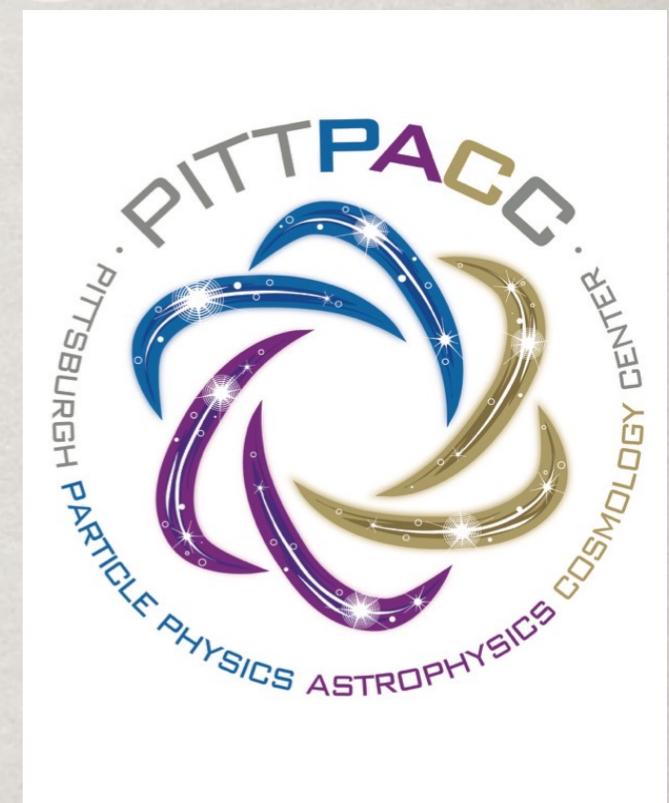


# HIGGS COUPLINGS TO FERMIONS

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Mitchell Conference @ Texas A&M  
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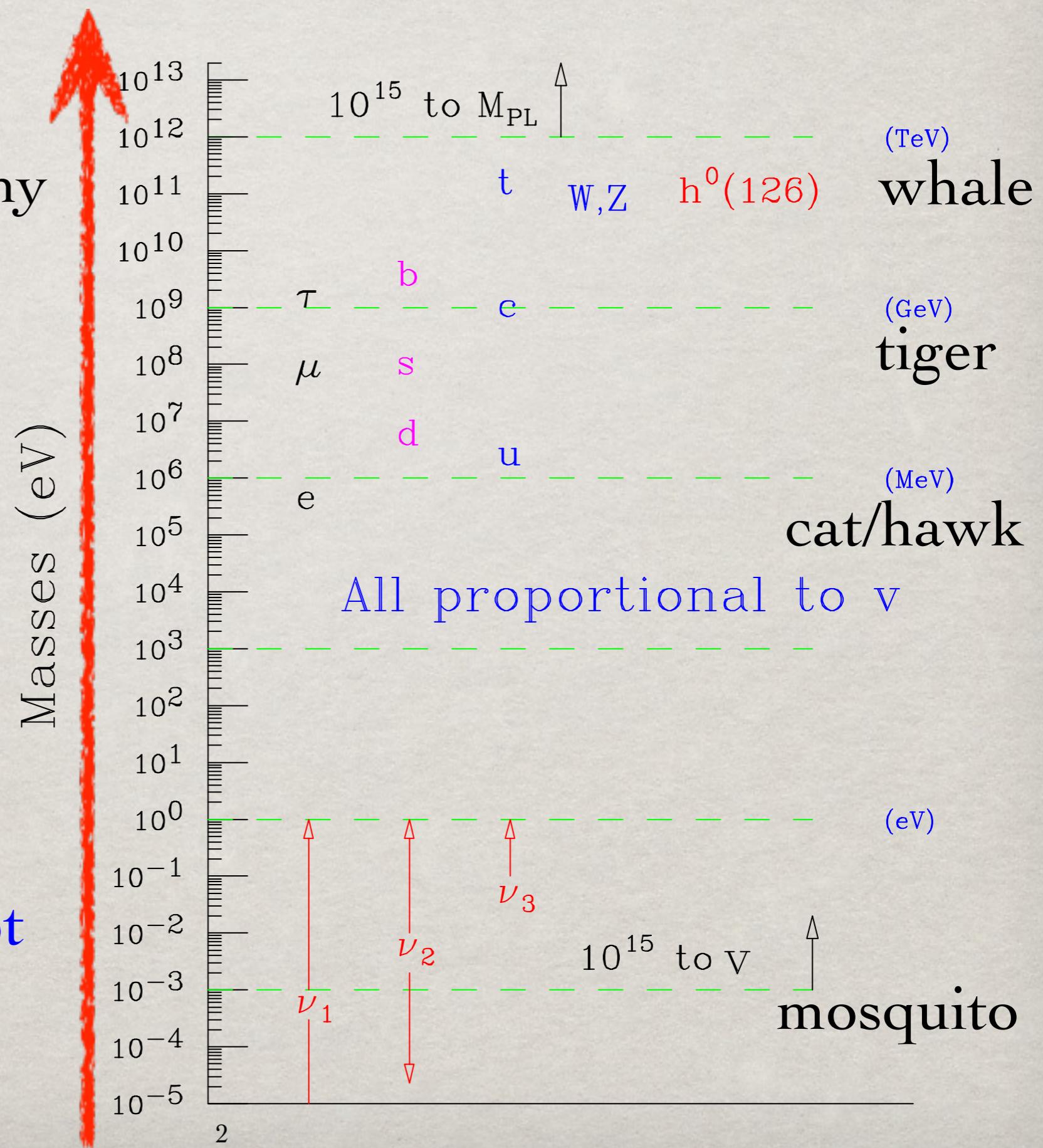


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# THE HIGGS MAGIC & BLEMISHES

- Single vev does it all!
- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- Tiny neutrino masses!
- New CP-violation sources?

Higgs Yukawa couplings as the pivot for all !



