Top quark and friends

DPG Spring Meeting
03.04.2025

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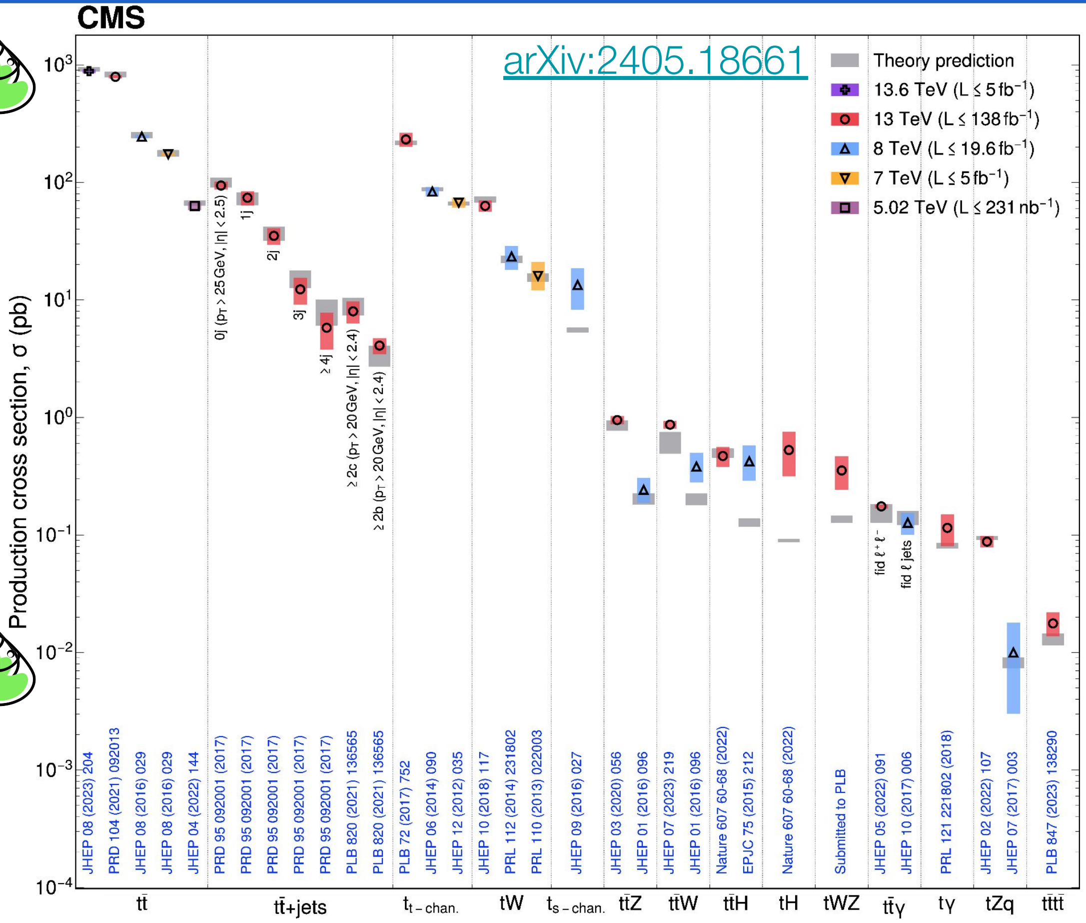
Top physics at the LHC



~100M events in Run 2

Physics program at ~5 orders of magnitude

~1000 events in Run 2

Friends of the top quark

1.

Top quarks and photons

CMS-TOP-PAS-23-002

2.

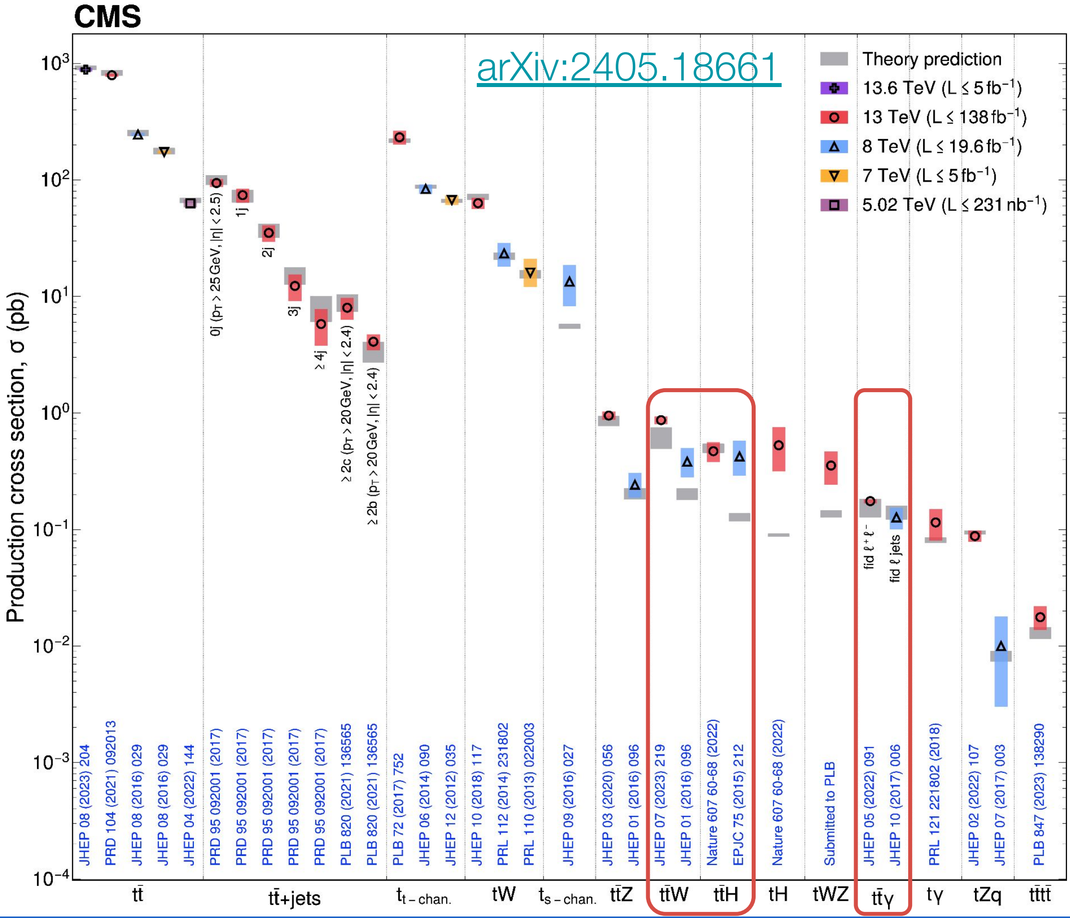
Top quarks and W bosons

CMS-TOP-PAS-24-003

3.

Top quarks, Higgs bosons and charm/bottom quarks

CMS-HIG-PAS-24-018



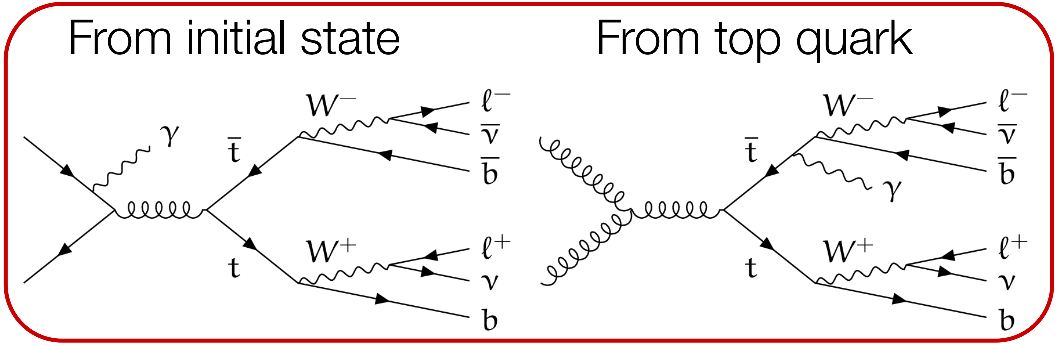
$tt + \gamma$

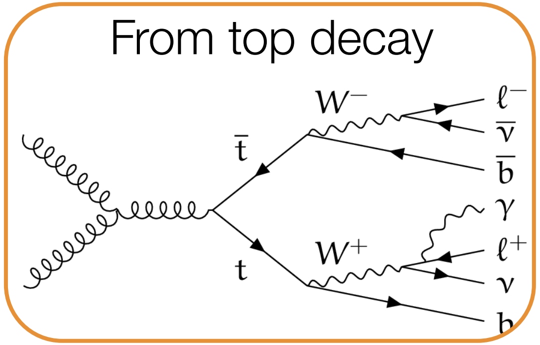
Why tt+ γ?

CMS-TOP-PAS-23-002

Photon origin?

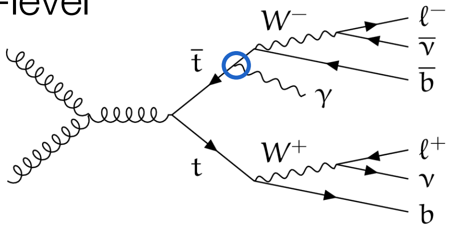
- Many options where γ can come from
  → Is this well described in simulation?
  - Photon from production
    (2→3 process)
  - Photon from decay
    (2→2→7 process or description via parton shower)





Top-γ coupling?

- Modifications from BSM physics processes?
  → Access to coupling (modification) at tree-level



→ tt+γ measurements possible at high precision
→ Very sensitive to possible modifications

Inclusive cross section of tt+ γ

Measurement of inclusive fiducial cross section in 2ℓ channel

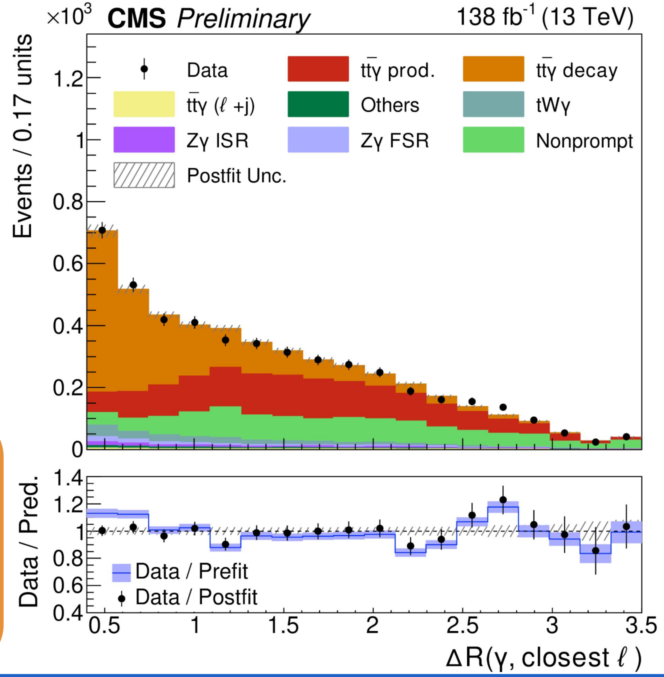
→ Good separation of photon origin via angle to closest lepton (ΔR(ℓ,γ))

→ Measure combined (production+decay) and separate (production) cross sections

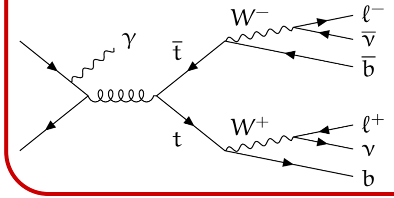
σ(tt+γ tot.) = 134 ± 3 (stat) ± 7 (syst) fb (5%)

σ(tt+γ prod.) = 54 ± 2 (stat) ± 4 (syst) fb (8%)

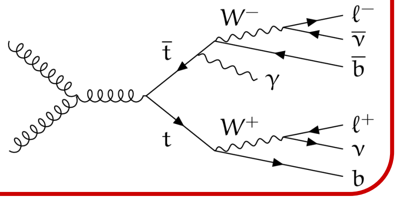
(Agreement with prediction from simulation)



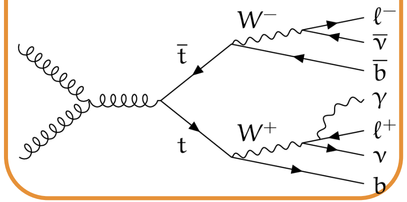
From initial state



From top quark



From top decay



Differential cross sections

CMS-TOP-PAS-23-002

Until now: only differential cross sections of γ kinematics

New: Probing the tt system in tt+γ

Differential cross sections

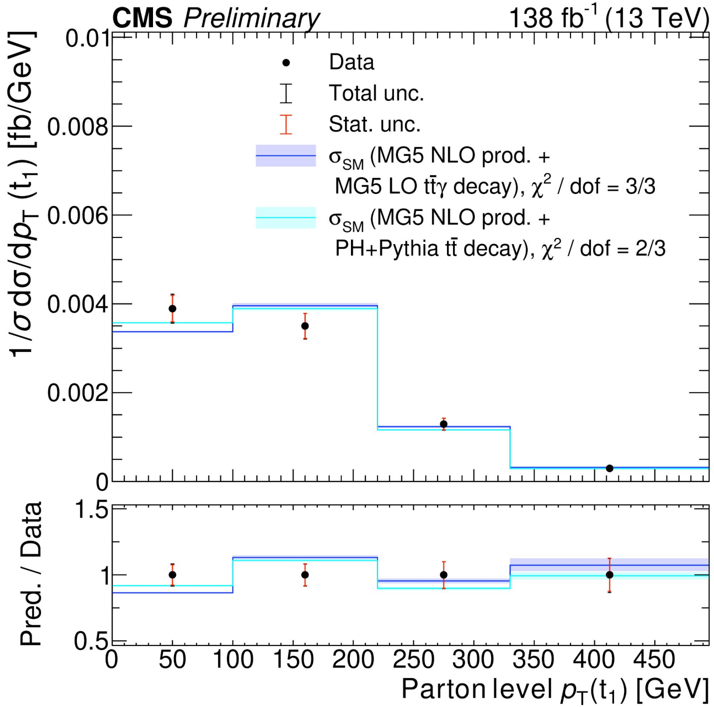
Until now: only differential cross sections of **γ** kinematics

New: Probing the tt system in tt+γ

→ **Same behaviour as in tt?**

→ Top quark momentum modelled well

→ No indications (yet) of mis-modeling observed in tt



Differential cross sections

CMS-TOP-PAS-23-002

Until now: only differential cross sections of γ kinematics

New: Probing the tt system in tt+γ

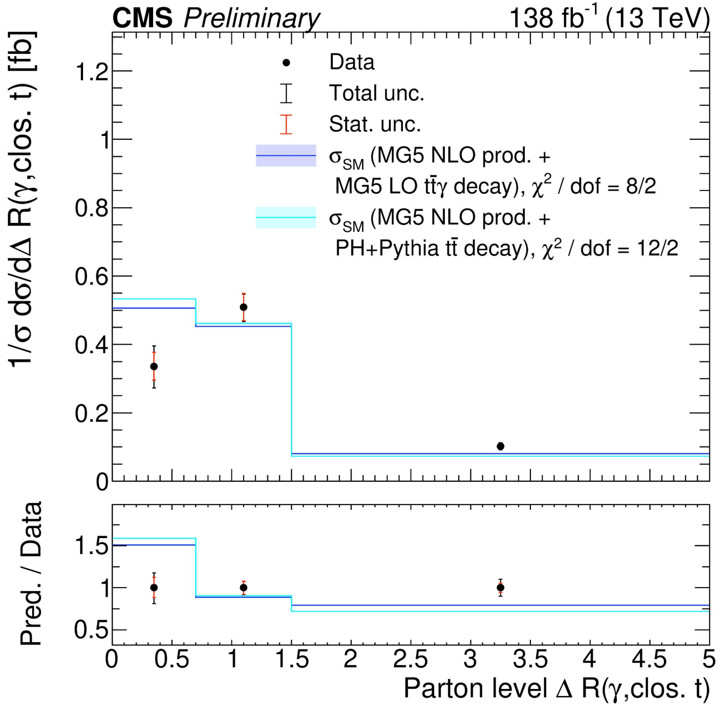
→ Same behaviour as in tt?

