Direct & indirect probes of the Higgs Yukawa couplings

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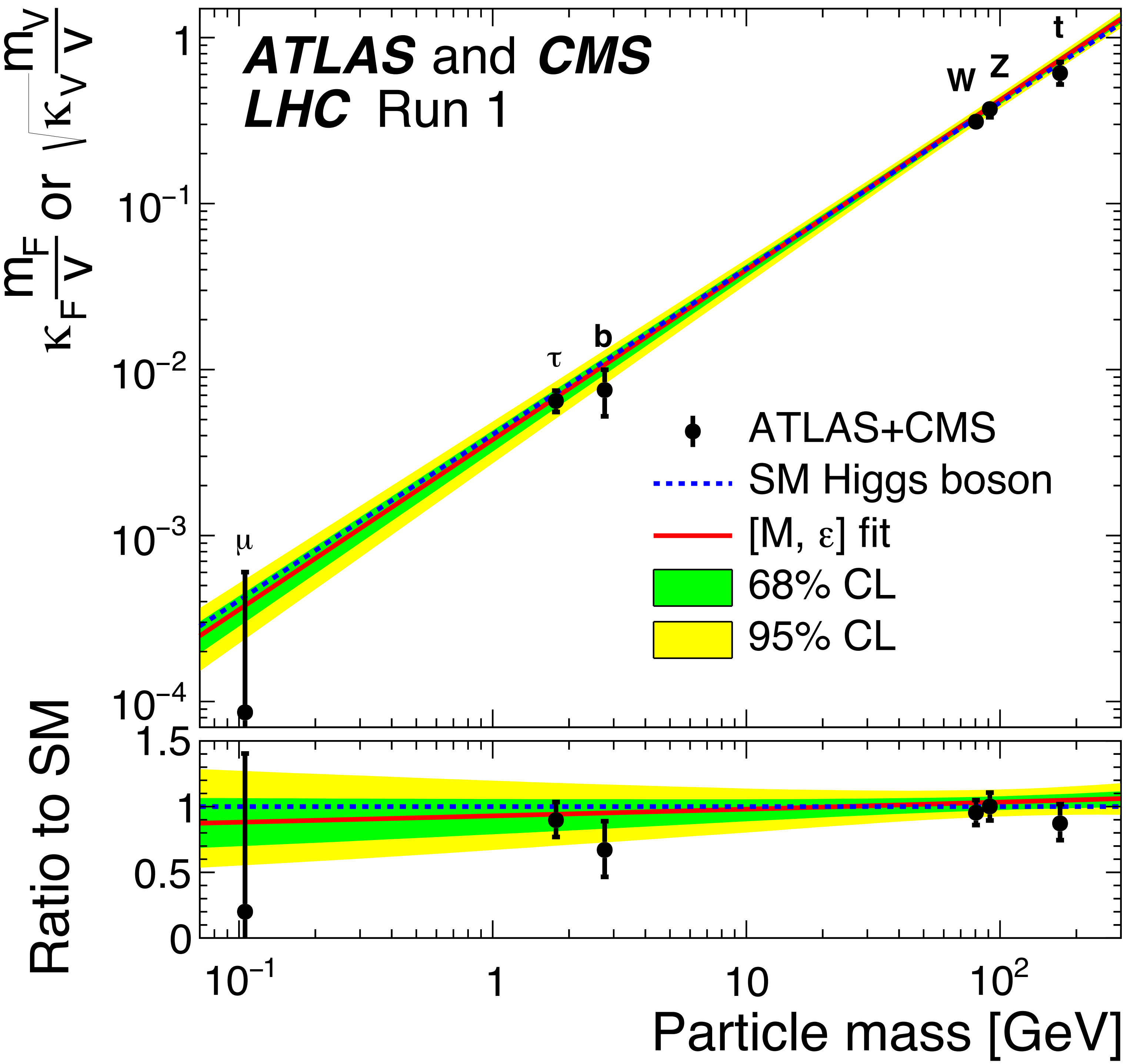
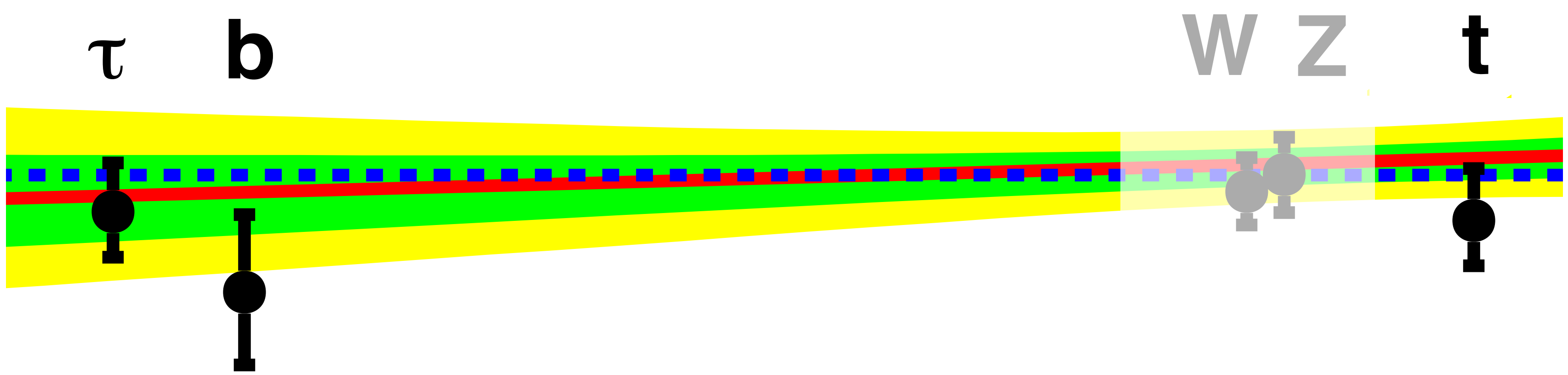
Les XXXI Rencontres de Physique de la Vallée d'Aoste,
La Thuile, 25th of February to 3rd of March 2018

Status of Higgs couplings

ATLAS & CMS, 1606.02266



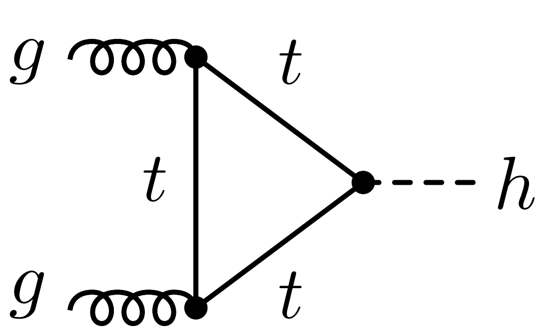
What do we know?

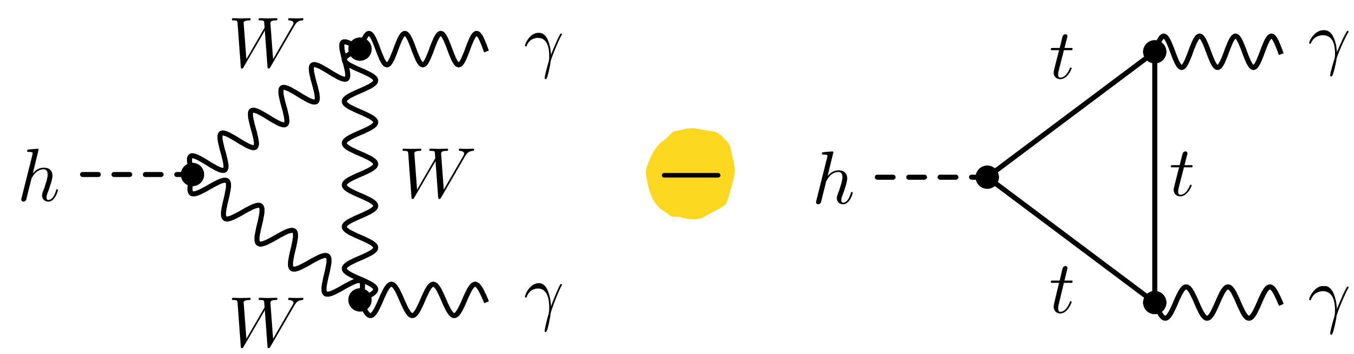


$$\mathcal{L}_{\rm SM} \supset (D_\mu H)^\dagger (D^\mu H) - \left(Y_f \bar{f}_L H f_R + \text{h.c.}\right) - V(H)$$

Yukawa interactions: top? gg→h, h→γγ ≡ indirect
bottom? Higgs decays ≡ indirect
tau? observed ≡ knowledge
1st & 2nd generation ≡ ignorance

Indirect probes of top Yukawa



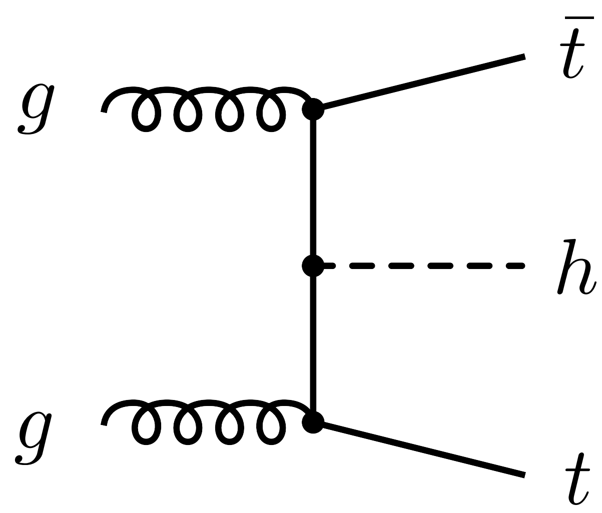


$$\frac{\sigma(pp \to h)}{\sigma(pp \to h)_{\mathrm{SM}}} \approx \kappa_t^2$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\mathrm{SM}}} \approx (1.3\kappa_W - 0.3\kappa_t)^2$$

In LHC analyses of Higgs properties, sensitivity to modifications $\kappa_t = y_t/y_t^{\mathrm{SM}}$ of top Yukawa arise indirectly from loop processes

Direct probe of top Yukawa

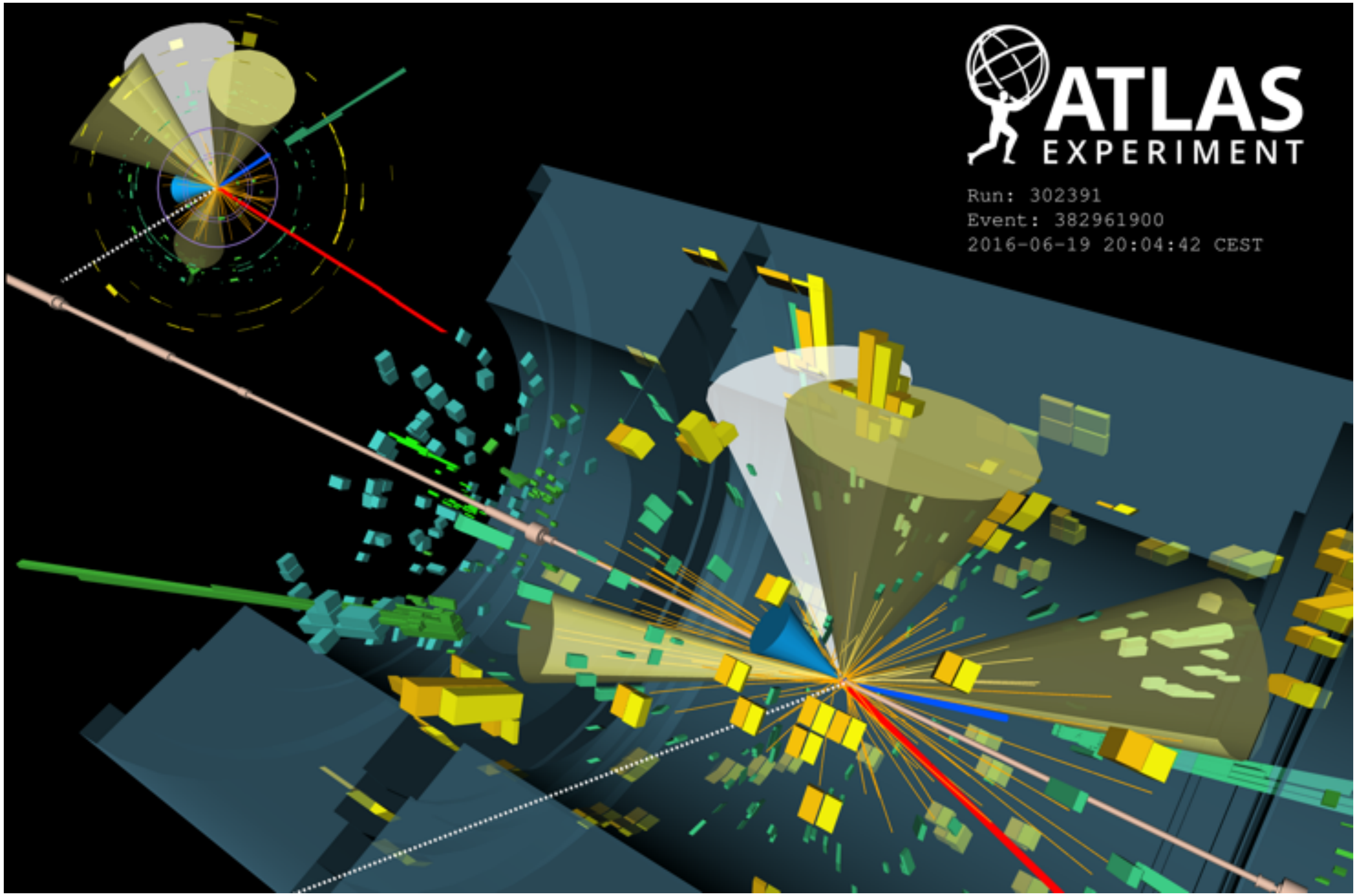


$$\frac{\sigma(pp \to t\bar{t}h)}{\sigma(pp \to t\bar{t}h)_{\rm SM}} \approx \kappa_t^2$$

Tree-level production of Higgs in association with top pairs provides direct excess to top Yukawa. Latest Run II searches by ATLAS & CMS see evidence for this production mode

ATLAS, 1712.08891, 1712.08895; CMS-PAS-HIG-17-003; CMS-PAS-HIG-16-038

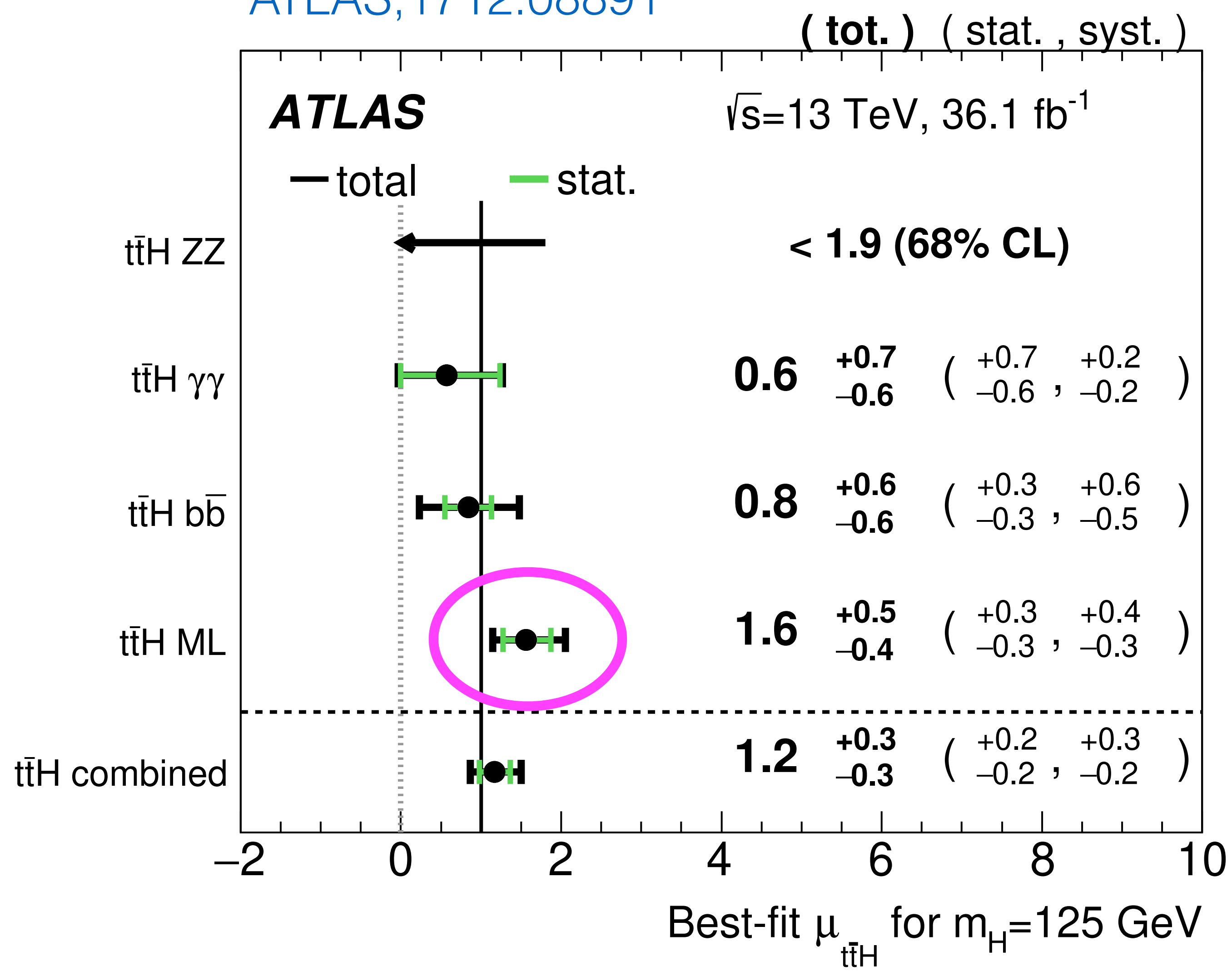
In reality things are more tricky …



ATLAS event display showing a candidate $e\mu\tau_{had}$ event in $2l1\tau_{had}$ category of $t\bar{t}h$ search

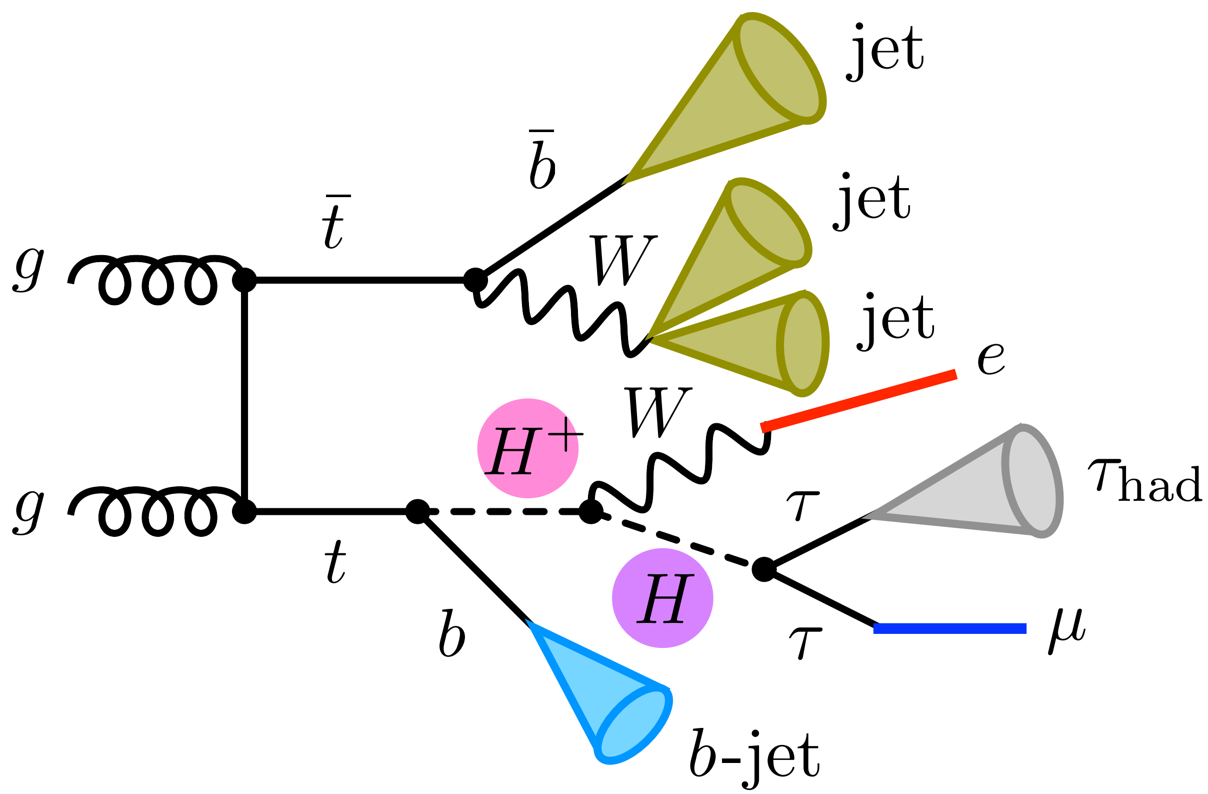
Direct probe of top Yukawa

ATLAS,1712.08891



Combined ATLAS $t\bar{t}h$ signal strength slightly above SM driven by small excess in multilepton channel. Hint of enhanced y_t?

Could mean $\kappa_t > 1$, but …



$$M_H = 95\,\text{GeV}\,,$$
$$M_{H^+} = 125\,\text{GeV}\,,$$
$$\tan\beta = 5.5\,,$$
$$\cos(\beta-\alpha) = 0.32$$

multilepton excess can be nicely explained in fermiophobic type-I two-Higgs doublet model. Model consistent with SM Higgs fit & can simultaneously address other small deviations in Higgs sector at CMS (diphoton), LEP (Zh) & Tevatron ($t\bar{t}h$)

Alves et al., 1703.06834; Fox & Weiner, 1710.07649; UH & Malinauskas, 1712.06599

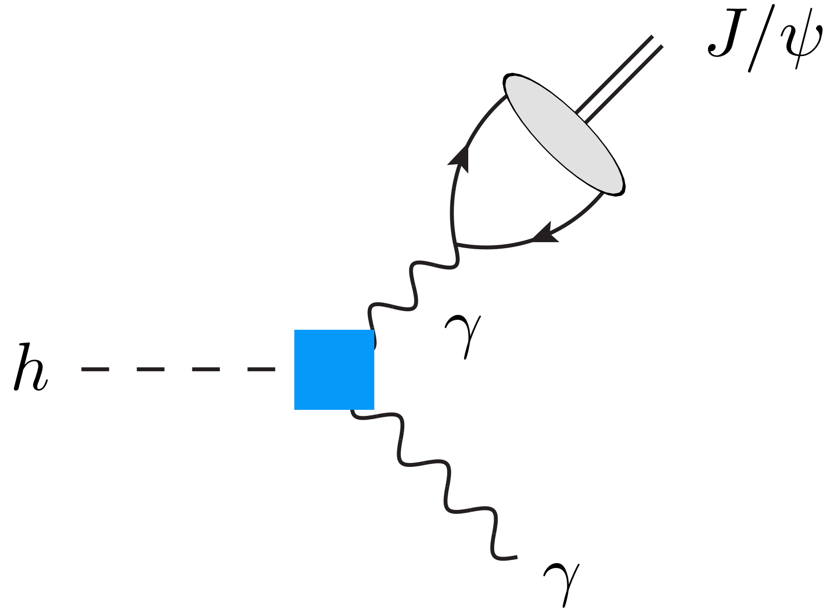
In the remainder of this talk …

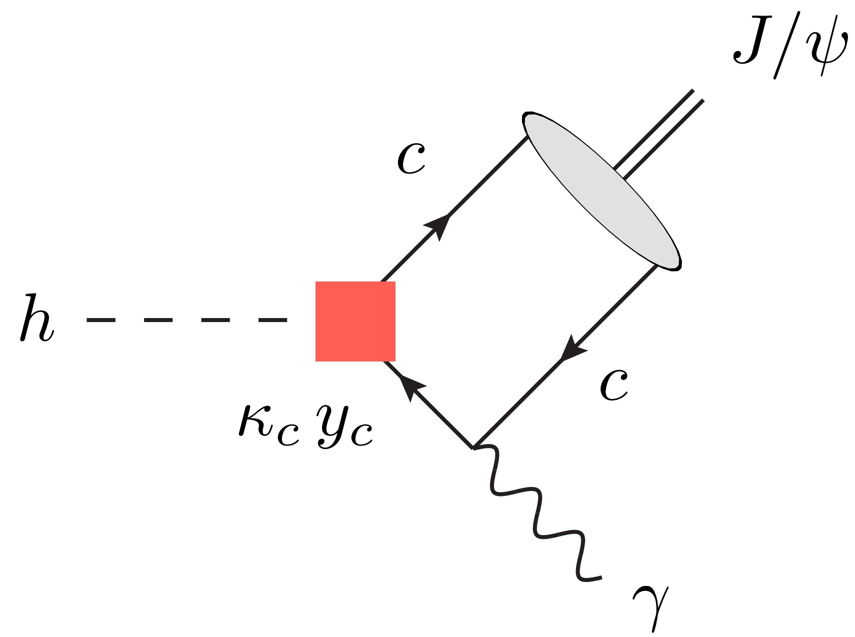
I will discuss direct & indirect methods to extract information on the charm Yukawa coupling y_c at the LHC — some comments about other quark & lepton Yukawas including CP-violating & flavour-changing ones can be found in the backup

LHC probes of charm Yukawa

- Exclusive $h \to J/\psi\gamma$ decay — Bodwin et al., 1306.5770 & 1407.6695; König & Neubert, 1505.03870
- Vh production & $pp \to hc$ — Perez, et al., 1503.00290 & 1505.06689; Brivio et al., 1507.02916; LHCb-CONF-2016-006; ATLAS, 1802.04329
- Higgs distributions — Bishara, UH, Monni & Re, 1606.09253; Soreq, Zhu & Zupan, 1606.09621
- $W^{\pm}h$ charge asymmetry — Yu, 1609.06592
- Radiative $h \to c\bar{c}\gamma$ decay — Han & Wang, 1704.00790

