Phenomenology of Enhanced Light Quark Yukawa Couplings

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[1603.xxxxx]

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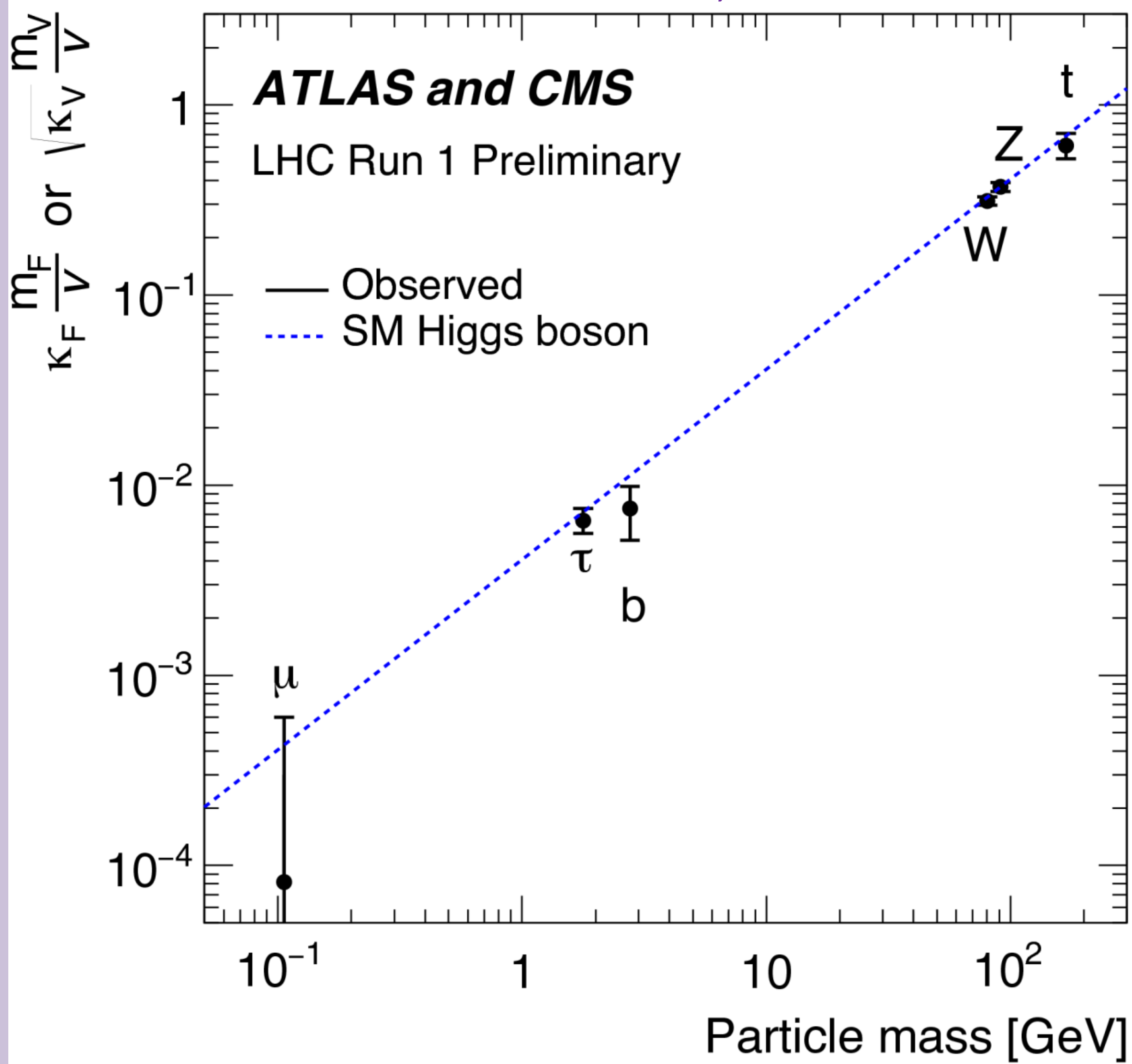
Introduction and Motivation

- Post-discovery precision Higgs program at LHC motivated by SM consistency test and NP expectations
  - Mass, spin/parity, couplings, total width, exotic production and decay modes
- Central role of Higgs in SM makes it a prime phenomenological target for NP models
  - Naturalness, DM, general Higgs portal, new gauge groups, flavor models

Mass-coupling degeneracy in SM

- Test one-to-one prediction between mass and Higgs coupling in SM
- Any deviation will signal profound new physics
- Prospects for light quark Yukawas?

ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002

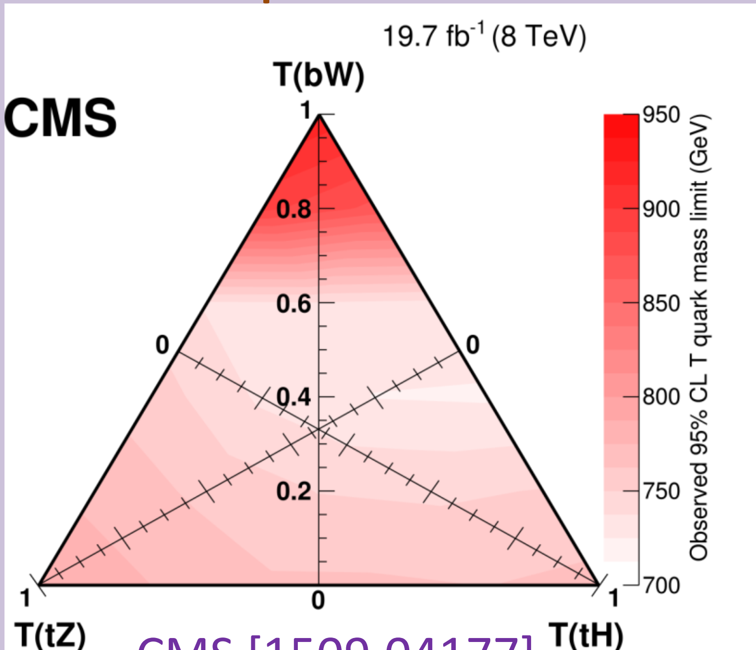


Outline

- Review current suite of measurement possibilities
- LHC $W^\pm h$ production charge asymmetry
  - Effects from nonstandard light quark Yukawas
- Collider study: same-sign leptons from $W^\pm h \to (l^\pm \nu)(l^\pm \nu jj)$
  - SM $W^\pm h$ discovery channel
- Signal strengths effects from enhanced light quark Yukawas
  - $W^\pm h$ production, *s*-channel Higgs production
- Conclusions

