Direct CP measurement of Higgs-top coupling

Benasque - 30.05.2018

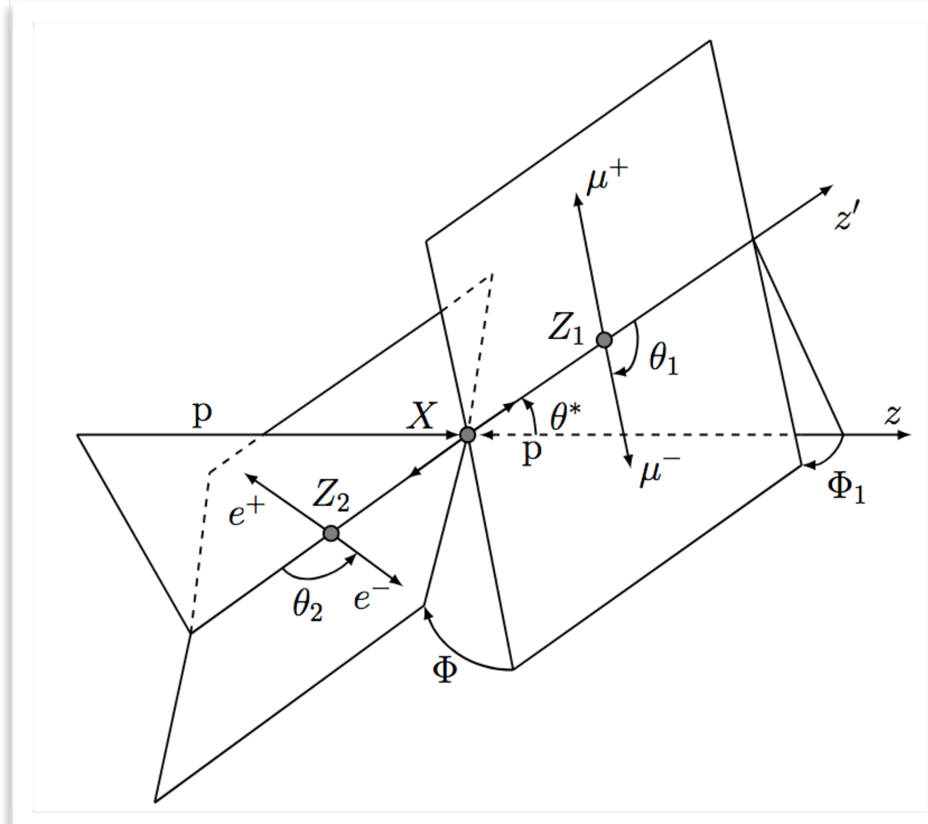
Dorival Gonçalves

Motivation

- Matter-antimatter unbalance requires new sources of CPV
- At LHC CPV HVV interaction is already extensively tested (clean target H>4leptons)

Gritsan, Melnikov Schulze, et al (2013)

$$\mathcal{L}_0 = g_1^{(0)}\, H V_\mu V^\mu - \frac{g_2^{(0)}}{4}\, H\, V_{\mu\nu} V^{\mu\nu} - \frac{g_3^{(0)}}{4}\, A\, V_{\mu\nu} \widetilde{V}^{\mu\nu}$$

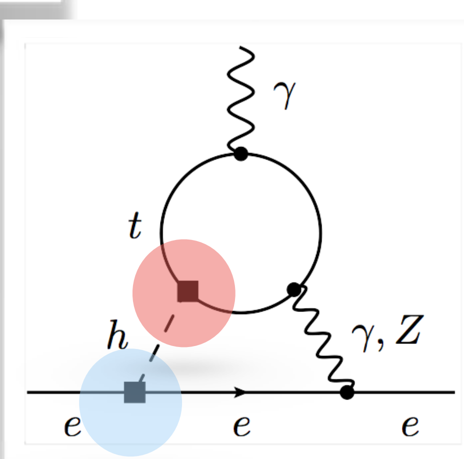


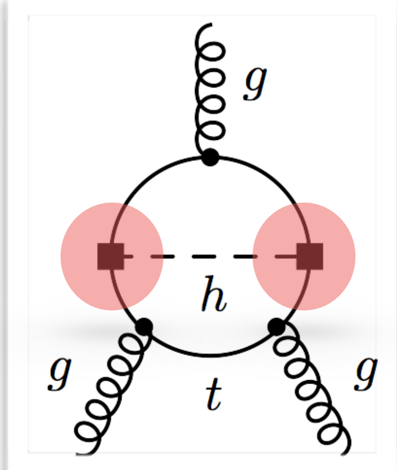
- While CP-odd HVV is loop suppressed, CP-odd Hff can manifest at tree-level:
  - → Mixture possible in some models, e.g., 2HDM
  - → Not excluded from Higgs measurements
  - → Top quark is the first obvious candidate

$$\mathcal{L} \supset -\frac{m_f}{v} K h \bar{f} (\cos\alpha + i\gamma_5 \sin\alpha) f$$

EDM constraints

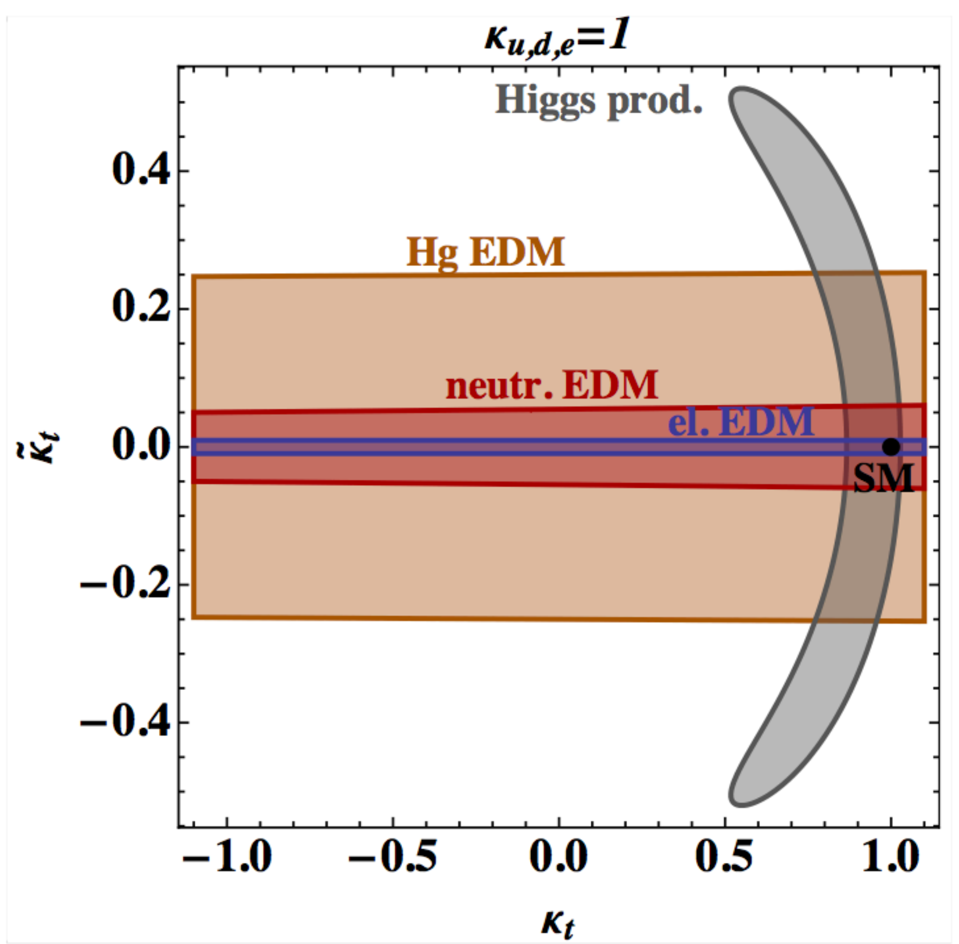
- Indirect constraints from eEDM very strong, yet assume:
  - → No other states in the spectrum
  - → Coupling strength/structure to light fermions

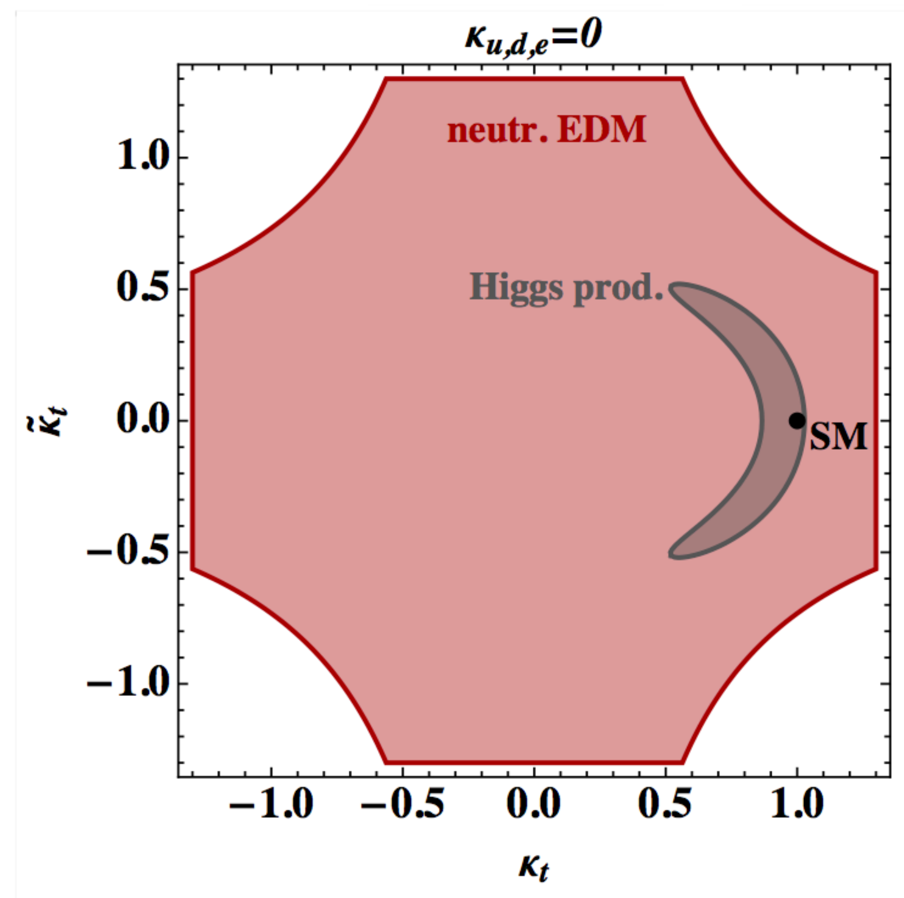




$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F m_e\left[\kappa_e\tilde{\kappa}_t\, f_1(x_{t/h}) + \tilde{\kappa}_e\kappa_t\, f_2(x_{t/h})\right]$$



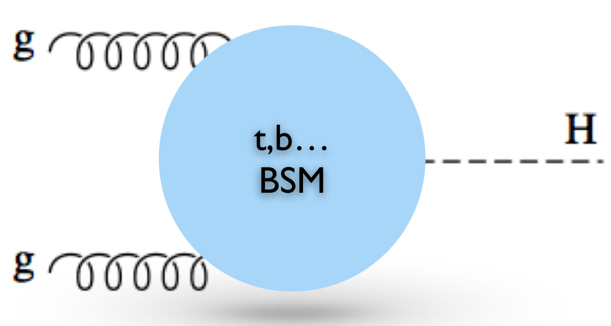


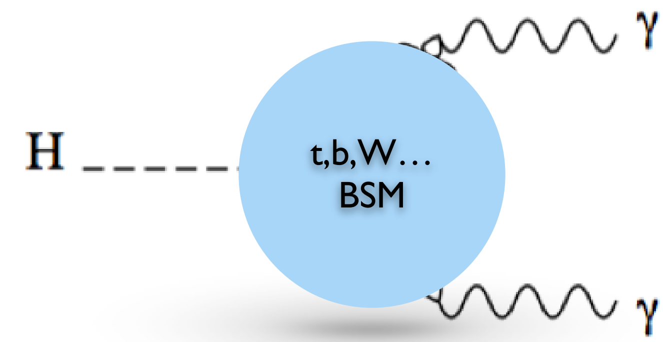
→ Model dependent interpretation

Brod, Haisch, Zupan (2013)

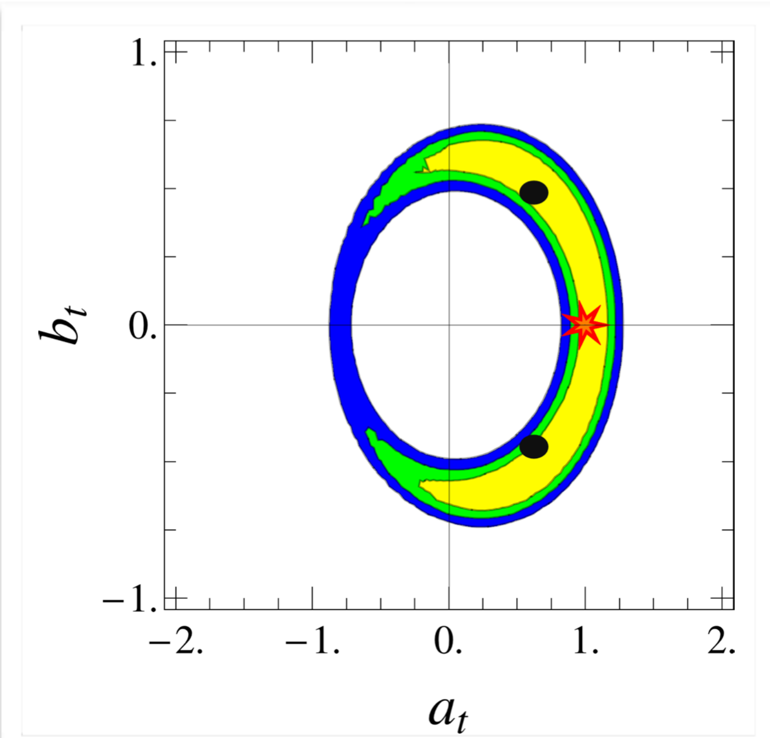
Indirect collider constraints

- Constraints from single H production & decay rates from ggh and $h\gamma\gamma$ vertices





- Fit Higgs-top CP-phase to combined LHC Run-I, assuming all other couplings to be SM-like



- Interpretation is somewhat model-dependent
  Loop-induced BSM $hG^{\mu\nu}G_{\mu\nu}, hG^{\mu\nu}\tilde{G}_{\mu\nu}$ $hF^{\mu\nu}F_{\mu\nu}, hF^{\mu\nu}\tilde{F}_{\mu\nu}$

$$
\begin{aligned}
\Gamma_{\gamma\gamma} &= \frac{G_F\alpha^2 m_H^3}{128\sqrt{2}\pi^3}\left\{\left|\kappa_W\, A_W^a(\tau_W) + \frac{4}{3}(a_t+\kappa_{\gamma\gamma})\, C_t^\gamma\, A_t^a(\tau_t)\right|^2 \right.\\
&\quad + \left.\left|\frac{4}{3}(b_t+\tilde{\kappa}_{\gamma\gamma})\, \tilde{C}_t^\gamma\, A_t^b(\tau_t)\right|^2\right\},\\
\Gamma_{gg} &= \frac{G_F\alpha_s^2 m_H^3}{16\sqrt{2}\pi^3}\left\{\left|\frac{1}{2}(a_t+\kappa_{gg})\, C_t^g\, A_t^a(\tau_t)\right|^2 \right.\\
&\quad + \left.\left|\frac{1}{2}(b_t+\tilde{\kappa}_{gg})\, \tilde{C}_t^g\, A_t^b(\tau_t)\right|^2\right\}.
\end{aligned}
$$

