Massachusetts Institute of Technology

ATLAS EXPERIMENT

CERN

CMS

Higgs Rare Decays

On behalf of the ATLAS and CMS Collaborations

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March 20, 2026

Phil Harris Lab @ MIT

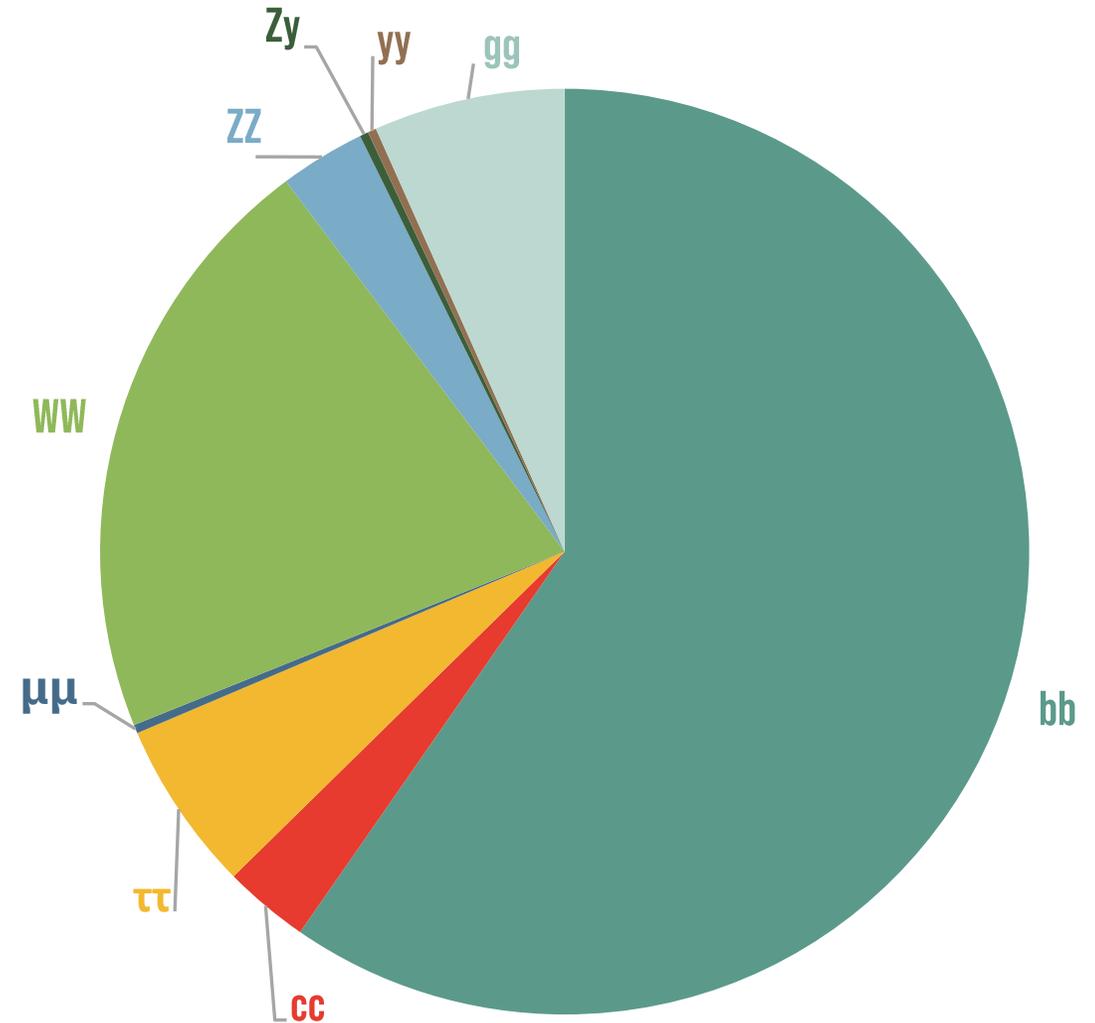60th Rencontres de Moriond (EWK), La Thuile (Italy)

Landscape of Higgs Searches

Over a decade since discovery

- Mass measured to per-mille precision
- ~90% of branching ratio observed

~24 Millions of Higgs bosons at ATLAS & CMS each

- Expecting ~170 Millions by end of HL-LHC
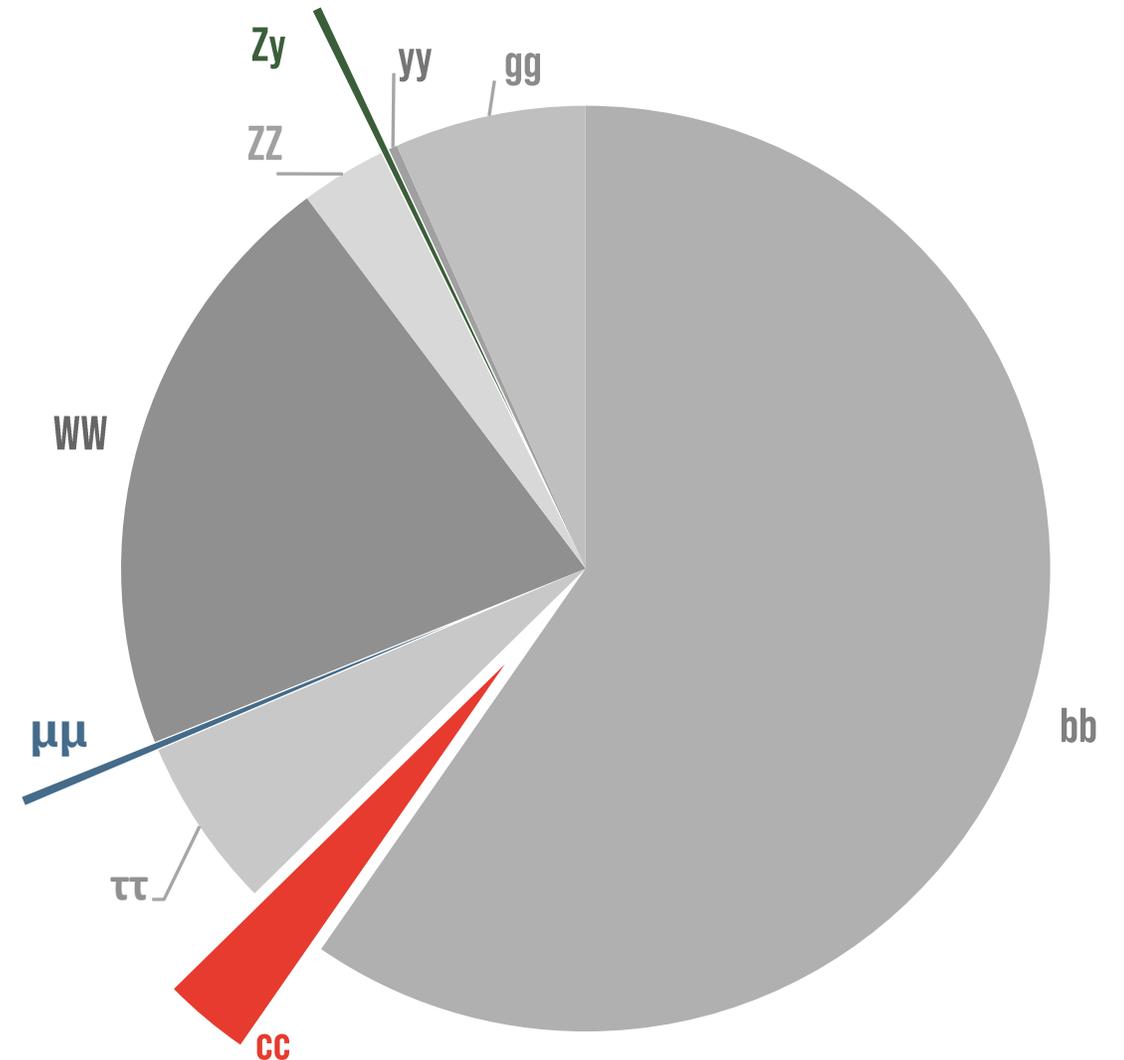- Enabling rare decay exploration

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~24 Millions of Higgs bosons at ATLAS & CMS each

- Expecting ~170 Millions by end of HL-LHC
- Enabling rare decay exploration
- Rare decay channels now accessible:
  - H → cc̄ (+ H+c associated production)
  - H → Zγ
  - H → μμ
- γH

Outline

| Analysis	ATLAS	CMS
H⟶cc (VBF)	HIGP-2024-21 (Nov 2025)	–
H⟶cc (ttH)	–	HIG-24-018 (Phys. Rev. Lett. 136 (2026) 011801)
H⟶WW + c	–	HIG-24-009 (Aug 2025)
H⟶γγ + c	–	HIG-23-010 (JHEP 11 (2025) 060)
H⟶Zγ	HIGP-2024-19 (Jul 2025)	HIG-25-012 (BRAND NEW!)
H⟶μμ	HIGP-2024-11 (Phys. Rev. Lett. 135 (2025) 231802)	–
γH	–	HIG-23-011 (Phys. Rev. D 112 (2025) 11200)

H → cc

2nd-generation quark Yukawa coupling

- Key SM test; with HH, next Higgs frontier

## Experimentally challenging

- 20× smaller BR than H → bb
- Less distinct charm signature in detector
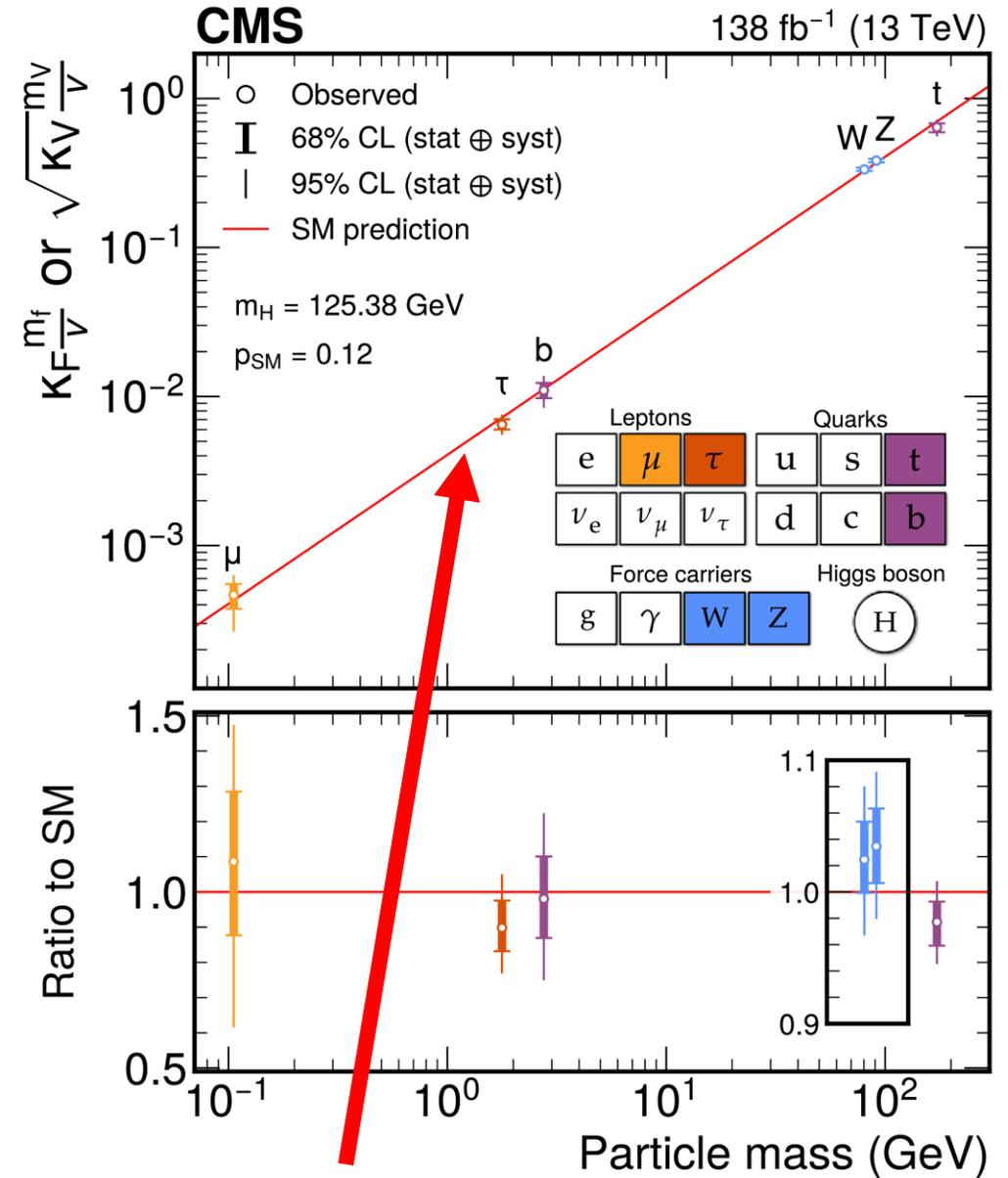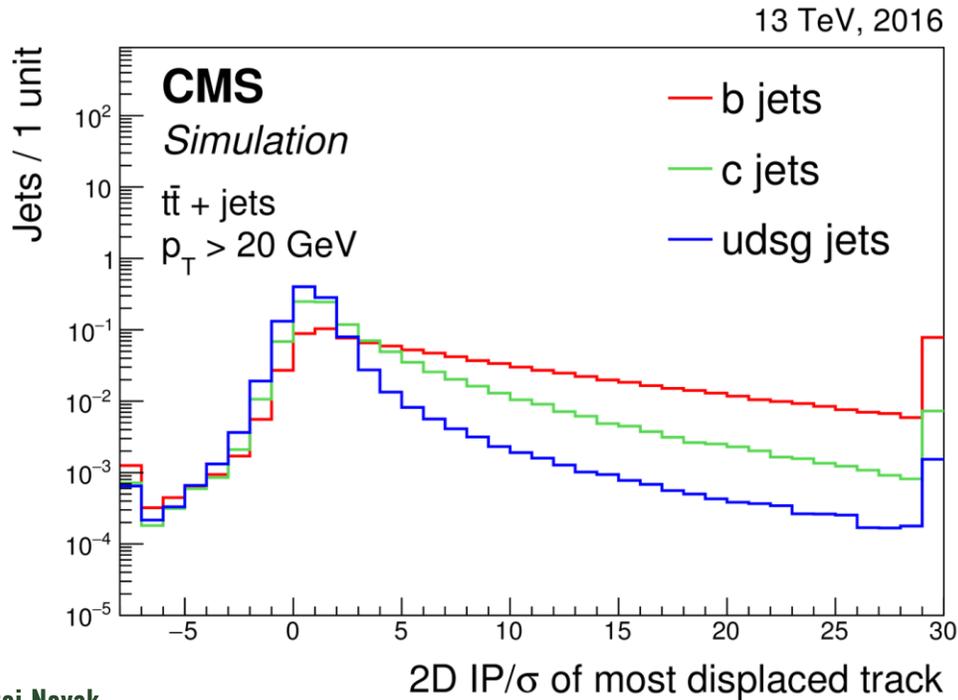
[ATLAS] H → cc in VBF Channel (Partial Run2+Run3 89fb⁻¹)

