The Next Frontier in Higgs Coupling Measurements

Fady Bishara

UNIVERSITY OF OXFORD

Based on: 1606.09253 – F. Bishara, U. Haisch, P. Monni, and E. Re
and 1611.xxxxx – FB, R. Contino, and J. Rojo

Motivation

- Does the Higgs couple to first and second generation fermions?

- If the Higgs couples to second generation quarks, can the LHC say anything about these couplings?

- Is EWSB in the SM minimal?
  - Is EWSB linearly realised?

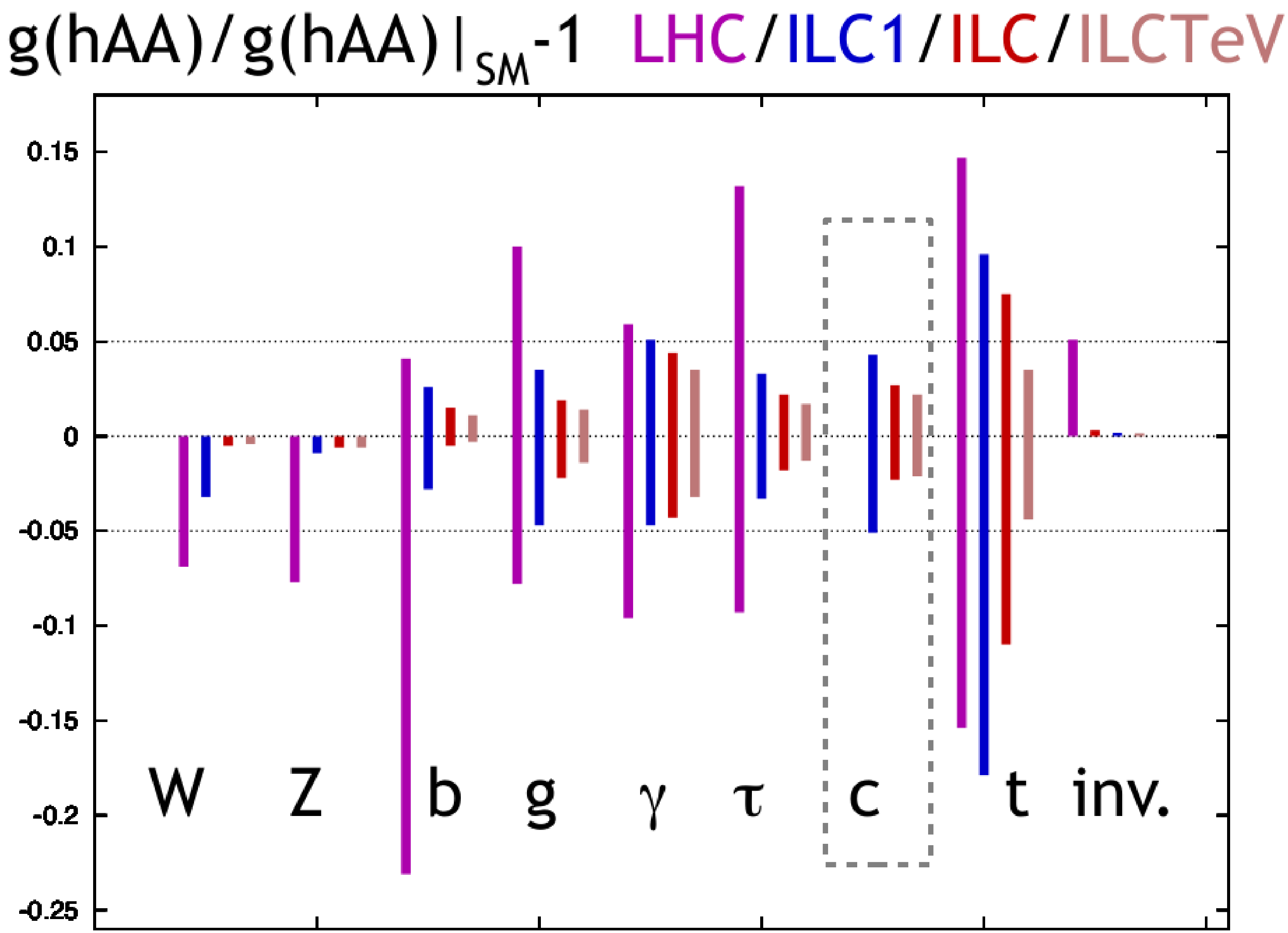
- If EWSB is non-linearly realised, can we test this directly? If not, indirectly?

Roadmap for this talk

1) The charm Yukawa coupling
   - → Progress thus far
   - → New ideas
   - → How well can the LHC do?

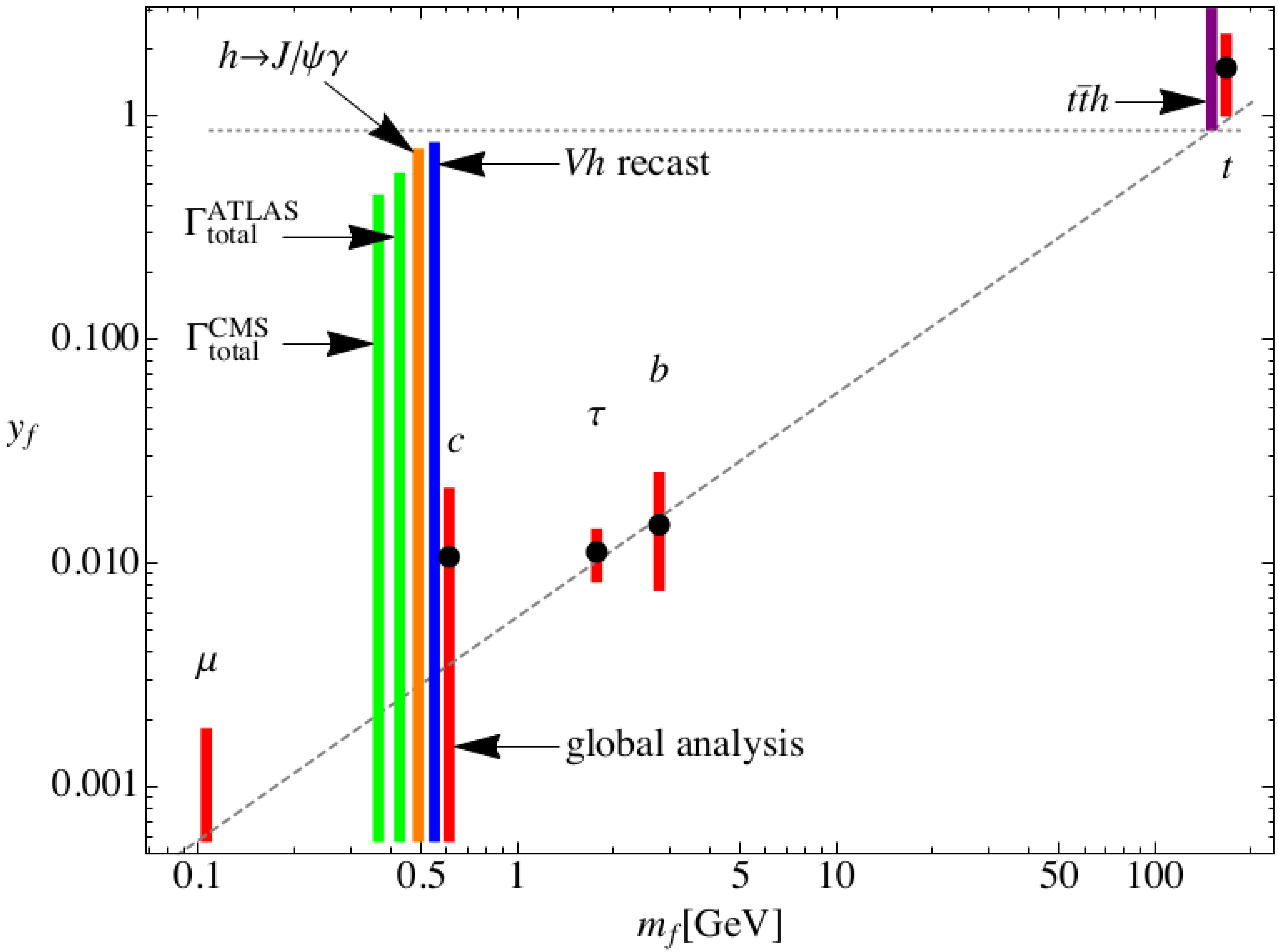
2) The hhVV coupling
   - → Why VBF
   - → How well can the LHC do?
   - → The ultimate precision at an FCC

