Constraints on Higgs-charm couplings
(from CMS)

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on behalf of the CMS collaboration

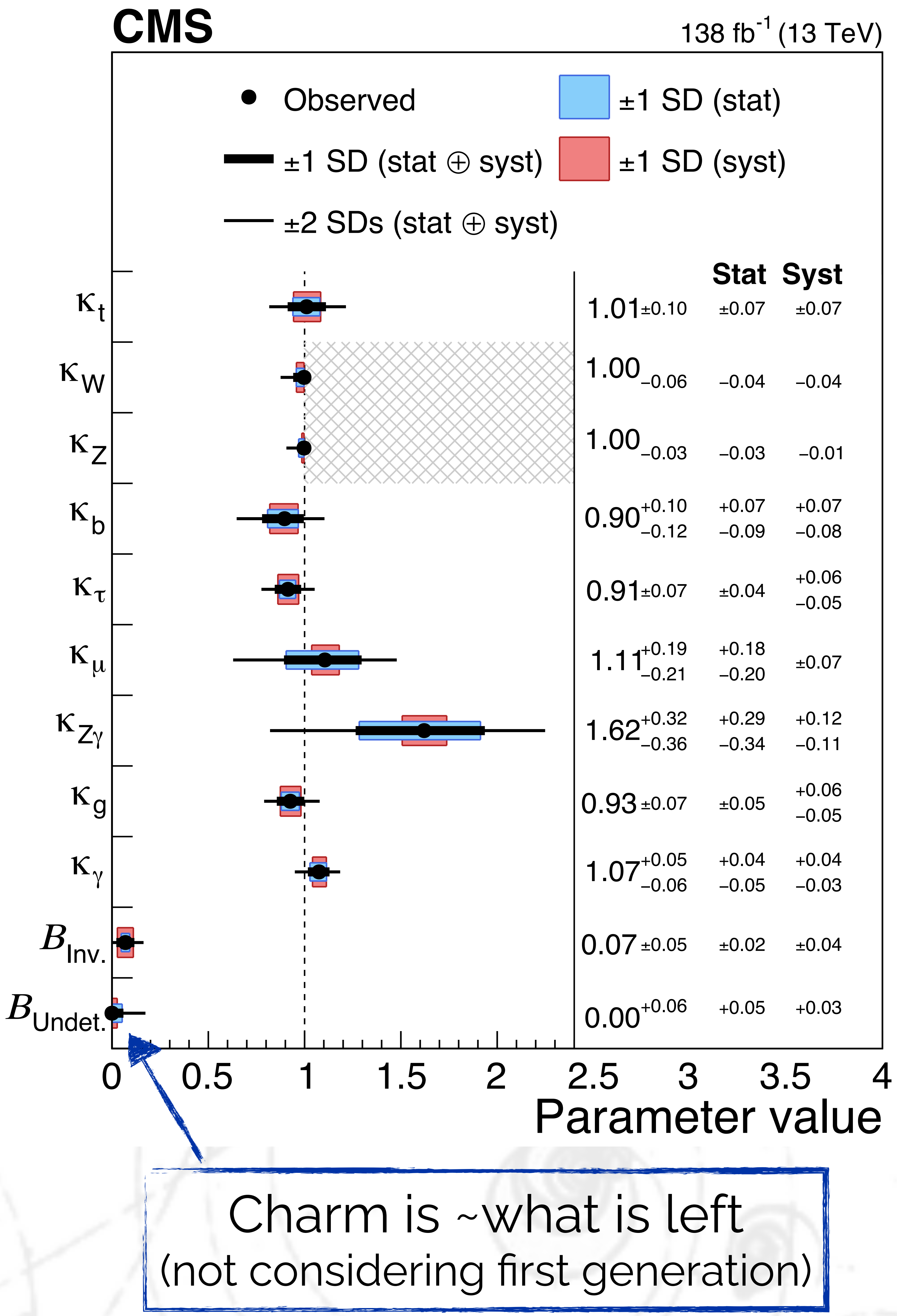
Higgs 2024

6 November 2024

Where do we stand?

[CMS-HIG-22-001]

- No clear indication of BSM physics → where to look at?
  - Higgs boson as discovery tool!
- 10+ years after the Higgs discovery:
  - In depth-characterisation of the Higgs boson
  - Couplings to third generation and bosons established (O(10%))
  - Evidence for coupling to muons
  - → Constrain the coupling to charm quarks!



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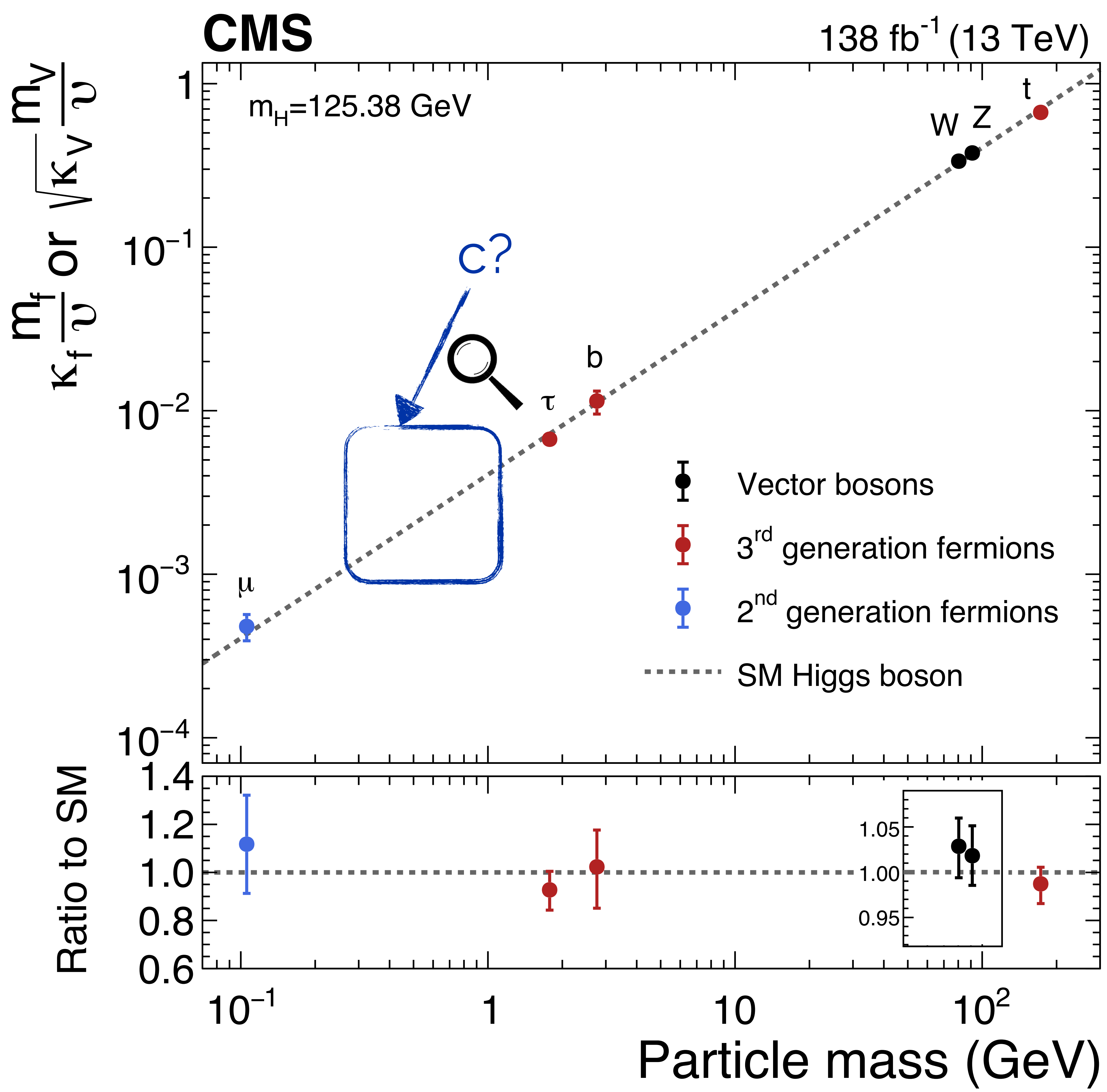
- Quark sector fundamentally harder than lepton sector
- We have to explore multiple avenues:

Indirect ← Model dependence? → Direct



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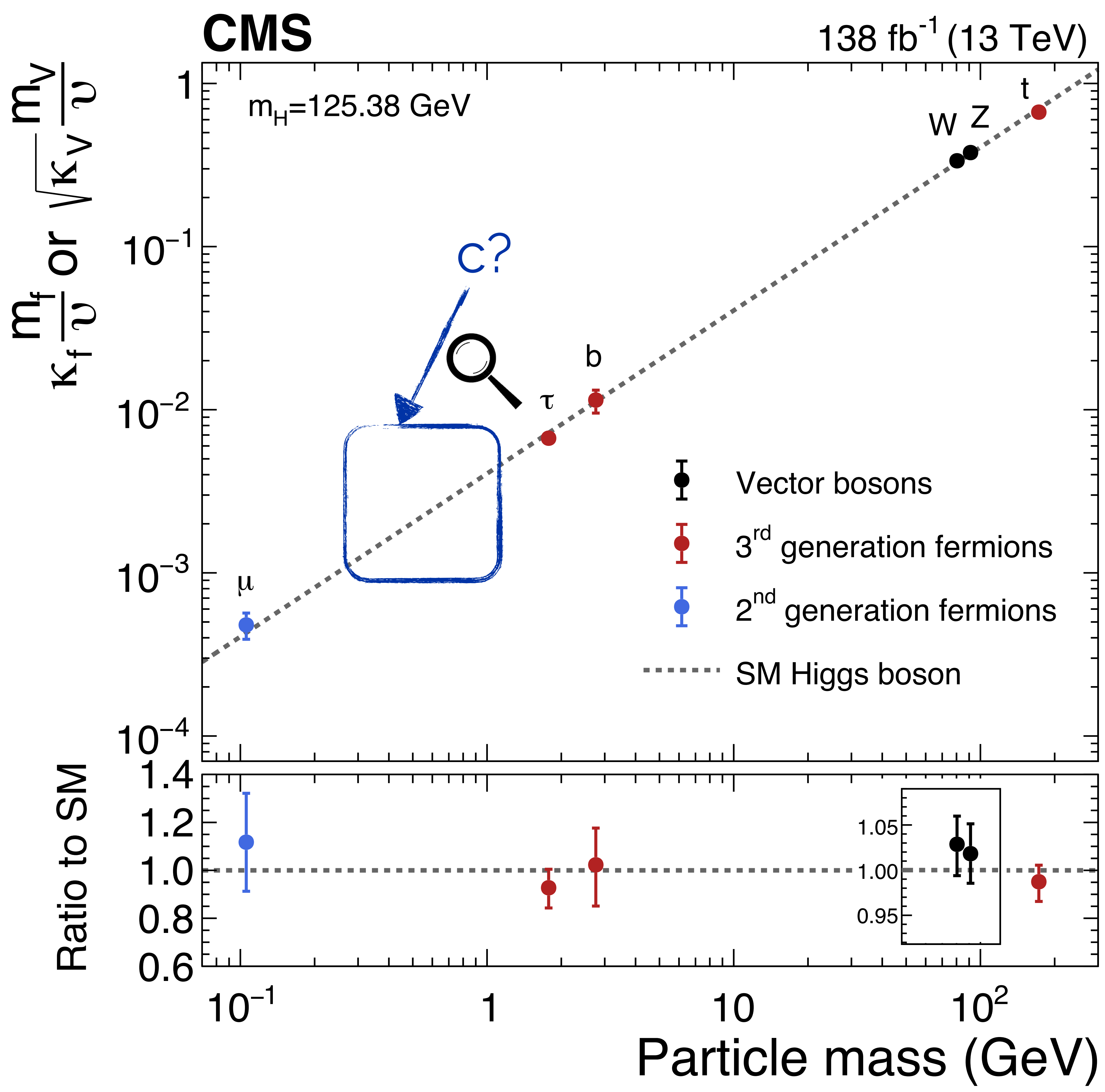


Indirect

Higgs kinematics and inclusive measurements

Direct

H → cc:
VH and ggH
& H+c

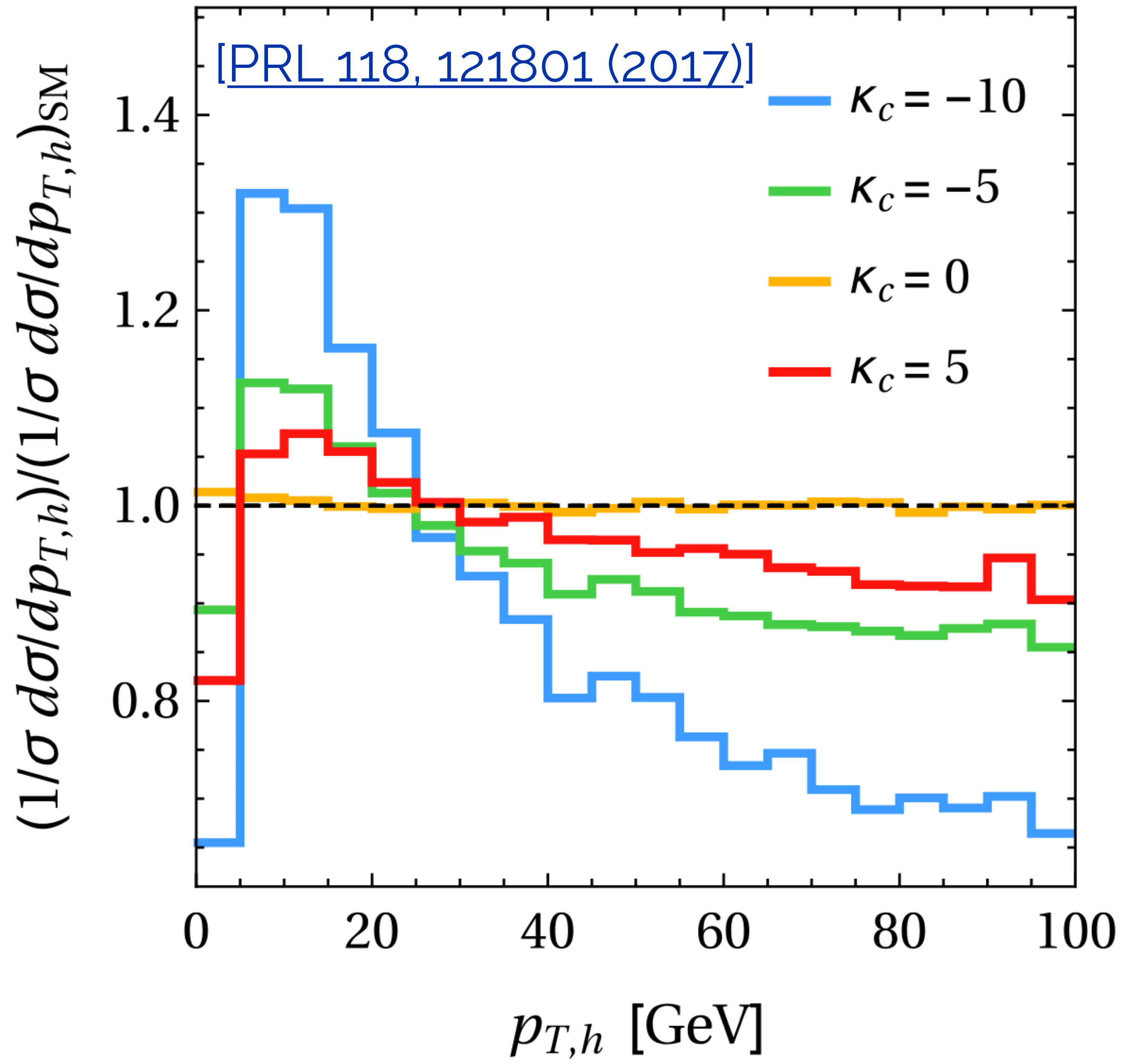
Rare decays:
Exclusive H decays to meson+boson

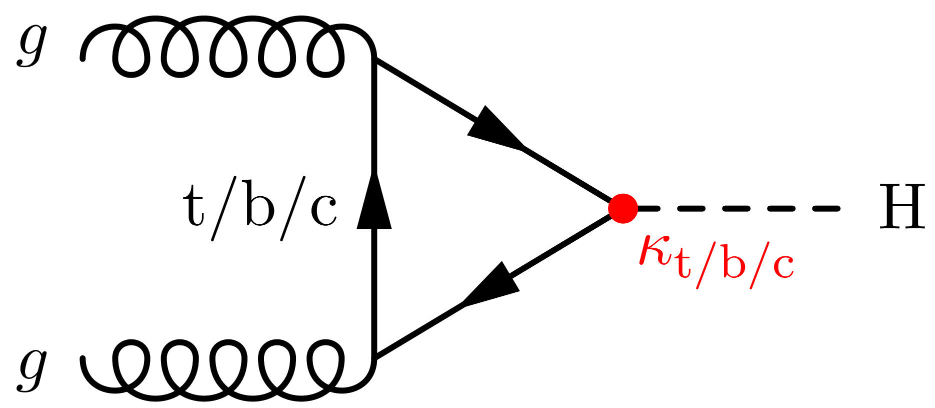
See also Anusree Vijay's talk yesterday

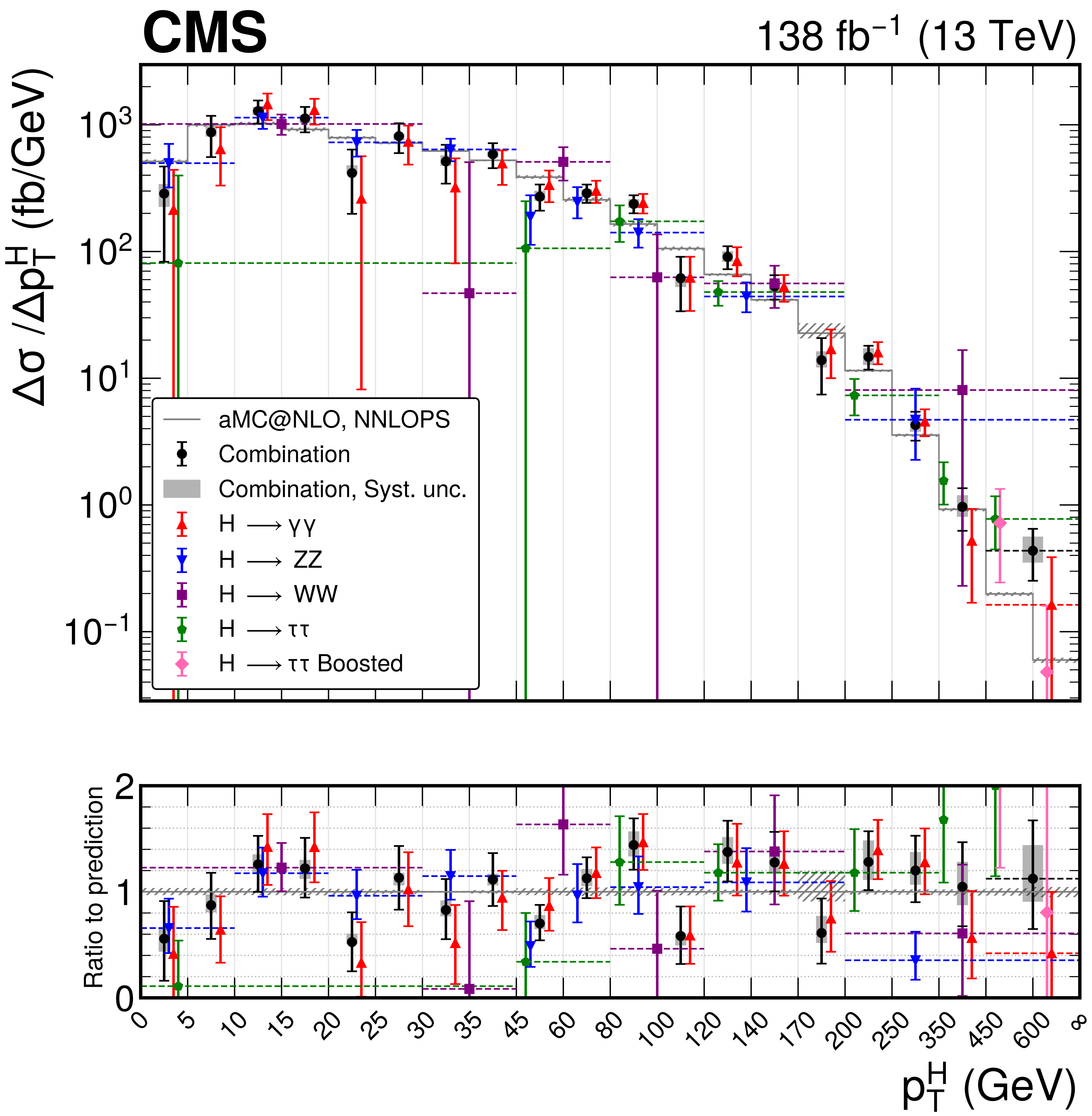
Indirect probes of y_c - differential Higgs p_T

[CMS-HIG-PAS-23-013]

- Differential distributions are sensitive to y_c (p_T, |y|, N_{Jets})
  - Able to separate c/b contributions







- Precise ggH p_T^H differential cross section obtained from combination CMS measurements:
  - γγ, ZZ(→4l), WW(→eμνν), ττ

- Simultaneous likelihood fit to detector level in uniform binning
- Extrapolated to full phase space

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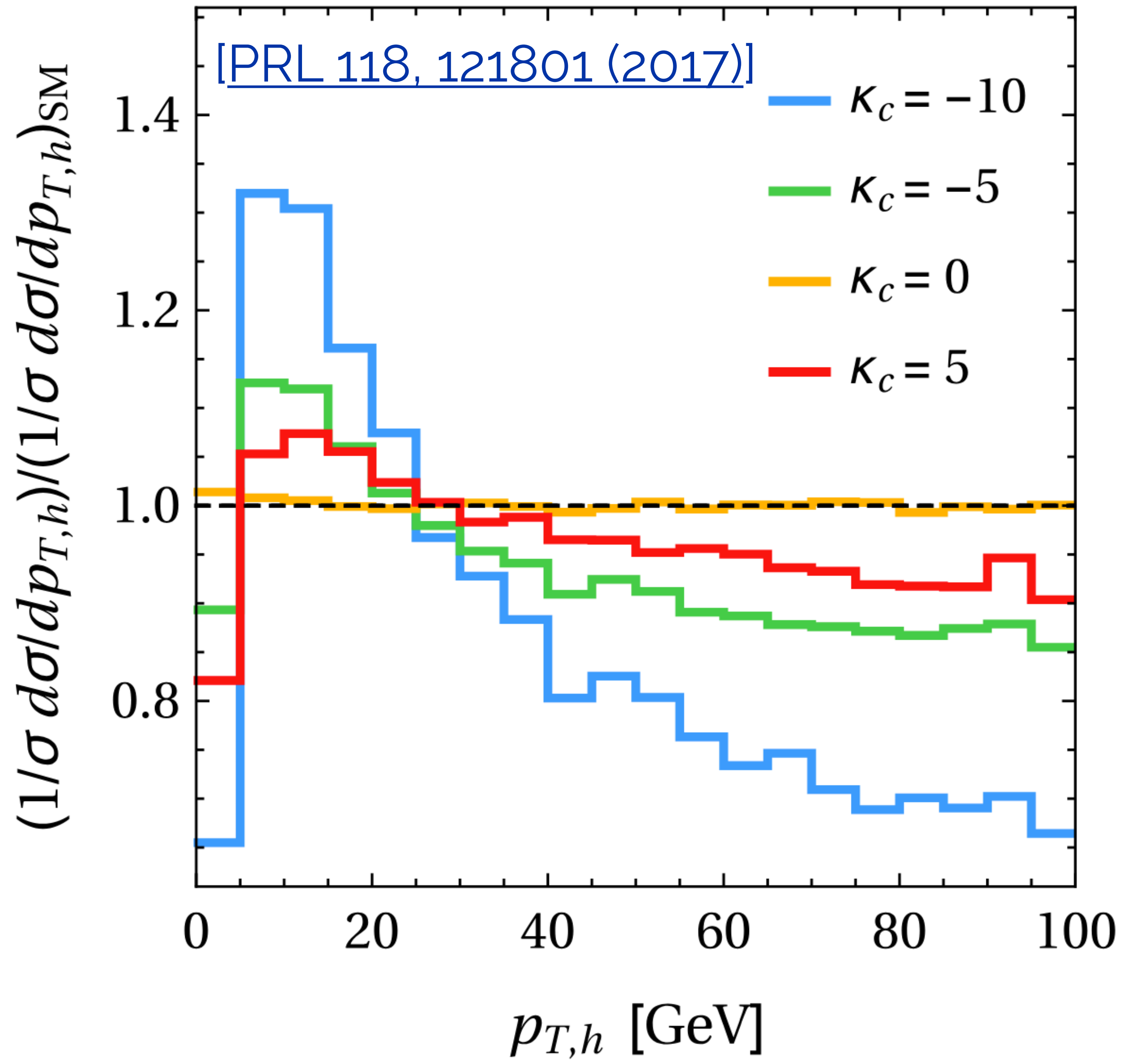

