From Higgs to Charm

Tao Han
PITT PACC, University of Pittsburgh

Standard Model @ the LHC
July 12, 2023

TH, X. Wang, arXiv:1704.00790; TH, B. Nachman, X. Wang, arXiv:1812.06992;
B. Carlson, TH, S.C.I. Leung, arXiv:2105.08738; TH, Y. Ma, et al. arXiv:2202.08273

Masses in the Standard Model

The good, the bad, and the ugly

(1). $M_{W,Z}$: the good!

Prediction: M_W, M_Z = g v/2 ; $\delta m_w^2 \sim m_w^2 \ln(\Lambda/m_w)$

BSM: all calculable and predictable → e.g. precision M_W

(2). m_H: the bad!

$m_H = \sqrt{2}\,\mu = (2\lambda)^{1/2}\,v = 125$ GeV

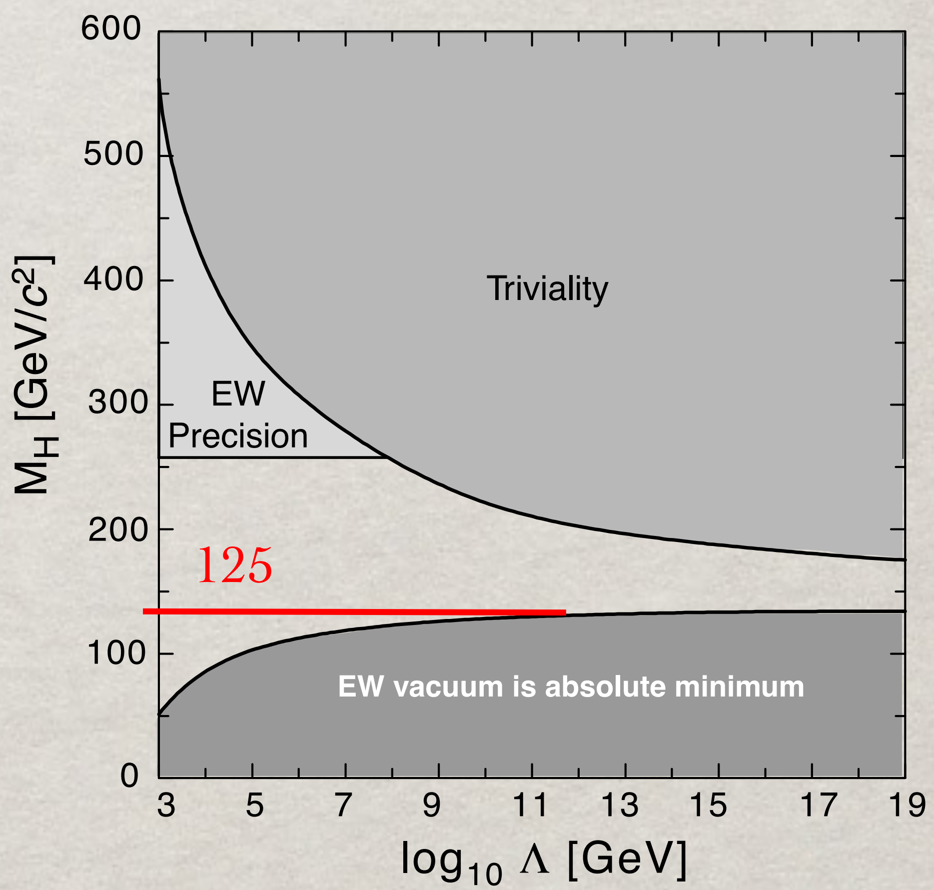
No prediction on m_H

Quadratic corrections from the new physics scale:

$$\delta m_H^2 \propto -\frac{k^2}{4\pi^2}\Lambda^2$$

→ "Naturalness" or "hierarchy puzzle" ?

Note: the quadratic mass corrections are NOT experimentally observable!

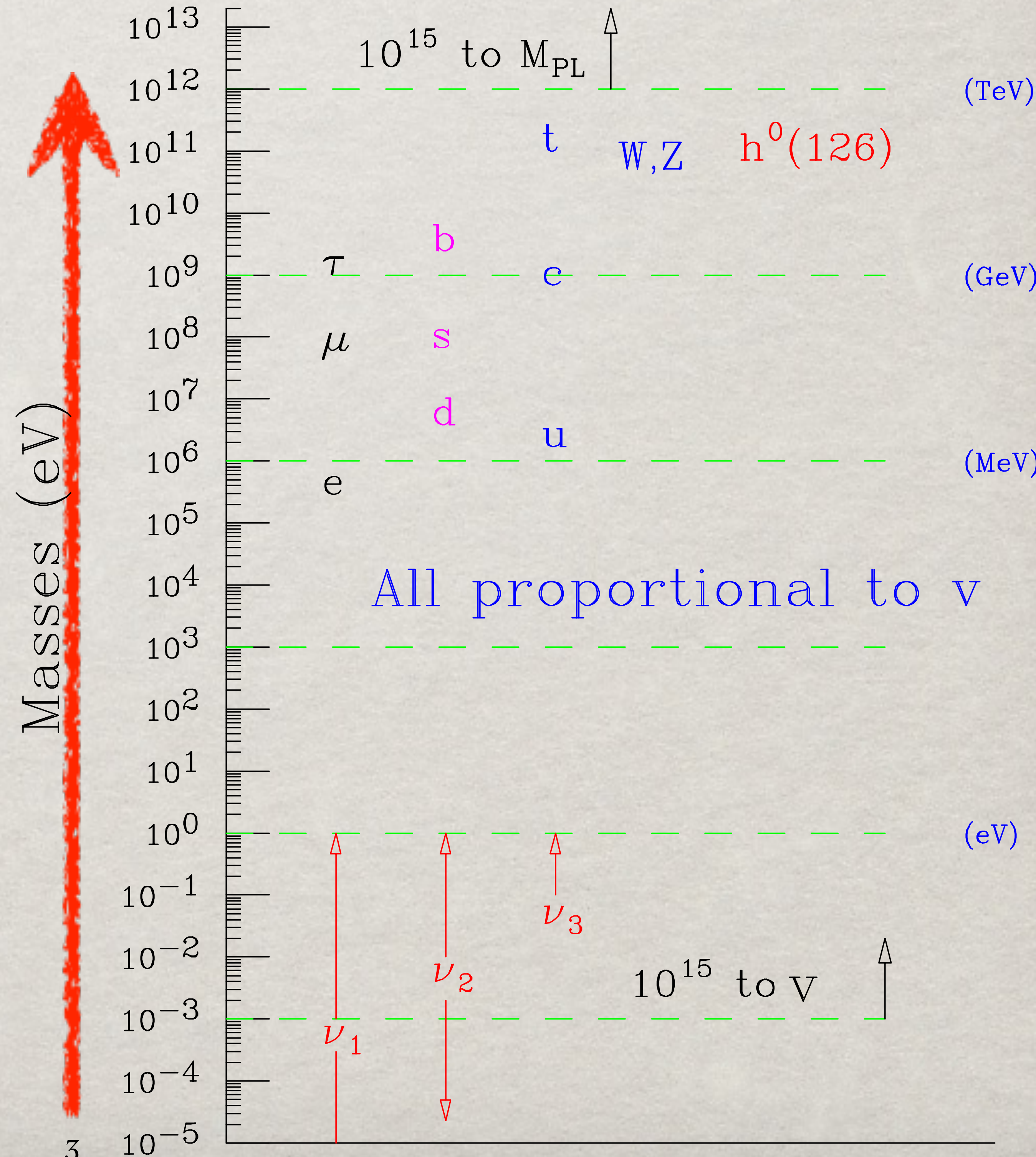


(3). mf: the ugly!

- Couplings are fixed by the masses:

$\mathcal{L}_Y \sim \sum_f m_f \bar{f} f (1 + H/v)$ $\delta m_f \sim m_f \ln(\Lambda/m_w)$ **(chiral symm)**

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- New CP-violation sources?
- Tiny neutrino masses!



Higgs Yukawa couplings as the pivot for all !

Yukawa Couplings - Theory:
(1). Generate flavor hierarchies

- Horizontal flavor symmetry: Froggatt-Nielson mechanism

SM fermions charged [q_i , u_i , d_i] under $U(1)_{FN}$ symmetry broken by $<\phi>/M \sim 0.2$

Froggatt & Nielsen (1979)

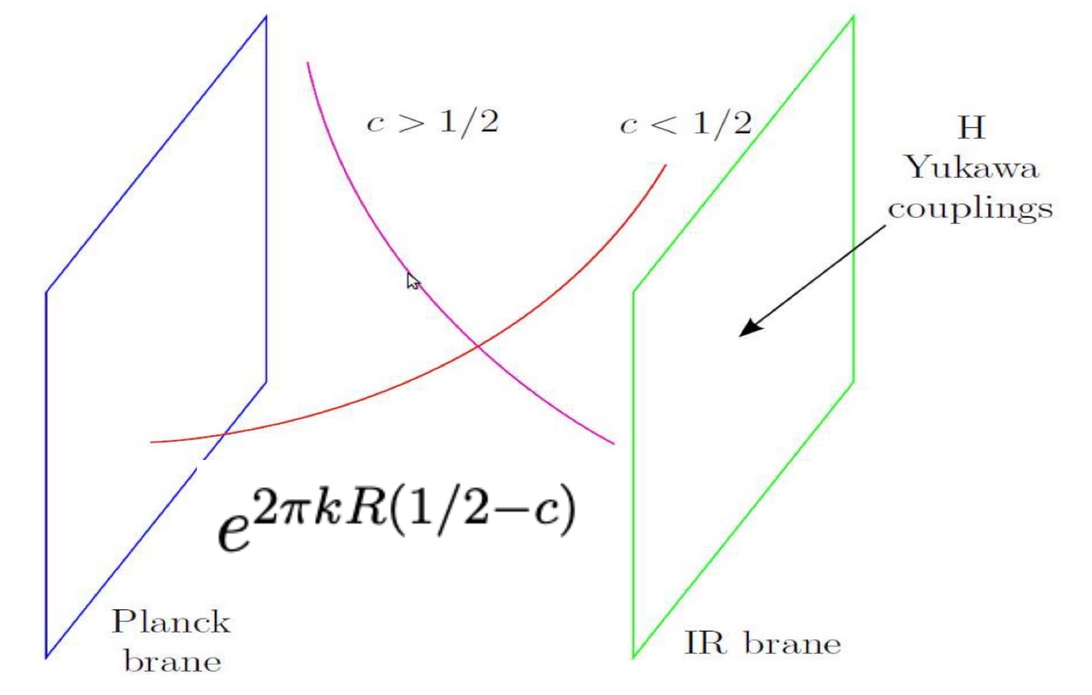
$$(Y_u)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[u_j]}, \qquad (Y_d)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[d_j]}$$

J. Zupan & W. Altmannshofer, 2203.07726

- Warped extra-dimension:

Yukawa couplings determined by the overlapping with the Higgs brane.
→ dual to (partial) composite model.