# THREE TYPES OF MASSES

## $M_{W,Z}$ versus $m_H$ versus $m_f$ :

$$V(|\Phi|) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

(1).  $M_{W,Z}$ : In the SM:  $\phi = \frac{1}{\sqrt{2}} e^{i \sum \xi^i L^i} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}$

$$\langle |\Phi| \rangle = v = (\sqrt{2} G_F)^{-1/2} \approx 246 \text{ GeV}$$

$$M_W^2 W^{\mu+} W_\mu^- (1 + \frac{H}{v})^2 + \frac{1}{2} M_Z^2 Z^\mu Z_\mu (1 + \frac{H}{v})^2$$

$\rightarrow M_W, M_Z = g v/2$  predicted, and:

$$\delta m_w^2 \sim m_w^2 \ln(\Lambda/m_w)$$

BSM: easy to break  $SU(2)_L$  gauge sector:

- Fundamental scalars (SUSY)
- Dynamical breaking (TC, composite ...)

$$\langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \sim v^3$$

- Non-linear realization (or even “Higgsless”)

$$\Phi = \frac{1}{\sqrt{2}} (v + H) U, \quad U = \exp[i\pi^a \tau^a/v]$$

## $M_{W,Z}$ versus $m_H$ versus $m_f$ :

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

In the SM, all fixed:  $\rightarrow \lambda \approx 0.13; \frac{1}{2}m_H^2 H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4$

The value itself doesn't matter much  $\sim$  EW scale

but quantum corrections:  $\delta\mu^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2 \quad (M_{\text{PL}}^2 \dots)$

$\rightarrow$  Quadratically sensitive to the new physics cutoff scale  
“Naturalness” or “Large hierarchy problem”?

BSM: easy to construct a scalar model / potential,  
but model-parameters quadratically sensitive to a  
new physics scale:

$$\delta m_H^2 \propto -\frac{k^2}{4\pi^2}\Lambda^2 \quad (M_{\text{SUSY}}^2, M_{\text{comp}}^2, \dots)$$

“Little hierarchy problem”  $\rightarrow$  We do not understand why,  
and how to predict/calculate  $m_H$ .

# M<sub>W,Z</sub> versus m<sub>H</sub> versus m<sub>f</sub>:

(3). Yukawa:  $\mathcal{L}_Y \sim - \sum_{i,j} (Y_{ij}^d \bar{Q}_{iL} \Phi d_{jR} + Y_{ij}^u \bar{Q}_{iL} \tilde{\Phi} u_{jR} + Y_{ij}^e \bar{L}_{iL} \Phi e_{jR} + Y_{ij}^\nu \bar{L}_{iL} \tilde{\Phi} \nu_{jR})$

In the SM:  $\mathcal{L}_Y \sim \sum_f m_f \bar{f} f (1 + H/v) \quad Y_f = \frac{\sqrt{2} m_f}{v}$



- Couplings are fixed by the masses & technically “natural”

$$\delta m_f \sim m_f \ln(\Lambda/m_w) \quad (\text{chiral symm})$$



- Vastly different hierarchical masses
- ad hoc flavor mixings and the CPV phase(s)
- Neutrino masses: Dirac vs. Majorana?

**Higgs is responsible for our existence!**

- Atoms/chemistry/biology governed by  $Y_e \sim m_e$ :
- $Y_t / m_t$ : not too large for vacuum stability!

atomic radius  $\propto \frac{1}{m_e}$

$$(3). \text{ m}_f : \mathcal{L}_Y \sim - \sum_{i,j} (Y_{ij}^d \bar{Q}_{iL} \Phi d_{jR} + Y_{ij}^u \bar{Q}_{iL} \tilde{\Phi} u_{jR} \\ Y_{ij}^e \bar{L}_{iL} \Phi e_{jR} + Y_{ij}^\nu \bar{L}_{iL} \tilde{\Phi} \nu_{jR})$$

BSM: much harder to accommodate

- to generate multiple mass scales
- to avoid FCNC
- to avoid Excessive CPV

$Q$ 's:

- Why the flavor mixing aligned with the SM Yukawa form?  
→ Minimal Flavor Violation (MFV)

$$M_{W,Z} / m_H / m_f$$

may well be from different mechanisms!

- Exploring flavor physics is complementary & rewarding.
- Measuring Higgs Yukawa couplings is indispensable:  
The smaller the coupling is, the more sensitive to deviations!

# THE HIGGS PURSUITS: more Higgs

Seeking for deviations from the SM:  $\kappa_f = \frac{Y_f}{Y_f^{\text{SM}}}$

$$\mathcal{L} = \kappa_Z \frac{m_Z^2}{v} h Z_\mu Z^\mu + \kappa_W \frac{2m_W^2}{v} h W_\mu^+ W^{\mu-} - \sum_{f=u,d,\ell} \kappa_f h \bar{f} f.$$

(1). e.g., 2HDM: SM Higgs coupling deviations  
( $\tan\beta = v_2/v_1$ ;  $\alpha$  the neutral Higgs mixing)

	Tree-level Normalized Higgs couplings			
	$\kappa_h^u$	$\kappa_h^d$	$\kappa_h^e$	$\kappa_h^V$
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:  
 $\kappa$ 's  $\rightarrow 1$

Seek for more Higgs bosons:  $H^0, A^0, H^\pm$ .

Also, perhaps flavor changing\*  $H \rightarrow \mu\tau$ !  
new CPv phases in Yukawa ...

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

# THE HIGGS PURSUITS: SMEFT

Seeking for deviations from the SM:  $\kappa_f = \frac{Y_f}{Y_f^{\text{SM}}}$

(2). SM Effective Field Theory:

a linear representation:  $\Phi$

$$= \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + h + i\phi^0 \end{pmatrix}$$

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

Yukawa coupling deviates from the mass relation!

At the dim-6 leading order:

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

This is the immediate target @ LHC!

\* TH, D. Marfatia, PRL 86, 1442 (2001); Harnik, Kopp, Zupan, arXiv:1209.1397.

