PHENOMENOLOGY OF ENHANCED LIGHT QUARK YUKAWA COUPLINGS

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[1609.verysoon]

ERC Workshop on EFTs for Collider Physics, Flavor Phenomena, and EWSB
Burg Crass, Eltville, September 15, 2016

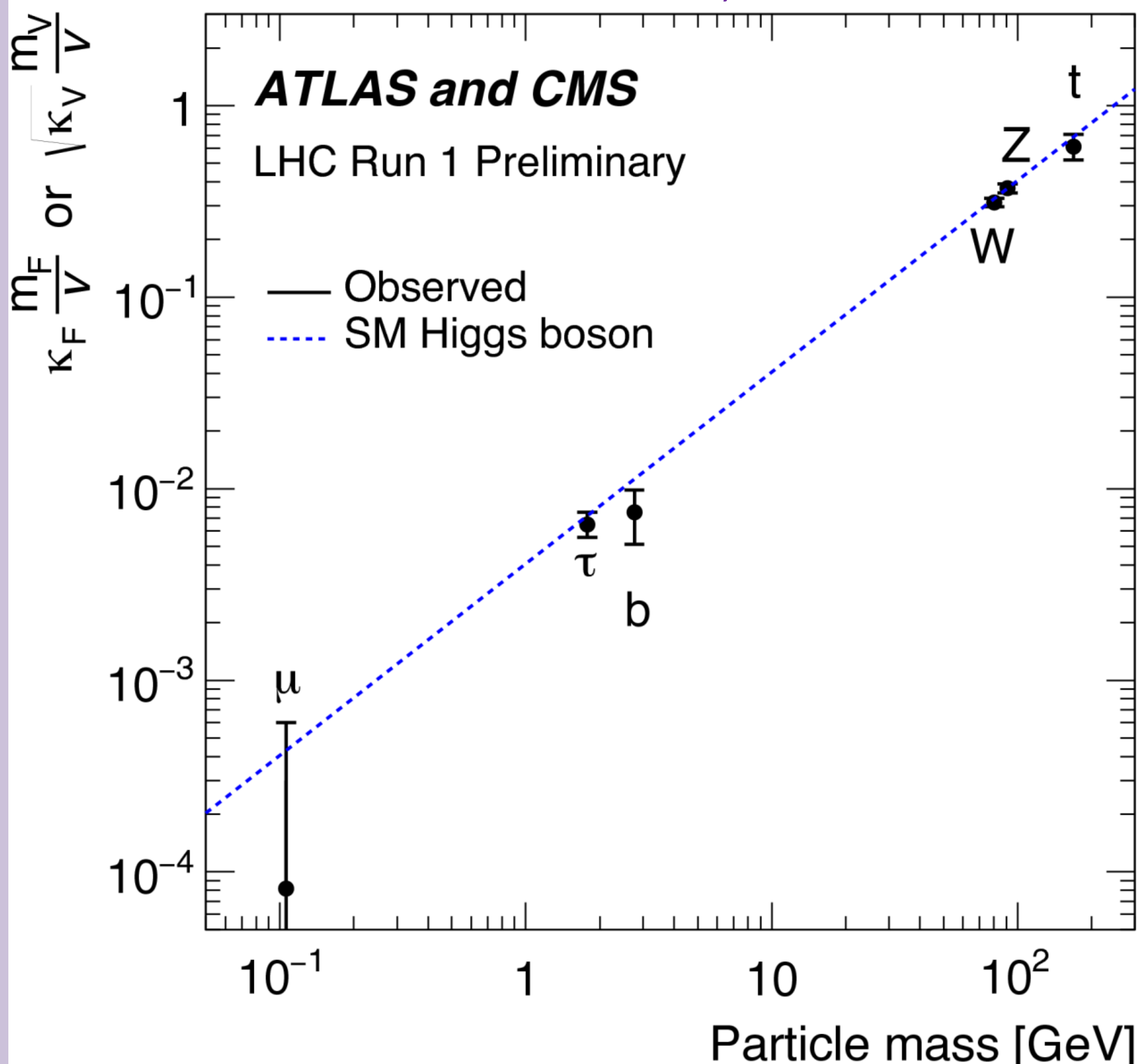
Introduction and Motivation

- 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
  - BSM connection to EWSB causes deviations in Higgs observables

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

- Overview of Yukawa measurement proposals
  - Direct tests vs. indirect tests
- LHC $W^\pm h$ production charge asymmetry
  - Effects from nonstandard light quark Yukawas
- Collider study: same-sign leptons from
  $$W^\pm h \to (l^\pm \nu)\,(l^\pm \nu jj)$$
  - Serves as SM discovery channel of Wh associated production
- Signal strengths from enhanced light quark Yukawas
  - $W^\pm h$ production, *s*-channel Higgs production
- Conclusions

Motivating non-standard Yukawas

- Effective operator estimate (integrate out VLQs)

$$\mathcal{L} \supset y_u \bar{Q}_L \tilde{H} u_R + y'_u \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R + y_d \bar{Q}_L H d_R + y'_d \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{ h.c. } ,$$

- Now diagonalize the mass combination

$$m_f = \frac{y_f v}{\sqrt{2}} + \frac{y'_f v^3}{2\sqrt{2}\Lambda^2}$$

  - Resulting Yukawa interactions are not necessarily diagonal, aligned, CP-conserving

$$y_{f,\text{ eff}}/\sqrt{2} = \frac{y_f}{\sqrt{2}} + \frac{3y'_f v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2y'_f v^2}{2\sqrt{2}\Lambda^2}$$

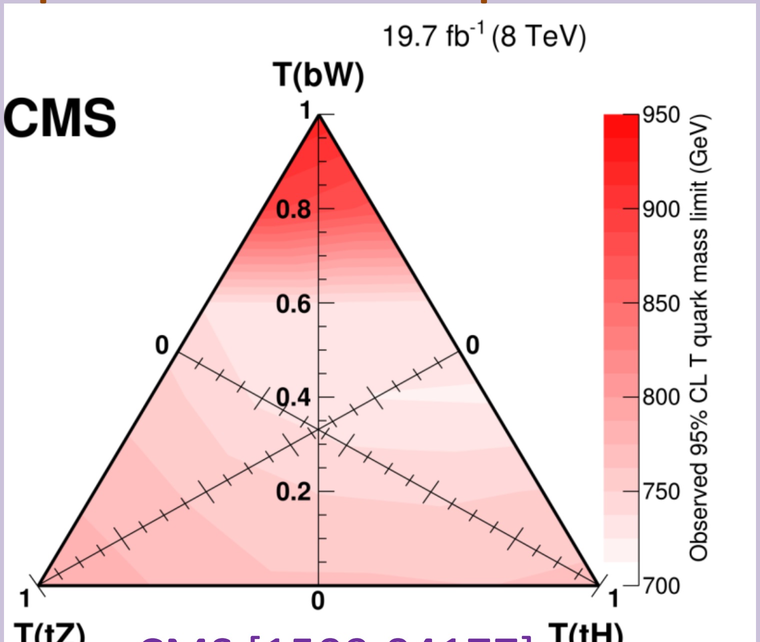
- UV completion needed to satisfy perturbative unitarity

$$E_f \simeq \frac{8\pi v^2 \xi}{|m_f - y_f v|}$$

ξ=1/√3 (quarks), ξ=1 (leptons)