Randall & Sundrun (1999); Huber & Shafi (2001); Agashe et al. (2005)



- Radiative generation of m_f :

The 3[rd] generation @ tree-level
Light generations by new particle loops $\sim 1/16\pi^2 \sim 10^{-2}$.

S. Weinberg (1972)

(2). The Higgs sector extension

- **2HDM (MSSM):** well-motivated
  ($\tan\beta = v_2/v_1$; α the neutral Higgs mixing)

Talks in HPNP2023:
Pilaftsis; Haber; Takeuchi; Yagyu; Ferreira; De Curtis; Song; Dey; Kartayama; Heinemeyer; Muta; Ivanov; Sakurai … …

	Tree-level Normalized Higgs couplings			
	κ_h^u	κ_h^d	κ_h^e	κ_h^V
Type-I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$
Type-II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$
Type-L	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$
Type-F	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$

Decoupling/
Alignment limit:
κ's → 1

H. Haber & Y. Nir (1990)

- **Plus a singlet S (NMSSM):**
  more mixing & flavor physics, connect to dark sector

- **Add a triplet Φ (Type-II seesaw):**
  $\phi^{\pm\pm}$, $\phi^{\pm}$, ϕ^0 ; connect to neutrino Majorana mass

For a review, see, i.e., G.C. Branco, M. Sher et al., arXiv:1106.0034 …

Along with searching for BSM new physics,
precision Higgs measurement is a must!
→ Parameterize Higgs couplings in a simple way

SMEFT

SM Effective Field Theory: a linear representation

SM-like Higgs $\boldsymbol{\Phi} = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + h + i\phi^0 \end{pmatrix}$

$$\mathcal{L}_Y \sim \sum_{n=0} \frac{Y_{ij}^n}{\Lambda^{2n}} (\Phi^\dagger \Phi)^n \bar{L}_{iL} \Phi e_{jR} \ \rightarrow \ m_f = \frac{v}{\sqrt{2}} \sum_{n=0} Y_n^f \frac{v^{2n}}{\Lambda^{2n}}$$

Yukawa coupling deviates from the mass relation!
At the dim-6 leading order:

$\rightarrow \delta\kappa_f \sim Y_1 \frac{v^2}{\Lambda^2} \sim O(\text{a few}\%)$ for $\Lambda \sim 2$ TeV!

This is the immediate target @ LHC!

HEFT

Higgs Effective Field Theory: a non-linear representation

$$U = e^{i\phi^a \tau_a / v} \quad \text{with} \quad \phi^a \tau_a = \sqrt{2} \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix}$$

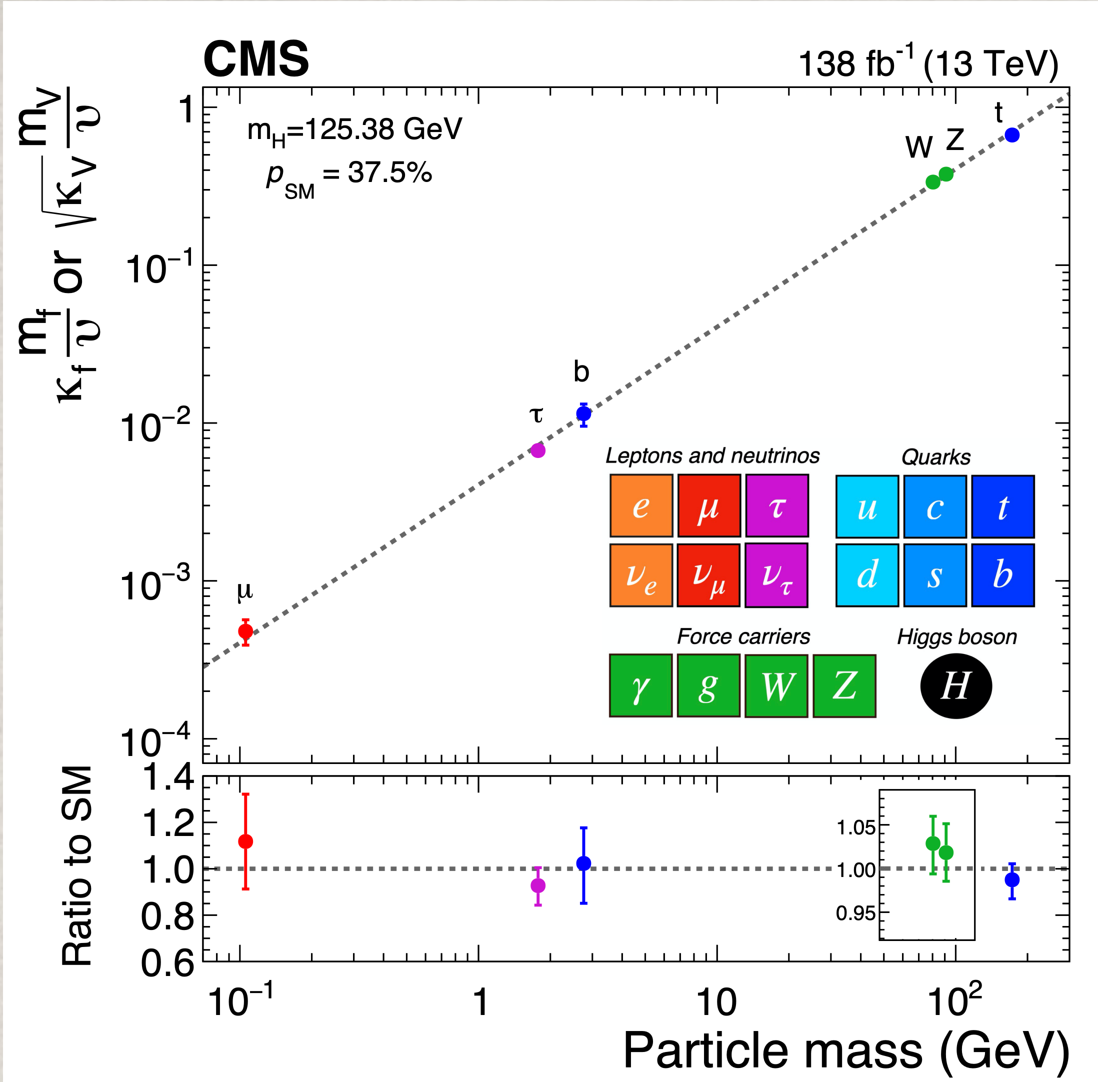
$$L_Y \sim -\frac{v}{2\sqrt{2}} \left[\sum_{n \geq 0} y_n \left(\frac{H}{v}\right)^n (\bar{\nu}_L, \bar{\mu}_L) U (1 - \tau_3) \begin{pmatrix} \nu_R \\ \mu_R \end{pmatrix} + \text{h.c.} \right]$$

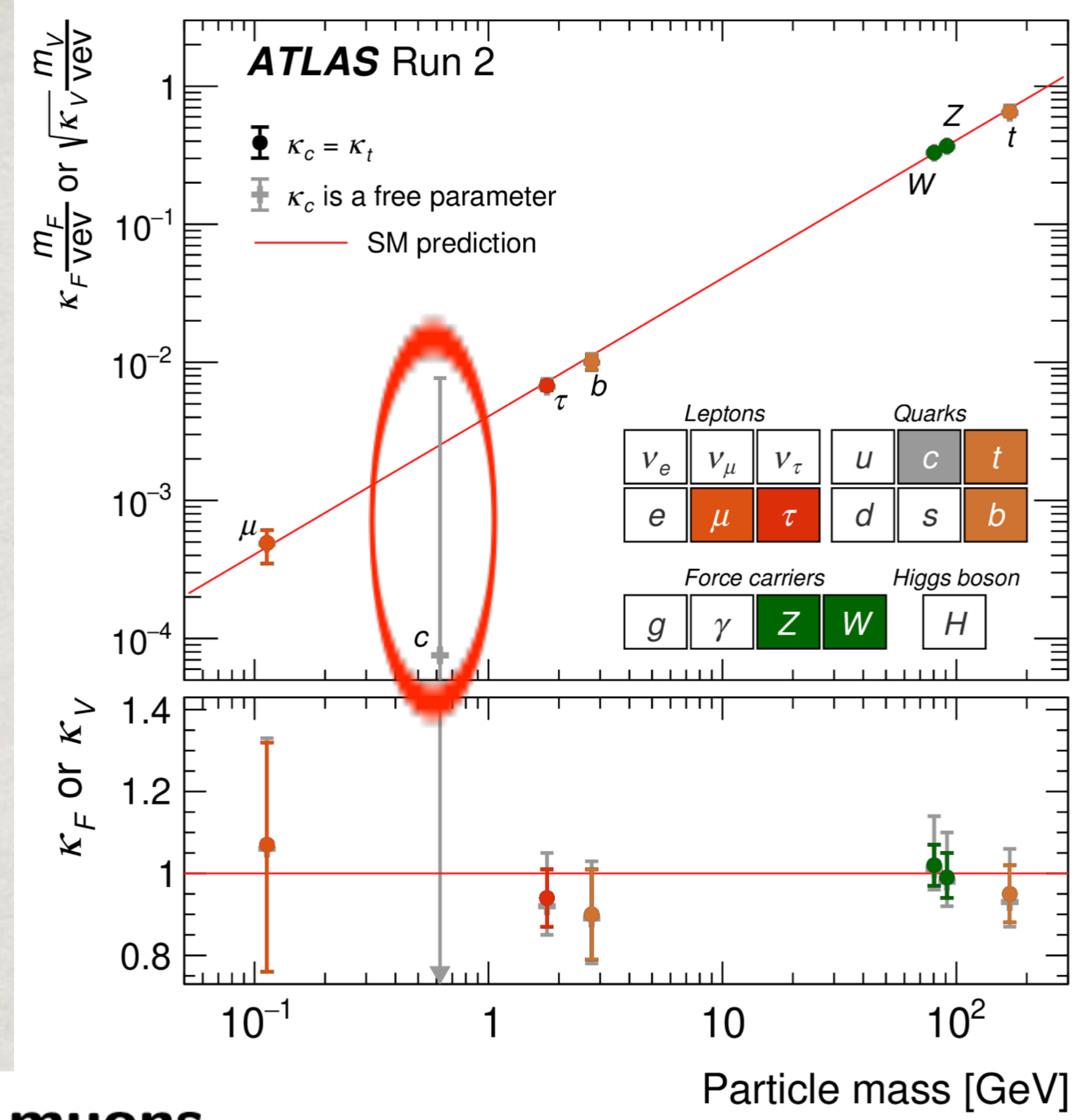
$$Y_f(H) = \frac{\sqrt{2} m_f}{v} + \sum_{n=1} y_{fn} (\frac{H}{v})^n$$

- The scale for new dynamics is at $\Lambda \sim 4\pi\, v$
  → close by! The deviation can be sizable:

$$\rightarrow \delta\kappa_f \sim Y_1 \frac{H}{v} \sim O(1)$$

- Multiple W_L/Higgs may be enhanced.