Exclusive Higgs decays: h→J/ψγ





$$\mathrm{Br}\,(h \to J/\psi\gamma) = 2.95 \cdot 10^{-6}\ (1.07 - 0.07\,\kappa_c)^2$$

Bodwin et al., 1306.5770 & 1407.6695; König & Neubert, 1505.03870

Exclusive Higgs decays: h→J/ψγ

Current bound:

$$\mathrm{Br}\,(h \to J/\psi\gamma) < 1.5 \cdot 10^{-3}$$

ATLAS, 1501.03276; CMS, 1507.03031

$$\longrightarrow \quad |\kappa_c| < 429$$

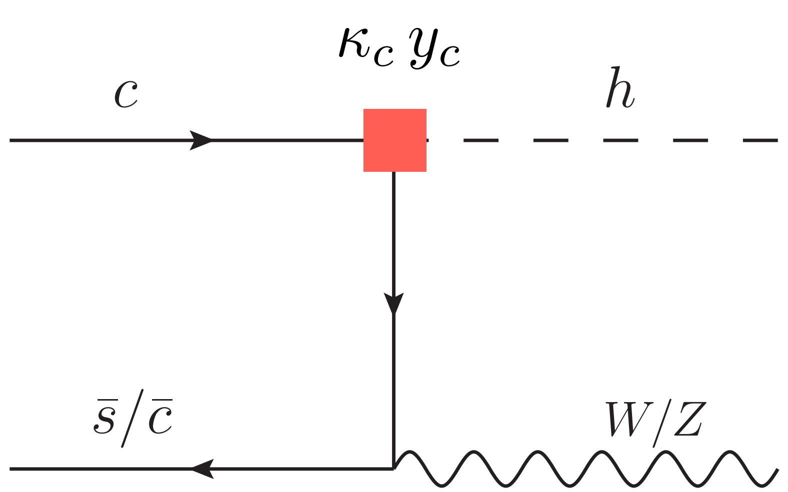
20% measurement:

$$\mathrm{Br}\,(h \to J/\psi\gamma) = 2.95\,(1 \pm 0.2) \cdot 10^{-6}$$

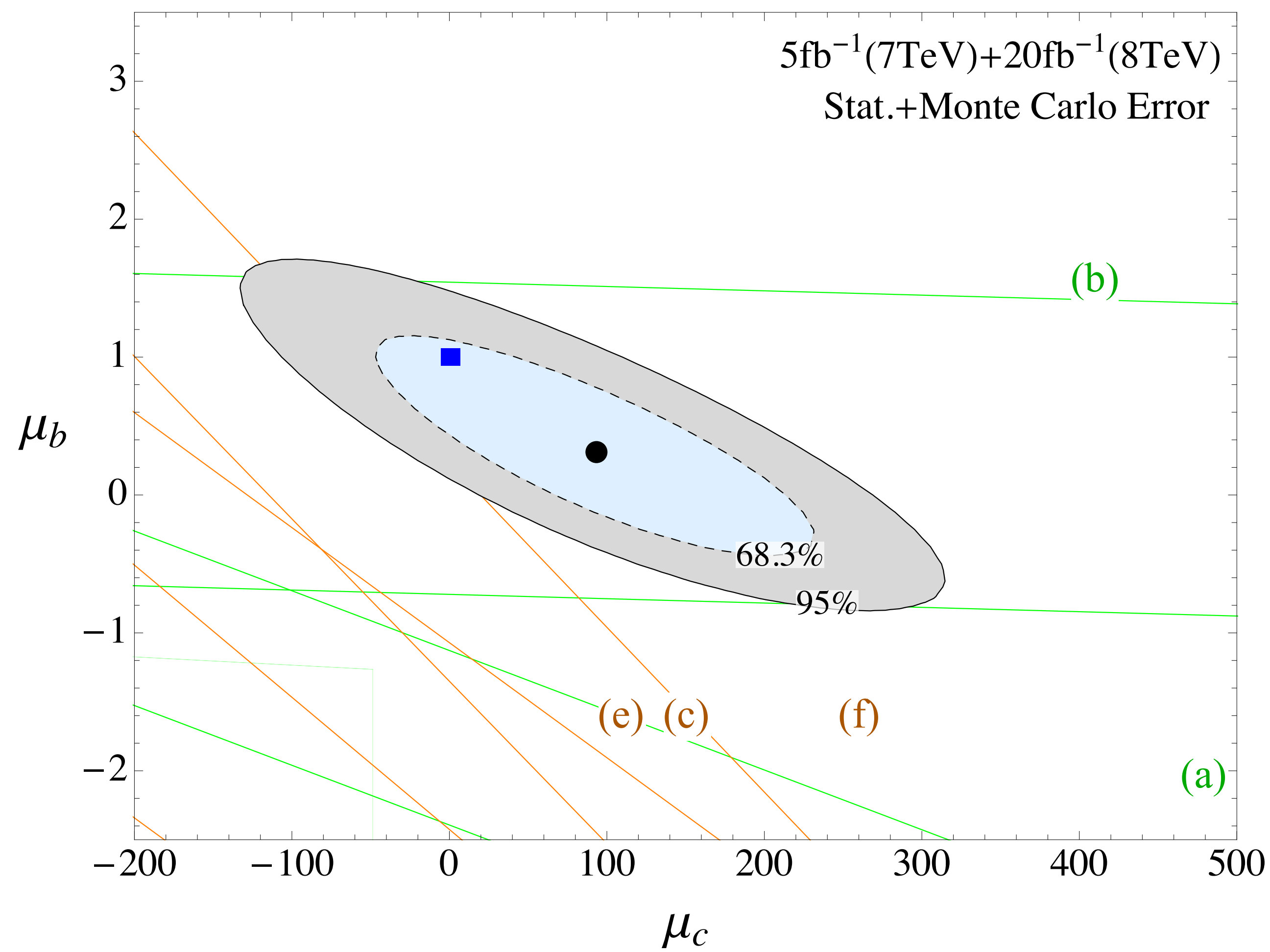
$$\longrightarrow \quad \kappa_c \in [-0.51, 3.07]$$

König & Neubert, 1505.03870

Vh production & flavour tagging

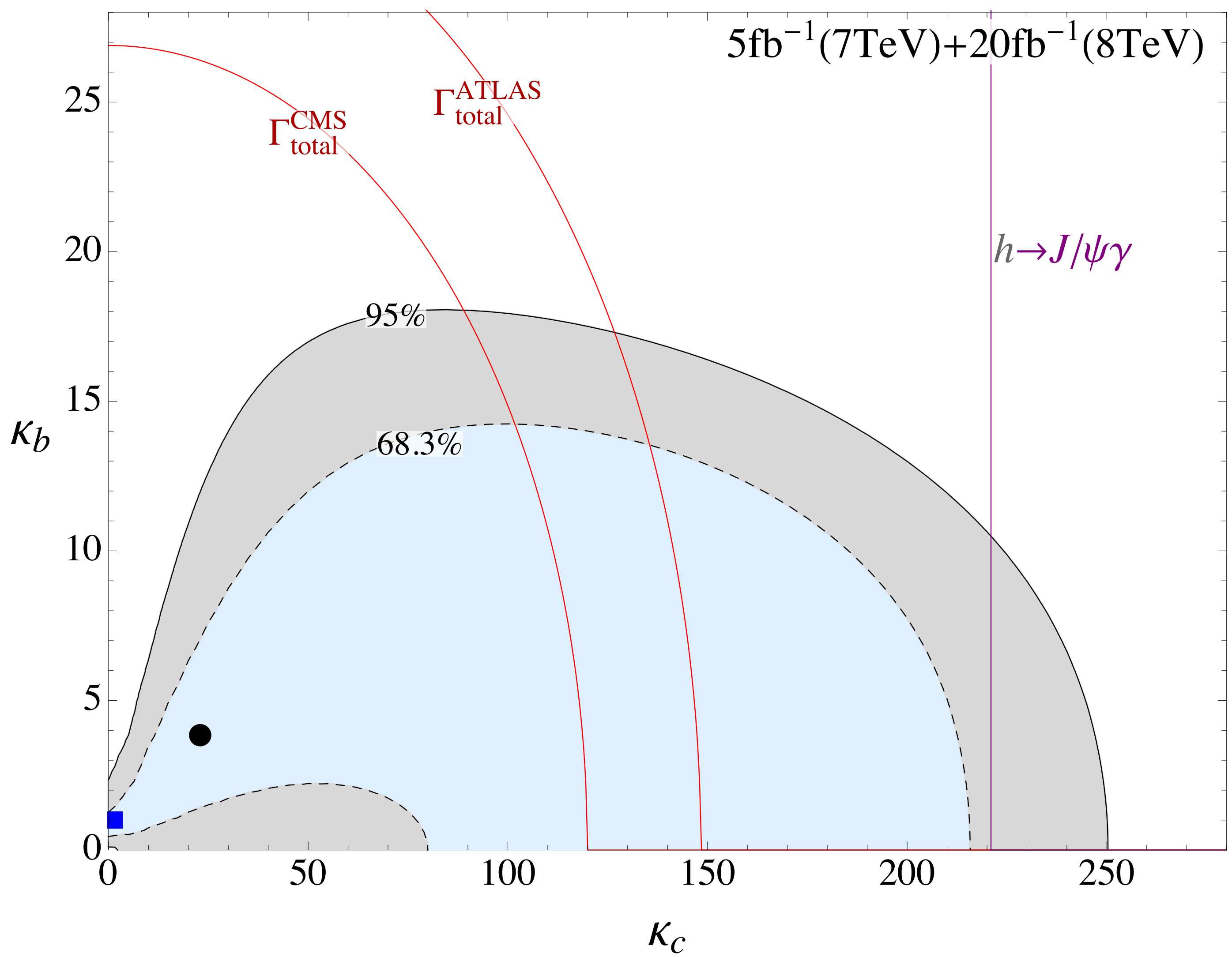


Perez, Soreq, Stamou & Tobioka, 1503.00290



Using several b-tagging algorithms (with different c-jet mis-tagging) one can recast $h\to b\bar{b}$ analyses to constrain $h\to c\bar{c}$ rate

Vh production & flavour tagging

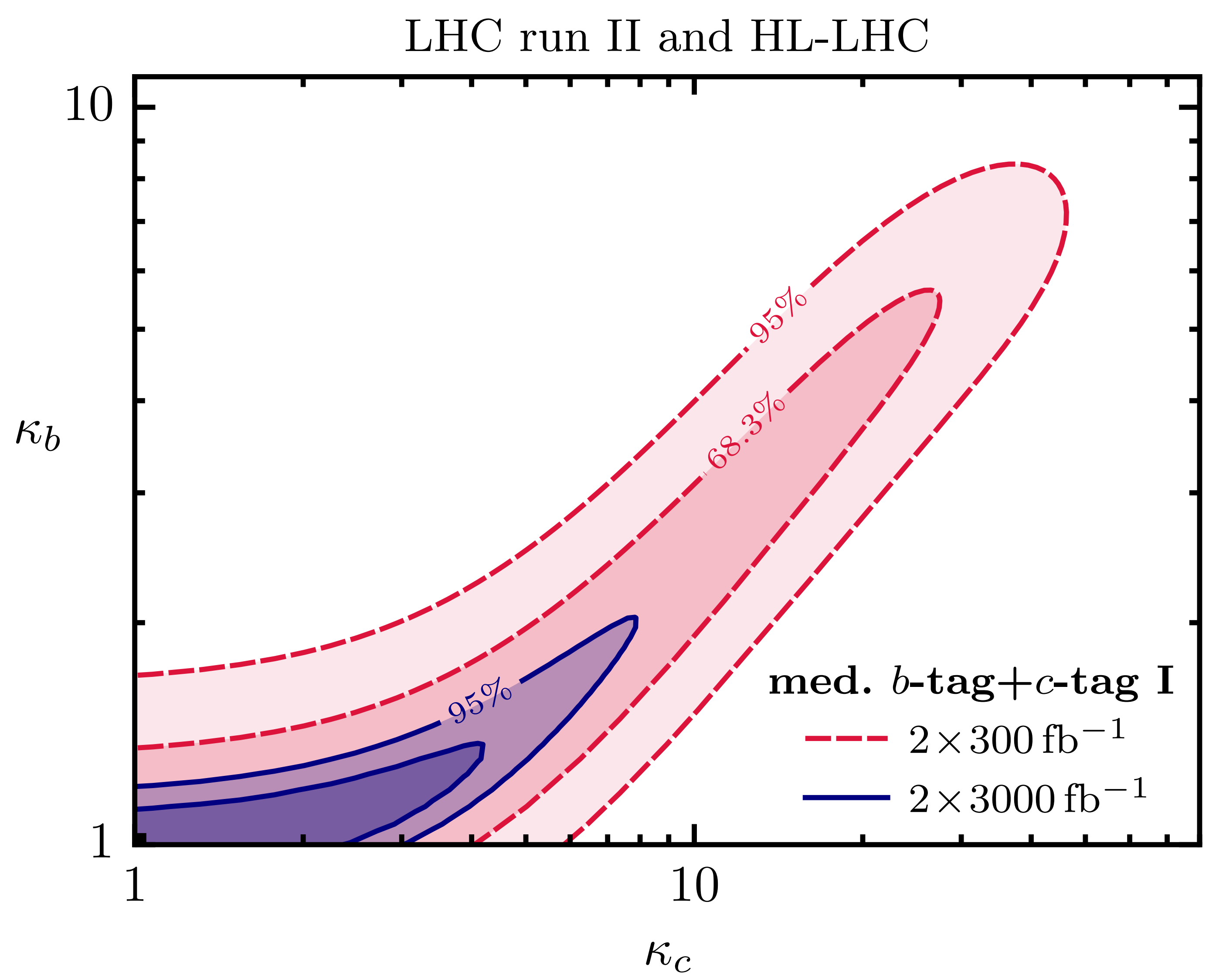


$\longrightarrow$ $\kappa_c \lesssim 234$

(LHC Run I)

Perez, Soreq, Stamou & Tobioka, 1503.00290

Vh production & flavour tagging



$\kappa_c < 38$

(LHC Run II)

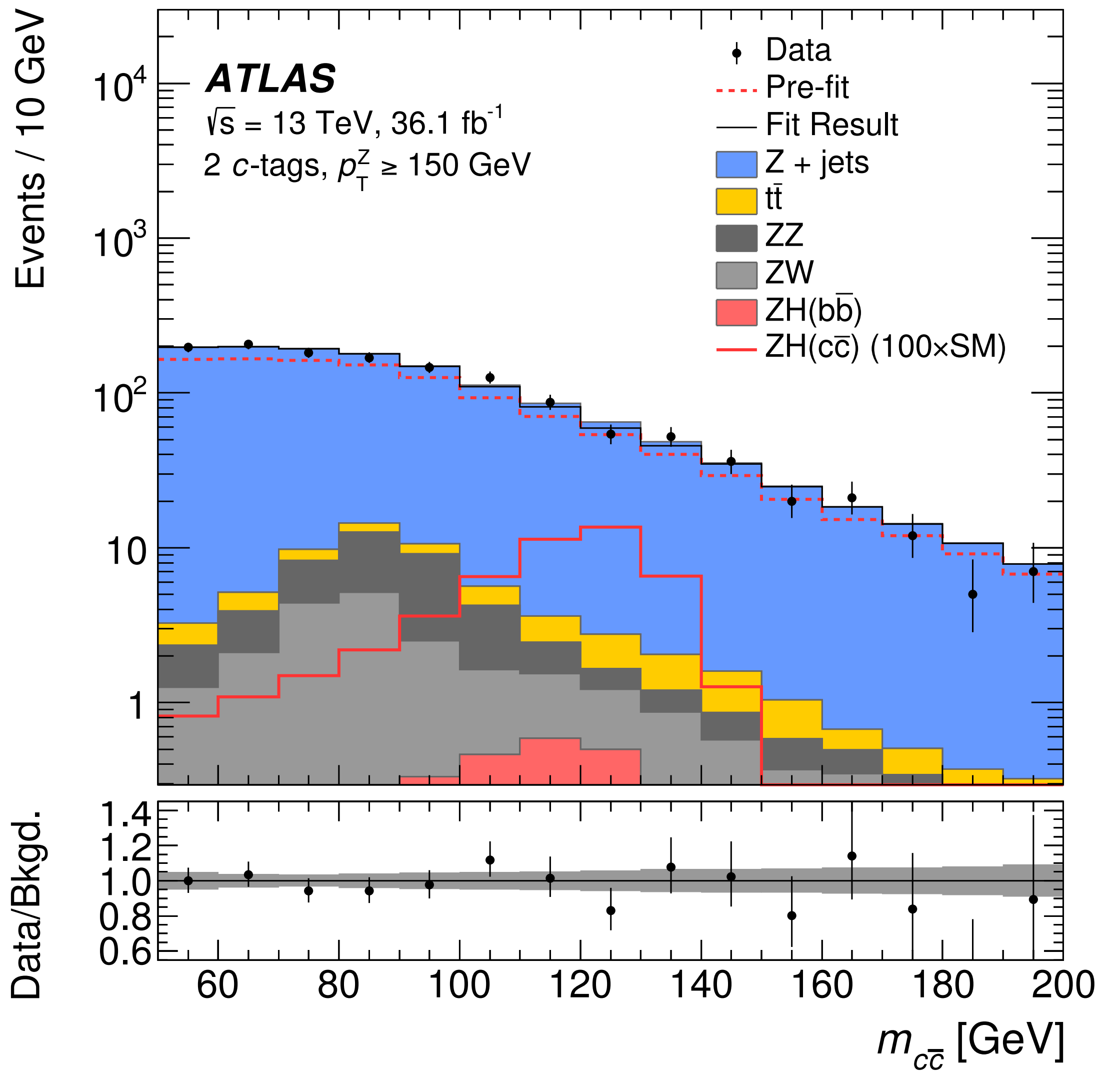
$\kappa_c < 5.6$

(HL-LHC)

Perez, Soreq, Stamou & Tobioka, 1505.06689

ATLAS search for pp→Zh→l⁺l⁻c$\bar{c}$

ATLAS, 1802.04329



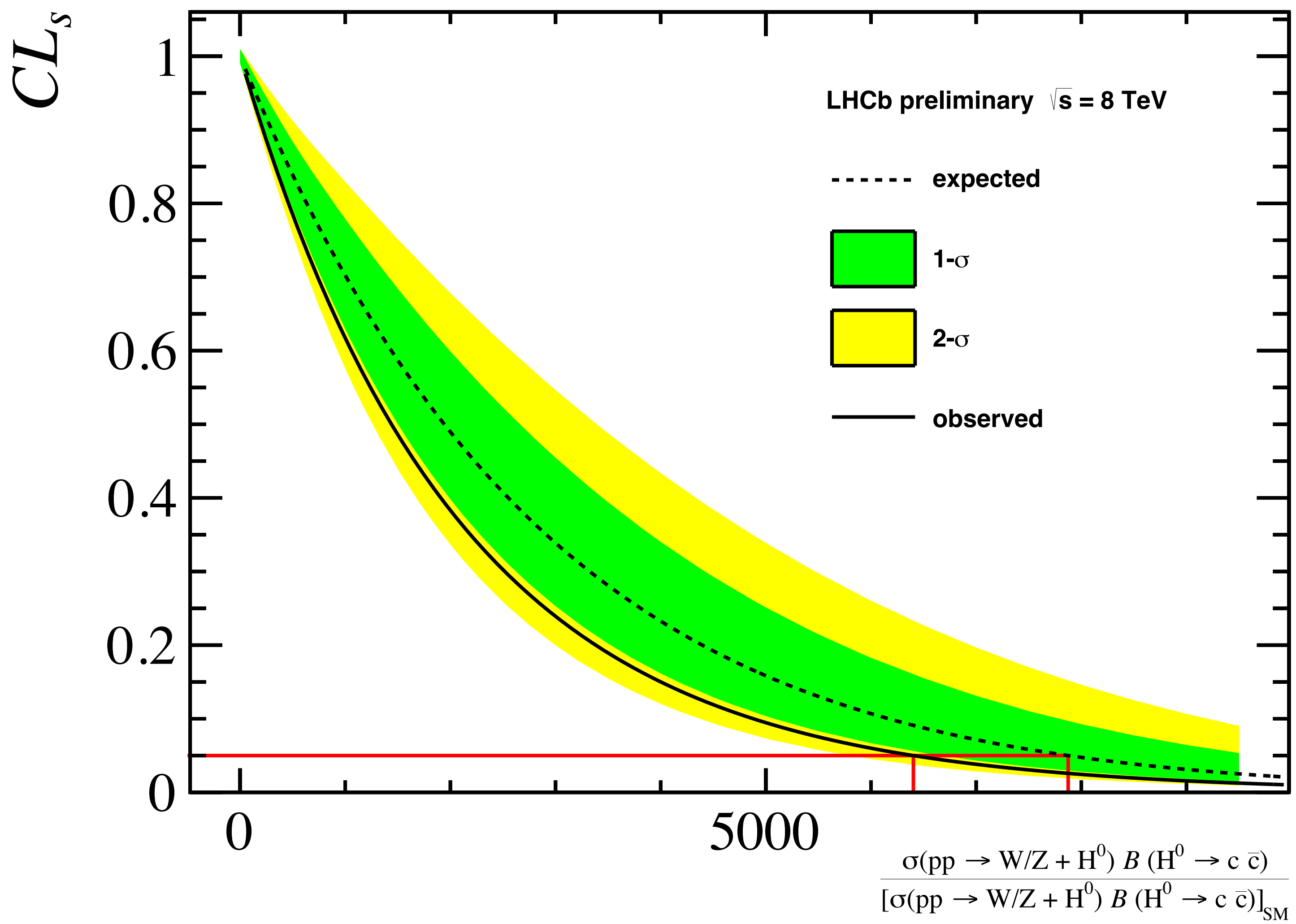
→ $|\kappa_c| \lesssim 11$

ATLAS sets 95% CL limit on σ(pp→Zh) BR(h→c$\bar{c}$) of 2.7 pb.

