The Next Frontier in Higgs Coupling Measurements

Fady Bishara

UNIVERSITY OF OXFORD

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University College London

Based on: 1606.09253 FB, U. Haisch, P. Monni, and E. Re
and 1611.03860 FB, R. Contino, and J. Rojo

Motivation

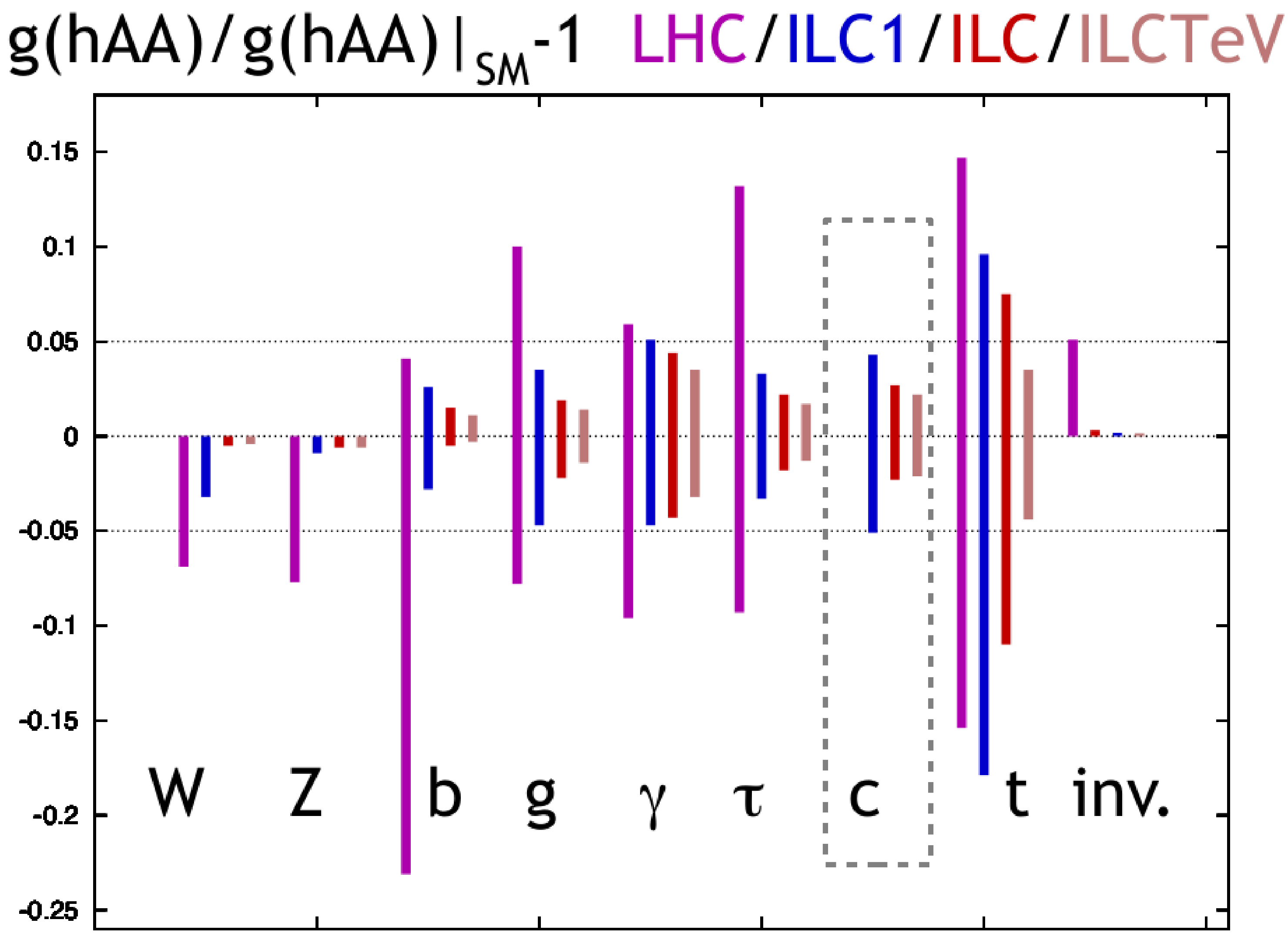
- Does the Higgs couple to first and second generation fermions?
- If it couples to second generation quarks, can the LHC say anything about these couplings?
- Is EWSB in the SM minimal?
  - Is EWSB linearly realised?
- If EWSB is non-linearly realised, can we test this directly? If not, indirectly?

Roadmap for this talk

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

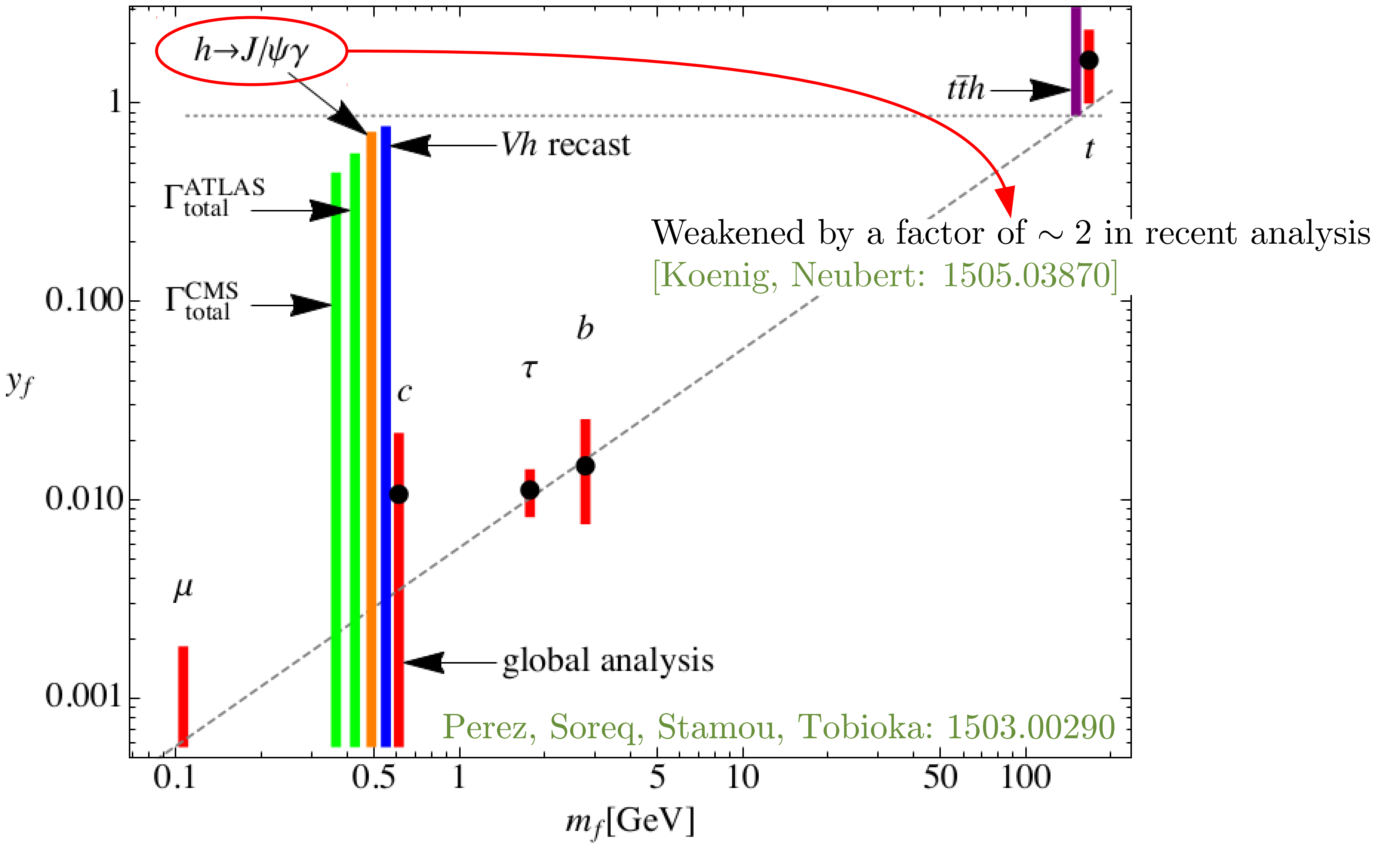
2) The hhVV coupling
   - → Why VBF
   - → How well can the LHC do?
   - → The ultimate precision at an FCC

The projections in 2013



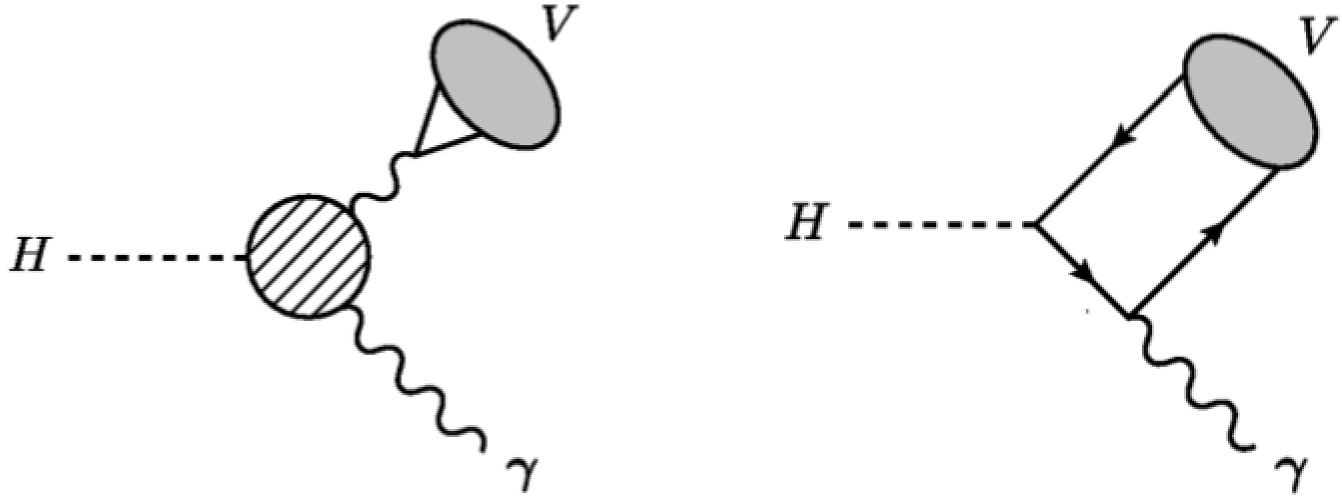
[Peskin: 1207.2516]

The picture in 2015



Can we do better? Yes we can!

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 Koenig, Neubert 15]

- ATLAS/CMS search: [ATLAS 1501.03276 / CMS 1507.03031]

$$\text{BR}(\text{h}\to J/\psi\gamma) < 1.5 \times 10^{-3} \text{ at } 95\% \text{ CL}$$

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

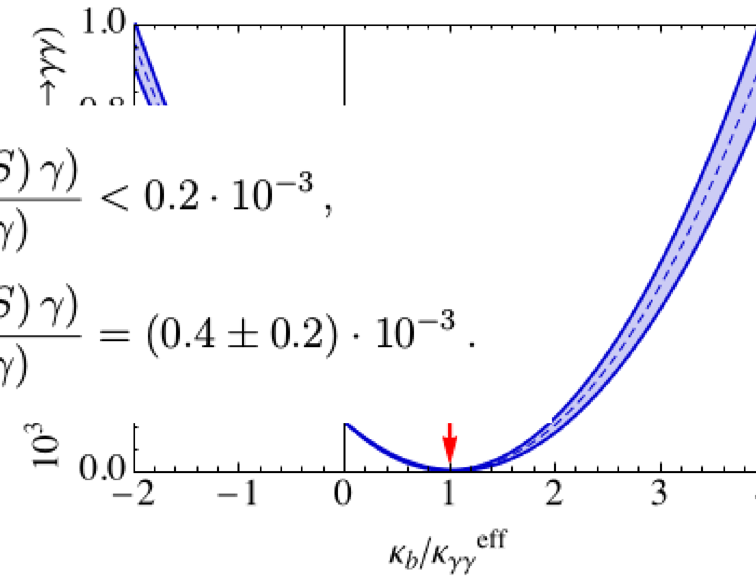
Kagan, Perez, Petriello, Soreq, Stoynev, and Zupan [1406.1722]