Evidence for Higgs boson decay to a pair of muons

ABSTRACT: Evidence for Higgs boson decay to a pair of muons is pr
combines searches in four exclusive categories targeting the productio
via gluon fusion, via vector boson fusion, in association with a vector
ciation with a top quark-antiquark pair. The analysis is performed
collision data at $\sqrt{s}$ = 13 TeV, corresponding to an integrated lun
recorded by the CMS experiment at the CERN LHC. An excess of e
ground expectation is observed in data with a significance of 3.0 s

CMS coll., arXiv:2009.04363

$h \to \mu^+\mu^-$ via gluon fusion at the LHC

Tao Han and Bob McElrath

Department of Physics, University of Wisconsin–Madison, WI 53706

Abstract

We study the observability of the $h \to \mu^+\mu^-$ decay in the Standard Model and the MSSM at the LHC. The observation of the $h\mu\mu$ coupling is important to determine whether the Higgs particle that generates mass for the weak bosons is also responsible for mass generation of the second generation of fermions. We find that the signal via the gluon fusion channel is comparable to that from the weak-boson fusion. By combining these two channels, observing $h \to \mu^+\mu^-$ is feasible at the LHC with a delivered luminosity of 300 fb^{-1} at 3σ statistical significance for 110 GeV $< m_h <$ 140 GeV in the Standard Model. This corresponds to a $h\mu\mu$ coupling determination at about 15% accuracy assuming $ht\bar{t}$, $hb\bar{b}$ couplings SM-like. The observation becomes more promising in the MSSM for $\tan\beta > 8$ and $M_A < 130$.

TH, B. McElrath, arXiv:hep-ph/0201023

Charm-quark Yukawa Coupling

$$y_f(h+\frac{v}{\sqrt{2}})\bar{f}f \quad \to \quad y_c^{SM}=\frac{\sqrt{2}m_c}{v}\sim 4\times 10^{-3}$$

In the **κ**-scheme for BSM: $y_c=\kappa_c\, y_c^{SM}$

Measuring $H\bar{c}c$ coupling at the LHC is very difficult:

- BR(h → cc)=2.9%
- Formidable QCD backgrounds
- c-tagging challenging
- … …

(1). H → cc at high pT The leading channel:

$$pp\to Vh,\quad \text{with } V\to \ell^+\ell^-,\ \ell^\pm\nu,\ h\to\bar{c}c$$

subject to huge backgrounds 2-jets, cc; h → bb …

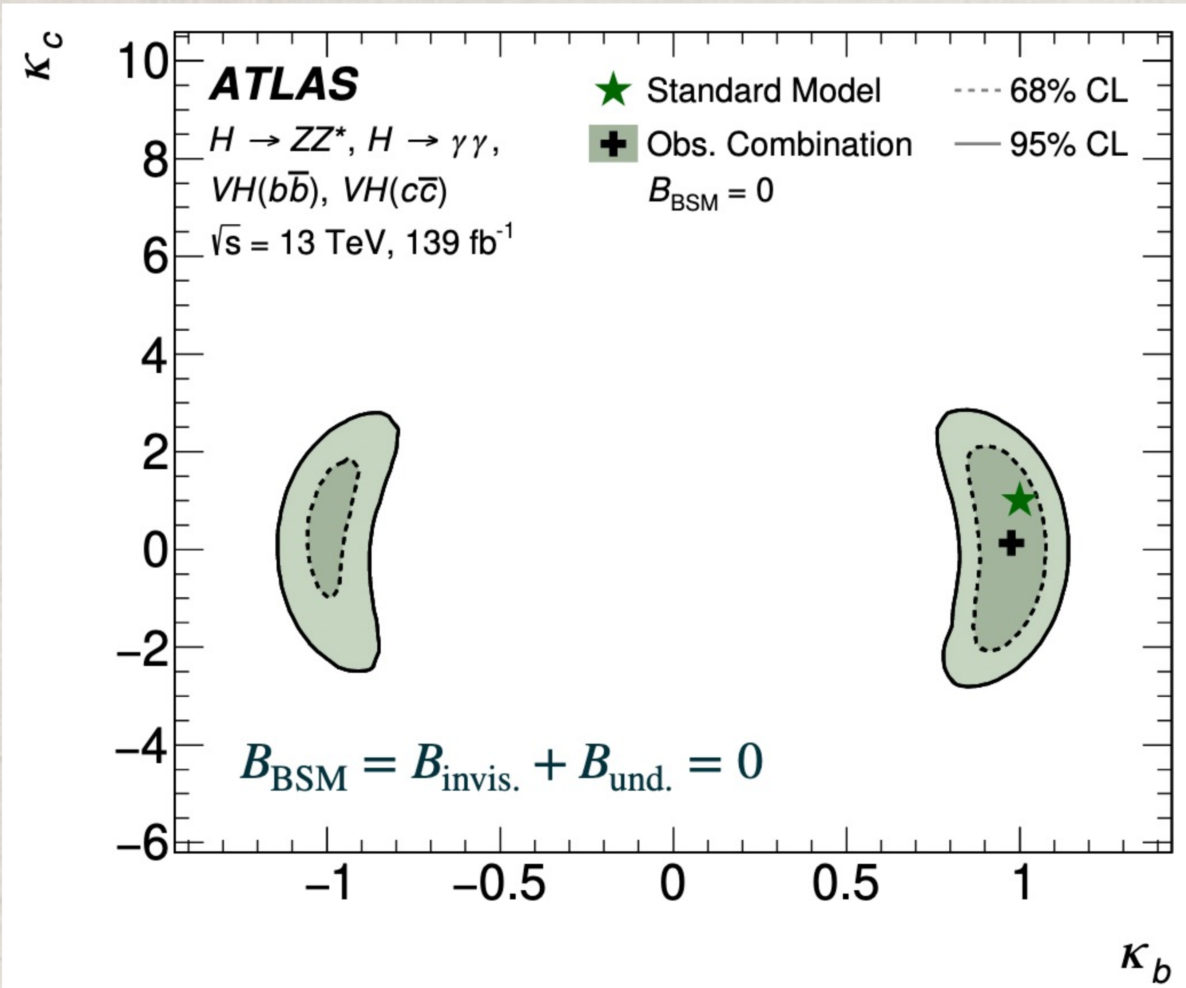
At LHC Run 2: **κ_c** < $8.5@2\sigma$ ATLAS-CONF-2021-021

Inclusive high pT(h → cc): **κ_c** < $6.9@2\sigma$ CMS: arXiv:2211.14181

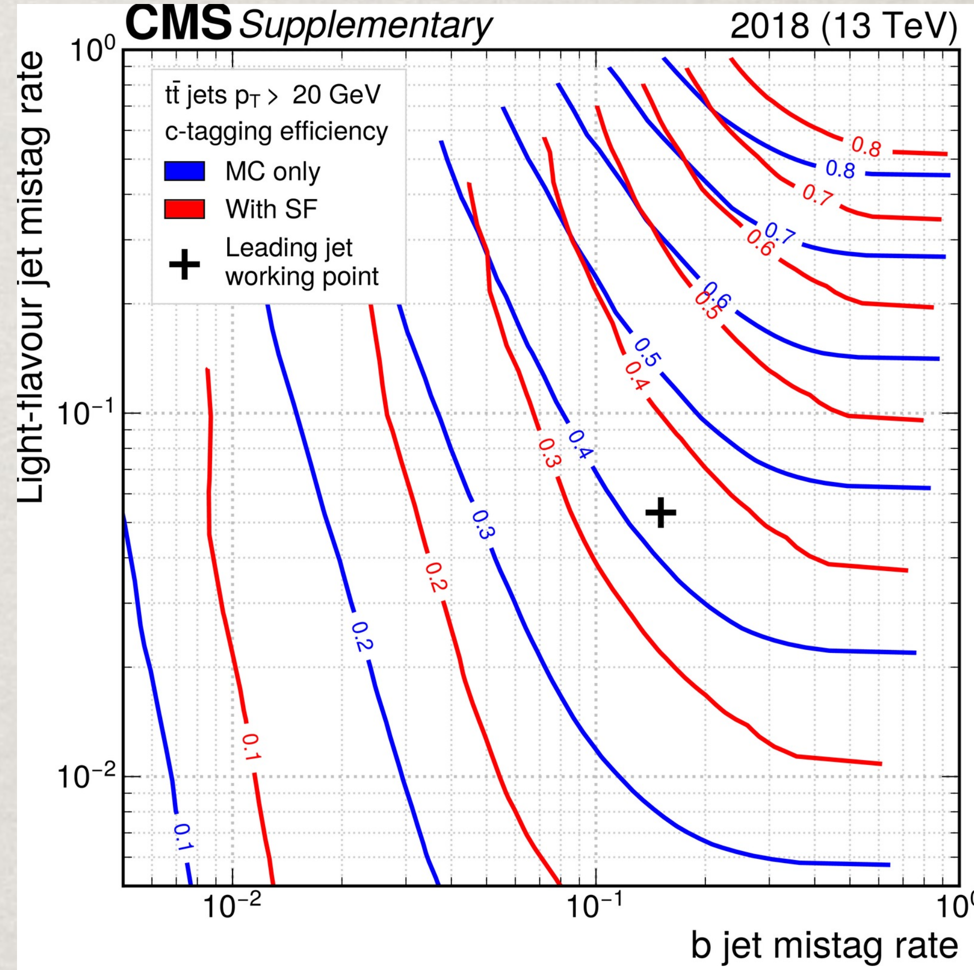
Nick Smith, next talk.

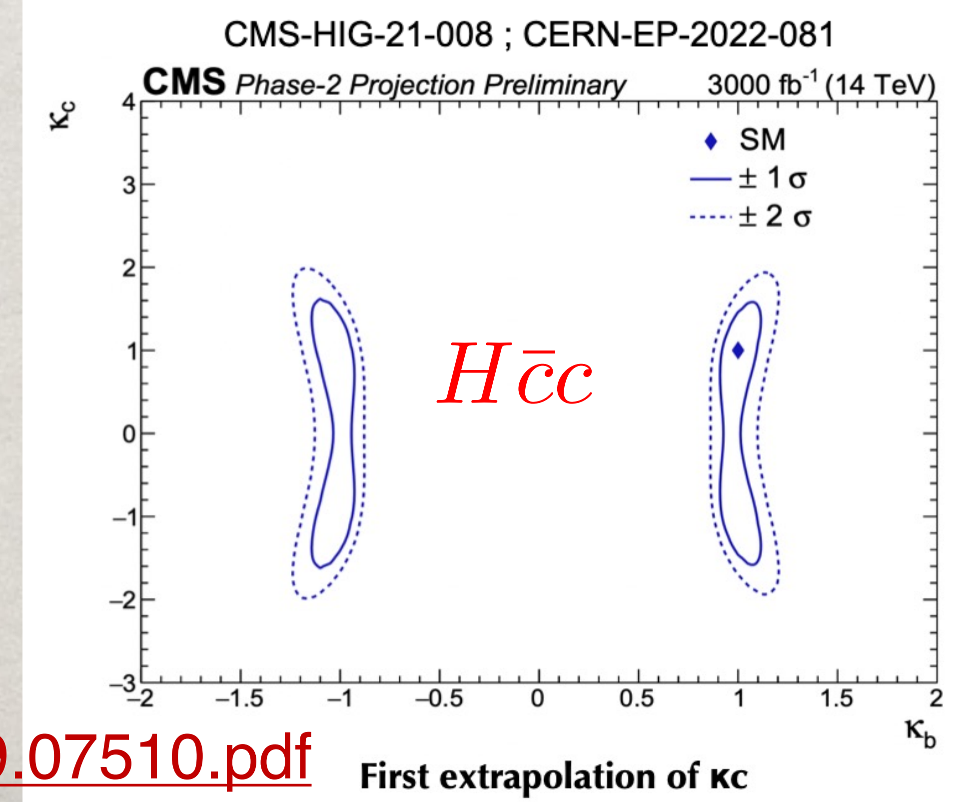
LHC Run2 fit:

Nick Smith, next talk.



