Increased CP sensitivity with a neural network constructed observable in an effective Higgs-gluon coupling

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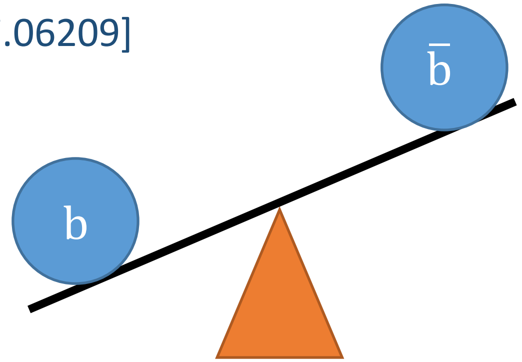
Motivation: Baryogenesis

- Observed baryon asymmetry of the universe (BAU) found to be $Y_B^{\mathrm{obs}} = (8.59 \pm 0.08) * 10^{-11}$ [Planck Collaboration, arXiv:1807.06209]



Sakharov conditions for baryogenesis:

[A. D. Sakharov (1967)]

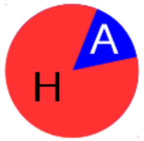
1. Baryon number violation
2. Charge (C) and charge-parity (CP) violation
3. Deviation from thermal equilibrium

→ BSM Higgs sectors can help fulfill conditions: 2HDM, MSSM etc.

[Basler et al., arXiv:2108.03580], [Athron et al., arXiv:1908.11847]

Challenge: Need enough CP violation → important to find constraints

The Higgs characterisation model



- Higgs ϕ assumed to be mixed CP state
- Modifiers for Higgs couplings: c_i, $\tilde{c}_i$ $\quad i$: SM particles
- SM obtained for $c_i = 1, \tilde{c}_i = 0$
- Measurable: $g_i^2 = ac_i^2 + b\tilde{c}_i^2, \tan\alpha_i = {}^{\tilde{c}_i}/_{c_i}$
- New effective couplings: $\mathcal{L}_{HC} \supset -\frac{1}{4}\left(c_g G_{\mu\nu}^a G^{a,\mu\nu} + \tilde{c}_g G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}\right)\phi$

"κ –framework:"
$c_i = \kappa_{H,i} \cos\alpha$
$\tilde{c}_i = \kappa_{A,i} \sin\alpha$

Contains SM quark loops + potential heavy new particles

Why CP sensitivity is important

Sensitivity to CP violation has direct effect on the constraints

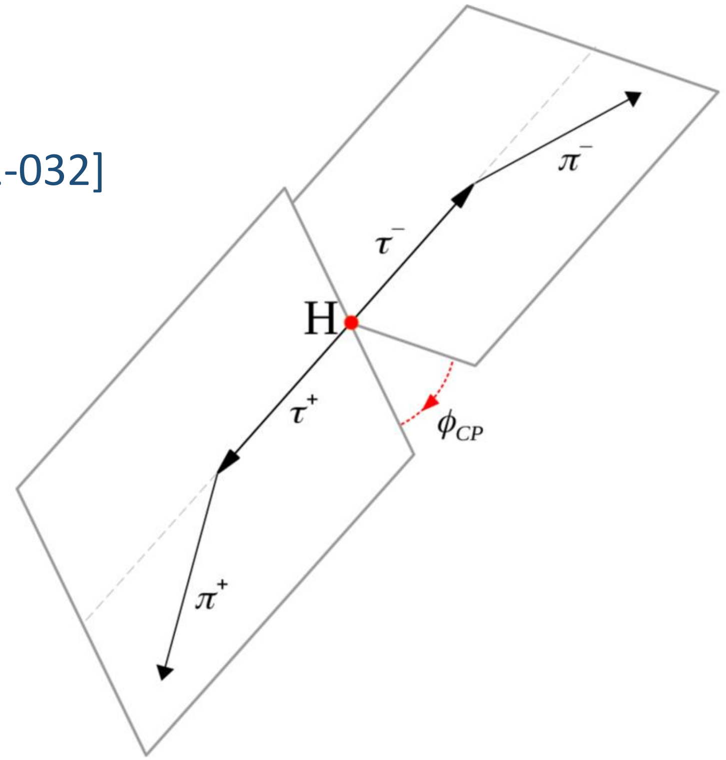
Example: Direct sensitivity to CP violation in $H \rightarrow \tau\tau$ decay [CMS Collaboration, arxiv:2110.04836] [ATLAS Collaboration, ATLAS-CONF-2022-032]

Measurement of angle between τ decay planes in Higgs rest frame

$$d\Gamma(H \rightarrow \tau^+\tau^-) \sim 1 - \cos(\phi_{CP} - 2\alpha_\tau)$$

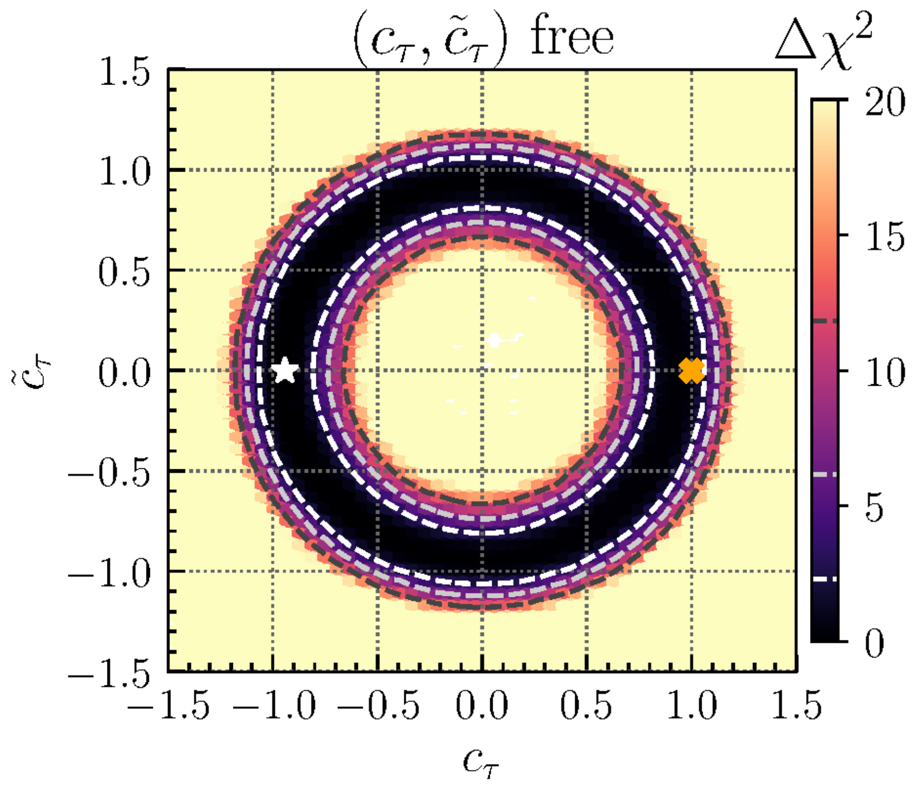
[Berge et al., arXiv:1410.6362]

"CP-mixing angle"