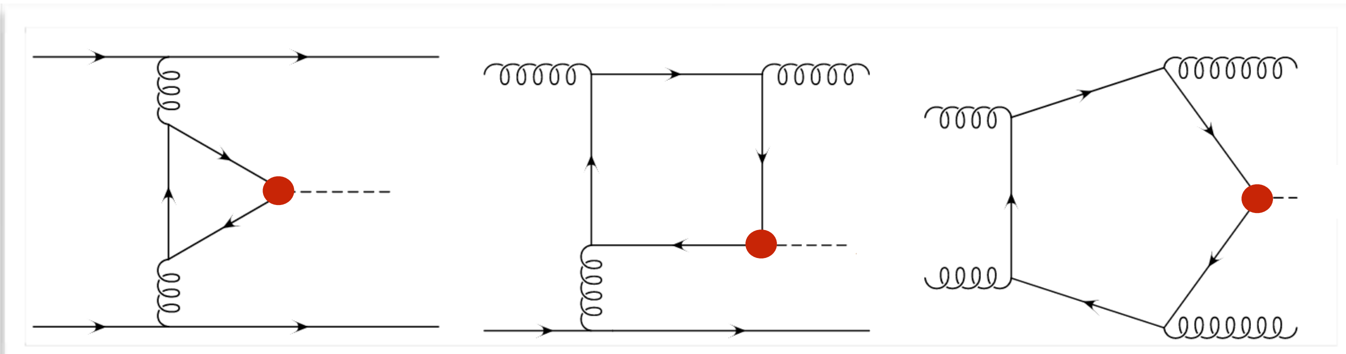
→ flat direction $b_t = -\tilde{\kappa}_{gg} = -\tilde{\kappa}_{\gamma\gamma}$

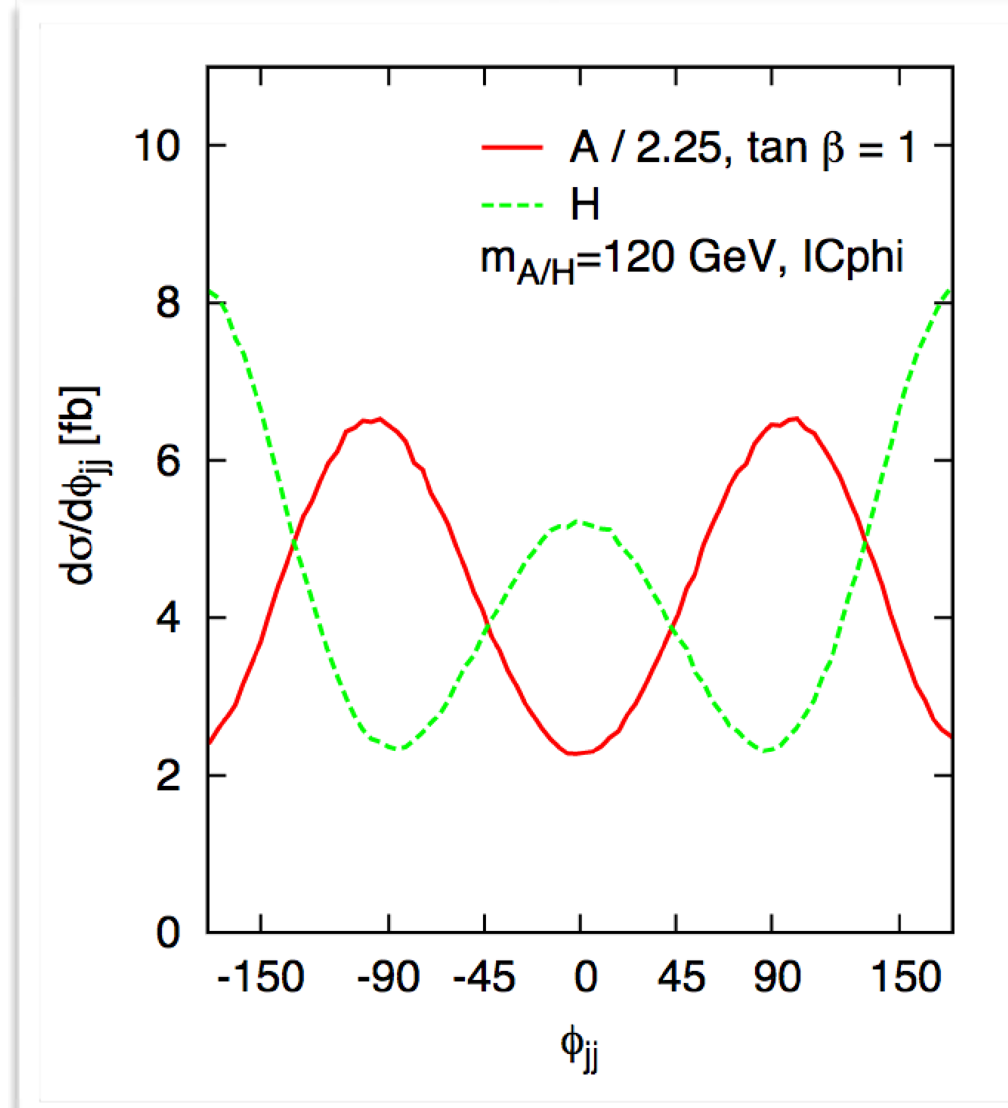
Boudjemaa, Godbole, Guadagnoli, Mohan (2015)

Indirect collider constraints

- Complementary top-Higgs CP measurement at LHC:

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha \right) t \; H$$





Plehn, Rainwater, Zeppenfeld (2001)
Zeppenfeld, Kubocz, Campanario (2010)
Englert, Goncalves, Mawatari, Plehn (2012)

- Sensitive to $\alpha = \pi/4$ with $50 fb^{-1}$

  Dolan, Harris, Jankowiak, Spannowsky (2014)

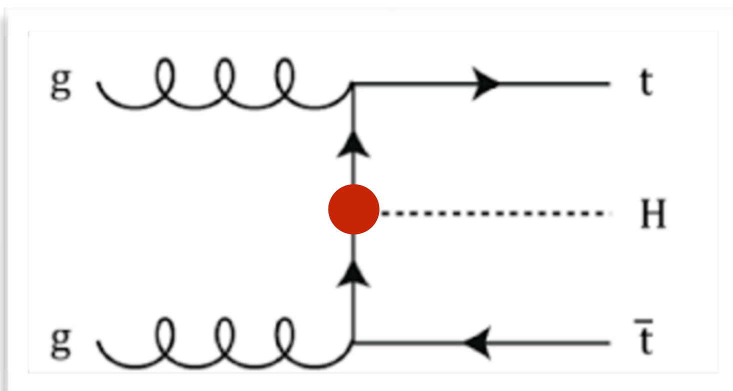
- Loop-induced: indirect constraints

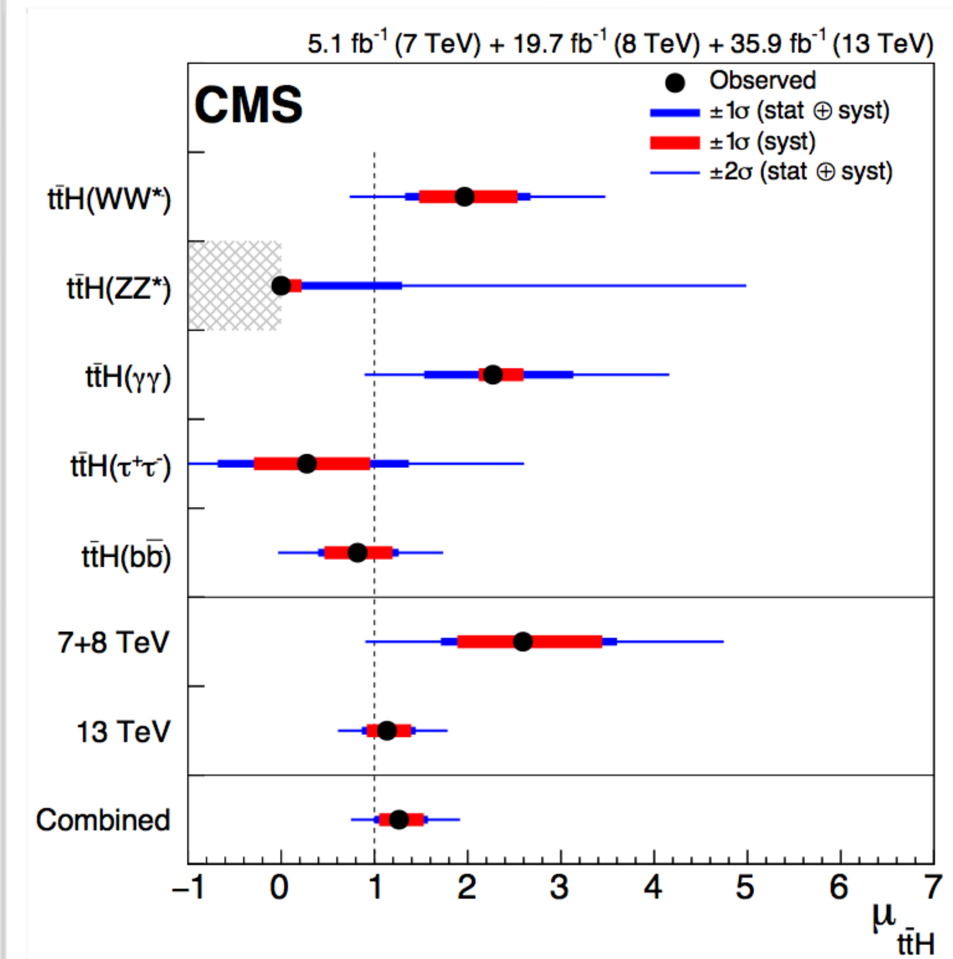
- Bottom line:

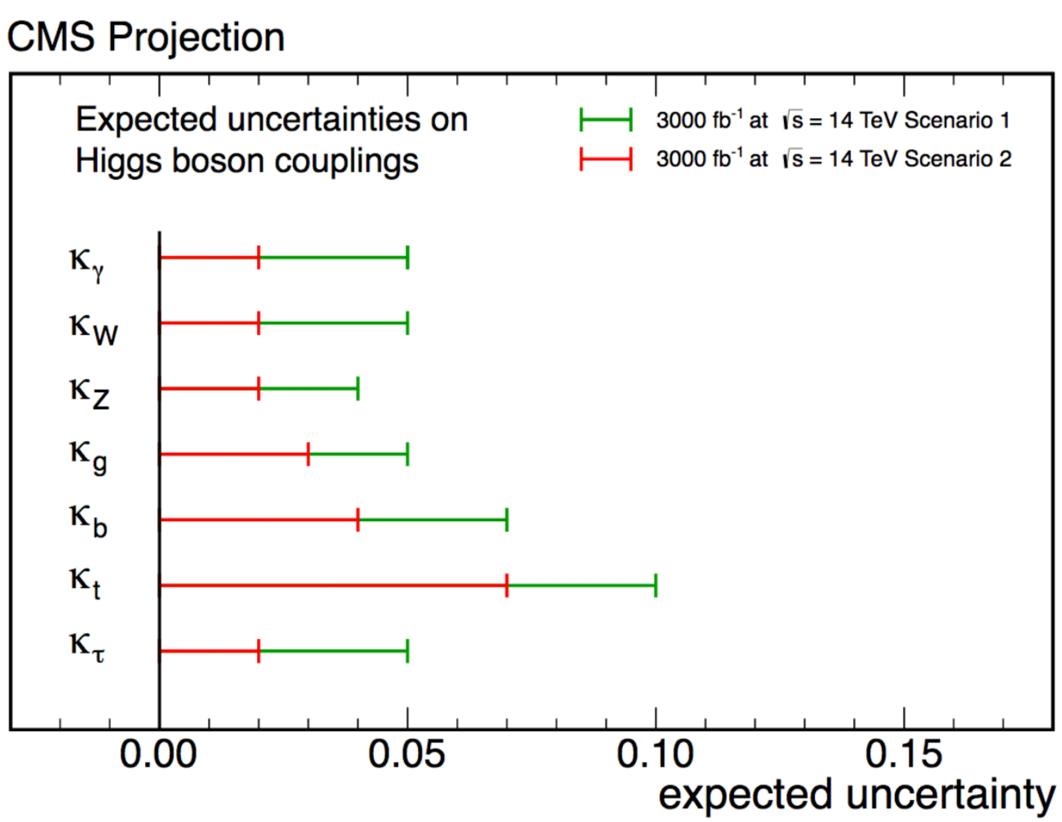
  Analogously to <u>direct</u> yt signal strength measurement the direct top-Higgs CP structure has in the ttH channel its most natural path

Exciting opportunities ahead!