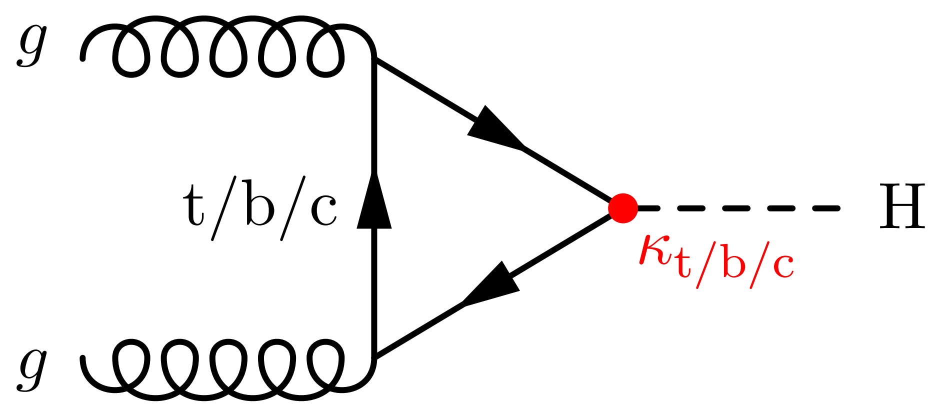

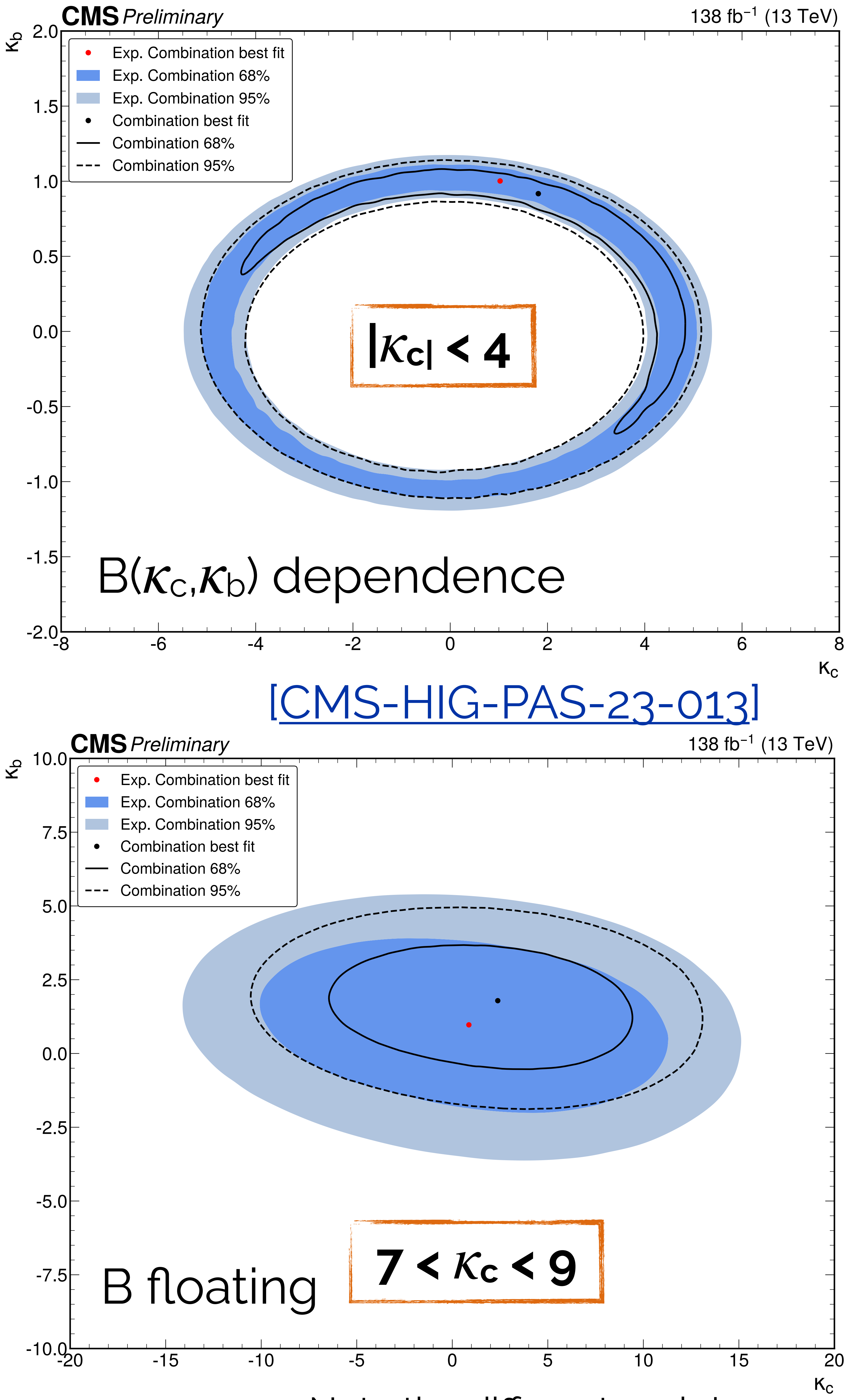

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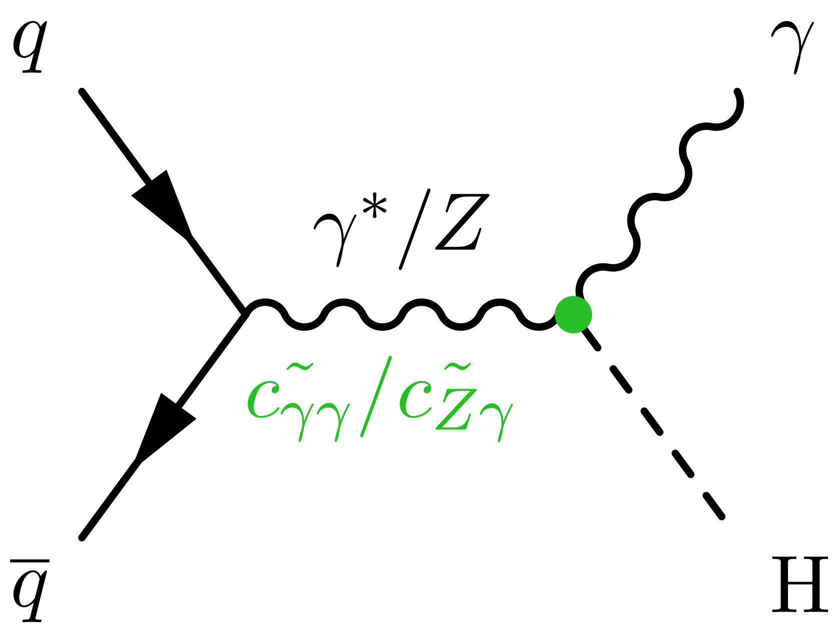
Note the different scale!

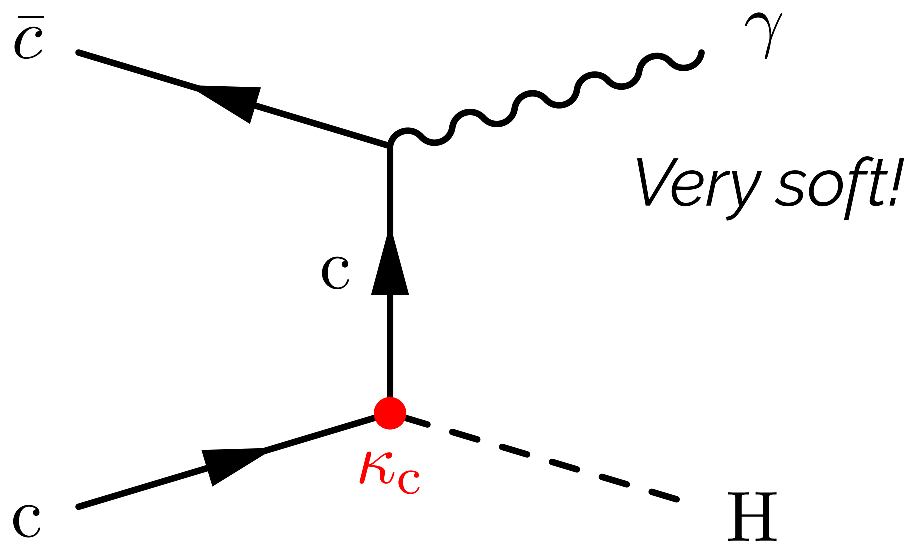
Indirect probes of y_c - H→4l + bb

[CMS-HIG-PAS-23-011]

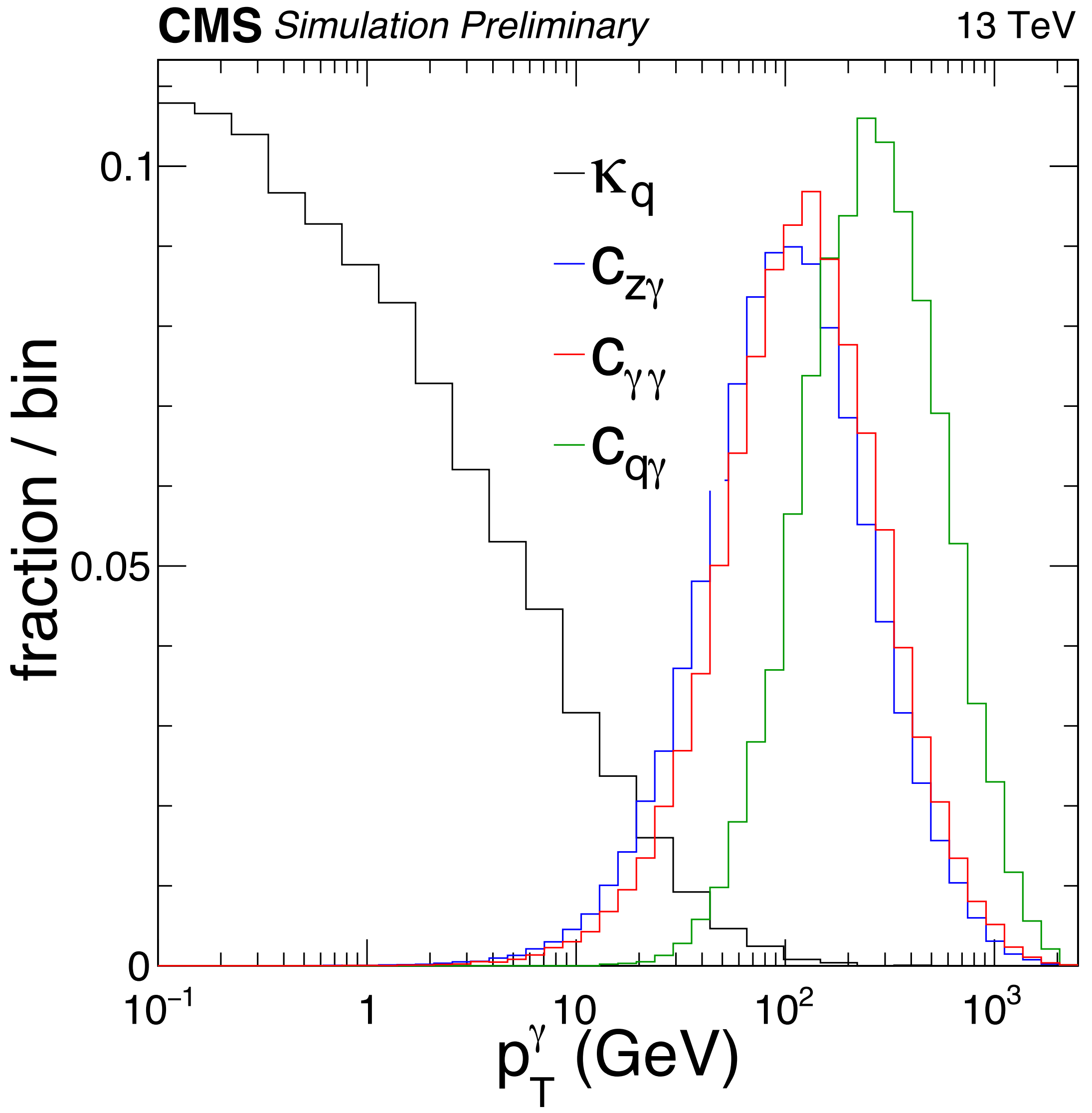
- Search for Hγ production w/ focus on boosted topology
  - Simultaneous analysis of H→bb and H→4l final states

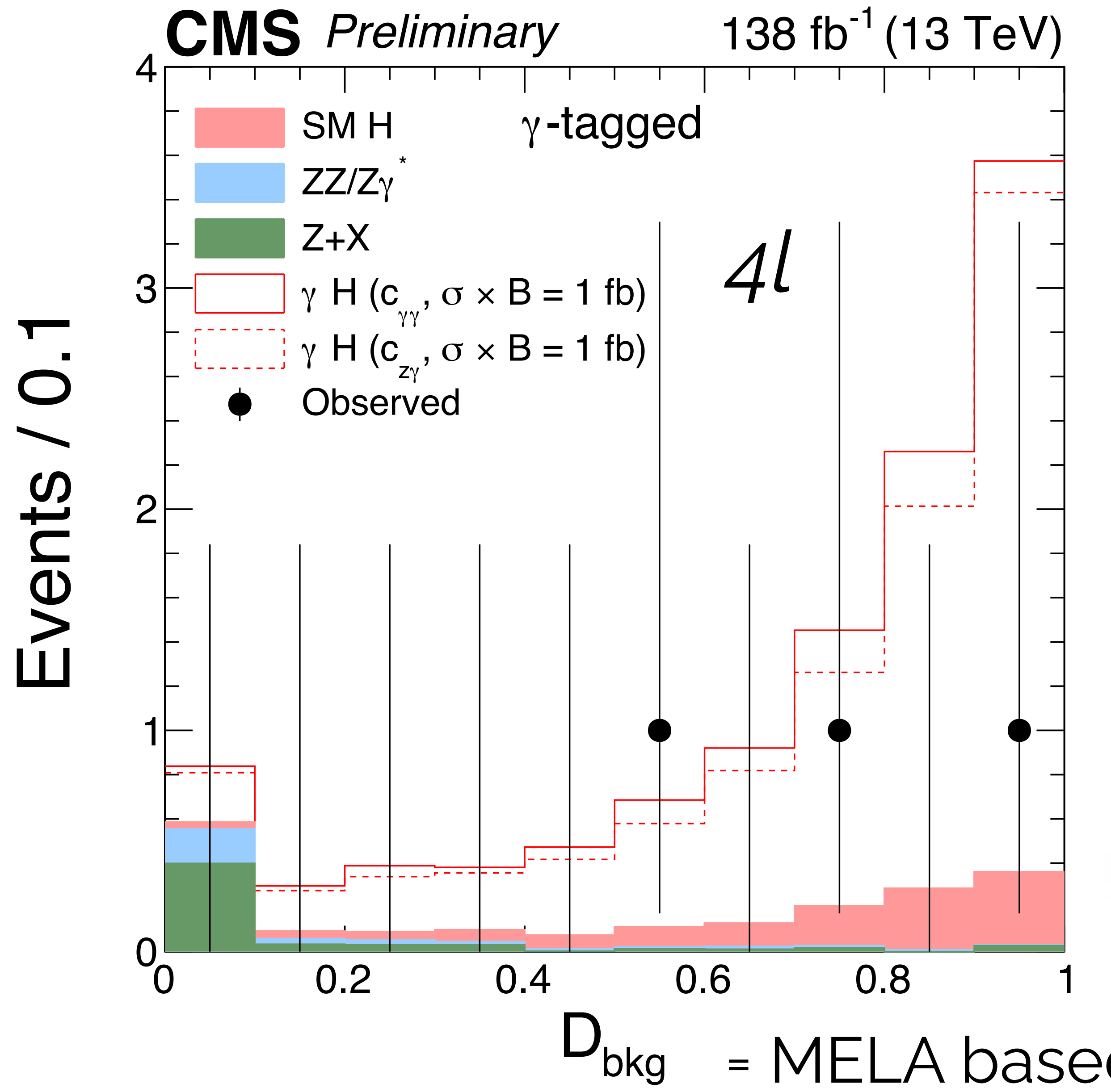


BSM motivation

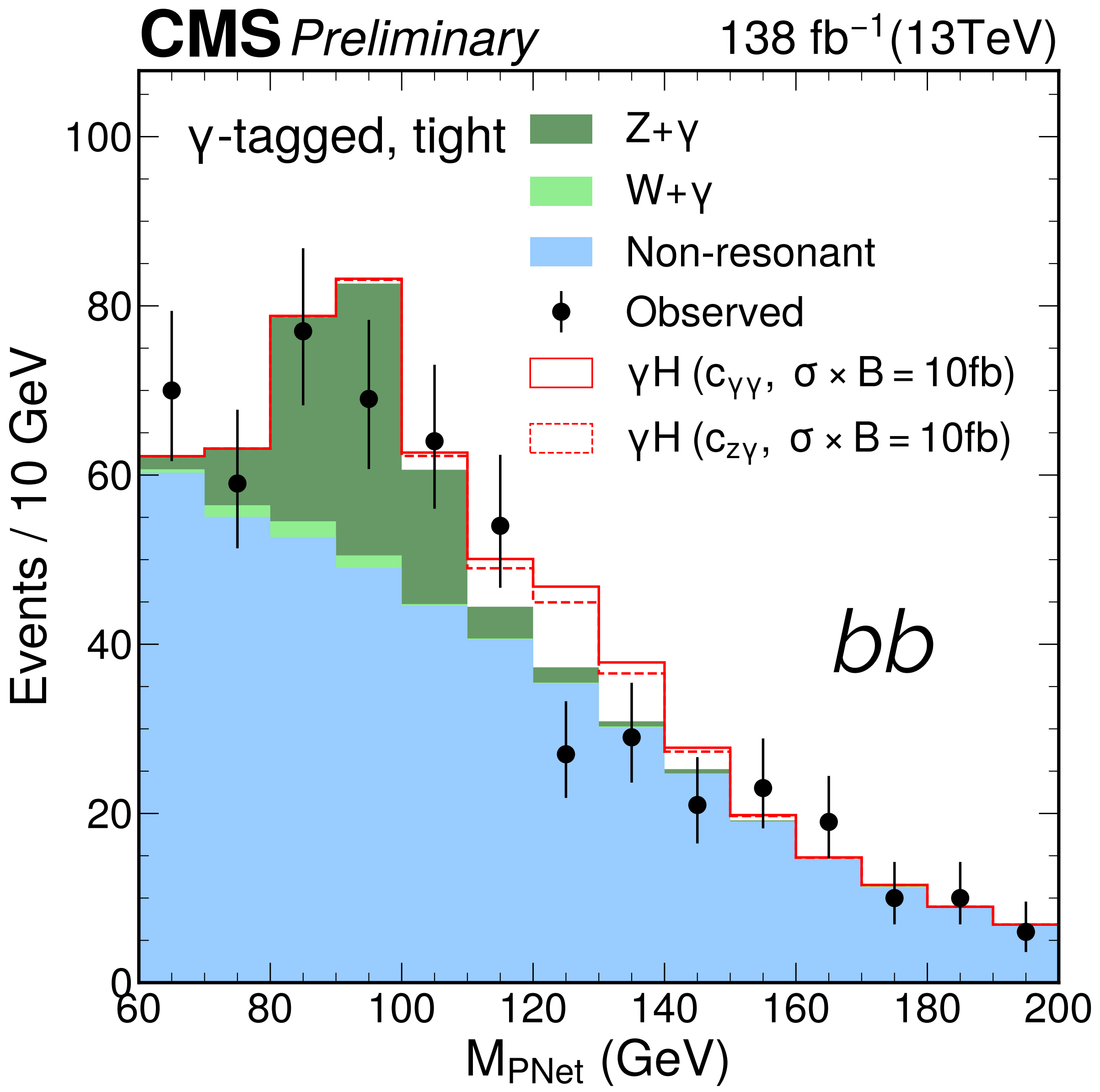


Dominant SM mode





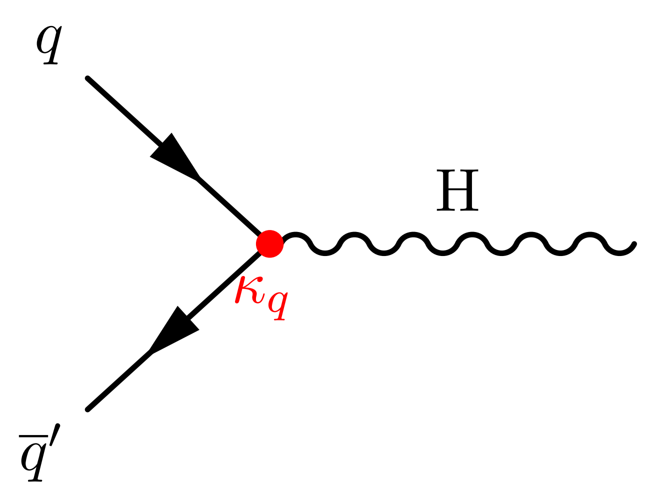
= MELA based discriminator

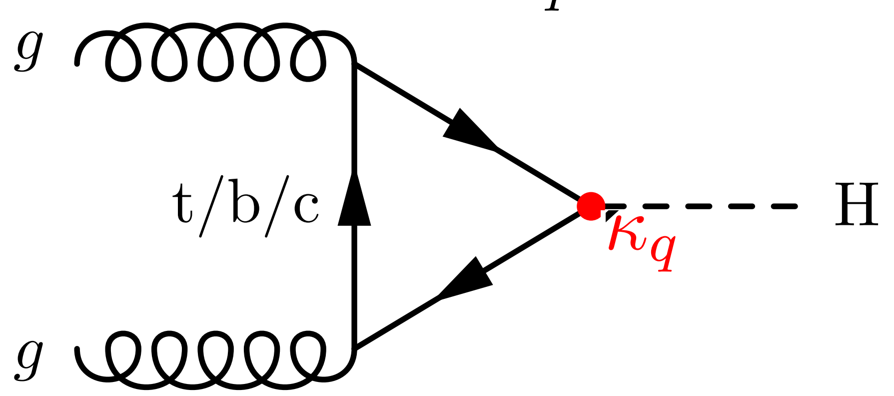


- Dedicated photon (un-)tagged categories w/ p_T^γ > 150 GeV

Indirect probes of y_c - H→4l

[CMS-HIG-PAS-23-011]





