Deep Learning Higgs Images

Jeong Han Kim

(Chungbuk Natl. U.)

Based on:

With K.C. Kong, K.T. Matchev, M. Park - [PRL. 122 (2019) 9, 091801]

With M. Kim, K.C. Kong, K.T. Matchev, M. Park - [JHEP 09 (2019) 047]

With L. Huang, S. Kang, K.C. Kong, J. Pi - [JHEP 08 (2022) 114]

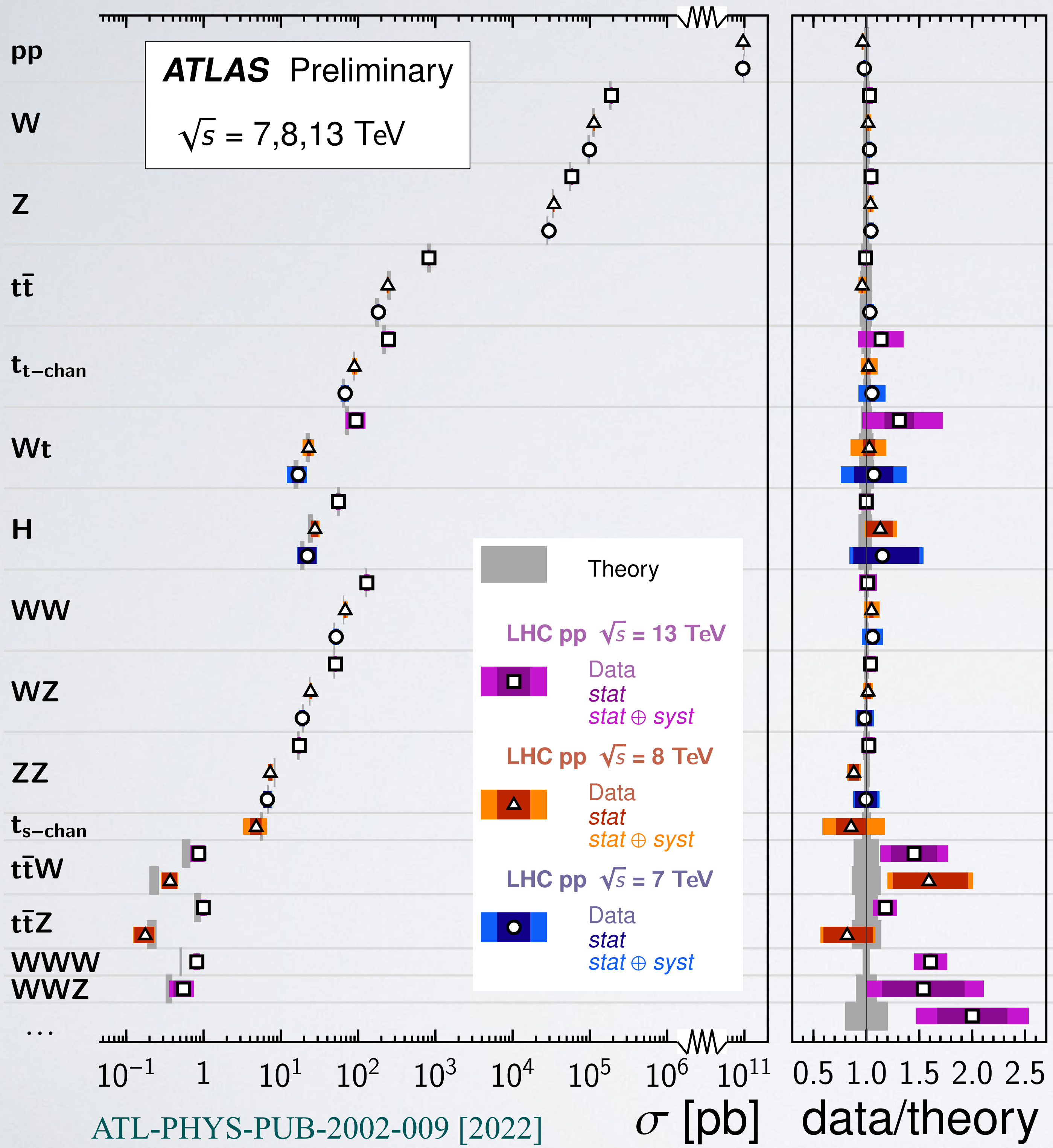
With D. Goncalves, K. C. Kong, and Y. Wu - [JHEP 01 (2022) 158]

With D. Goncalves and K. C. Kong - [JHEP 06 (2018) 079]

Outline

- Motivation & Overview
- Probing the Trilinear Higgs self-coupling at
    1. HL-LHC with Deep Neural Networks
    2. Future Colliders
- Impact of the CP Phase of the Top Yukawa Coupling
    1. How to probe it at the HL-LHC
- Summary

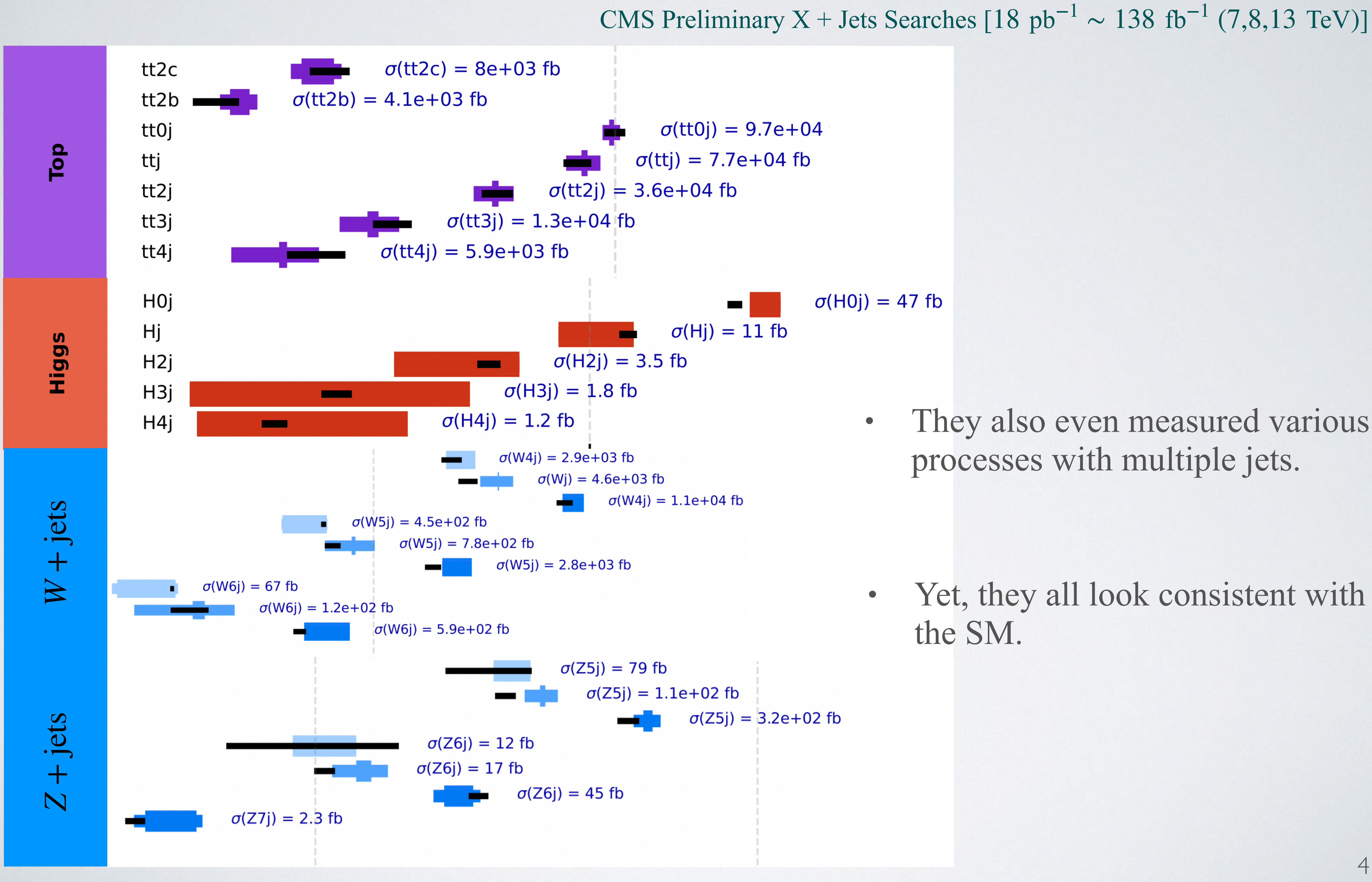
What We Have Found So Far



ATL-PHYS-PUB-2002-009 [2022]

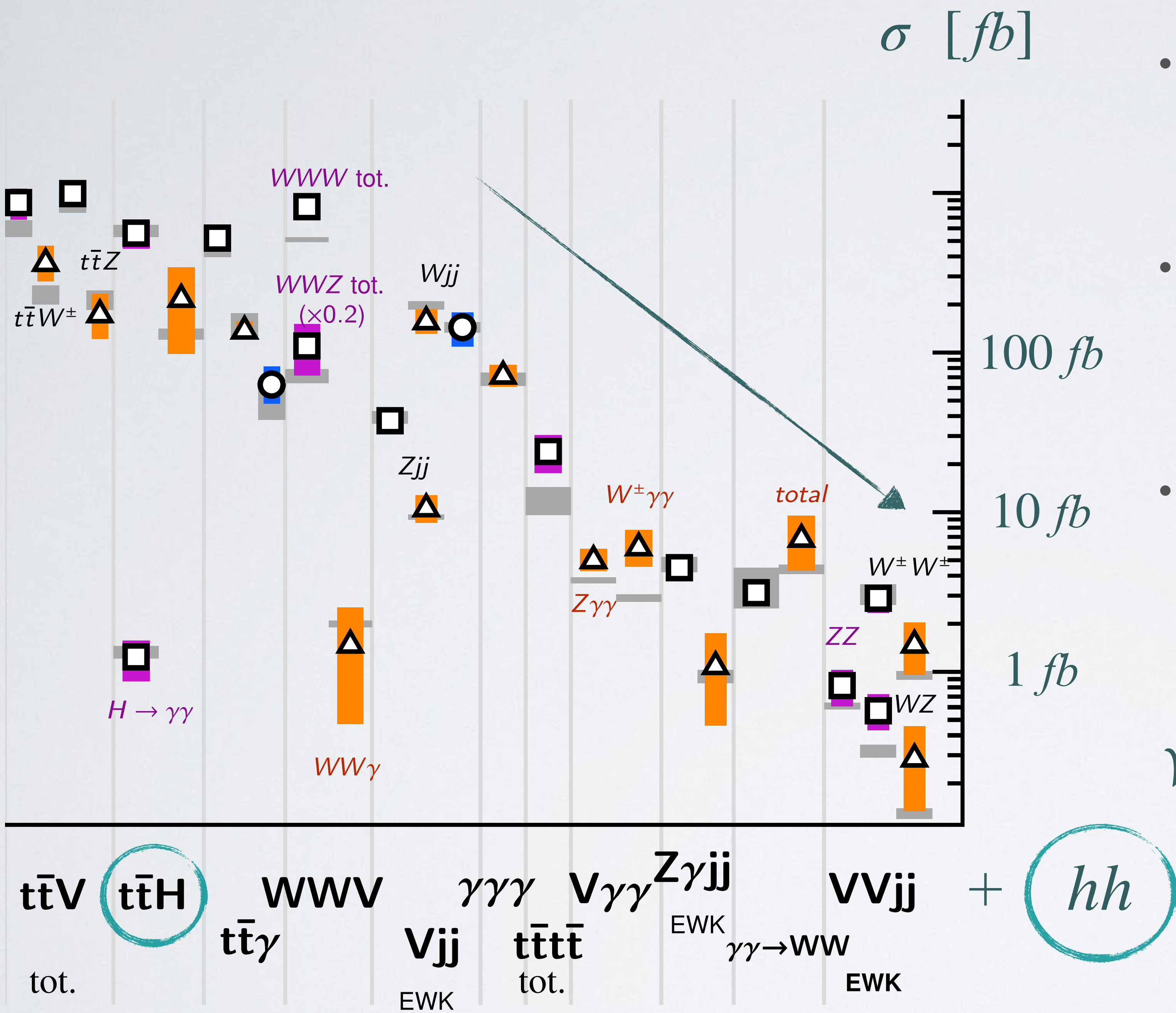
- After a long period of searches at the LHC…
- CMS and ATLAS probed various processes looking for a hint of new physics lurking in the structure of the SM.
- Although we should carefully study their differential distributions…
- If we only take a rate information, measured processes appear to be highly compatible with the SM.

What We Have Found So Far



- They also even measured various processes with multiple jets.
- Yet, they all look consistent with the SM.

What We Have Found So Far

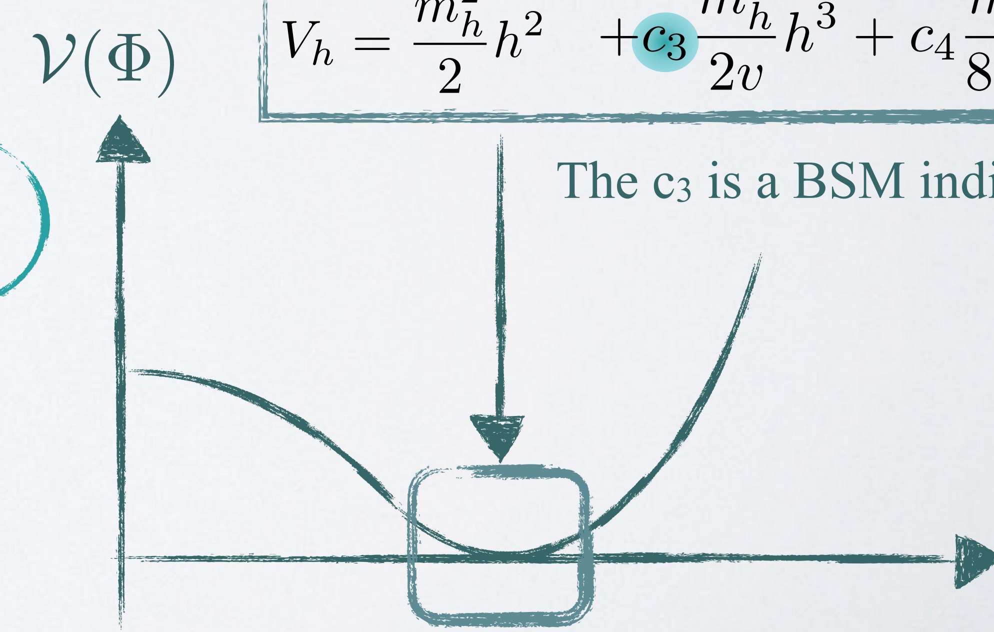


ATL-PHYS-PUB-2002-009 [2022]

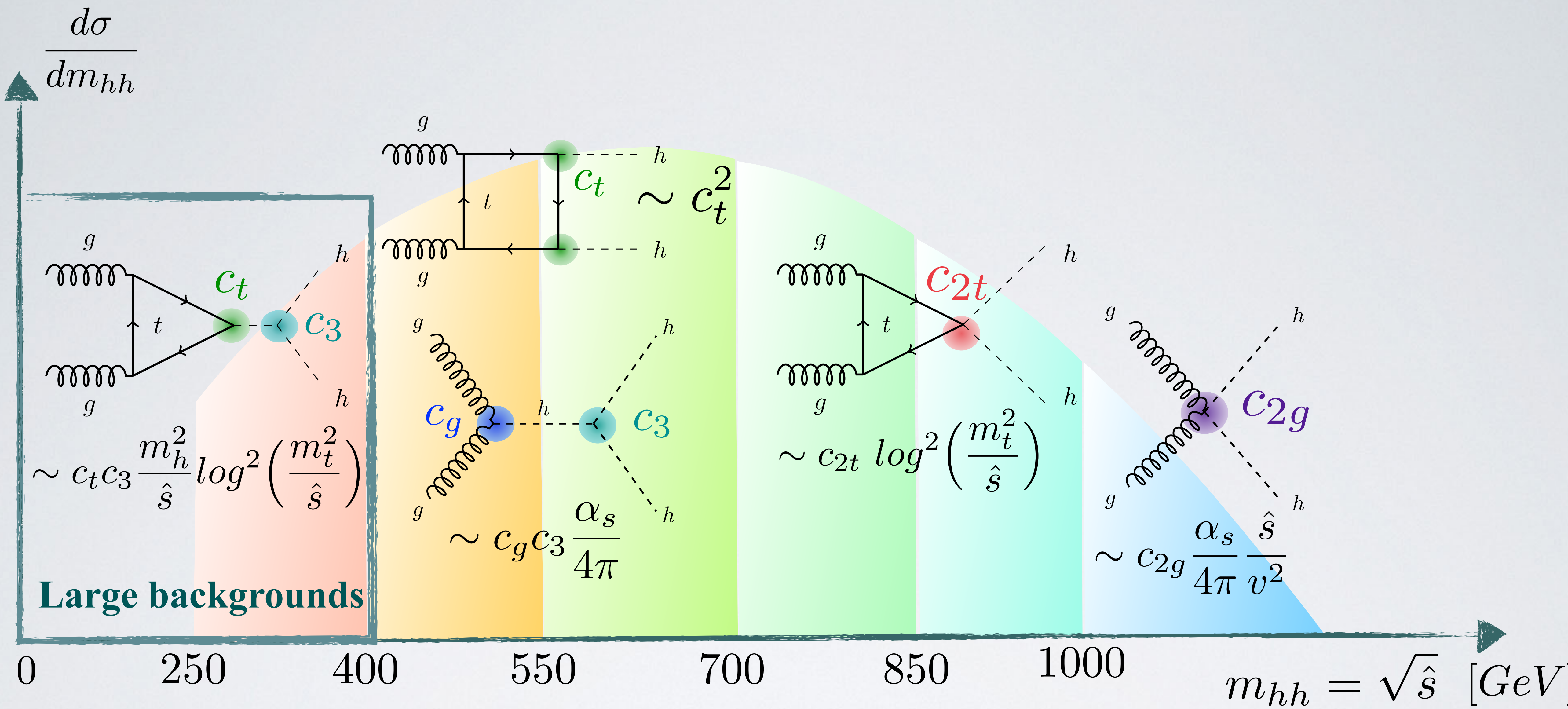
- New physics events are expected to be rare..
- I'll focus on the *hh* production to probe the Higgs trilinear coupling.
- I'll also show how it interferes with the CP phase of top Yukawa coupling.