The interesting case of $\Upsilon+\gamma$

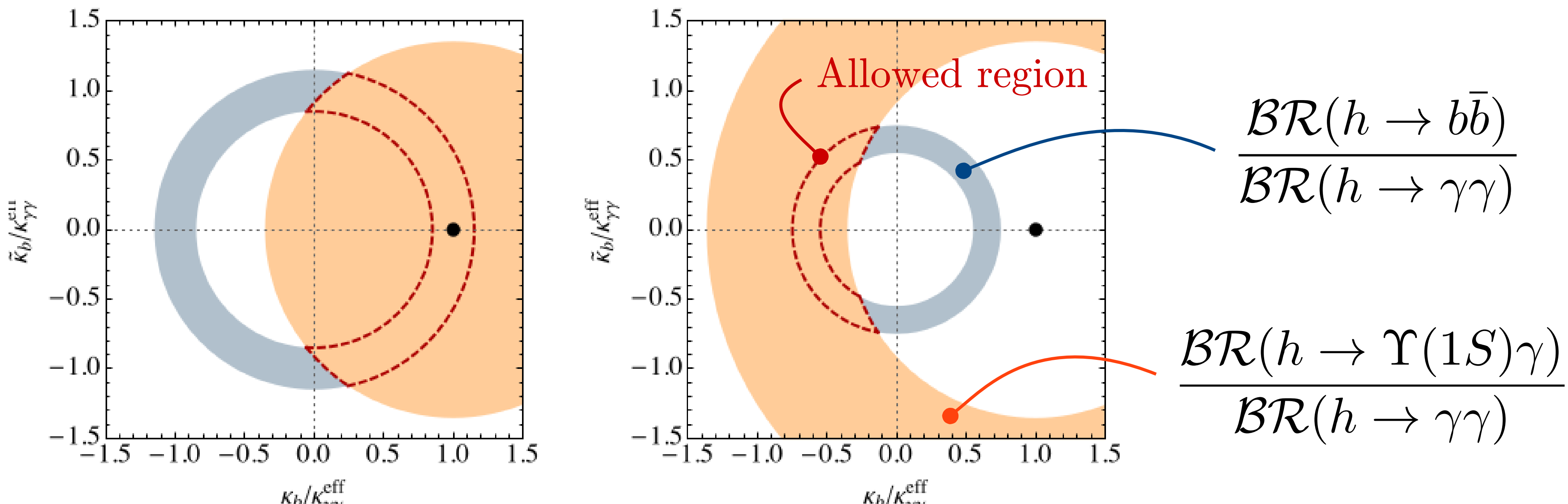
- Interference → sensitive to sign of y_b
- Stror betw constributions → extremely sen- sitive to deviations from SM

$$\text{(I)} \qquad \lambda_{b\gamma} = 1.0 \pm 0.15\,, \qquad \frac{\mathrm{Br}(h\to\Upsilon(1S)\,\gamma)}{\mathrm{Br}(h\to\gamma\gamma)} < 0.2\cdot 10^{-3}\,,$$

$$\text{(II)} \qquad \lambda_{b\gamma} = 0.65 \pm 0.10\,, \qquad \frac{\mathrm{Br}(h\to\Upsilon(1S)\,\gamma)}{\mathrm{Br}(h\to\gamma\gamma)} = (0.4\pm0.2)\cdot 10^{-3}\,.$$



Konig, Neubert: 1505.03870



The interesting case of $\Upsilon+\gamma$

$$\lambda_{b\gamma} \equiv \sqrt{\left|\frac{\kappa_b}{\kappa_{\gamma\gamma}^{\text{eff}}}\right|^2 + \left|\frac{\tilde{\kappa}_b}{\kappa_{\gamma\gamma}^{\text{eff}}}\right|^2}\,.$$

$$\text{(I)} \qquad \lambda_{b\gamma} = 1.0 \pm 0.15\,, \qquad \frac{\text{Br}(h \to \Upsilon(1S)\,\gamma)}{\text{Br}(h \to \gamma\gamma)} < 0.2 \cdot 10^{-3}\,,$$

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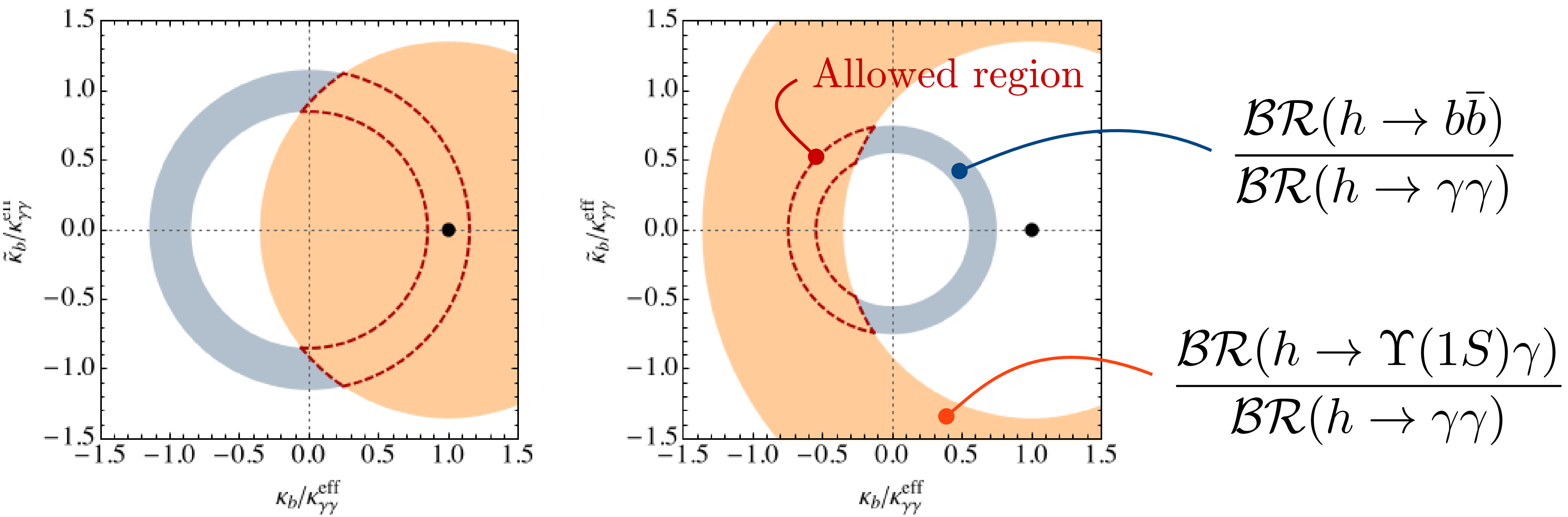
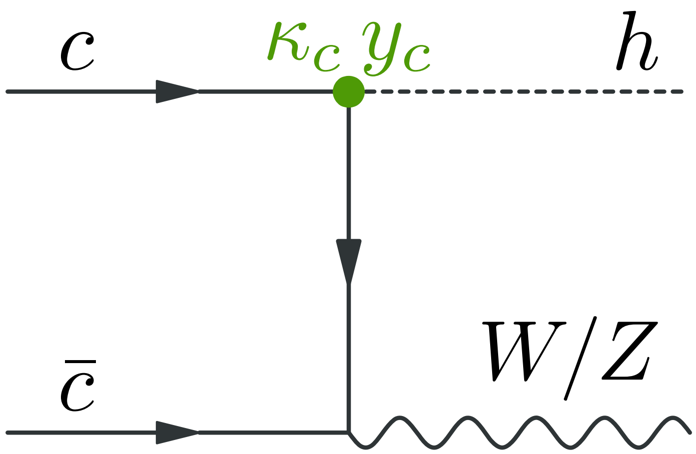
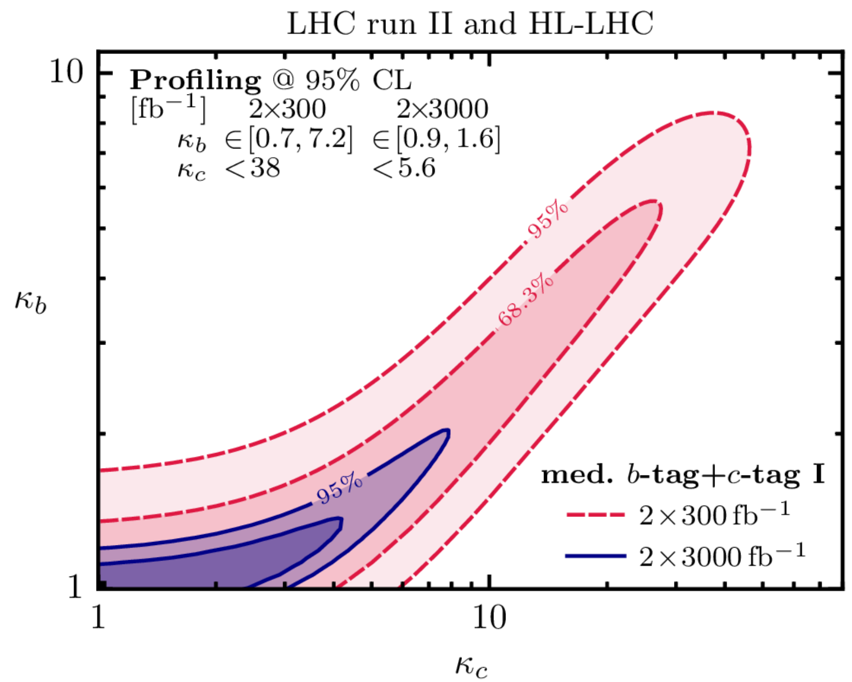
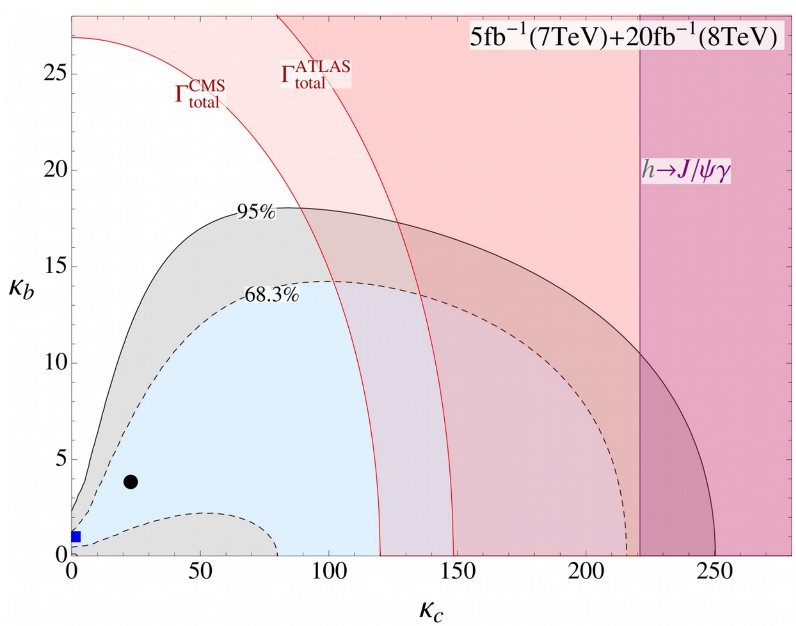


VH production + flavour tagging





Perez et al.: 1505.06689



Perez et al.: 1503.00290

$$\left(\mu_b + \frac{\mathrm{BR}^{\mathrm{SM}}_{c\bar{c}}}{\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\mu_c\right) \Big/ \left(1 + \frac{\mathrm{BR}^{\mathrm{SM}}_{c\bar{c}}}{\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\right)$$

