Dihedral Angle Observable for Measuring CP Property of Top-Higgs Interaction

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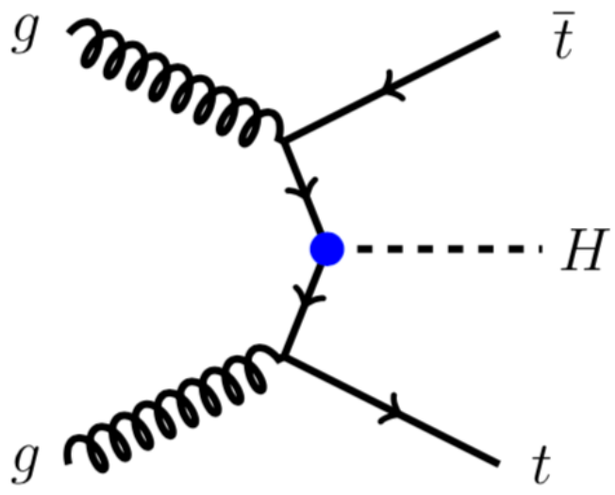
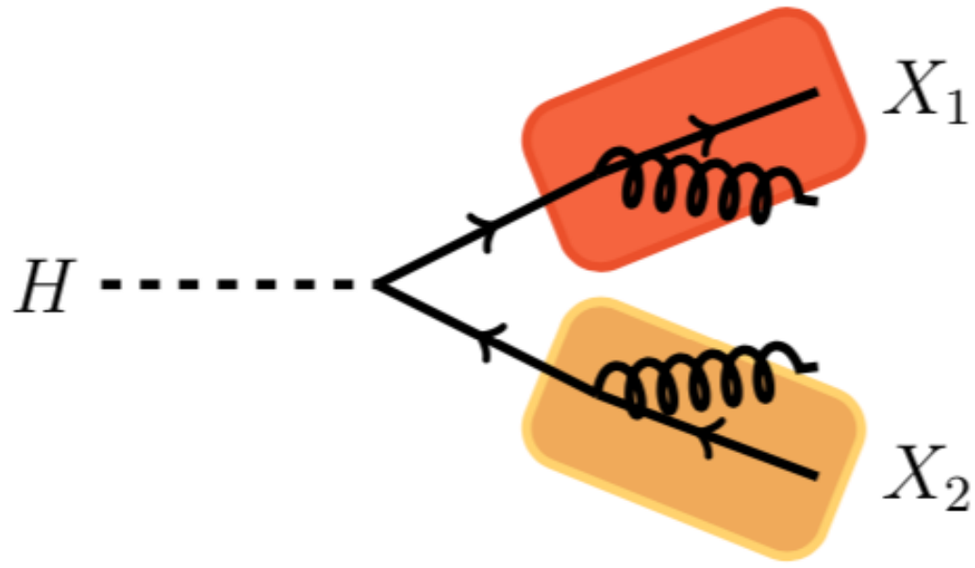
and further work

Direct Search of Higgs CP



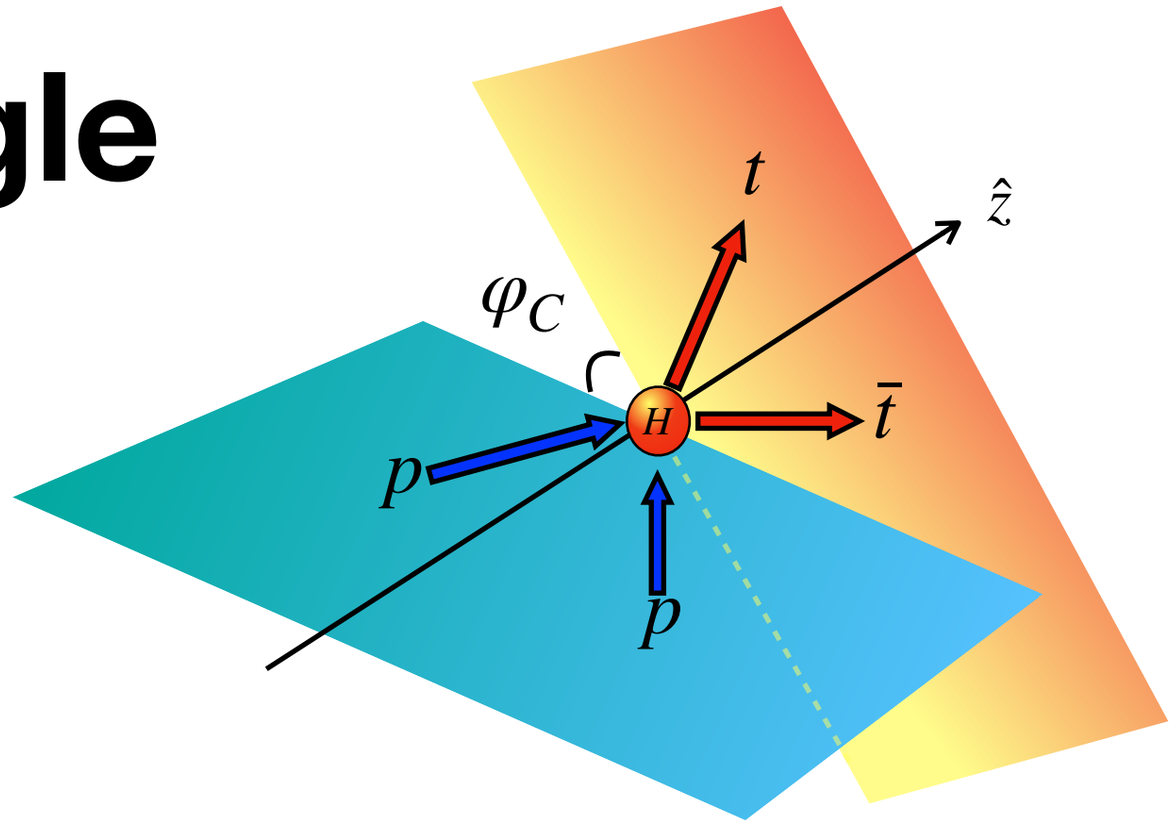


$$\mathscr{L}_{Ht\bar{t}} = -\kappa_t \frac{m_t}{v}\bar{t}e^{i\xi\gamma_5}t \equiv -\frac{m_t}{v}\bar{t}\left(a_t + ib_t\gamma_5\right)t$$

$$\sigma(H \to XX) = \begin{cases} p_{X_1}\cdot p_{X_2} - m_{X_1}m_{X_2} & \text{CP even} \\ p_{X_1}\cdot p_{X_2} + m_{X_1}m_{X_2} & \text{CP odd} \end{cases}$$

$p_t - p_g$ move faster for CP even

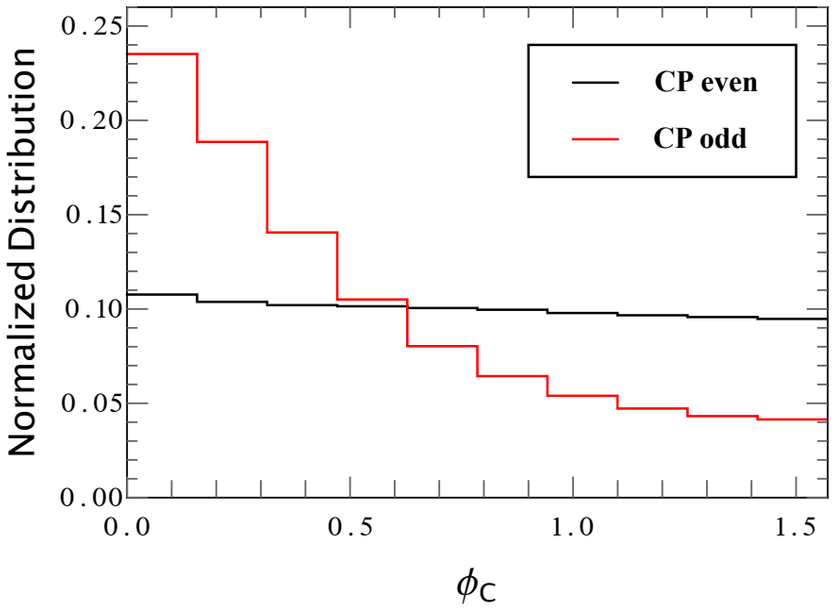
Dihedral Angle



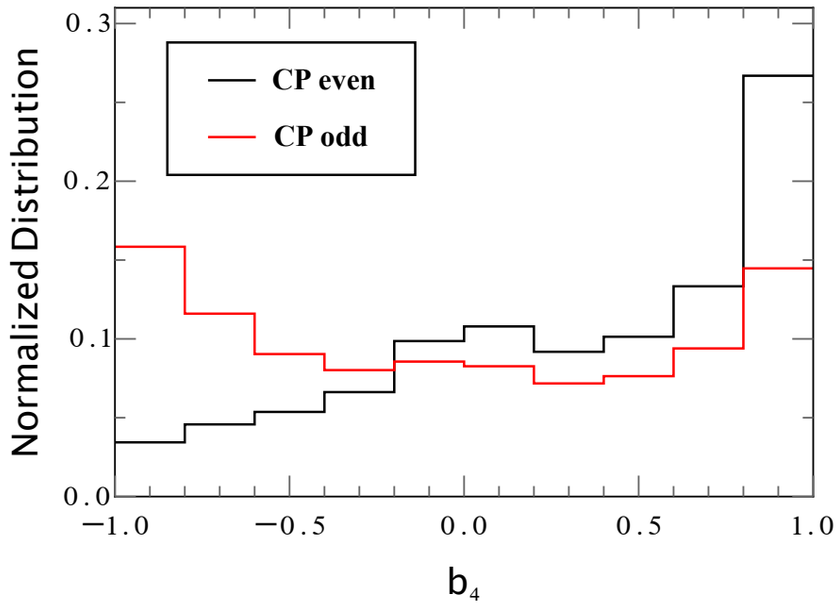
- boost invariance
- no top decay information
- only $p \cdot t$ contribute (t channel)
- CP-even: flat distribution

This work

ϕ_C : $< \vec{p}_t \times \vec{p}_{\bar{t}}, \vec{p}_{g_1} \times \vec{p}_{g_2} >$ in Higgs rest frame

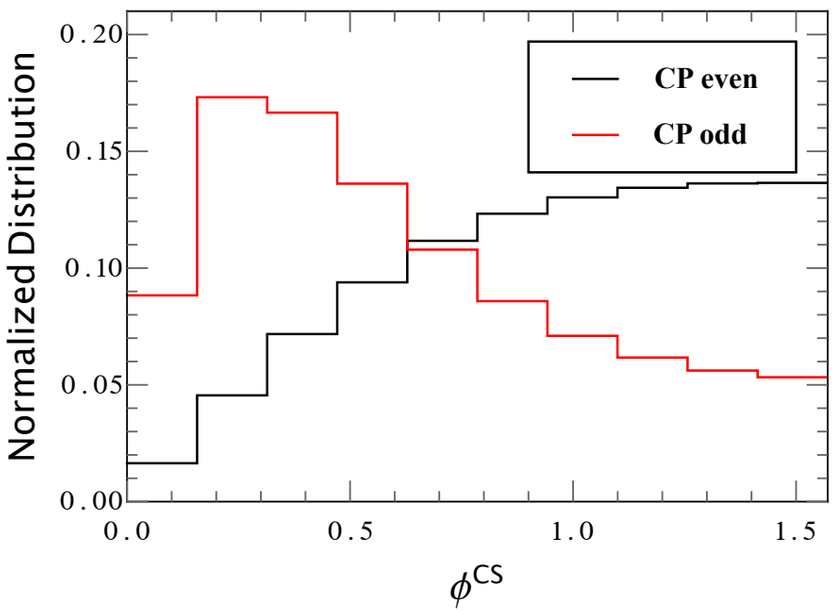


b_4 : $\frac{p_t^z p_{\bar{t}}^z}{|p_t||p_{\bar{t}}|}$ Gunion, He 1996

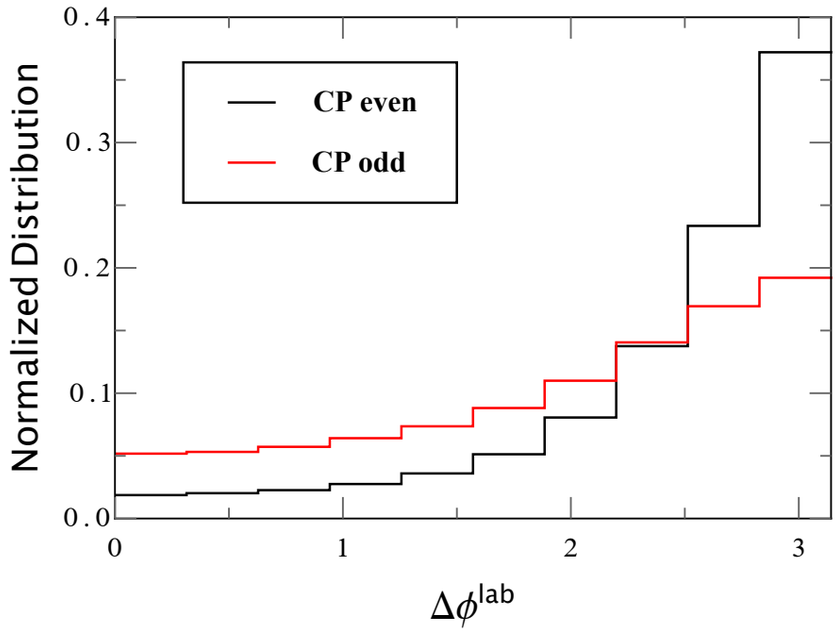


Collins, Soper 1977

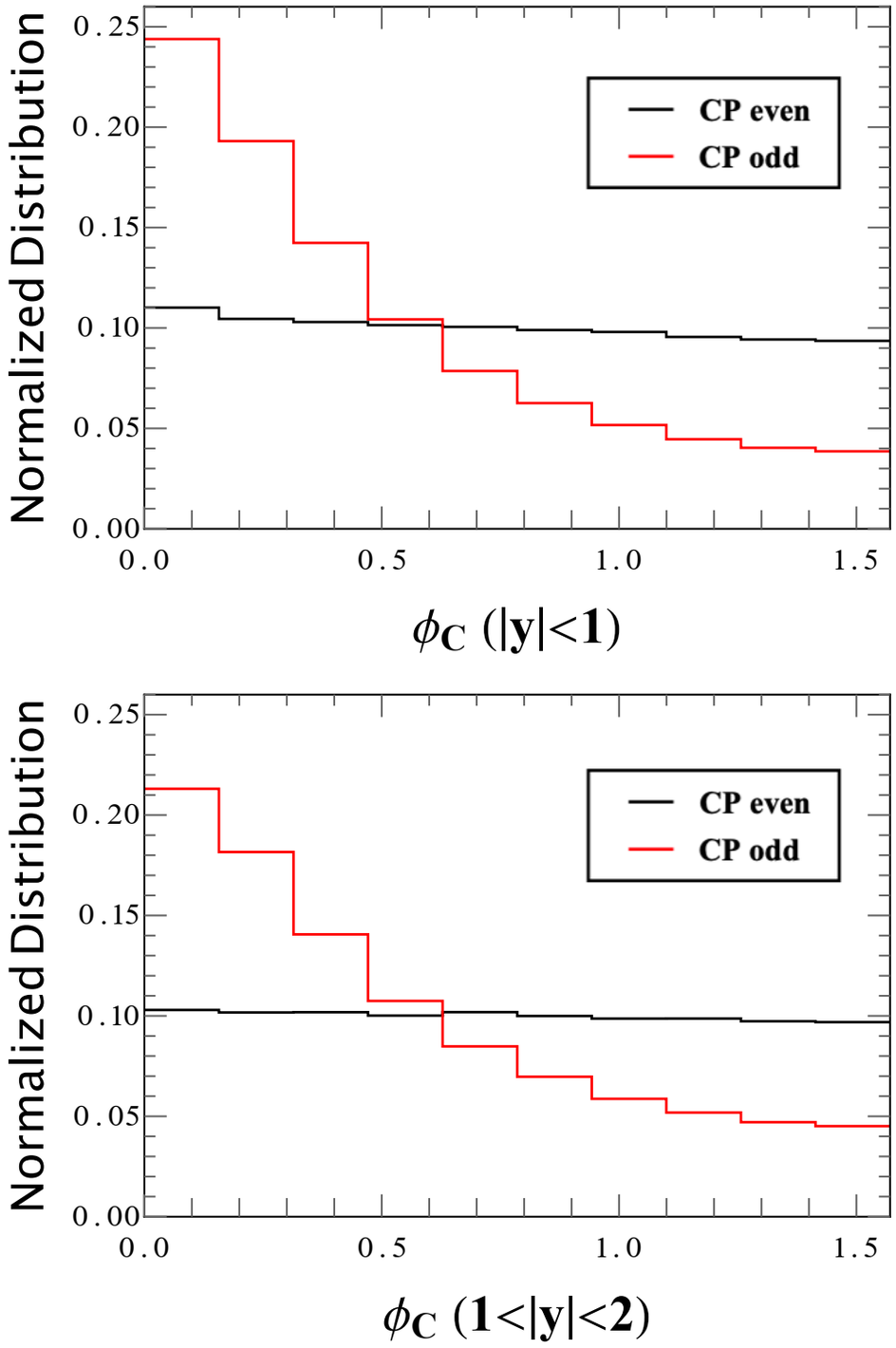
ϕ^{CS} : $< \frac{\vec{p}_t}{|p_t|} - \frac{\vec{p}_{\bar{t}}}{|p_{\bar{t}}|}, \frac{\vec{p}_{g_1}}{|p_{g_1}|} - \frac{\vec{p}_{g_2}}{|p_{g_2}|} >$ in $t\bar{t}$ rest frame