Suite of measurement possibilities

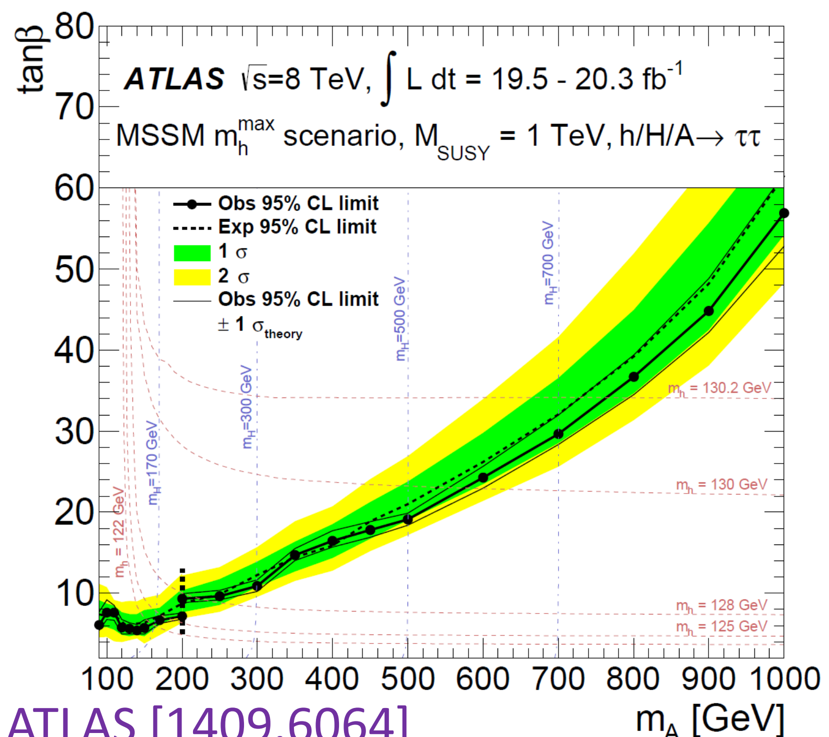
- SM fermions are chiral, hence Yukawa deviations require new sources of $SU(2)_L$ breaking or new fermions with vector-like masses
  - Motivates direct searches for new vector-like fermion partners – top partners are a prime example



CMS [1509.04177]

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
  - Also, search for heavy Higgses: H^0, A, $H^\pm$
  - New Yukawa structures
    - Generally induce FCNCs



ATLAS [1409.6064]

Suite of measurement possibilities

- Indirectly measure in rare decays: *e.g.* $h \to J/\psi\ \gamma$
  – 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]

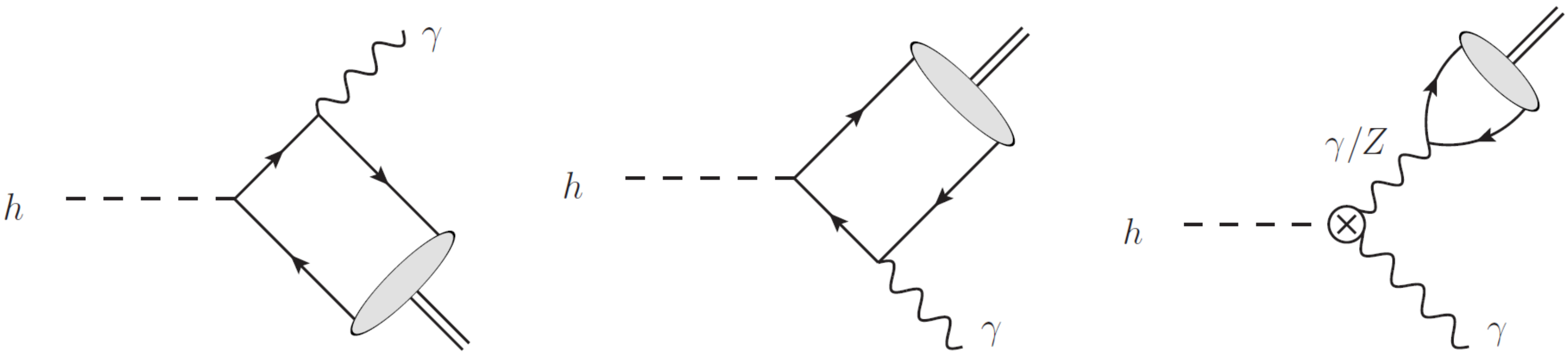


Fig. from König, Neubert [1505.03870]

Indirectly measure in rare decays

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

Bodwin, et. al. [1407.6695]

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

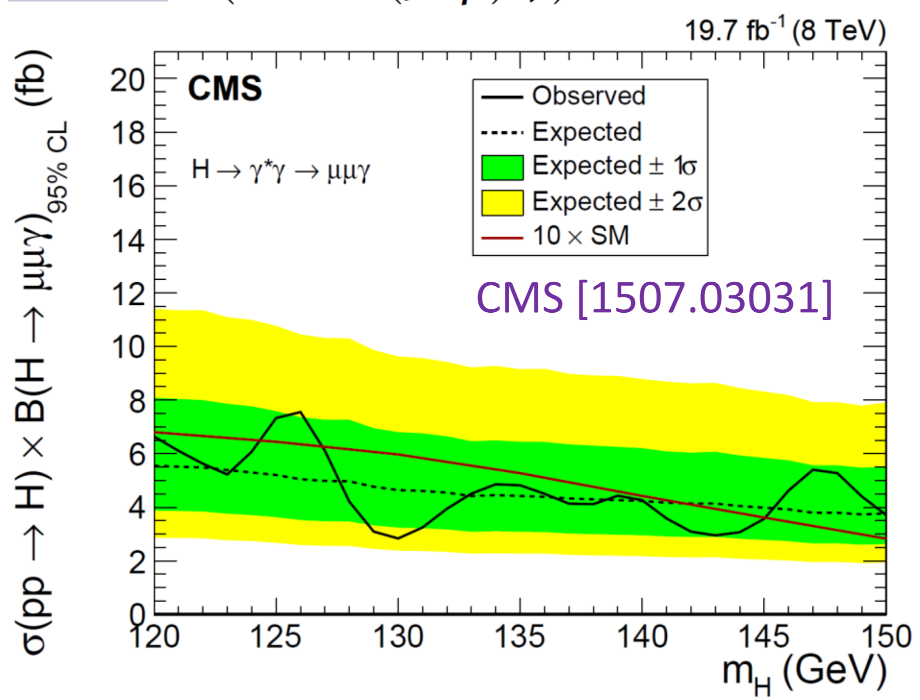
$$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma) = (4.61 \pm 0.06_{f_{\Upsilon(1S)}}\ {}^{+1.75}_{-1.21}{}_{\rm direct} \pm 0.22_{h\to\gamma\gamma}) \cdot 10^{-9}\,,$$

König, Neubert [1505.03870]

	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]

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



CMS [1507.03031]

Suite of measurement possibilities

- Directly measure in $q\bar{q}$ decays
  - Use bottom and charm tagging in tandem to profile over enhanced *c* 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]

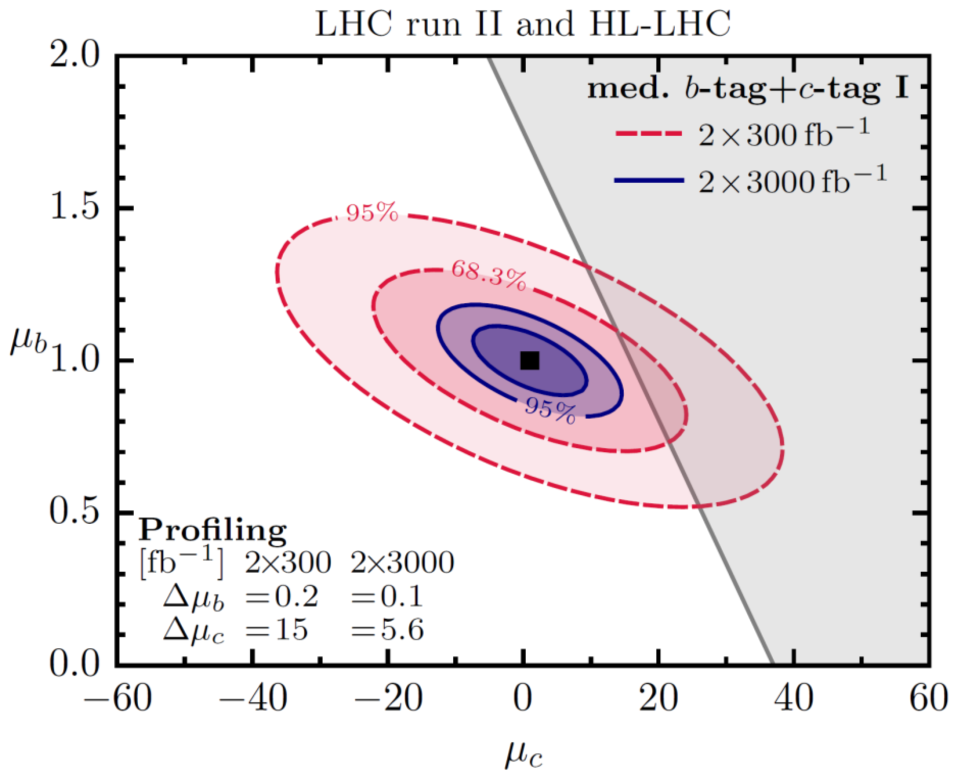
$$\mu_b \equiv \frac{\sigma_h \mathrm{BR}_{b\bar{b}}}{\sigma_h^{\mathrm{SM}} \mathrm{BR}_{b\bar{b}}^{\mathrm{SM}}} \to \frac{\sigma_h \mathrm{BR}_{b\bar{b}} \epsilon_{b_1} \epsilon_{b_2} + \sigma_h \mathrm{BR}_{c\bar{c}} \epsilon_{c_1} \epsilon_{c_2}}{\sigma_h^{\mathrm{SM}} \mathrm{BR}_{b\bar{b}}^{\mathrm{SM}}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