Suite of measurement possibilities

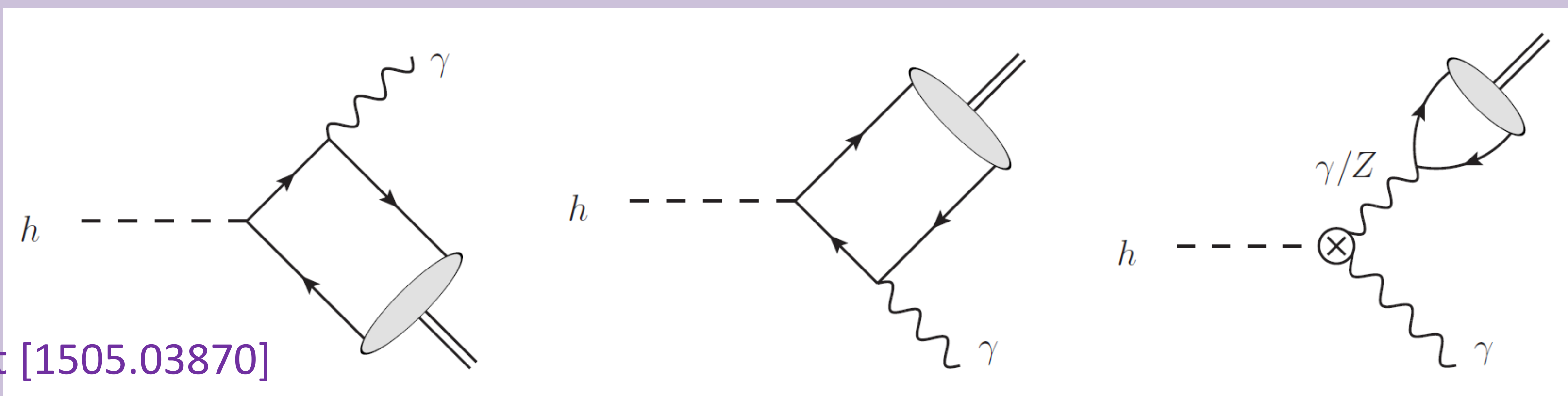
- SM fermions are chiral, hence Yukawa deviations require new sources of $SU(2)_L$ breaking or new fermions with vector-like masses
  - Motivates direct searches for new vector-like fermion partners – top partners are a prime example
  - Also, search for heavy Higgses
    - 2HDM particles: H^0, A, $H^{\pm}$
    - Many possible Yukawa structures



CMS [1509.04177]

Suite of measurement possibilities

- Measure in rare decays: *e.g.* h → J/ψ γ
  - Yukawa contribution interferes with loop-induced vertex with virtual gamma/Z
    - Isidori, Manohar, Trott [1305.0663]
    - Kagan, Perez, Petriello, Soreq, Stoynev, Zupan [1406.1722]
    - Bodwin, Chung, Ee, Lee, Petriello [1407.6695]
    - Perez, Soreq, Stamou, Tobioka [1503.00290, 1505.06689]
    - König, Neubert [1505.03870]



König, Neubert [1505.03870]

Measure in rare decays

Bodwin, et. al. [1407.6695]

$$\mathcal{B}_{\rm SM}(H \to J/\psi + \gamma) = 2.79^{+0.16}_{-0.15} \times 10^{-6},$$

$$\mathrm{Br}(h \to J/\psi\,\gamma) = (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\rm direct} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}\,,$$

$$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma) = (4.61 \pm 0.06_{f_{\Upsilon(1S)}}\,{}^{+\,1.75}_{-\,1.21}{}_{\rm direct} \pm 0.22_{h\to\gamma\gamma}) \cdot 10^{-9}\,,$$

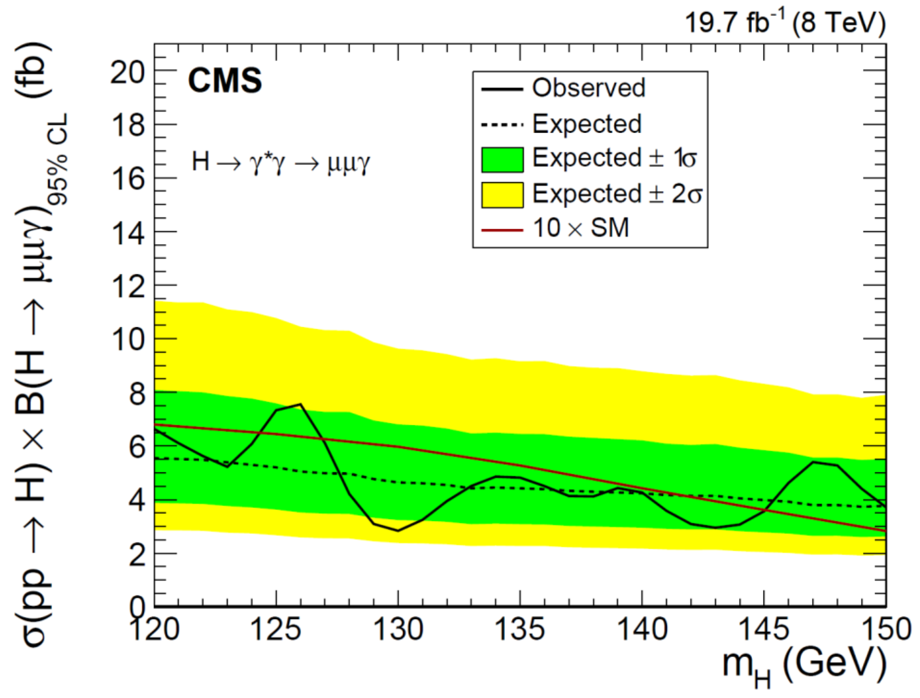
König, Neubert [1505.03870]

CMS [1507.03031]

$$\mathcal{B}(\mathrm{H} \to (\mathrm{J}/\psi)\gamma) < 1.5 \times 10^{-3}$$

	95% CL Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum_n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\gamma)\,[10^{-6}]$					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H \to \mathcal{Q}\gamma)\,[10^{-3}]$					
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]					
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44

ATLAS [1501.03276]



Suite of measurement possibilities

- Measure in direct decays
  - Use bottom and charm tagging in tandem to profile over enhanced charm content in Higgs decays

M_H = 125 GeV	BR	Rel. error
H→bb	5.77E-1	+/- 3%
H→cc	2.91E-2	+/- 12%
H→ss	2.46E-4	+/- 5%
H→μμ	2.19E-4	+/- 6%