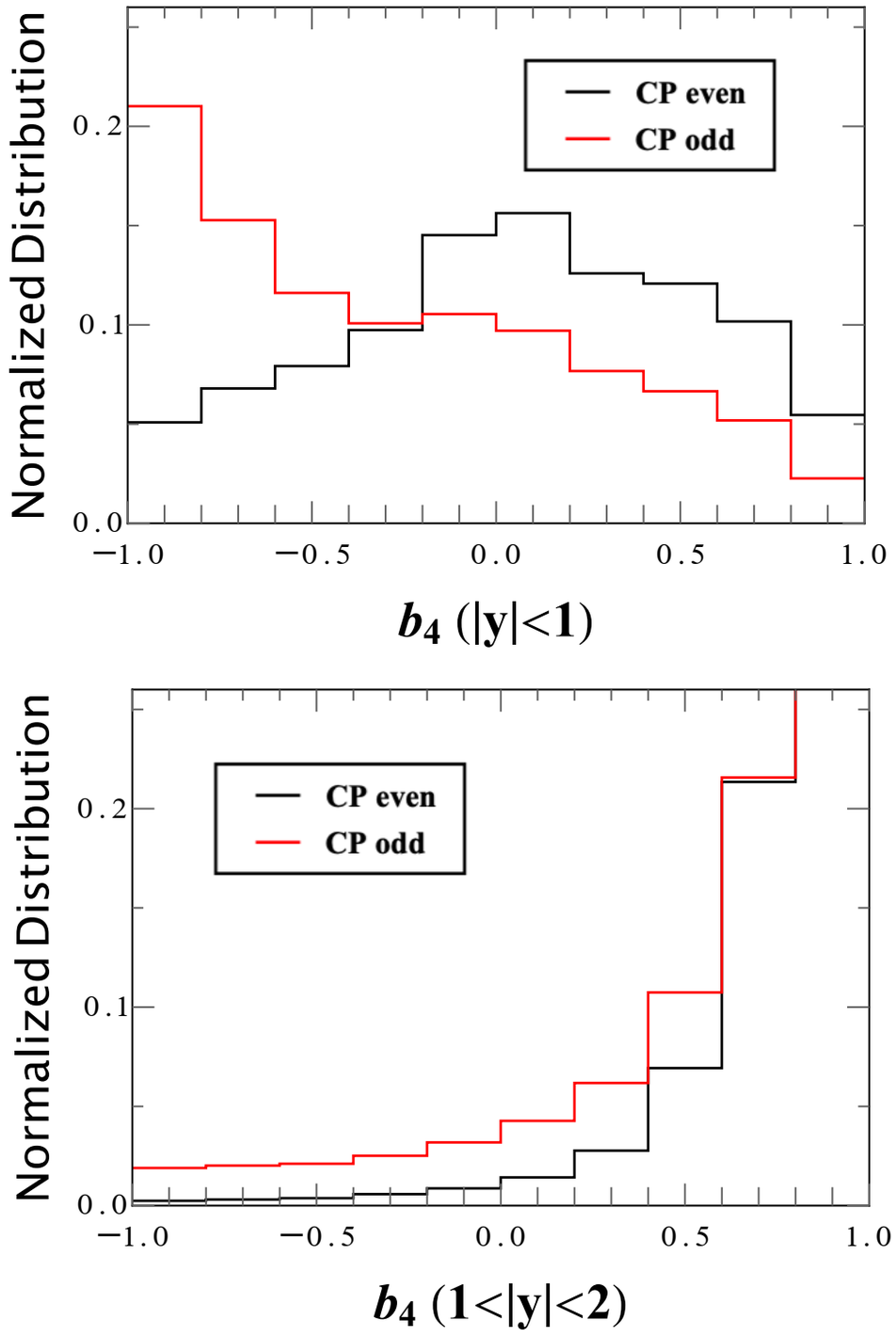


$\Delta\phi^{\text{lab}}$: $|\phi(t) - \phi(\bar{t})|$ Buckley, Gonçalves 2015



The distribution is boost invariant.



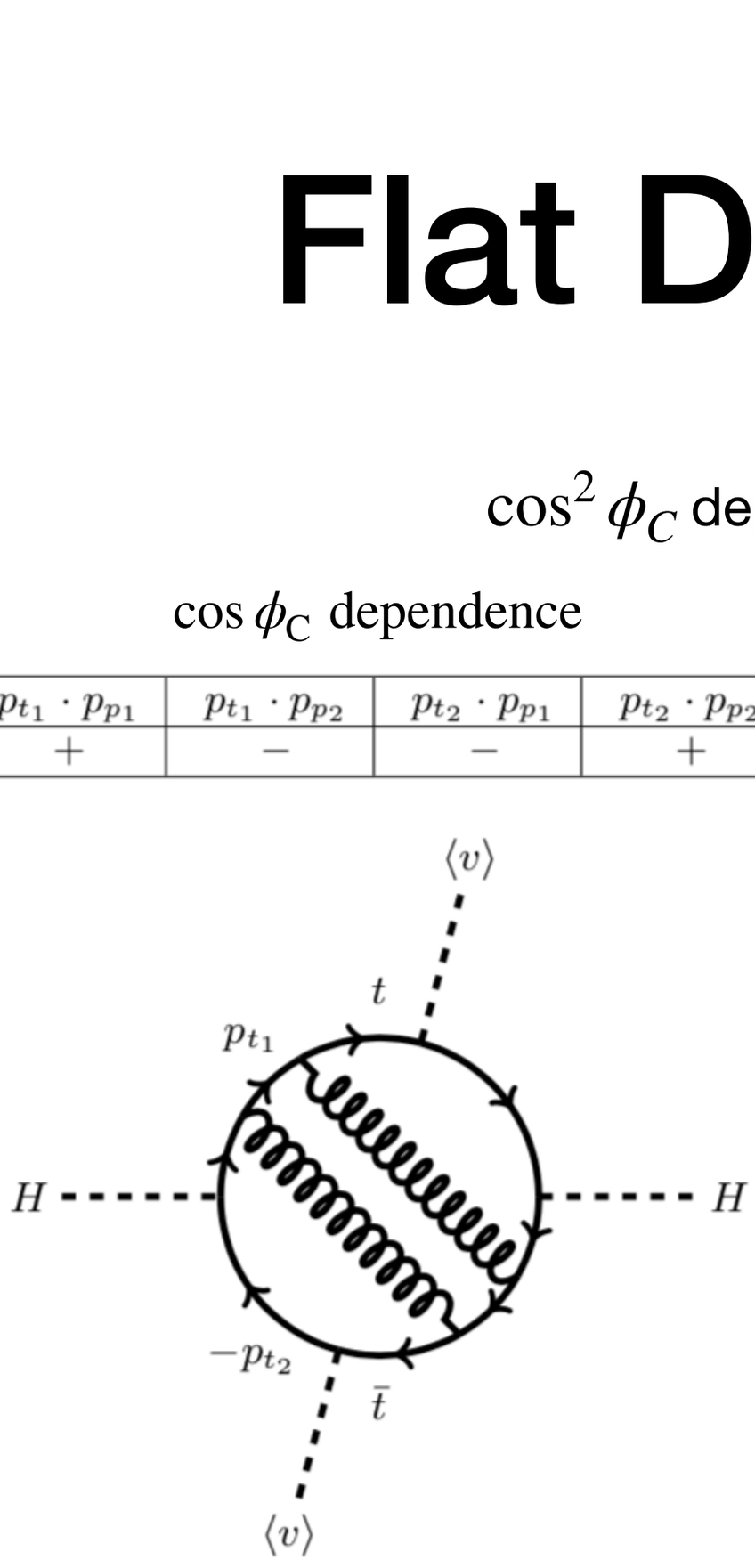


Flat Distribution

$\cos^2\phi_C$ dependence: $(p_{t_1}\cdot p_{p_1})(p_{t_2}\cdot p_{p_2})$ or $(p_{t_1}\cdot p_{p_2})(p_{t_2}\cdot p_{p_1})$

$\cos\phi_C$ dependence

$p_{t_1}\cdot p_{p1}$	$p_{t_1}\cdot p_{p2}$	$p_{t_2}\cdot p_{p1}$	$p_{t_2}\cdot p_{p2}$
+	−	−	+



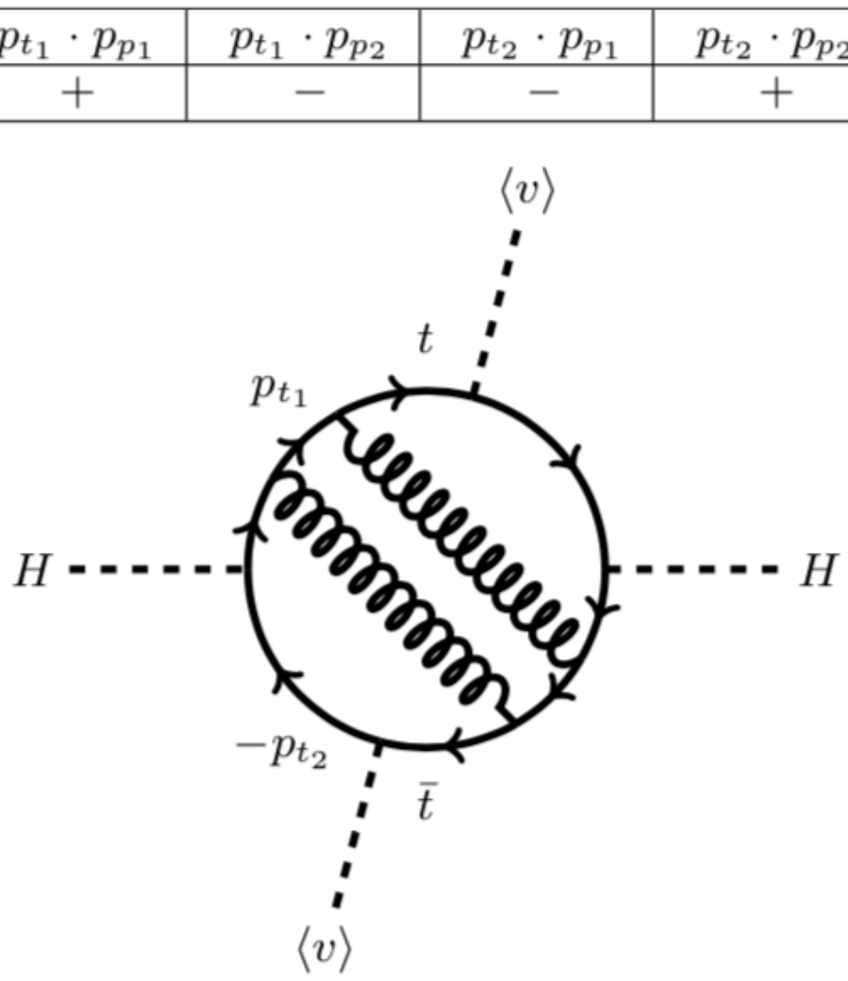
Flat Distribution

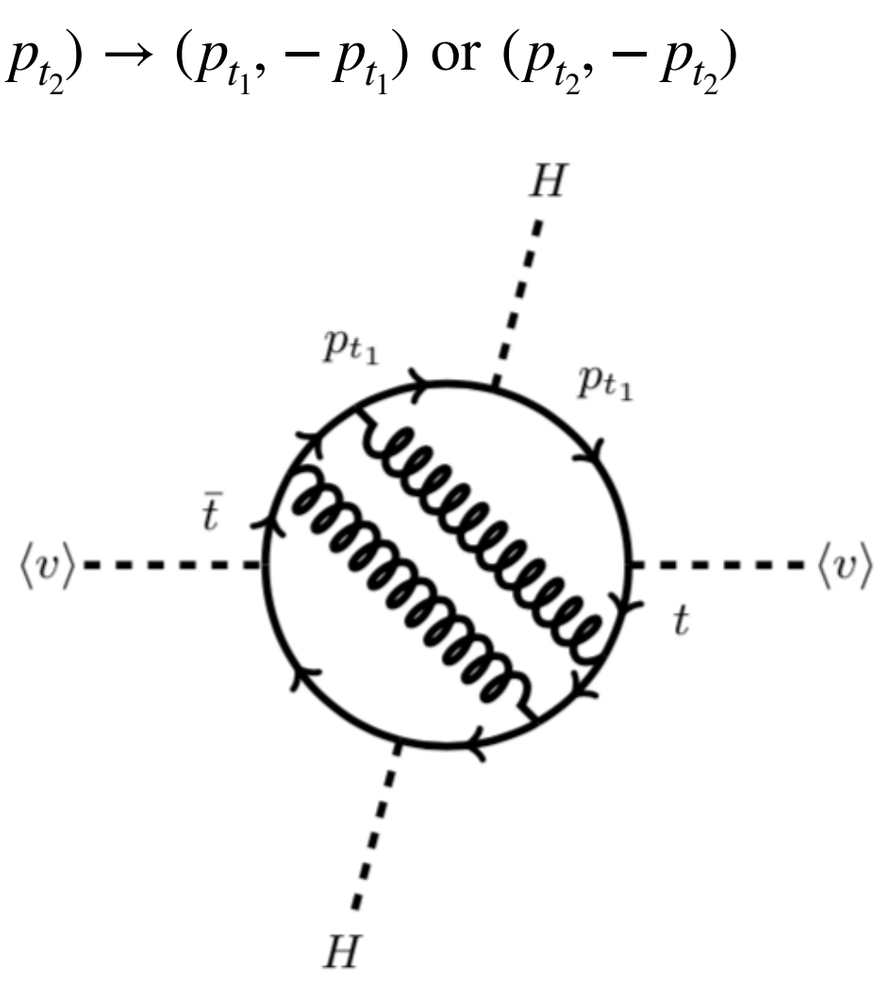
$\cos^2\phi_C$ dependence: $(p_{t_1}\cdot p_{p_1})(p_{t_2}\cdot p_{p_2})$ or $(p_{t_1}\cdot p_{p_2})(p_{t_2}\cdot p_{p_1})$