$$V_h = \frac{m_h^2}{2}h^2 + c_3\frac{m_h^2}{2v}h^3 + c_4\frac{m_h^2}{8v^2}h^4$$

The c_3 is a BSM indicator

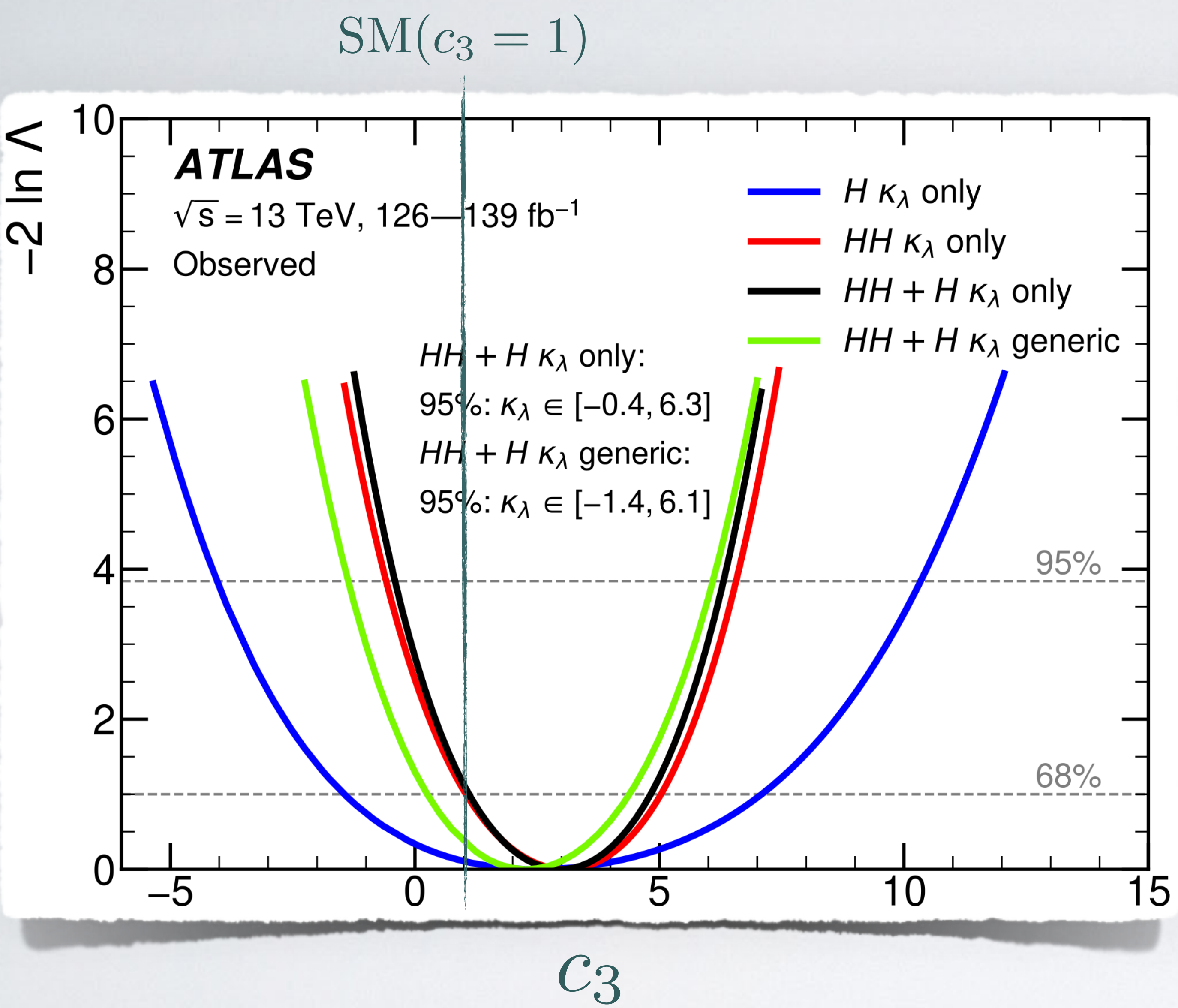


Double Higgs Production

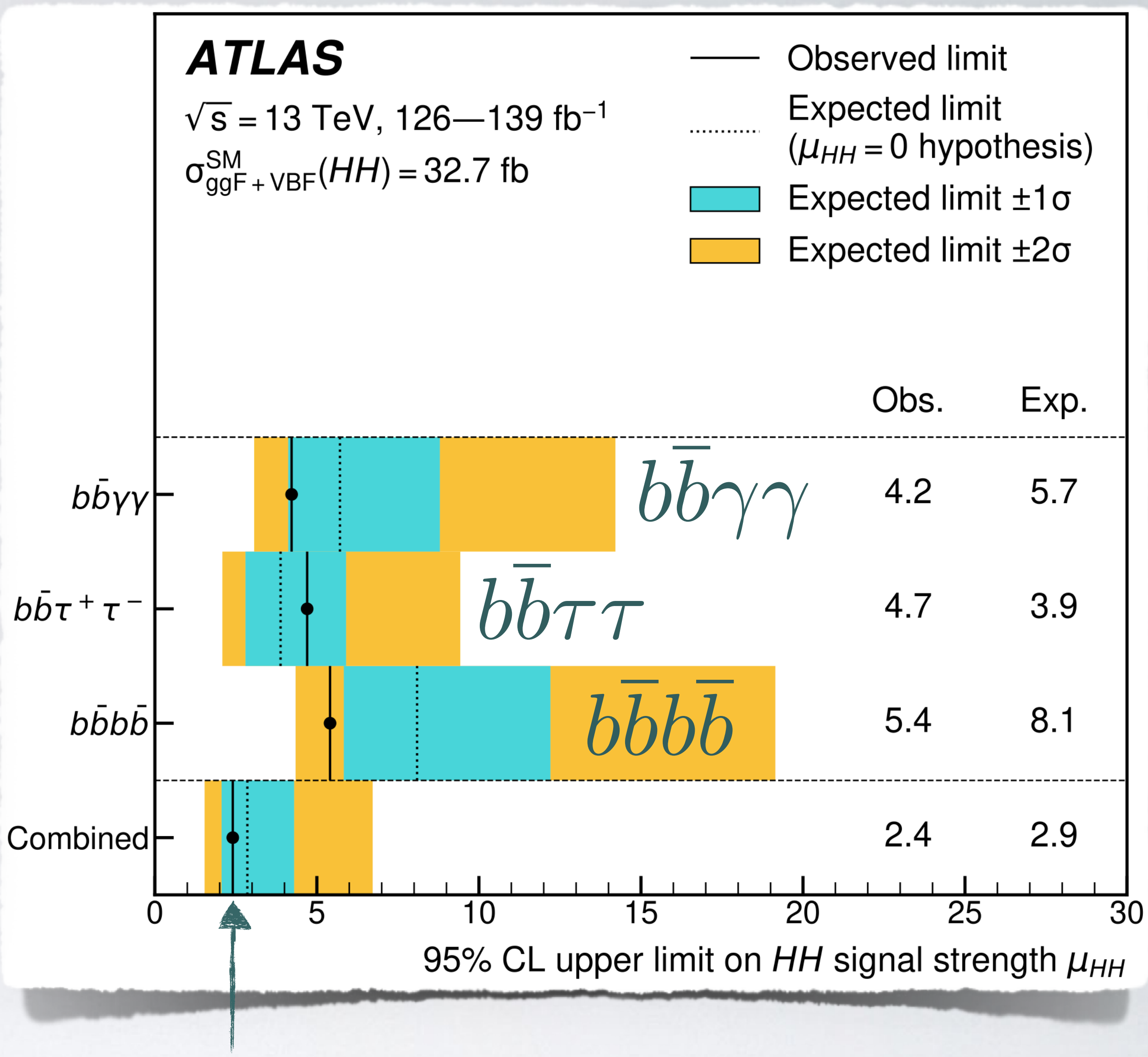


- Amplitudes containing these couplings display different Energy-dependences.
- The triple Higgs self-coupling (c_3) is sensitive at lower-energy bins.
- That's why it's hard to measure!

Current Bound on c_3 @ LHC 13 TeV



[ATLAS] 2211.01216



- 95% probability bound on c_3.

$$-0.4 < c_3 < 6.3$$

- The bound is weak…

- Allowed range of *hh* cross sections.

$$\sigma_{hh}^{\text{observed}} / \sigma_{hh}^{\text{sm}} = 2.4$$

- At least, we may be able to observe the *hh* production at the HL-LHC!

Need to Discover the *hh* Production First…

$3\ \mathrm{ab}^{-1}(14\ \mathrm{TeV})$

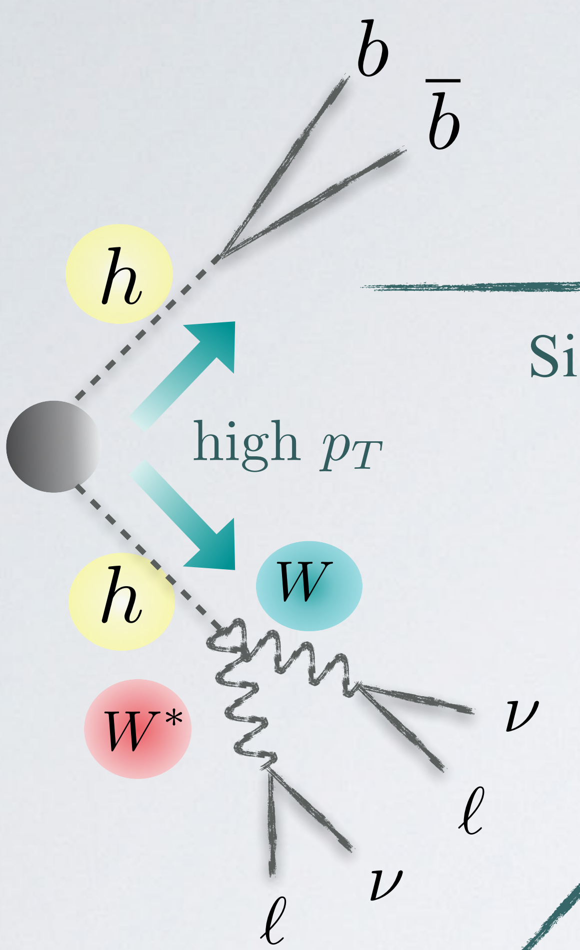
	Channels	Significances	Combined	Combined
ATLAS ATL-PHYS-PUB-2018-053	$bb\gamma\gamma$	2.1	3.5	$c_3 = 1$
	$bb\tau\tau$ (fully-hadronic) + $bb\tau\tau$ (semi-leptonic)	2.5		
	$bbbb$	1.4		
CMS CMS-FTR-18-019-PAS	$bb\gamma\gamma$	1.8	2.8	**4.5**
	$bb\tau\tau$ (fully-hadronic) + $bb\tau\tau$ (semi-leptonic)	1.6		
	$bbbb$	1.2		
	$bbWW^*$ ($\ell\ell\nu\nu$)	0.59		
	$bbZZ^*$ ($\ell\ell\ell\ell$)	0.37		

	bb	WW^*	$\tau\tau$	ZZ^*	$\gamma\gamma$
bb	33%				
WW^*	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ^*	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.1%	0.028%	0.012%	0.0005%

Previously overlooked and less studied

- Since no single channel gives us 5σ , combining channels is essential.
- Recent analyses show that the combined significance is expected to be 4.5σ at the HL-LHC.
- Any potential improvement on the individual channel means a lot to discover the *hh*.

Previously on $hh \rightarrow bbWW^*$



Signal

Low-level variables
(highly correlated)

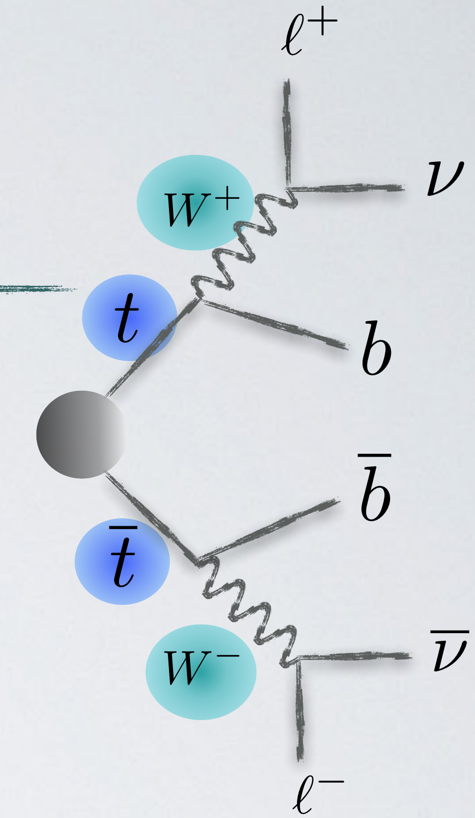
$\not{p}_T$ $\quad p_{T,\ell_1}$ $\quad p_{T,\ell_2}$

$p_{T,bb}$ $\quad p_{T,\ell\ell}$

$\Delta R_{\ell\ell}$ $\quad \Delta R_{bb}$ $\quad \Delta\phi_{bb,\ell\ell}$

$m_{\ell\ell}$ $\quad m_{bb}$

Major
background



Using
Neural
Network

significance $= 0.59\sigma$

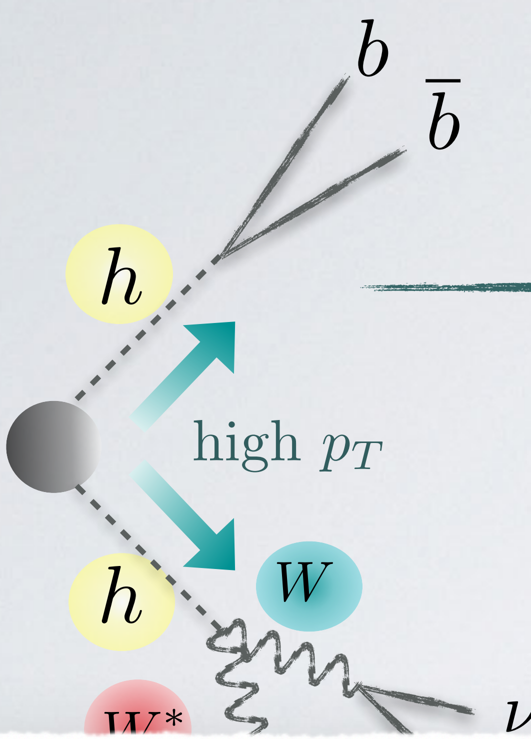
CMS-FTR-18-019-PAS

Combining
high-level
variables

Topness	*Higgsness*
$M_{T2}^{(b)}$	$M_{T2}^{(\ell)}$
$\hat{s}_{min}^{(bb\ell\ell)}$	$\hat{s}_{min}^{(\ell\ell)}$

J. H. Kim, K. C. Kong, K. T. Matchev, M. Park
[PRL 122 (2019) 9, 091801]

Previously on $hh \to bbWW^*$



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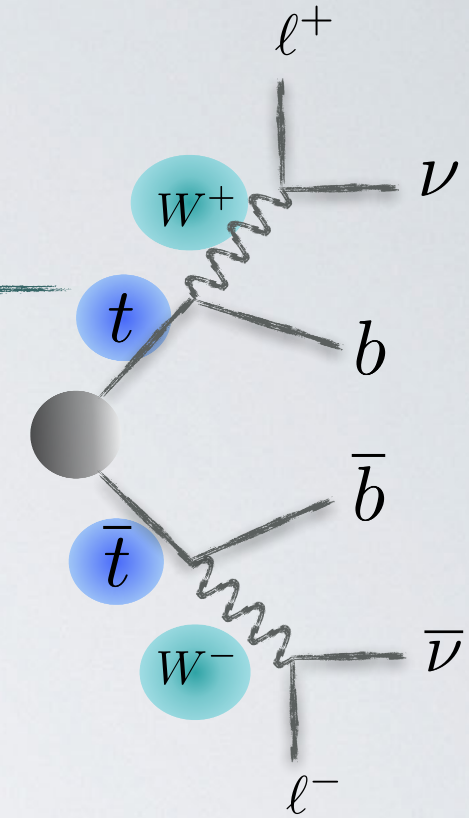
$m_{\ell\ell}$ $\quad m_{bb}$