- ttH channel observation:
  5.2σ observed (4.2σ expected) – CMS
  4.2σ observed (3.8σ expected) – ATLAS



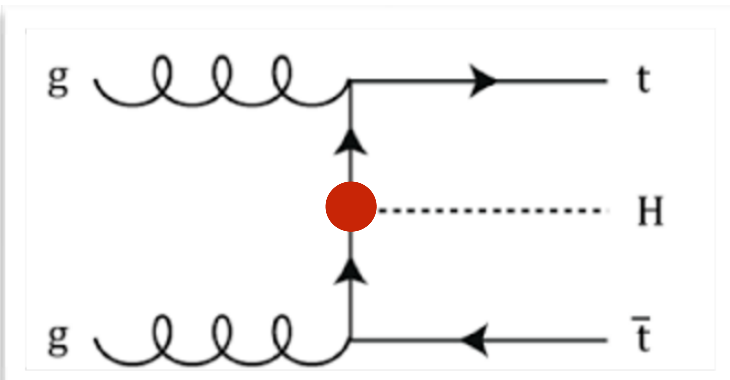


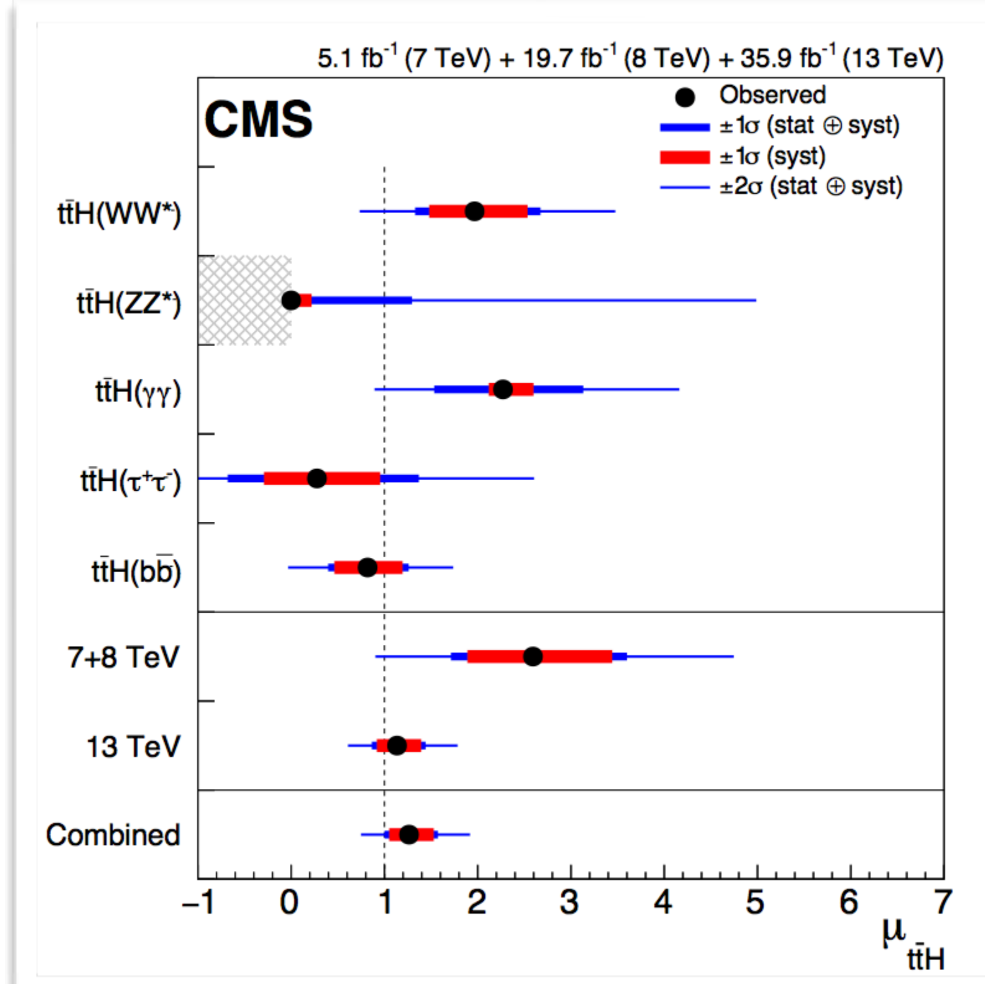


- Expected precisions:
  - → Scenario I: systematic uncertainties same as now
  - → Scenario II: theoretical uncertainty divided by 1/2 and systematic by 1/sqrt(L)

Exciting opportunities ahead!

- ttH channel observation:
  5.2σ observed (4.2σ expected) – CMS
  4.2σ observed (3.8σ expected) – ATLAS





- Analogously to direct Higgs-top Yukawa strength measurement, tth offers a more model independent probe to Higgs-top CP-structure. Important target!

- Can we directly measure Higgs-top CP structure at the LHC?

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\, t\; H$$

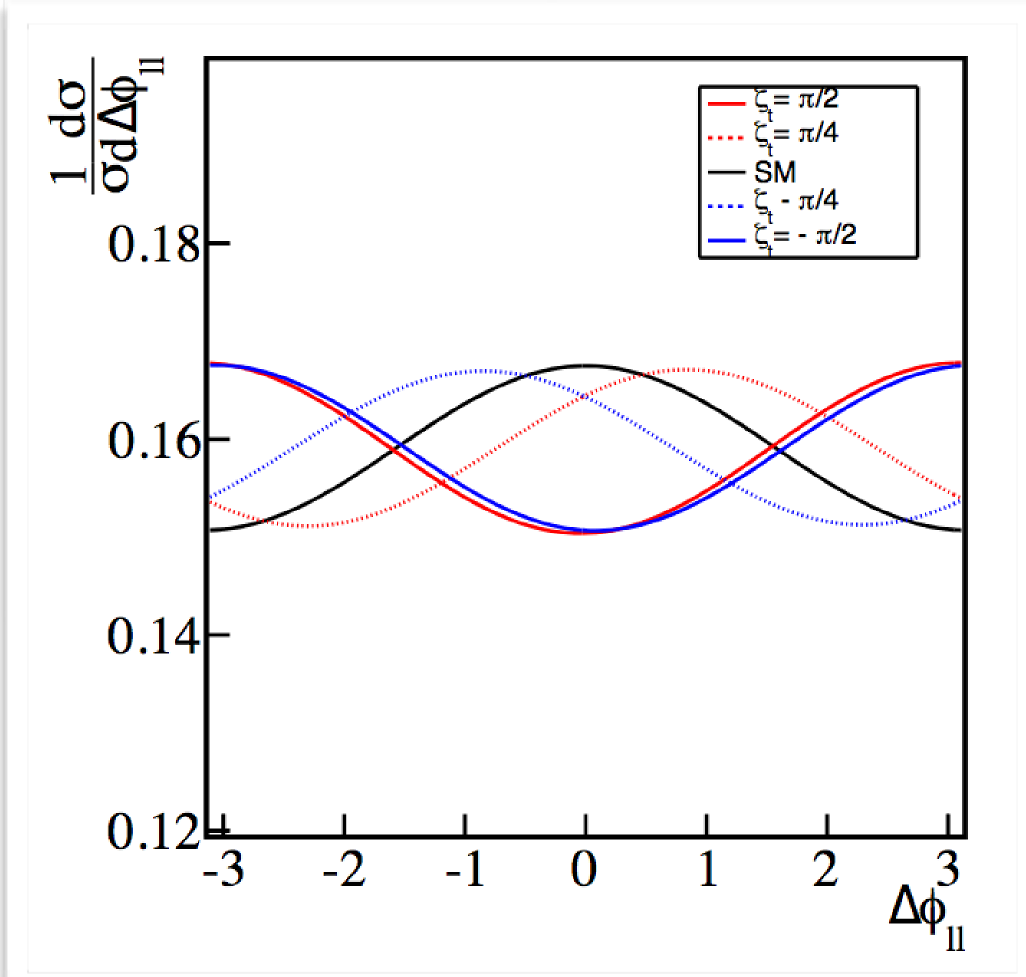
J. Ellis, Hwang, Sakurai, Takeuchi (2014)
Boudjemaa, Godbole, Guadagnoli,Mohan (2015)
Buckley, DG (2015); Amor dos Santos et al. (2017)

Directly measuring ttH CP-structure

- Proposal looking only at the signal and at parton level, showing that it could be done via angular correlations J. Ellis, Hwang, Sakurai, Takeuchi (2014); Boudjemaa, Godbole, Guadagnoli,Mohan (2015)

$$\Delta\phi_{ll} = sign[\vec{p}_t.(\vec{p}_{l-} \times \vec{p}_{l+})]arccos[|(\hat{\vec{p}}_{l+} \times \hat{\vec{p}}_t).(\hat{\vec{p}}_{l-} \times \hat{\vec{p}}_t)|]|_{t\bar{t}}$$

- Good correlations but presents large experimental uncertainties at hadron collider due to top reconstruction, frame change…

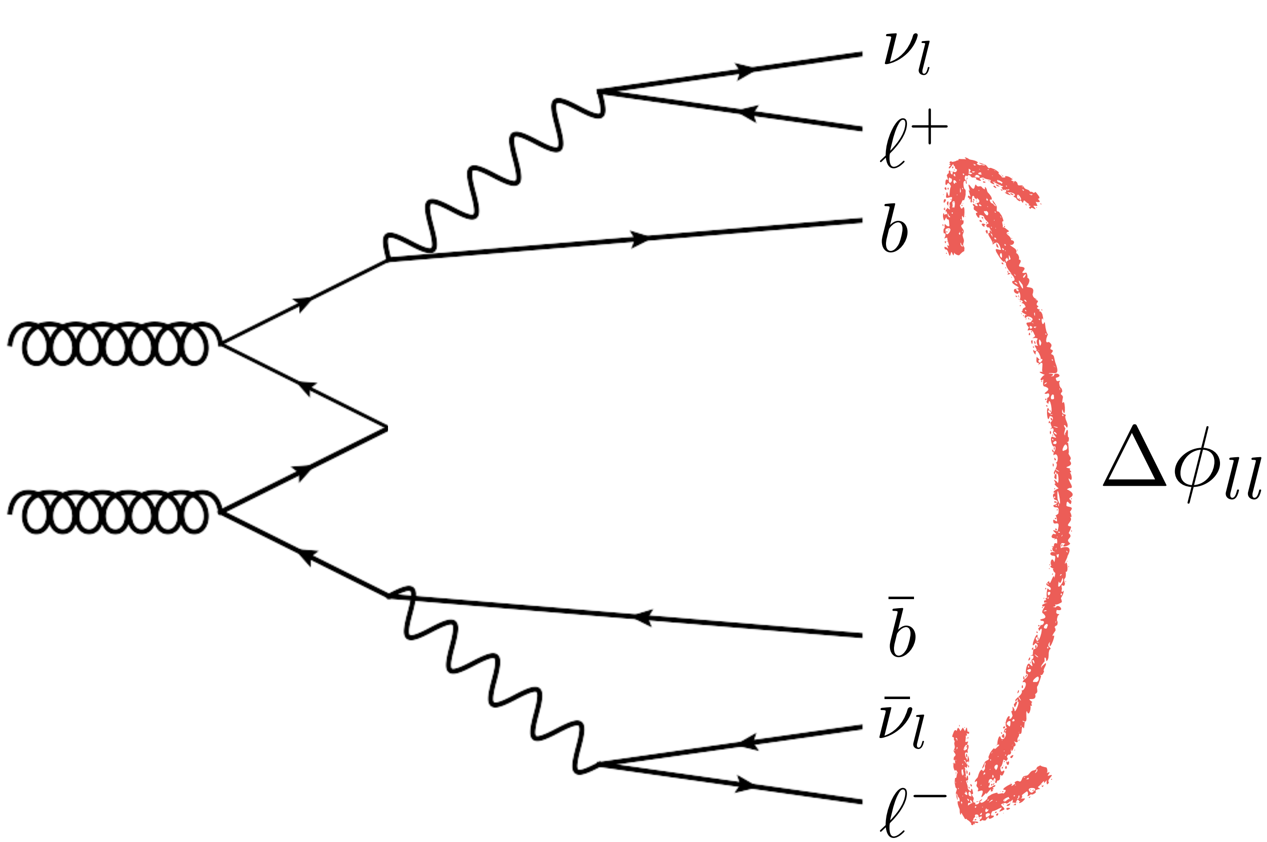


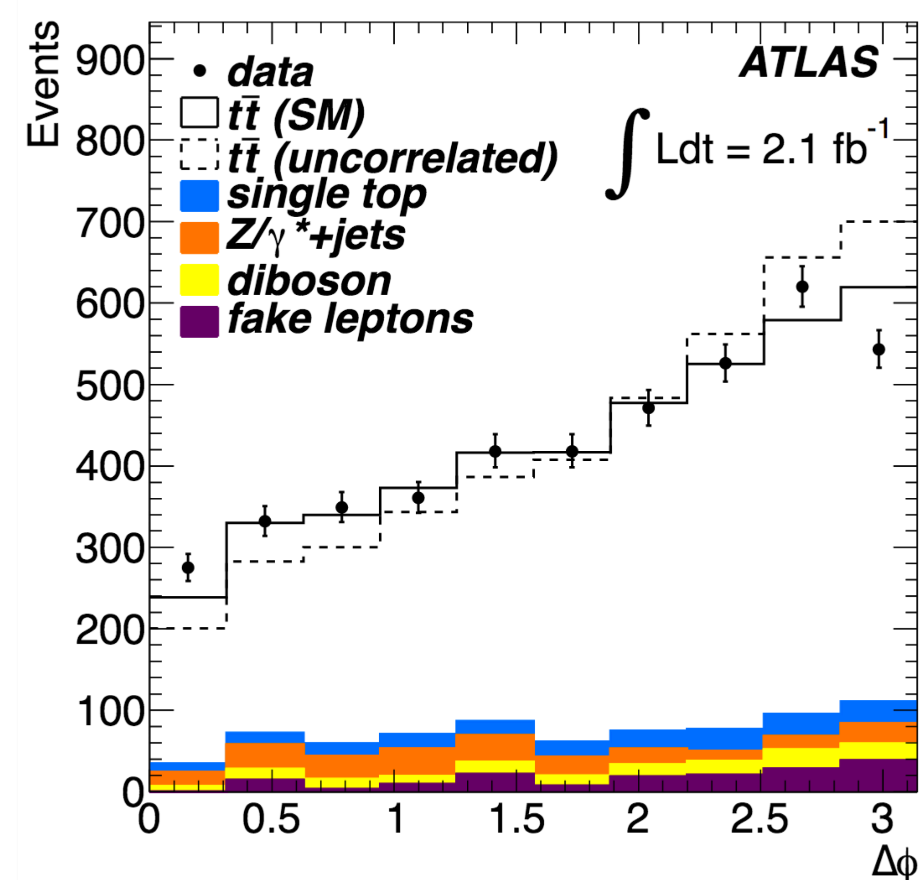
Directly measuring ttH CP-structure

- Proposal looking only at the signal and at parton level, proposing that it could be done via angular correlations J. Ellis, Hwang, Sakurai, Takeuchi (2014); Boudjemaa, Godbole, Guadagnoli,Mohan (2015)

$$\Delta\phi_{ll} = sign[\vec{p}_t.(\vec{p}_{l^-} \times \vec{p}_{l^+})]arccos[|(\hat{\vec{p}}_{l^+} \times \hat{\vec{p}}_t).(\hat{\vec{p}}_{l^-} \times \hat{\vec{p}}_t)||]_{t\bar{t}}$$

- Good correlations but presents large experimental uncertainties at hadron collider due to top reconstruction, frame change…
- Analogous situation at tt correlated vs uncorrelated top decays Parke, Mahlon (1996,2010)