→ Top quark momentum modelled well

→ No indications (yet) of mis-modeling observed in tt

→ **Modeling of top-γ system?**

→ Angular distributions tend to have some discrepancies



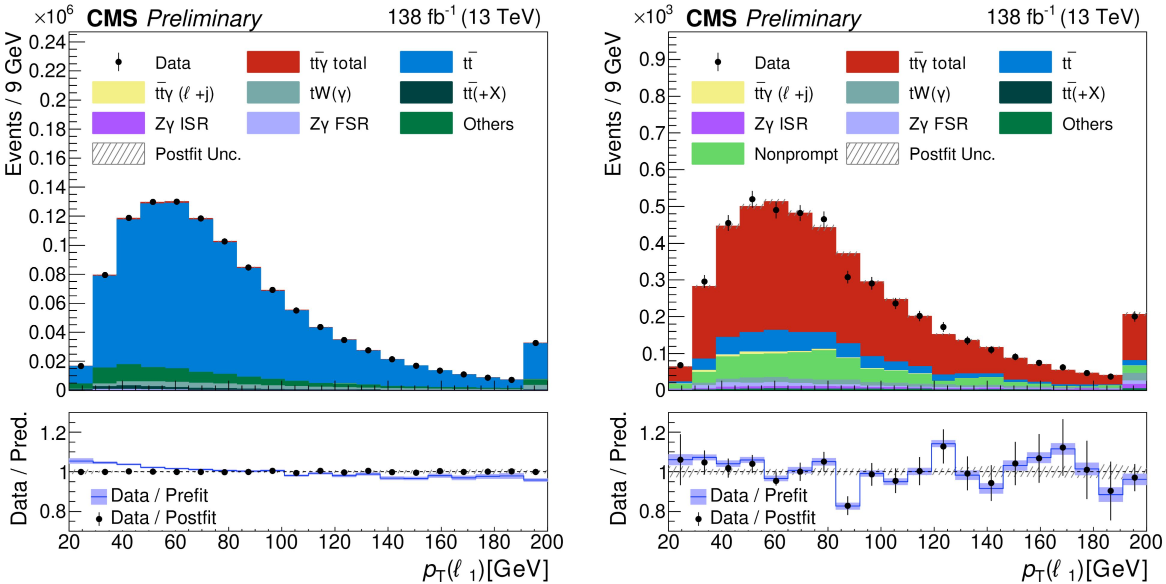
Ratio to tt production

First measurement of tt+γ / tt ratios

→ Sensitive to possible BSM modifications – many systematics cancel in ratio

tt cross section with 2% uncertainty as side product

Inclusive ratio: R(ttγ/(tt+ttγ)) = (1.25 ± 0.05) %

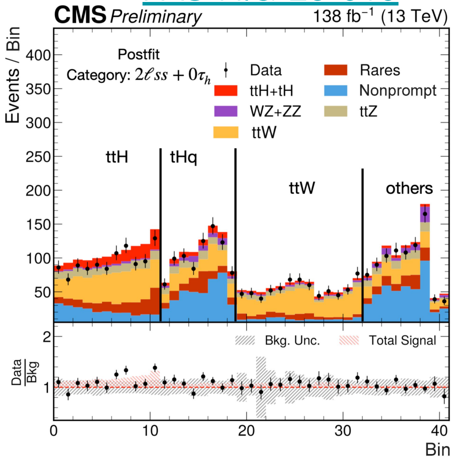


Also differentially as function of lepton / top quark: compatible with SM tt+W

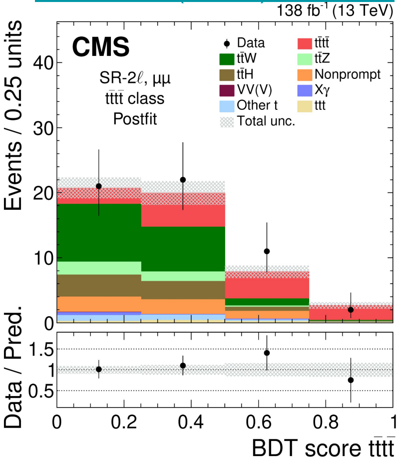
Why ttW?

- **As an important background**
  → tttt or ttH(multilepton) measurements
  → Limited by overwhelming ttW backgrounds

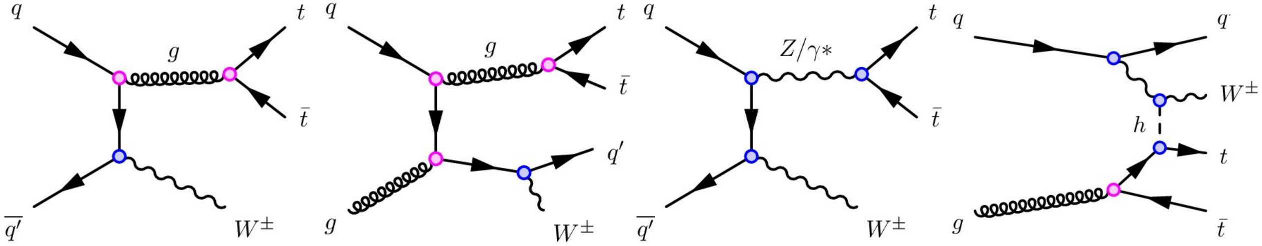
PAS-HIG-23-015

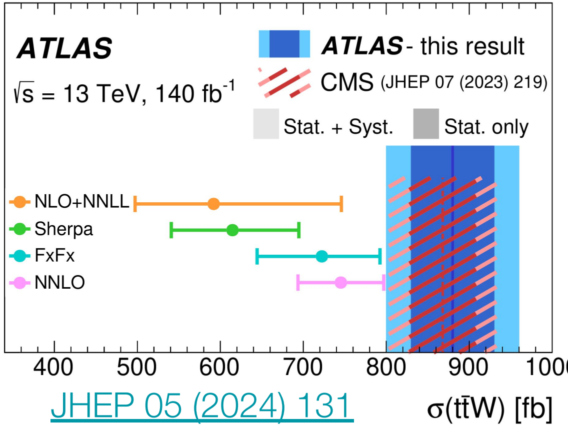


PLB 847 (2023) 138290



- **Difficult modeling**
  → Many contributing propagators (QCD / EW)





JHEP 05 (2024) 131

- **Discrepancy between predictions and measurements?**
  → Measurements ~2 std. dev. higher than all predictions

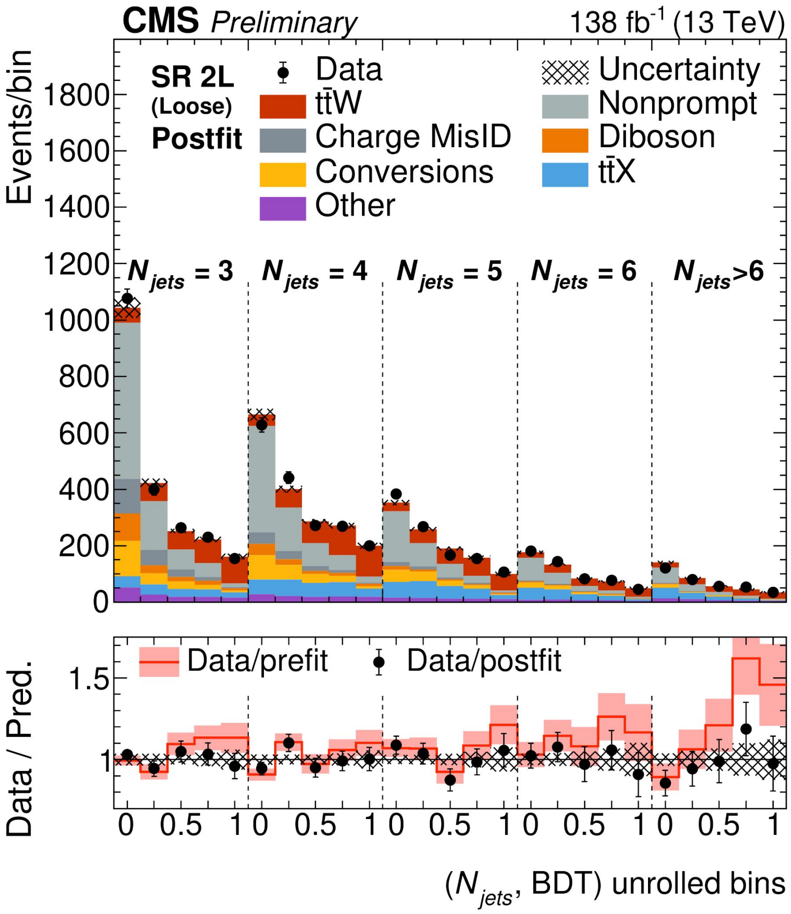
Scope of new CMS measurement

- **First differential ttW cross sections by CMS**
  → Insights into process modeling
  → Any discrepancies? Disagreement only inclusive?

  (ATLAS published first diff. XS already last year JHEP 05 (2024) 131)

- **Two complementary methods in one paper**
  - **Counting strategy:** focused on purity
    → tight selections, no MVA
  - **MVA strategy:** focused on signal acceptance
    → loose selection, MVA for signal/background sep.

⇒ Valuable cross-validation of measurement strategies



Results

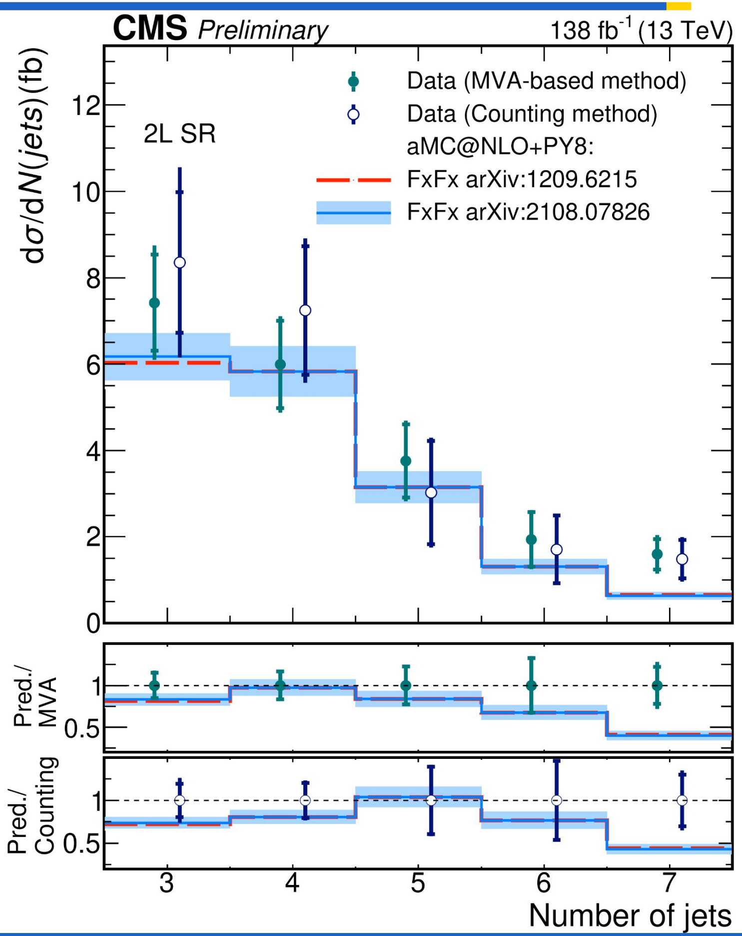
CMS-TOP-PAS-24-003

What kind of observables are measured?

Results

What kind of observables are measured?

- Things important for background measurements
  → High H_T / **jet multiplicity**
  → Underprediction at high jet multiplicity



Results

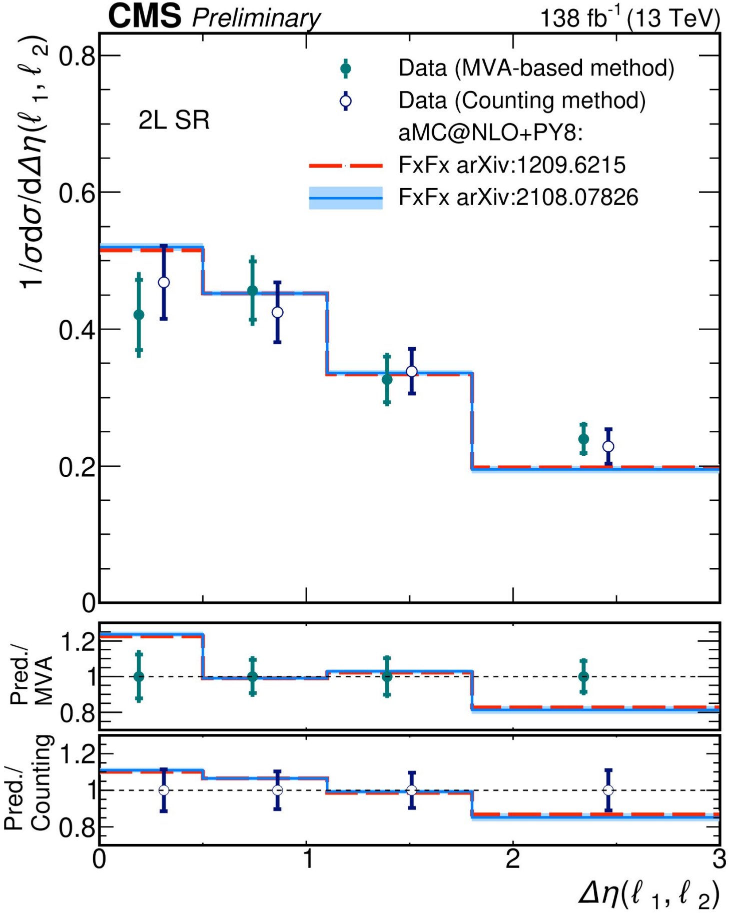
CMS-TOP-PAS-24-003

What kind of observables are measured?

- Things important for background measurements
  → High H_T / jet multiplicity
  → Underprediction at high jet multiplicity

- General ttW modeling
  → Jet, lepton kinematics, etc

  Example: **Top and W decay lepton angle**
  → Indications of small trend in data w.r.t. modeling



tt+H(bb/cc)

Best friend of Higgs boson: Top quark

One of the next milestones in Higgs physics:

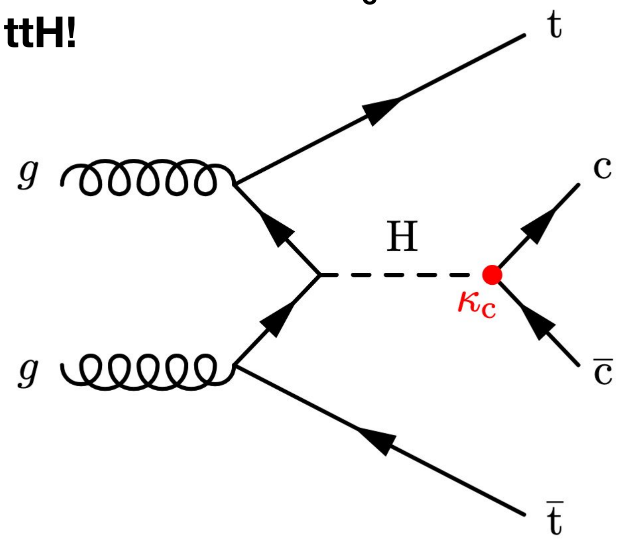
Measurement of Higgs charm coupling

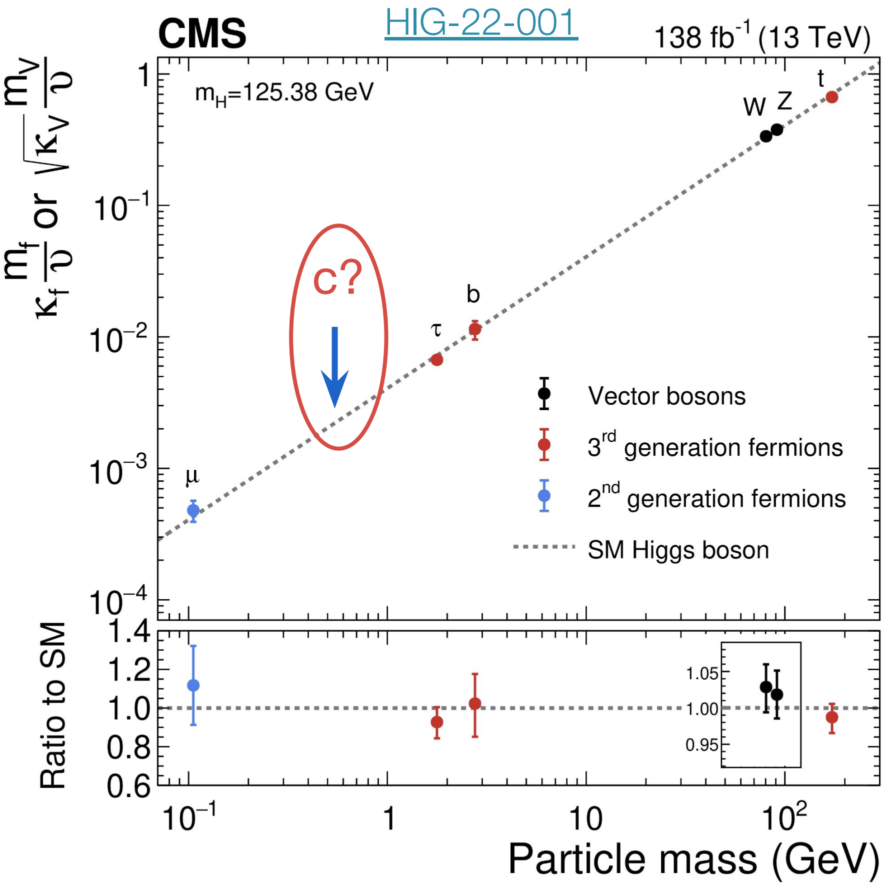
→ Probe Higgs couplings in all possible ways

Many channels already exploited

Best limits so far by VH(cc): $\kappa_c \lesssim$ 3–4 x SM

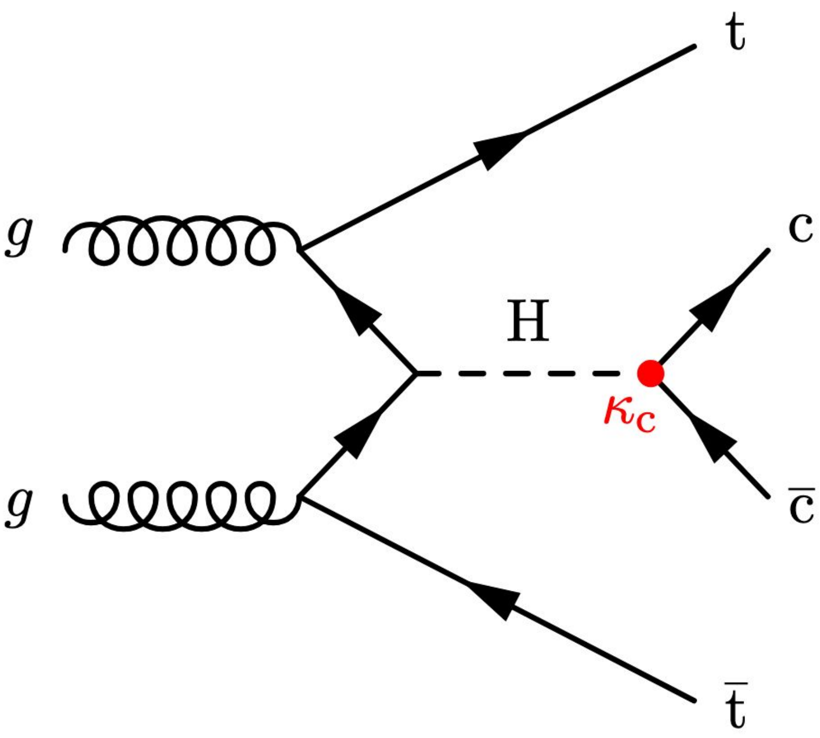
→ now also ttH!