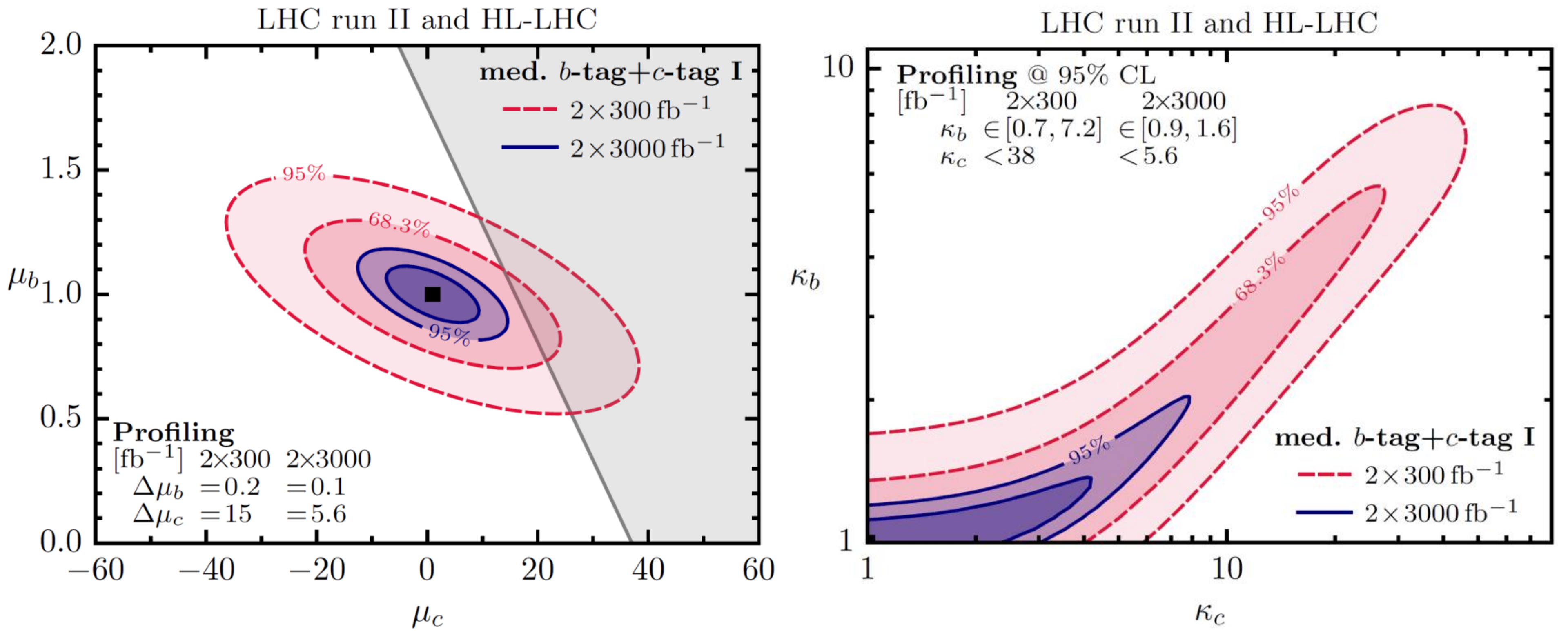
Higgs XSWG [1307.1347]

$$\mu_b \equiv \frac{\sigma_h \mathrm{BR}_{b\bar{b}}}{\sigma_h^{\mathrm{SM}} \mathrm{BR}_{b\bar{b}}^{\mathrm{SM}}} \to \frac{\sigma_h \mathrm{BR}_{b\bar{b}} \epsilon_{b_1} \epsilon_{b_2} + \sigma_h \mathrm{BR}_{c\bar{c}} \epsilon_{c_1} \epsilon_{c_2}}{\sigma_h^{\mathrm{SM}} \mathrm{BR}_{b\bar{b}}^{\mathrm{SM}} \epsilon_{b_1} \epsilon_{b_2} + \sigma_h^{\mathrm{SM}} \mathrm{BR}_{c\bar{c}}^{\mathrm{SM}} \epsilon_{c_1} \epsilon_{c_2}}$$

Perez, et. al. [1505.06689]

Suite of measurement possibilities

- Measure in direct decays
  - Use bottom and charm tagging in tandem to profile over enhanced charm content in Higgs decays



Perez, et. al. [1505.06689]

Suite of measurement possibilities

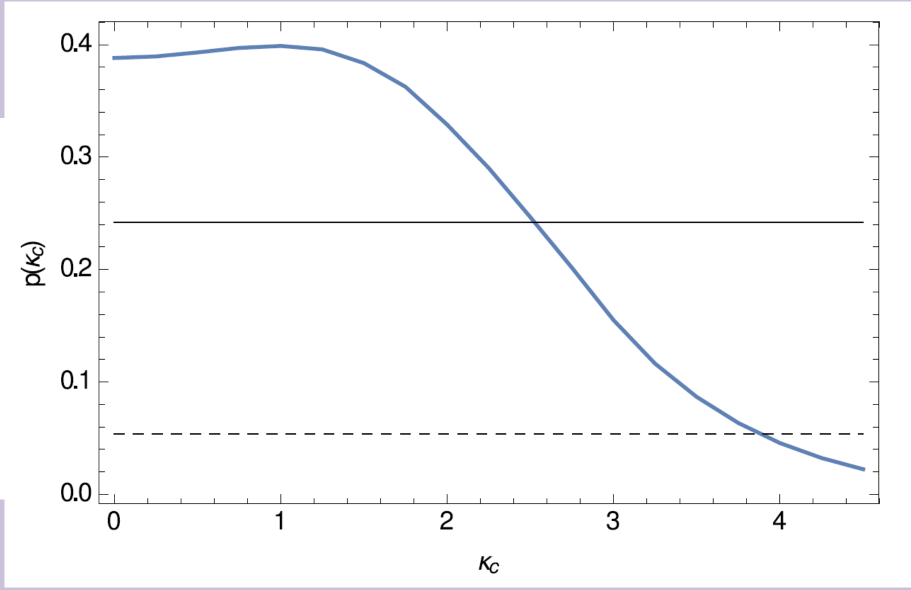
- Charm Yukawa: Measure in h+c production, use $h \to \gamma\gamma$ (fixed to SM BR)
  - $p_T(j) > 20$ GeV
  - charm tag = 40%, gluon fake rate = 1%, b fake rate= 30%

Brivio, Goertz, Isidori [1507.02916]

κ_c	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2
S	874	877	885	899	917	941	973	1008	1052

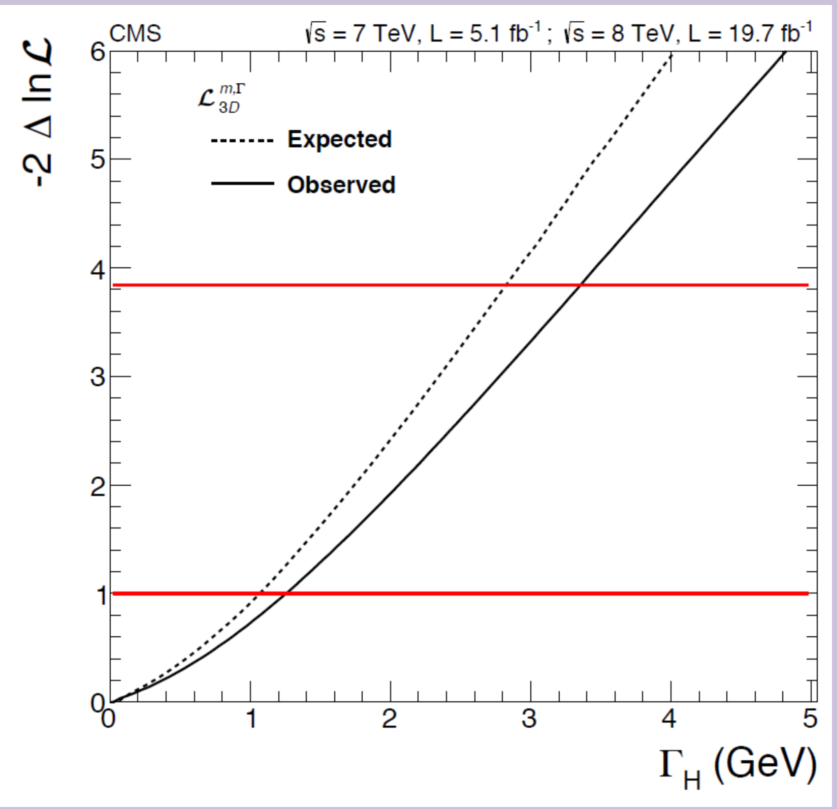
κ_c	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5
S	1097	1148	1206	1276	1350	1424	1504	1590	1683	1786