Bound largely independent of assumed Zh(b$\bar{b}$) background

Vh production at LHCb

LHCb-CONF-2016-006



$\longrightarrow \quad |\kappa_c| \lesssim 80$

Given its good b/c-tagging capabilities LHCb able to bound pp→Vh→Vc$\bar{c}$ cross section despite lower acceptance

LHCb, 1504.07670

acc(Vbb) = 4.9%, acc(Vcc) = 4.6%

A simple observation

ATLAS & CMS, 1606.02266

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{\mathrm{BSM}} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

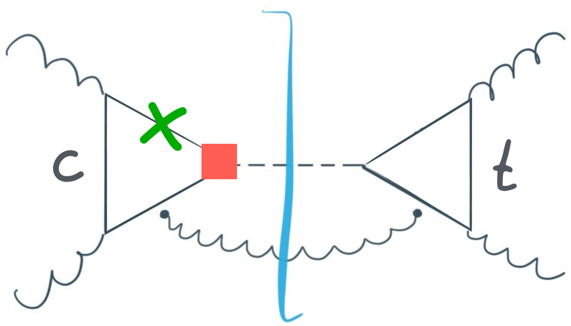
$$- 0.07 \cdot \kappa_t\kappa_b$$

A simple observation

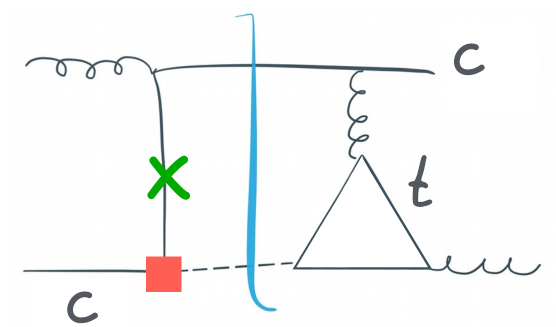
- In the SM, the interference between top & bottom loops does not only change the total Higgs production cross section but also distributions in $pp \to hj$, e.g. $p_{T,h}$, y_h, $p_{T,j}$, …
- Potential to constrain Yukawa modifications $\kappa_c = y_c/y_c^{SM}$ from measurements of shapes of distributions at moderate $p_{T,h}$
- At HL-LHC with $3\,ab^{-1}$, low-$p_{T,h}$ measurements are not statistics limited. Future bounds on κ_c from Higgs spectra thus depend sensitively on size of systematic & theory uncertainties

Bishara, UH, Monni & Re, 1606.09253

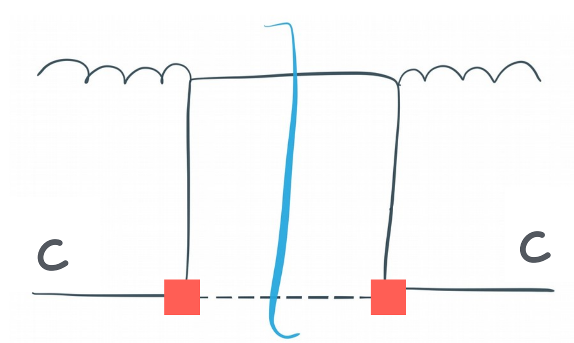
Charm contributions to pp→hj



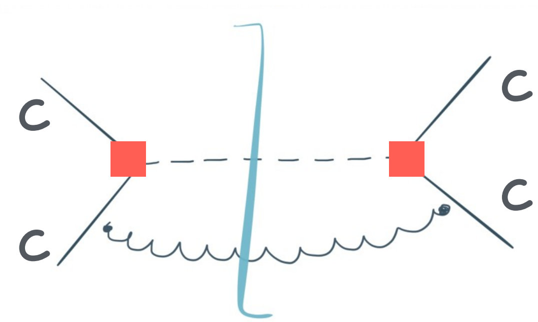
$$\sim \alpha_s^3\, y_c\, m_c \ln^2\left(\frac{p_T^2}{m_c^2}\right)$$



$$\sim \alpha_s \alpha_s^2\, y_c\, m_c \qquad (= 0 \text{ in 4, 5 flavour scheme})$$



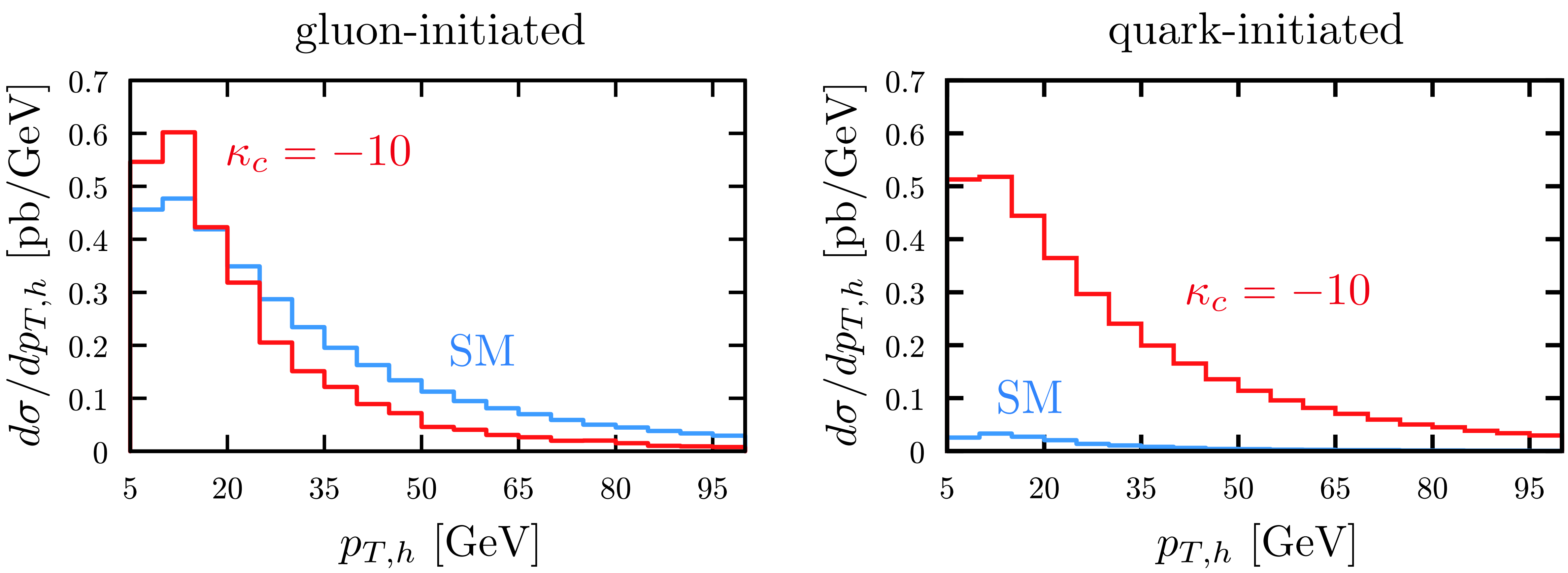
$$\sim \alpha_s \alpha_s\, y_c^2$$



$$\sim \alpha_s^2 \alpha_s\, y_c^2$$

- chirality flip (green)
- extra powers of α_s from charm PDF (blue)

Charm contributions to pp→hj

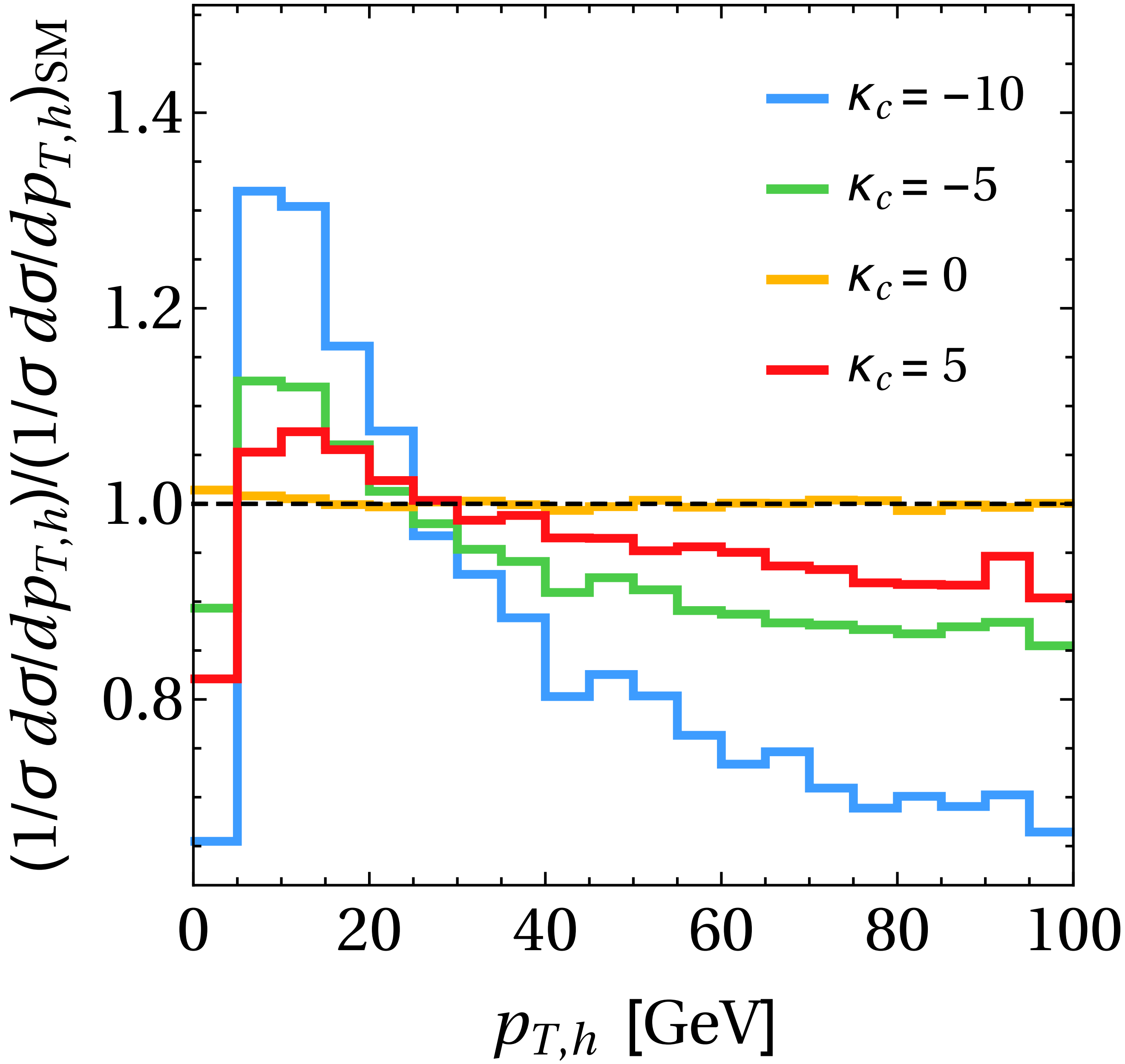


For $|\kappa_c| < O(10)$ gg-channel dominates, while for $|\kappa_c| > O(10)$ gq- & q$\bar{q}$-production become as relevant. For $y_{s,d,u}$, quark-channels dominate given LHC sensitivities of $|\kappa_{s,d,u}| \gg 10$

Bishara, UH, Monni & Re, 1606.09253; Soreq, Zhu & Zupan, 1606.09621

Normalised $p_{T,h}$ spectra

Bishara, UH, Monni & Re, 1606.09253

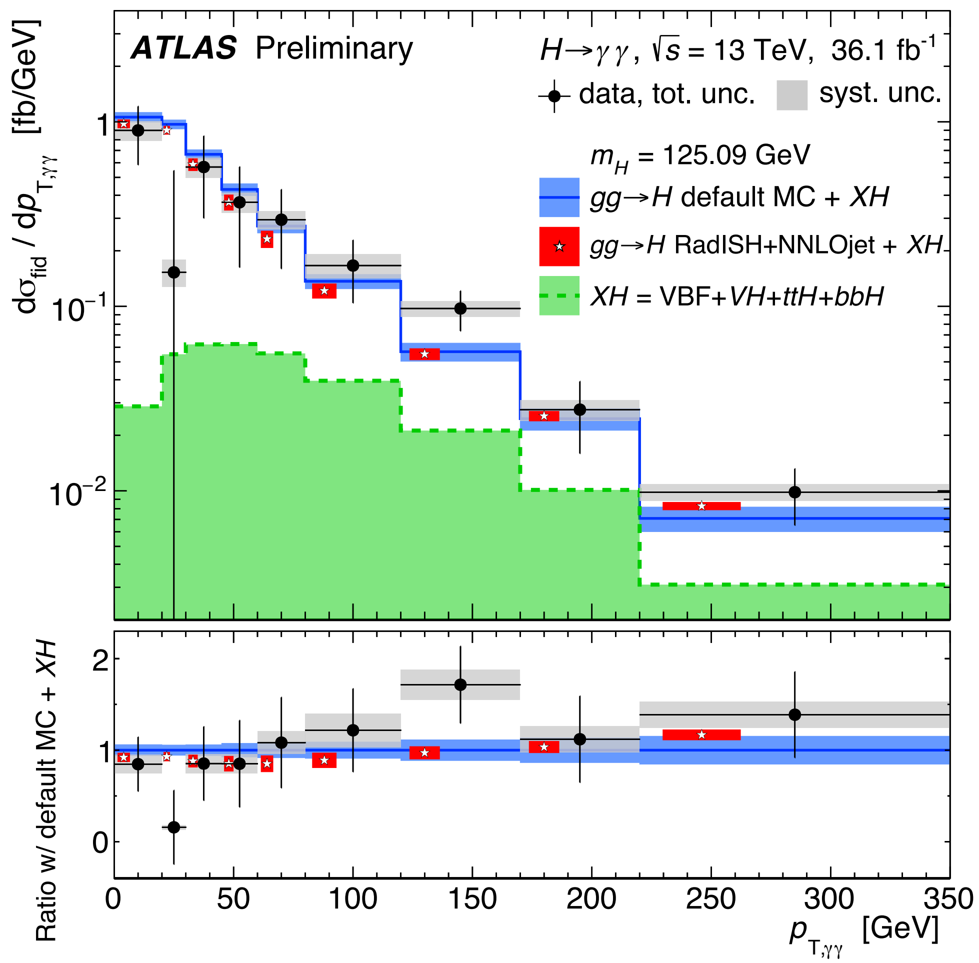


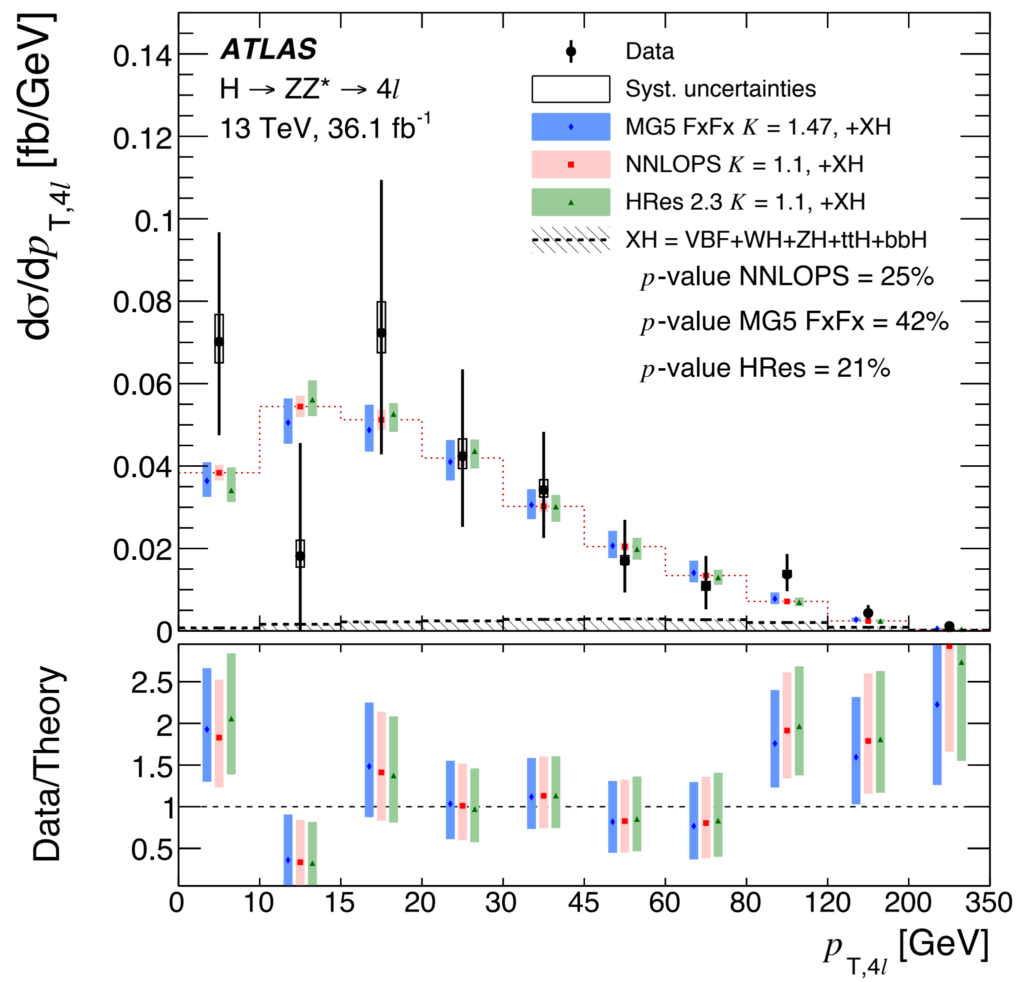
O(1) deviations in κ_c lead to few % effects in $p_{T,h}$ distribution

$p_{T,h}$ spectra at 13 TeV

ATLAS-CONF-2017-045

ATLAS, 1708.02810



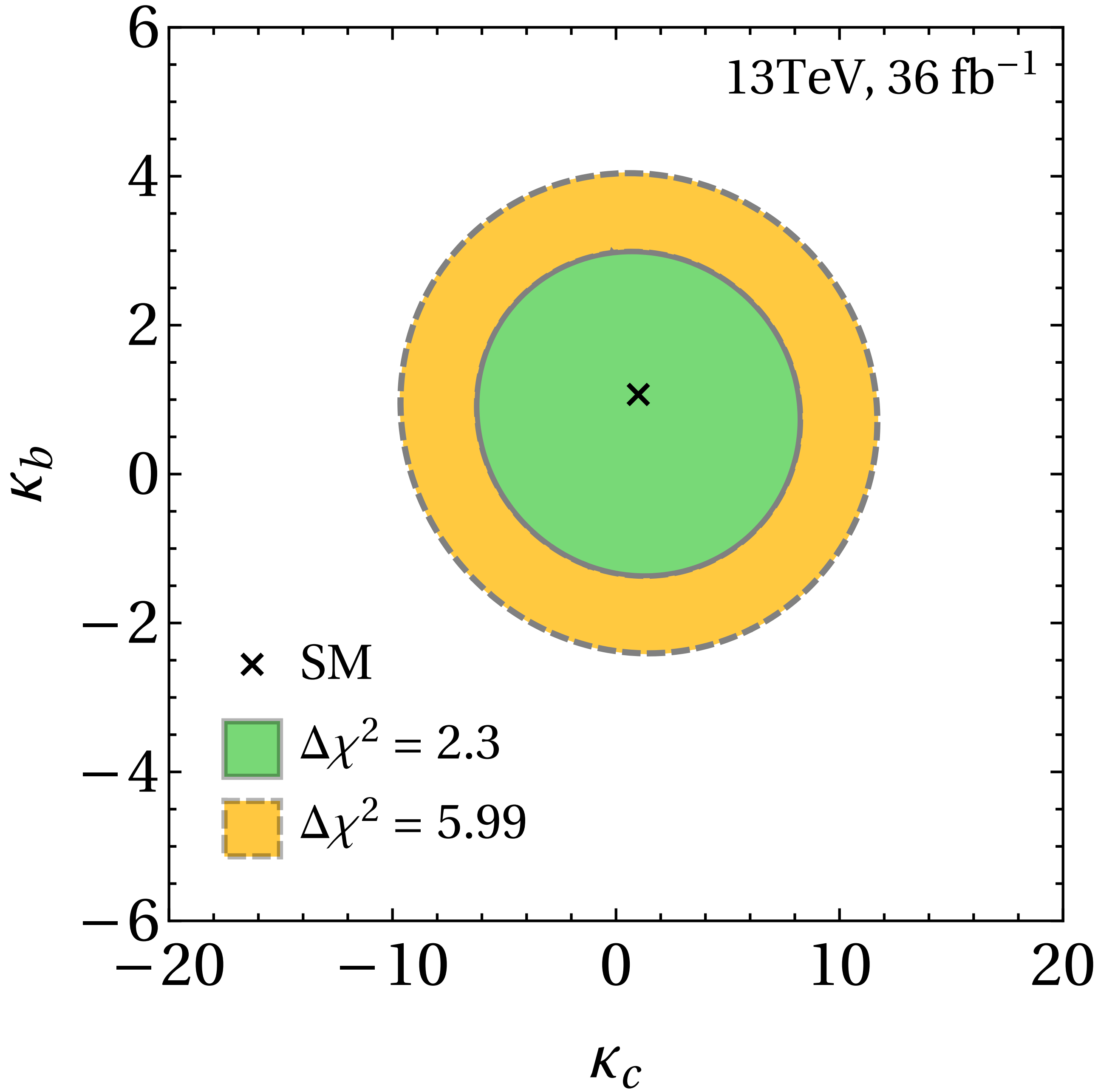


Improved statistics & better agreement with theory predictions compared to 8 TeV data, but no combination of channels yet

see also CMS-HIG-17-015; CMS, 1706.09936

Current $\kappa_{c,b}$ bounds from $p_{T,h}$

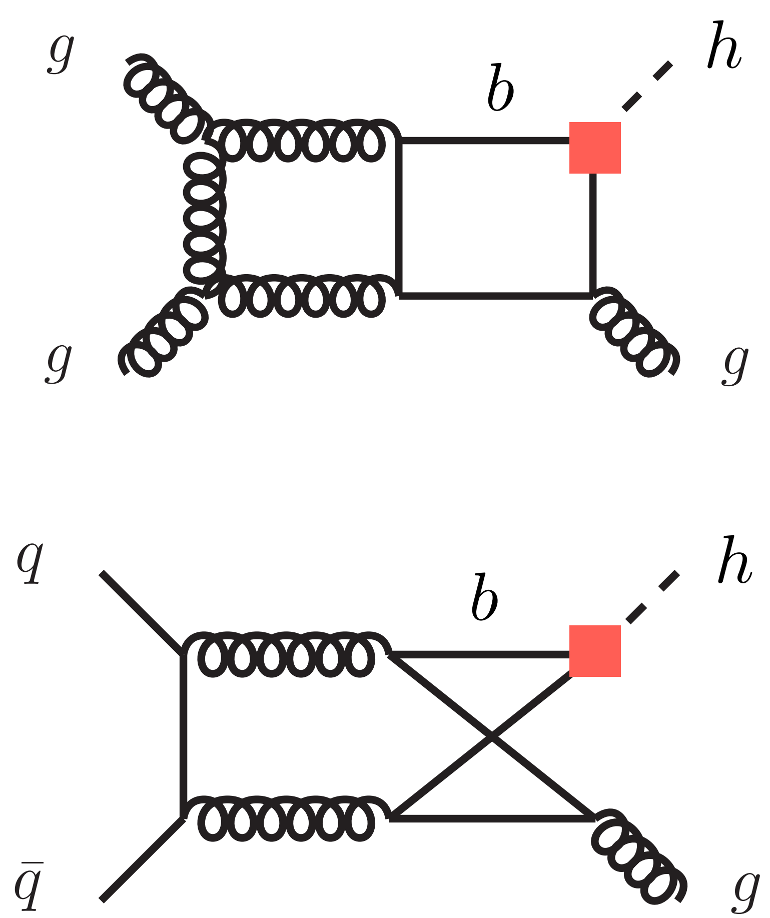
Bishara et al., update based on 1606.09253

