HH Production Theory
Double Higgs Production at HL-LHC

(focus on $bb\ell\ell\nu\nu$ channel)

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Why double Higgs (*hh*) ?

- Measurement of the triple and quartic Higgs self-couplings provides crucial input to confirm SM prediction, and is essential to understand EWSB.
- Triple Higgs coupling can be probed via double Higgs production at the LHC.
- Resonant / non-resonant double Higgs production is interesting, theoretically and experimentally.
  - Triple Higgs coupling is easily modified in many extensions of SM.
  - Double Higgs production is a guaranteed physics at HL-LHC with high impact (a new collider is needed to probe quartic coupling).
  - Double Higgs production provides measurement of the first non-trivial term (cubic term) in the Higgs potential.
  - Destructive interference between box and triangle diagrams in SM makes it difficult to probe the triple Higgs coupling.
  - The cubic coupling is sensitive at lower-energy bins where the backgrounds are large.
  - It is challenging experimentally.
  - It brings many different final states.

For Higgs EFT, see talks by Adam Martin and Andrea Sciandra.

Decays

$$\sigma(hh)^{NNLO}_{SM} \simeq 40.7 \text{ fb} \quad (\text{ 14 TeV })$$

higher branching ratios

cleaner final state

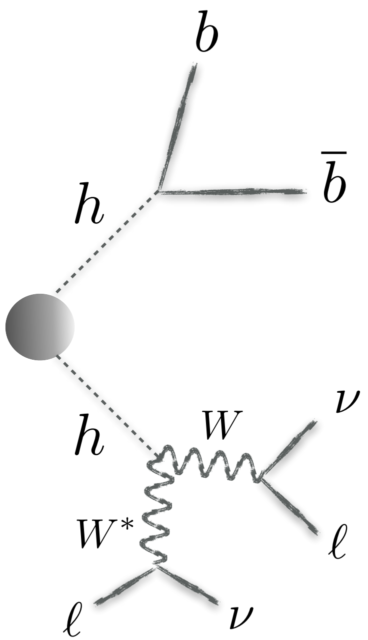
	bb	WW^*	$\tau\tau$	ZZ^*	$\gamma\gamma$
bb	33%				
WW^*	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ^*	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.1%	0.028%	0.012%	0.0005%

1902.00134	**Statistical-only**		**Statistical + Systematic**	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

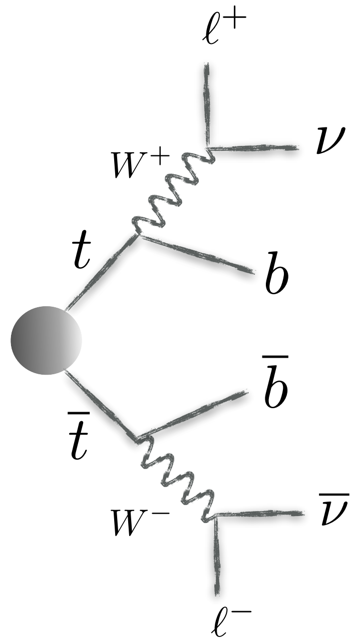
4σ expected for ATLAS+CMS!

- Measurements of the triple Higgs coupling is challenging due to a small σ (hh) and large backgrounds.
- No single channel is expected to reach 3 sigma at HL-LHC.
- The combination of various channels is crucial. bbWW dilepton channel has good potential for further improvement. (Focus of this talk)

Previous (theory) study on $hh \to bbWW^*$



Signal



Major background

$$\sigma_{bknd} \sim 10^5 \sigma_{hh}$$

- $hh \to bbWW^*$ channel suffers from the large $t\bar{t}$ background.

- Most studies report that the sensitivity of signal in the di-leptonic channel is very poor.

CMS-FTR-15-002-PAS

Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

- The situation in the semi-leptonic mode is even worse.

