CONSTRAINING HIGGS CP-PROPERTIES IN GLUON FUSION

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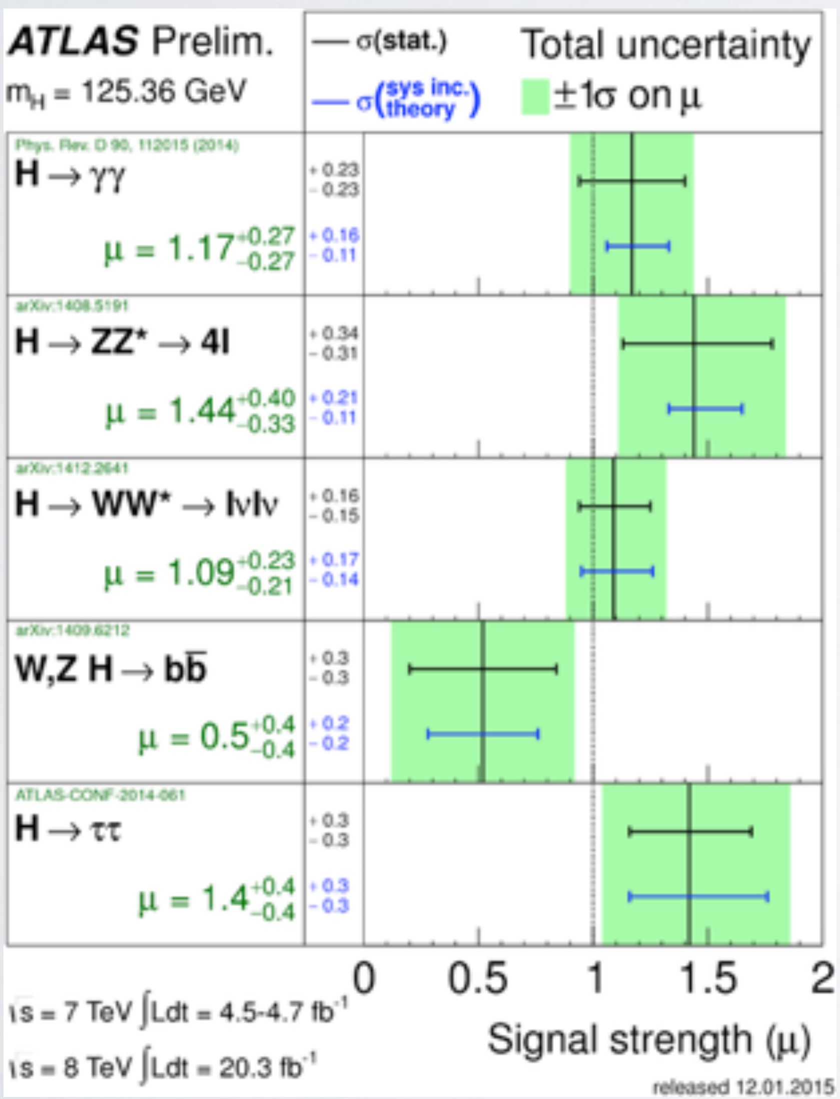
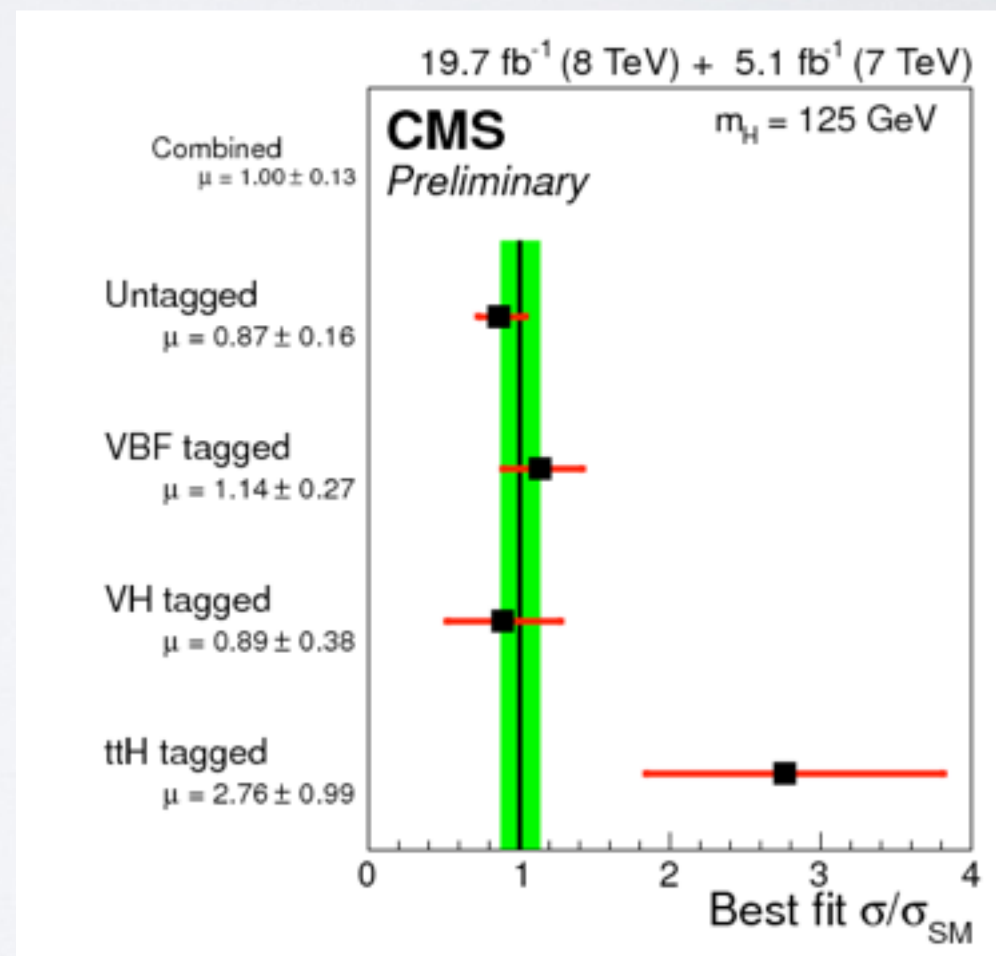
Introduction

- Run I showed the Higgs boson is broadly SM-like
- How can we constrain the CP-properties of the Higgs?