Major
background



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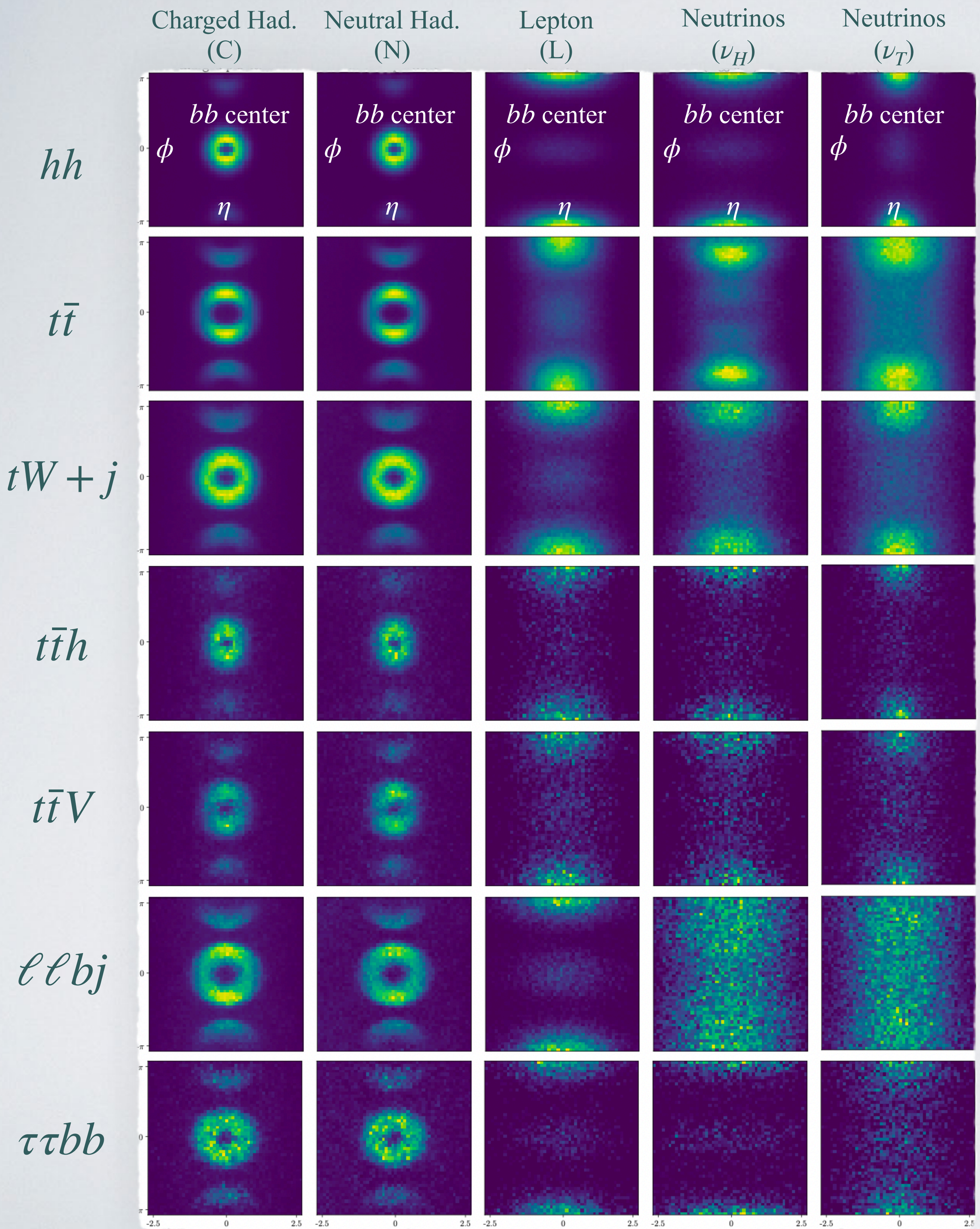
J. H. Kim, K. C. Kong, K. T. Matchev, M. Park
[PRL 122 (2019) 9, 091801]

Higgsness and Topness plots for non-resonant HH production in the single lepton $bbWW$ decay channel

The ATLAS Collaboration

ATL-PHYS-PUB-2019-040

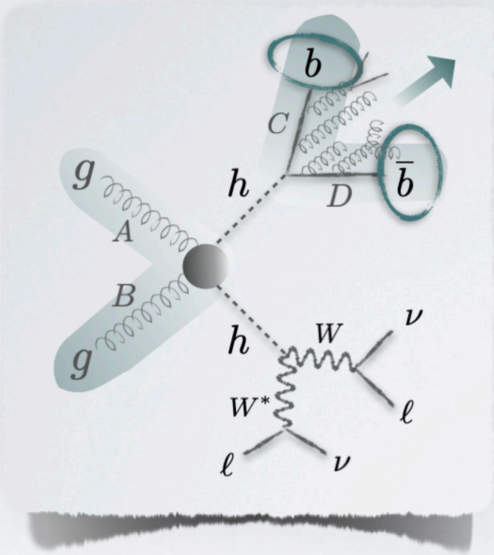
This note presents a set of plots that are intended for non-resonant $HH \to bbWW^*$ single lepton analysis using truth-level information. These plots show interesting new variables named Higgsness and Topness using Monte-Carlo samples for the non-resonant $HH \to bbWW^* \to bbqql\nu$ signal and $t\bar{t} \to bbWW \to bbqql\nu$ background. Also shown is the distribution of the invariant mass of the lepton-neutrino system for the signal sample.

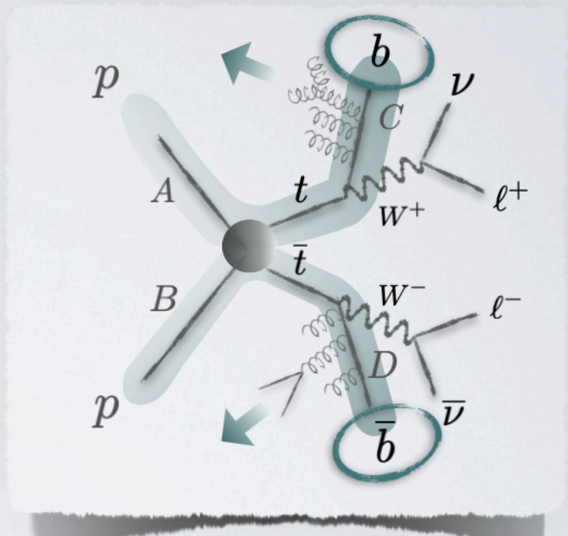


The Di-Higgs Photography

J. H. Kim, M. Kim, K.C. Kong, M. Park [1904.08549]

L. Huang, S. Kang, **J. H. Kim**, K. C. Kong, J. Pi [2203.11951]





Color-flow information is encoded in jet-images

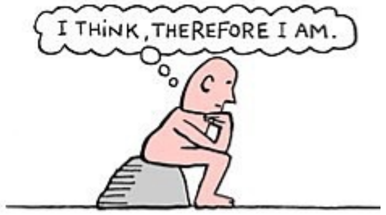
- Apply minimal basic cuts

$$70 < m_{bb} < 140 \text{ GeV}, \;\; \Delta R_{bb} < 2$$

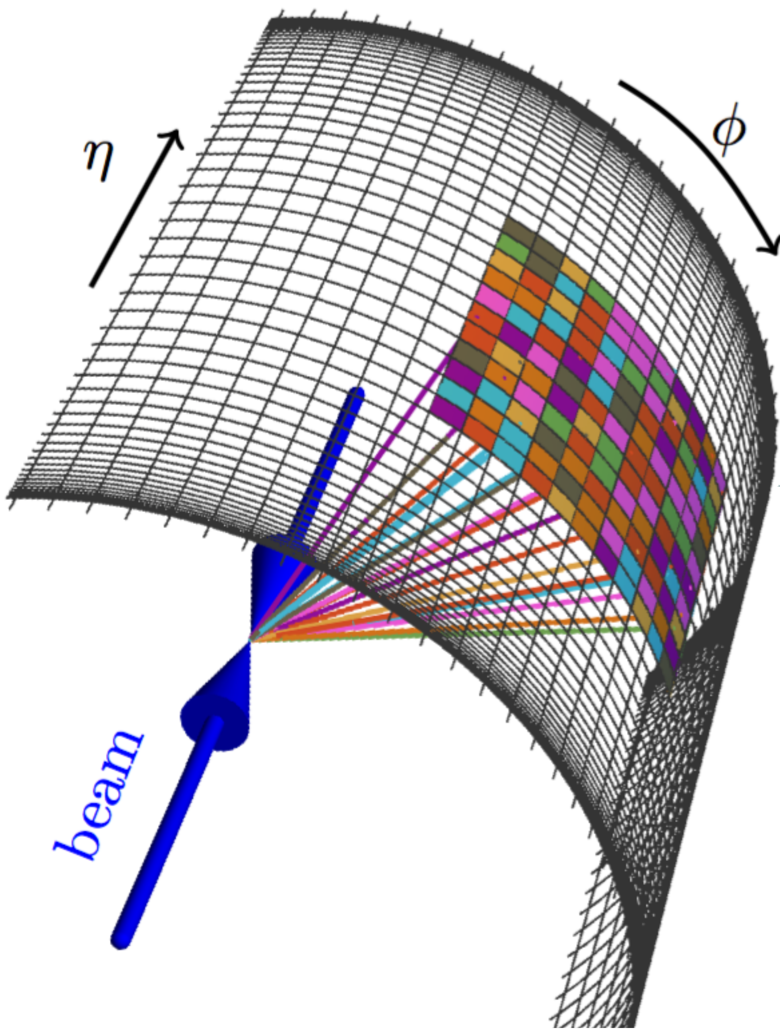
$$m_{\ell\ell} < 70 \text{ GeV}, \;\; \Delta R_{\ell\ell} < 1.5$$

- Let deep neural networks figure out correlations among jets and leptons.

How to Best Utilize Deep Neural Nets?



- What type of input is most suitable?
- What is the best neural network?



Basic Reconstructions

$70 < m_{bb} < 140$ GeV

$m_{\ell\ell} < 70$ GeV

$\Delta R_{\ell\ell} < 1.5$

$\Delta R_{bb} < 2 \quad \cdots$

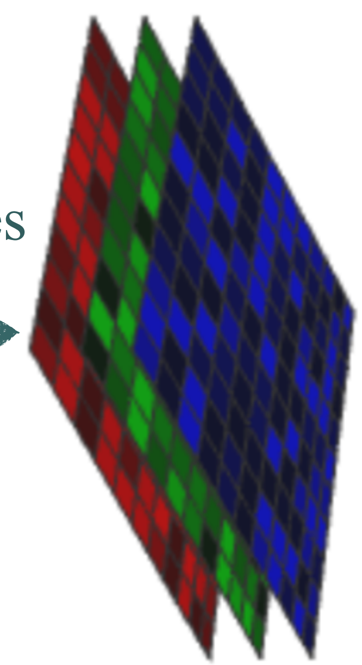
Low-level kinematic variables

$\not{p}_T \quad p_{T,\ell_1} \quad p_{T,\ell_2}$

$p_{T,bb} \quad p_{T,\ell\ell} \quad m_{\ell\ell} \quad m_{bb}$

$\Delta R_{\ell\ell} \quad \Delta R_{bb} \quad \Delta\phi_{bb,\ell\ell}$

Images



Four-momenta

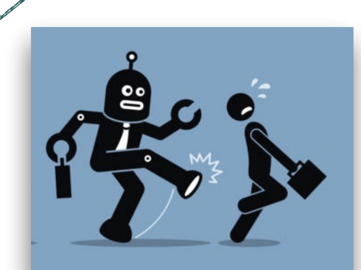
$p(b_1)\ p(b_2)\ p(\ell_1)\ p(\ell_2)$

$p(\nu_1)\ p(\nu_2)$

High-level kinematic variables

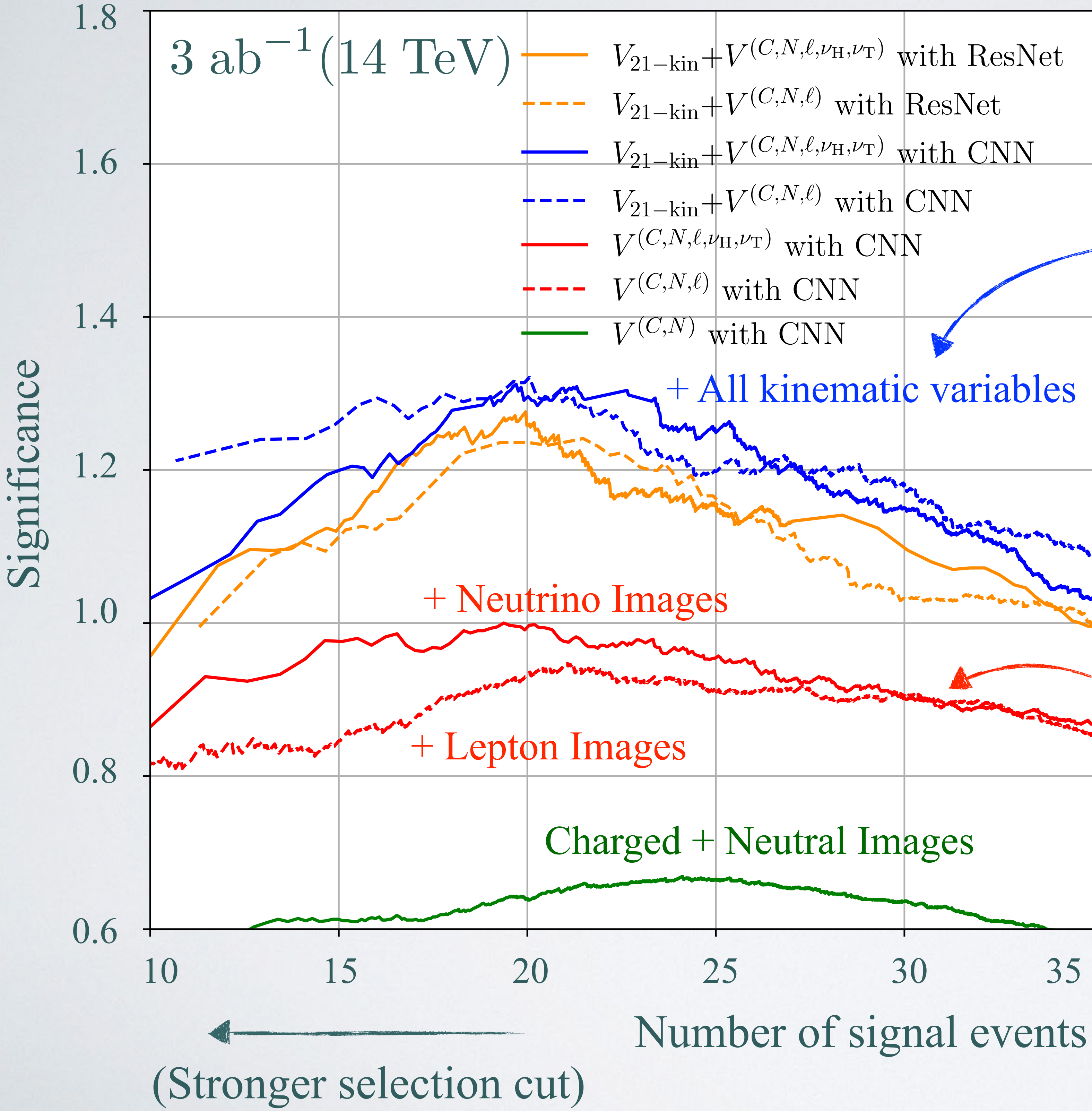
$Topness \quad Higgsness$

$M_{T2}^{(b)} \quad M_{T2}^{(\ell)} \quad \hat{s}_{min}^{(bb\ell\ell)} \quad \hat{s}_{min}^{(\ell\ell)}$



Traditional Convolutional Neural Networks (CNN)

L. Huang, S. Kang, **J. H. Kim**, K. C. Kong, J. Pi [2022]



- The best performance comes when we combine the image information and kinematic variables.
- The neural net can efficiently learn from the human engineered variables, while taking additional color-flow information from the image data.
- This implies that the usage of high-level kinematic variables is still important.

Projected Sensitivities at the HL-LHC

It didn't include important backgrounds such as tW

Channel	Statistical only	
	ATLAS	CMS
$hh \to b\bar{b}b\bar{b}$	1.4	1.2
$hh \to b\bar{b}\tau^+\tau^-$	2.5	1.6
$hh \to b\bar{b}\gamma\gamma$	2.1	1.8
$hh \to b\bar{b}VV(\ell\ell\nu\nu)$ Previous result	-	0.59
$hh \to b\bar{b}ZZ(4\ell)$	-	0.37
combined	3.5	2.8
Significance:	combined 4.5	
combined with the new results on $hh \to b\bar{b}VV(\ell\ell\nu\nu)$ in this study	3.8	3.0
Significance:	combined 4.8	

$\to$ 1.3σ

(factor of 2 improvement)

- Any potential improvement on the individual channel may be able to pin down hh.

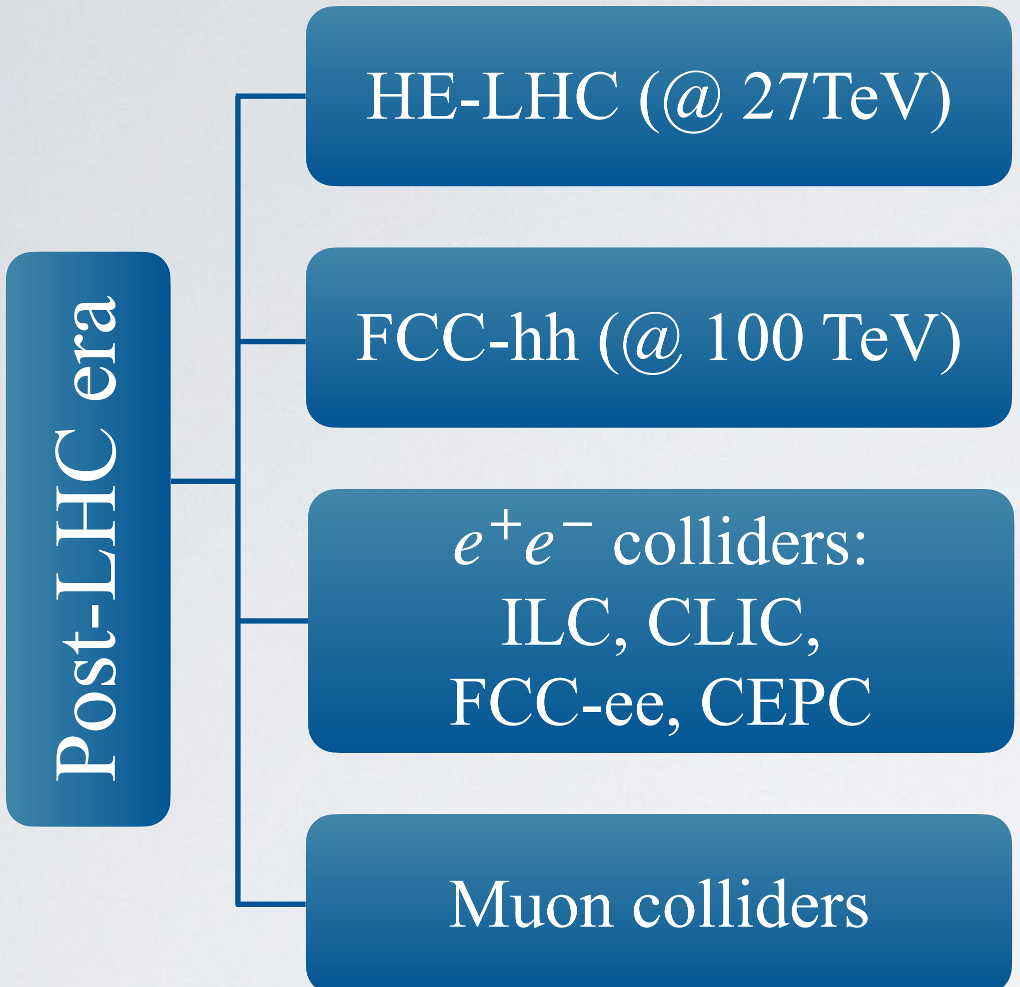
- HL-LHC could offer a sufficiently accurate determination of c_3 .