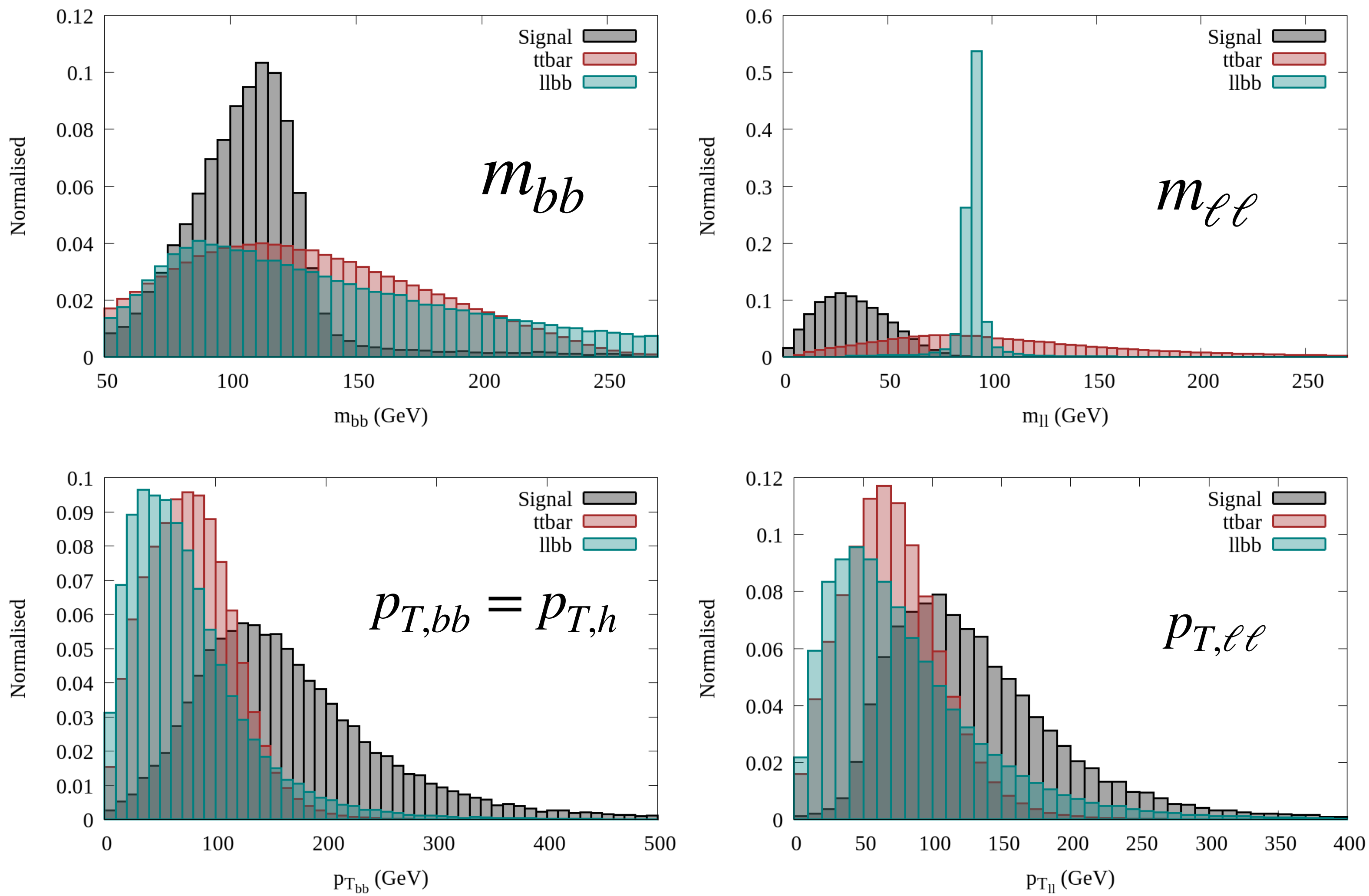
Dolan, Englert, Spannowsky 2012

Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

cf) Papaefstathiou, Yang, Zurita 2012

For current ATLAS/CMS studies, see talks by Louis D'Eramo and David Zuolo

$hh \to bbWW^*$: *dilepton channel*



10 variables: $p_{T,\ell_{1/2}},\ \not{E}_T,\ m_{\ell\ell},\ m_{bb},\ \Delta R_{\ell\ell},\ \Delta R_{bb},\ p_{T,bb},\ p_{T,\ell\ell},\ \Delta\phi_{bb\ \ell\ell}$

Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

$hh \to bbWW^*$: dilepton channel

HL-LHC, 14 TeV, L=3 ab^{-1}

Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi JHEP 2017

$\not{E}_T$

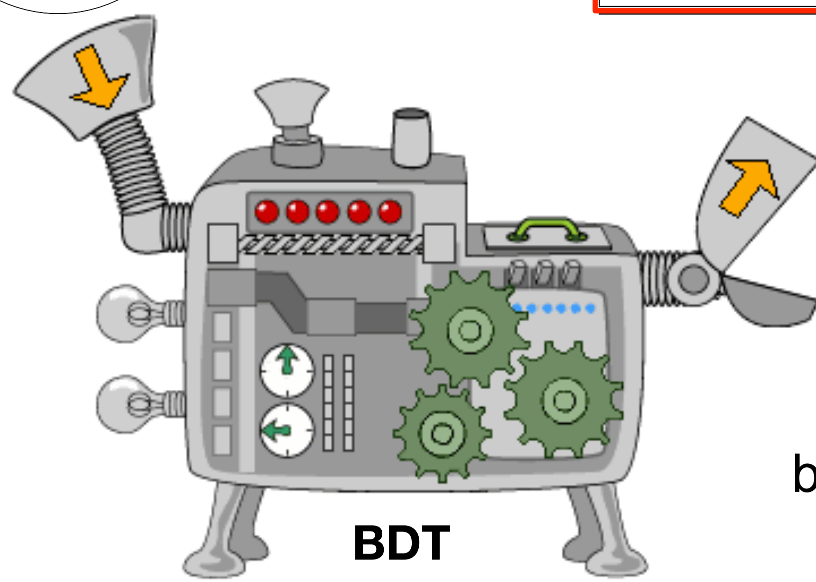
$p_{T,\ell_{1/2}}$ $\Delta\phi_{bb\,\ell\ell}$

$\Delta R_{\ell\ell}$ ΔR_{bb}

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

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

Sl. No.	Process	Order	Events
Background	$t\bar{t}$ lep	NNLO [128]	2080.52
	$t\bar{t}h$	NLO [111]	131.66
	$t\bar{t}Z$	NLO [130]	106.31
	$t\bar{t}W$	NLO [129]	35.97
	$hb\bar{b}$	NNLO (5FS) + NLO (4FS) [111]	~ 0
	$\ell\ell b\bar{b}$	LO	842.72
	Total		3197.18
Signal ($hh \to b\bar{b}WW \to b\bar{b}\ell\ell + \not{E}_T$)		NNLO [70]	35.20
Significance ($S/\sqrt{B}$)			0.62

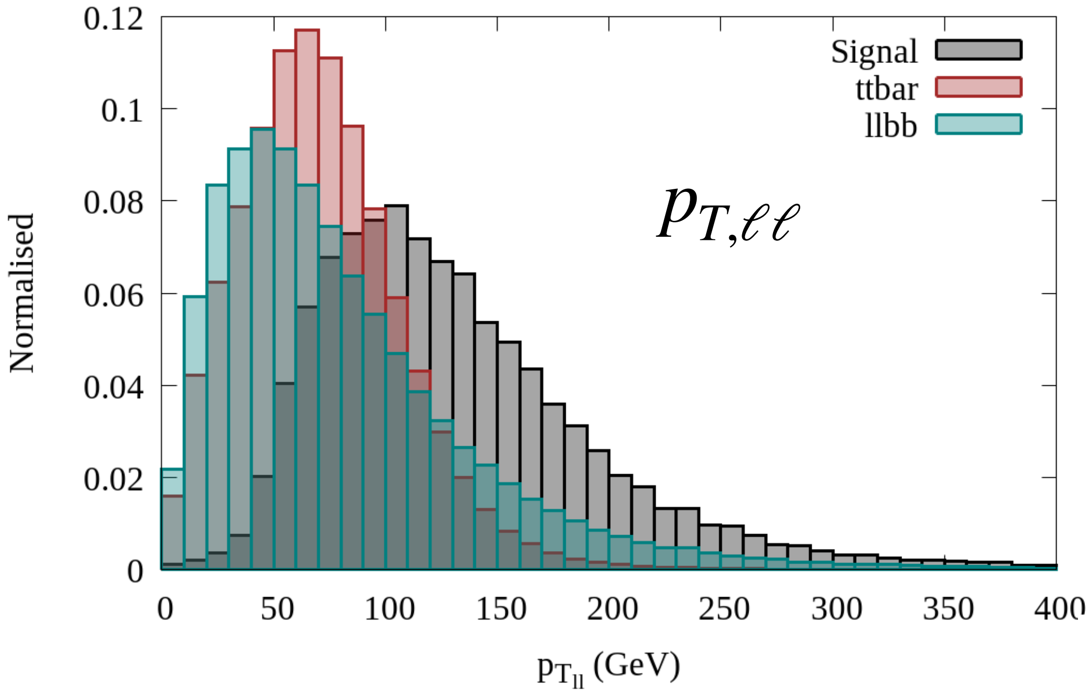


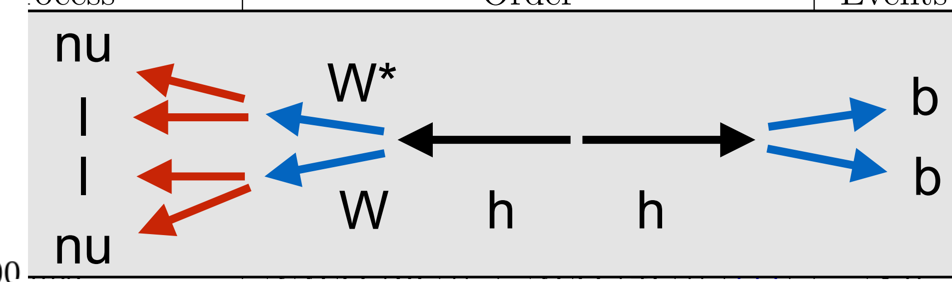
Note that tW background is not included here.