The projections in 2013



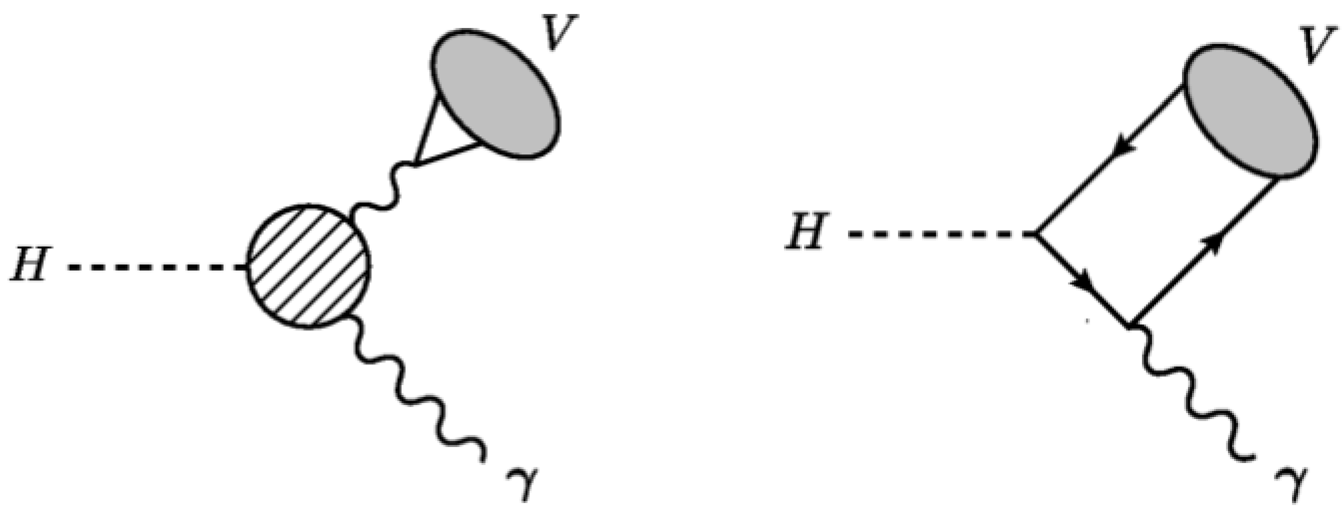
ILC TDR – vol. II: 1306.6352

The picture in 2015



Perez et al.: 1503.00290

Exclusive Higgs decays: $h \to J/\psi\gamma$



$$\Gamma_{h\to J/\psi\gamma} = |(11.9 \pm 0.2)\kappa_\gamma - (1.04 \pm 0.14)\kappa_c|^2 \cdot 10^{-10} \ \text{GeV}$$

[Bodwin et al 13, 14]
[Improved predictions König, Neubert 15]

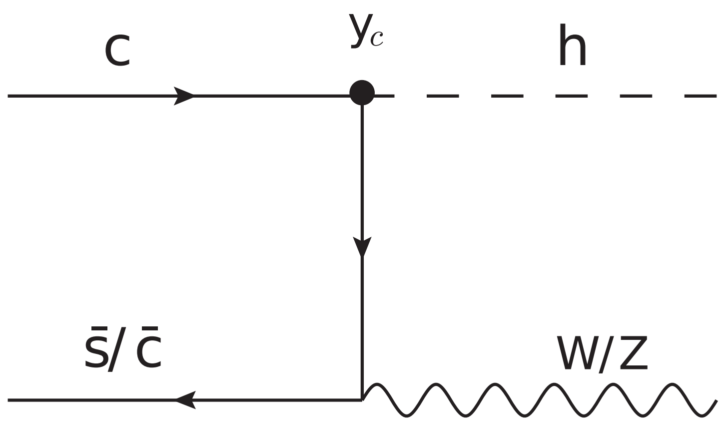
- ATLAS/CMS search:

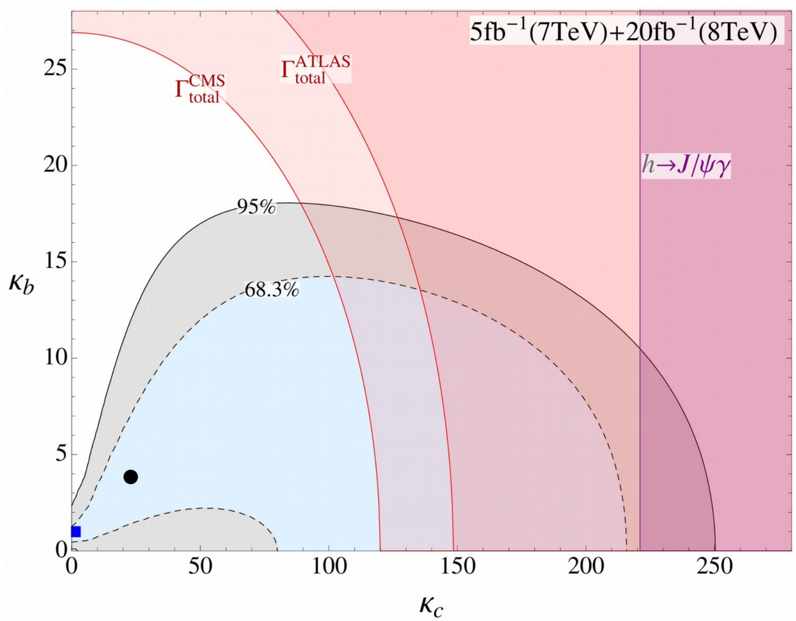
  $\sigma \cdot \mathcal{BR}(h \to J/\psi\gamma) < 33 \ \text{ with } 7.3\,\text{fb}^{-1} \text{ at } 95\% \text{ CL}$