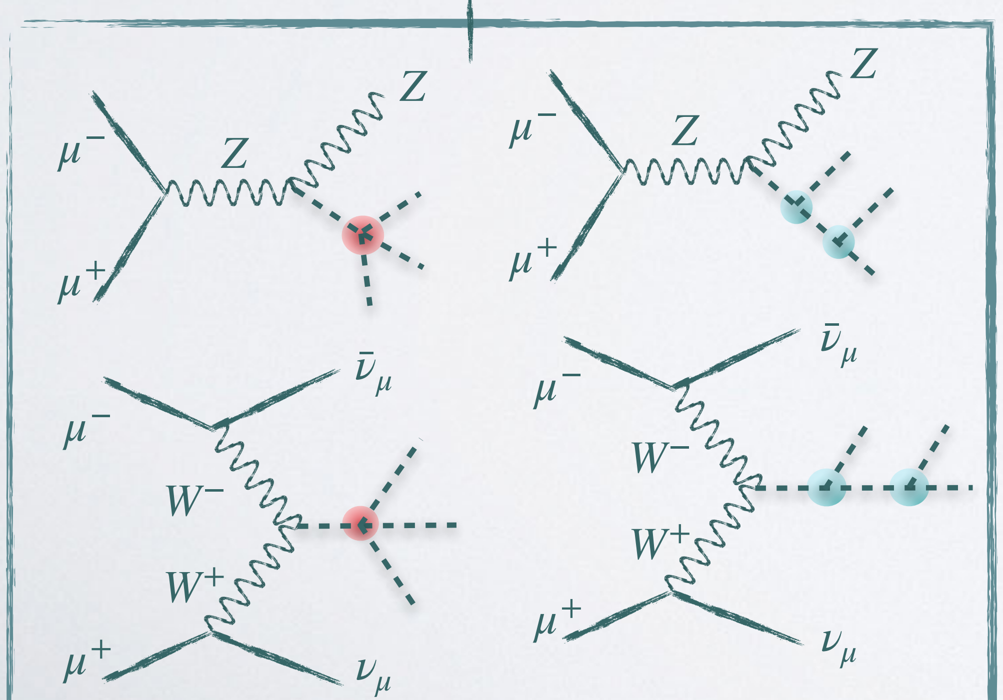
$0.5 < c_3 < 1.5$ [68% probability bound] $\longrightarrow$ $\delta c_3 = 0.5$

$0.1 < c_3 < 2.3$ [95% probability bound]

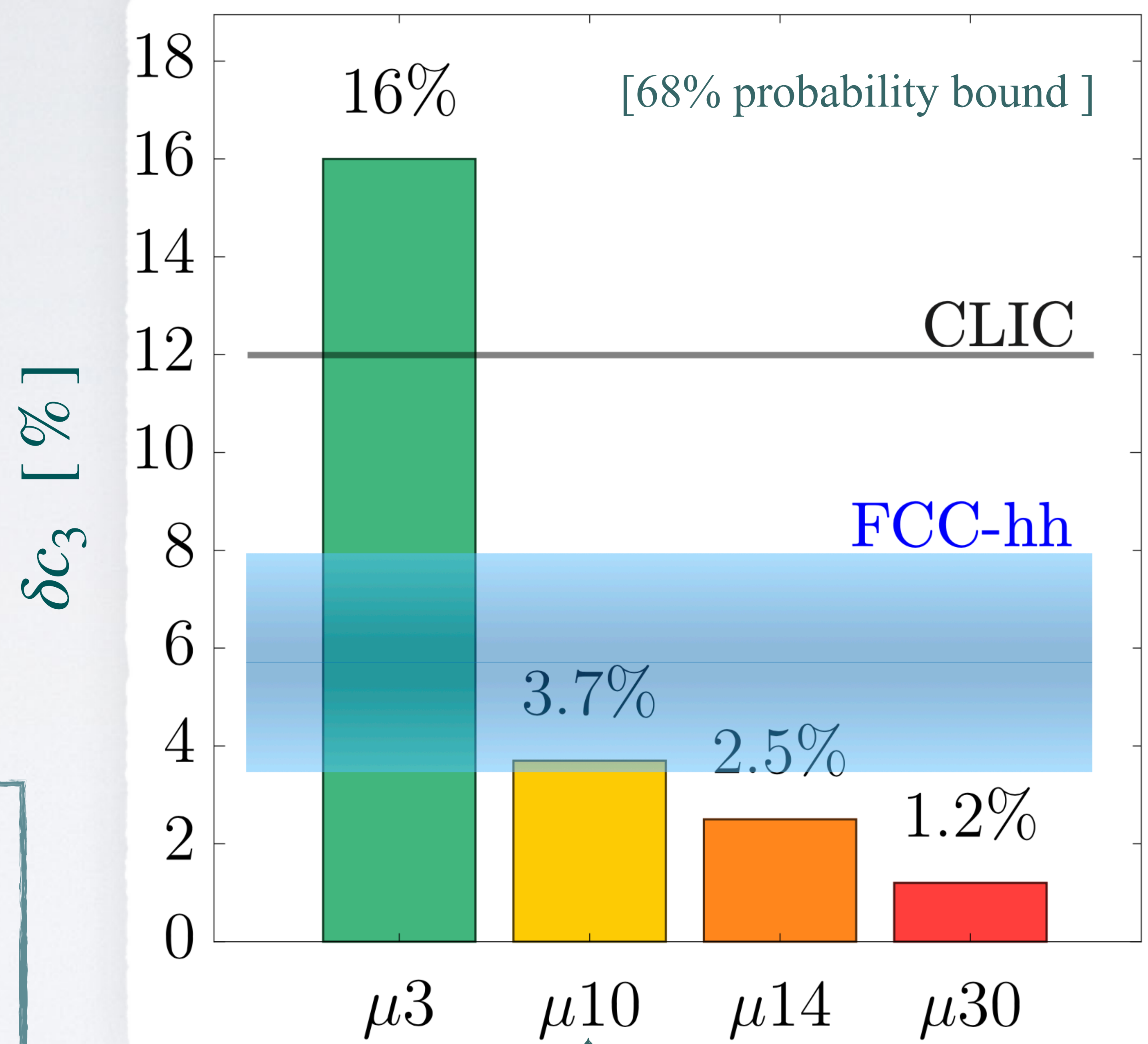
Report from Working Group 2 [1902.00134]

Post-LHC Era: Where Do We Head For?





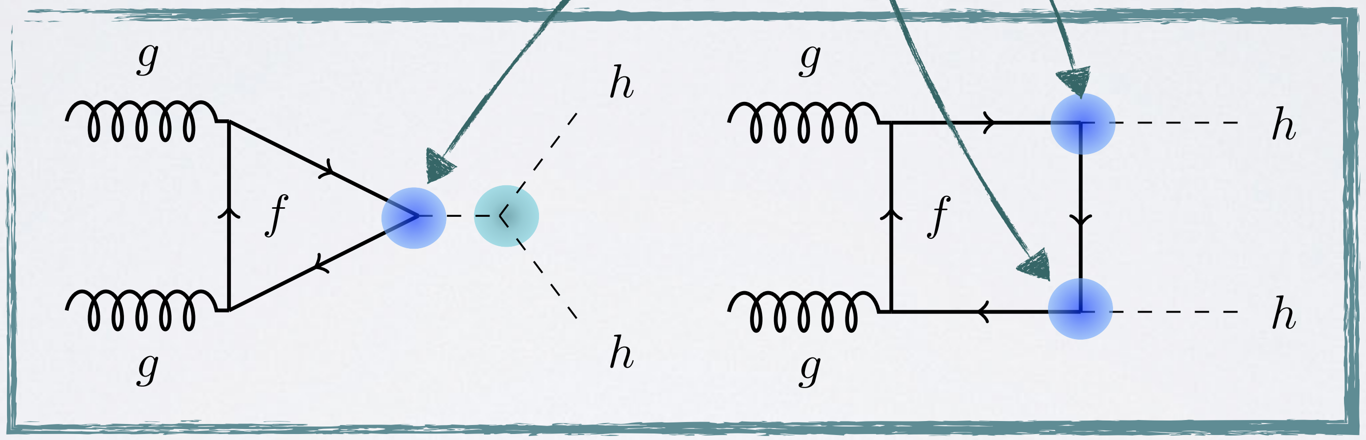
Accettura et al. [2303.08533]



10 TeV muon collider

The CP Phase of Top Yukawa Coupling As a Stepping Stone

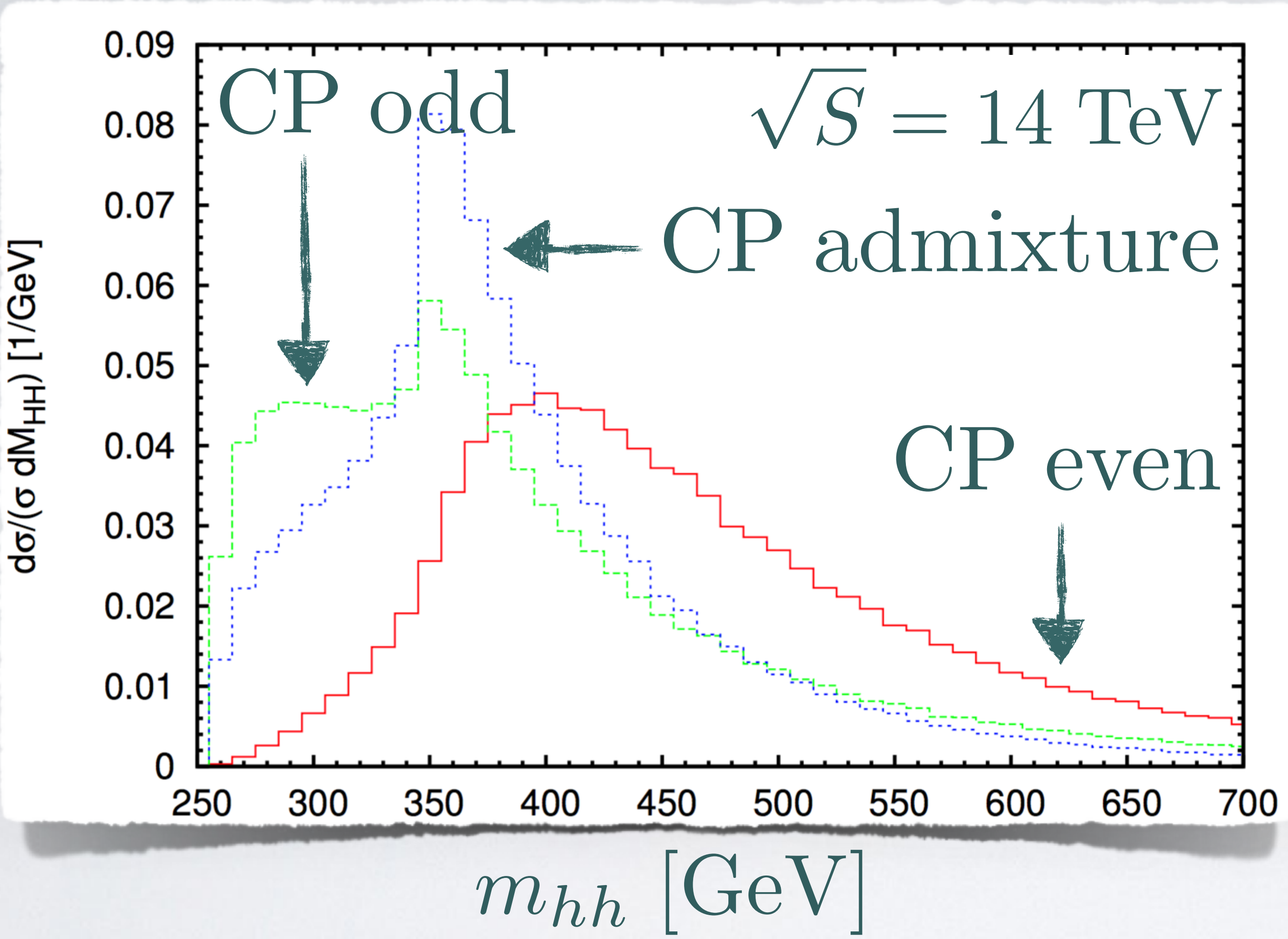
$$\mathscr{L} \supset -\frac{m_t}{v} c_t \, \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) th$$

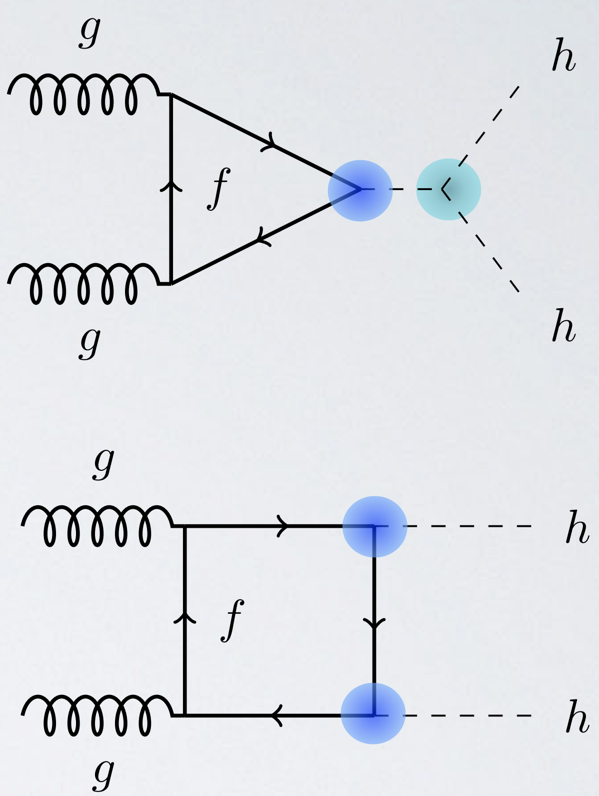


- We often underestimate the presence of the top Yukawa which appears everywhere.
- The Higgs-top coupling is an indispensable ingredient to understand EWSB.
- Its CP phase can be a source to explain the matter-antimatter assymmetry.

Impact of the CP Phase of Top Yukawa Coupling

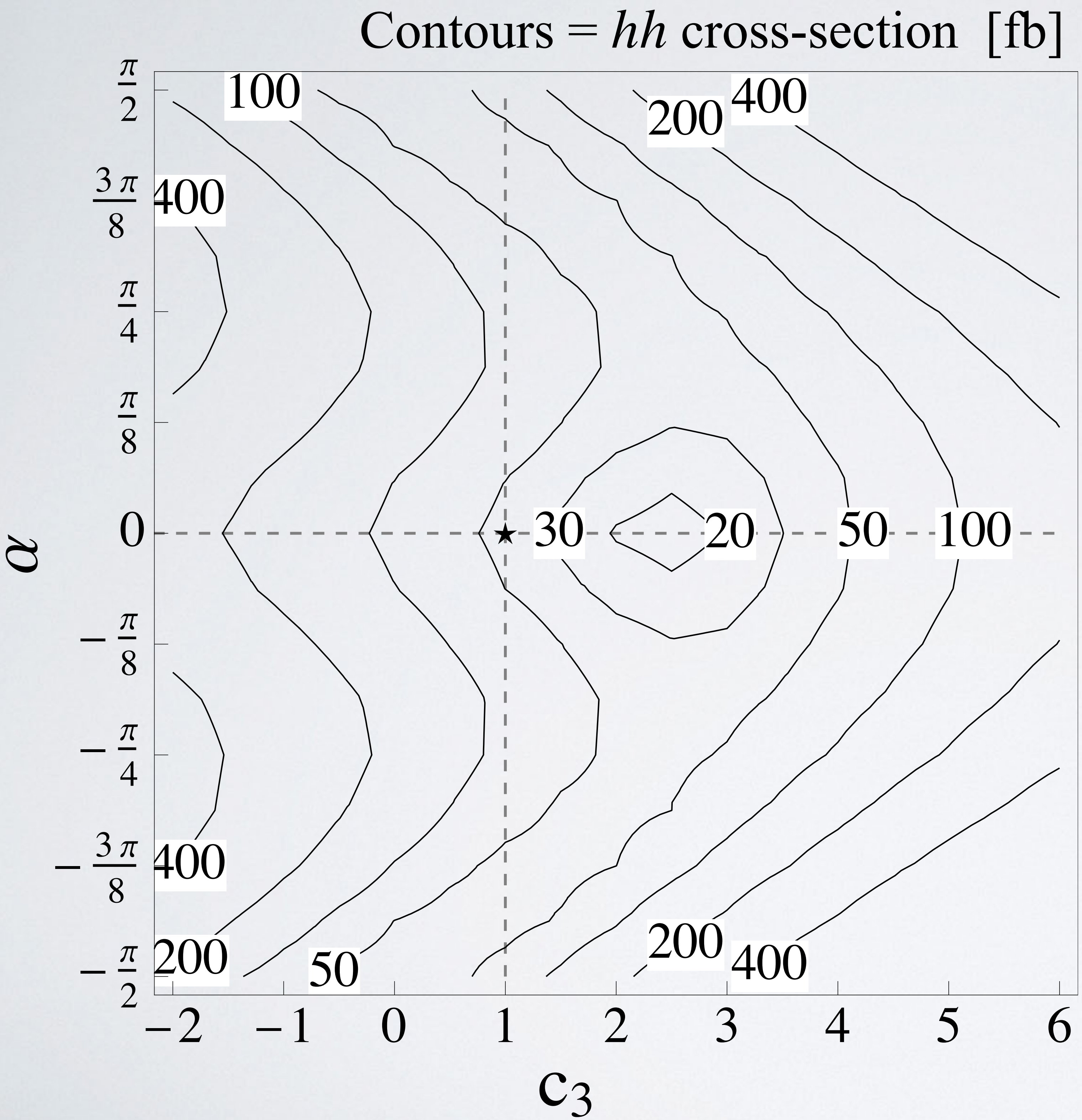
K. Nishiwaki, S. Niyogi, A. Shivaji [2014]





- Recall constructive and destructive interferences in double Higgs.
- It is well-known that the CP phase can significantly distort the m_{hh} distribution.
- This will significantly chage the kinematics of the Higgs productions that we assumed.