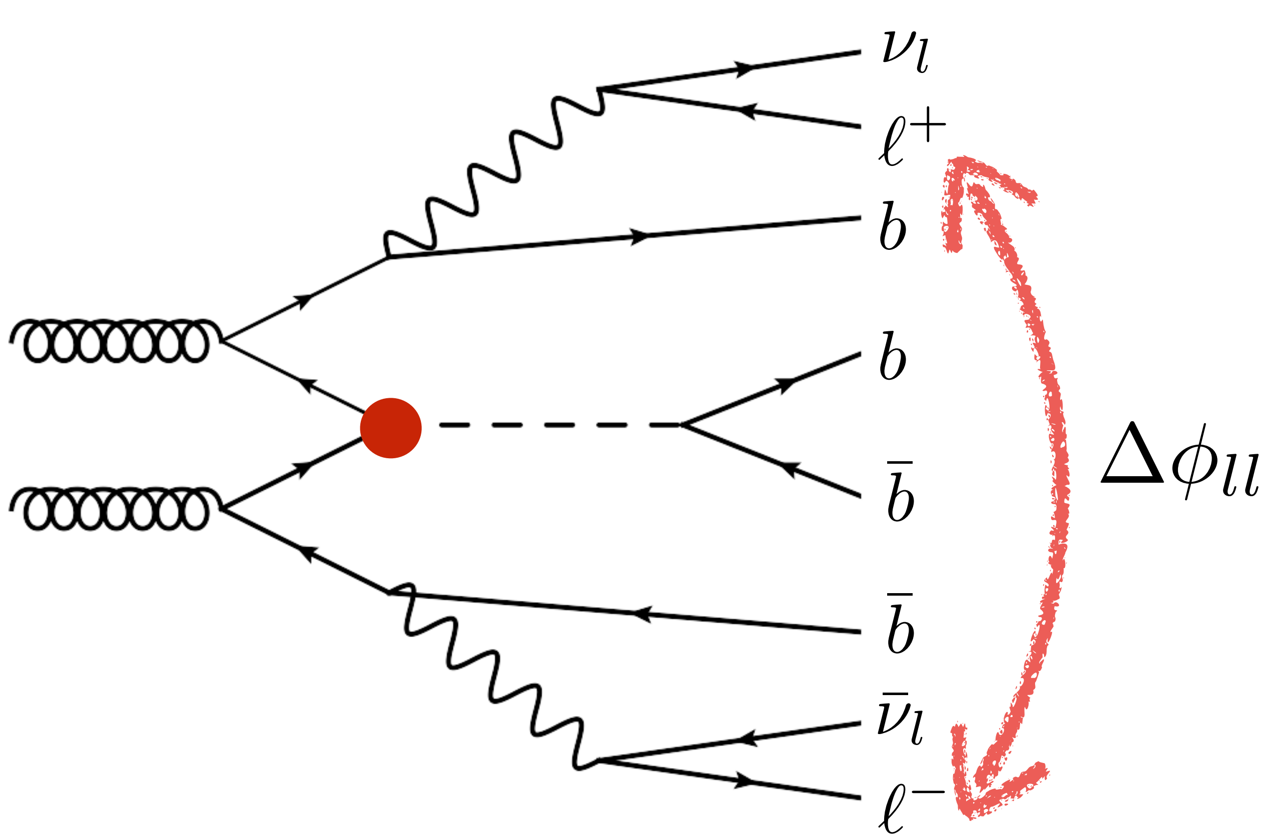


Directly measuring ttH CP-structure

- Proposal looking only at the signal and at parton level, proposing that it could be done via angular correlations J. Ellis, Hwang, Sakurai, Takeuchi (2014); Boudjemaa, Godbole, Guadagnoli,Mohan (2015)

$$\Delta\phi_{ll} = sign[\vec{p}_t.(\vec{p}_{l^-} \times \vec{p}_{l^+})]arccos[|(\hat{\vec{p}}_{l^+} \times \hat{\vec{p}}_t).(\hat{\vec{p}}_{l^-} \times \hat{\vec{p}}_t)|]|_{t\bar{t}}$$

- Good correlations but presents large experimental uncertainties at hadron collider due to top reconstruction, frame change…
- Analogous situation at tt correlated vs uncorrelated top decays Parke, Mahlon (1996,2010)

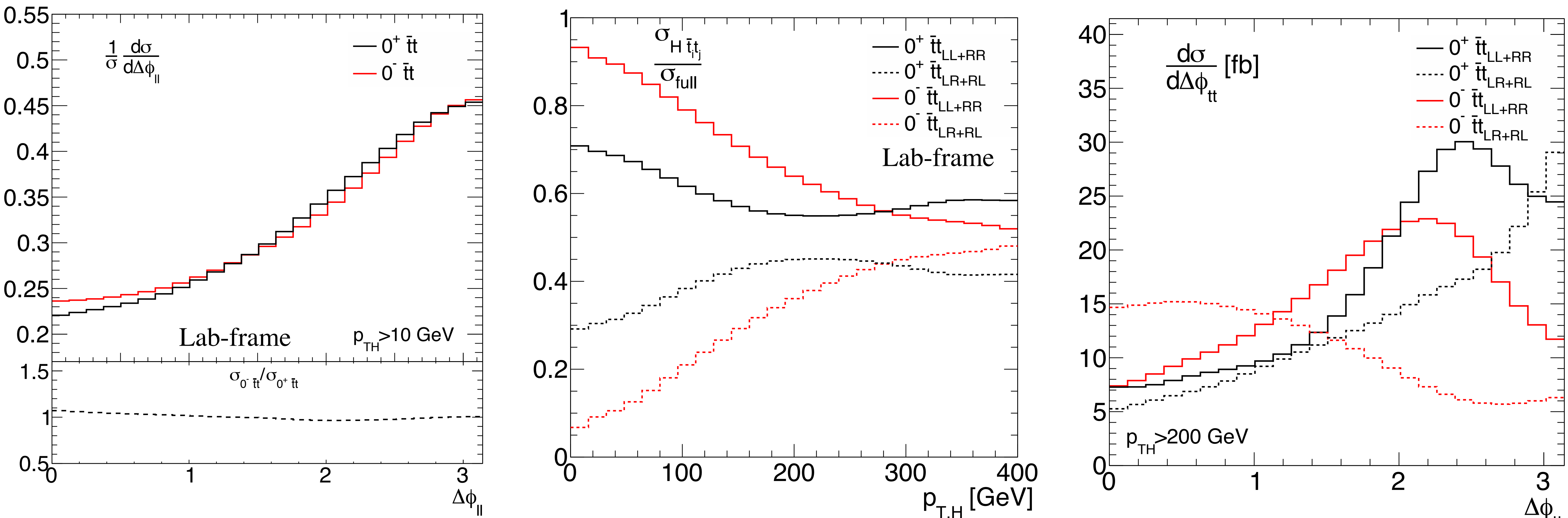


$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\,t\ H$$

Directly measuring ttH CP-structure

- Spin correlations of top and anti-top affected by nature of interaction
  $\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$:

$$\mathcal{L} \supset -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$



➡ Top mass effects in presence of a further massive H boson pushes chiral limit to higher scales

$$\mathcal{M}_{0+t\bar{t}_{LR+RL}} \propto \sin\left(\frac{\Delta\phi_{tt}}{2}\right) \qquad \mathcal{M}_{0-t\bar{t}_{LR+RL}} \propto \cos\left(\frac{\Delta\phi_{tt}}{2}\right)$$

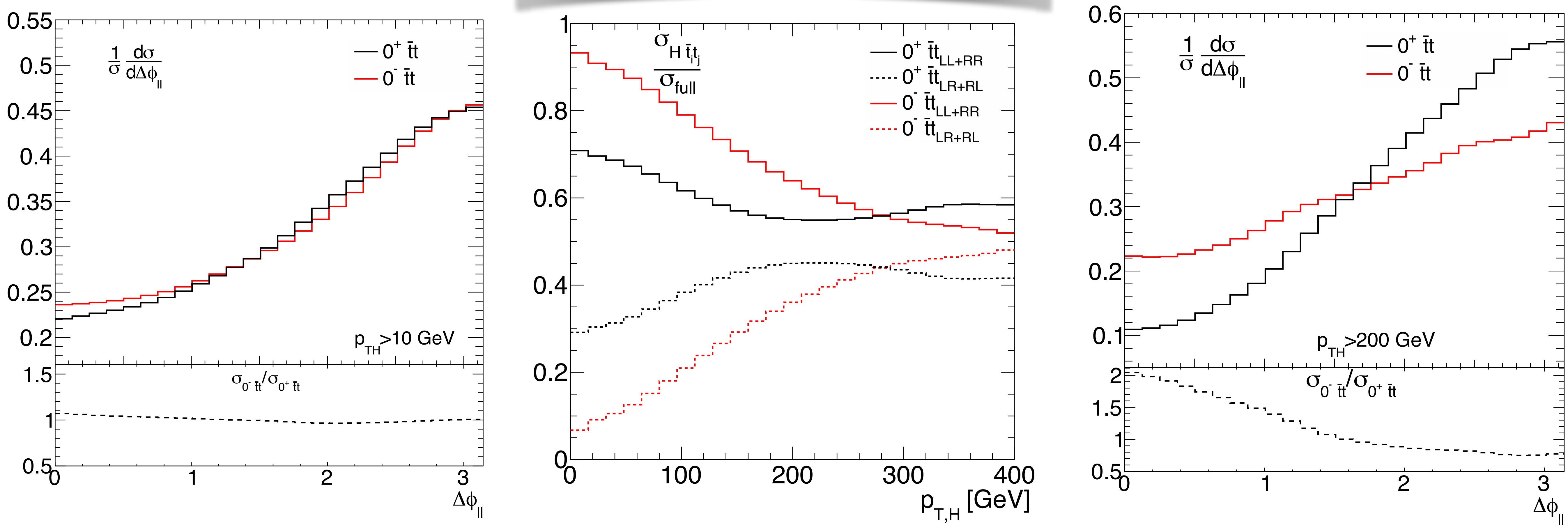
Buckley, DG (2015)

Directly measuring ttH CP-structure

- Spin correlations of top and anti-top affected by nature of interaction
  $\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$:

Parke, Mahlon (2010)

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha \right) t \; H$$



➡ Boosted Higgs (p_{TH}>200GeV) nicely match with H>bb BDRS algorithm

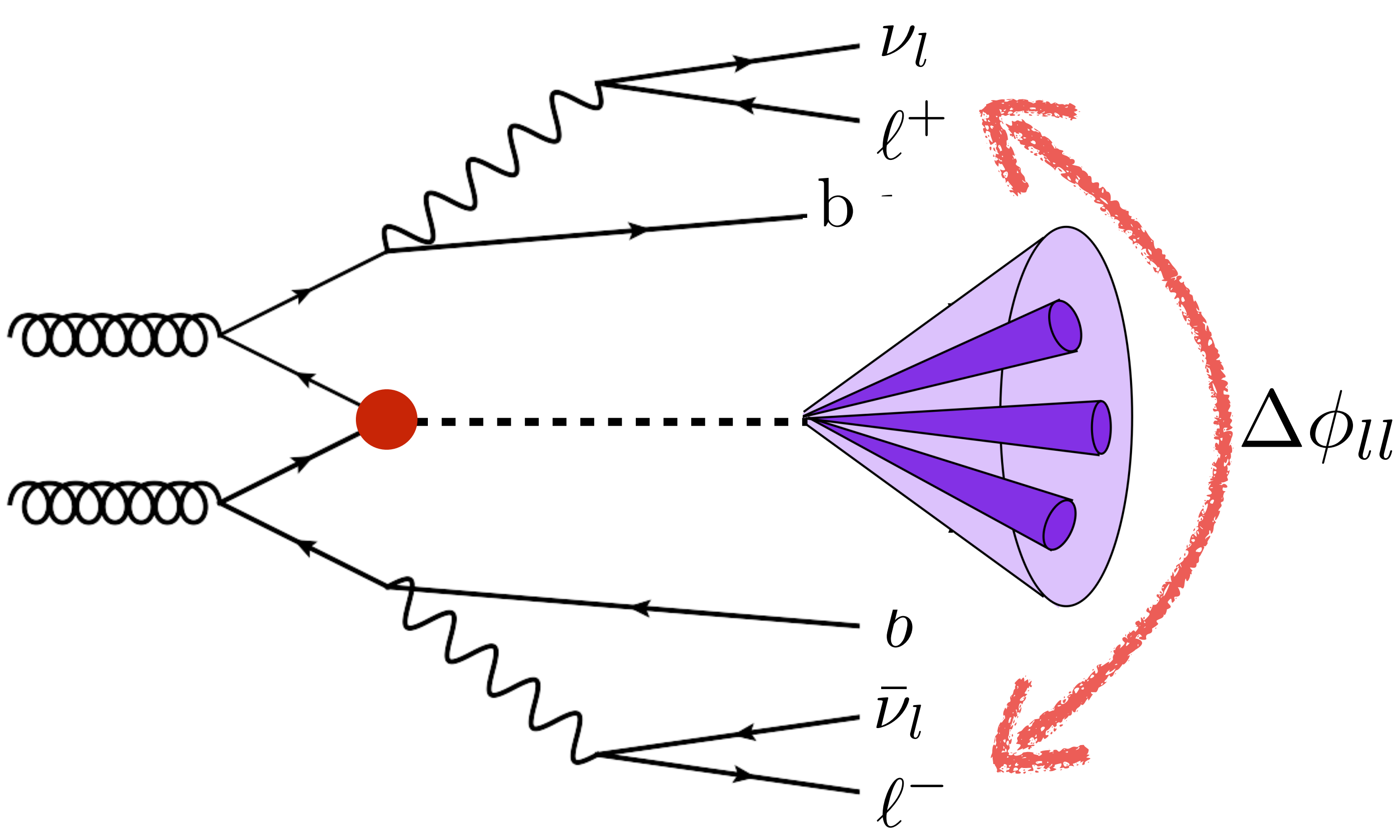
Buckley, DG (2015)
Plehn, Salam, Spannowsky (2009)

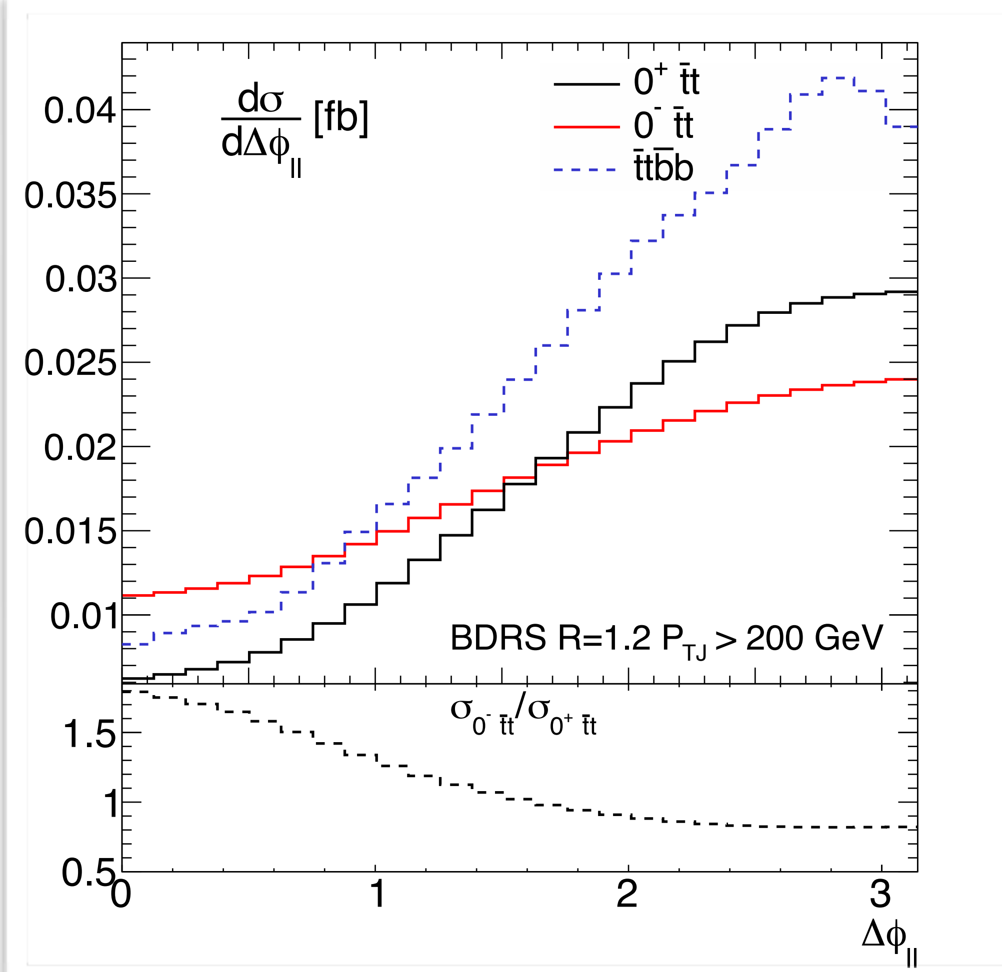
Directly measuring ttH CP-structure

- Higgs candidate is genuinely part of a multi-jet system:

  Proper modelling of the QCD emissions indispensable requirement for robust analysis

→ Signal & backgrounds are @NLO (MC@NLO), accounting for spin correlation on top decays





BDRS H-tag, $p_{T\ell} > 15$ GeV, $|\eta_\ell| < 2.5$
$p_{Tj} > 30$ GeV, $|\eta_j| < 2.5$, $n_j \geq 2$, $n_l = 2$
two extra b-tags (four in total)
$|m_H^{\rm BDRS} - m_H| < 10$ GeV, $m_{b\bar{b}} > 110$ GeV

- The full analysis and higher-order effects did not degrade our observable!