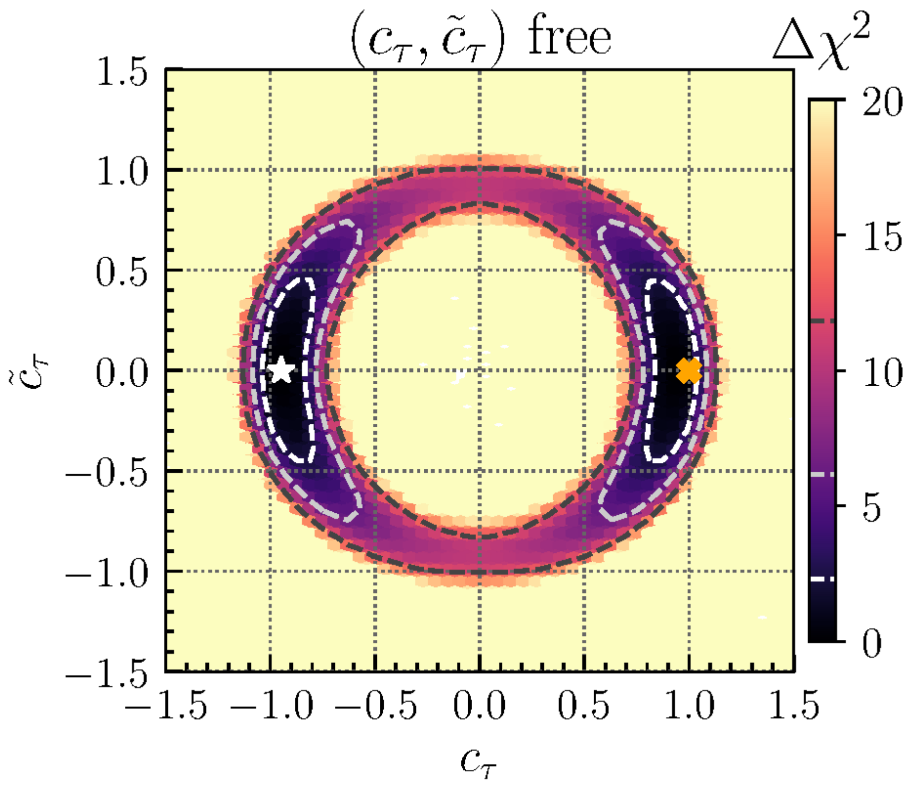


Why CP sensitivity is important

Comparison of constraints in indirect vs direct measurement:



Only $H \to \tau\tau$ signal strength measurement



Including direct ϕ_{CP} measurement

[Bahl, Fuchs, Heinemeyer, Katzy, MM, Peters, Saimpert, Weiglein, arXiv:2202.11753]

Building a CP-odd observable

$$\mathcal{L}_{HC} \supset -\frac{1}{4}\left(c_g G^a_{\mu\nu} G^{a,\mu\nu} + \tilde{c}_g G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\right)\phi$$

Size of coupling modifiers visible in gluon-fusion cross section:

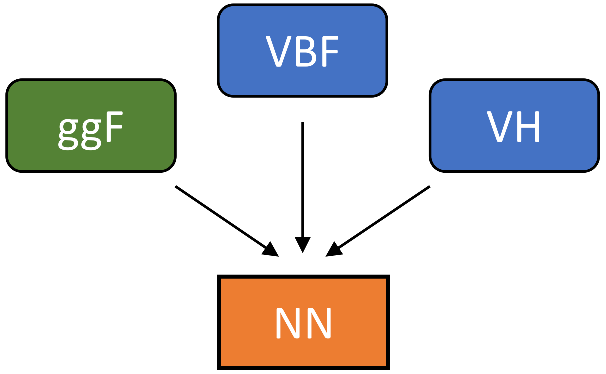
$$\sigma_{ggF} \propto c_g^2 \left|\mathcal{M}_{ggF}^{CP-even}\right|^2 + \tilde{c}_g^2 \left|\mathcal{M}_{ggF}^{CP-odd}\right|^2 \quad \text{} \} \text{ CP-even}$$

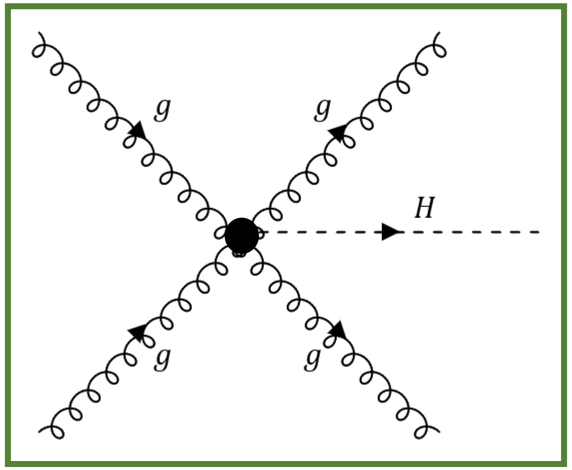
$$+2 c_g \tilde{c}_g \Re\left[\mathcal{M}_{ggF}^{CP-even} \mathcal{M}_{ggF}^{CP-odd^*}\right] \quad \} \text{ CP-odd}$$

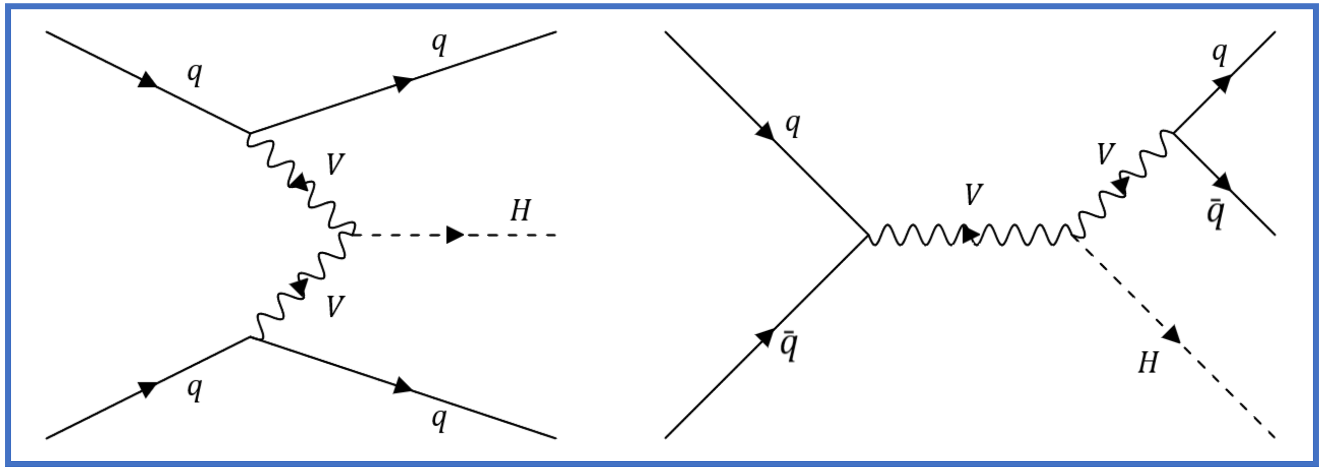
→ CP-odd contribution gives asymmetry in CP-sensitive observables

Building a CP-odd observable

- Simulate events for $gg \to Hjj$ (signal) and VBF, VH (background) with $H \to \gamma\gamma$ and detector simulation
- Effective $H\gamma\gamma$ coupling assumed to be SM-like
- Train classifier for signal-background separation





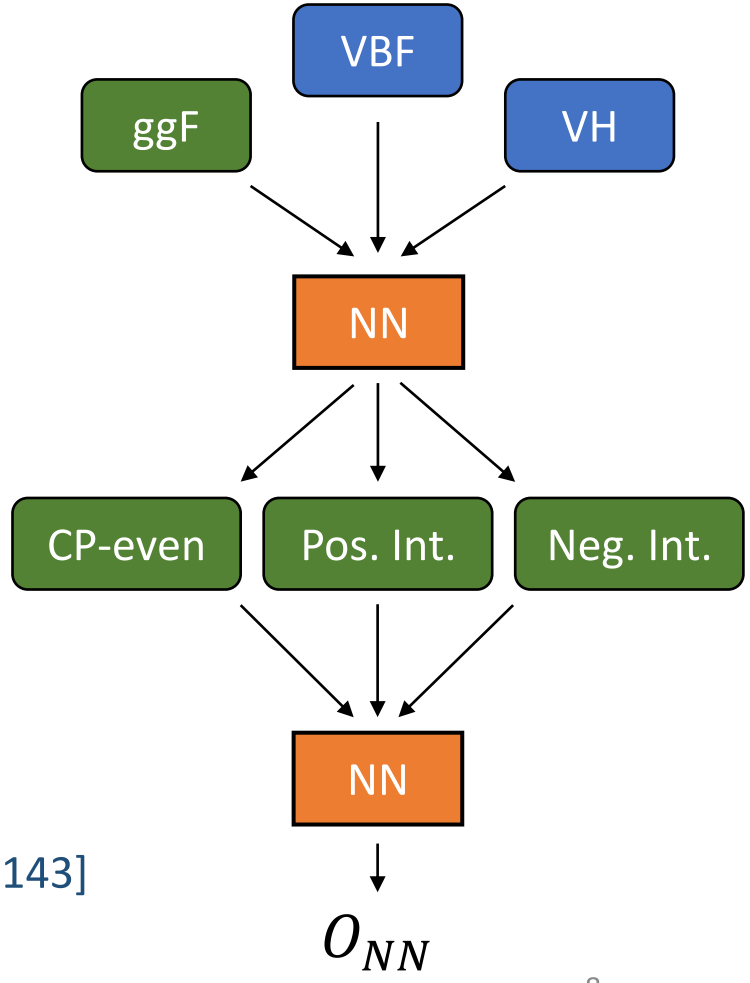


Building a CP-odd observable

- Interference events were generated separately
- Train classifier for CP-structure separation
- CP-odd observable: $O_{NN} = P_{+} - P_{-}$