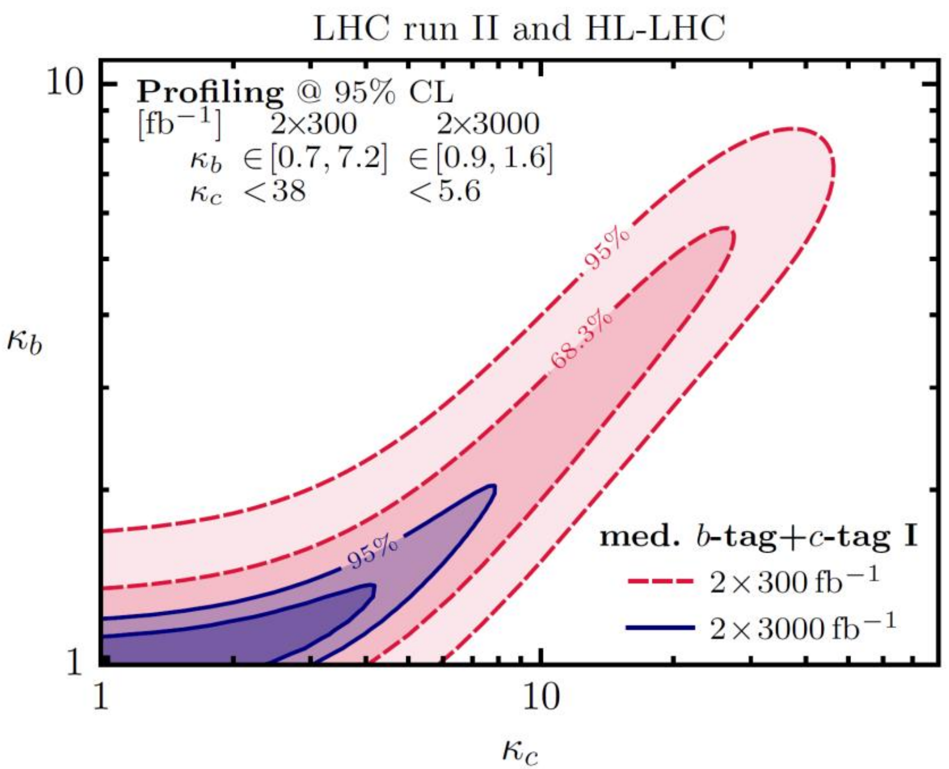
Perez, et. al. [1505.06689]

Suite of measurement possibilities

	ϵ_b	ϵ_c	ϵ_l
b-tagging	70%	20%	1.25%
c-tagging I	13%	19%	0.5%
c-tagging II	20%	30%	0.5%
c-tagging III	20%	50%	0.5%

- Directly measure in $q\bar{q}$ decays
  - Use bottom and charm tagging in tandem, profile over enhanced *c* content in Higgs decays





Suite of measurement possibilities

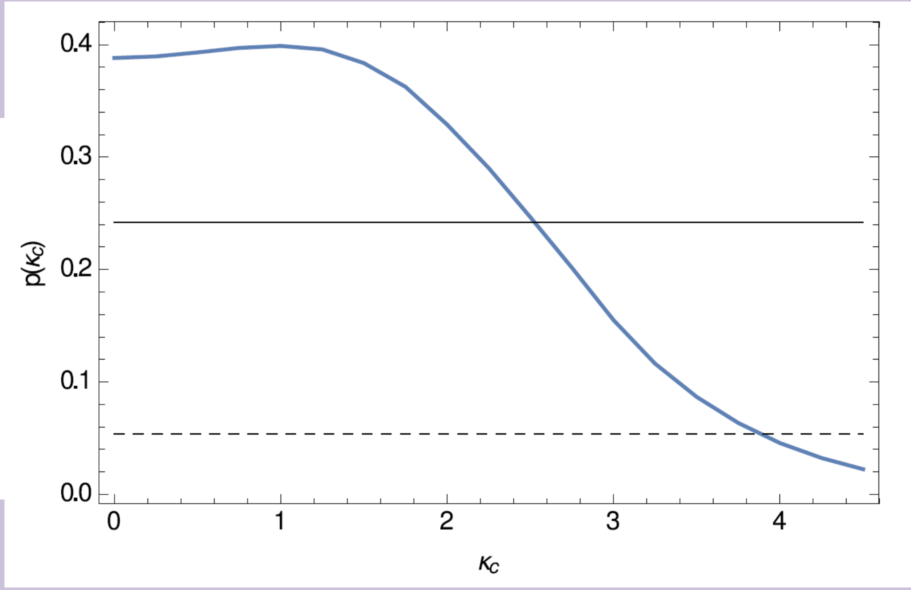
- Charm Yukawa: Measure in h+c production, use h→γγ decay (fixed to SM BR)
  - $p_T(j) > 20$ GeV
  - charm tag = 40%, gluon fake rate = 1%, b fake rate= 30%

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

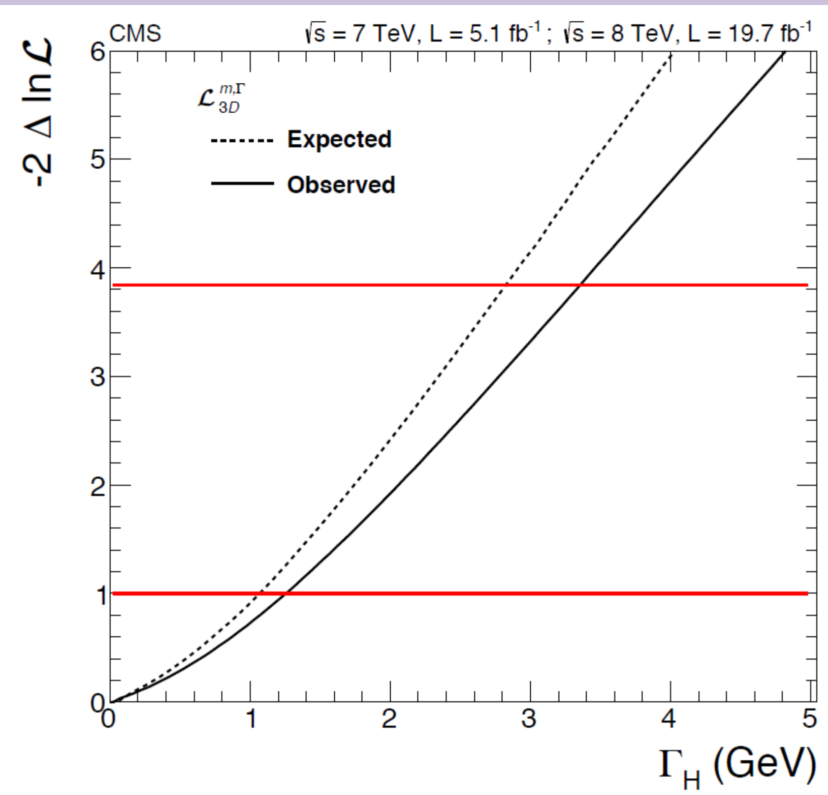
κ_c	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5
S	1097	1148	1206	1276	1350	1424	1504	1590	1683	1786