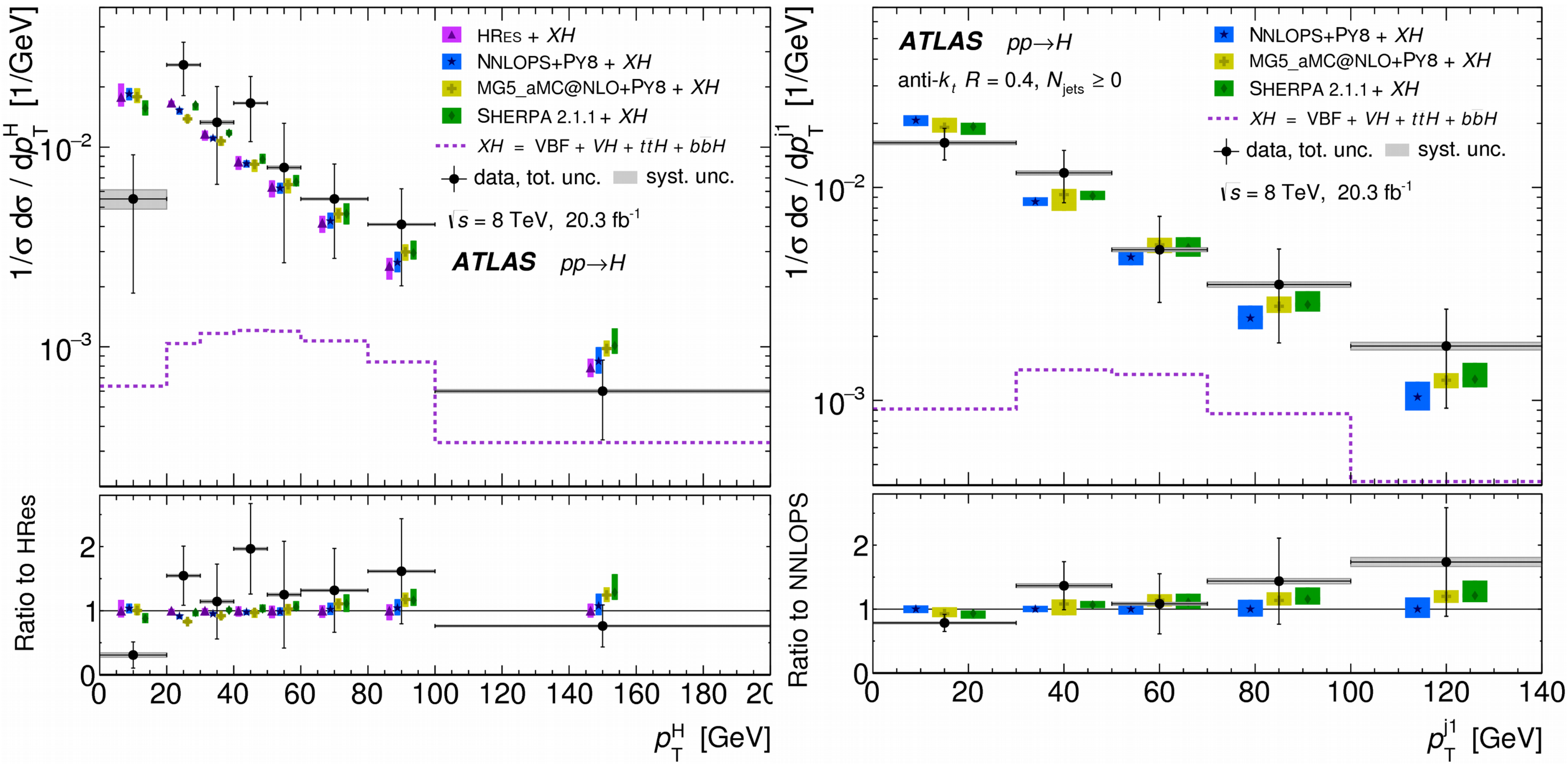
See also: [Brivio, Goertz, Isidori 1507.02916]

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

See also: [Soreq, Zhu, & Zupan: 1606.09621] for similar work on the u and d yukawas

Measured distributions



ATLAS: 1504.05833

Contributions and their scaling

- Many contributions with different scaling in the $m_Q \lesssim p_T \lesssim m_h$ region

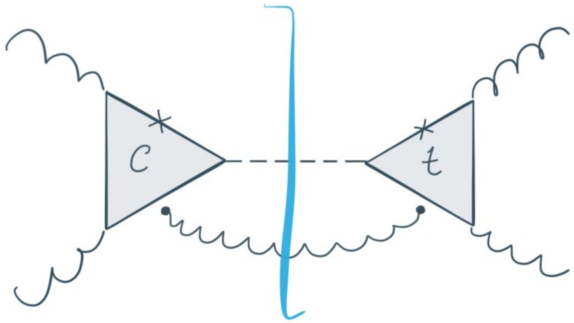
- The quark initiated contribution dominates for $\kappa_Q \gg 1$ [Soreq, Zhu, & Zupan: 1606.09621]

- Normalized distributions in this regime are sensitive to light d.o.f. but heavy new physics can affect the tail

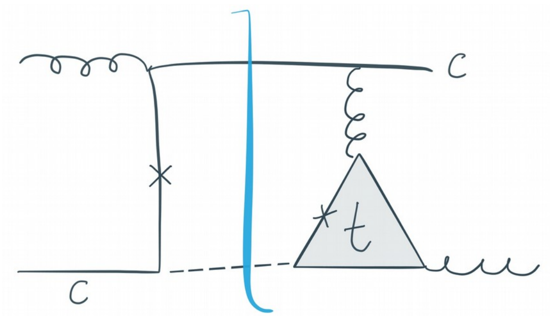
[Banfi, Martin, Sanz: 1606.09621]
[Buschmann, Goncalves, Kuttimalai, Schonherr, Krauss, Plehn: 1410.5806]
[Buschmann, Englert, Goncalves, Plehn, Spannowsky: 1405.7651] + others

$\Rightarrow$ use normalized differential distributions to probe light quark Yukawas

Contributions and their scaling

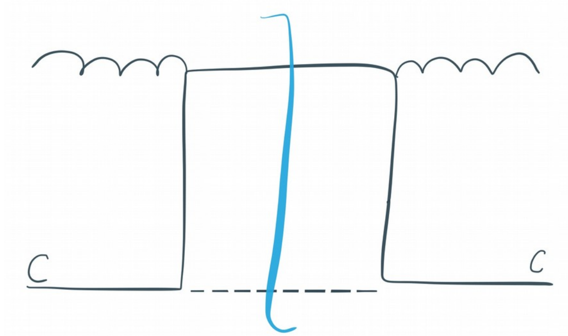


$$\sim \left(\frac{\alpha_s^3}{16\pi^2}\right) \kappa_c \, \frac{m_c^2}{m_h^2} \ln^2\left(\frac{p_\perp^2}{m_c^2}\right)$$



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

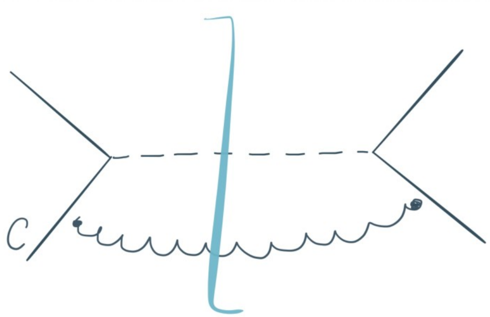
{ Absent in the $n_f = 4, 5$ schemes }



$$\sim \left(\frac{\alpha_s^2}{4\pi}\right) \kappa_c^2 \, \frac{m_c^2}{m_h^2}$$

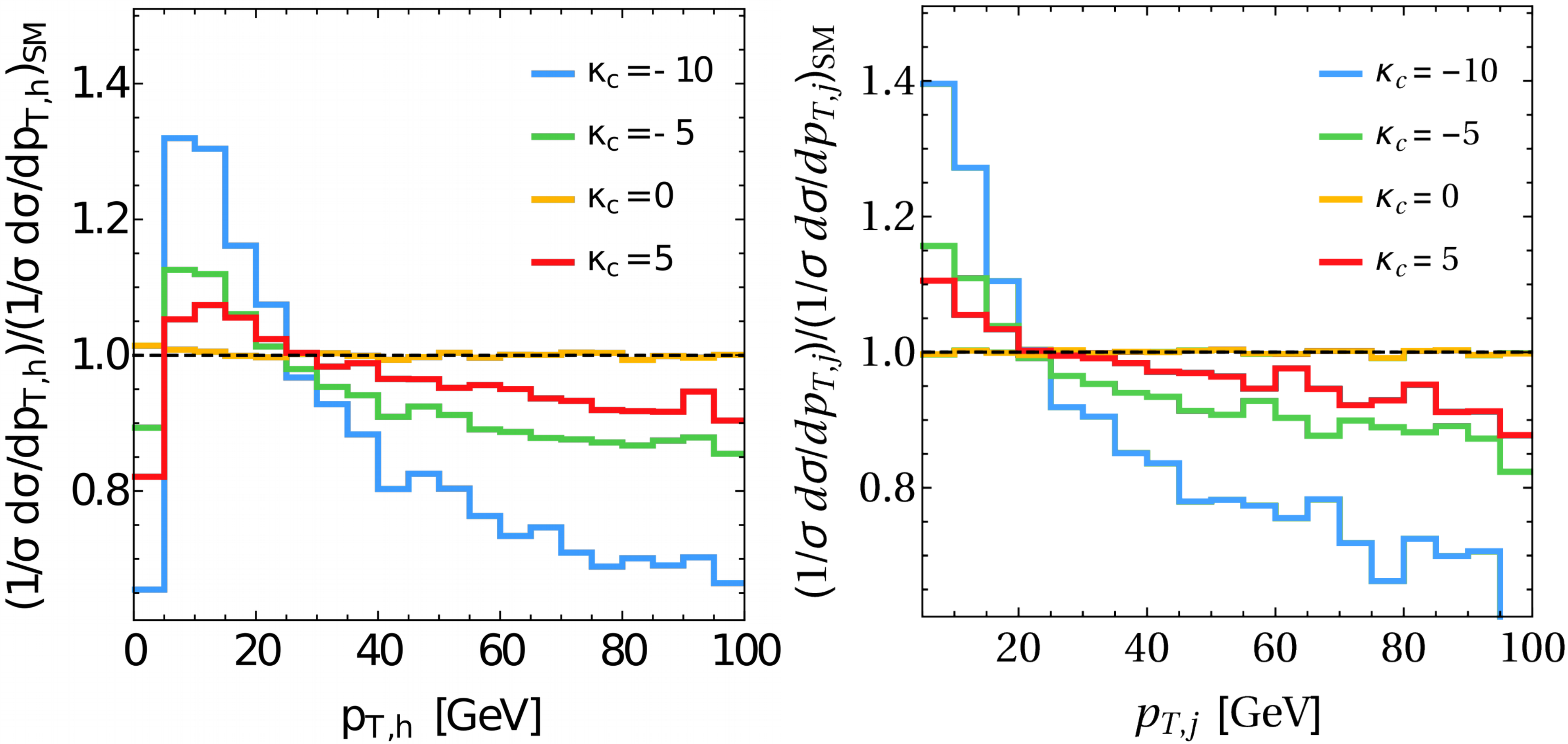
The extra powers of $\left(\frac{\alpha_s}{4\pi}\right)$ are due to the charm PDF

[Sullivan, Nadolsky: hep-ph/0111358]



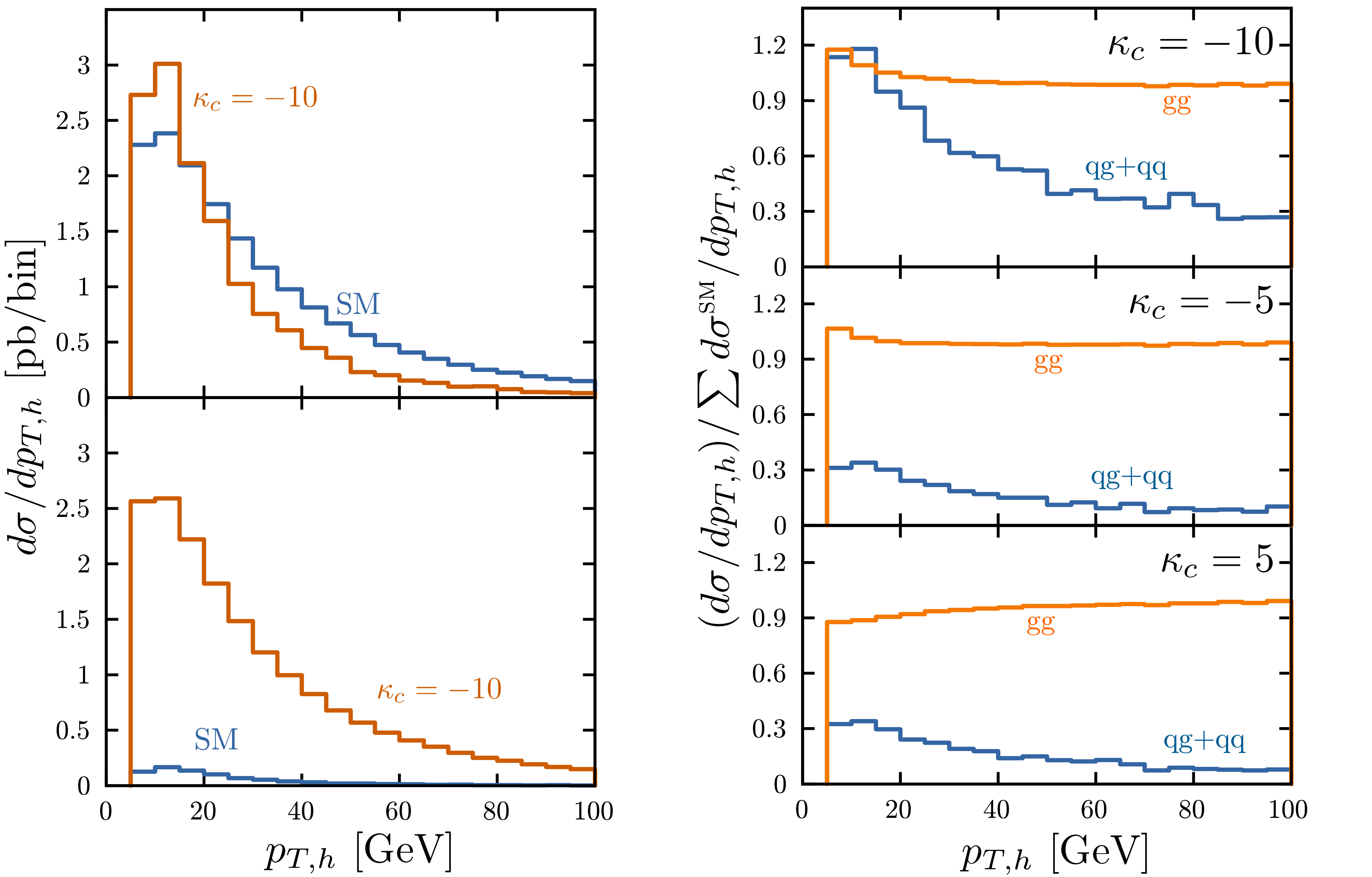
$$\sim \left(\frac{\alpha_s^3}{16\pi^2}\right) \kappa_c^2 \, \frac{m_c^2}{m_h^2}$$