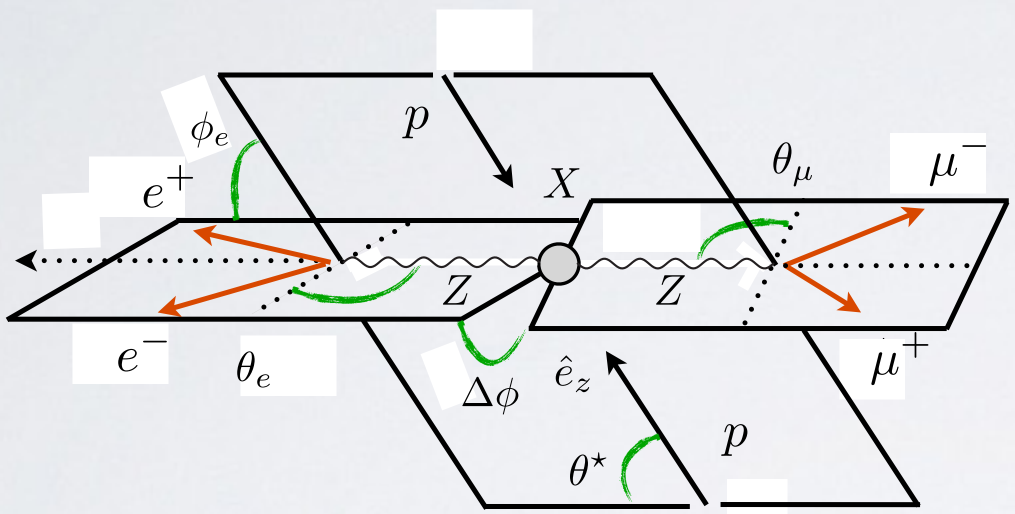


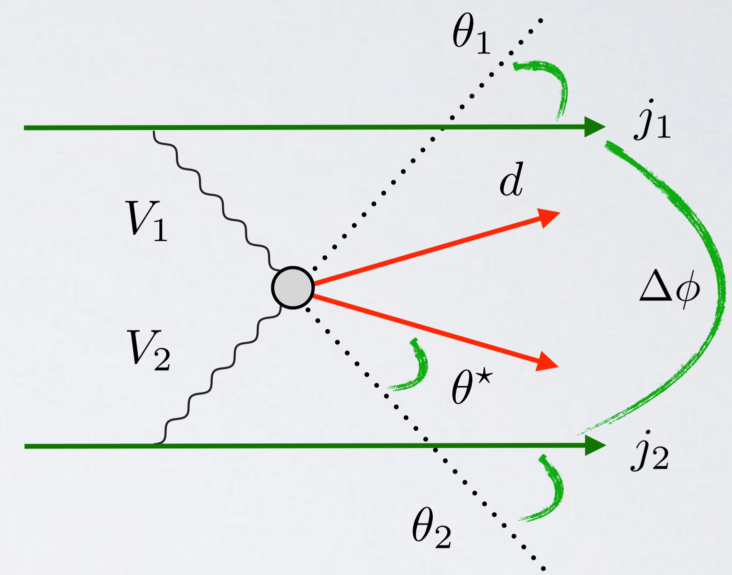
Introduction

- Higgs an even eigenstate of CP in the SM
- Many BSM theories include CP-odd scalars (pseudoscalars)
- Or have CP-violation in the Higgs sector
- Physical Higgs then not an eigenstate of CP

Don't ask 'is the Higgs CP-even or odd' but 'how much'?

- Traditional analyses rely on angular correlations between decay products in $X \to ZZ \to 4\ell$

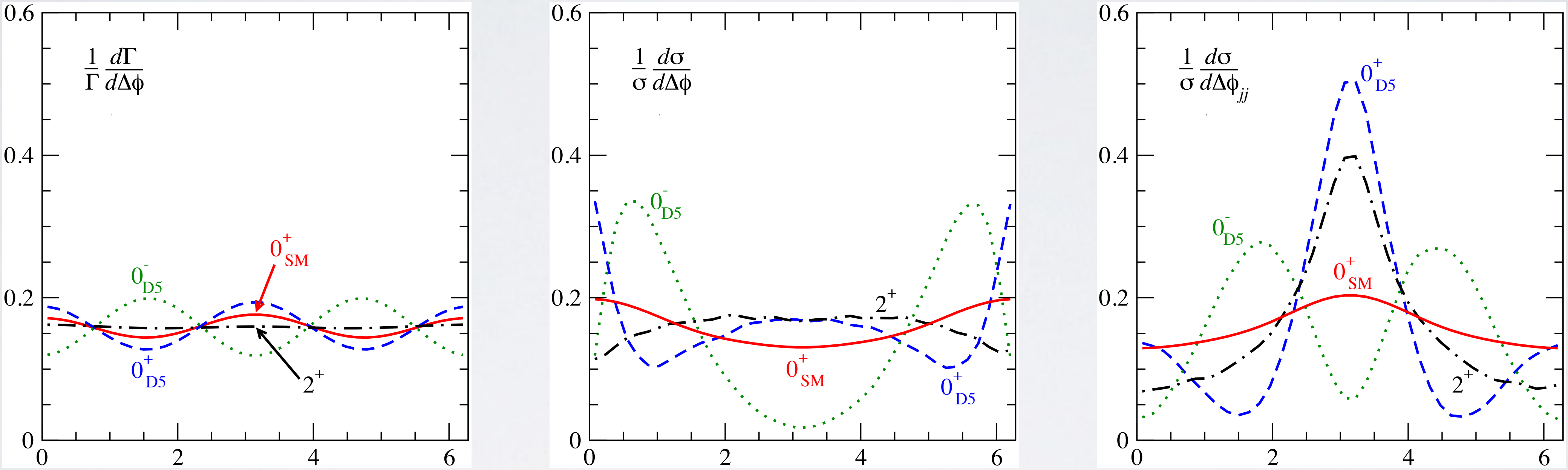




Or in correlations between tagging jets and decay products in weak boson fusion (WBF)

From Englert et al, 1212.0840

Pseudoscalars do not have renormalisable couplings to massive vector bosons



Leading order scalar couplings are d=3 $hV^\mu V_\mu$

Leading order pseudoscalar couplings are d=5 $hV^{\mu\nu}\widetilde{V}_{\mu\nu}$

From Englert et al, 1212.0840

Results from ATLAS-CONF-2015-008

Sets constraints on

$$\mathcal{L}_0^V = \Big\{c_\alpha \kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] \\ -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\} X_0.$$

$s_\alpha = \sin_\alpha,\, c_\alpha = \cos\alpha$ mixing angles and higher dimension operators suppressed by scale Λ

Tree-level SM is $\kappa_{SM} = 1,\, c_\alpha = 1, \Lambda \to \infty$

How large should CP-violating effects be?