Probability for positive interference (P_{+})

Probability for negative interference (P_{-})



Idea from [Bhardwaj et al., arXiv:2112.05052] & [Clarke-Hall et al., arXiv:2202.05143]

CP sensitivity: distributions

"Traditional" CP observable:

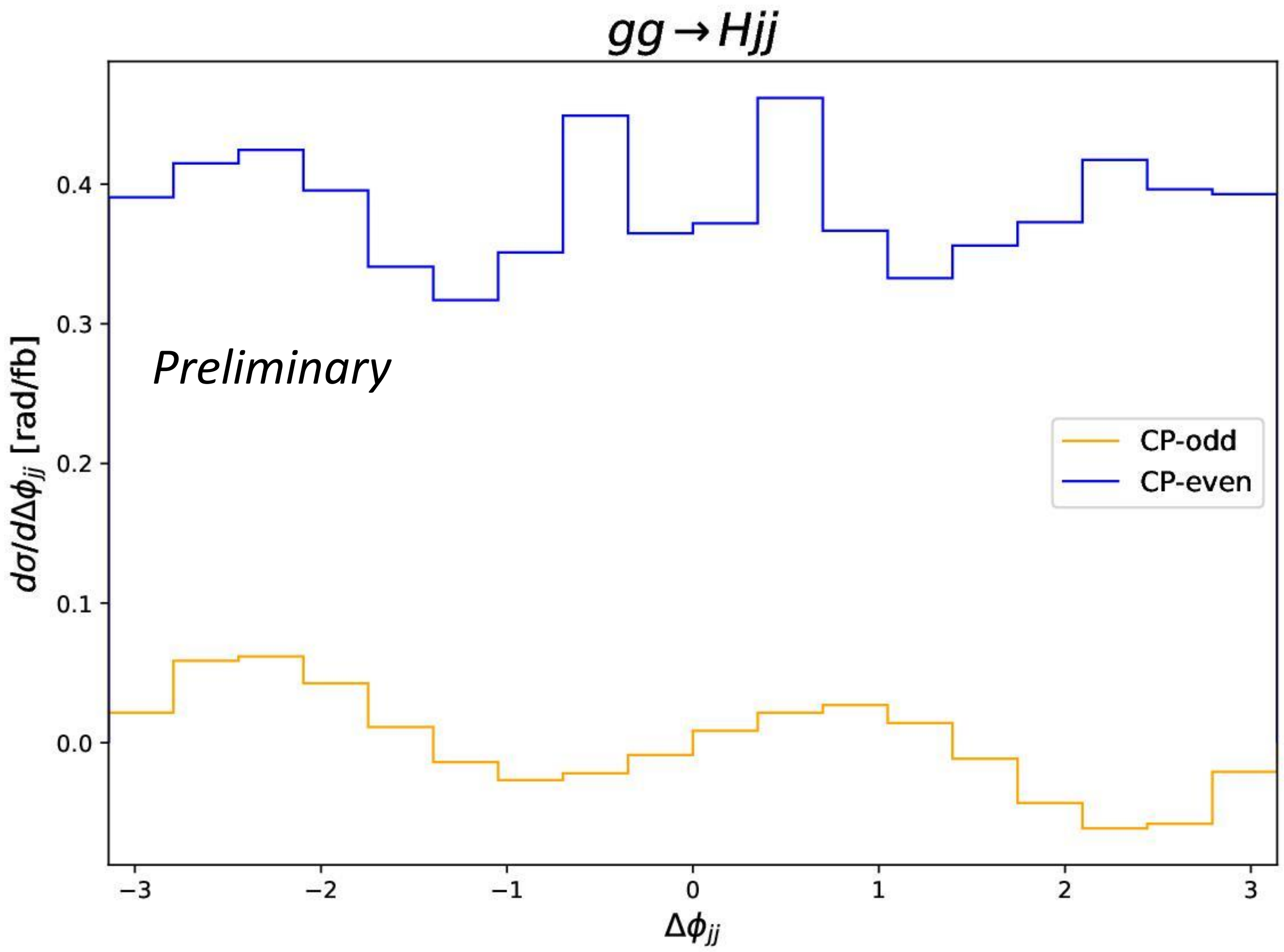
[Englert et al., arXiv:1203.5788]

$$\Delta\phi_{jj} = \phi_{j1} - \phi_{j2}\,;\, \eta_{j1} > \eta_{j2}$$

Asymmetry in cross section could be measurable

→ Constraints on CP violation

→ Not full kinematics

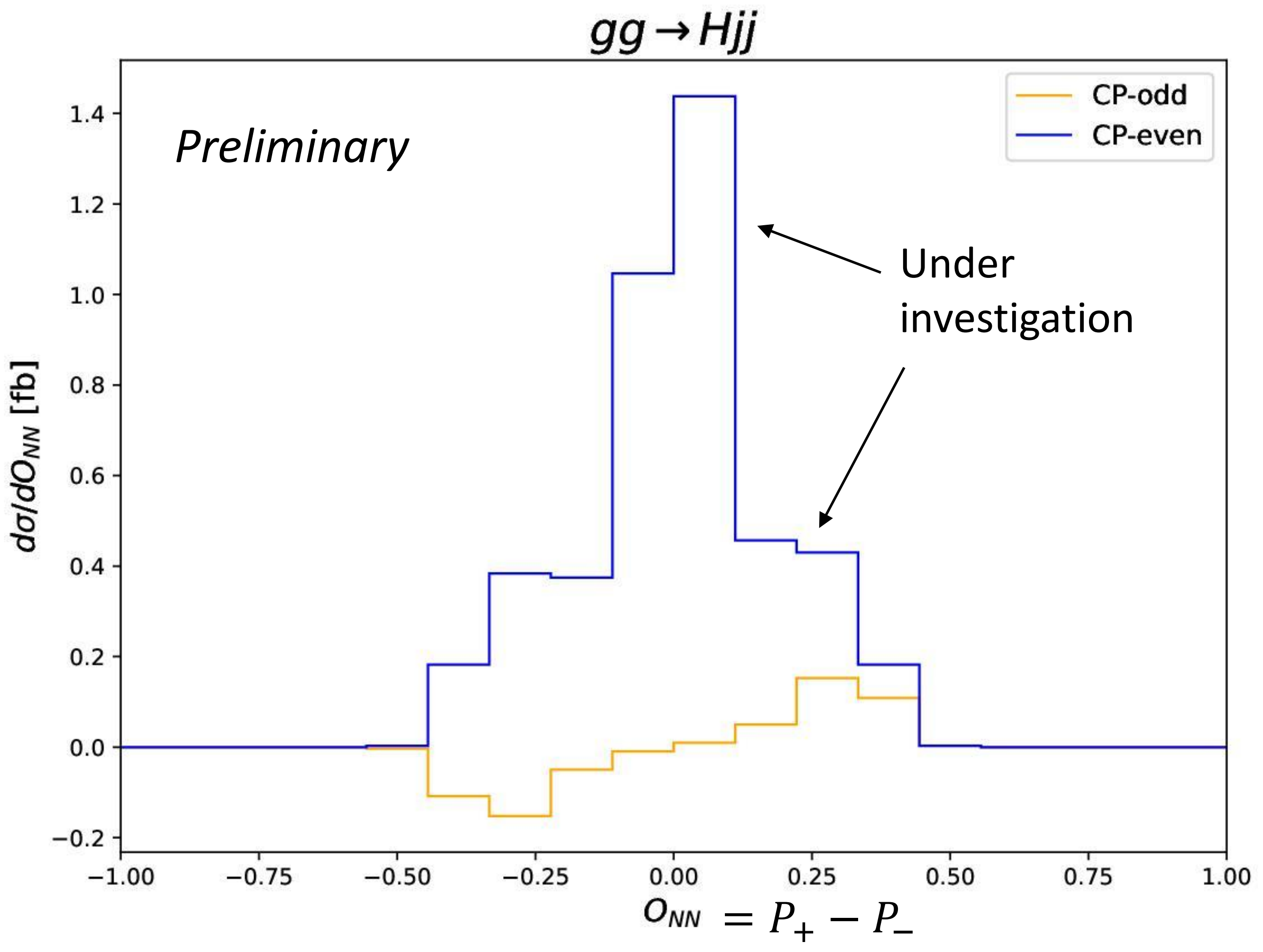


CP sensitivity: distributions

Input for neural network:

E, p_T, η and ϕ of reconstructed Higgs and two leading order jets
→ Full kinematics

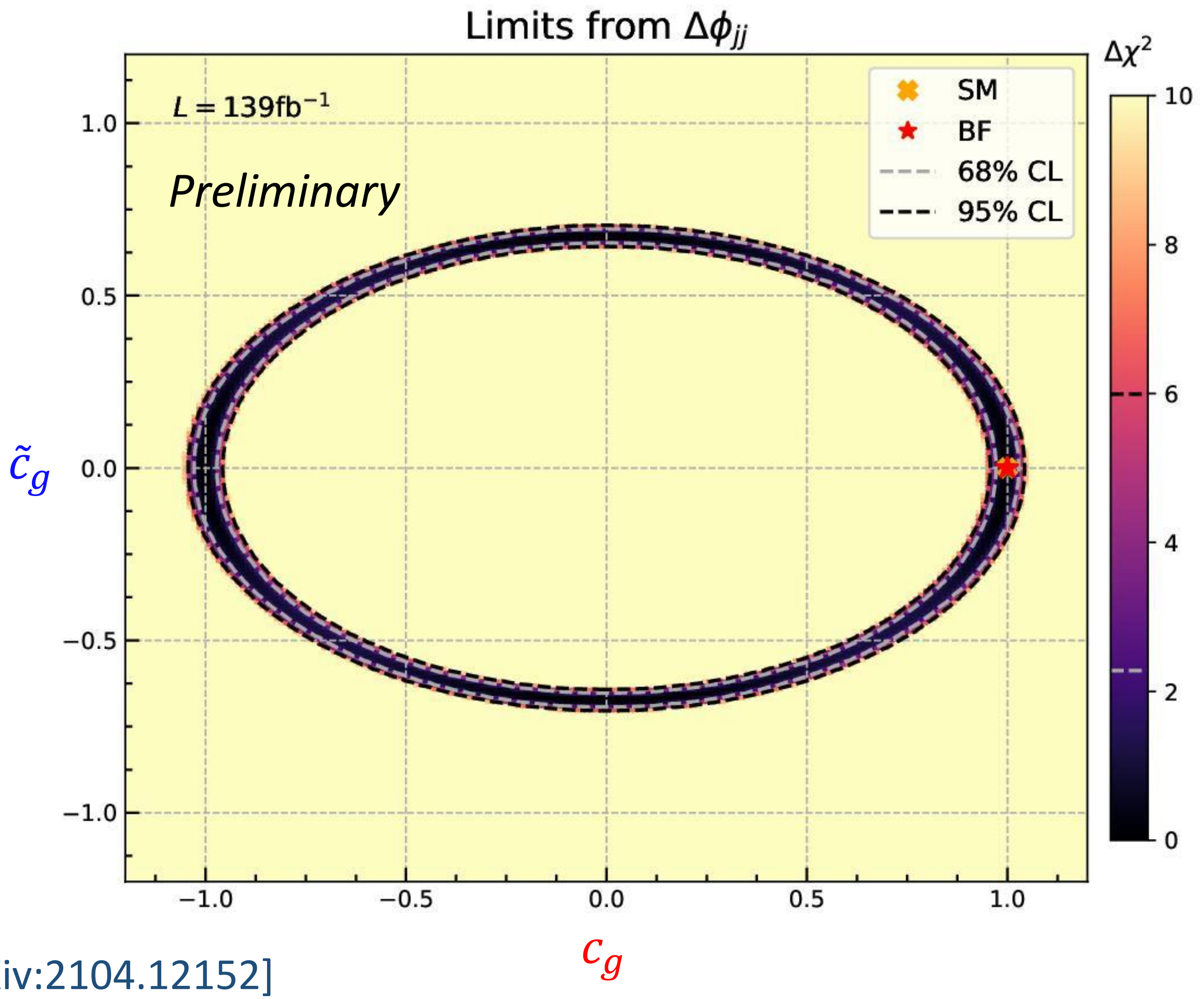
Additionally: $m_{jj}, \Delta\phi_{jj}, \Delta\eta_{jj}$
→ Not needed but make training faster



CP sensitivity: Limits

Ellipse in $c_g, \tilde{c}_g$ plane due to different contributions to σ_{ggF}

Neither large values of $\tilde{c}_g$, nor large $c_g \cdot \tilde{c}_g$ mixing disfavored

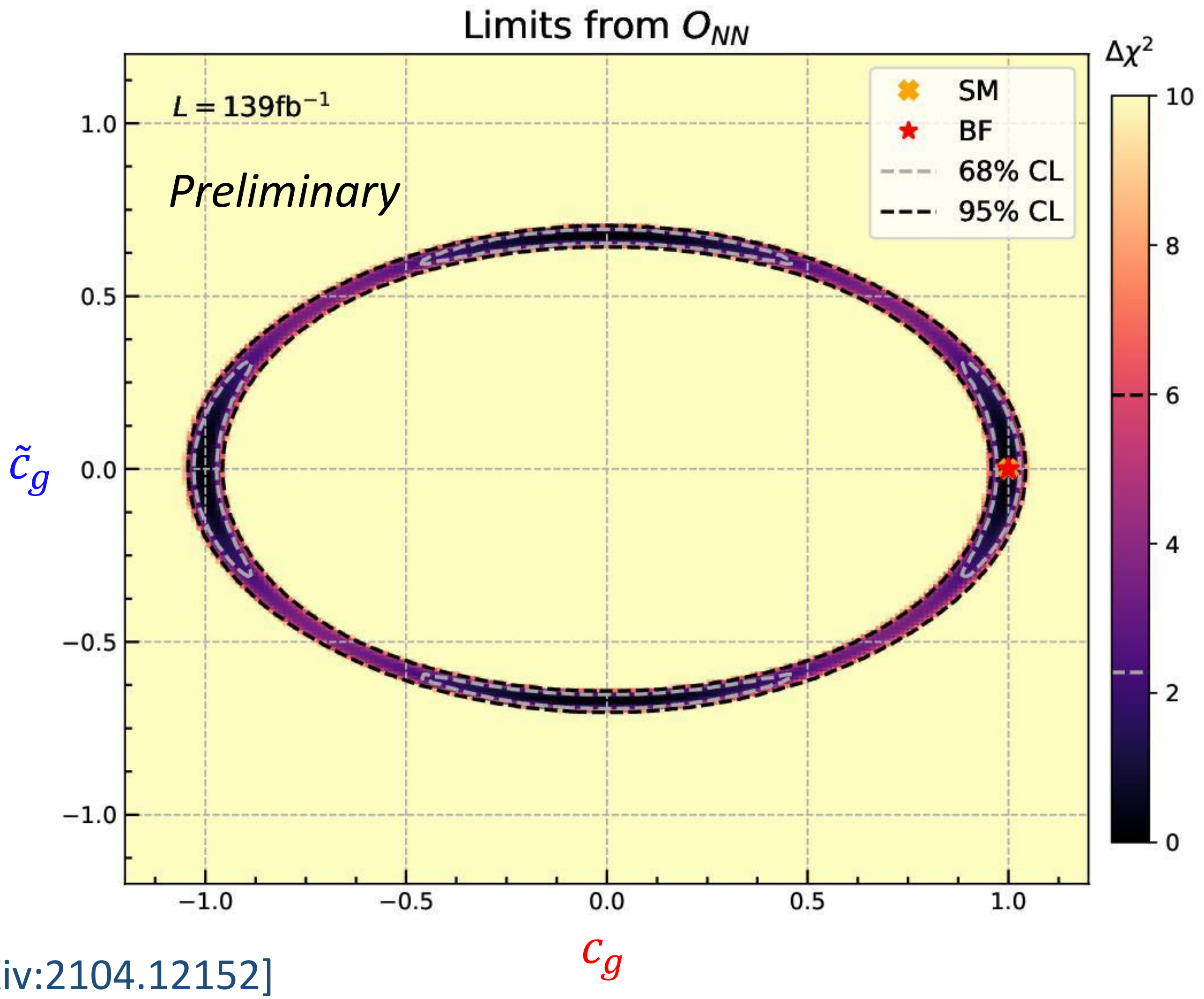


Note: Large $\tilde{c}_g$ disfavored in VBF-like events: [arXiv:2104.12152]