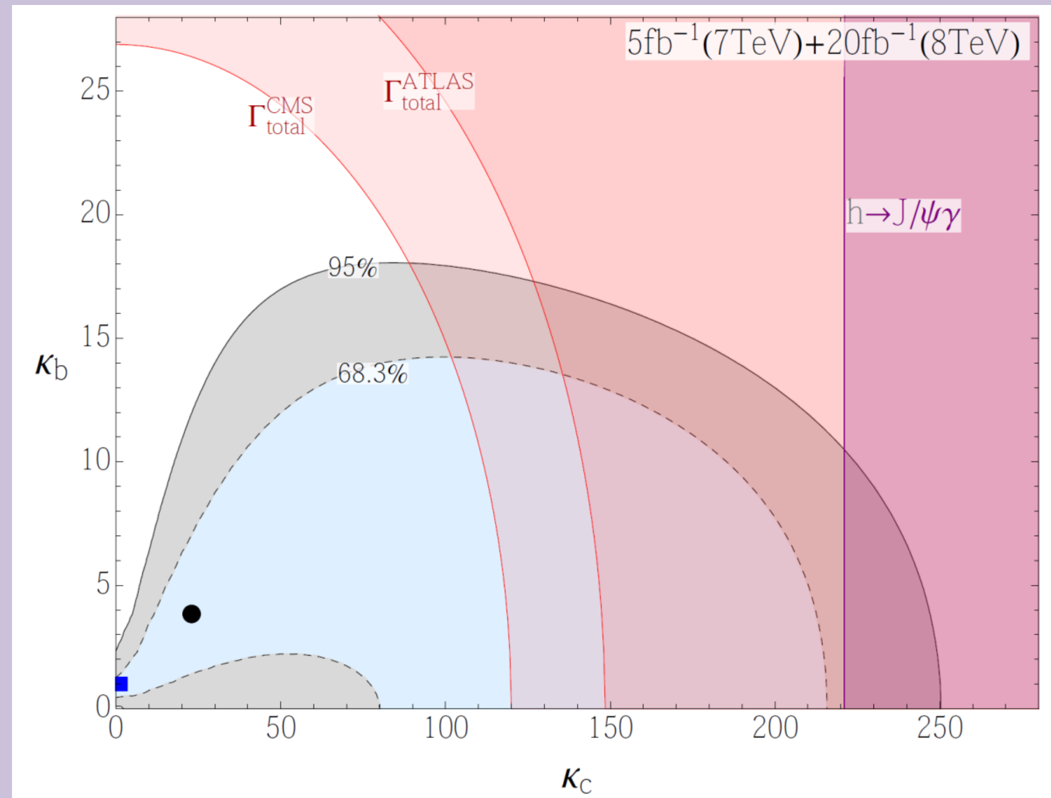
TABLE I. Number of Signal events $S(\kappa_c)$ in dependence on the charm-quark Yukawa coupling. See text for details.



Suite of measurement possibilities

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





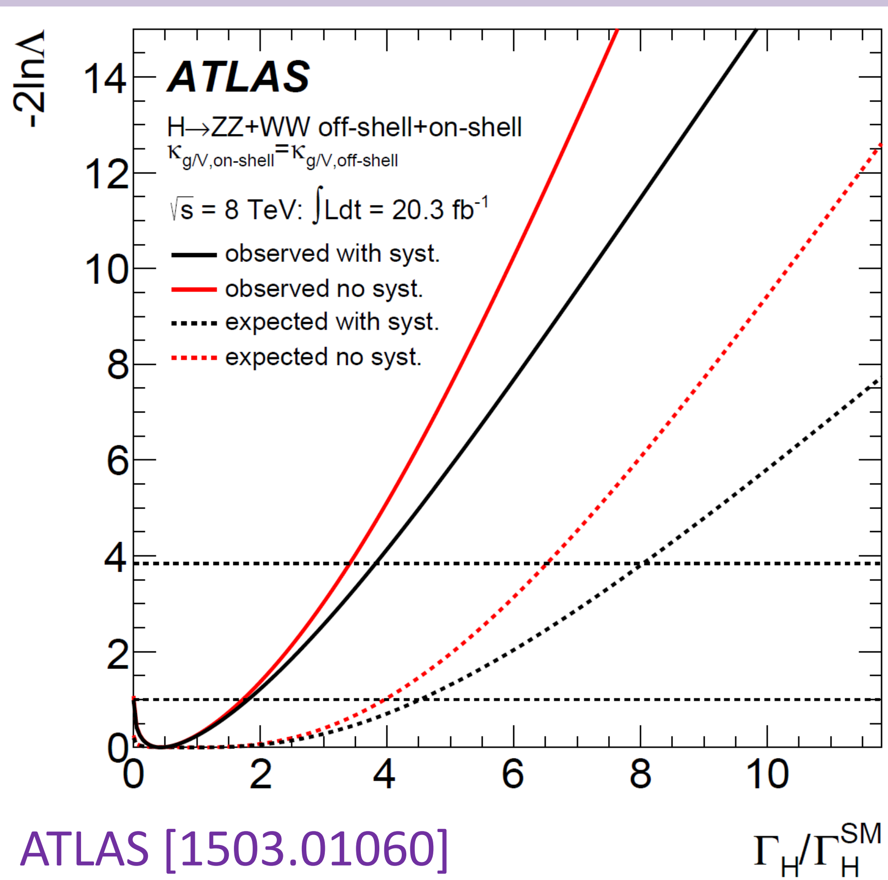
CMS [1312.5353]

Perez, et. al. [1503.00290]

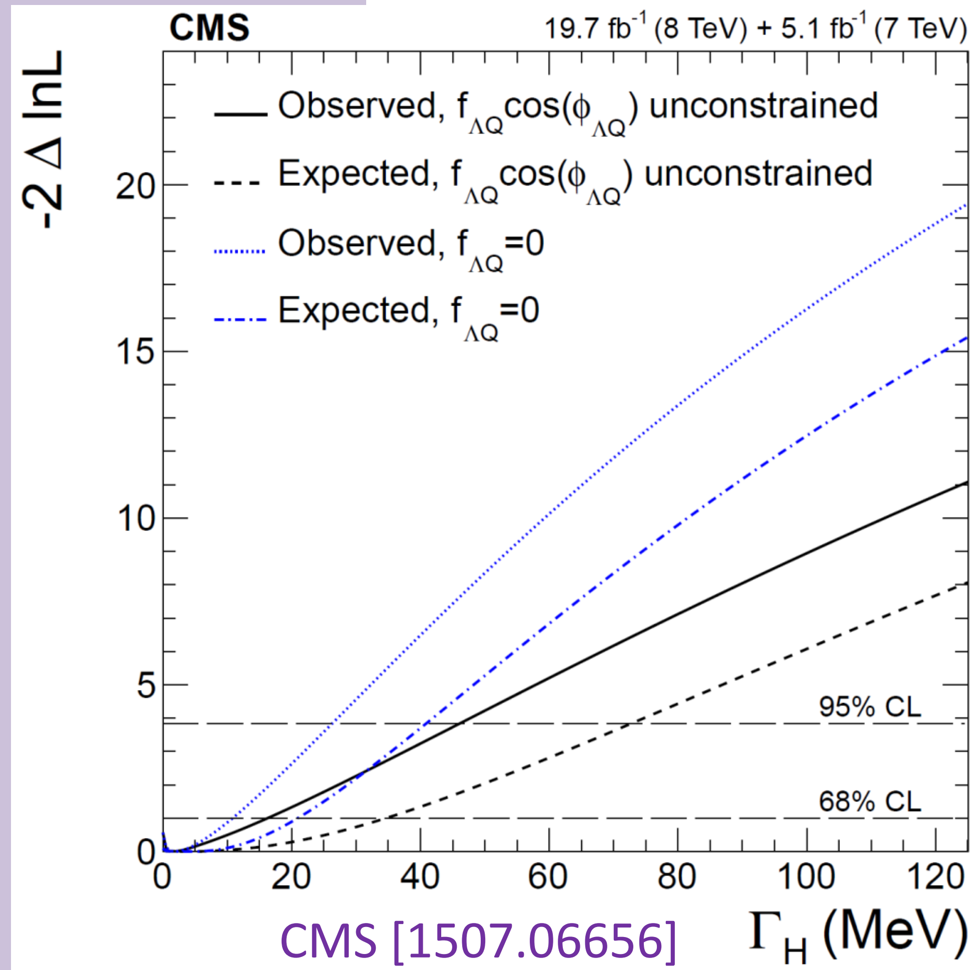
Suite of measurement possibilities

- Indirect Higgs width measurements
  - Lower and upper bound

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



ATLAS [1503.01060]