$\cos\phi_C$ dependence

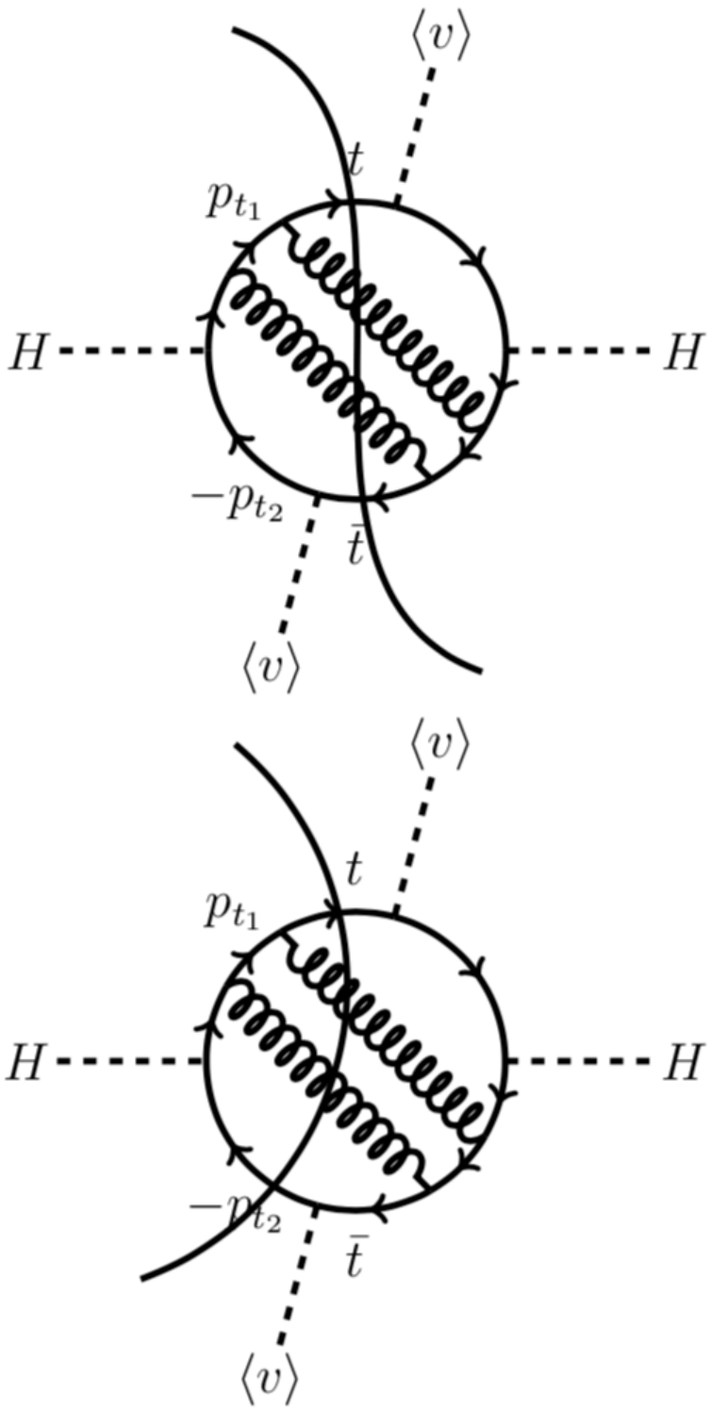
$p_{t_1}\cdot p_{p1}$	$p_{t_1}\cdot p_{p2}$	$p_{t_2}\cdot p_{p1}$	$p_{t_2}\cdot p_{p2}$
+	−	−	+

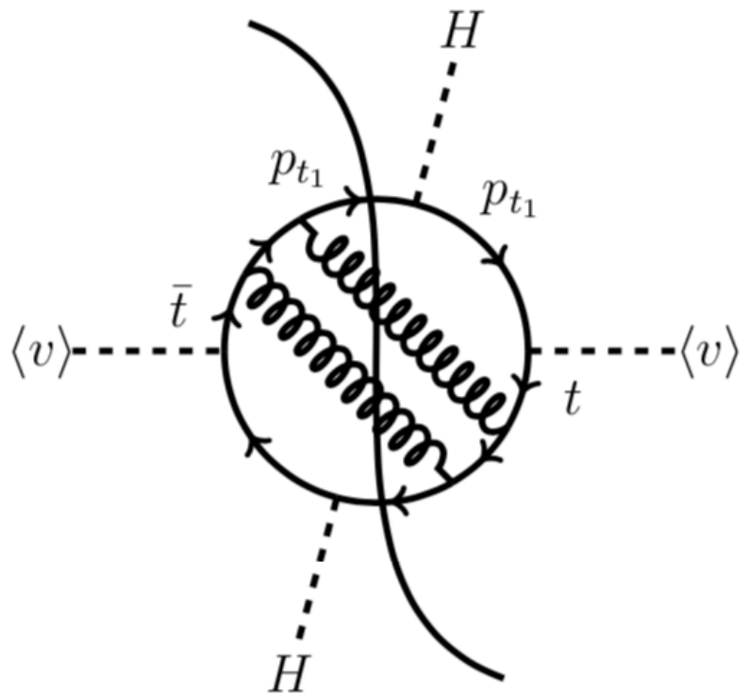
$(p_{t_1}, p_{t_2}) \to (p_{t_1}, -p_{t_1})$ or $(p_{t_2}, -p_{t_2})$





Flat Distribution





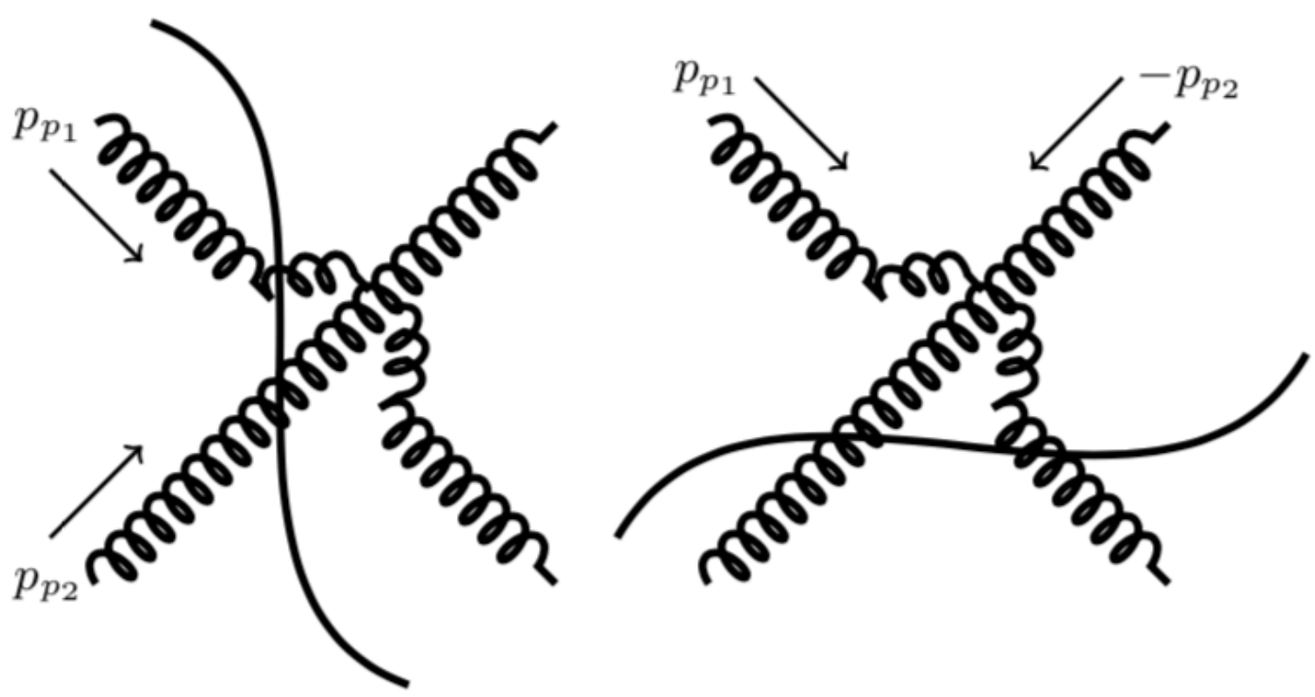
Flat Distribution

$\cos^2\phi_C$ dependence: $(p_{t_1}\cdot p_{p_1})(p_{t_2}\cdot p_{p_2})$ or $(p_{t_1}\cdot p_{p_2})(p_{t_2}\cdot p_{p_1})$

$\cos\phi_C$ dependence

$p_{t_1}\cdot p_{p1}$	$p_{t_1}\cdot p_{p2}$	$p_{t_2}\cdot p_{p1}$	$p_{t_2}\cdot p_{p2}$
+	−	−	+

$(p_{p_1}, p_{p_2}) \to (p_{p_1}, -p_{p_2})$



Simulation

$H \to b\bar{b}$ channel ($t\bar{t} \to b\bar{b}\ell^+\ell^-\nu\bar{\nu}$)

14 TeV LHC 3000 fb^{-1}

$4b + 2\ell + \mathrm{MET}$

background: $t\bar{t}b\bar{b}$,$t\bar{t}bj$,$t\bar{t}c\bar{c}$...

lepton fake the top quark

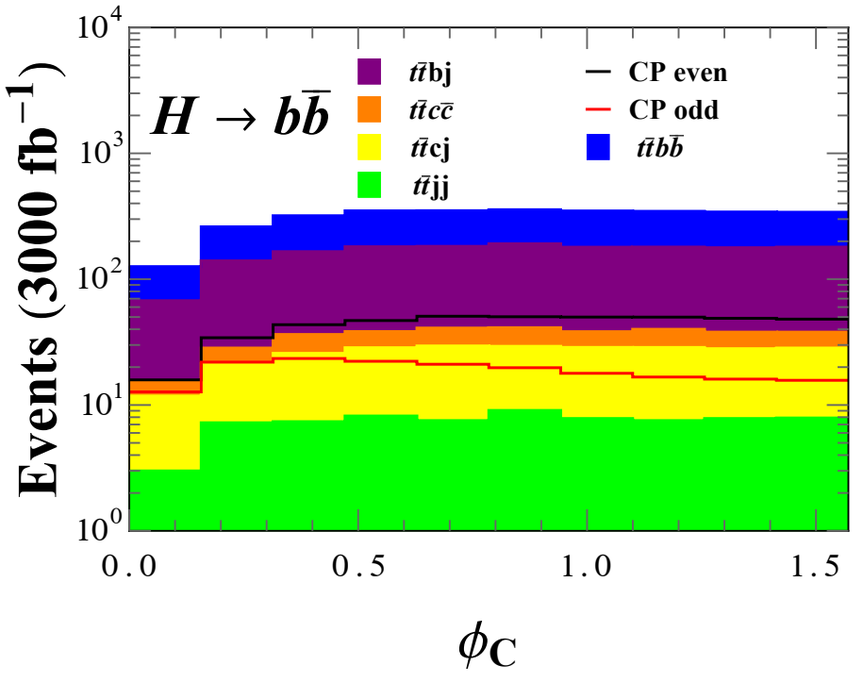
$H \to \gamma\gamma$ channel ($t\bar{t} \to b\bar{b}jj\ell^{\pm}\nu$)

