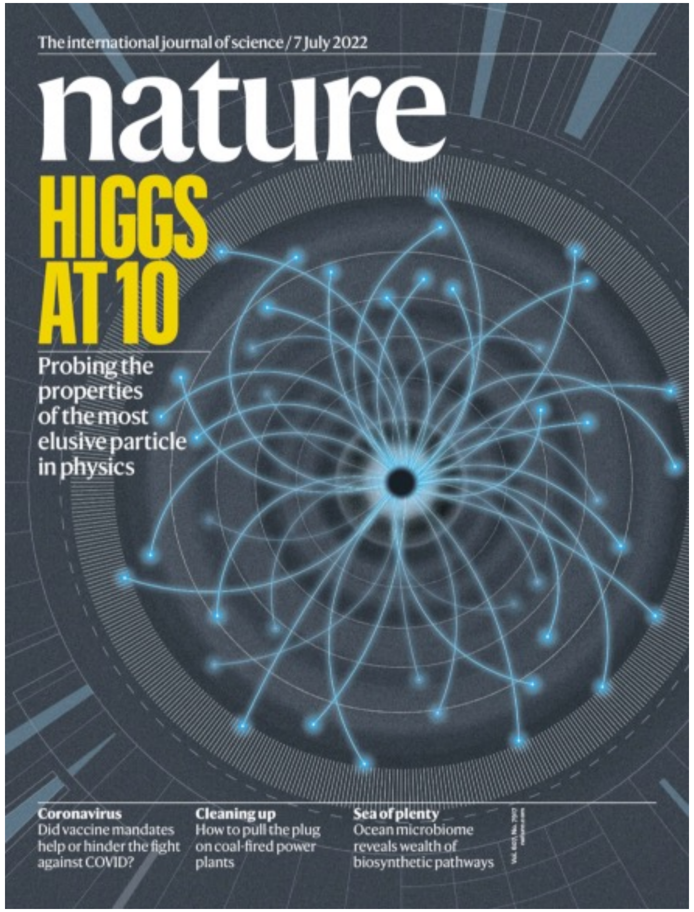
1. **Focus on production cross sections & couplings from the combination of single Higgs boson measurements in CMS with Run 2 data (138 fb^{-1} at 13 TeV)**

Results included in the combination:

Prod/decay	ggH	qqH	VH	ttH/tH
$H\rightarrow\gamma\gamma$	✓	✓	✓	✓
H→ZZ	✓	✓	✓	✓
H→WW	✓	✓	✓	✓
$H\rightarrow\tau\tau$	✓	✓	✓	✓
$H\rightarrow b\bar{b}$	✓	✓	✓*	✓*
$H\rightarrow\mu\mu$	✓	✓	✓	✓
$H\rightarrow c\bar{c}$				
$H\rightarrow Z\gamma$	✓	✓	✓	✓
H→inv.	✓	✓	✓	

Individual results already presented by Matteo Bonanomi

* not using full stat.



[Nature 607, 60-68 (2022)]

Combination released in Nature in July 2022

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H→$b\bar{b}$	✓	✓	✓*	✓*
H→$\mu\mu$	✓	✓	✓	✓
H→$c\bar{c}$	✺		✺	
H→Zγ	✓	✓	✓	✓
H→inv.	✓	✓	✺	✺

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2. **Highlight two recent results not included in the combination:**

- H→$c\bar{c}$, VH and boosted ggH [arXiv:2205.05550, HIG-21-012]
- H→invisible, in association with a pair of top quarks or a vector boson [HIG-21-007]

Other recent results from CMS described by other speakers:

- Simplified template cross section for $VHb\bar{b}$: Saswat Mishra [HIG-20-001]
- BSM searches (X→HY→$b\bar{b}\gamma\gamma$, H→AA→ $\gamma\gamma\gamma\gamma$): Alexandre Nikitenko [HIG-21-011, arXiv:2209.06197]
- Double Higgs combination: Roberto Salerno [Nature 607, 60-68 (2022)]

Combined measurements: introduction

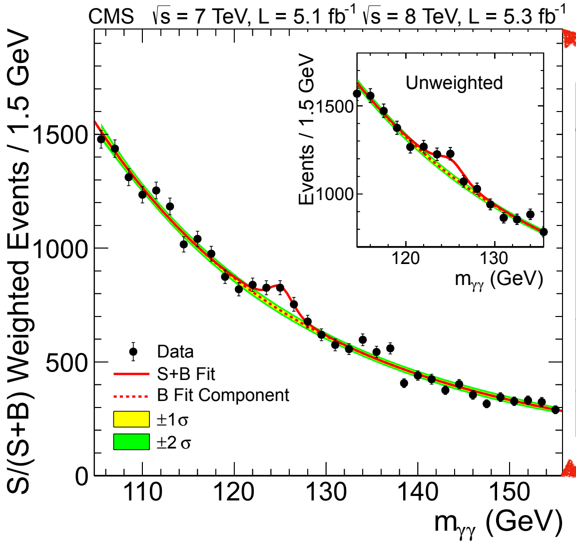
Several open questions in particle physics call for a deeper understanding of the Higgs boson
⇒ Test compatibility with the SM, probe possible BSM effects inducing deviations
Individual analyses study **specific** Higgs boson characteristics
➔ need to **combine** them to get a **full portrait** of the Higgs boson, **with reduced uncertainties**

Will show today:

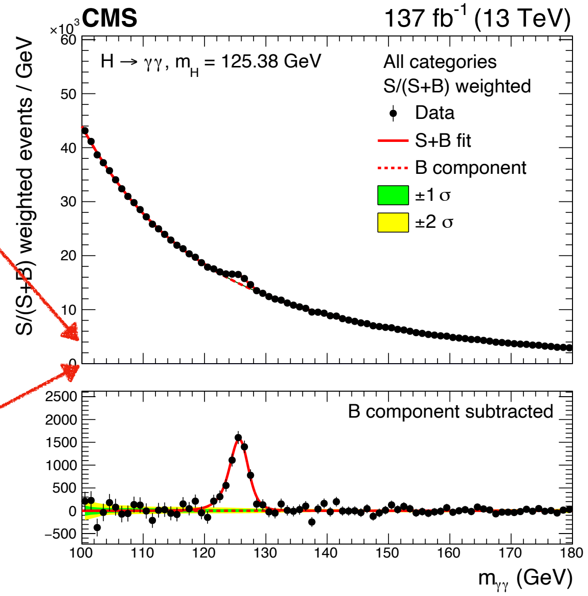
- Main Higgs boson production XS and decay BR
- Couplings to fermions and vector bosons

Ingredients: a big step from discovery to Run2!

- **Luminosity:** 138 fb^{-1} versus about 10 fb^{-1}
- **Increased energy:** 13 TeV versus 7/8 TeV
  ⇒ production cross-sections x 2 to 4



[Phys. Lett. B 716 (2012) 30]



[JHEP 07 (2021) 27]

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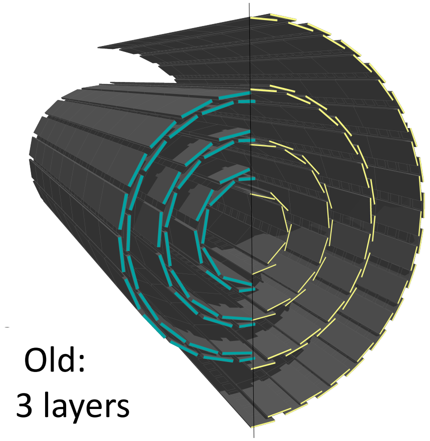
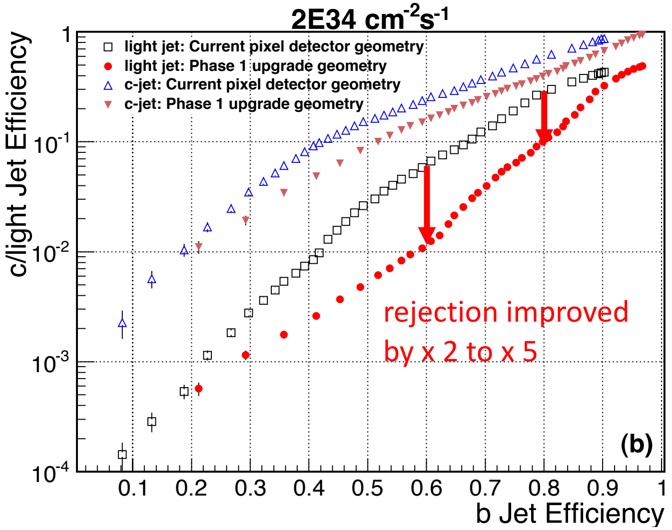
New silicon pixel detector → × 2 improvement in H → $b\bar{b}$ sensitivity, improved L1 trigger





[CERN-LHCC-2012-016, arXiv:2012.14304]

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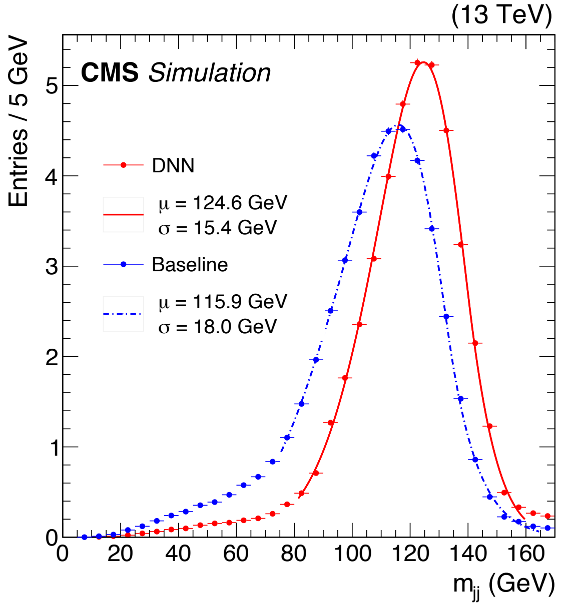
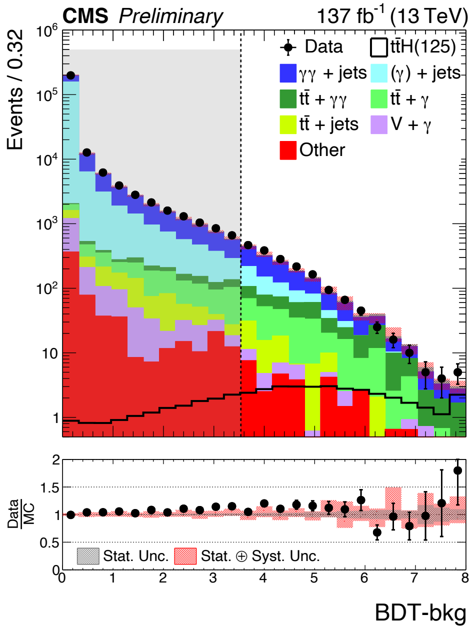


[Computing and Software for Big Science **4** (2020) 10]

b-jet energy regression



[Phys. Rev. Lett. 125 (2020) 061801]

Bkg rejection for ttH, H→$\gamma\gamma$

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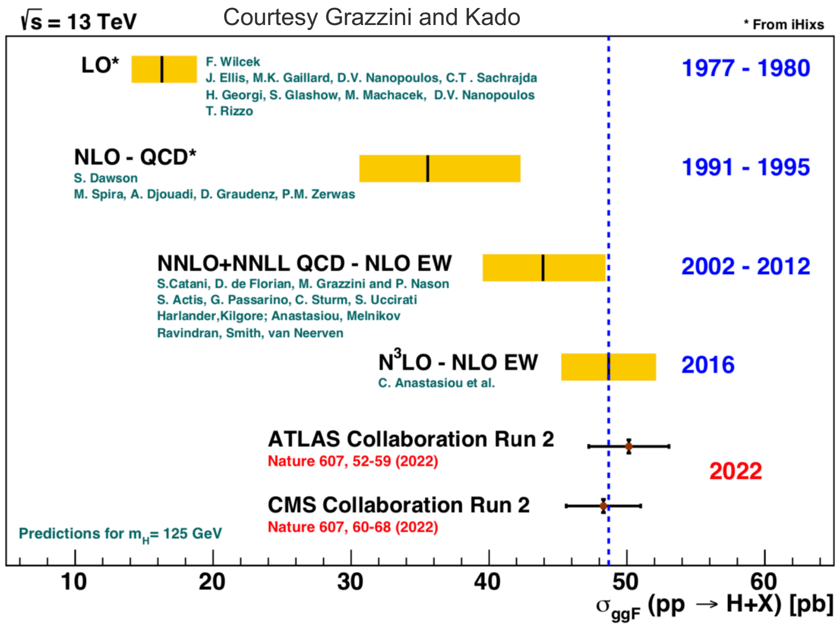
- **Analysis methods:** extensive use of machine learning in regression and classification algorithms
- **Theoretical calculations:** a huge leap in precision

ggH cross section prediction



[M. Kado, GGI seminars, YR4 arXiv:1610.07922]