CMS [1507.06656]

Importance of direct probes

- Combined fit for Higgs couplings can and do give the 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

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

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

FY [1404.2924]

    - New exotic production modes of the Higgs readily break κ-coupling framework, Higgs EFT, well-motivated by NP

Importance of direct probes

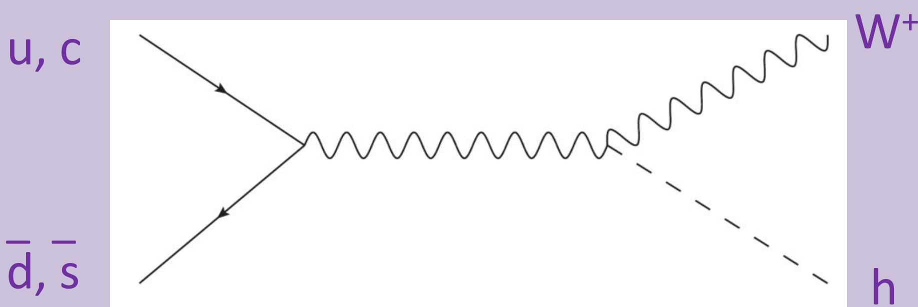
- Many indirect tests:
  - Searches for fermion partners, heavy Higgses
  - Rare decays, *e.g.* $h \to J/\psi\ \gamma$: SM expectation very small
  - Indirect width measurement: many caveats to NP interpretation
  - Combined fit: best sensitivity, requires assumptions
- Few (semi-)direct tests
  - $h \to bb$, cc: only possible for charm
  - $h+c$ production, $h \to \gamma\gamma$: many backgrounds, only for charm
  - Direct width measurement: GeV resolution
- Direct tests needed most
  - Especially for up, down, strange quarks

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

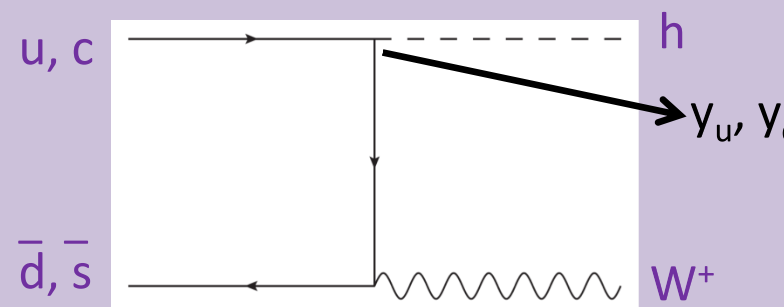
- $W^{\pm}h$ production asymmetric at LHC
  - Asymmetry driven by proton PDFs
  - Consider $W^{+}h$:
    - Unitarity violation requires NP completion

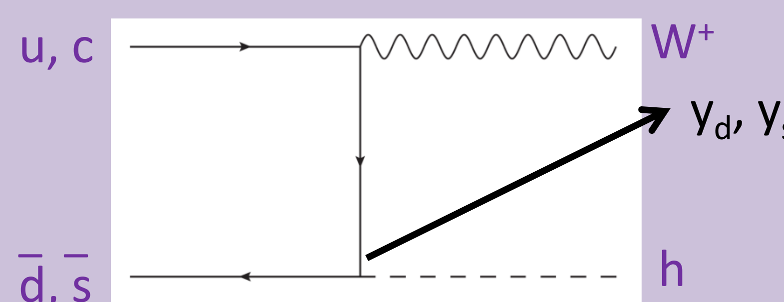
14 TeV: $W^{+}H$ (pb)	$W^{-}H$ (pb)
0.922	0.591

Higgs XSWG



Insensitive to Yukawas





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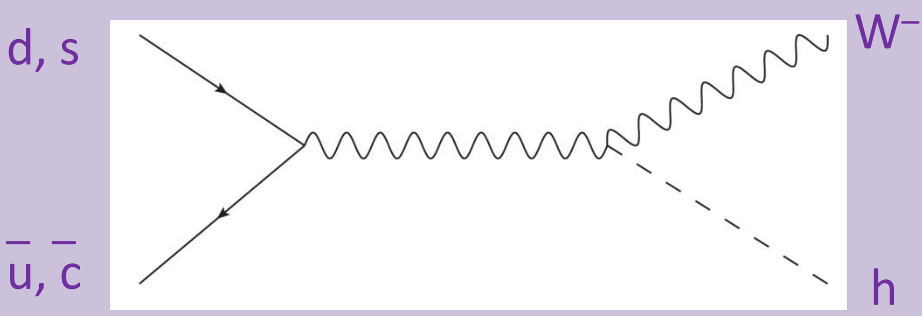
Higgs XSWG



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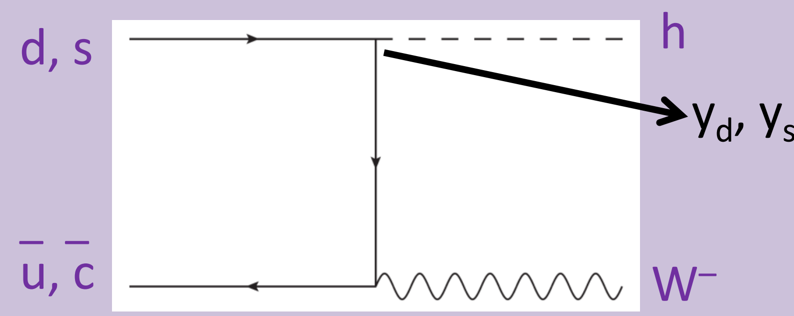
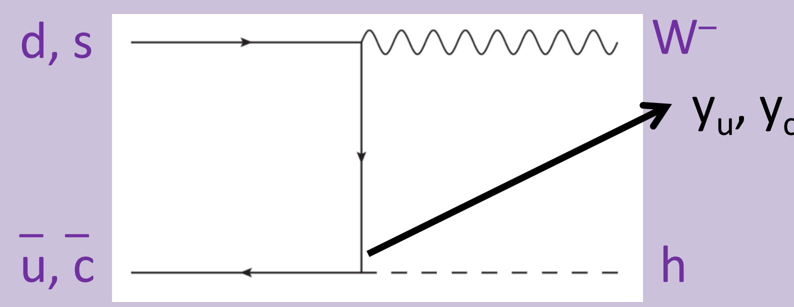
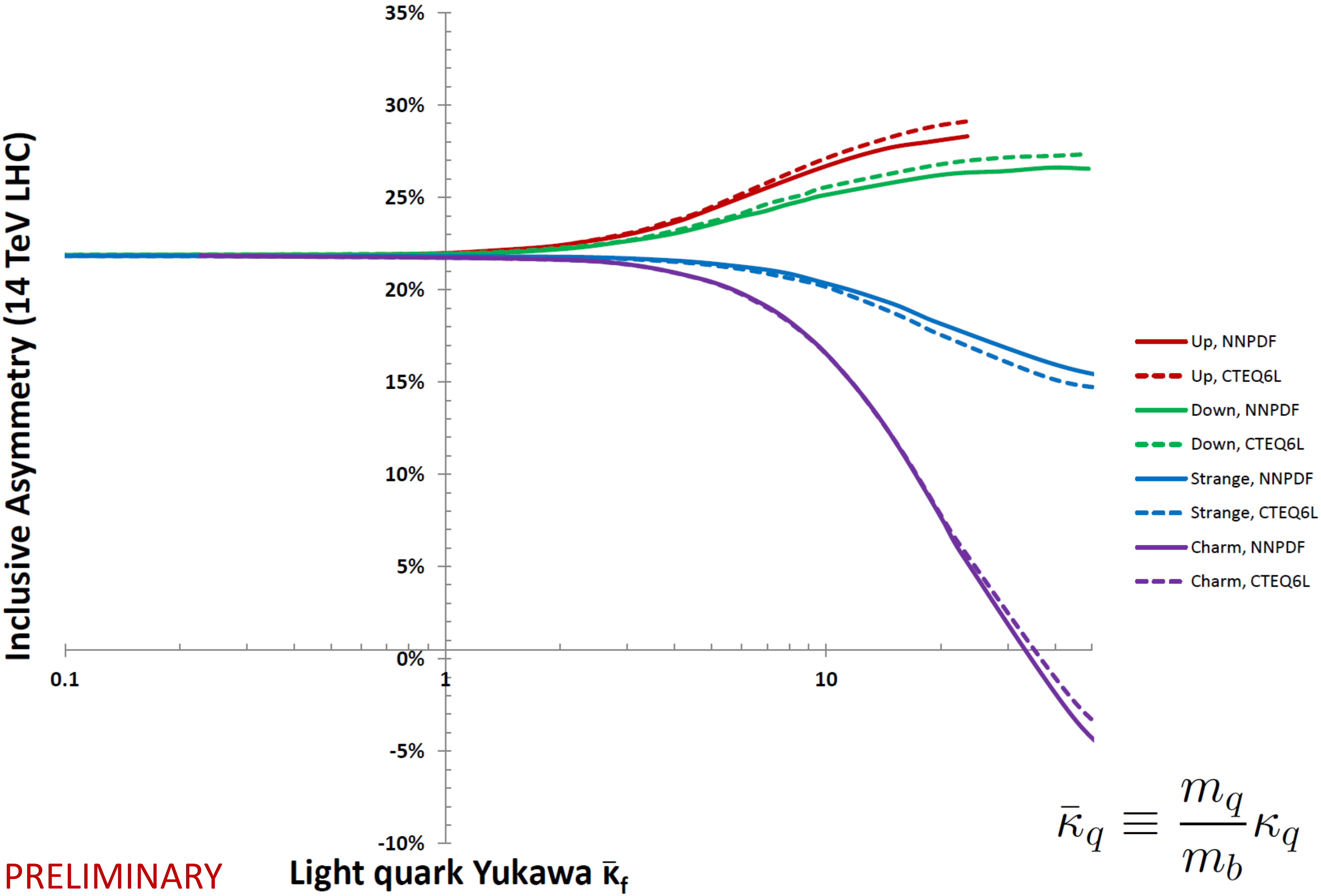