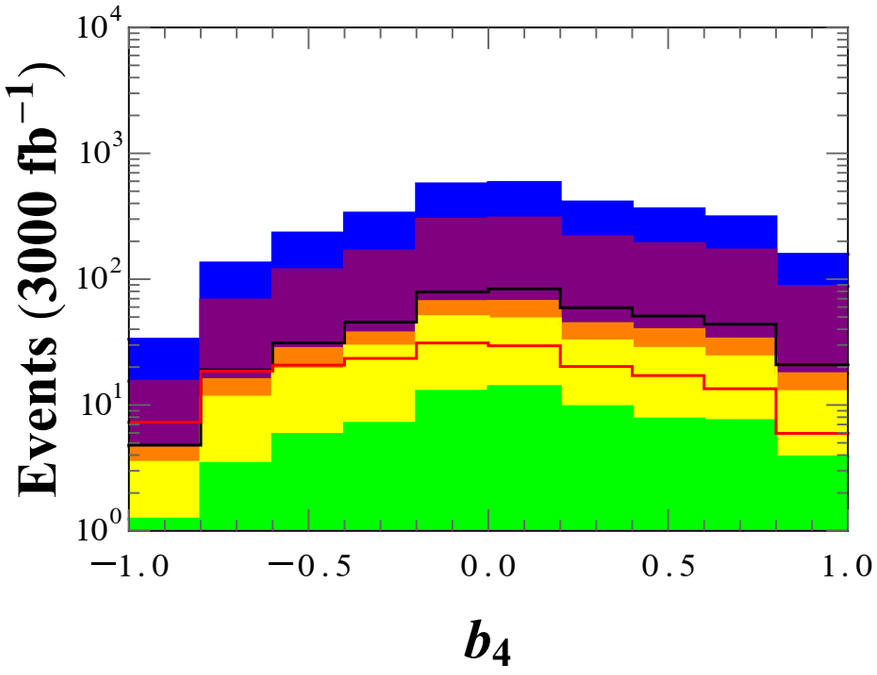
$2b + 1\ell + 2\gamma + \mathrm{MET}$

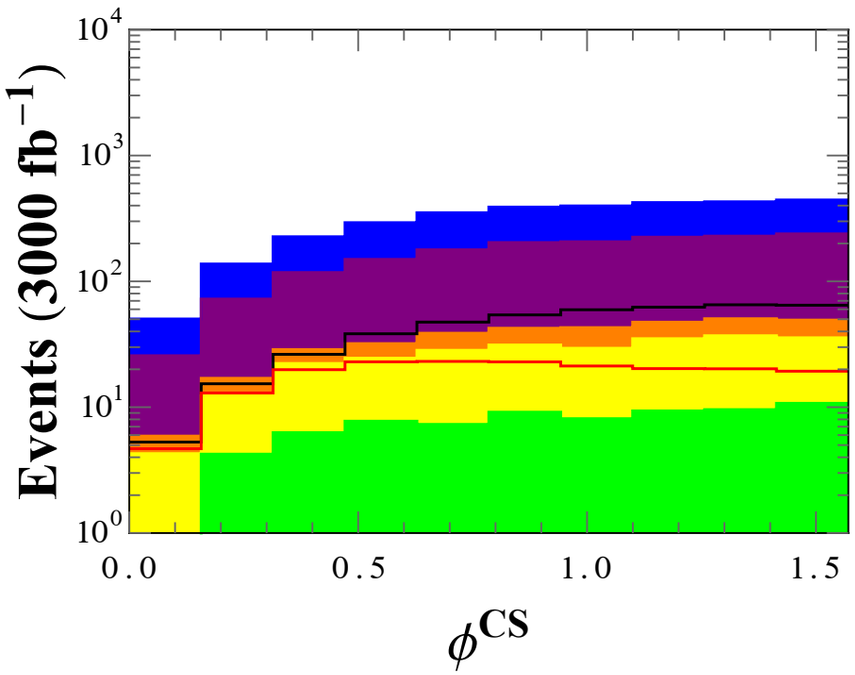
background: $t\bar{t}\gamma\gamma$

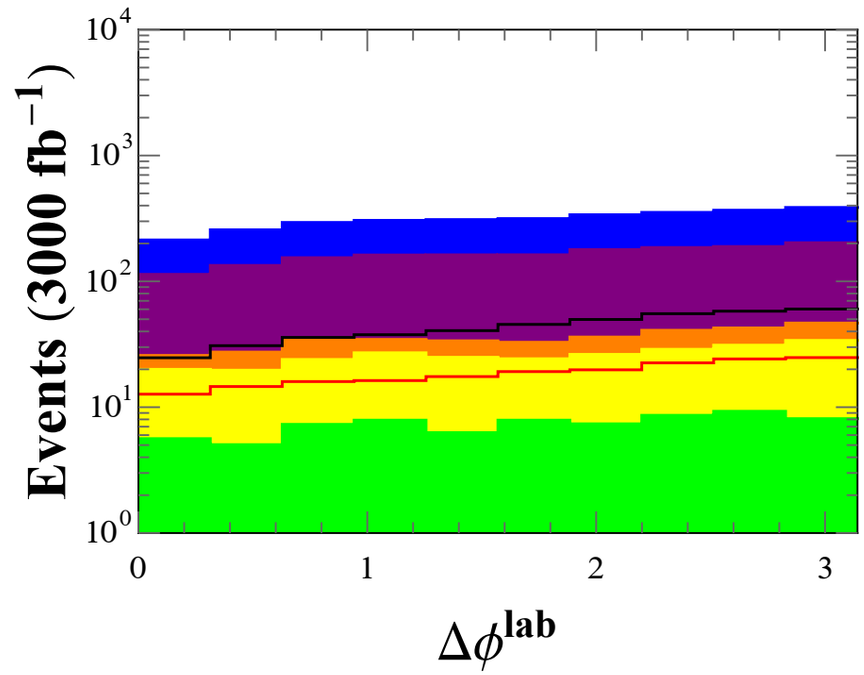
reconstruct the top quark

Results

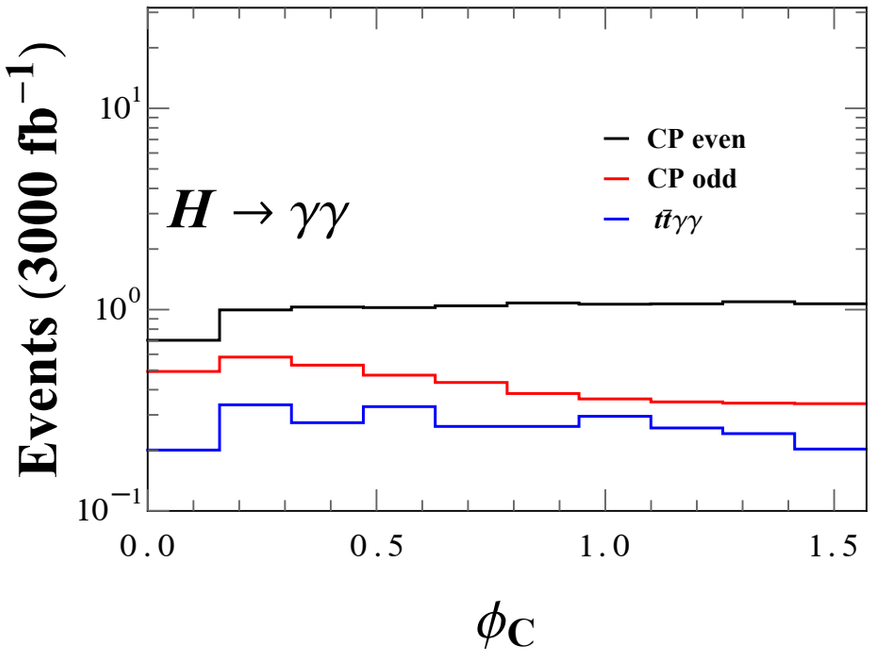

$H \to b\bar{b}$
$t\bar{t}$bj
$t\bar{t}c\bar{c}$
$t\bar{t}$cj
$t\bar{t}$jj
CP even
CP odd
$t\bar{t}b\bar{b}$
Events (3000 fb^{-1})
ϕ_C

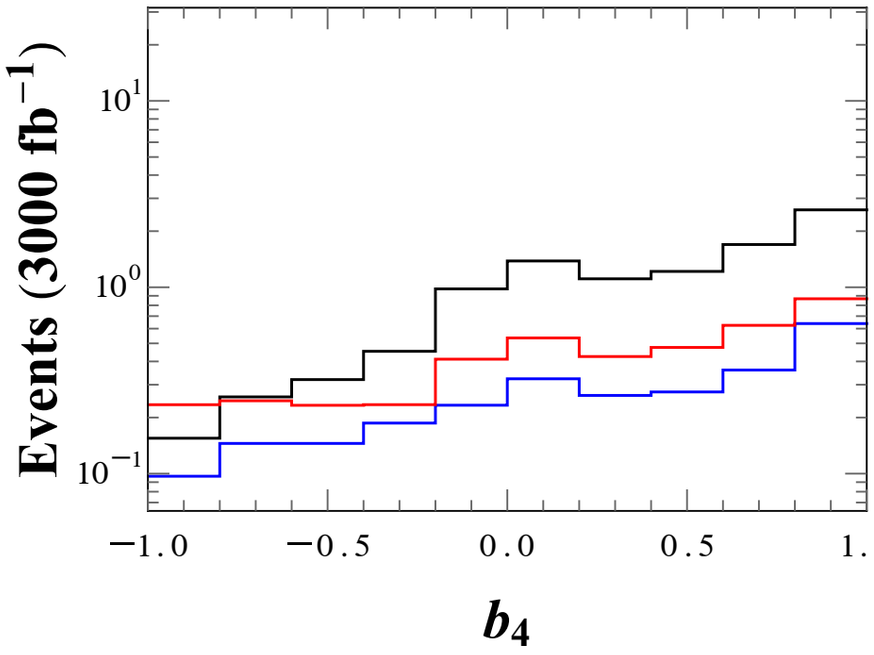

Events (3000 fb^{-1})
b_4

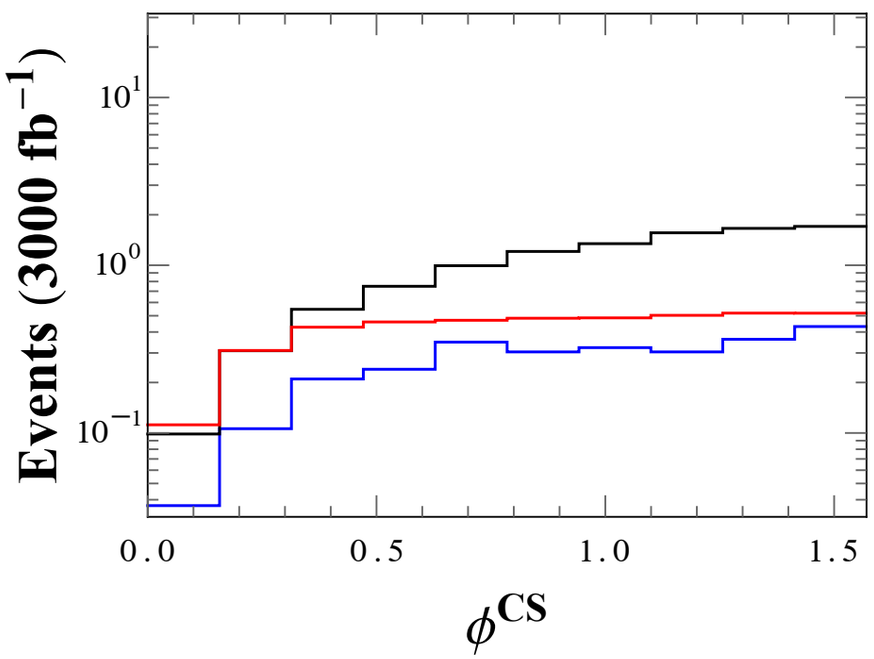

Events (3000 fb^{-1})
ϕ^{CS}

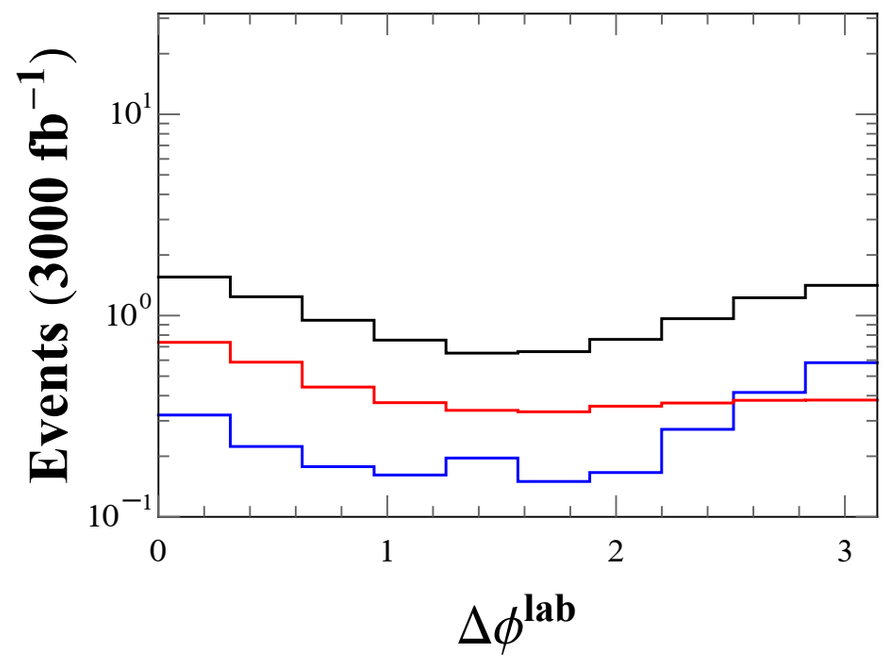

Events (3000 fb^{-1})
$\Delta\phi^{lab}$

Results


Events (3000 fb^{-1})
10^{1}
10^{0}
10^{-1}
$H \to \gamma\gamma$
CP even
CP odd
$t\bar{t}\gamma\gamma$
0.0
0.5
1.0
1.5
ϕ_C

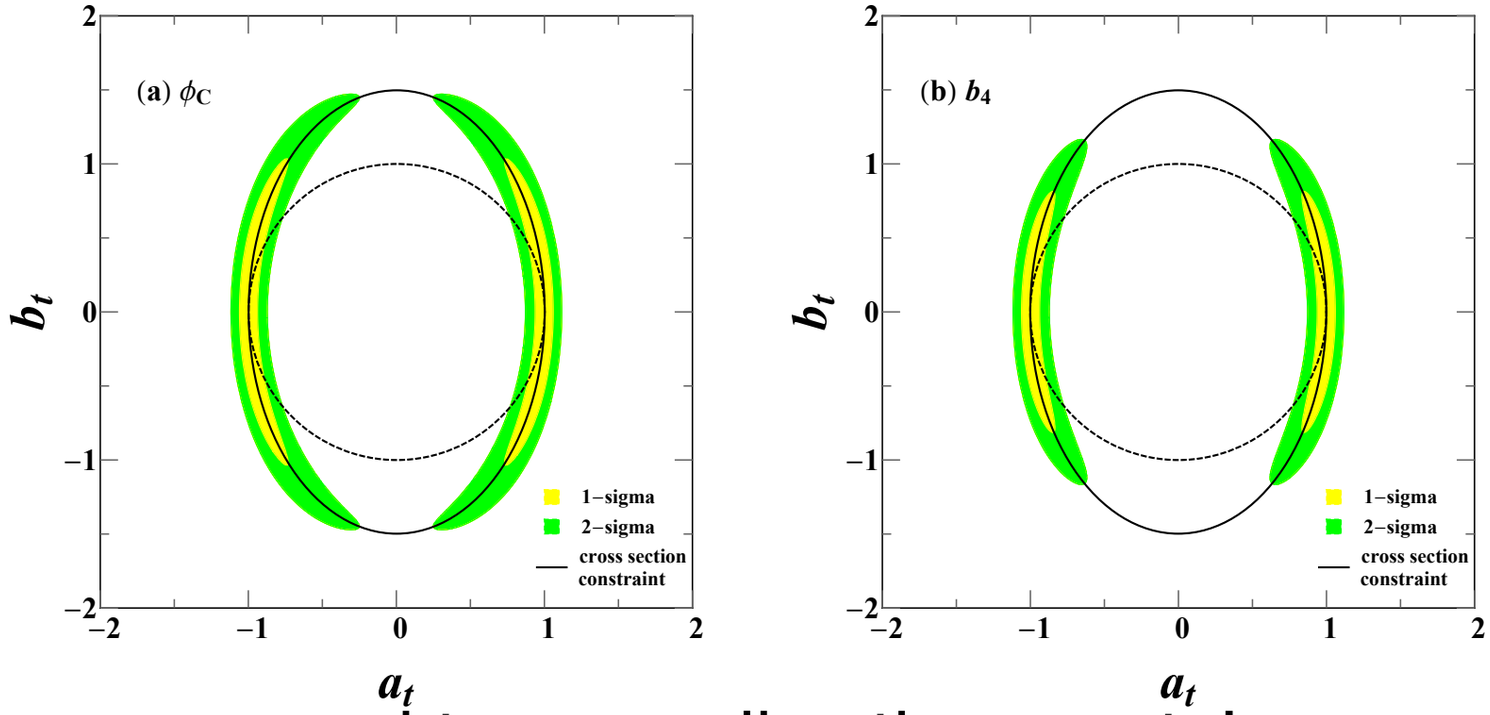

Events (3000 fb^{-1})
10^{1}
10^{0}
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
b_4