- Can be extended to strange quark (even u & d)

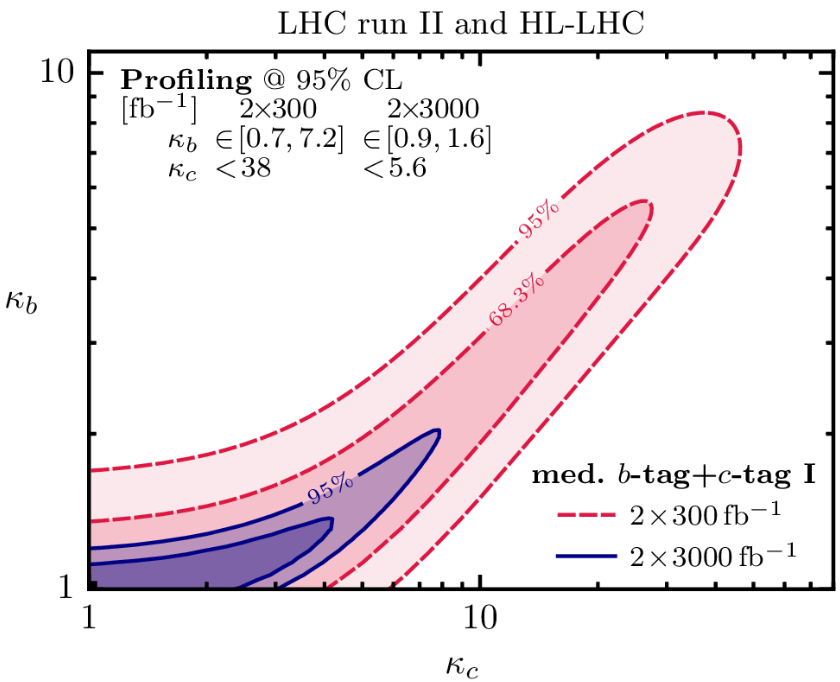
Kagan et al. [1406.1722]

VH production + flavour tagging





Perez et al.: 1503.00290



Perez et al.: 1505.06689

See also: Brivio et al. 1507.02916

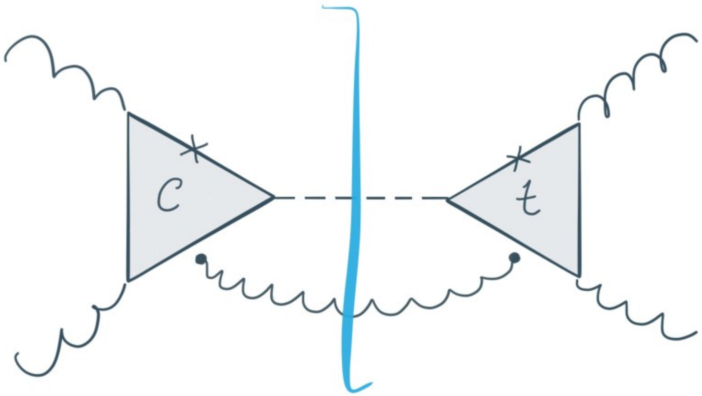
A new idea

- Additional emissions probe the structure of the loop in $gg \to h + jets$
- The loop has a chirality suppression but ...
- The charm is special $\to$ non-Sudakov double logs dynamically enhance its contribution
- The p_T spectra of the Higgs and the jet have been measured by ATLAS & CMS

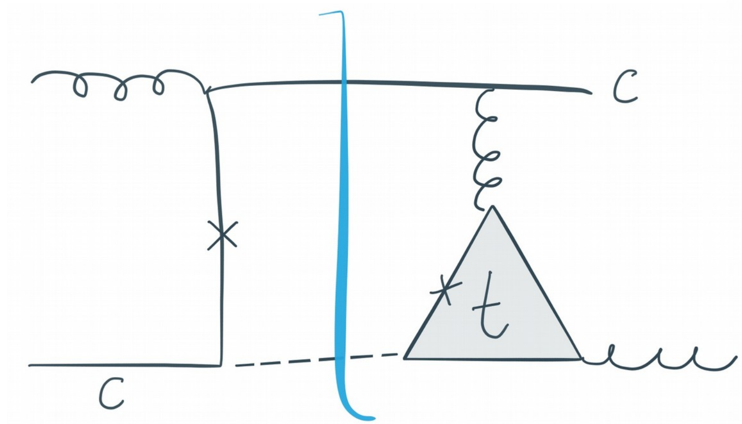
$\Rightarrow$ use differential distributions to probe y_c

See also: Soreq et al. 1606.09621 for similar work on the u and d yukawas

Contributions and their scaling

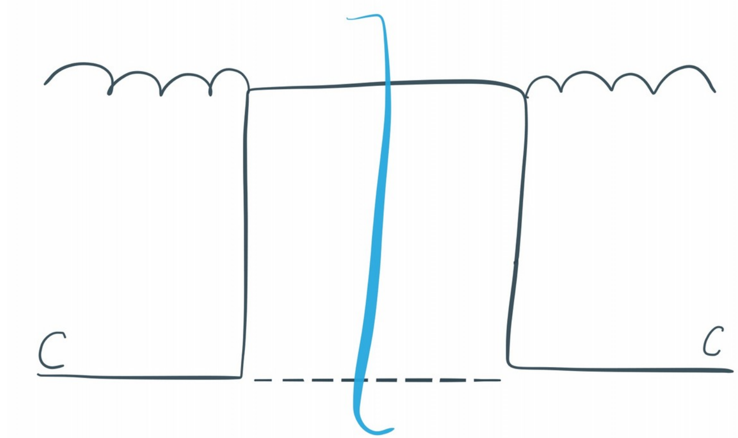


$$\sim \left(\frac{\alpha_s^3}{16\pi^2}\right)\, \kappa_c\, \frac{m_c^2}{m_h^2}\, \ln^2\left(\frac{p_\perp^2}{m_c^2}\right)$$