Naive expectation: $$\frac{1}{\Lambda} \sim \frac{\alpha}{2\pi v}$$

$$\kappa_{SM} \sim 1,\ \kappa_{AVV} \sim 1$$

$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV} \sim \frac{\alpha}{8\pi} \sim 10^{-3}$$

$$(\tilde{\kappa}_{AVV}/\kappa_{SM})\tan\alpha \sim 10^{-3}\tan\alpha$$

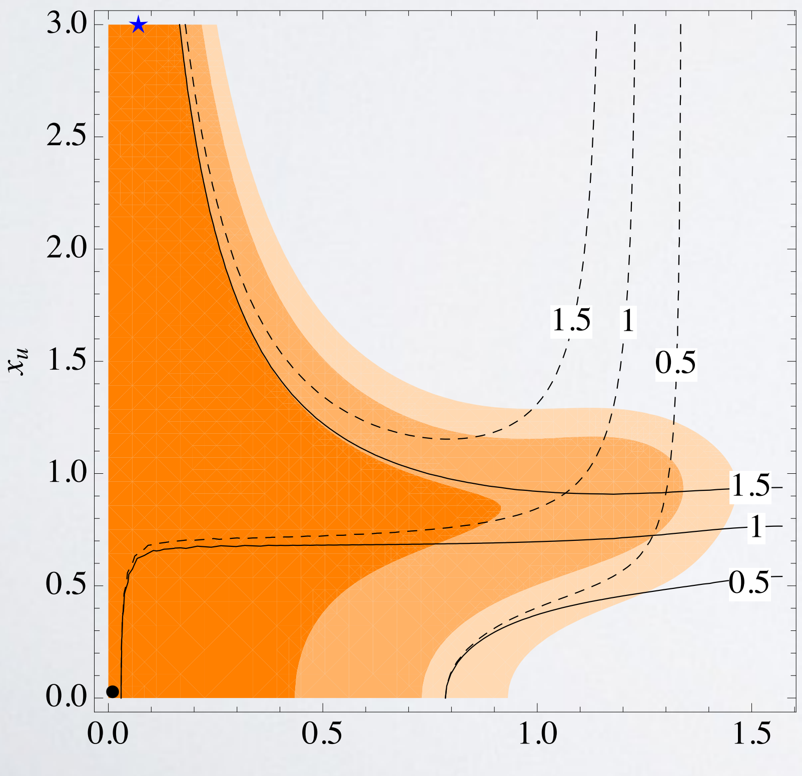
Coupling ratio	Best fit value		95% CL Exclusion Regions	
Combined	Expected	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\mathrm{SM}}$	0.0	−0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\mathrm{SM}}) \cdot \tan\alpha$	0.0	−0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

Information in Higgs production too

$BR(h \to ZZ^*)$ and WBF negligible for a pure CP-odd state

Gluon fusion increases by a factor ~9/4

Signal strength info rules out pure pseudoscalar at 4σ



$\alpha < 0.76 \qquad (95\%\ \text{C.L.})$

Freitas, Schwaller 1211.1980
Djouadi, Moreau 1303.6591

What Other Couplings Can Be Probed?

- Scalar and pseudoscalar couplings to fermions and massless vector bosons arise at the same order

Tree-level couplings to fermions

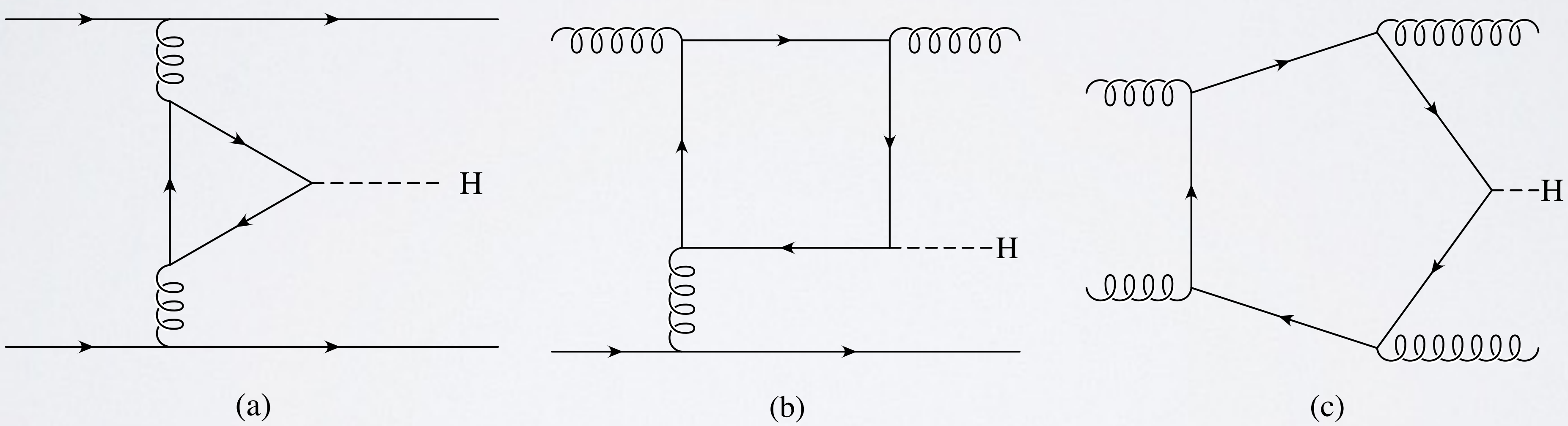
$$h\bar{f}f \qquad h\bar{f}\gamma^5 f$$

1-loop couplings to gluons/photons

$$hG^{\mu\nu}G_{\mu\nu} \qquad hG^{\mu\nu}\widetilde{G}_{\mu\nu}$$

What Other Couplings Can Be Probed?

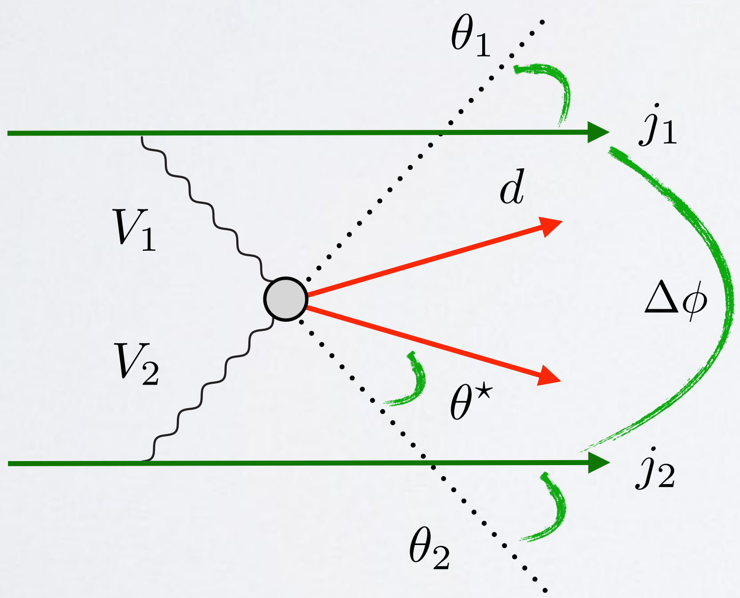
- Will focus on CP-sensitive variables in Higgs production
- Production via gluon fusion arises at same order in both cases