Events (3000 fb^{-1})
10^{1}
10^{0}
10^{-1}
0.0
0.5
1.0
1.5
ϕ^{CS}

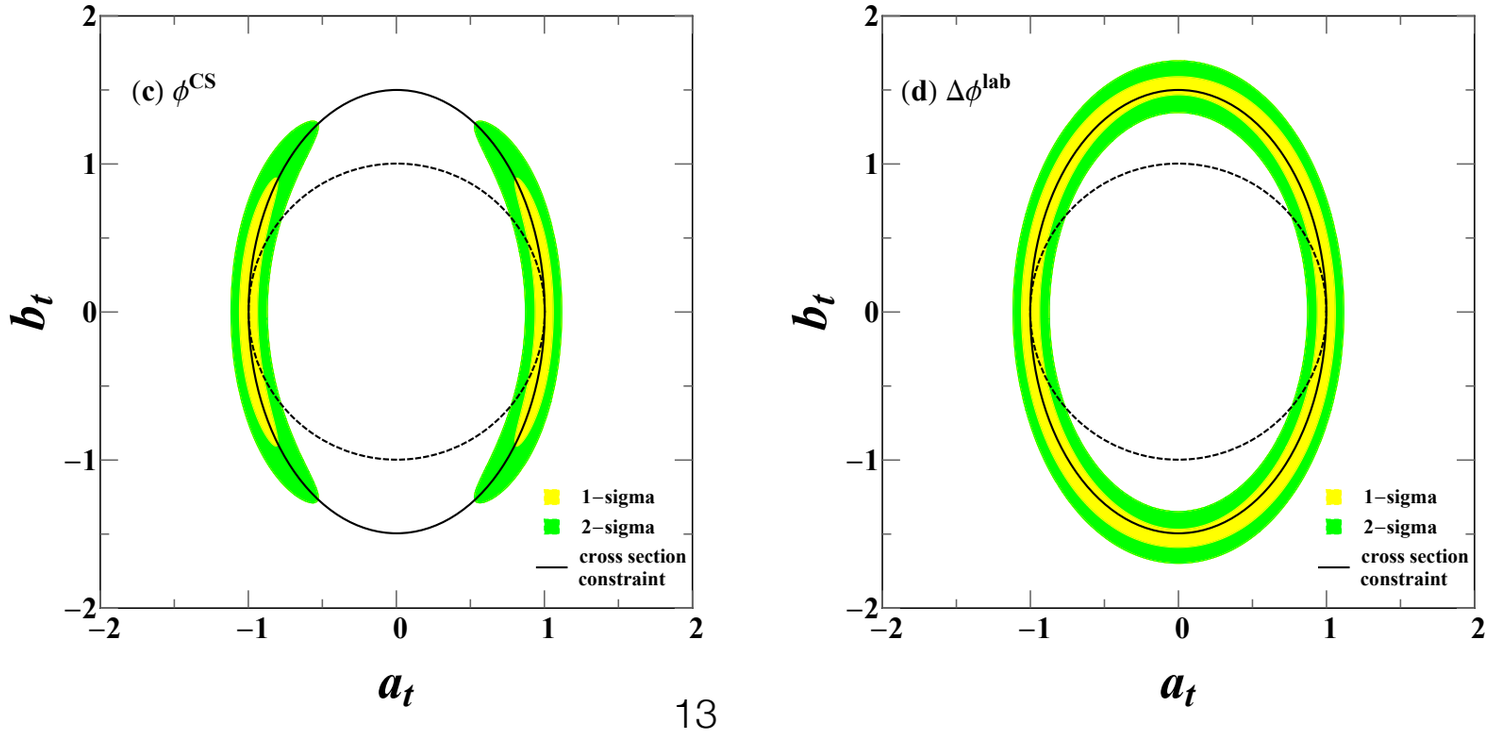

Events (3000 fb^{-1})
10^{1}
10^{0}
10^{-1}
0
1
2
3
$\Delta\phi^{lab}$

Results

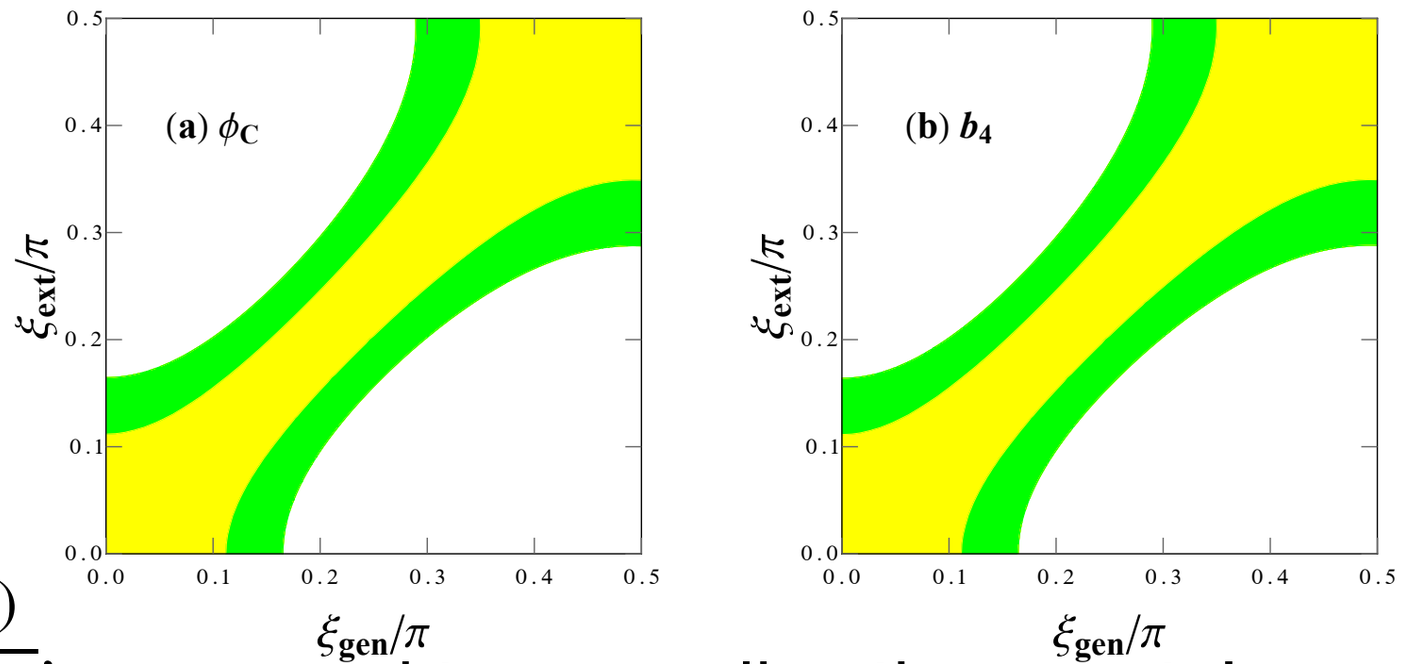
14 TeV 3000 fb^{-1}



need to normalize the events!

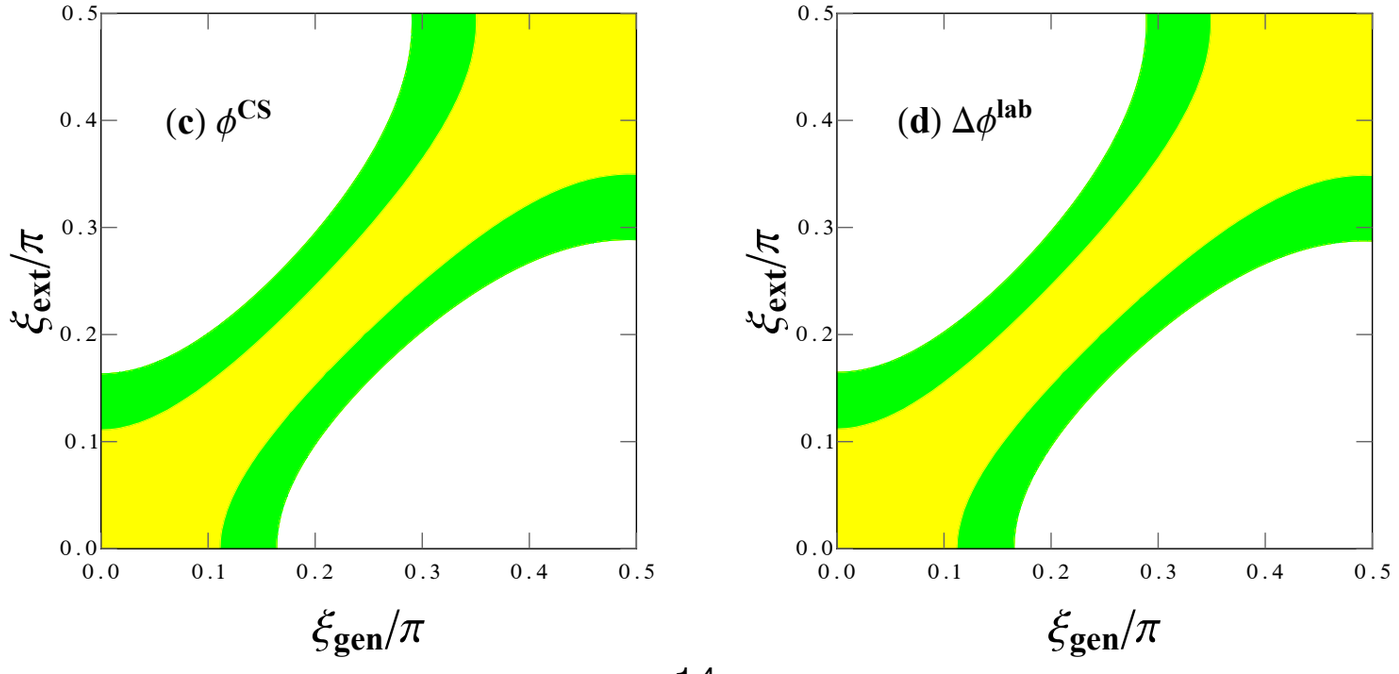


Results (w/· events number)



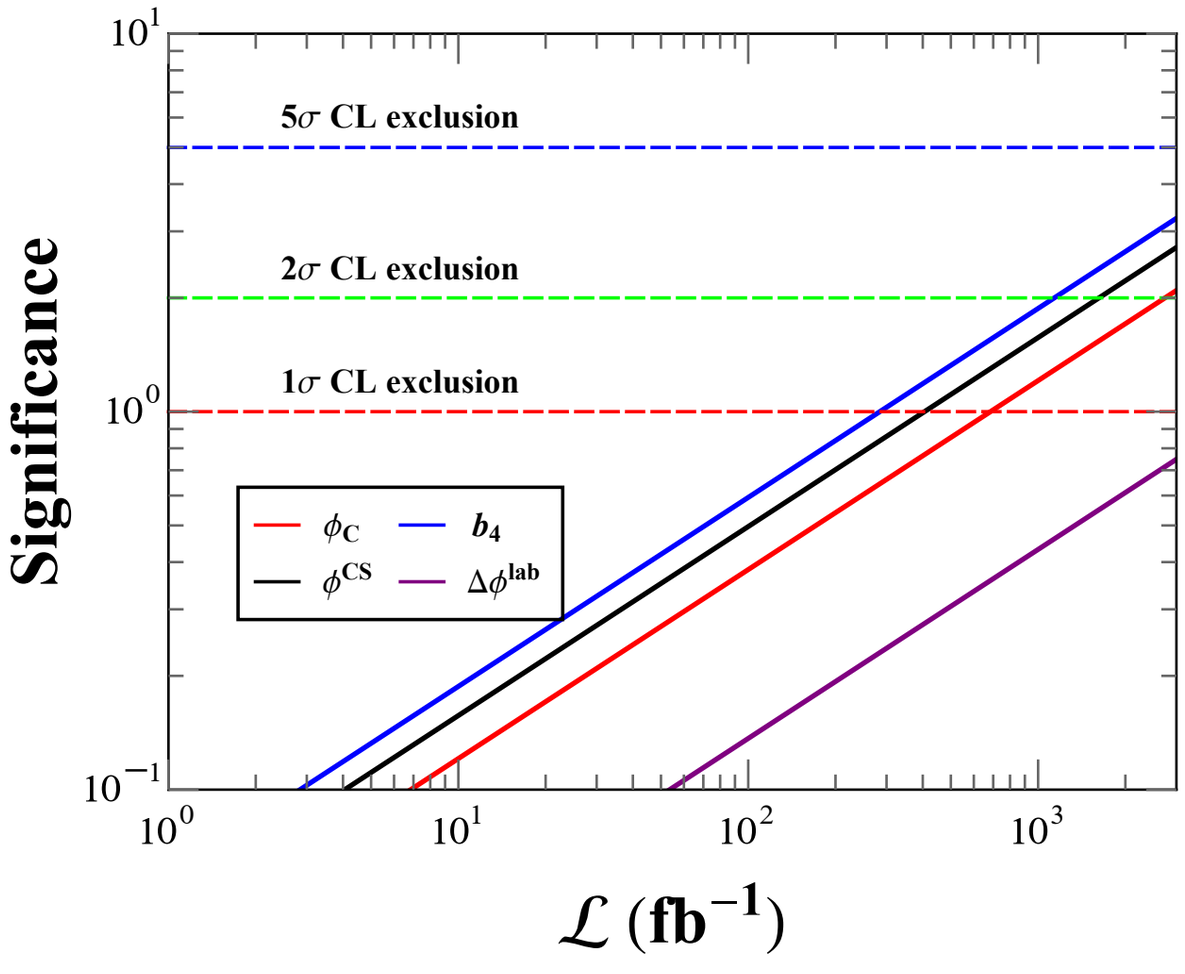
$$\chi^2 = -2\log\frac{L(\xi_{\text{extract}})}{L(\xi_{\text{generate}})},$$

need to normalize the events!

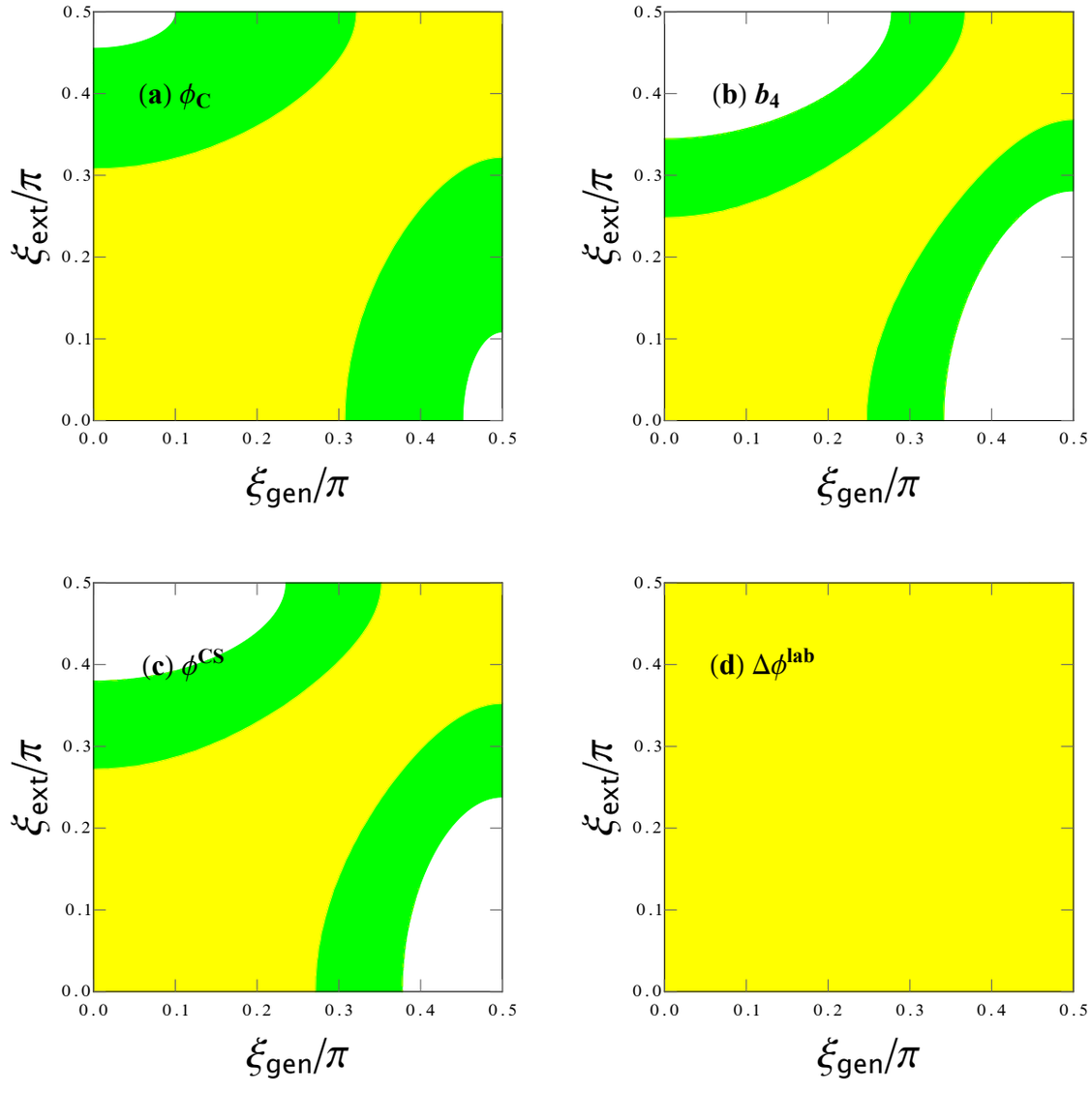


Summary

Combining $H \to b\bar{b}$ and $H \to \gamma\gamma$ channel



needs 2700 fb^{-1} to exclude pure CP odd



Thank you!