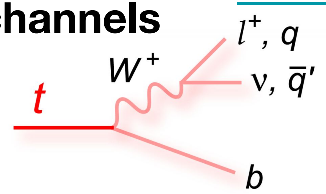


CMS-HIG-PAS-24-018

Analysis scope:



All three tt decay channels
→ 0L / 1L / 2L



Resolved Higgs boson final state
→ Two AK4 c jets

Full Run 2 data set
→ ~2000 ttH(cc) events expected
~63 expected in our measurement
(→ 3% selection eff.)

Simultaneous measurement of ttH(bb)
→ Cross section ~x30 higher than ttH(cc)
(basically same final state)
→ Impossible to ignore

Challenge #1 – jet flavor tagging

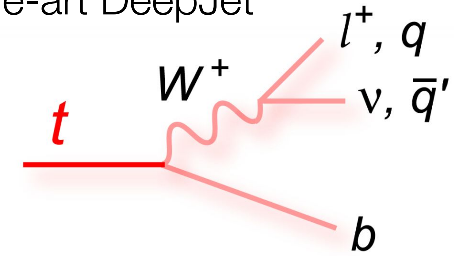
CMS-HIG-PAS-24-018

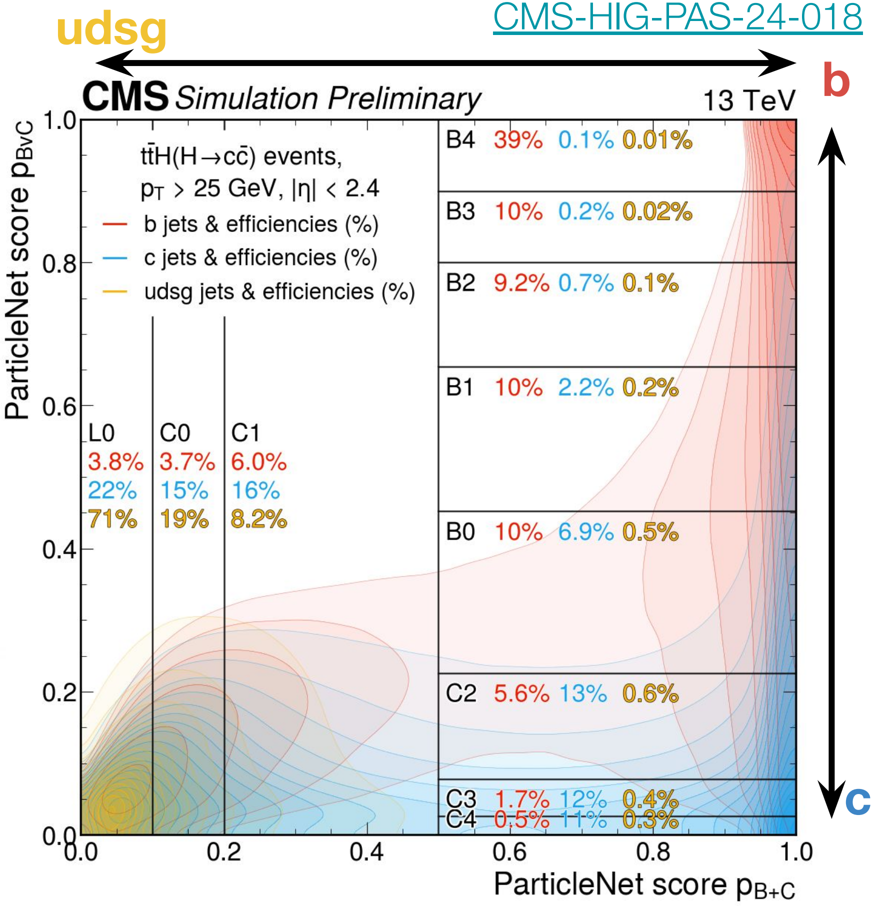
- **Multiple b/c jets in final state**
  → b jets from top, c/b jets from Higgs,
  u/d/s/c from W→qq')
  → Simultaneous b and c jet identification

  → Custom b/c tagging with particleNet tagger

  → High purity individually in each jet flavor

~2x improvement in background rejection compared to Run 2 state-of-the-art DeepJet





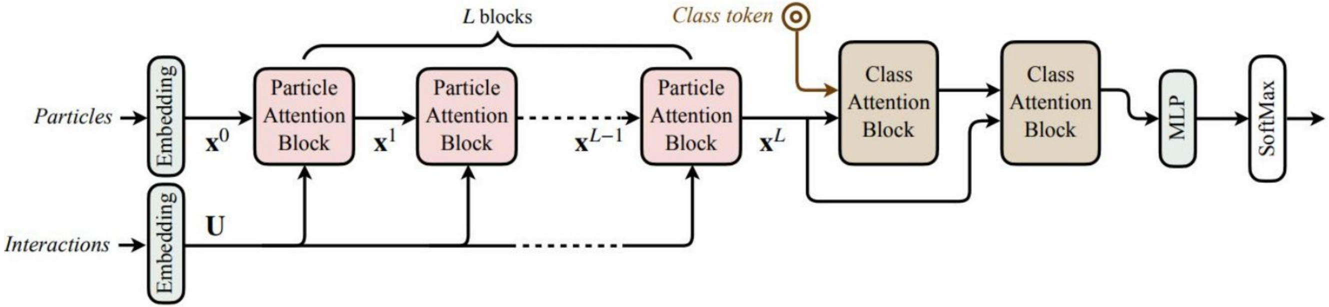
Challenge #2 – event reconstruction / classification

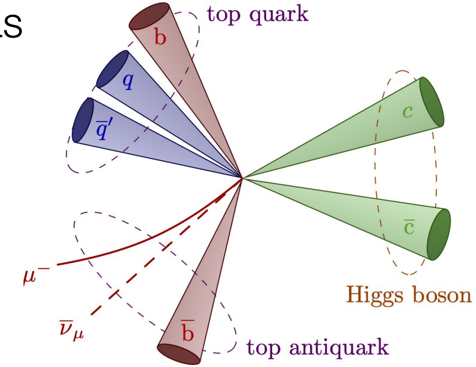
CMS-HIG-PAS-24-018

- **The challenge**
  - tt+bb/cc has the same signature as tt+H/Z→bb/cc
  - Too many jets to reconstruct Higgs bosons efficiently
  - Kinematics overall too similar to make “simple” cuts

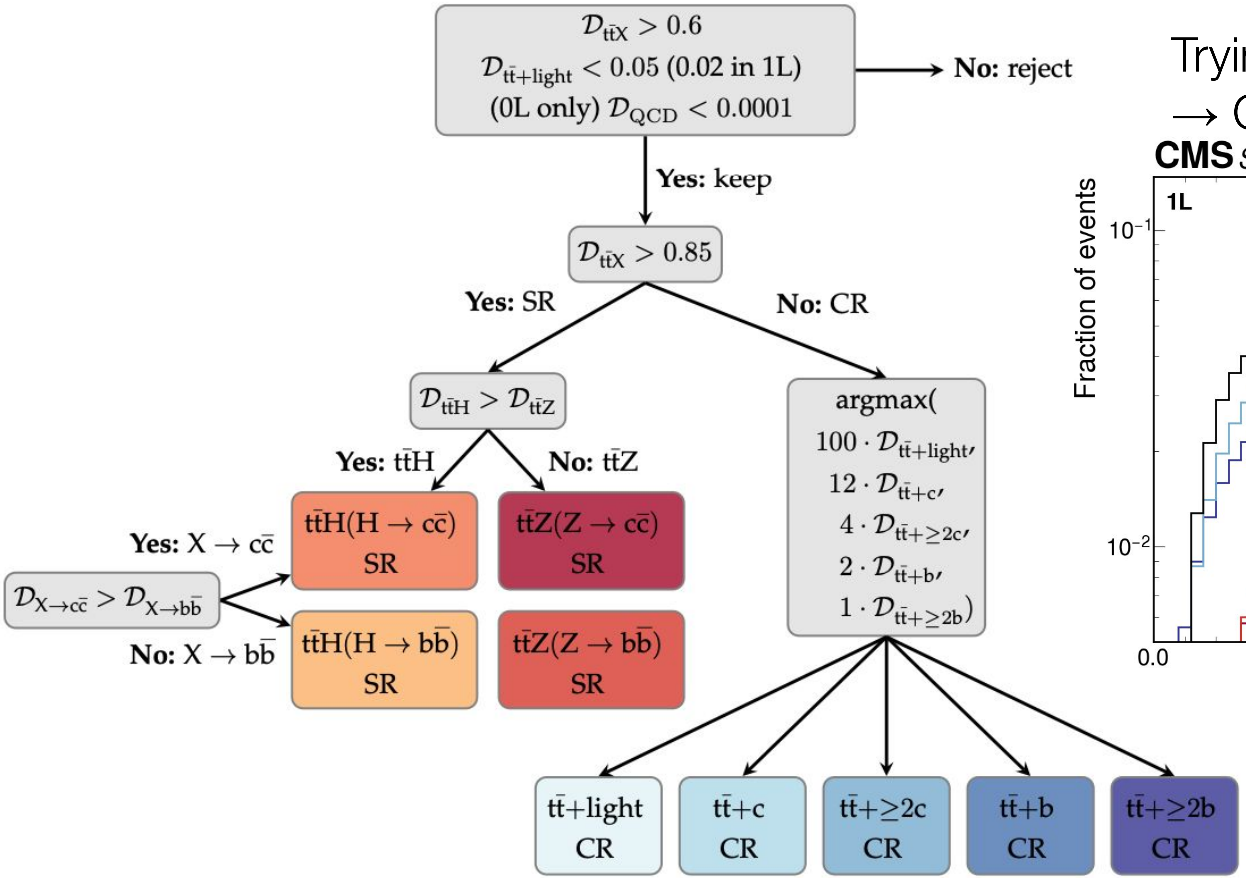
$$
\begin{aligned}
\Delta &= \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2},\\
k_\mathrm{T} &= \min(p_{\mathrm{T},a}, p_{\mathrm{T},b})\Delta,\\
z &= \min(p_{\mathrm{T},a}, p_{\mathrm{T},b})/(p_{\mathrm{T},a} + p_{\mathrm{T},b}),\\
m^2 &= (E_a + E_b)^2 - \|\mathbf{p}_a + \mathbf{p}_b\|^2,
\end{aligned}
$$

- **The solution –** *PMLR 162:18281-18292, 2022*
  - State-of-the-art machine learning (**ParticleTransformer** architecture)
  - Adapted to event classification (using jets / leptons / MET as points in particle clouds)
  - **Input features:** ln(p_T), ln(E), η, flavor tagging bins
  - **Pairwise connections:** distance, momentum balance, invariant mas

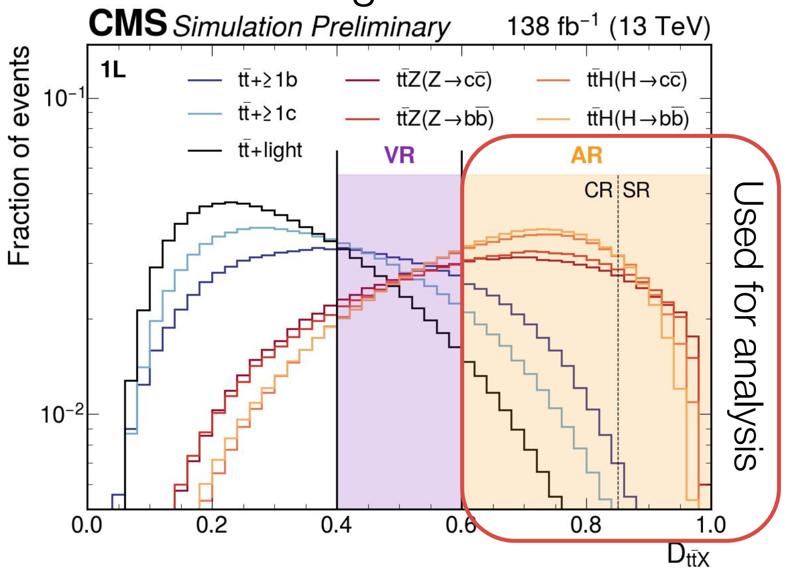




Challenge #2 – event reconstruction / classification



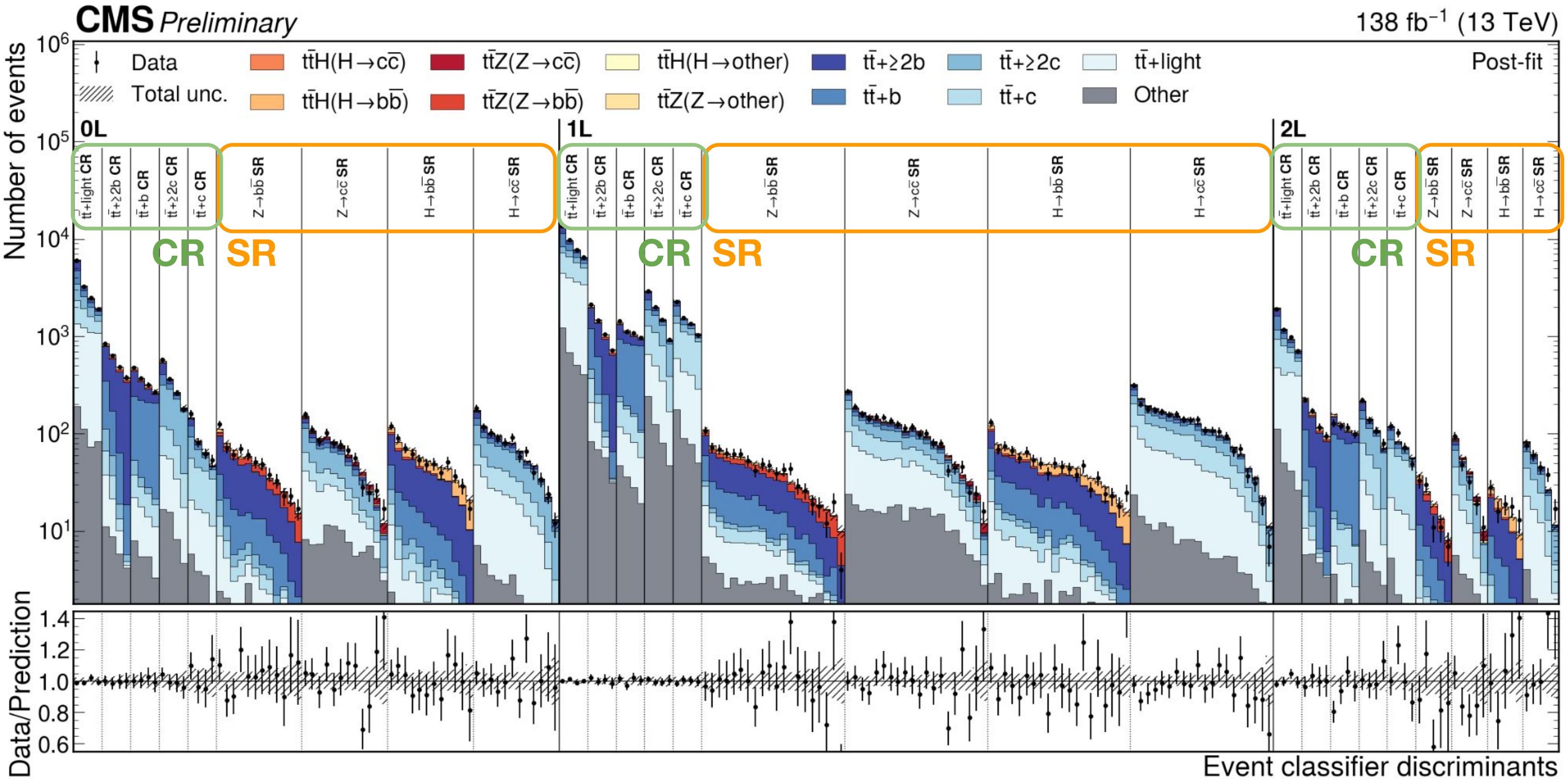
Trying to reduce extrapolation
→ Cut on signal-like score