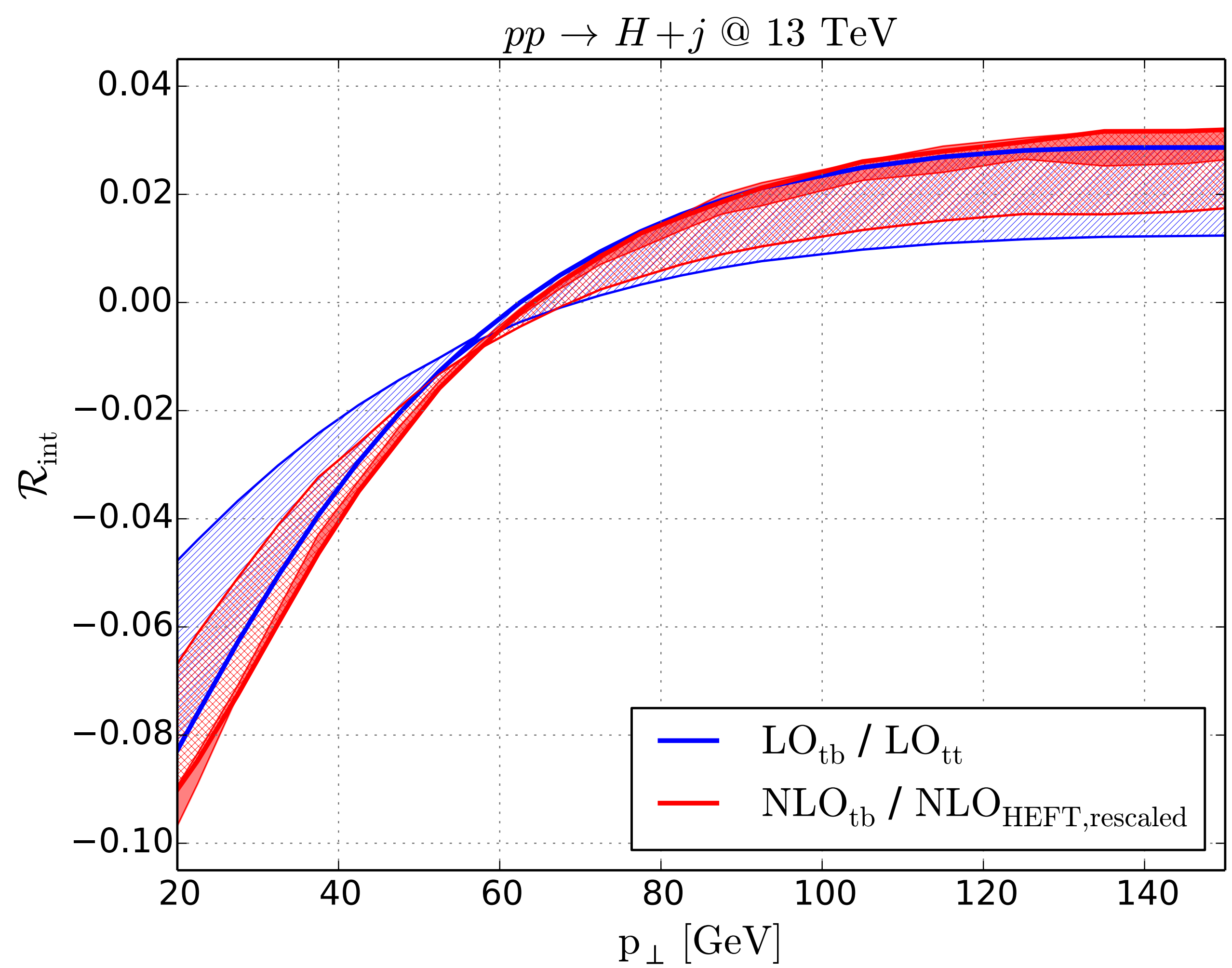


$\longrightarrow$ $\kappa_c \in [-7, 9]^\dagger$

† 95% CL bound at LHC Run I was $\kappa_c \in [-16, 18]$

Top-bottom interference at NLO

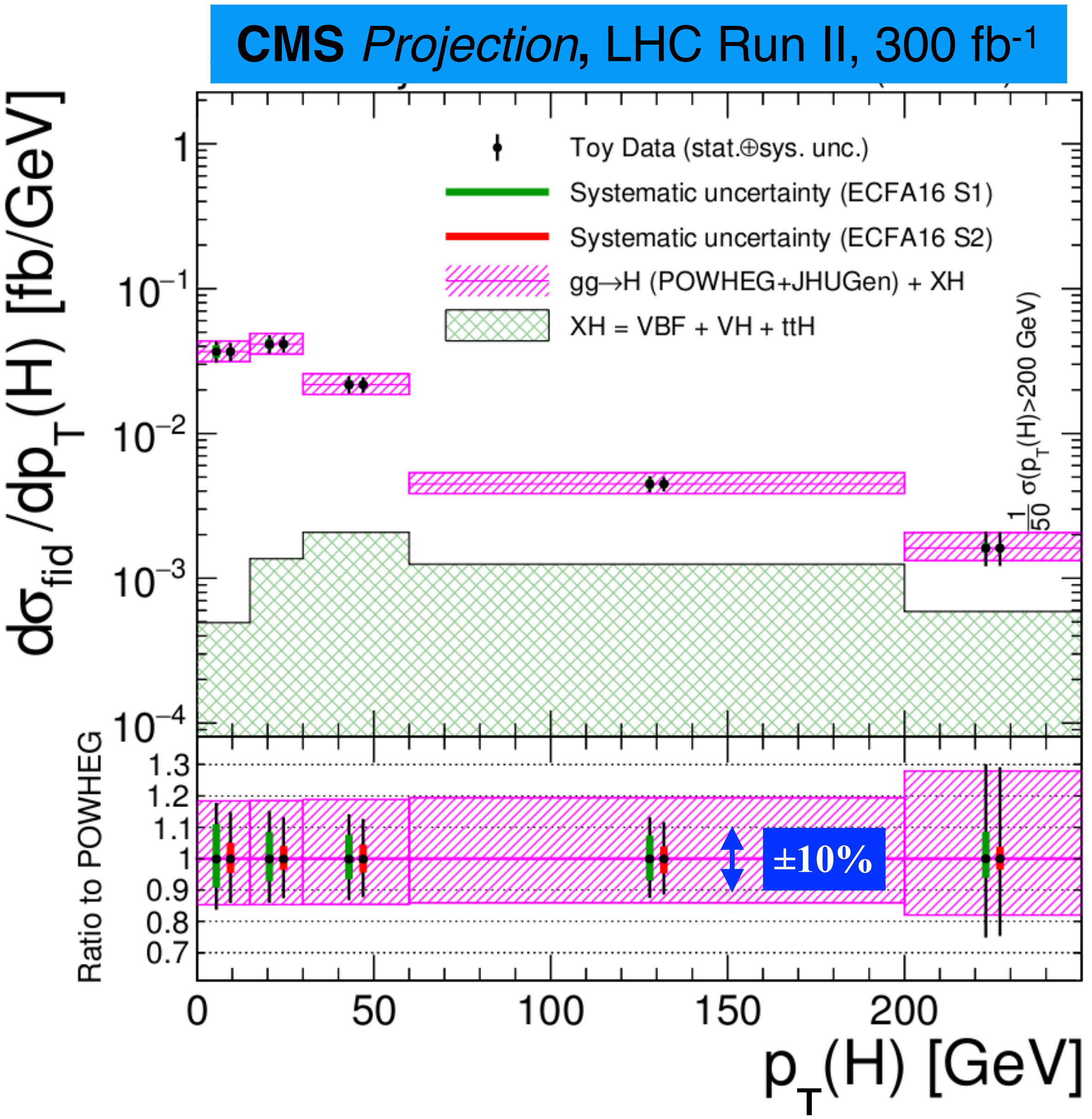


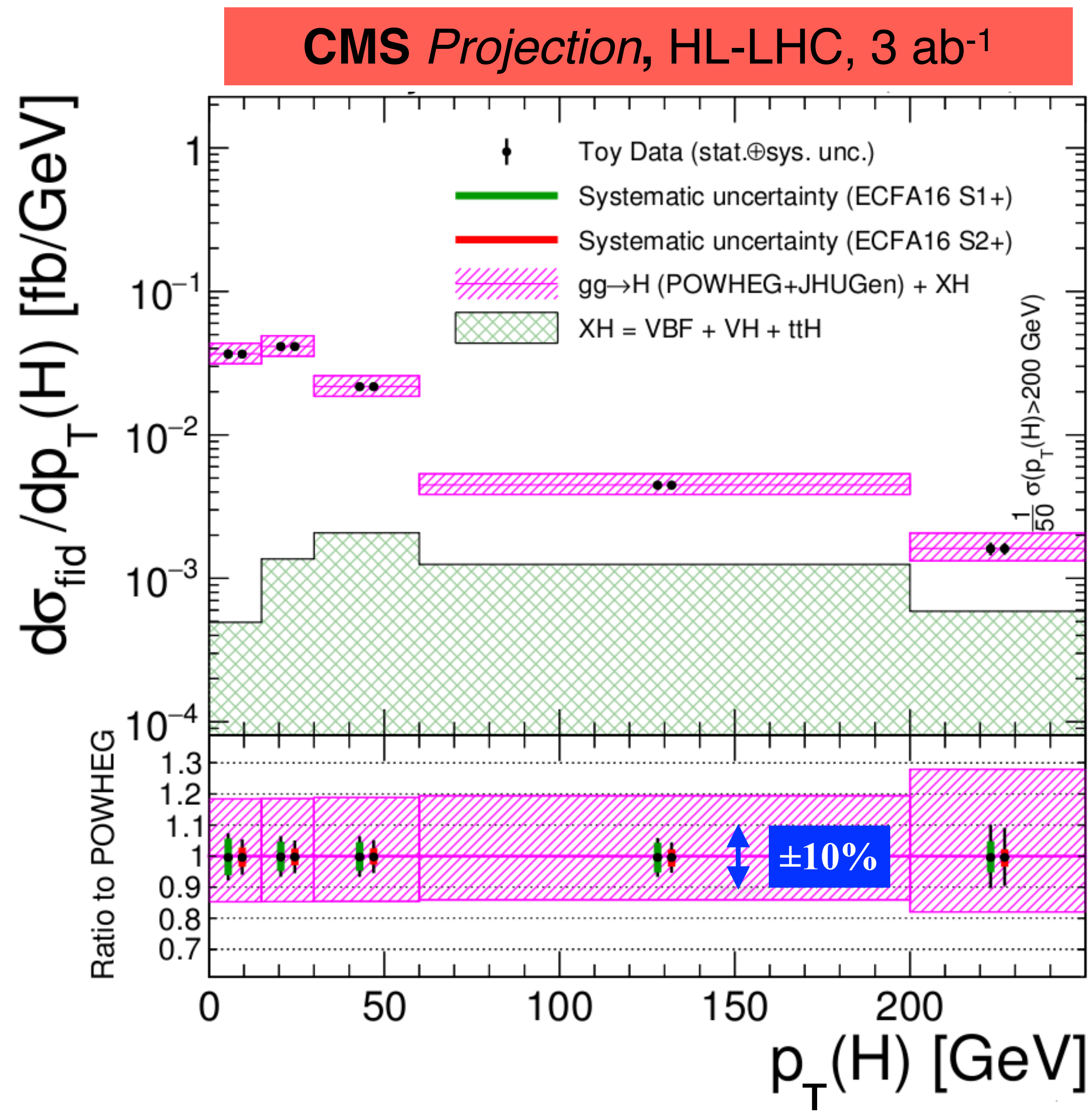


NLO corrections of O(50%) but closely track QCD effects to top-mediated contribution. For $p_{T,h}$ < 30 GeV inclusion of NLO effects lead to a O(2) reduction of scheme ambiguity related to m_b

Melnikov, Tancredi & Wever, 1610.03747; 1702.00426; Lindert, Melnikov, Tancredi & Wever, 1703.03886

$p_{T,h}$ spectra at future LHC runs

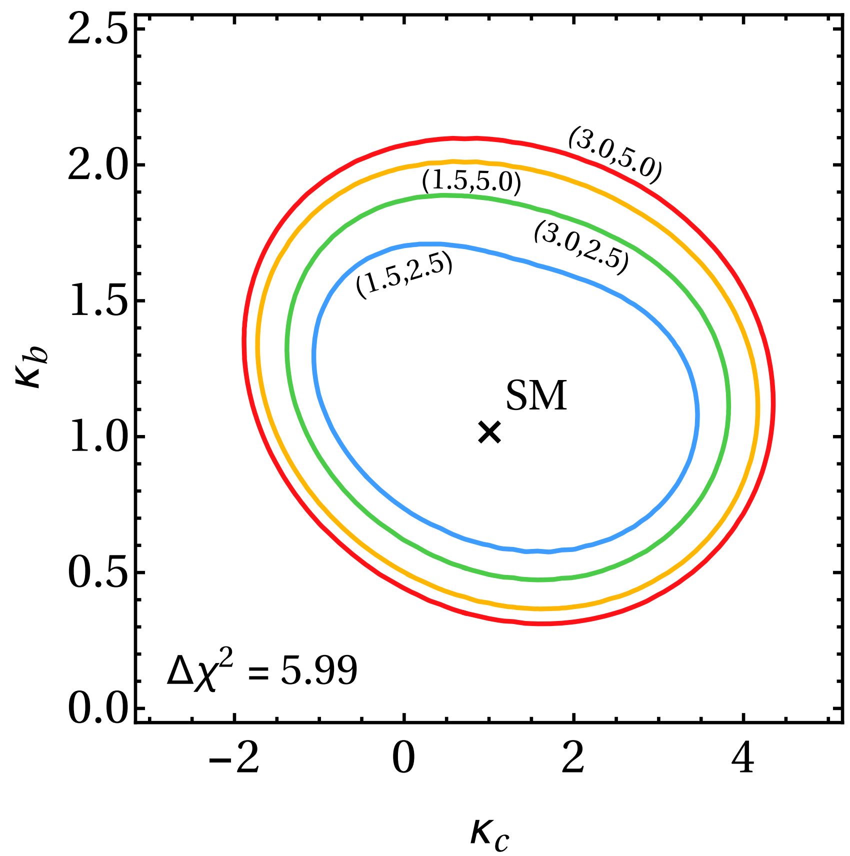




CMS-DP-2016-064

Systematic errors of a few % should be achievable at HL-LHC

$\kappa_{c,b}$ bounds: HL-LHC



	experimental [%]	theoretical [%]	$\kappa_c \in$
S_1	1.5	2.5	[-0.6, 3.0]
S_2	3.0	2.5	[-0.9, 3.3]
S_3	1.5	5.0	[-1.2, 3.6]
S_4	3.0	5.0	[-1.3, 3.7]

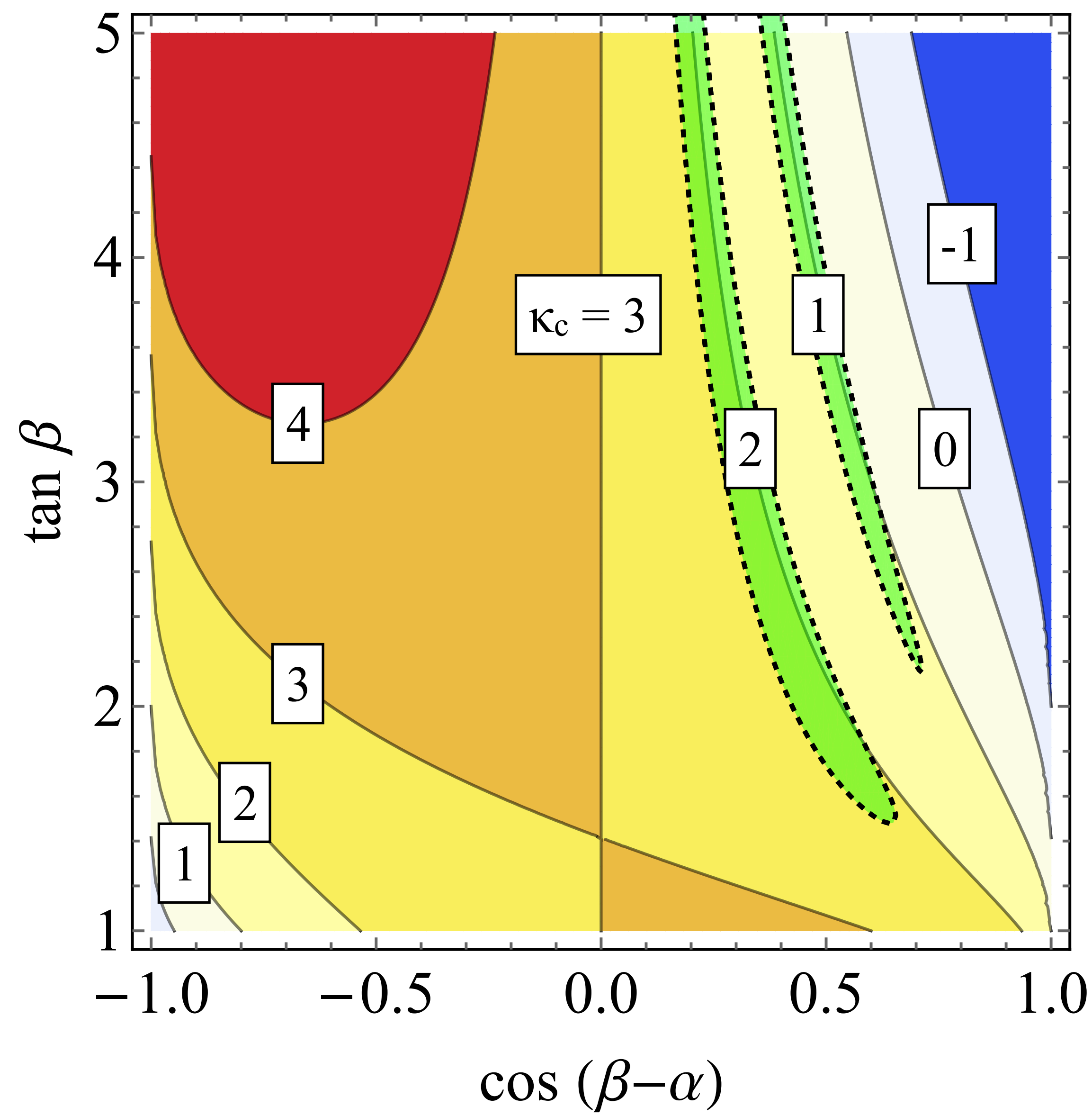
Under realistic assumptions about experimental & theoretical progress possible to probe $|\kappa_c| = O(\text{few})$ using $p_{T,h}$ spectrum

Bishara, UH, Monni & Re, supplemental material to 1606.09253

Models with Higgs-dependent y_c

$$\mathcal{L} \supset y^u_{ij} \left(\frac{H_u H_d}{\Lambda^2} \right)^{a_i - a_{u_j} - a_{H_u}} \bar{Q}_i H_u u_{Rj}$$

UH based on Bauer et al., 1506.01719



allowed by global fit to LHC Run I Higgs data

In models with Higgs-dependent Yukawa couplings, one can obtain O(few) modifications of y_c & while satisfying Higgs measurements

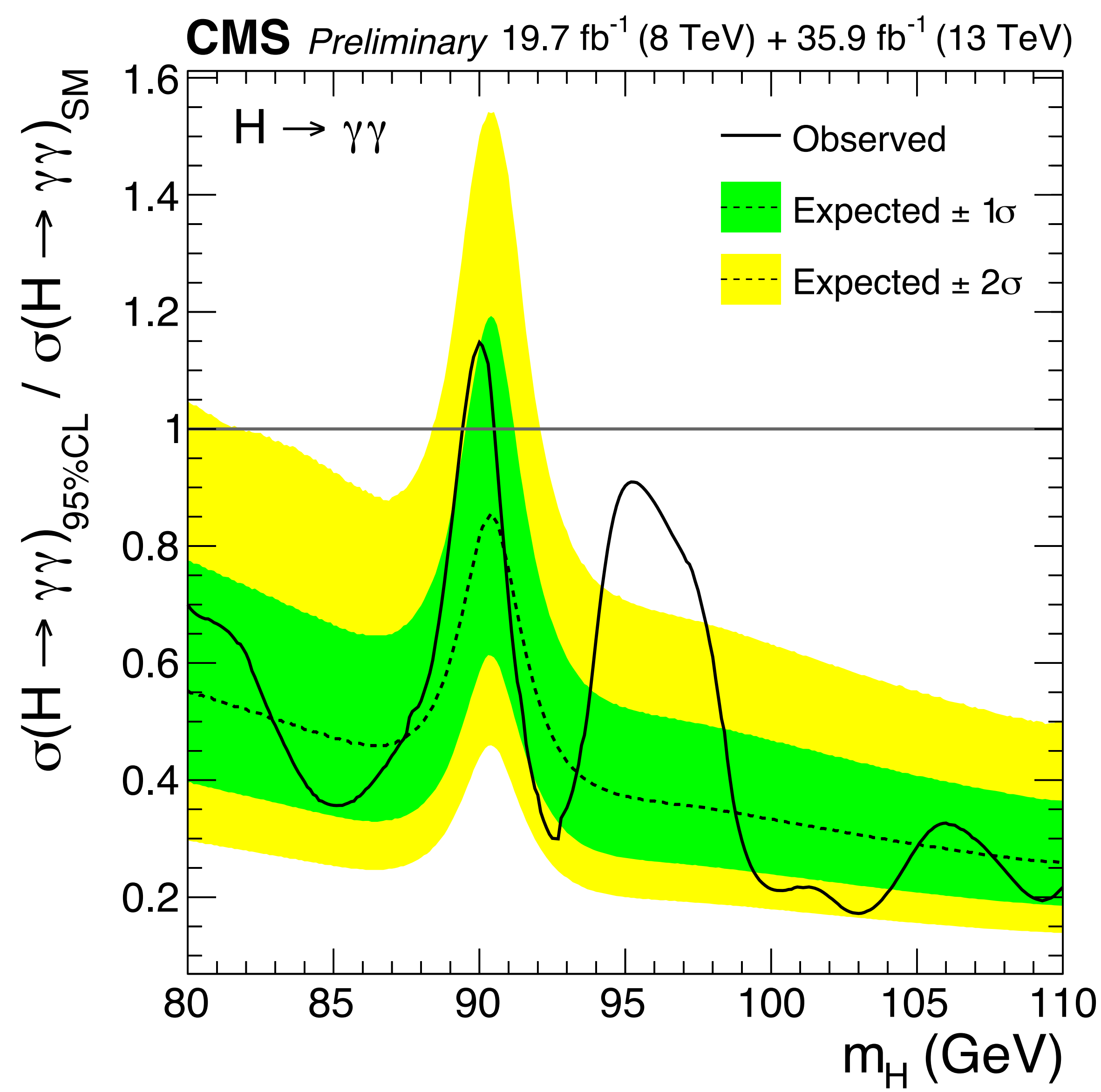
see e.g. Babu & Nandi, hep-ph/9907213; Giudice & Lebedev, 0804.1753

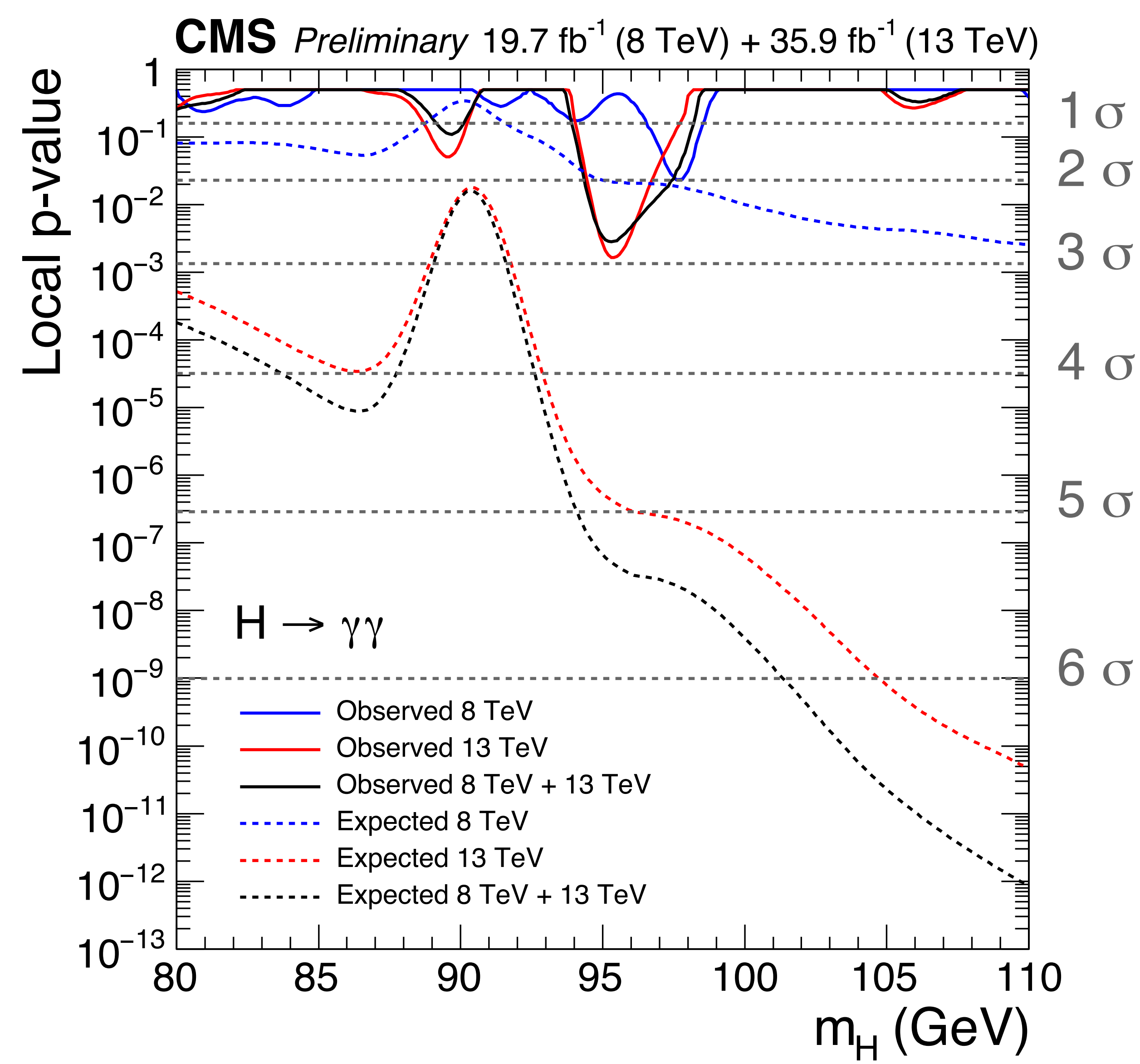
Conclusions

- In my opinion no hard separation between direct & indirect probes of Higgs Yukawa couplings. Even direct tests such as extractions of κ_t using $t\bar{t}h$ production depend on assumptions
- Sensitivity of LHC to charm Yukawa higher than anticipated. Complementary strategies exist that should be combined to tighten bounds on κ_c