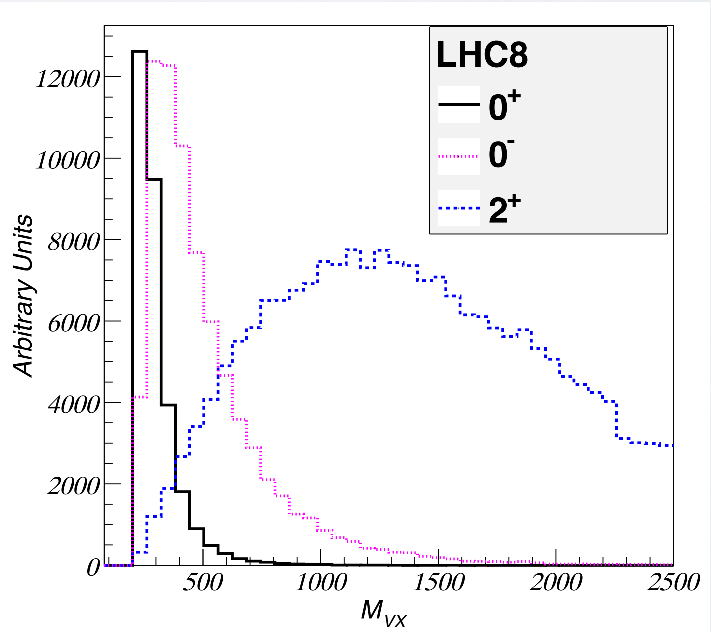


For decay see Felix and Marco's talks

What Other Couplings Can Be Probed?

- Will focus on CP-sensitive variables in Higgs production
- WBF amenable to angular analysis
- Gauge-Higgs invariant mass in associated production