Global signal strength: evolution since discovery

Fitting data from all production modes/decay channels with a common signal strength : $\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$

$$\mu = 1.002 \pm 0.057$$
$$= 1.002 \pm 0.036\,(\text{th}) \pm 0.033\,(\text{syst}) \pm 0.029\,(\text{stat})$$

[Nature 607, 60-68 (2022)]

- **At discovery:** $\mu = 0.87 \pm 0.23$ dominated by statistics
- **Full run 1:** $\mu = 1.00 \pm 0.14$
  $= 1.00 \pm 0.08\,(\text{th}) \pm 0.07\,(\text{syst}) \pm 0.09\,(\text{stat})$

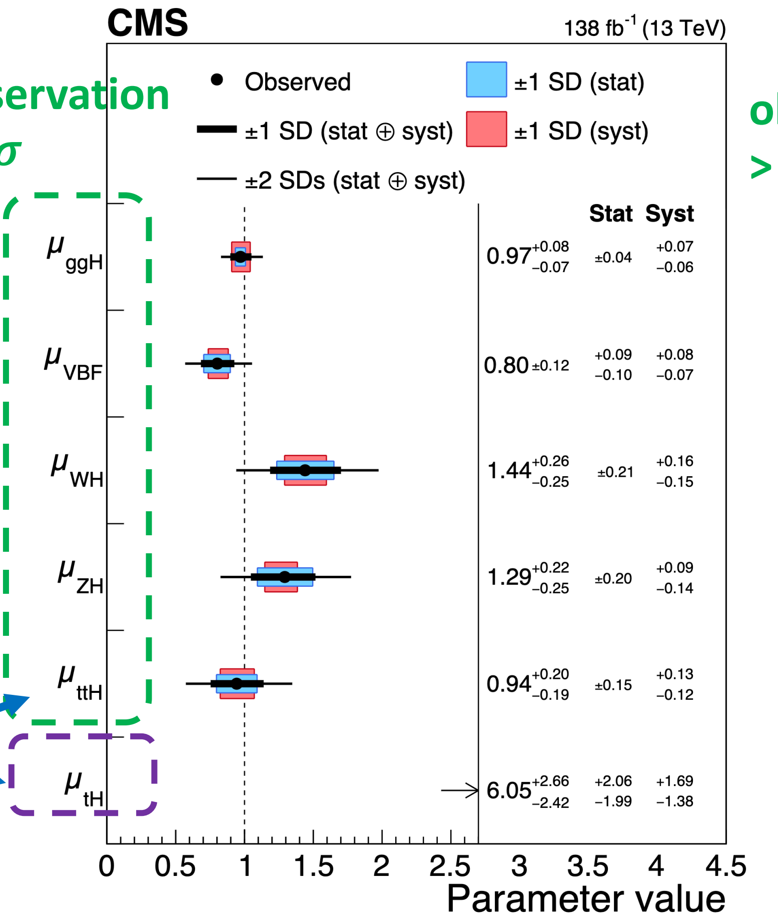
Fourfold improvement in precision with regard to the discovery
Theoretical uncertainty and systematic uncertainty at the same level as the statistical uncertainty

Production modes and decay channels

Assuming different scaling for production and decay:

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathcal{B}^f}{\mathcal{B}^f_{\mathrm{SM}}} \qquad \mu_i^f = \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

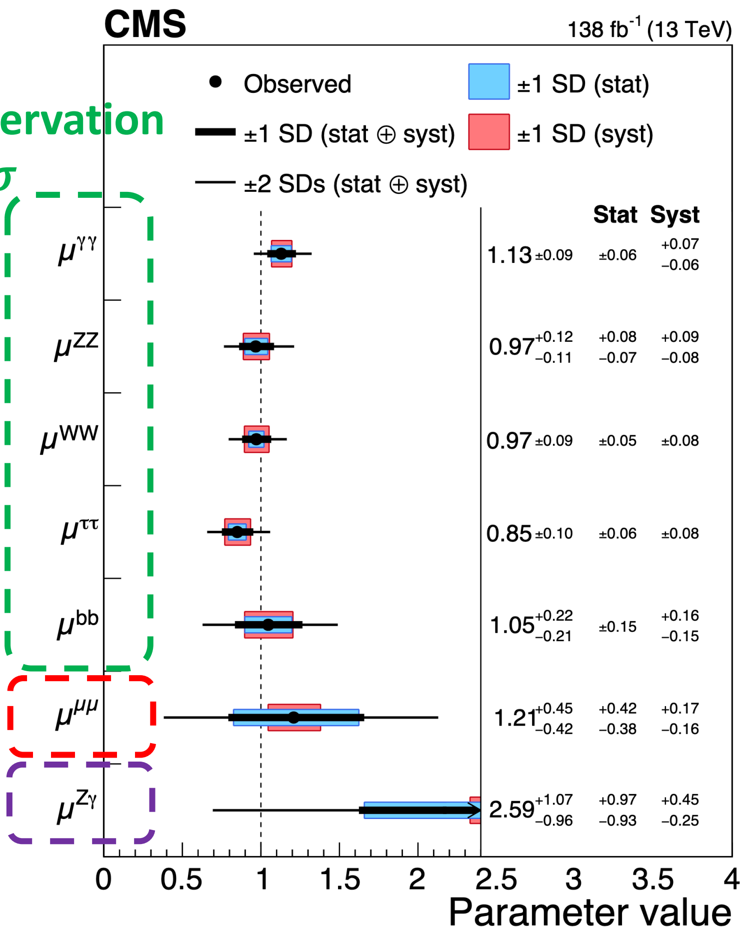
observation > 5σ



ttH and tH constrained separately

production

observation > 5σ



decay

first evidence 3σ

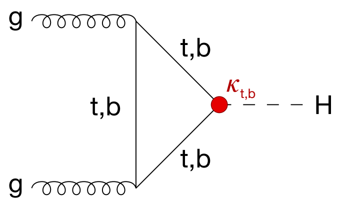
small excesses with large uncertainties

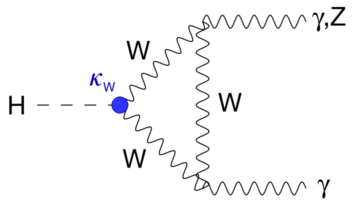
[Nature 607, 60-68 (2022)]

Couplings, κ framework

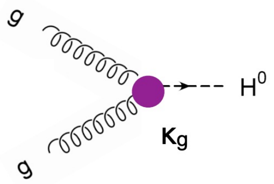
Coupling modifiers κ to quantify couplings deviations from SM predictions

$$\kappa_j^2 = \frac{\sigma^j}{\sigma^j_{SM}} \qquad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{SM}}$$





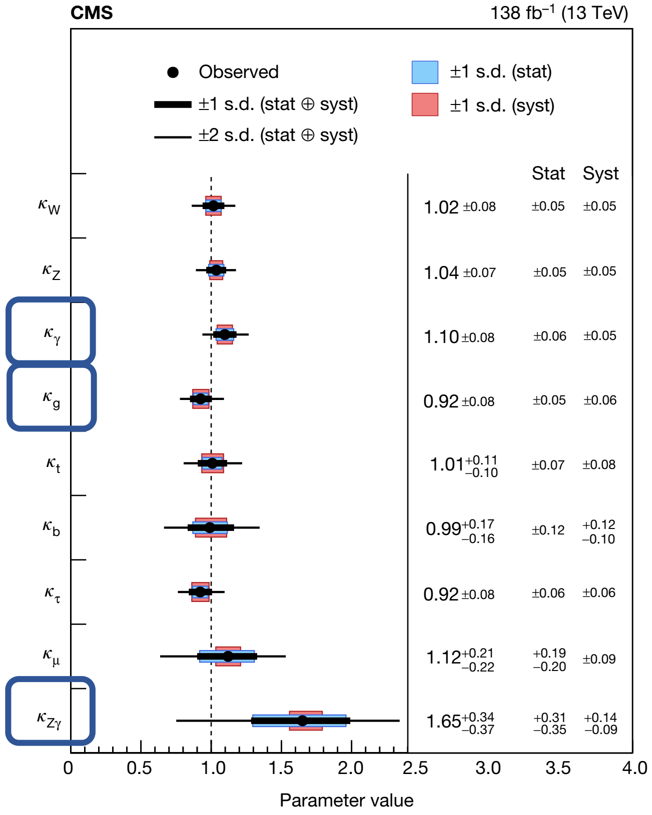
Alternatively, the loop could not be resolved and an effective coupling could be used:



Invisible (ν, DM = M_{ET}) or undetected decay (non-closure of other BRs to unity)

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\kappa_H^2}{(1 - \mathcal{B}_{inv} - \mathcal{B}_{undet})}$$

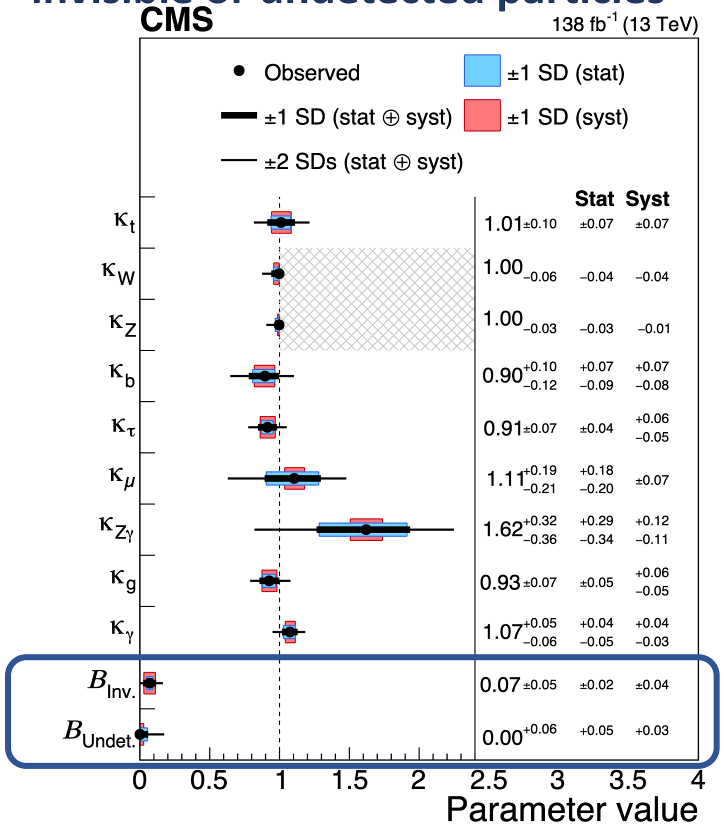
Scenario assuming effective couplings for ggH, H→γγ, H→Zγ



Compatibility with SM within 10%

Stat. unc ≅ syst unc except for k_μ and and $k_{Z\gamma}$

Also assuming Higgs boson decays to invisible or undetected particles

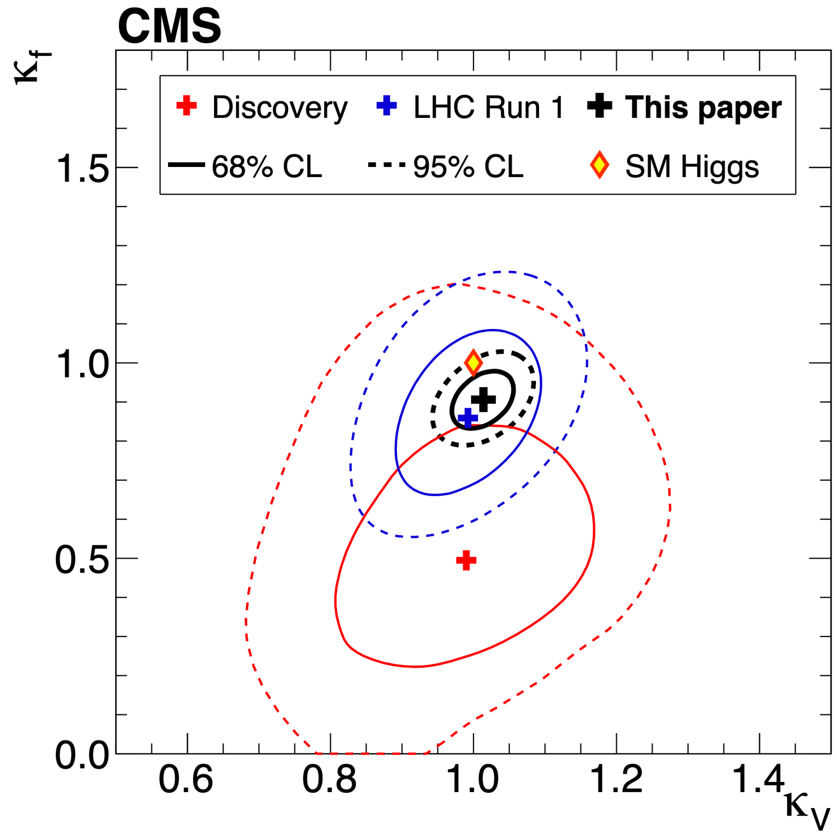


[Nature 607, 60-68 (2022)]