- Restructure the analysis:
  - Inclusive H→4l cross-section analysis
  - Merging (un-) tagged categories

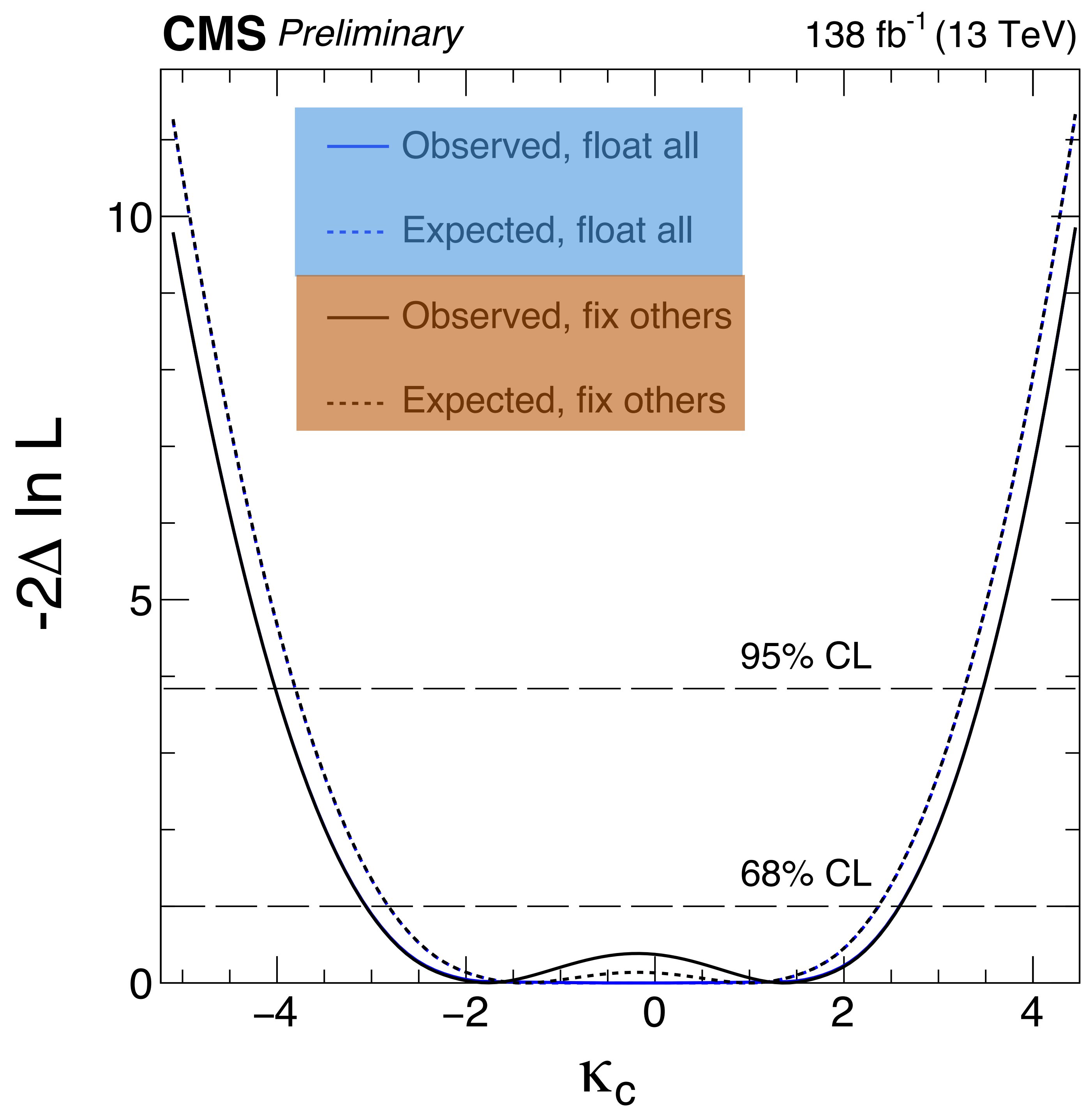
- Parametrize inclusive H signal:

$$\Gamma_{\mathrm{H}} = R_{\mathrm{gg}}(\kappa_{\mathrm{u,d,s,c,b}}) \cdot \Gamma^{\mathrm{SM}}_{\mathrm{H}\to\mathrm{gg}} + \sum_{\mathrm{q=u,d,s,c,b}} \kappa^2_{\mathrm{q}} \cdot \Gamma^{\mathrm{SM}}_{\mathrm{H}\to\mathrm{q\bar{q}}} + \sum_{\mathrm{VV'}} \kappa^2_{\mathrm{VV'}} \cdot \Gamma^{\mathrm{SM}}_{\mathrm{H}\to\mathrm{VV'}} + \sum_{\ell} \Gamma^{\mathrm{SM}}_{\mathrm{H}\to\ell\ell} + \Gamma^{\mathrm{BSM}}_{\mathrm{H}}$$

$$\sigma_{\mathrm{H}\to4\ell} = \frac{\Gamma^{\mathrm{SM}}_{\mathrm{H}\to4\ell} \cdot \kappa^2_{\mathrm{ZZ}}}{\Gamma_{\mathrm{H}}(\kappa_{\mathrm{u,d,s,c,b}})} \left(R_{\mathrm{gg}}(\kappa_{\mathrm{u,d,s,c,b}}) \cdot \sigma^{\mathrm{SM}}_{\mathrm{ggH}} + \sum_{\mathrm{q}} \kappa^2_{\mathrm{q}} \cdot \sigma^{\mathrm{SM}}_{\mathrm{q\bar{q}H}} + \sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}H}} + \sigma^{\mathrm{SM}}_{\mathrm{tH}} + \sum_{\mathrm{VV}} \kappa^2_{\mathrm{VV}} \cdot \sigma^{\mathrm{SM}}_{\mathrm{VVH}} \right)$$

- Fix $\kappa_b = \kappa_t = 1$ due to constraints from other measurements
  - $\kappa_{ZZ} = \kappa_{WW} = \kappa_{Z\gamma} = \kappa_{\gamma\gamma} = 1$
  - Constrained fit: $\Gamma_H^{BSM} = 0$, $\kappa_{ZZ}^2 = 1$, $\kappa_{q'} = 1$
  - Unconstrained fit: $\Gamma_H^{BSM} \geq 0$, $\kappa_{ZZ}^2 \leq 1$, $\kappa_{q'}$ = free

$-4.4 < \kappa_c < 3.4$



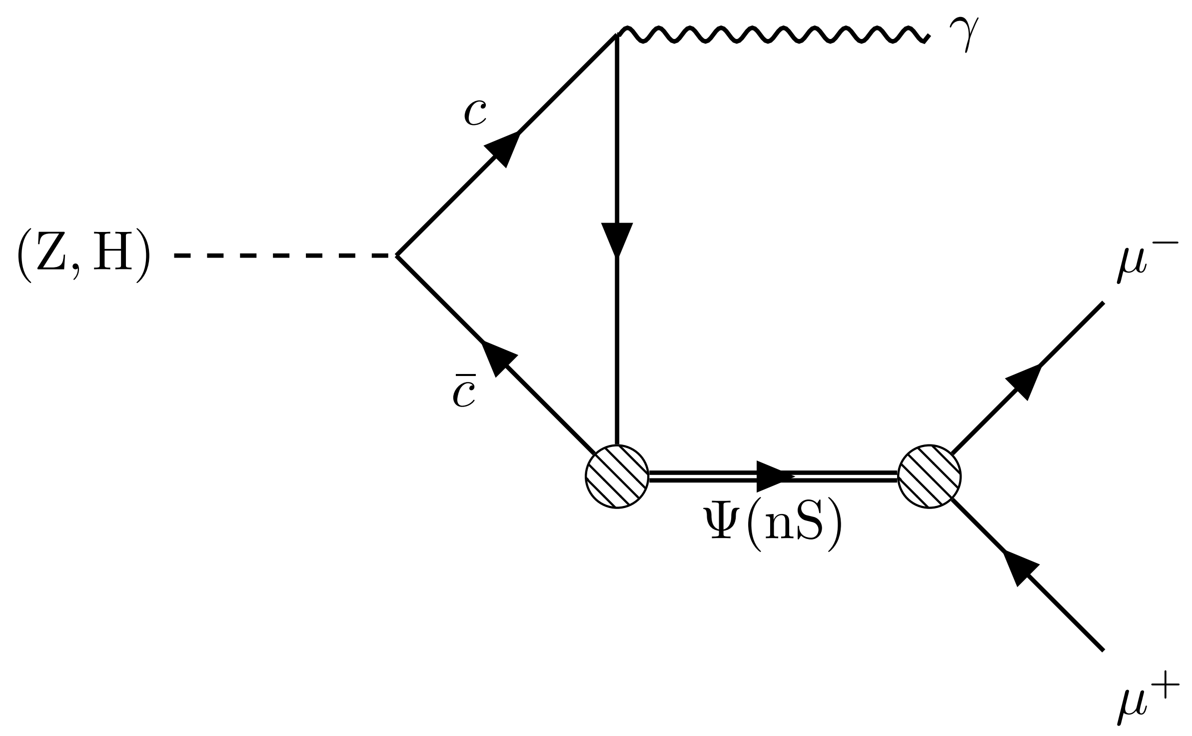
Parameter	Scenario	Observed		Expected	
κ_u	float all	$(0.0 \pm 1.5) \times 10^3$	$[-2.4, 2.4] \times 10^3$	$(0.0 \pm 1.8) \times 10^3$	$[-2.6, 2.6] \times 10^3$
κ_u	fix others	$(0.0 \pm 1.4) \times 10^3$	$[-2.3, 2.3] \times 10^3$	$(0.0 \pm 1.6) \times 10^3$	$[-2.5, 2.5] \times 10^3$
κ_d	float all	$(0.0 \pm 7.1) \times 10^2$	$[-1.0, 1.0] \times 10^3$	$(0.0 \pm 7.4) \times 10^2$	$[-1.0, 1.0] \times 10^3$
κ_d	fix others	$(1.5^{+5.0}_{-8.0}) \times 10^2$	$[-9.7, 9.7] \times 10^2$	$(0.0 \pm 6.5) \times 10^2$	$[-9.7, 9.7] \times 10^2$
κ_s	float all	0^{+33}_{-34}	$[-46, 44]$	1^{+32}_{-31}	$[-44, 42]$
κ_s	fix others	11^{+19}_{-42}	$[-44, 42]$	1^{+26}_{-30}	$[-41, 40]$
κ_c	float all	$0.0^{+2.7}_{-3.0}$	$[-4.0, 3.4]$	$1.0^{+1.4}_{-3.8}$	$[-3.8, 3.2]$
κ_c	fix others	$1.4^{+1.2}_{-4.4}$	$[-4.0, 3.5]$	$1.0^{+1.3}_{-3.8}$	$[-3.8, 3.2]$
Γ_H^{BSM} (MeV)	float all	$0.0^{+0.9}_{-0.0}$	< 1.6	$0.0^{+0.7}_{-0.0}$	< 1.4

κ_b fixed

Rare decays - Z/H→J/Ψ + γ

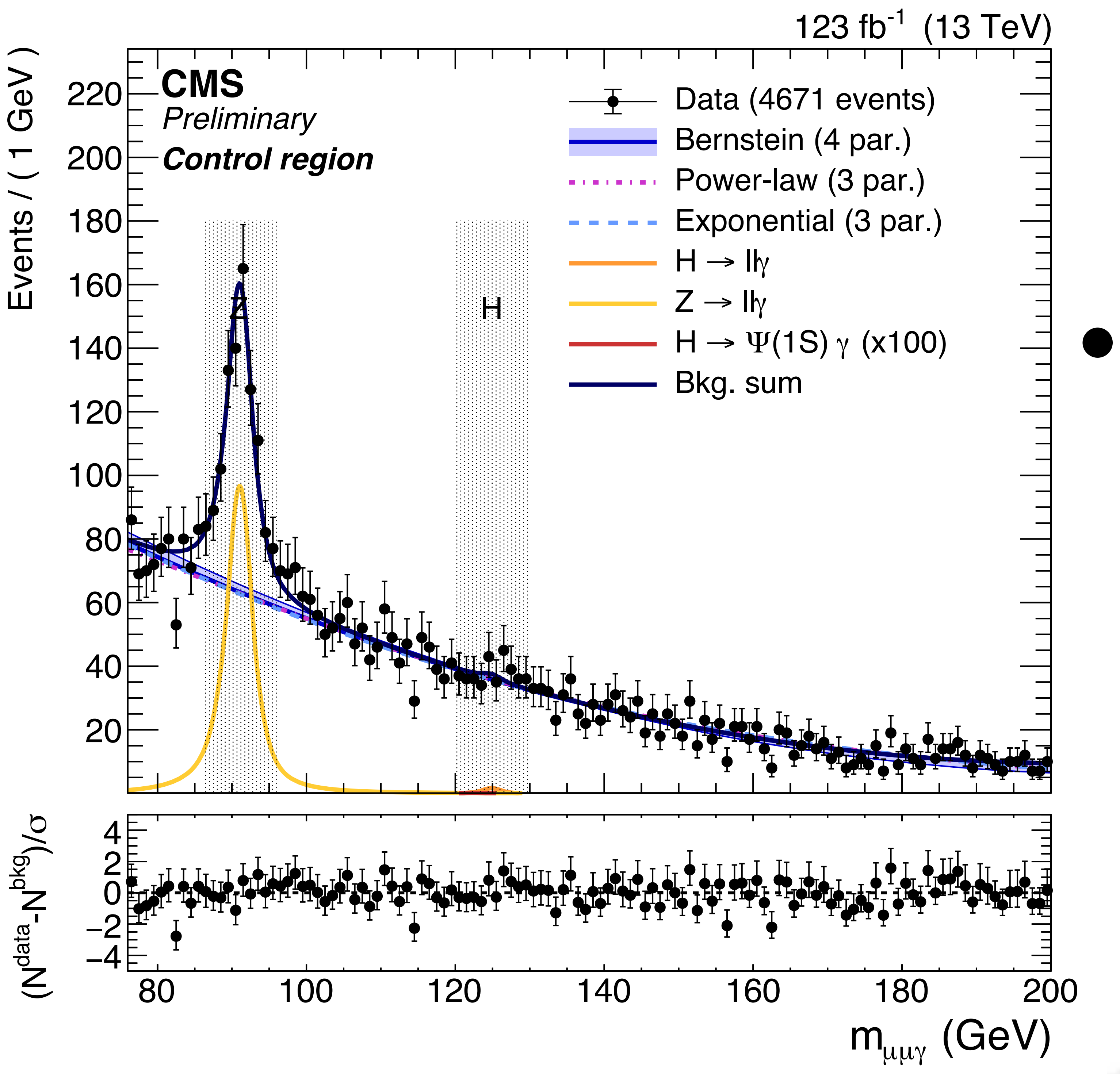
[CMS-SMP-PAS-22-012]

- Higgs decay via c-quark loops to photon + charmonia

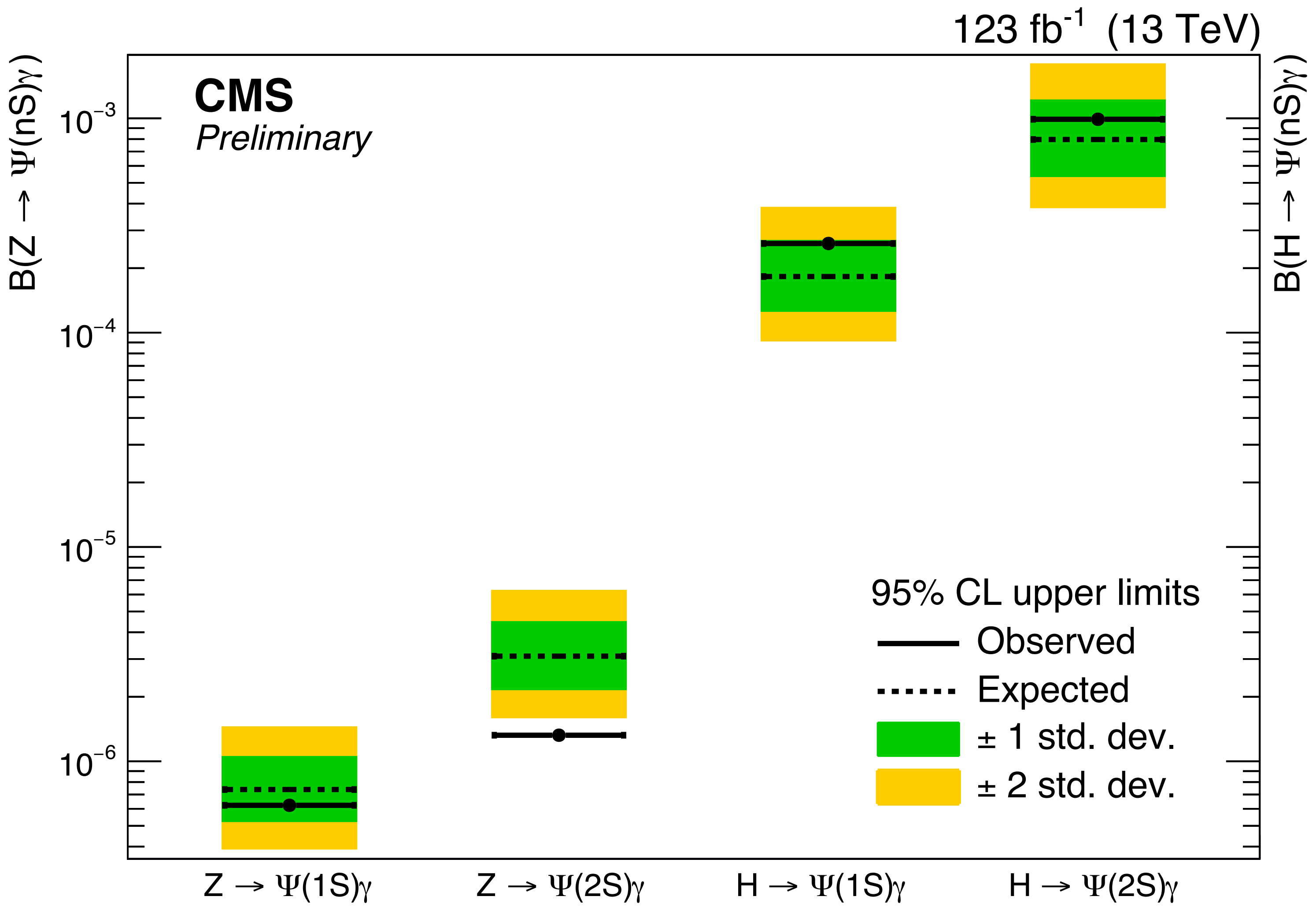


- Exploit excellent muon reconstruction of CMS
  - Dimuon + photon final state
- Z boson equivalent ~100 more frequent
- Branching fractions < 10^{-6}

Process	$\mathcal{B}$
$H \to \Psi(1S)\gamma$	$3.01^{+0.15}_{-0.15} \times 10^{-6}$
$Z \to \Psi(1S)\gamma$	$8.96^{+1.51}_{-1.38} \times 10^{-8}$
$H \to \Psi(2S)\gamma$	$1.03^{+0.06}_{-0.06} \times 10^{-6}$
$Z \to \Psi(2S)\gamma$	$4.83^{+1.02}_{-0.91} \times 10^{-8}$
$\Psi(1S) \to \mu^+\mu^-$	$5.961^{+0.033}_{-0.033} \times 10^{-2}$
$\Psi(2S) \to \mu^+\mu^-$	$8.0^{+0.6}_{-0.6} \times 10^{-3}$



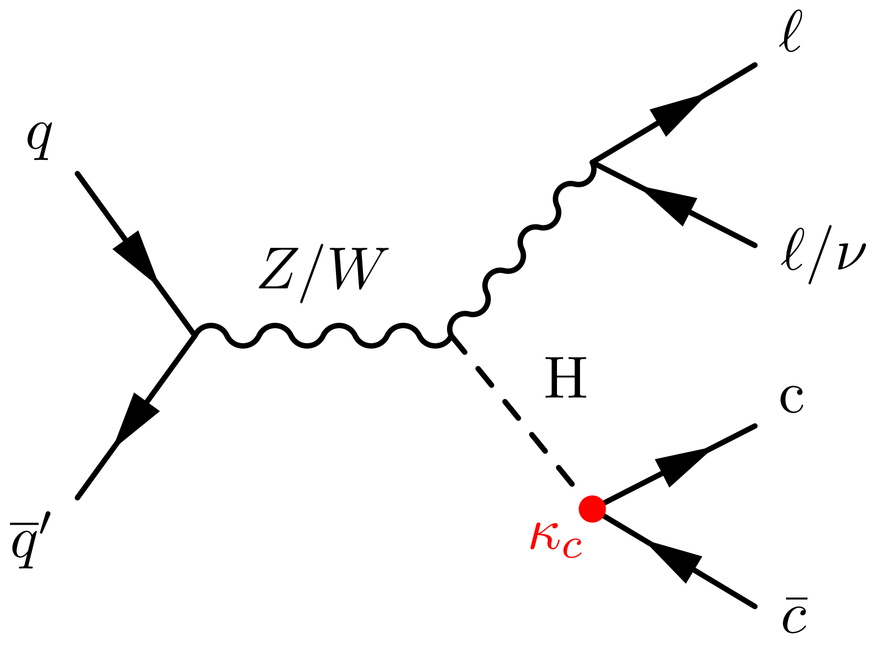
- Fit to VBF, ggH, HF (ttH+bbH) SRs + CR



- Assuming $\kappa_\gamma = 1$ → **$-166 < \kappa_c < 208$**
- **More than factor 2 improvement wrt. 2016 search**

"The golden channel": VH(→cc)

- Direct measurements require (ideally):
  - Sharp mass peak
  - Suppressed and well understood background
- Learn from history of VH(bb) measurements



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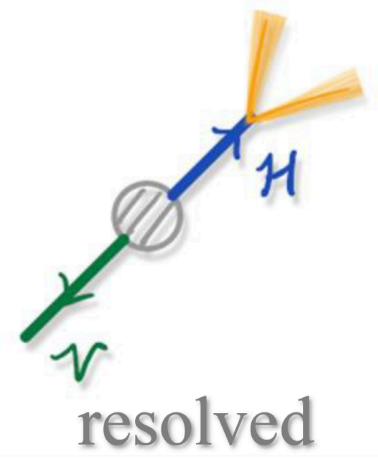