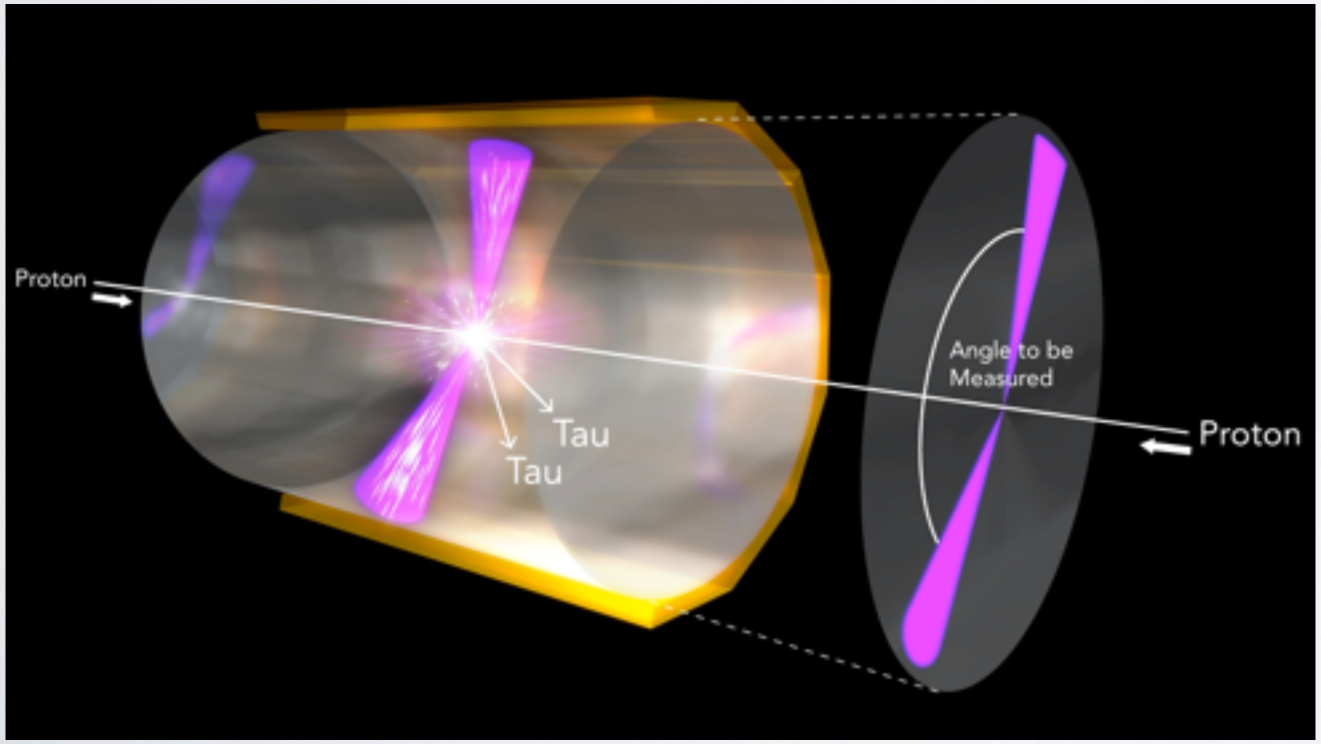


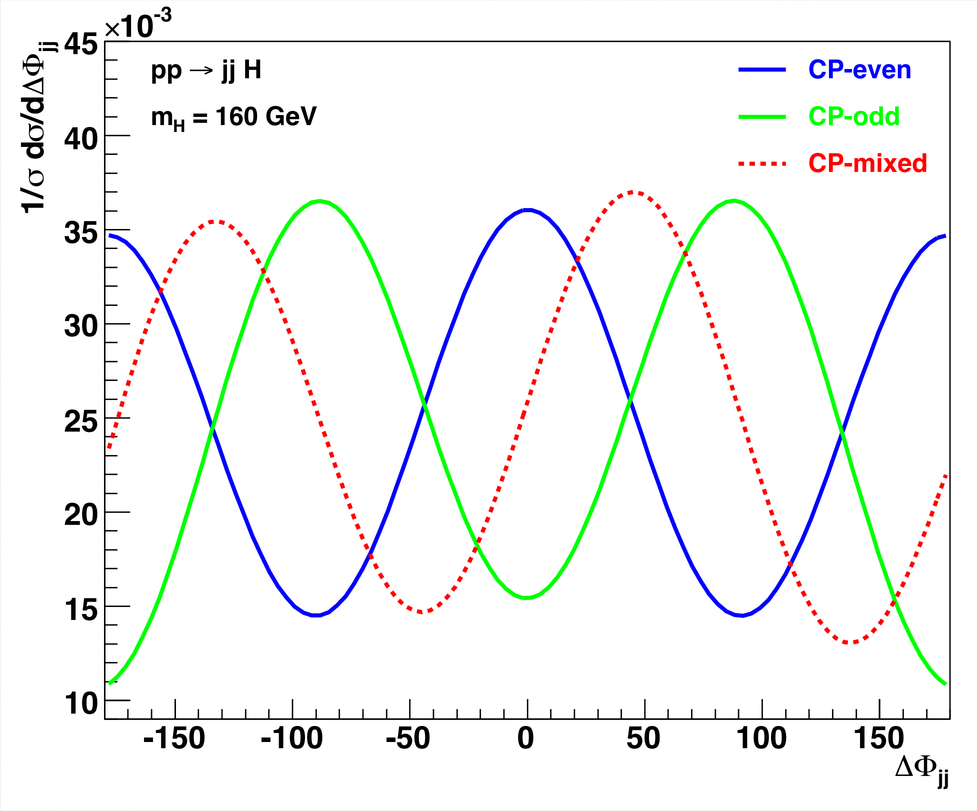
For decays see Felix and Marco's talks

Ellis, Sanz, You 1208.6002

What Other Couplings Can Be Probed?

- Higgs plus two jet production is known to be sensitive to the Higgs CP properties through angular correlations in the jets
- In particular differences between azimuthal angles $\Delta\phi_{jj}$





Klamke, Zeppenfeld '07

We will consider a mixed CP-state with couplings

$$\mathcal{L}_{h\bar{f}f} = \cos\alpha\, y_f \bar{\psi}_f \psi_f h + \sin\alpha\, \widetilde{y}_f \bar{\psi}_f i\gamma_5 \psi_f h\,.$$

$$\mathcal{L}_{hVV} \supset \cos\alpha\, \frac{2m_W^2}{v} h W_\mu W^\mu + \cos\alpha\, \frac{2m_Z^2}{v} h Z_\mu Z^\mu$$

This generates couplings to gluons

$$\mathcal{L}_{hgg} = \cos\alpha\, \frac{\alpha_S}{12\pi v} h G^a_{\mu\nu} G^{a,\mu\nu} + \sin\alpha\, \frac{\alpha_S}{4\pi v} h G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$$

Mixing parametrised by angle α

$\alpha = 0$ is pure CP-even

$\alpha = \pi/2$ is pure CP-odd

Event Generation

We generate signal using VBFNLO 2.6.3 at 8 and 14 TeV

Gluon fusion generated at NLO

WBF generated at LO

Background using Sherpa 2.0.0

Generate Zjj (QCD + EW), W+jets and $t\bar{t}$

QCD multijets assumed to be flat across phase-space

Cross-Sections

In the CP-odd limit the WBF cross-section vanishes at tree-level

The CP-odd GF cross-section is larger than the CP-even case by 9/4

α	8 TeV GF cross-section (fb)	8 TeV WBF cross-section (fb)	14 TeV GF cross-section (fb)	14 TeV WBF cross-section (fb)
0.00	250	467	1141	1481
0.30	278	426	1268	1351
0.60	352	318	1606	1009
0.90	447	181	2038	572
1.20	529	61	2411	194

We focus on $h \to \tau\tau$

Event Selection

We consider four different final states: di-hadronic, semi-leptonic and leptonic (e+mu)

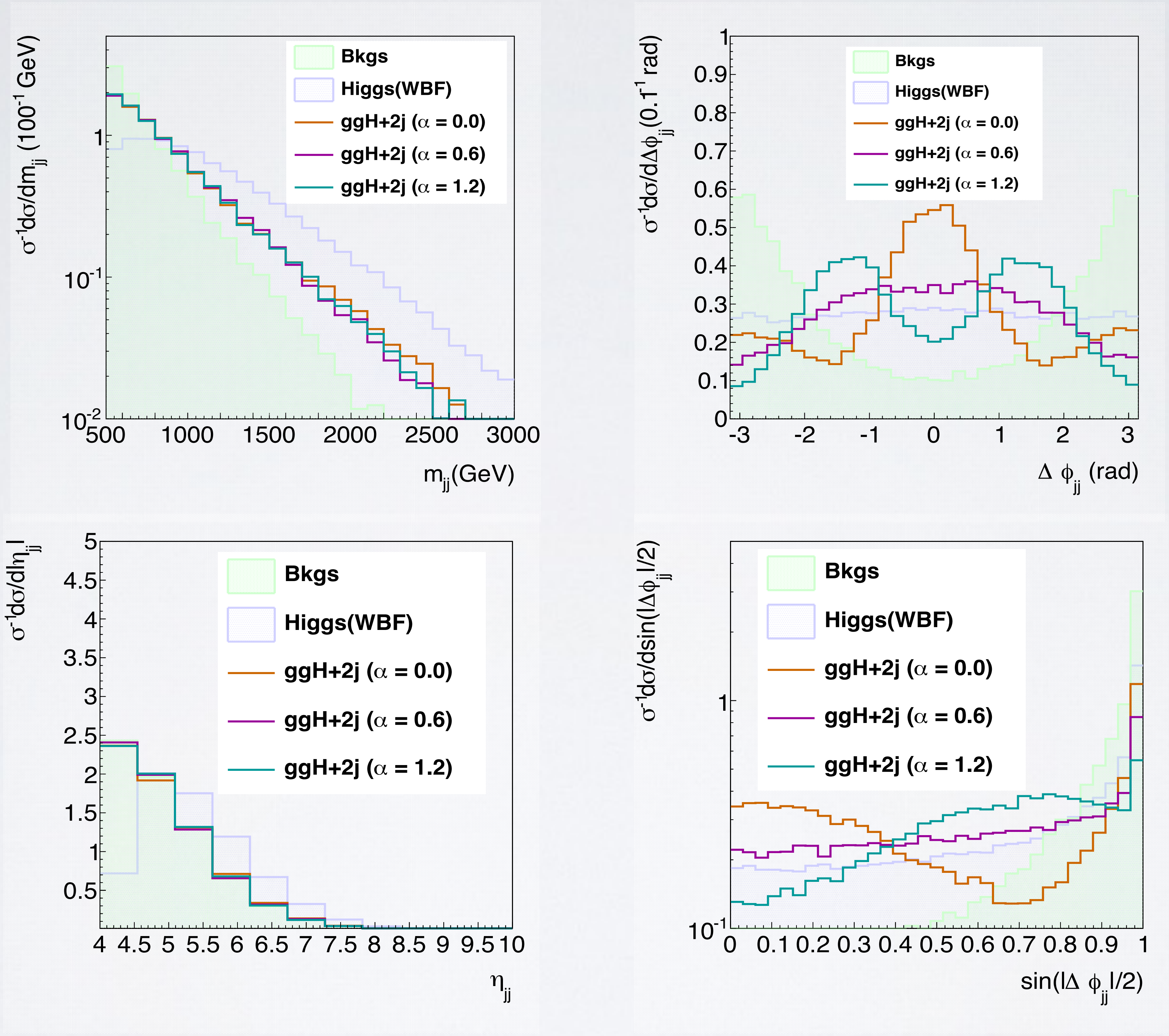
Cuts designed to mimic ATLAS/CMS di-tau analyses