Backup

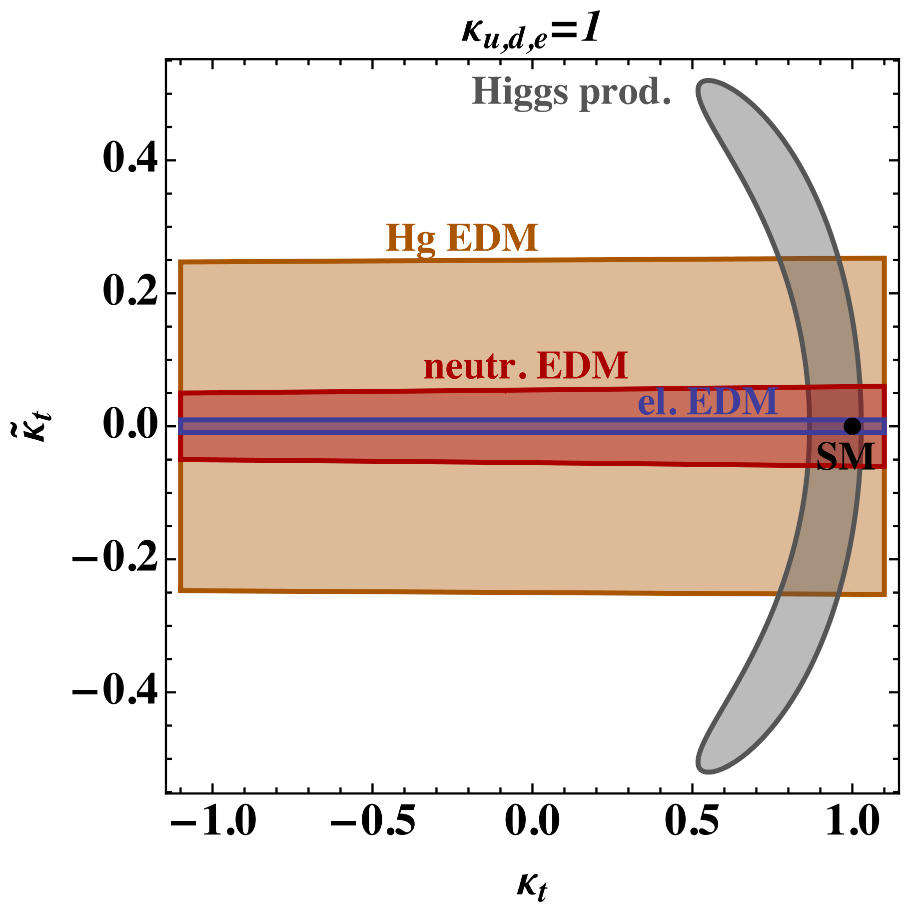
CMS diphoton excess

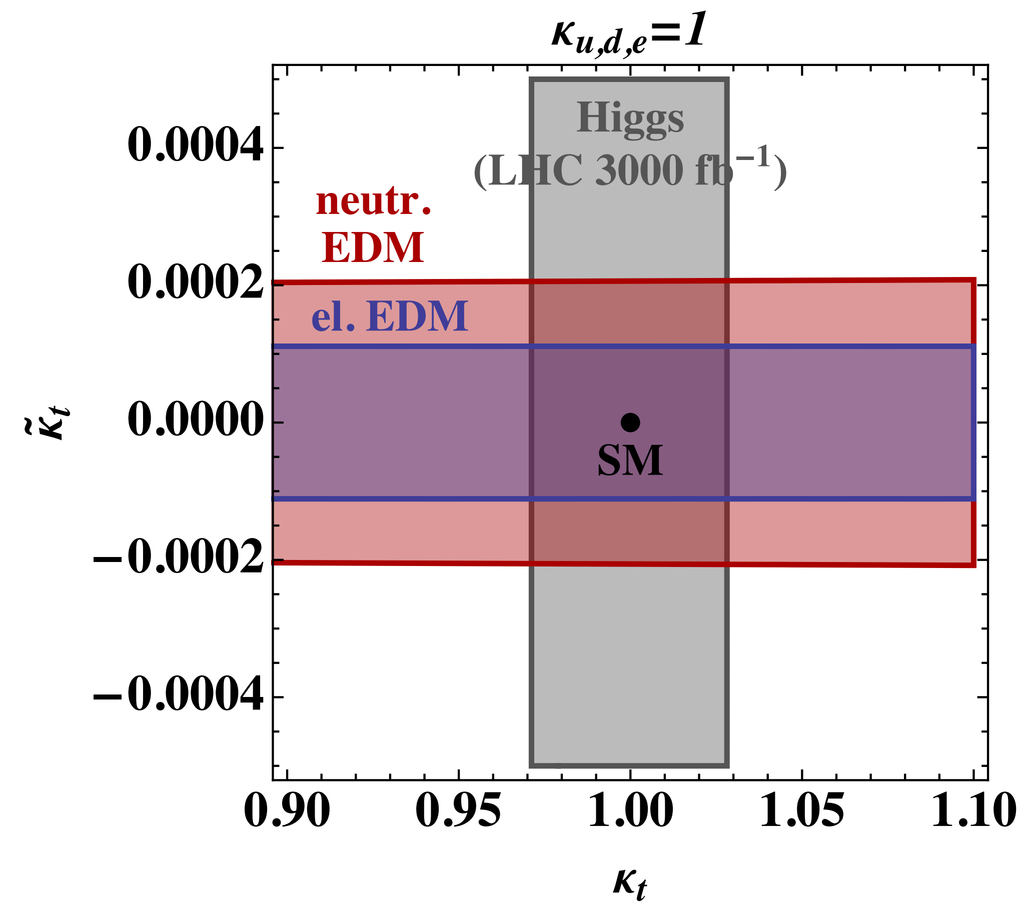


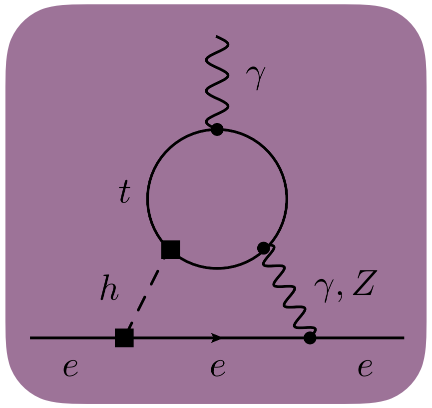


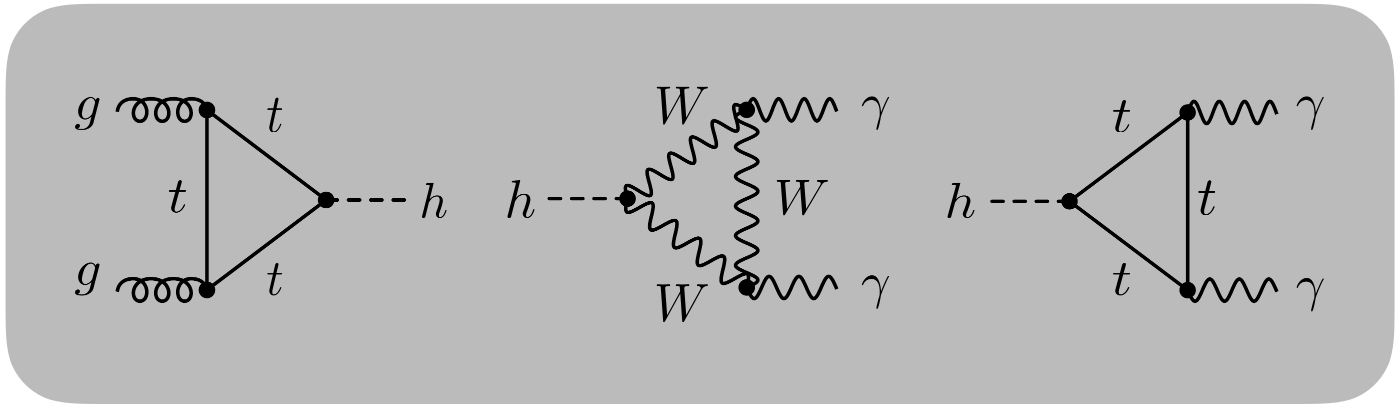
CMS-PAS-HIG-17-013

CP-violating top-Higgs coupling





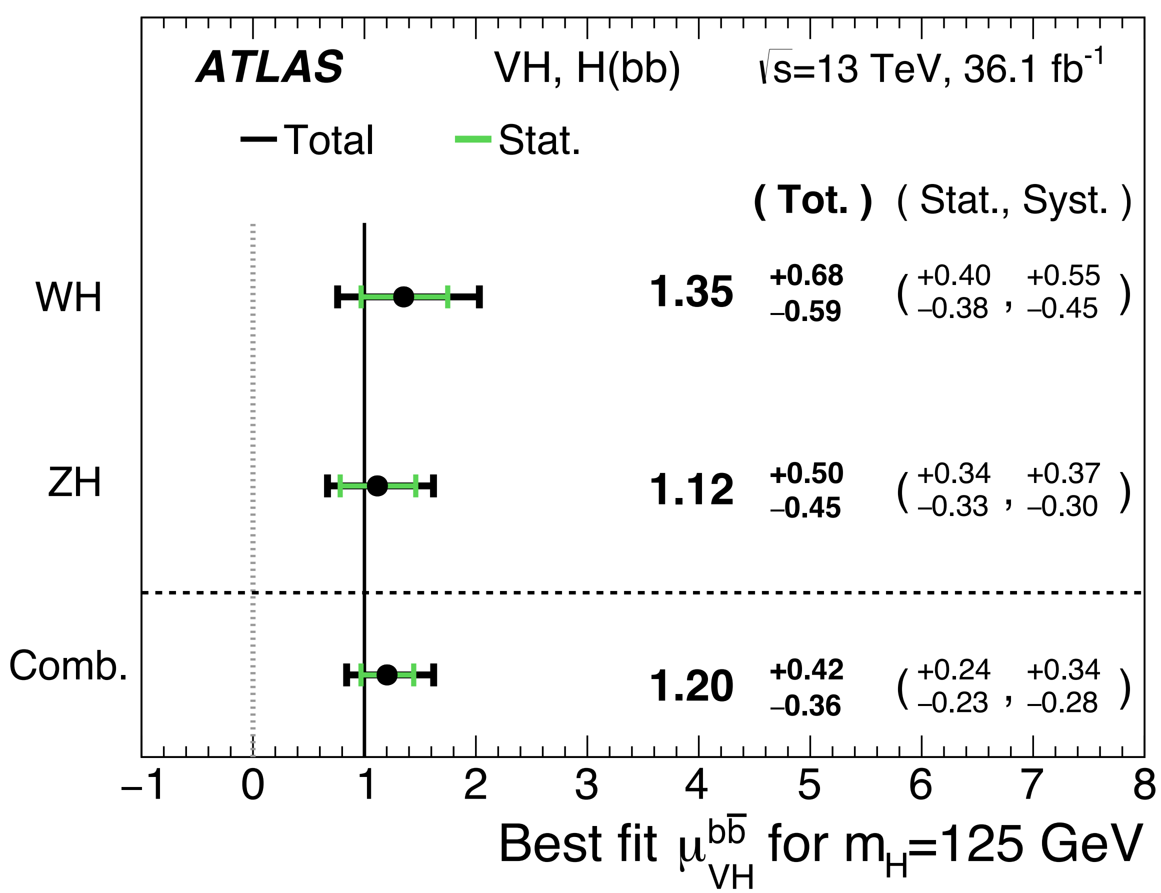


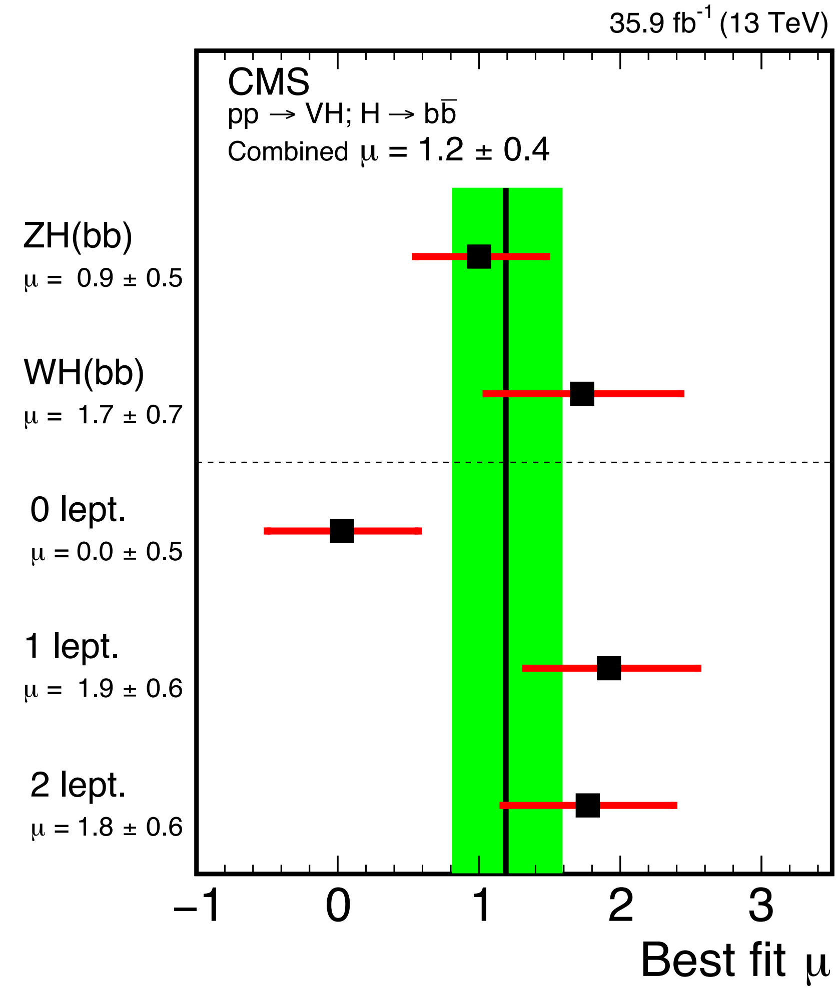


Brod, UH & Zupan, 1310.1385

Searches for $b\bar{b}$ in Vh production

ATLAS, 1708.03299

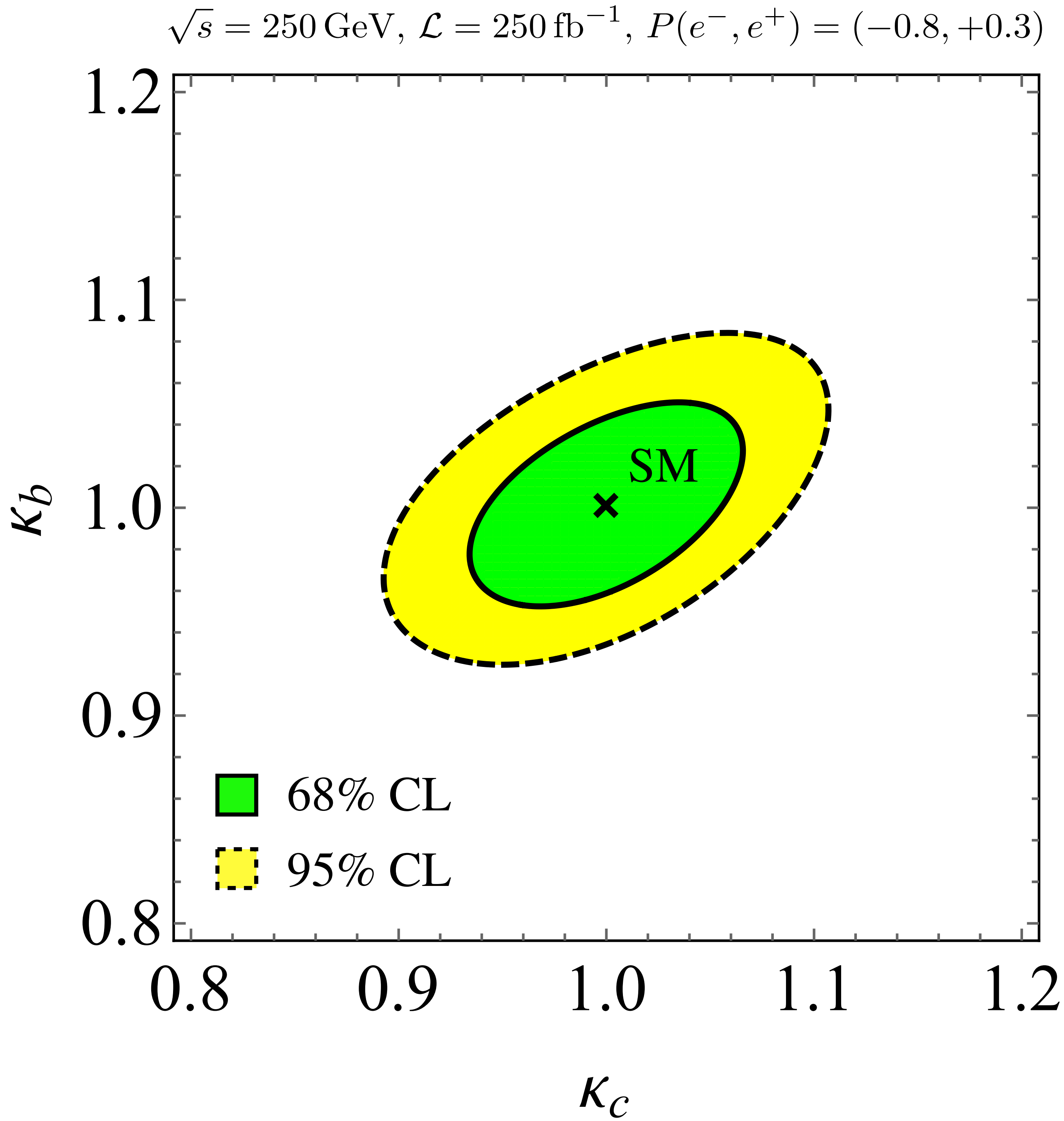




CMS, 1709.07497

Both ATLAS & CMS find evidence for $(Vh)b\bar{b}$ signature in Run II.
Combinations with Run I lead to results that agree to 30% with SM

$\kappa_{c,b}$ bounds: ILC



UH based on Ono & Miyamoto, 1207.0300

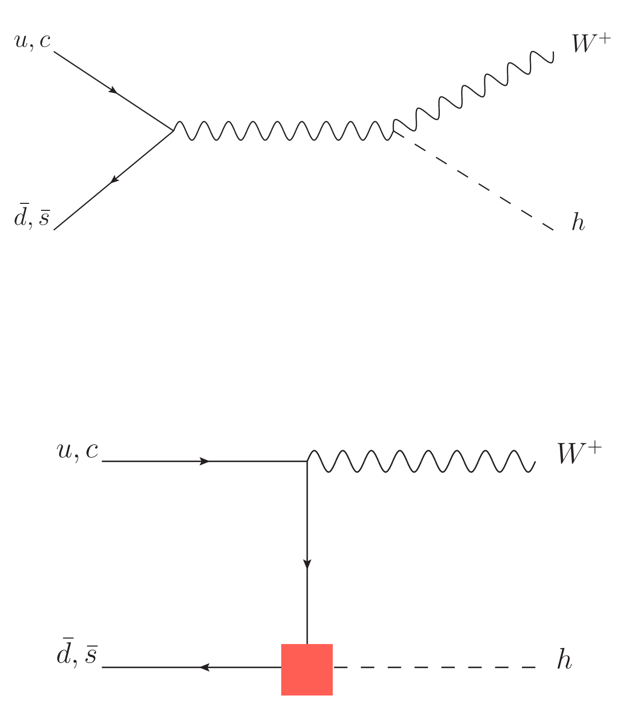
Searches for h→ϕ/ργ

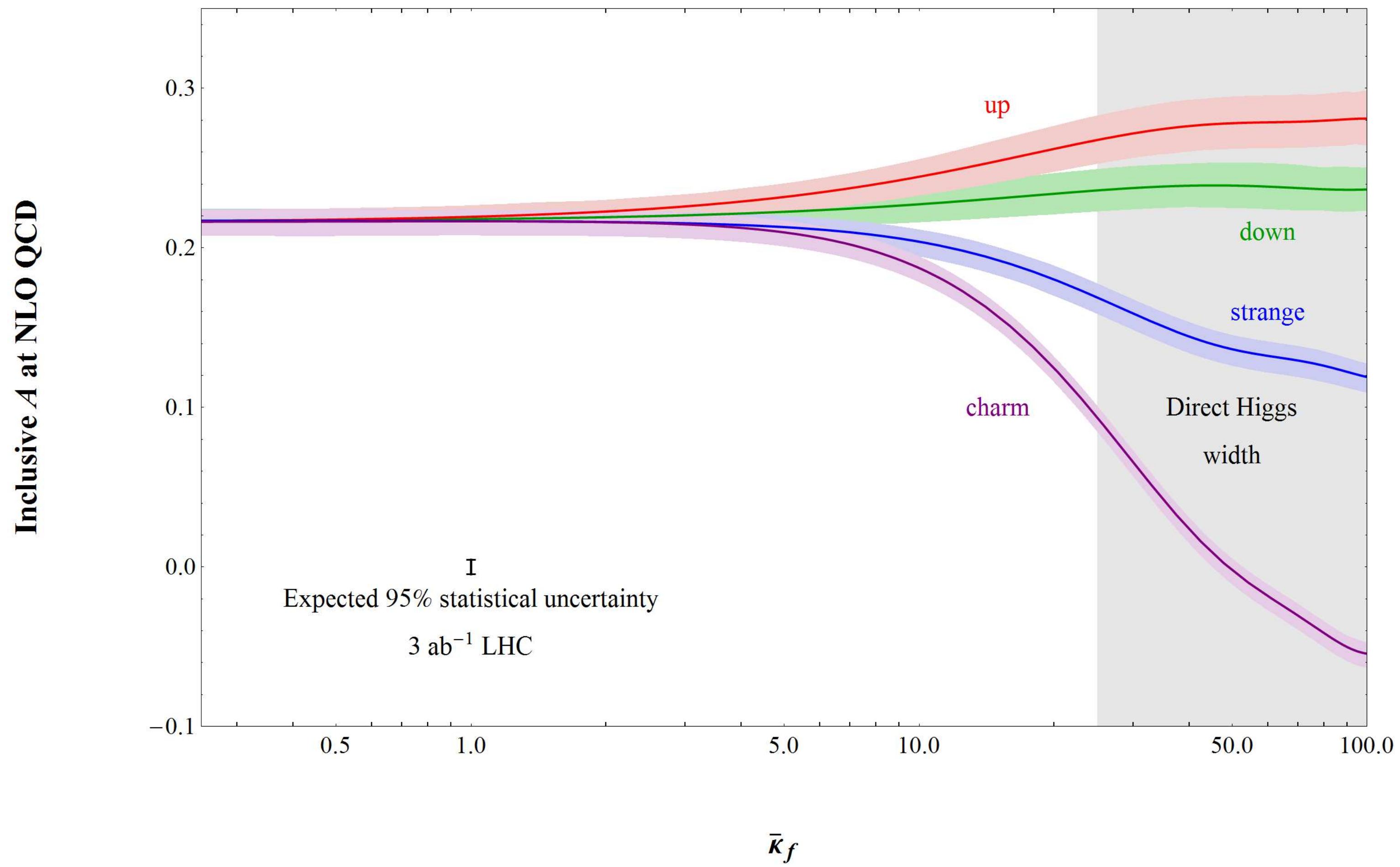
ATLAS, 1712.02758

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}\,(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}\,(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}\,(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}\,(Z \to \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25

$$\frac{\mathrm{BR}(h \to \phi\gamma)}{\mathrm{BR}(h \to \phi\gamma)_{\mathrm{SM}}} \lesssim 200 \quad \longrightarrow \quad |\kappa_s| \lesssim 10000$$

W±h charge asymmetry



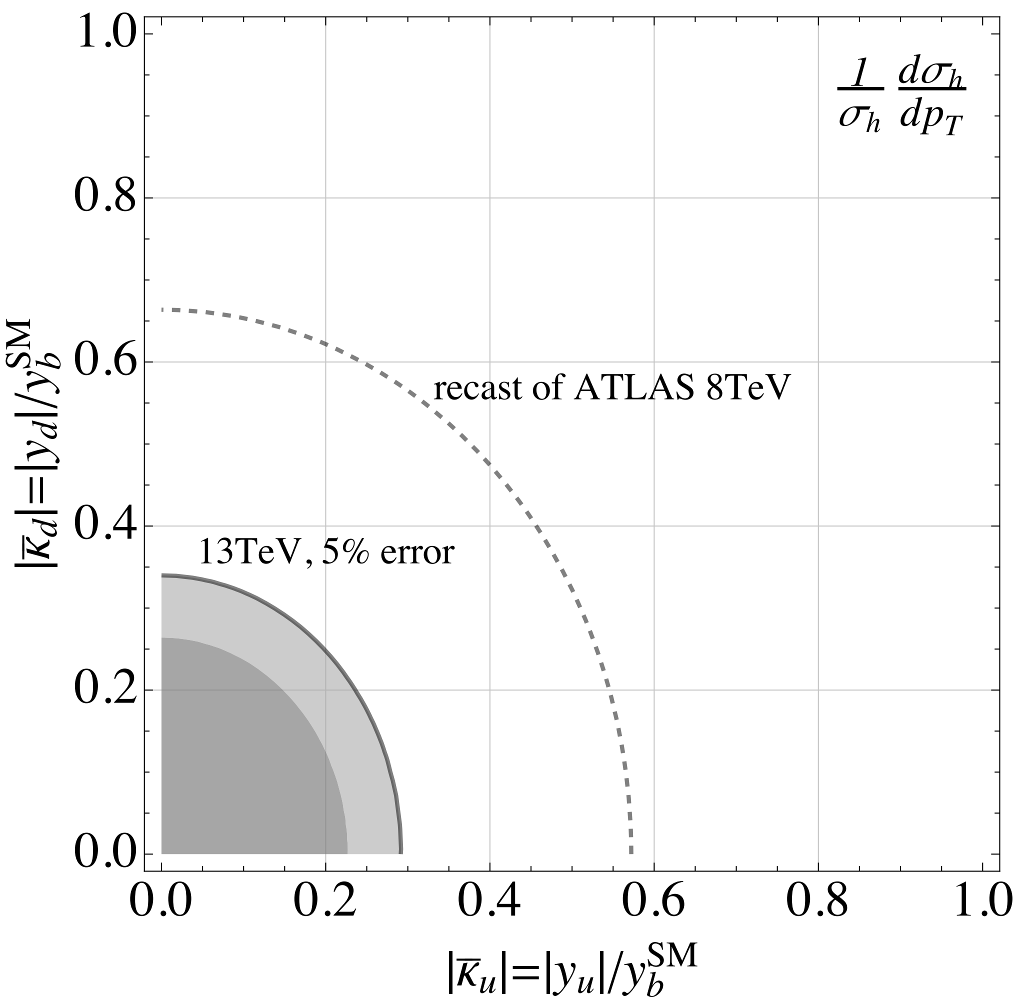


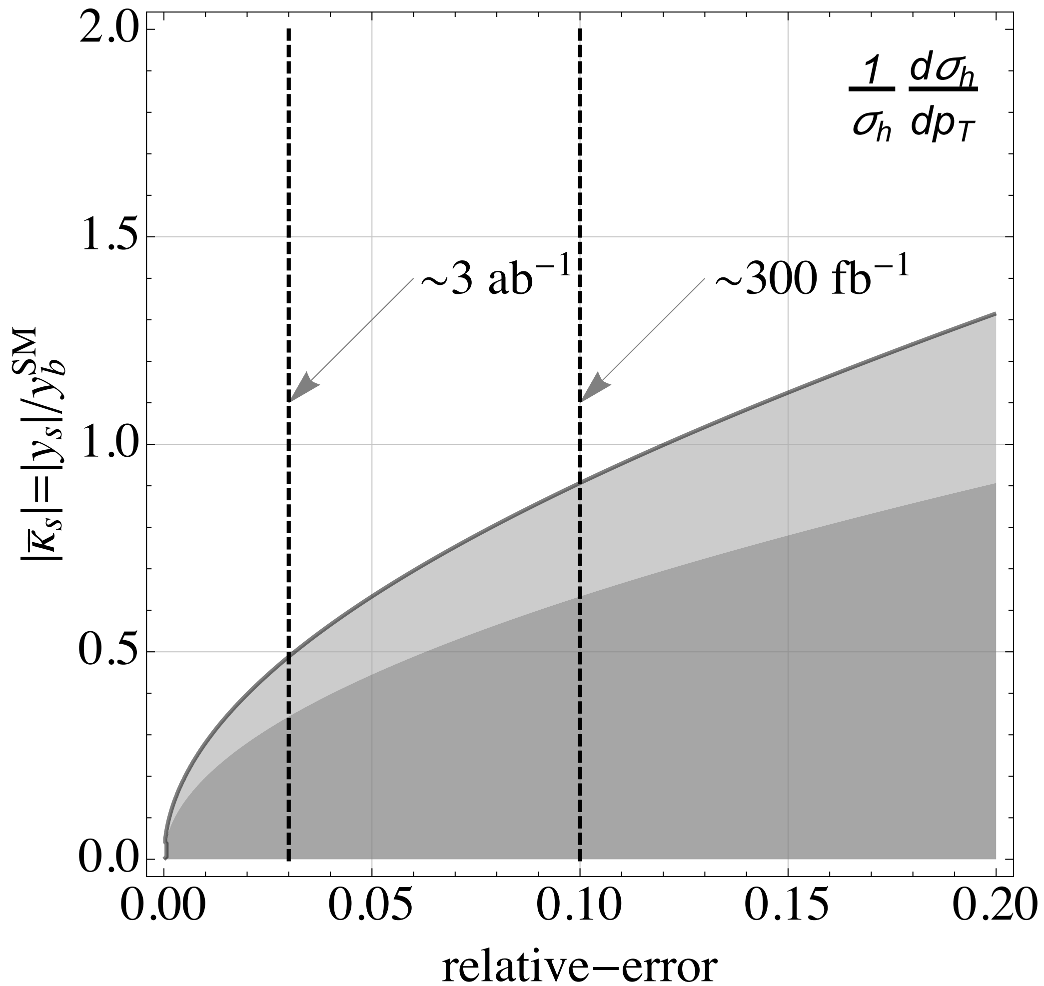
$$\kappa_d < 1270\,,\quad \kappa_u < 2860\,,\quad \kappa_s < 53\,,\quad \kappa_c < 5 \quad \text{(HL-LHC)}$$