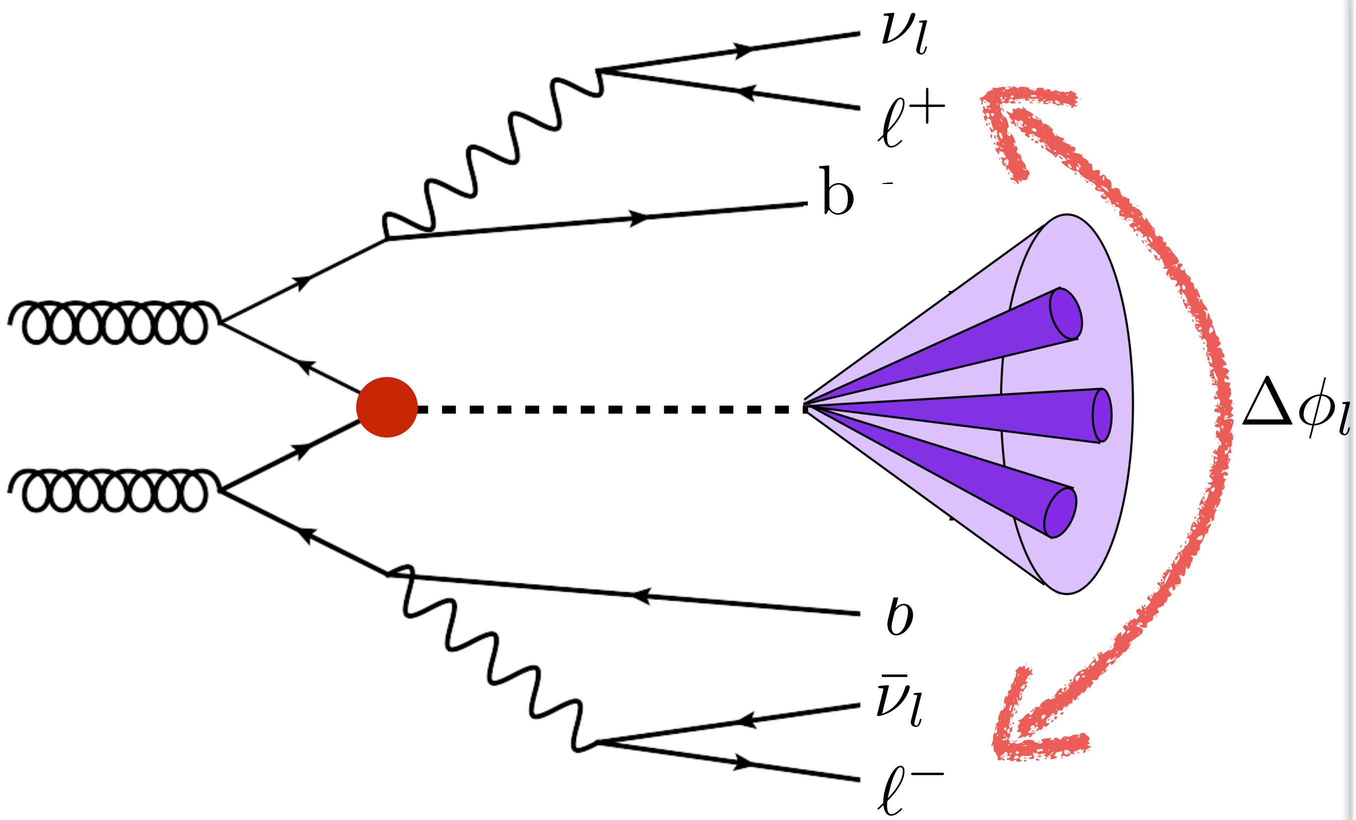
Buckley, DG (2015)

Directly measuring ttH CP-structure

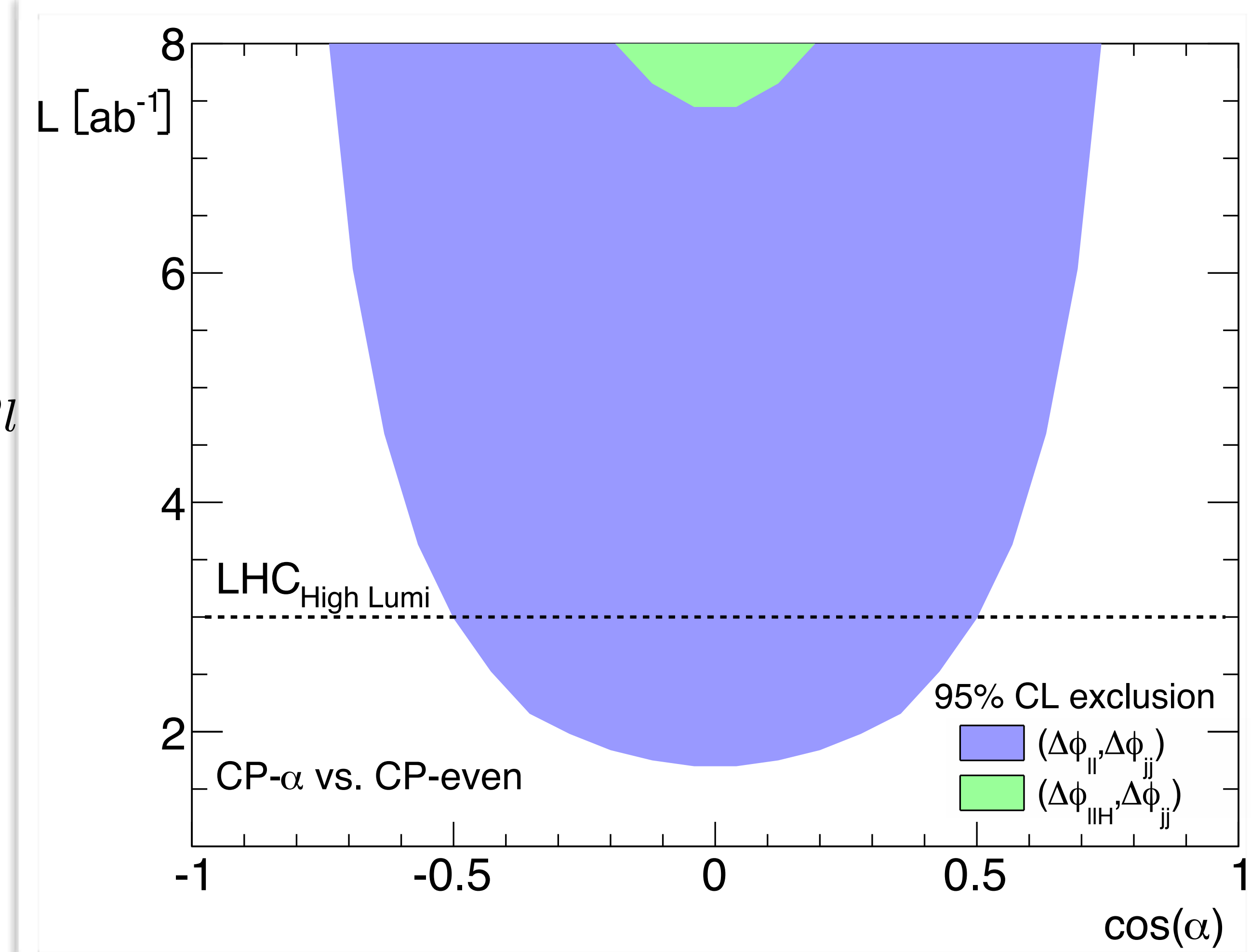
- Higgs candidate is genuinely part of a multi-jet system:

  Proper modelling of the QCD emissions indispensable requirement for robust analysis

→ Signal & backgrounds are @NLO (MC@NLO), accounting for spin correlation on top decays



BDRS H-tag, $p_{T\ell} > 15$ GeV, $|\eta_\ell| < 2.5$
$p_{Tj} > 30$ GeV, $|\eta_j| < 2.5$, $n_j \geq 2$, $n_l = 2$
two extra b-tags (four in total)
$|m_H^{\mathrm{BDRS}} - m_H| < 10$ GeV, $m_{b\bar{b}} > 110$ GeV

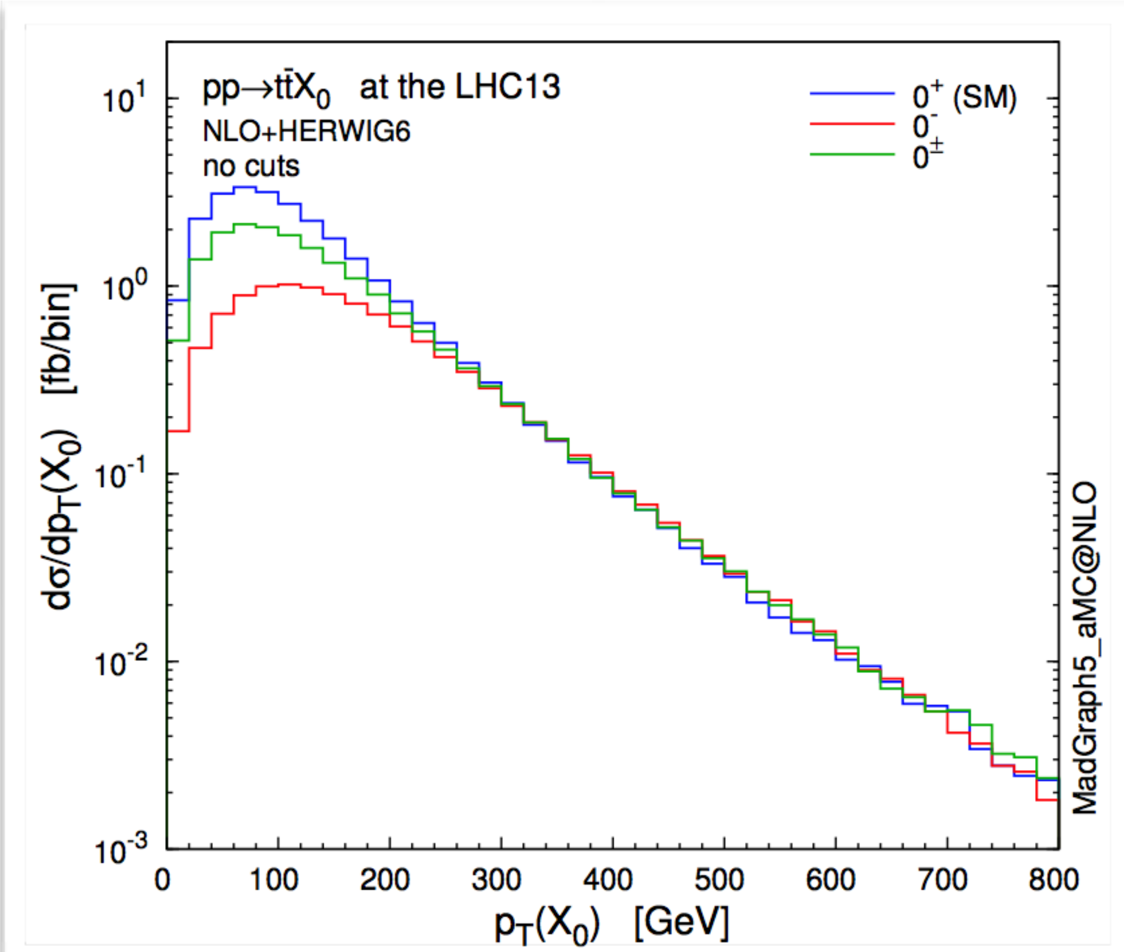


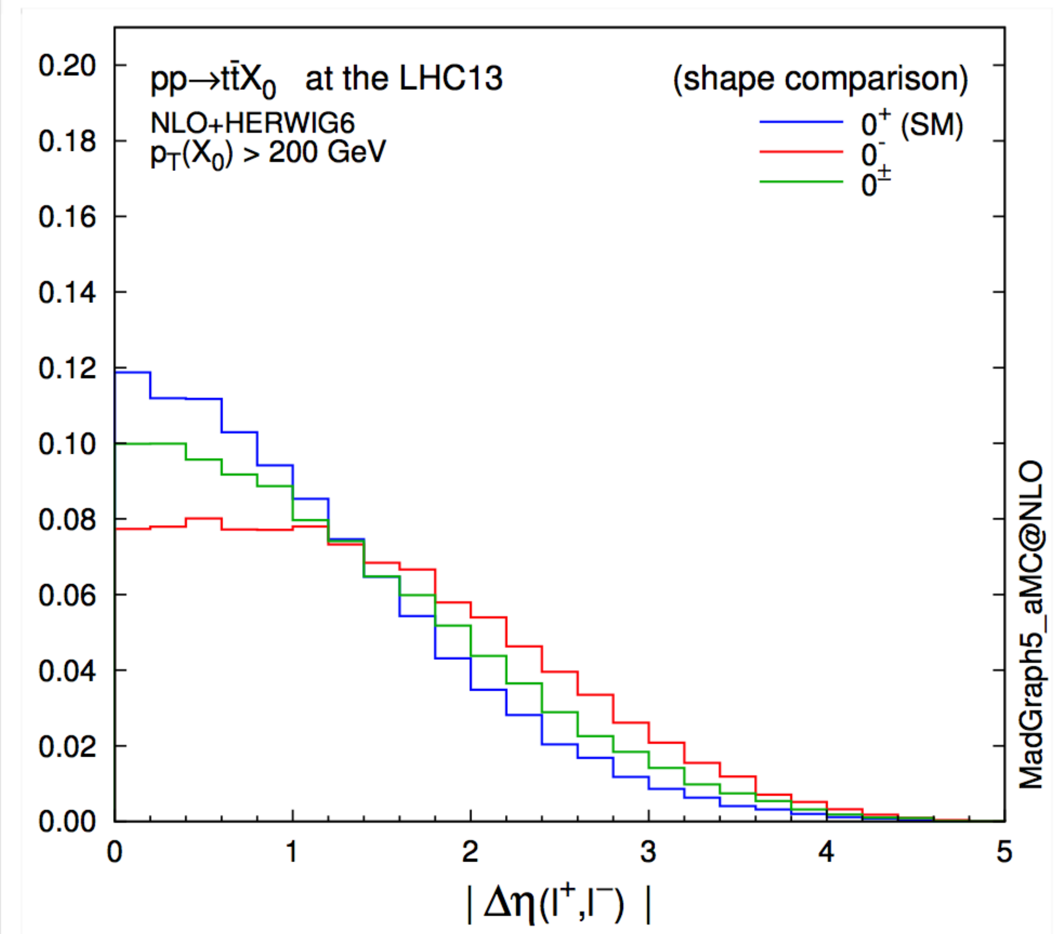
$$\mathcal{L} \supset -\frac{m_t}{v} K \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\, t\; H$$