Submitted to JHEP [2207.08615]





At HL-LHC with 3 ab^{-1}:

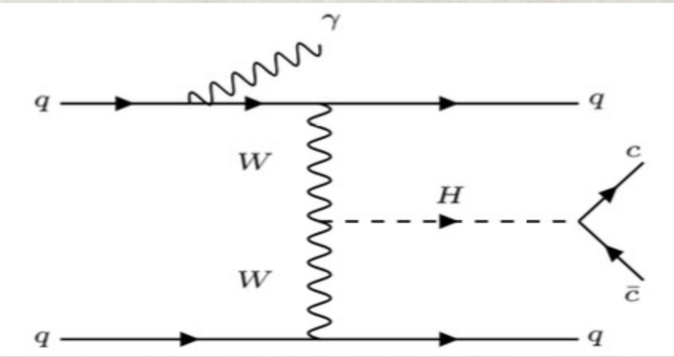
arXiv:1902.10229; ATLAS-CONF-2021-021

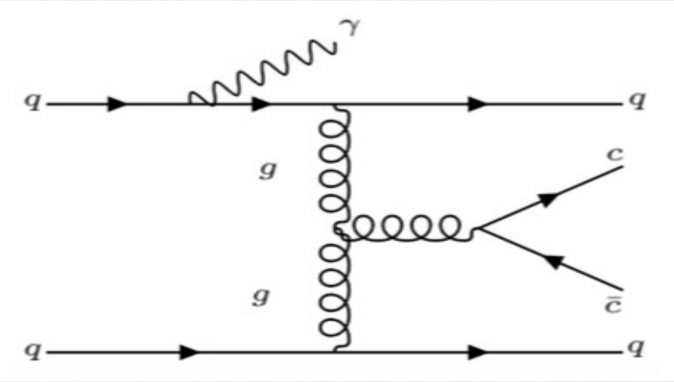
EF01/02 report: https://arxiv.org/pdf/2209.07510.pdf

Higgs production rate is high: #H@LHC ~ 50 M /ab !
Need new ideas!
(2). Higgs to charm+γ in VBF

A New Approach: VBF + γ

- Striking signatures and sizable signal events
- Additional photon results in lower rate
- Compensated by
  - Extra handle to trigger on
  - Suppression of gluon-rich background





$$p_T^j > 35\,\text{GeV}, \quad |\eta_j| < 5, \qquad p_T^\gamma > 25\,\text{GeV}, \quad |\eta_\gamma| < 3.$$

	13 TeV	14 TeV	30 TeV	100 TeV
$\sigma_{\text{VBF}+\gamma}$ (pb)	0.024	0.027	0.099	0.43
$\sigma_{pp\to 4j+\gamma}$ (pb)	830	940	3700	21000

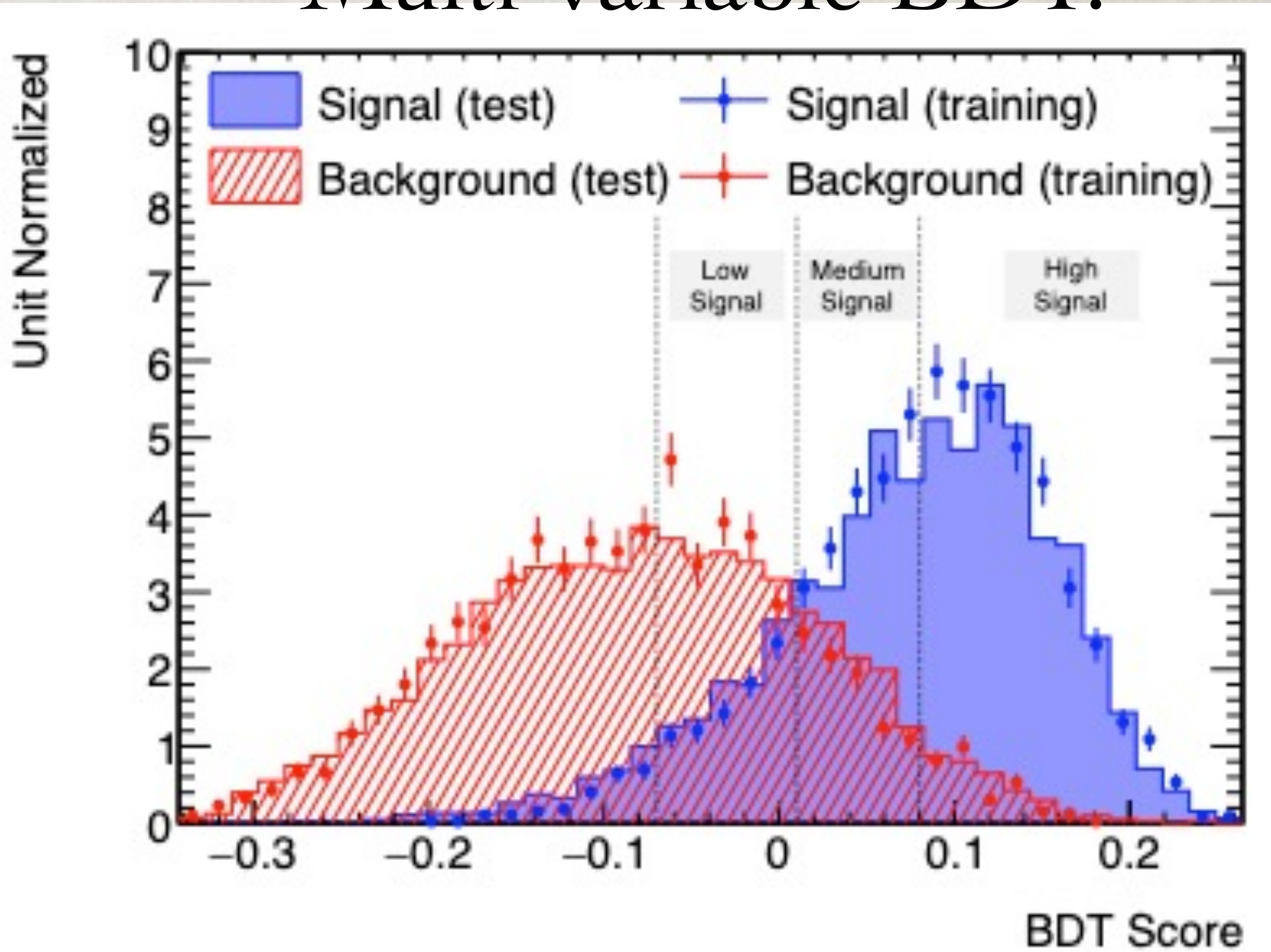
Table 2: Cross sections of signal and background at different center-of-mass energies, with the basic acceptance cuts in Sec. 2.1.

B. Carlson, TH, S.C.I. Leung, aXive:2105.08738

(2). Higgs to charm+γ in VBF

Multi-variable BDT:

- Photon $E_T^\gamma > 30$ GeV;
- At least four jets with $p_T^j > 40$ GeV;
- At least one pair of jets with $m_{jj} > 700$ GeV;
- At least one b-tagged jet with 77% efficiency.



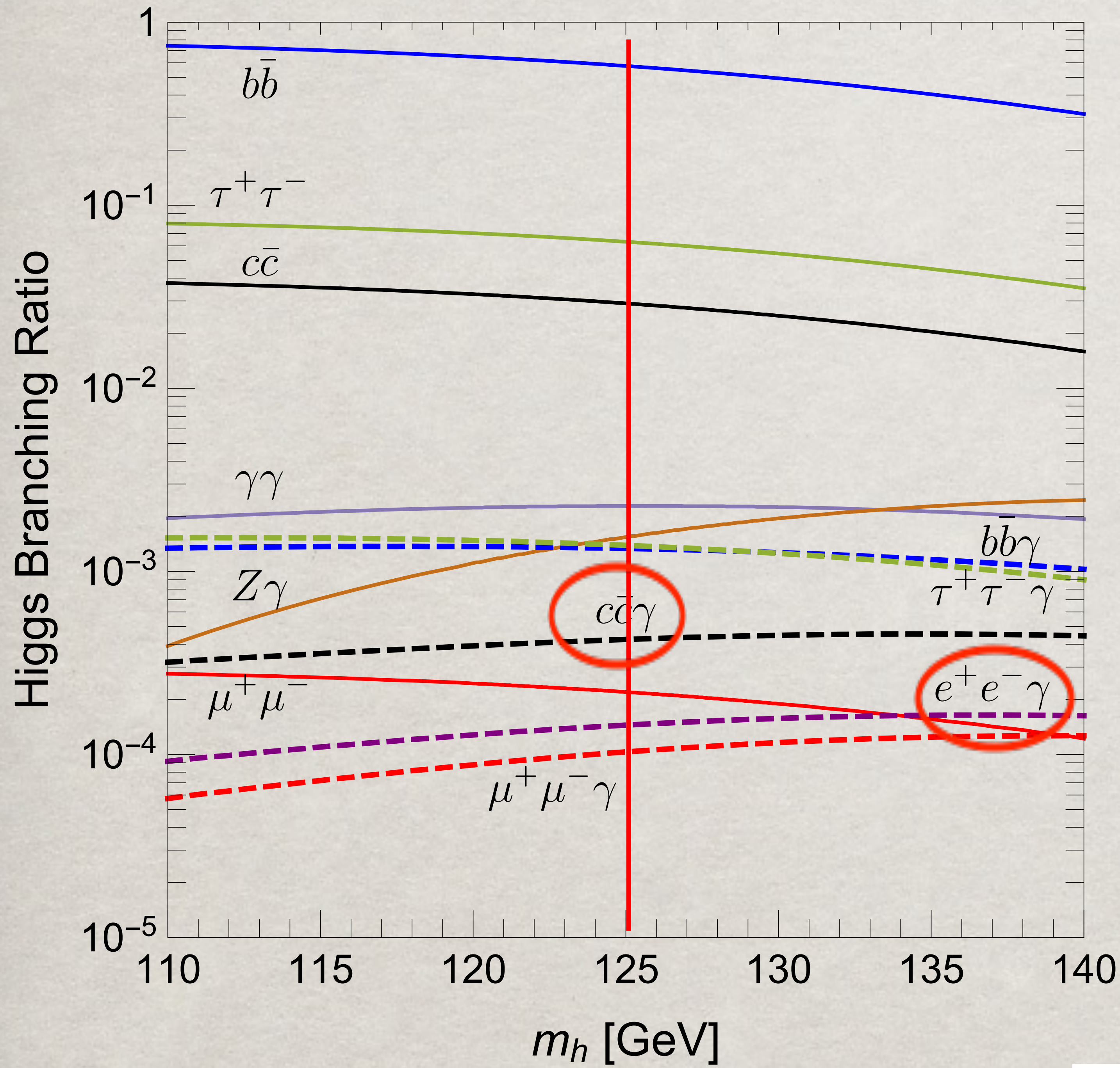
	LHC	Cut-based	BDT	ZH [16, 17]	Fit [33]	Hc [31]	$H \to c\bar{c}\gamma$ [41]
κ_c	36.1 fb^{-1}	20	16	10	-	-	-
	3 ab^{-1}	6.5	5.4	2.5	1.2	2.6 - 3.9	8.6

Table 5: The expected 95% CL_s upper limit on the charm-Yukawa coupling from this analysis using 36.1 fb^{-1} and 3 ab^{-1} of data at 13 TeV, respectively, in comparison with other searches as quoted.