Yu, 1609.06592

$\kappa_{u,d,s}$ from Higgs distributions

Soreq, Zhu & Zupan, 1606.09621



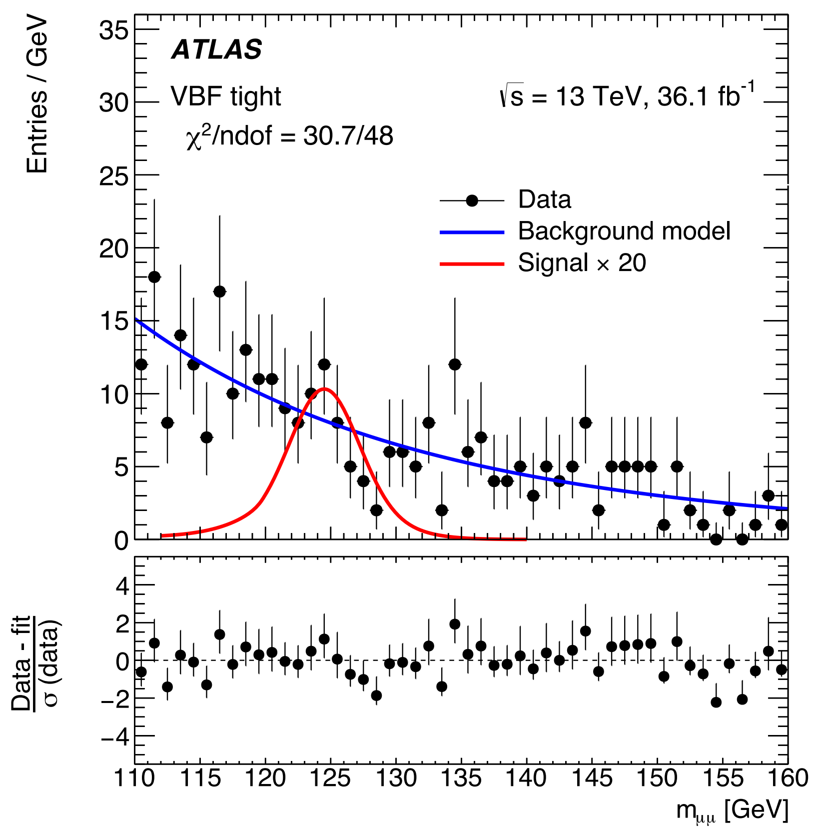


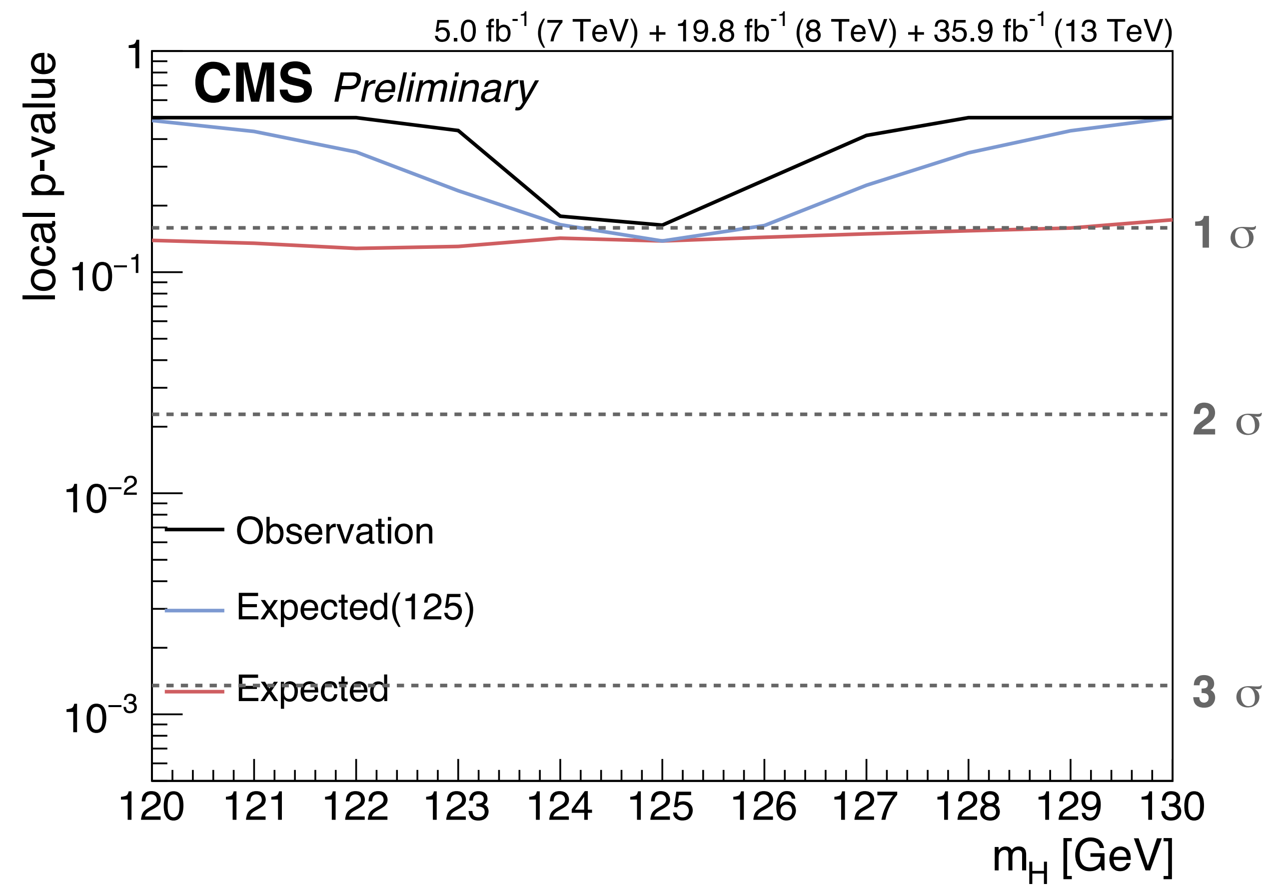
$$|\kappa_u| \lesssim 830\,, \quad |\kappa_d| \lesssim 500\,, \quad |\kappa_s| \lesssim 30 \quad \text{(HL-LHC)}$$

Bishara, UH, Monni & Re, 1606.09253; Soreq, Zhu & Zupan, 1606.09621

Bounds on muon Yukawa

ATLAS, 1705.04582





CMS-HIG-17-019-PAS

$$|\kappa_\mu| \lesssim 1.7$$

Bounds on electron Yukawa

Altmannshofer, Brod & Schmaltz, 1503.04830

$h \to e^+e^-$	LHC8 (25/fb)	$\|\kappa_e\| \lesssim 600$	$M \gtrsim 6$ TeV
	LHC14 (300/fb)	$\|\kappa_e\| \sim 260$	$M \sim 9$ TeV
	LHC14 (3/ab)	$\|\kappa_e\| \sim 150$	$M \sim 12$ TeV
	100 TeV (3/ab)	$\|\kappa_e\| \sim 75$	$M \sim 17$ TeV
$e^+e^- \to h$	LEP II	$\|\kappa_e\| \lesssim 2000$	$M \gtrsim 3$ TeV
	TLEP (1/fb)	$\|\kappa_e\| \sim 50$	$M \sim 20$ TeV
	TLEP (100/fb)	$\|\kappa_e\| \sim 10$	$M \sim 50$ TeV
d_e	current	$\mathrm{Im}\,\kappa_e \lesssim 0.017$	$M \gtrsim 1000$ TeV
	future	$\mathrm{Im}\,\kappa_e \sim 0.0001$	$M \sim 10^4$ TeV
$(g-2)_e$	current	$\mathrm{Re}\,\kappa_e \lesssim 3000$	$M \gtrsim 2.5$ TeV
	future	$\mathrm{Re}\,\kappa_e \sim 300$	$M \sim 8$ TeV

LHC8 bound obtained from CMS, 1410.6679

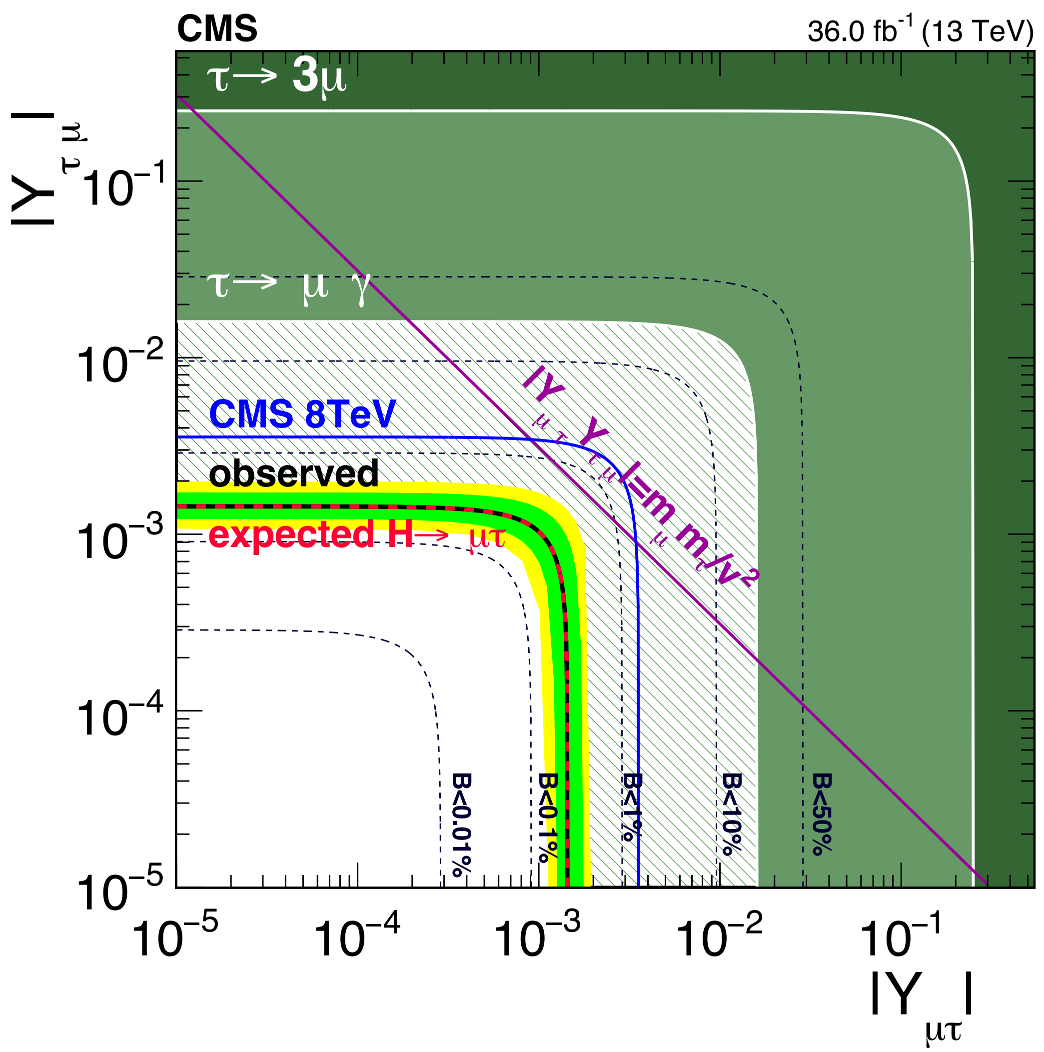
Top flavour-changing Yukawas

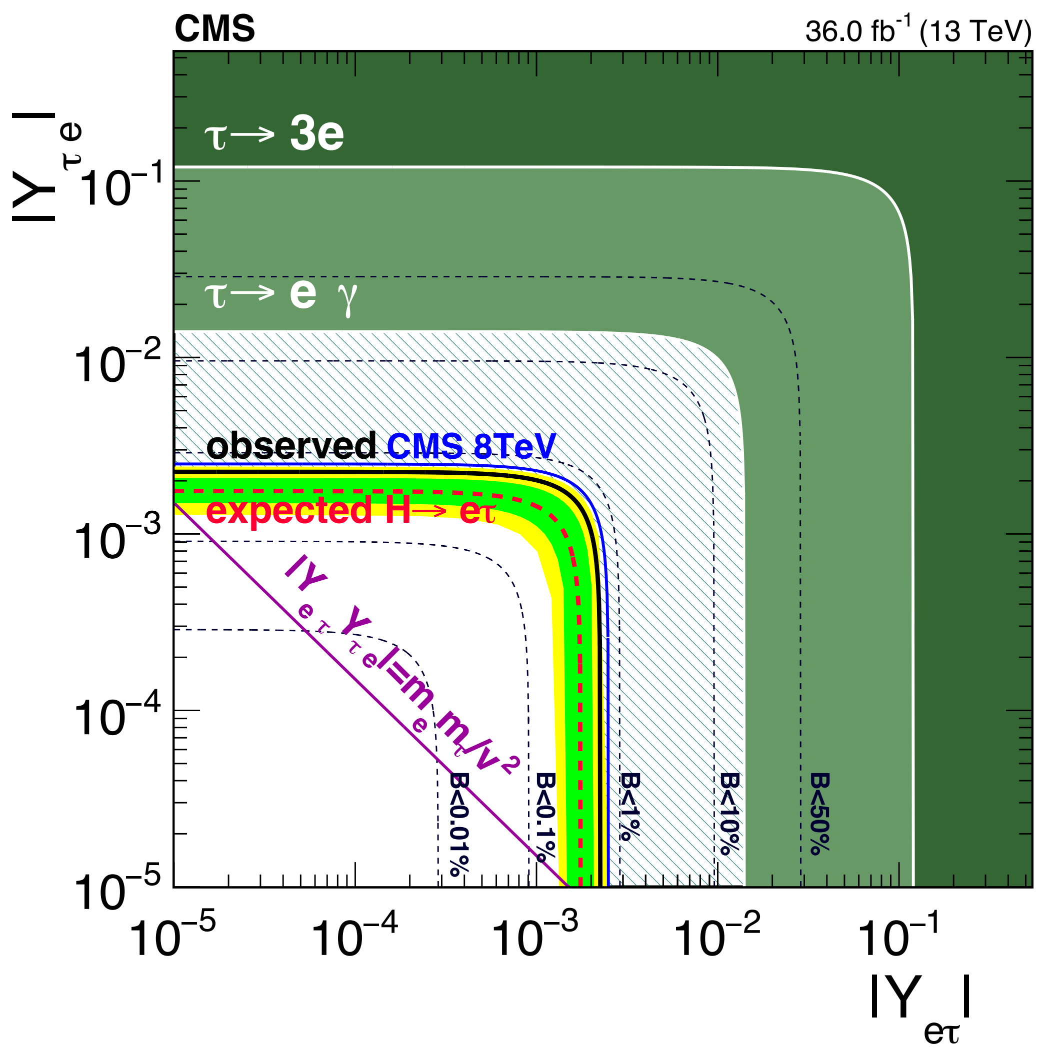
Observable	Coupling	Present bound	Future sensitivity
LHC searches	$\sqrt{\lvert Y_{tc}\rvert^2 + \lvert Y_{ct}\rvert^2}$	$9.0 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$
	$\sqrt{\lvert Y_{tu}\rvert^2 + \lvert Y_{ut}\rvert^2}$	$9.4 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$
d_n	$\lvert \mathrm{Im}\,(Y_{tc}Y_{ct})\rvert$	$5.0 \cdot 10^{-4}$	$1.7 \cdot 10^{-6}$
	$\lvert \mathrm{Im}\,(Y_{tu}Y_{ut})\rvert$	$4.3 \cdot 10^{-7}$	$1.5 \cdot 10^{-9}$
d_D	$\lvert \mathrm{Im}\,(Y_{tc}Y_{ct})\rvert$	—	$1.7 \cdot 10^{-7}$
	$\lvert \mathrm{Im}\,(Y_{tu}Y_{ut})\rvert$	—	$1.7 \cdot 10^{-11}$
ΔA_{CP}	$\lvert \mathrm{Im}\,(Y_{ut}^* Y_{ct})\rvert$	$4.0 \cdot 10^{-4}$	—
D–$\bar{D}$ mixing	$\sqrt{\lvert \mathrm{Im}\,(Y_{tc}^* Y_{ut}^* Y_{tu} Y_{ct})\rvert}$	$4.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$

update of Gorbahn & UH, 1404.4873; present LHC bounds from ATLAS, 1707.01404

Leptonic flavour-changing Yukawas

CMS,1712.07173



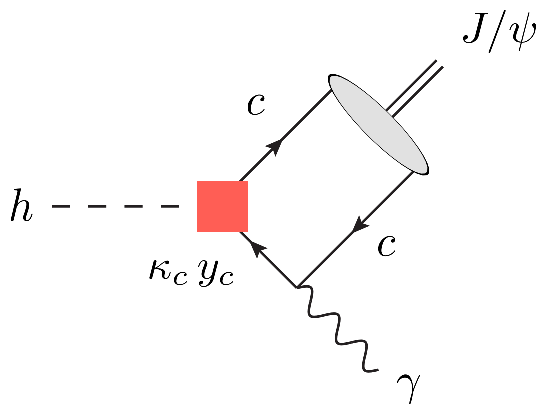


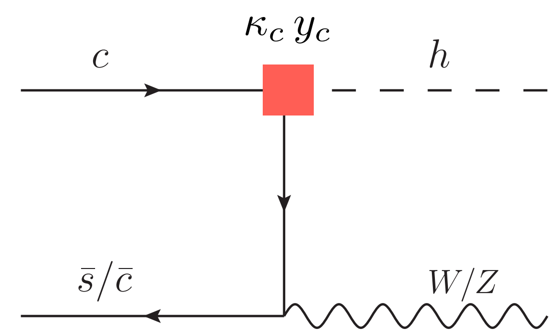
$$\sqrt{|Y_{\mu\tau}|^2+|Y_{\tau\mu}|^2} < 1.43\cdot 10^{-3}$$

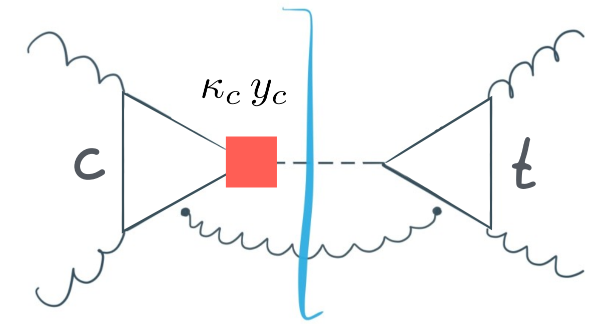
$$\sqrt{|Y_{e\tau}|^2+|Y_{\tau e}|^2} < 2.26\cdot 10^{-3}$$

see also ATLAS, 1604.07730

Assortment of bounds on κ_c







LHC Run I	$\lvert\kappa_c\rvert < 429$	$\lvert\kappa_c\rvert < 234$	$\kappa_c \in [-16, 18]$
LHC Run II	$\lvert\kappa_c\rvert \lesssim 80$	$\lvert\kappa_c\rvert < 21$	$\kappa_c \in [-1.4, 3.8]$
HL-LHC	$\lvert\kappa_c\rvert \lesssim 45$	$\lvert\kappa_c\rvert < 3.7$	$\kappa_c \in [-0.6, 3.0]$

Perez et al., 1503.00290, 1505.06689; König & Neubert, 1505.03870; Bishara et al., 1606.09253

LHCb upgrade II: bounds on κ_c

300 fb^{-1} at 14 TeV: $|\kappa_c| \lesssim 7$

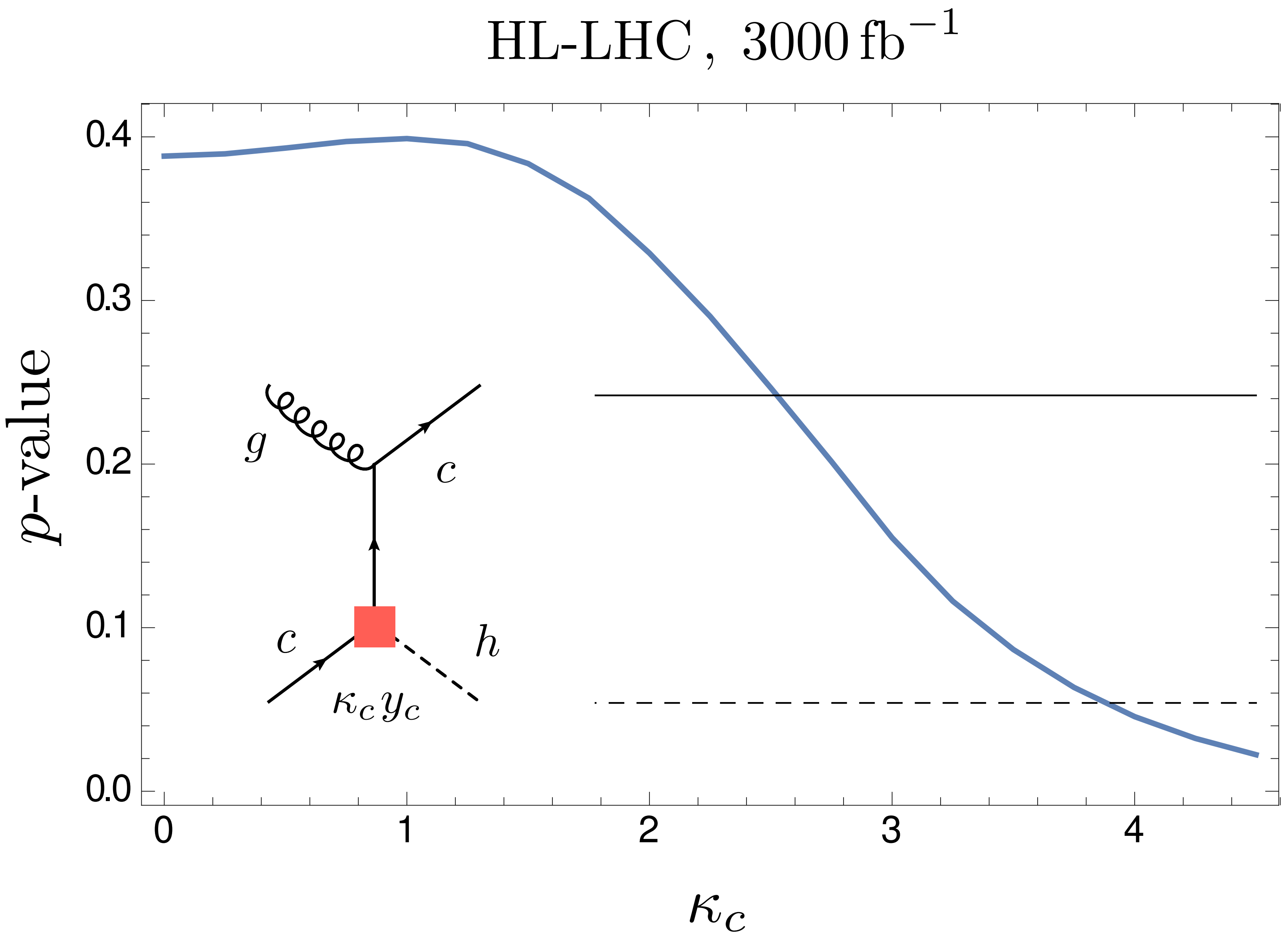
30% di-c-tagging efficiency: $|\kappa_c| \lesssim 4$