CP sensitivity: Limits

Large interference effects $c_g \cdot \tilde{c}_g$ excluded on a 68% confidence level

Large values of $\tilde{c}_g^2$ still allowed due to similar kinematics to c_g^2



Note: Large $\tilde{c}_g$ disfavored in VBF-like events: [arXiv:2104.12152]

CP sensitivity: Limits

NN unable to differentiate c_g^2 and $\tilde{c}_g^2$ terms

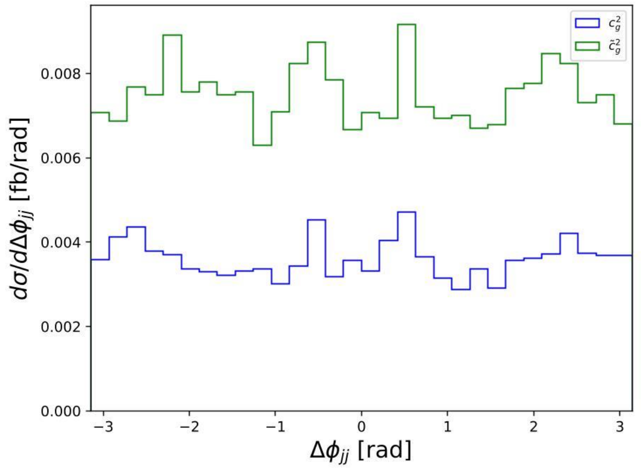
- Most CP information in qq initial states

- Jets in gg and gq states from gluon radiation → washout of CP distribution

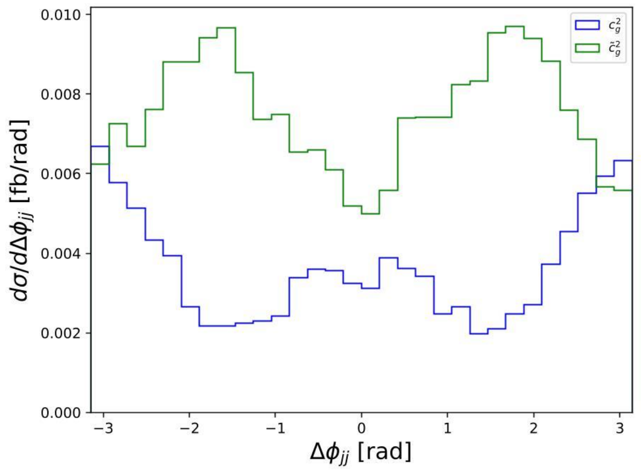
- Most qq events have same topology as VBF → discarded as background

⇒ Need analysis in ggF and VBF region

gg initial state



qq initial state




THANK YOU FOR
LISTENING TO MY PRESENTATION

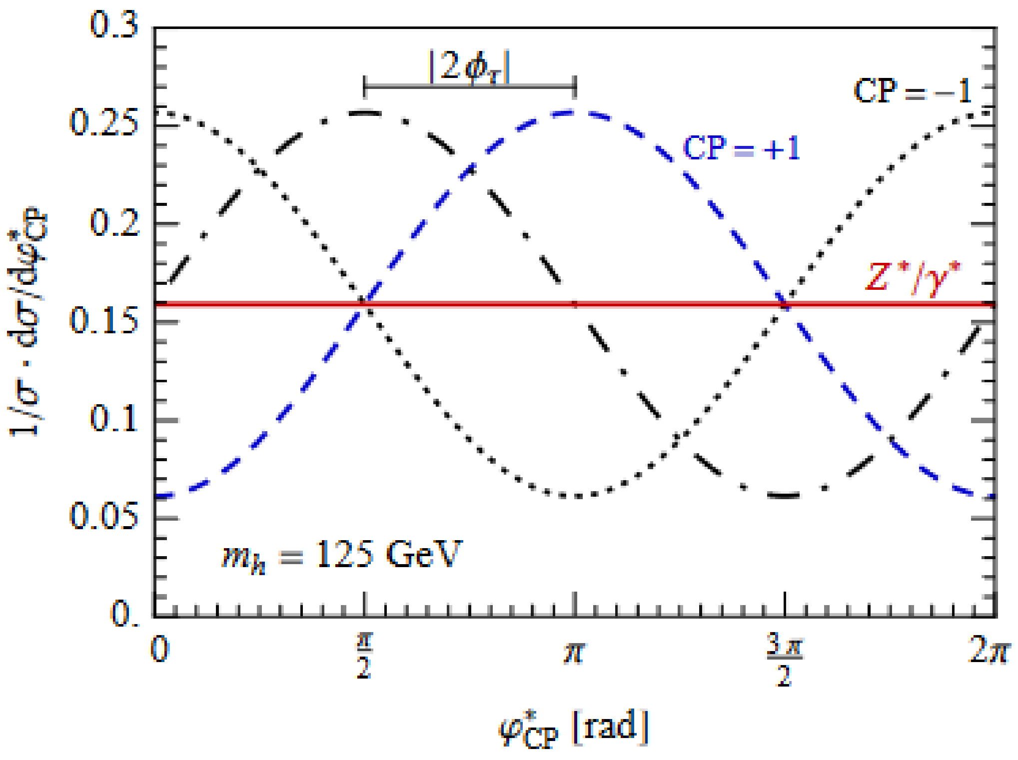
Backup slides

Full HC Lagrangian

$$\mathcal{L}_{J=0} = -\sum_{f=t,b,\tau} \bar{\Psi}_f \left(c_f g_{Hff} + i\tilde{c}_f g_{Aff}\gamma_5\right)\Psi_f \phi$$
$$+\Big\{c_V\,[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}]$$
$$-\frac{1}{4}[c_\gamma g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + \tilde{c}_\gamma g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu}]$$
$$-\frac{1}{4}[c_{Z\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + \tilde{c}_{Z\gamma} g_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu}]$$
$$-\frac{1}{4}[c_g g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tilde{c}_g g_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}]$$
$$-\frac{1}{4}\frac{1}{\Lambda}[c_Z Z_{\mu\nu} Z^{\mu\nu} + \tilde{c}_Z Z_{\mu\nu} \tilde{Z}^{\mu\nu}]$$
$$-\frac{1}{2}\frac{1}{\Lambda}[c_W W^+_{\mu\nu} W^{-\mu\nu} + \tilde{c}_W W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}] - \cdots\Big\}\phi$$