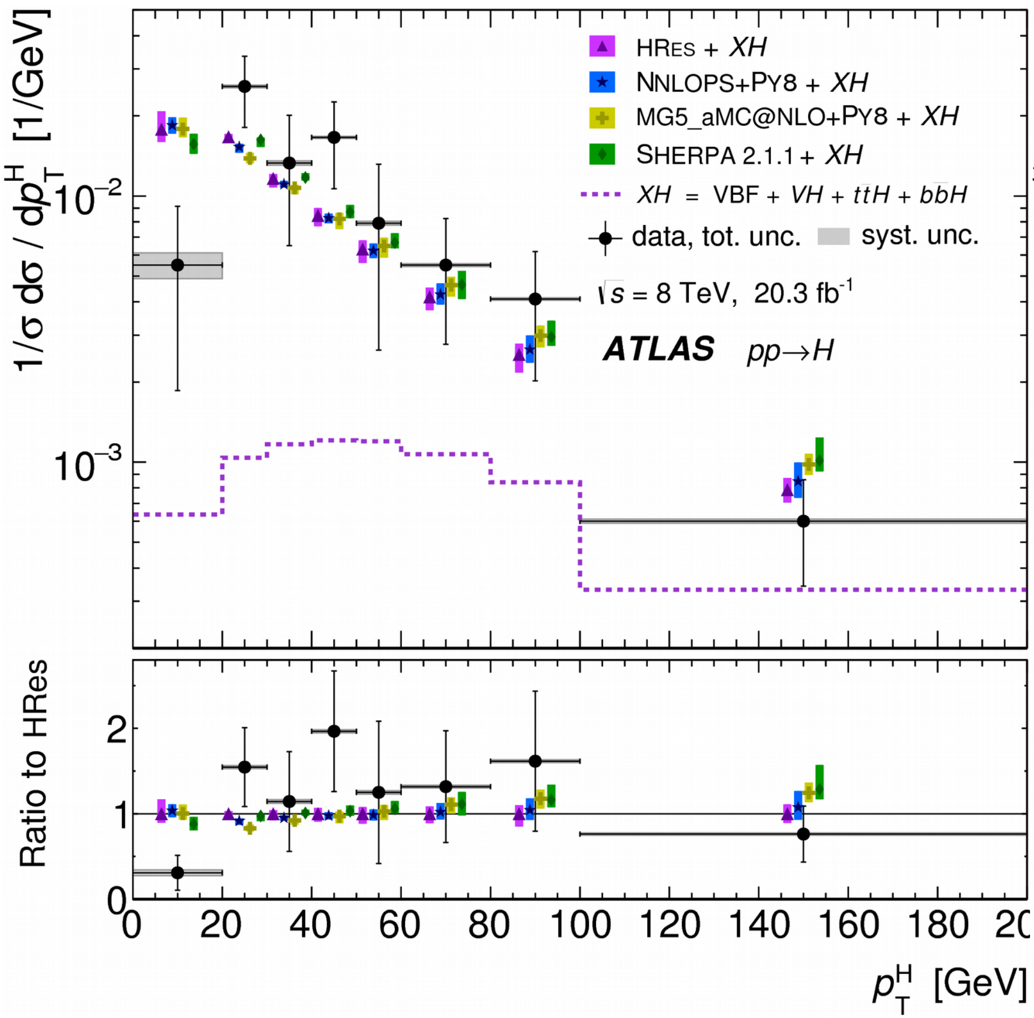
$$\sim \boxed{\left(\frac{\alpha_s^3}{16\pi^2}\right)}\, \kappa_c\, \frac{m_c^2}{m_h^2}$$

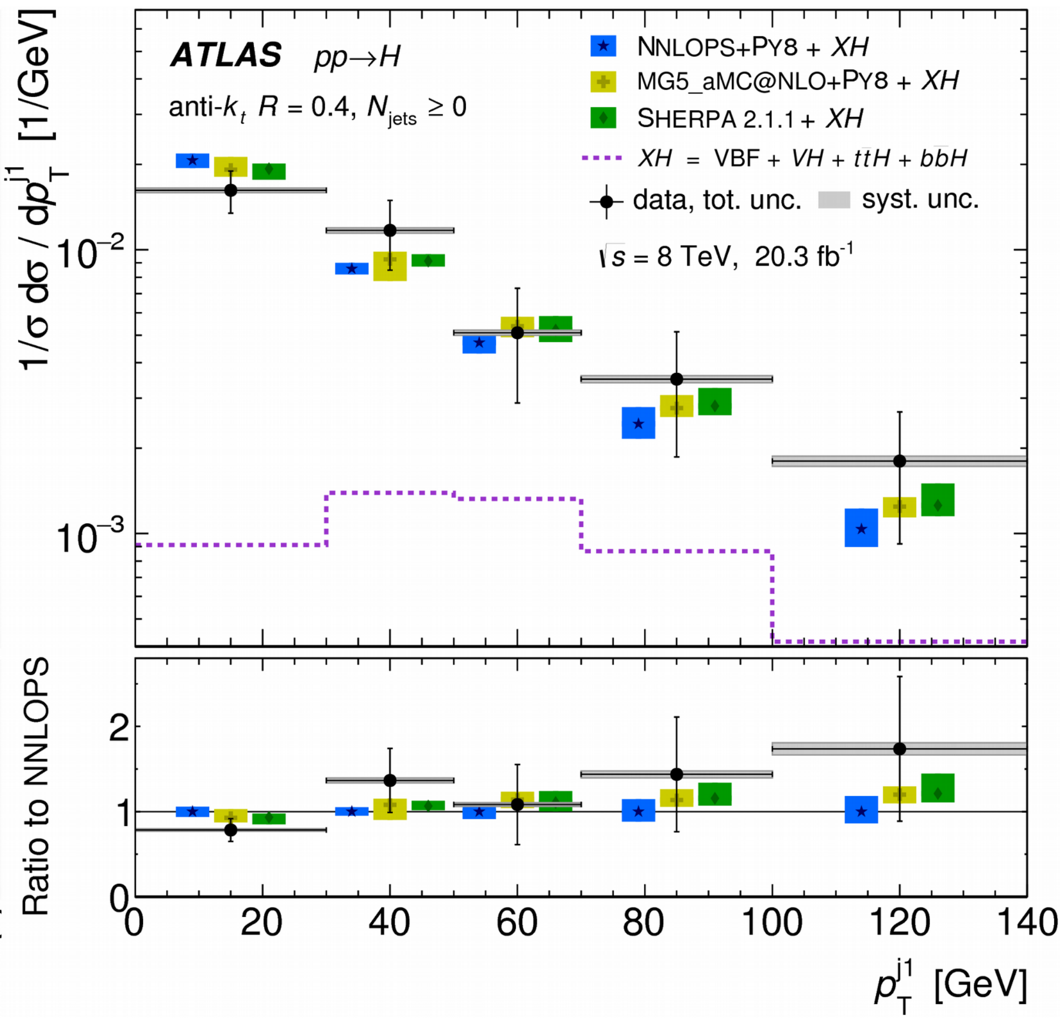
The extra powers of $\left(\frac{\alpha_s}{4\pi}\right)$ are due to the charm PDF



$$\sim \boxed{\left(\frac{\alpha_s^3}{16\pi^2}\right)}\, \kappa_c^2\, \frac{m_c^2}{m_h^2}$$