Impact of the CP Phase of Top Yukawa Coupling

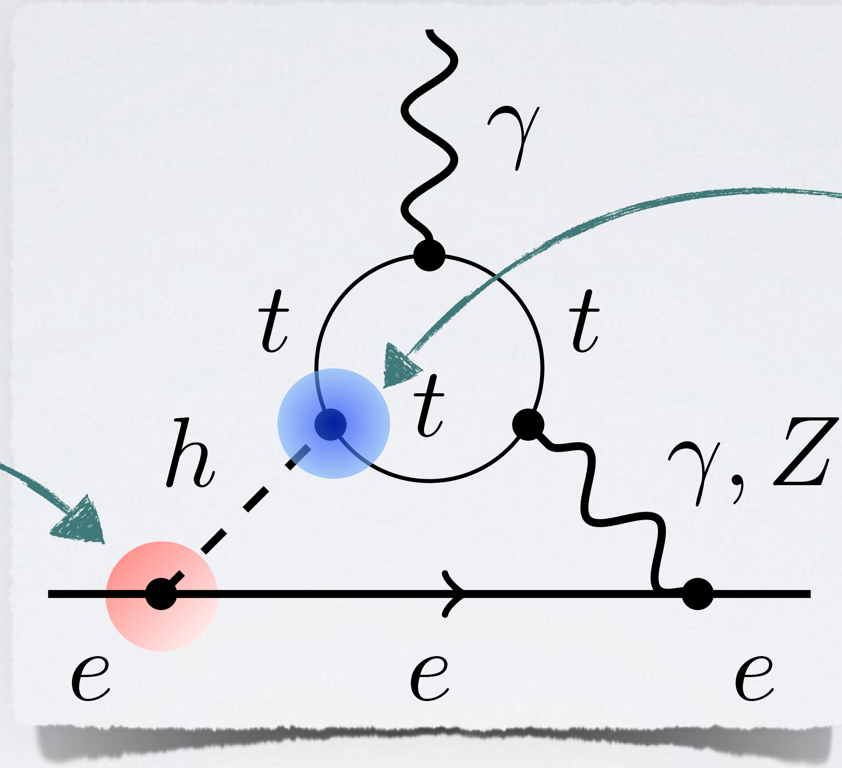


- It has a direct impact on the *hh* production.
- This is why the precise knowledge on this coupling is important.

$$\mathscr{L} \supset -\frac{m_t}{v} c_t \, \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha \right) th$$

Indirect non-LHC constraints

J. Brod, U. Haisch, J. Zupan [2013]



assumptions

2σ bound

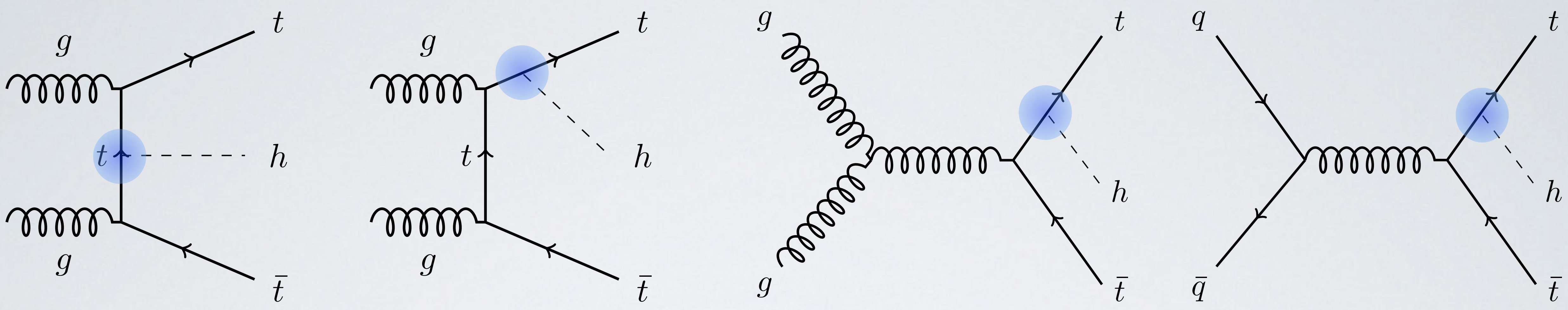
$$|c_t \sin\alpha| < 0.01$$

(If $c_t = 1$)

$$\alpha = \left[-0.6^\circ, 0.6^\circ\right]$$

- There are also indirect non-LHC constraints from electron dipole-moment (EDM) measurements.
- The bound looks very constraining.
- But the critical assumption is that the Higgs interactions with first-generation fermions must be exactly the SM one.
- So again, its interpretation is model-dependent.

Direct LHC constraints



- The direct way to probe the Higgs-top coupling is the $t\bar{t}h$ production.
- The cross section is higher than the *th* channel: $\sigma_{\rm NLO}(t\bar{t}h) = 611$ fb $\quad \sqrt{S} = 14$ TeV
- It provides a rich spectrum of final states.
- Motivated by relatively recent observations for the $t\bar{t}h$ signals

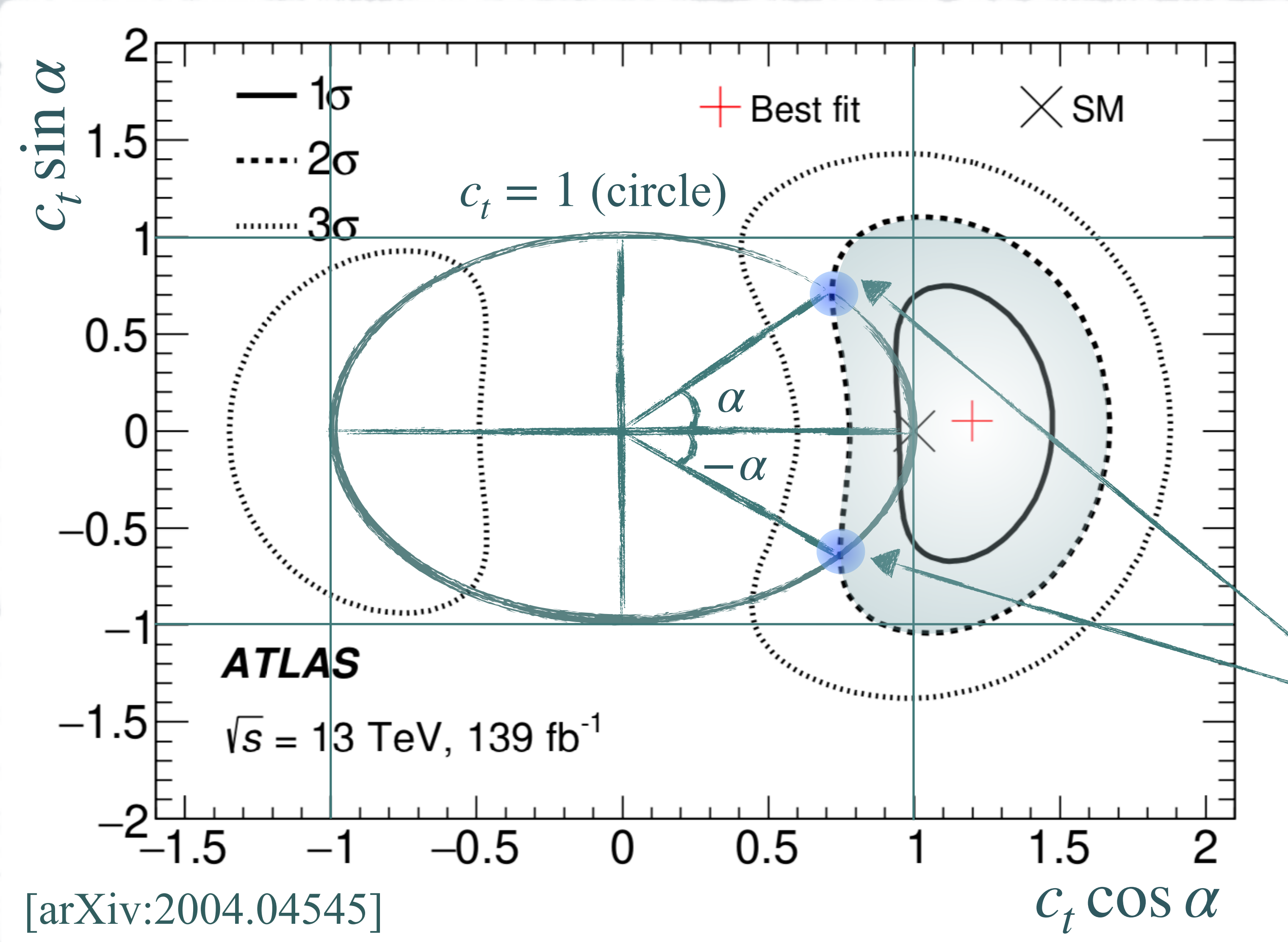
(Background only hypothesis)

$\boxed{5.2\sigma \text{ (observed)}}$ Phys.Rev.Lett. 120 (2018) 23 [CMS]

$\boxed{6.3\sigma \text{ (observed)}}$ Phys.Lett.B 784 (2018) 173-191 [ATLAS]

Current Bounds on the CP Phase

13 TeV $(139\ \mathrm{fb}^{-1})$ $t\bar{t}h(\to\gamma\gamma)$



[arXiv:2004.04545]

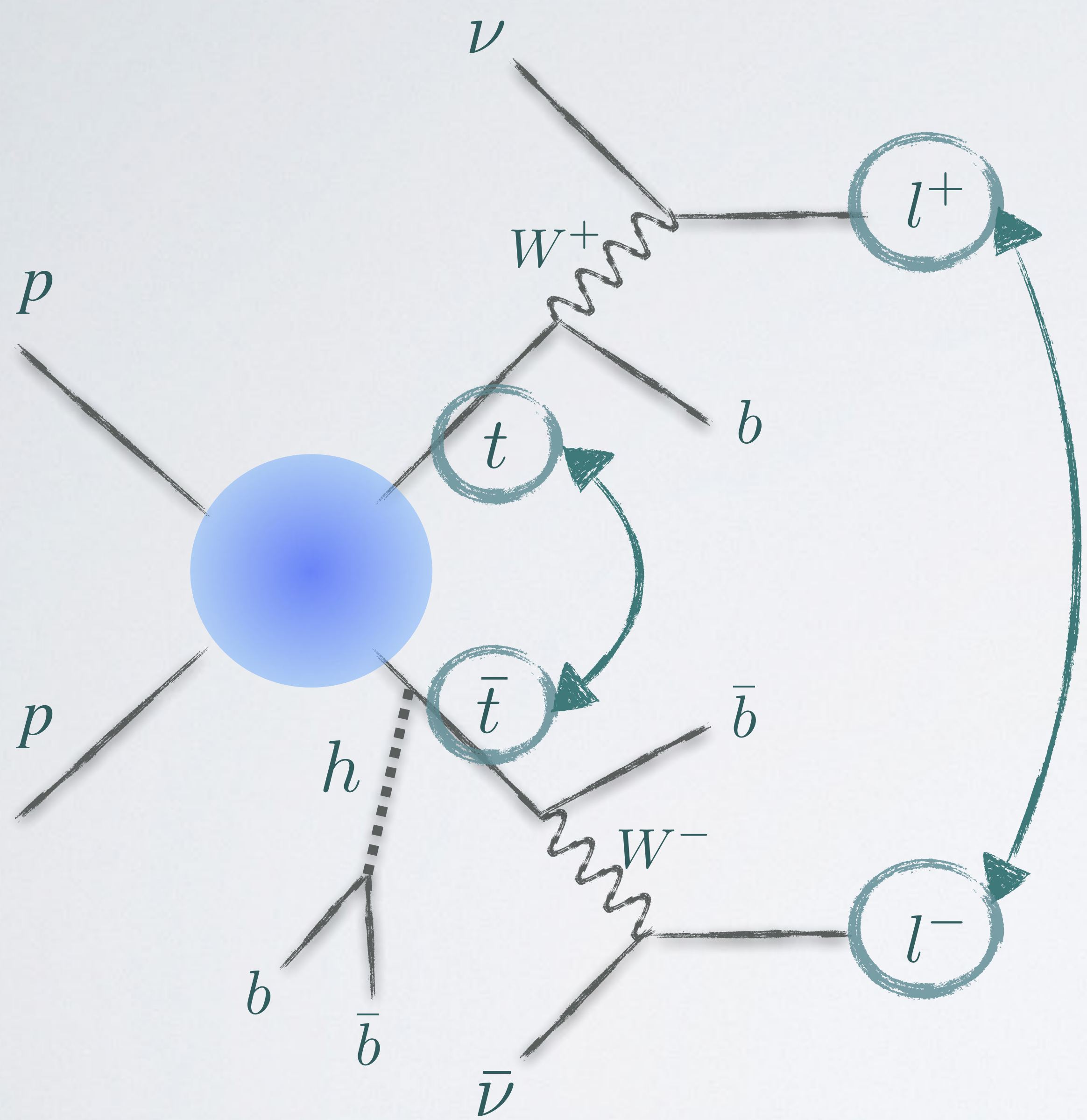
- As more data is collected, they are able to utilize differential information.
- The direct measurement on the CP phase is relatively new.
- For fixed $c_t = 1$ we find

$$\alpha = \left[-43^\circ, 43^\circ\right] \qquad (2\sigma \text{ bound})$$

$$\mathscr{L} \supset -\frac{m_t}{v} c_t \, \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\, th$$

- Note that the pure CP odd case seems to be very excluded.

How Precisely Can We Probe CP-Phase?

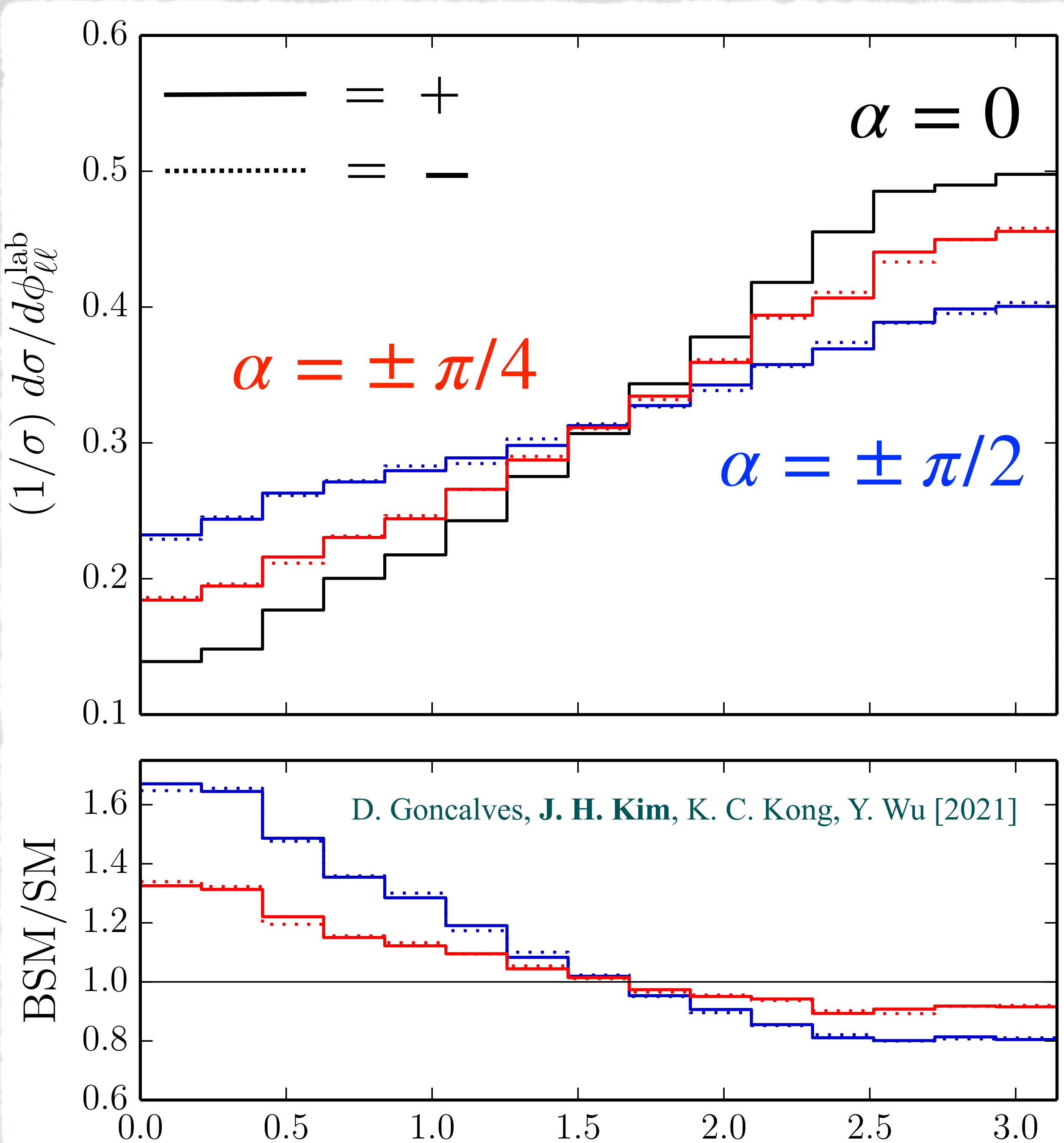


- The Higgs-top CP structure affects the $t\bar{t}$ spin correlation, that can propagate to the top decay products.
- Since charged leptons are the best spin analyzers, it's best to look at dileptonic top decays.
- But the spin-correlation effects are directly accessible in the $t\bar{t}$ rest frame.