Buckley, DG (2015)

Multivariate analysis problem

- Rich final state with many more relevant observables:

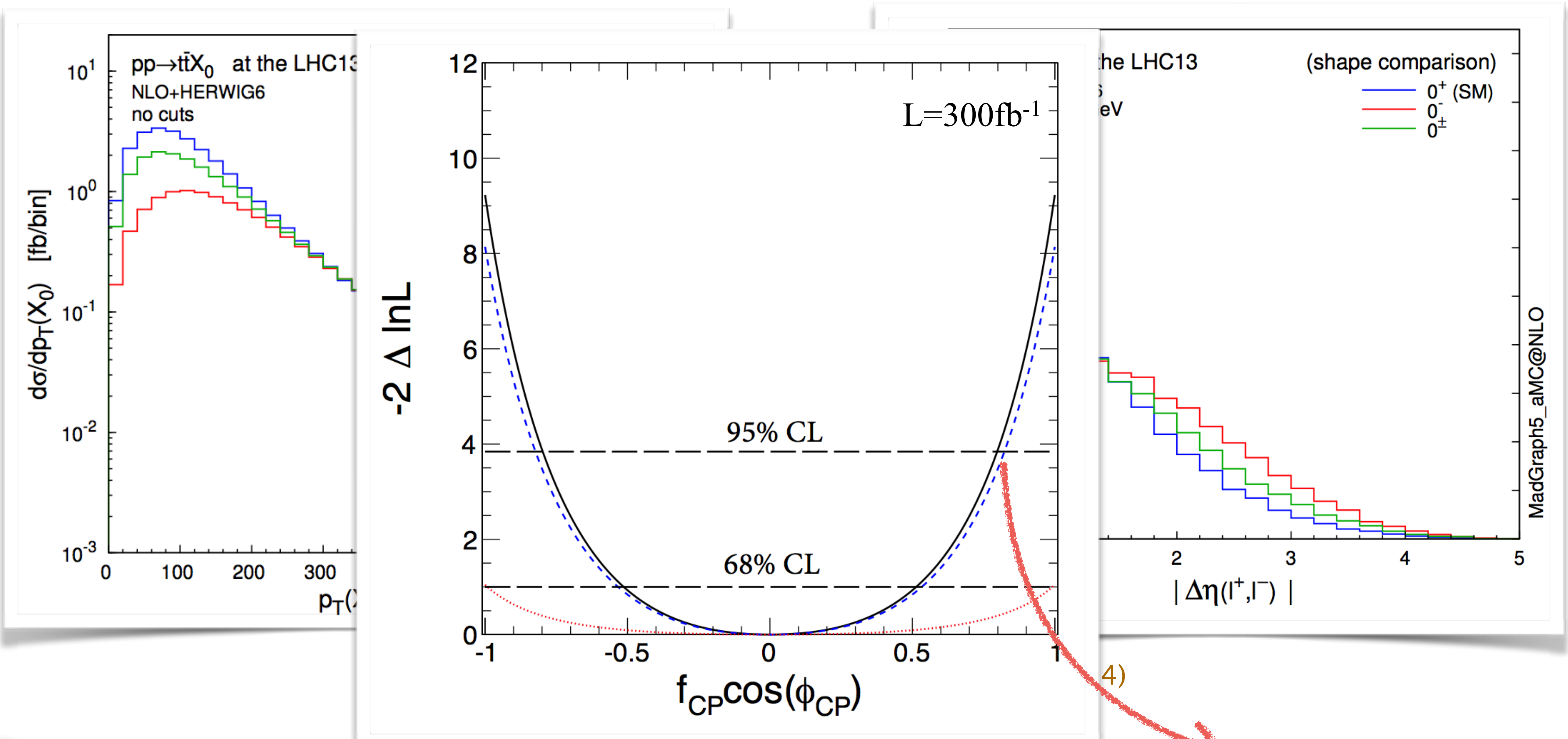




Demartin, Maltoni, Mawatari, Page, Zaro (2014)

Multivariate analysis problem

- Rich final state with many more relevant observables:



$|f_{CP} \cos\phi_{CP}| \gtrsim 0.8$, are excluded at 2σ

$$f_{CP} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}$$

- Final target: multivariate analysis

Gritsan, Rontsch, Schulze, Xiao (2016)

dileptonic tops: Amor dos Santos et al. (2017)

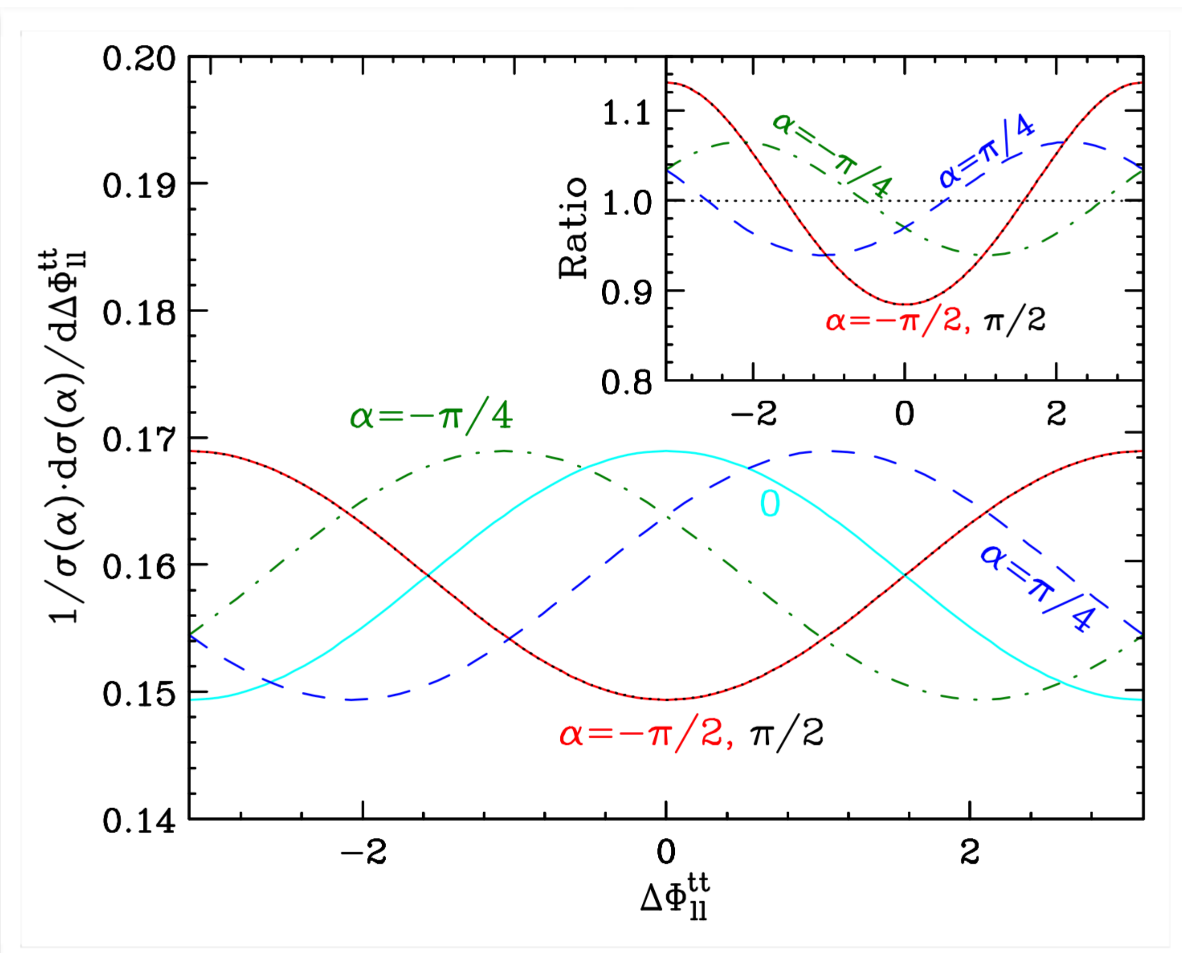
Semileptonic tops: Azevedo, Onofre, Filthaut, Gonçalo (2017)

CPV Higgs-top measurement

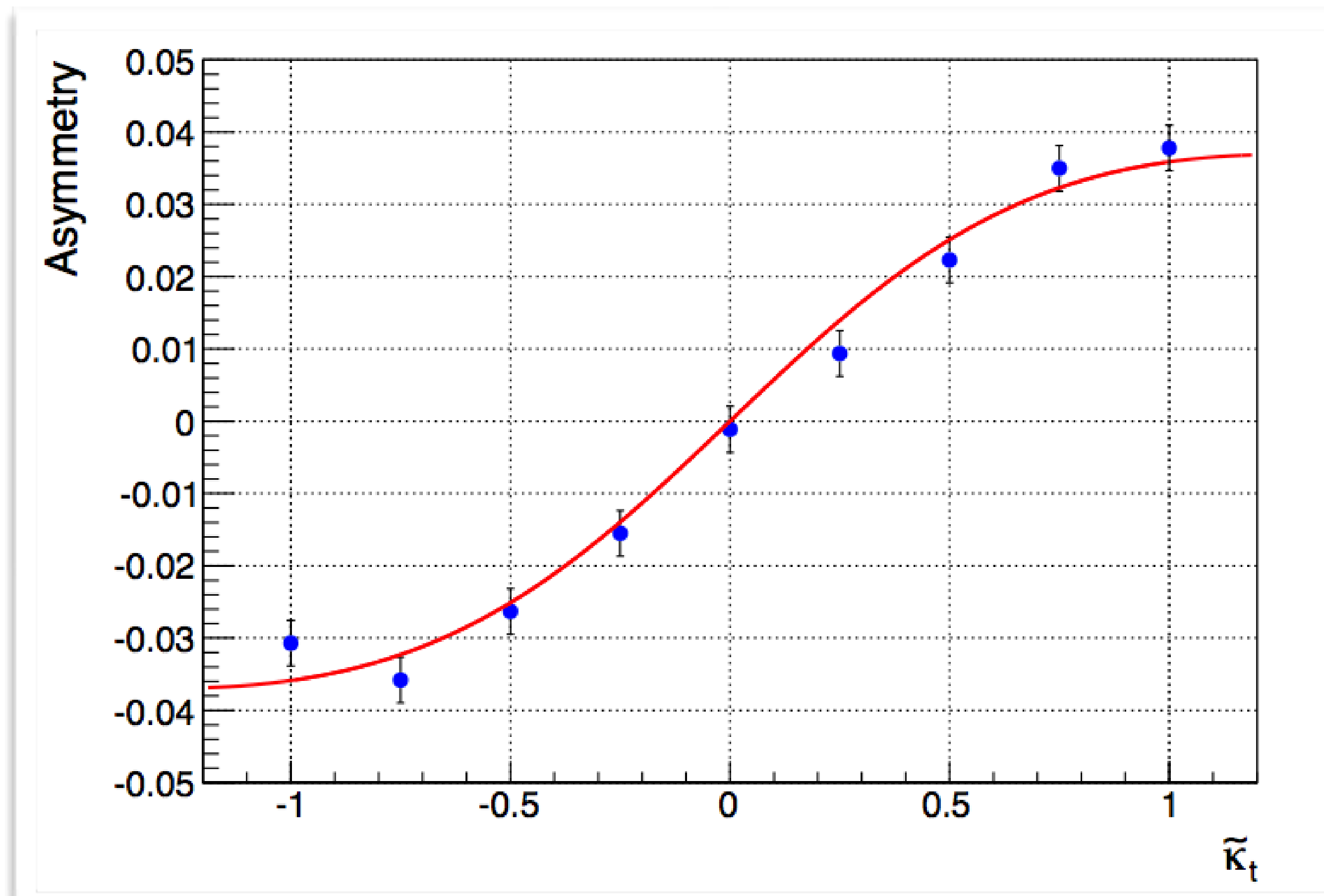
- CPV observable best defined at the ttbar rest frame:

$$\Delta\phi_{\ell\ell}^{t\bar{t}} = \text{sgn}\left[\hat{p}_t \cdot (\hat{p}_{\ell+} \times \hat{p}_{\ell-})\right] \arccos\left[(\hat{p}_t \times \hat{p}_{\ell+}) \cdot (\hat{p}_t \times \hat{p}_{\ell-})\right]$$

$$\mathcal{A}_{\ell\ell} \equiv \frac{N(\Delta\phi_{\ell\ell}^{t\bar{t}} > 0) - N(\Delta\phi_{\ell\ell}^{t\bar{t}} < 0)}{N(\Delta\phi_{\ell\ell}^{t\bar{t}} > 0) + N(\Delta\phi_{\ell\ell}^{t\bar{t}} < 0)}$$



DG, Kong, Kim (2018)

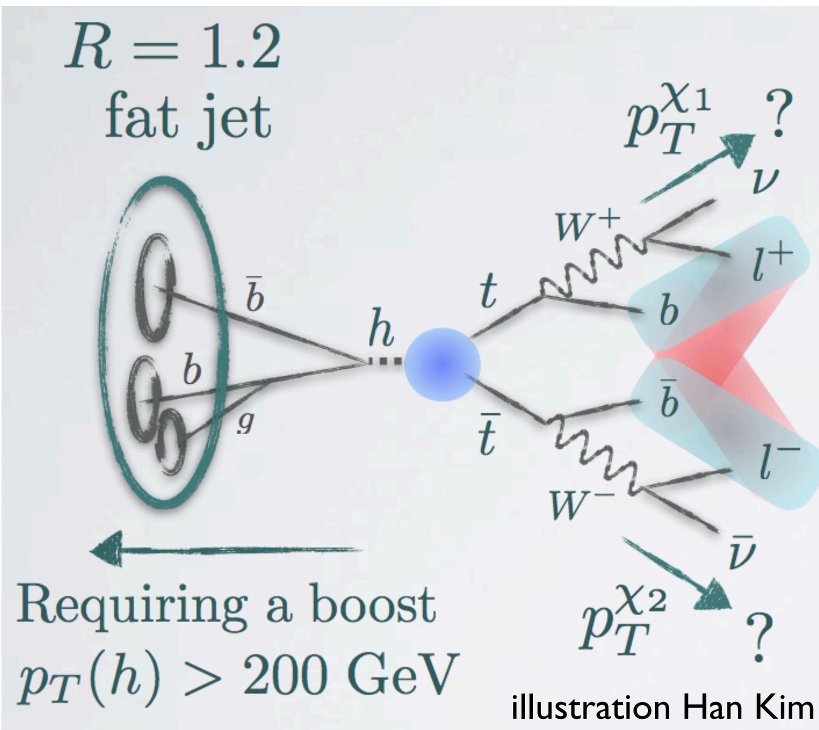


Mileoa, Kiersb, Szynkmana, Craneb, Gegner (2016)