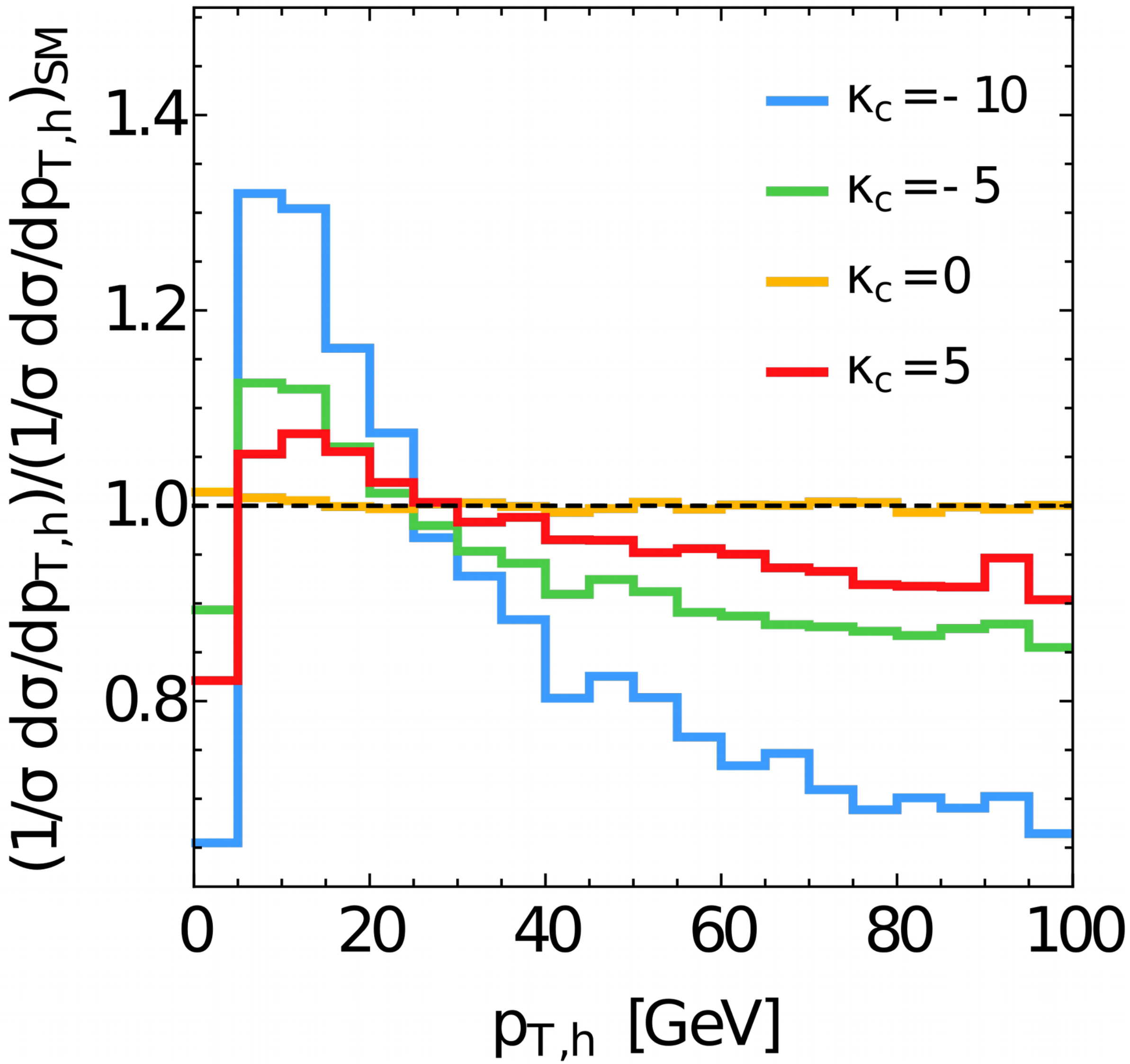
Measured distributions



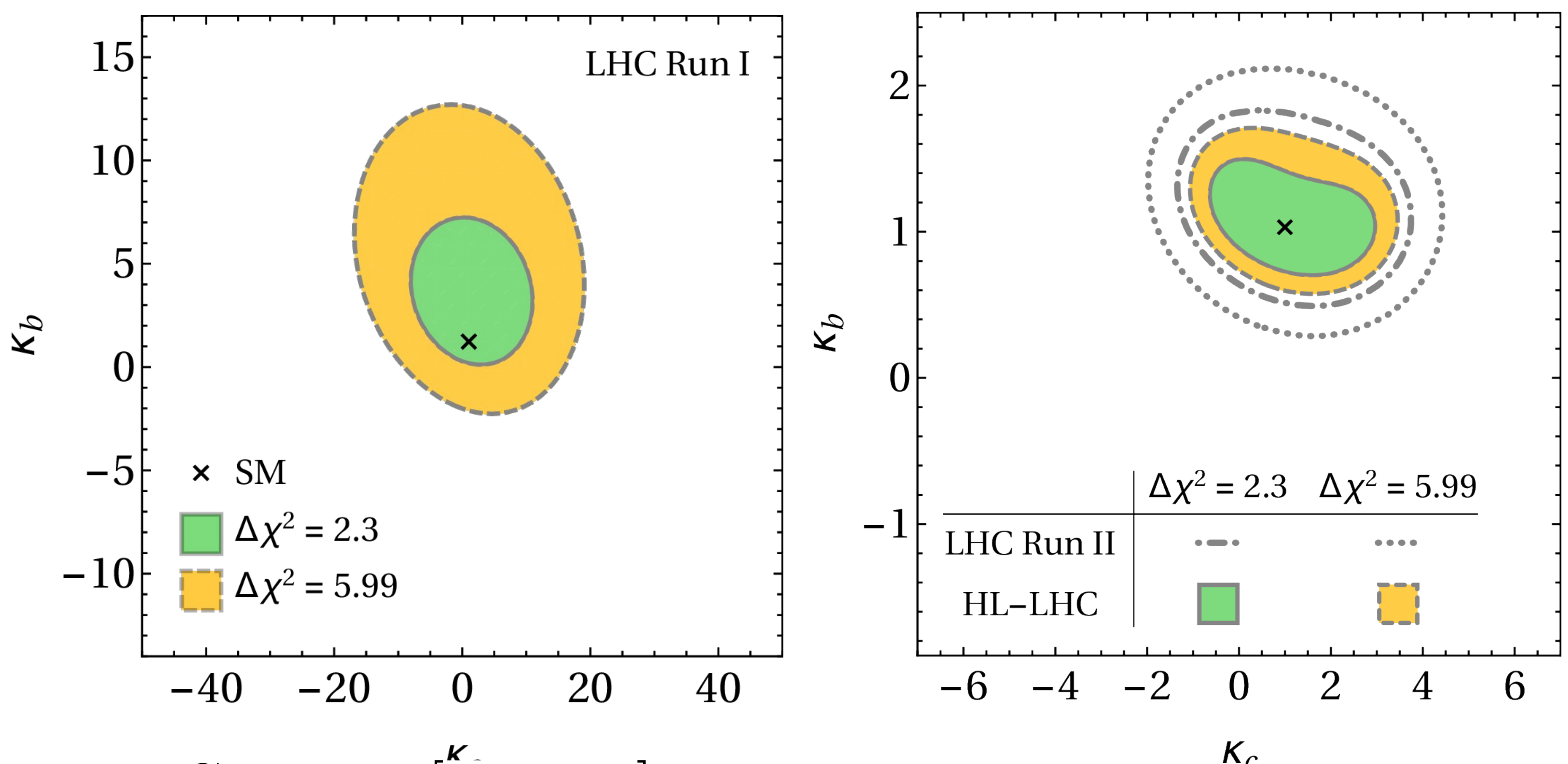


ATLAS: 1504.05833

Normalised distributions



Results



LHC Run I: $[-16, 18]$

LHC Run II: $[-1.4, 3.8]$

HL-LHC: $[-0.6, 3.0]$

95% C.I. after profiling over κ_b

Summary I

- Higgs p_T distribution is sensitive so modified charm Yukawa

- Different channels have different functional dependence on κ_c

- Constraint at HL-LHC on modification of $\kappa_c \in$ [-0.6,3.0] at 95% CL will cut into parameter space of realistic models of flavour (e.g. modified GL)

Part II

Double Higgs Production in VBF

Is EWSB (non-)linearly realised?

$$\Sigma = e^{i\sigma^a \pi^a / v}$$

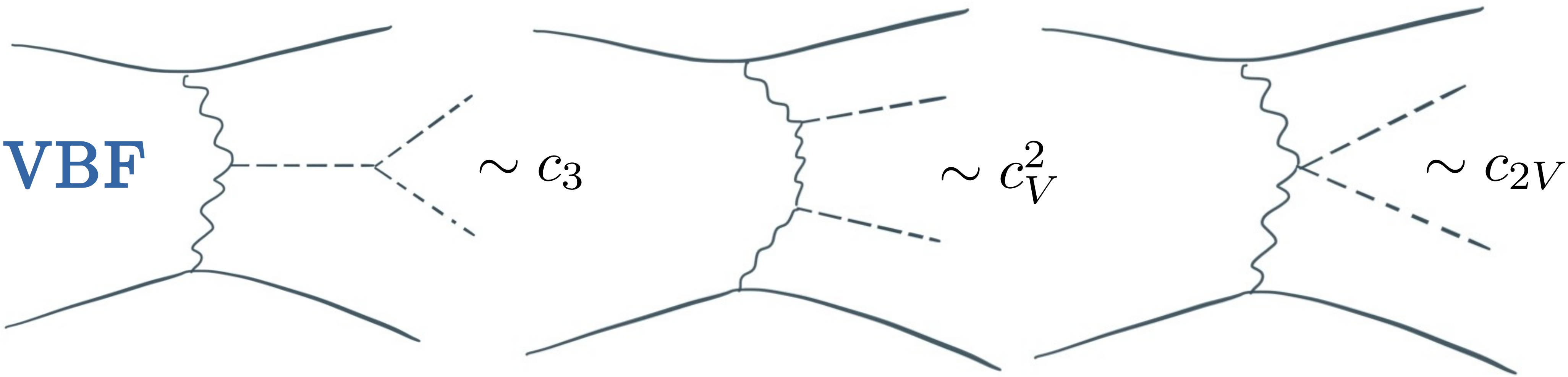
$$\begin{aligned}\mathcal{L} \supset \frac{1}{2}(\partial_\mu h)^2 - V(h) \\ + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \boxed{\Sigma^\dagger} D^\mu \Sigma\right)\left[1 + 2c_V\,\frac{h}{v} + c_{2V}\,\frac{h^2}{v^2} + \ldots\right] \\ - m_i\,\bar{\psi}_{Li}\,\Sigma\left(1 + c_\psi\,\frac{h}{v} + \ldots\right)\psi_{Ri} + \text{h.c.