If we can fully reconstruct $\mathrm{t\bar{t}}$

What are useful observables?

14 TeV (detector-level)

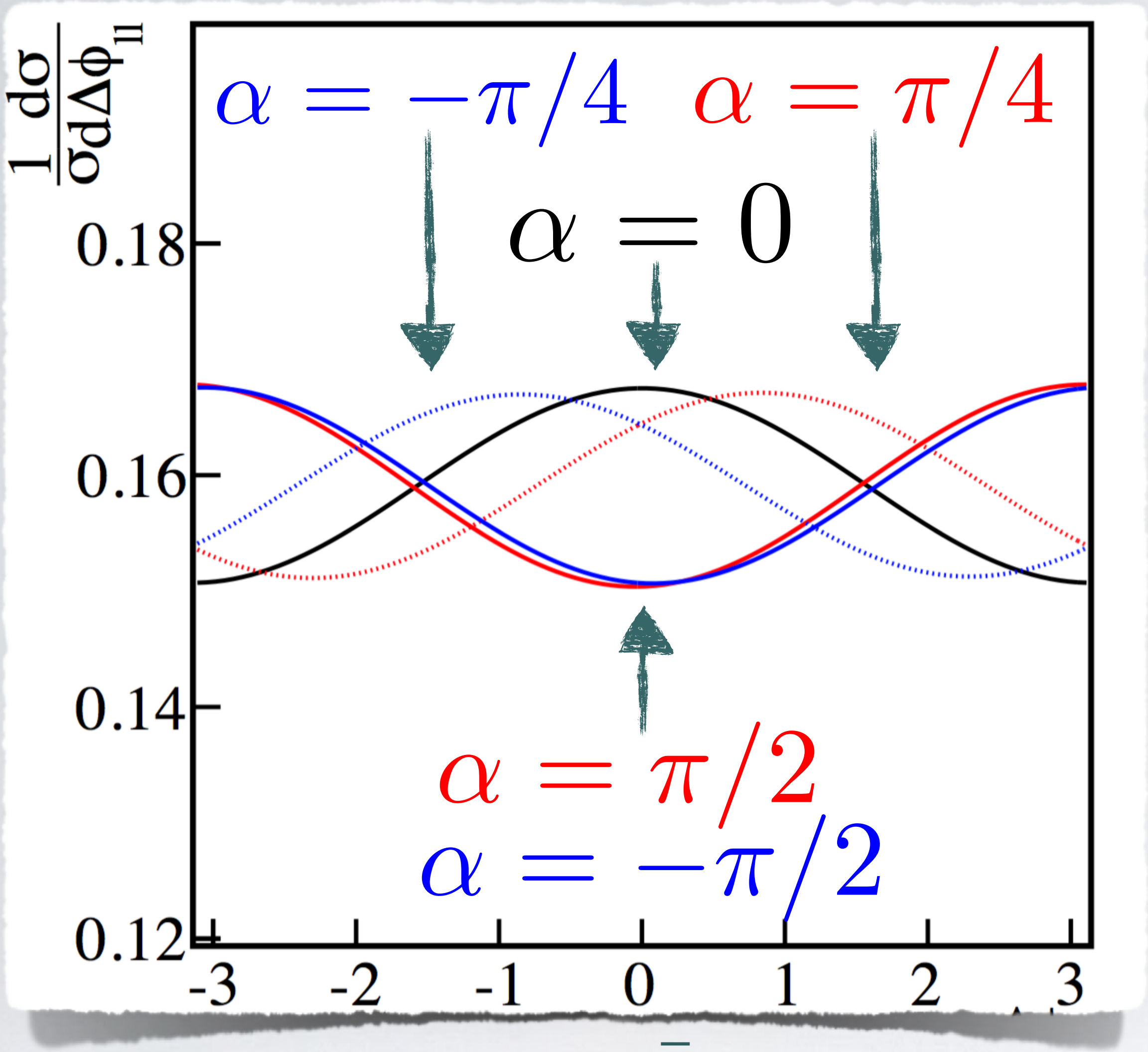


$\Delta\phi_{\ell\ell}^{\rm lab}$

- $\Delta\phi_{\ell\ell}^{\rm lab}$ in the lab-frame provides a good probe of spin-correlation effect.
- A clean distinction between a pure CP odd and even states.
- It's not sensitive to a sign of α.

$t\,\bar{t}$ - rest frame observables

J. Ellis, D. S. Hwang, K. Sakurai, M. Takeuchi [2014]



$\Delta\phi_{\ell\ell}^{t\bar{t}}$

14 TeV (parton-level)

(using truth information)

- The direct sensitivity to spin correlations can be achieved in the $t\bar{t}$ rest frame.
- It is sensitive to different signs of α
- But there is no feasibility study whether this is really achievable.

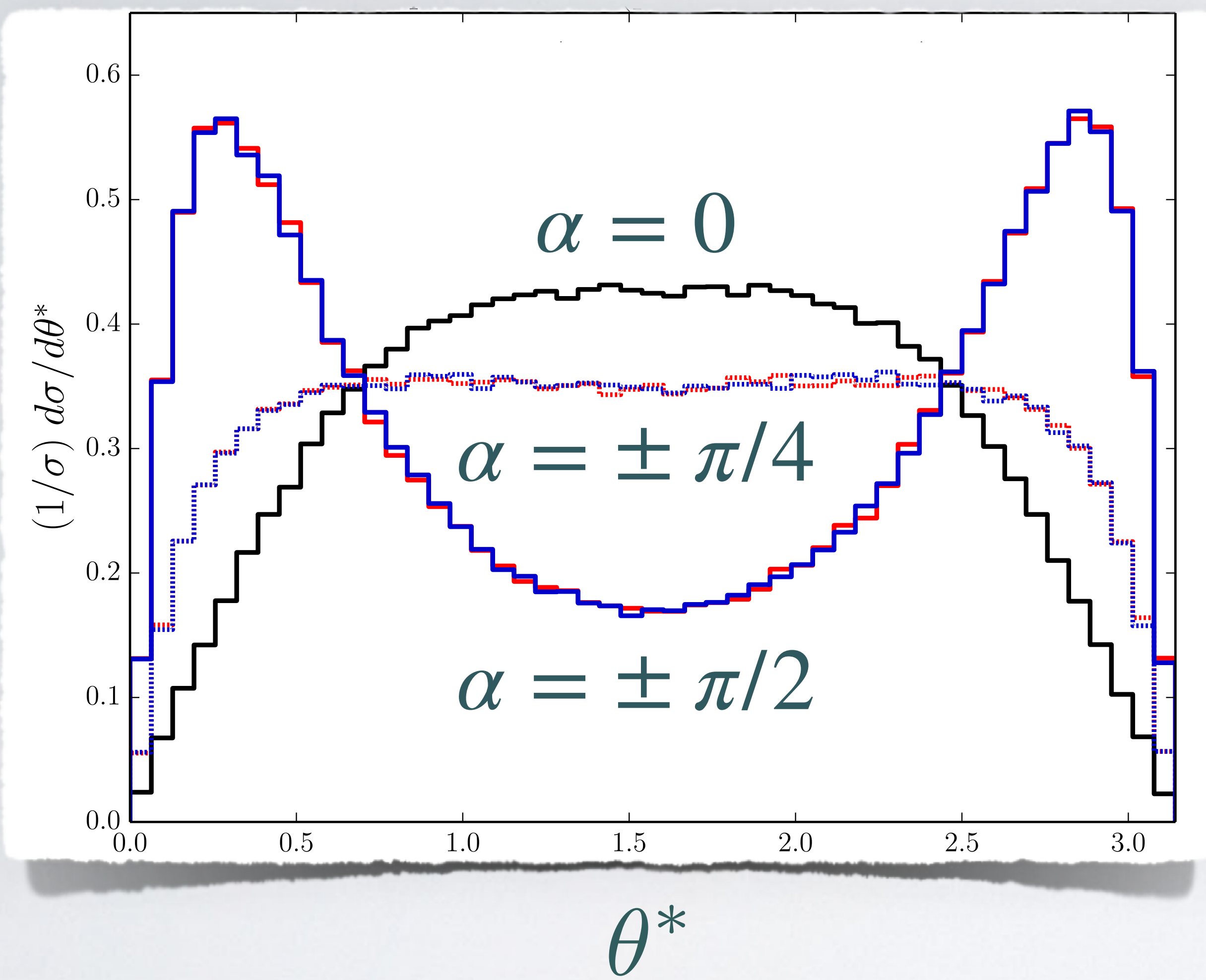
Difficult to reconstruct $t\bar{t}$

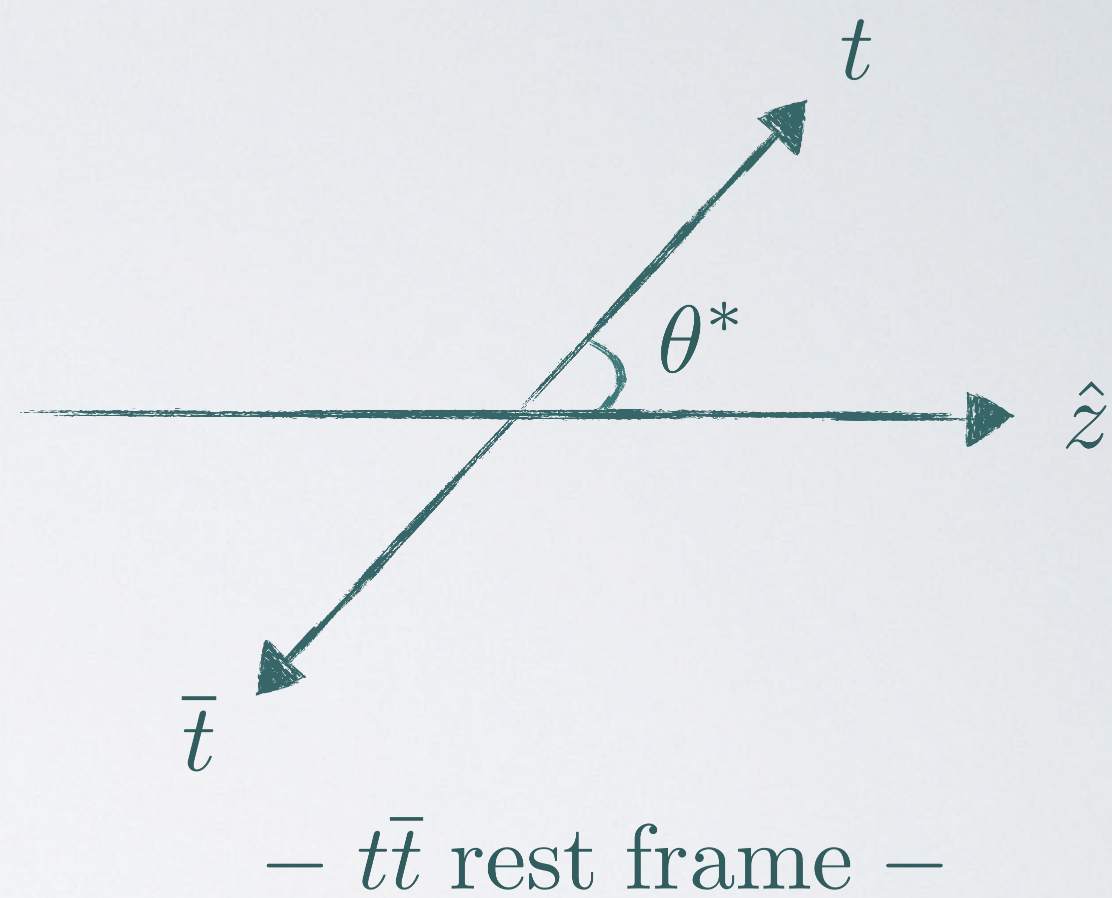
$t\ \bar{t}$ - rest frame observables

D. Goncalves, K. C. Kong, **J. H. Kim**, Yongcheng Wu [2108.01083]

D. Goncalves, K. C. Kong, **J. H. Kim** [1804.05874]

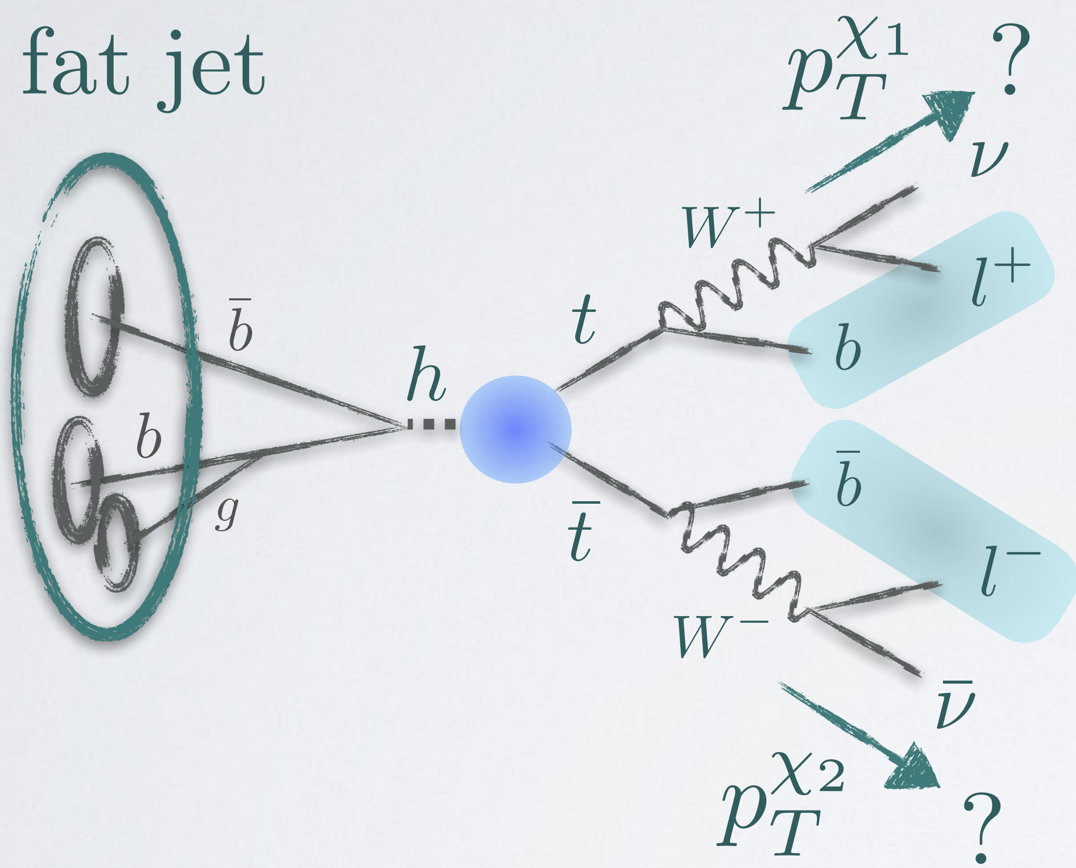
14 TeV (particle-level)





- The Collins-Soper angle θ^* of a top in the $t\bar{t}$ rest frame displays much simpler distributions.
- It shows clear distinctions for different magnitude of α .
- But it cannot tell different signs of α .