Normalised distributions @ 8 TeV



$\mathcal{O}(1)$ deviations in $\kappa_c \rightarrow \;\sim$ few % effect on the shape

Contributions to spectrum @ 8 TeV



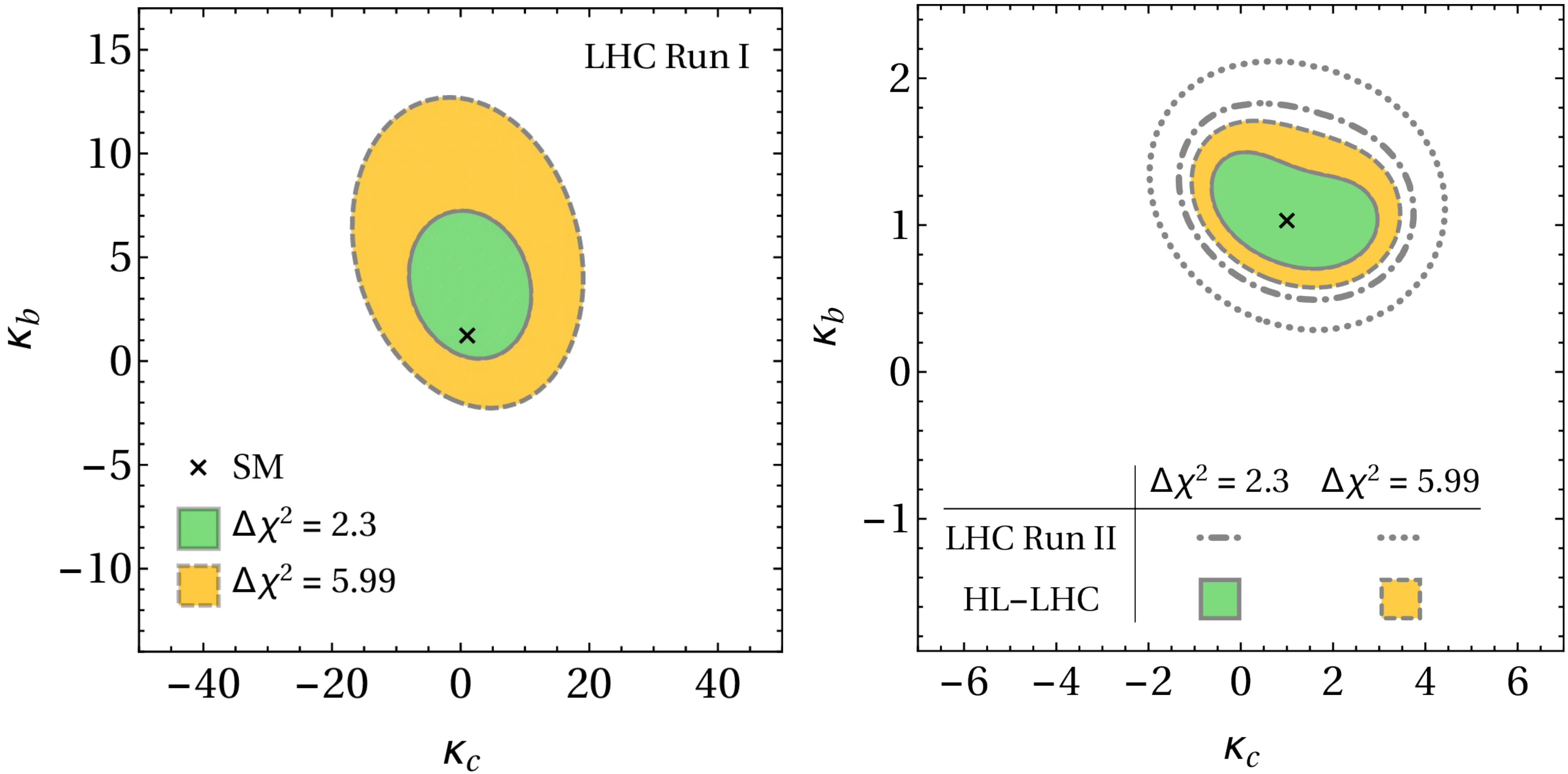
Quark mass effects

- Exact mass dependence only known at L.O.
  [Ellis, Hinchliffe, Soldate, and van der Bij: Nuc.Phys. B297 (1988)]
  [Baur and Glover: Nuc.Phys. B339 (1990)]
- L.O. differential distributions include non-factorizing terms $\sim \ln^2(p_\perp^2/m_Q^2)$
  [Mantler, Wiesemann [1210.8263], [Banfi, Monni, and Zanderighi: 1308.4634], [Grazzini and Sargsyan 1306.4581]
- These $\ln^2$ terms do not exist for $p_T < m_Q$
- Recent progress in the direction of NLO, NLL

  → Soft double Logs resummed in the abelian limit [Melnikov, Penin: 1602.09020]

  → Two loop virtual corrections in the $m_Q \to 0$ limit [Melnikov, Tancredi, Wever: 1610.03747 and 1702.00426]

Results for $p_{\mathrm{T,h}}$

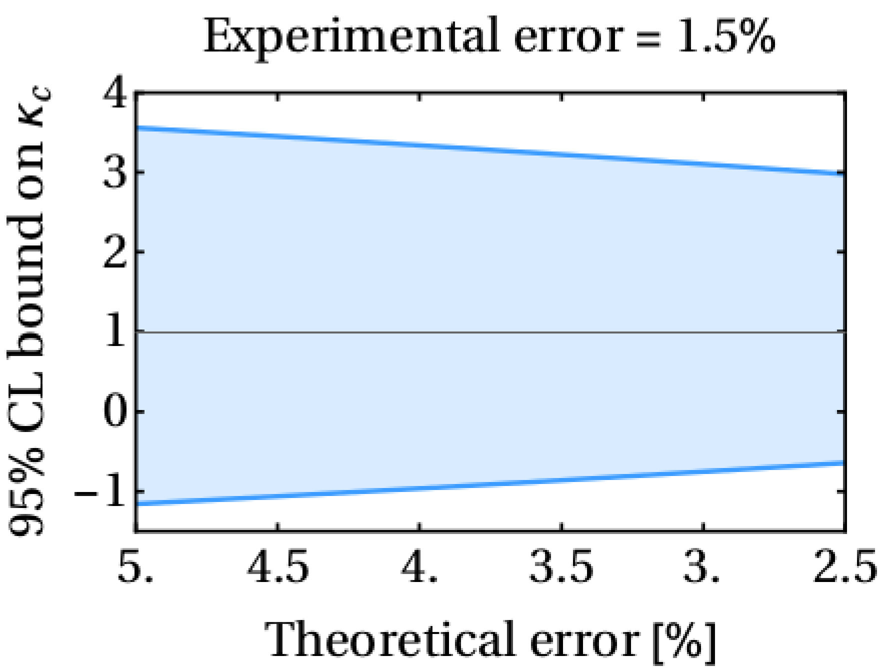


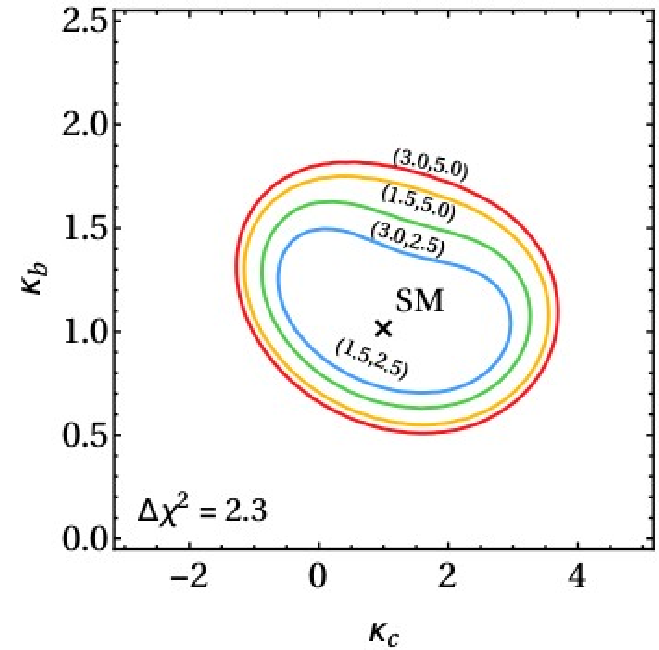
LHC Run I: $[-16, 18]$

LHC Run II: $[-1.4, 3.8]$ 95% C.I. after profiling over κ_b

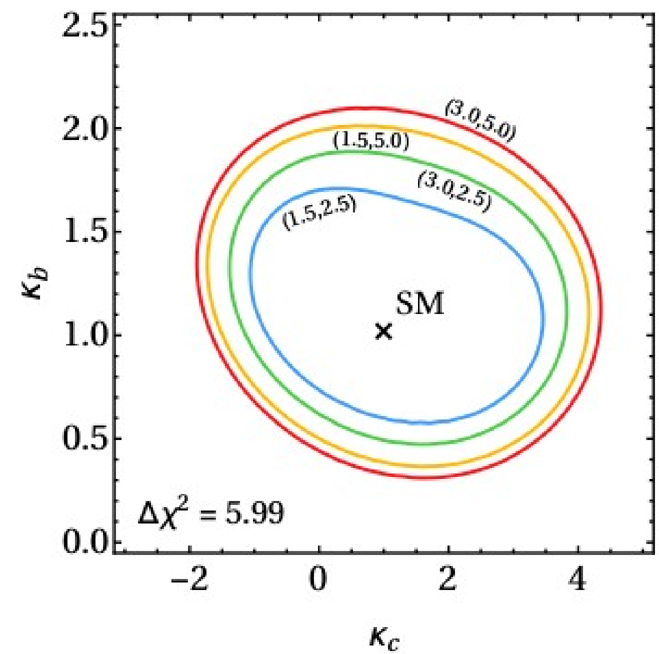
HL-LHC: $[-0.6, 3.0]$

Varying the systematic errors...





	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]



Yukawa modifications in flavour models

Model	κ_t	$\kappa_{c(u)}/\kappa_t$	$\tilde{\kappa}_t/\kappa_t$	$\tilde{\kappa}_{c(u)}/\kappa_t$
SM	1	1	0	0
MFV	$1+\frac{\text{Re}(a_u v^2+2b_u m_t^2)}{\Lambda^2}$	$1-\frac{2\,\text{Re}(b_u)m_t^2}{\Lambda^2}$	$\frac{\text{Im}(a_u v^2+2b_u m_t^2)}{\Lambda^2}$	$\frac{\text{Im}(a_u v^2)}{\Lambda^2}$
NFC	$V_{hu}\, v/v_u$	1	0	0
MSSM	$\cos\alpha/\sin\beta$	1	0	0
FN	$1+\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$	$1+\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$	$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$	$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$
GL2	$\cos\alpha/\sin\beta$	$\simeq 3(7)$	0	0
RS	$1-\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\bar{Y}^2\right)$	$\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\bar{Y}^2\right)$	$\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\bar{Y}^2\right)$
pNGB	$1+\mathcal{O}\left(\frac{v^2}{f^2}\right)+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$1+\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v^2}{M_*^2}\right)$

- Generally, modifications $\sim v^2/\Lambda^2 \ll \mathcal{O}(1)$
- Exception: GL2 (modified GL) where

[Giudice, Lebedev: 0804.1753]
[FB, Brod, Uttayarat, Zupan: 1504.04022]
[Carena, Gemmler, Bauer: 1506.01719, 1512.03458]

$$\mathcal{L}_{\text{yuk}} = c_{ij}^f \left(\frac{H_1^\dagger H_1}{M^2}\right)^{n_{ij}^f} \bar{F}_L^i\, f_R^j\, H_{1,2}$$

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

VBF double Higgs production in 4b final state

Is EWSB (non-)linearly realised?