}\,,\end{aligned}$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + c_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + c_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$

- In the minimal SM, linear realization
  → $c_V = c_{2V} = c_3 = 1$ and all … terms vanish
- Measuring $c_{2V} \neq 1$ → non-linearity!

Double Higgs production

VBF



GGF

A concrete example

- In minimal SO(5)/SO(4) models, the couplings $\mathrm{c_V}$ and $\mathrm{c_{2V}}$ are given by

Agashe et al. [hep-ph/0412089]
Contino et al. [hep-ph/0612048]

$$\mathrm{c}_V = \sqrt{1-\xi}\,, \qquad c_{2V} = 1 - 2\xi$$

where $\quad \xi = v^2/f^2$

- And, looking at the longitudinal vector boson scattering we see that

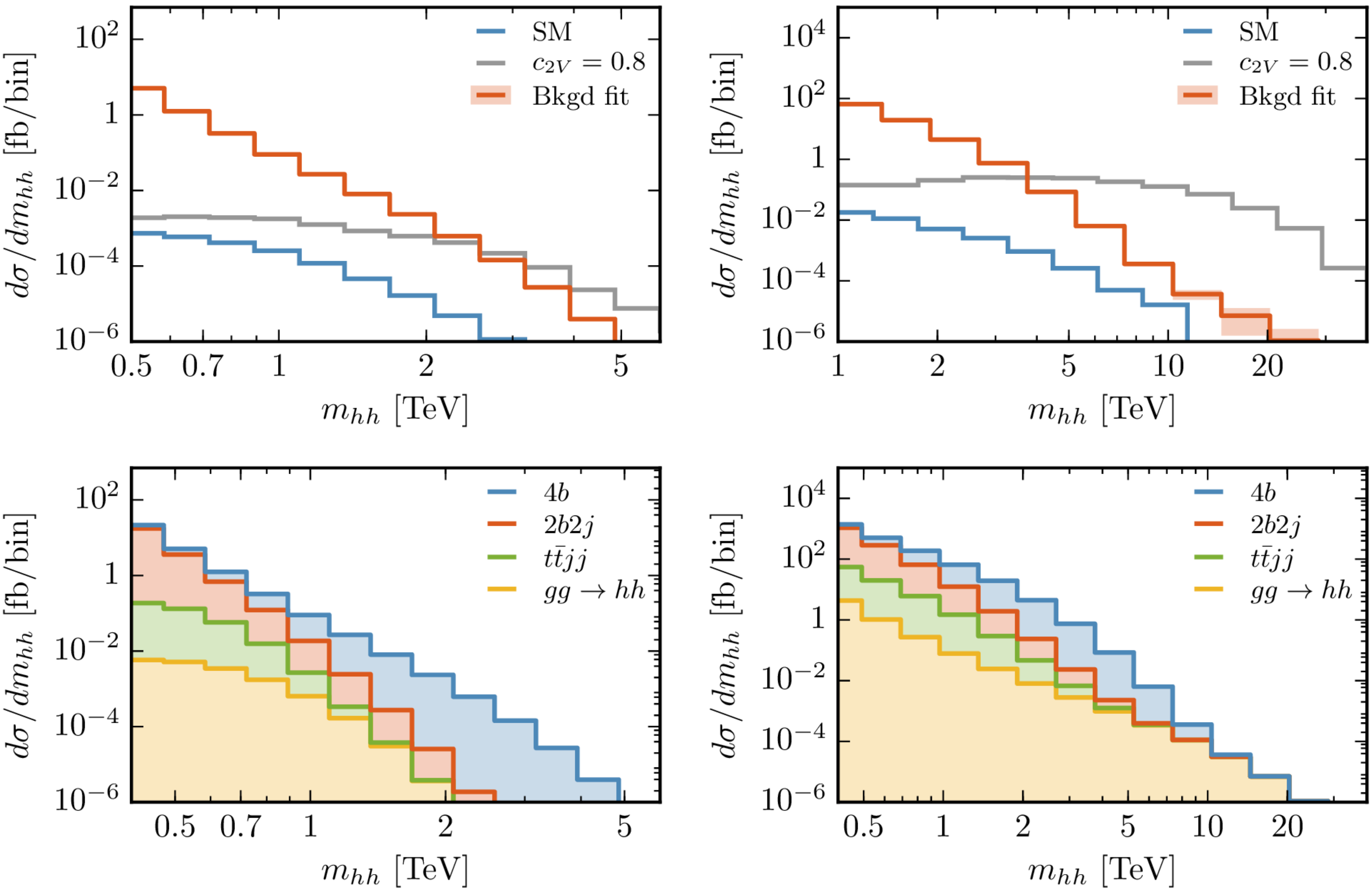
$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