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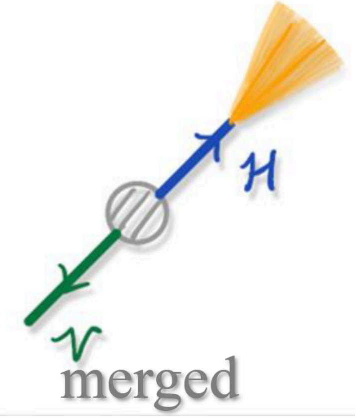
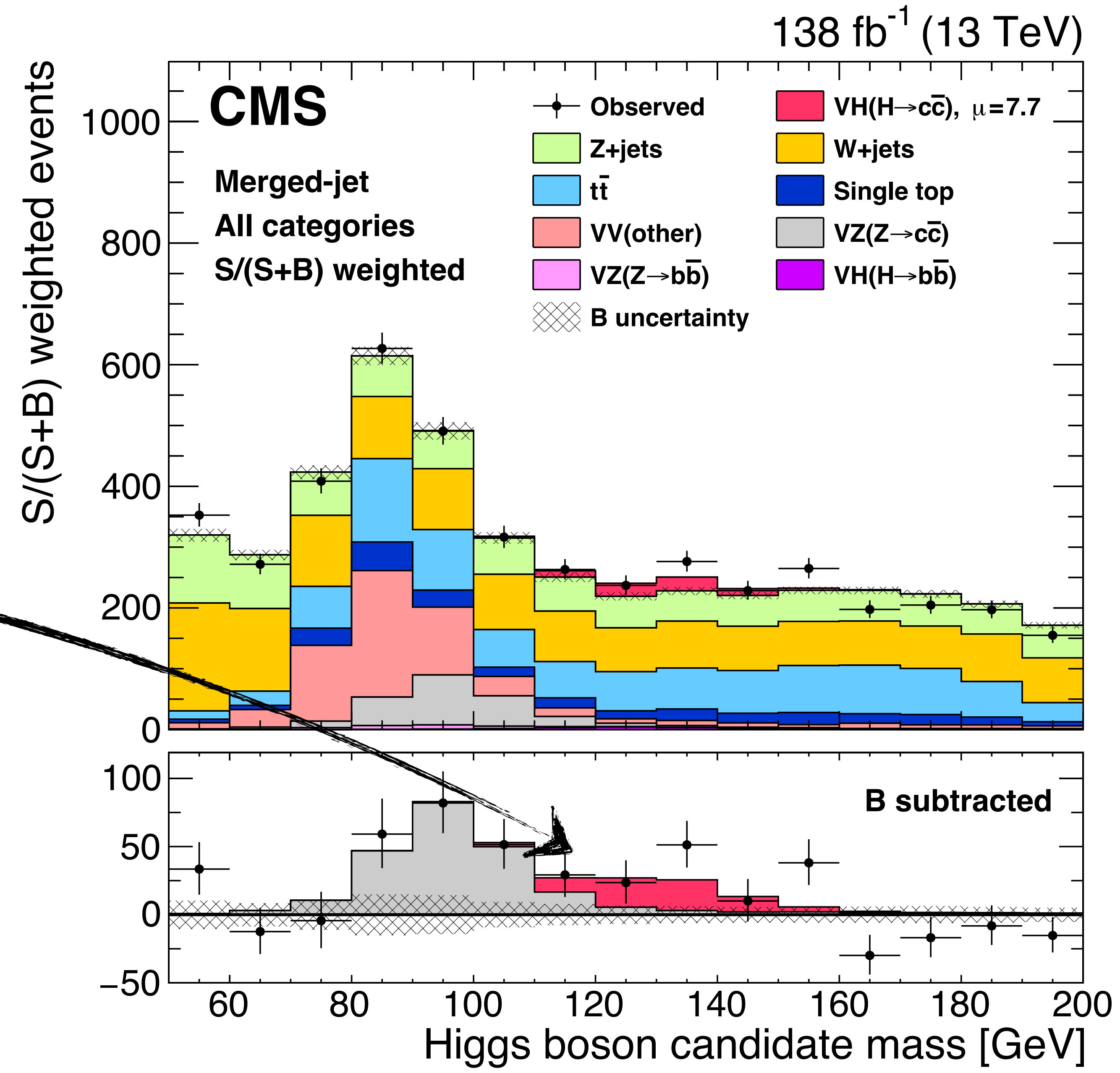
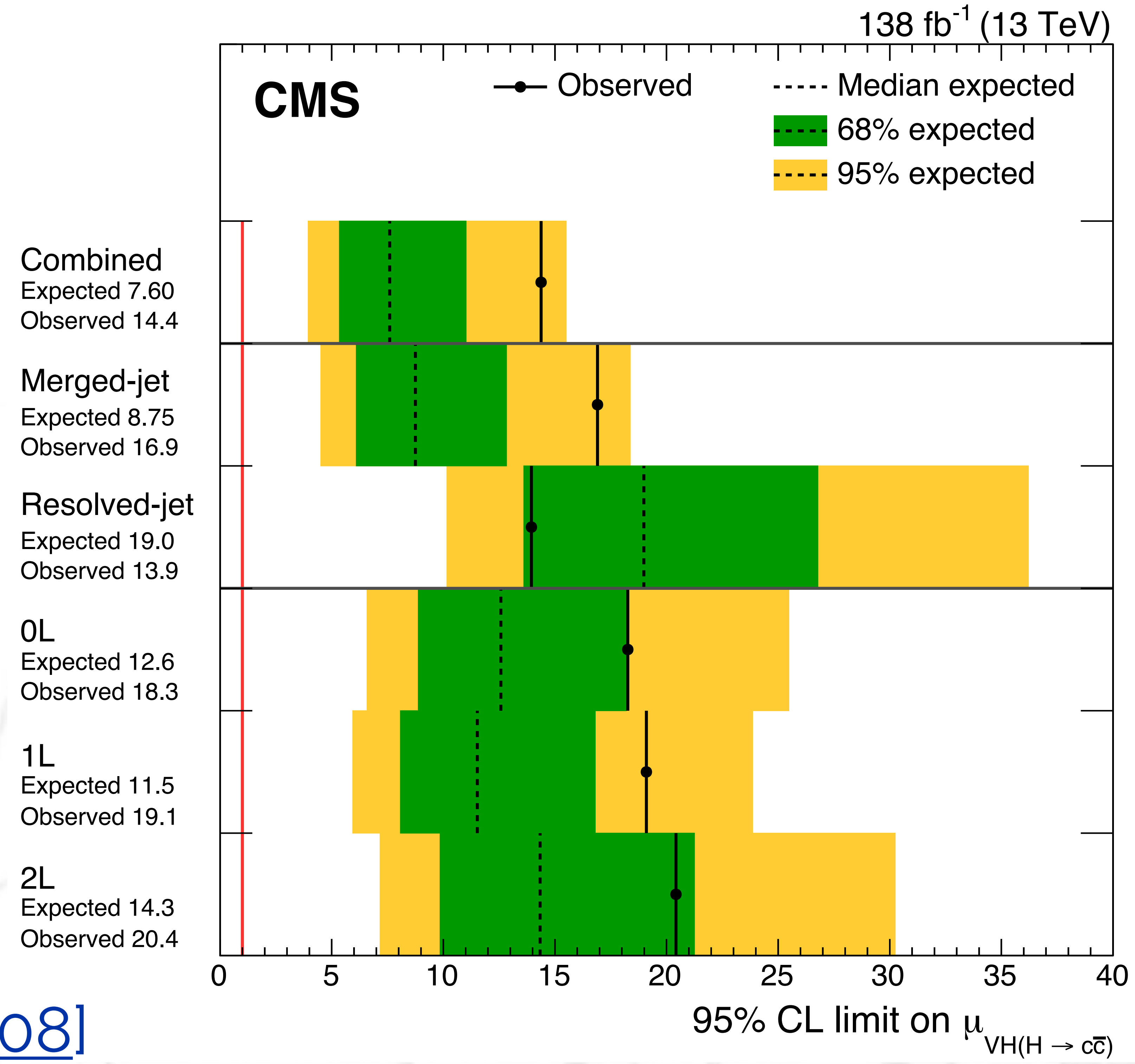




Boosted channel

- 0L, 1L, and 2L categories (Z→νν, W→lν, Z→ll)
- "Resolved" and "boosted" channels (transition at p_T 300 GeV)
- Exploit Z→cc SM candle: First observation at hadron colliders with 5.7σ
- Observed (expected) upper limit on VH(cc) signal: μ < 14 (7.6)
- If we assume all other couplings to have SM values: **1.1 < κ_c < 5.5**
  - **Strongest direct constraints to date**

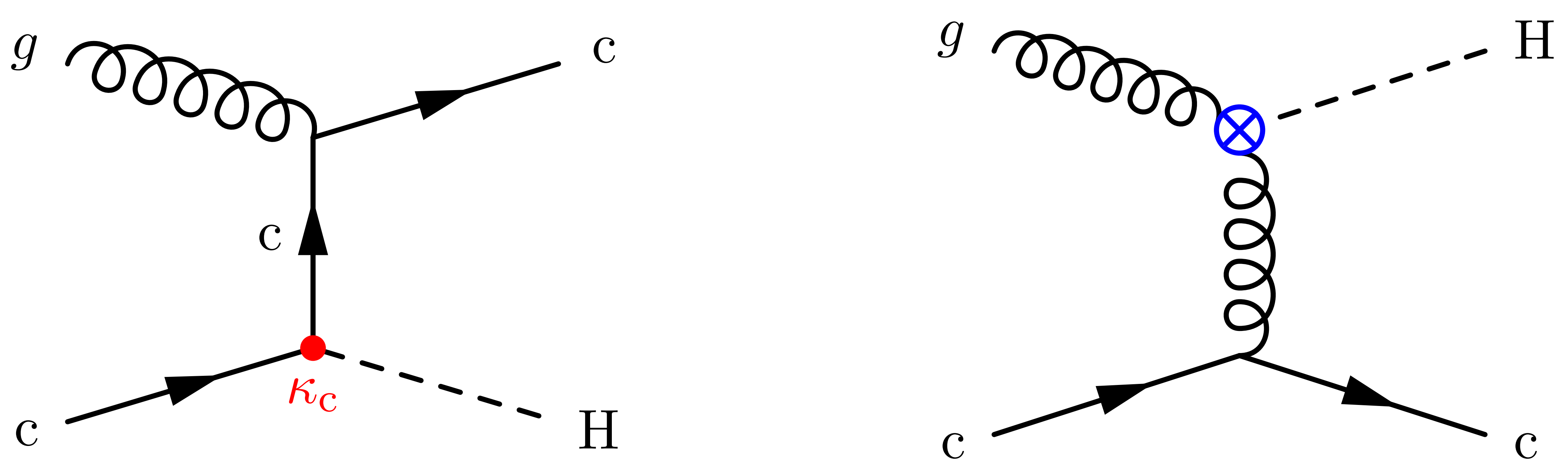


[CMS-HIG-21-008]

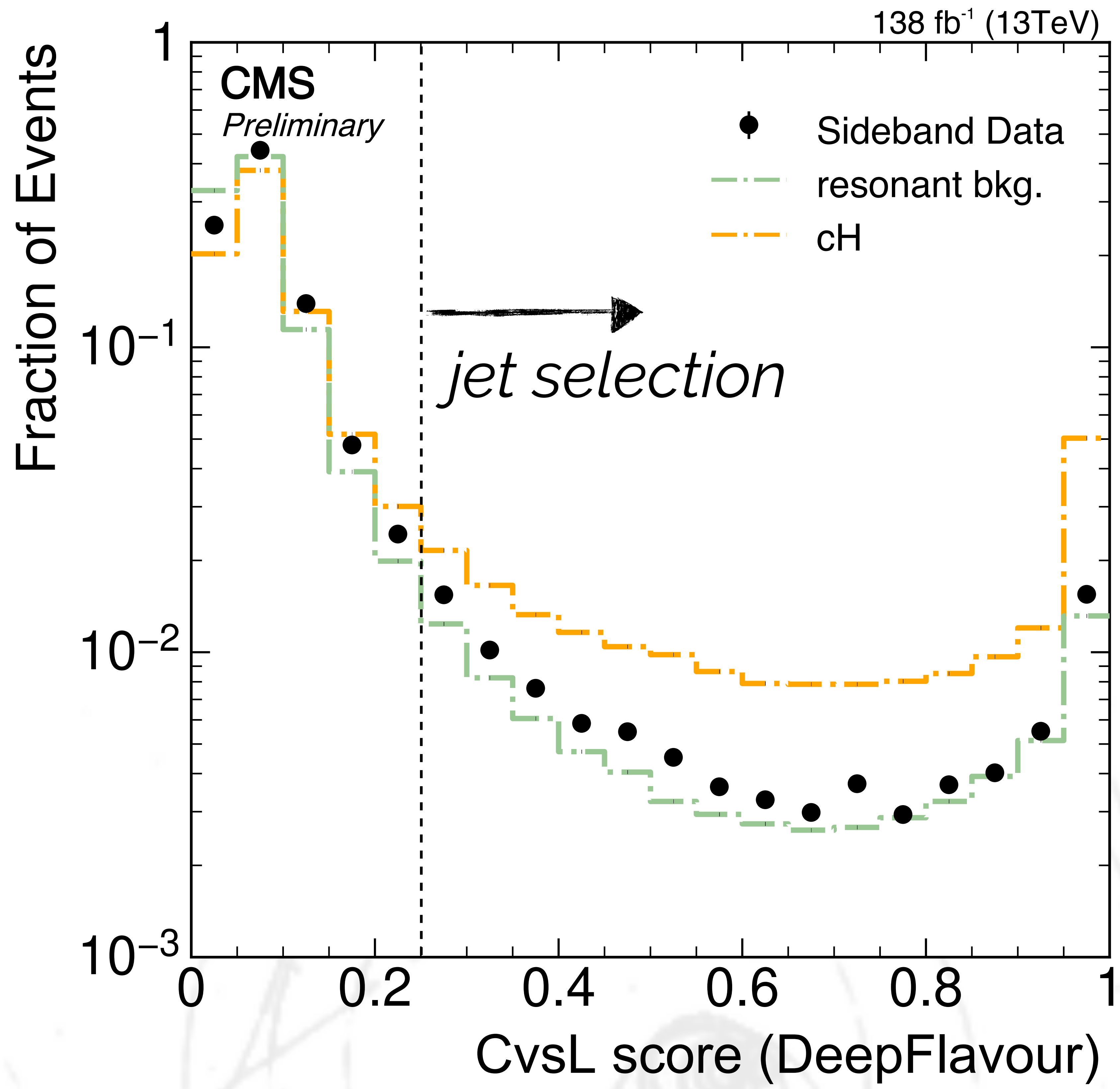
H+c associated production

Motivation from [arXiv:1507.02916]

- Clear advantage: Use any Higgs decay, ideally with low background



[CMS-PAS-HIG-23-010]



- However: signal-sensitive cross section ~90 fb
- Very difficult background: ggH and insensitive H+c production

- Use the high-purity final state with two photons
  - Base on the “standard” H→γγ strategy and knowledge
  - In the analysis selection: ~0.06 expected signal events (22500 bkg)

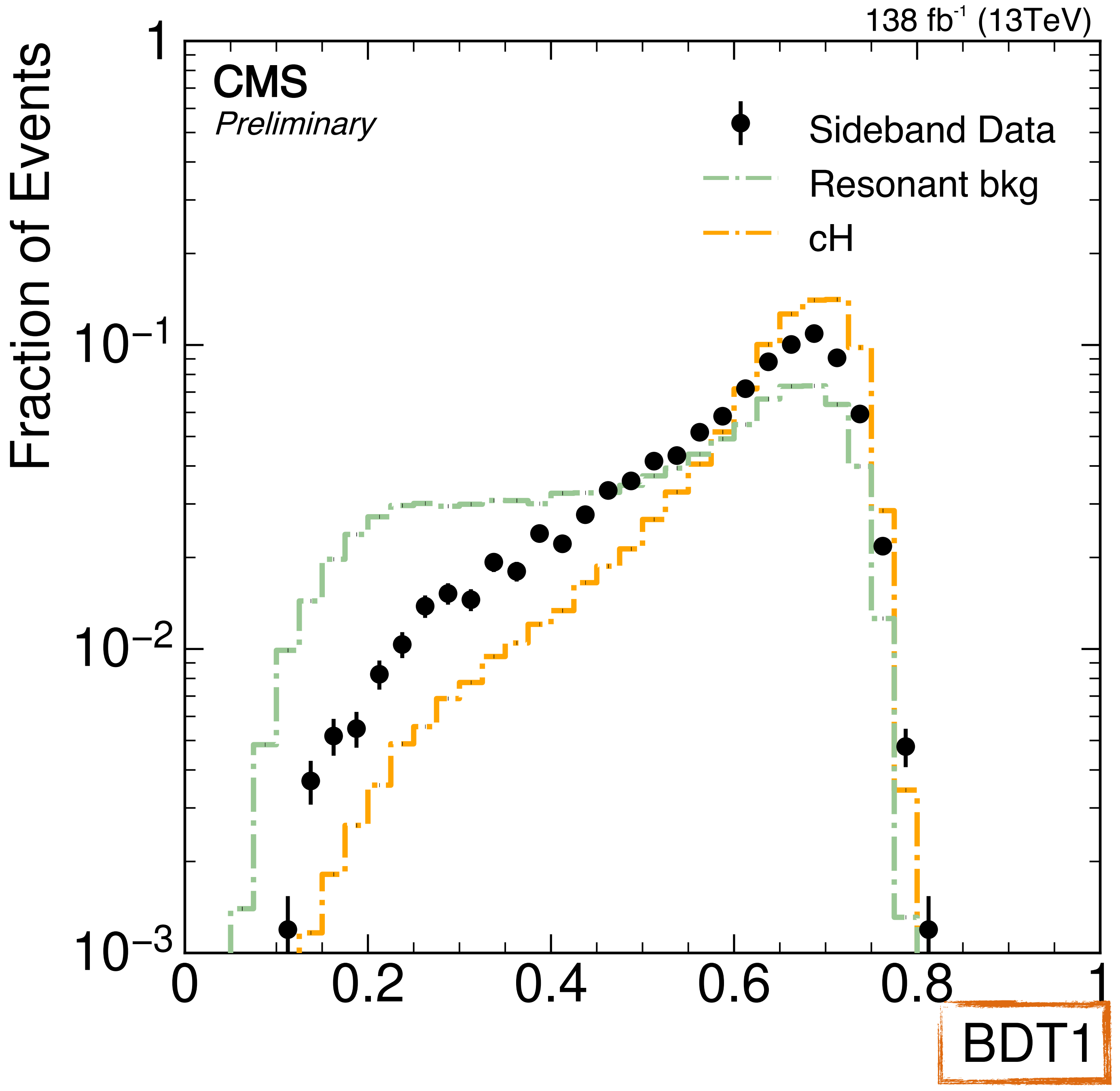
- Also here: charm-tagging is a crucial ingredient

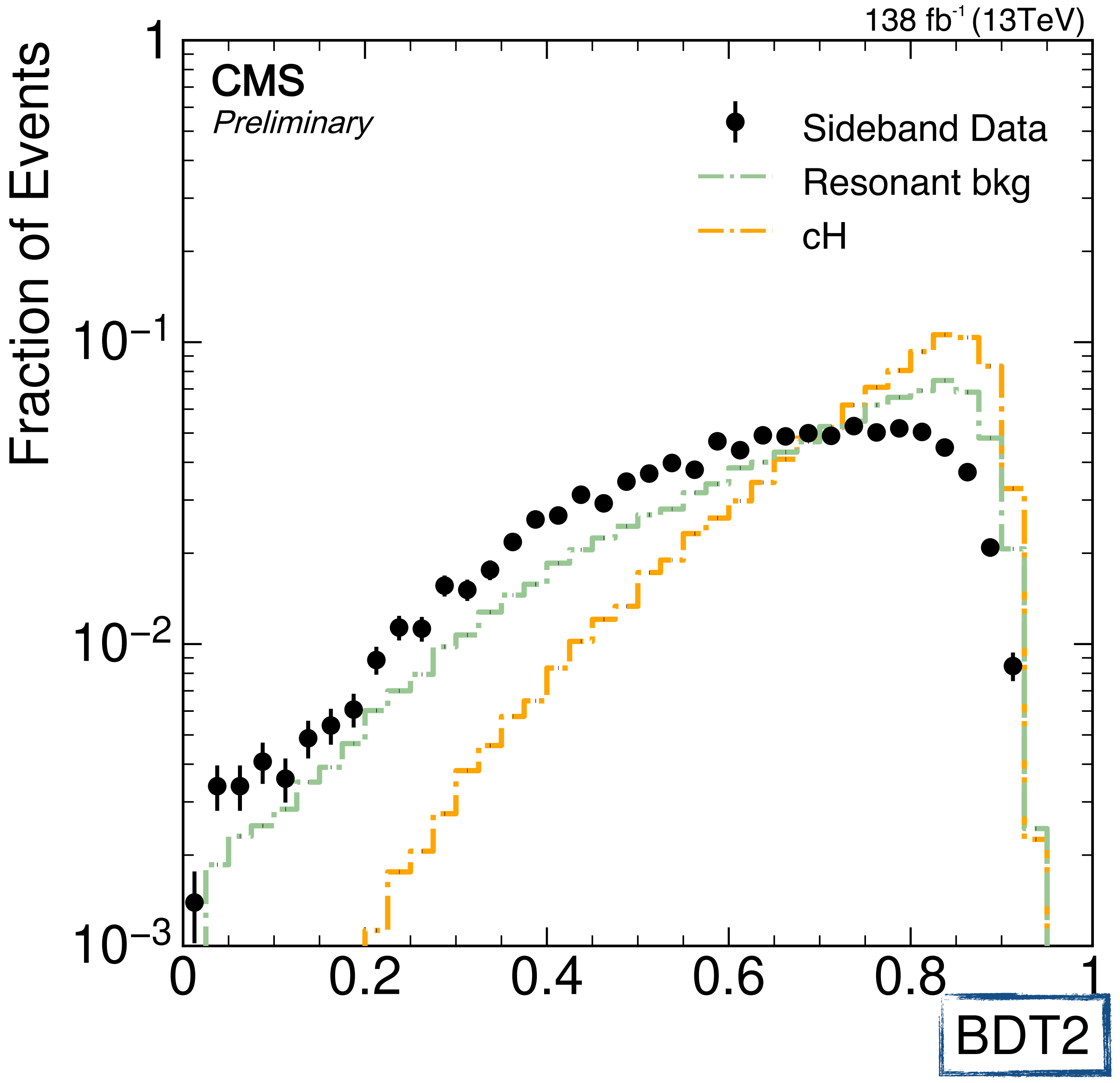
See also Tiziano Bevilacqua’s talk

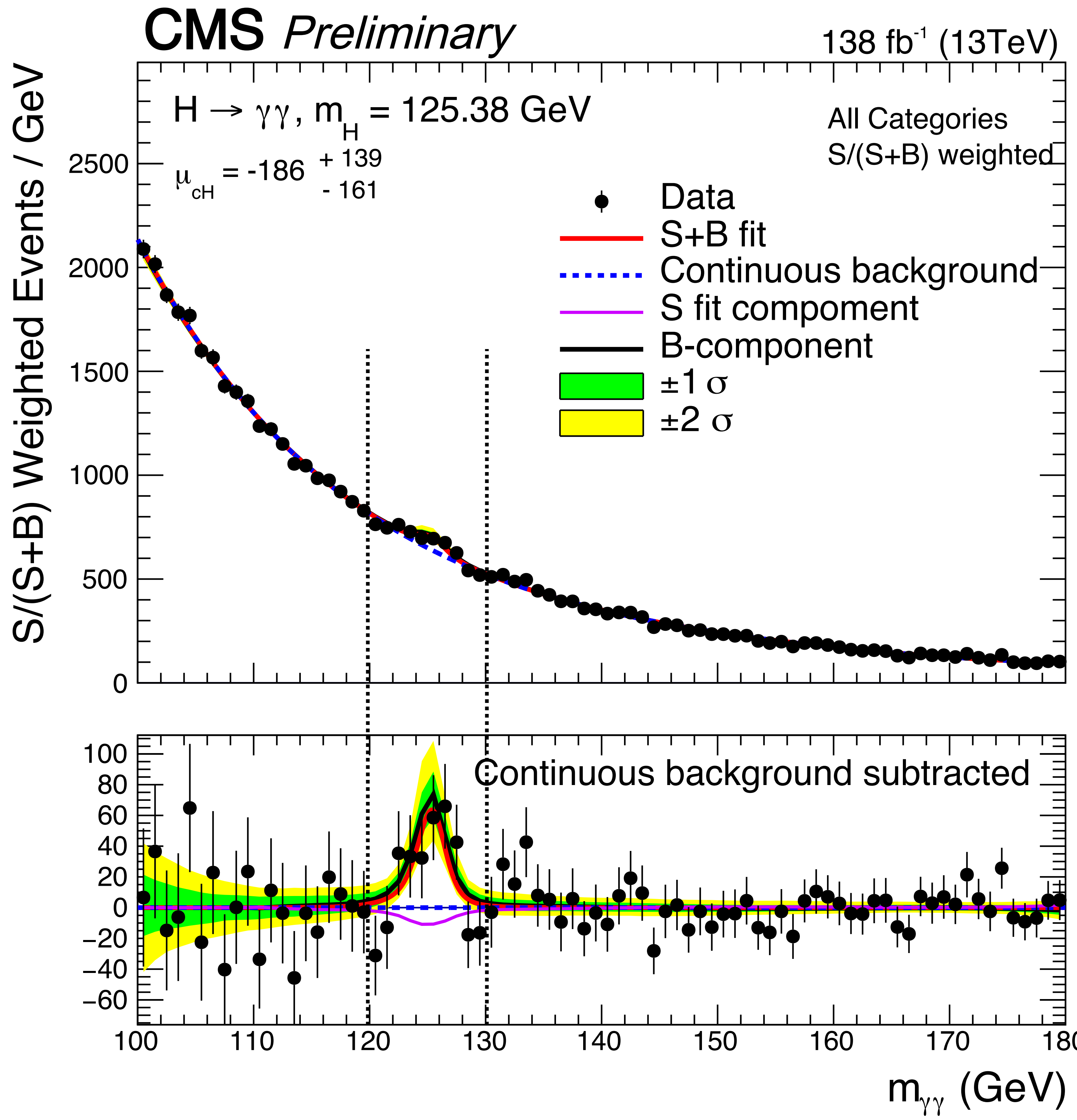
H+c associated production

- Diphoton event selection + charm-tagged additional jet
- Employ two BDTs to separate ggH (BDT 1) and continuous backgrounds (BDT 2)