# THE HIGGS PURSUITS: HEFT

Seeking for deviations from the SM:  $\kappa_f = \frac{Y_f}{Y_f^{\text{SM}}}$

(3). Higgs Effective Field Theory:  
a non-linear representation:

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

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

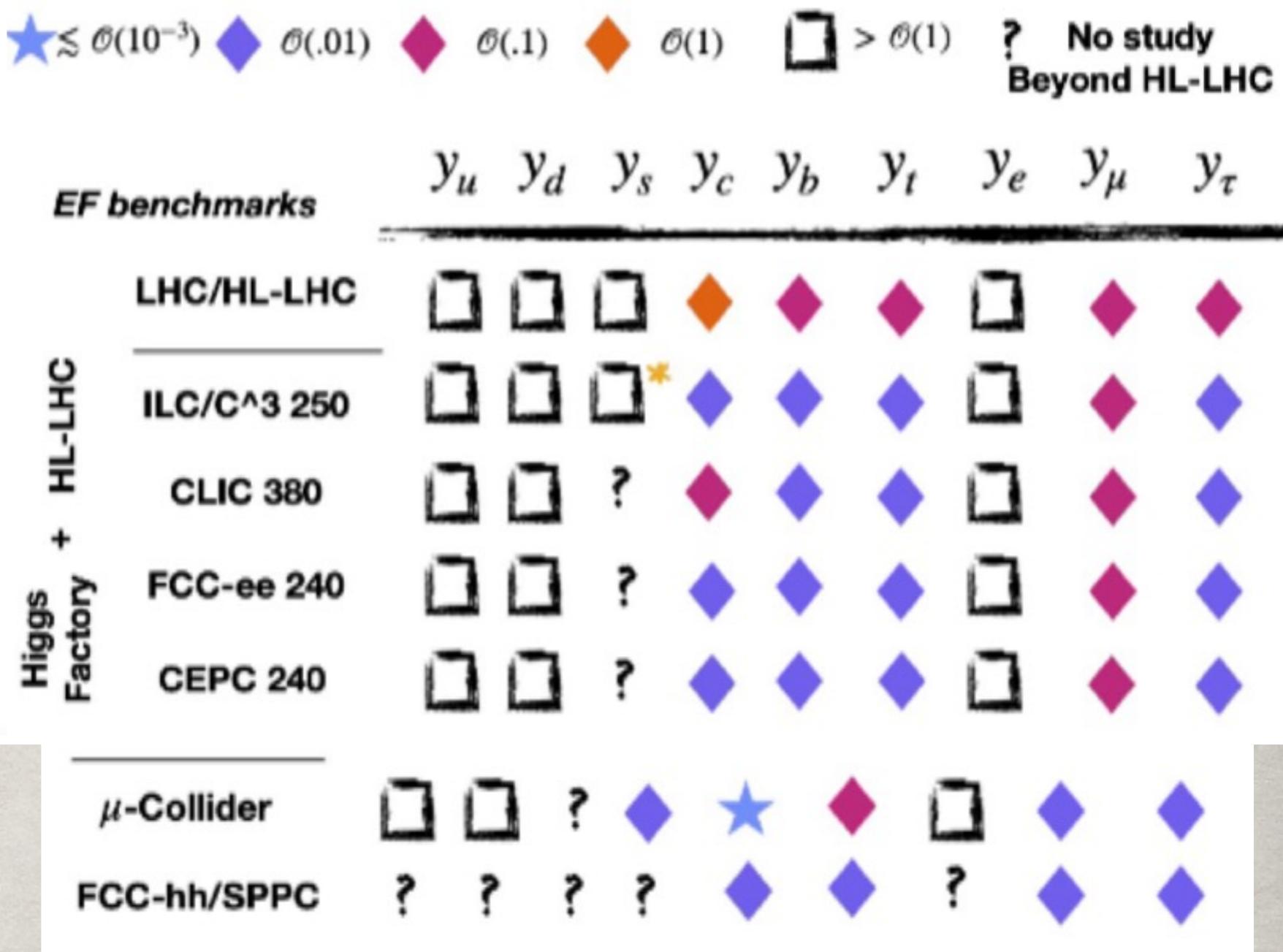
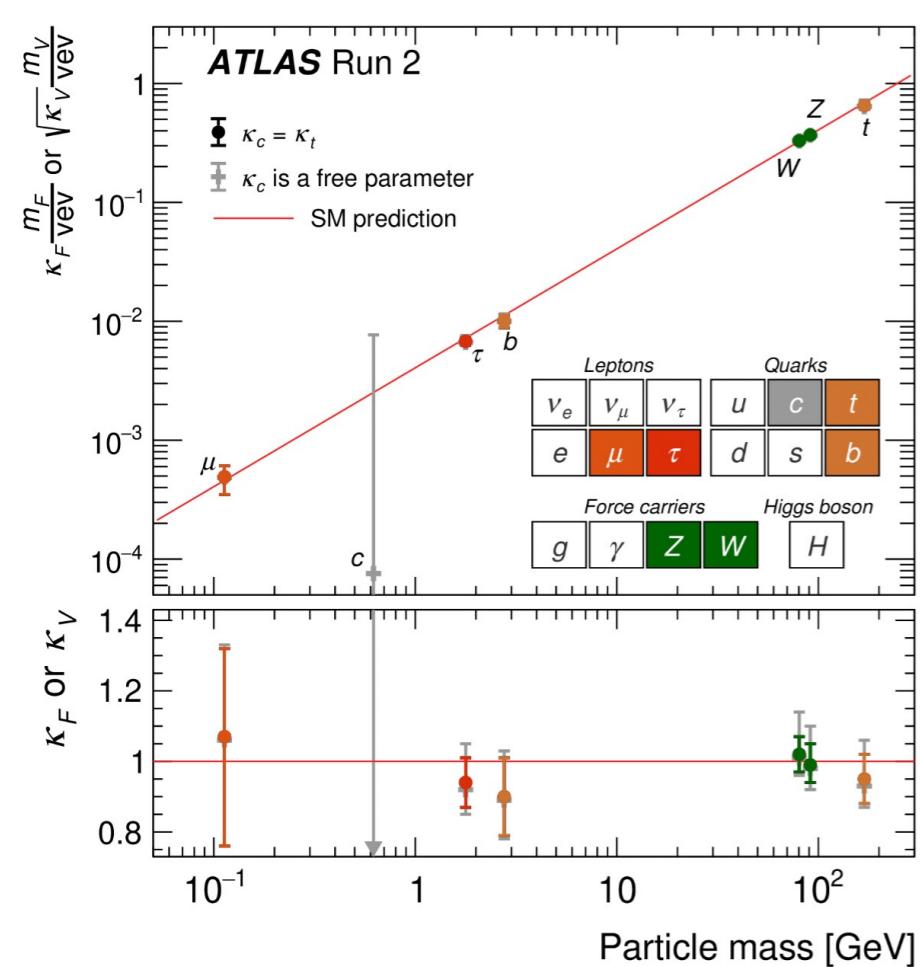
$$Y_f(H) = \frac{\sqrt{2}m_f}{v} + \sum_{n=1} y_{fn} \left( \frac{H}{v} \right)^n$$