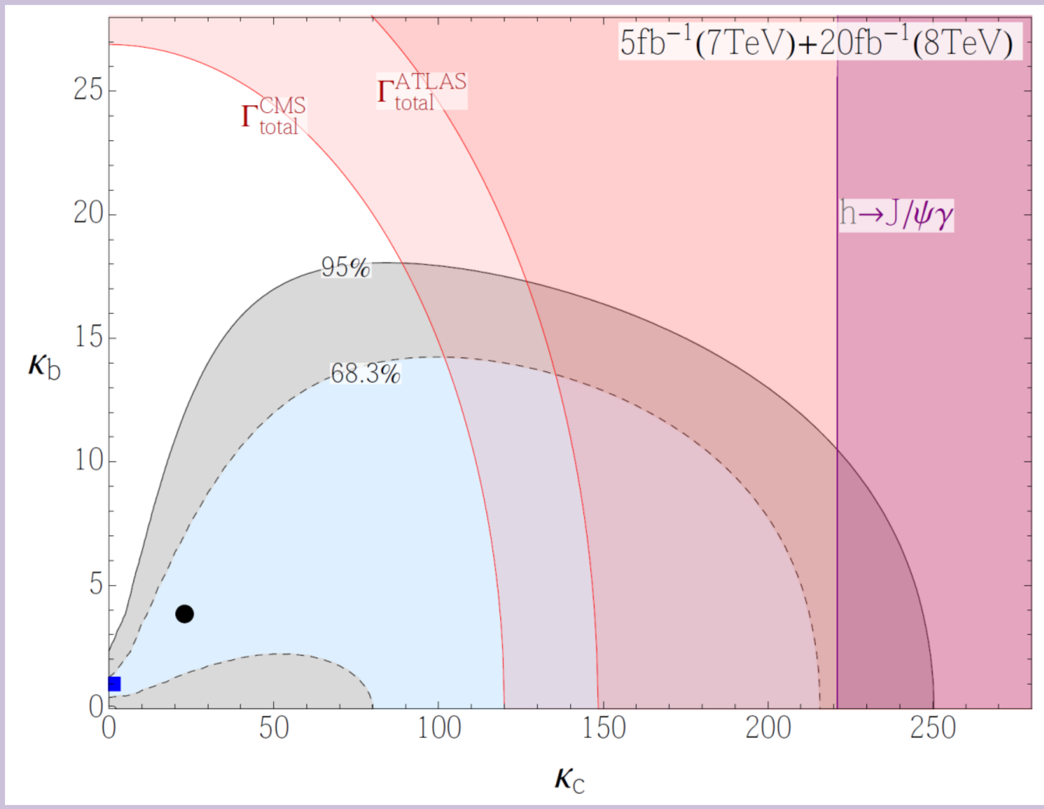
TABLE I. Number of Signal events $S(\kappa_c)$ in dependence on the charm-quark Yukawa coupling. See text for details.



Suite of measurement possibilities

- Direct Higgs width measurements
  - Generally expect large Yukawas to rapidly increase Higgs width





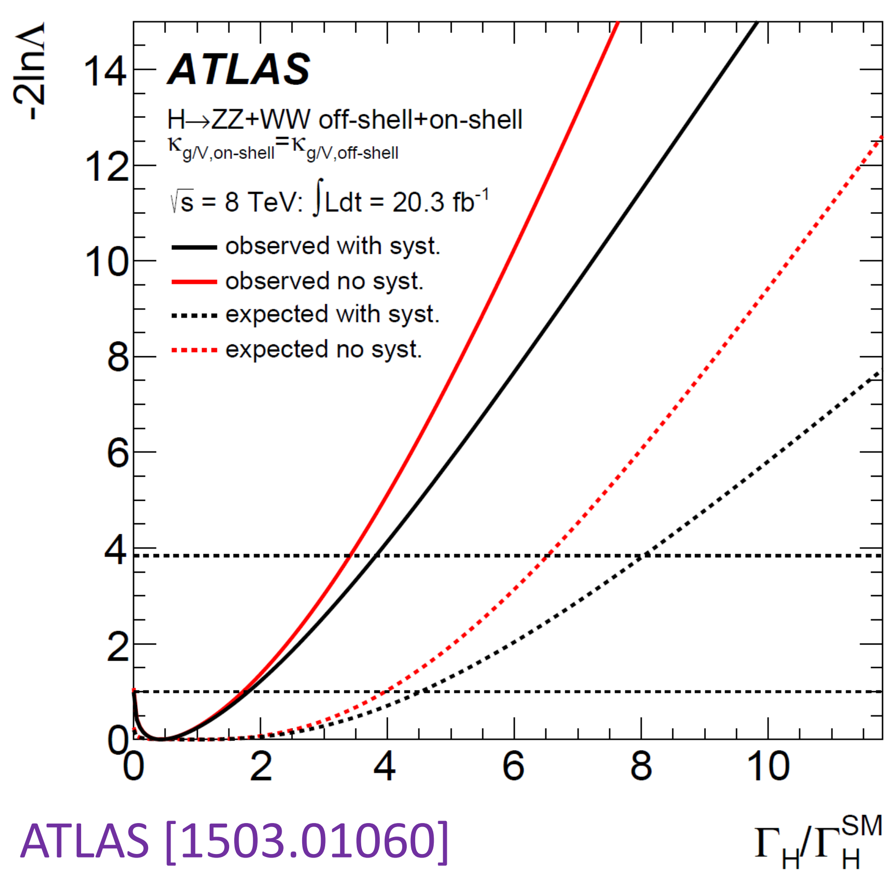
CMS [1312.5353]

Perez, et. al. [1503.00290]