Group picture of all friends

- **The result:**

CMS-HIG-PAS-24-018

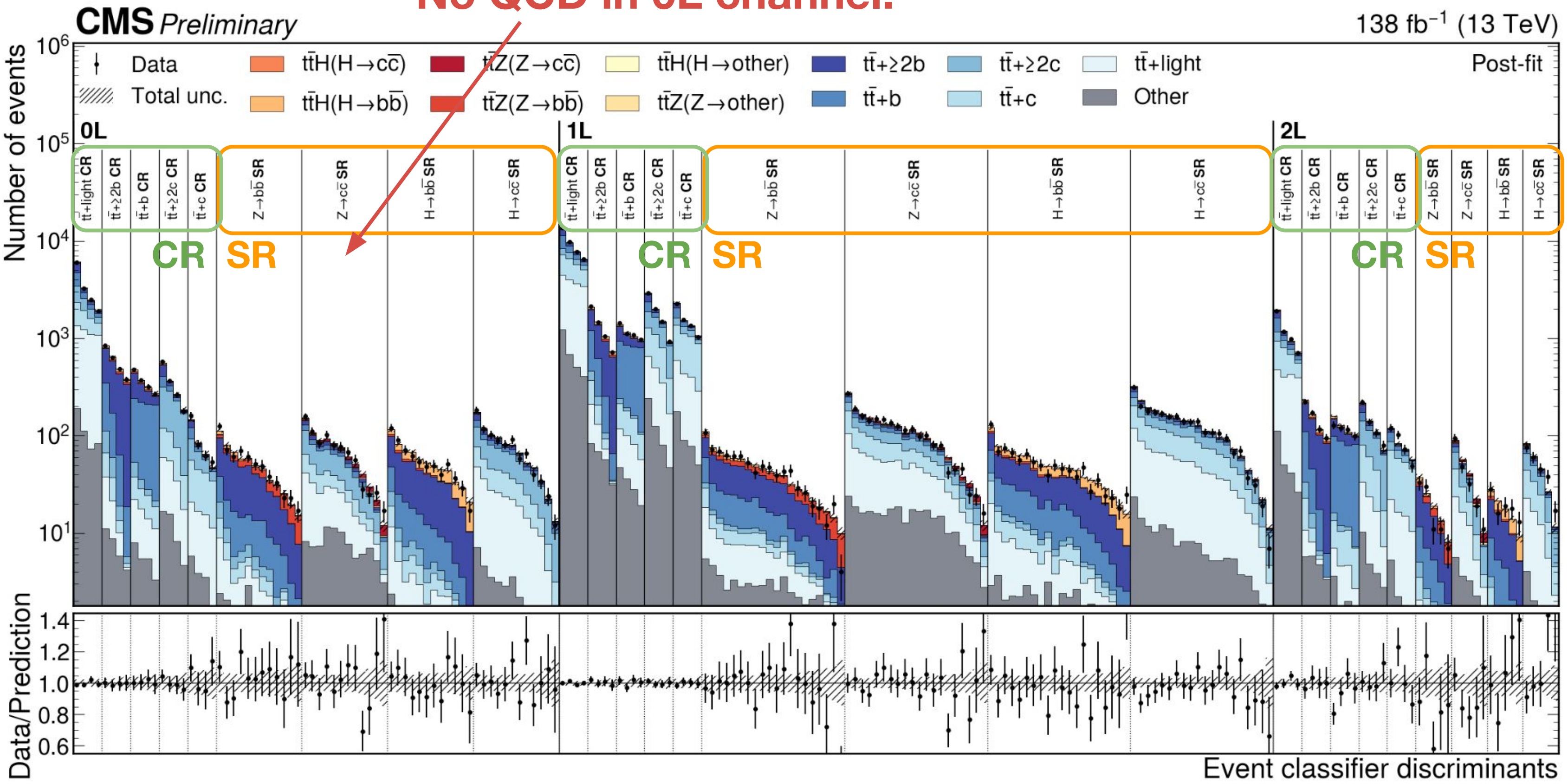


Group picture of all friends

- **The result:**

CMS-HIG-PAS-24-018

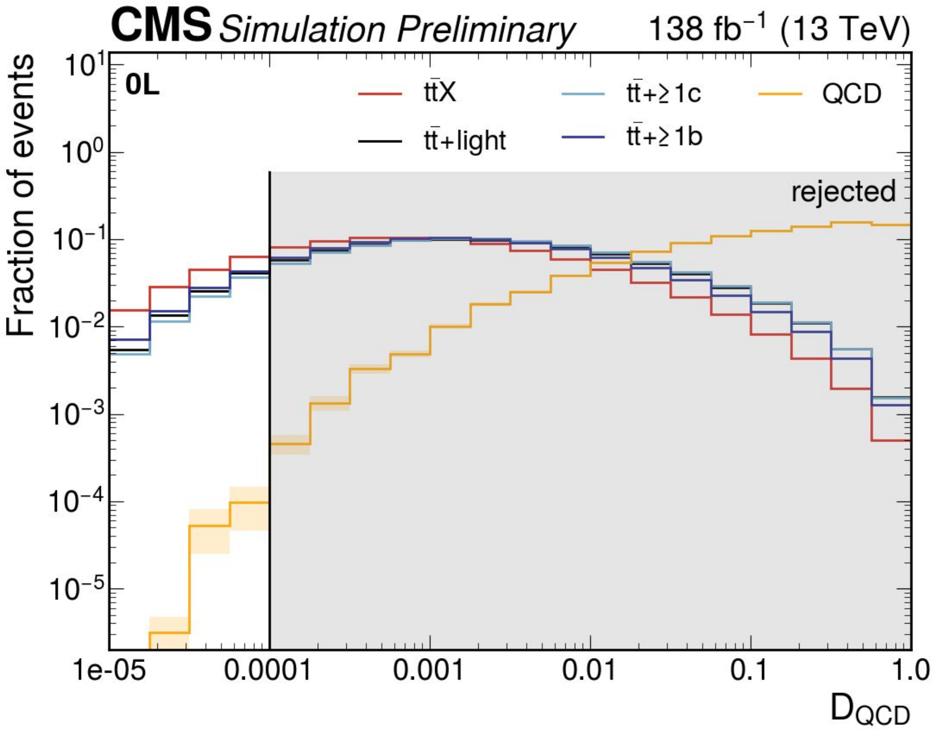
No QCD in 0L channel!



Challenge #3 – background estimation

CMS-HIG-PAS-24-018

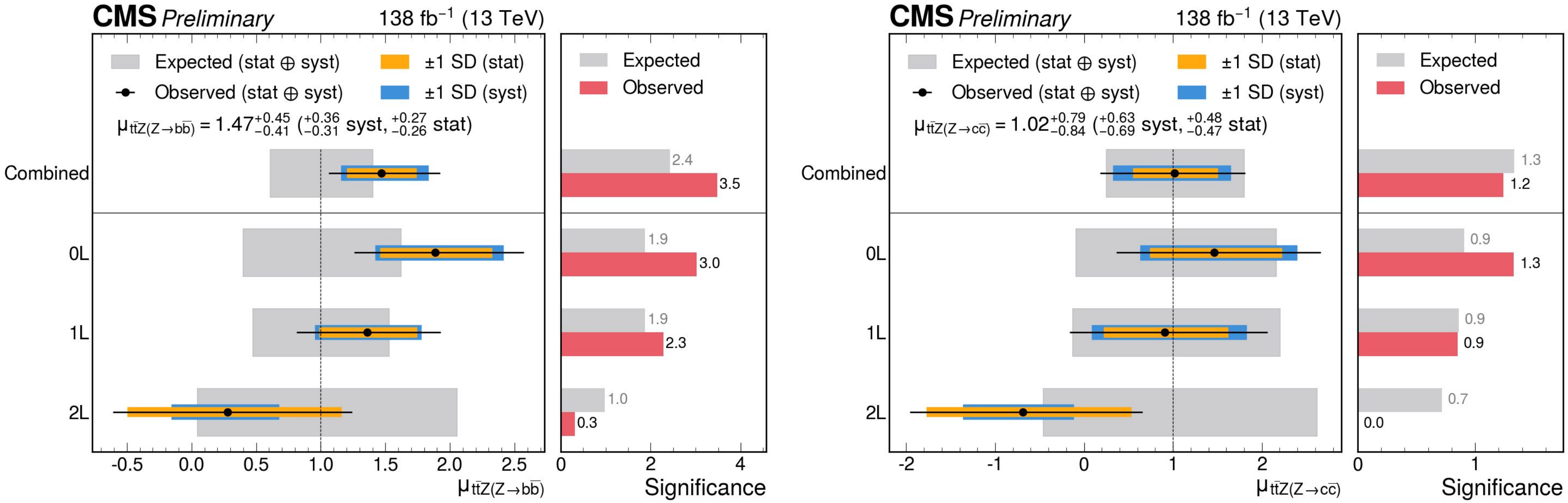
- **QCD multijet background in fully hadronic channel:**
  - Tight cut on classifier QCD score (<10^{-4})
    → Reduced to negligible levels (<1%)



Validation

CMS-HIG-PAS-24-018

- **Fit of ttZ(bb/cc) signal strengths:**
  - ttZ and ttH very similar in kinematics
    → use ttZ as validation of strategy (same as in VH/VZ)
  - Perform fits in analysis regions (without ttH SRs and ttH POIs)



  - Consistent results with ttZ multilepton measurements!

Results

[CMS-HIG-PAS-24-018](CMS-HIG-PAS-24-018)

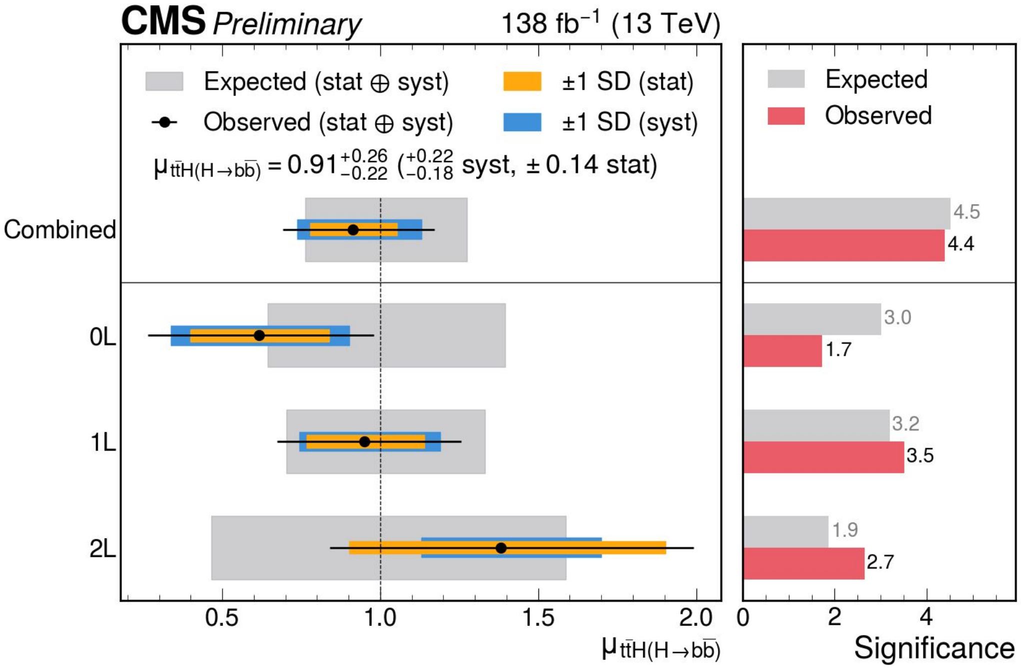
- **ttH(bb)**

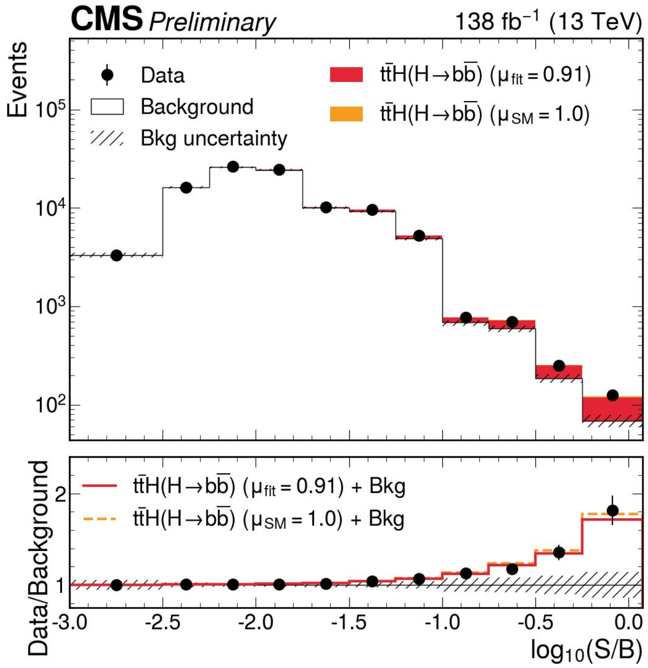
$\mu = 0.91\ ^{+0.26}/_{-0.22}$ — 4.4σ observed

→ Compatible with SM!

→ Robust to modifications of tt+jets background model (backup)

Estimate ~10% p-value compatibility with previous CMS ttH(bb) measurement



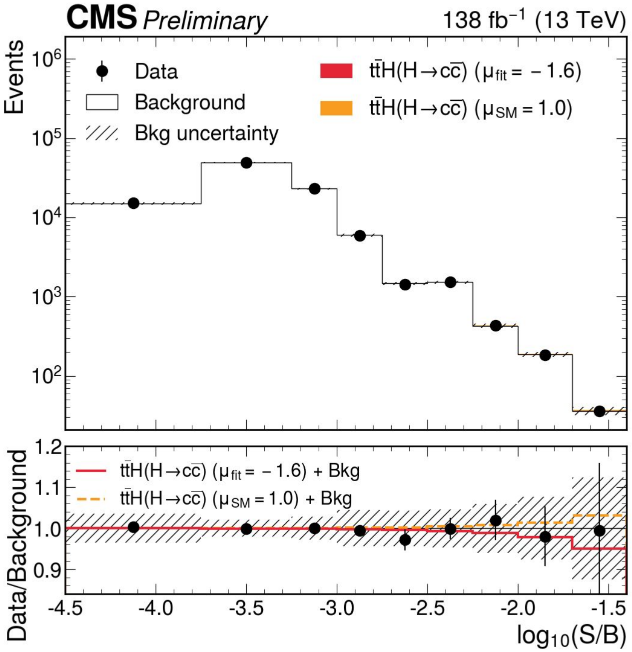


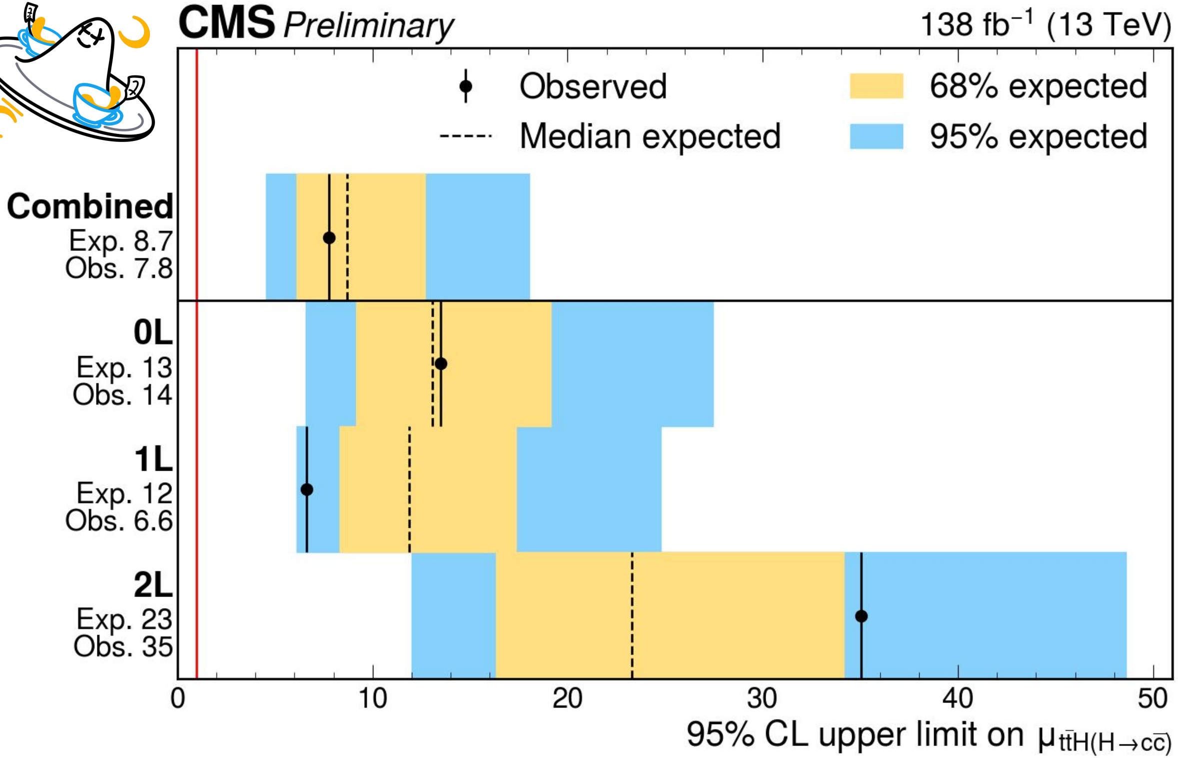
Results

[CMS-HIG-PAS-24-018](CMS-HIG-PAS-24-018)