[Grinstein and Trott: [0704.1505]
[Contino, Grojean, Moretti, Piccinini, Rattazzi: 1002.1011]

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

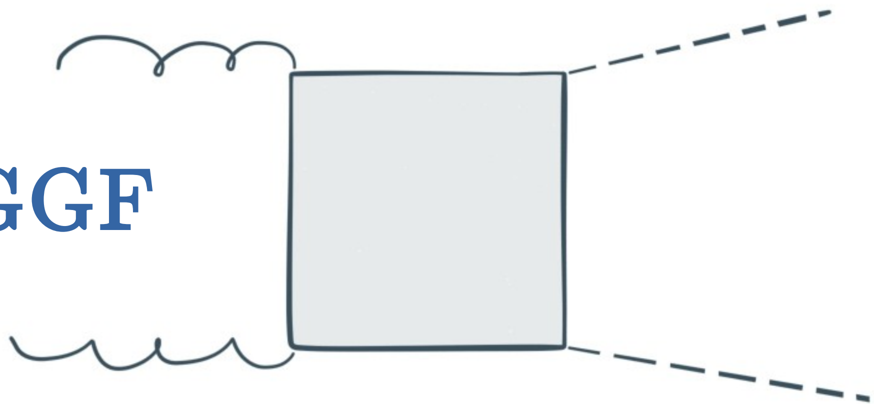
$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu h)^2 - V(h)$$
$$+ \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2c_V \frac{h}{v} + c_{2V}\frac{h^2}{v^2} + \dots\right]$$
$$- m_i \bar{\psi}_{Li}\, \Sigma \left(1 + c_\psi \frac{h}{v} + \dots\right)\psi_{Ri} + \mathrm{h.c.}\,,$$

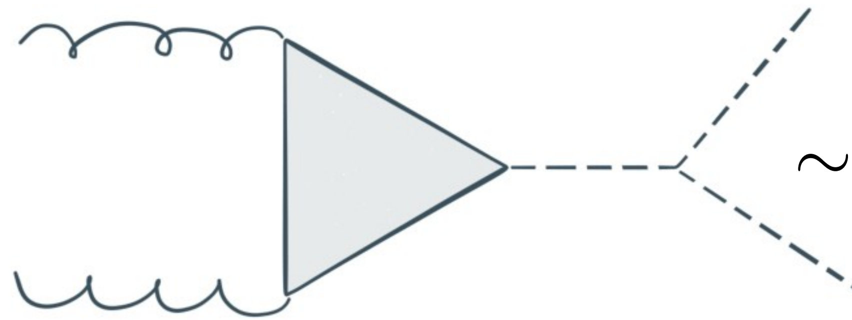
$$V(h) = \frac{1}{2}m_h^2 h^2 + c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + c_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right) h^4 + \dots$$

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

Double Higgs production

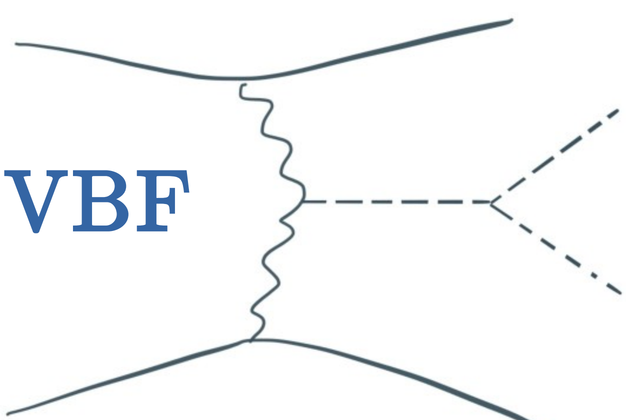
GGF



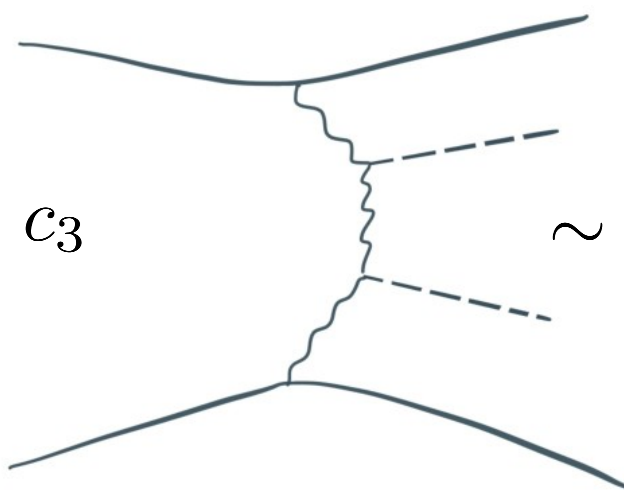


$\sim c_3$

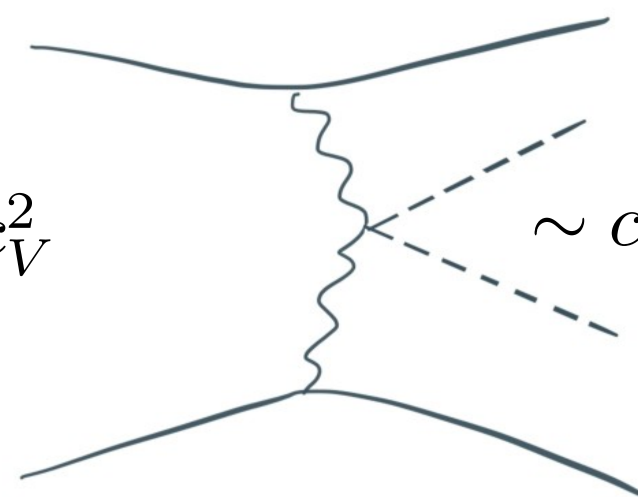
VBF



$\sim c_3$



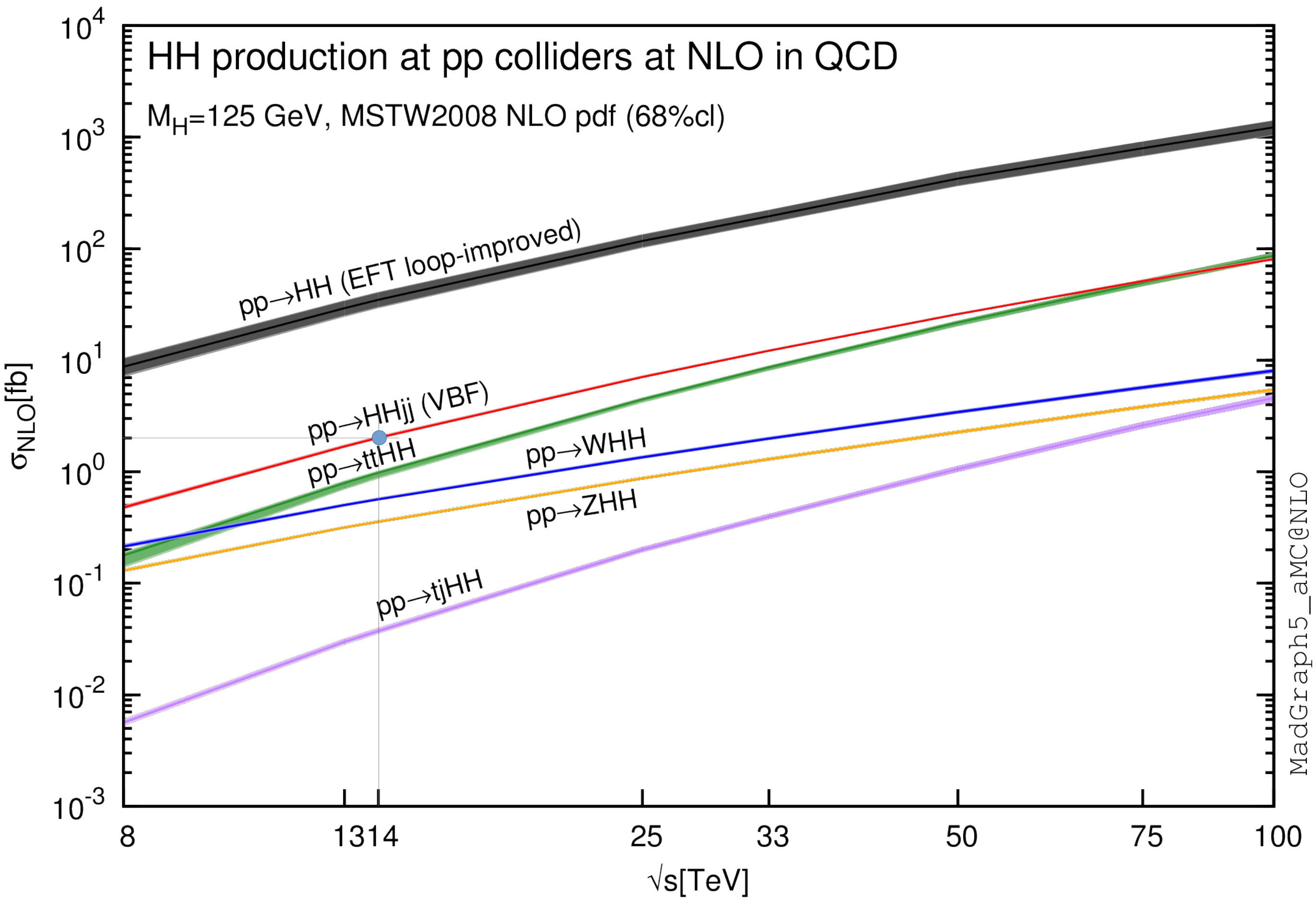
$\sim c_V^2$



$\sim c_{2V}$

HH production at pp colliders

- VBF cross-section at the LHC is small ~ 2 [fb] w/o $\mathcal{BR}$s
- But, is a unique probe of the EWSB mechanism



Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro: 1401.7340

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]

$$c_V = \sqrt{1-\xi}\,, \qquad c_{2V} = 1 - 2\xi$$

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

- 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]

Kinematic cuts & b-tagging

Final cuts:

			14 TeV	100 TeV
Acceptance cuts		p_{T_j} (GeV) $\geq$	25	40
		p_{T_b} (GeV) $\geq$	25	35
		$\lvert\eta_j\rvert \leq$	4.5	6.5
		$\lvert\eta_b\rvert \leq$	2.5	3.0
VBF cuts		$\lvert\Delta y_{jj}\rvert \geq$	5.0	5.0
		m_{jj} (GeV) $\geq$	700	1000
	Central jet veto:	$p_{T_{j_3}}$ (GeV) $\leq$	45	65
		m_{hh} (GeV) $\geq$	500	1000

B-tagging parameters:

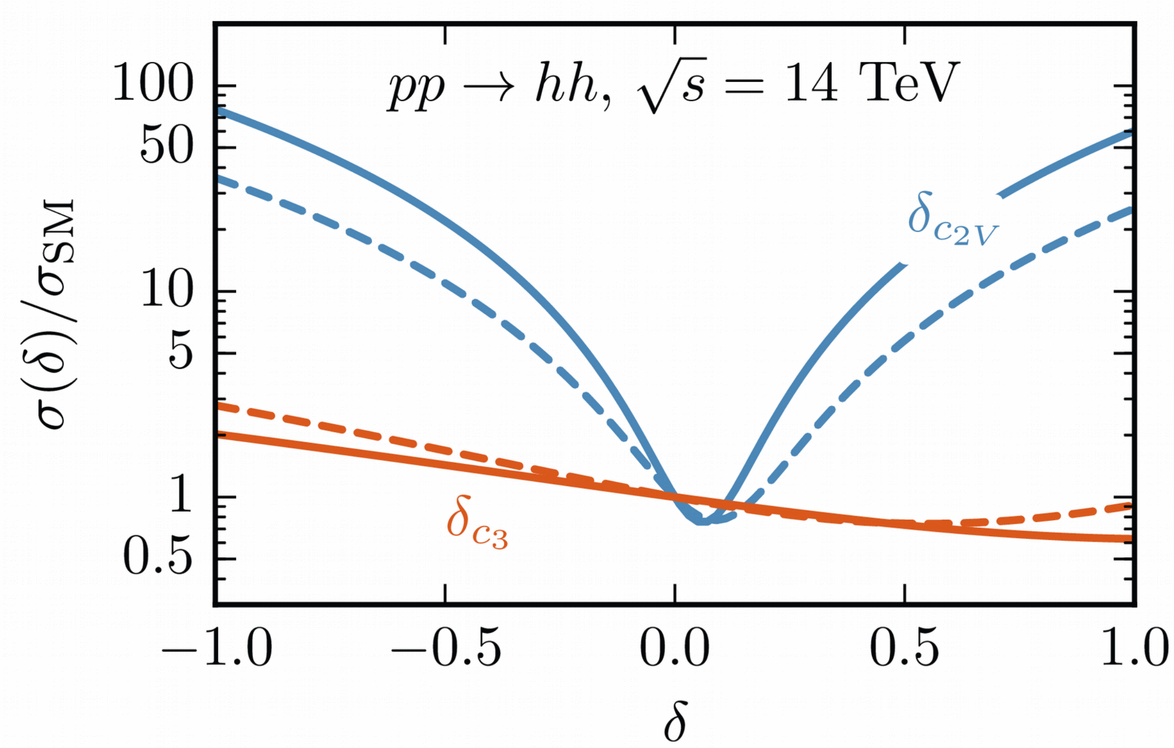
$$\varepsilon(b\text{-tag}) = 0.75\,, \quad \varepsilon(c\text{-mistag}) = 0.1\,, \qquad \varepsilon(q,g\text{-mistag}) = 0.01$$