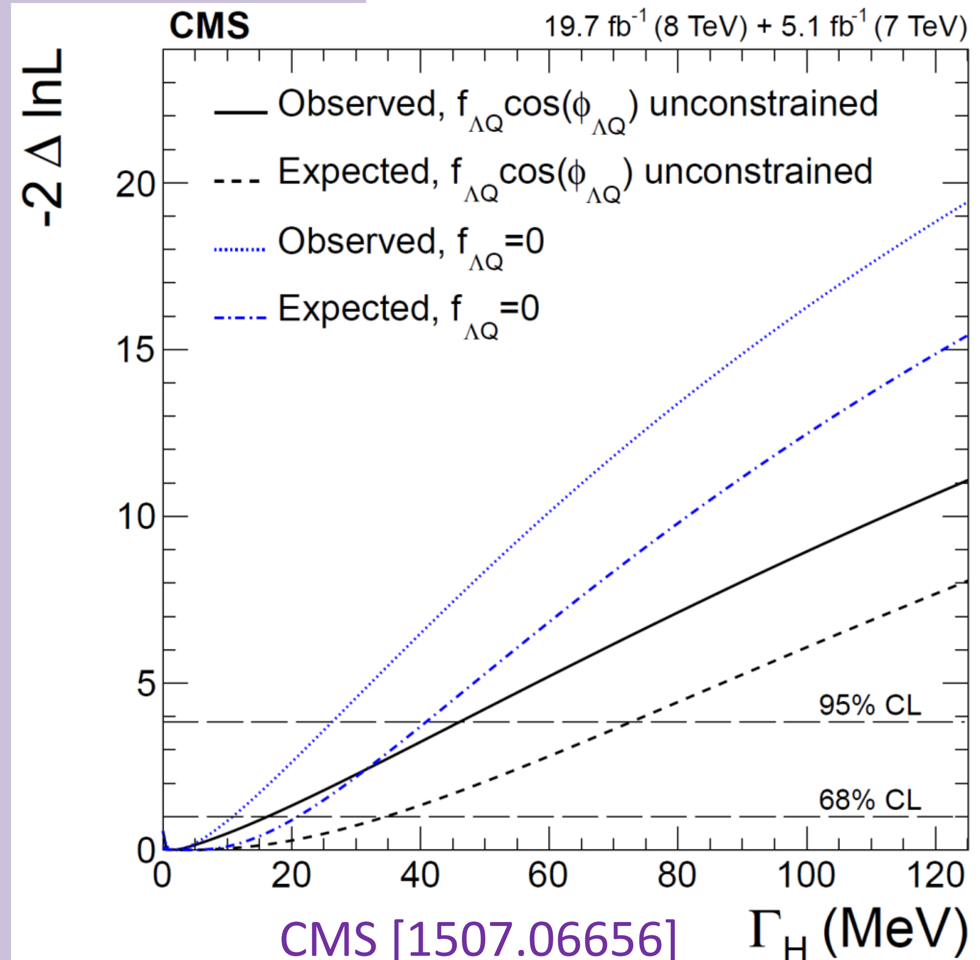
Suite of measurement possibilities

- Indirect Higgs width measurements
  - Lower and upper bound

$$\Gamma_H > 3.5 \times 10^{-9}\ \text{MeV}$$



ATLAS [1503.01060]



CMS [1507.06656]

Importance of direct probes

- Combined fit for Higgs couplings can and do give best sensitivity to nonstandard Yukawas
  - Caveat: need model-dependent assumptions to over-determine system of constraints
    - At LHC, total Higgs width is not (expected to be) directly measurable

$$N_{\text{events}} = \mathcal{L}\sigma \times B \propto \frac{g_p^2 g_d^2}{\Gamma_{\text{tot}}} \sim \frac{g_p^2 g_d^2}{\sum_i \Gamma_{i,\text{vis}} + \Gamma_{\text{unobs}}}$$

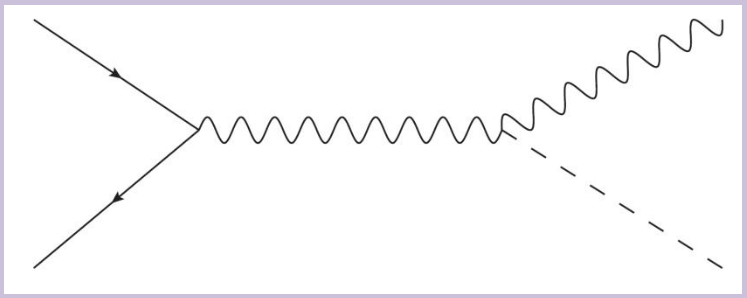
  - Cannot go beyond self-consistency test without assumptions about nature of NP

New feature: $W^{\pm}h$ charge asymmetry

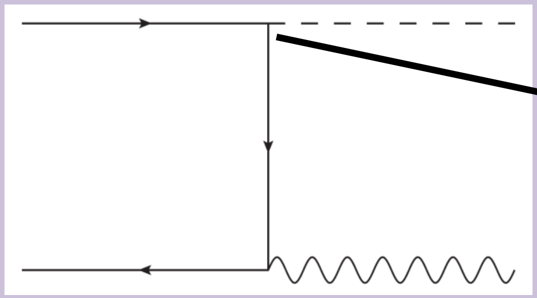
- $W^{\pm}h$ production asymmetric at LHC
  - Asymmetry driven by PDFs
  - Consider $W^{+}h$:

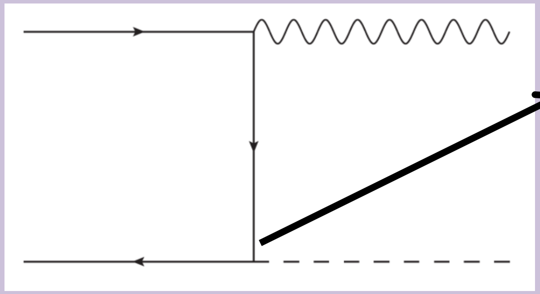
8 TeV: $W^{+}H$ (pb)	$W^{-}H$ (pb)
0.445	0.2597

Higgs XSWG [1307.1347]



Insensitive to Yukawas





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8 TeV:	
$W^{+}H$ (pb)	$W^{-}H$ (pb)
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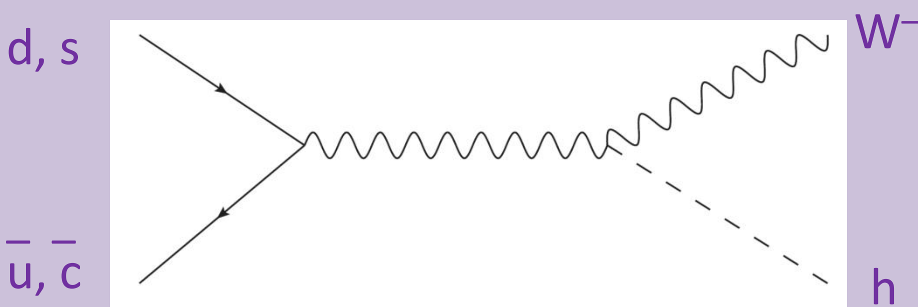
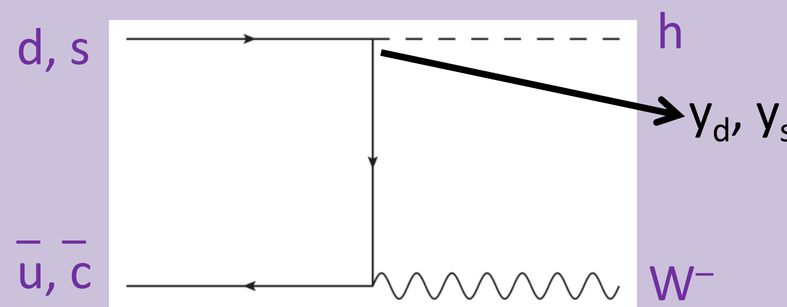
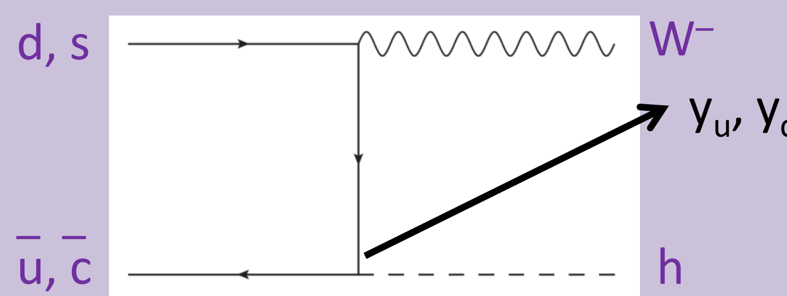
Higgs XSWG [1307.1347]