Both invisible and undetectable BR's compatible with zero

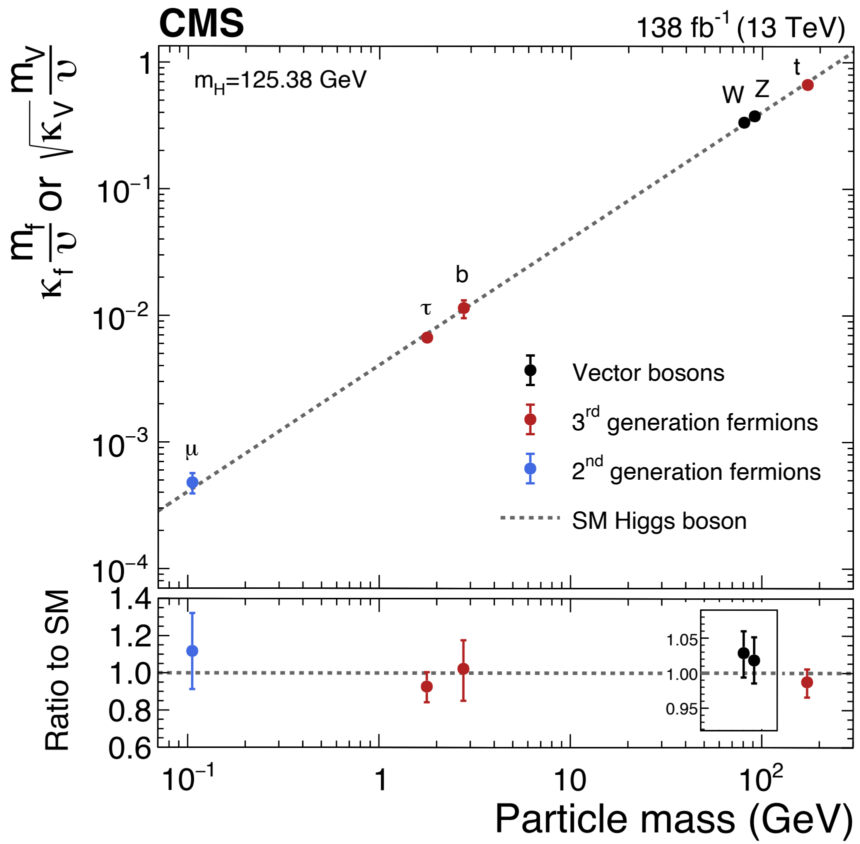
Couplings, κ framework

Couplings to fermions and vector bosons



Compatibility with SM within 10%
Improvement by ~5x wrt discovery

Couplings versus particle mass: scenario with resolved loops



[Nature 607, 60-68 (2022)]

Agreement with SM for masses within 0.1- 200 GeV
Stat. and syst. uncertainties at the same level except for κ_μ

Higgs-charm coupling: introduction

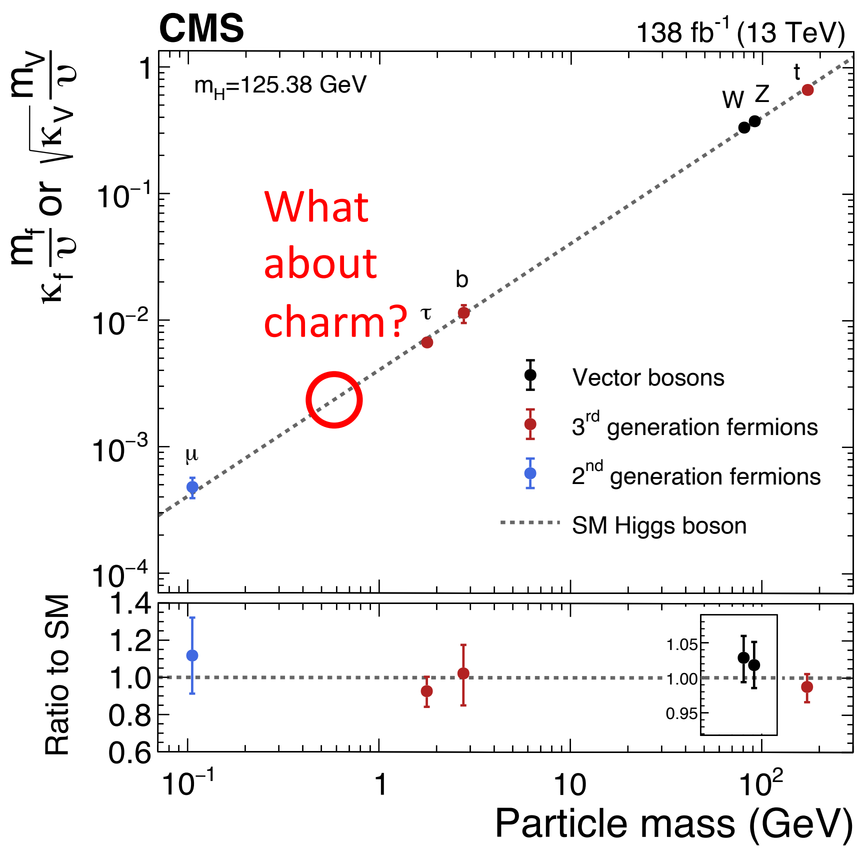
Few ways to constrain Higgs charm coupling at CMS:

- **Direct search for H → $c\bar{c}$ decay:**
  - **in VH** [arXiv:2205.05550]
  - **in ggH boosted** (recent!) [HIG-21-012]
- Indirect constraints from Higgs kinematics
- Rare H → J/ψ + γ decay

H → $c\bar{c}$ extremely challenging to be measured at SM value

- Small BR (~3%) and large backgrounds at hadron collider
- Charm quark ID is the key: CMS developed new charm tagging techniques for resolved and boosted jets
- Current analyses sensitive to NP that would increase the coupling to charm ~10 x SM
- Calibration candle is the **Z→** $c\bar{c}$ decay

Couplings versus particle mass: scenario with resolved loops

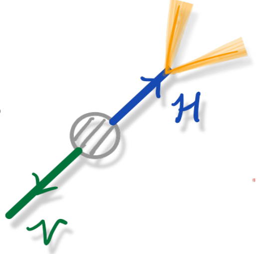


[Nature 607, 60-68 (2022)]

VH, H→$c\bar{c}$: analysis strategy

- **Three channels for the boson decay:**
  Z → νν (0L), W → lν (1L), Z → ll (2L) [l = e, μ]
- **Main backgrounds:**
  - V+jets, single and pair production of top quarks, dibosons
  - VH(H → $b\bar{b}$): small but hard to reduce
- **Two approaches for the reconstruction of H→$c\bar{c}$:**

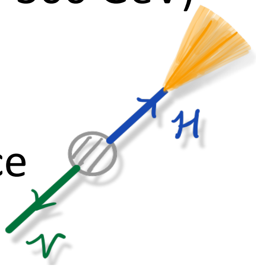
Resolved-jet topology



- with two small-R jets (R=0.4, “AK4”)
- bulk (>95%) of signal acceptance

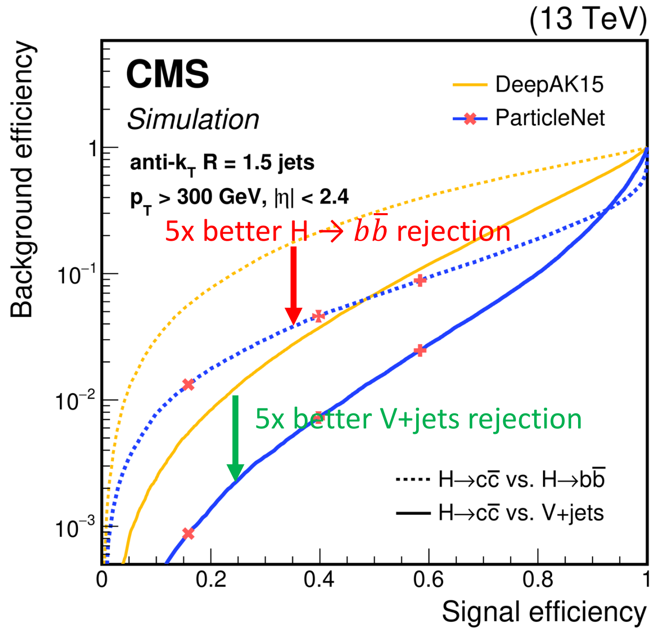
- c-tagger to reject b/light jets (deepJet)
- Fit BDT score (including mass as input)
- Mass regressed + kinematic fit (2L)
- CR to control V+jets, $t\bar{t}$

Merged jet topology (pT> 300 GeV)



- with one large-R jet (R=1.5, “AK15”)
- Small signal acceptance (<5%), high purity

- Kinematic BDT to reject V+jets, $t\bar{t}$
- cc-tagger to reject $b\bar{b}$
- Fit mass of the H candidate (jet mass, dedicated regression)
- CR to normalise V+jets, $t\bar{t}$



[Phys. Rev. D 101, 056019, CMS-DP-2020-002]

ParticleNet: charm tagger for AK15

Same spirit as deepJet:

- a multi-class DNN jet classifier
- using jet constituents (PF candidates, secondary vertices)

Improvements: GNN instead of 1D CNN, novel mass decorrelation technique

> 2x improvement on the final sensitivity

VH, H→$c\bar{c}$: results

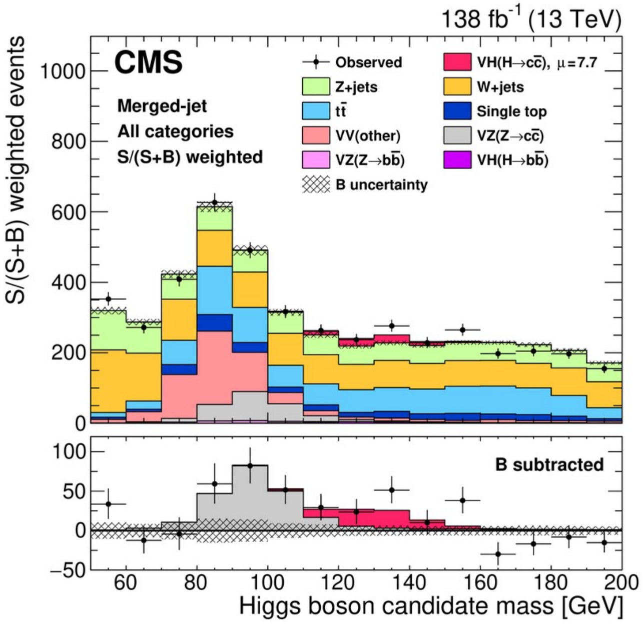
Final result combines merged and resolved:

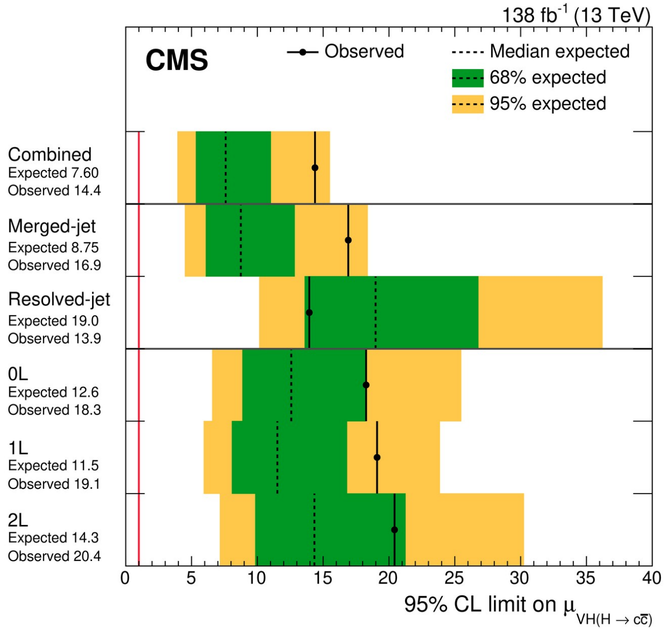
- Observed (expected) upper limit on VH (H→$c\bar{c}$) signal strength:

$$\mu_{VH(H\to c\bar{c})} < 14\ (7.6)\ @\ 95\%\ CL$$

Strongest limit on VH (H→$c\bar{c}$) process to date!

- Best fit signal strength: $\mu_{VH(H\to c\bar{c})} = 7.7^{+3.8}_{-3.5}$
- Upper limits from each topology:
  - **Resolved-jet** topology: **14 (19) × SM**
  - **Merged-jet** topology: **17 (8.8) × SM**





[arXiv:2205.05550]

Analysis validated with the candle Z → $c\bar{c}$:

$\mu_{VZ(Z\to c\bar{c})} = 1.01^{+0.23}_{-0.21}$, significance 5.7σ

First observation of Z → $c\bar{c}$ at a hadron collider!