- Choose a benchmark with $\mathrm{c_{2V}} = 0.8$ (to roughly correspond to $\xi = 0.1$ which is at the boundary of exclusion by ATLAS)

ATLAS: [1509.00672]

The hh invariant mass distribution

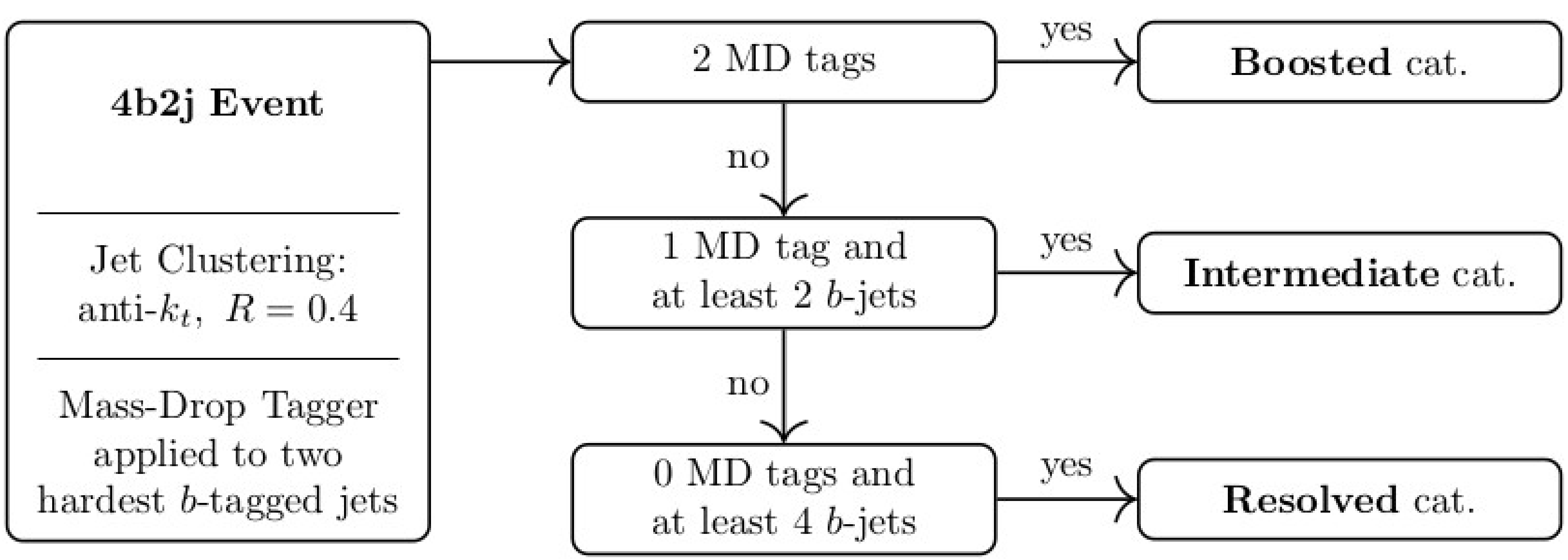
14 TeV **100 TeV**



Scale invariant tagging

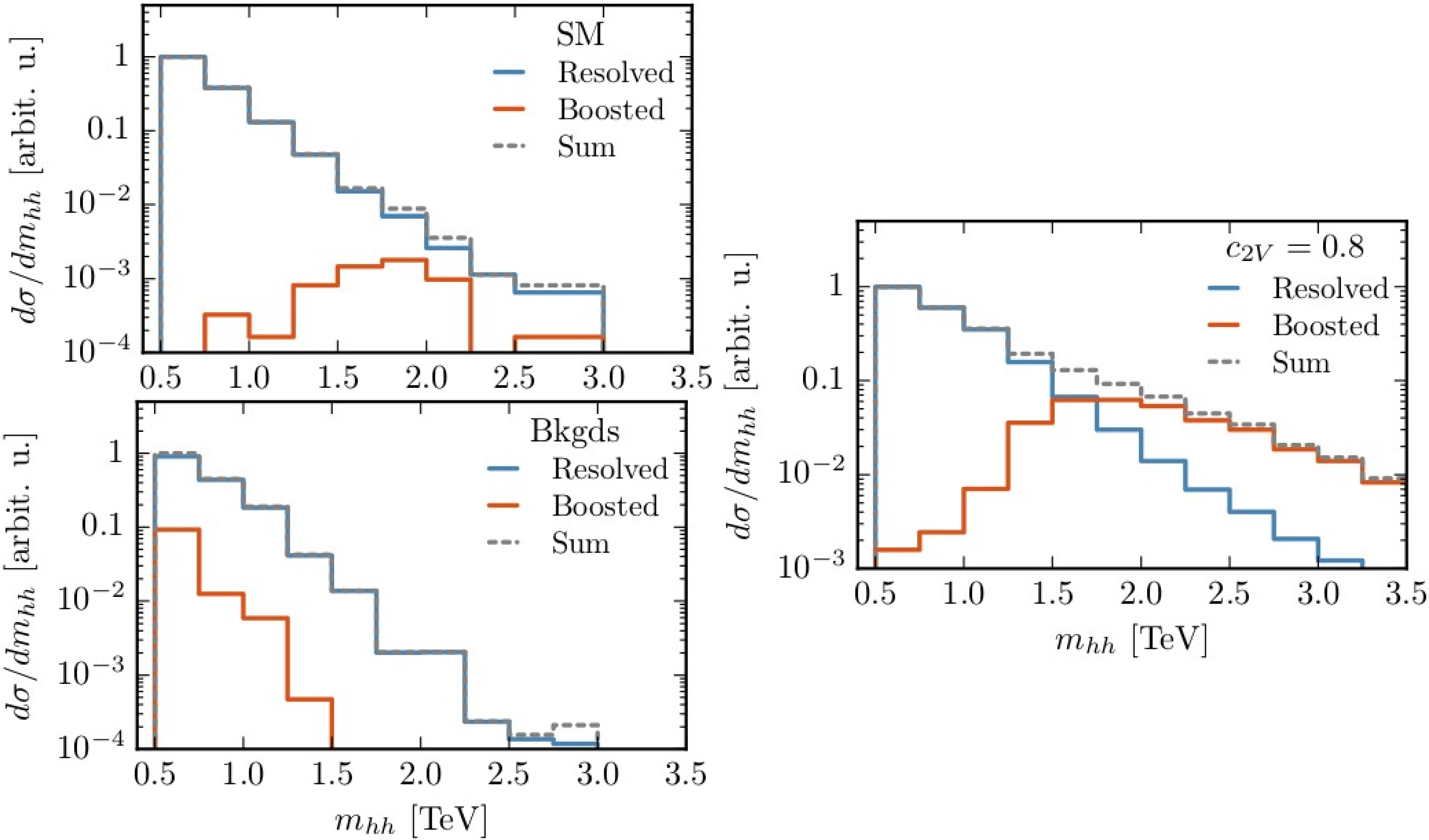
Gouzevitch et al. [1303.6636]