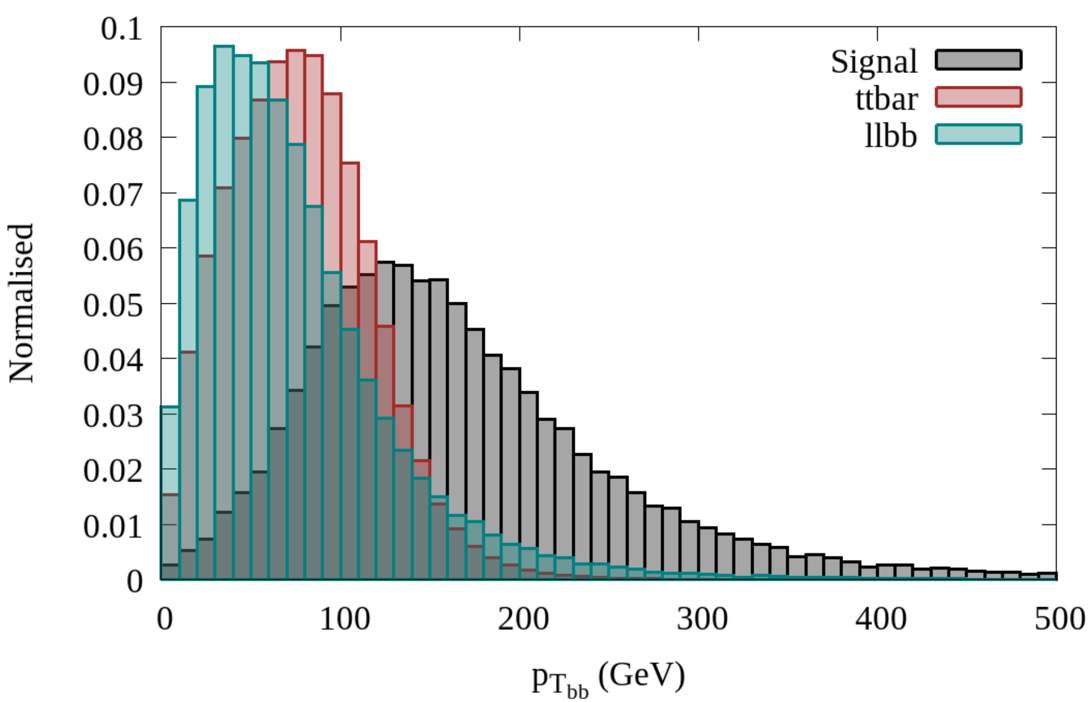
dilepton channel

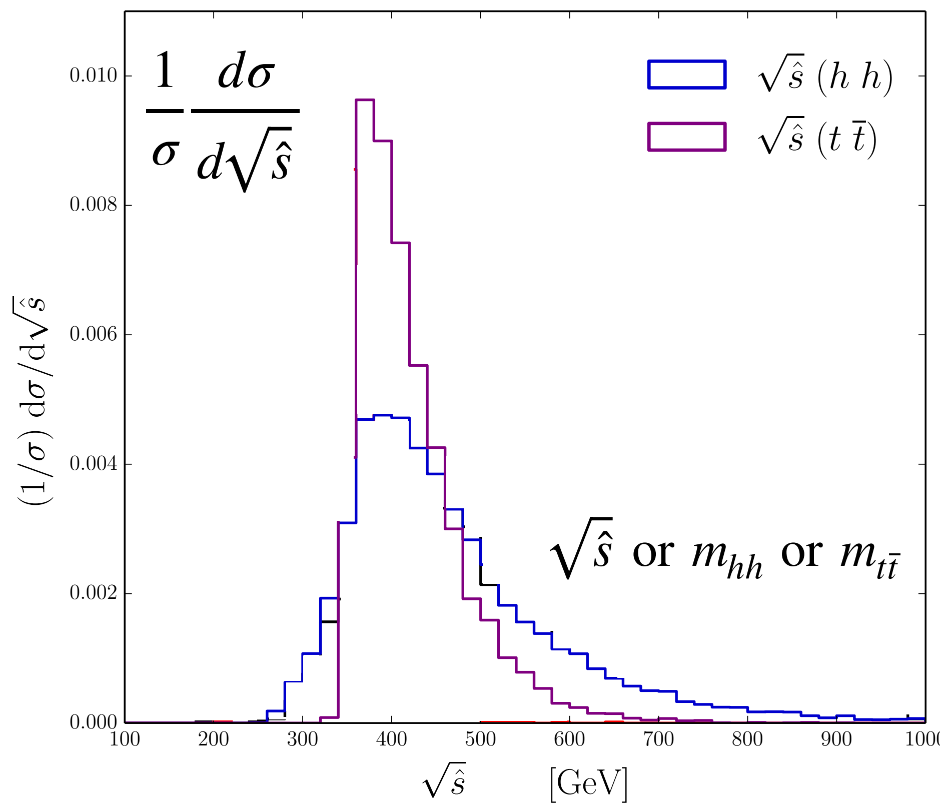
hikary, Banerjee, Barman, Bhattacherjee, Niyogi JHEP 2017