Simulation

$$L_{bb}(m) = \frac{1}{\sqrt{2\pi} \times 18.36\ \text{GeV}} \exp[-(m-109.6)^2/$$
$$(22.62 - 0.06868(m-109.6) + 0.003688(m-109.6)^2)^2]$$
$$L_{b\ell}(m) = \frac{m}{(103.8)^2\ \text{GeV}} \left[1 + \left(\frac{m}{56.6}\right)^2\right] \left\{1 - \right.$$
$$\left. \tanh^2\left[\frac{m}{158.0} + \left(\frac{m}{135.3}\right)^4\right]\right\},$$
$$L_{\ell\nu}(m) = \frac{1}{\sqrt{2\pi} \times 4.73\ \text{GeV}} \exp[-(m-79.84)^2/$$
$$(5.388 + 0.005231(m-79.84) + 0.01385(m-79.84)^2)^2]$$
$$L_{b\ell\nu}(m) = \frac{1}{\sqrt{2\pi} \times 14.45\ \text{GeV}} \exp[-(m-167.8)^2/$$
$$(17.21 - 0.06578(m-167.8) + 0.004544(m-167.8)^2)^2]$$
$$L_{jj}(m) = \frac{1}{\sqrt{2\pi} \times 19.36\ \text{GeV}} \exp[-(m-76.55)^2/$$
$$(13.35 + 0.1945(m-76.55) + 0.005776(m-76.55)^2)^2],$$
$$L_{bjj}(m) = \frac{1}{\sqrt{2\pi} \times 33.58\ \text{GeV}} \exp[-(m-160.2)^2/$$
$$(32.57 + 0.1726(m-160.2) + 0.00188(m-160.2)^2)^2],$$

Simulation

$H \to b\bar{b}$ channel ($t\bar{t} \to b\bar{b}\ell^+\ell^-\nu\bar{\nu}$)

14 TeV LHC

$$p_{\mathrm{T}}^{\ell} > 15\ \mathrm{GeV}\,,\ p_{\mathrm{T}}^{\ell_1} > 25\ \mathrm{GeV}\,,\ \ |\,\eta^{\ell}\,| < 2.4\,,$$

$$p_{\mathrm{T}}^{j} > 30\ \mathrm{GeV}\,,\ \ |\,\eta^{j}\,| < 2.4\,.$$

For e^+e^- and $\mu^+\mu^-$ channels:

$$p_{\mathrm{T}}^{\mathrm{miss}} > 40\ \mathrm{GeV}\,,\ |m_{\ell^+\ell^-} - m_{\mathrm{Z}}| > 15\ \mathrm{GeV}\,,\ m_{\ell^+\ell^-} > 20\ \mathrm{GeV}\,.$$

$$D = -39.78 - 8.30 \log L_{bb} - 0.02\sqrt{\log^2 L_{b\ell^+} + \log^2 L_{b\ell^-}} < 0$$

$$\sigma(t\bar{t}H) = 613.7\ \mathrm{fb}(\cos^2\xi + 0.446\sin^2\xi)$$

$$\mathrm{Br}(H \to b\bar{b}) = 0.5824$$

$$\mathrm{Br}(t \to b\ell^+\nu) = 0.2134$$

$$\mathrm{Br}(t \to bjj) = 0.6741$$

$H \to \gamma\gamma$ channel ($t\bar{t} \to b\bar{b}jj\ell^{\pm}\nu$)

$$\mathrm{Br}(H \to \gamma\gamma) = 0.2270\,\%\,((0.282\cos\xi - 1.282)^2 + 0.185\sin^2\xi)$$

$$\begin{gathered}
p_{\mathrm{T}}^{\ell} > 20\ \mathrm{GeV}\,,\ \ |\,\eta^{\ell}\,| < 2.4\,,\\
p_{\mathrm{T}}^{j} > 25\ \mathrm{GeV}\,,\ \ |\,\eta^{j}\,| < 2.4\,,\\
p_{\mathrm{T}}^{\gamma 1} > 30\ \mathrm{GeV}\,,\ p_{\mathrm{T}}^{\gamma 2} > 20\ \mathrm{GeV}\,,\ \ |\,\eta_{\gamma}\,| < 2.5\,,\\
115\ \mathrm{GeV} < m_{\gamma\gamma} < 135\ \mathrm{GeV}\,,\\
|\,m_{e,\gamma} - m_Z\,| > 5\ \mathrm{GeV}\,,\\
p_{\mathrm{T}}^{\gamma 1}/m_{\gamma\gamma} > 1/2\,,\ p_{\mathrm{T}}^{\gamma 2}/m_{\gamma\gamma} > 1/4\,,\\
R(\ell,\gamma) > 0.35\,,\ R(j,\gamma) > 0.4\,,\ R(j,\ell) > 0.4\,,
\end{gathered}$$

$$-2\log L_{b\ell} - 2\log L_{b\ell\nu} - 2\log L_{\ell\nu} - 2\log L_{jj} - 2\log L_{bjj}$$

Simulation

$H \to b\bar{b}$ channel ($t\bar{t} \to b\bar{b}\ell^+\ell^-\nu\bar{\nu}$)

14 TeV LHC 3000 fb^{-1}

$4b + 2\ell + \mathrm{MET}$

440 signal 3000 background

background: $t\bar{t}b\bar{b}$,$t\bar{t}bj$,$t\bar{t}c\bar{c}$...

lepton fake the top quark

$H \to \gamma\gamma$ channel ($t\bar{t} \to b\bar{b}jj\ell^{\pm}\nu$)

$2b + 1\ell + 2\gamma + \mathrm{MET}$

10 signal 3 background

background: $t\bar{t}\gamma\gamma$

reconstruct the top quark

Simulation

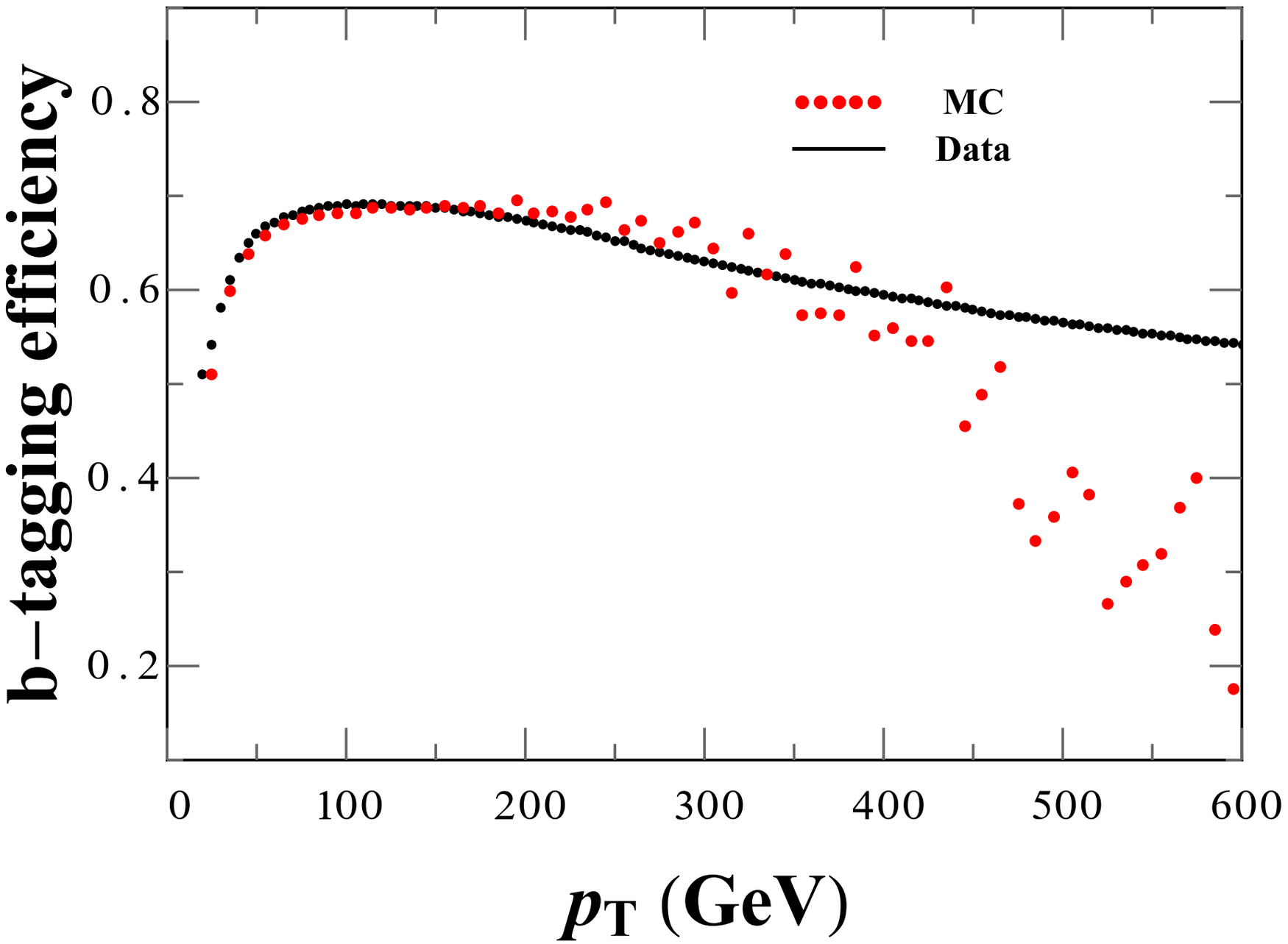
$H \to b\bar{b}$ channel ($t\bar{t} \to b\bar{b}\ell^+\ell^-\nu\bar{\nu}$)

$$pp \to t\bar{t}j'j', t \to j'\ell^+\nu_\ell, \bar{t} \to j'l^-\bar{\nu}_\ell$$
$$pp \to t\bar{t}b\bar{b}, t \to b\ell^+\nu_\ell, \bar{t} \to \bar{b}l^-\bar{\nu}_\ell$$

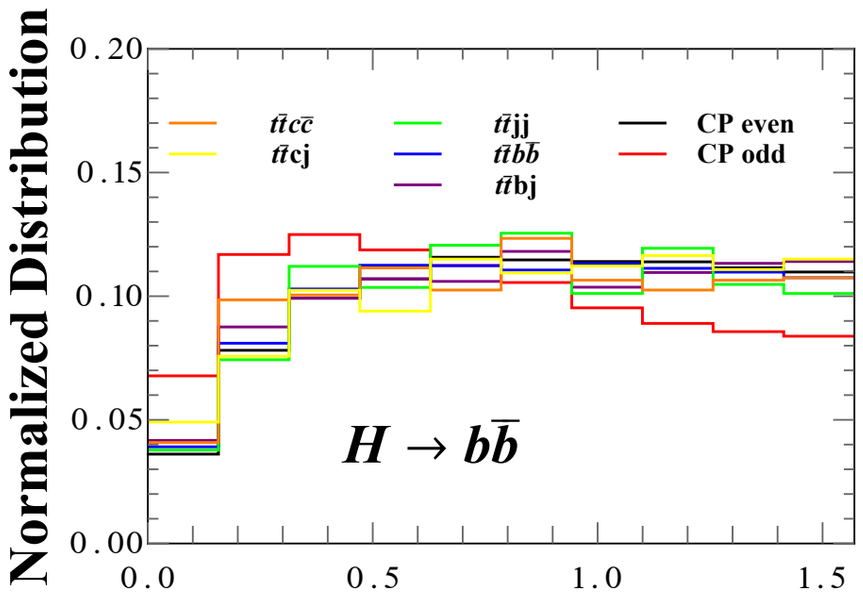
$$\epsilon(pp \to t(\to b)\bar{t}(\to \bar{b})j'j')$$
$$= \sqrt{\epsilon(pp \to t(\to j')\bar{t}(\to j')j'j') \times \epsilon(pp \to t(\to b)\bar{t}(\to \bar{b})b\bar{b})}$$