- **95% CL limits on ttH(cc)**

  μ ≲ 8 x SM observed



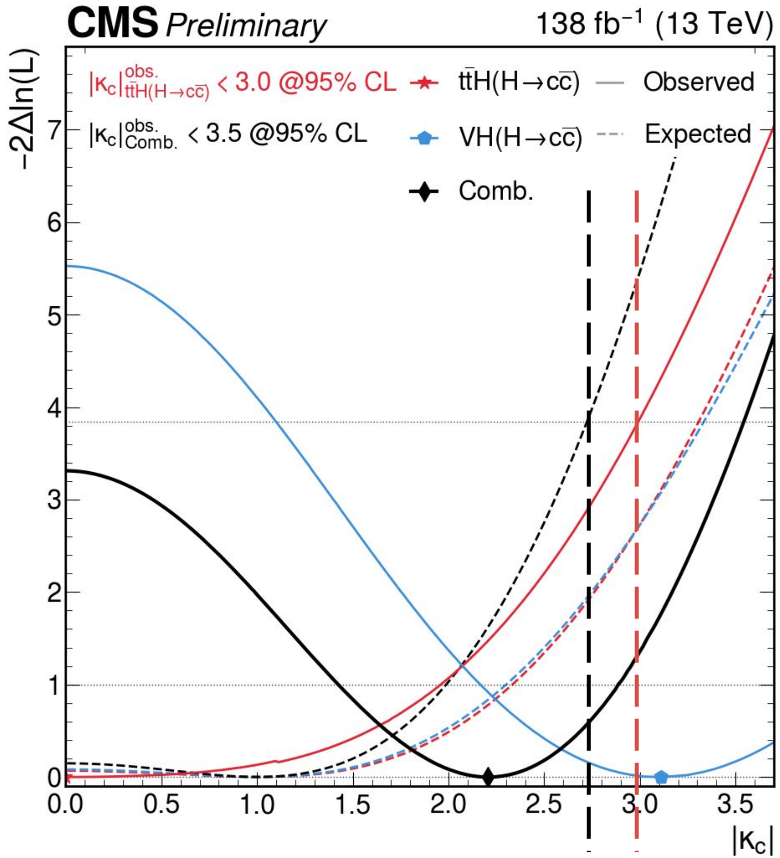


CMS-HIG-PAS-24-018

- **95% CL limits on κ_c**

  $|\kappa_c| \lesssim 3$ observed

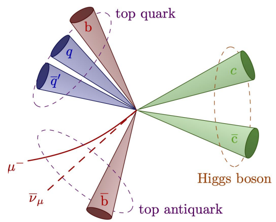
Combination with CMS VH(cc) measurement
→ reduces expected limit to **$|\kappa_c| \lesssim 2.7$**

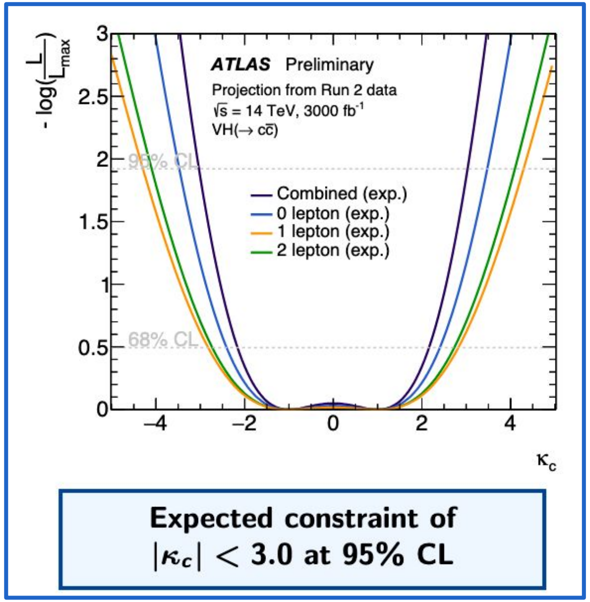


Outlook for Higgs-charm

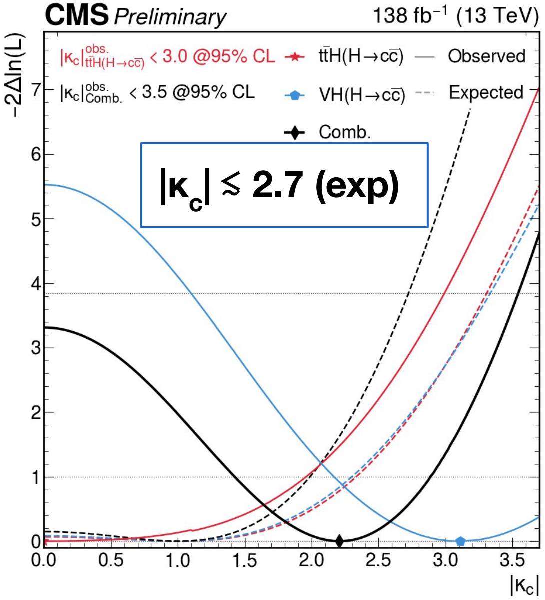
CMS-HIG-PAS-24-018

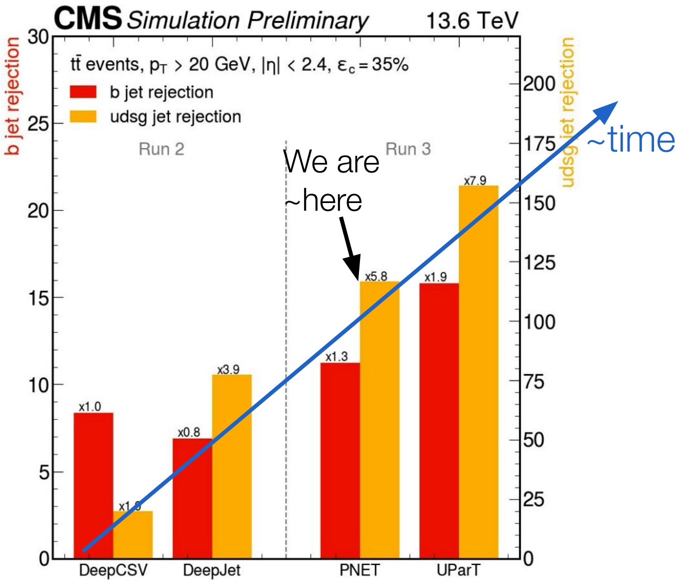
- **Already surpassing the 3/ab projections from 3 year ago**
  → Run 3 as of yet unexplored
  → Run 3 taggers even more powerful for c jets!
  → ttH(cc) boosted regime also still unexplored





CERN Seminar A. Chisholm (2022)



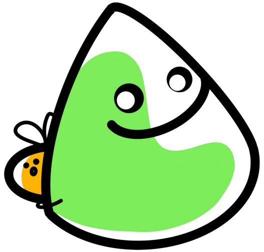


CMS-DP-2024-025

Summary

1. Top quarks and photons CMS-TOP-PAS-23-002

- High precision inclusive and differential tt+γ cross sections
  → First time as function of top quark observables
  → First time as ratio to tt cross sections



2. Top quarks and W bosons CMS-TOP-PAS-24-003

- First differential ttW cross sections by CMS
- Small trends between measurement and predictions
  → But often covered by uncertainties

3. Tops, Higgs bosons and charm/bottom quarks CMS-HIG-PAS-24-018

- First time ttH(cc) is explored!
- Limit on κ_c competitive to VH(cc) ATLAS/CMS results
- Simultaneous extraction of ttH(bb) signal strength
  → Compatible with SM

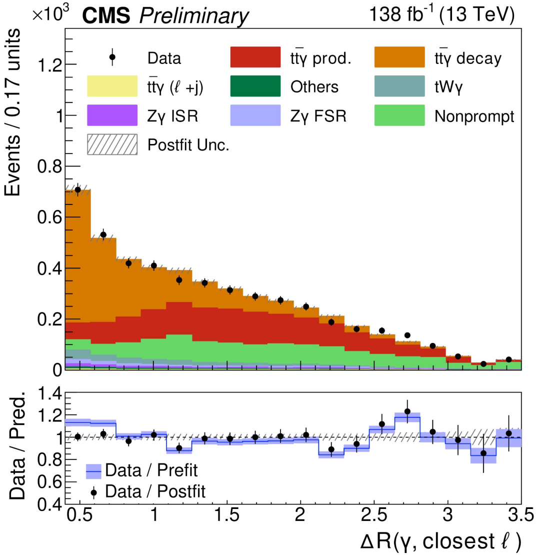
The End

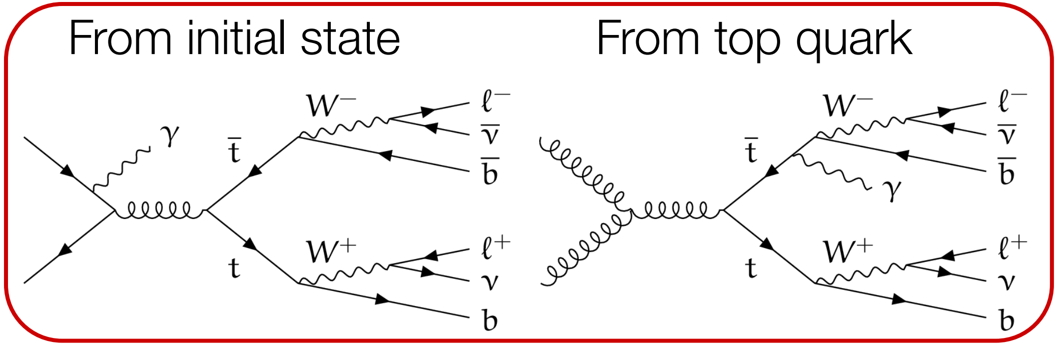
What is tt+ γ?

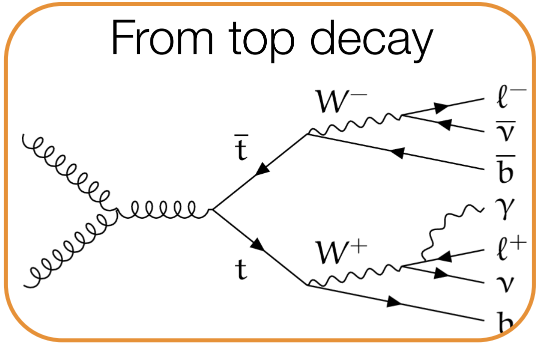
Photon origin in tt+γ:

- **Photon from production:**
  - Can be described as 2→3 process (@NLO QCD)
- **Photon from decay:**
  - Radiation off final-state particles
  - Description at LO
    (2→2→7 ME process or 2→2 tt@NLO with γ from PS)

⇒ Good separation via angle to closest lepton







$t\bar{t}+\gamma$ differential cross sections

Until now: only differential cross sections of γ kinematics

New: Probing the tt system in tt+γ

→ Insights into top-γ coupling and potential BSM modifications

→ Same behaviour as in tt?

→ Top quark momentum modelled well

→ No indications (yet) of mismodeling observed in tt

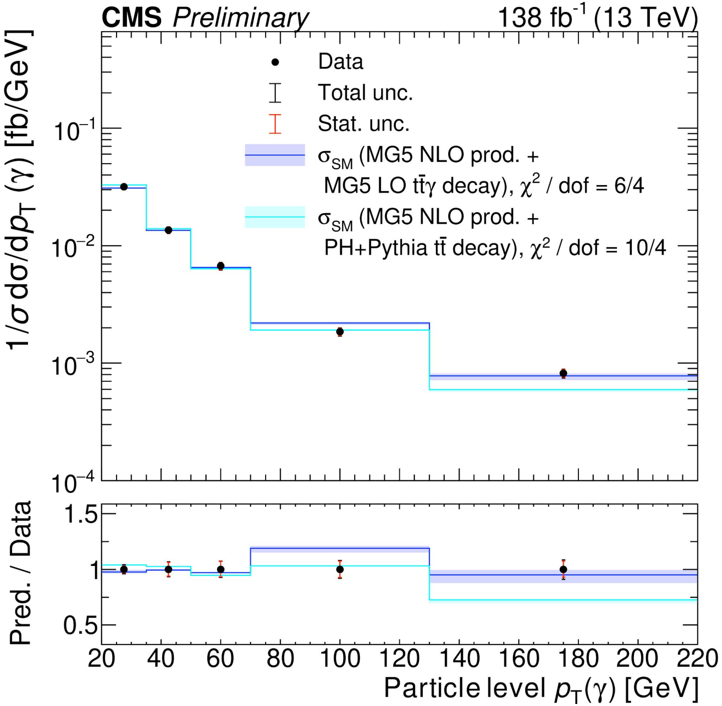
→ Modeling of top-γ system?

→ Angular distributions tend to have some discrepancies

→ **Modeling differences of ME vs PS γ in decay?**

→ No differences in top-γ system observed

→ Only γ momentum and overall cross sections differ



ttW results

What kind of observables are measured?

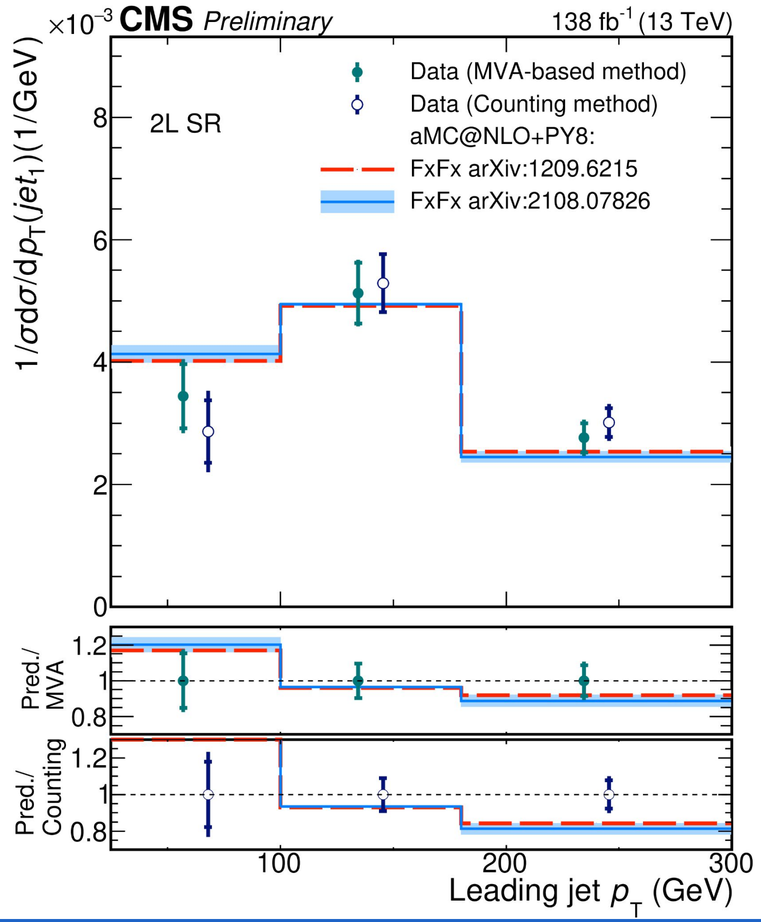
- Things important for background measurements
  → High H_T / jet multiplicity

  Example: Jet multiplicity
  → Underprediction at high jet multiplicity

- General ttW modeling
  → Jet, lepton kinematics, etc

  Example: **Leading jet momentum**
  → Indications of small trend in data w.r.t. modeling

  Example: Top and W decay lepton angle
  → Indications of small trend in data w.r.t. modeling



Why is ttW a difficult process?