rocess	Order	Events

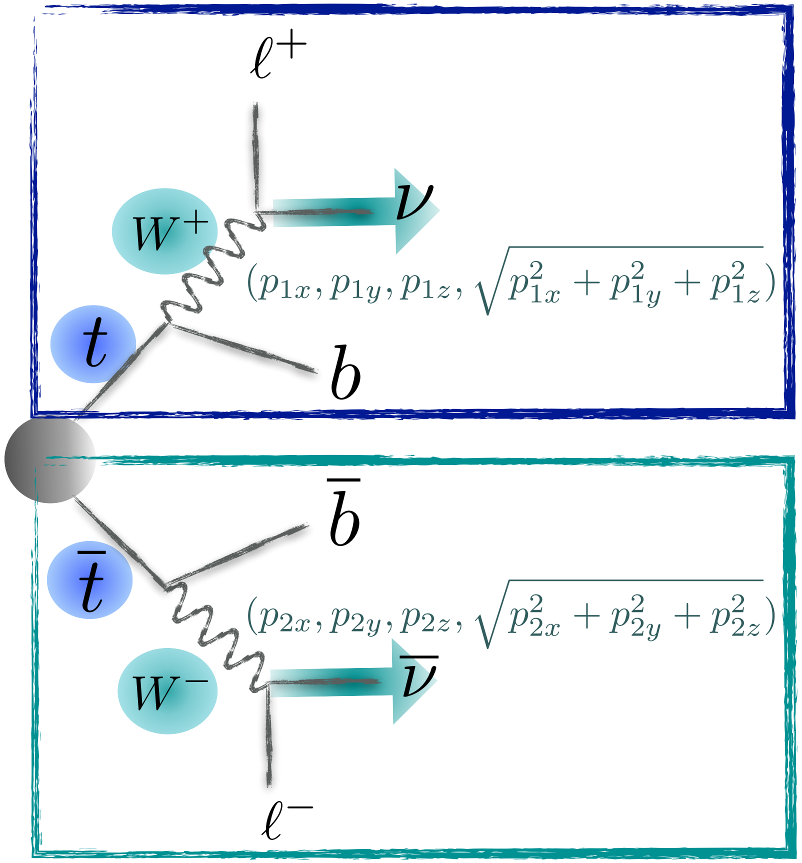








How to reduce $t\bar{t}$ background: Topness (T)



$$\chi^2_{ij} \equiv \min_{\vec{p}\!\!/_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{b_i \ell^+ \nu} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^+ \nu} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{b_j \ell^- \bar{\nu}} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^- \bar{\nu}} - m_W^2\right)^2}{\sigma_W^4} \right]$$

$$T \equiv min\left(\chi^2_{12}\,,\ \chi^2_{21}\right)$$

two possible ways of paring b and ℓ

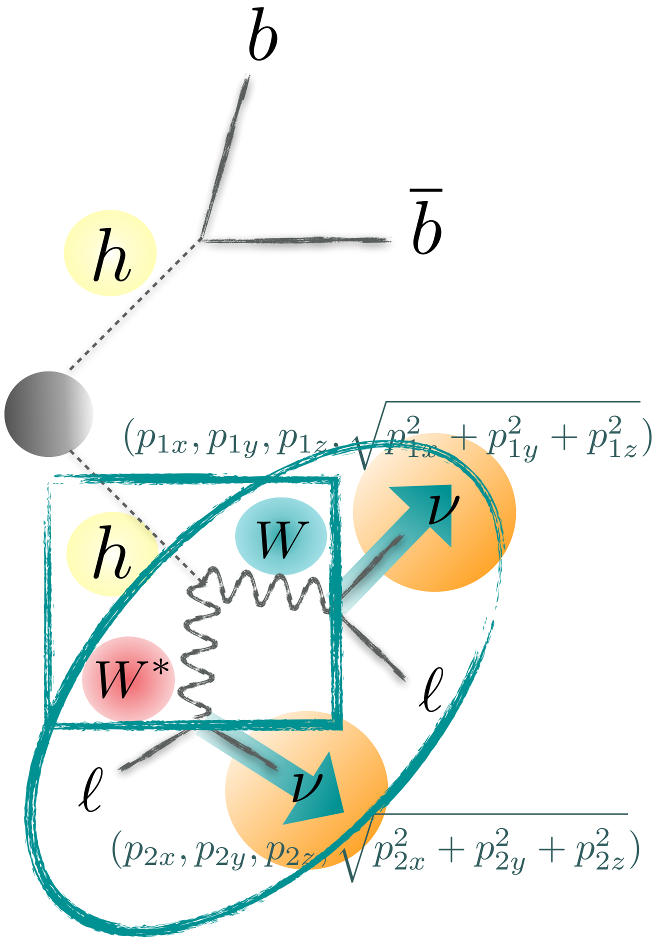
- Topness provides a degree of consistency to dileptonic $t\bar{t}$ production.
- It scans over 6 unknowns of neutrino momenta with four on-shell masses and missing E_T constraints.
- And find the minimum of the likelihood function.
- $t\bar{t}$ events will give a smaller value of Topness than hh events.

Grasser, Shelton, Park, PRL 2013

Kim, Kong, Matchev, Park, PRL 2019

Kim, Kim, Kong, Matchev, Park, JHEP 2019

How to reduce $t\bar{t}$ background: Higgsness (H)



$$H \equiv \min_{\not{\vec{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{\ell^+\ell^-\nu\bar{\nu}} - m_h^2\right)^2}{\sigma^4_{h_\ell}} + \frac{\left(m^2_{\nu\bar{\nu}} - m^2_{\nu\bar{\nu},peak}\right)^2}{\sigma^4_\nu} + min\left(\frac{\left(m^2_{\ell^+\nu} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{\ell^-\bar{\nu}} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}}, \frac{\left(m^2_{\ell^-\bar{\nu}} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{\ell^+\nu} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}} \right) \right],$$