- **First (at LHC) VBF H→cc̄ search**
  - Enabled by **inclusive VBF trigger**
    - No b-tag, $m_{jj} > 1\,\text{TeV}$, > 90/95% eff

- Key Strategy Elements:
  - **GN2 transformer tagger** for flavour identficatation
    - WP-cut and count passing b/c jets
  - **Adversarial NN** decorrelated from di-jet Higgs-candidate mass
  - Six SRs; joint fit floating $\mu_{c\bar{c}}$ and μ_{bb}

- Data-driven multijet (99%)
- Shape from SR6, bias unc. 26–56% of stat.
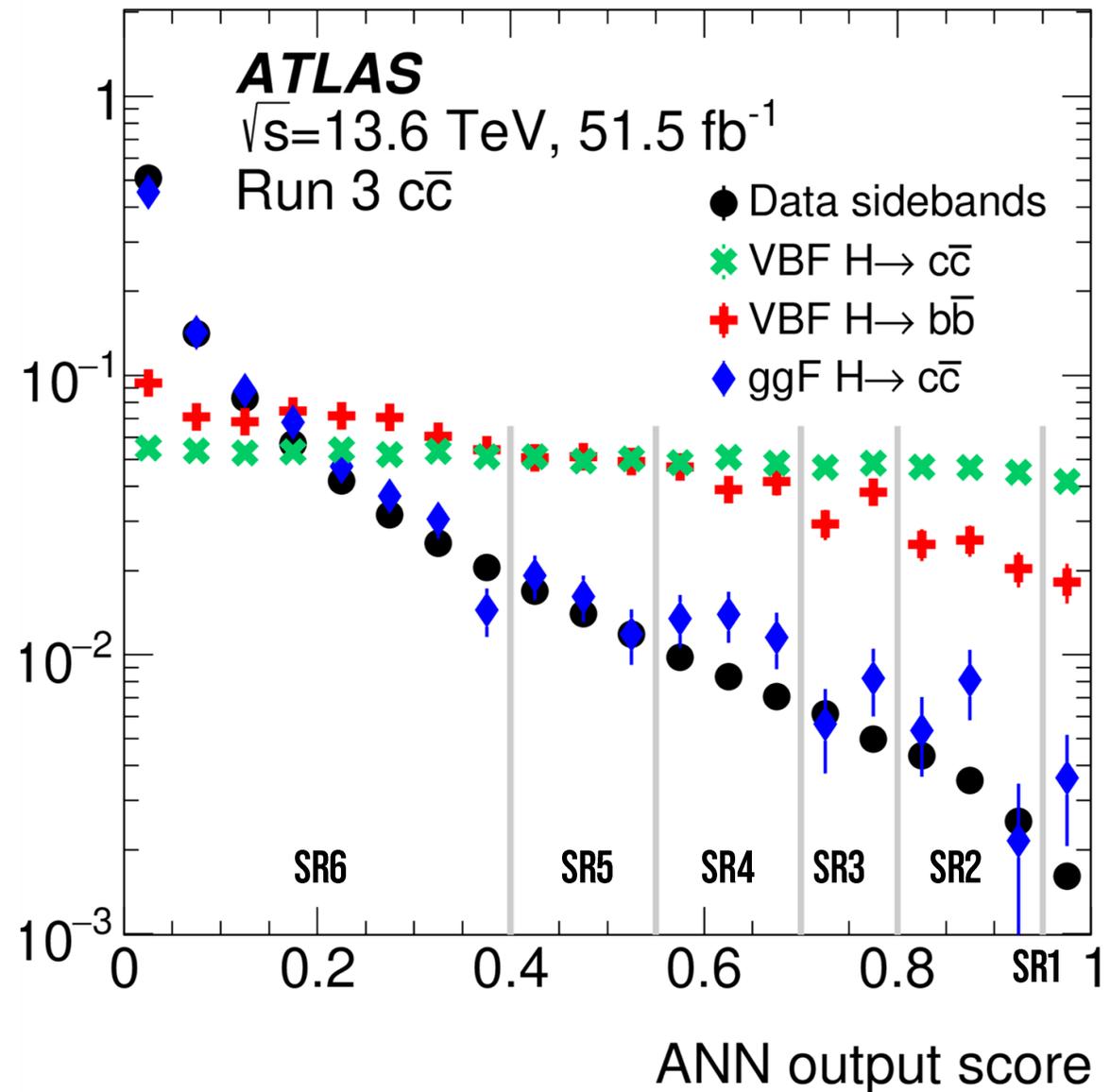
# [ATLAS] H → cc in VBF Channel (Partial Run2+Run3 89fb⁻¹)

- **H→cc̄:**
  - $\mu_{c\bar{c}} = 18 \pm 13 \rightarrow \mu_{c\bar{c}}^{95\%CL} < 41\ (28)$
  - VBF+VH: $|\kappa_c| < 4.7\ (3.9\ exp) - 8\%$ over VH-alone

- **H→bb:**
  - $\mu = 0.97^{+0.57}_{-0.50}$
  - Combination w/ Run2 **3.2σ** → first VBF H→bb evidence

- Statistically limited
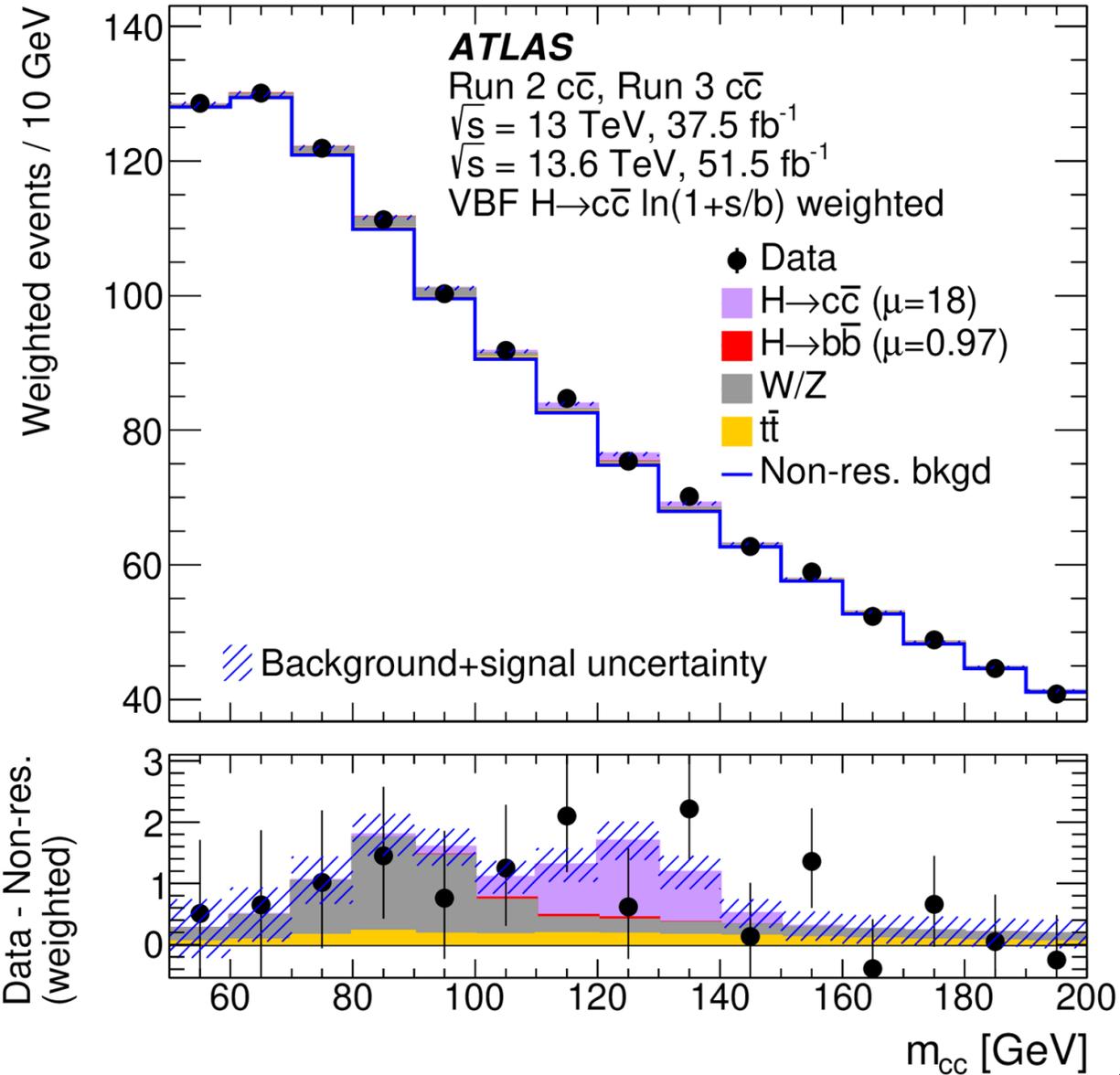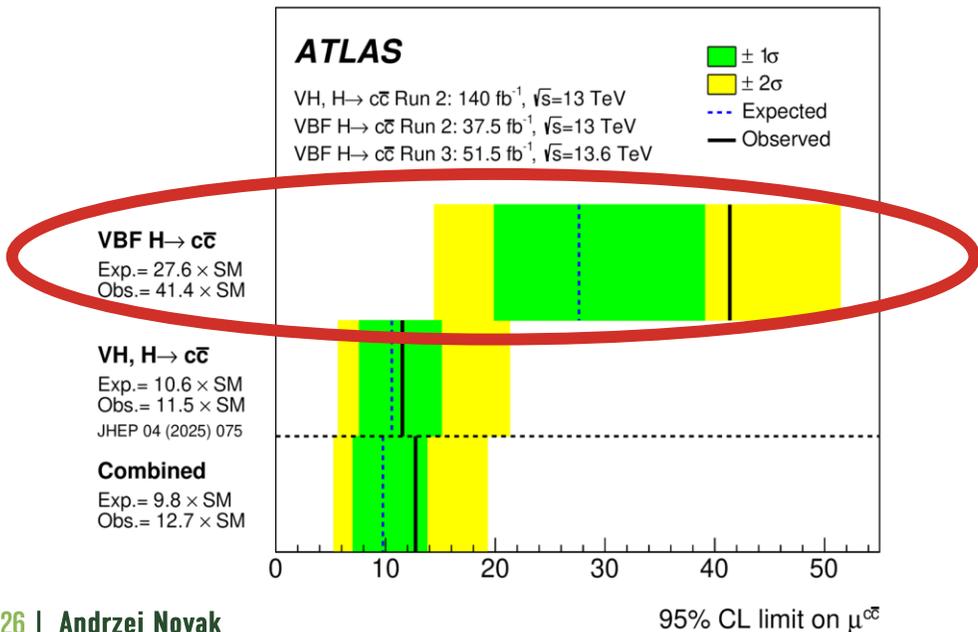
[CMS] H → cc in ttH Channel (Run2 138fb⁻¹)

- **First (at LHC) ttH H→cc̄ search (**0L/1L/2L)

  - Key challenges: many jets, complex combinatorics

- **ParticleNet** jet tagger (11 cats, 2× rejection)

- **Particle Transformer** event classifier (10-class, no explicit reco).

- tt+HF background constrained from data CRs with floating normalizations.

- Validated with ttZ(Z→cc̄/bb̄)
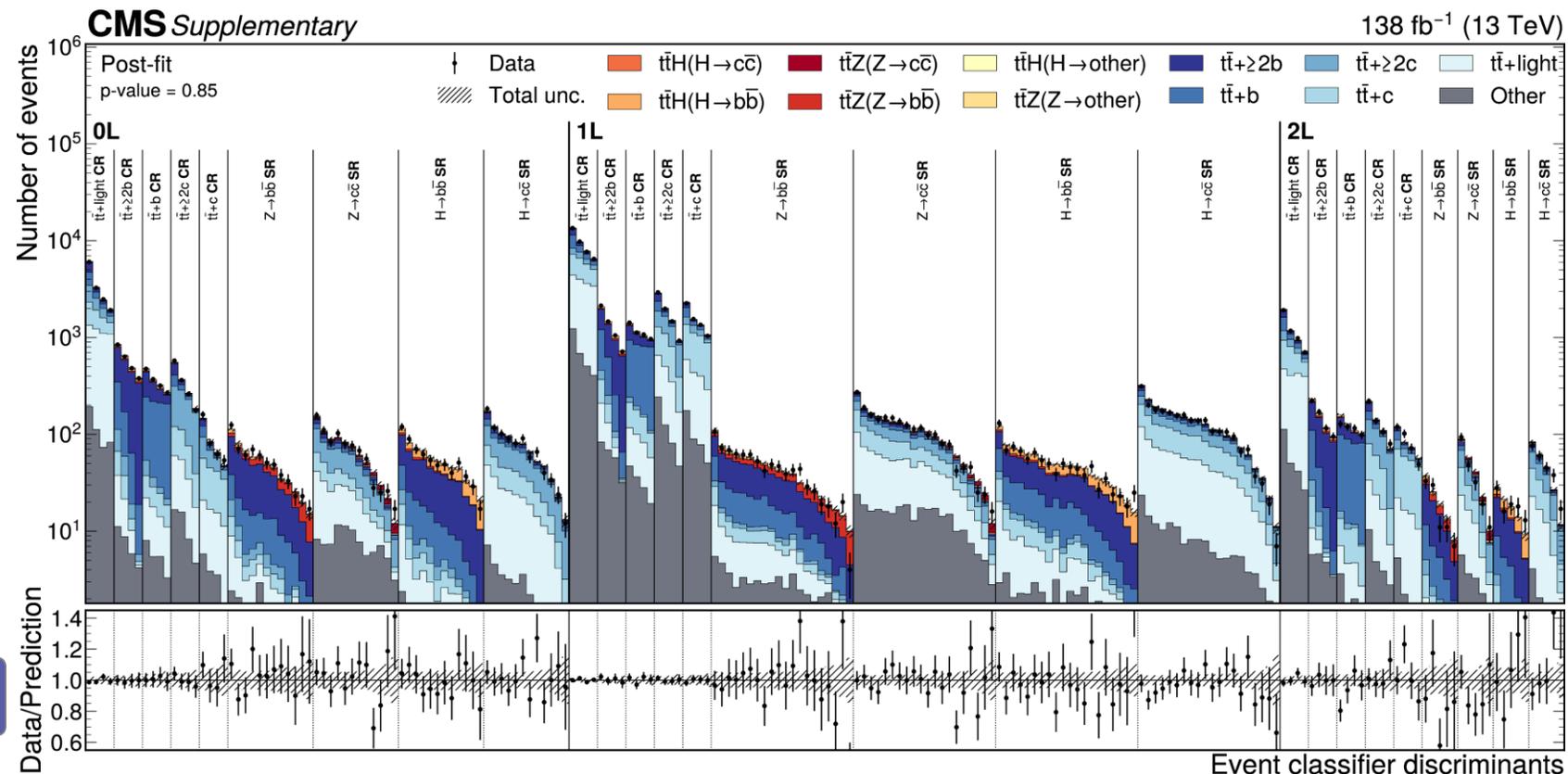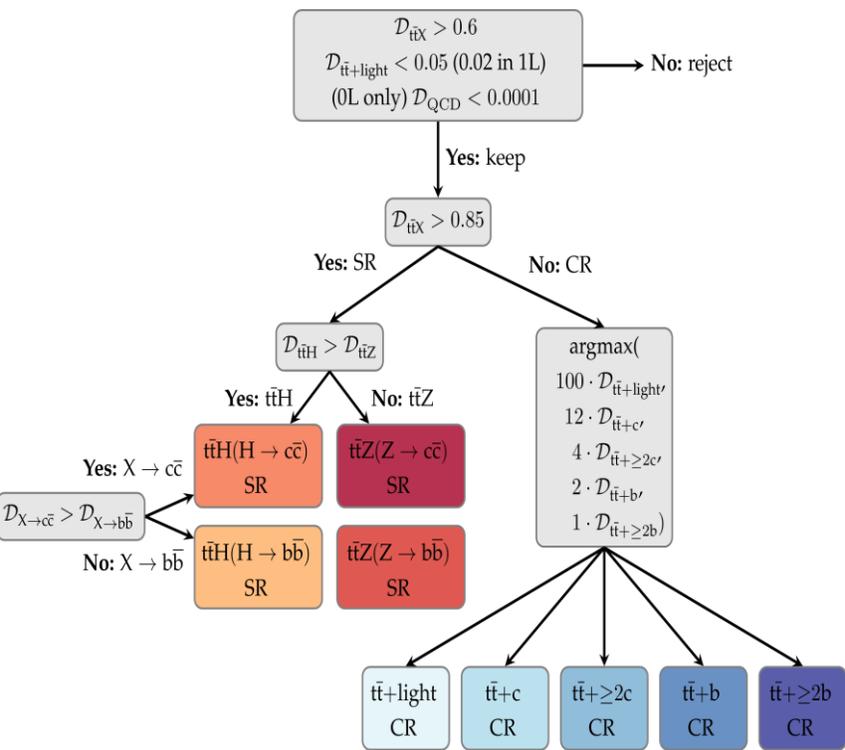
[CMS] H → cc in ttH Channel (Run2 138fb⁻¹)