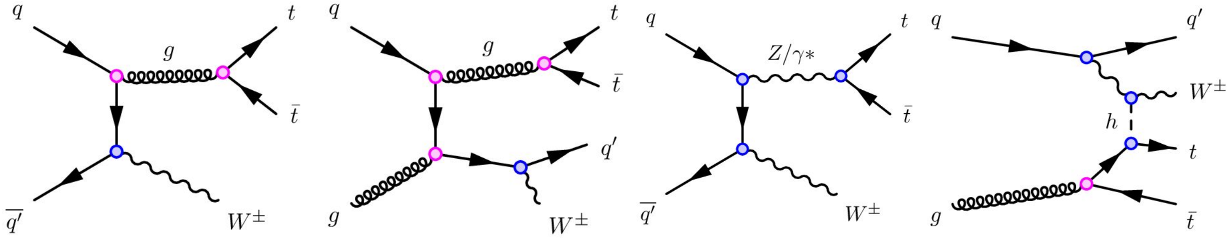
A theorist's view…

- qq-induced at LO ($\sim\alpha_S^2\alpha$)
- qg-induced at NLO ($\sim\alpha_S^3\alpha$)
- qq-induced LO EW contributions ($\sim\alpha^3$)
- qg-induced NLO EW contributions ($\sim\alpha^3\alpha_S$)
- virtual 2-loop contributions at NNLO difficult

NNLO QCD + NLO EWK

σ(ttW) = 745 fb ± 50 fb (scale)
± 13 fb (2-loop approx.)
± 19 fb (PDF, α_S)

NLO QCD only: 711 fb, real NLO EW +5%, virtual EW -2.4%, remaining EW +7%



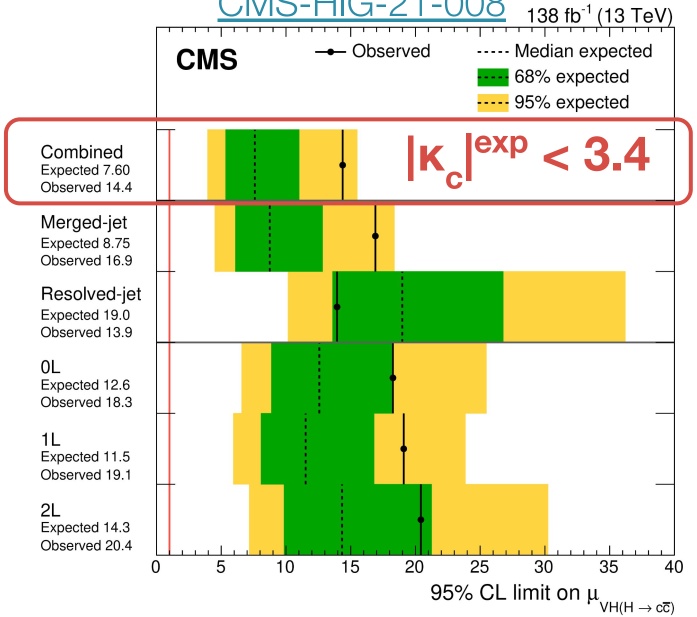
Current state of Higgs-charm coupling

Best limits on Higgs-charm coupling so far:

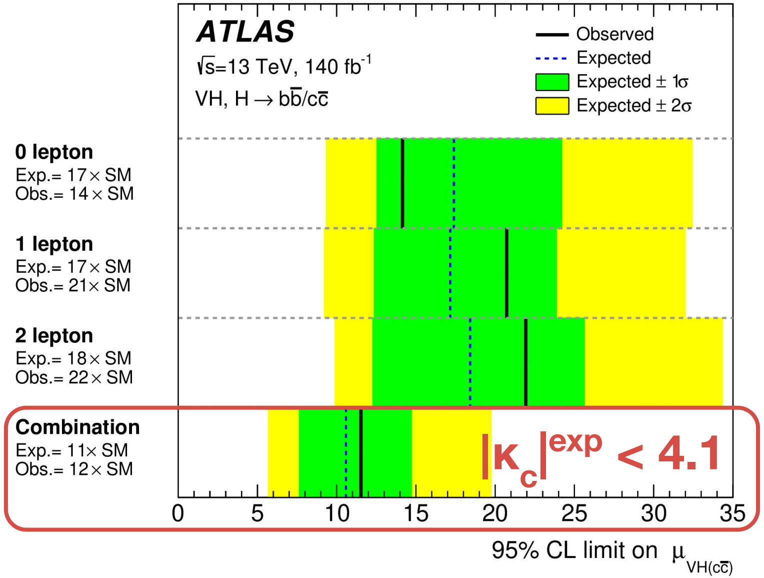
VH(cc) measurements of ATLAS and CMS

($\mu(H \to cc)$ ~10 x SM, $|\kappa_c| \lesssim 4$ @ 95% CL)

CMS-HIG-21-008



ATLAS-HIGG-2020-20

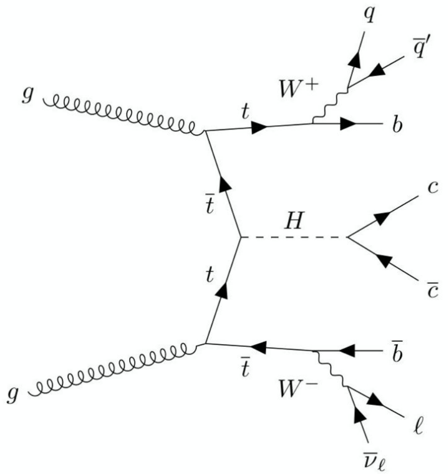


→ Exploit as many channels as possible to reduce limit on **Higgs-charm Yukawa coupling**

Analysis setup

- Three orthogonal lepton channels (for all tt decay modes)
  - Fully Hadronic (0L):
    - 0 isolated e/μ
    - ≥ 7 jets
  - Semileptonic (1L):
    - 1 isolated e/μ
    - ≥ 5 jets
  - Dileptonic (2L):
    - 2 isolated e/μ
    - ≥ 4 jets

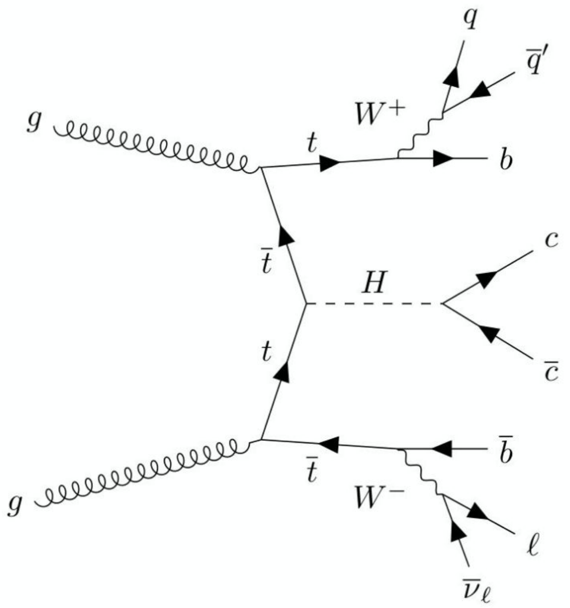
Selection criteria	0L channel	1L channel	2L channel
Number of leptons	0	1	2
Sign and flavor of leptons	—	$e^{\pm}$, $\mu^{\pm}$	e^+e^-, $\mu^{\pm}e^{\mp}$, $\mu^+\mu^-$
Min. p_T of p_T-leading electron [GeV]	—	29/30/30	25
Electron identification	—	Tight (80% efficiency)	Loose (90% efficiency)
Electron isolation	—	Tight (80% efficiency)	Loose (90% efficiency)
Min. p_T of p_T-leading muon [GeV]	—	26/29/26	25
Max. muon relative isolation	—	0.15	0.25
Min. $m_{ee/\mu\mu}$ [GeV]	—	—	20
$m_{ee/\mu\mu}$ [GeV]	—	—	<76, >106
Min. p_T of jets [GeV]	25	25	25
Min. p_T of 6th jet [GeV]	40	—	—
Max. $\lvert\eta\rvert$ of jets	2.4	2.4	2.4
Min. number of jets	7	5	4
Min. number of b-tagged jets	1	1	1
Min. number of HF (b- or c-tagged) jets	3	3	3
Min. H_T [GeV]	500	—	—
Min. p_T^{miss} [GeV]	—	20	20



- Enriching in tagged jets: ≥ 1 b-tagged jet, ≥ 3 b/c-tagged jets
- Using PUPPI jets and custom jet flavor calibration

Analysis setup

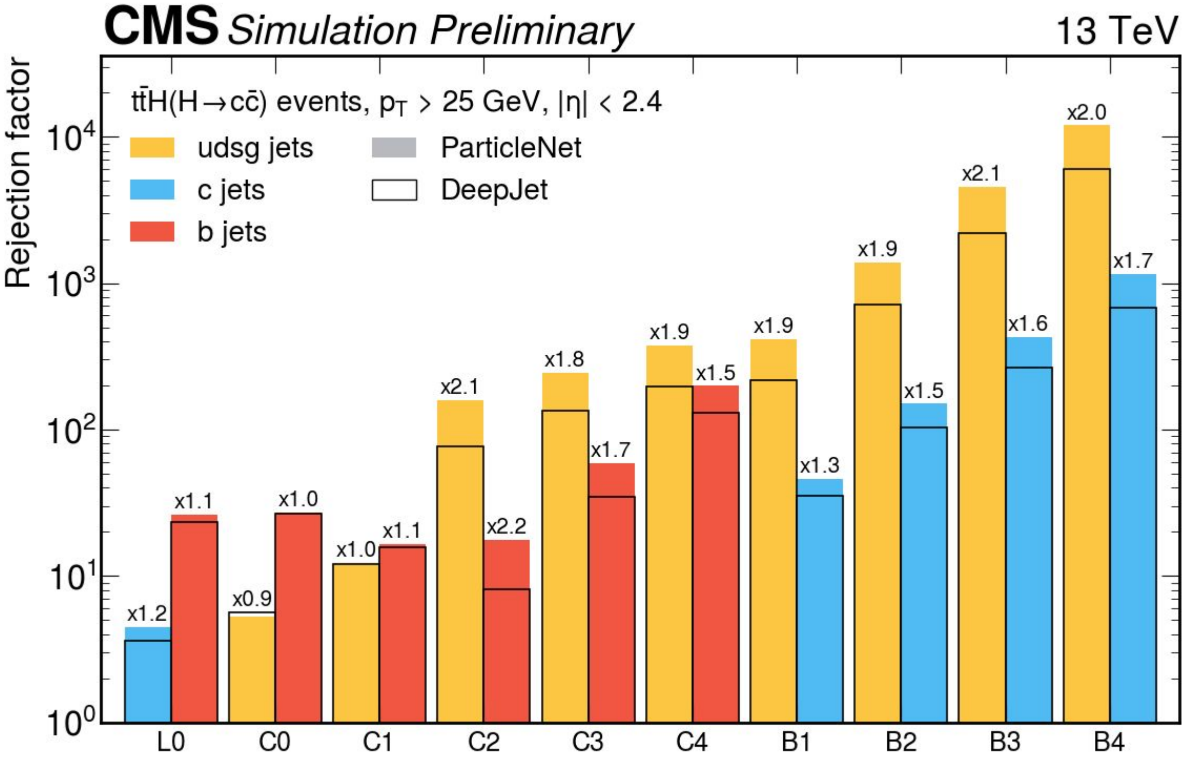
- Additional selections in classifier nodes
  - **ttHbb / ttZbb / ttbb / ttbj:**
    - ≥ 3 b-tagged jets
  - **ttHcc / ttcc:**
    - ≥ 2 c-tagged jets
  - **ttc:**
    - ≥ 1 c-tagged jet



→ Removes some more background events
→ All events in SR + CRs more signal-like

Challenge #1 – jet flavor tagging

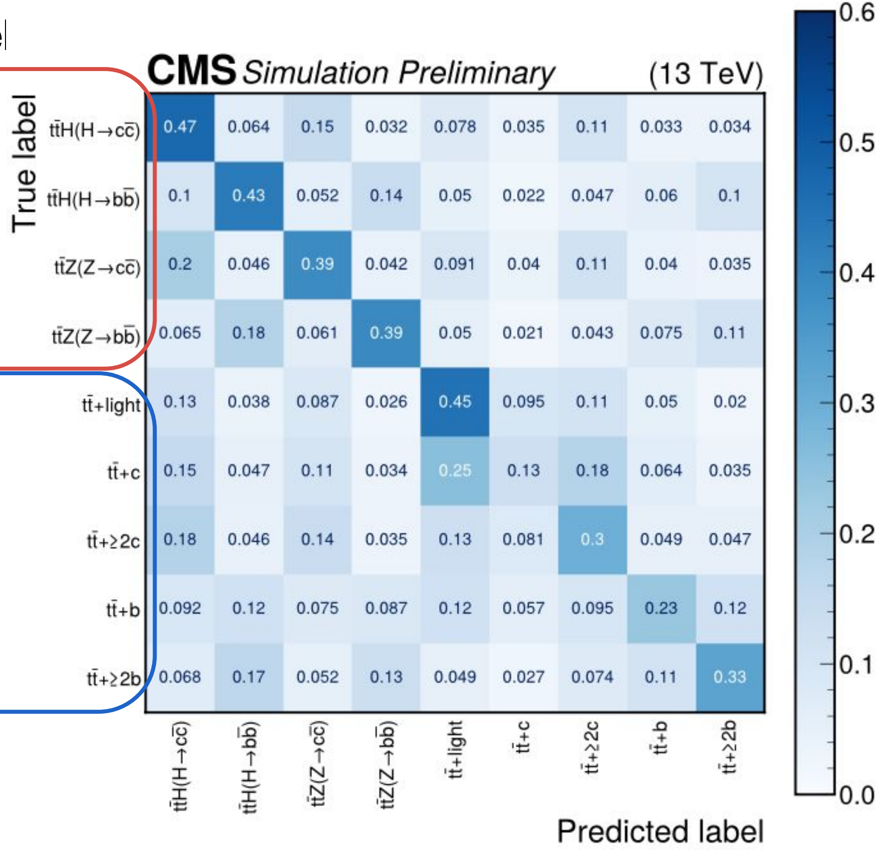
- ~2x improvement in background rejection
  compared to Run 2 state-of-the-art DeepJet



Challenge #2 – event reconstruction / classification

CMS-HIG-PAS-24-018

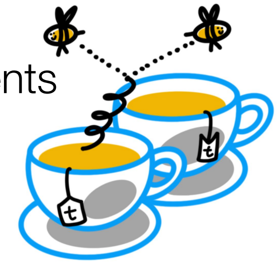
- **The target**
  - Nine different classes (+1 for hadronic channel
  - Four signal-like classes:
    ttH(cc), ttH(bb), ttZ(bb), ttZ(cc)
  - Five tt-like classes:
    tt+≥2b, tt+b, tt+≥2c, tt+c, tt+light
  - (for hadronic channel):
    QCD

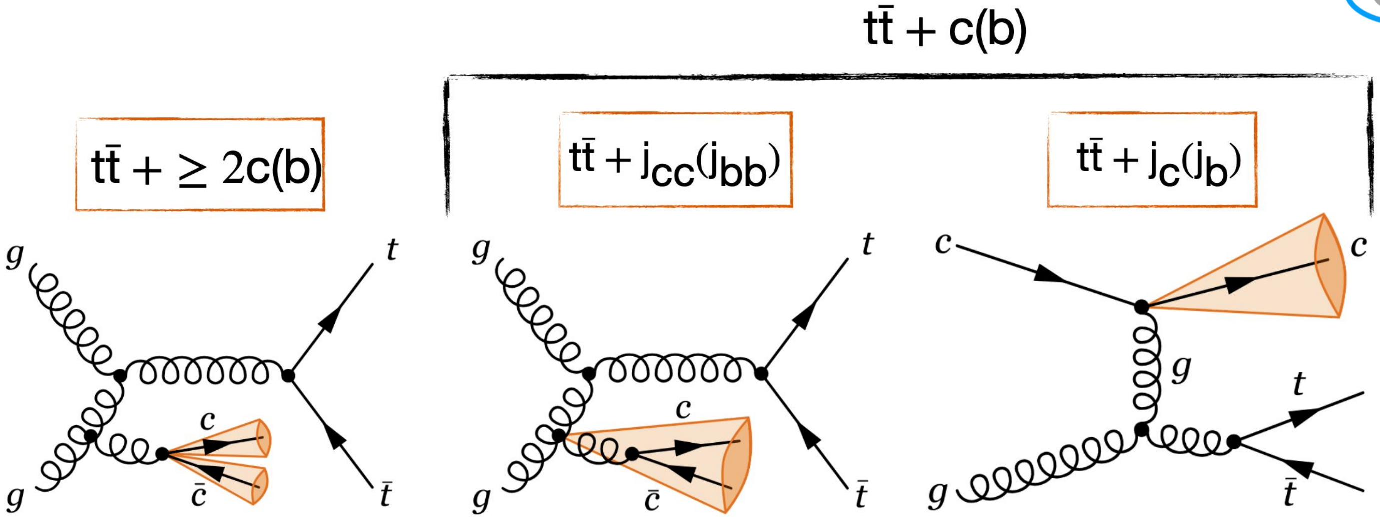


Challenge #3 – background estimation

CMS-HIG-PAS-24-018

- **tt+jets background estimation:**
  - CRs for each separate component (tt+≥2b, tt+b, tt+≥2c, tt+c, tt+light)
  - State-of-the-art background modeling for all individual background components
  - Freely-floating parameters in the fits for each separate component