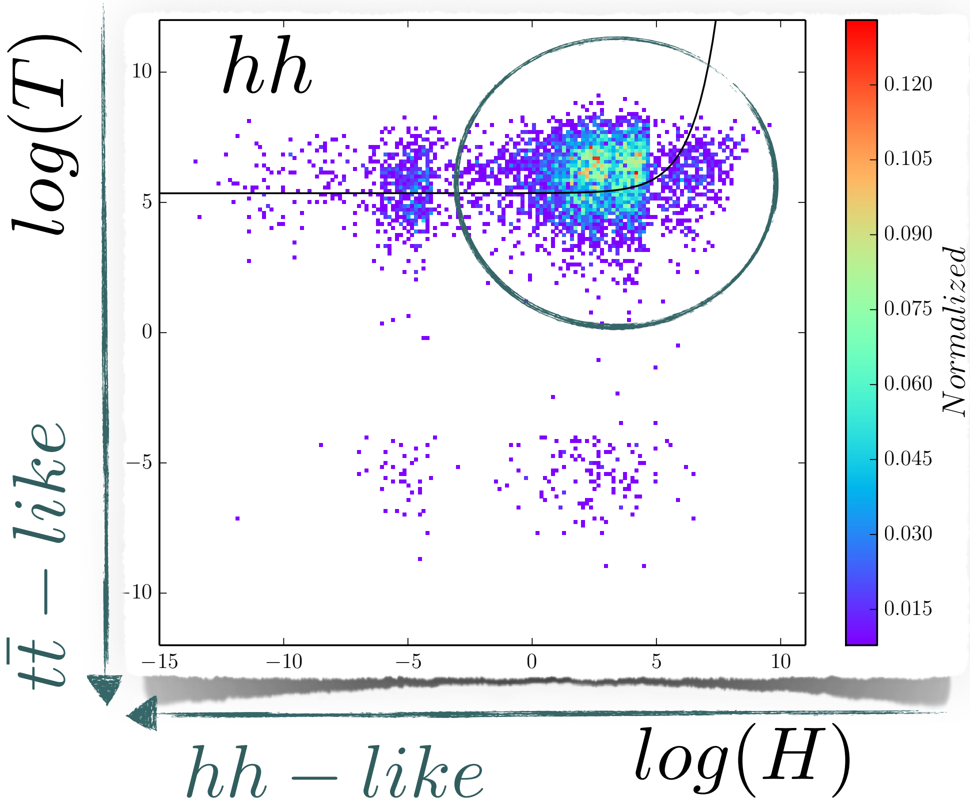
two possible ways of paring ν and ℓ

$\sim m_h - m_W$ off-shell

- Higgsness provides a degree of consistency to dileptonic $h \to WW^*$ system.
- The off-shell W also has an end-point near m_h - m_W.
- Its distribution is wide, but there is a peak, which can constrain hh system further.
- $t\bar{t}$ events will give a larger value of Higgsness than hh events.

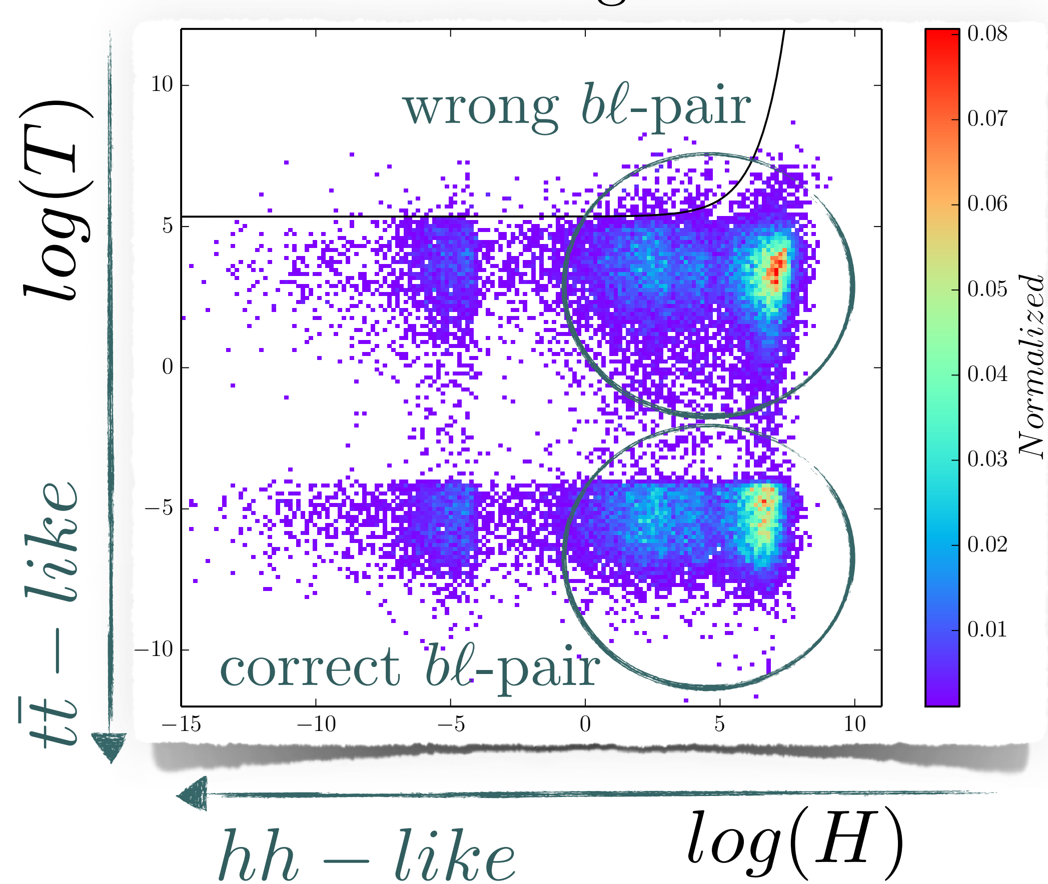
Kim, Kong, Matchev, Park, PRL 2019
Kim, Kim, Kong, Matchev, Park, JHEP 2019

Distributions of (*log H* , *log T*) after baseline selection cuts



- A clear separation between *hh* and backgrounds ($t\bar{t}$ is dominant)