- **ttH(H→c$\bar{c}$):** $\mu_{c\bar{c}}^{95\%CL} < 7.8\ (8.7)$
  - Combined with VH: $|\kappa_c| < 3.5\ (2.7\ exp) -$ best to date

- **ttH(H→bb):** $\mu = 0.91^{+0.26}_{-0.22}$
  - Sensitivity comparable to VH
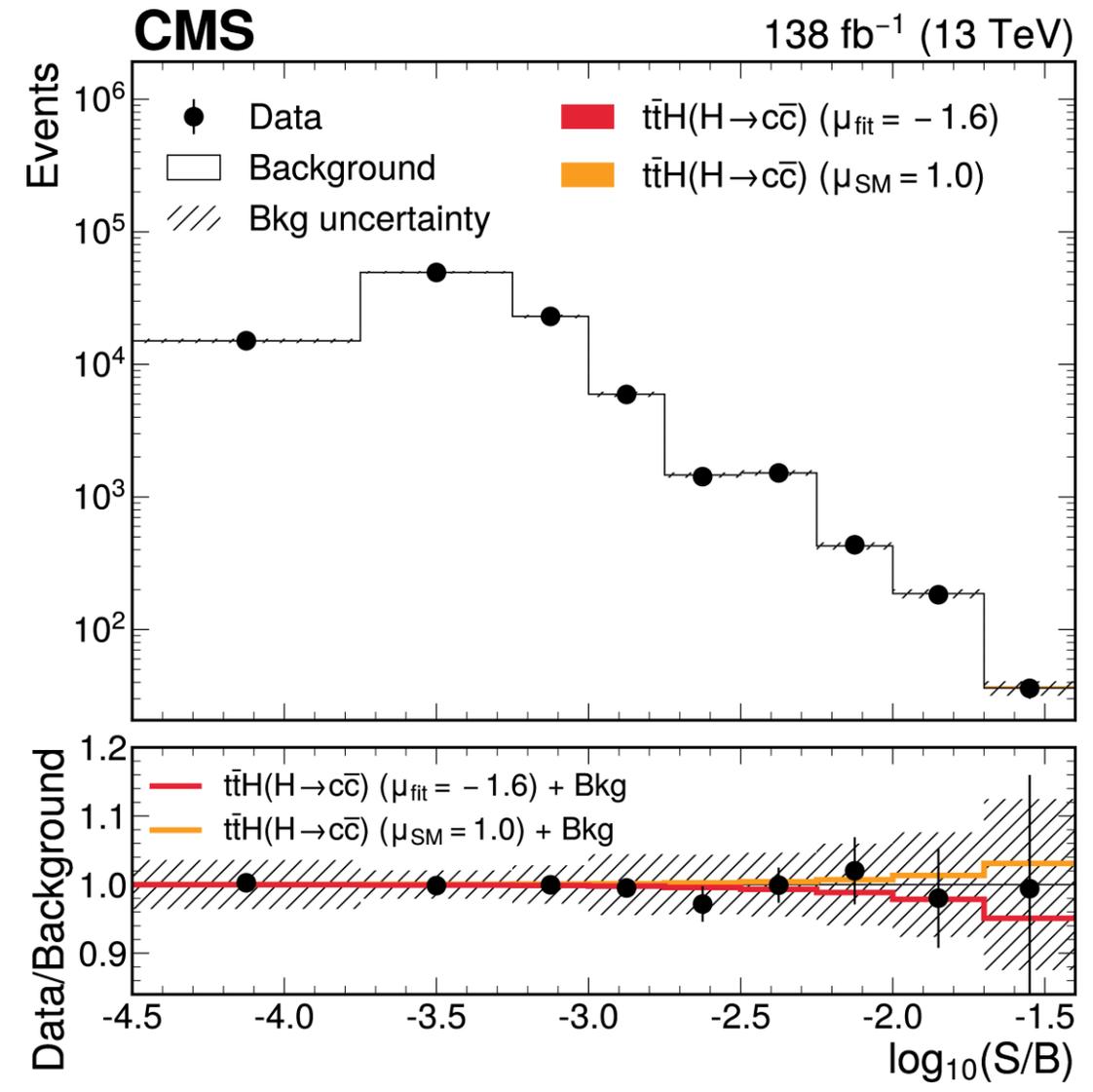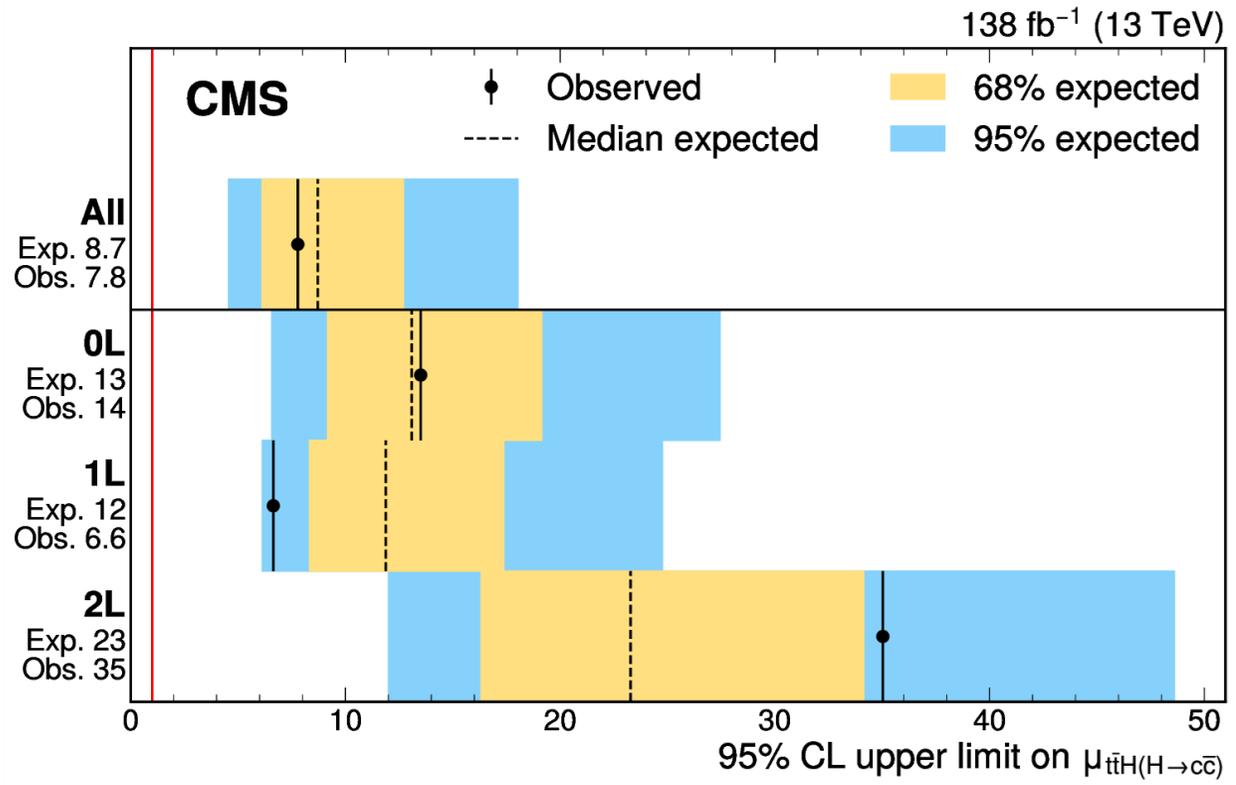
H + c: Probing the Charm Yukawa Coupling

Complementary probe of κ_c

- H $\rightarrow$ c$\bar{c}$ limited by ε^2 c-tagging penalty + QCD bkg

- pp $\rightarrow$ Hc alternative (Brivio et al., PRL 115)
  - Only 1 c-tag (charm at production vertex)
  - y_c interferes with ggH $\rightarrow$ **linear** κ_c sensitivity
  - $\Gamma \propto \kappa_c^2$ (weak); $\sigma \propto \kappa_c$ (tighter bounds)

- Two analyses presented:

- **H$\rightarrow\gamma\gamma$+c** – clean mass peak, high S/B

  - Earlier ATLAS result HIGG-2021-06 – 5.3 ± 3.2pb (2.9 ± 3.1pb expected)

- **H$\rightarrow$WW+c** – larger BR, leptonic W
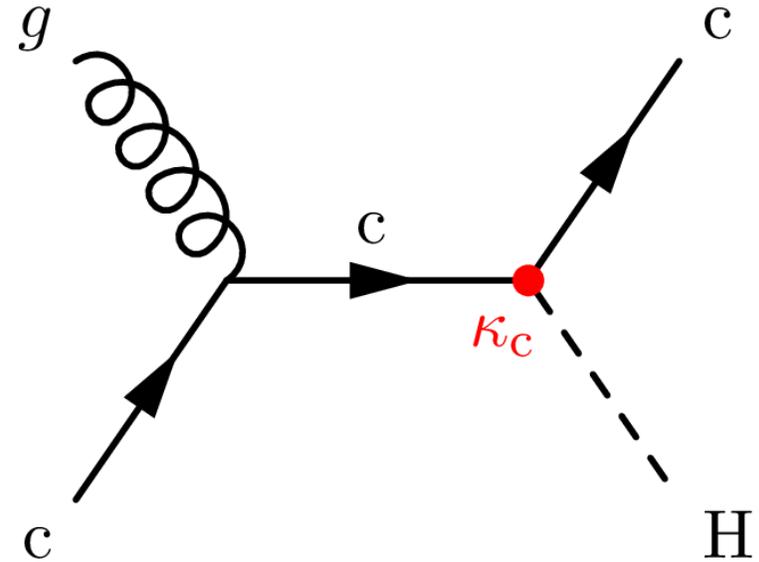
[CMS] H→ γγ + c (Run2 138fb⁻¹)
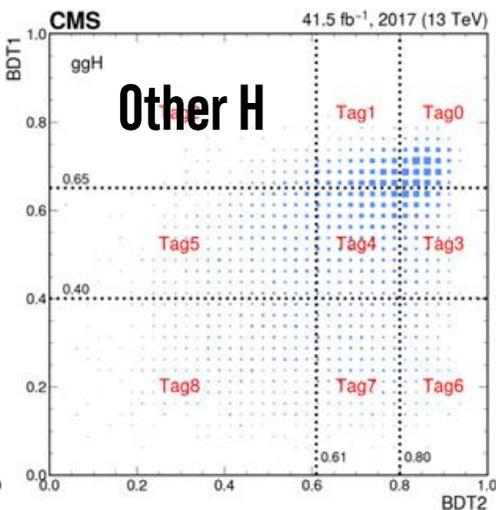
- H→γγ for clean $m_{\gamma\gamma}$ peak.

- Two BDTs (vs resonant Higgs bkg + vs continuum)
  - 27 cats (9 x 3 years) × $m_{\gamma\gamma}$ fit. c-tagging enriches cH over ggH.