[CMS-PAS-HIG-23-010]







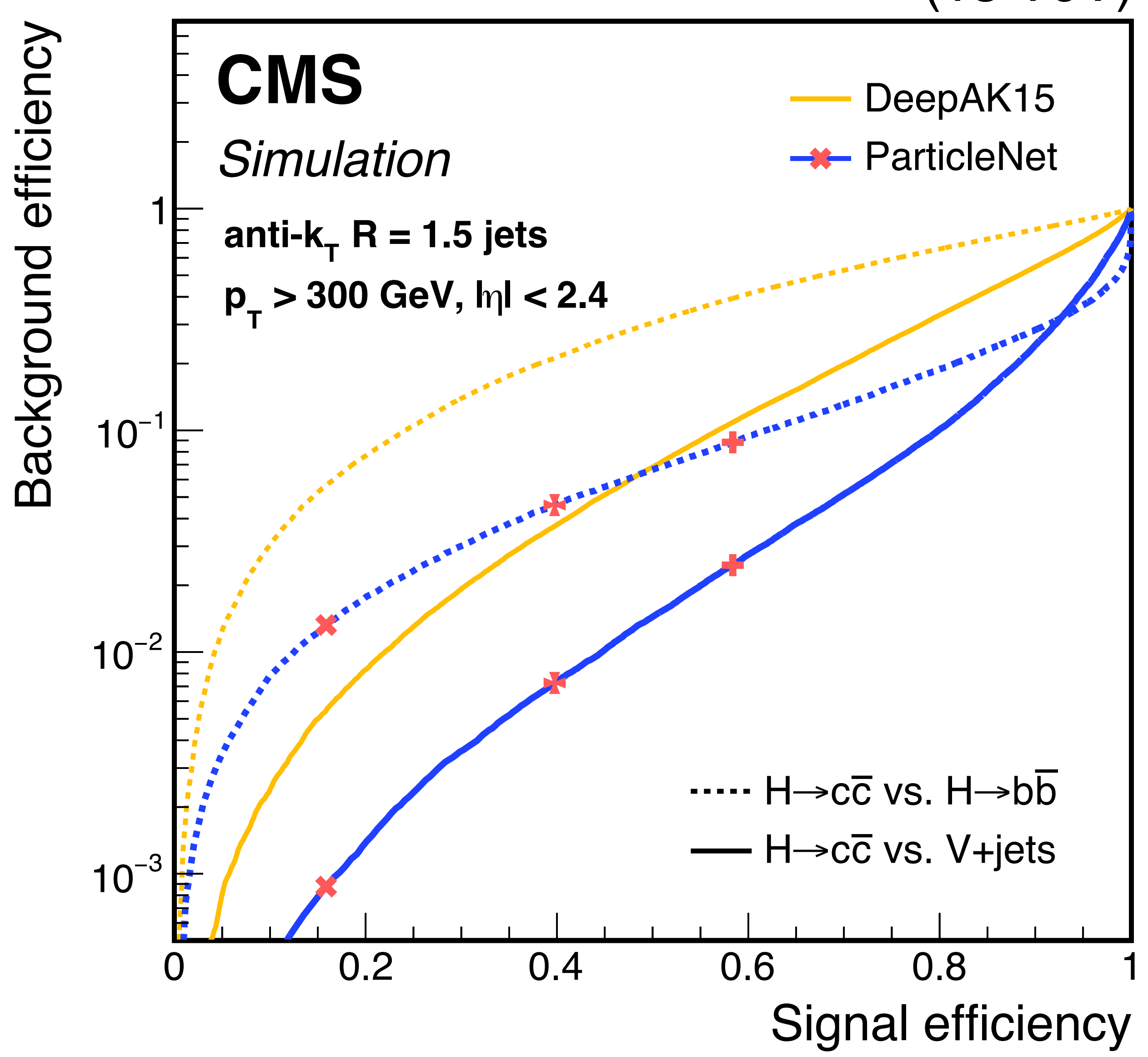
- 2D category optimisation → 9 orthogonal regions (per year)
- Parametric model for resonant backgrounds and signal

$|\kappa_c|$ < 38.1 (72.5) observed (expected)

Our most important tool: jet flavor tagging

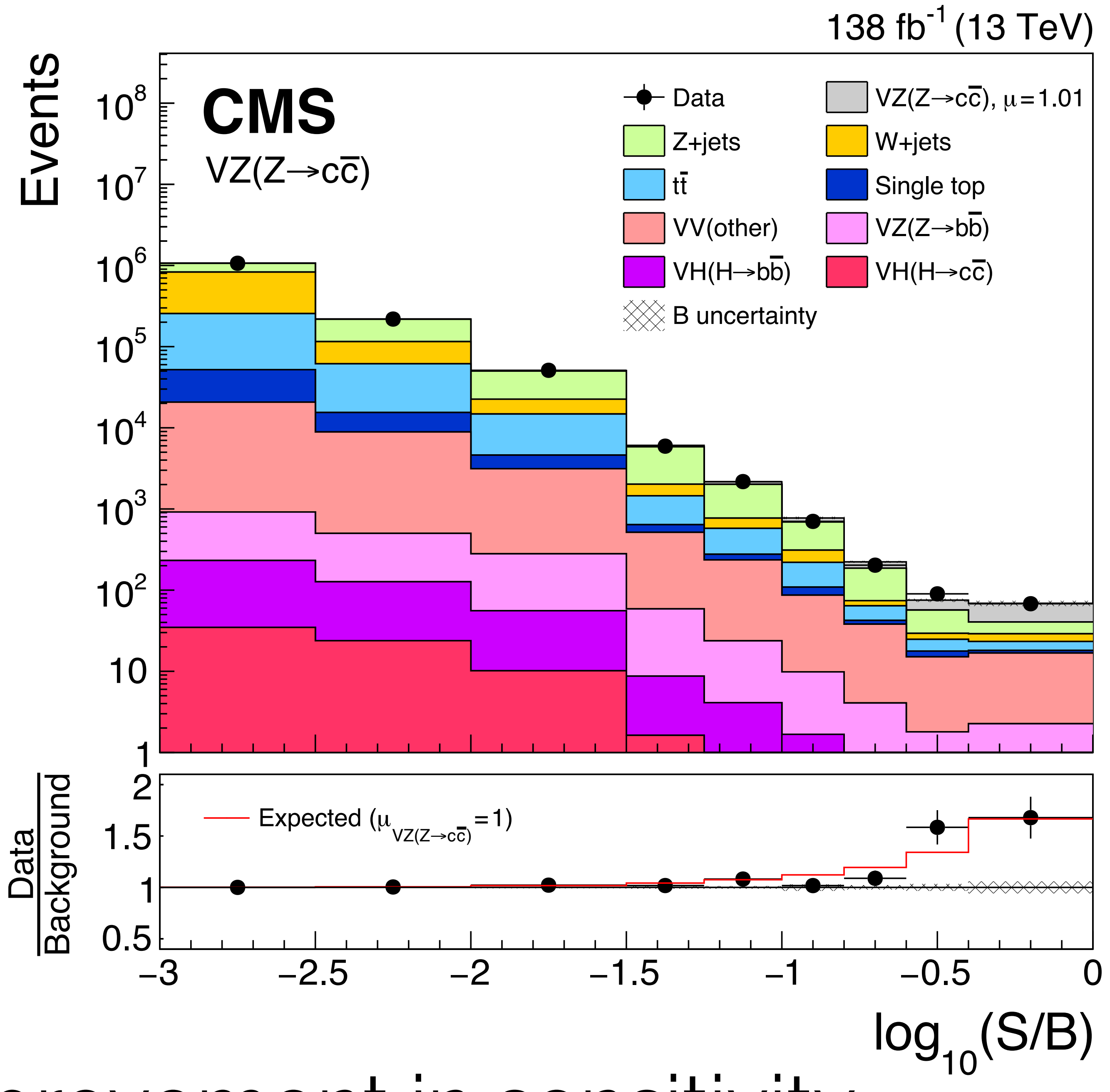
- We have made significant progress in resolved and boosted tagging

From first usage of GNN-based tagger



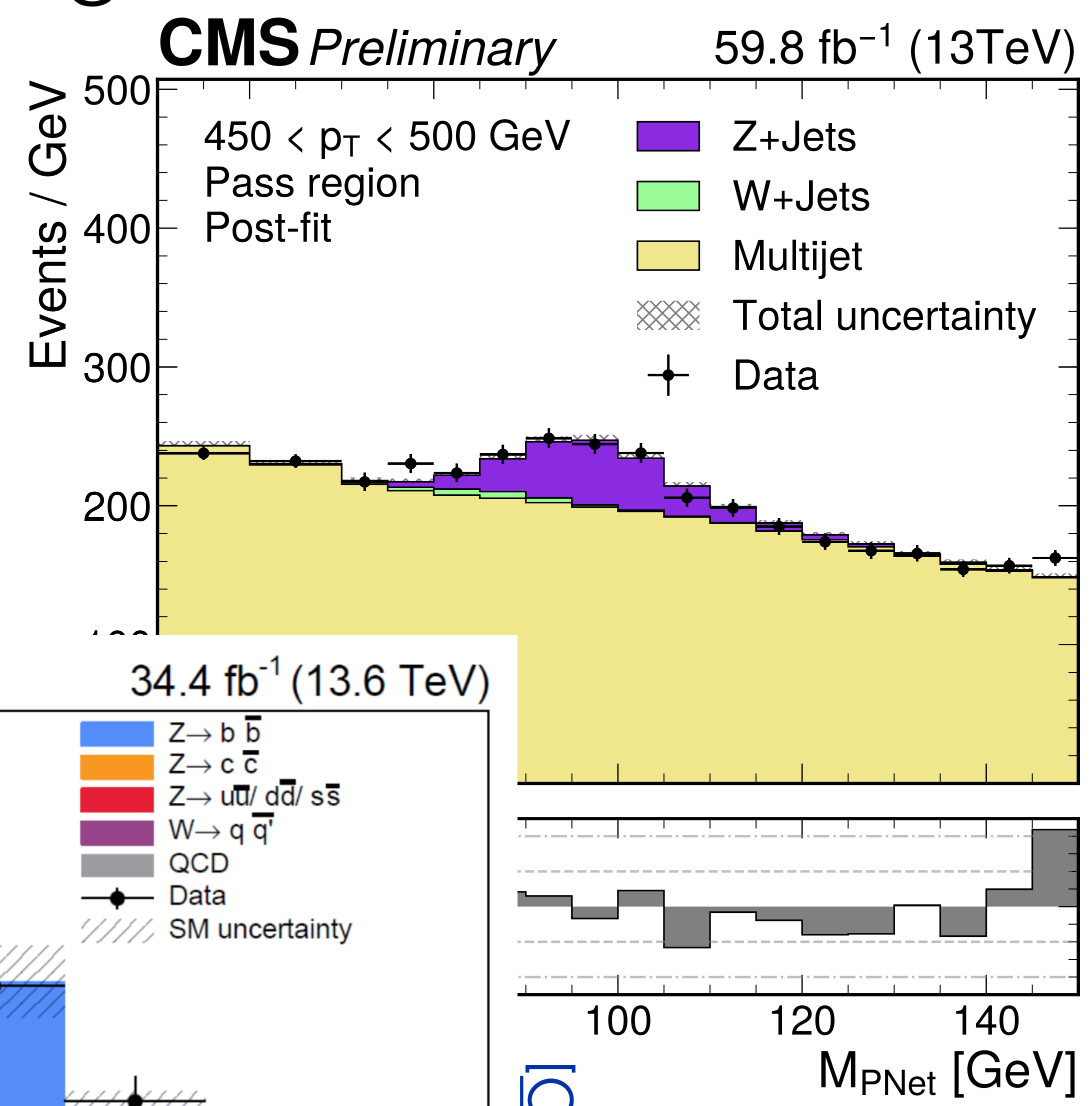
[CMS-HIG-21-008]

Over Z(→ cc) observation

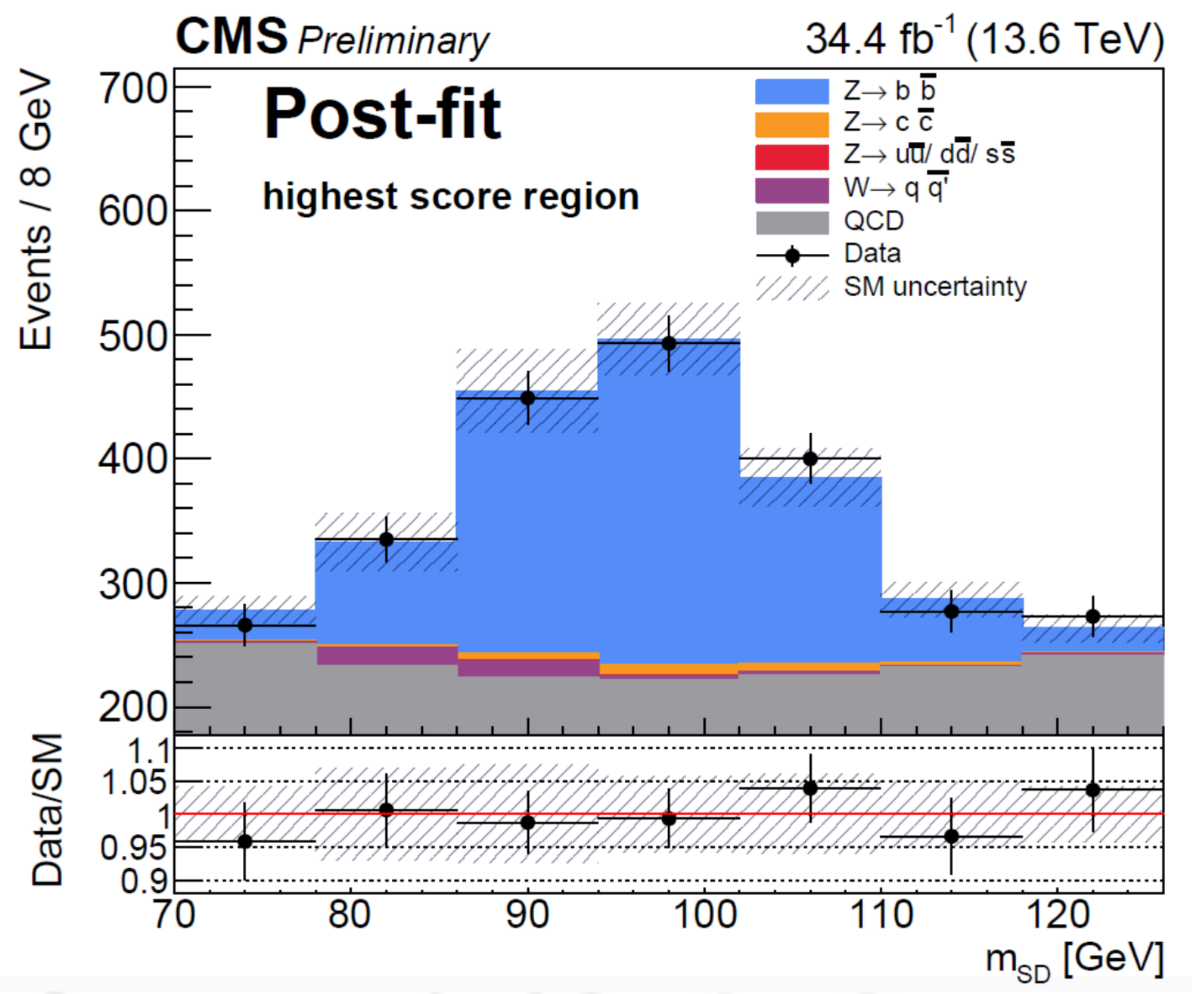


[CMS-HIG-21-008]

To using it for calibration!



[CMS-PAS-BTV-22-001]



[CMS-DP-24-055]

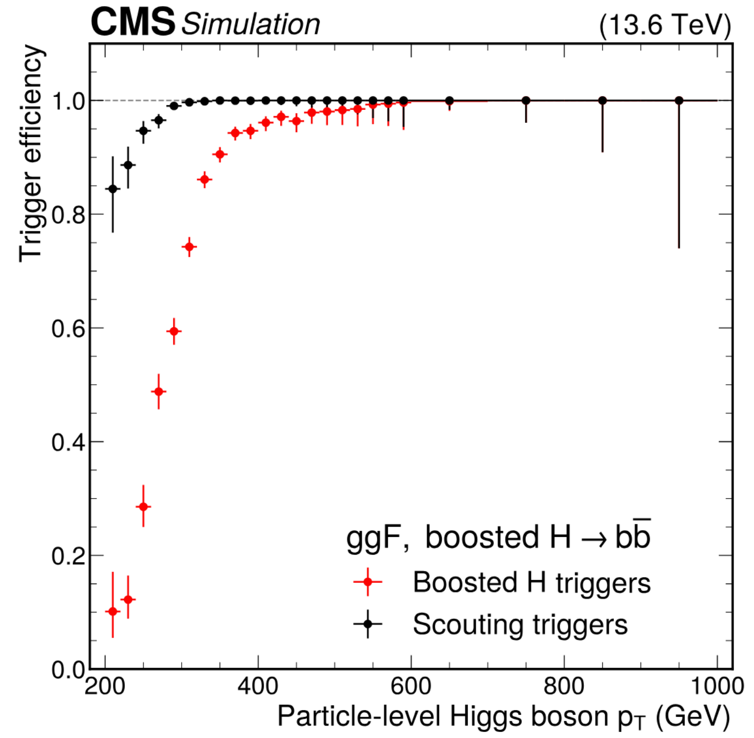
~5X better rejection → ~2x improvement in sensitivity

Now moving to transformers

[PMLR 162:18281-18292, 2022]

	All classes		$H \to b\bar{b}$	$H \to c\bar{c}$
	Accuracy	AUC	$\text{Rej}_{50\%}$	$\text{Rej}_{50\%}$
PFN	0.772	0.9714	2924	841
P-CNN	0.809	0.9789	4890	1276
ParticleNet	0.844	0.9849	7634	2475
ParT	**0.861**	**0.9877**	**10638**	**4149**
ParT (plain)	0.849	0.9859	9569	2911

And use it for triggers and scouting

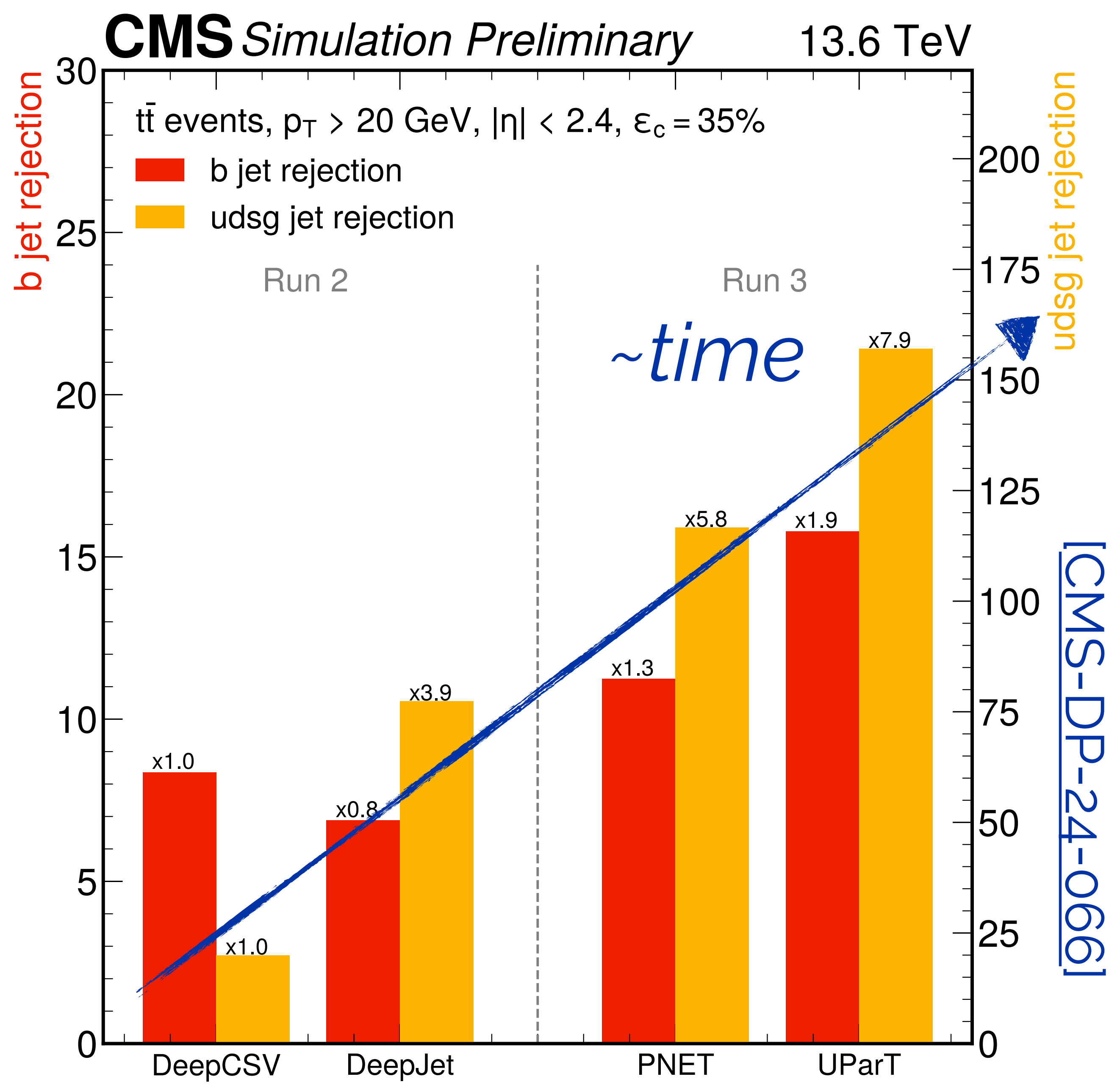


[CMS-EXO-23-007]

Our most important tool: jet flavor tagging

- We have made significant progress in resolved and boosted tagging

Where does this scaling law of taggers lead us?