better electron reconstruction: $|\kappa_c| \lesssim 3$

further improvements: $|\kappa_c| \lesssim 2.2$

projections taken from “Beyond the LHCb Phase-I Upgrade” talk by Williams

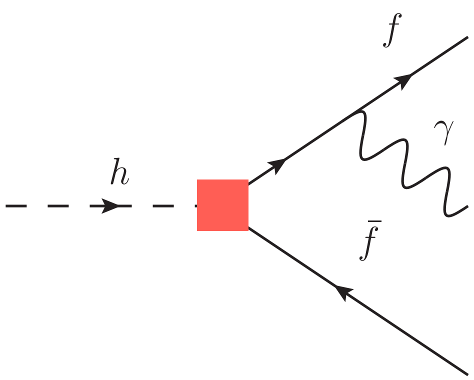
Higgs & charm production

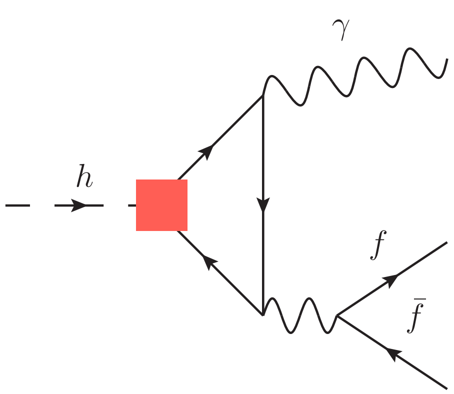


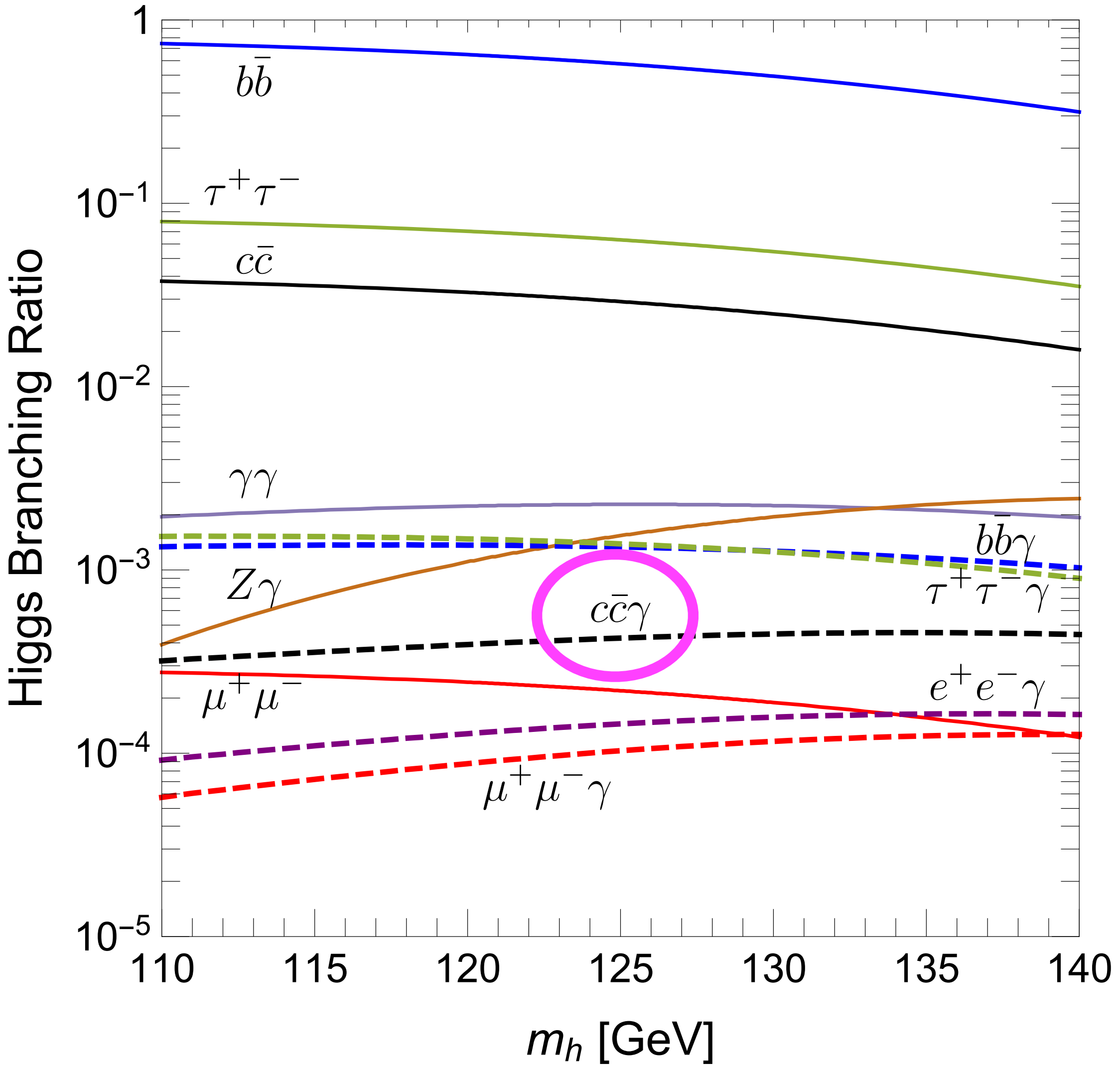
$\longrightarrow \quad \kappa_c < 3.9$

Brivio, Goertz & Isidori, 1507.02916

Charm Yukawa from h→c$\bar{c}$γ





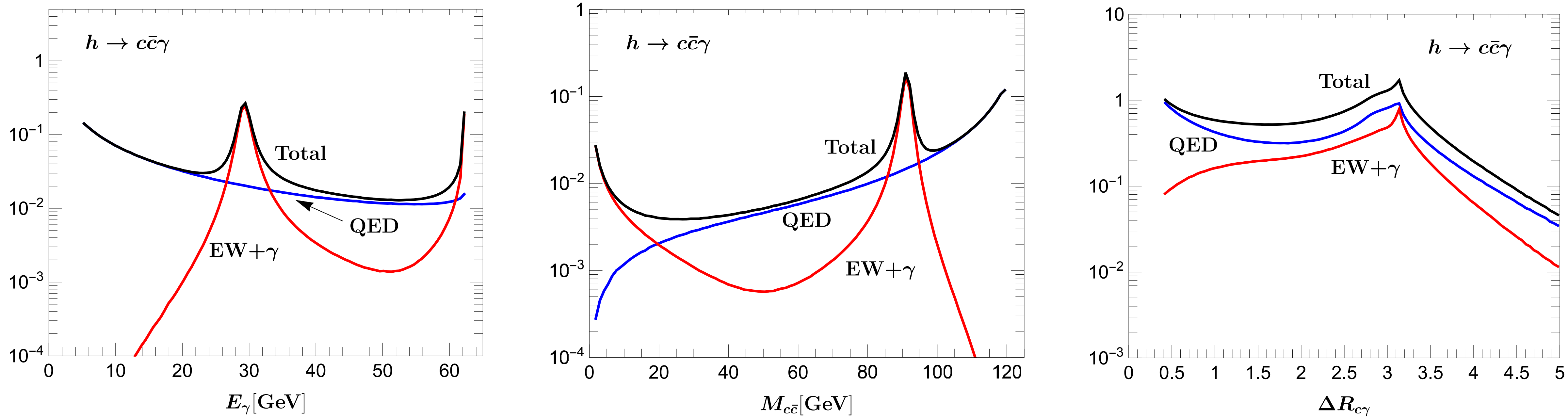


$$\mathrm{Br}(h \to J/\psi\gamma) \simeq 3 \cdot 10^{-6}$$

$$\mathrm{Br}(h \to c\bar{c}\gamma) \simeq 4 \cdot 10^{-4}$$

Han & Wang, 1704.00790

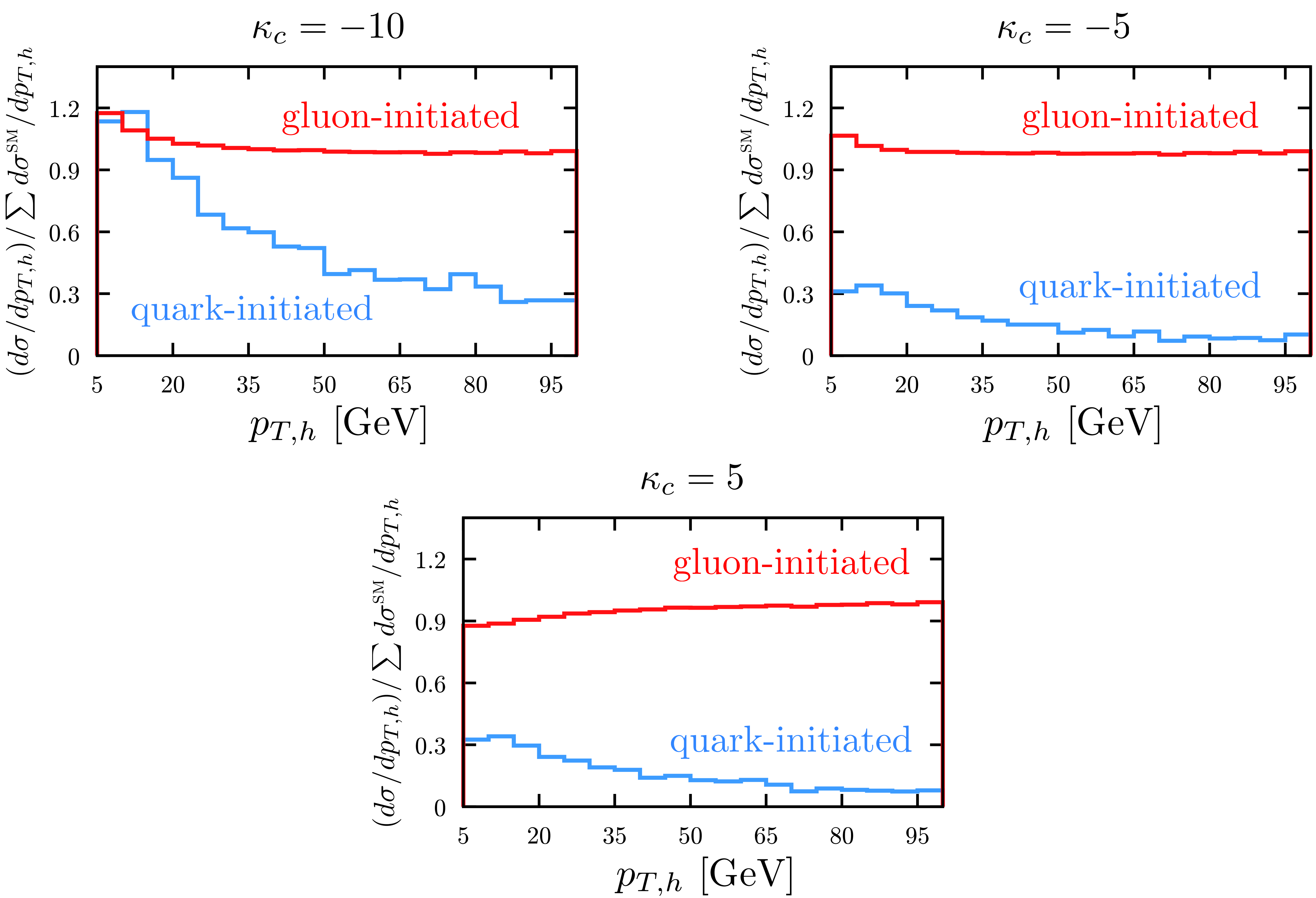
Charm Yukawa from h→cc̄γ



$$|\kappa_c| < 6.3 \quad \text{(HL-LHC)}$$

Han & Wang, 1704.00790

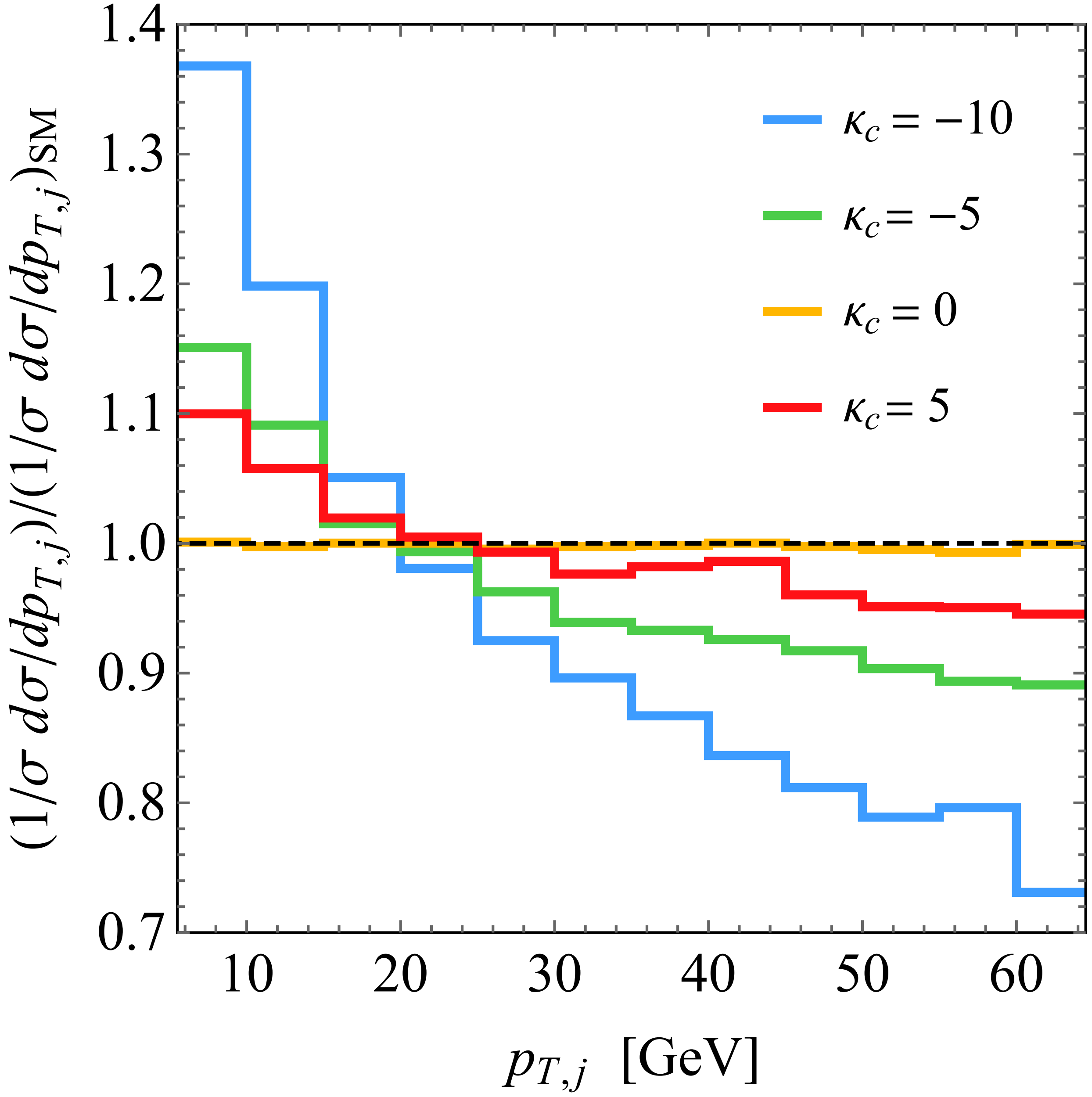
Charm contributions to pp→hj



Bishara, UH, Monni & Re, unpublished

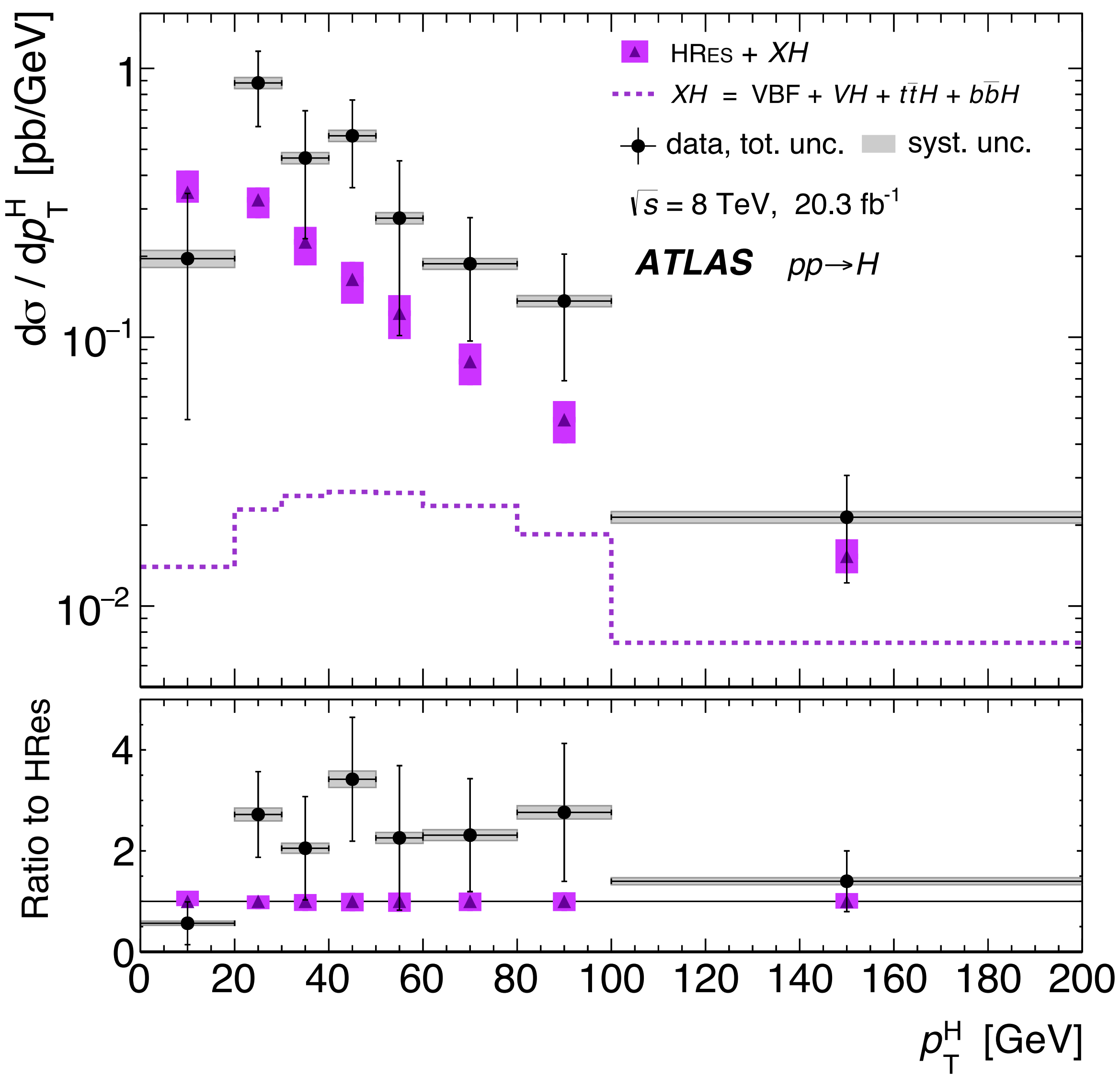
Normalised $p_{T,j}$ spectra

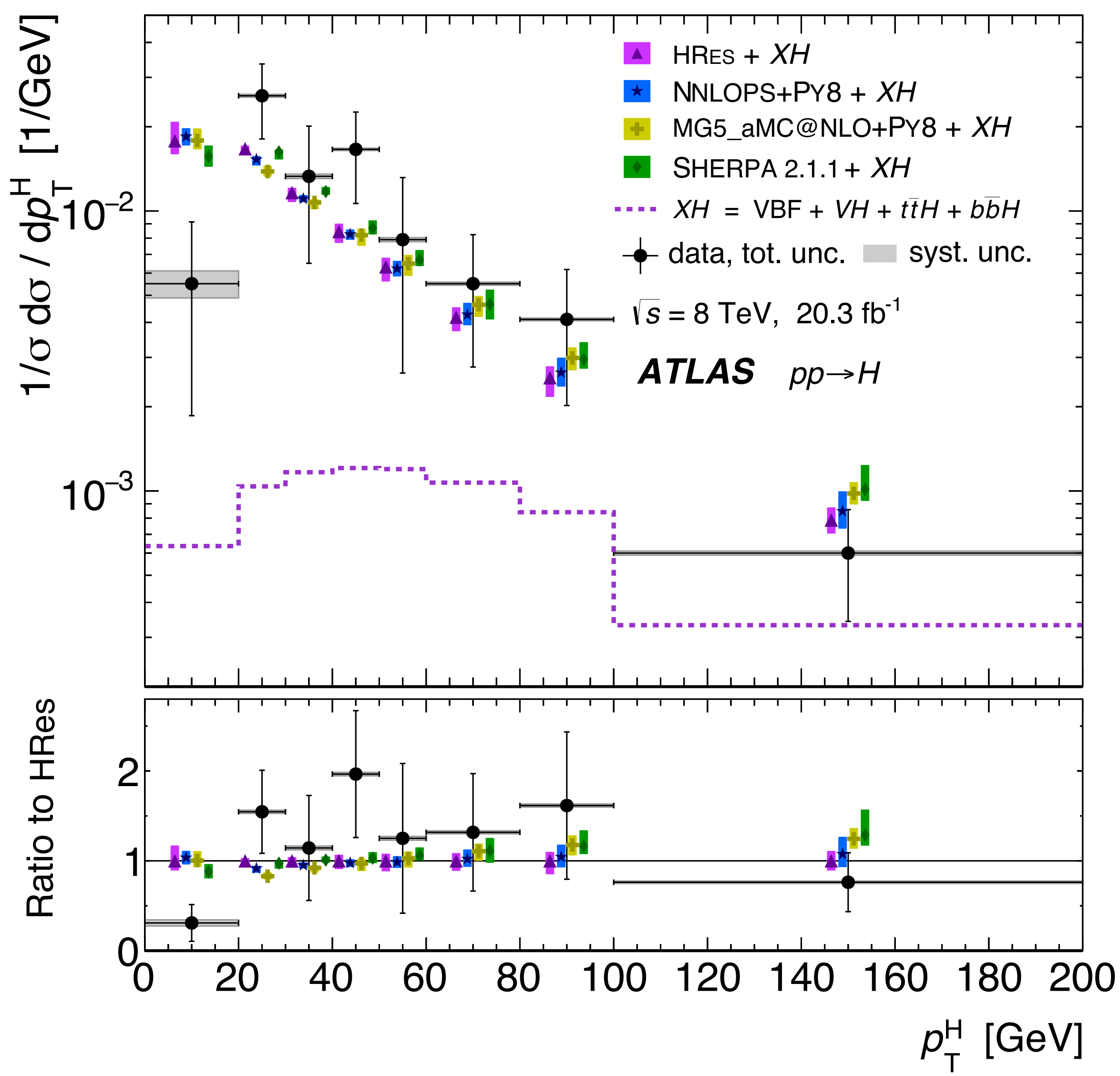
Bishara, UH, Monni & Re, 1606.09253



O(1) deviations in κ_c lead to few % effects in $p_{T,j}$ distribution

(Un)Normalised $p_{T,h}$ spectra



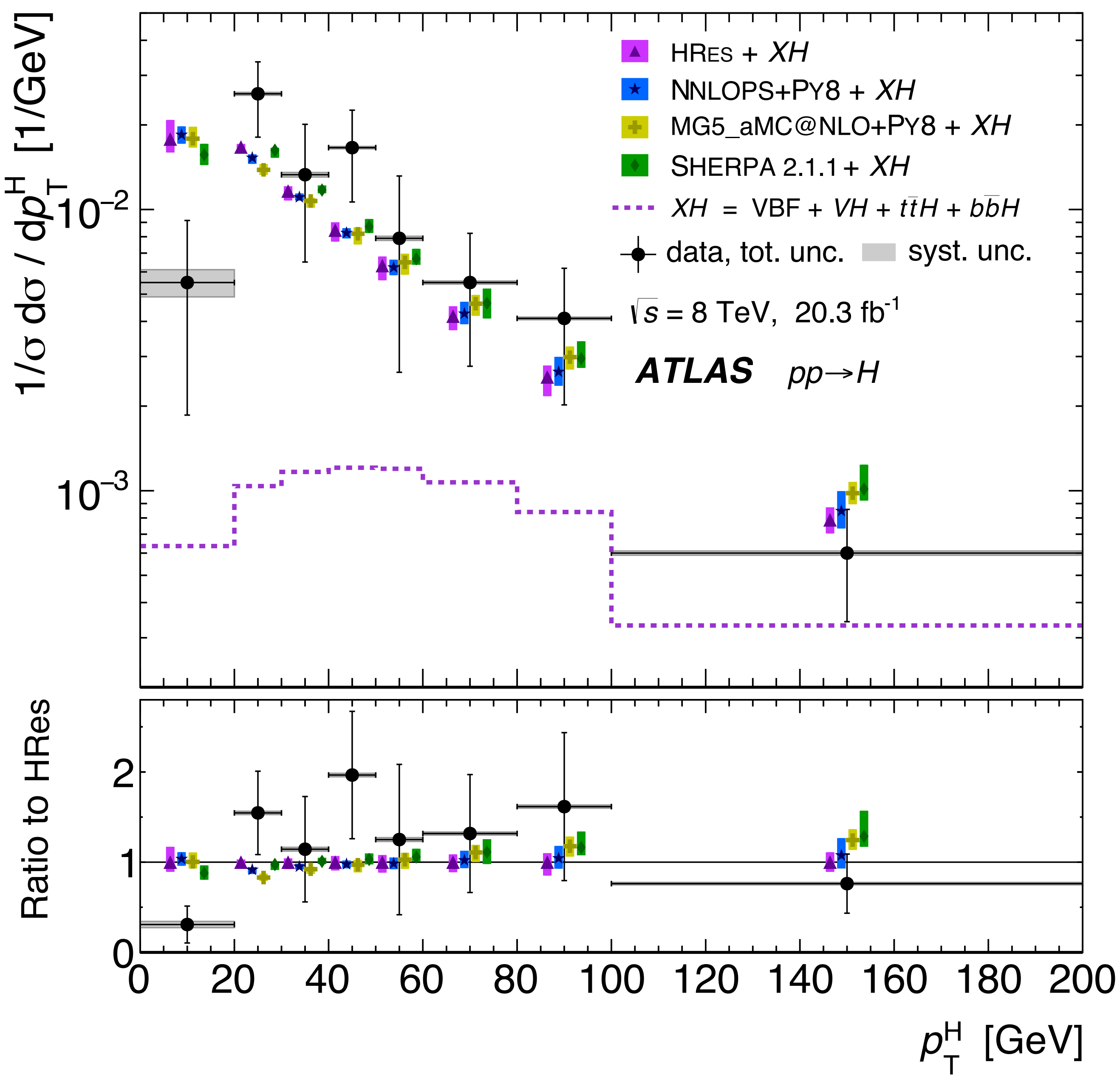


Systematic uncertainties largely cancel in normalised $p_{T,h}$ distribution. Same is true for some of the theory errors