	$\tau_h\tau_h$	$\mu\tau_h$	$e\tau_h$	$e\mu$
lepton selection	$p_T^\tau > 45$ GeV	$p_T^\mu > 20$ GeV $p_T^\tau > 30$ GeV	$p_T^e > 25$ GeV $p_T^\tau > 30$ GeV	$p_T^{\rm lead} > 20$ GeV $p_T^{\rm trail} > 10$ GeV
kinematic selection	$p_T^H > 100$ GeV	$m_T^\mu < 30$ GeV	$m_T^e < 30$ GeV	b-tag veto with $p_T^b > 20$ GeV
loose jet selection	$m_{jj} > 500$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.5$	$m_{jj} > 500$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.5$	$m_{jj} > 500$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.5$	$m_{jj} > 500$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.5$
tight jet selection		$m_{jj} > 700$ GeV $\lvert\Delta\eta_{jj}\rvert > 4.5$ $p_T^H > 100$ GeV	$m_{jj} > 700$ GeV $\lvert\Delta\eta_{jj}\rvert > 4.5$ $p_T^H > 100$ GeV	$m_{jj} > 700$ GeV $\lvert\Delta\eta_{jj}\rvert > 4.5$ $p_T^H > 100$ GeV

CMS: 1401.5041

ATLAS-CONF-2013-108 updated to 1501.04943

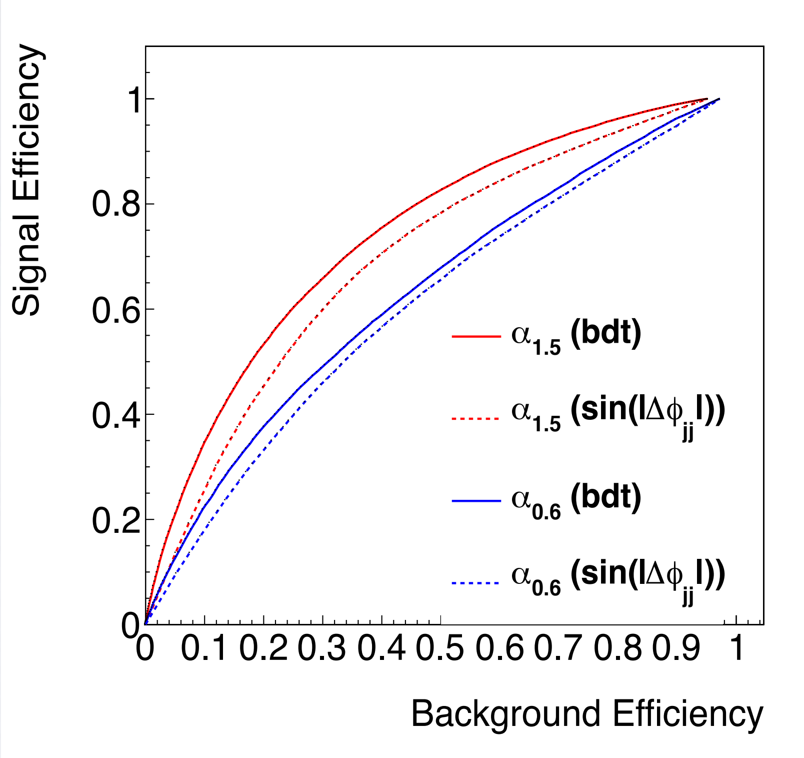
Kinematic Distributions



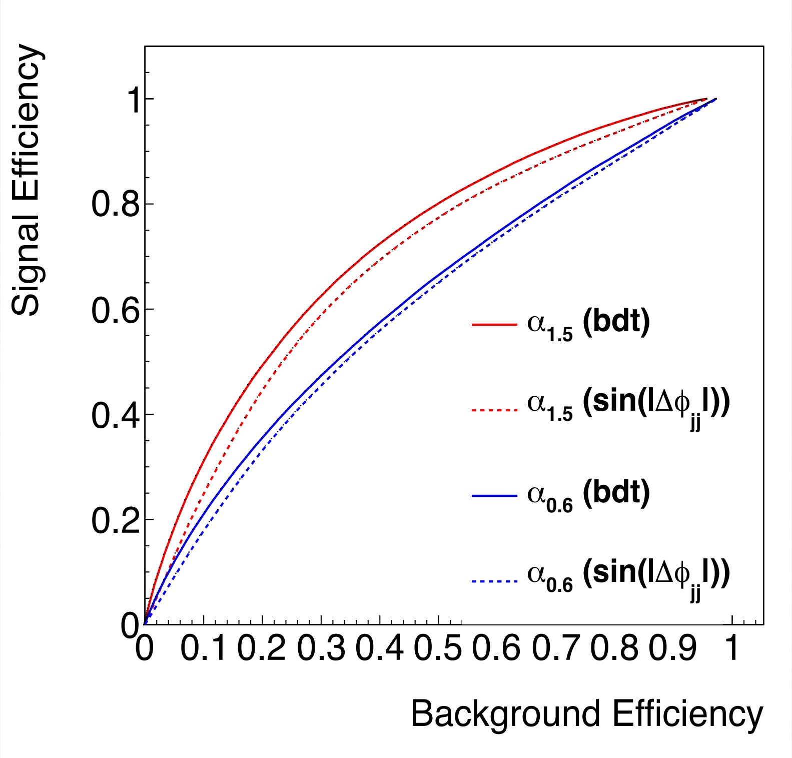
Most sensitive variable is $\Delta\phi_{jj} = \phi_{y>0} - \phi_{y<0}$

$\Delta\phi_{jj} = \phi_{y>0} - \phi_{y<0}$ is pretty optimal

Trained a BDT to discriminate between two gluon fusion samples with $\alpha = 0$ and $\alpha = 1.2$