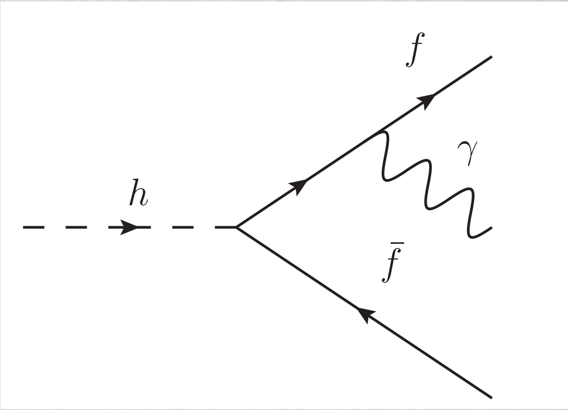
B. Carlson, TH, S.C.I. Leung, aXive:2105.08738;
[33]: J. de Blas et al., JHEP 01 (2020) 139, [1905.03764]

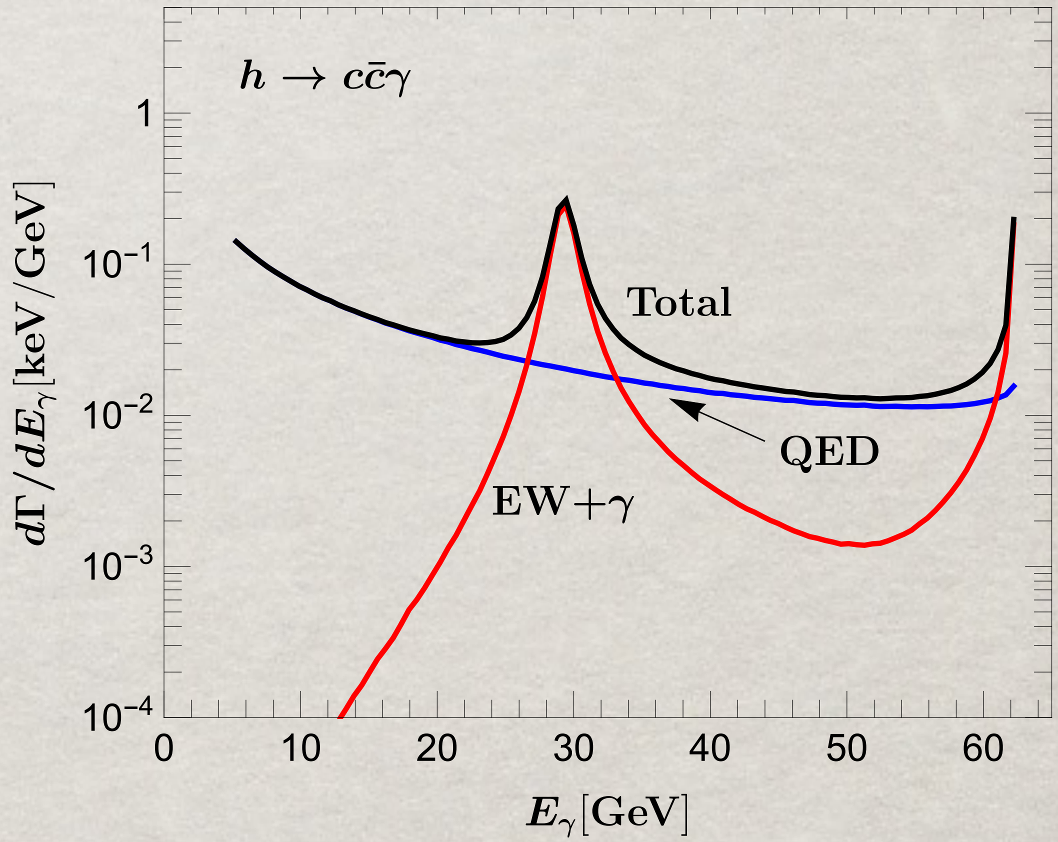
(3). Higgs radiative decay

TH and X. Wang, arXiv:1704.00790

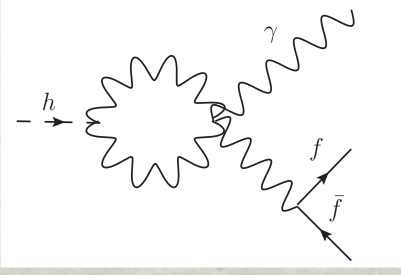


→ additional γ to trigger on:





Not EW+ γ, insensitive to κ_c



$$E_\gamma = \frac{m_h}{2}\left(1 - \frac{m_Z^2}{m_h^2}\right) \approx 30 \text{ GeV}, \text{ for } \gamma Z \text{ production},$$

$$E_\gamma = \frac{m_h}{2}\left(1 - \frac{m_{\gamma^*}^2}{m_h^2}\right) \approx 63 \text{ GeV}, \text{ for } \gamma\gamma^* \text{ production}.$$

Results for $gg \to h \to c\,\bar{c}\,\gamma$:

Operating Point	ϵ_c	ϵ_b	ϵ_j
I	20%	33%	0.13%
II	30%	33%	1%
III	41%	50%	3.3%

c-tagging efficiency;
b and jet mis-tagging rates

	Working Point	Signal (QED)	Background events	Background event rate [Hz]	$S/\sqrt{S+B}$ $[10^{-2}]$
Level-1 (L1)	No Tag	-	-	9.55×10^3	-
1 c-tag	I	269	3.37×10^8	5.62	1.47
	II	349	5.18×10^8	8.63	1.54
	III	401	8.83×10^8	14.7	1.35
2 c-tags	I	29	1.14×10^7	0.191	0.878
	II	66	2.23×10^7	0.371	1.42
	III	126	5.79×10^7	0.966	1.66

Table 2: Expected numbers of events of the signal and background, and event rates, in the range of $100 < M_{jj\gamma} < 140$ GeV at the HL-LHC with $\mathcal{L} = 3$ ab^{-1}. The first row gives the event rate at L1, with only the requirements in Sec. 2 applied. Systematic uncertainties are not accounted for in the significance calculation in the last column.

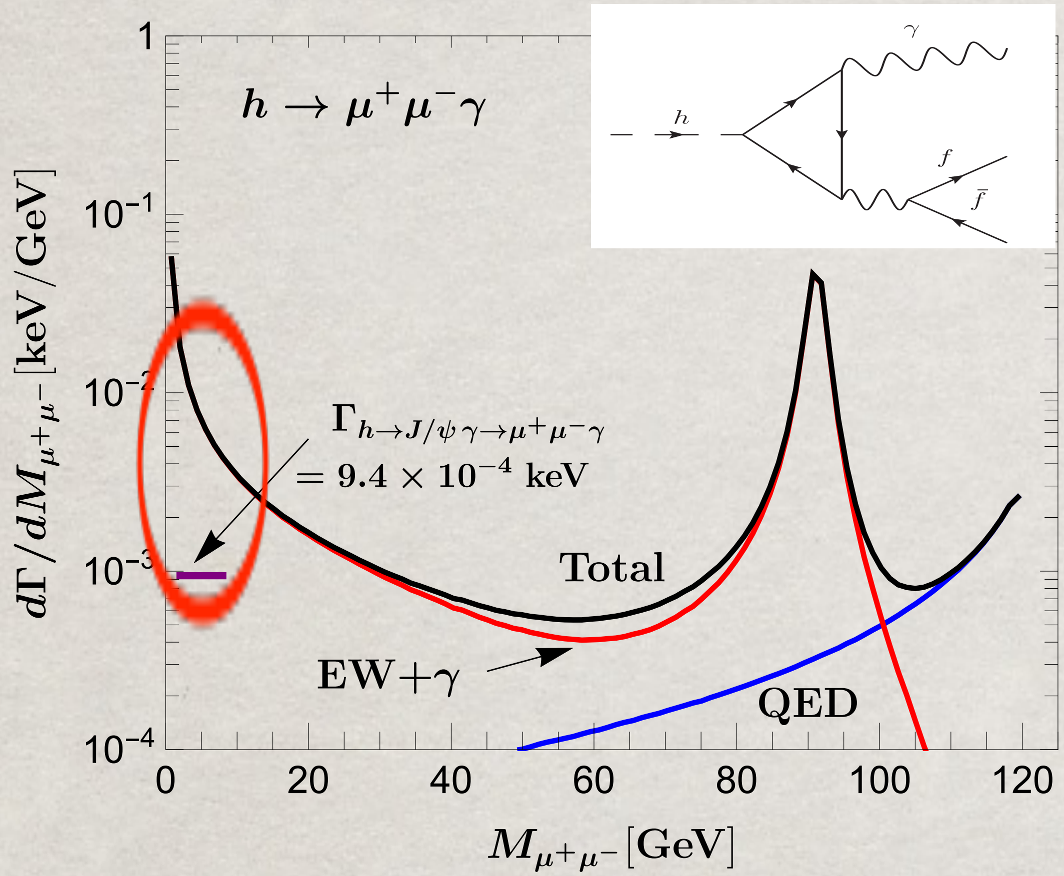
95% CL$_s$ upper limit on the signal strength via BDT-based analysis to be