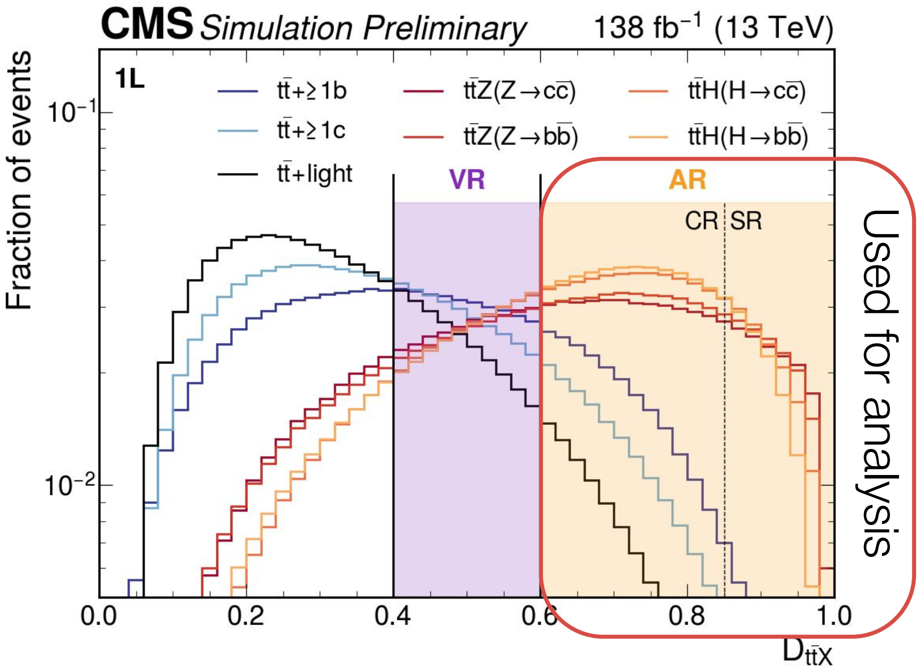


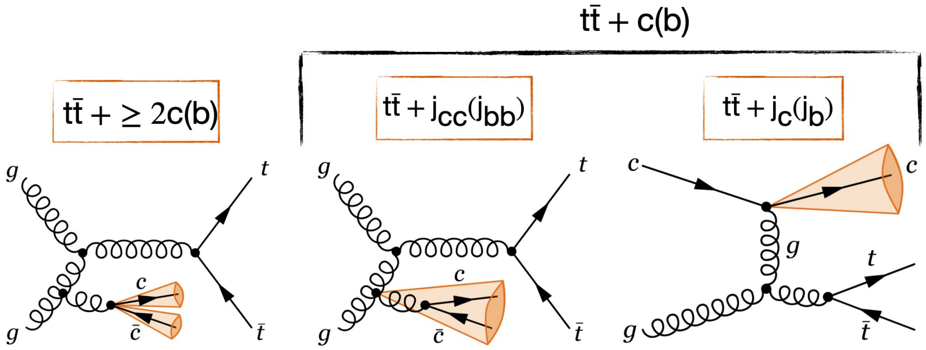


Challenge #3 – background estimation

CMS-HIG-PAS-24-018

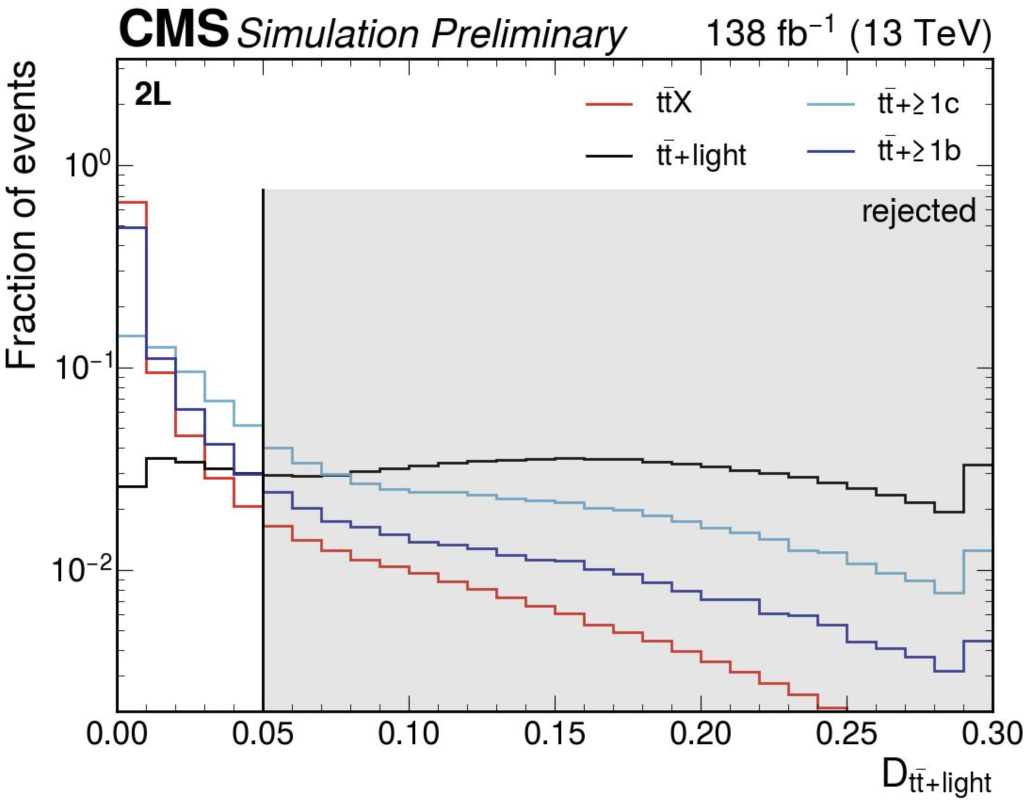
- **Try to reduce extrapolation!**
  - Cut on signal-like (ttX=ttHbb+ttHcc+ttZbb+ttZcc) score
    → Backgrounds and signals similar kinematics
    → No extrapolation of difficult tt+jets backgrounds to different kinematic regimes





Challenge #3 – background estimation

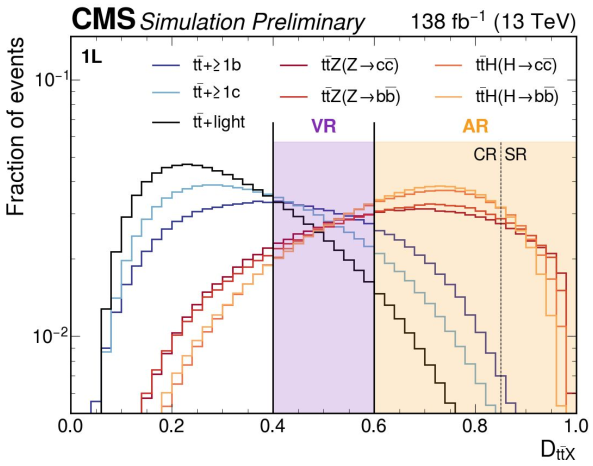
- **Cutting on tt+light jet score to reduce large background**



Validation of analysis strategy

- **Validation #1 – fit to CRs:**
  - CRs for each separate component
  - Freely-floating parameters in the fits for each separate component (*2 x 5 parameters*)
  - Very detailed scheme of tt+jets background modeling uncertainties (*50+ nuisance params.)*

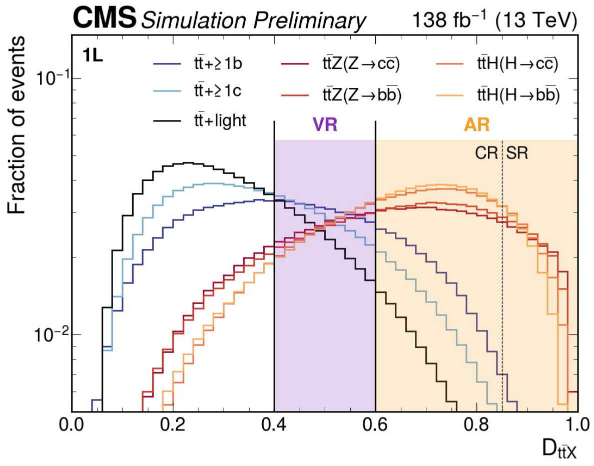
- **Validation #2 – low signal score:**
  - Perform fits in signal-depleted region (**VR**)
    → fitting only tt+jets SFs
  - Try as best as possible to mimic background compositions /

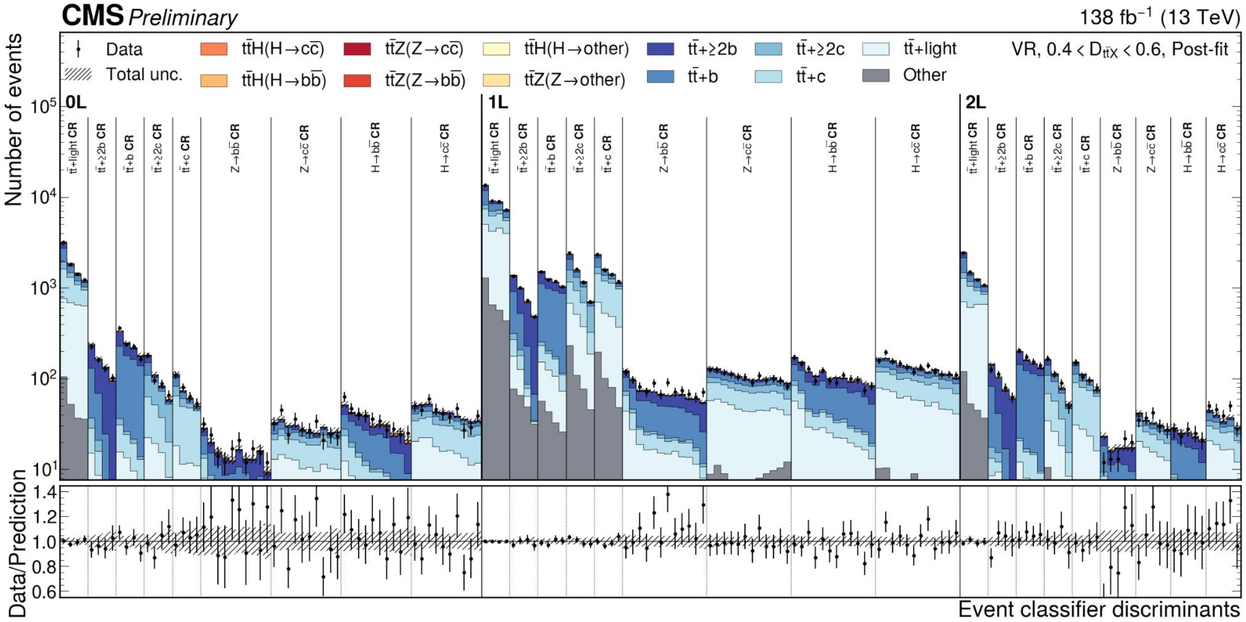


- **Validation #3 – fit of ttZ(bb/cc) signal strengths:**
  - ttZ and ttH very similar in kinematics
    → use ttZ as validation of strategy (same as in VH/VZ)
  - Perform fits in analysis regions (without ttH SRs and ttH POIs)

Validation

- **Validation #1 – low signal score:**
  - Perform fits in signal-depleted region (VR) – fitting only tt+jets SFs
  - Try as best as possible to mimic background compositions / etc



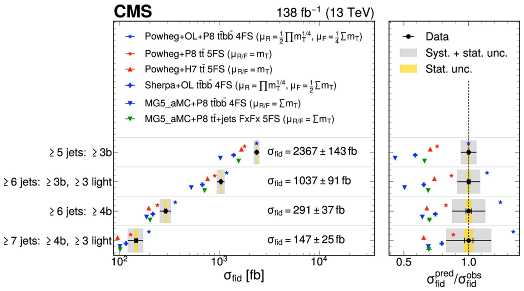


Validation

- **Validation #1 – fit to CRs:**
  - CRs for each separate component
  - Freely-floating parameters in the fits for each separate component (*2 x 5 parameters*)
  - Very detailed scheme of tt+jets background modeling uncertainties (*50+ nuisance params.)*

Results from central fit (Validation results similar)

Channels	$t\bar{t}+\geq 2b$	$t\bar{t}+b$	$t\bar{t}+\geq 2c$	$t\bar{t}+c$	$t\bar{t}+\text{light}$
2ℓ & 1ℓ	0.88±0.07	0.92±0.16	1.39±0.23	1.41±0.36	0.89±0.11
0ℓ	1.12±0.11	0.89±0.18	2.03±0.41	0.95±0.34	0.89±0.17

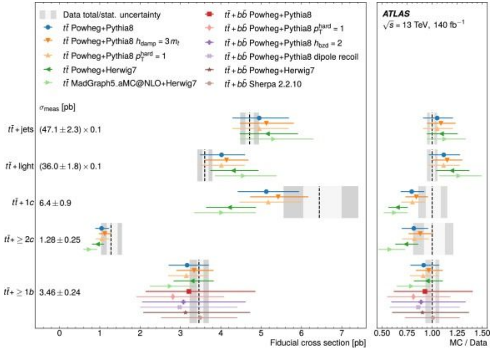


tt+b below pre-fit → consistent with dedicated CMS tt+b measurement

JHEP05(2024)042

tt+c above pre-fit → consistent with recent ATLAS measurements

PLB(2024)139177



Systematic uncertainties

	Source	Corr. (period)	Corr. (process)	Processes
Experimental	Integrated luminosity	$\sim$	✓	all
	Electron reconstruction and identification	✓	✓	all
	Muon reconstruction and identification	✓	✓	all
	Trigger efficiencies	$\times$	✓	all
	Pileup reweighting	✓	✓	all
	Jet energy scale (11 sources)	$\sim$	✓	all
	Jet energy resolution	$\times$	✓	all
	Unclustered $p_{\mathrm{T}}^{\mathrm{miss}}$	$\times$	✓	all
	Jet flavor tagging	$\sim$	✓	all
Modeling	Incl. cross sections & normalization	✓	$\sim$	all
	μ_{R} scale	✓	$\times$	$\mathrm{t\bar{t}}$+jets, $\mathrm{t\bar{t}X}$, single top
	μ_{F} scale	✓	$\times$	$\mathrm{t\bar{t}}$+jets, $\mathrm{t\bar{t}X}$, single top
	PDF shape	✓	$\times$	$\mathrm{t\bar{t}}$+jets, $\mathrm{t\bar{t}X}$
	PS scales: ISR	✓	$\times$	$\mathrm{t\bar{t}}$+jets, $\mathrm{t\bar{t}X}$, single top
	PS scales: FSR	✓	$\times$	$\mathrm{t\bar{t}}$+jets, $\mathrm{t\bar{t}X}$, single top
	ME-PS matching (h_{damp})	✓	$\times$	$\mathrm{t\bar{t}}$+jets
	ME (4*vs.* 5 flavor scheme)	✓	$\times$	$\mathrm{t\bar{t}}+\geq 1\mathrm{b}$