All backgrounds

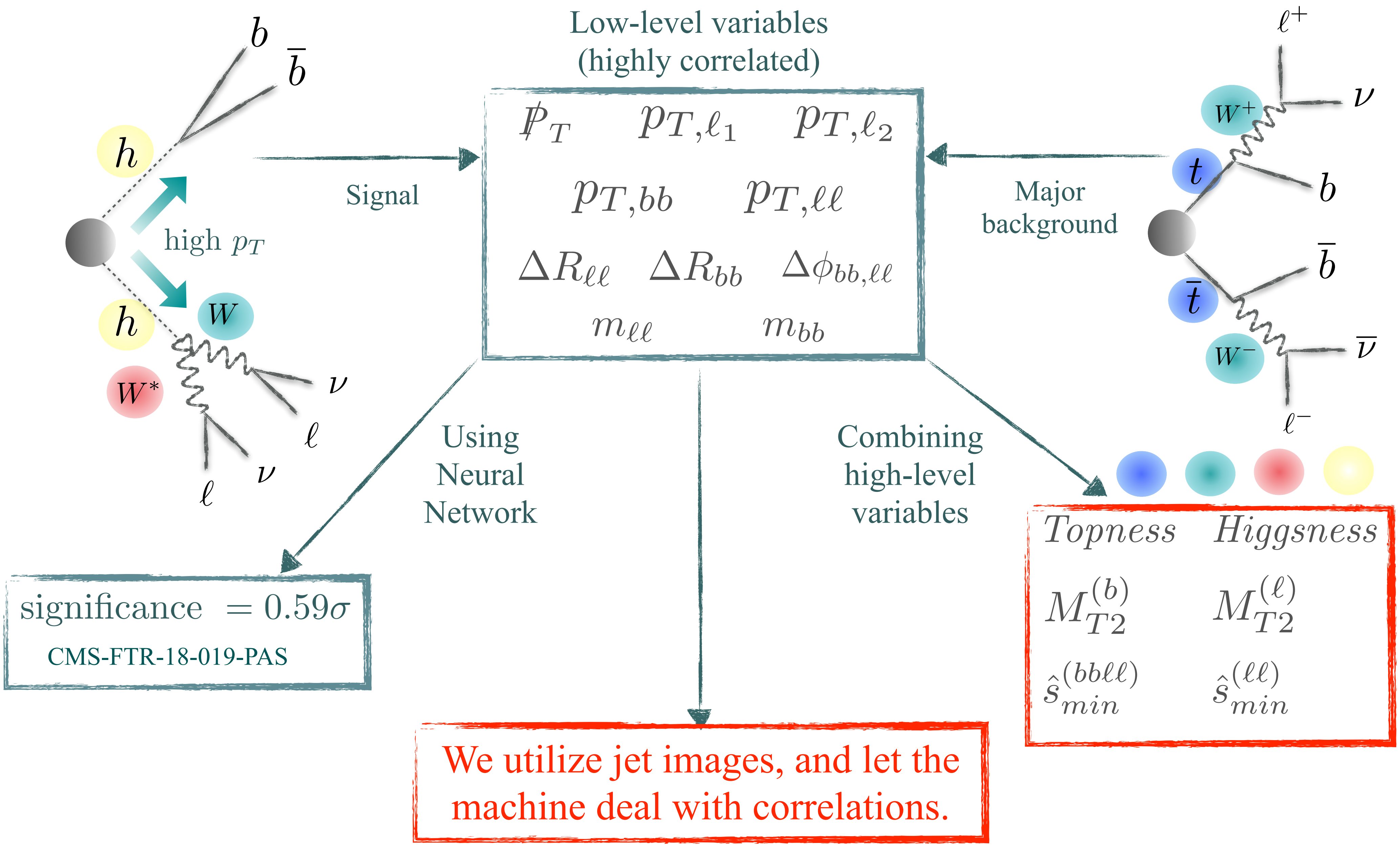


- Since there is a two-fold ambiguity in $b\ell$-paring, Topness displays the island-nature.

Kim, Kong, Matchev, Park, PRL 2019

Kim, Kim, Kong, Matchev, Park, JHEP 2019

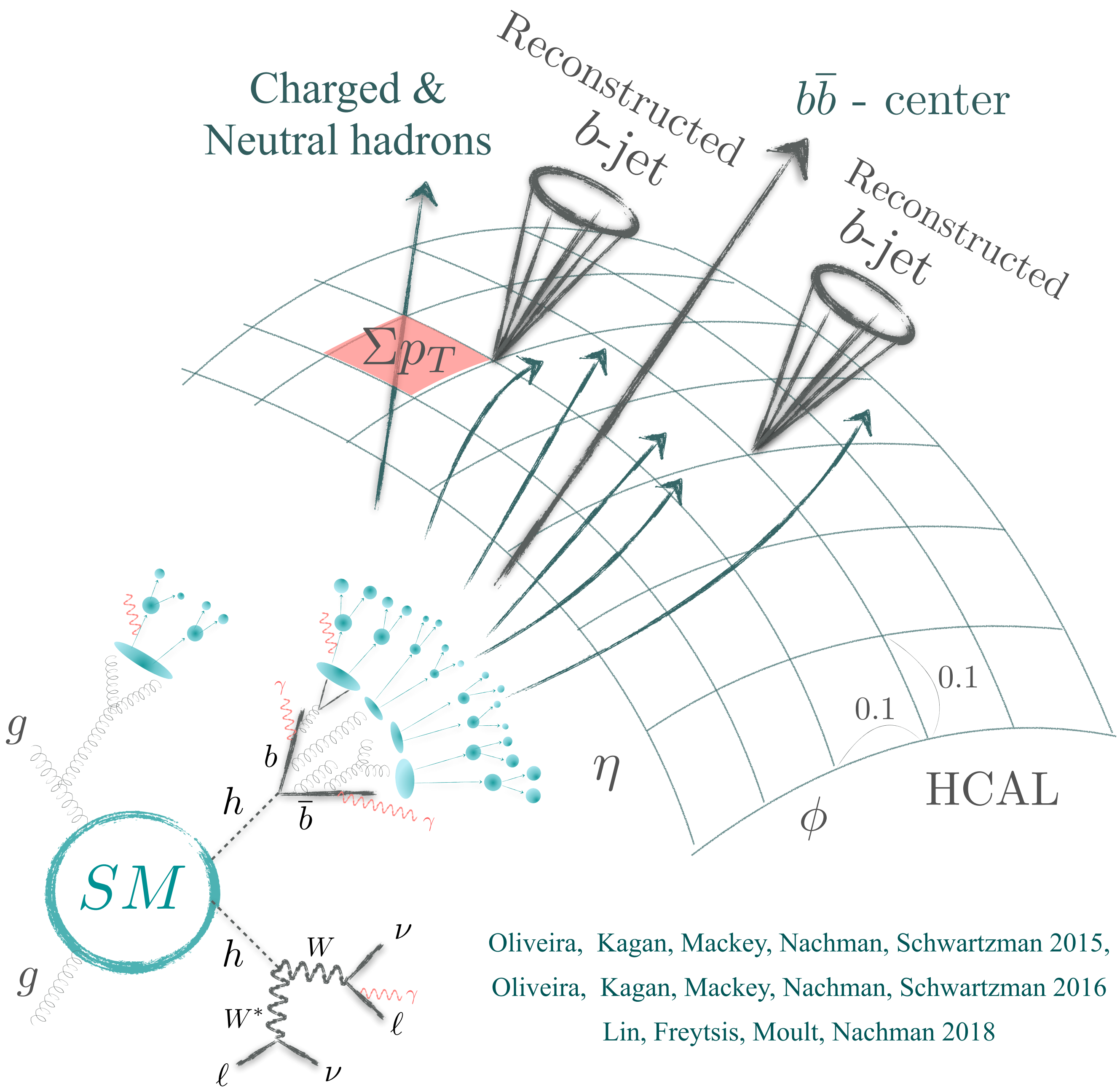
How to reduce backgrounds further



Kim, Kong, Matchev, Park, PRL 2019

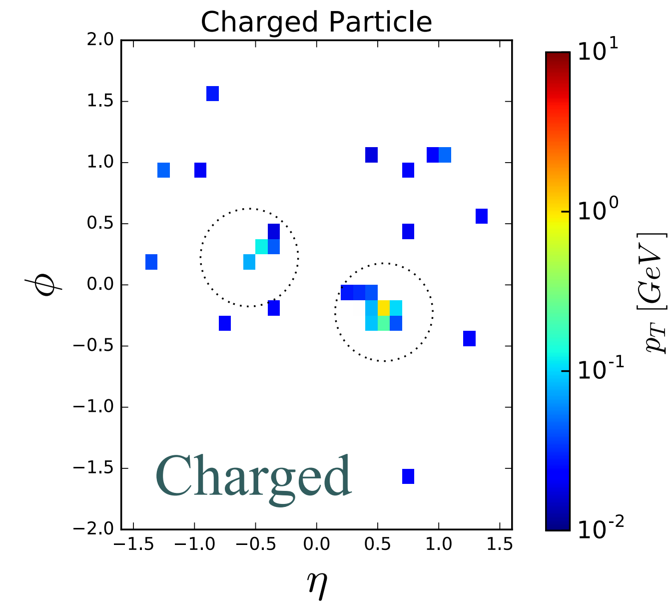
Kim, Kim, Kong, Matchev, Park, JHEP 2019