CP mixing Higgs-tau

CP violation is visible as a shift in the angle between the τ decay planes



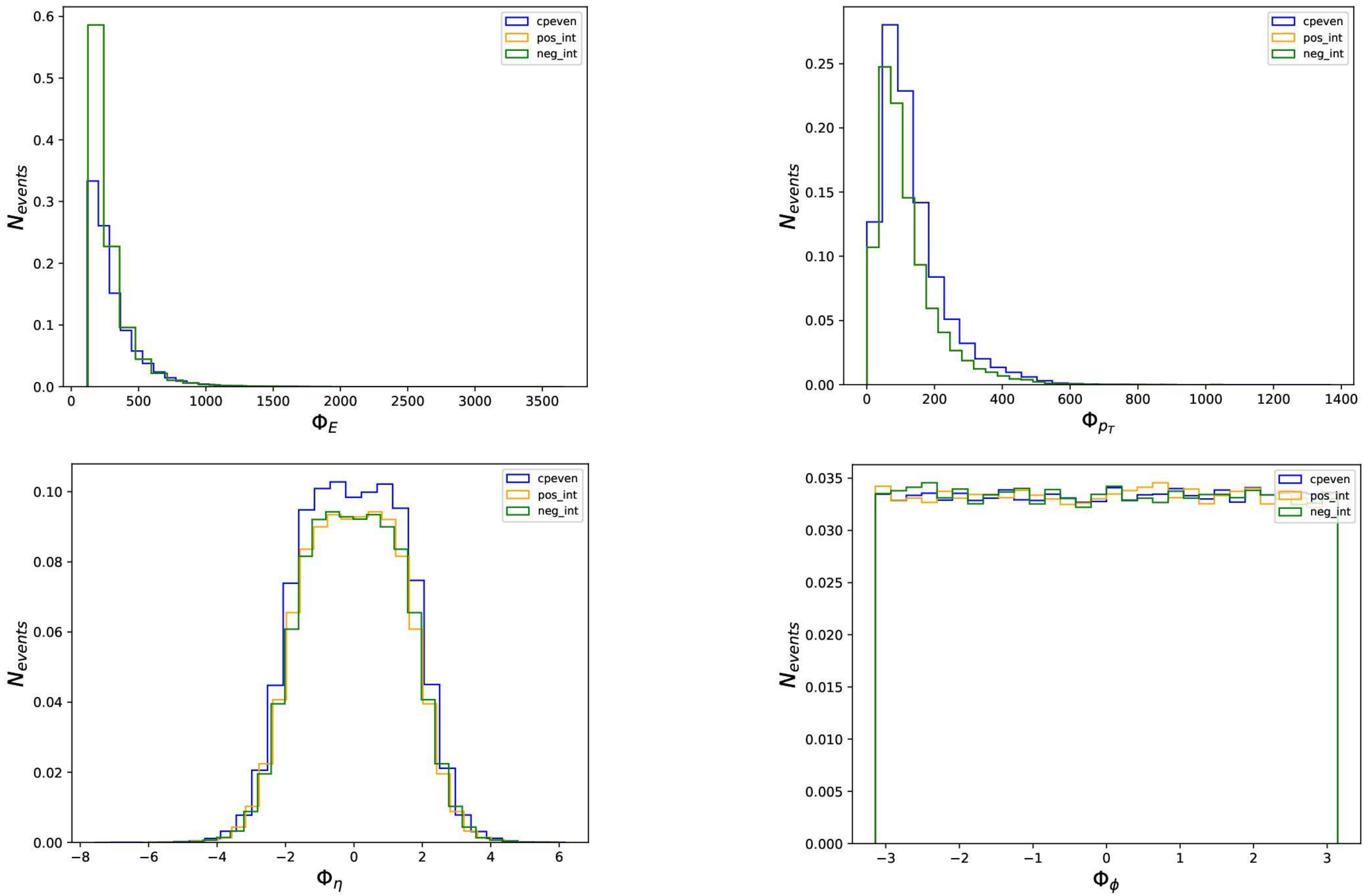
[Berge et al., arXiv:1410.6362]

$$d\Gamma(H \to \tau^+\tau^-) \sim 1 - \cos(\phi_{CP} - 2\alpha_\tau)$$

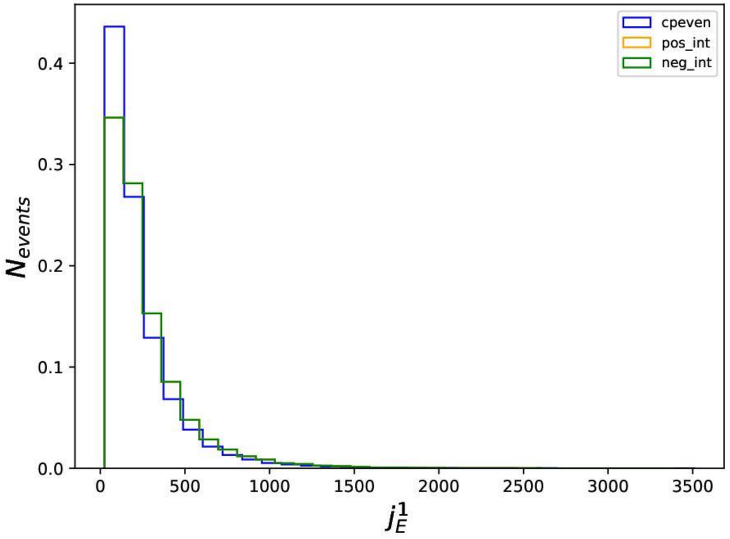
Cuts

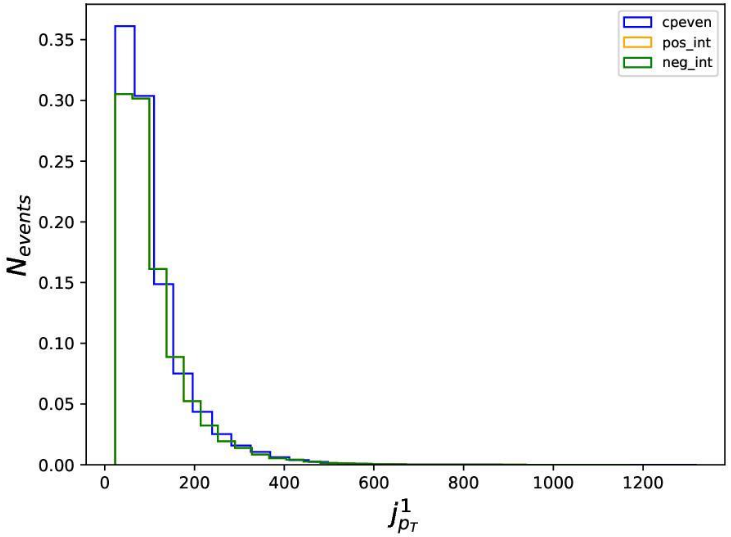
Applied cuts	Usage
$N_j \geq 2, N_\gamma \geq 2$	Construct CP variable & reconstruct Higgs
$110 \leq m_{\gamma\gamma} \leq 140$ [GeV]	Exclude non-Higgs background
$\lvert\eta_j\rvert \leq 2.5, \lvert\eta_\gamma\rvert \leq 2.5$	Simulate covered detector area
$p_T^j > 20\text{GeV}$	Exclude very soft jets
$p_T^{\gamma 1}/m_{\gamma\gamma} > 0.35$	Exclude photons from $q\bar{q}$-background
$p_T^{\gamma 2}/m_{\gamma\gamma} > 0.25$	
$\Delta\eta_{jj} \leq 3.5$	Reduce VBF background in data
$m_{jj} \leq 500\text{GeV}$	