- The scale for new dynamics is at  $\Lambda \sim 4\pi v$   
 $\rightarrow$  close by! The deviation can be significant:  
 $\rightarrow \delta \kappa_f \sim Y_1 \frac{H}{v} \sim O(1)$
- Multiple Higgs couplings may be sizeable!
- Achievable in composite/dynamical models.

# Higgs couplings measurements

Sensitivities to Yukawa couplings at Higgs factories  
 Achieving percentage/sub-percentage level!

Symbols of sensitivities:



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

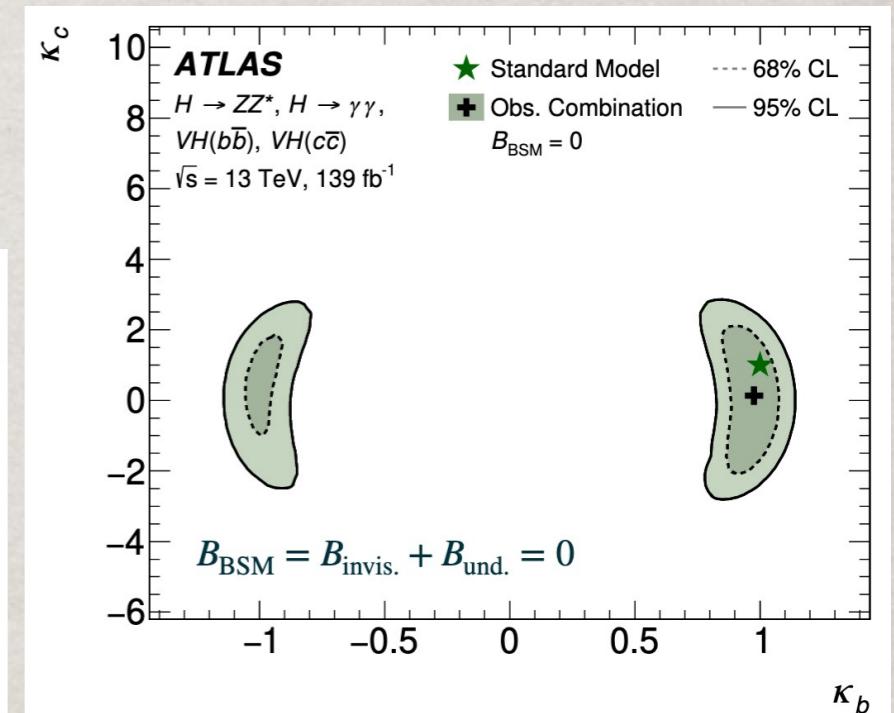
# THE NEXT TARGET 1: The 2<sup>nd</sup> generation quark $y_c$ : The real challenge!

The current LHC sensitivity:  $BR_{H \rightarrow c\bar{c}}^{\text{SM}} = (2.88^{+0.16}_{-0.06})\%$

LHC Run 2: ATLAS  $\kappa_c \leq 8.5$  [2201.11428], CMS  $1.1 < |\kappa_c| < 5.5$  [2205.05550]

Adding the VH(cc) and VH(bb) datasets  
**Miha Muškinja** Submitted to JHEP [2207.08615]

Scenario	Upper limit on $\kappa_c$ of 4.8×SM at 95% CL	
	Observed 68% confidence interval	Observed 95% confidence interval
$B_{\text{BSM}} = 0$	[-1.61, 1.70]	[-2.47, 2.53]
No assumption	[-2.63, 3.01]	[-4.46, 4.81]



HL-LHC sensitivity projection: a factor of few from SM

Future HL-LHC:  $\kappa_c \leq 3$ . [2201.11428]

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

arXiv: 1503.00290, 1507.02916, 1606.09621, 1609.06592,  
 1611.05463, 1702.05753, 1705.09295, 1812.06992, 1905.03764,  
 1905.09360, 1909.05279, 2008.12538, 2101.04119

# Tackling the charm: $y_c$

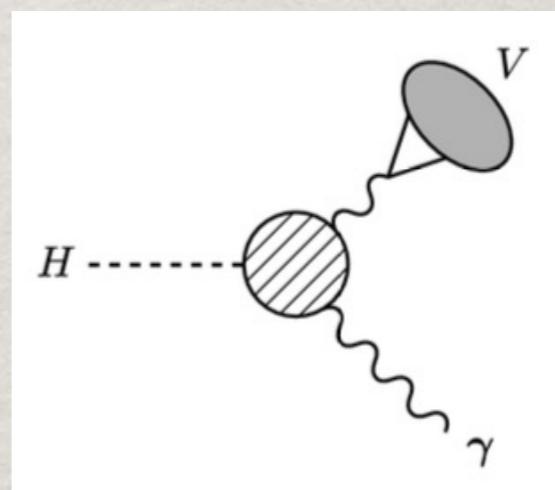
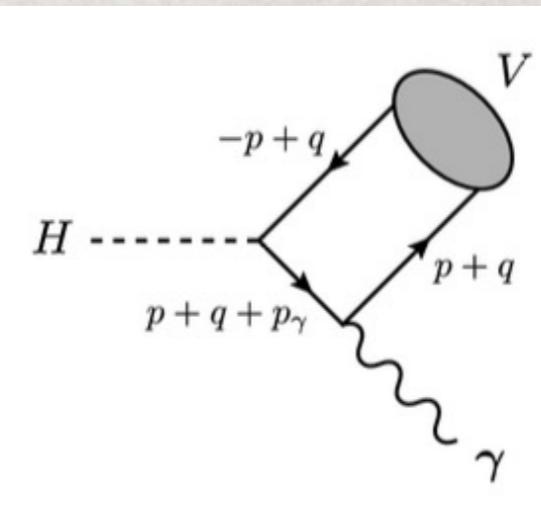
Higgs production rate is high: #H@LHC  $\sim 50 \text{ M /ab}$  !  
New ideas?