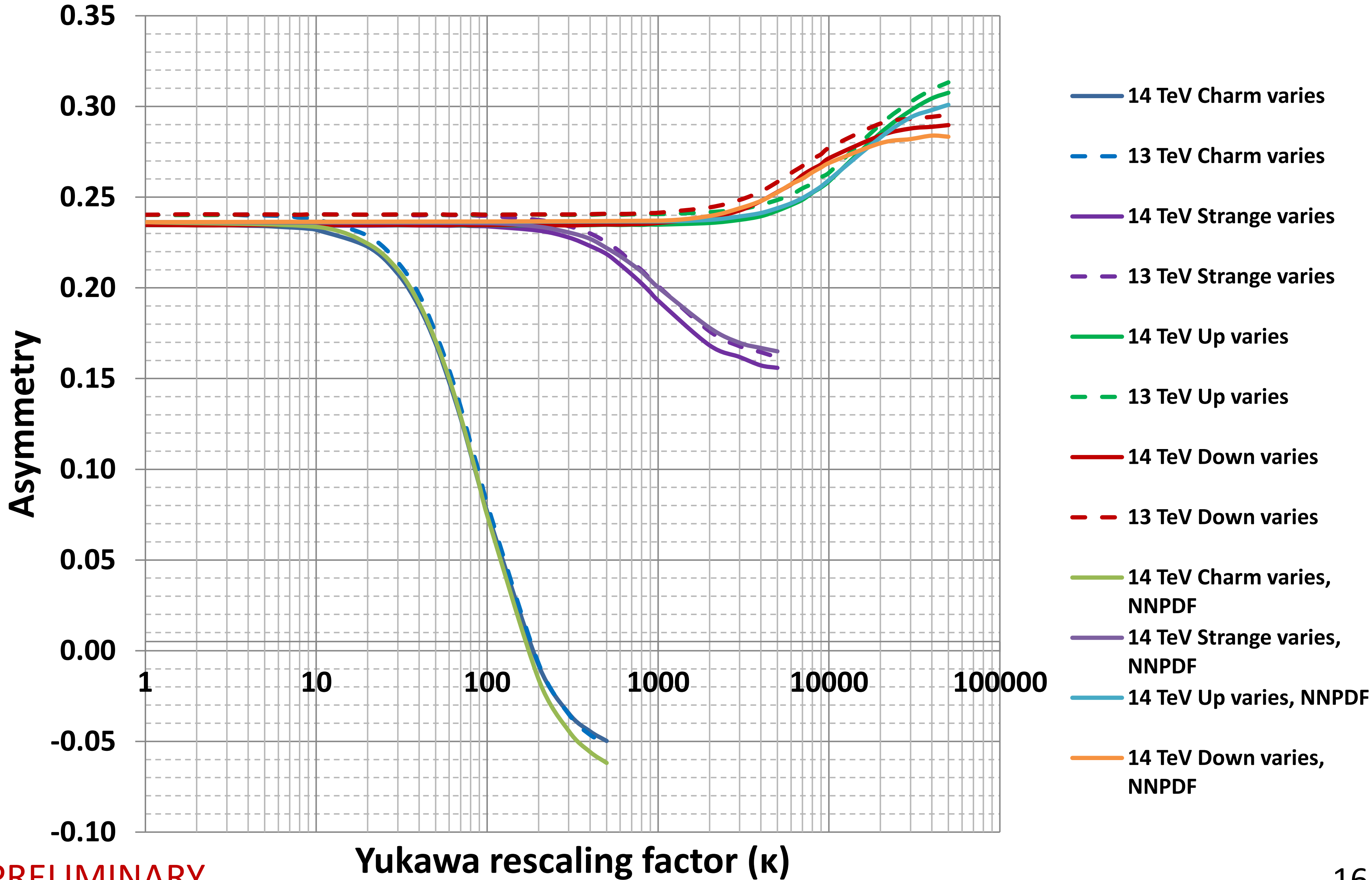


Insensitive to Yukawas





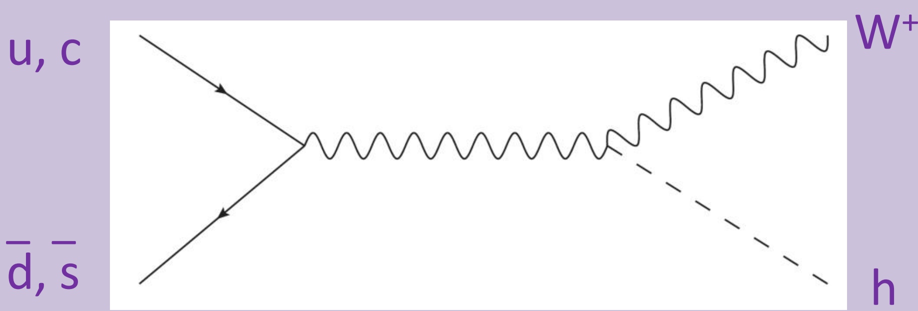
Inclusive charge asymmetry



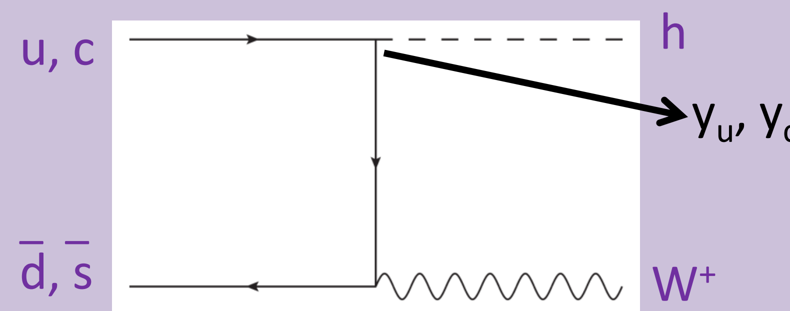
PRELIMINARY

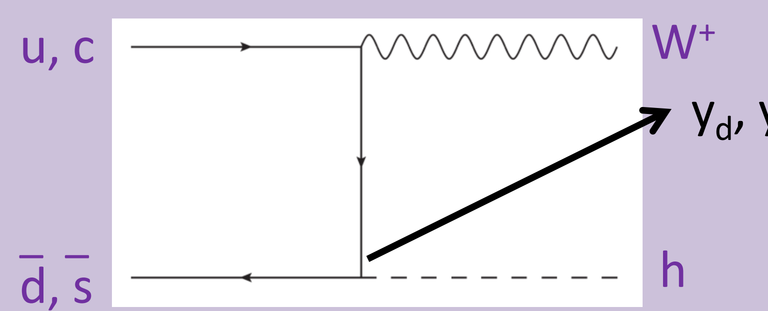
PDF behavior

- In SM, net positive asymmetry driven by $u\bar{d}$, mitigated by $c\bar{s}$ (neglect Cabibbo angle)
  - For enhanced y_d or y_u, charge-asymmetric PDFs take over
  - For enhanced y_s or y_c, charge-symmetric PDFs dominate
    - Important, subleading corrections from Cabibbo angle