- So far, Run 2 analyses have been performed using DeepCSV/DeepJet
  - We expect a **factor of 2 improvement for c-jets**
  - Plus the progress we are making on calibration
  - Run 2+Run 3 data (factor 3 larger!)

Back-of-the-envelope estimate

- Assuming factor 3 in luminosity and 2 in c-tagging eff. with same background:
  - VH(cc) resolved: → upper limit of ~8 for μ
  - H+c (γγ): → upper limit of ~144 for μ
- But backgrounds are also real charm…

- At HL-LHC (3000fb-1):
  - VH(cc): Extrapolation gives ~ μ < 1.6
  - H+c cross section of ~170fb

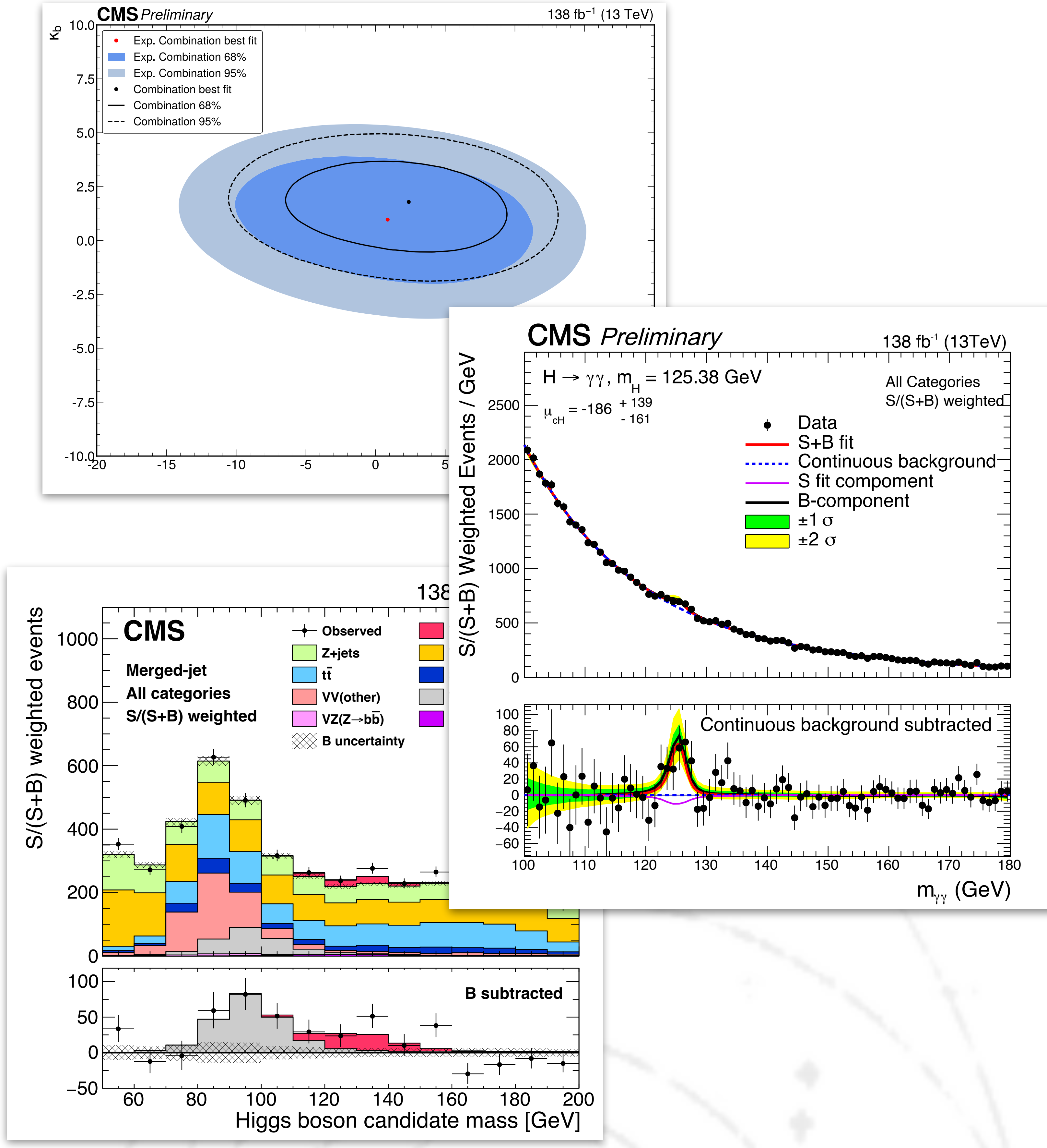
    → 2300 signal events in the γγ channel!
    - Higgs discovery 180/750
    - Benefits from soft charm tagging improvements

Conclusion

- The hunt for y_c is an exciting and active field
  - Impressive progress in the last years
  - Hand-in-hand with technological improvements and flavour-tagging

- Exploring complementary ways:
  - New indirect probes: Combination of differential measurements
  - Rare decays: H→J/Psi + photon
  - New avenues: H+c associated production

- Charming journey ahead:
  - Combination of CMS (and ATLAS) current results
  - Addition of additional candidates?
    - ttH(cc), VBF, H+c (→ZZ, WW, $\tau\tau$)
    - Hadronic channels (data parking & scouting)



Thank you very much for your attention!

Backup

Indirect probes of y_c - differential Higgs p_T

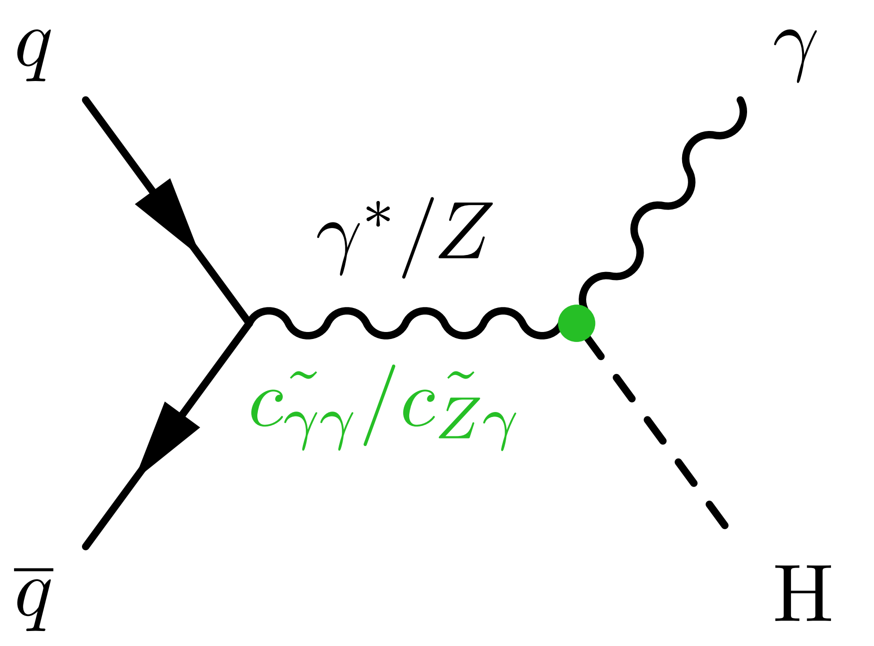
p_T^H [GeV]	Best fit (fb)
σ_{0-5}	$2.86^{+0.49}_{-0.58}(\text{syst.})^{+1.75}_{-1.95}(\text{stat.}) \times 10^2$
σ_{5-10}	$8.73^{+0.89}_{-0.54}(\text{syst.})^{+2.90}_{-3.13}(\text{stat.}) \times 10^2$
σ_{10-15}	$1.28^{+0.08}_{-0.08}(\text{syst.})^{+0.26}_{-0.25}(\text{stat.}) \times 10^3$
σ_{15-20}	$1.12^{+0.06}_{-0.08}(\text{syst.})^{+0.26}_{-0.24}(\text{stat.}) \times 10^3$
σ_{20-25}	$4.16^{+0.56}_{-0.00}(\text{syst.})^{+2.14}_{-2.19}(\text{stat.}) \times 10^2$
σ_{25-30}	$8.13^{+0.25}_{-0.43}(\text{syst.})^{+2.14}_{-2.11}(\text{stat.}) \times 10^2$
σ_{30-35}	$5.14^{+0.52}_{-0.32}(\text{syst.})^{+1.74}_{-1.68}(\text{stat.}) \times 10^2$
σ_{35-45}	$5.85^{+0.23}_{-0.24}(\text{syst.})^{+1.28}_{-1.29}(\text{stat.}) \times 10^2$
σ_{45-60}	$2.71^{+0.26}_{-0.16}(\text{syst.})^{+0.62}_{-0.59}(\text{stat.}) \times 10^2$
σ_{60-80}	$2.88^{+0.17}_{-0.13}(\text{syst.})^{+0.46}_{-0.45}(\text{stat.}) \times 10^2$
σ_{80-100}	$2.37^{+0.18}_{-0.14}(\text{syst.})^{+0.36}_{-0.35}(\text{stat.}) \times 10^2$
$\sigma_{100-120}$	$6.16^{+0.00}_{-0.83}(\text{syst.})^{+2.97}_{-2.65}(\text{stat.}) \times 10^1$
$\sigma_{120-140}$	$9.07^{+0.86}_{-0.66}(\text{syst.})^{+1.73}_{-1.70}(\text{stat.}) \times 10^1$
$\sigma_{140-170}$	$5.31^{+0.50}_{-0.37}(\text{syst.})^{+1.08}_{-1.06}(\text{stat.}) \times 10^1$
$\sigma_{170-200}$	$1.39^{+0.22}_{-0.15}(\text{syst.})^{+0.65}_{-0.63}(\text{stat.}) \times 10^1$
$\sigma_{200-250}$	$1.47^{+0.22}_{-0.18}(\text{syst.})^{+0.25}_{-0.24}(\text{stat.}) \times 10^1$
$\sigma_{250-350}$	$4.28^{+0.59}_{-0.43}(\text{syst.})^{+1.00}_{-0.97}(\text{stat.}) \times 10^0$
$\sigma_{350-450}$	$9.67^{+2.09}_{-1.49}(\text{syst.})^{+3.27}_{-3.08}(\text{stat.}) \times 10^{-1}$
$\sigma_{>450}$	$4.37^{+1.19}_{-0.80}(\text{syst.})^{+1.77}_{-1.66}(\text{stat.}) \times 10^{-1}$

Channel	$H \to \gamma\gamma$	$H \to ZZ^{(*)} \to 4\ell$	$H \to W^+W^{-(*)} \to e^\pm\mu^\mp\nu_1\bar{\nu}_1$	$H \to \tau^+\tau^-$	$H \to \tau^+\tau^-$ boosted
p_T^H bin boundaries (GeV)	0 - 5	0 - 10	0 - 30	0 - 45	
	5 - 10				
	10 - 15	10 - 20			
	15 - 20				
	20 - 25	20 - 30			
	25 - 30				
	30 - 35	30 - 45	30 - 45		
	35 - 45				
	45 - 60	45- 60	45 - 80	45 - 80	
	60 - 80	60 - 80			
	80 - 100	80 - 120	80 - 120	80 - 120	
	100 - 120				
	120 - 140	120 - 200	120 - 200	120 - 140	
	140 - 170			140 - 170	
	170 - 200			170 - 200	
	200 - 250	200 - ∞	200 - ∞	200 - 350	
	250 - 350				
	350 - 450			350 - 450	
	450 - ∞			450 - ∞	450 - 600
					600 - ∞

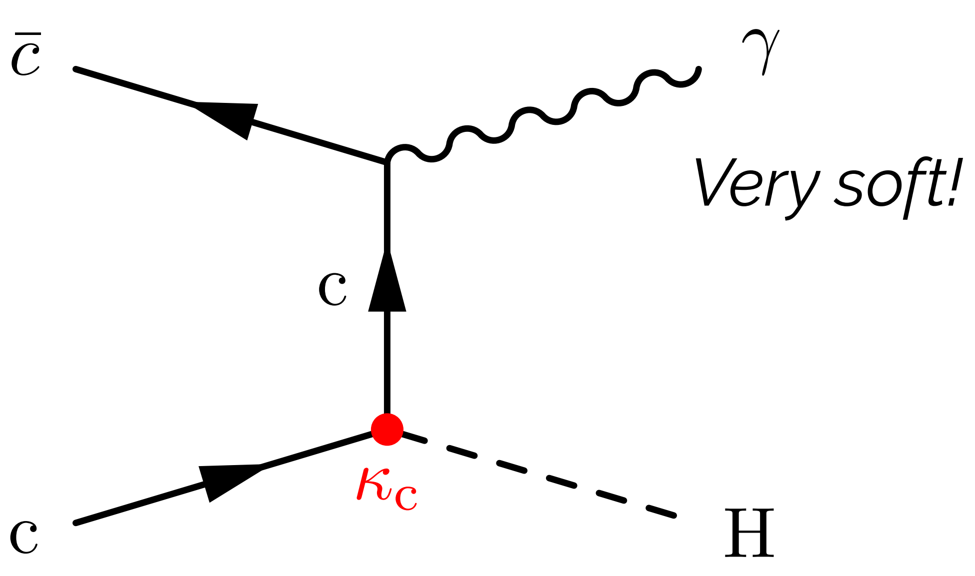
Indirect probes of y_c - H→4l + bb

[CMS-HIG-PAS-23-011]

- Search for Hγ production w/ focus on boosted topology
  - Simultaneous analysis of H→bb and H→4l final states