→ We need an efficient method to reconstruct the top momenta

CPV Higgs-top measurement

- To obtain top momenta M2 method: based on mass minimization, being more flexible for BSM studies



Debnath, Kim, Kong, Matchev (2017)
DG, Kong, Kim (2018)

→ **Reconstruction of the Higgs: BDRS**

→ **Reconstruction of top momenta: Optimass**

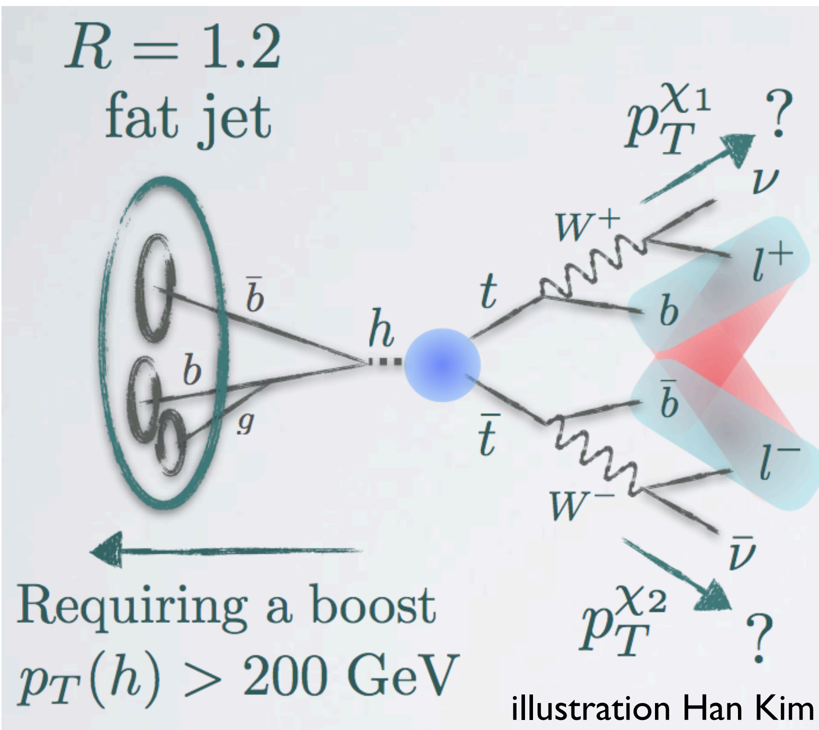
a) **guess neutrino momenta**
b) **solve combinatorial problem**

Generalization of MT2 with mass constraints:

$$M_{2CW}^{(b\ell)} \equiv \min_{\vec{q}_1, \vec{q}_2} \{\max [M_{t_1}(\vec{q}_1, \tilde{m}), \; M_{t_2}(\vec{q}_2, \tilde{m})]\}$$
$$\vec{q}_{1T} + \vec{q}_{2T} = \vec{P}\!\!\!/_T$$
$$M_{t_1} = M_{t_2}$$
$$M_{W_1} = M_{W_2} = m_W$$

CPV Higgs-top measurement

- To obtain top momenta M2 method: based on mass minimization, being more flexible for BSM studies



Debnath, Kim, Kong, Matchev (2017)
DG, Kong, Kim (2018)

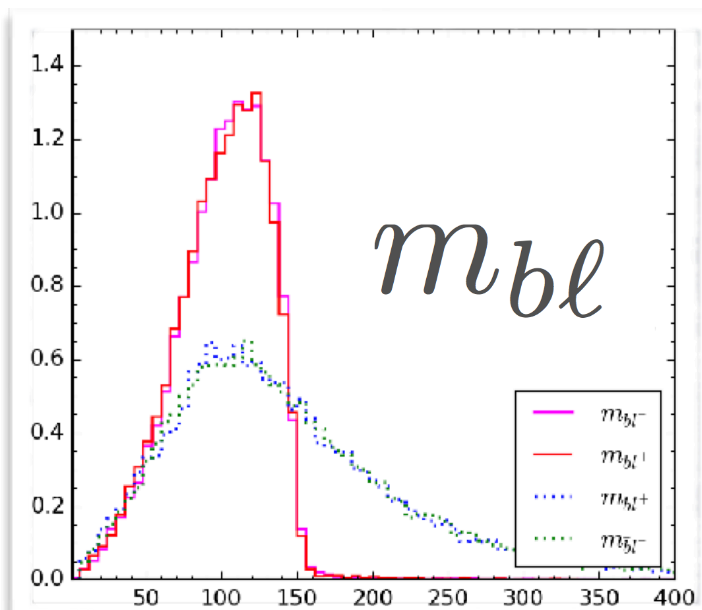
➡ **Reconstruction of the Higgs: BDRS**

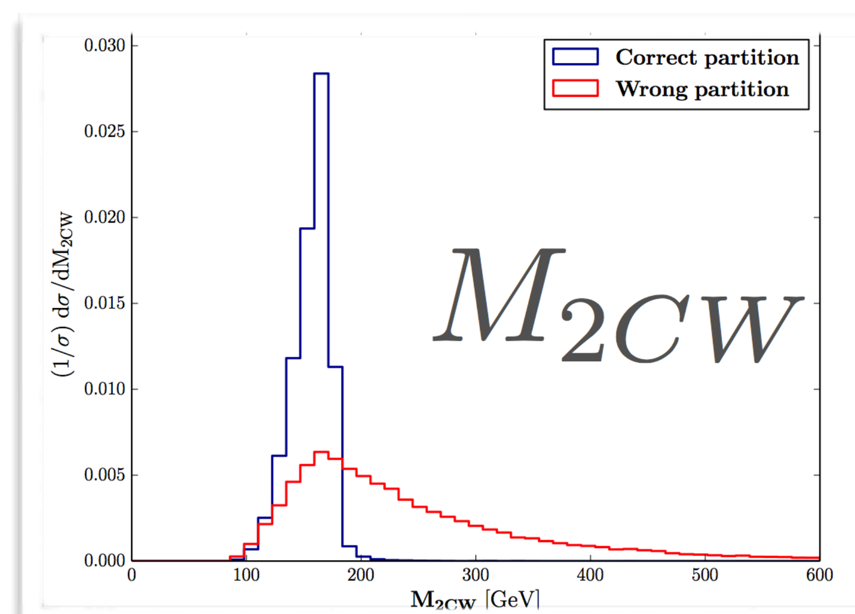
➡ **Reconstruction of top momenta: Optimass**

a) guess neutrino momenta
b) solve combinatorial problem

$M_{2CW}^{\text{correct}} \longrightarrow p_T^{\chi_1}(\text{correct}) \quad p_T^{\chi_2}(\text{correct})$

$M_{2CW}^{\text{wrong}} \longrightarrow p_T^{\chi_1}(\text{wrong}) \quad p_T^{\chi_2}(\text{wrong})$

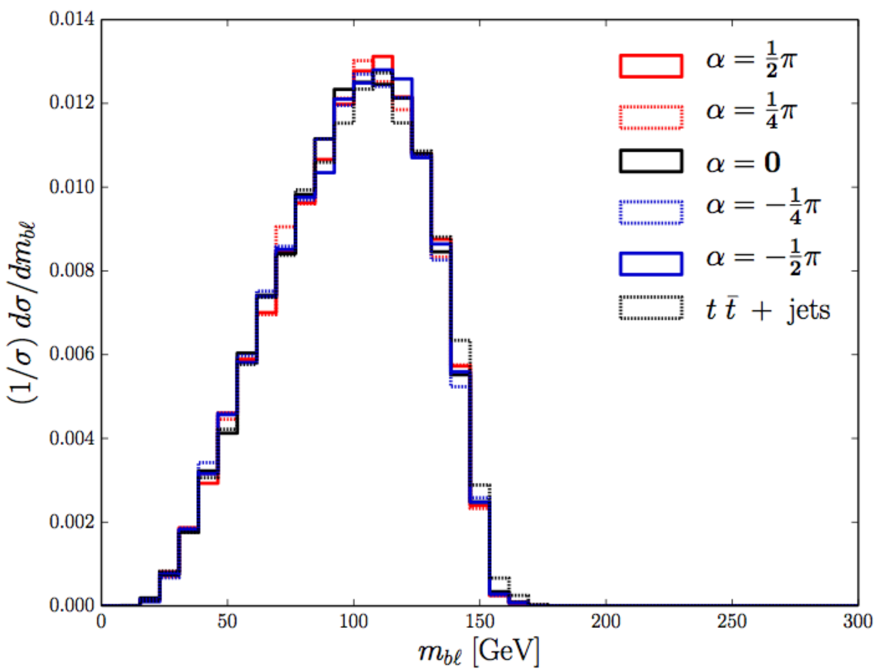


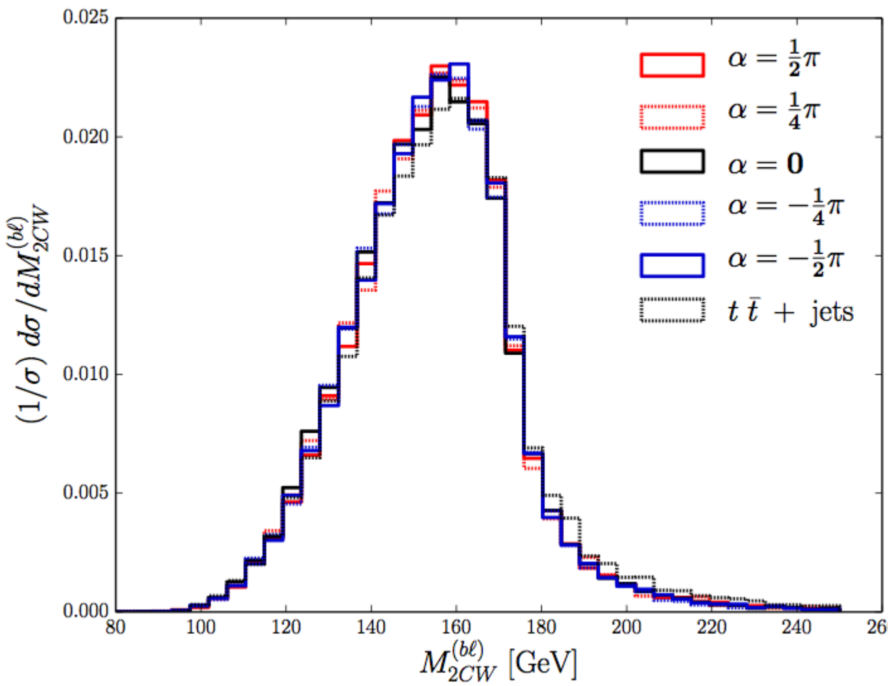


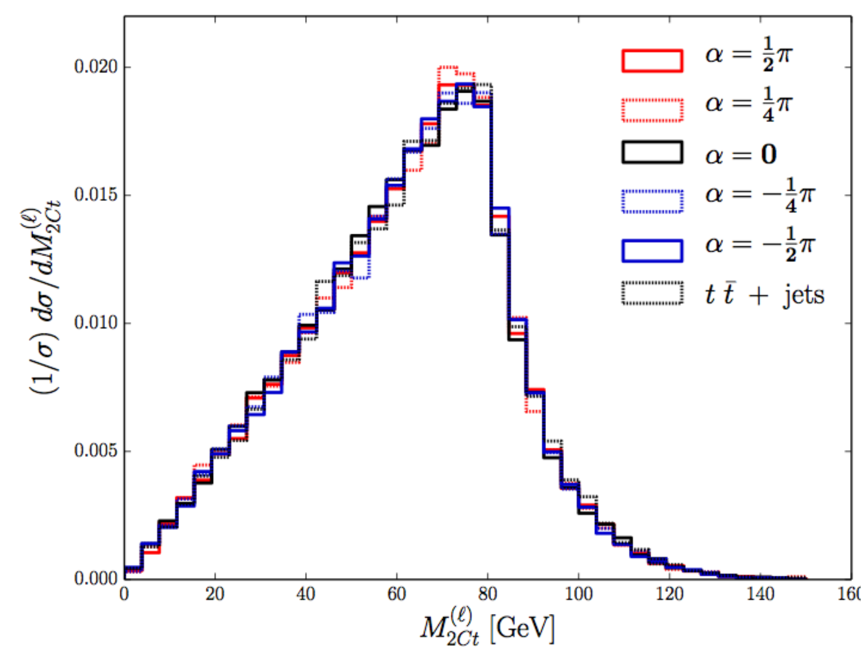
- The wrong partition often violates the end-points: Optimass uses it to pick up correct one
  The method choses the correct partition with efficiency of 83% (resolved)

CPV Higgs-top measurement

- Reconstruction method is purely based on mass minimization:
  It is less sensitive to BSM modifications