- $H \rightarrow J/\psi + \gamma$   
 $\rightarrow \mu^+ \mu^- + \gamma$

for Higgs coupling to charm

Note:  $\text{BR}(H \rightarrow J/\psi + \gamma) = 2.8 \times 10^{-6}$

➤ Dominated by VMD  $\gamma^* \rightarrow J/\psi$ ,  
not  $H \text{ cc}$  coupling.



→ No chance to probe  $y_c$  !

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

# Tackling the charm: $y_c$

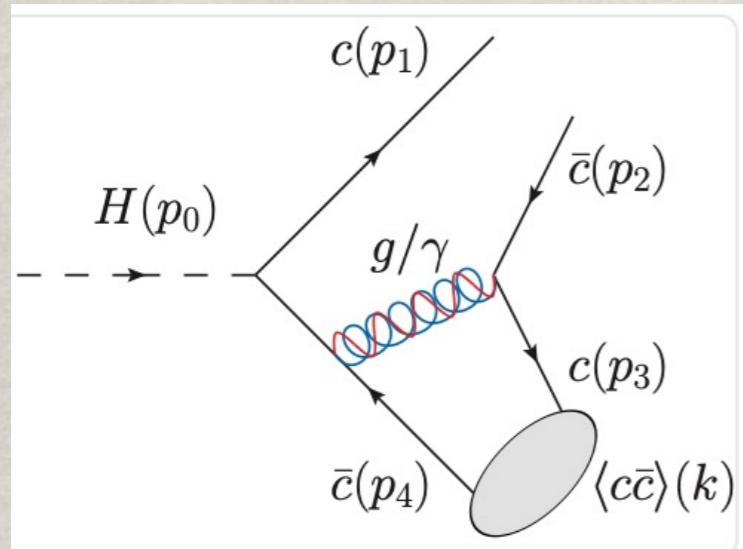
Higgs production rate is high: #H@LHC  $\sim 50 \text{ M /ab}$  !  
New ideas?

- $H \rightarrow J/\psi$  via charm-quark fragmentation:

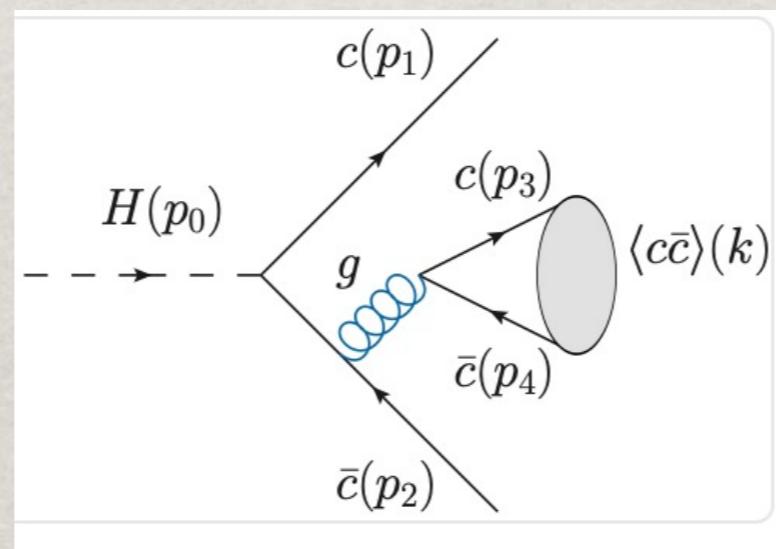
$$H \rightarrow c + \bar{c} + J/\psi (\text{or } \eta_c)$$

- Enhanced from the fragmentation
- Direct coupling to charm!

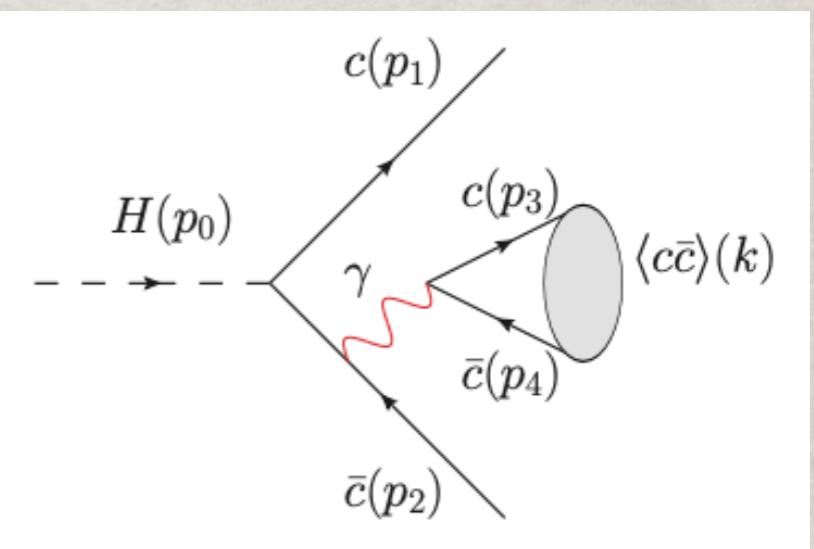
Color-singlet (CS)



Color-octet (CO)