Inclusive charge asymmetry

$$A = \frac{\sigma\left(W^{+}h\right) - \sigma\left(W^{-}h\right)}{\sigma\left(W^{+}h\right) + \sigma\left(W^{-}h\right)}$$

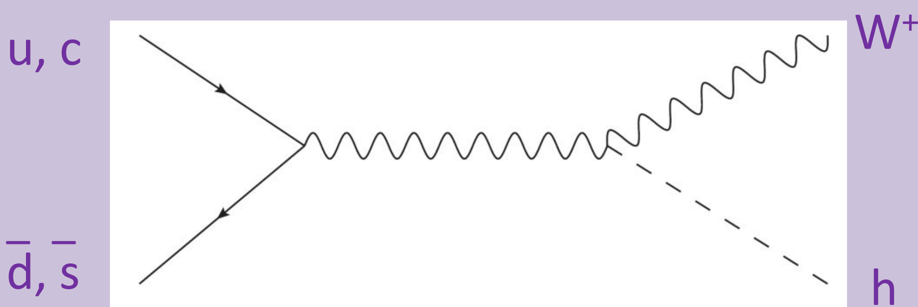


PRELIMINARY

$$\bar{\kappa}_q \equiv \frac{m_q}{m_b}\kappa_q$$

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



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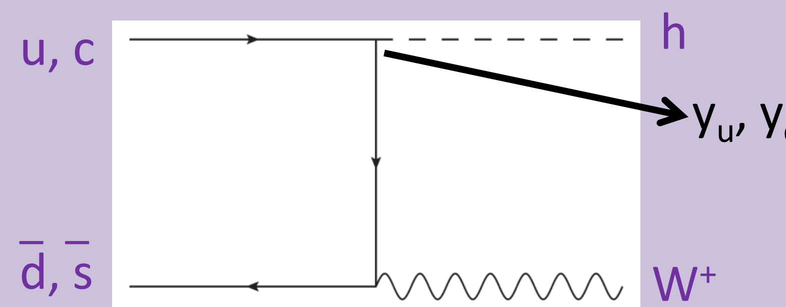
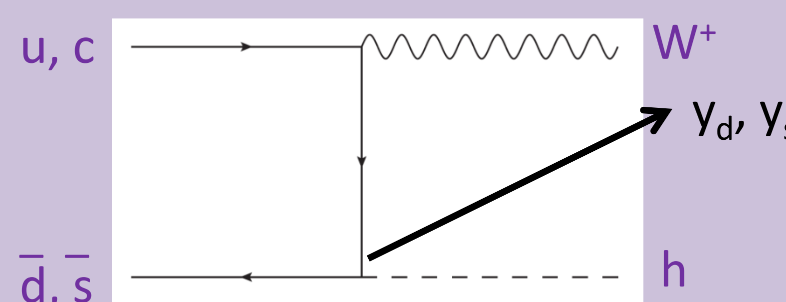




Measuring W^+h, W^-h rates

PRELIMINARY

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

Using Standard Model BRs, include e, μ decays of W, # events for 14 TeV LHC

Mode	Luminosity	H→bb	H→ττ	H→γγ	H → l+l- l+l- (l=e,μ)	H → l+ l- νl νl (l=e or μ, ν=any)	H → l+ l- q q (l=e or μ, q=udcsb)	H → l+ νl q q (l=e or μ, q=udcsb)
W^+h	300 fb^{-1}	35742	3916	142	8	659	155	1970
W^-h	300 fb^{-1}	22939	2513	91	5	423	99	1265

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

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

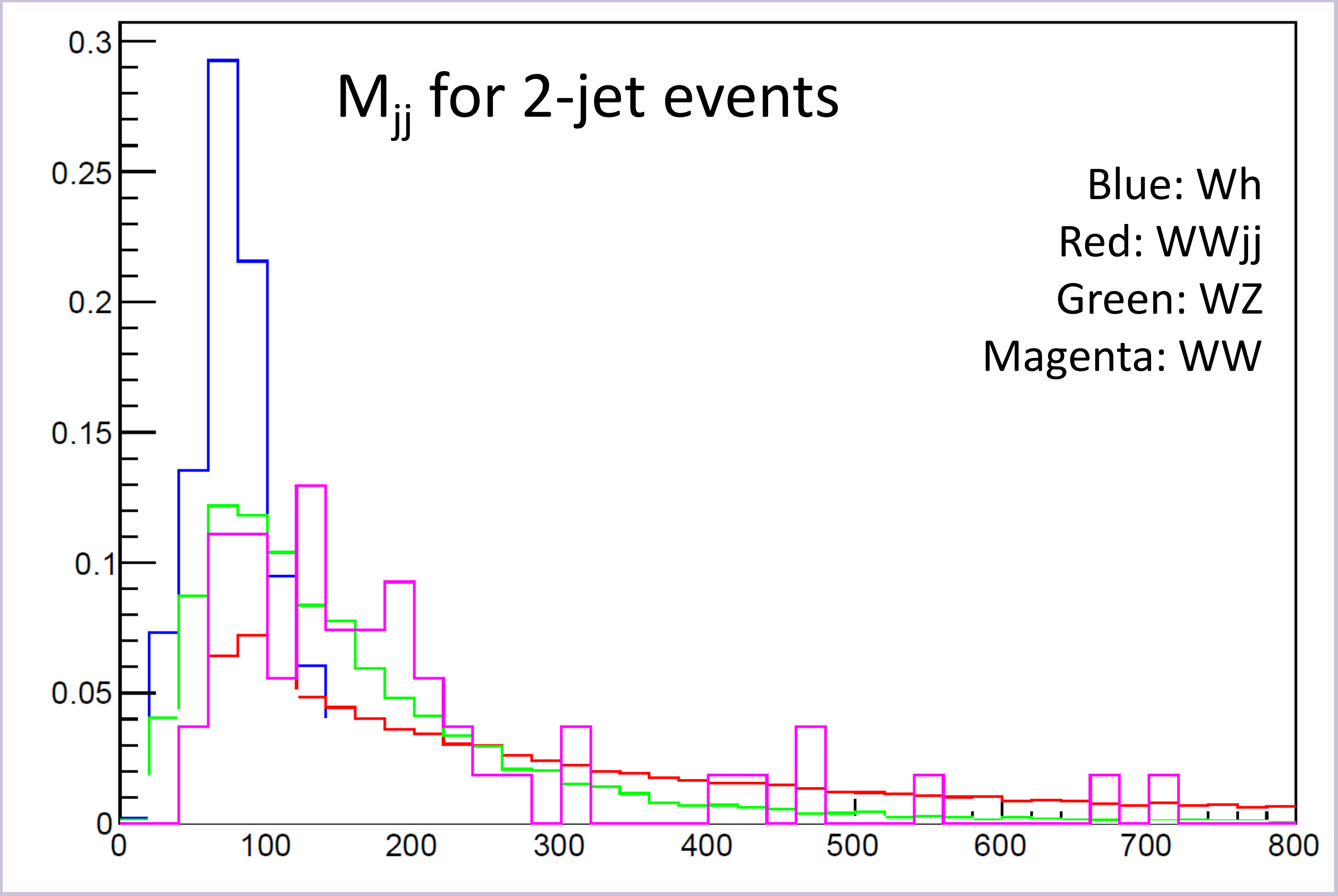
- Initial efficiencies already account for leptonic BRs
- Reduce W^+W^- by same charge requirement
- Reduce $W^\pm W^\pm jj$ by $60 < m_{jj} < 100$ GeV cut
  - Also cut on transverse mass differences