Systematic uncertainties

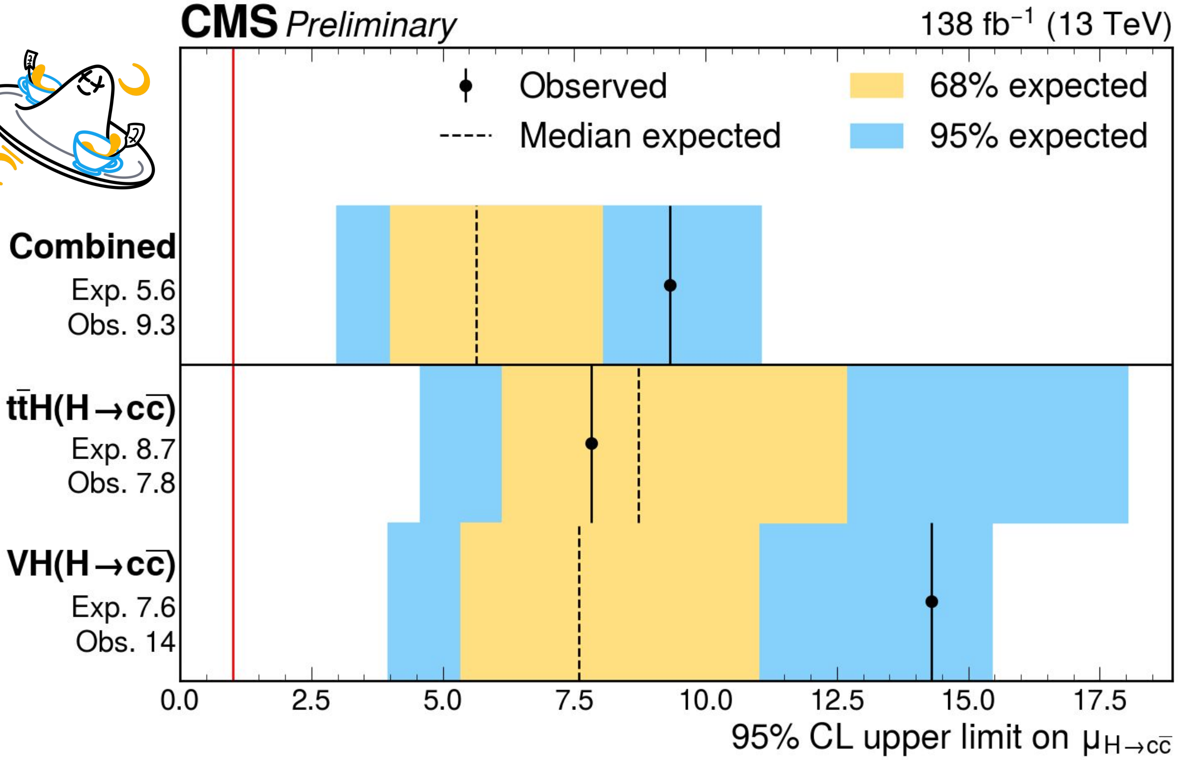
Uncertainty source	$\Delta\mu$ ($\Delta\mu/\Delta\mu_{tot}$) $\mu_{t\bar{t}H(H\to c\bar{c})}$		$\mu_{t\bar{t}H(H\to b\bar{b})}$	
Statistical	3.3	(74%)	0.14	(57%)
$t\bar{t}$+jets normalizations	1.4	(32%)	0.06	(26%)
$t\bar{t}Z$ normalizations	0.4	(8.4%)	0.06	(30%)
Theory	2.1	(47%)	0.18	(75%)
Signal	0.7	(15%)	0.11	(47%)
$t\bar{t}+\geq 1b$	0.7	(15%)	0.14	(60%)
$t\bar{t}+\geq 1c$	1.4	(32%)	0.01	(5.8%)
$t\bar{t}$+light	1.3	(29%)	0.01	(5.2%)
Minor backgrounds	0.2	(4.6%)	0.01	(4.6%)
Experimental	2.0	(47%)	0.07	(31%)
Jet flavor tagging	1.7	(39%)	0.07	(28%)
Sizes of the simulated samples	1.1	(24%)	0.05	(21%)
Jet energy scale and resolution	0.8	(18%)	0.02	(8.6%)
Lepton identification	0.3	(6.0%)	0.02	(6.3%)
Integrated luminosity	0.1	(2.0%)	0.02	(6.2%)

Results

- Competitive sensitivity compared to VH(cc) measurements!

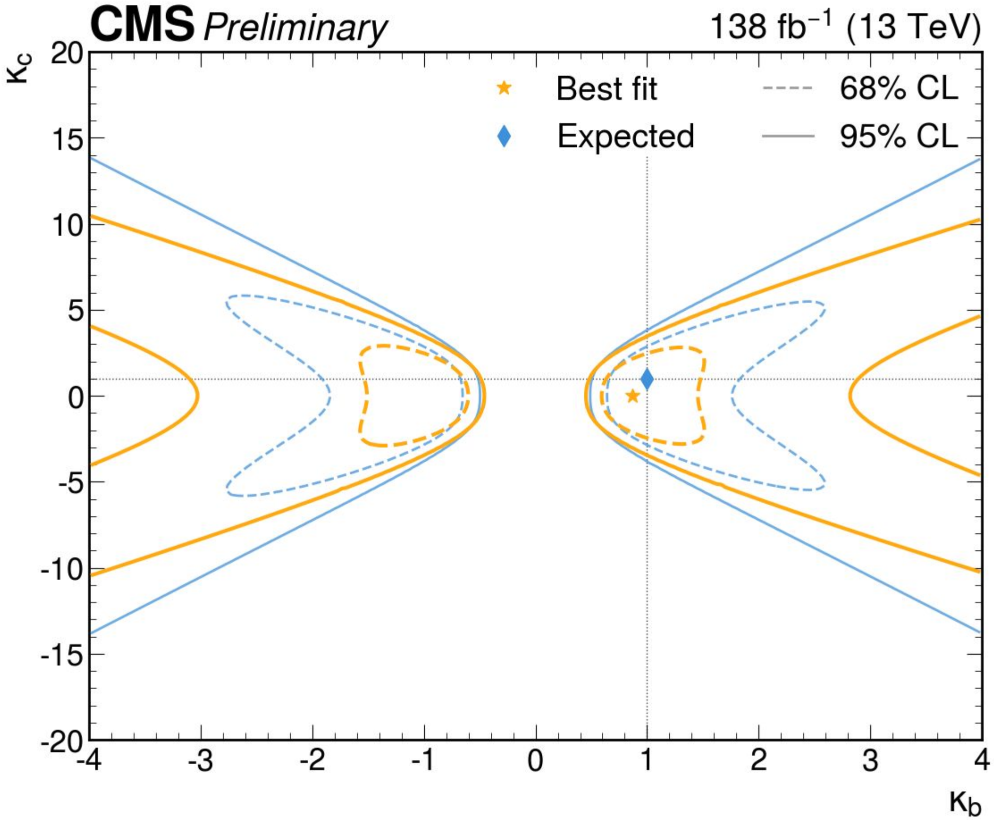
→ **Combined limit on H(cc)**

H(cc) ≲ 5.6 x SM expected



Results

Two dimensional limits on Higgs-charm and Higgs-bottom Yukawa couplings



tt+jets background model

	$t\bar{t}$ NLO (5FS)	$t\bar{t}b\bar{b}$ NLO (4FS)
ME generator	POWHEG v2	POWHEG-BOX-RES
Parton shower	PYTHIA v8.230	PYTHIA v8.230
Flavor scheme	5FS	4FS
PDF set	NNPDF31_nnlo_hessian_pdfas	NNPDF31_nnlo_as_0118_nf_4
m_t	172.5 GeV	172.5 GeV
m_b	0	4.75 GeV
μ_R	$\sqrt{\frac{1}{2}\left(m^2_{T,t} + m^2_{T,\bar{t}}\right)}$	$\frac{1}{2}\sqrt[4]{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$
μ_F	μ_R	$\frac{1}{4}\left[m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + m_{T,g}\right]$
h_{damp}	$1.379 m_t$	$1.379 m_t$
Tune	CP5	CP5

Fits to alternative tt+jets models

$t\bar{t}+\geq1b$ bkg. model	$\mu_{t\bar{t}H(H\to c\bar{c})}$	(95% CL)	$\mu_{t\bar{t}H(H\to b\bar{b})}$	(Sign. [s.d.])	$\mu_{t\bar{t}Z(Z\to c\bar{c})}$	(Sign. [s.d.])	$\mu_{t\bar{t}Z(Z\to b\bar{b})}$	(Sign. [s.d.])
Default	-1.6 ± 4.5	(<7.8)	$0.91^{+0.26}_{-0.22}$	(4.4)	$1.02^{+0.79}_{-0.84}$	(1.2)	$1.47^{+0.45}_{-0.41}$	(3.5)
Simple PS	-0.4 ± 4.4	(<8.8)	$0.91^{+0.27}_{-0.22}$	(4.4)	$0.94^{+0.82}_{-0.73}$	(1.3)	$1.47^{+0.44}_{-0.39}$	(3.6)
$\mu_F \times 2$	$-1.7^{+4.2}_{-4.3}$	(<8.0)	$0.94^{+0.26}_{-0.23}$	(4.4)	$1.06^{+0.77}_{-0.75}$	(1.4)	$1.62^{+0.43}_{-0.38}$	(4.1)
$\mu_F \times 2$ & Simple PS	-1.0 ± 4.4	(<8.5)	$0.97^{+0.28}_{-0.23}$	(4.5)	$1.04^{+0.77}_{-0.78}$	(1.3)	$1.67^{+0.42}_{-0.37}$	(4.2)
5FS	-1.8 ± 4.3	(<7.7)	$0.97^{+0.24}_{-0.20}$	(5.7)	$1.17^{+0.77}_{-0.71}$	(1.6)	$1.14^{+0.41}_{-0.38}$	(3.0)
5FS & Simple PS	-0.9 ± 4.5	(<7.6)	$1.02^{+0.26}_{-0.21}$	(6.0)	$1.19^{+0.77}_{-0.71}$	(1.6)	$1.10^{+0.40}_{-0.37}$	(2.9)

$t\bar{t}+\geq1b$ background model	$t\bar{t}+\geq2b$	$t\bar{t}+b$
Default	0.90 ± 0.08 (1.14 ± 0.12)	0.87 ± 0.15 (0.83 ± 0.16)
Simple PS	0.88 ± 0.07 (1.12 ± 0.11)	0.92 ± 0.16 (0.89 ± 0.18)
$\mu_F \times 2$	0.89 ± 0.06 (1.37 ± 0.10)	0.94 ± 0.17 (1.05 ± 0.21)
$\mu_F \times 2$ & Simple PS	0.90 ± 0.05 (1.41 ± 0.10)	0.95 ± 0.16 (1.06 ± 0.22)
5FS	1.54 ± 0.11 (2.06 ± 0.19)	0.91 ± 0.36 (0.62 ± 0.64)
5FS & Simple PS	1.57 ± 0.09 (2.25 ± 0.21)	0.83 ± 0.34 (0.60 ± 0.62)

HIG-19-011 correlation study

Estimation of statistical overlap (1L channel):

→ Small data overlap – 7% (15% in sensitive bins)

→ Classifier scores softly correlated (~30%)

→ Bootstrapping test: μ(ttHbb) correlated ~15%

Systematic correlation:

→ Different tagger / selections / classifier / background model

→ Assume it to be small

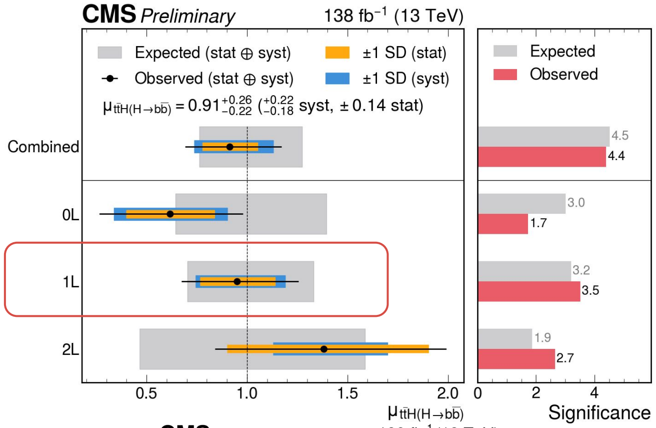
Overall compatibility:

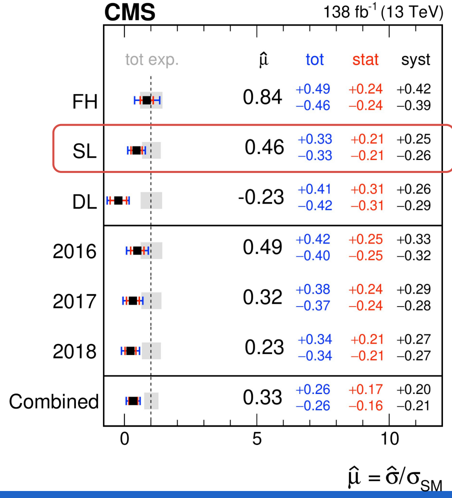
→ Assuming no syst. correlation:

10% p-value

→ Assuming strong (50%) syst. correlation:

3% p-value





Post-fit event yields

Process	2L	1L	0L	Total
$t\bar{t}H(H\to c\bar{c})$	-9 ± 18 (6 ± 11)	-62 ± 69 (38 ± 42)	-33 ± 42 (20 ± 25)	-100 ± 130 (64 ± 78)
$t\bar{t}H(H\to b\bar{b})$	137 ± 56 (151 ± 62)	1060 ± 220 (1150 ± 240)	580 ± 140 (630 ± 150)	1770 ± 410 (1930 ± 450)
$t\bar{t}Z(Z\to c\bar{c})$	32 ± 27	210 ± 110	112 ± 65	360 ± 200
$t\bar{t}Z(Z\to b\bar{b})$	75 ± 53	580 ± 210	290 ± 130	940 ± 400
$t\bar{t}+\geq 2b$	1060 ± 180	8420 ± 650	4670 ± 480	14100 ± 1300
$t\bar{t}+b$	1310 ± 260	12100 ± 1000	3730 ± 530	17100 ± 1800
$t\bar{t}+\geq 2c$	940 ± 160	7320 ± 610	3850 ± 460	12100 ± 1200
$t\bar{t}+c$	1730 ± 290	15600 ± 1200	3220 ± 390	20600 ± 1900
$t\bar{t}+\text{light}$	1700 ± 140	17080 ± 670	4990 ± 280	23800 ± 1100
Other	430 ± 200	5040 ± 810	870 ± 320	6300 ± 1300
Total	7410 ± 240	67300 ± 1400	22270 ± 720	97000 ± 2400
Data	7366	67370	22271	97007

Post-fit event yields

Process	$t\bar{t}H(H\to c\bar{c})$ **SR**	$t\bar{t}H(H\to b\bar{b})$ **SR**	$t\bar{t}Z(Z\to c\bar{c})$ **SR**	$t\bar{t}Z(Z\to b\bar{b})$ **SR**	$t\bar{t}+\geq 2b$ **CR**	$t\bar{t}+b$ **CR**	$t\bar{t}+\geq 2c$ **CR**	$t\bar{t}+c$ **CR**	$t\bar{t}+$light **CR**
$t\bar{t}H(H\to c\bar{c})$	-27 ± 40 (17 ± 25)	-0.9 ± 6.7 (0.5 ± 3.8)	-5 ± 16 (3.2 ± 9.5)	-0.3 ± 3.7 (0.2 ± 2.1)	-2.0 ± 5.4 (1.2 ± 3.1)	-0.8 ± 3.6 (0.5 ± 2.1)	-16 ± 16 (9.8 ± 9.8)	-6.3 ± 9.3 (3.9 ± 5.7)	-46 ± 28 (28 ± 17)
$t\bar{t}H(H\to b\bar{b})$	35 ± 31 (38 ± 34)	310 ± 100 (340 ± 110)	16 ± 20 (17 ± 21)	81 ± 45 (88 ± 49)	441 ± 65 (475 ± 71)	220 ± 45 (242 ± 50)	71 ± 22 (75 ± 24)	40 ± 15 (43 ± 17)	557 ± 67 (607 ± 73)
$t\bar{t}Z(Z\to c\bar{c})$	25 ± 28	2.0 ± 7.6	105 ± 63	2.9 ± 9.4	5.8 ± 7.3	2.7 ± 5.3	51 ± 23	21 ± 14	143 ± 40
$t\bar{t}Z(Z\to b\bar{b})$	10 ± 21	57 ± 51	14 ± 25	220 ± 110	218 ± 58	108 ± 40	34 ± 20	22 ± 15	263 ± 58
$t\bar{t}+\geq 2b$	194 ± 88	770 ± 180	152 ± 76	730 ± 170	4680 ± 260	1530 ± 140	862 ± 95	335 ± 53	4890 ± 240
$t\bar{t}+b$	300 ± 160	320 ± 160	250 ± 140	270 ± 150	1830 ± 200	3740 ± 310	1050 ± 150	800 ± 120	8520 ± 450
$t\bar{t}+\geq 2c$	830 ± 210	50 ± 49	710 ± 190	41 ± 43	244 ± 56	96 ± 39	2950 ± 220	850 ± 100	6330 ± 320
$t\bar{t}+c$	920 ± 270	84 ± 78	640 ± 230	64 ± 70	321 ± 77	358 ± 94	2210 ± 230	2960 ± 250	13030 ± 590
$t\bar{t}+$light	1050 ± 160	102 ± 51	810 ± 140	92 ± 49	257 ± 39	280 ± 47	1362 ± 99	1430 ± 96	18390 ± 410
Other	240 ± 180	58 ± 76	450 ± 250	82 ± 88	303 ± 87	169 ± 56	630 ± 140	453 ± 100	3950 ± 350
Total	3580 ± 160	1750 ± 100	3150 ± 140	1580 ± 97	8300 ± 210	6500 ± 200	9210 ± 290	6910 ± 240	56040 ± 950
Data	3545	1744	3143	1593	8322	6492	9245	6909	56014