Main uncertainties: limited statistics of data, V+jets samples statistics, charm tagging efficiencies

Results used to place new constraints on κ_c

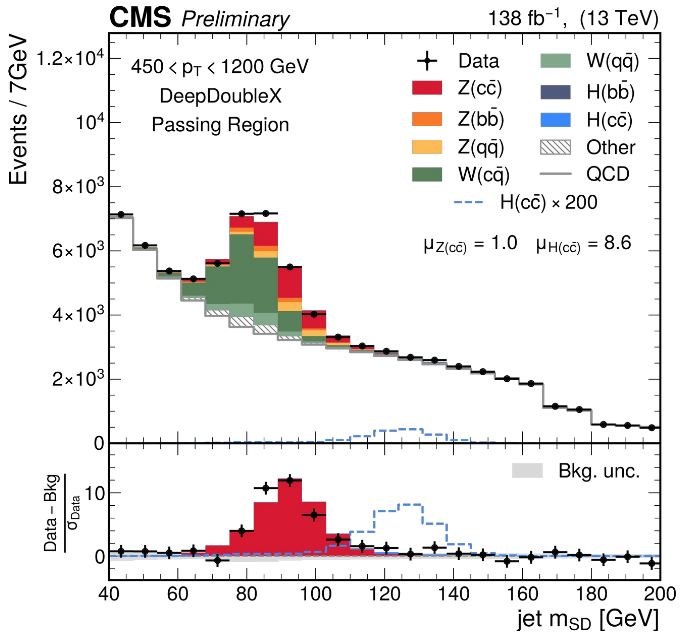
- Only considering effects on B(**H→$c\bar{c}$**) and fixing other couplings to SM
- 95% CL intervals:
  - **observed: 1.1 < $|\kappa_c|$ < 5.5**
  - expected: $|\kappa_c|$ < 3.4

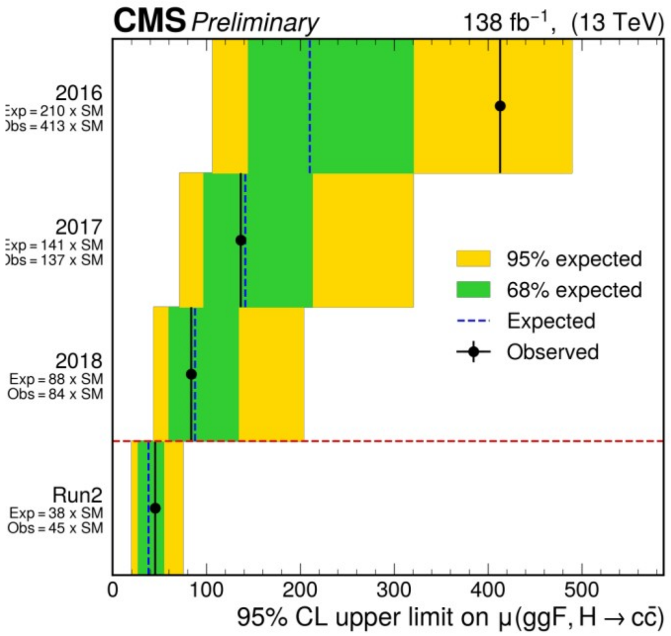
Strongest constraints on | κ_c | to date!

ggH boosted, H→$c\bar{c}$ (recent!)

- Higgs candidate is reconstruted as a single fat jet of cone radius 0.8 (AK8) with p_T> 450 GeV
- Inclusive in production mode, primarily targeting the ggF (50%) and VBF (30%) → **complementary to VH (H→$c\bar{c}$) analysis**
- Similar strategy as ggF H→ $b\bar{b}$ analysis [JHEP12 (2020) 085]
- Signal identification with *DeepDoubleX* tagger
  - DNN with low-level inputs [CMS-DP-2018-046]
  - Mass-independent
  - Used to define signal and control regions
- Fit jet mass distributions in signal and control regions

- **Limit set @95% C.L.: 45 (38) x SM**
  - Not yet sensitive to κ_c





[HIG-21-012]

Validation with Z→$c\bar{c}$ measurement:
First observation of Z → $c\bar{c}$ in Z+jets at LHC

H→*invisible*: introduction

- **H(125) to invisible decays very small in the SM:**
  SM $\mathcal{B}$(H→ZZ*→4ν) ~ 0.1%

- **Combination of direct searches + indirect constraints**:
  best fit $\mathcal{B}$(H→inv.) ~ 7% ± 5%

- **Several models predict an enhancement**
  - H(125) could decay to a pair 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
  - Observation would be a very exciting sign of New Physics
  - Using M_{ET}+X signatures

Searches in CMS:

Signal type	Reference
MonoJet	EXO-20-004 JHEP 11(2021) 153
MonoV	
ZH, Z→$\ell\ell$	EXO-19-003 EPJC 81, 1 (2021) 13
VBF	HIG-20-003 PRD 105(2022) 092007
$t\bar{t}$H semi leptonic	SUS-19-009 JHEP 05 (2020) 032
$t\bar{t}$H fully leptonic	SUS-19-011 EPJC8 1 (2021) 3
$t\bar{t}$H hadronic	HIG-21-007
VH hadronic	
combination	

← most sensitive (HIG-20-003)

← most recent: shown today (HIG-21-007)

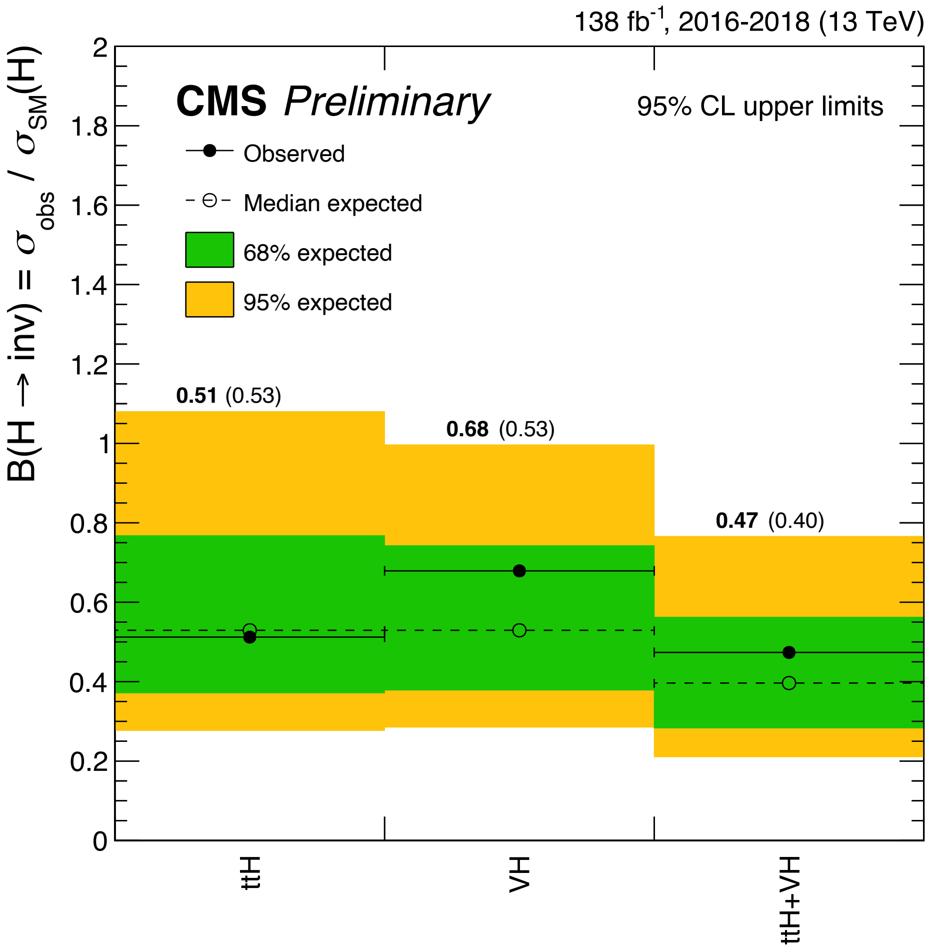
H→*invisible*: $t\bar{t}H$ / VH hadronic (recent!)

- **Common selection:** large $H_{T,miss}$, large $p_{T,miss}$, large leading jet p_T
- **Categorisation:** VH resolved, ttH resolved, ttH boosted
  - based on jet and b-jet multiplicity, m_{jj} for VH category
  - $t\bar{t}H$ boosted: top quarks/W bosons reconstructed as a single large-cone jet (AK8). Use of DeepAK8 taggers.
- **Backgrounds:** Z $\rightarrow \nu\nu$, $t\bar{t}$+ jets, W+jets, controlled with CR with lepton(s) or photons, remaining QCD background estimated with sidebands and MC derived transfer factor
- **Fit to $p_{T,miss}$ distribution simultaneously in SR and CR**

Results:

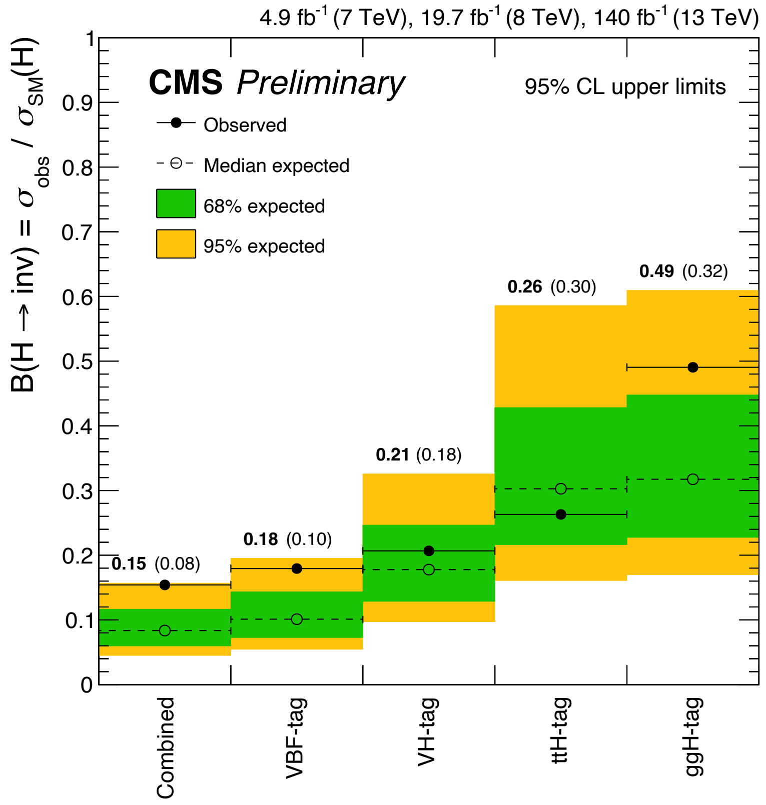
- ttH hadronic and VH resolved yielding similar performance in terms exclusion limits
- **Observed (expected) upper limit:**

$\mathcal{B}$(H→inv.) < 47% (40%) @ 95% C.L.



[HIG-21-007]

H→*invisible*: combination (recent!)



[HIG-21-007]

Channels grouped by production mode:

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

Combining all Run1 and Run2 results

- Overlap between analyses made negligible with specific cuts
- **Combined observed (expected) upper limit:**

$\mathcal{B}$(H→inv.) < 15% (8%) @ 95% C.L.

Strongest expected exclusion limit to date from direct searches!