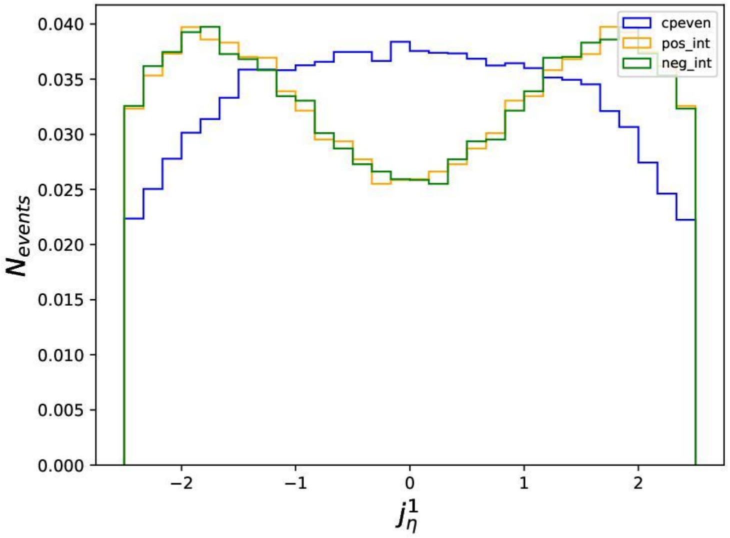
Kinematic variables – Higgs

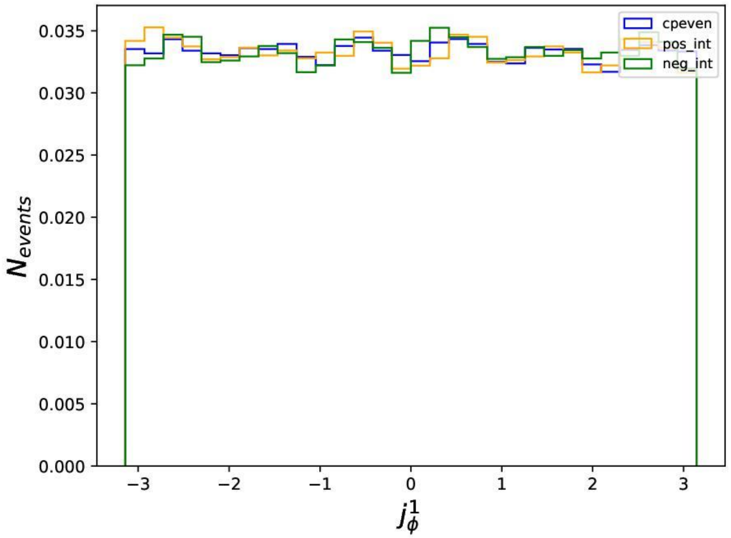


Kinematic variables – Jet 1

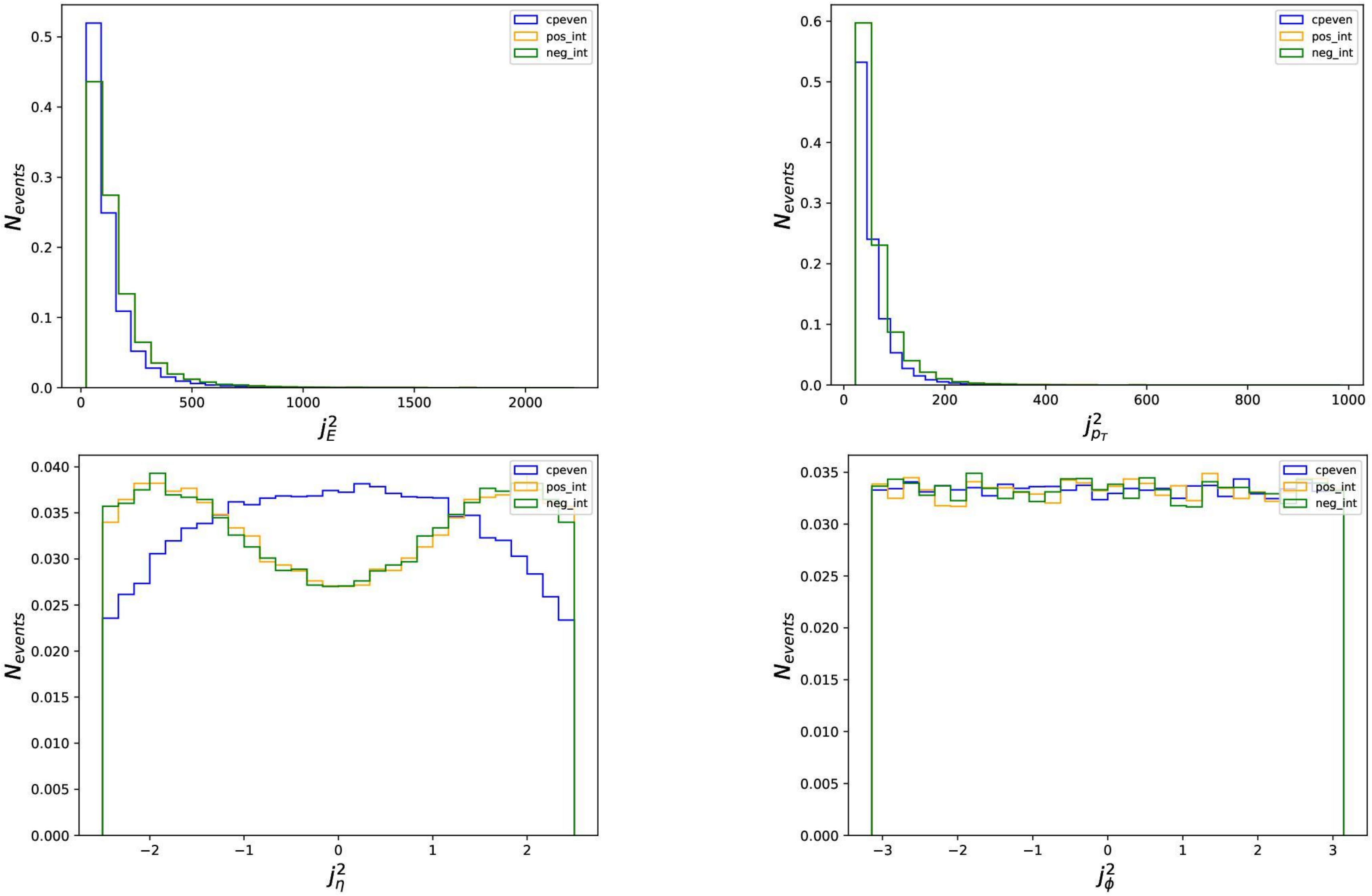




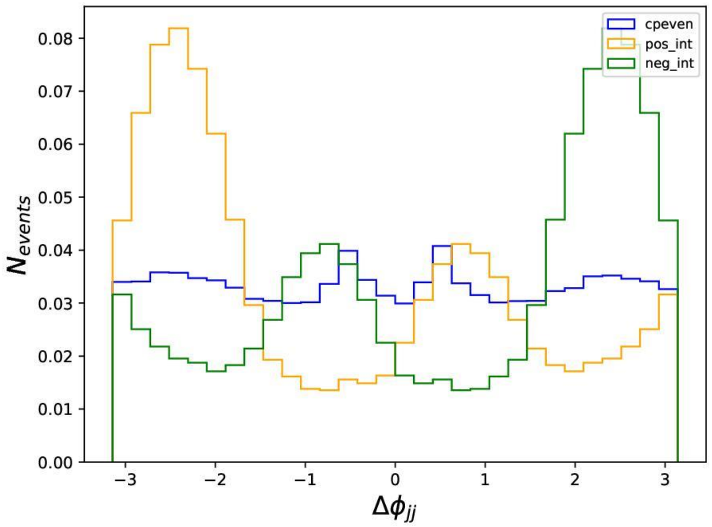


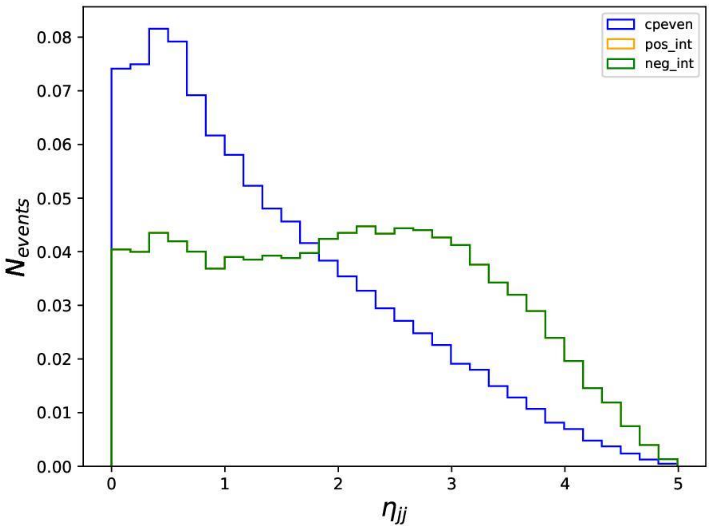


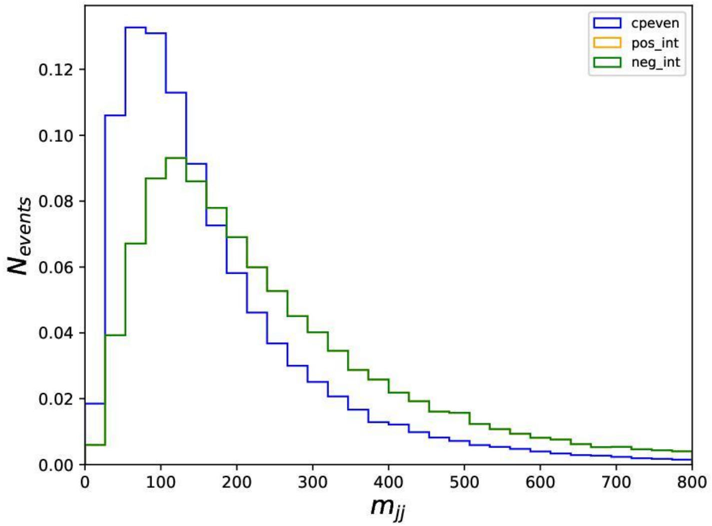