Sensitivity to δ_{c_3} and $\delta_{c_{2V}}$

- To illustrate, consider total σ before and after cuts with $\sigma/\sigma_{\text{SM}} = 1 + a\,\delta + b\,\delta^2$
- Sensitivity to $\delta_{c_{2V}}\,(\delta_{c_3})$ is enhanced (suppressed) by the cuts

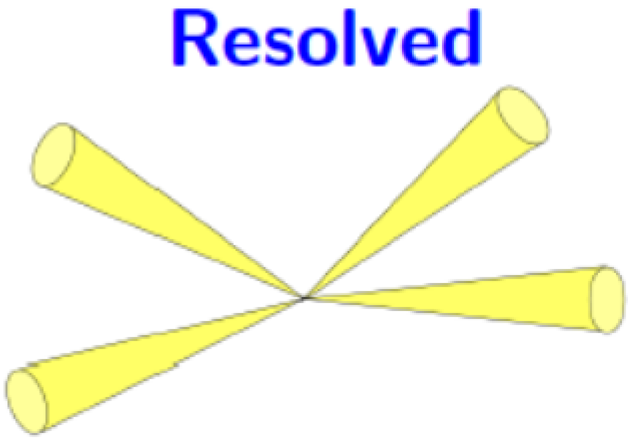
$$\delta_i \equiv c_i - 1$$

dashed : before cuts
solid : after cuts



Higgs reconstruction

[Butterworth, Davison, Rubin, Salam: 0802.2470]



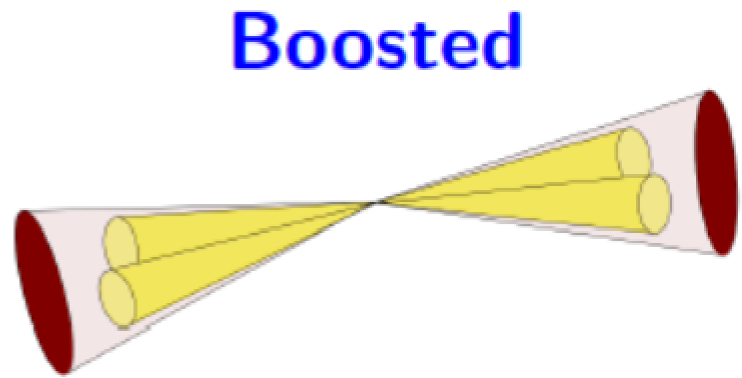


Figure credit: Juan Rojo

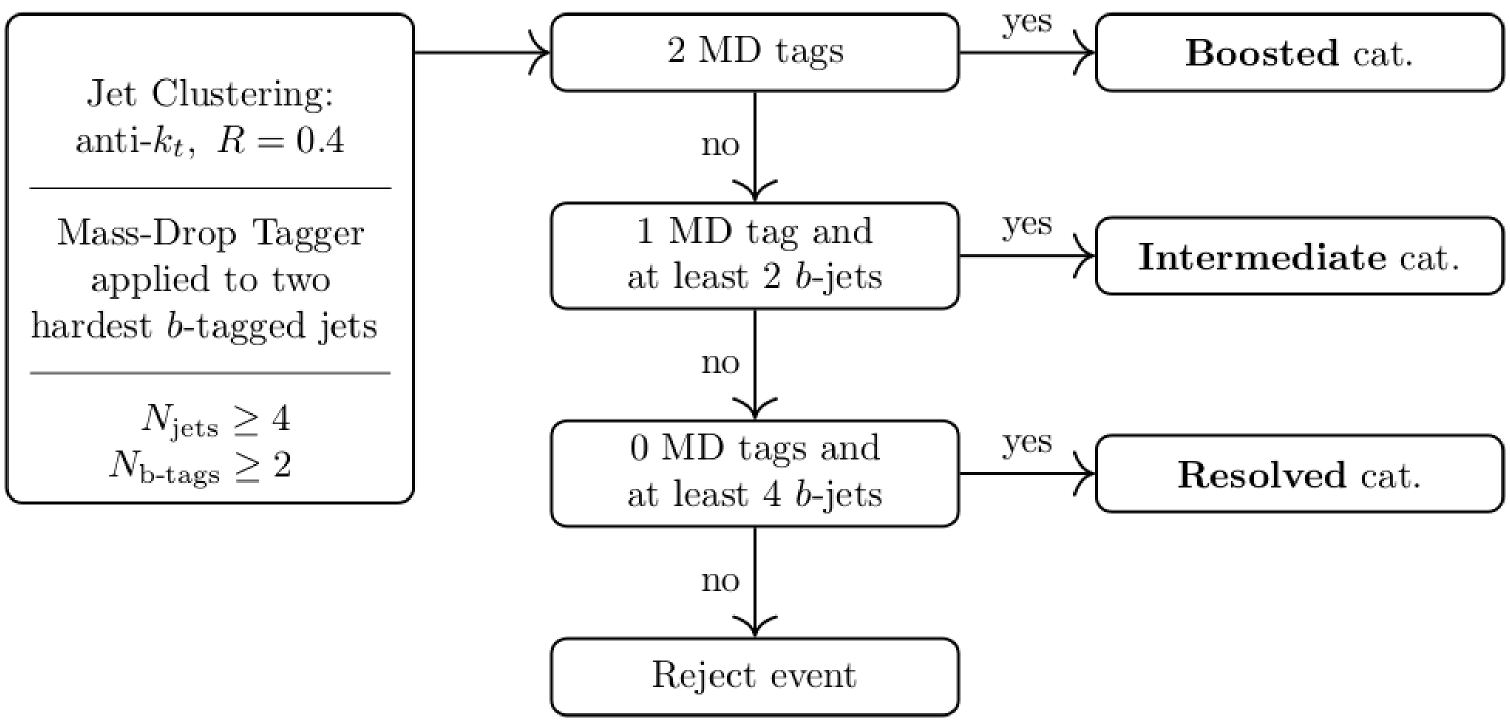
- 4 small-R b-tagged jets
- Consider hardest 6
- $h_1 \leftrightarrow$ b-jet pair with $\min\{|m_{bb} - 125|\}$
- $h_2 \leftrightarrow$ b-jet pair with $\min\{|m_{bb} - m_{h_1}|\}$

- 2 large-R jet $\supset$ 2 b-quarks each
- $h_1 \leftrightarrow$ large-R jet with $\min\{|m_j - 125|\}$
- $h_2 \leftrightarrow$ large-R with $\min\{|m_{j_2} - m_{j_1}|\}$

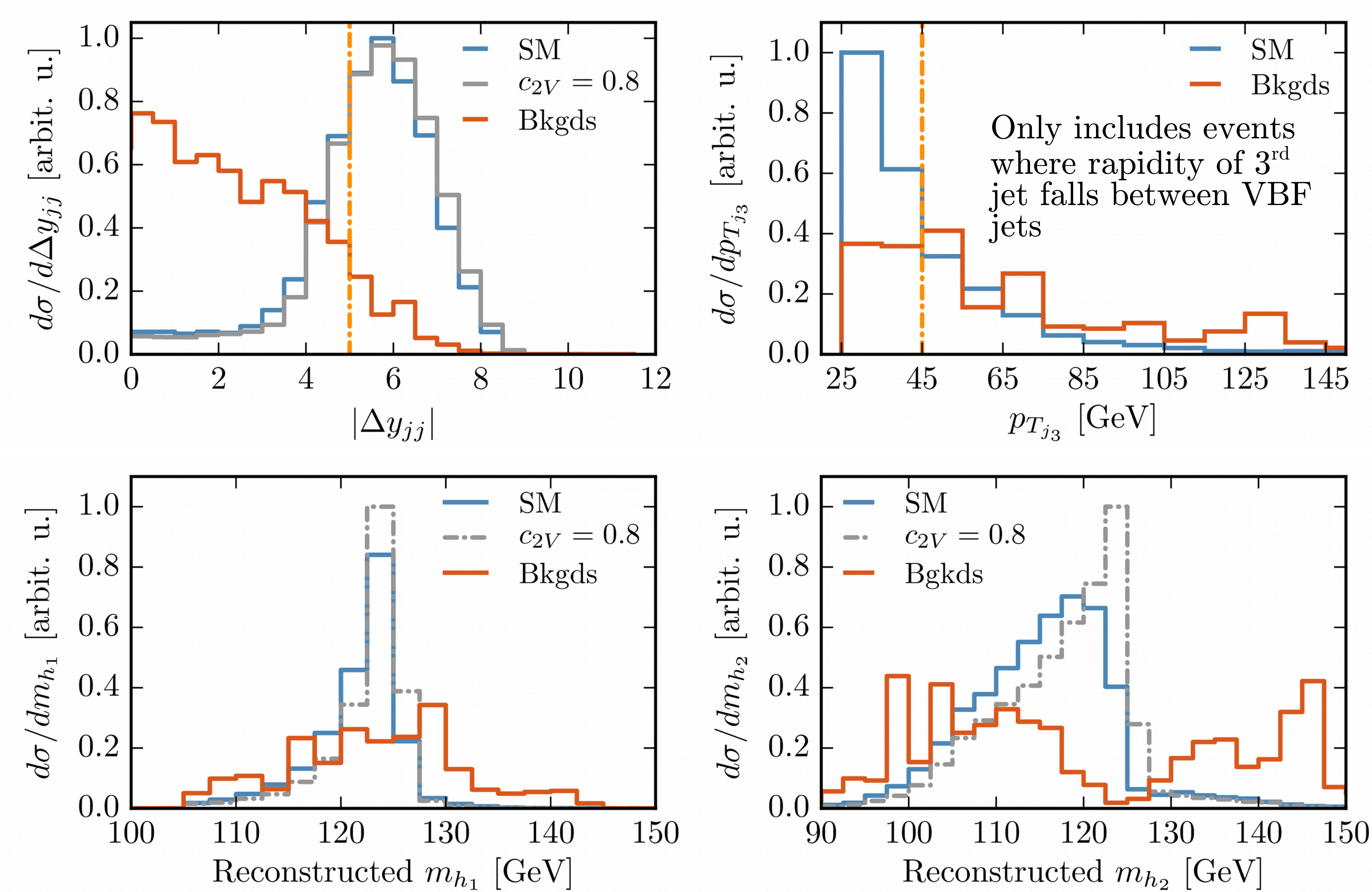
Scale invariant tagging

Gouzevitch, Oliveira, Rojo, Rosenfeld, Salam, Sanz [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