QED



# Tackling the charm: $y_c$

- $H \rightarrow J/\psi$  via charm-quark fragmentation:

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

$$\Gamma = \sum_{\mathbb{N}} \hat{\Gamma}_{\mathbb{N}}(H \rightarrow (Q\bar{Q})[\mathbb{N}] + X) \times \langle \mathcal{O}^h [\mathbb{N}] \rangle.$$

- **Short distance coefficient (SDC):**

$$d\hat{\Gamma}_{\mathbb{N}} = \frac{1}{2m_H} \frac{|\mathcal{M}|^2}{\langle \mathcal{O}^{Q\bar{Q}} \rangle} d\Phi_3$$

- **Long distance matrix element (LDME)  $\langle \mathcal{O}^h [{}^{2S+1}L_J^{[\text{color}]}] \rangle$**

CS calculable (potential model)

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

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

CO fitted from data (CMS/CDF)

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

- $H \rightarrow J/\psi$  via charm-quark fragmentation:  
Relative contributions

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

**Table 4.** The ratios of the SDCs to their pure QCD values [1] for the pure QED contribution, QCD/QED interference, and EW QCD×QED, and EW, respectively.

	Charm fragmentation			SPF	SGF
	QCD	QED	QCD×QED	QED	QCD
CS	16/9	1	4/3	9	-
CO	2/9	8	-4/3	-	2

	$\hat{\Gamma}_N/\hat{\Gamma}_N^{\text{QCD}}$	${}^1S_0^{[1]}$	${}^3S_1^{[1]}$	${}^1S_0^{[8]}$	${}^3S_1^{[8]}$
QCD	1.0	1.0	1.0	1.0	1.0
QED	$1.1 \times 10^{-4}$	0.077	0.0073	$1.1 \times 10^{-5}$	
QCD×QED	0.021	0.14	-0.17	0.0012	
EW	0.24	0.051	0.28	$2.6 \times 10^{-4}$	

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

$$\text{BR}(H \rightarrow c\bar{c} + J/\psi) = (2.0 \pm 0.5) \times 10^{-5}$$

$$\text{BR}(H \rightarrow c\bar{c} + \eta_c) = (6.0 \pm 1.0) \times 10^{-5}$$

## Signal sensitivity:

- ▶ Assume the detection efficiency  $\epsilon \sim 10\%$
- ▶ The signal event number is given by

$$N = L\sigma_H \epsilon \text{BR}(H \rightarrow c\bar{c}\ell^+\ell^-) \approx 12 \kappa_c^2 \times \frac{L}{ab^{-1}} \times \frac{\epsilon}{10\%}$$

▶ Sensitivity  $S \simeq N_{\text{signal}}/\sqrt{N_{\text{Background}}}$   
⇒ It is possible to reach  $2\sigma$  for  $\kappa_c \approx 2.4$ .

▶ systematic effect  $N_{\text{signal}}/N_{\text{Background}} = 2\%$  for  $\kappa_c \approx 2.4$ .

→ At the end, should be better than  $J/\psi + \gamma$ :  $\kappa_c \sim 50$   
→ May not beat  $W/Z+H \rightarrow W/Z+cc$  :  $\kappa_c \sim 3$

**Active study/simulation on-going!**

# THE NEXT TARGET 2:

The 2<sup>nd</sup> generation lepton  $\text{Y}_\mu$ : The next hope!

The current LHC sensitivity:  $BR_{H \rightarrow \mu^+ \mu^-}^{\text{SM}} = (2.17 \pm 0.04) \times 10^{-4}$

Observation: ATLAS:  $2.0\sigma$ ; CMS  $3.0\sigma$

Talk by Stefano Rosati, P. Lenzi, Giulio Umoret

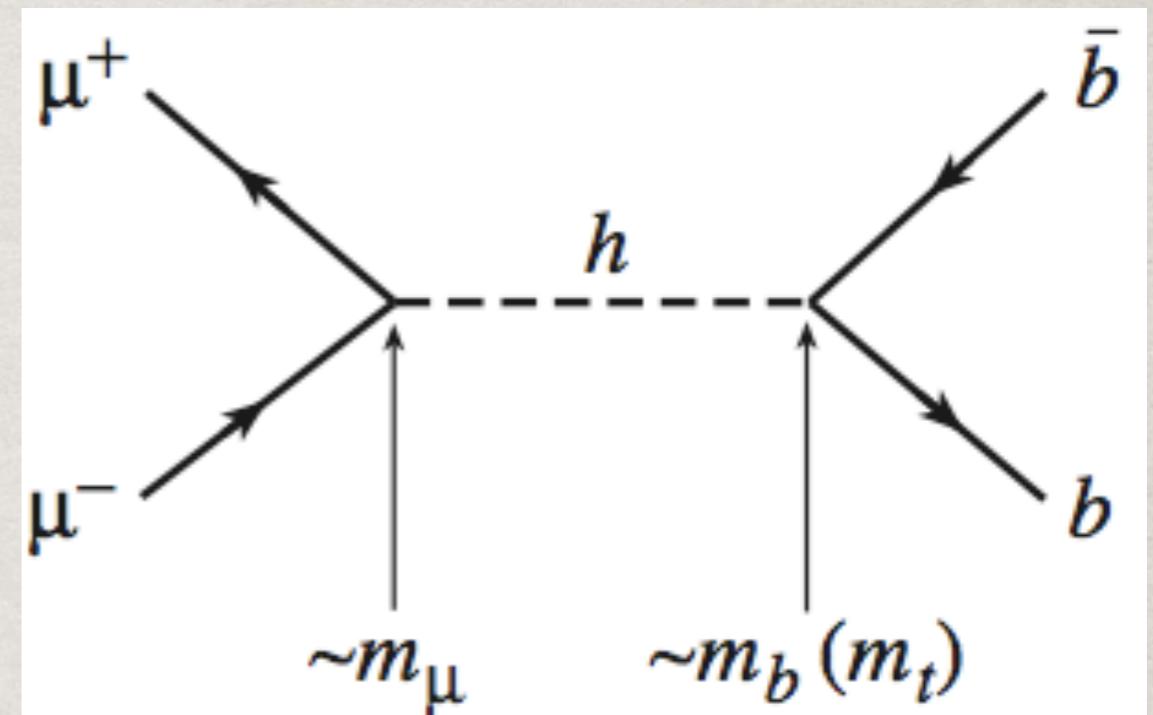
HL-LHC sensitivity projection:  $\text{BR}(H \rightarrow \mu\mu) < 10\%$   
(assuming the SM width,  
But won't know better than a factor of 2-ish)