- $\mu_{cH}^{95\%CL} < 243\ (355\ exp);\ |\kappa_c| < 38.1\ (72.5\ exp)$

- Complementary to H→c$\bar{c}$; sensitivity $\propto \kappa_c^4 \rightarrow$ scales rapidly
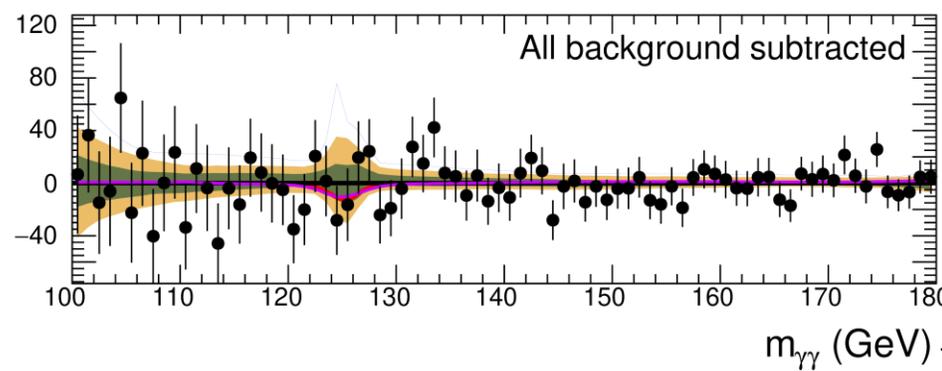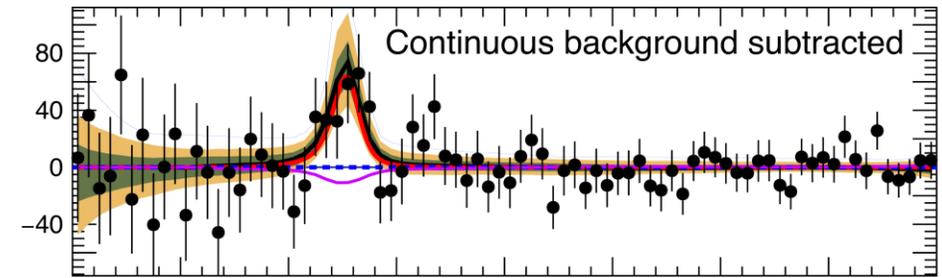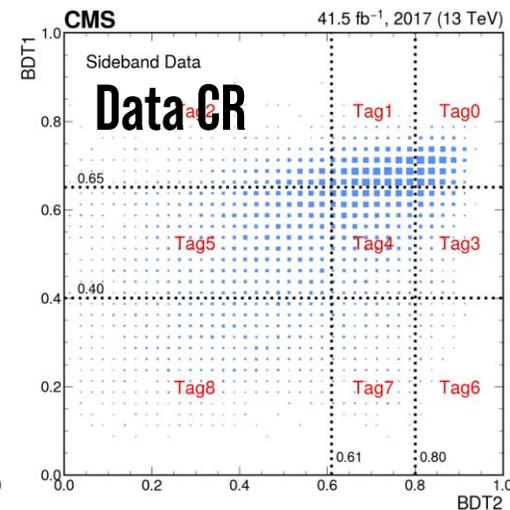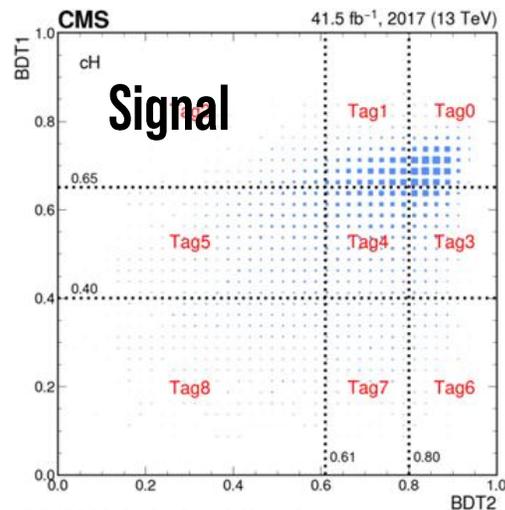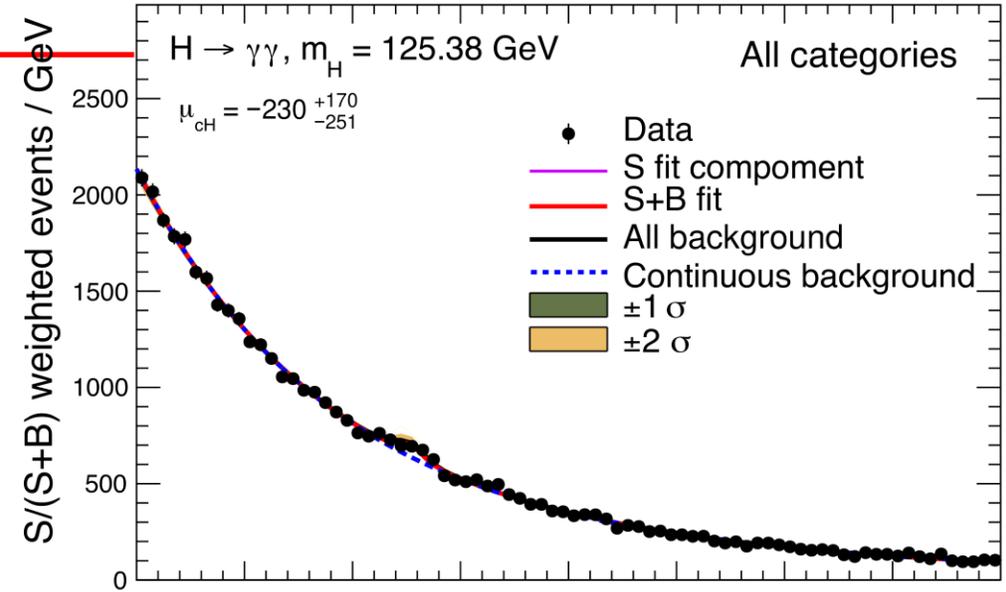
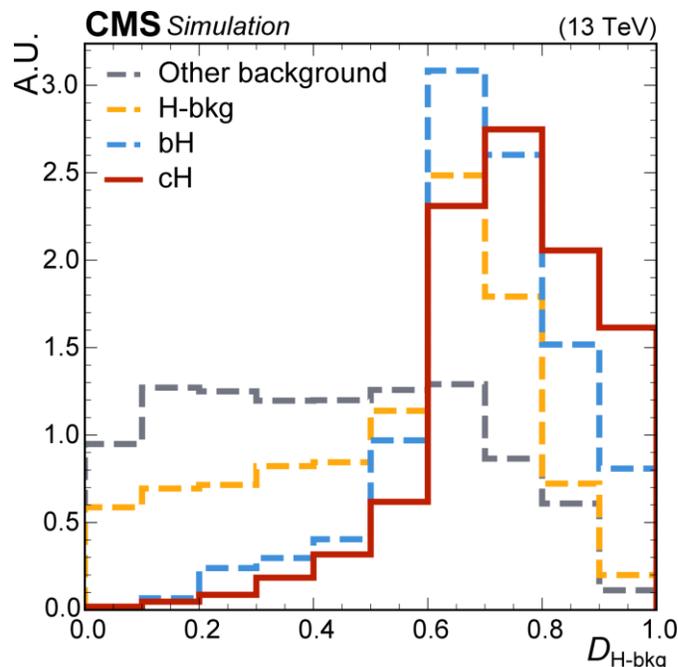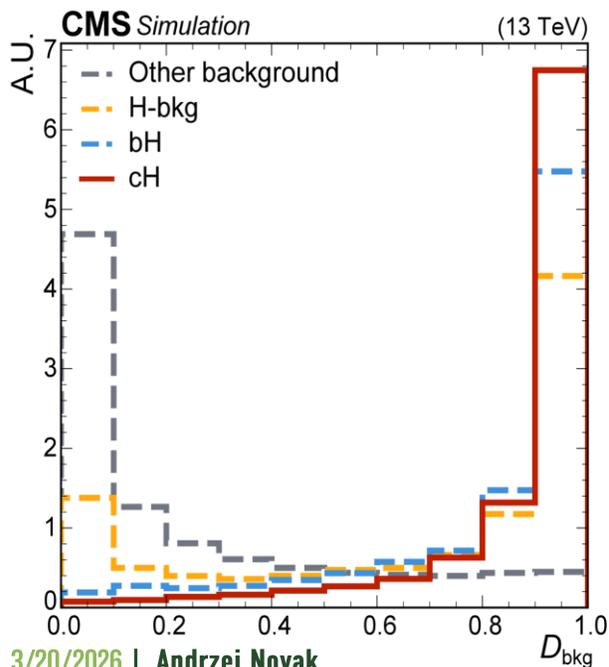# [CMS] H→ WW + c (Run2 138fb⁻¹)

- **H→WW** larger BR (21.4% vs 0.227%) x harder bkgs.
  - eμ suppresses Z+jets (21.4% incl → 1% leptonic)
- DeepJet CvsL/CvsB c-tagging for cH
- Two BDTs: D_{bkg} (vs tt) + D_{H-bkg} (vs other Higgs)
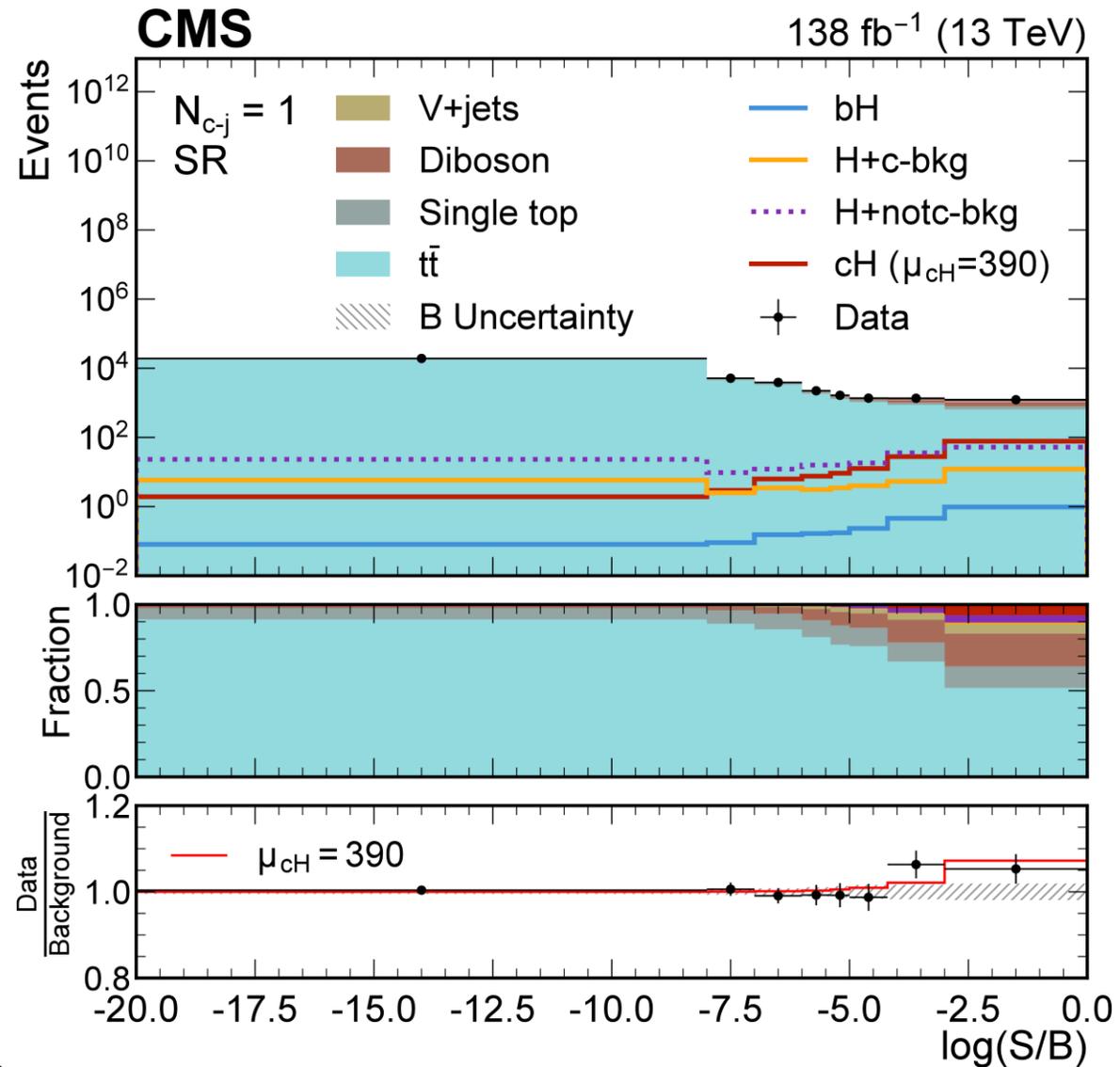
[CMS] H→ WW + c (Run2 138fb⁻¹)

- $\mu_{cH}^{95\%CL} < 1065\ (506\ exp)$
  - Combined cH(γγ+WW): $|\kappa_c| < 47\ (51\ exp)$

- Weaker than H(γγ) mostly due to tt

- Validates cH in new decay mode

- Production-mode κ_c in early days
  - Grows with lumi + c-tagging improvements
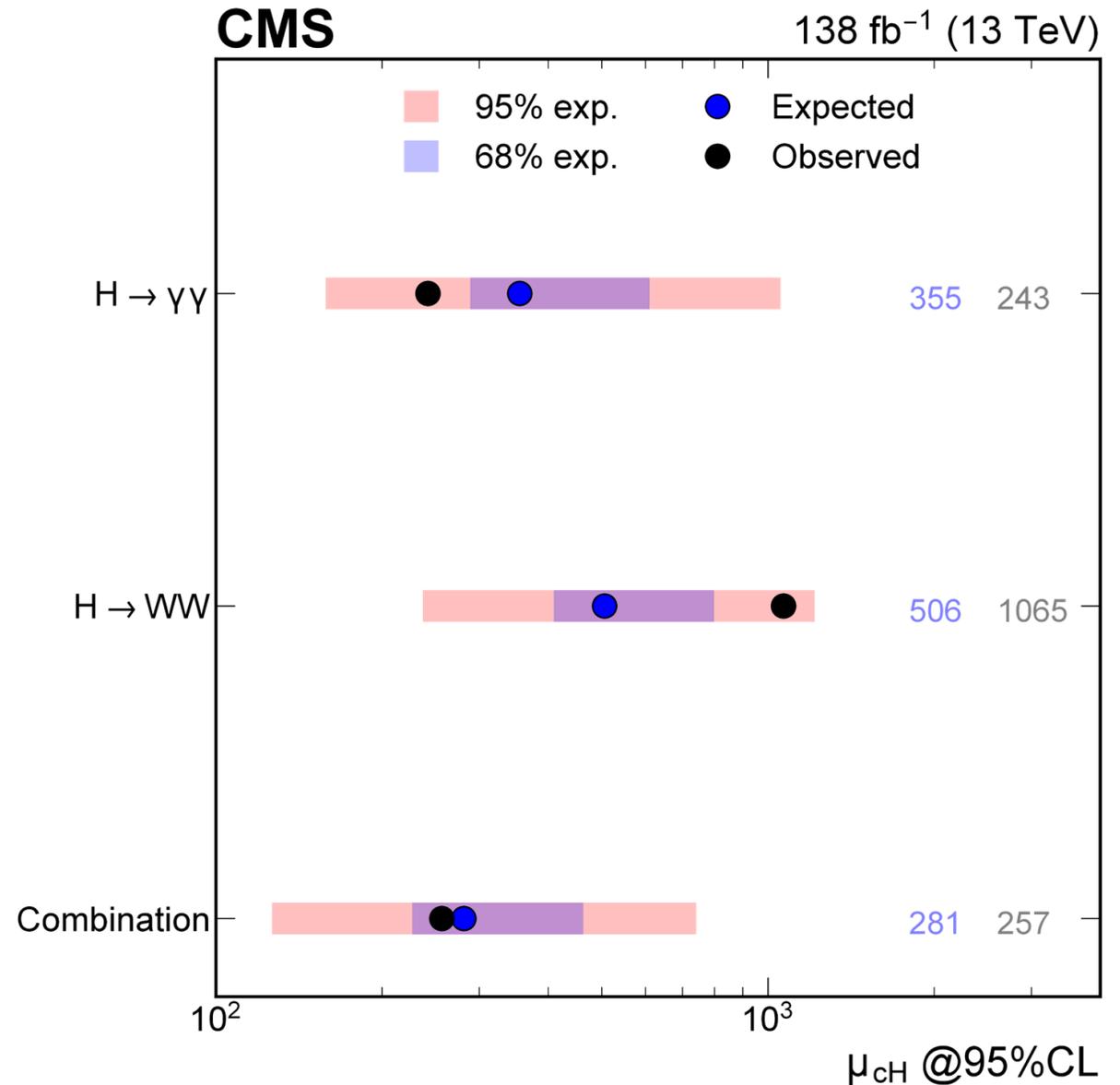
Higgs-Charm Coupling: Status of κ_c