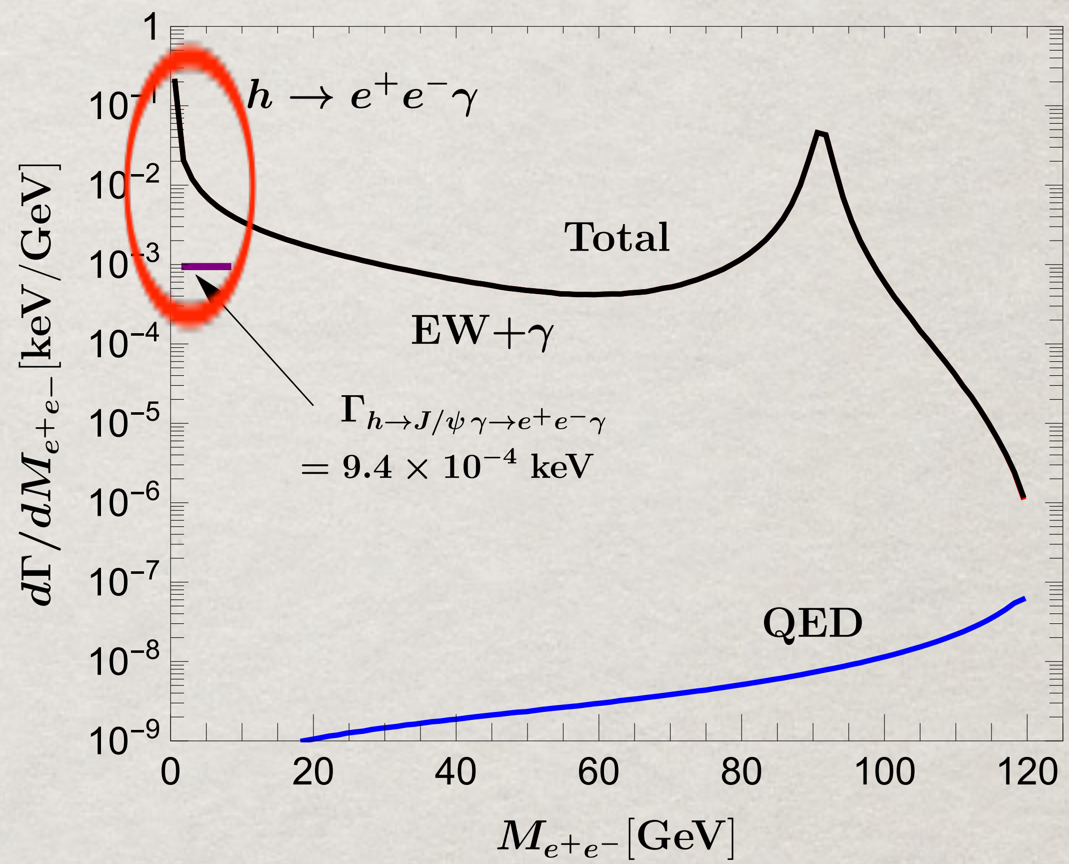
$$\mu < 89, \quad 71, \quad 70, \quad \Rightarrow \quad \kappa_c < 9.4, \quad 8.4, \quad 8.3.$$

TH, B. Nachman, X. Wang, arXiv:1812.06992

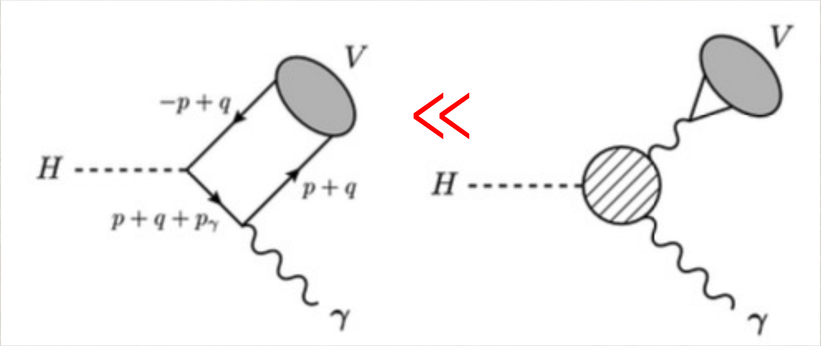
A remark on $gg \to h \to J/\psi\, \gamma \to \ell^+ \ell^- \gamma$:

Bodwin, Petriello et al. (2013, 2014, 2017); Konig, Neubert (2015)





J/ψ γ is more than an order of magnitude smaller;
Further, the dominant contribution is from the
"vector-meson dominance" **γ*→ J/ψ,**
insensitive to the direct hcc Yukawa:



TH and X. Wang, arXiv:1704.00790

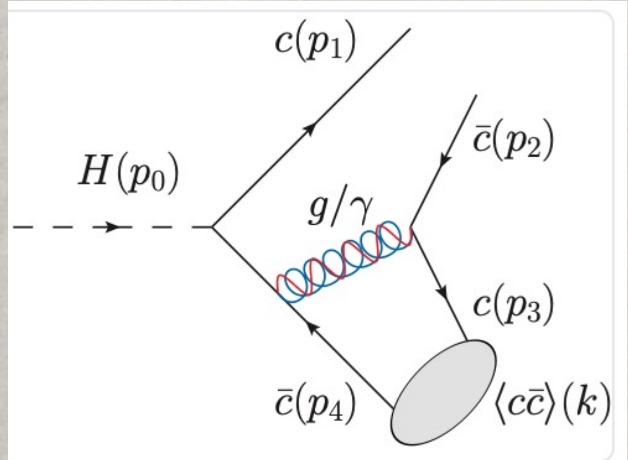
(4). Higgs decay to charmonia: c-fragmentation

- H → J/ψ via charm-quark fragmentation:

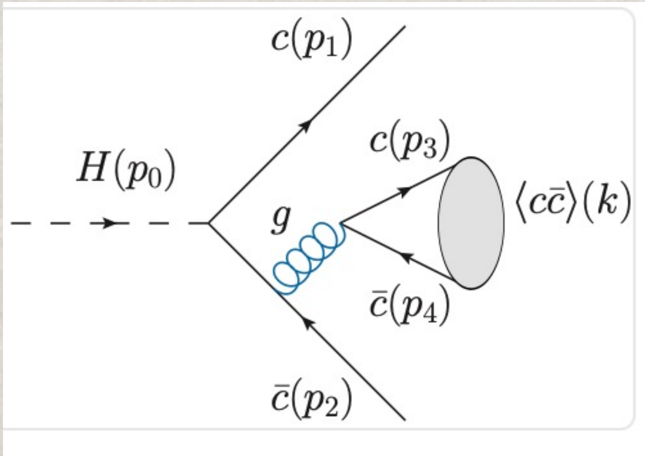
$$H \to c + \bar{c} + J/\psi \, (\text{or} \, \eta_c)$$

➢ Enhanced from the fragmentation
➢ Direct coupling to charm!

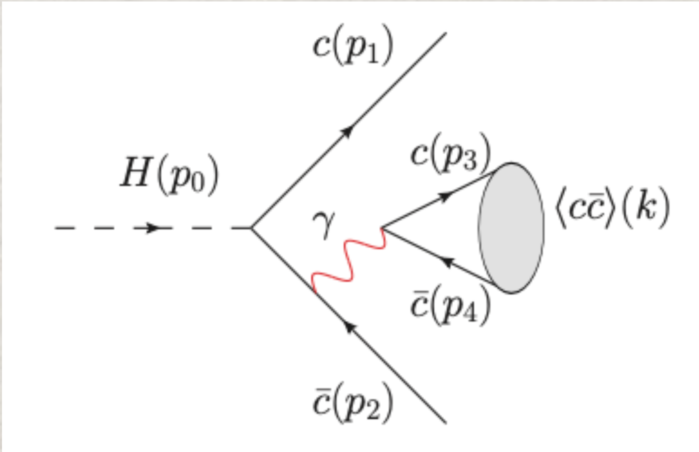
Color-singlet (CS) (leading)



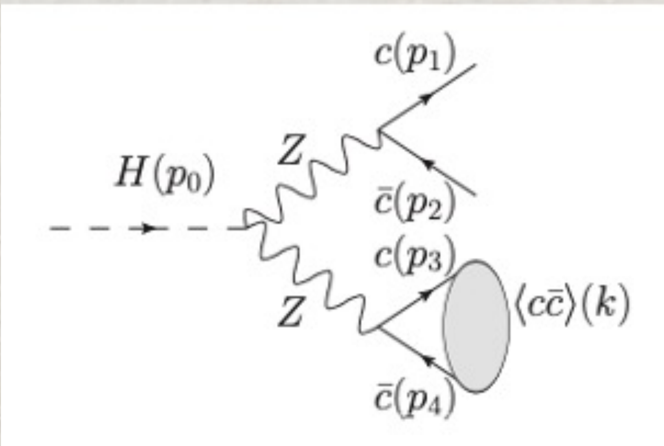
Color-octet (CO) (sub-leading, ½ of CS)



QED (sub-leading, ¼ of CS)



EW (sub-sub-leading)



TH, A. Leibovich, Y. Ma, X.Z. Tan: aXive:2202.08273

Nonrelativistic QCD framework

$$\Gamma = \sum_{\mathbb{N}} \hat{\Gamma}_{\mathbb{N}}(H \to (Q\bar{Q})[\mathbb{N}] + X) \times \langle \mathcal{O}^h[\mathbb{N}] \rangle, \quad d\hat{\Gamma}_{\mathbb{N}} = \frac{1}{2m_H} \frac{|\mathcal{M}|^2}{\langle \mathcal{O}^{Q\bar{Q}} \rangle} d\Phi_3$$

Long distance matrix element (LDME)

Related to the wave function at origin

$$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{[1]}] \rangle = \frac{3N_c}{2\pi}|R(0)|^2, \quad \langle \mathcal{O}^{\eta_c}[{}^1S_0^{[1]}] \rangle = \frac{N_c}{2\pi}|R(0)|^2$$

$$\langle \mathcal{O}^{Q\bar{Q}} \rangle = 6N_c, \text{ for } {}^3S_1^{[1]}, \quad \langle \mathcal{O}^{Q\bar{Q}} \rangle = 2N_c, \text{ for } {}^1S_0^{[1]}$$

A quarkonium can also be produced through color-octet $Q\bar{Q}$ Fork states

New states involved: ${}^3S_1^{[8]}$, ${}^1S_0^{[8]}$, ${}^3P_J^{[8]}$, and ${}^1P_1^{[8]}$

The LDMEs $\langle \mathcal{O}^h[{}^{2S+1}L_J^{[\text{color}]}] \rangle$ need to be fitted from experimental data