Model-independent direct measurement:

A muon collider

Higgs factory:

Resonant Production:



$$\sigma(\mu^+ \mu^- \rightarrow h \rightarrow X) = \frac{4\pi \Gamma_h^2 \text{Br}(h \rightarrow \mu^+ \mu^-) \text{Br}(h \rightarrow X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$

$$\begin{aligned} \sigma_{peak}(\mu^+ \mu^- \rightarrow h) &= \frac{4\pi}{m_h^2} BR(h \rightarrow \mu^+ \mu^-) \\ &\approx 71 \text{ pb at } m_h = 125 \text{ GeV}. \end{aligned}$$

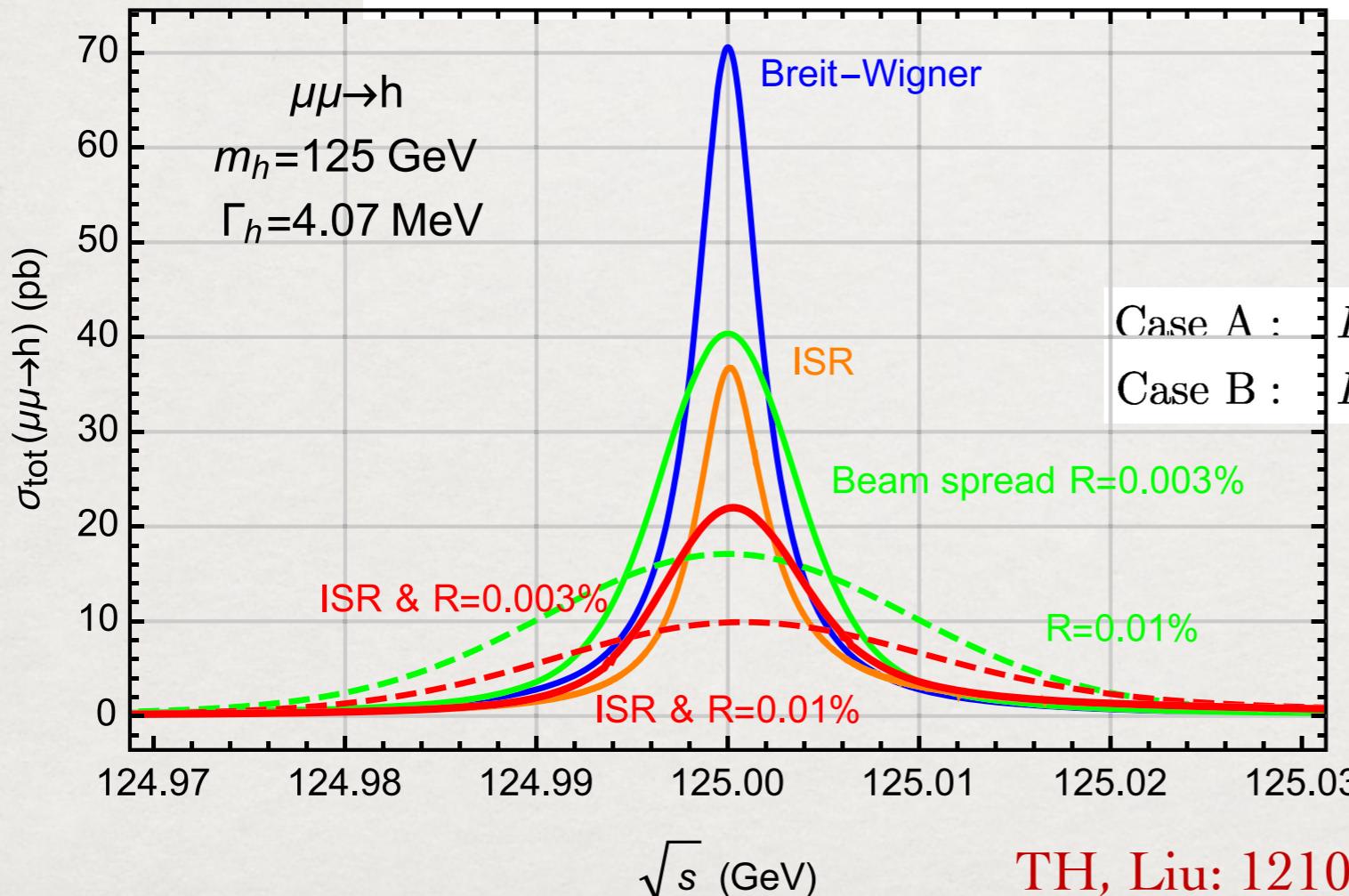
About  $\mathcal{O}(70k)$  events produced per  $\text{fb}^{-1}$

# At $m_h=125$ GeV, $\Gamma_h=4.2$ MeV

$$\frac{\exp[-(\sqrt{\hat{s}} - \sqrt{s})^2/(2\sigma_{\sqrt{s}}^2)]}{\sqrt{2\pi}\sigma_{\sqrt{s}}}$$

$$\frac{4\pi\Gamma(h \rightarrow \mu\mu)\Gamma(h \rightarrow X)}{(\hat{s} - m_h^2)^2 + m_h^2[\Gamma_h^{\text{tot}}]^2}$$

$$\begin{aligned} \sigma_{\text{eff}}(s) &= \int d\sqrt{\hat{s}} \frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}} \sigma(\mu^+ \mu^- \rightarrow h \rightarrow X) \\ &\propto \begin{cases} \Gamma_h^2 B / [(s - m_h^2)^2 + \Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B \exp[-(m_h - \sqrt{s})^2 / 2\Delta^2] (\frac{\Gamma_h}{\Delta}) / m_h^2 & (\Delta \gg \Gamma_h). \end{cases} \end{aligned}$$