Analysis	μ obs (exp)	|κc| obs (exp)	Lumi
CMS ttH (H→cc̄)	< 7.8 (8.7)	< 3.0 (3.3)	138 fb^{-1}
CMS VH+ttH (H→cc̄)	< 9.3	< 3.5 (2.7)	138 fb^{-1}
ATLAS VH (H→cc̄) upd.	< 11.5 (10.6)	< 4.2	140 fb^{-1}
CMS VH (H→cc̄)	< 14.4	< 5.5 (3.4)	138 fb^{-1}
ATLAS VBF+VH (H→cc̄)	< 41 (28)	< 4.7 (3.9)	89 fb^{-1}
ATLAS VH (H→cc̄) '22	< 26 (31)	< 8.5 (12.4)	139 fb^{-1}
CMS ggH (H→cc̄)	< 45	—	138 fb^{-1}
CMS cH→γγ	< 243 (355)	< 38.1 (72.5)	138 fb^{-1}
CMS cH→WW	< 1065 (506)	—	138 fb^{-1}
ATLAS cH→γγ	σ < 10.6 (8.8) pb	—	140 fb^{-1}

- **Best direct |κc| = 3.5** (CMS ttH+VH combo); ATLAS updated VH reaches 4.2
- Direct H→cc̄ still 8–28× SM; cH production probes κc via production (complementary)
- Multiple channels converging; HL-LHC + improved c-taggers essential for SM sensitivity

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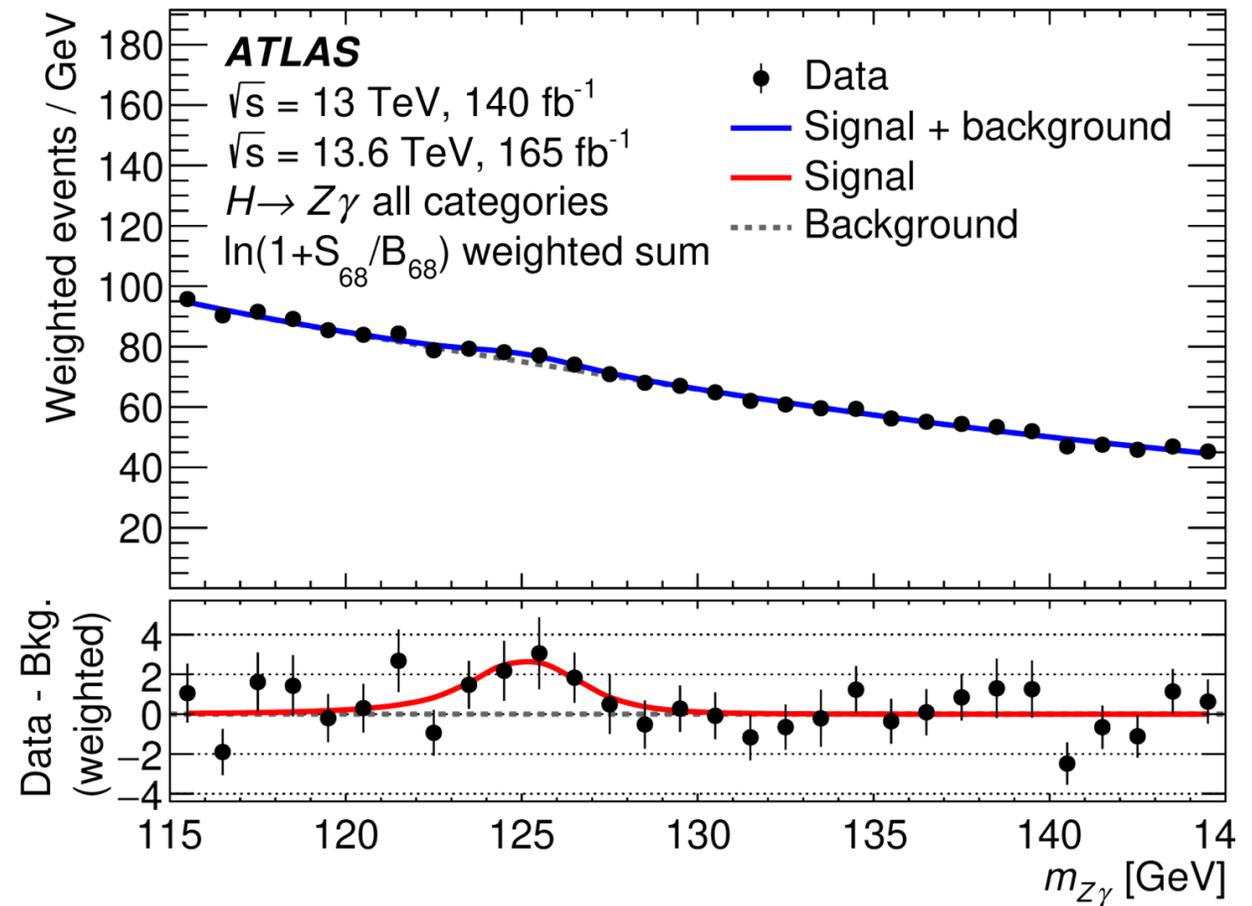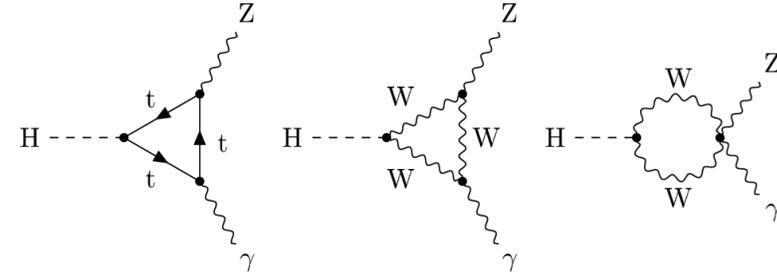- ~90% of branching ratio observed

~24 Millions of Higgs bosons at ATLAS & CMS each

- Expecting ~170 Millions by end of HL-LHC
- Enabling rare decay exploration
- Rare decay channels now accessible:
- $H \longrightarrow c\bar{c}$ (+ H+c associated production)
- $H \longrightarrow Z\gamma$
- $H \longrightarrow \mu\mu$
- γH
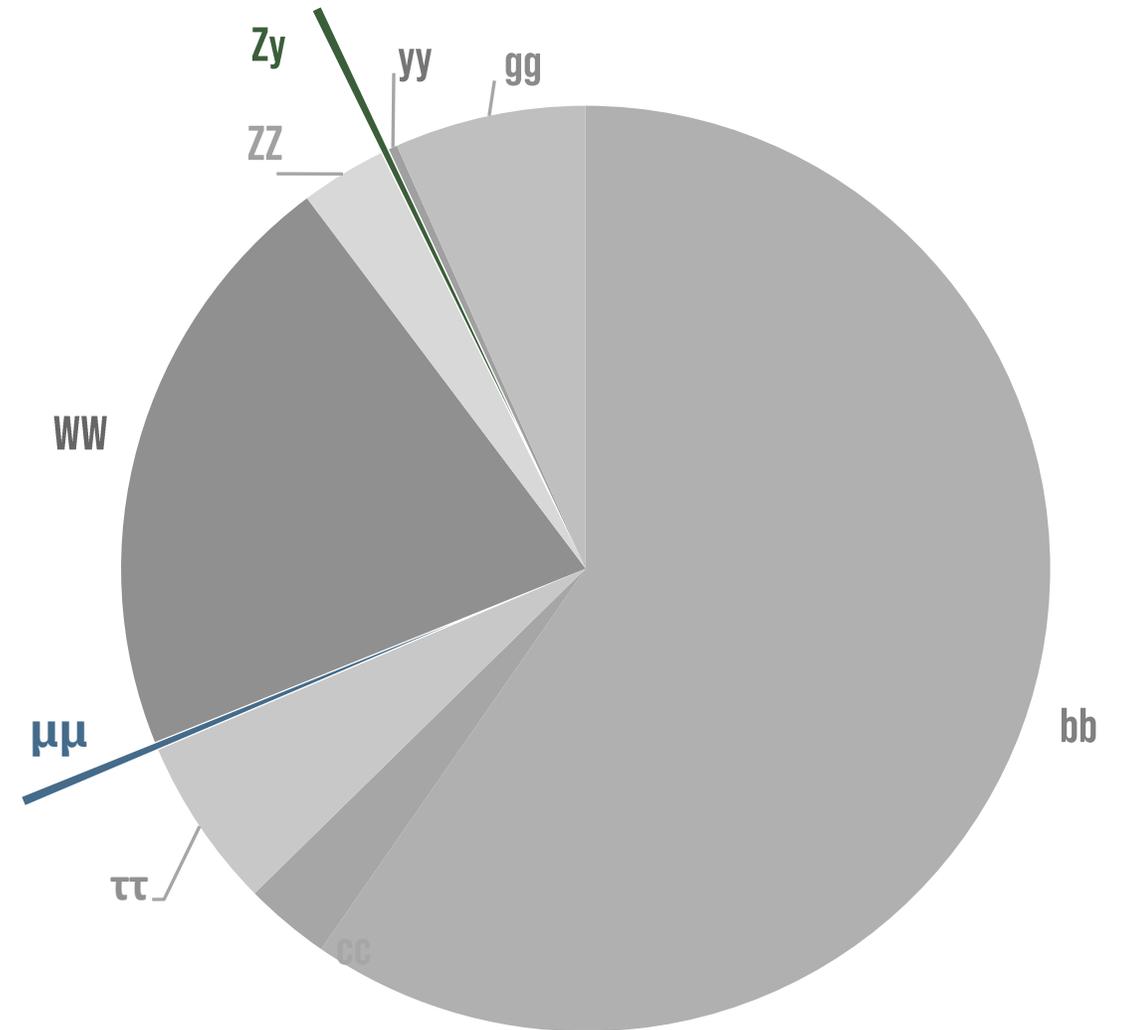
[ATLAS] H→Zγ (Run2 + Partial Run3 '22, '23, '24)

- Zγ is loop-induced
  - BSM-sensitive to new particles entering loop diagrams
    - Uniquely sensitive to composite Higgs models (1308.2676)

- BR = 0.154%
  - Z→ll (6.6%) limits rate.
    - Z → ee/μμ

- Key Strategy Elements:
  - 13 categories with XGBoost BDTs
    - Improvement over cut-based Run2 analysis
  - Z-mass kin fit improves $m_{Z\gamma}$ resolution
    - +17% electrons
    - +11% muons
 - p_T thresholds relaxed due to improved calibrations

[ATLAS] H→Zγ (Run2 + Partial Run3 '22, '23, '24)

- Run 3:
  - $\mu = 0.9^{+0.7}_{-0.6} \rightarrow$ 1.4σ (1.5σ exp.)
- **Combined w/ Run2:**
  - $\mu = 1.3^{+0.6}_{-0.5} \rightarrow$ **2.5σ (1.9σ exp.)**
  - Best single-experiment (until this week)
    - 19% over ATLAS+CMS Run 2
      - 3.4σ obs. due to excess in data (μ=2.2±0.7)

- Completing EW decay suite
  - (γγ ✓, ZZ* ✓, WW* ✓, Zγ → next)
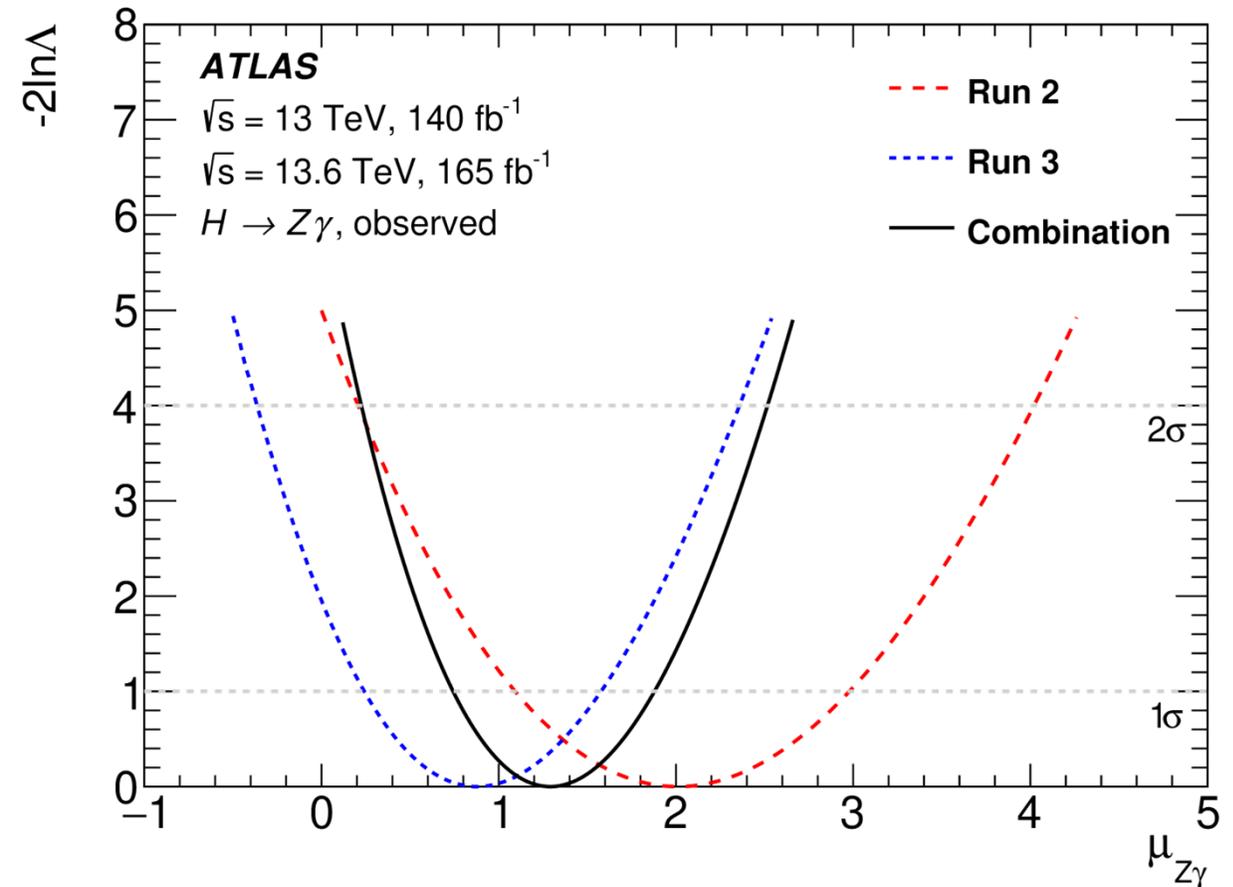
# [CMS] H→Zγ (Run2 + Partial Run3 '22, '23)