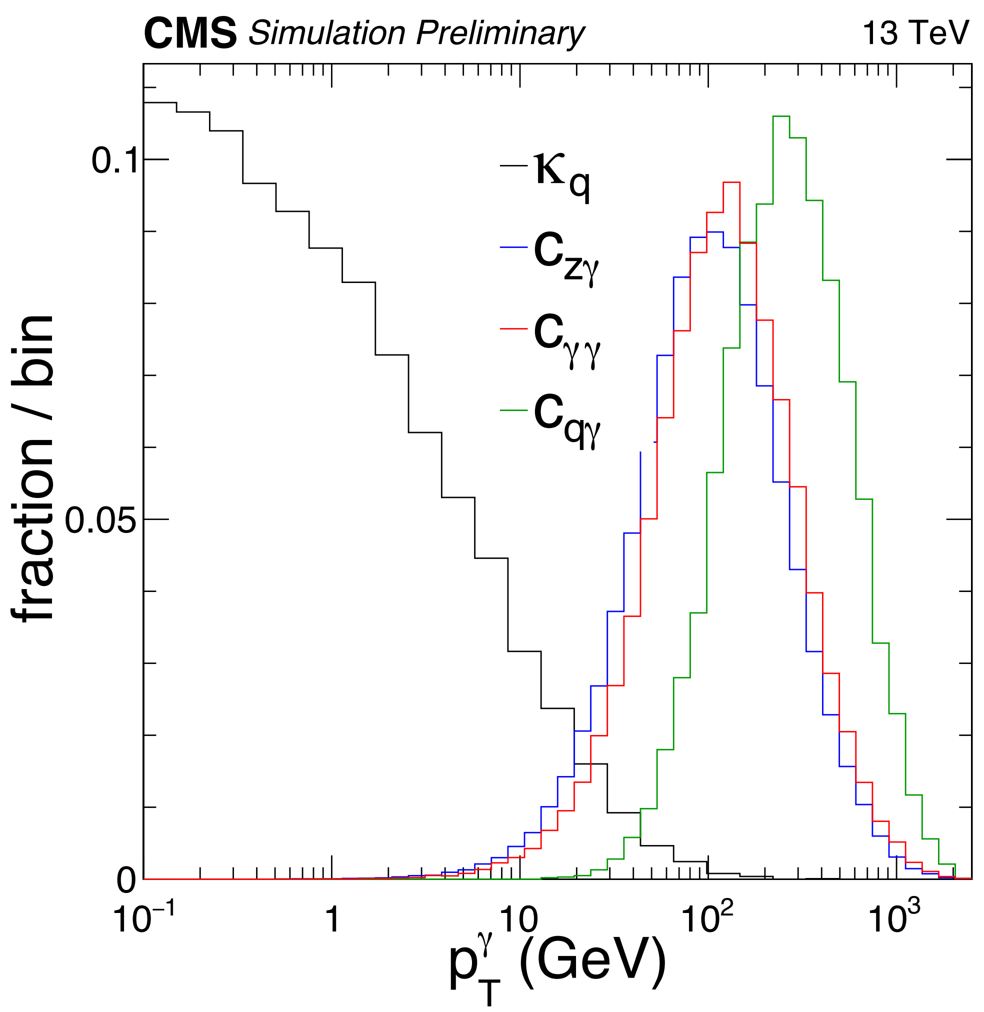


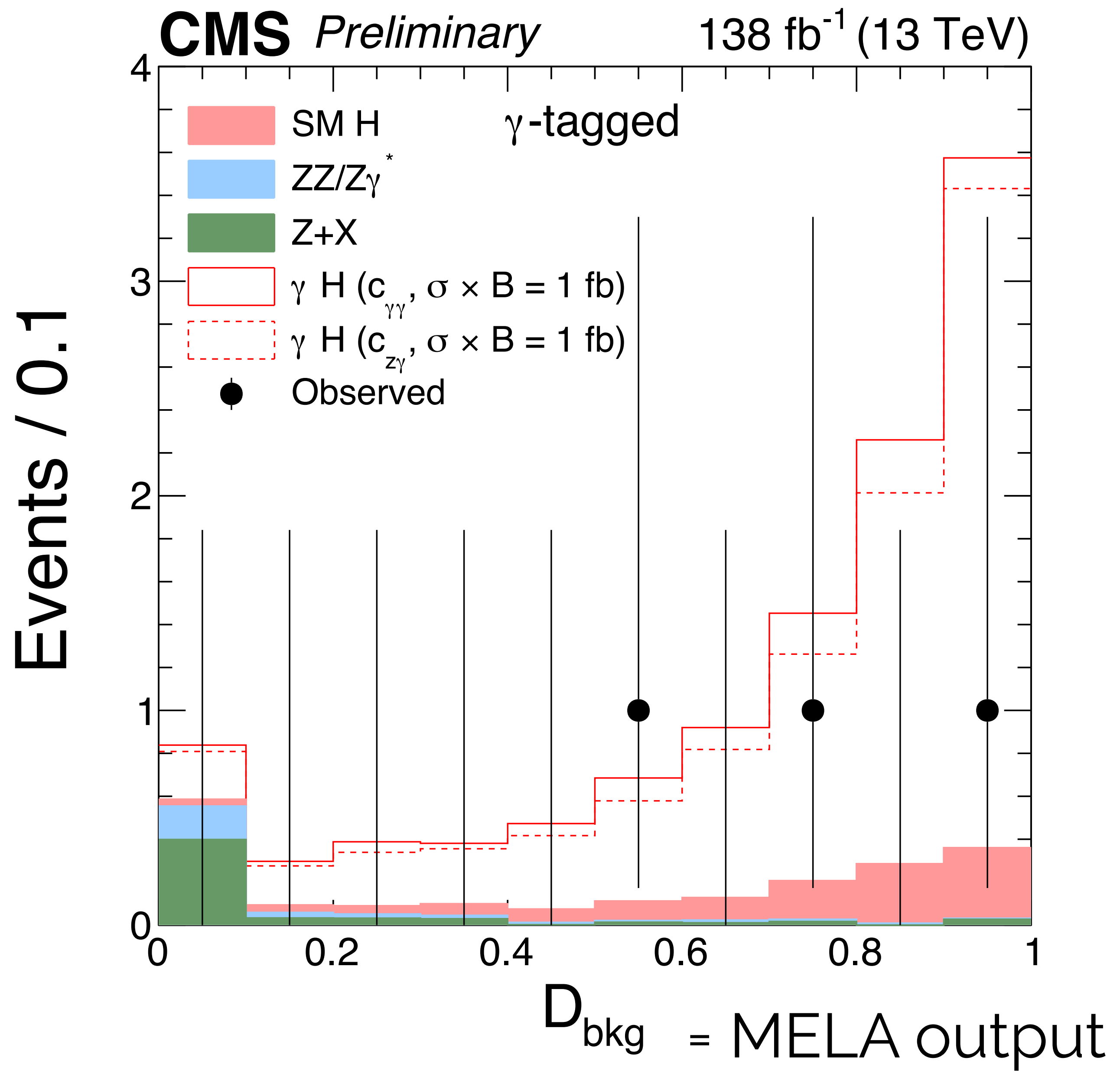
BSM motivation

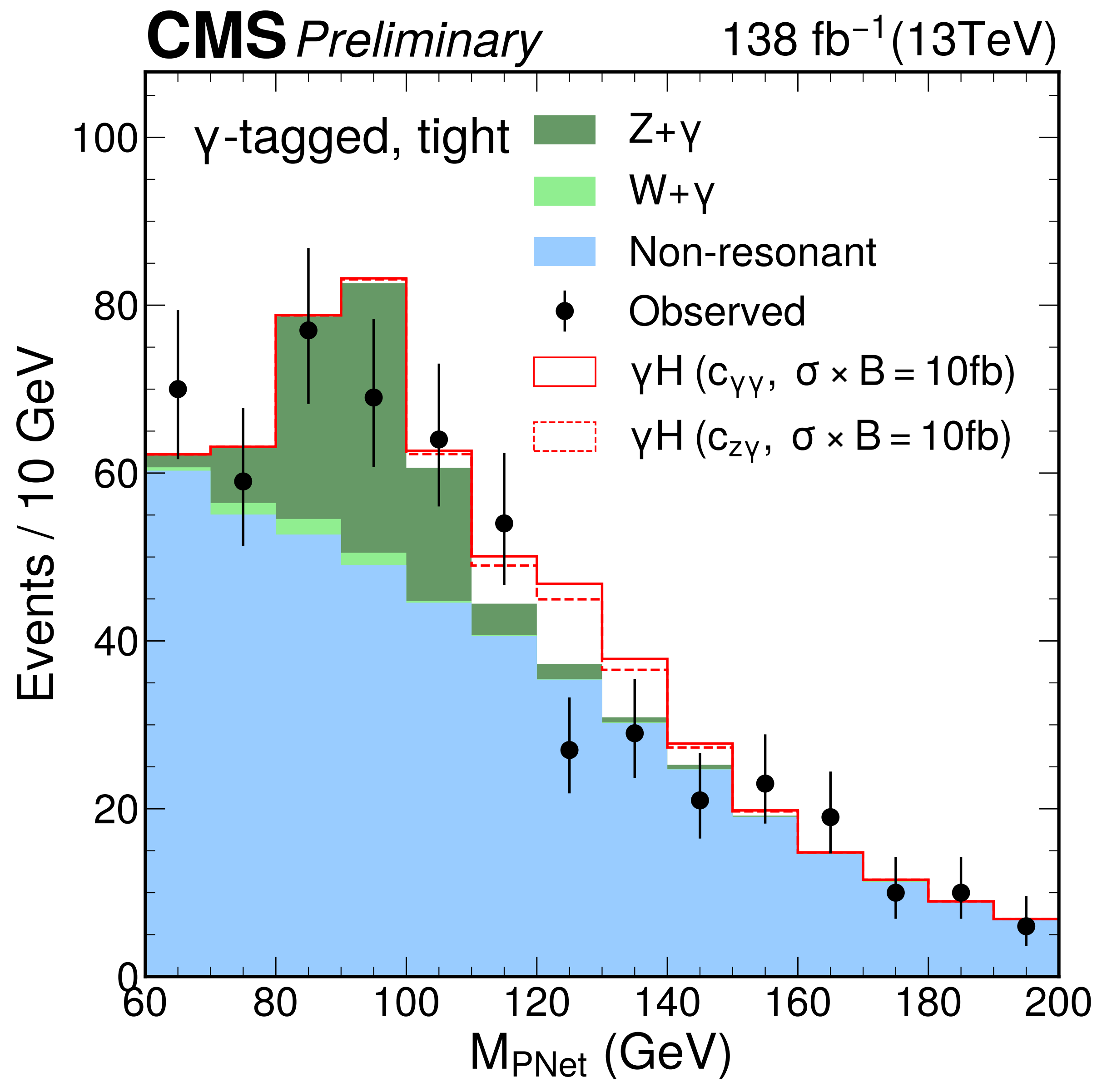


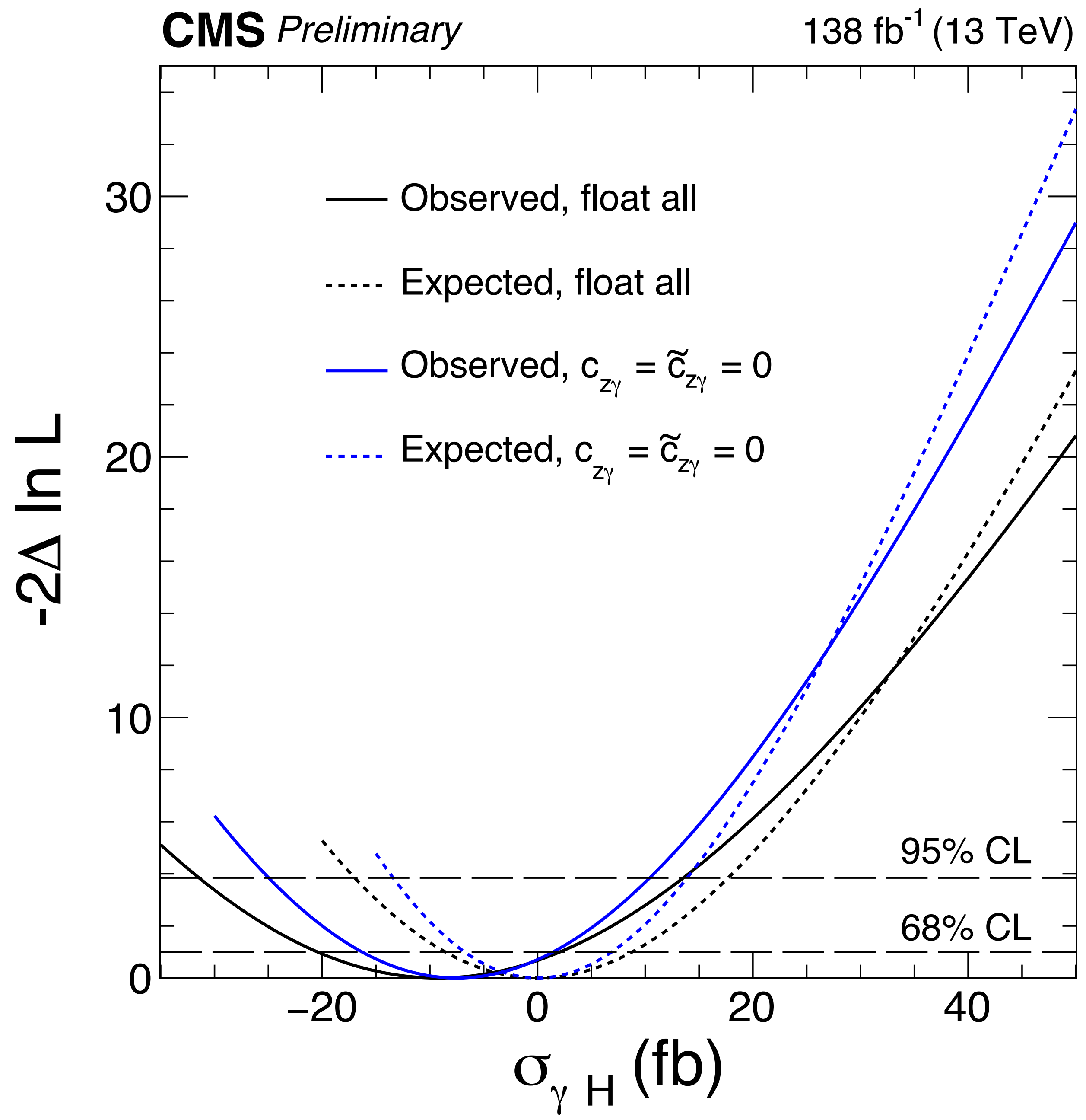
Dominant SM mode

- Dedicated photon (un-)tagged categorie w/ $p_T^\gamma > 150$ GeV





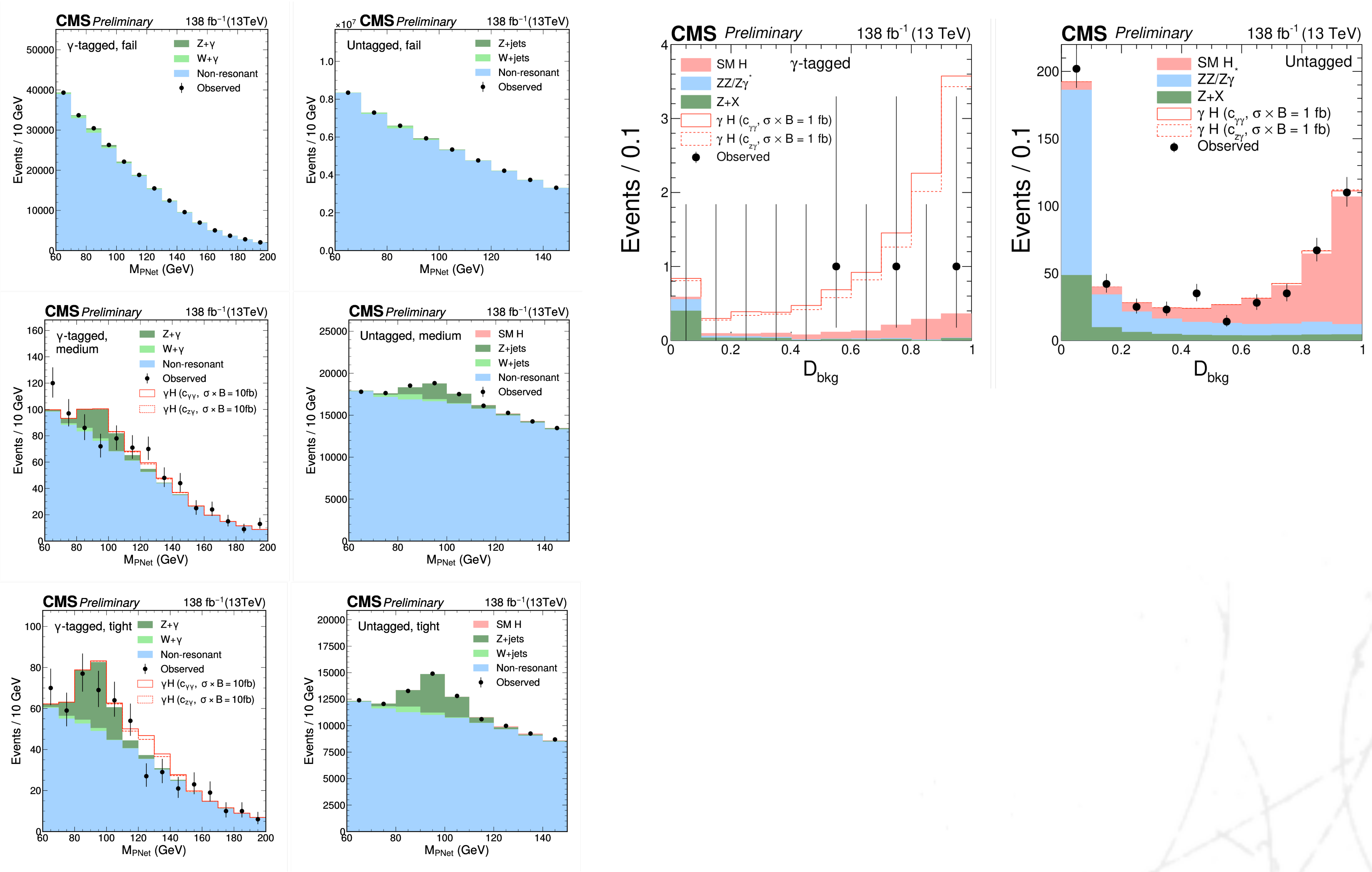




Dominated by bb channel

Indirect probes of y_c - H→4l + bb

[CMS-HIG-PAS-23-011]



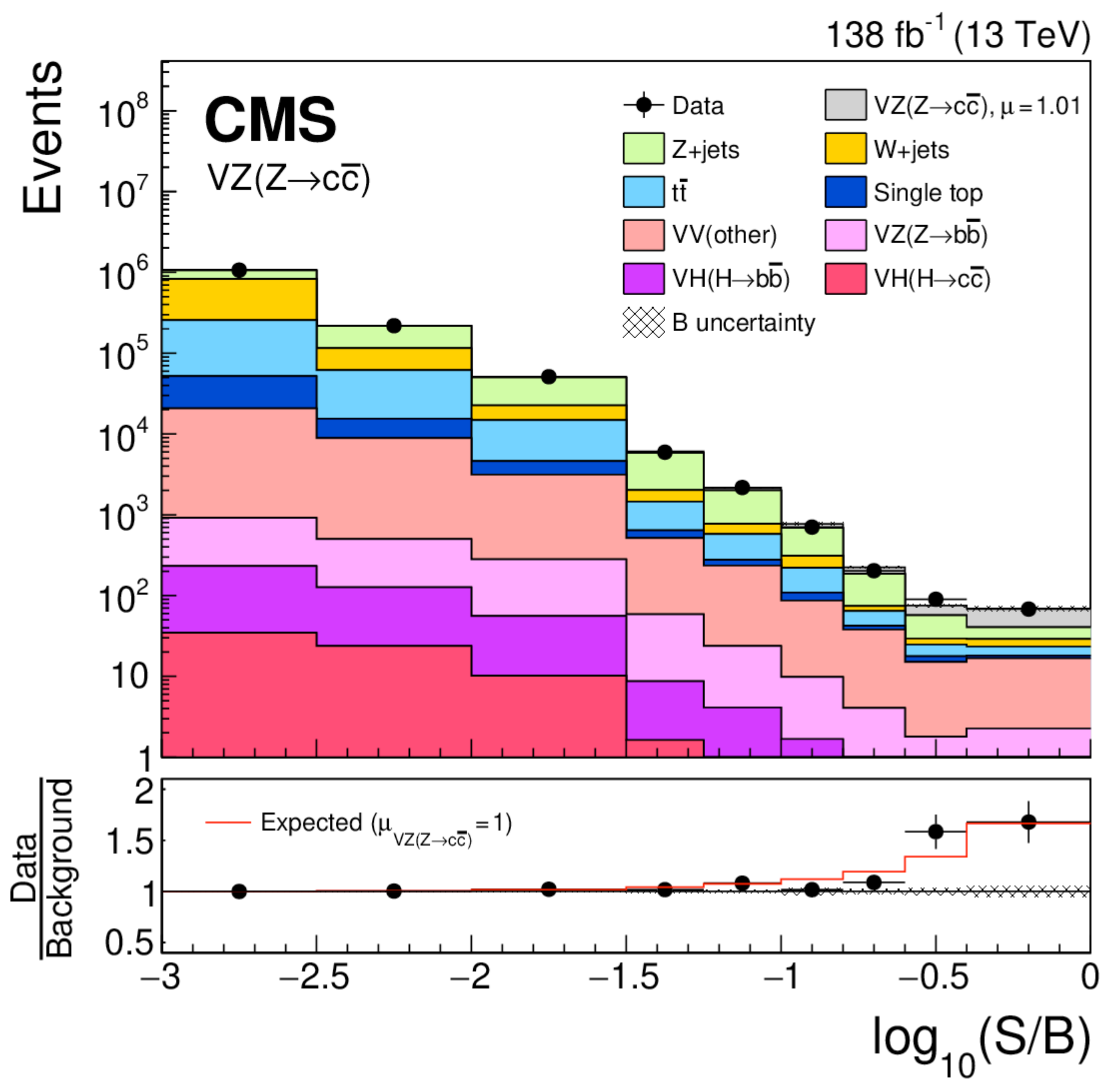
Rare decays - Z/H→J/Ψ + γ

Source	Backgrounds: QCD	Backgrounds: $Z \to \mu\mu\gamma$	Signals: $Z \to \Psi(nS)\gamma$	Signals: $H \to \Psi(nS)\gamma$
Integrated luminosity	—	—	1.6%	1.6%
Normalization uncertainties	From data	From CR		
QCD scale	—	—	3.5%	5.6%
PDF	—	—	1.7%	3.2%
Detector simulation, reconstruction	—	—		
Pileup weight	—	—	0.9%	0.8%
Trigger efficiency	—	—	3.5%	3.5%
Trigger timing shift	—	—	0.6%	2.7%
Muon identification/isolation	—	—	2.0%	1.4%
Photon identification	—	—	1.5%	1.5%
Pixel seed veto	—	—	1.0%	1.0%
Jet energy scale (VBF category)	—	—	—	2.9%
Jet energy resolution (VBF category)	—	—	—	1.0%
Jet b tagging (HF category)	—	—	—	5.4%
Background model	Discrete			
Signal model	—	1%	1%	1%
$m_{\mu\mu\gamma}$ mean (MC stat)	—	0.06%	0.06%	0.06%
$m_{\mu\mu\gamma}$ width (MC stat)	—	0.1%	0.1%	0.1%
$m_{\mu\mu\gamma}$ mean (μ calibration)	—	0.05%	0.05%	0.05%
$m_{\mu\mu\gamma}$ width (μ calibration)	—	0.8%	0.8%	0.8%
$m_{\mu\mu\gamma}$ mean (γ energy)	—	0.04%	0.04%	0.04%
$m_{\mu\mu\gamma}$ width (γ energy)	—	3.4%	3.4%	3.4%
$m_{\mu\mu\gamma}$ width (γ resolution)	—	1.8%	1.8%	1.8%

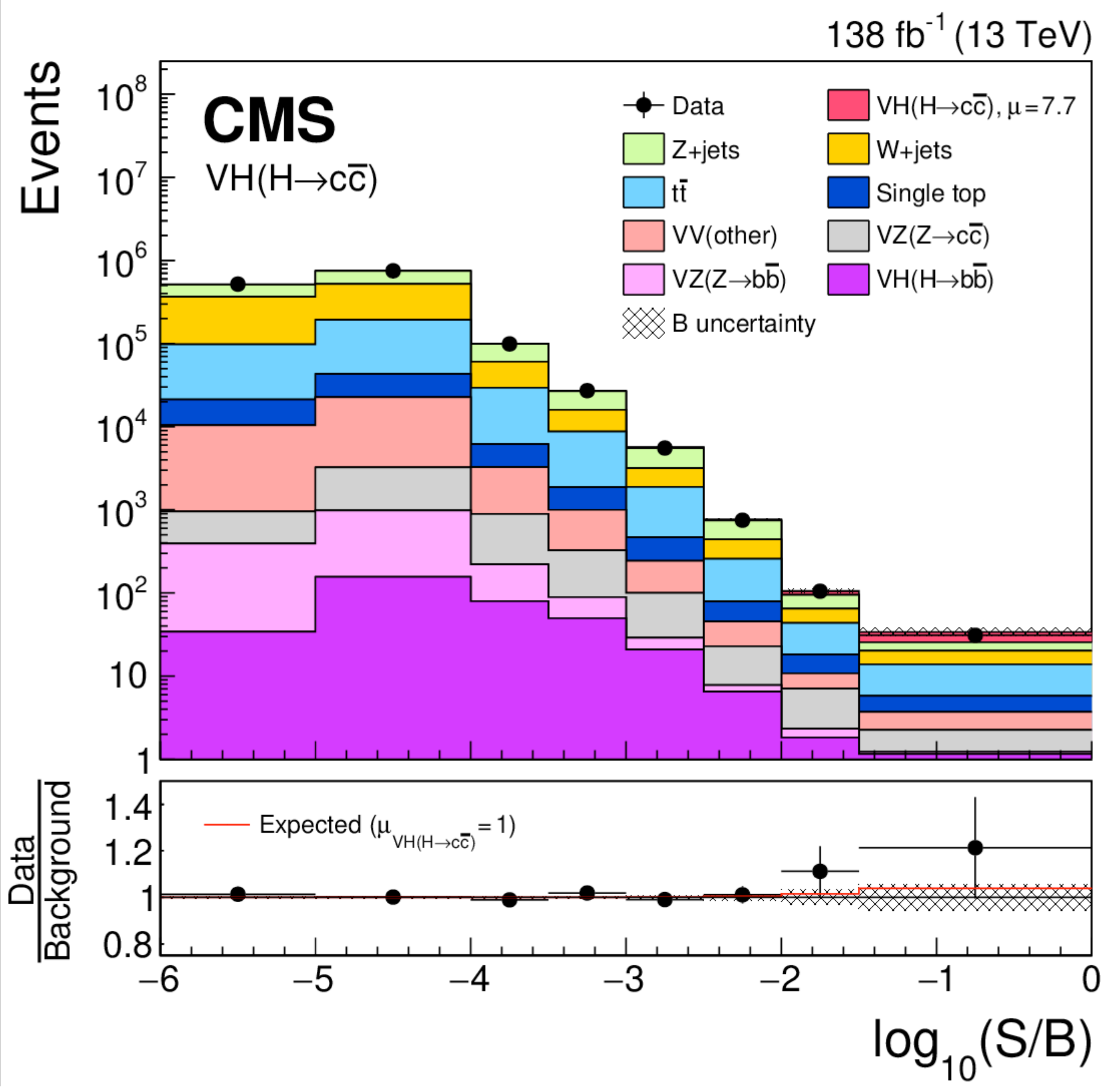
Rare decays - Z/H→J/Ψ + γ

Process	This analysis (123 fb^{-1})			CMS (36 fb^{-1}) [13]	ATLAS (139 fb^{-1}) [15]
	$\mu_{obs}(\mu_{exp})$	$\sigma_{obs}(\sigma_{exp})$ [pb]	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$
$Z \to \Psi(1S)\gamma$	$7.2\ \left(8.6^{+4.1}_{-2.7}\right)$	$3.8\ \left(4.4^{+1.9}_{-1.3}\right) \times 10^{-2}$	$0.6\ \left(0.7^{+0.3}_{-0.2}\right) \times 10^{-6}$	$1.5\ \left(1.7^{+0.7}_{-0.5}\right) \times 10^{-6}$	$1.2\ \left(0.6^{+0.3}_{-0.2}\right) \times 10^{-6}$
$Z \to \Psi(2S)\gamma$	$29\ \left(68^{+36}_{-22}\right)$	$8\ \left(19^{+8}_{-6}\right) \times 10^{-2}$	$1.3\ \left(3.1^{+1.4}_{-0.9}\right) \times 10^{-6}$	—	$2.3\ \left(2.9^{+1.3}_{-0.8}\right) \times 10^{-6}$
$H \to \Psi(1S)\gamma$	$88\ \left(62^{+30}_{-19}\right)$	$1.4\ \left(1.0^{+0.5}_{-0.3}\right) \times 10^{-2}$	$2.6\ \left(1.8^{+0.9}_{-0.6}\right) \times 10^{-4}$	$7.6\ \left(5.2^{+2.4}_{-1.6}\right) \times 10^{-4}$	$2.1\ \left(1.9^{+0.8}_{-0.5}\right) \times 10^{-4}$
$H \to \Psi(2S)\gamma$	$970\ \left(781^{+417}_{-259}\right)$	$5.5\ \left(4.4^{+2.3}_{-1.5}\right) \times 10^{-2}$	$9.9\ \left(8.0^{+4.2}_{-2.6}\right) \times 10^{-4}$	—	$10.9\ \left(8.5^{+3.8}_{-2.4}\right) \times 10^{-4}$

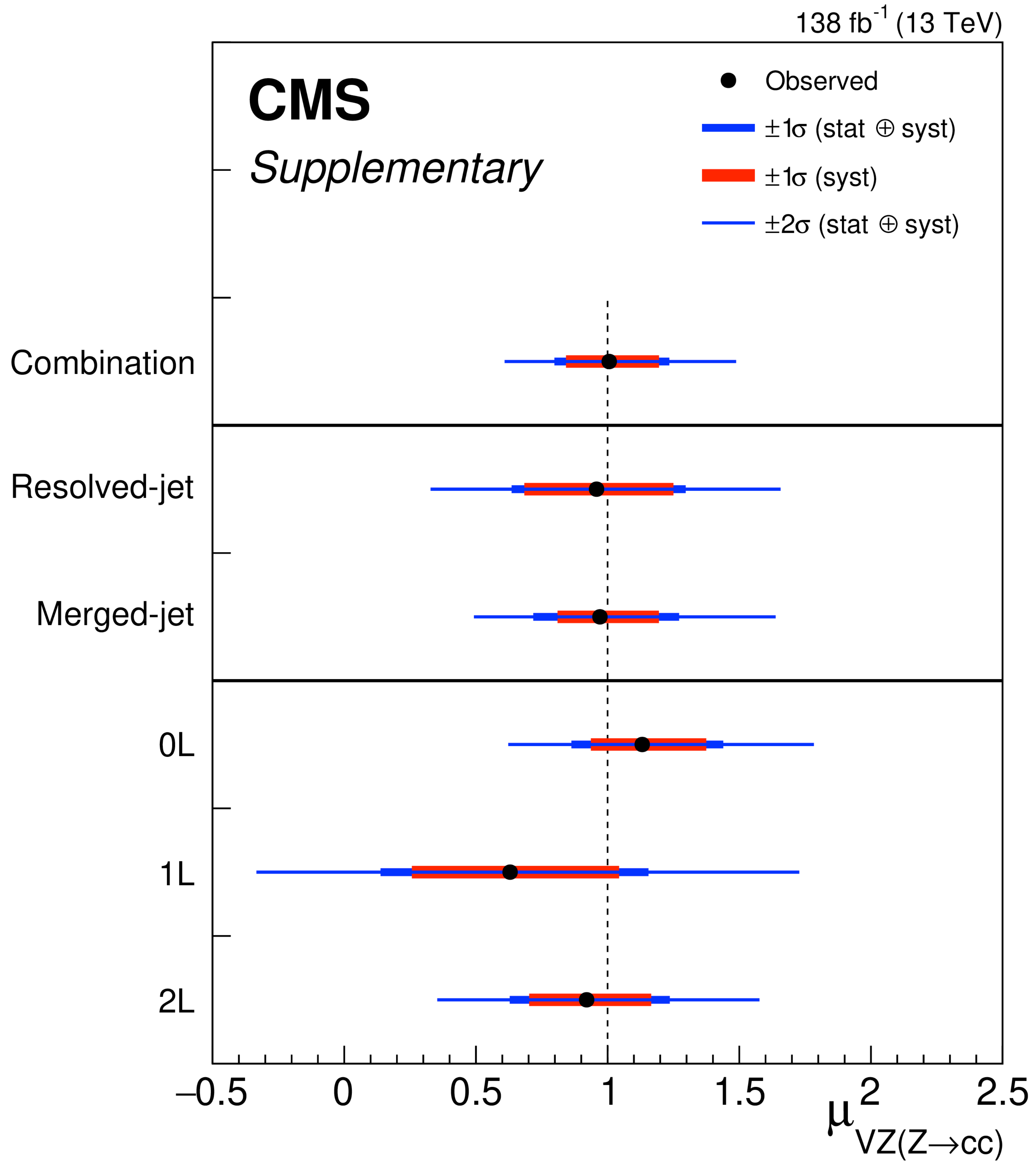
VH(cc)