- **Best fit signal strength: $\mu_{H\to inv}$= 0.08 ± 0.04**
  excess wrt bkg only hypothesis at 1.9σ

Conclusion

Run 2 combination of single Higgs boson results:

- **Fourfold improvement in precision** with respect to the discovery in most of the results
- Coupling modifiers show **excellent agreement with SM predictions**
- Statistical and systematic uncertainties at the same level for most couplings

H → $c\bar{c}$:

- **VH, H→$c\bar{c}$:**
  - $\mu_{VH(H\rightarrow c\bar{c})}$ < 14 (7.6) @95% C.L., **strongest limit on VH (H→$c\bar{c}$) process to date!**
  - 1.1 < κ_c < 5.5 @ 95 C.L., **strongest constraint on | κ_c | to date!**
- **ggH boosted, H→$c\bar{c}$:** upper limit @95% C.L.: 45 (38) x SM

H→invisible:

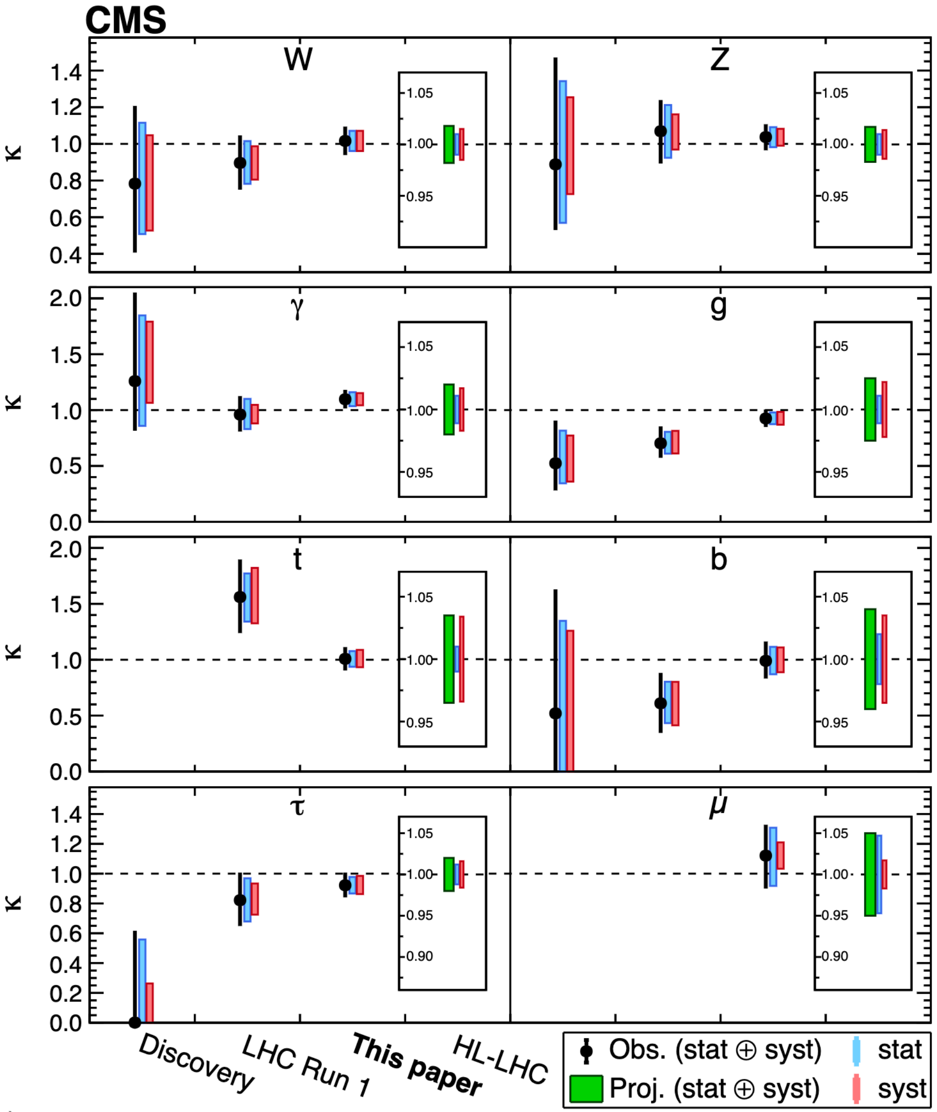
- **$t\bar{t}H/VH$ hadronic:** $\mathcal{B}$(H→inv.) < 47% (40%) @ 95% C.L.
- **Combined results:** $\mathcal{B}$(H→inv.) < 15% (8%) @ 95% C.L., strongest expected exclusion limit to date from direct searches!

Great progress in understanding the Higgs boson since its discovery and exciting times ahead!

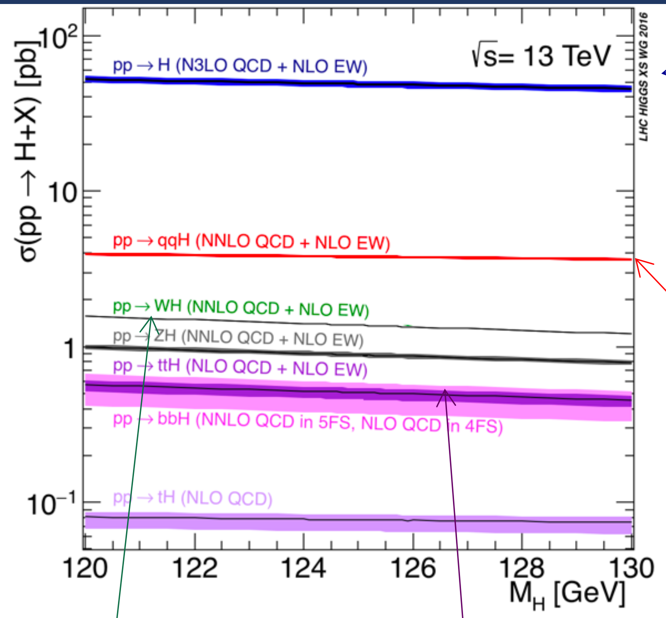
Backup slides

Projections

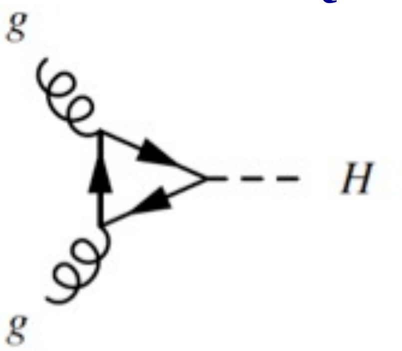
- At HL-LHC precision below 5% for all considered couplings
- Potential for more extensive tests of SM e.g. EFT