- Brand new result approved last week

- Key Strategy Elements:
  - Mass fit across 13 categories - all production modes
  - BDTs used for ggF and VBF categories – 4 each
    - ttH and VH categories are newly included
  - Z kin fit improves mass resolution
  - 10% improvement due to improved triggers

- Run2 reanalyzed with updated methods
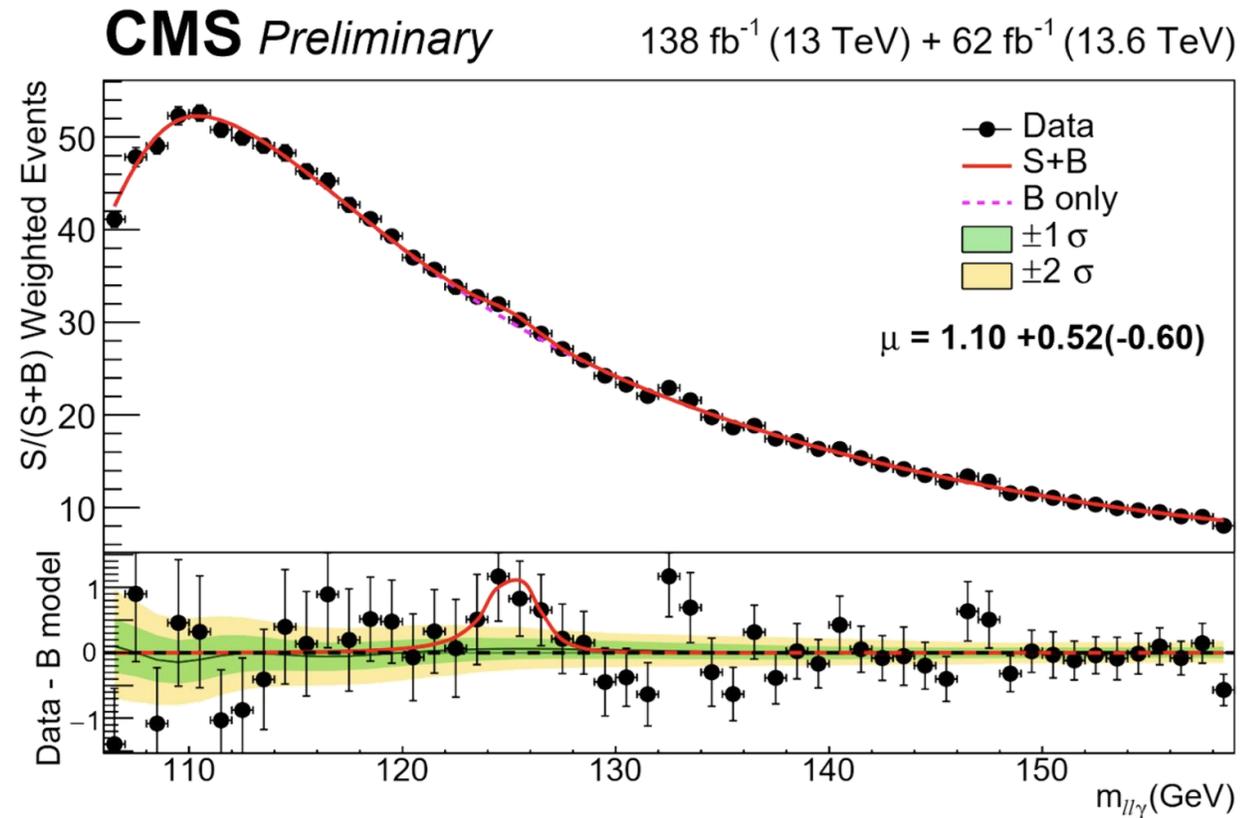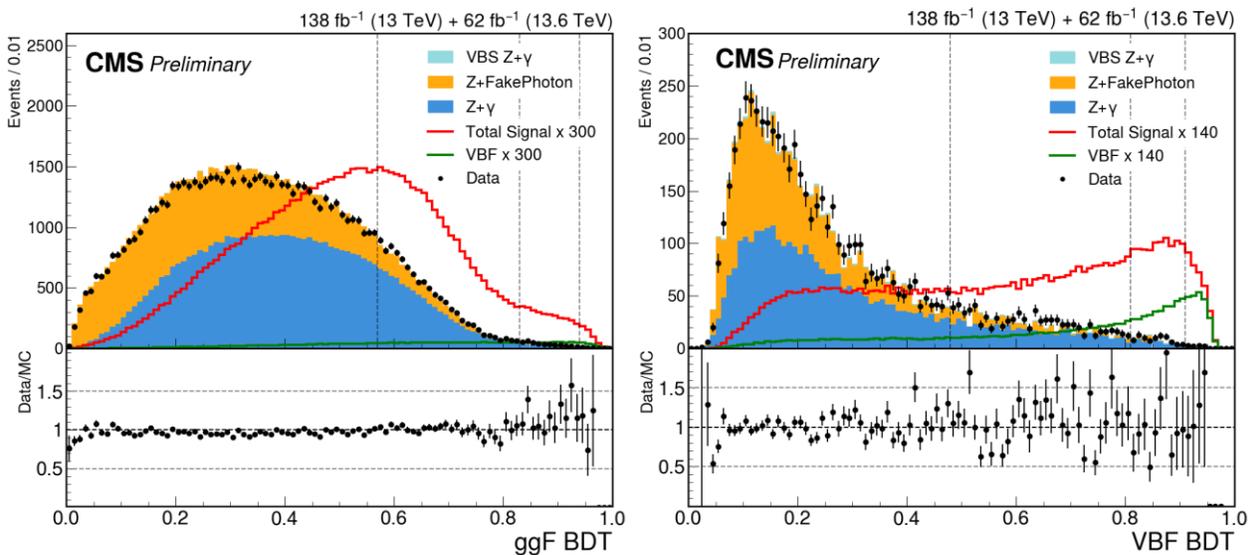
[CMS] H→Zγ (Run2 + Partial Run3 '22, '23)

Preliminary numbers:

- $\mu = 1.10^{+0.52}_{-0.61} \rightarrow 1.9\sigma$ (2.3σ exp.)
  - $1.00^{+0.49}_{-0.46}$ expected
  - Central value compatible with SM expectation
- Channel compatibility: p = 0.75
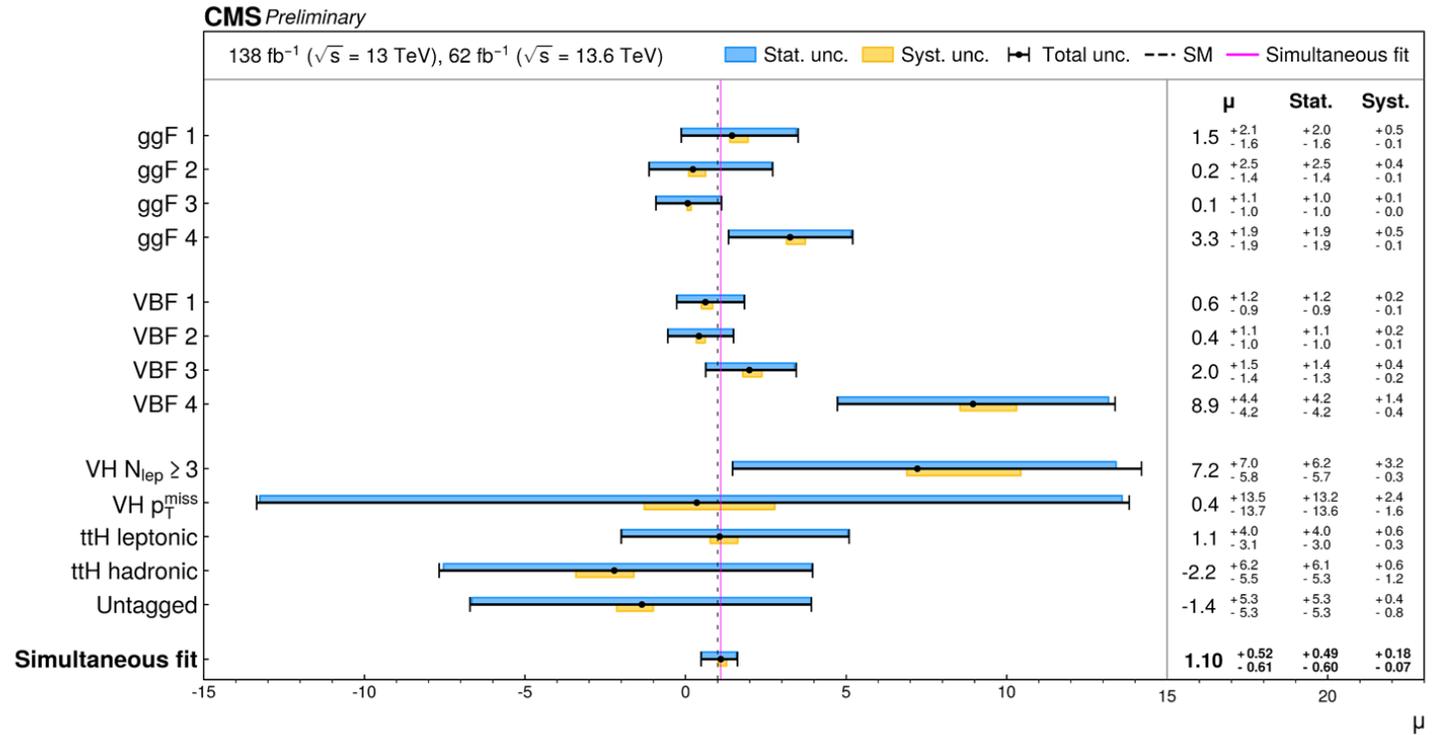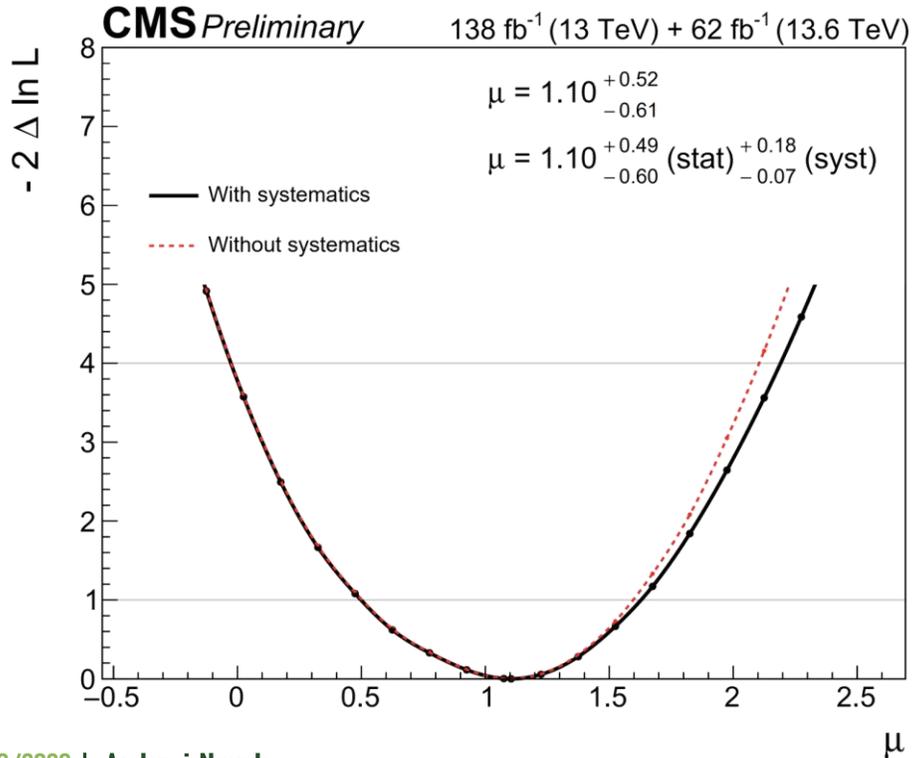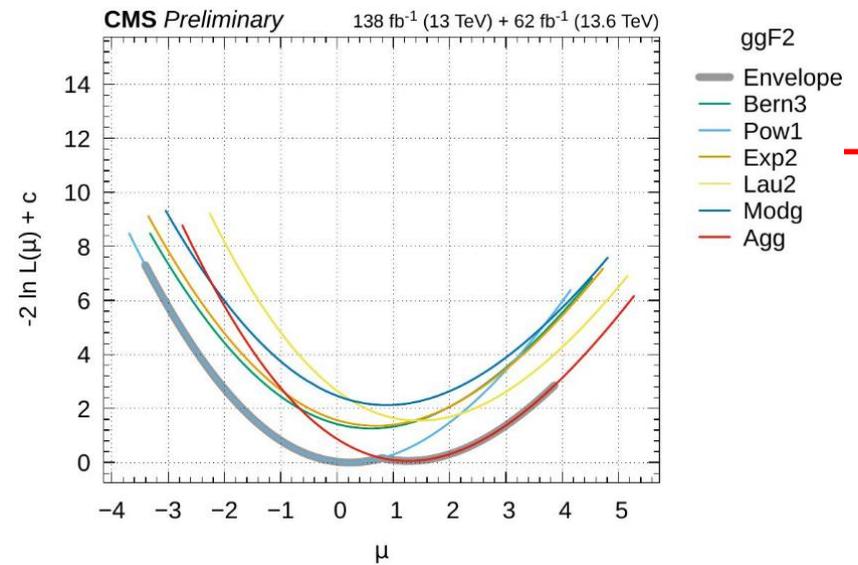
[ATLAS] H→µµ (Run3 '22, '23, '24, 165fb^{-1})

- H→µµ: **narrow resonance in m$_{µµ}$** atop DY (S/B~10^{-3}). BR=0.022%.

- 23 categories (ggF/VBF/VH/ttH), BDTs + NN. 5B NLO DY MC, vertex fit (+2% res.).