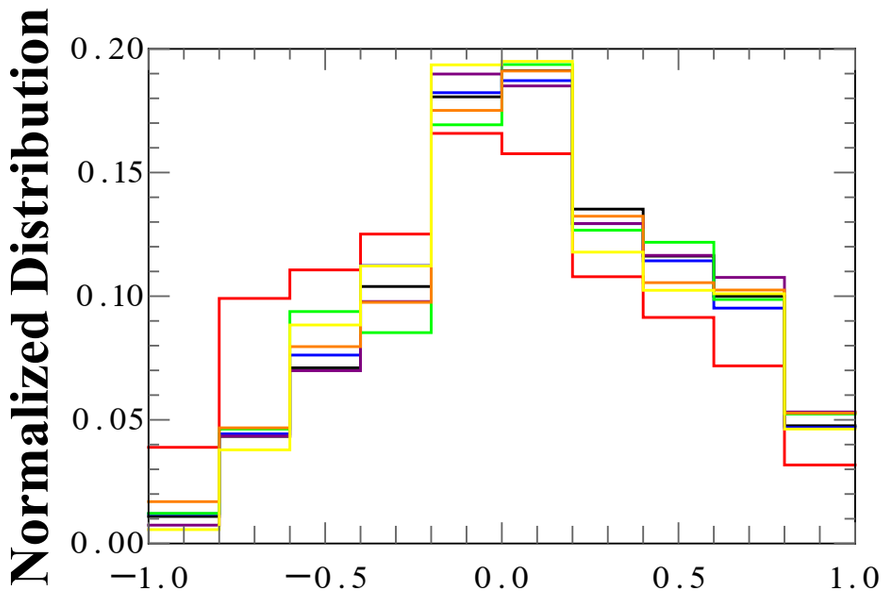
B-Tagging Efficiency

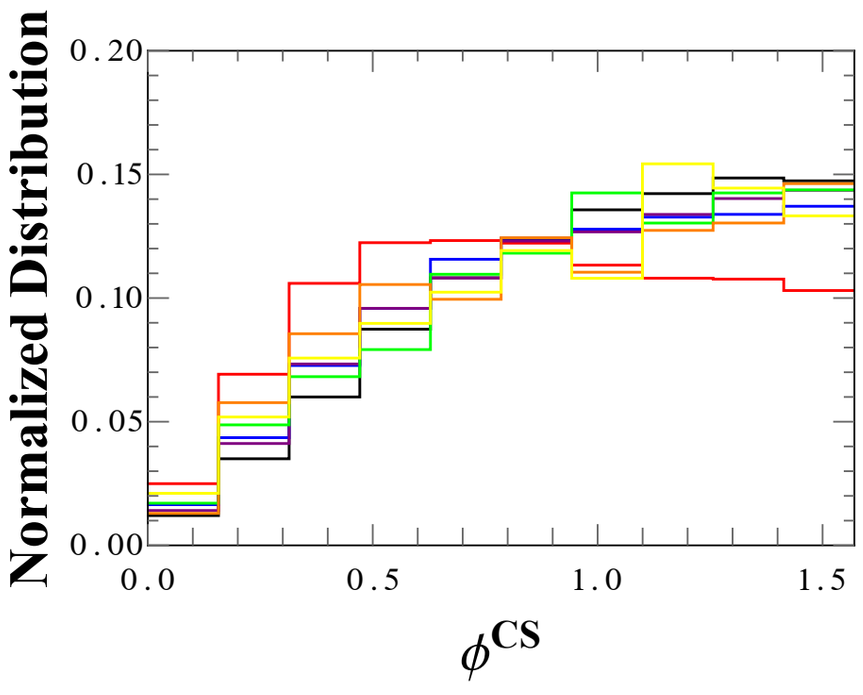
Follow CMS 1712.07158

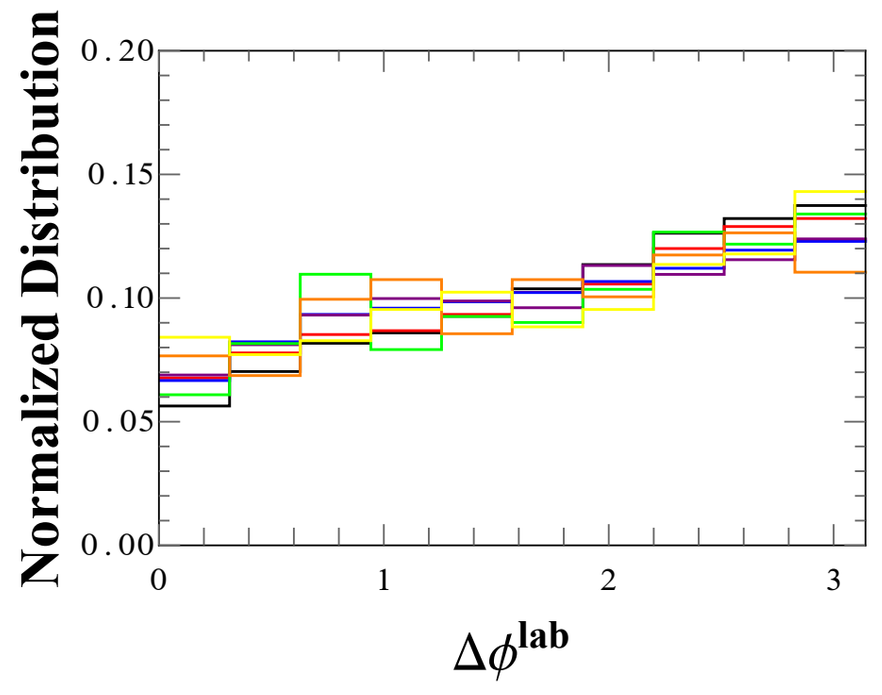


Results

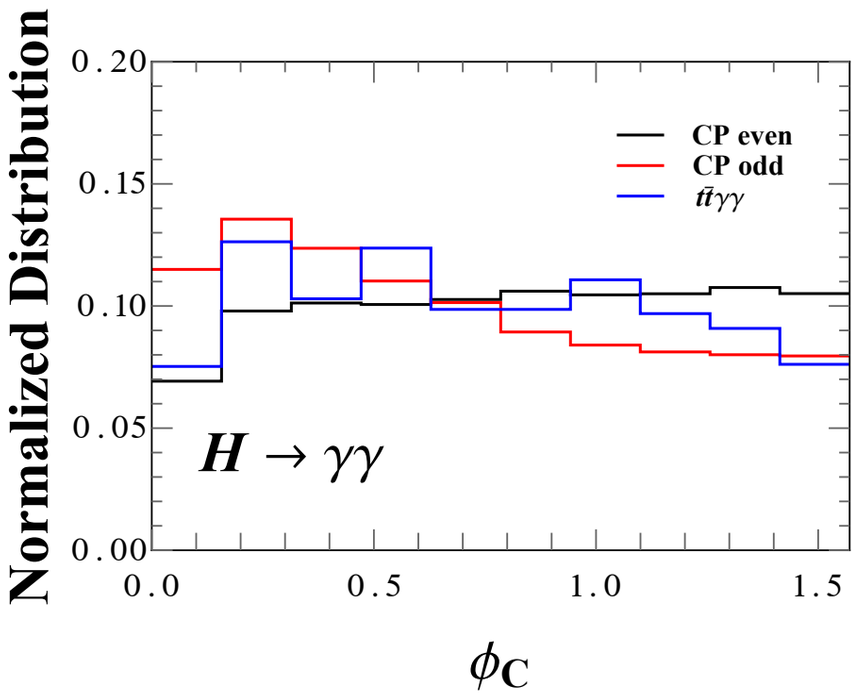

Normalized Distribution
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
$t\bar{t}c\bar{c}$
$t\bar{t}$cj
$t\bar{t}$jj
$t\bar{t}b\bar{b}$
$t\bar{t}$bj
CP even
CP odd
$H \to b\bar{b}$
ϕ_C
ϕ^{CS}

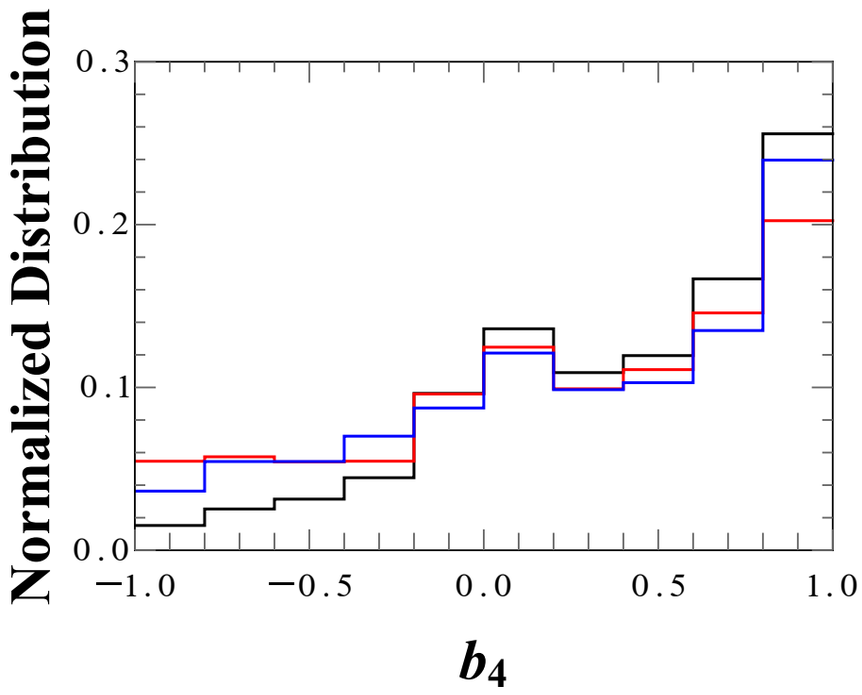

Normalized Distribution
0.20
0.15
0.10
0.05
0.00
−1.0
−0.5
0.0
0.5
1.0
b_4

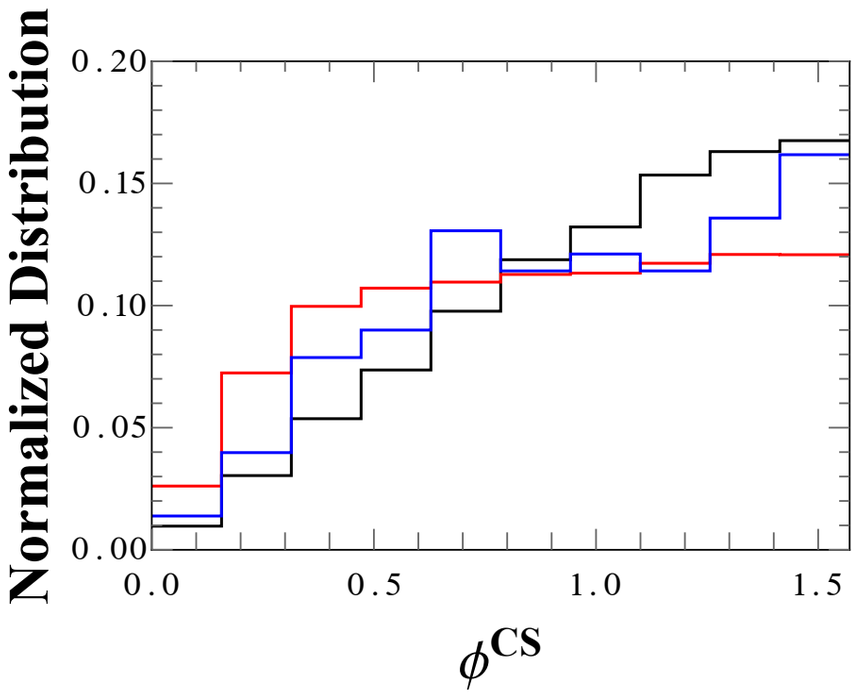

Normalized Distribution
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
ϕ^{CS}

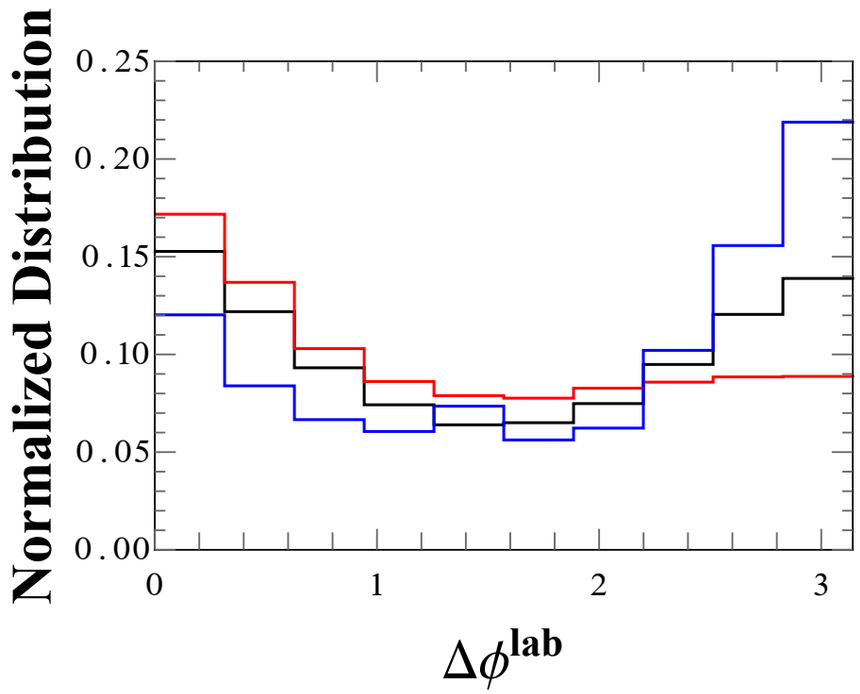

Normalized Distribution
0.20
0.15
0.10
0.05
0.00
0
1
2
3
$\Delta\phi^{lab}$

Results


Normalized Distribution
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
CP even
CP odd
$t\bar{t}\gamma\gamma$
$H \to \gamma\gamma$
ϕ_C

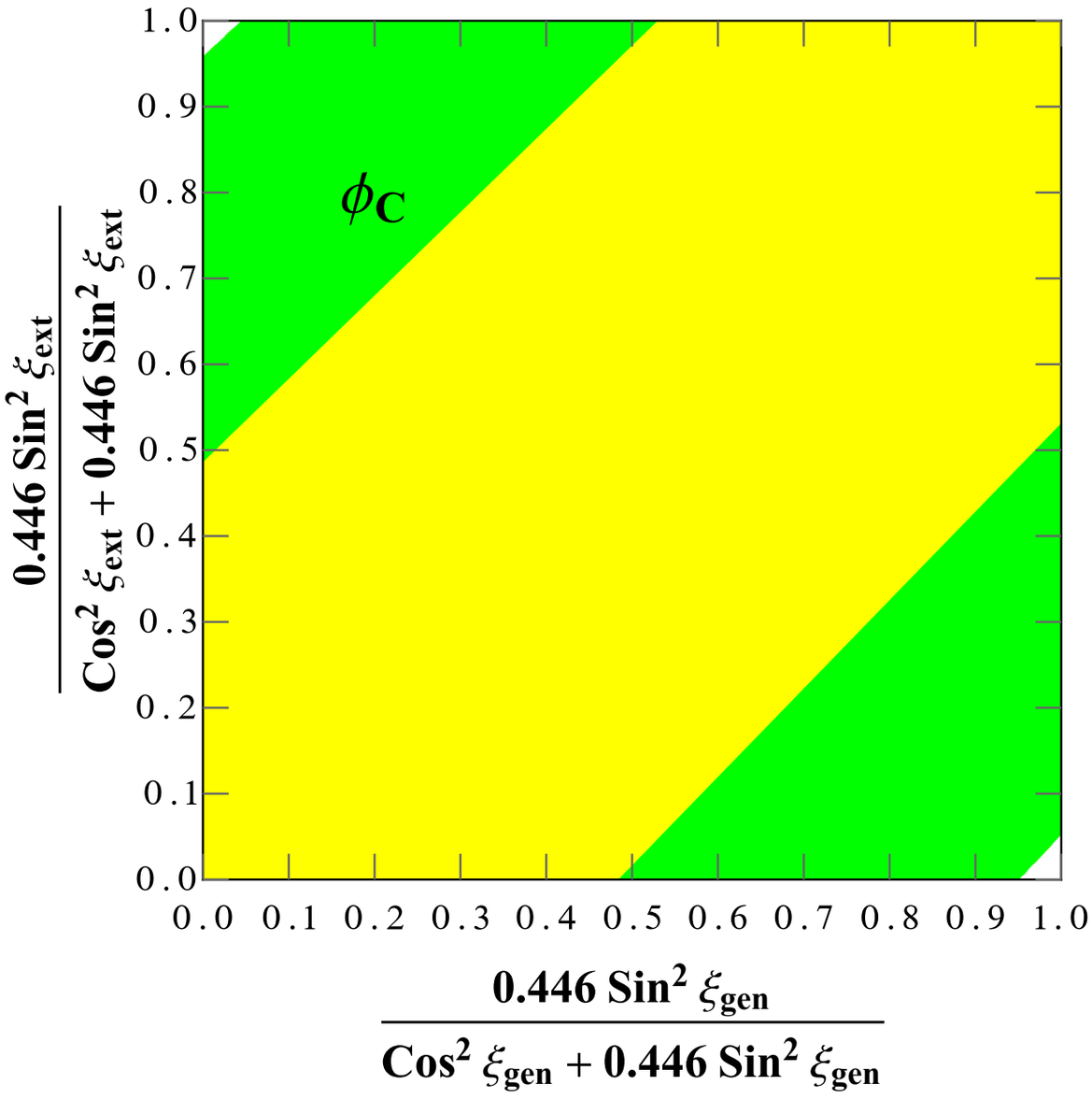

Normalized Distribution
0.3
0.2
0.1
0.0
−1.0
−0.5
0.0
0.5
1.0
b_4


Normalized Distribution
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
ϕ^{CS}


Normalized Distribution
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
$\Delta\phi^{lab}$

Results

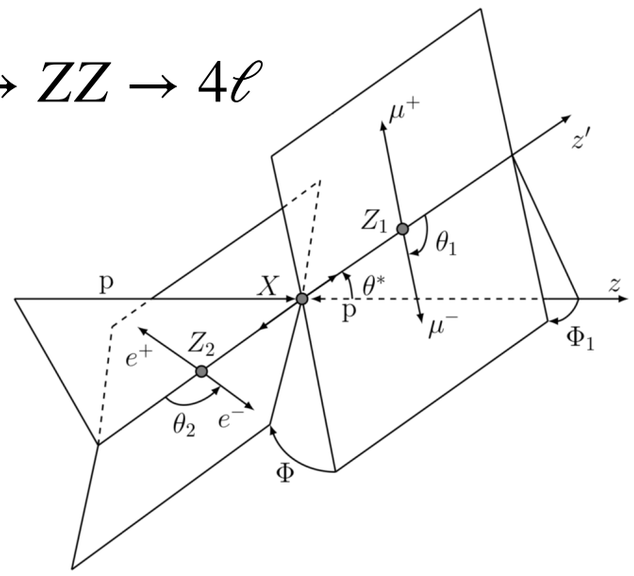
$$\Delta\left(\frac{1}{\cos^2\xi + a\sin^2\xi}\right) \propto \frac{\sin 2\xi}{(\cos^2\xi + a\sin^2\xi)^2}\Delta\xi + \frac{(1-a)\sin^2 2\xi + \cos 2\xi(\cos^2\xi + a\sin^2\xi)}{(\cos^2\xi + a\sin^2\xi)^3}(\Delta\xi)^2$$