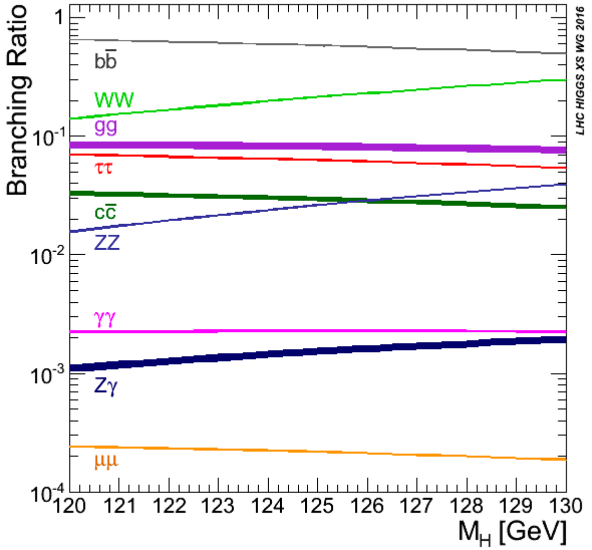


XS & BR

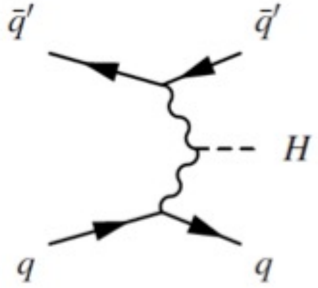


ggF: NNNLO+NNLL QCD + NLO EW

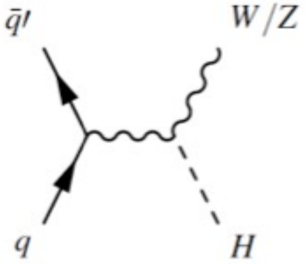


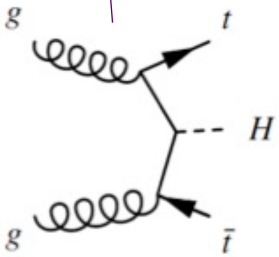


qqH: NNLO QCD + NLO EW

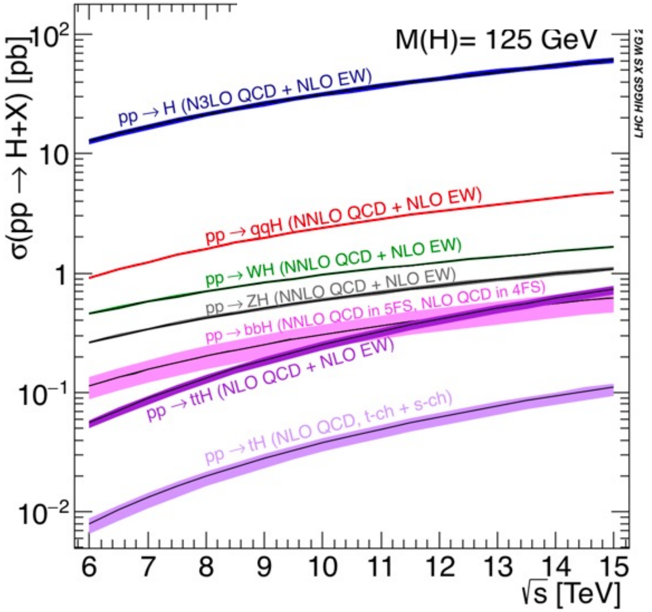


WH: NNLO QCD + NLO EW
ZH: NNLO QCD + NLO EW





ttH: NLO QCD



From 8 to 13 TeV

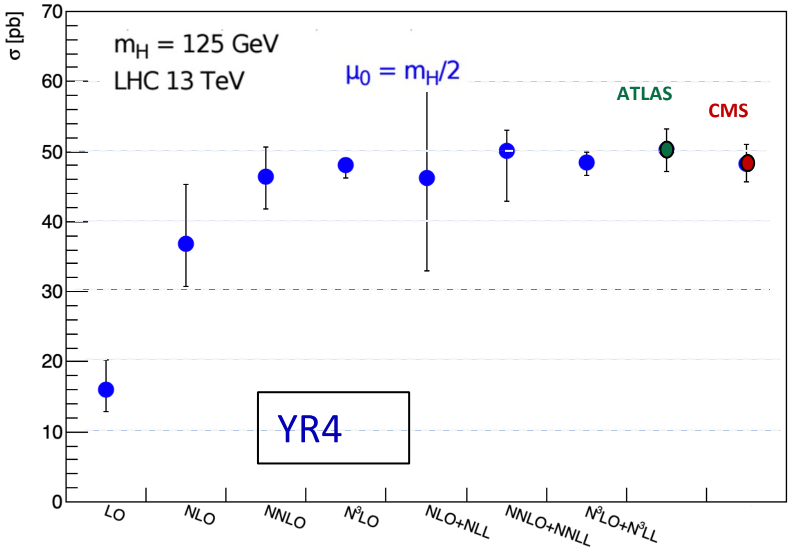
σ (ggF, VBF, VH) ~2 times larger

σ(ttH) ~4 times larger

Theory progress

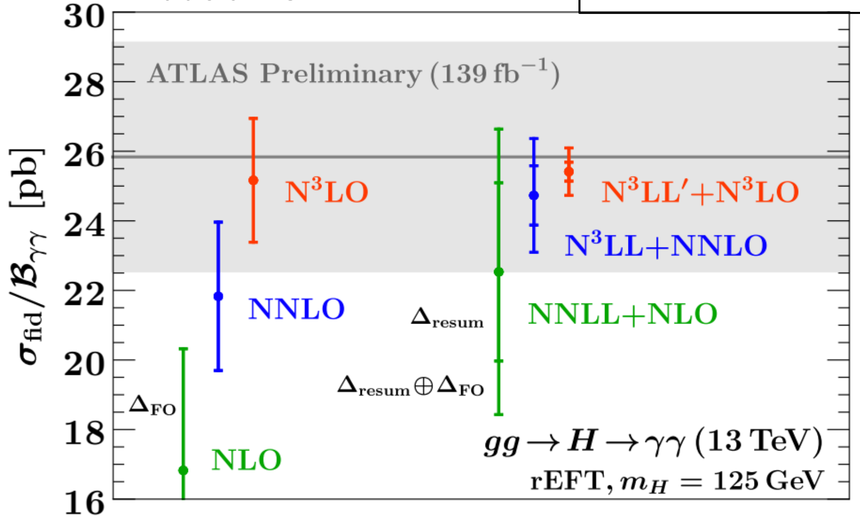
ggH

Higgs cross section: gluon fusion



Fiducial XS

arXiv:2102.08039v2

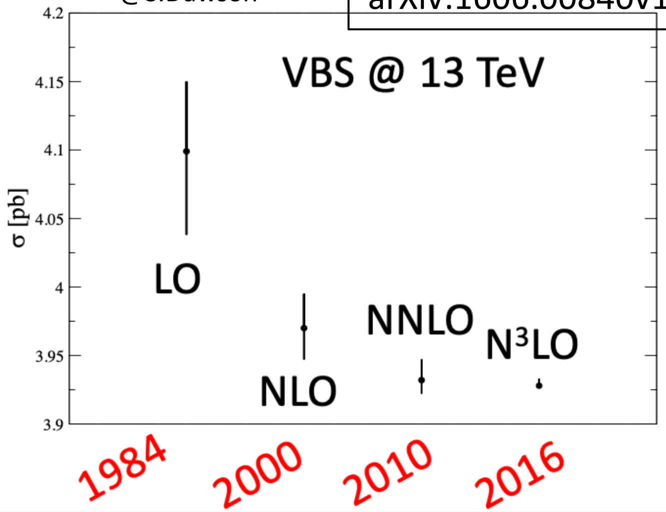


LHCHXSWG

qqH

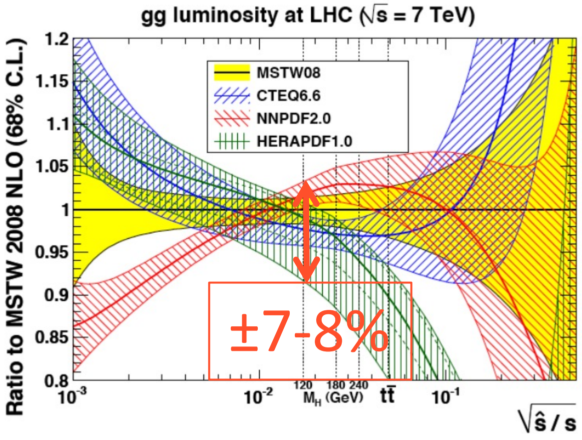
@S.Dawson

arXiv:1606.00840v1

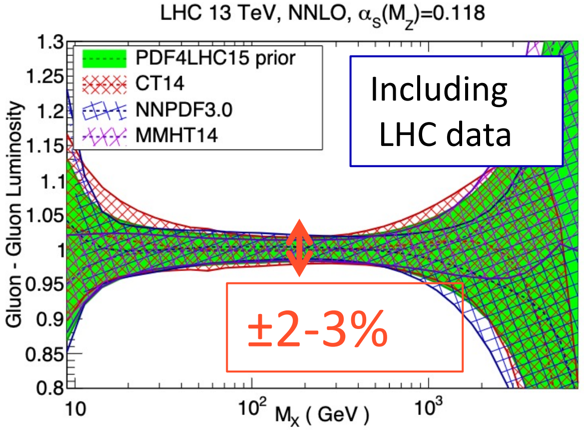


PDF

A huge improvement in the gluon PDF understanding

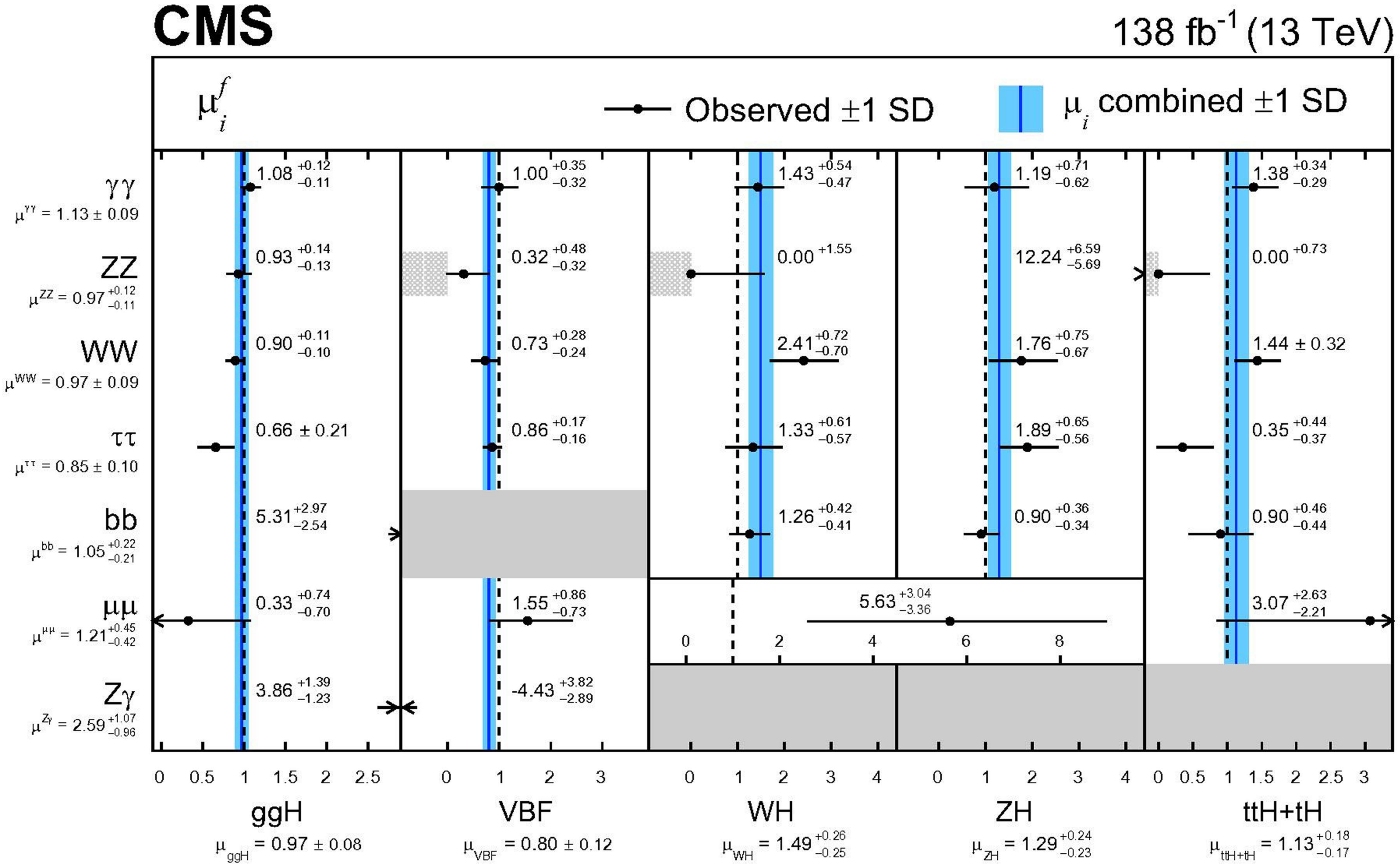


PDF4LHC-2011



PDF4LHC 2022

Test XS and BR compatibility with the SM

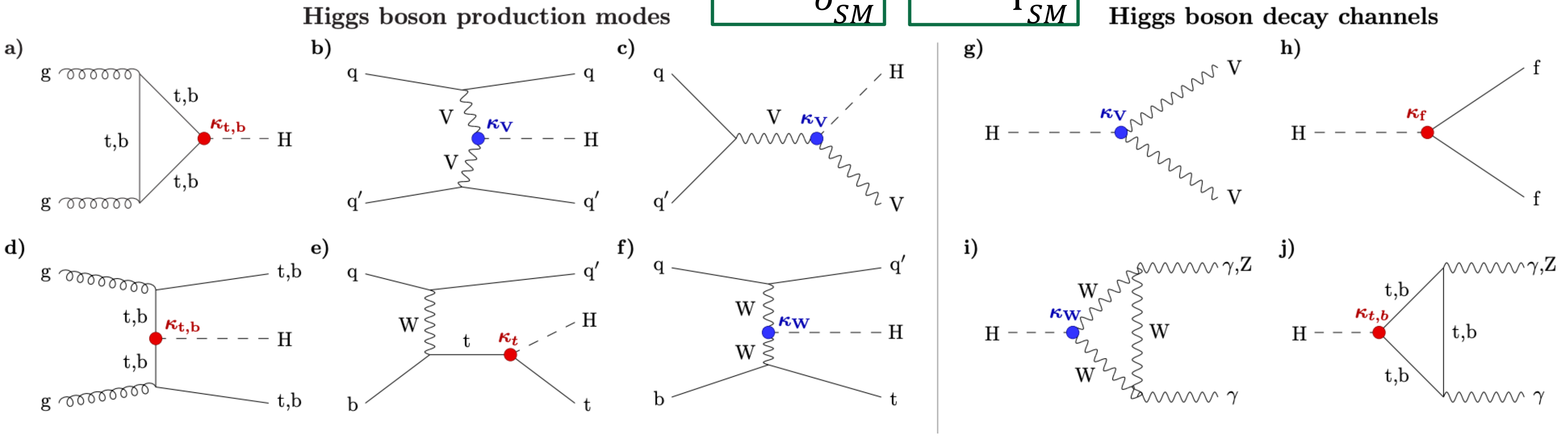


More general test of the SM with all μ_i^f floated also shows good agreement

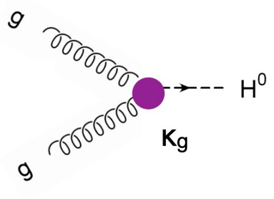
Couplings: κ framework

Coupling modifiers k to quantify couplings deviations from SM predictions

$$\kappa_j^2 = \frac{\sigma^j}{\sigma^j_{SM}} \qquad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{SM}}$$



Alternatively, the loop could not be resolved and an effective coupling could be used:

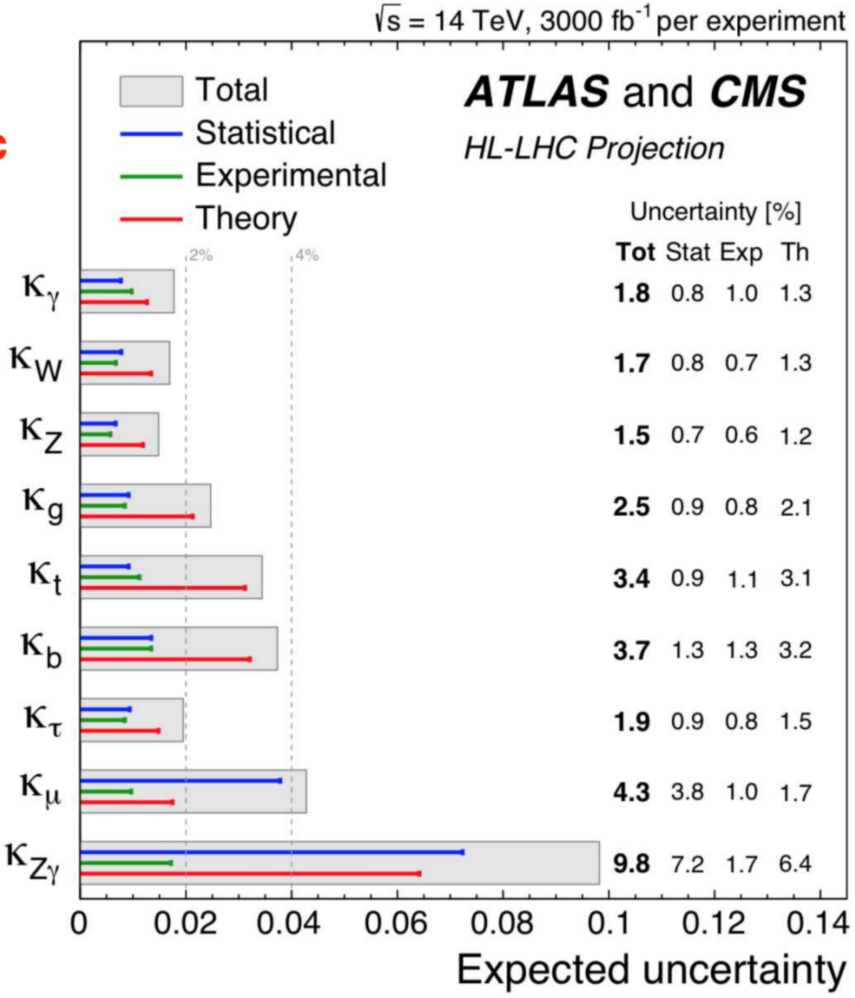


Invisible (ν, DM…) or Undetected decay:

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\kappa_H^2}{(1 - \mathcal{B}_{inv} - \mathcal{B}_{undet})}$$

Couplings: precision evolution

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		

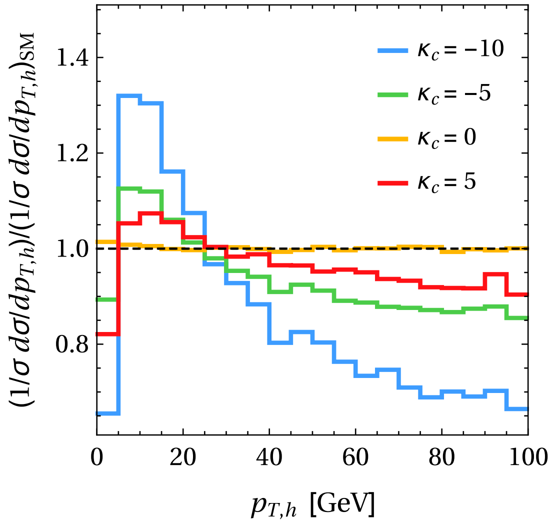


TH Uncertainties dominant (assumed to be 1/2 of Run 2)

Higgs charm coupling

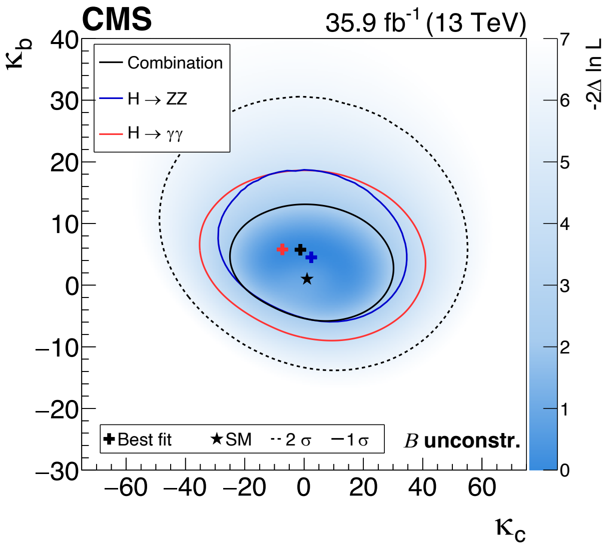
Indirect constraint from Higgs kinematics