ATLAS, 1504.05833

$p_{T,h}$ spectra at 8 TeV

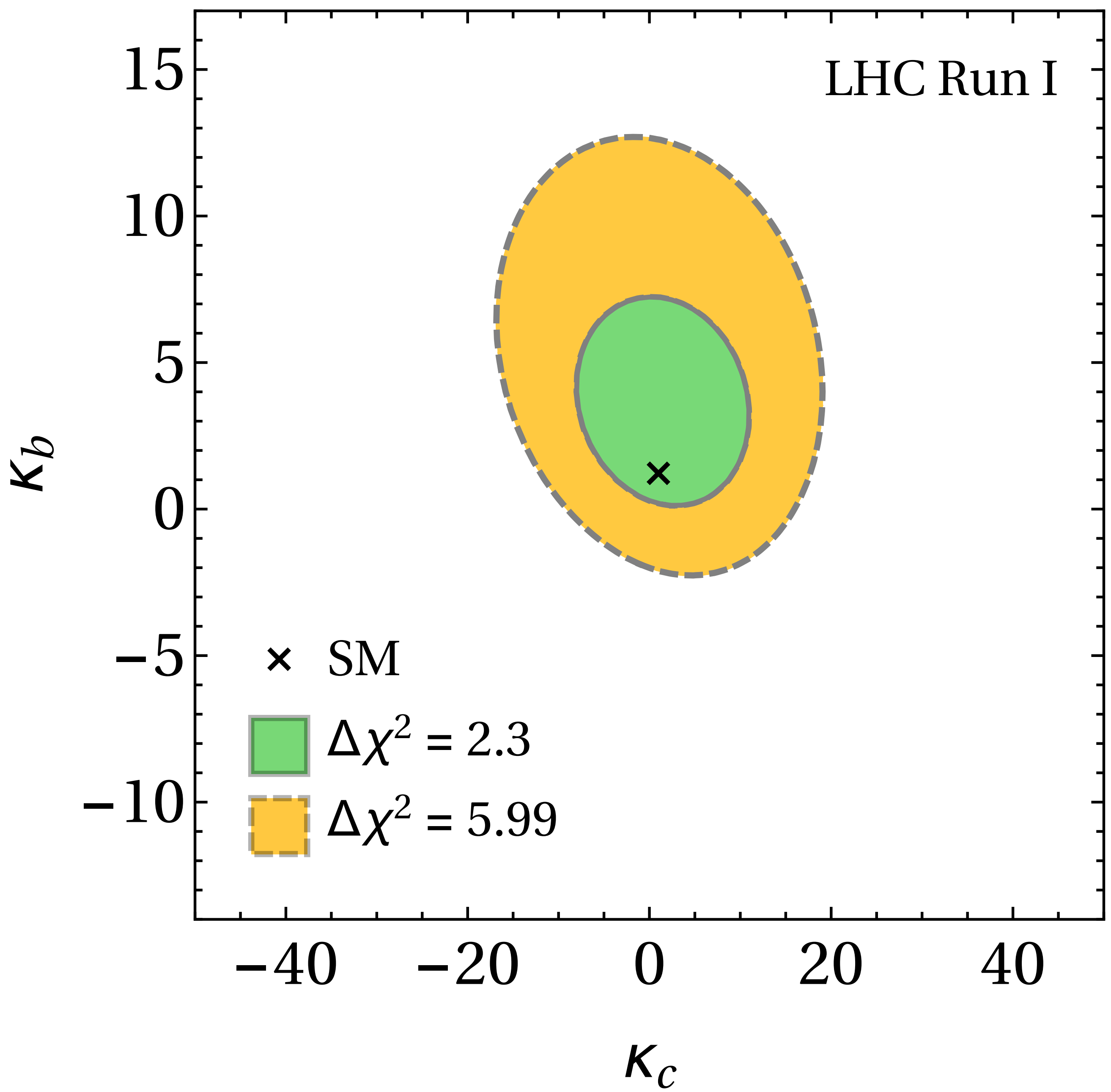
ATLAS, 1504.05833



Statistics limited & ATLAS data not in full agreement with theory

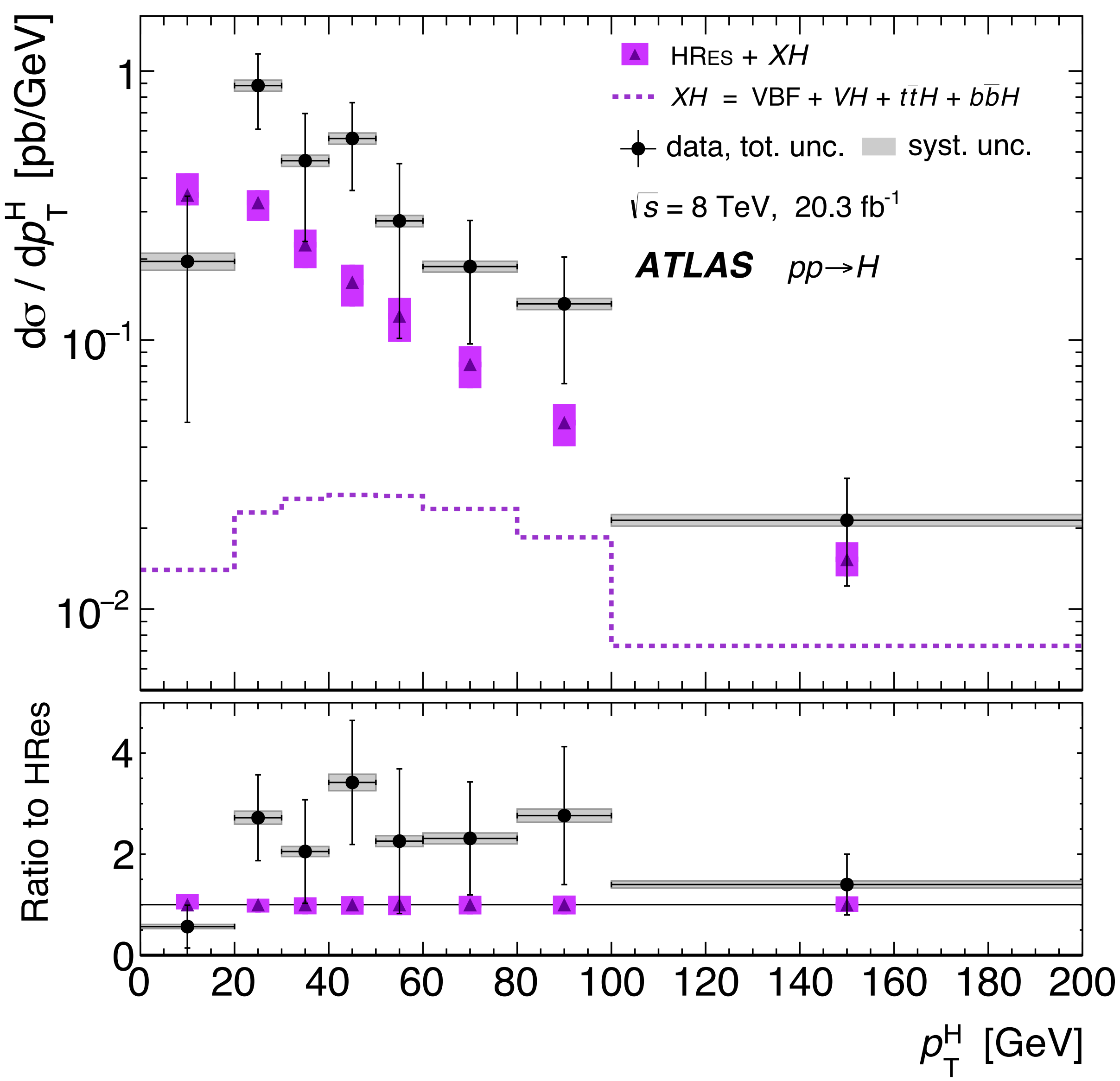
$\kappa_{c,b}$ bounds: LHC Run I

Bishara, UH, Monni & Re, 1606.09253

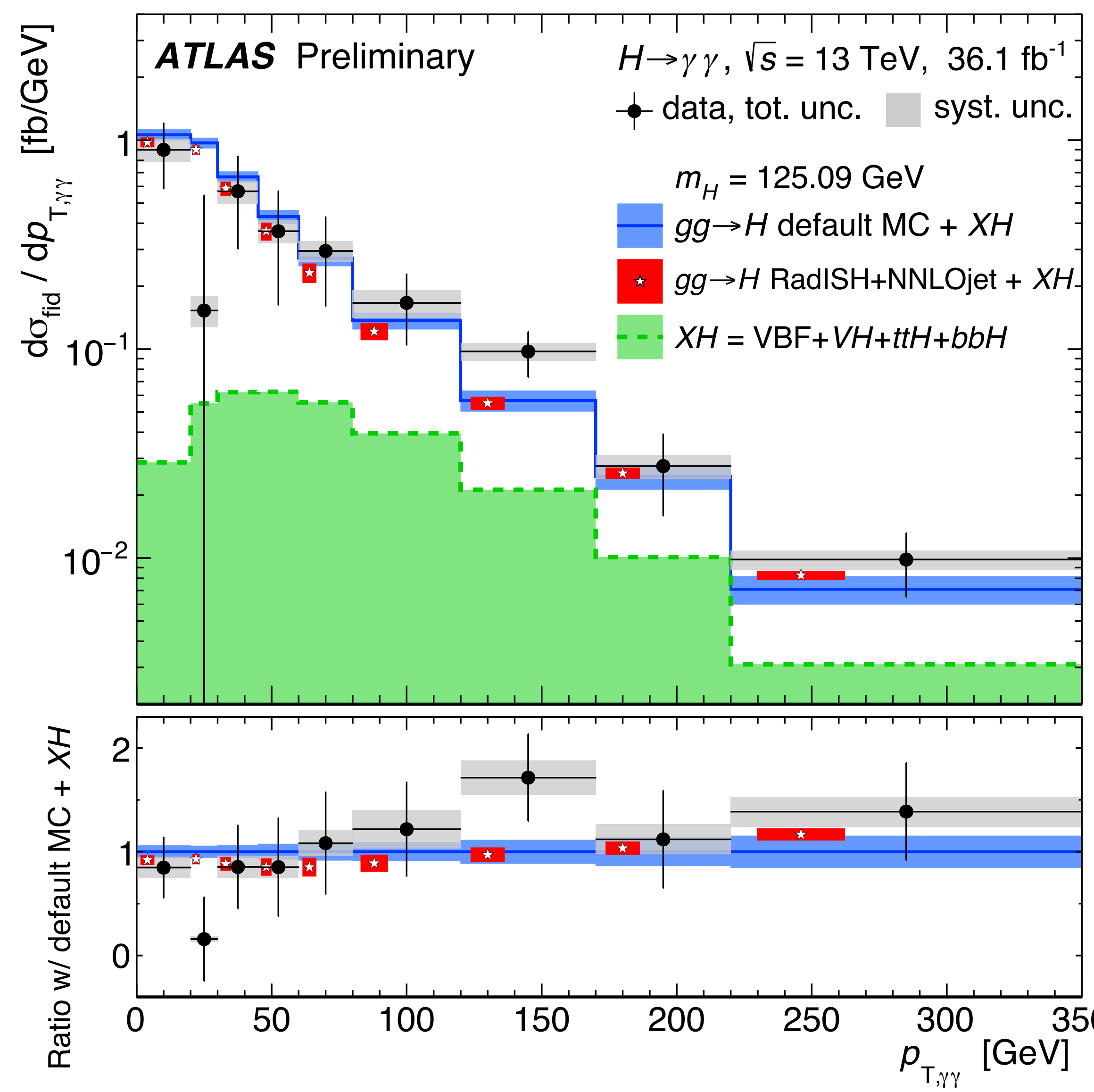


$$\kappa_c \in [-16, 18]$$

ATLAS $p_{T,h}$ spectra: 8 TeV vs.13 TeV

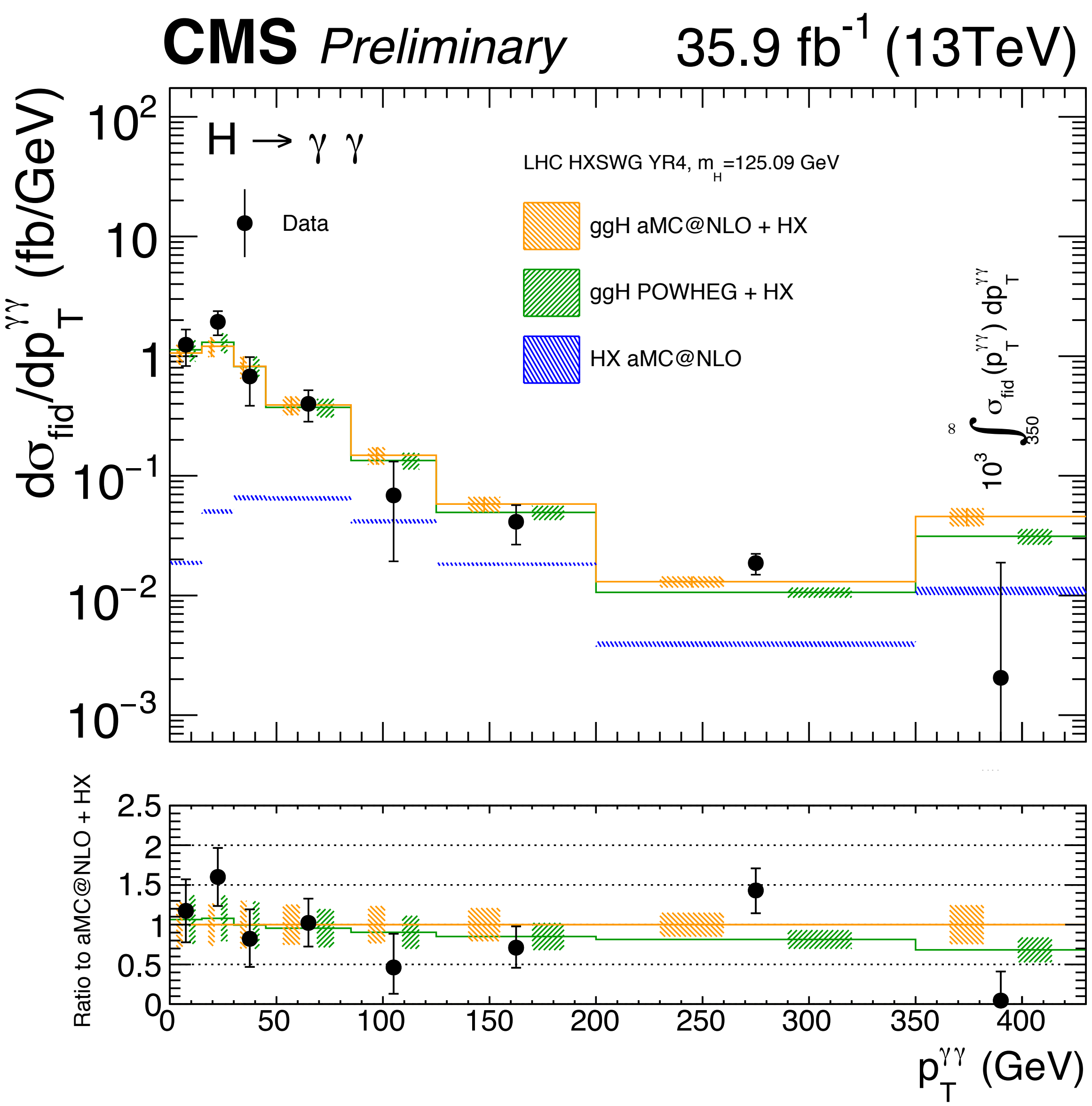


ATLAS, 1504.05833

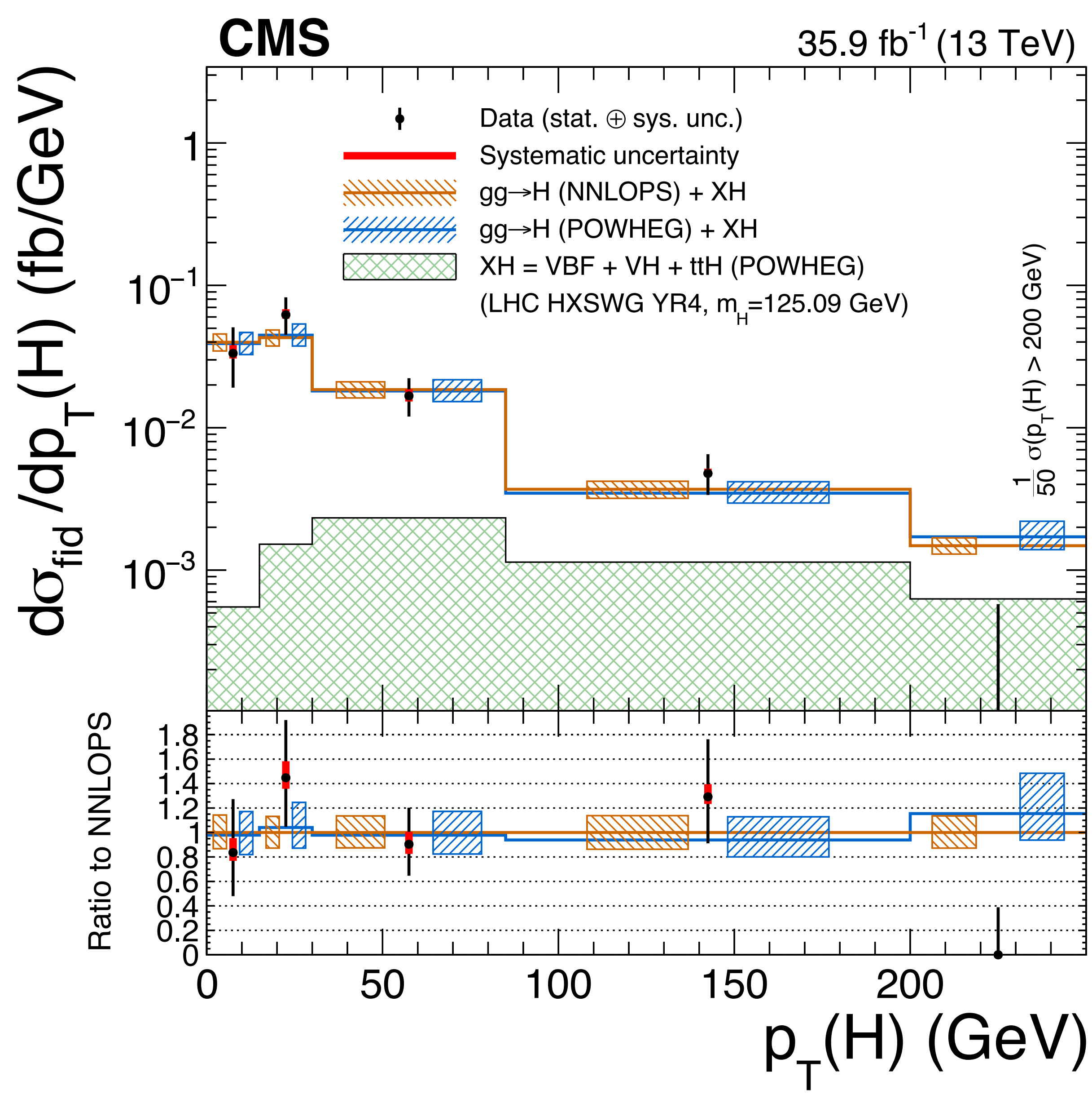


ATLAS-CONF-2017-045

CMS $p_{T,h}$ spectra at 13 TeV



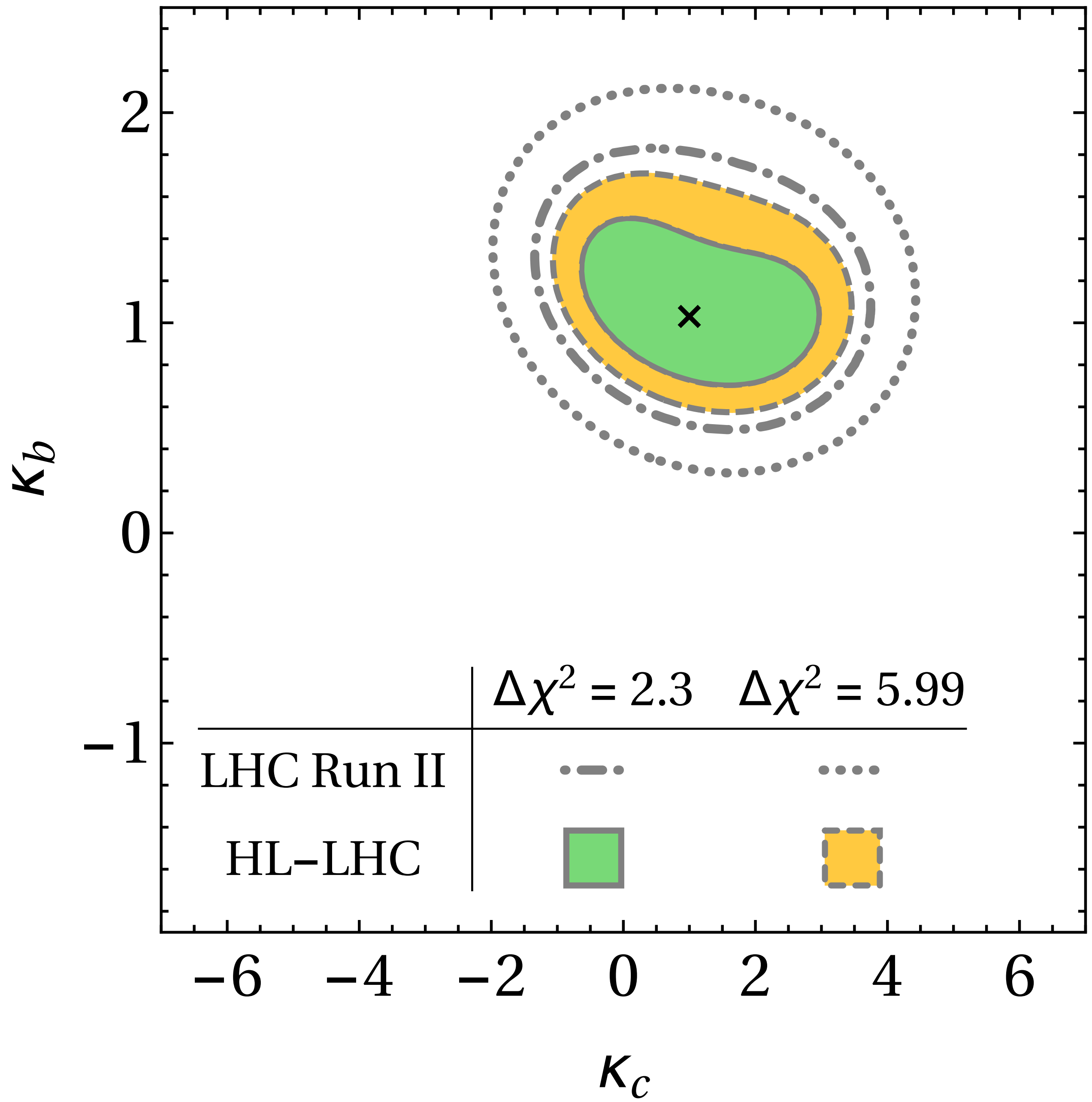
CMS-HIG-17-015



CMS, 1706.09936

Constraints on $\kappa_{c,b}$: prospects

Bishara, UH, Monni & Re, 1606.09253



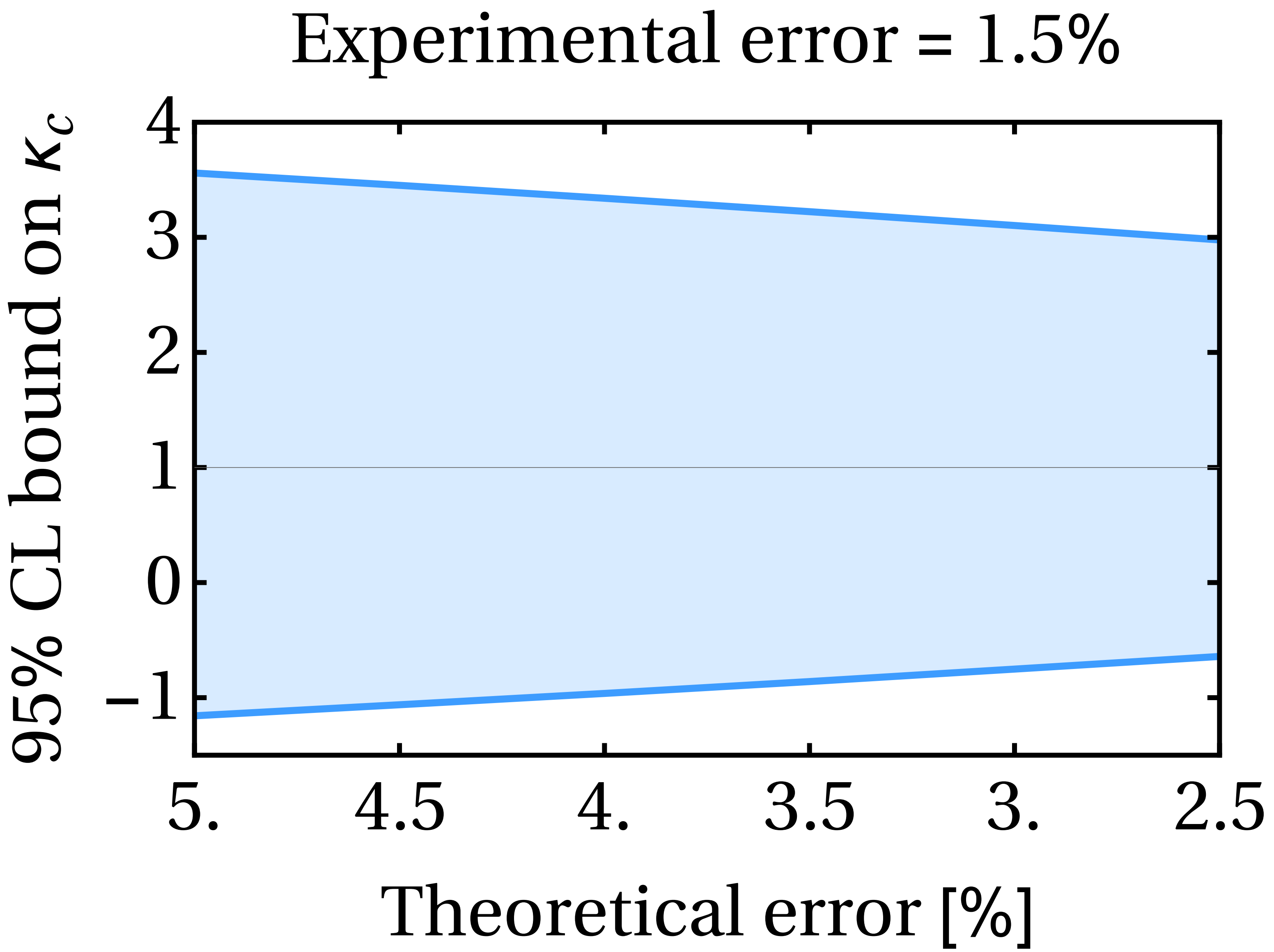
$$\kappa_c \in [-1.4, 3.8]$$

(LHC Run II)

$$\kappa_c \in [-0.6, 3.0]$$

(HL-LHC)

Impact of theory error at HL-LHC



Bishara, UH, Monni & Re, supplemental material to 1606.09253