8 TeV



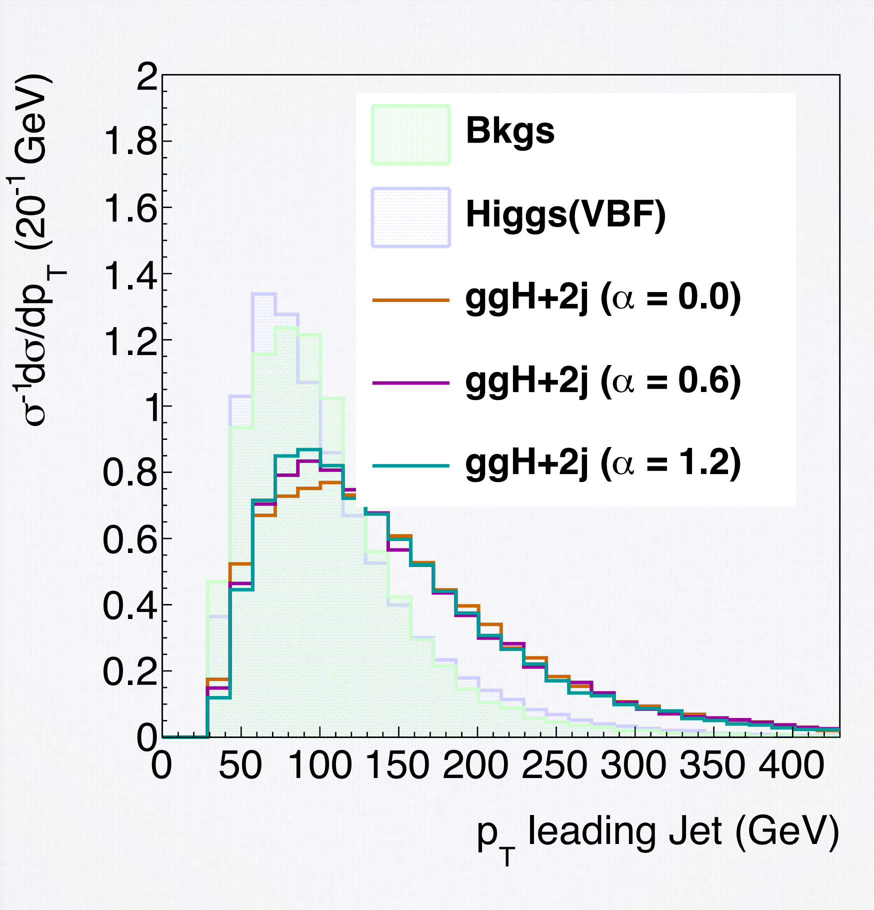
14 TeV

Also trained a BDT to discriminate between GF+WBF signal and sum of backgrounds

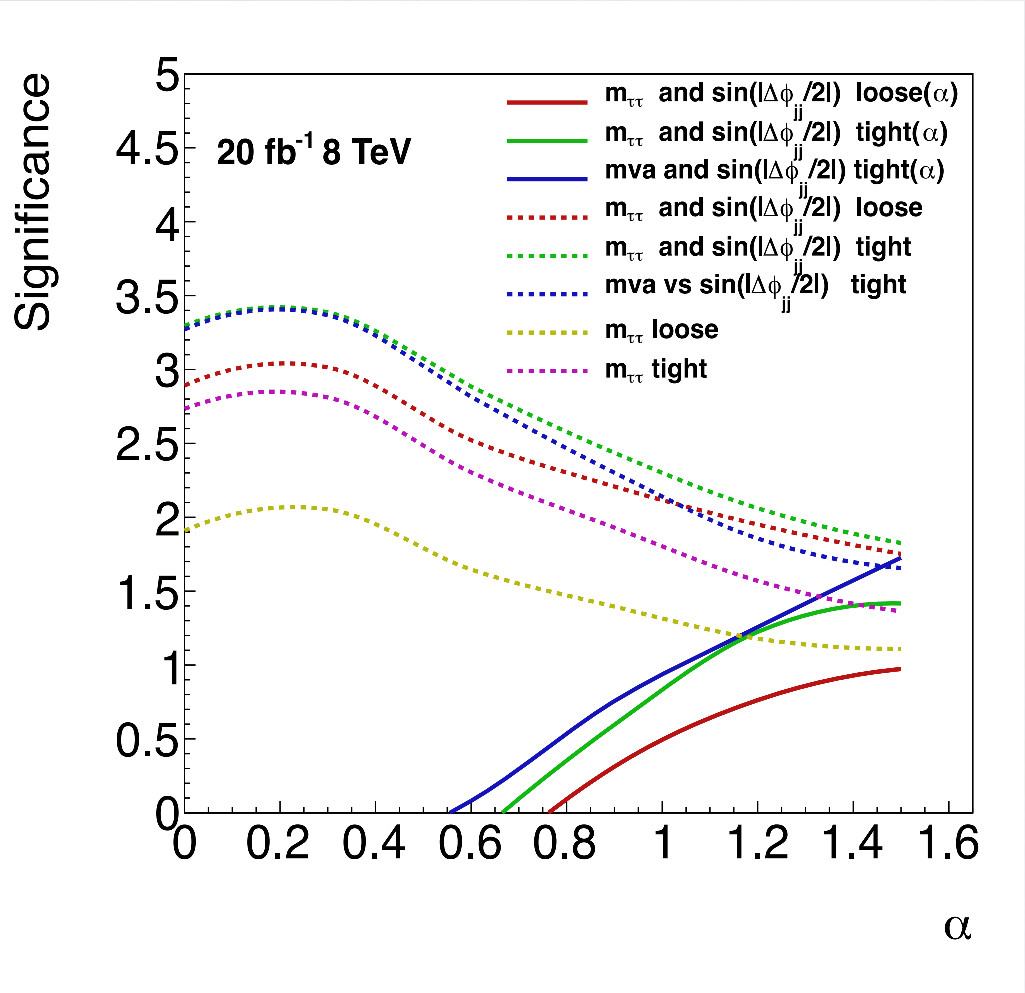
A category-based analysis using only

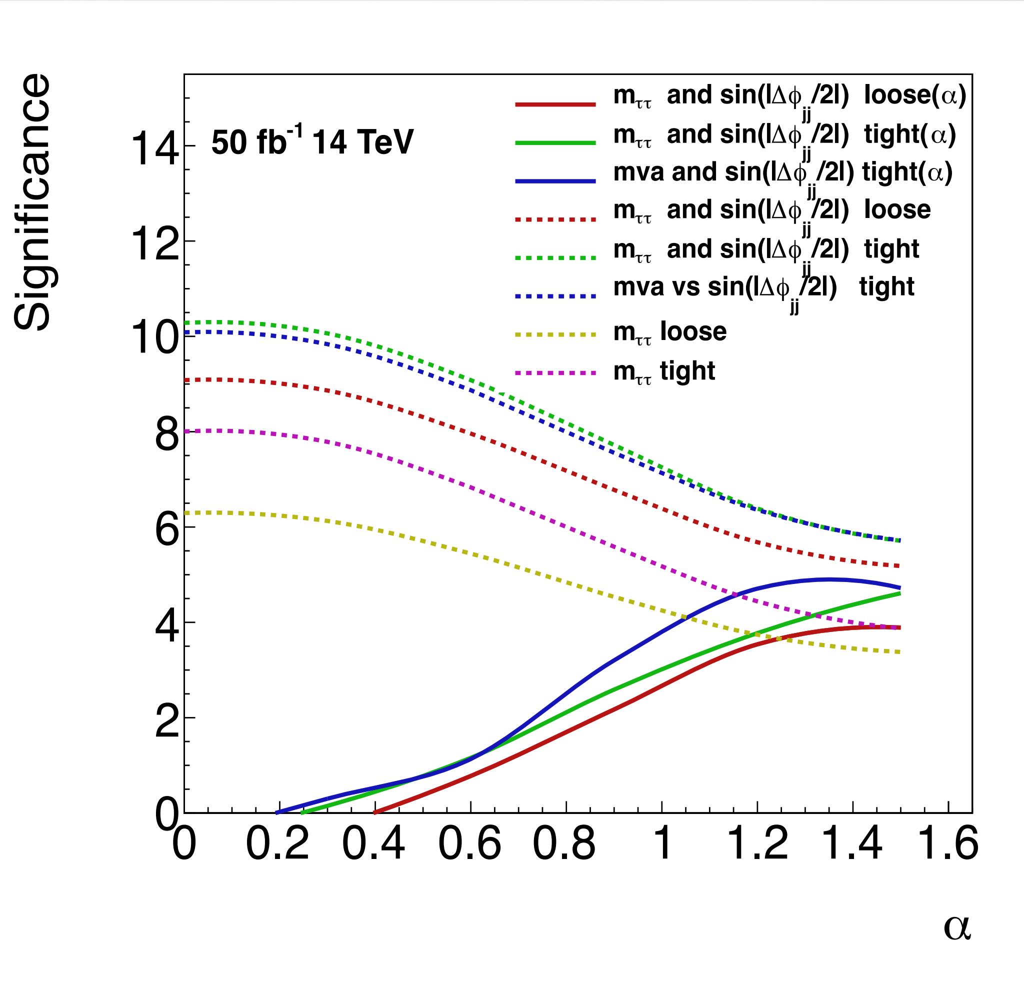
$$m_{\tau\tau},\ \Delta\phi_{jj},\ m_{jj},\ \Delta\eta_{jj}$$

does about as well as the BDT trained on full set of variables



Constraints



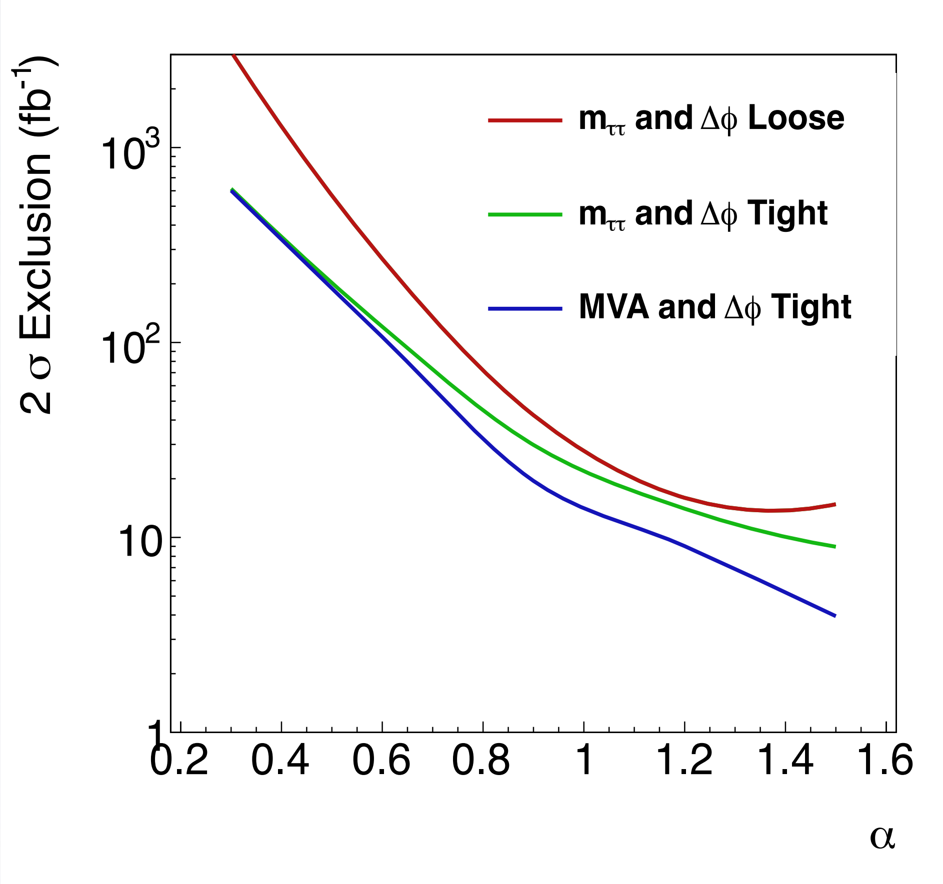


Dashed: Significance of total signal over SM background

Solid: Exclusion significance relative to $\alpha = 0$ case

$\alpha \leq 0.7$ with 50/fb at 14 TeV

Constraints



Expected exclusion limit as a function of integrated luminosity at 14 TeV

Comments

We set limits assuming mixed interactions between the Higgs and matter fields: probed CP nature of $h\bar{t}t$

Could also interpret in terms of SM + higher dimensional operators

Orthogonal to limits derived from WBF/4l angular correlations

Info from hadronic event shapes?: 1203.5788

Conclusions

- Higgs CP properties important part of Run II program: probe as many couplings as possible!
- Lots of information available from Higgs production
- Gluon fusion a promising avenue for constraining Higgs CP properties
- Limits on mixing angles: $\alpha \leq 0.9$ with 20/fb, $\alpha \leq 0.3$ with 500 /fb
- Further improvements possible with decay information

Conclusions

It would be cool to have this plot for CP properties!