The Reconstruction of $t\bar{t}$

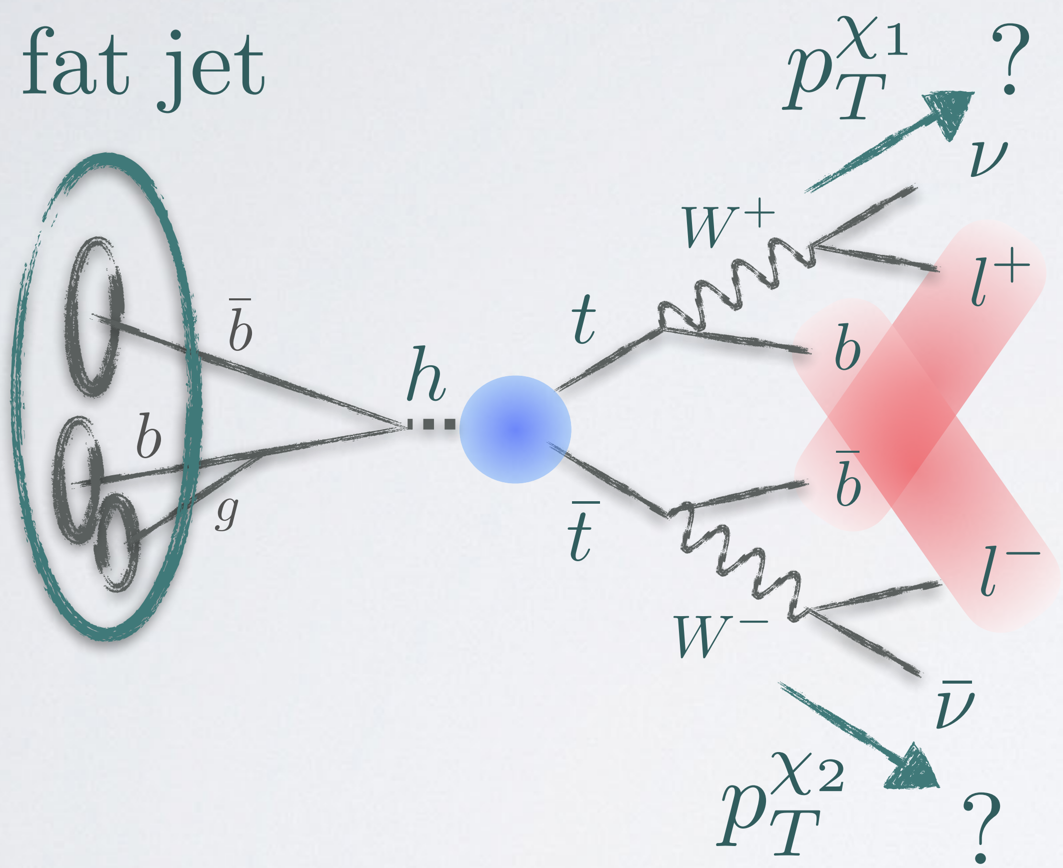


- **Challenging Problems**

  1. Guess neutrinos momenta

  2. Solve a combinatorial problem

The Reconstruction of $t\bar{t}$



- **Challenging Problems**

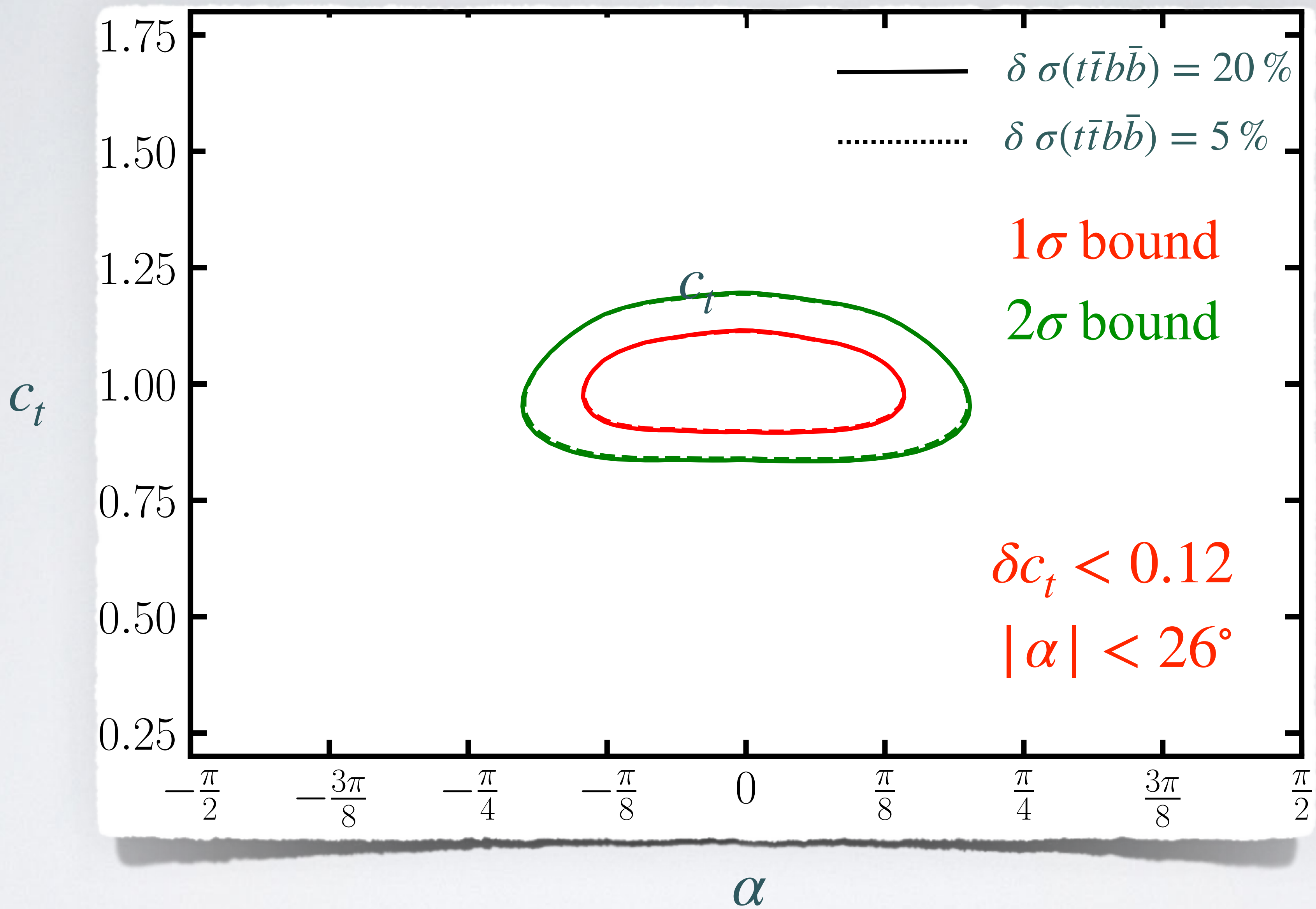
1. Guess neutrinos momenta

2. Solve a combinatorial problem

Projected Limits at HL-LHC

14 TeV ($3ab^{-1}$)

D. Goncalves, **J. H. Kim**, K. C. Kong, Y. Wu [2021]

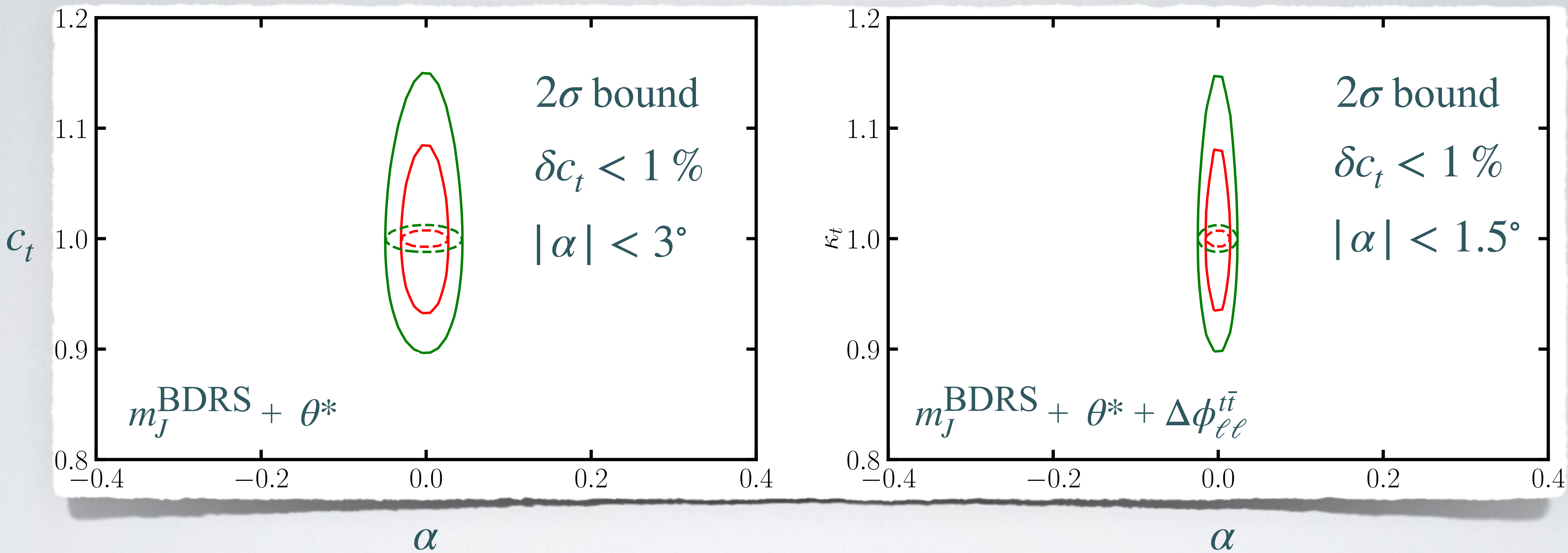


- A binned log-likelihood analysis using all observables may be able to constrain α .
- Probing the sign difference in α will remain challenging.

Projected Limits at the 100 TeV FCC

100 TeV ($30 ab^{-1}$)

D. Goncalves, **J. H. Kim**, K. C. Kong, Y. Wu [2021]



- At the 100 TeV FCC, the both c_t and α can be probed with a greater precision.
- The precise measurement of α is one of the important opportunities at the 100 TeV FCC.

Projected Limits at Future Colliders

Snowmass 2021 [2203.08127]

Bounds on α at 95% CL ($\kappa_t = 1$)	Channel	Collider	Luminosity
$\lvert\alpha\rvert \lesssim 36^\circ$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 25^\circ$ [2]	$t\bar{t}(h \to \gamma\gamma)$ combination	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 3^\circ$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	100 TeV FCC	30 ab^{-1}
$\lvert\alpha\rvert \lesssim 9^\circ$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	10 TeV $\mu^+\mu^-$	10 ab^{-1}
$\lvert\alpha\rvert \lesssim 3^\circ$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	30 TeV $\mu^+\mu^-$	10 ab^{-1}

Summary

- The Trilinear Higgs self-coupling

  1. HL-LHC

     $0.5 < c_3 < 1.5$ [68% bound]

     $0.1 < c_3 < 2.3$ [95% bound]

  2. Muon Collider (e.g. 10 TeV)

     $\delta c_3 = 3.5\ \%$ [68% bound]

[HL-LHC]

Channel	Statistical only	
	ATLAS	CMS
$hh \to b\bar{b}b\bar{b}$	1.4	1.2
$hh \to b\bar{b}\tau^+\tau^-$	2.5	1.6
$hh \to b\bar{b}\gamma\gamma$	2.1	1.8
$hh \to b\bar{b}VV(\ell\ell\nu\nu)$	-	0.59
$hh \to b\bar{b}ZZ(4\ell)$	-	0.37
combined	3.5	2.8
hh discovery potential	combined 4.5	

- The CP Phase of the Top Yukawa Coupling

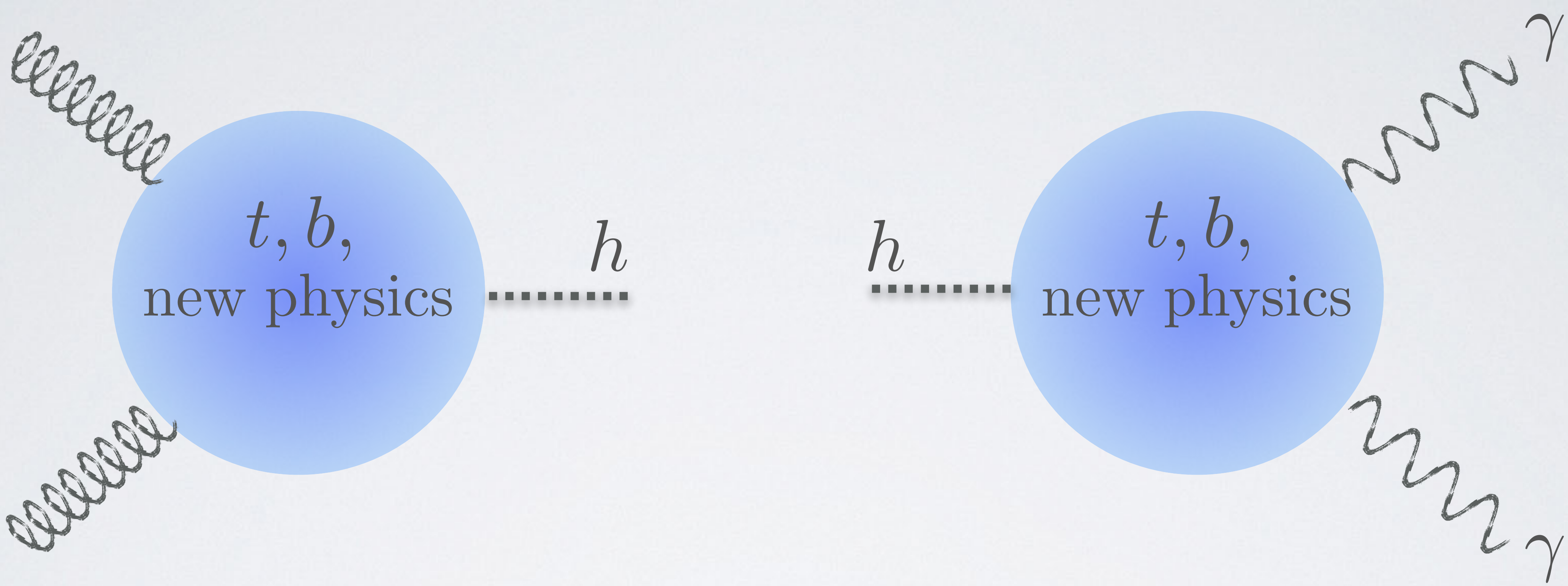
  1. HL-LHC $|\alpha| \lesssim 25^\circ$ [95% bound]

  2. FCC-hh Collider (100 TeV) $|\alpha| \lesssim 3^\circ$ [95% bound]

  3. Muon Collider (10 TeV) $|\alpha| \lesssim 9^\circ$ [95% bound]

Back-up

Indirect LHC Constraints

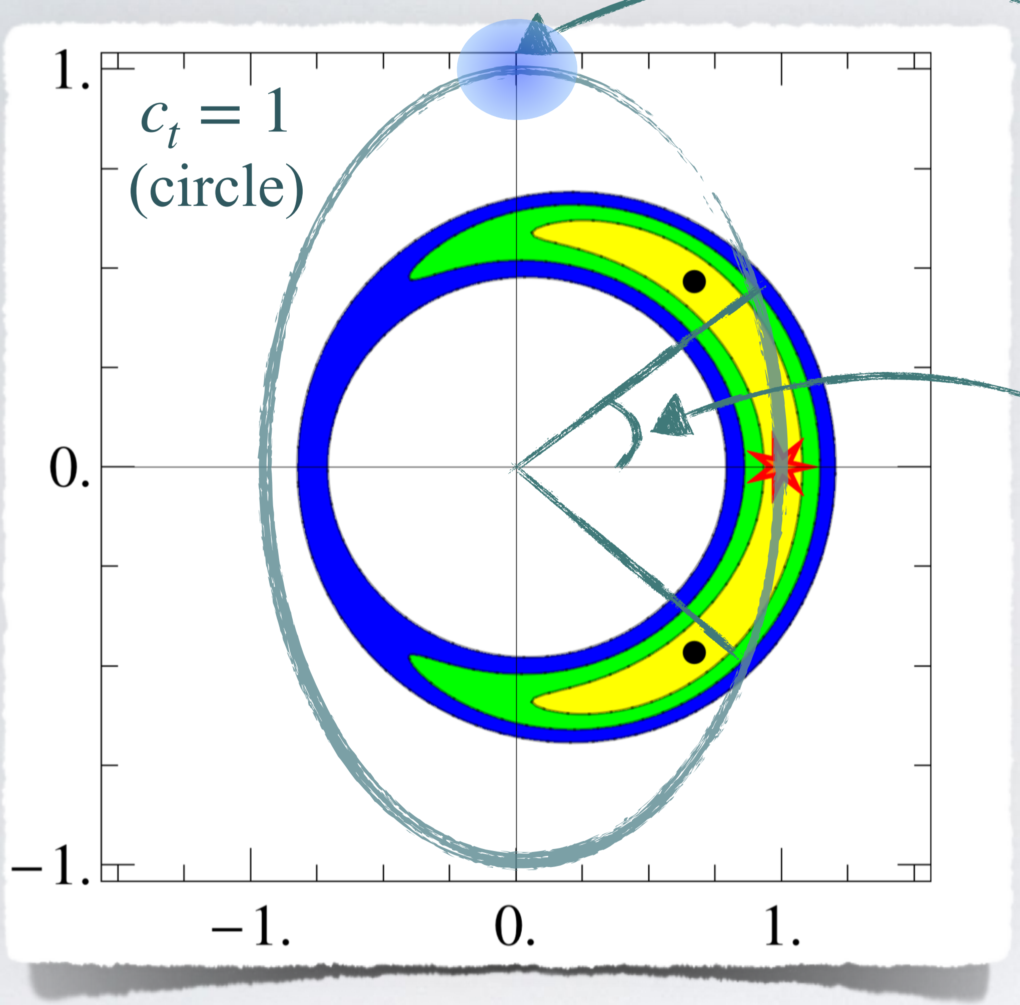


- The single Higgs production is the first avenue to probe the Higgs-top coupling.
- But the interpretation of these vertices is model-dependent.
- Since some new physics effects can contribute to these vertices…

Indirect LHC Constraints

F. Boudjemaa, R. M. Godbole, D. Guadagnoli, K. A. Mohan [2015]

$c_t \sin\alpha$



$c_t \cos\alpha$

Pure CP odd

2σ bound

$\alpha = \left[-25^\circ, 25^\circ\right]$

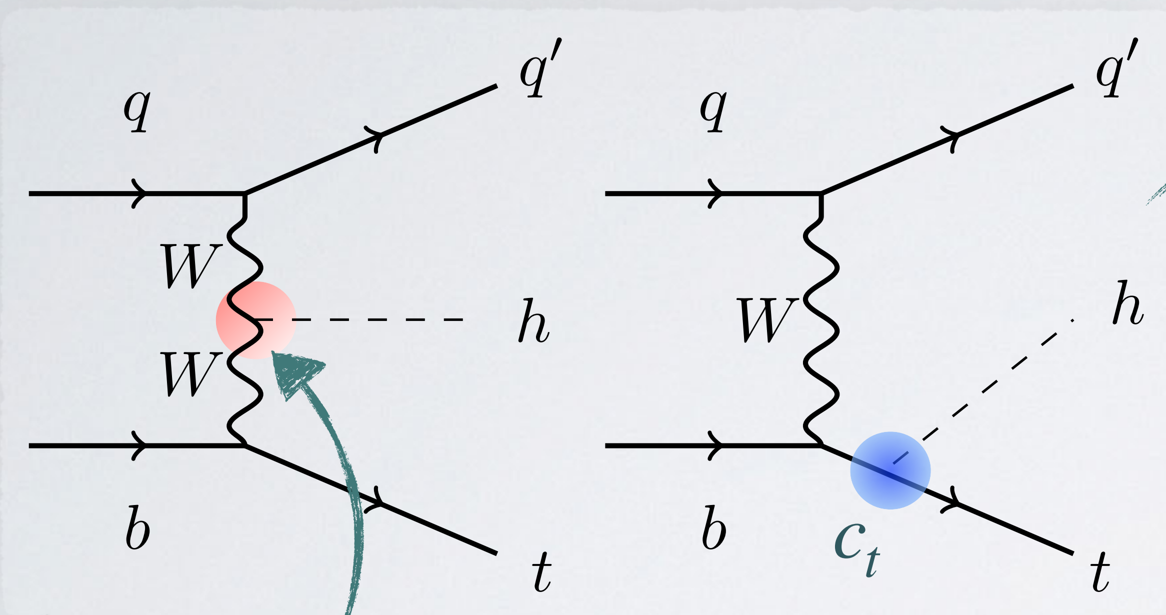
$$\mathscr{L} \supset -\frac{m_t}{v} c_t \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t h$$

- Fixing $c_t = 1$, α is constrained $\alpha = \left[-25^\circ, 25^\circ\right]$.
- Apparently the pure CP odd case seems to be very excluded.
- But still various CP admixture states are allowed.