Cut, survival efficiency	**SM** $W^\pm h$	$W^\pm W^\pm jj$	W^+Z	W^-Z	W^+W^-
Exactly two leptons, $p_T > 15$ GeV	59.4%	29.0%	33.4%	32.9%	40.7%
Same-charge leptons	59.1%	28.4%	6.5%	6.5%	0.059%
Either one or two jets, $p_T > 25$ GeV	38.5%	20.1%	3.1%	3.3%	0.030%
60 GeV $< m_{jj} <$ 100 GeV	31.4%	10.4%	2.4%	2.6%	0.020%
$m_{T,\,\text{subleading}\ \ell jj} < 150$ GeV	21.9%	2.4%	1.5%	1.6%	0.010%
Number of events	425 + 277	516 + 307	2790 + 8	6 + 2068	144 + 115
Statistical significance, 300 fb^{-1}, $S/\sqrt{S+B}$	$6.82\sigma,\ 5.26\sigma \Rightarrow 8.61\sigma$				

Same-sign lepton collider study

PRELIMINARY

- Each contribution is unit-normalized



$d\sigma/dM_{jj}$

M_{jj} (GeV)

Same-sign lepton collider study

PRELIMINARY

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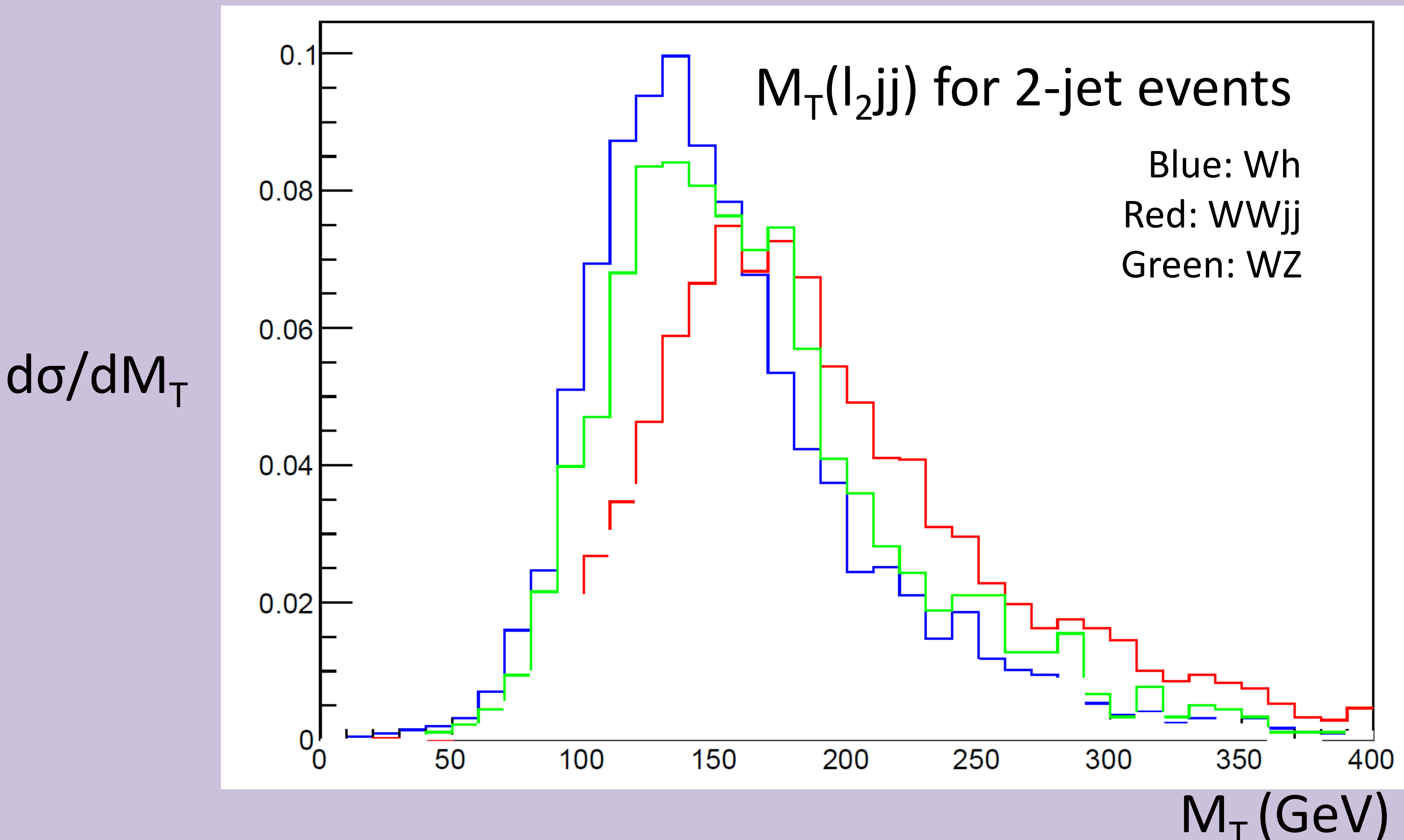

Same-sign lepton collider study

PRELIMINARY

- Discovery sensitivity for *each* W^+h and W^-h production with 300 fb^{-1} luminosity

Cut, survival efficiency	**SM** $W^{\pm}h$	$W^{\pm}W^{\pm}jj$	W^+Z	W^-Z	W^+W^-
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Same-sign lepton collider study

PRELIMINARY

- Discovery sensitivity for *each* W^+h and W^-h production with 300 fb^{-1} luminosity
- Scaling to 3 ab^{-1}, statistical sensitivity is ≈0.4%
  - However, effective BR for $h \rightarrow l^{\pm}\nu jj$ decreases as Higgs width increases from large Yukawas
  - Strong Yukawa sensitivity arises only in aggressive NP models with enhanced Higgs-vector couplings (or if SM contributions to Higgs width are not present)
  - Also requires dedicated studies of PDF uncertainties at Higgs scale