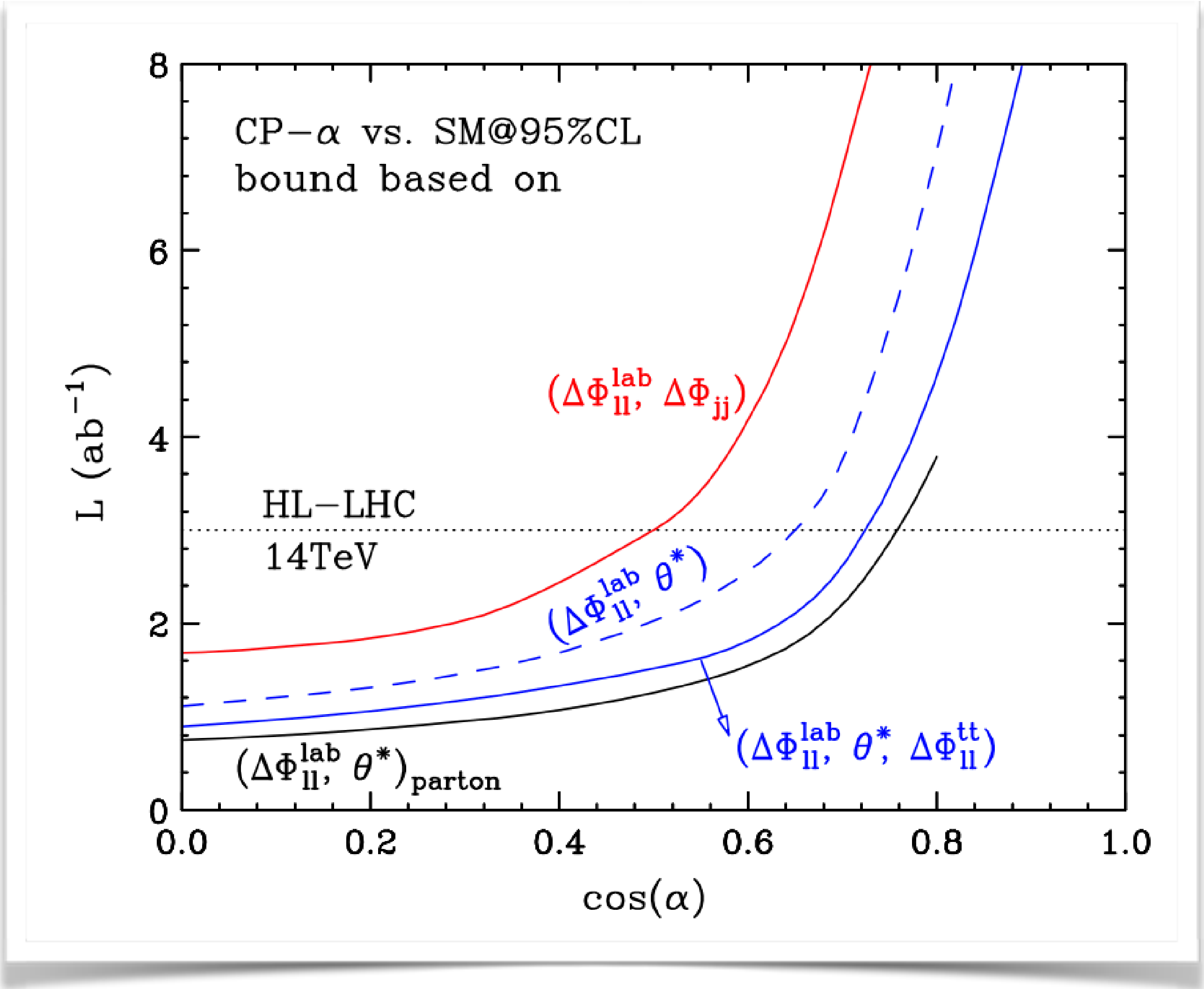
CP-phase	$\mathcal{A}_{\ell\ell}$ (parton-truth)	$\mathcal{A}_{\ell\ell}$ (resolved)	$\mathcal{A}_{\ell\ell}$ (resolved, cut)
$\alpha = \frac{1}{2}\pi$	0.001	0.0005	0.0004
$\alpha = \frac{1}{4}\pi$	0.032	0.021	0.027
$\alpha = 0$	0.001	−0.0002	−0.0005
$\alpha = -\frac{1}{4}\pi$	−0.036	−0.024	−0.031
$\alpha = -\frac{1}{2}\pi$	−0.001	−0.0008	−0.001

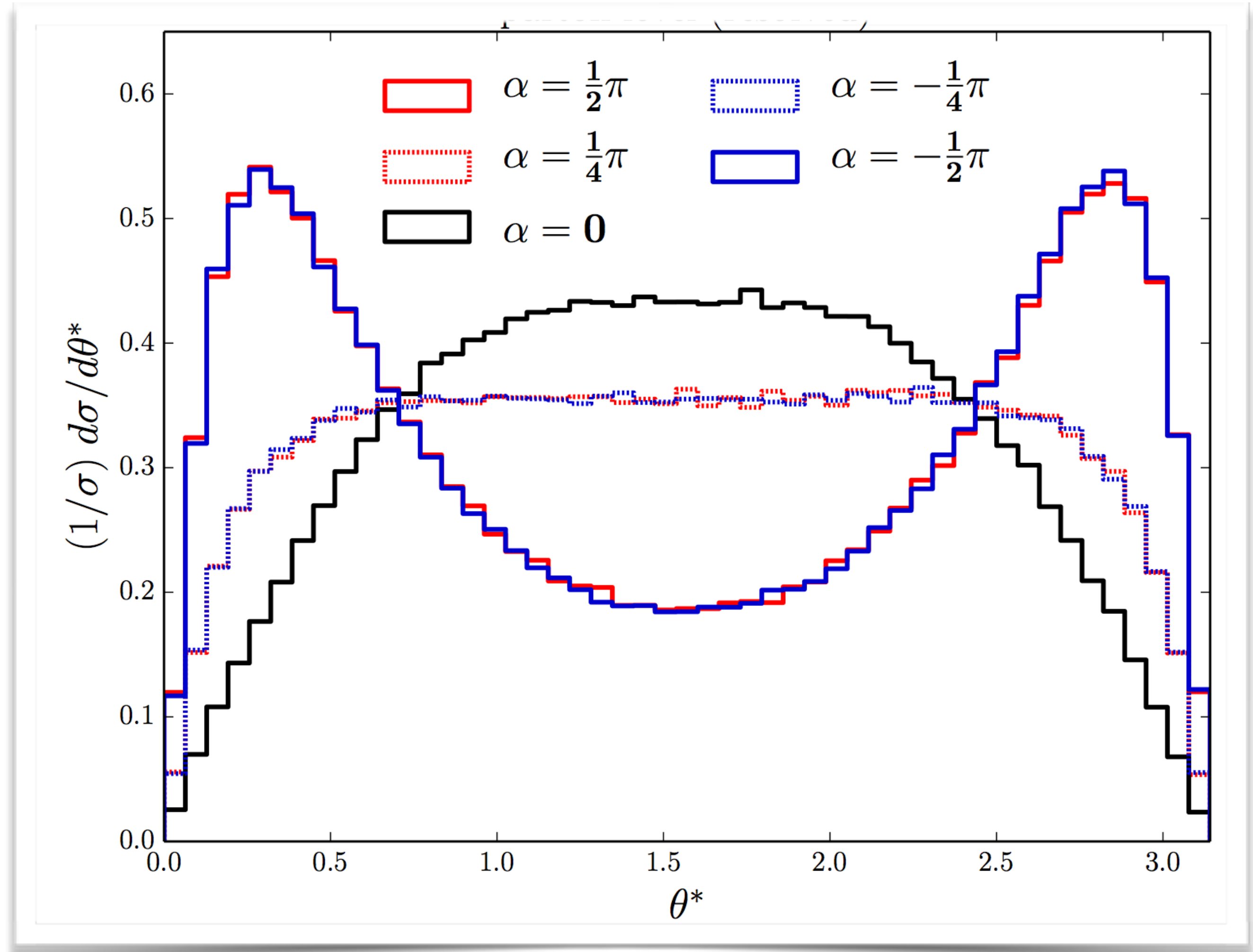
- Additional top mass window cuts make it even better

DG, Kong, Kim (2018)

CPV Higgs-top measurement

- How well can we probe the CP-phase?





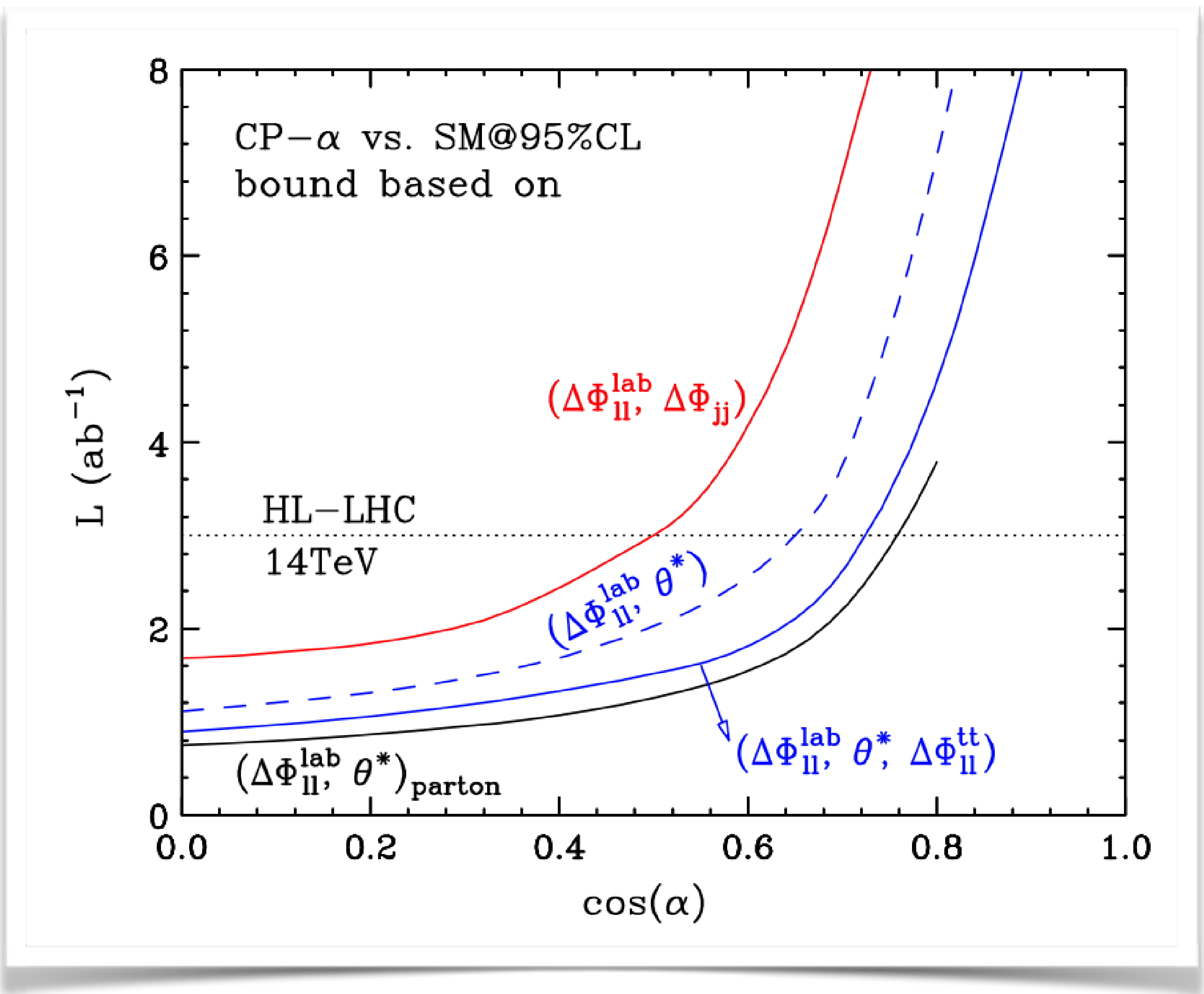
→ At the HL-LHC, we can probe the top Yukawa CP up to cosα=0.7

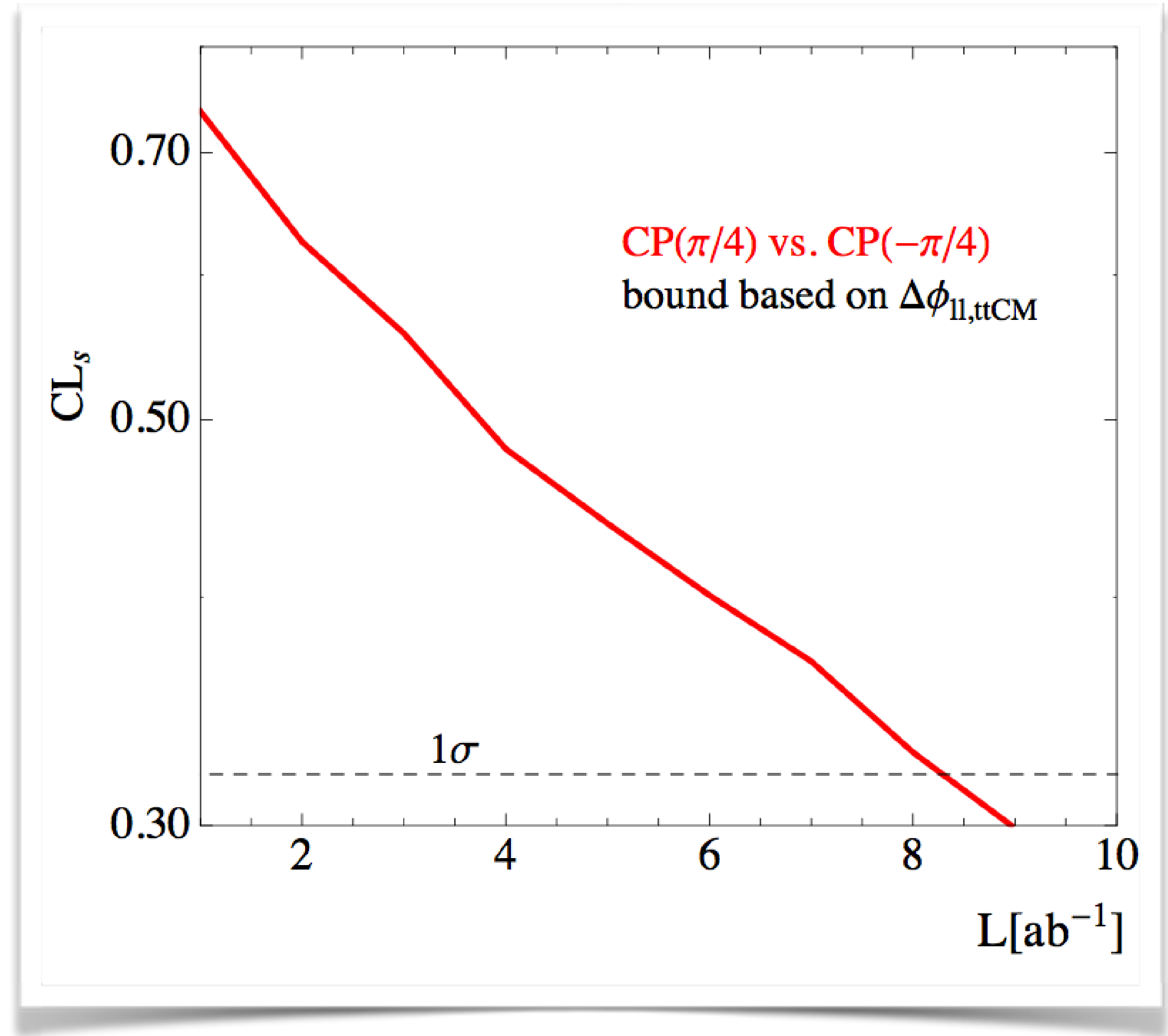
→ New powerful observables can be defined at tt CM frame, e.g, θ*

DG, Kong, Kim (2018)
Dolan, Spanno, Yu (2016)

CPV Higgs-top measurement

- How well can we probe the CP-phase?





→ At the HL-LHC, we can probe the top Yukawa CP up to cosα=0.7

→ CP(α) vs. CP(-α) measurement challenging

DG, Kong, Kim (2018)

Summary

- Higgs-top CP measurement is even more theoretically motivated than standard HVV studies
- Analogously to the Higgs-top signal strength measurement, ttH provides a direct probe Higgs top CP-structure
- Boosted Higgs analysis nicely match with CP-structure measurement
- Theoretical estimation looks encouraging: $\cos\alpha<0.7$ @95CL
- Relevant target for the forthcoming experimental analyses

Thank you for your attention!