- Key feature: m_{hh} tail is harder when $c_V^2 \neq c_{2V}$ due to unitarity "violation"
- Signal events will have boosted Higgs pairs $\rightarrow$ handle to cut on backgrounds



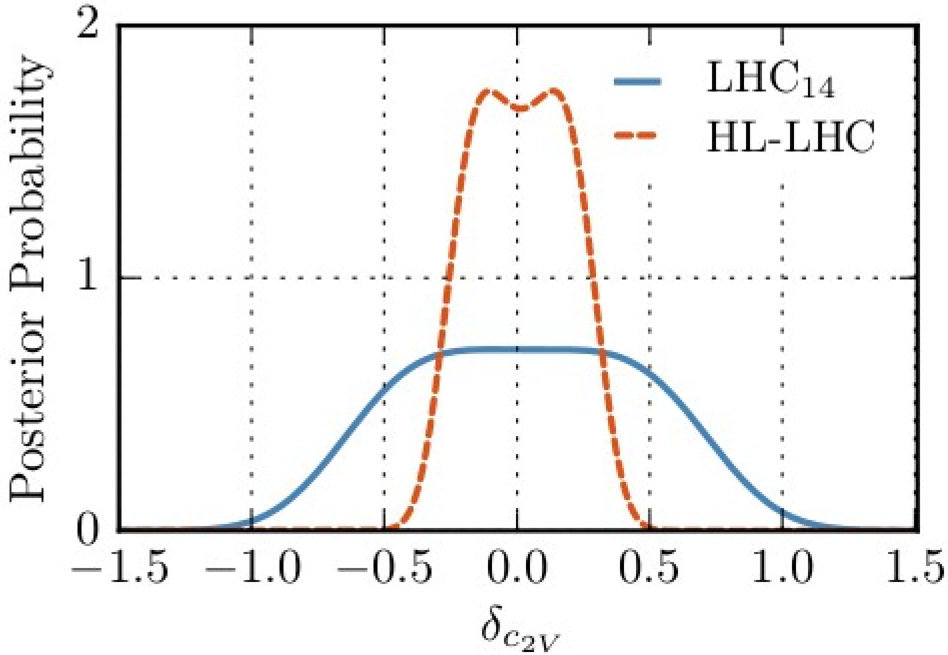
Scale invariant tagging

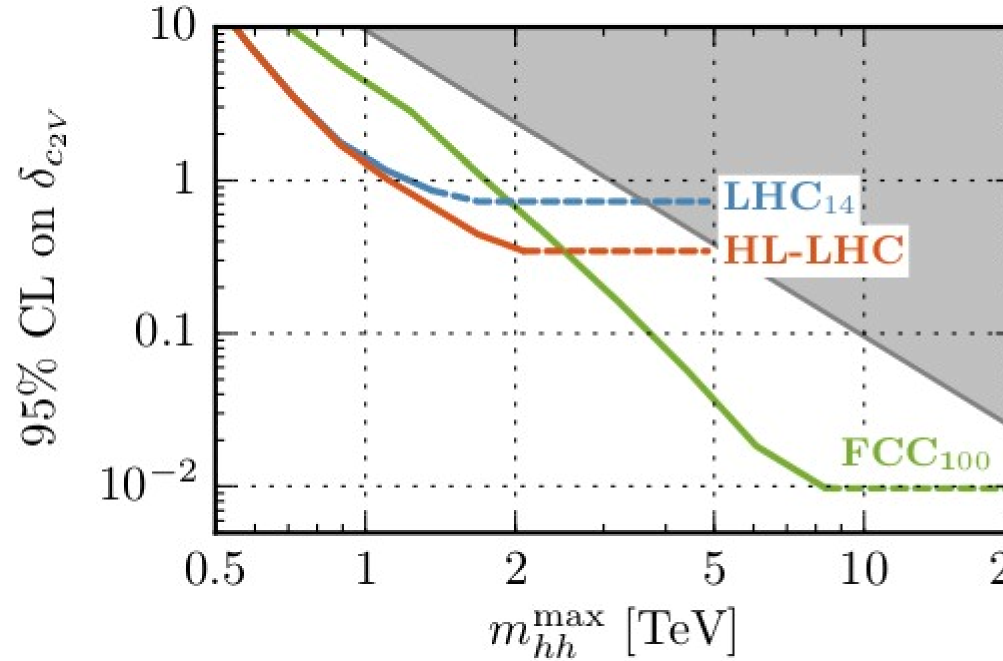
LHC 14 TeV



Probability intervals on δc_{2V}

$$\boxed{\delta_{c_{2V}} \equiv c_{2V} - 1}$$





95% probability

$$\mathrm{LHC}_{14} : [-0.79, 0.86]$$
$$\text{HL-LHC} : [-0.31, 0.35]$$
$$\mathrm{FCC}_{100} : [-0.01, 0.01]$$

Summary II

- Double Higgs production in VBF is useful to constrain hhVV couplings
- Boosted kinematics gives a crucial handle to tame backgrounds
- 30% precision achievable at the HL-LHC reaching the 1% level at a 100 TeV FCC