Phys. Rev. Lett. 118, 121801



Variation of $p_T(H)$ shape as a function $\kappa_c = y_c/y_c^{SM}$

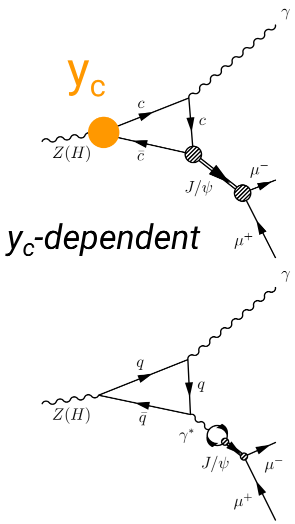
Phys. Lett. B 792 (2019) 369



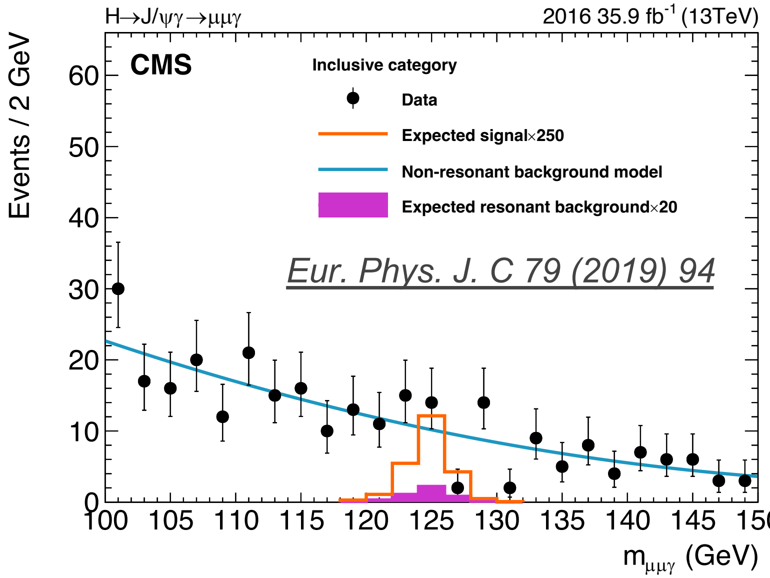
$-33 < \kappa_c < 38$ (obs.)

$-31 < \kappa_c < 36$ (exp.)

Search for exclusive H → J/Ψγ decays



Phys.Rev.D 90 (2014) 11, 113010
JHEP 08 (2015) 012
Phys.Rev.D 95 (2017) 5, 054018
Phys.Rev.D 100 (2019) 5, 054038



Eur. Phys. J. C 79 (2019) 94

$\mathcal{B}$(H → J/Ψγ) < 220x SM(obs.)

$\mathcal{B}$(H → J/Ψγ) < 170x SM(exp.)

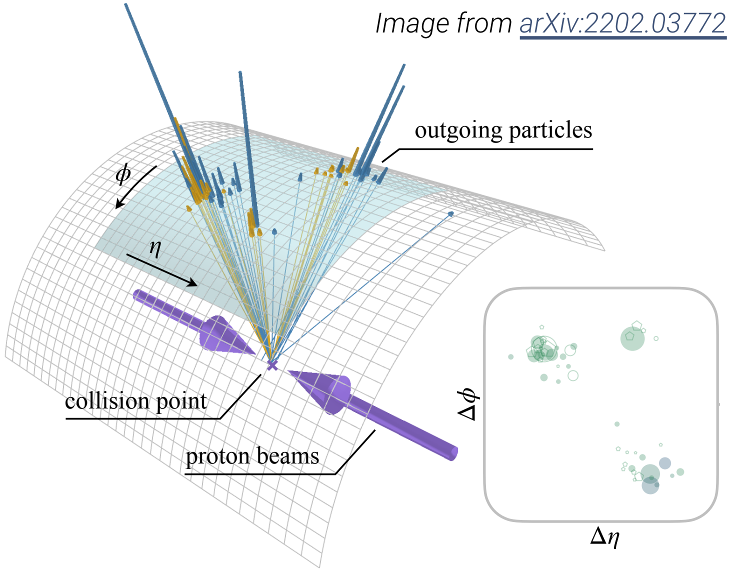
Roughly translates to $\kappa_c < O(100)$

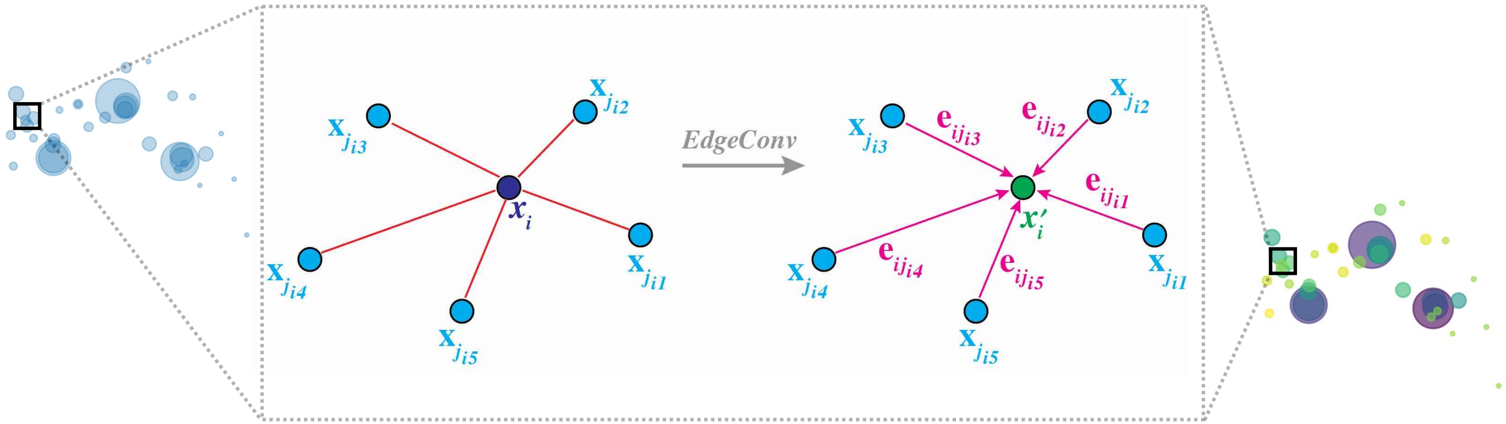
ParticleNet architecture

- New jet representation: "particle cloud"
  - treating a jet as an unordered set of particles in the η – φ space

- ParticleNet [Phys.Rev.D 101 (2020) 5, 056019]
  - graph neural network architecture adapted from DGCNN [arXiv:1801.07829]
  - permutation-invariant architecture leads to significant performance improvement

Image from arXiv:2202.03772

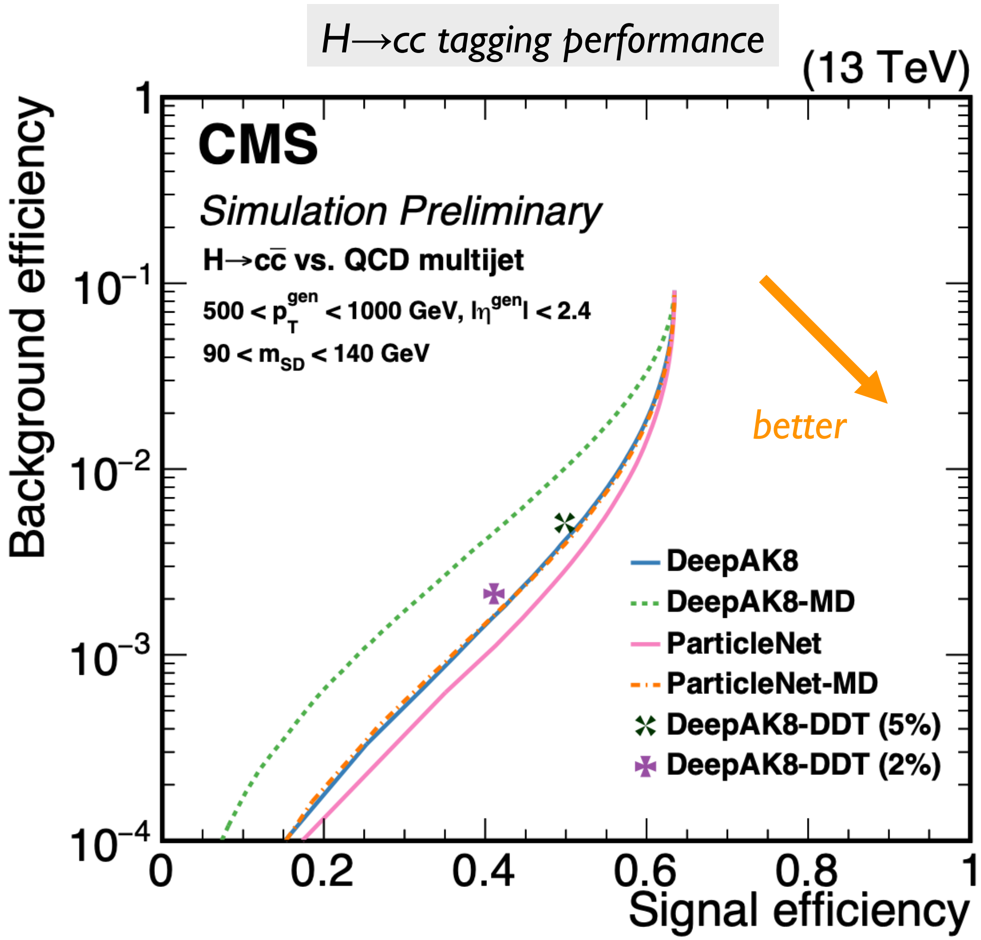




Performance on top quark tagging benchmark
[SciPost Phys. 7, 014 (2019)]

	$1/\varepsilon_b$ at $\varepsilon_s = 30\%$
ResNeXt-50	1147 ± 58
P-CNN	759 ± 24
PFN	888 ± 17
ParticleNet-Lite	1262 ± 49
ParticleNet	$\mathbf{1615 \pm 93}$

Mass decorrelation

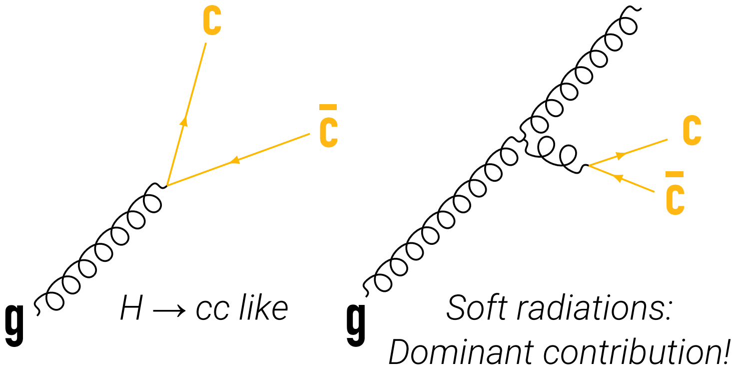


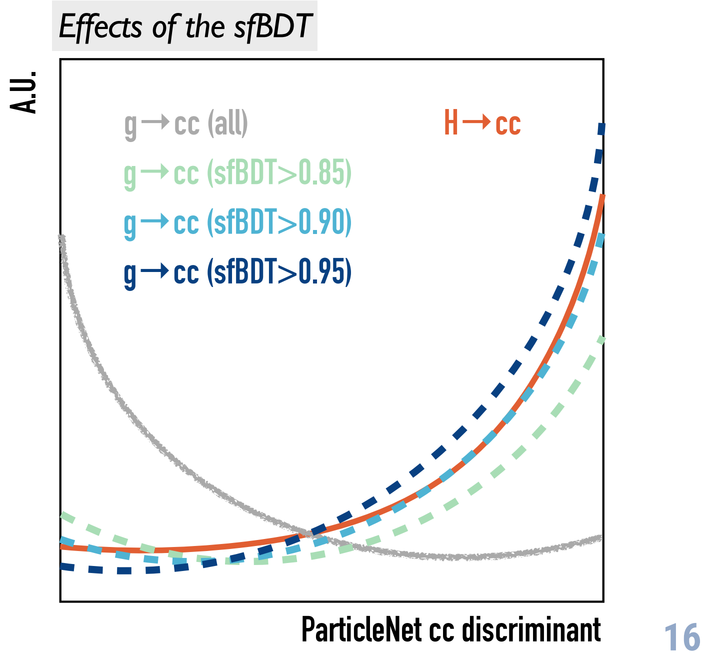
CMS-DP-2020-002

- "Mass sculpting": background jet mass shape becomes similar to signal after tagger selection
- New approach to prevent mass sculpting
  - using a special signal sample for training
    - hadronic decays of a spin-0 particle X
      - X → bb, X → cc, X → qq
    - not a fixed mass, but a **flat mass spectrum**
      - m(X) ∈ [15, 250] GeV
  - allows to easily reweight both signal and background to a ~flat 2D distribution in (p_T, mass) for the training
- Performance loss due to mass decorrelation greatly reduced compared to the previous approach (DeepAK8-MD, based on "adversarial training")