Kinematic variables – Jet 2



Kinematic variables – Other



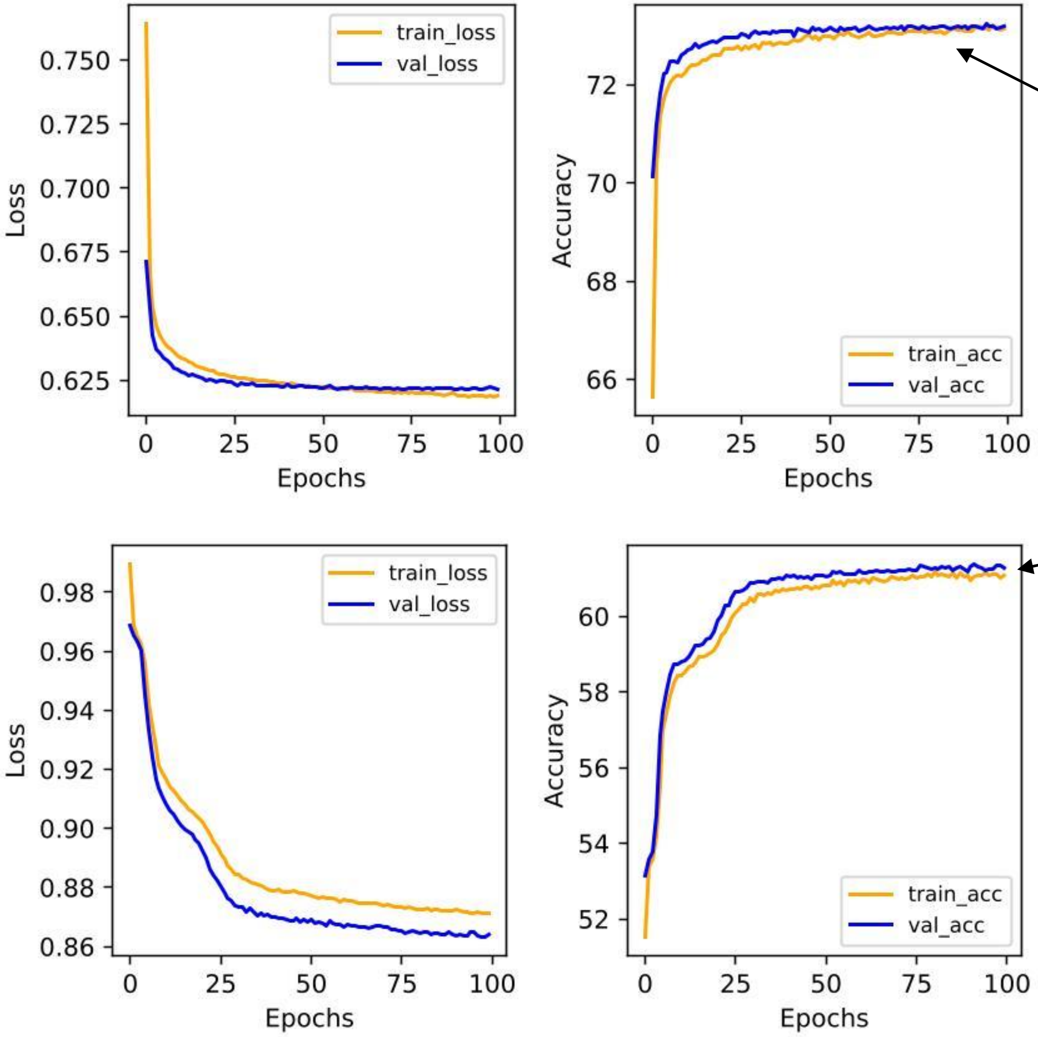




NN learning parameters

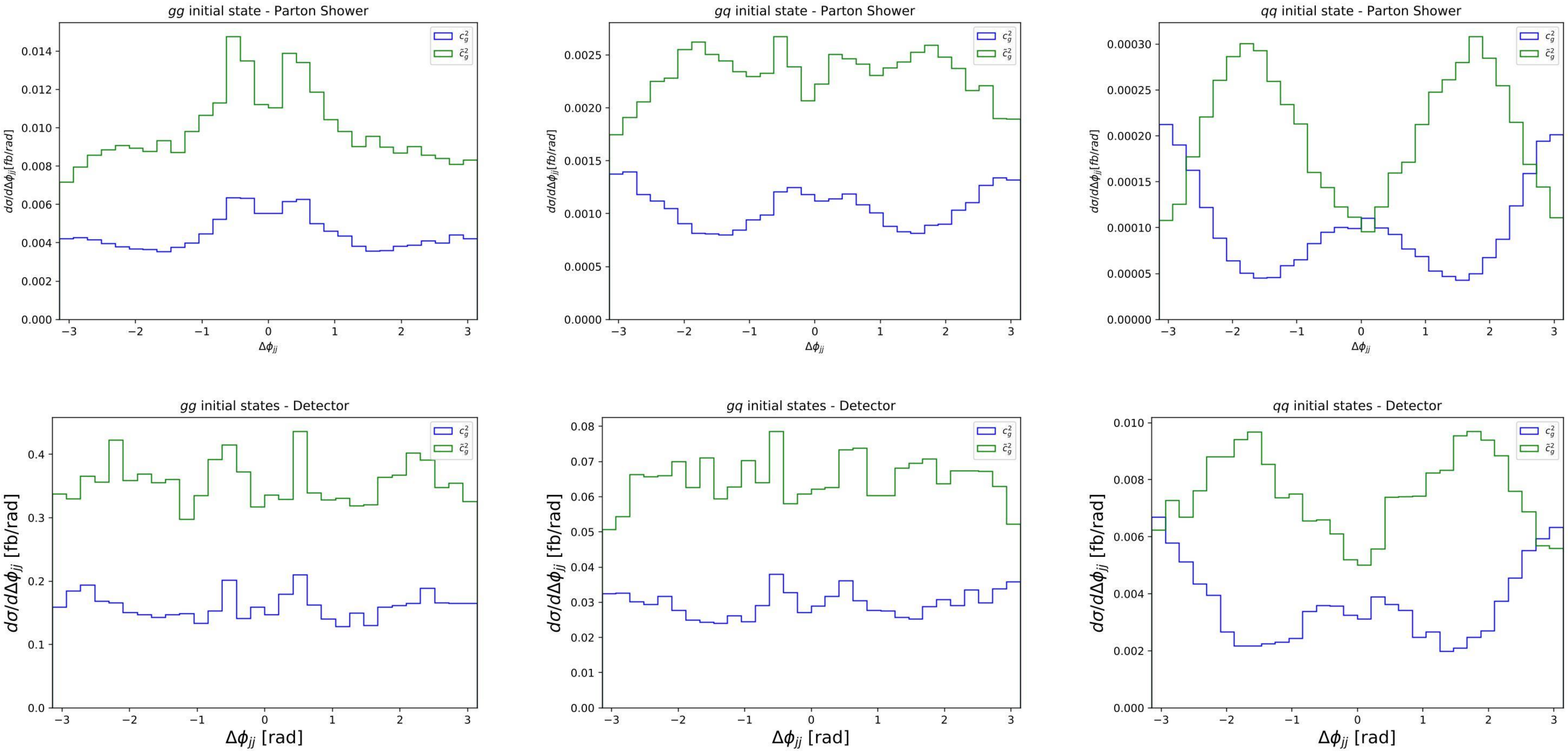
BG NN:

CP NN:



Differences due to Dropout

Initial state CP information



Marco Menen, LUH / PTB Braunschweig

Limits at HL-LHC