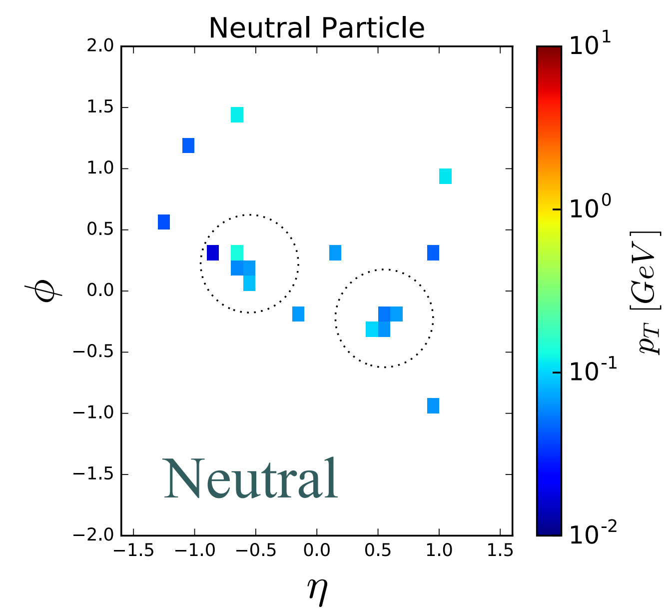
Processing Hadron Images (hh)



Oliveira, Kagan, Mackey, Nachman, Schwartzman 2015,
Oliveira, Kagan, Mackey, Nachman, Schwartzman 2016
Lin, Freytsis, Moult, Nachman 2018

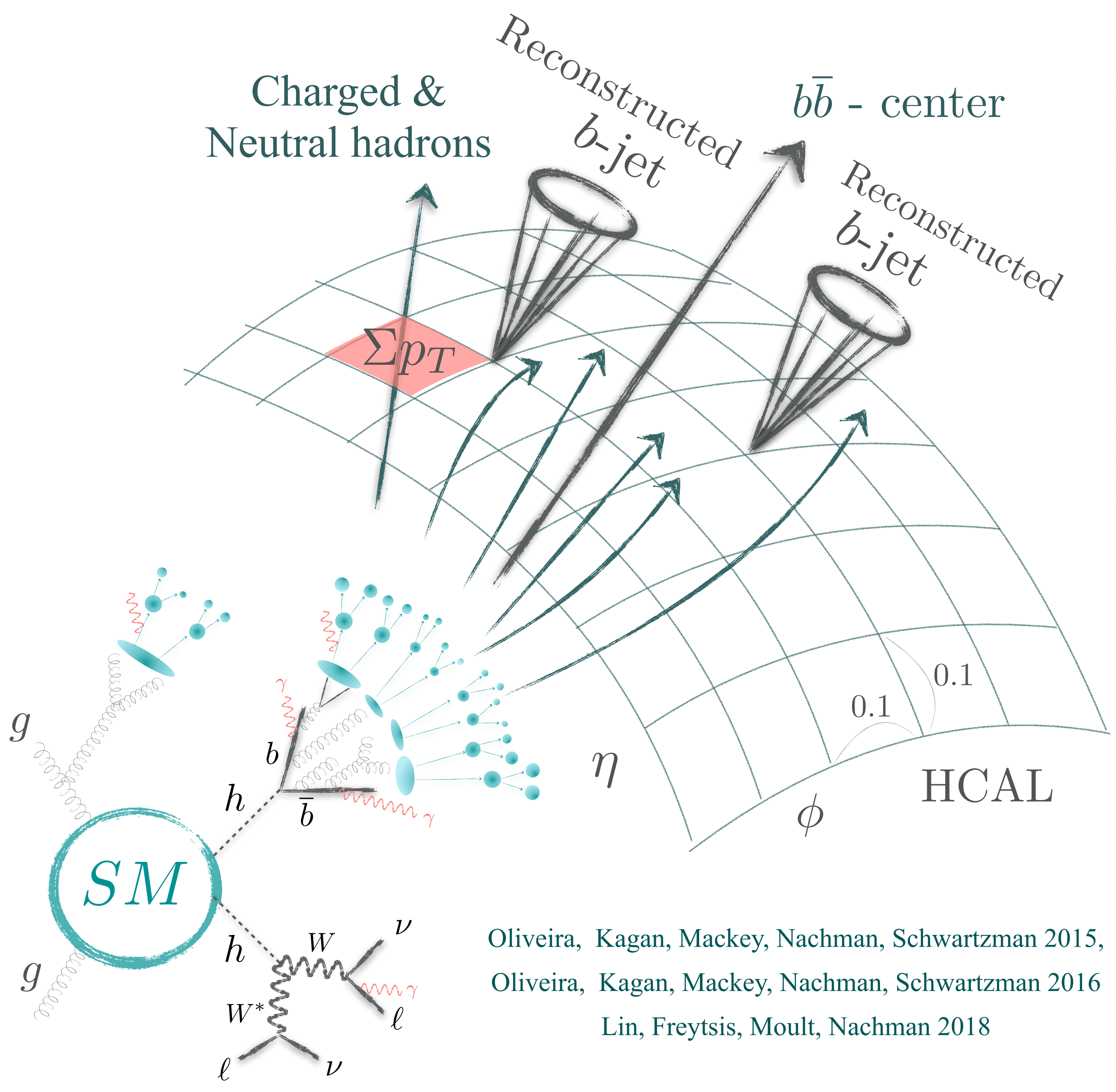
Each event



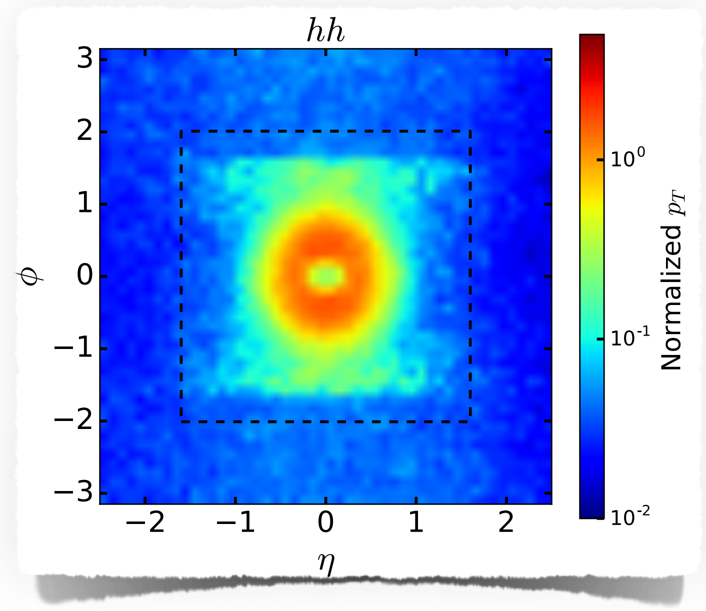


Kim, Kong, Matchev, Park JHEP 2019

Processing Hadron Images (hh)