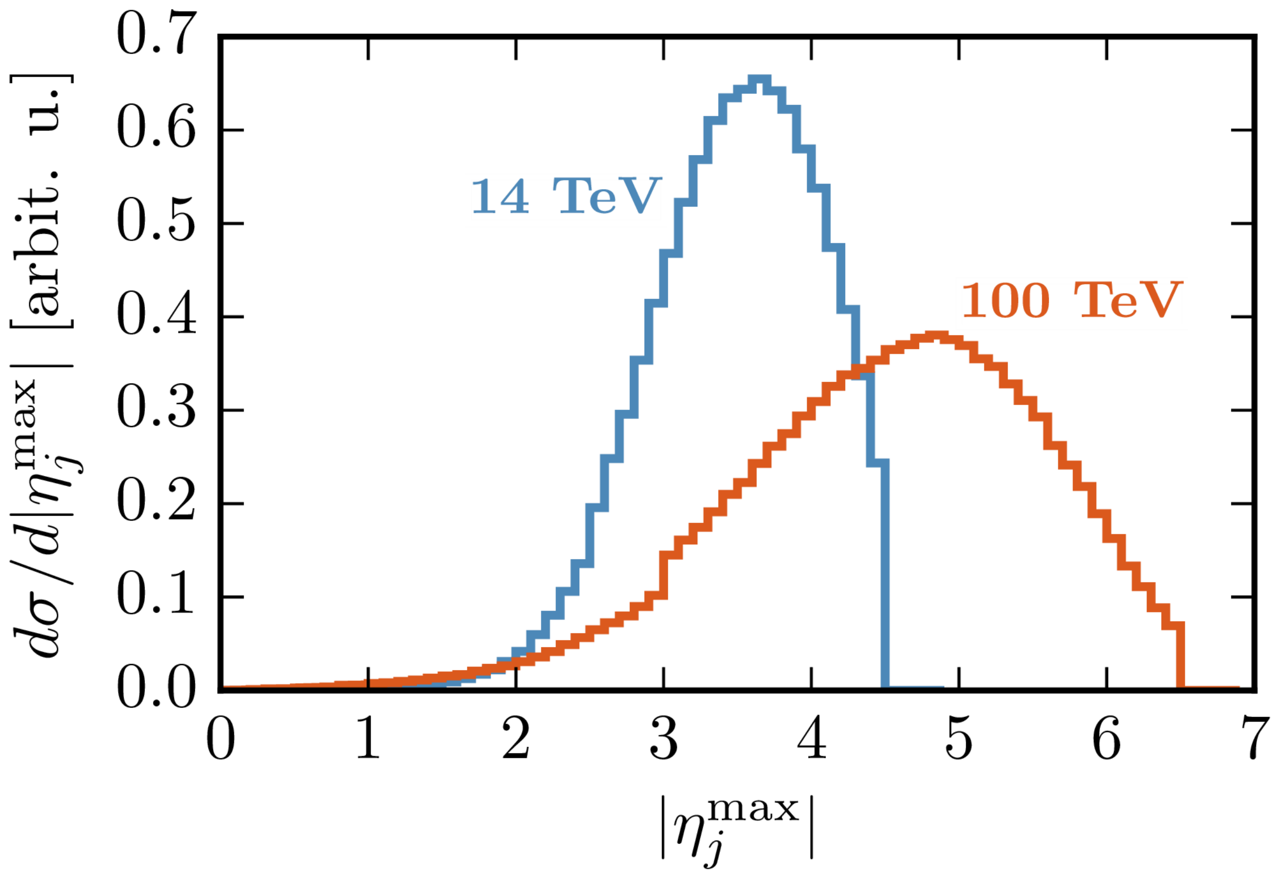


Taming the background

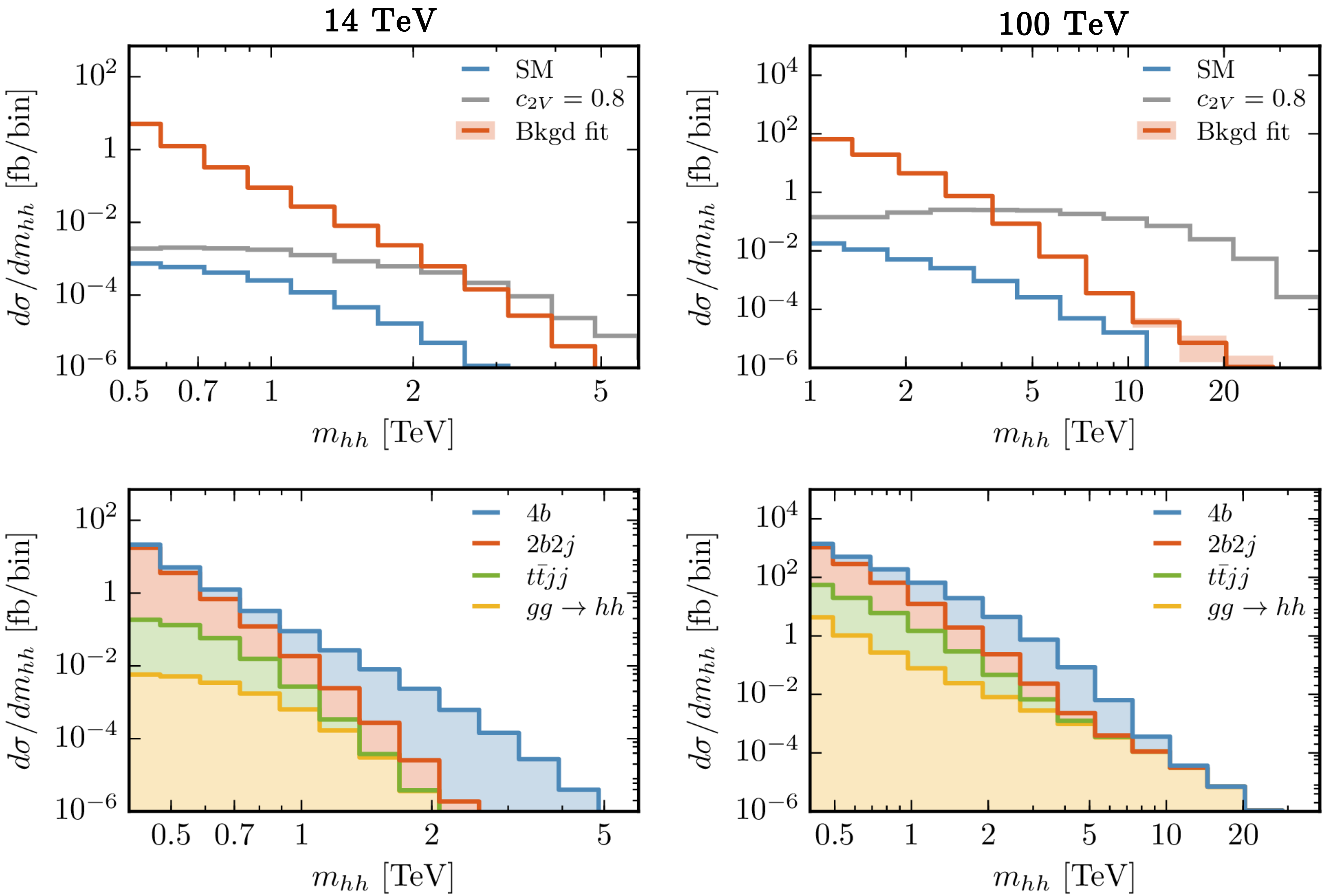


PSA: detector coverage at an FCC

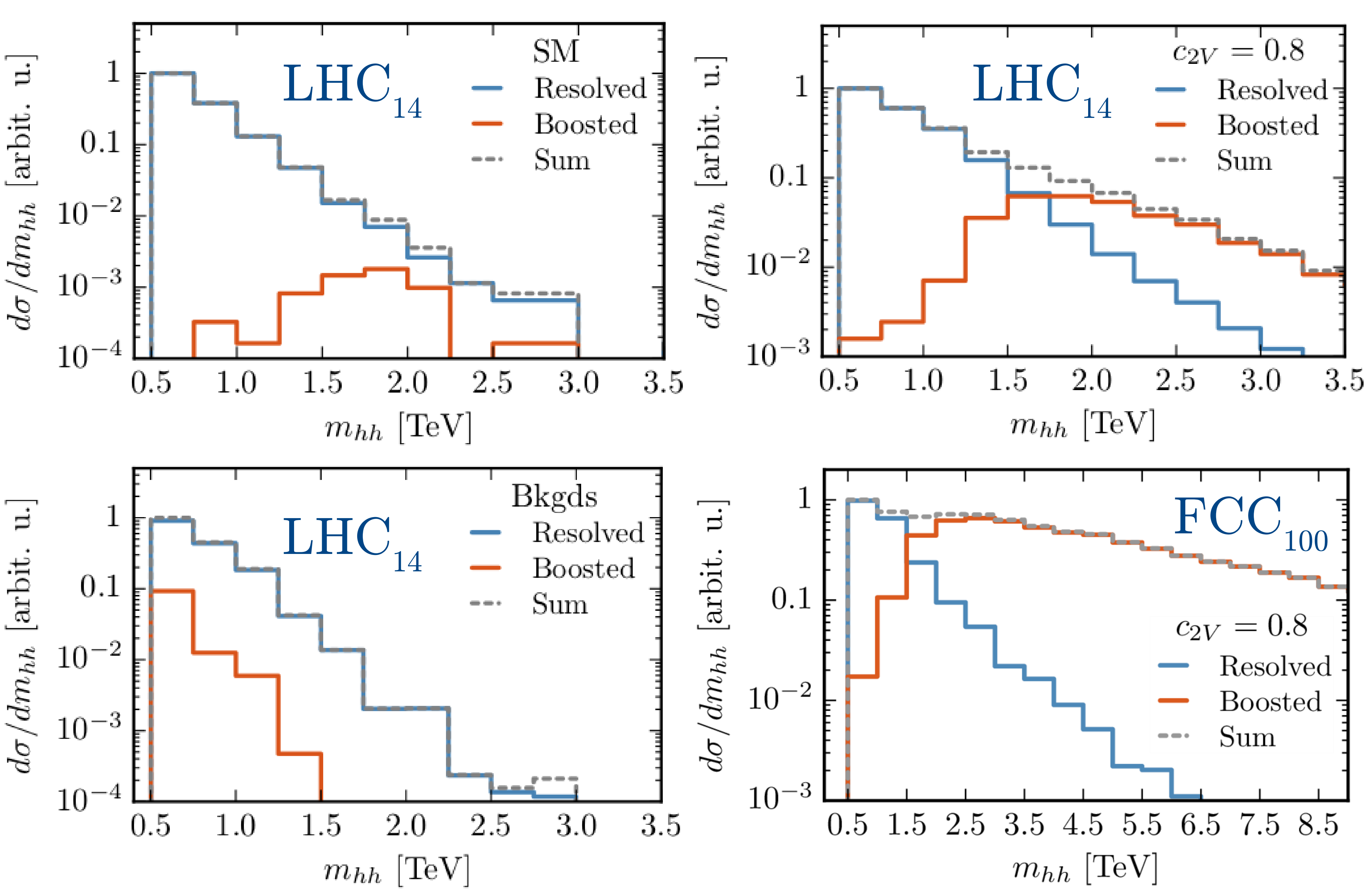
- VBF jet with max η peaks ~ 5
- If coverage only extended to $|\eta| < 5$, would lose $\sim 50\%$ of signal events