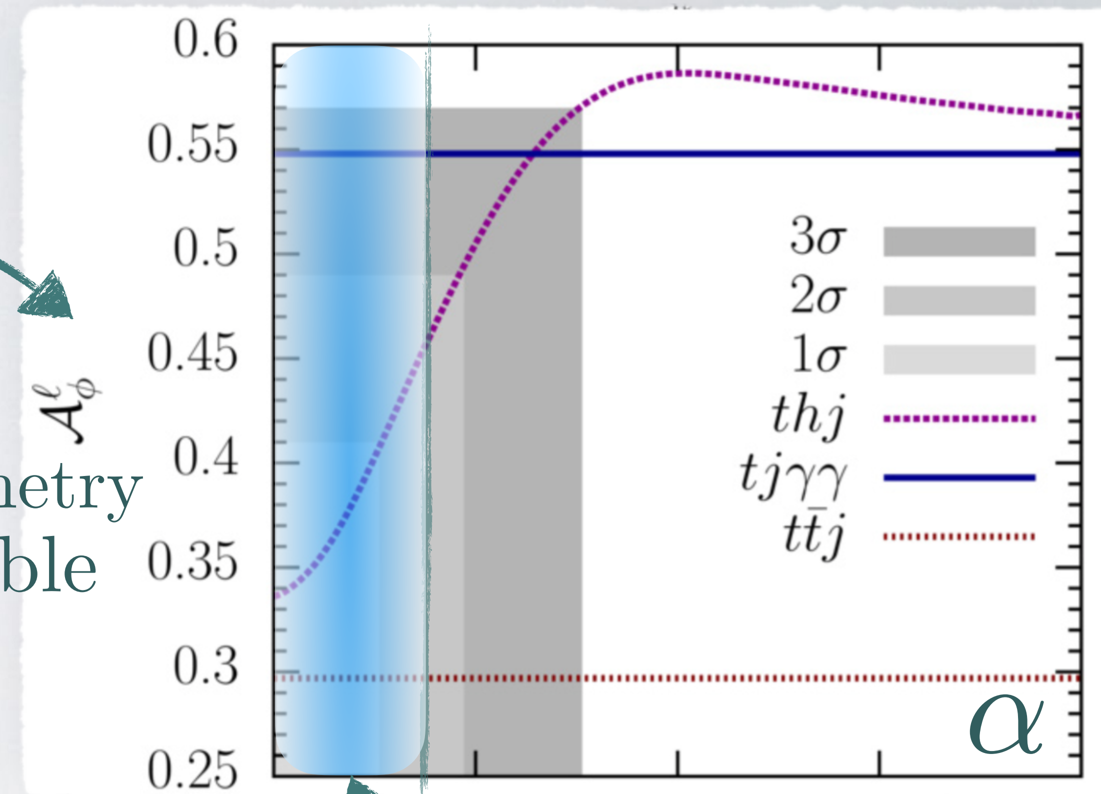
Semi-direct LHC Constraints

$3000\ \mathrm{fb}^{-1}$

S. D. Rindani, P. Sharma, A. Shivaji [2016]



Asymmetry variable



assumptions

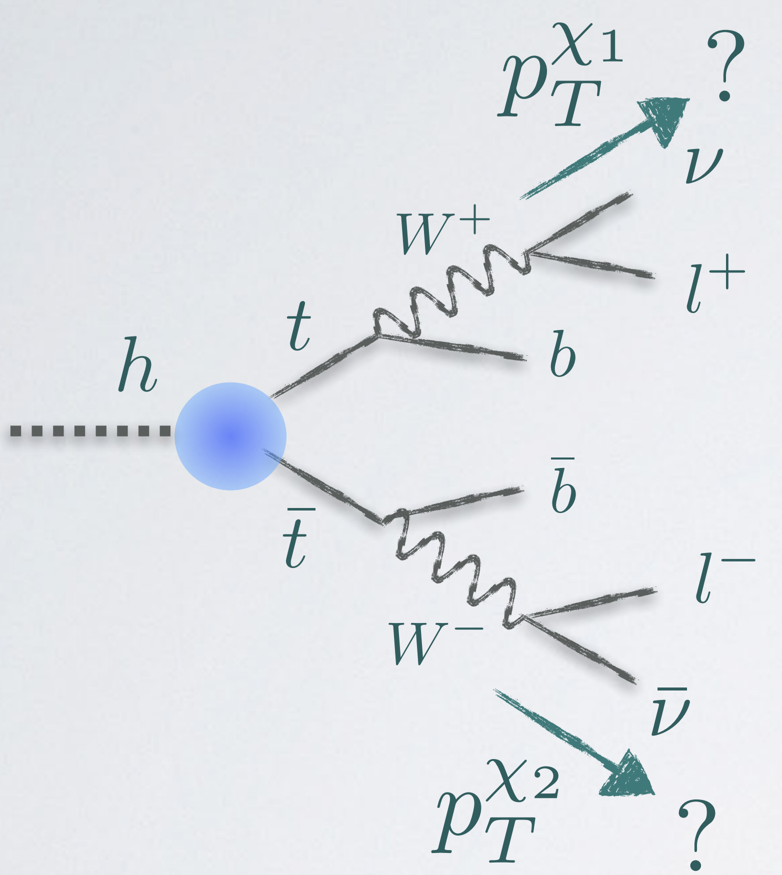
$\alpha = [0^\circ, 30^\circ]$

Allowed region (2σ)

- The *th* production has less assumptions.
- Assuming that WWh coupling sits exactly on the SM.
- The *th* production is sensitive to the sign of the CP phase.
- The downside is the cross section is small: $\sigma_{\mathrm{NLO}}(thj) = 70$ fb $\quad \sqrt{S} = 14$ TeV

The reconstruction of $t\ \bar{t}$

D. Kim, Matchev, Moortgat, Pape [2017]



- Scanning 4-momenta of two neutrinos until it minimizes the following target function :

$$\underbrace{M_{2CW}\left(m_\chi^{\text{test}}\right)}_{m_t^{reco}} \equiv \min_{\mathbf{p}_T^{\chi_1}+\mathbf{p}_T^{\chi_2}=\not{\mathbf{p}}_T} \left[\max \underbrace{\left\{M^{(1)}(\mathbf{p}^{\chi_1}, m_\chi^{\text{test}}), M^{(2)}(\mathbf{p}^{\chi_2}, m_\chi^{\text{test}})\right\}}_{\text{invariant masses}}\right]$$

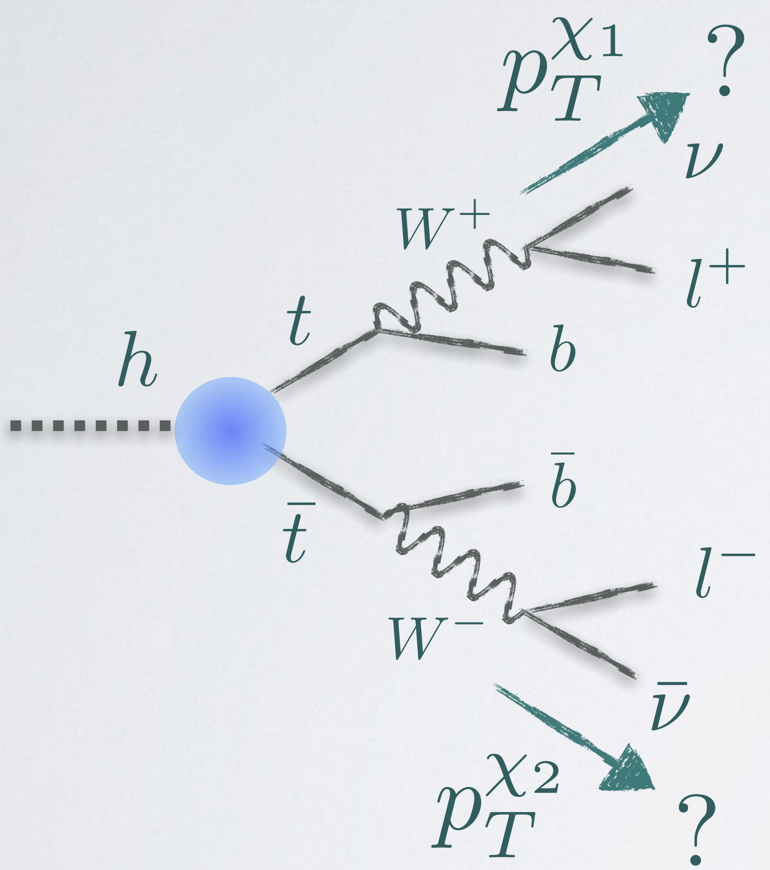
$$\boxed{\begin{array}{c} M_{t1} = M_{t2} \\ M_{W1} = M_{W2} = 81.4\ \ \text{GeV} \end{array}}$$

We can impose various mass constraints during the minimization.

- If we form up the target function in terms of transverse masses, then it is the same as M_{T2} .
- Then it's not trivial to use the above mass relations during the minimization.

The reconstruction of $t\ \bar{t}$

D. Kim, Matchev, Moortgat, Pape [2017]



- And scanning again with on-shell top mass constraints as well as the symmetry requirement on W masses:

$$M_{2CT}\left(m_\chi^{\text{test}}\right) \equiv \min_{\mathbf{p}_T^{\chi_1}+\mathbf{p}_T^{\chi_2}=\not{\mathbf{p}}_T} \left[\max\left\{M^{(1)}(\mathbf{p}^{\chi_1}, m_\chi^{\text{test}}), M^{(2)}(\mathbf{p}^{\chi_2}, m_\chi^{\text{test}})\right\}\right]$$

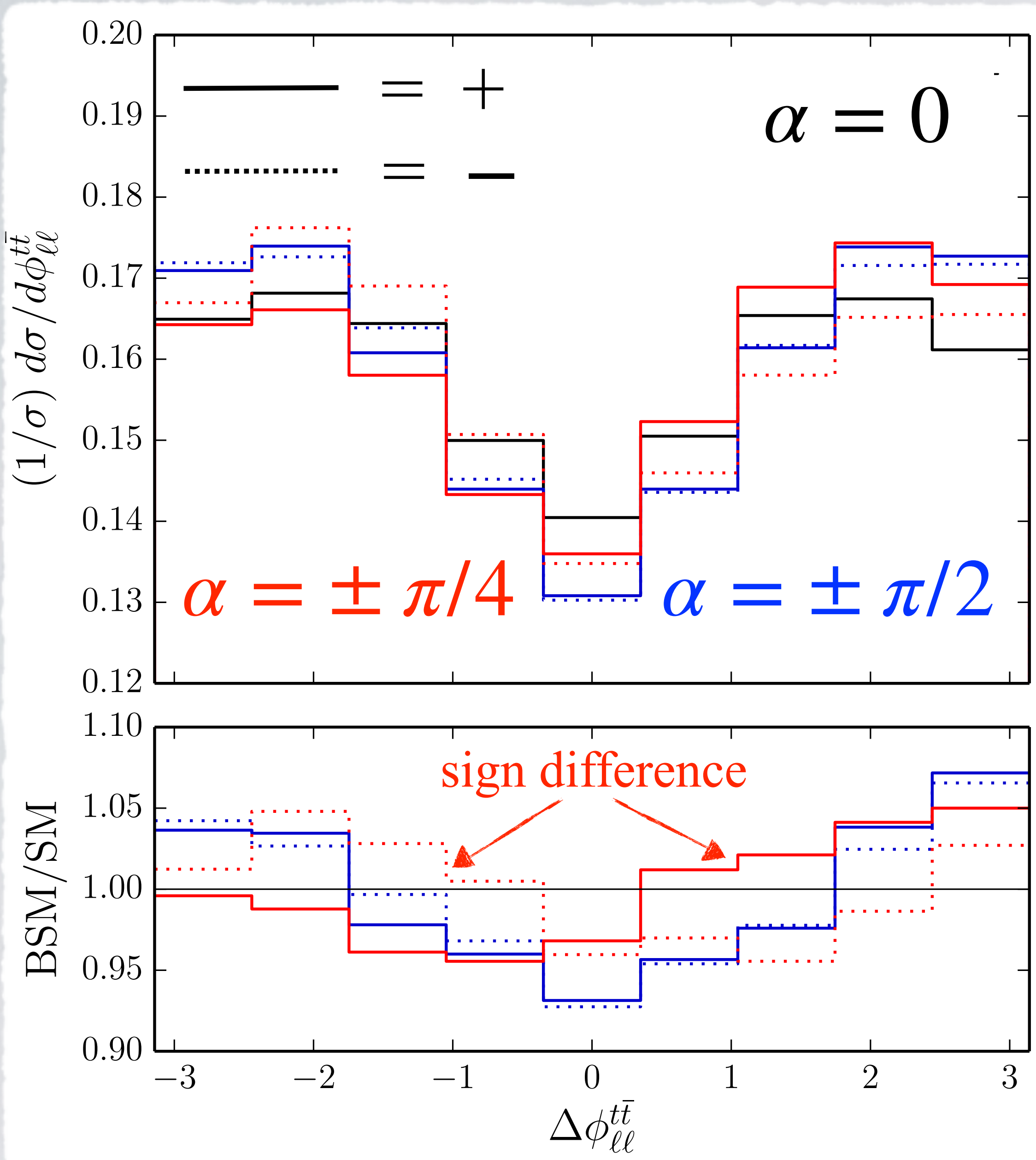
m_W^{reco}

$$\boxed{\begin{gathered} M_{t1} = M_{t2} = 173\ \text{GeV} \\ M_{W1} = M_{W2} \end{gathered}}$$

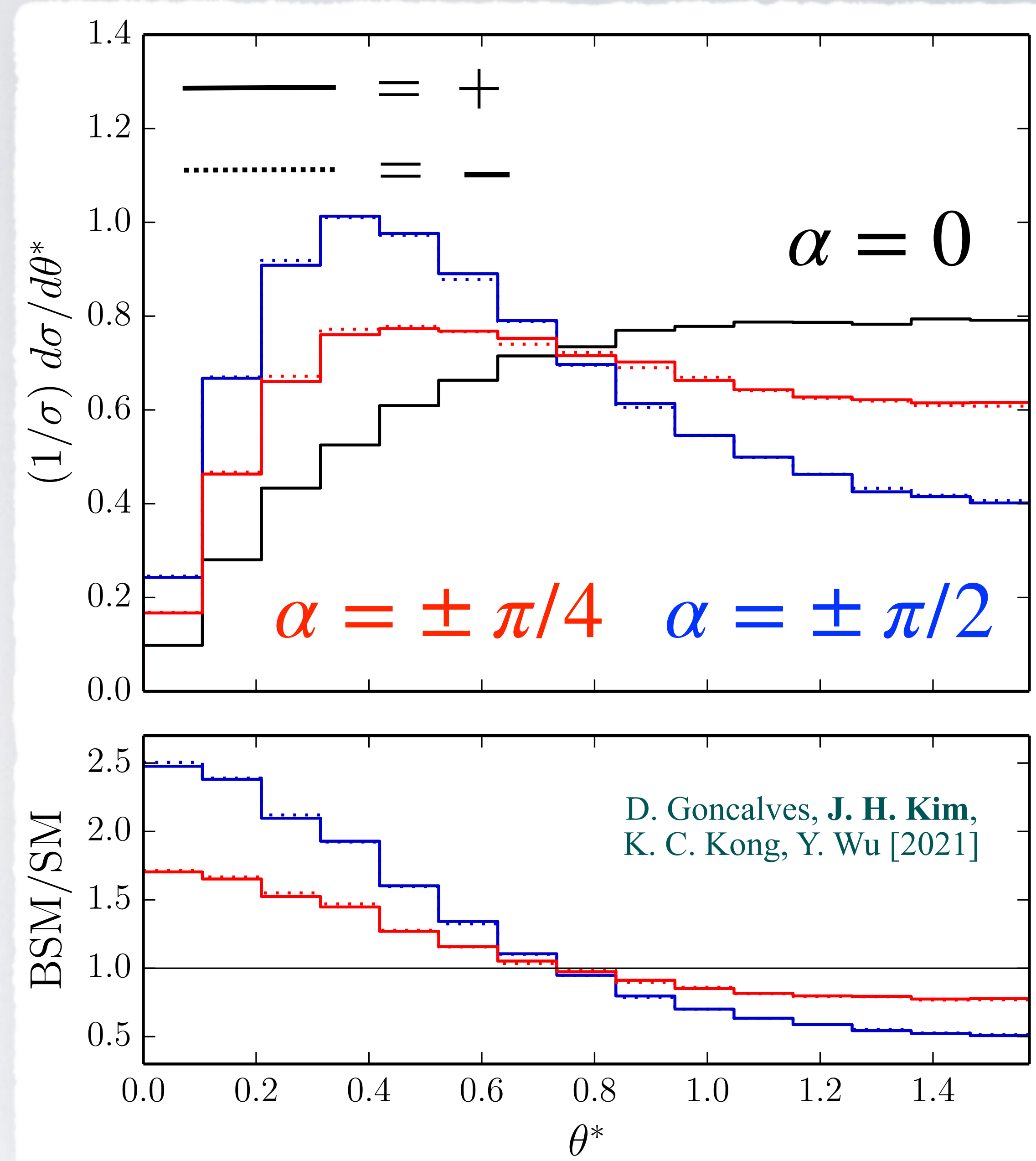
- The minimized value itself is the reconstructed W mass.
- And the neutrino 4-momenta that minimize the target function is our best guess!

$t\ \bar{t}$ - rest frame observables

14 TeV (detector-level)



14 TeV (detector-level)



- The $\Delta\phi_{\ell\ell}^{t\bar{t}}$ displays $5 \sim 10\,\%$ differences for different signs of α at detector-level.
- It's not a huge effect, but good to have an additional handle to probe the sign difference.
- The θ^* has a powerful discrimination power on the magnitude of α at detector-level.