Insensitive to Yukawas





Measuring W^+h, W^-h rates

PRELIMINARY

- Consider all possible final states that can give clean lepton asymmetry measurement

Using Standard Model BRs, include leptonic decays, # events for 14 TeV LHC

		$H \to bb$	$H \to \gamma\gamma$	$H \to l^+l^- l^+l^-$ ($l=e,\mu,\tau$)	$H \to l^+l^- l^+l^-$ ($l=e,\mu$)	$H \to l^+ l^- \nu_l \nu_l$ ($l=e$, μ or τ, ν=any)	$H \to l^+ l^- \nu_l \nu_l$ ($l=e$ or μ, ν=any)	$H \to \tau\tau$	$H \to l^+ l^-$ q q ($l=e,\mu$ or τ, q=udcsb)	$H \to l^+ \nu_l$ q q (*) ($l=e$ or μ, q=udcsb)
W^+h	300 fb^{-1}	31382	124	15	7	1288	579	3438	204	1730
W^+h	3 ab^{-1}	313816	1244	152	69	12880	5785	34383	2036	17301
W^-h	300 fb^{-1}	19150	76	9	4	786	353	2098	124	1056
W^-h	3 ab^{-1}	191498	759	93	42	7860	3530	20982	1242	10557

- Focus on same-sign dilepton signature
  - Inherits charge asymmetry from production

Same-sign lepton collider study

- Signal
  - $W^{\pm} h \rightarrow (l^{\pm}\nu)\ (l^{\pm}\nu jj)$: Final state is two same-sign leptons, one or two resolved jets, some missing transverse energy
- Backgrounds
  - $W^{\pm}W^{\pm}jj$
  - $W^{\pm}Z$, Z decays leptonically (and OS lepton lost)
  - $W^{+}W^{-}$ with charge mis-identification rates:
    - electrons: 0.16% for $0 < |\eta| < 1.479$, 0.3% for $1.479 < |\eta| < 3$
    - muons: negligible

CMS-DP-2015-035

Same-sign lepton collider study

PRELIMINARY

- Initial efficiencies already account for leptonic BRs
- Reduce W^+W^- by same charge requirement
- Reduce $W^\pm W^\pm jj$ by $m_{jj} < 120$ GeV cut
  - Also cut on transverse mass differences

Cut, survival efficiency	**SM** $W^\pm h$	$W^\pm W^\pm jj$	W^+Z	W^-Z	W^+W^-
Exactly two leptons, $p_T > 20$ GeV	46.3%	23.9%	34.8%	34.4%	34.2%
Same-charge leptons	46.2%	23.4%	6.9%	7.2%	0.054%
Either one or two jets, $p_T > 20$ GeV	31.6%	15.8%	3.6%	4.0%	0.026%
$m_{jj} < 120$ GeV	28.7%	8.8%	3.0%	3.3%	0.020%
$m_{T,\text{ subleading } \ell jj} < 150$ GeV	19.0%	2.0%	1.7%	1.9%	0.0078%
Number of events	360 + 236	292 + 166	1960 + 5	3 + 1423	58 + 70
Statistical significance, 300 fb^{-1}, $S/\sqrt{S+B}$	6.97σ, 5.42σ				

Same-sign lepton collider study

PRELIMINARY

- Further optimization still underway
  - Separating transverse mass cuts by jet multiplicity
  - Adding overall ΔR separation between subleading lepton and jets

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Same-sign lepton collider study

PRELIMINARY

- Discovery senstivity for W^+h and W^-h production with 300 fb^{-1} luminosity
  - However, effective BR for $h \to l^\pm \nu jj$ decreases as Higgs width increases from large Yukawas

Cut, survival efficiency	**SM** $W^\pm h$	$W^\pm W^\pm jj$	W^+Z	W^-Z	W^+W^-
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Effective signal strengths from large Yukawas

- Individually rescale light quark Yukawas
- Width increase partially mitigated by new production modes
  - $W^{\pm}h$ associated production

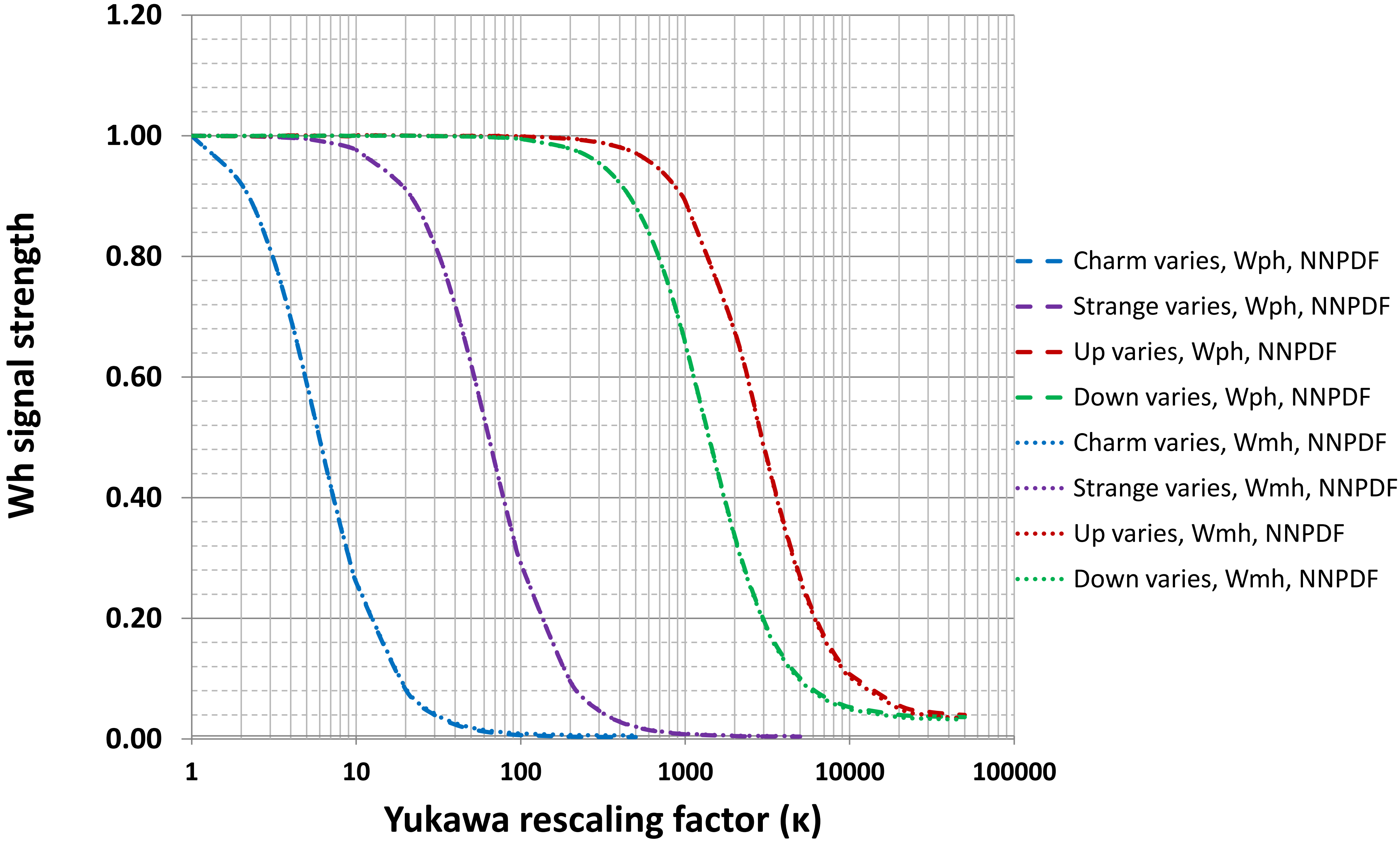
$$\mu_{Wh} = \frac{(\sigma_{Wh}^{\rm NP})}{(\sigma_{Wh}^{\rm SM})} \times \frac{\Gamma(h \to X)^{\rm NP}/\Gamma_{\rm tot}^{\rm NP}}{\Gamma(h \to X)^{\rm SM}/\Gamma_{\rm tot}^{\rm SM}}$$