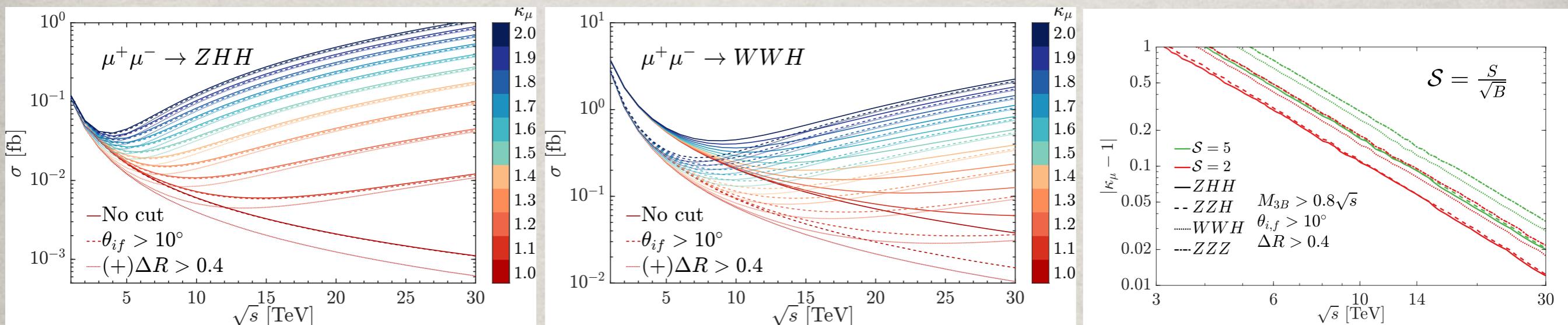
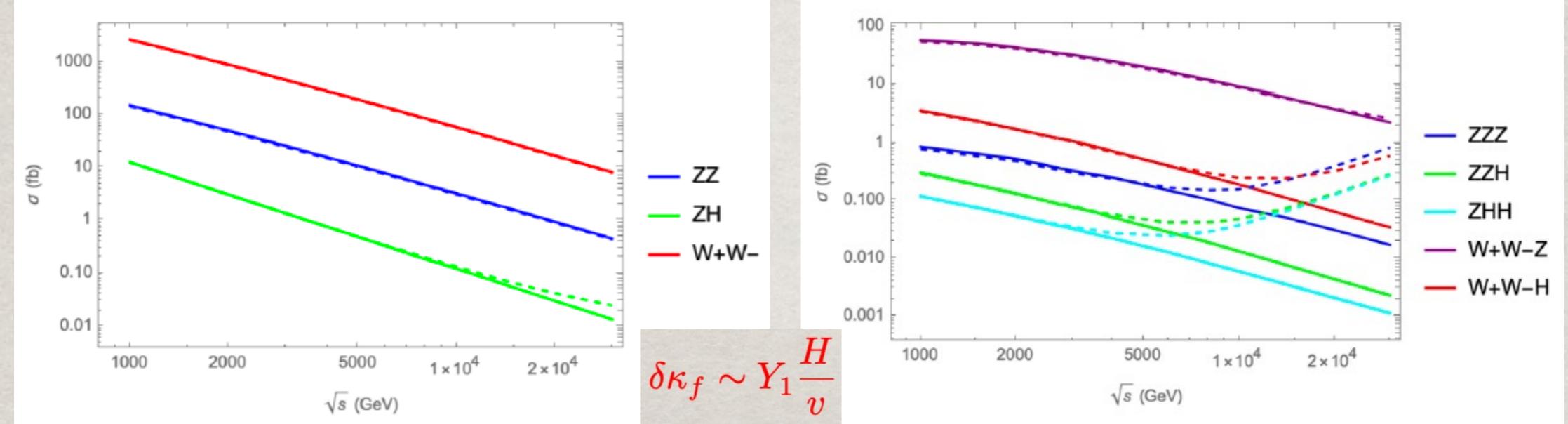
**“Muon Collider Quartet”:**  
Barger-Berger-Gunion-Han  
PRL & Phys. Report (1995)

$R = 0.01\%$  ( $\Delta = 8.9$  MeV),  $L = 0.5$   $\text{fb}^{-1}$ ,  
 $R = 0.003\%$  ( $\Delta = 2.7$  MeV),  $L = 1$   $\text{fb}^{-1}$ .

An optimal fitting could reach  
 $\delta\Gamma_h \sim 0.15$  MeV, or 3.5%

# High energy option

- To enhance the Yukawa coupling effects, multiple Higgs/Goldstone boson production more beneficial.



At 30 TeV:  $\delta\kappa_\mu \sim 1\% - 4\%$ , corresponding to  $\Lambda \sim 30 \text{ TeV} - 100 \text{ TeV}$ .

TH, W. Kilian, N. Kreher, Y. Ma, J. Reuter, T. Striegl, K. Xie: <https://arxiv.org/abs/2108.05362>;  
E. Celada, TH, W. Kilian, N. Kreher, Y. Ma, F. Maltoni, D. Pagani, J. Reuter, T. Striegl, K. Xie; to appear.

# Conclusions:

- The fermion sector involves multiple scales; numerous mixing parameters, CP phase(s)  
→ rich physics, but least predictive!
- Exploring flavor physics is complementary & rewarding, measuring Higgs Yukawa couplings is indispensable
- SMEFT sets a target:  $\delta\kappa_f \sim Y_1 \frac{v^2}{\Lambda^2} \sim O(\text{a few}\%)$
- HEFT could be close by:  $\delta\kappa_f \sim Y_1 \frac{H}{v} \sim O(1)$
- Immediate targets on Yukawa couplings:  
 $t\bar{t}H$ @high scale; 2<sup>nd</sup> generations  $H\mu\mu$  &  $Hcc$  !
- Look for flavor violating decays, invisible decays, more Higgses, ...

**More work to do & push for the next discovery!**