Recent Observables

CERN-PH-EP-2015-114

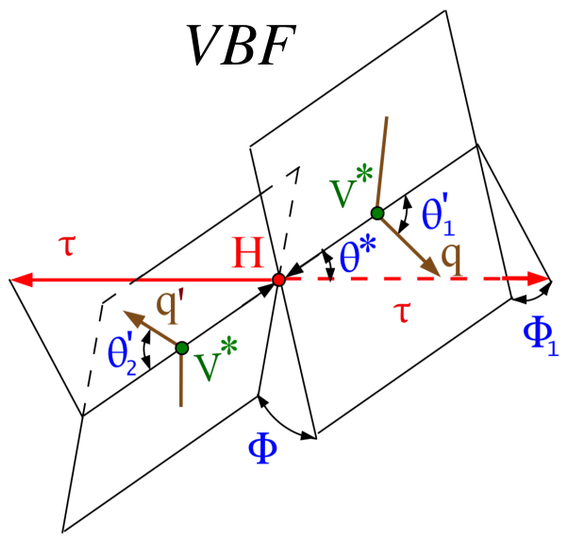
$H \to ZZ \to 4\ell$



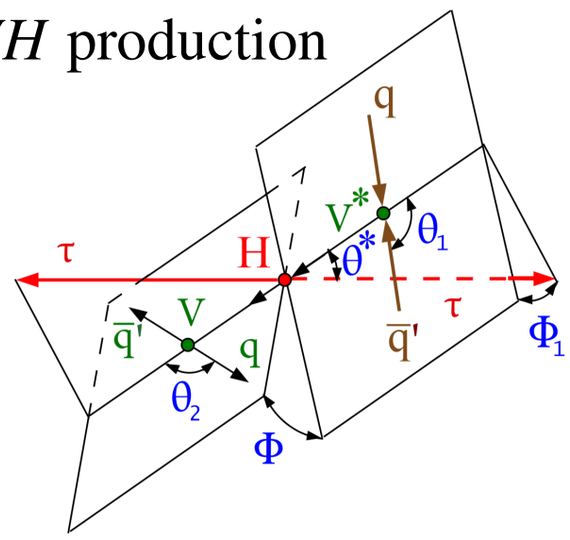
$H \to \tau\tau$

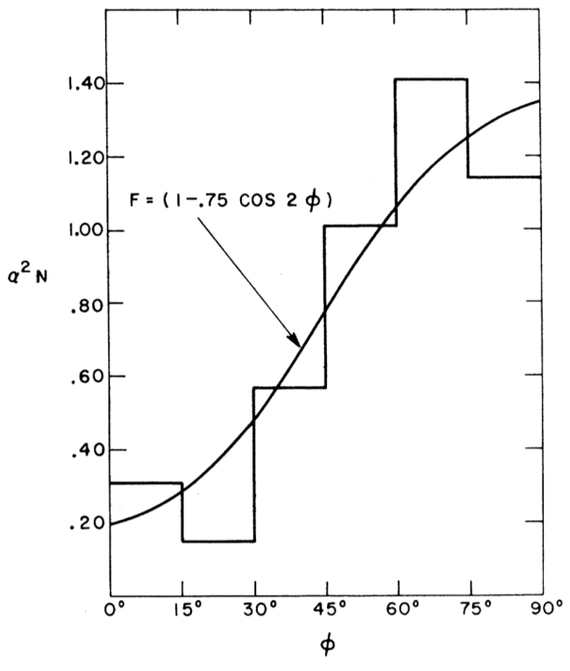
CMS-HIG-17-034

VBF



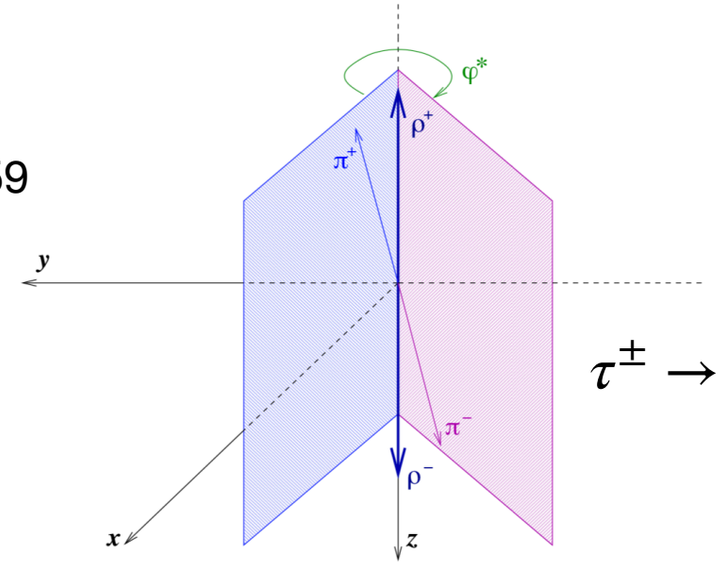
VH production





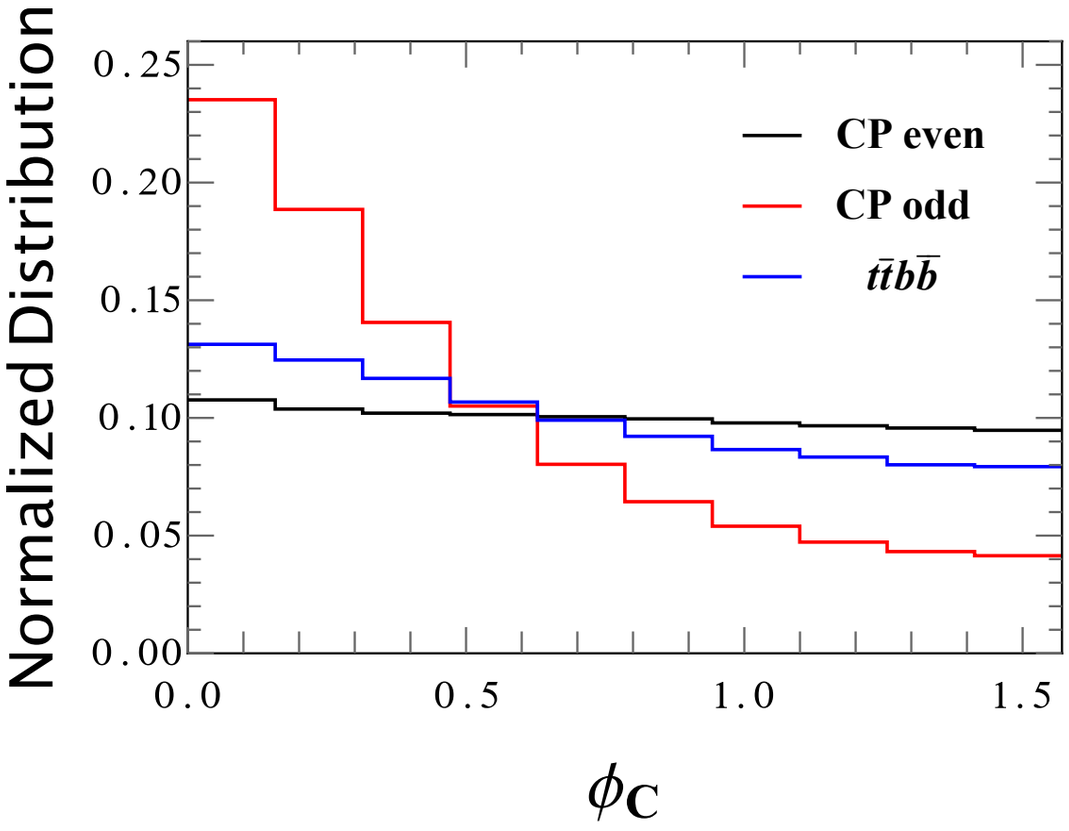
R. Piano, et al. 1959

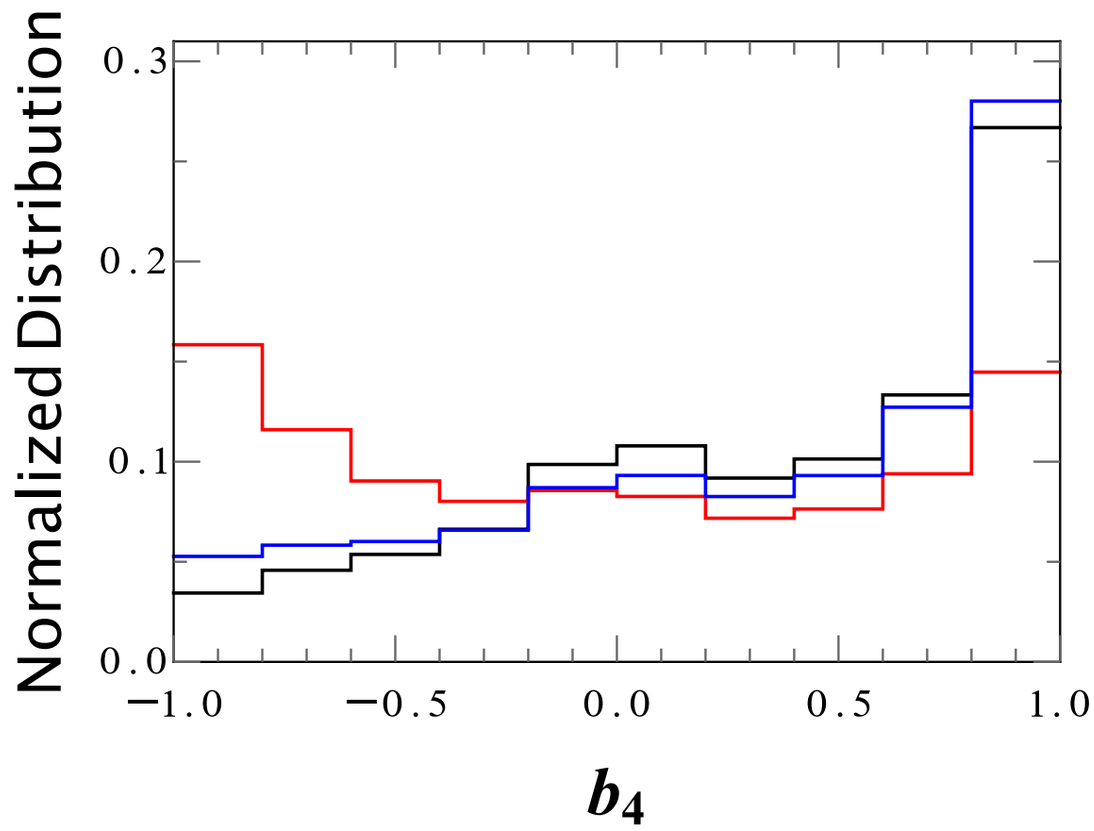
$\pi^0 \to \gamma\gamma$

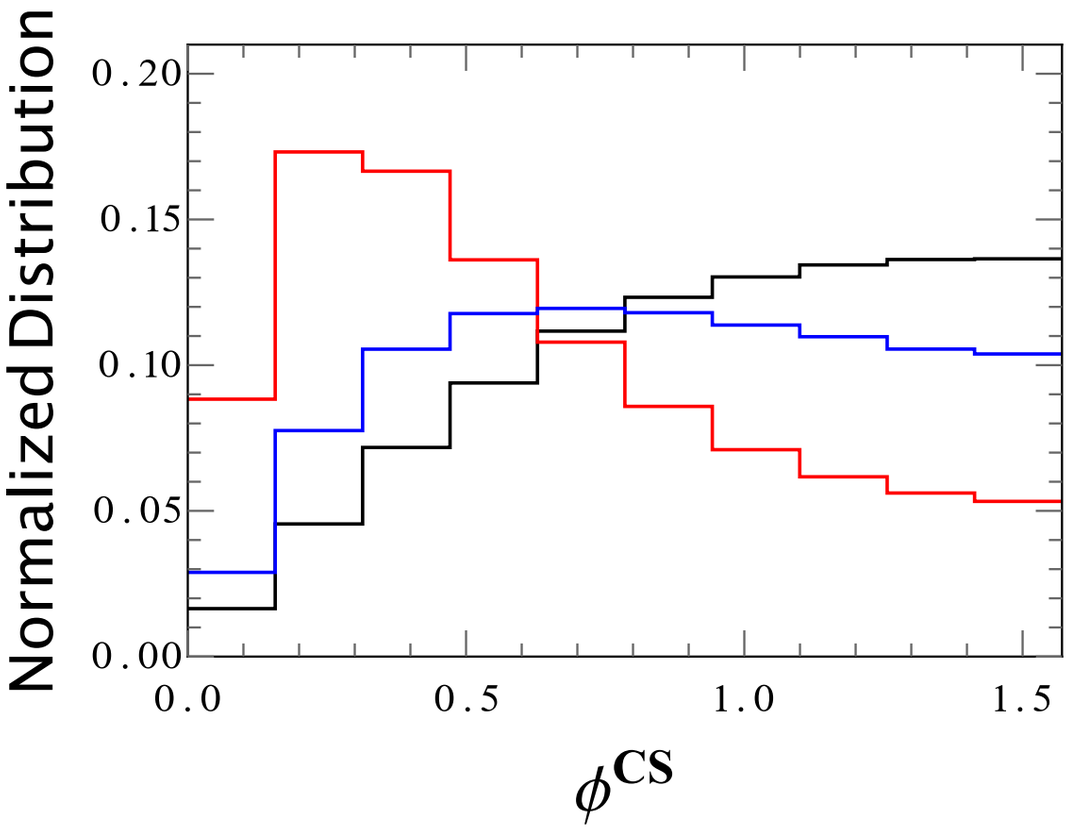


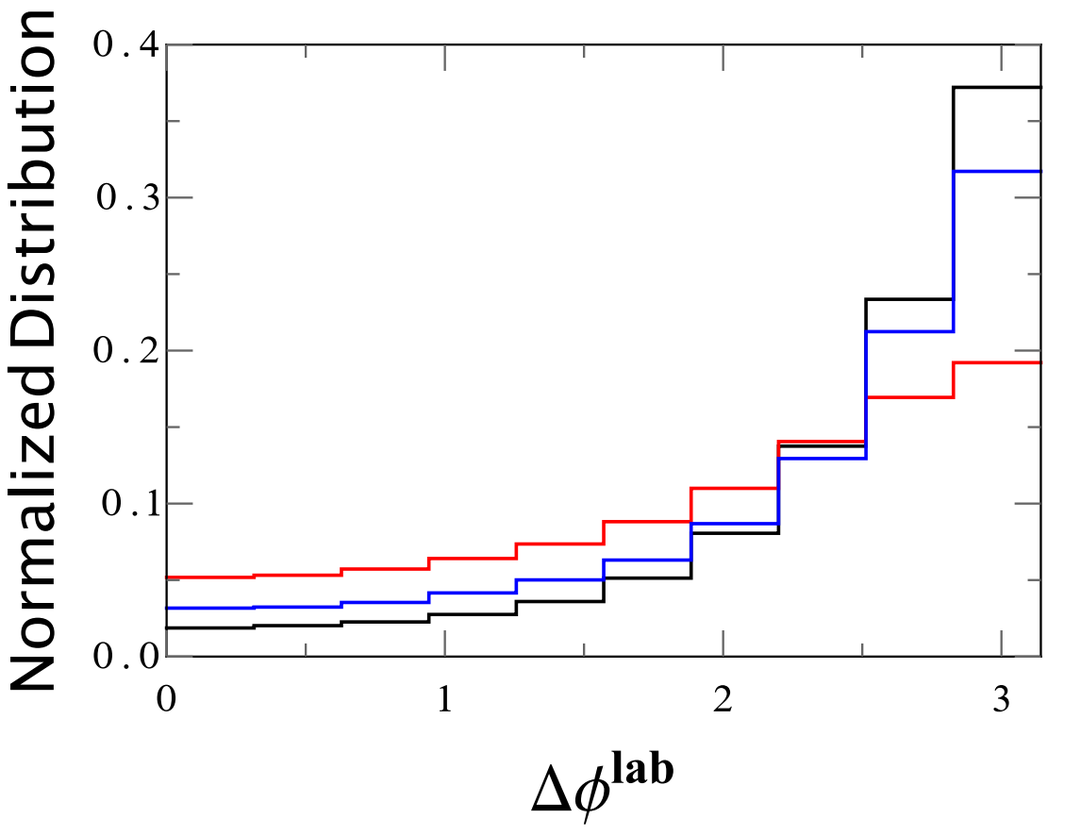
CERN-TH-2002-054

$\tau^\pm \to \rho^\pm \nu_\tau \to \pi^\pm \pi^0 \nu_\tau$


Normalized Distribution
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
CP even
CP odd
$t\bar{t}b\bar{b}$
ϕ_C


Normalized Distribution
0.3
0.2
0.1
0.0
−1.0
−0.5
0.0
0.5
1.0
b_4


Normalized Distribution
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
ϕ^{CS}


Normalized Distribution
0.4
0.3
0.2
0.1
0.0
0
1
2
3
$\Delta\phi^{lab}$