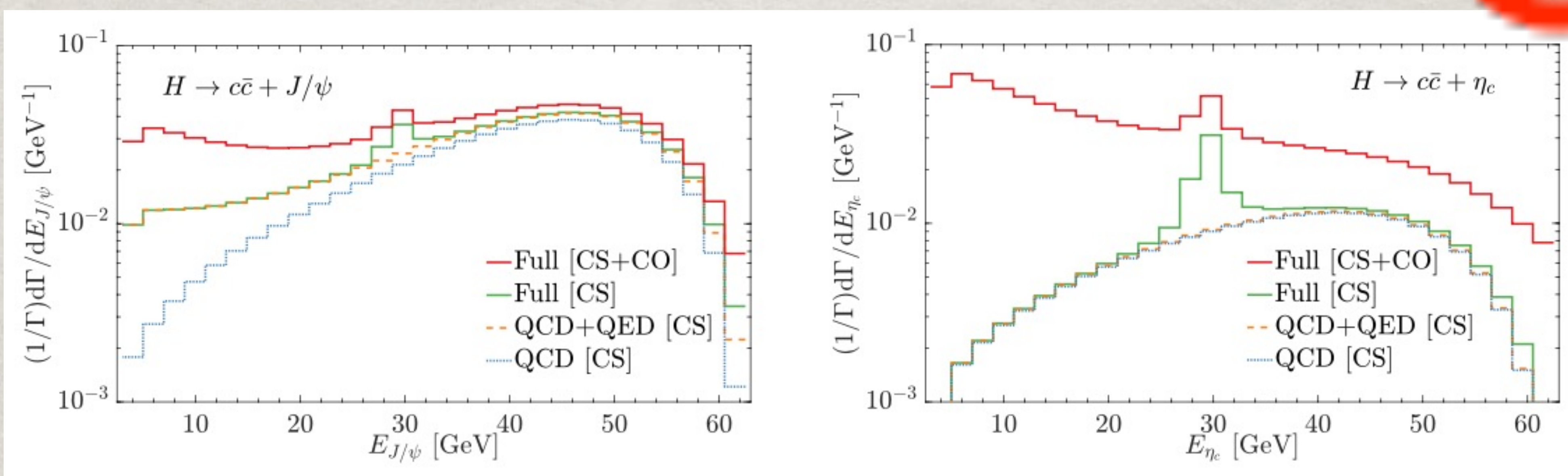
Reference	$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}] \rangle$	$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{[8]}] \rangle$	$\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}] \rangle / m_c^2$
G. Bodwin,	$(9.9 \pm 2.2) \times 10^{-2}$	$(1.1 \pm 1.0) \times 10^{-2}$	$(4.89 \pm 4.44) \times 10^{-3}$
K.T. Chao,	$(8.9 \pm 0.98) \times 10^{-2}$	$(3.0 \pm 1.2) \times 10^{-3}$	$(5.6 \pm 2.1) \times 10^{-3}$
Y. Feng,	$(5.66 \pm 4.7) \times 10^{-2}$	$(1.77 \pm 0.58) \times 10^{-3}$	$(3.42 \pm 1.02) \times 10^{-3}$

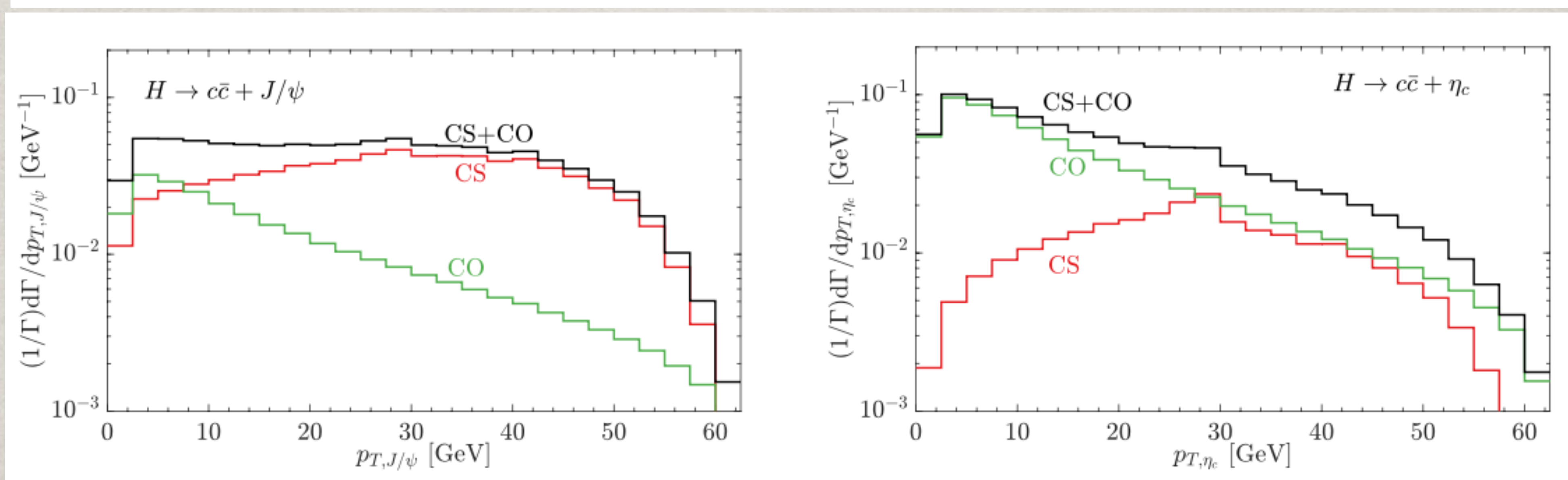
Our results:

TH, A. Leibovich, Y. Ma, X.Z. Tan: aXive:2202.08273

Decay width and branching fraction

	QCD [CS]	QCD+QED [CS]	Full [CS]	Full [CO]	Full [CS+CO]
$\Gamma(H \to c\bar{c} + J/\psi)$ (GeV)	4.8×10^{-8}	5.8×10^{-8}	6.1×10^{-8}	2.2×10^{-8}	8.3×10^{-8}
$\mathrm{BR}(H \to c\bar{c} + J/\psi)$	1.2×10^{-5}	1.4×10^{-5}	1.5×10^{-5}	5.3×10^{-6}	2.0×10^{-5}
$\Gamma(H \to c\bar{c} + \eta_c)$ (GeV)	4.9×10^{-8}	5.1×10^{-8}	6.3×10^{-8}	1.8×10^{-7}	2.4×10^{-7}
$\mathrm{BR}(H \to c\bar{c} + \eta_c)$	1.2×10^{-5}	1.2×10^{-5}	1.5×10^{-5}	4.5×10^{-5}	6.0×10^{-5}





Higgs production cross section at LHC σ_H ~ 50M / ab^{-1}

Detection efficiency ε for the final state $c\bar{c}+\ell^+\ell^-$

$\mathrm{BR}(J/\psi \to \ell^+\ell^-) \sim 12\%$, $\mathrm{BR}(H \to J/\psi + c\bar{c}) \sim 2\times 10^{-5}$

Event number

$$N = L\sigma_H\ \varepsilon\ \mathrm{BR}(\ell^+\ell^-) \approx 24\ \kappa_c^2 \times \frac{L}{\mathrm{ab}^{-1}} \times \frac{\varepsilon}{20\%}$$

Considering the statistical error only $\delta N \sim \sqrt{N}$ gives

$$\Delta\kappa_c \approx 10\% \times (\frac{L}{\mathrm{ab}^{-1}} \times \frac{\varepsilon}{20\%})^{-1/2}$$

With $\varepsilon \sim 20\%$, we see $\Delta\kappa_c \sim 6\%$ at ATLAS and CMS. for 3 ab^{-1}

Formidable backgrounds:

Prompt J/ψ production $\mathrm{BR}(J/\psi \to \mu^+\mu^-) \times \sigma(pp \to J/\psi) \simeq 860$ pb

Cross section of $pp \to J/\psi + c\bar{c}$ at high p_T ~ 25 fb

→ At the end, should be better than J/ψ +γ: κ_c ~ 50

→ May not beat W/Z+H → W/Z+cc : κ_c ~ 3

Active study/simulation on-going!

Summary on Hcc Coupling

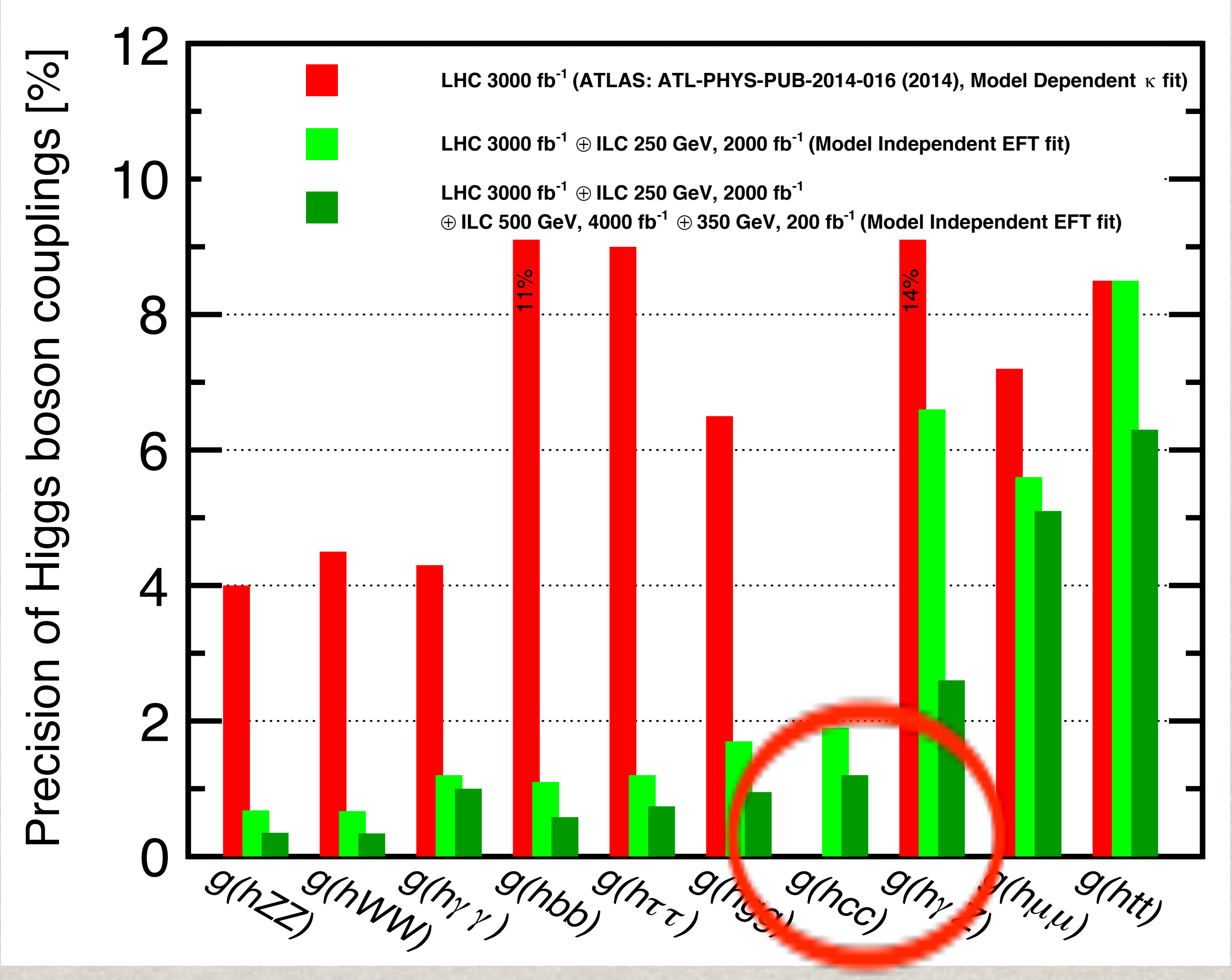
κ_c sensitivity @ HL-LHC:

$gg \to h \to c\,\bar{c}\,\gamma$: 8.3 Vh: hc kinematics: Global fit:

charm+γ in VBF : 5.4 2.5 3.0 1.5

$h \to J/\psi + c\bar{c}$: hopeful Need to combine all !