Effective signal strengths from large Yukawas

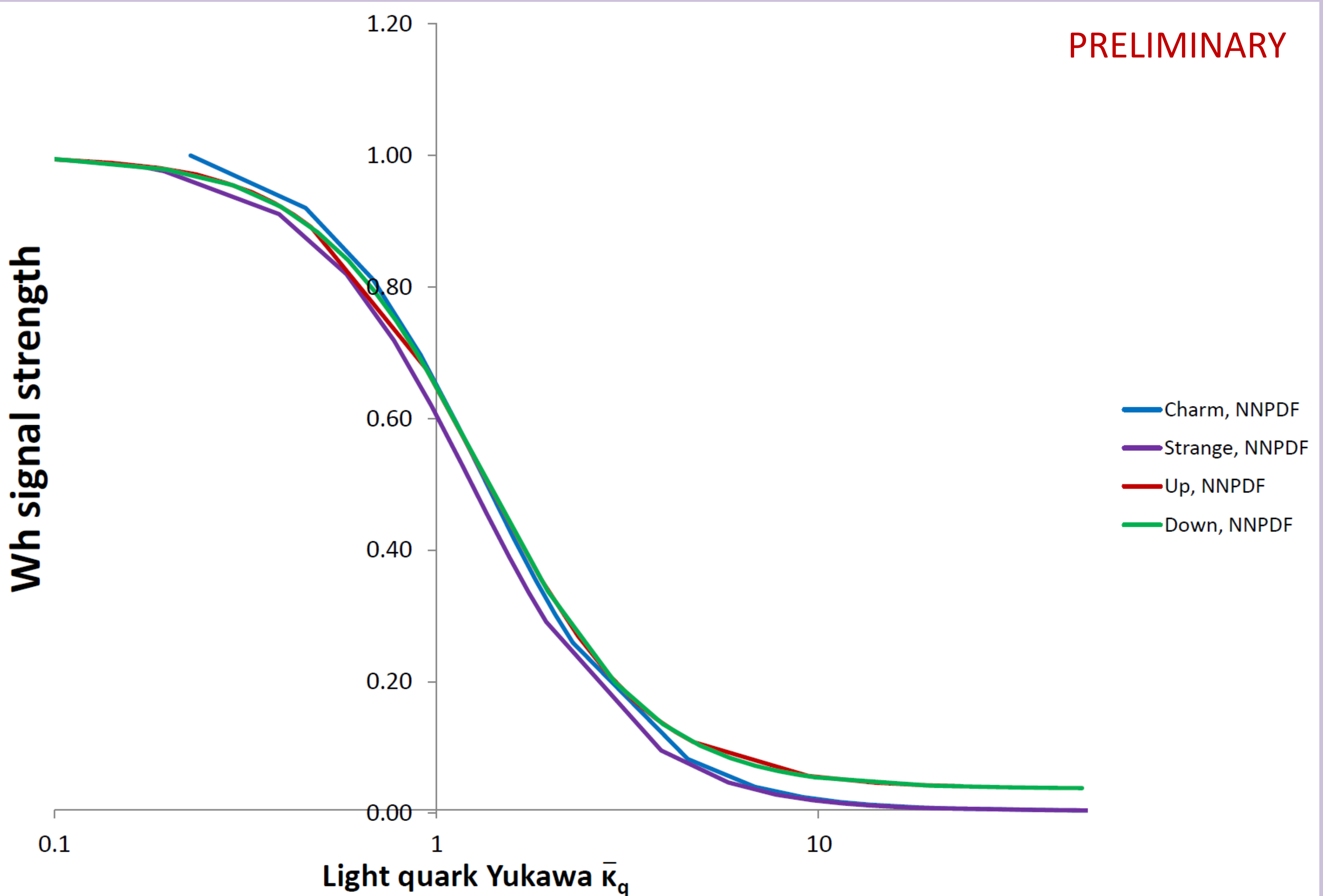
- Individually rescale light quark Yukawas
- Width increase partially mitigated by new production modes
  - $W^{\pm}h$ associated production

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

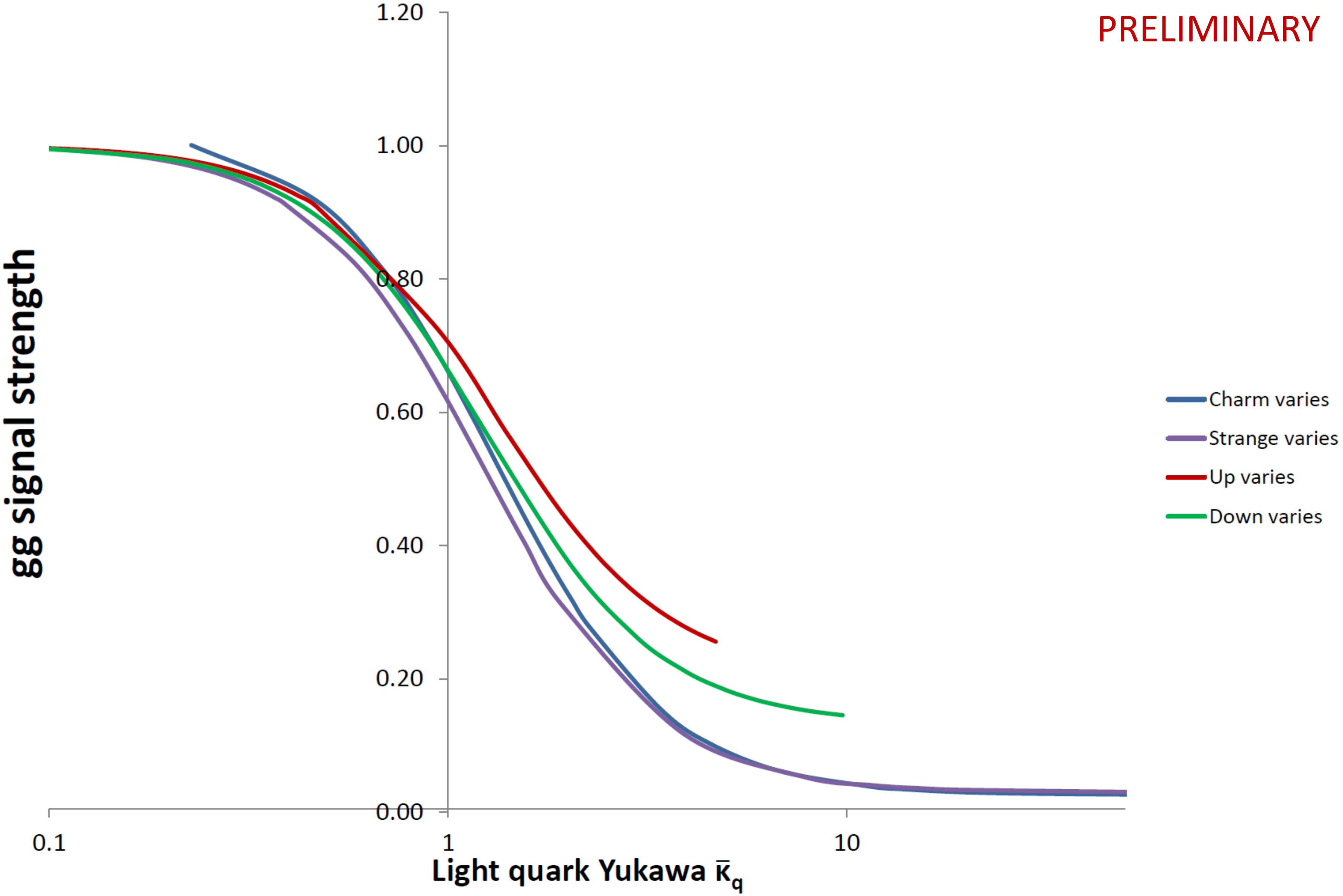
  - Gluon fusion and quark-initiated *s*-channel production

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

Wh signal strength



gg signal strength



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
  - Possibilities to disentangle *s*-channel Higgs via quark annihilation vs. gluon fusion [1606.09253], [1606.09621], [1608.04376]

CEPC study [1608.01746]

- 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
  - Different systematics and experimental challenges than charm tagging and rare decays – easily extrapolated to HL-LHC
  - Theoretical uncertainty on charge asymmetry mainly from PDFs, QCD corrections cancel
    - For models with enhanced hVV coupling or decreased SM partial widths (*e.g.* hbb), charge asymmetry probe can cover same range as other techniques
    - Need UV completion to fully determine nonstandard Yukawa prospects
- Same-sign lepton channel also useful probe for Higgs coupling to vectors
  - No immediate test to disentangle many simultaneous Yukawa deviations
  - Important (and straightfoward) consistency test that is yet to be performed using LHC data

Atomic force probes

- Analogous to DM direct detection scattering, consider short-range Higgs force in isotope shifts of atomic physics enhanced by Yukawas
    - Delaunay, Ozeri, Perez, Soreq [1601.05087]
    - Frugiuele, Fuchs, Perez, Schlaffer [1602.04822]
    - Delaunay, Soreq [1602.04838]
  - Needs electron Yukawa, strong bounds possible

$$V_{\text{Higgs}}(r) = -\frac{y_e y_A}{4\pi}\frac{e^{-r m_h}}{r}$$

$$\begin{aligned} y_n &\simeq 7.7 y_u + 9.4 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g \,, \\ y_p &\simeq 11 y_u + 6.5 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g \,, \end{aligned}$$