The hh invariant mass distribution

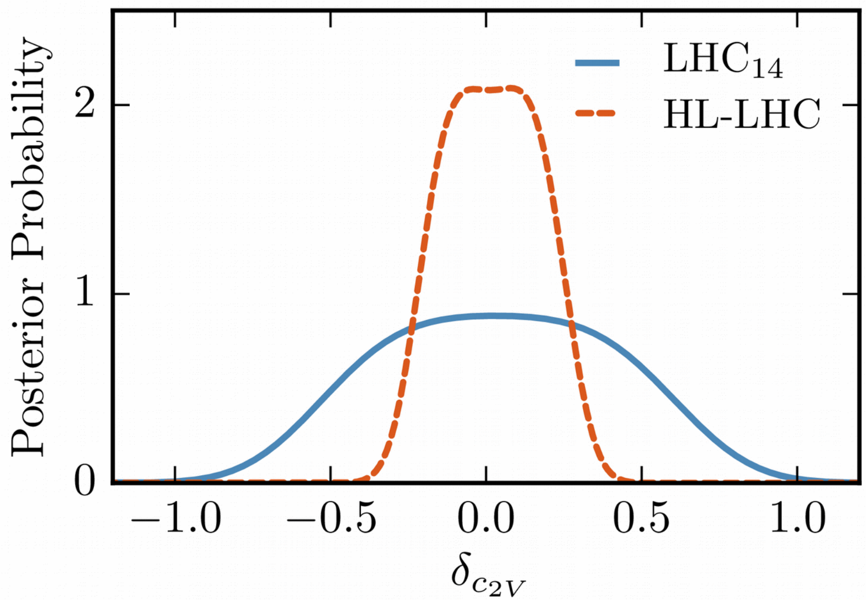


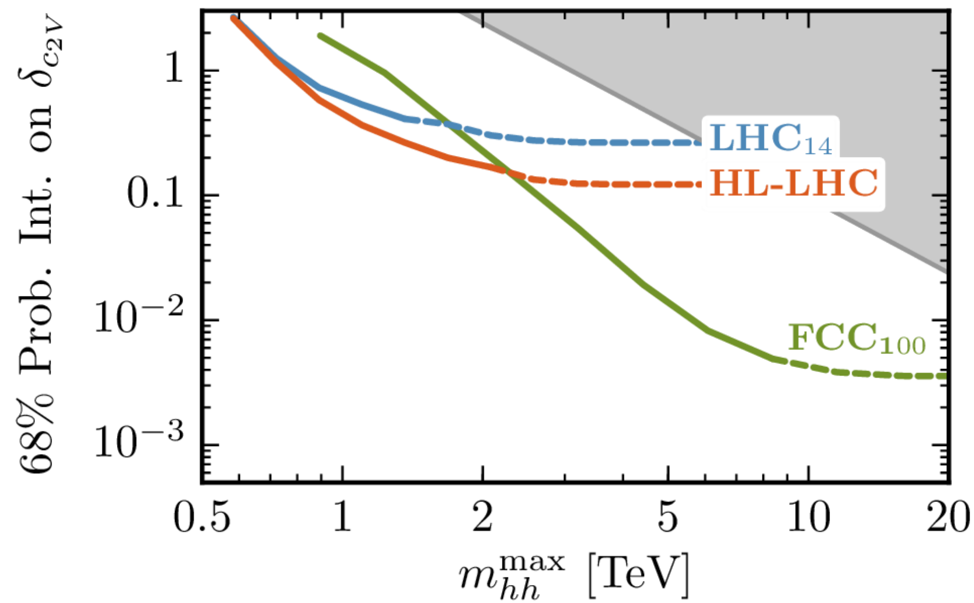
Scale invariant tagging



Results: probability intervals on δc_{2V}

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





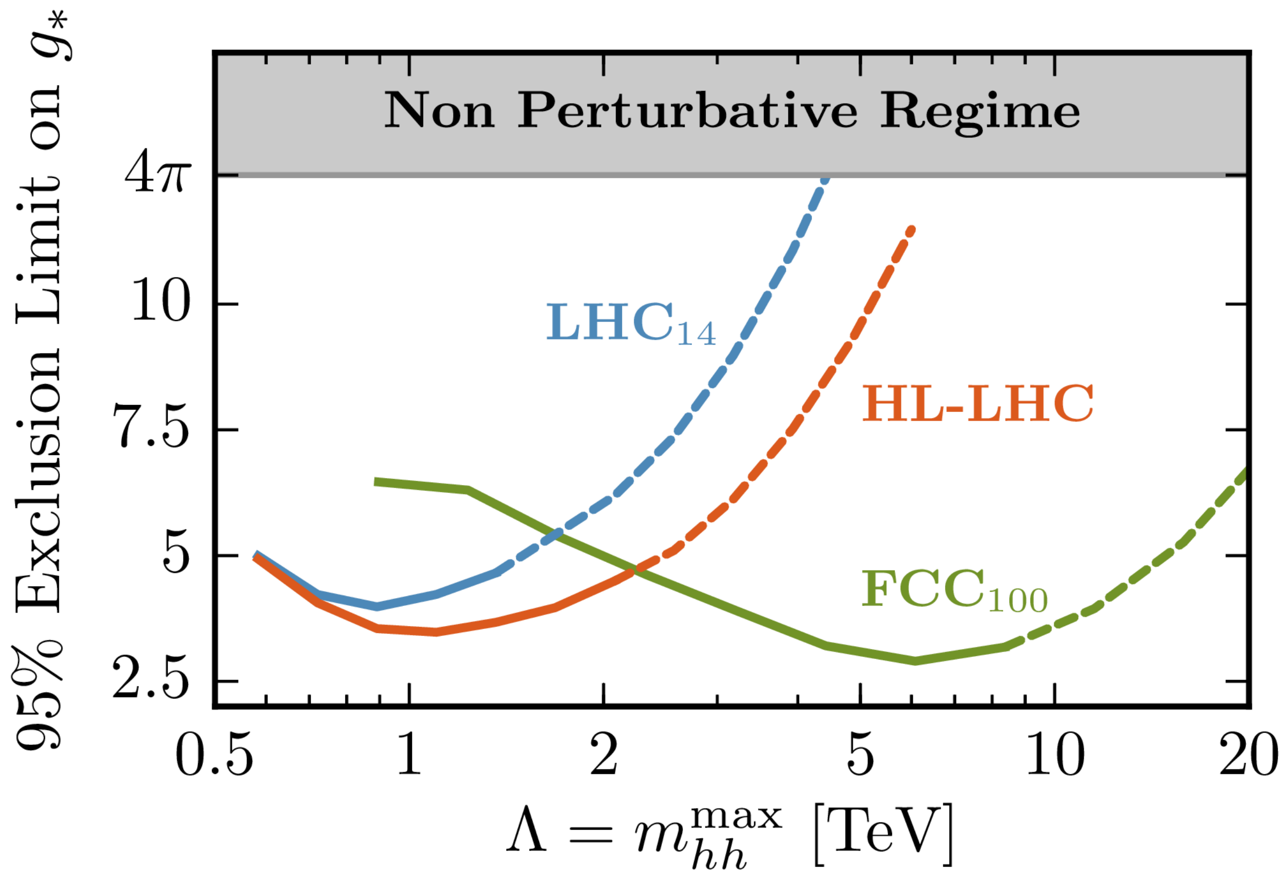
	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{bkg}$	$3 \times \sigma_{bkg}$
LHC_{14}	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC_{100}	$[0, 0.01]$	$[-0.01, 0.01]$

	95% probability upper limit on μ	
	$1 \times \sigma_{bkg}$	$3 \times \sigma_{bkg}$
LHC_{14}	109	210
HL-LHC	49	108
FCC_{100}	12	23

Validity of the EFT description

- If NP is characterized by couping g_* and scale Λ
- One expects $\delta_{c_{2V}} \approx g_*^2 v^2/\Lambda^2$ See, e.g., [Giudice, Grojean, Pomarol, Rattazzi: hep-ph/0703164]
- Saturating the strong coupling limit then gives $\delta_{c_{2V}} \approx 16\pi^2 v^2/\Lambda^2$

This procedure was outlined in [Contino, Falkowski, Goertz, Grojean, Riva: 1604.06444]

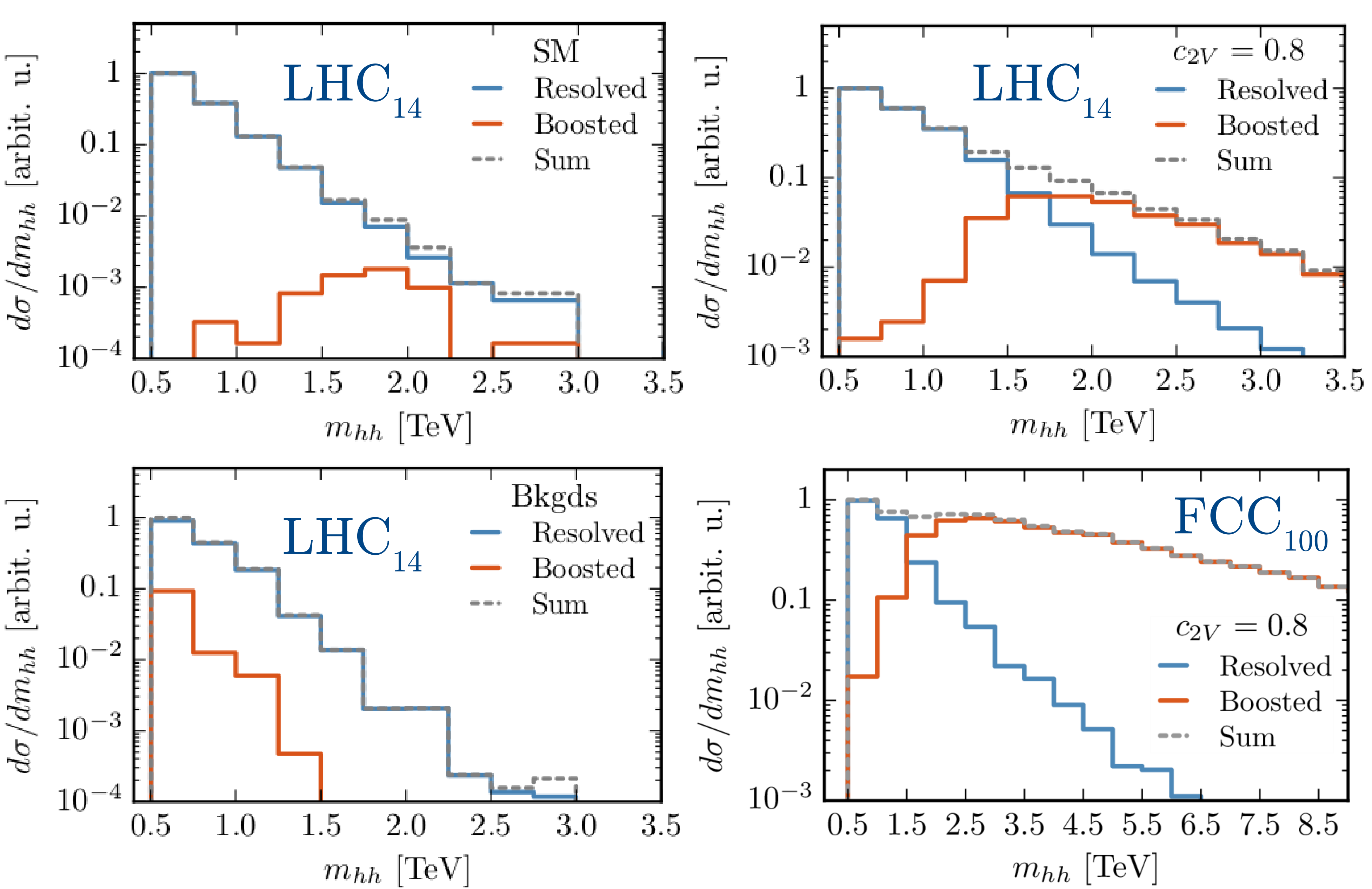


Summary II

- Double Higgs production in VBF is useful to constrain hhVV couplings
- Boosted kinematics gives a crucial handle to tame backgrounds
- 20% precision achievable at the HL-LHC reaching the 1% level at a 100 TeV FCC

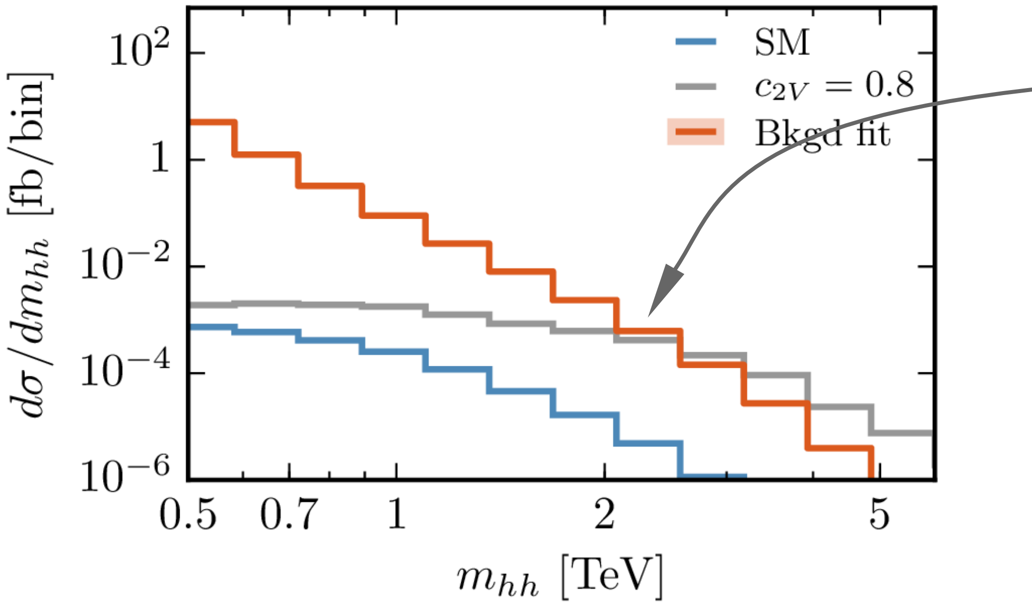
Thank you!

Scale invariant tagging



Populating the tail in our analysis

- Sensitivity is driven by the tail. Therefore good modelling is imperative



$d\sigma/db_j/(\sum_i d\sigma/db_i) \sim 10^{-6}$
→ need 1M events to get 1 event in this bin.
→Accounting for efficiency of all cuts and requiring 100 events here means need to generate 10^{12} events!

- Solution: generate weighted events and fit the background
- For signal, can also put generation cut on m_{hh} but this does not work for background