- Crystal Ball signal (σ≈2.8–3.2 GeV), bkg fits in m$_{µµ}$ in 110–160 GeV.
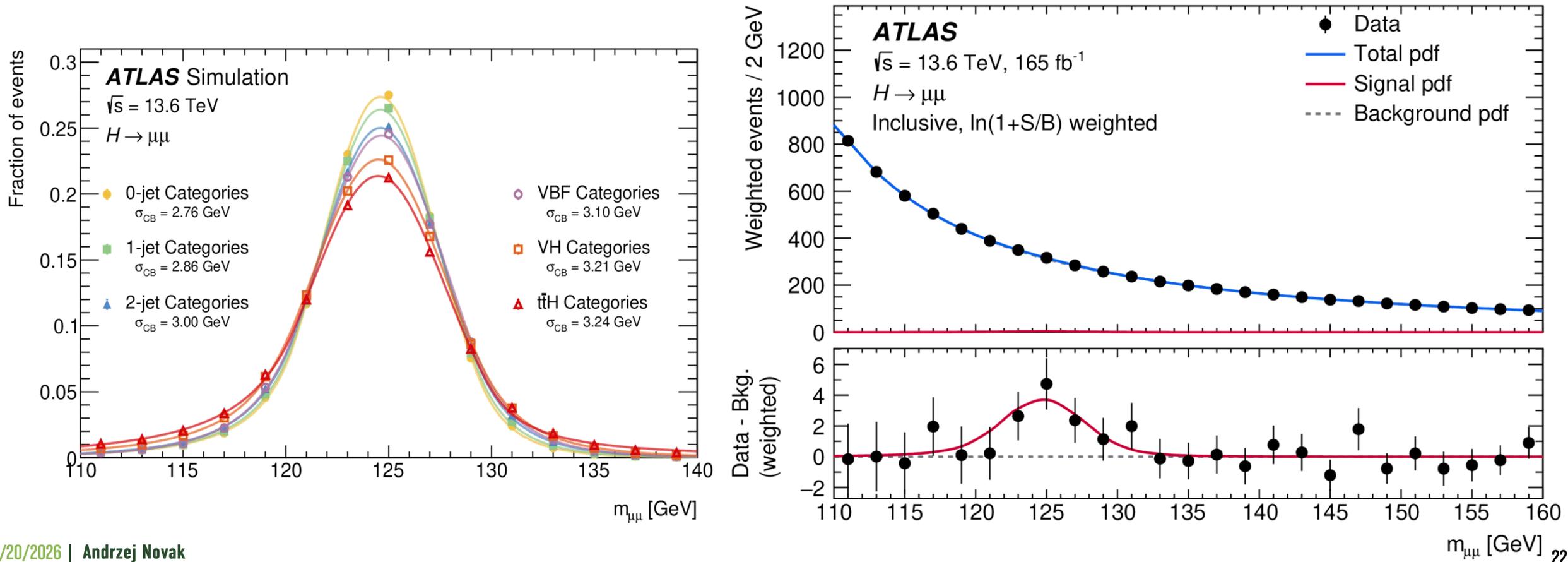
[ATLAS] H→μμ (Run2 + Run3 '22, '23, '24 – 205fb⁻¹)

- Run 3: μ=1.6±0.6, 2.8σ

- **Combined: μ=1.4±0.4, 3.4σ (2.5σ exp)** — first ATLAS evidence

- Direct 2nd-gen Yukawa; syst ~5% — stat-limited

- With CMS (3.0σ Run 2) → 5σ in reach with full Run 3

23
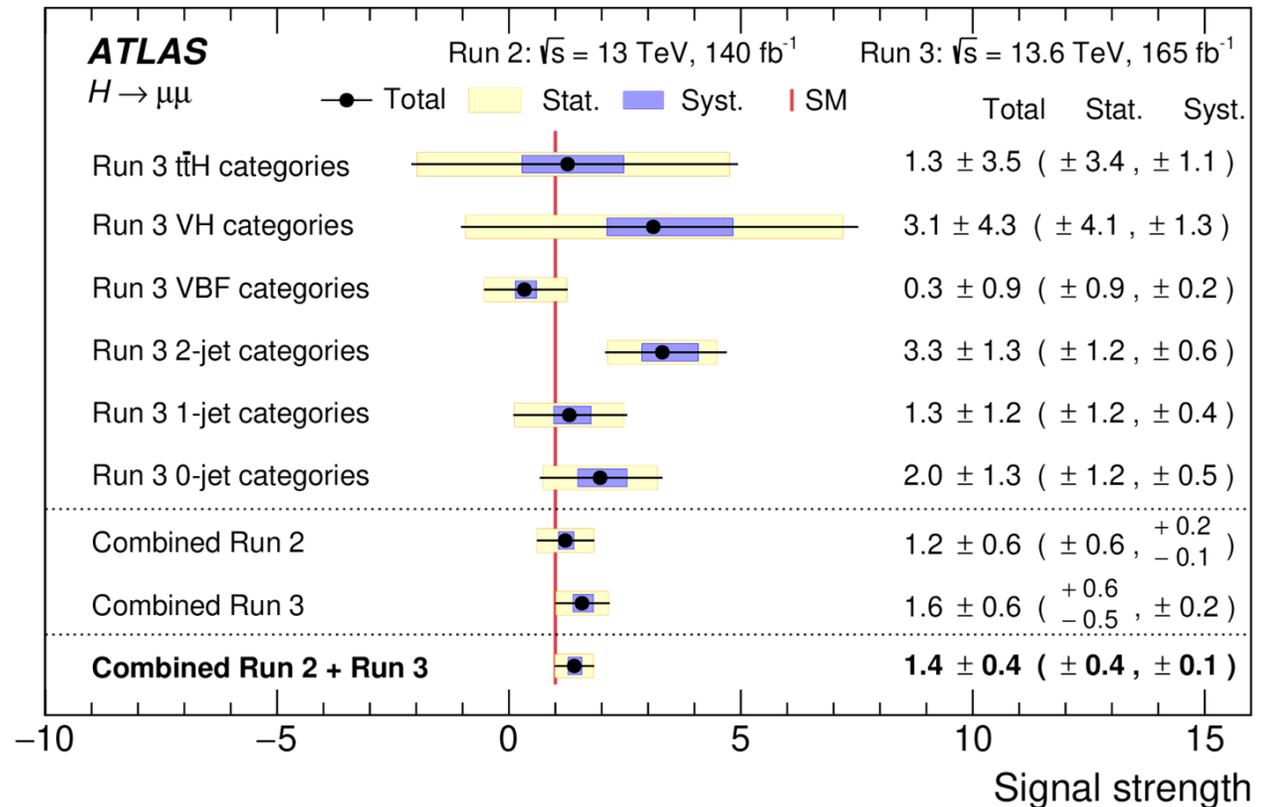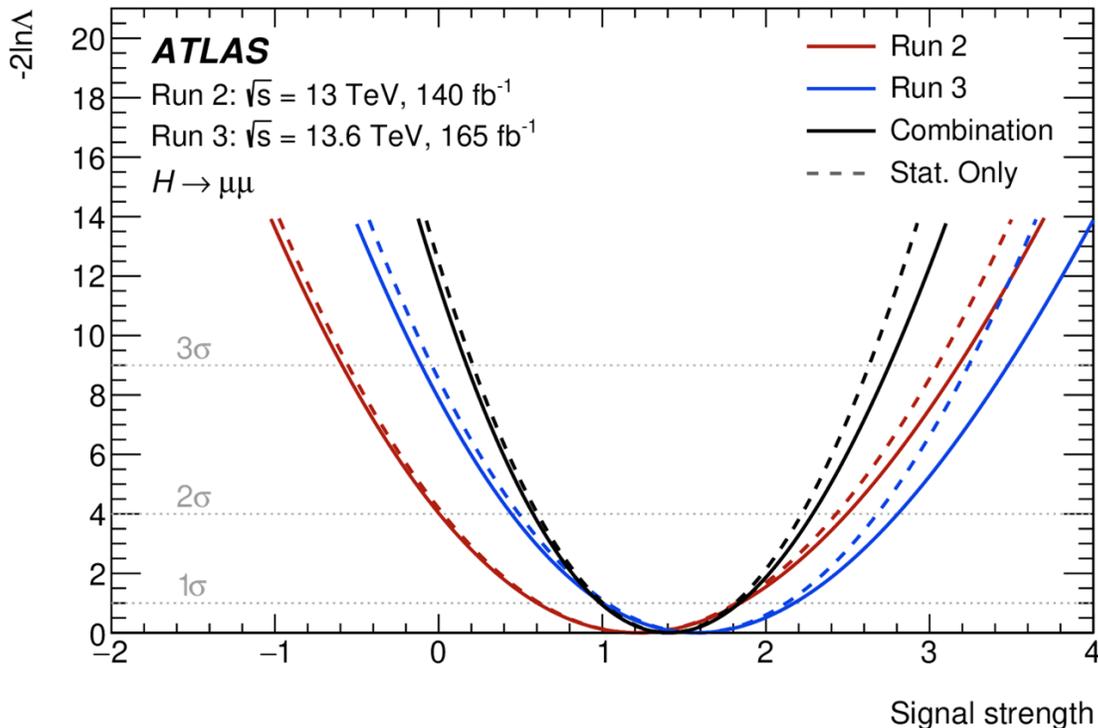
[CMS] γH + Light Quark Yukawas

- **Boosted Higgs recoiling against a high-energy photon (trigger)**
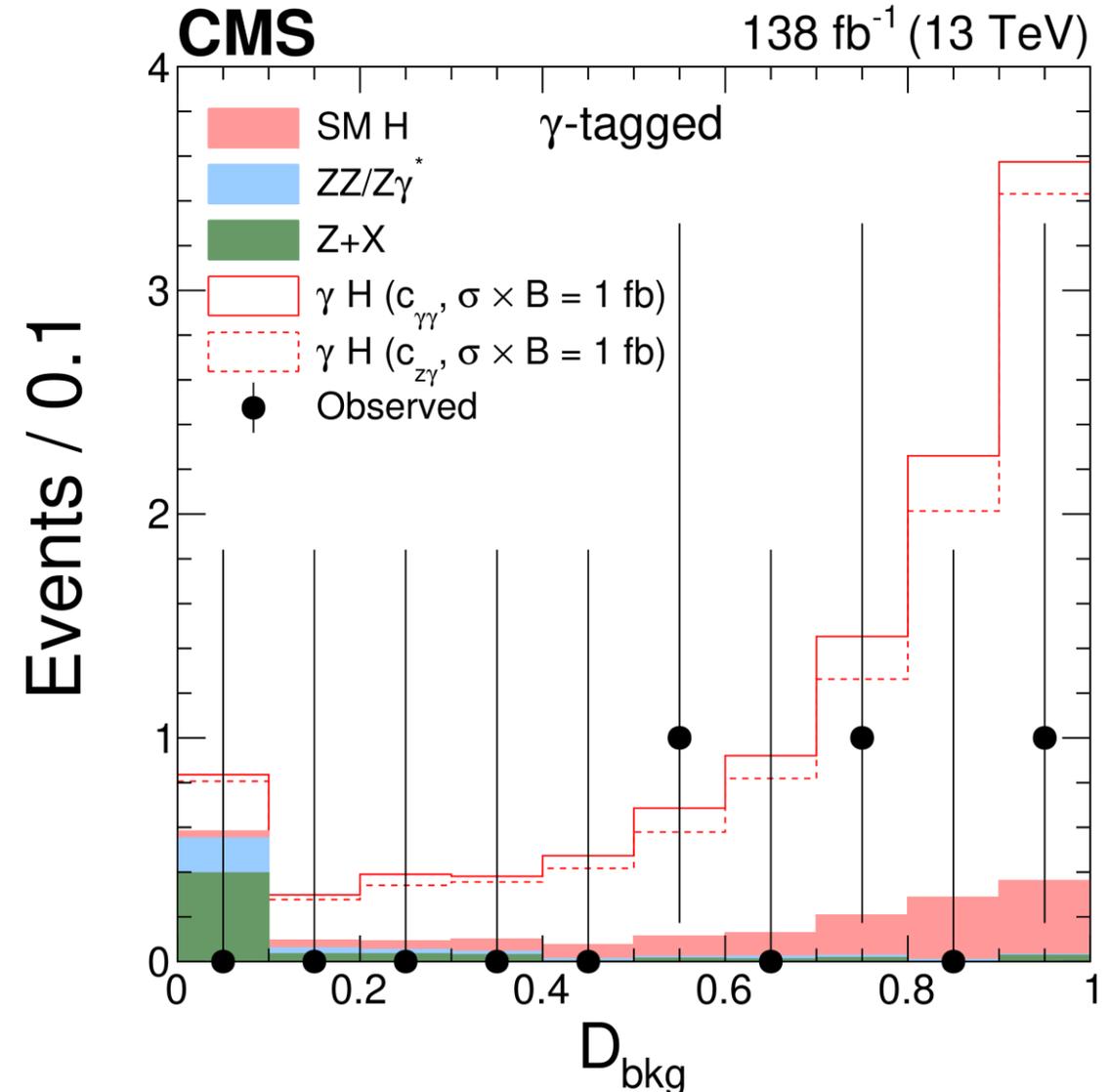 - $H \to bb$ (boosted, ParticleNet AK8, $p_T > 300$ GeV, mass-decorrelated)
  - $H \to 4l$ f(MELA). γ-tagged + Untagged.