  - Gluon fusion and quark-initiated *s*-channel production

$$\mu_{gg} = \frac{(\sigma_{gg}^{\rm NP} + \sigma_{qq}^{\rm NP})}{(\sigma_{gg}^{\rm SM})} \times \frac{\Gamma(h \to X)^{\rm NP}/\Gamma_{\rm tot}^{\rm NP}}{\Gamma(h \to X)^{\rm SM}/\Gamma_{\rm tot}^{\rm SM}}$$

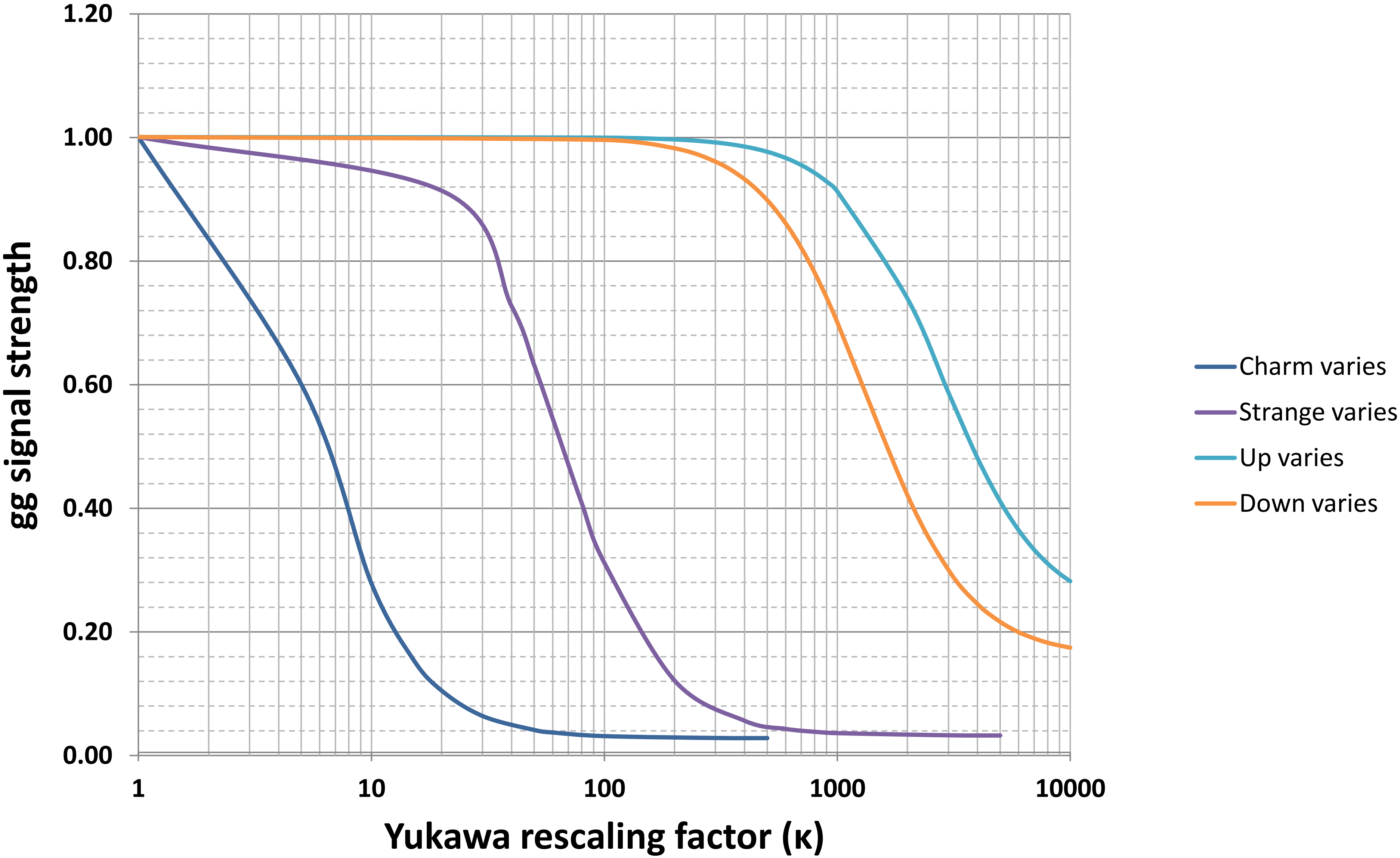
Wh signal strength

PRELIMINARY



gg signal strength

PRELIMINARY



Effective signal strengths from large Yukawas

- Extra colored states (new vector-like quarks to induce large Yukawas for light quarks) can easily bring gg signal strength back to SM expectation
- More difficult for Wh signal strength
  - Careful balance between hVV coupling and Yukawa
  - Large y_d, y_u deviations possible with little observable effect
- Same-sign lepton and charge asymmetry study still useful self-consistency test of Higgs
  - On same footing as indirect width test

Conclusions

- New same-sign dilepton channel for testing Higgs properties
  - Need UV completion to fully determine nonstandard Yukawa prospects
  - For model with enhanced hVV coupling or decreased SM partial widths (*e.g.* hbb), charge asymmetry probe can cover same range as other techniques
    - Different systematics and experimental challenges than charm tagging and rare decays
- Same-sign lepton channel also useful probe for Higgs coupling to vectors
  - O(1000) deviation in y_u and y_d should be probed with ggF tests, Higgs + jet measurements
  - No immediate test to disentangle many simultaneous Yukawa deviations

Suite of measurement possibilities

- Deviations in y_s or y_c (or any Yukawa) must be NP
  - Effective operator estimate (integrate out VLQs)

$$\mathcal{L} \supset yH\overline{Q}_L u_R + y' \frac{H^\dagger H}{\Lambda^2} H\overline{Q}_L u_R + \text{ h.c.}$$

$$m_q = v\left(y + y'\frac{v^2}{\Lambda^2}\right)$$

$$y_q = \left(y + 3y'\frac{v^2}{\Lambda^2}\right)$$

$$\kappa_q \equiv \frac{y_q}{m_q/v} = \frac{\left(y + 3y'\frac{v^2}{\Lambda^2}\right)}{\left(y + y'\frac{v^2}{\Lambda^2}\right)} = 1 + \frac{2y'\frac{v^2}{\Lambda^2}}{y_{SM}}$$

  - General argument to obtain large Yukawas for light fermions