Calibration of the cc tagger

- Need to measure ParticleNet cc-tagging efficiency in data
  - no pure sample of H → cc jets (or even Z → cc) in data
  - using g → cc in QCD multi-jet events as a proxy
- Difficulty: select a phase-space in g → cc that resembles H → cc
  - solution: a dedicated **sfBDT** developed to distinguish **hard 2-prong splittings** (*i.e., high quark contribution to the jet momentum*) from **soft cc radiations** (*i.e., high gluon contribution to the jet momentum*)
  - also allows to adjust the similarity between proxy and signal jets
    - by varying the sfBDT cut — treated as a systematic uncertainty
- Perform a fit to the secondary vertex mass shapes in the "passing" and "failing" regions simultaneously to extract the scale factors
  - three templates: cc (+ single c), bb (+ single b), light flavor jets
- Derived cc-tagging scale factors typically 0.9—1.3
  - corresponding uncertainties are 20—30%

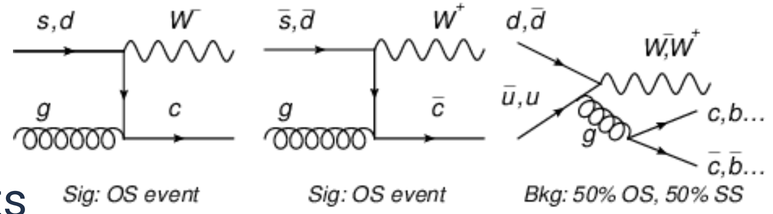


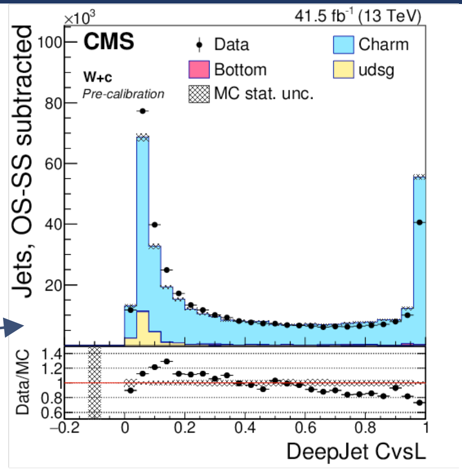


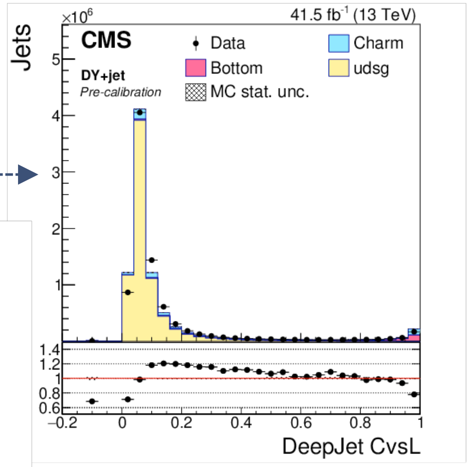
Calibration of the charm tagger

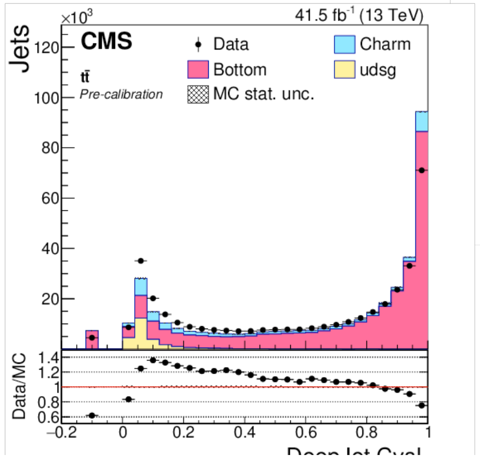
- Methodology
  - Iterative approach exploiting 3 distinct control regions, each enriched in b-jets, c-jets, or light-flavour jets
- Selecting an abundant and pure source of charm-jets
  - Target W production in association with charm quarks (W+c)
  - Major background has 50% chance to have SS or OS final states
    - performing an OS-SS subtraction reduces considerably the W+gluon process
  - To enrich in b-jets and light-jets: semi-(di-)leptonic $t\bar{t}$+jets and DY($Z \rightarrow \mu\mu/ee$)+jets

(from arXiv:2111.03027)









- First time that a calibration method to correct the 2D distribution of c-tagging discriminator shapes is presented

➔ arXiv:2111.03027 (**accepted by *JINST***)

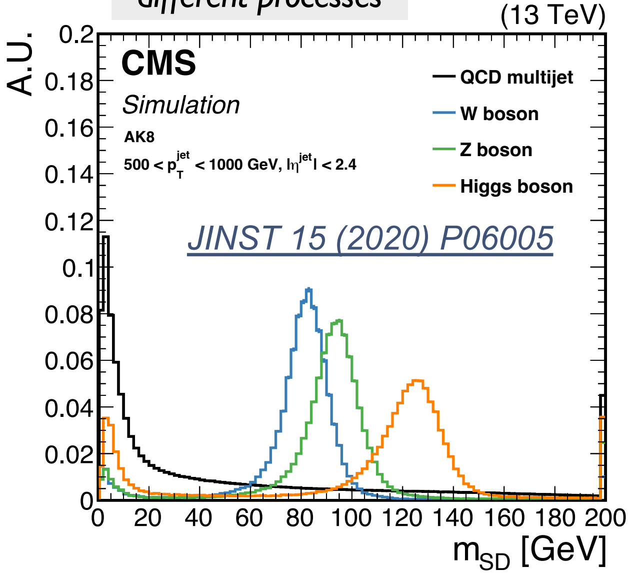
Large-R jet mas regression

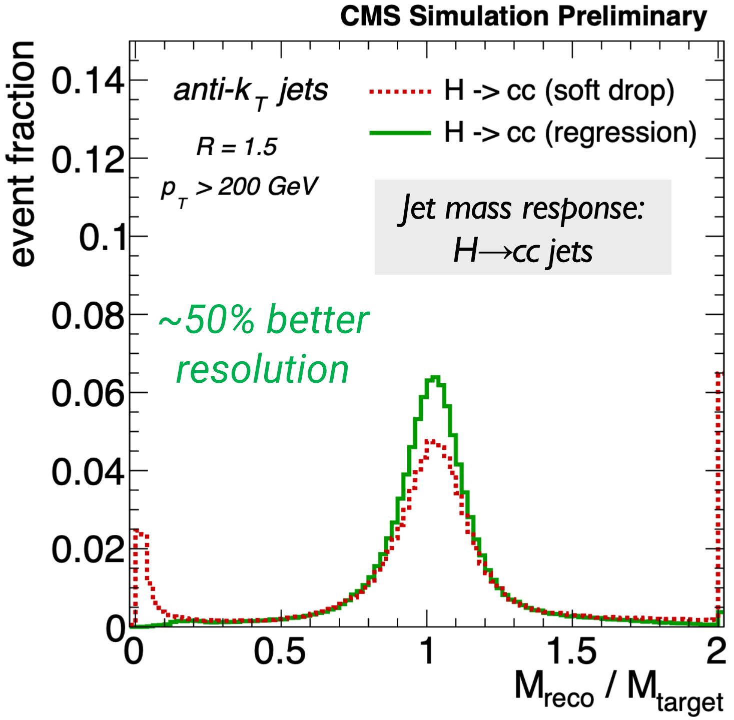
- Jet mass: one of the most powerful observable to distinguish signal and backgrounds
- New ParticleNet-based regression algorithm to improve the large-R jet mass reconstruction
  - training setup similar to the ParticleNet tagger; the regression target:
    - signal (X → bb/cc/qq): generated particle mass of X [flat spectrum in 15 – 250 GeV]
    - background (QCD) jets: soft drop mass of the particle-level jet

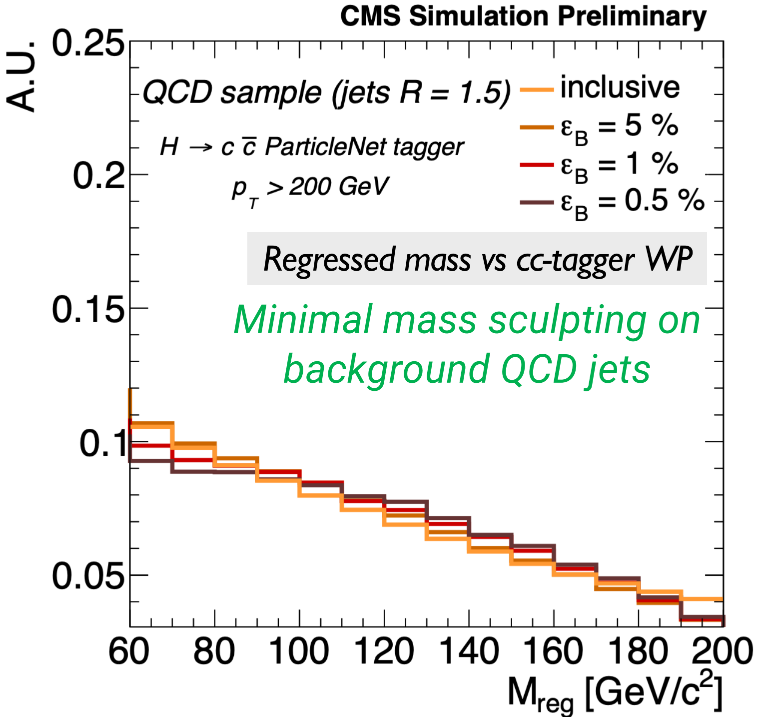
CMS DP-2021/017

20 – 25% improvement in the final sensitivity

Large-R jet mass of different processes







Invisible combination

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

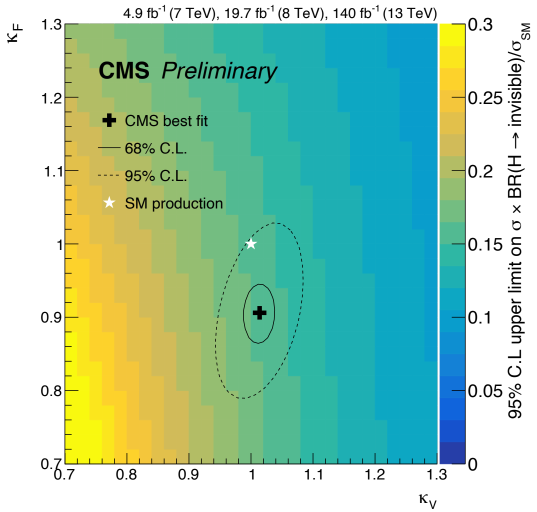
- Theo. signal systematics → correlated
- Theo. background systematics → uncorrelated (≠ phase space)
- Luminosity → correlated
- Trigger → correlated if same paths / datasets
- Lepton efficiencies → correlated if identical
- JES & JER → correlated between VBF/MonoJet/MonoV
- Everything else → uncorrelated

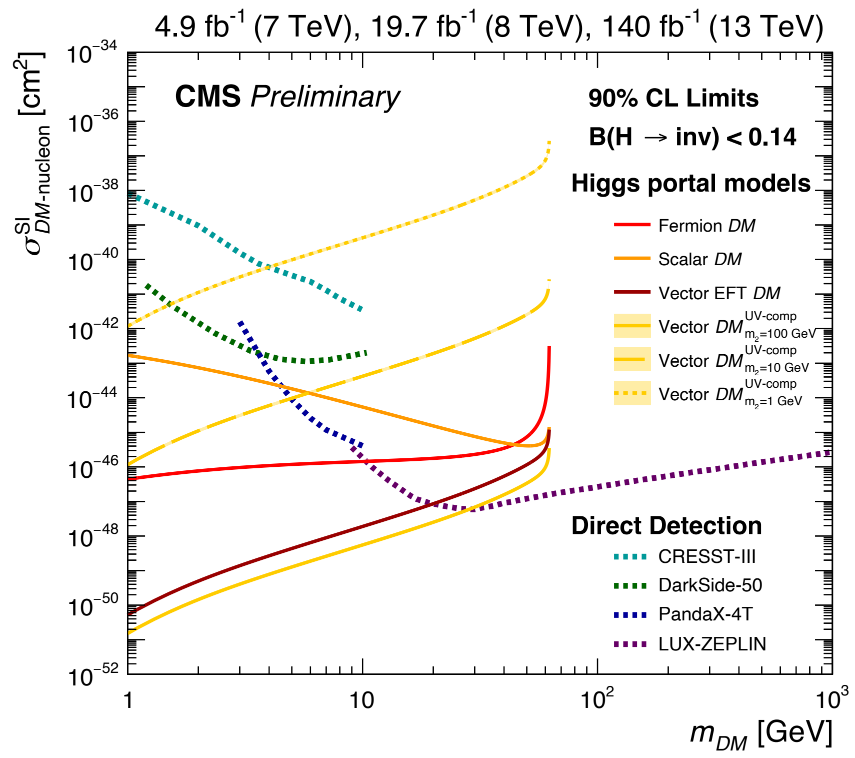
Invisible combination

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)