- **Effectively two analyses:**

  1. γH to probe anomalous couplings

  2. Light-quark Yukawas via $H \to 4l$.
  - Enhanced κ_q boosts $q\bar{q} \to H$
  - Simultaneous 4-param fit.
  - ggF loop must be refit simultaneously.
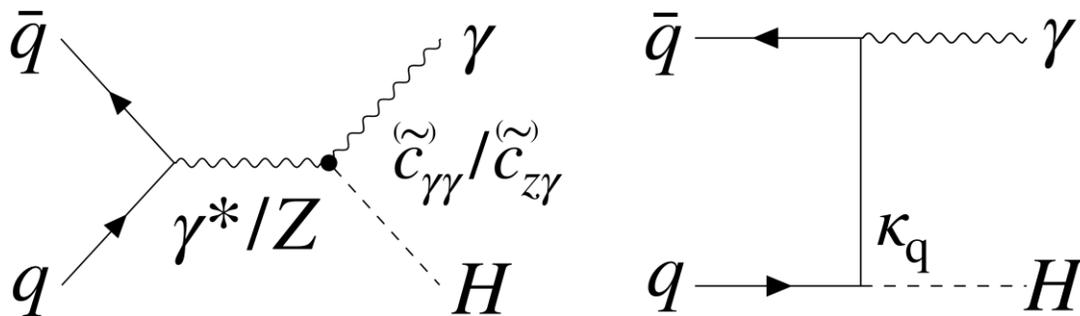
[CMS] γH + Light Quark Yukawas

- $\sigma_{\gamma H} < 16.4\ fb$
  - 4 anomalous HVγ couplings (CP-even/odd)
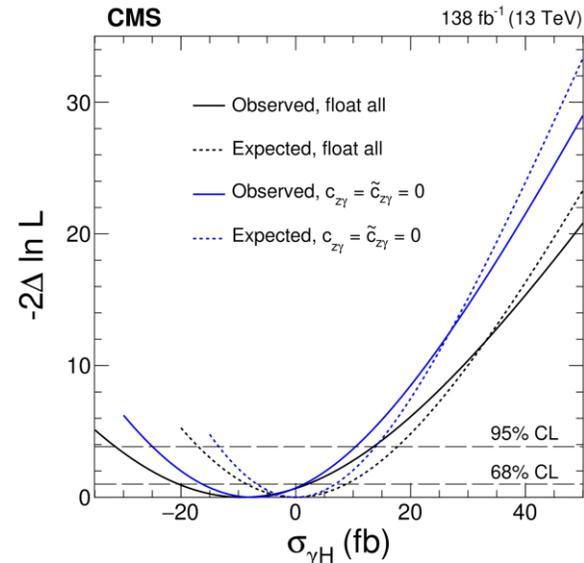
- $\kappa_u = (0 \pm 1.5) \times 10^3,$
- $\kappa_d = (0 \pm 6.8) \times 10^2,$
- $\kappa_s = 0 \pm 31$
- $\kappa_c = 0.0^{+2.3}_{-2.8}$
  - First simultaneous light-quark Yukawa constraints
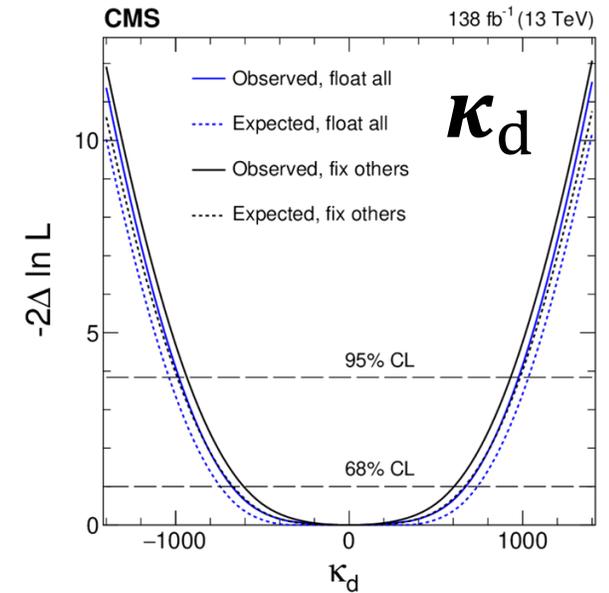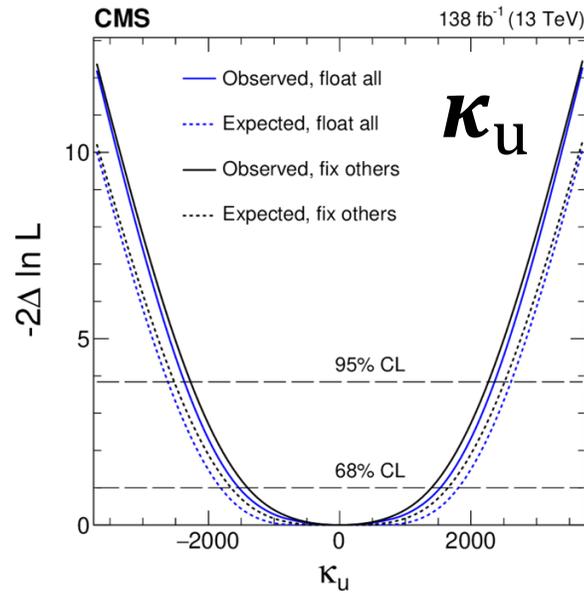
Summary

Charm Yukawa — Tightest constraints yet

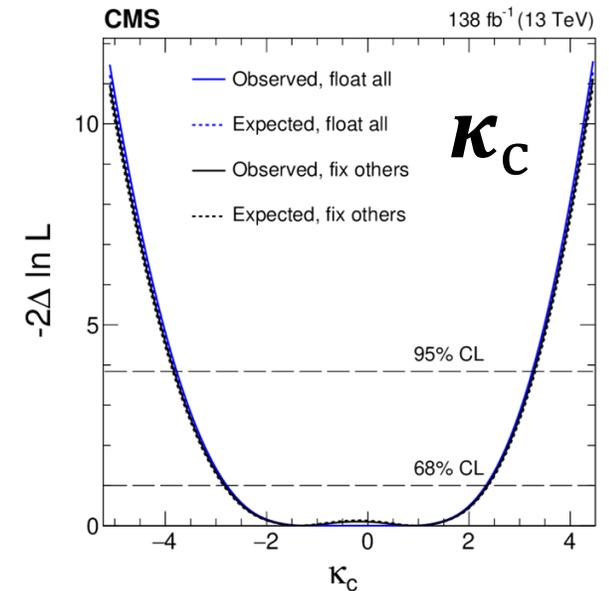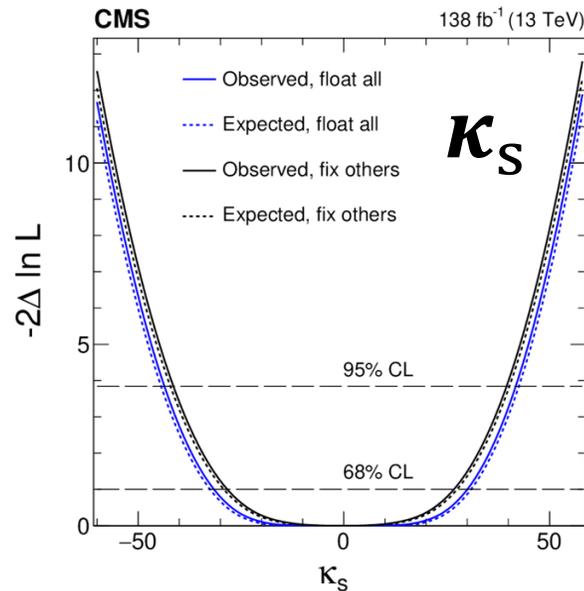▸ CMS ttH+VH sets $|\kappa c|$ < **3.5** (2.7 exp) — best to date. ATLAS VBF H$\rightarrow$bb first evidence at **3.2σ**

H$\rightarrow$μμ — Observation within reach

▸ ATLAS evidence at **3.4σ** (μ=1.4±0.4);

▸ CMS 3.0σ, Together with ATLAS 5σ liekly with full Run 3

H$\rightarrow$Zγ — EW decay suite nearing completion

▸ ATLAS combined **2.5σ** (μ=1.3)

▸ CMS combined **1.9σ** (μ=1.1)

Light quarks — First simultaneous multi-coupling constraints

▸ CMS: simultaneous κ_u, κ_d, κ_s, κ_c. Rules out 1st/2nd-gen = 3rd-gen at **>95% CL**

Thank You

Classifier – Jet Tagging

- FCNN - DeepCSV ~2016
- CNN->RNN->FCN – DeepDoubleX (1) ~2017
- GNN - ParticleNet (2) ~ 2019
- Transformer – ParT (3) ~2022

(1)

(2)

(3)

CMS *Simulation Preliminary* (13 TeV)

$H \to b\bar{b}$ vs QCD

$450 < p_T < 600$ GeV, $|\eta| < 2.4$

$90 < m_{SD} < 140$ GeV

Background efficiency vs Signal efficiency

7‰
2‰
1‰

- ParticleNet-MD bbvsQCD
- DeepDoubleBvL
- DeepAK8-MD bbvsQCD
- double-b
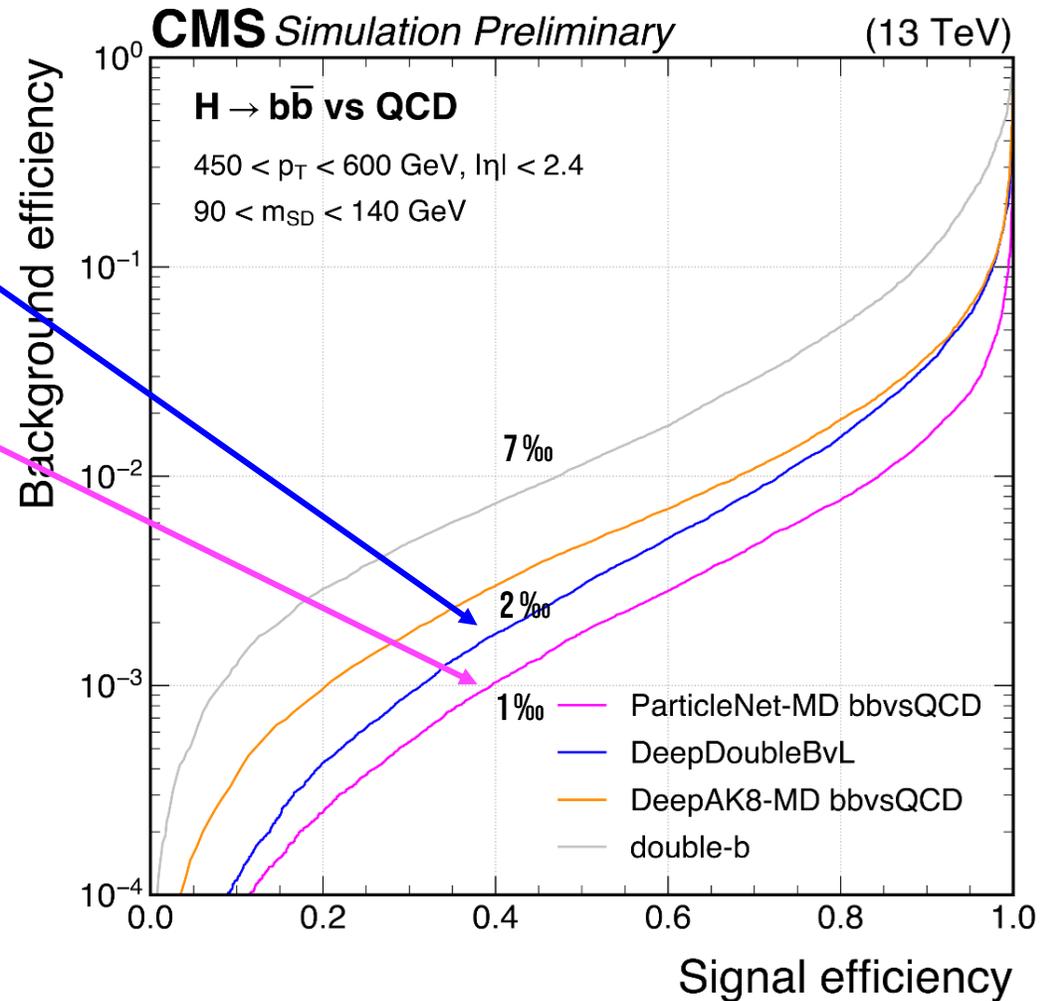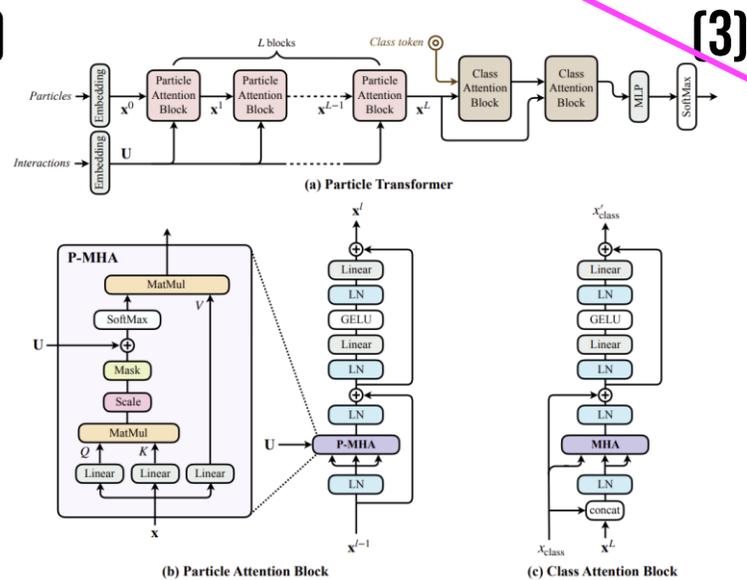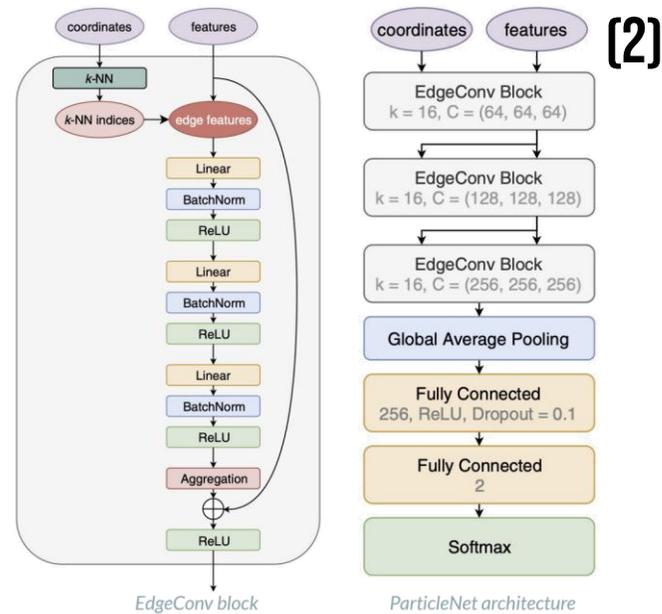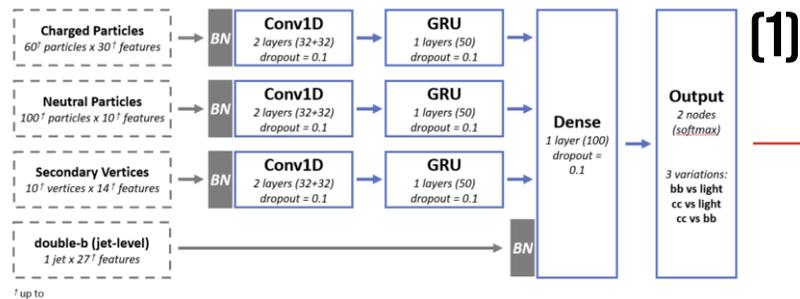
Classifier – Jet Tagging Calibration

- **No pure bb/cc signal region to calibrate on**
- Use **g → bb/cc** as a **proxy** (not entirely signal-like)
- Two ways of "forcing" a good proxy – compatible results
  - Use **soft-muon** presence to select Higgs-like cc jets
  - Train a **BDT** to select Higgs-like cc jet

Effects of the BDT

g→cc (all)
g→cc (sfBDT>0.85)
g→cc (sfBDT>0.90)
g→cc (sfBDT>0.95)
H→cc

cc discriminant

CMS *Preliminary*   59.74 fb^{-1} (13 TeV)

Pre-fit (pass)

MC (flvC)
MC (flvB)
MC (flvL)
BKG total unce.
Data

Events / bin

Data / MC

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jets from QCD multijet events

g
g
g
$b(c)$
$\bar{b}(\bar{c})$

sfBDT selection

proxy jets

$b(c)$
$\bar{b}(\bar{c})$
g

similar characteristics

signal jets

$b(c)$
$\bar{b}(\bar{c})$
H