138 fb^{-1} (13 TeV)
CMS
VZ(Z→cc̄)
Data
VZ(Z→cc̄), μ = 1.01
Z+jets
W+jets
tt̄
Single top
VV(other)
VZ(Z→bb̄)
VH(H→bb̄)
VH(H→cc̄)
B uncertainty
Events
Data / Background
Expected ($\mu_{VZ(Z\to c\bar{c})}$ = 1)
$\log_{10}(S/B)$



138 fb^{-1} (13 TeV)
CMS
VH(H→cc̄)
Data
VH(H→cc̄), μ = 7.7
Z+jets
W+jets
tt̄
Single top
VV(other)
VZ(Z→cc̄)
VZ(Z→bb̄)
VH(H→bb̄)
B uncertainty
Events
Data / Background
Expected ($\mu_{VH(H\to c\bar{c})}$ = 1)
$\log_{10}(S/B)$



138 fb^{-1} (13 TeV)
CMS
Supplementary
Observed
±1σ (stat ⊕ syst)
±1σ (syst)
±2σ (stat ⊕ syst)
Combination
Resolved-jet
Merged-jet
0L
1L
2L
$\mu_{VZ(Z\to cc)}$

VH(cc)

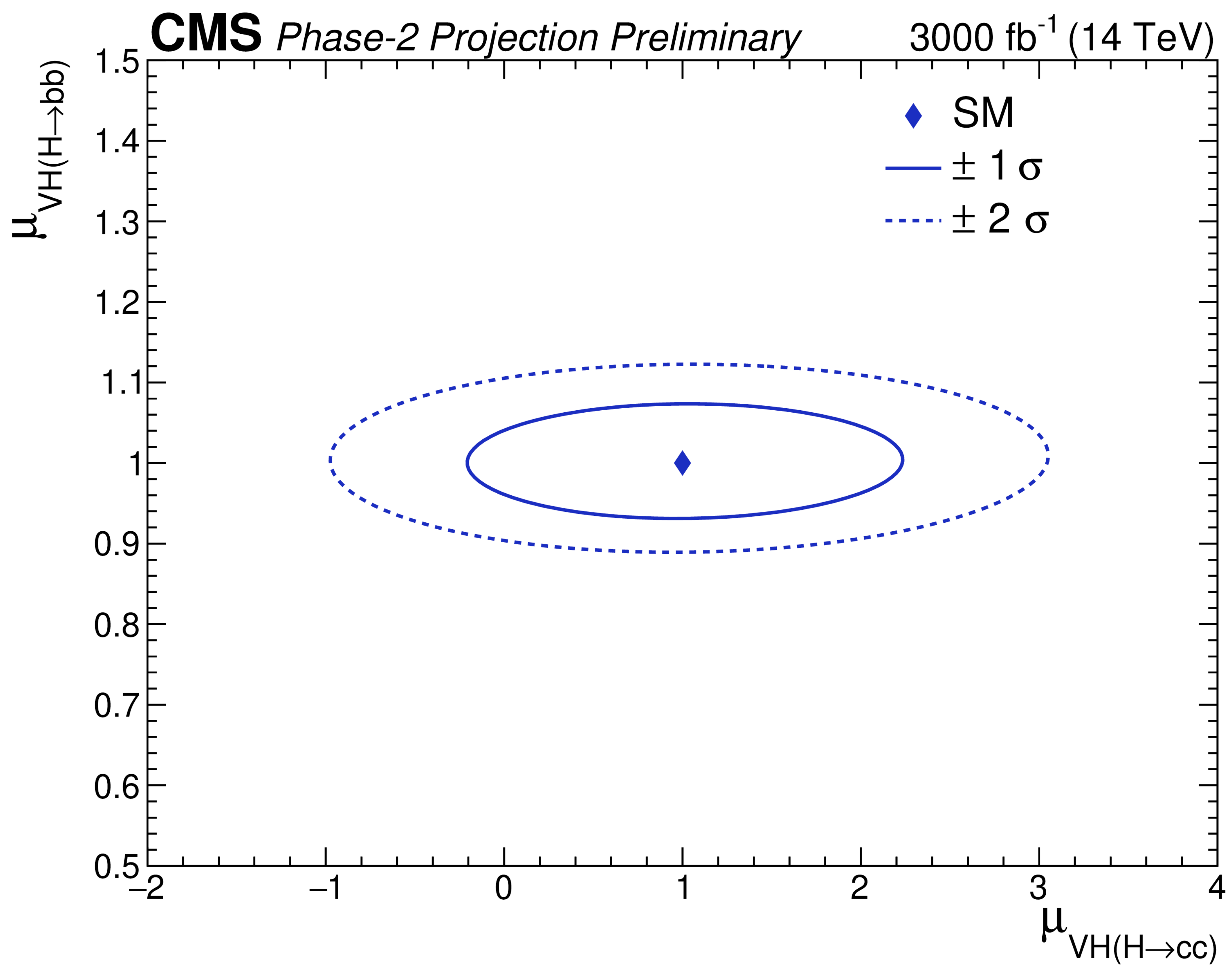
Uncertainty source	$\Delta\mu / (\Delta\mu)_{tot}$
Statistical	**88%**
Background normalizations	39%
Experimental	**40%**
Sizes of the simulated samples	24%
Charm identification efficiencies	26%
Jet energy scale and resolution	15%
Simulation modeling	1%
Luminosity	5%
Lepton identification efficiencies	2%
Theory	**25%**
Backgrounds	21%
Signal	14%

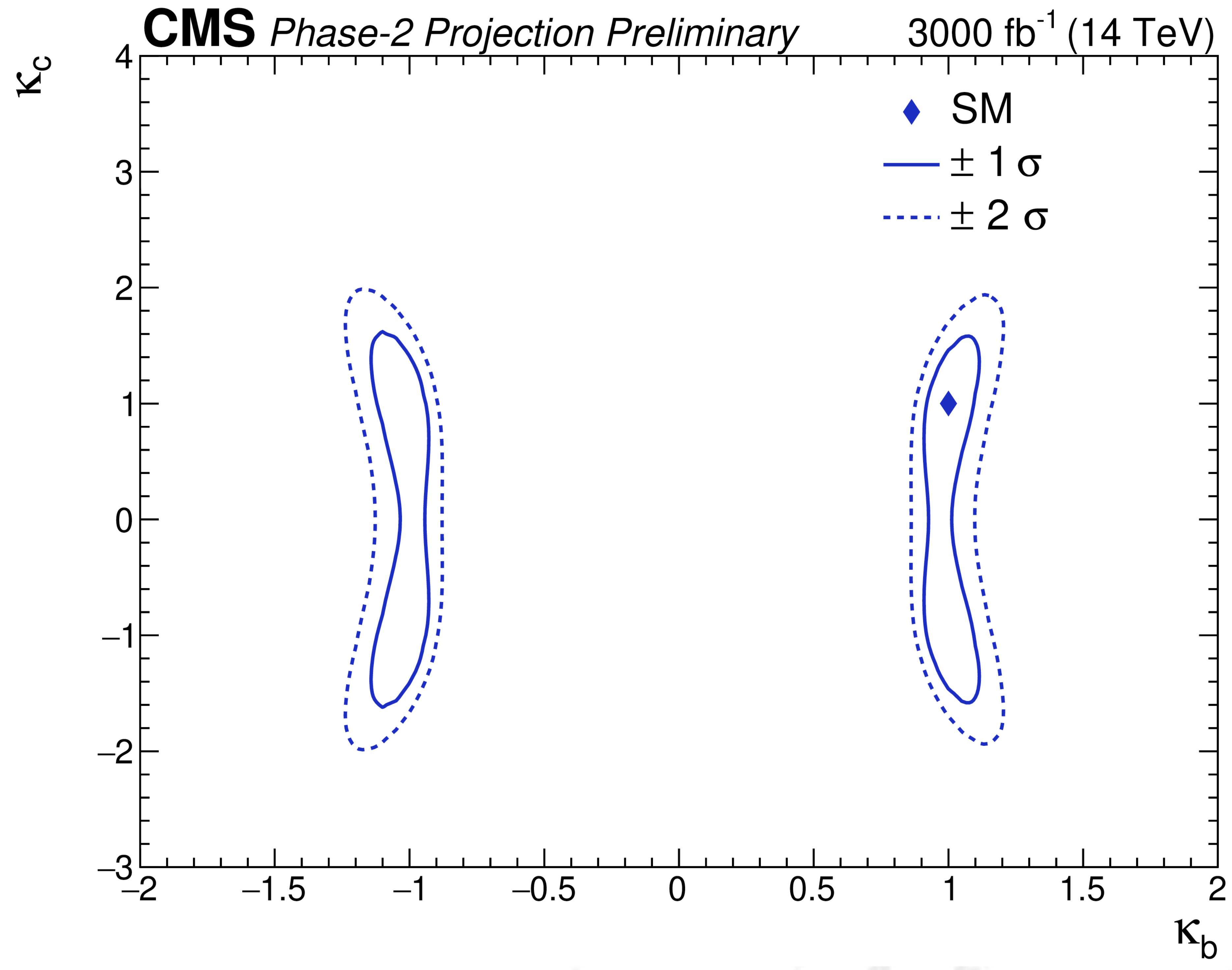
Merged

Uncertainty source	$\Delta\mu / (\Delta\mu)_{tot}$
Statistical	**66%**
Background normalizations	28%
Experimental	**72%**
Sizes of the simulated samples	59%
Charm identification efficiencies	27%
Jet energy scale and resolution	17%
Simulation modeling	20%
Luminosity	13%
Lepton identification efficiencies	10%
Theory	**22%**
Backgrounds	21%
Signal	7%

Resolved

VH(cc)


CMS Phase-2 Projection Preliminary
3000 fb-1 (14 TeV)
SM
± 1 σ
± 2 σ
μVH(H→cc)
μVH(H→bb)

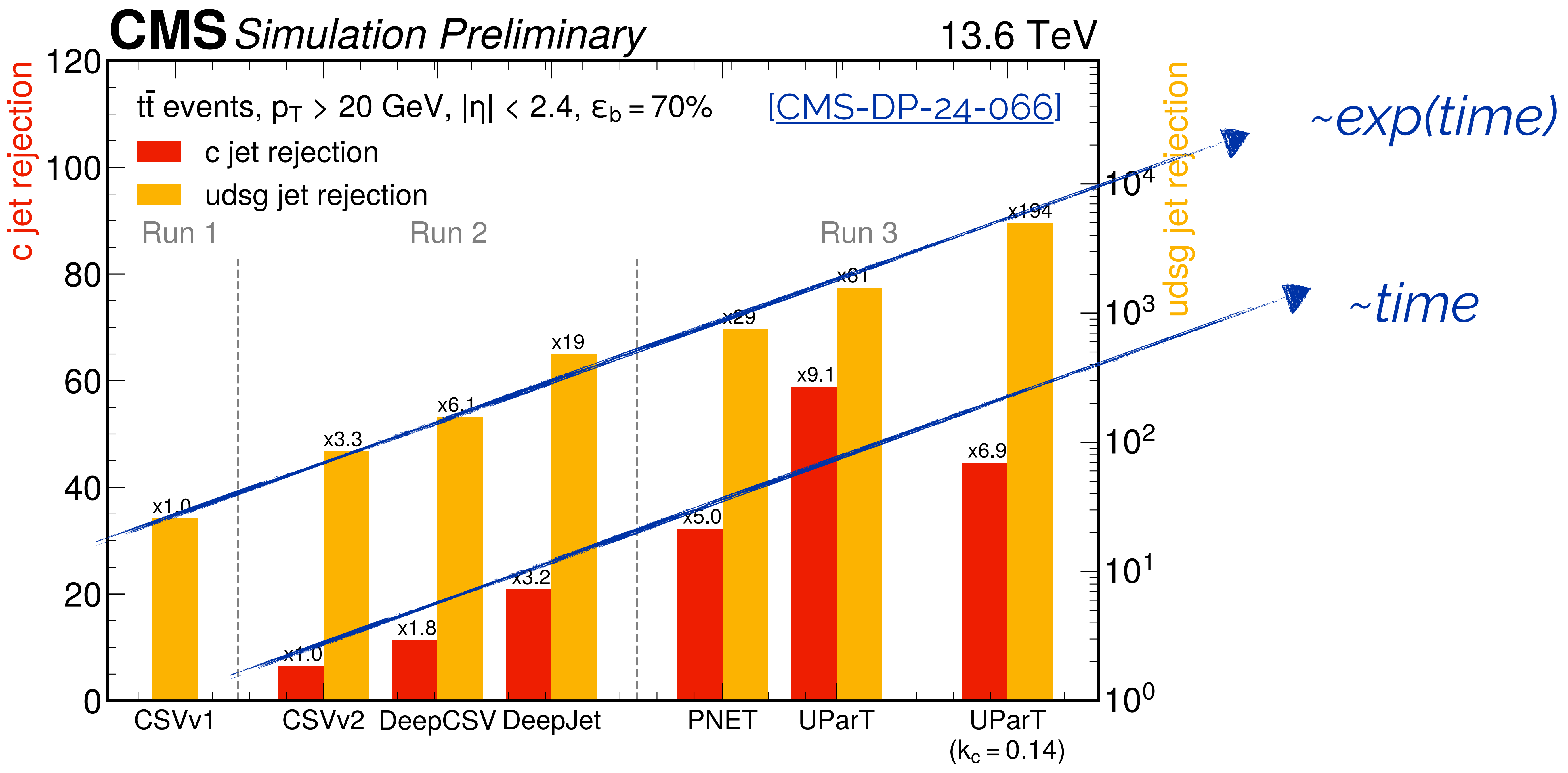

CMS Phase-2 Projection Preliminary
3000 fb-1 (14 TeV)
SM
± 1 σ
± 2 σ
κb
κc

H+c

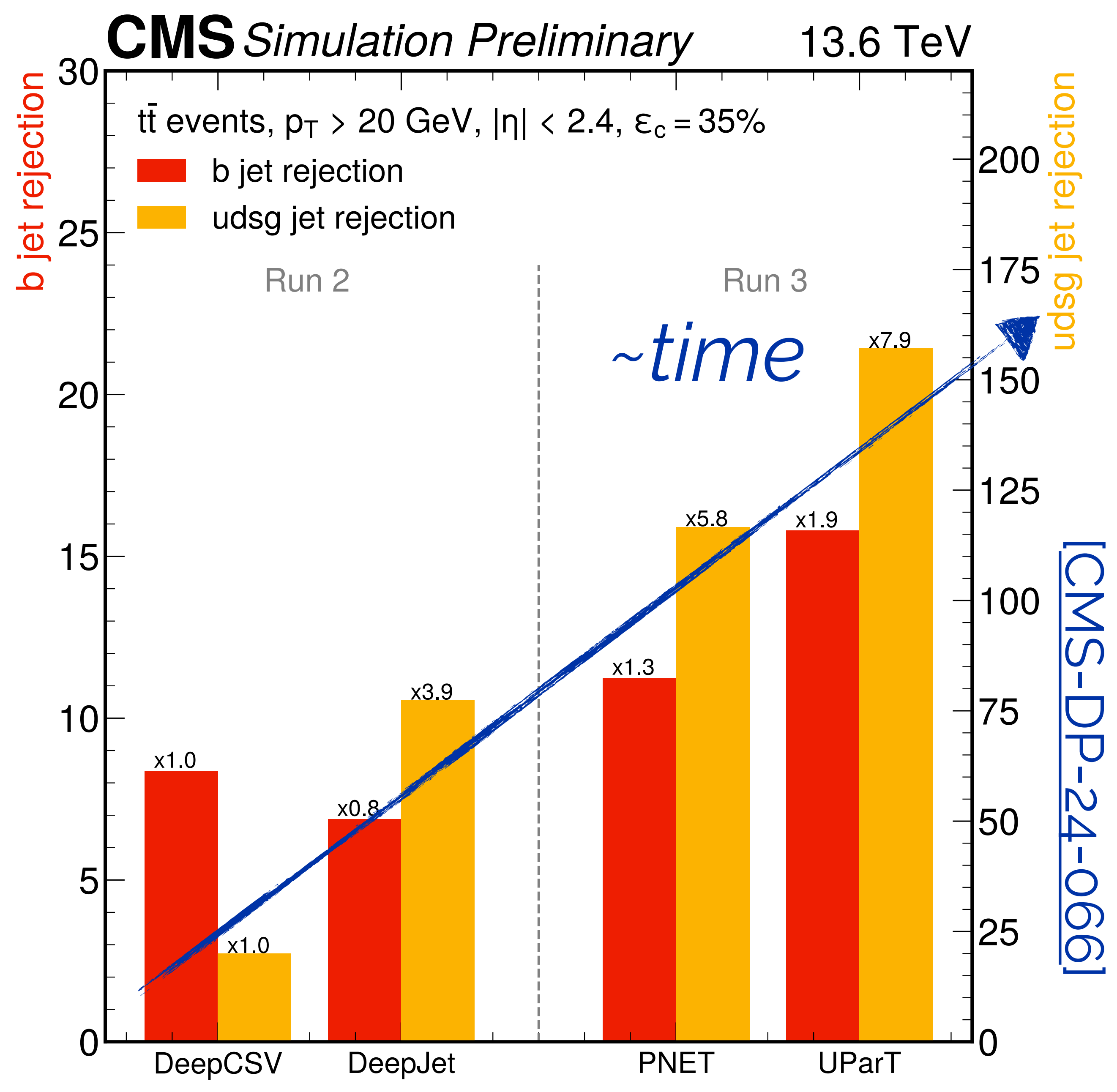
	Signal	Resonant bkg.						Continuous bkg.	S/B
	cH	ggH	ttH	VBF	VH	bH	Total	$(\times 10^3)$	$(\times 10^{-5})$
Category 0	0.0128	83.8%	$< 0.1\%$	5.3%	3.4%	7.5%	2.43	0.50	2.55
Category 1	0.0158	78.7%	0.3%	7.3%	6.3%	7.3%	3.31	1.53	1.03
Category 2	0.0072	72.2%	4.0%	8.3%	9.1%	6.4%	1.77	7.43	0.10
Category 3	0.0034	72.3%	0.1%	16.2%	5.9%	5.6%	1.29	0.17	2.03
Category 4	0.0087	68.0%	1.2%	16.0%	9.9%	4.9%	3.52	0.96	0.90
Category 5	0.0094	53.7%	14.5%	14.7%	13.5%	3.6%	5.11	9.87	0.10
Category 6	0.00029	42.0%	1.9%	42.5%	12.2%	1.5%	0.52	0.02	1.47
Category 7	0.00095	43.1%	13.8%	25.1%	16.8%	1.3%	1.83	0.16	0.59
Category 8	0.00165	35.7%	31.5%	15.0%	16.7%	1.1%	3.32	1.89	0.09
All categories	0.060	61.4%	9.4%	13.9%	10.8%	4.5%	23.1	22.5	0.27

Theoretical uncertainties on cH signal	38%
Theoretical uncertainties on resonant background	59%
Experimental uncertainties on yields	27%
Experimental uncertainties on mass shapes	negligible
Luminosity uncertainties	negligible

jet flavor tagging



For b vs light: Mistagging one b in 100000 light jets!



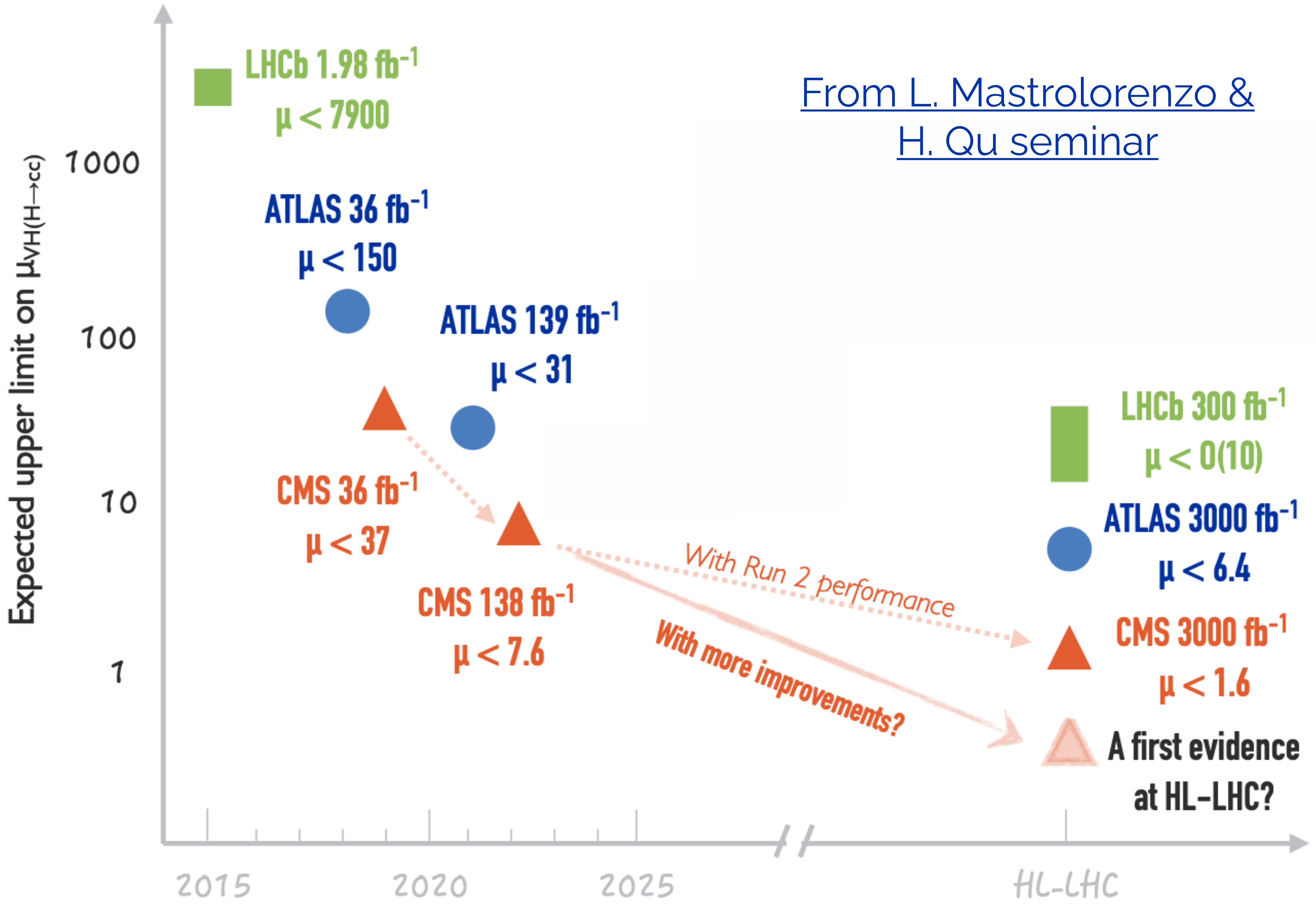
Prospects for the (near) future

- Back-of-the-envelope estimate
  - Assuming factor 3 in luminosity and 2 in c-tagging efficiency with same background rate

  - VH(cc) resolved: ➞ upper limit of ~8 for μ
  - H+c (γγ): ➞ upper limit of ~144 for μ

  - But backgrounds are also real charm…

- At HL-LHC (3000fb-1):
  - VH(cc): Extrapolation gives ~ μ < 1.6
  - H+c cross section of ~170fb
    ➞ 2300 signal events in the γγ channel!
    - Higgs discovery 180/750
    - Benefits from soft charm tagging improvements



From L. Mastrolorenzo & H. Qu seminar

From $\mathcal{O}(1000)$ to $\mathcal{O}(100)$ to $\mathcal{O}(10)$ in ~5 years.
A combined effort and creativity from instrumentation, physics objects and analysis techniques!