Snowmass report → lepton colliders help!



Yc measurement challenging & important!

Higgs Boson Properties:

Run 1 + 2016 results: 15 Feb 2020, PLB 805 (2020) 135425

125.38 ± 0.14 GeV (~1 ppm) $\Gamma_H = 4.0^{+1.3}_{-1.0}$ MeV

Run 1 + Run 2:

expect precision better than 100 MeV

HL-LHC:

Statistical uncertainty ~10 MeV

The game will be all about reducing systematics

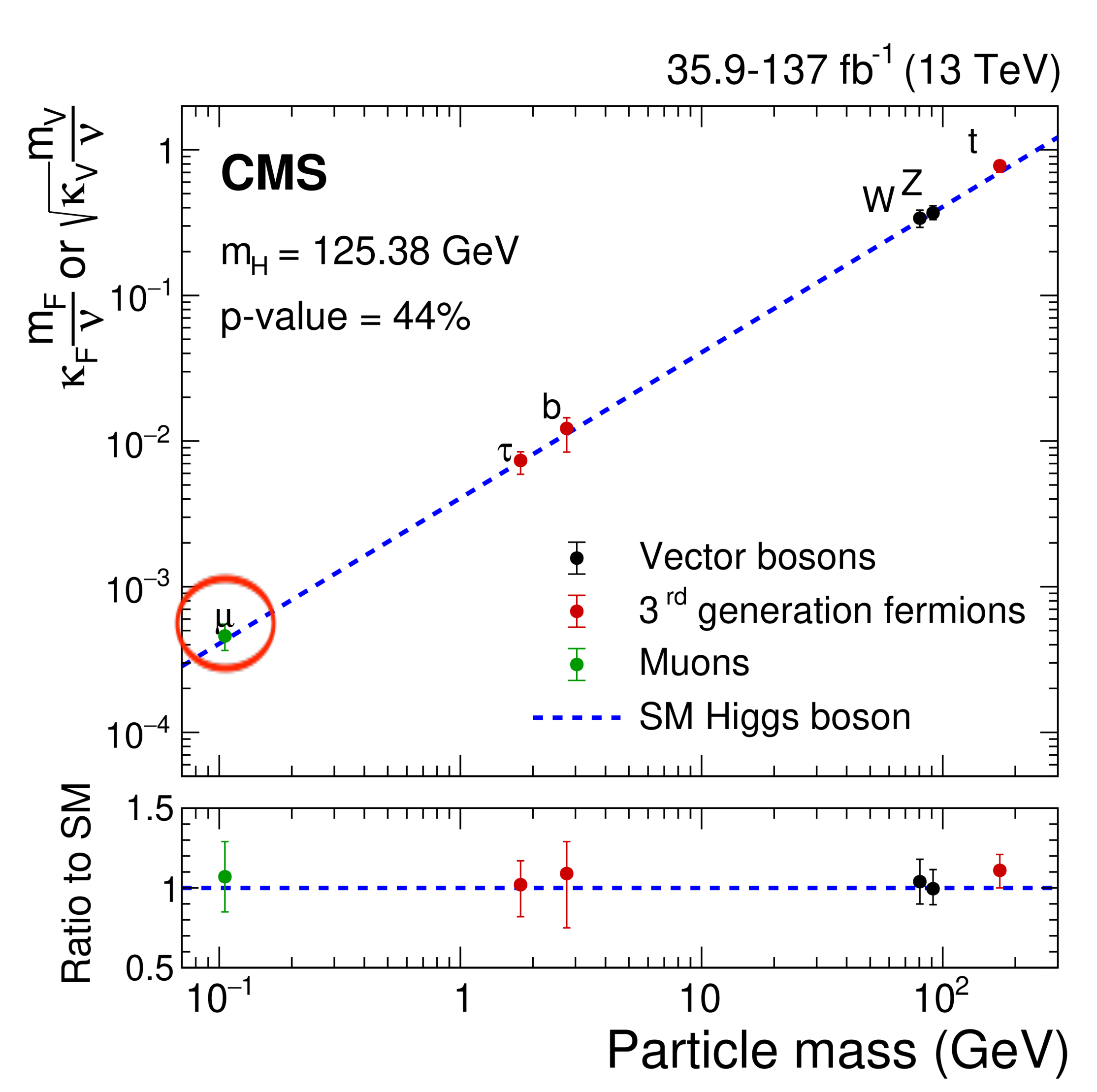
Latest updates for the well-established decays (>5σ):

$H \to \gamma\gamma$:	$\mu = 1.12 \pm 0.09$	12 Mar 2021, arXiv:2103.06956 [Run 2]
$H \to ZZ$:	$\mu = 0.94 \pm 0.11$	8 Mar 2021, arXiv:2103.04956 [Run 2]
$H \to WW$:	$\mu_{fid} = 1.05 \pm 0.12$	4 July 2020, JHEP 03 (2021) 003 [Run 2]
$H \to \tau\tau$:	$\mu = 0.85 \pm 0.12$	31 July 2020, HIG-19-010 [Run 2]
$H \to bb$:	$\mu = 1.04 \pm 0.20$	PRL 121 (2018) 121801 [2016+2017 data]

Evidence for $H \to \mu\mu$ 9 Sep 2020, JHEP 01 (2021) 148 [Run 2]

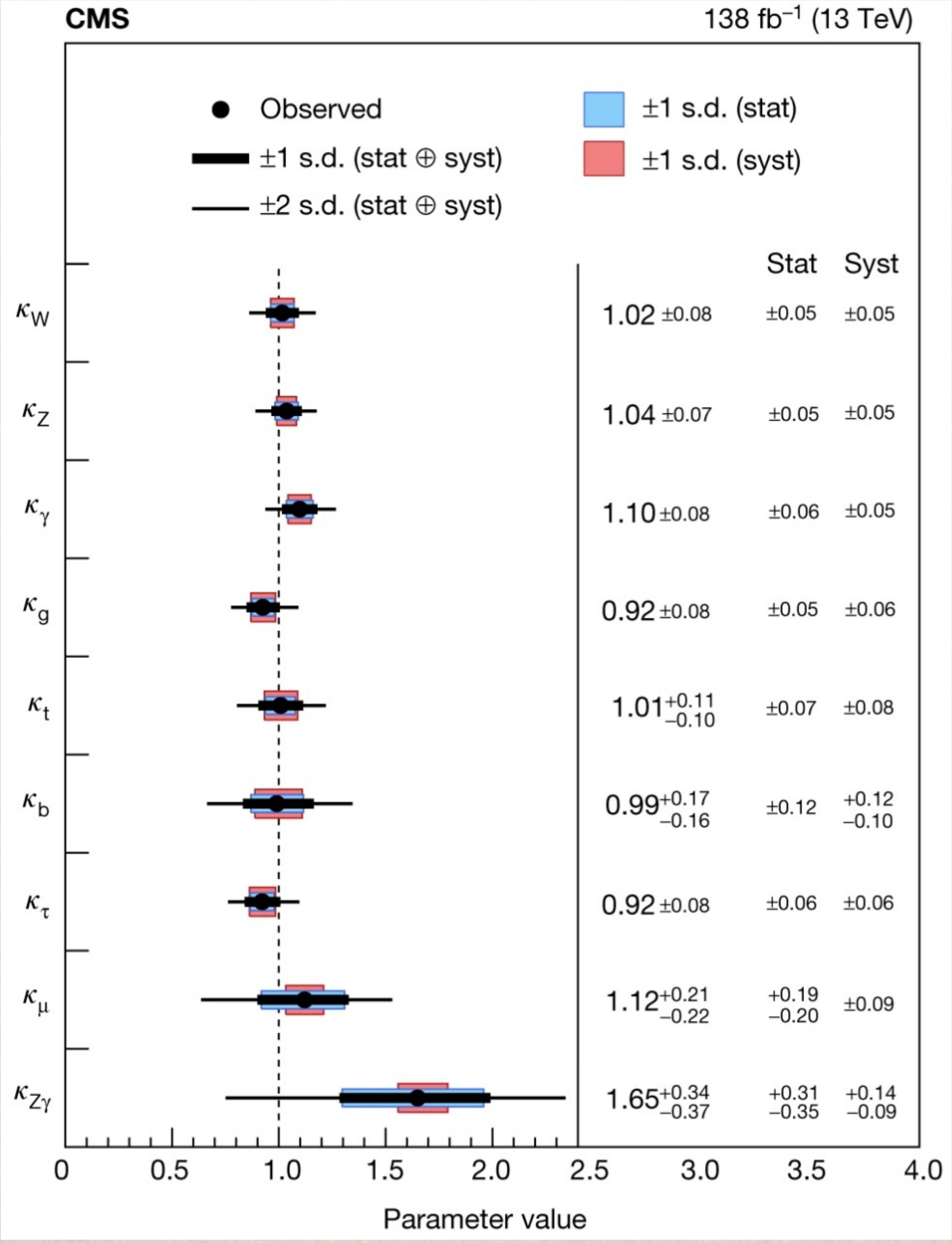
- Significance 3.0
- Signal strength $\mu = 1.19 \pm 0.42$

Korytov@NPHP21



- Monumental achievements in theory & experiment!
- Higgs boson brings in new fundamental questions…
- A driver in precision & energy frontiers!

The next target: the Higgs boson to charm!


CMS
138 fb^{-1} (13 TeV)
Observed
±1 s.d. (stat ⊕ syst)
±2 s.d. (stat ⊕ syst)
±1 s.d. (stat)
±1 s.d. (syst)
Stat
Syst
κ_W 1.02 ±0.08 ±0.05 ±0.05
κ_Z 1.04 ±0.07 ±0.05 ±0.05
κ_γ 1.10 ±0.08 ±0.06 ±0.05
κ_g 0.92 ±0.08 ±0.05 ±0.06
κ_t $1.01^{+0.11}_{-0.10}$ ±0.07 ±0.08
κ_b $0.99^{+0.17}_{-0.16}$ ±0.12 $^{+0.12}_{-0.10}$
κ_τ 0.92 ±0.08 ±0.06 ±0.06
κ_μ $1.12^{+0.21}_{-0.22}$ $^{+0.19}_{-0.20}$ ±0.09
$\kappa_{Z\gamma}$ $1.65^{+0.34}_{-0.37}$ $^{+0.31}_{-0.35}$ $^{+0.14}_{-0.09}$
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Parameter value