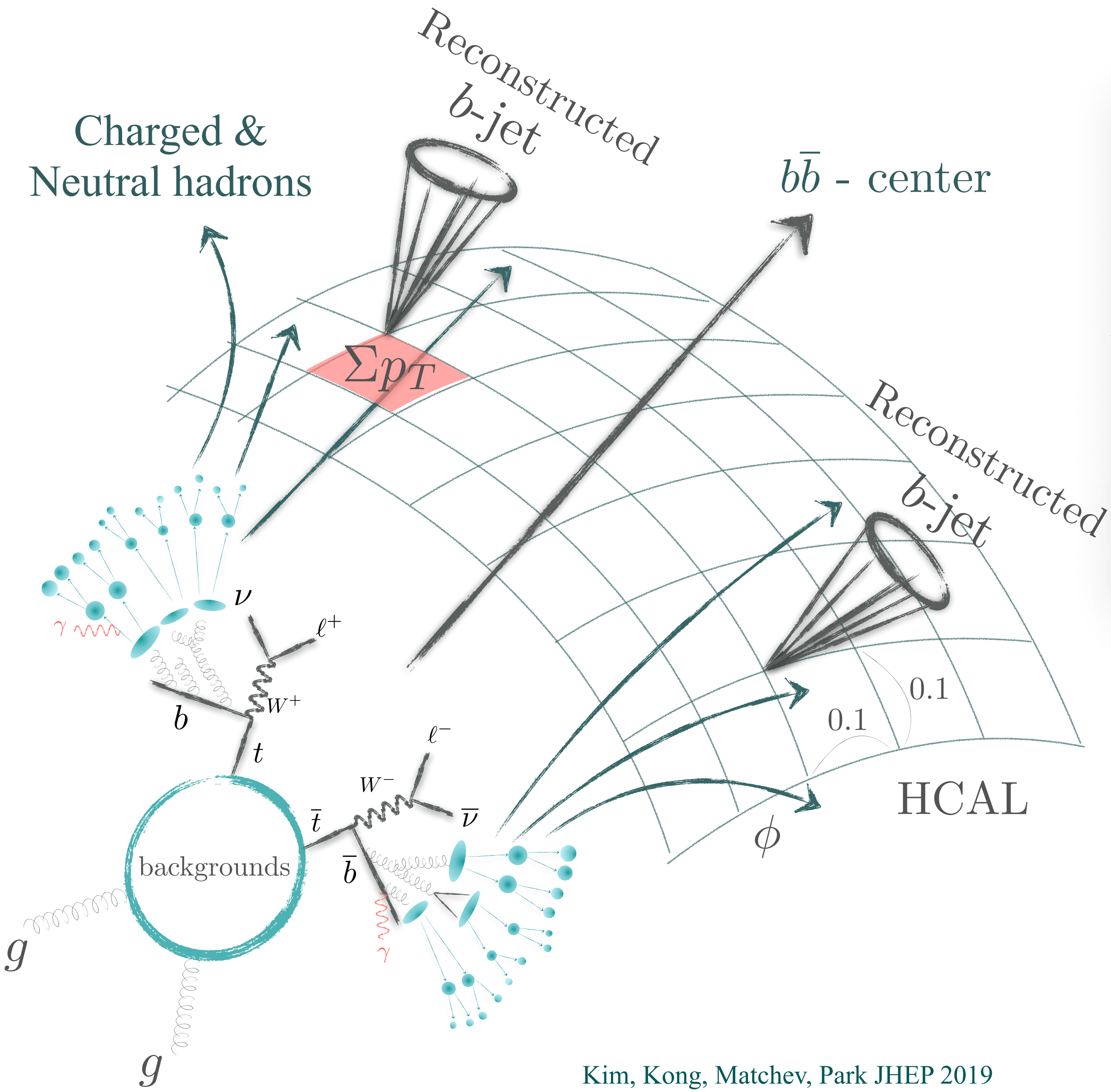
Sum of all events



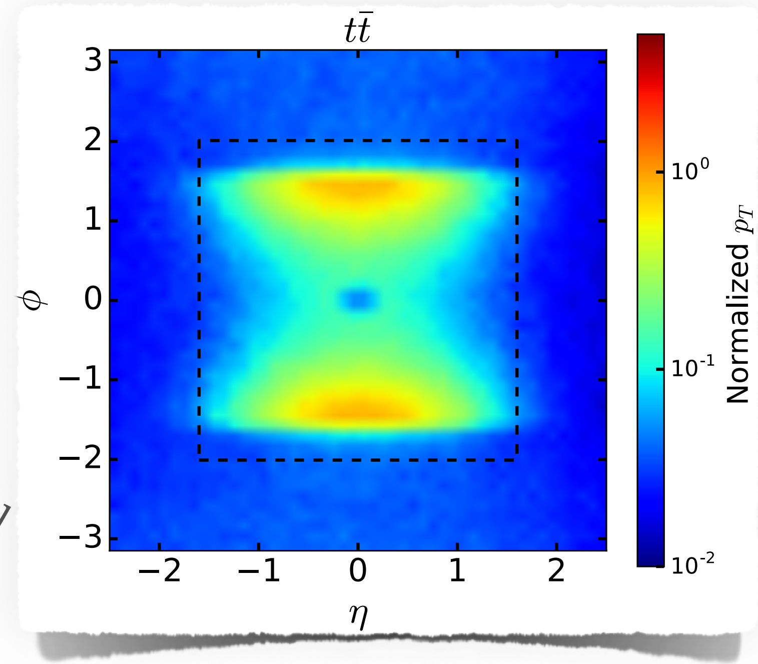
Oliveira, Kagan, Mackey, Nachman, Schwartzman 2015,
Oliveira, Kagan, Mackey, Nachman, Schwartzman 2016
Lin, Freytsis, Moult, Nachman 2018

Kim, Kong, Matchev, Park JHEP 2019

Processing Hadron Images (tt)



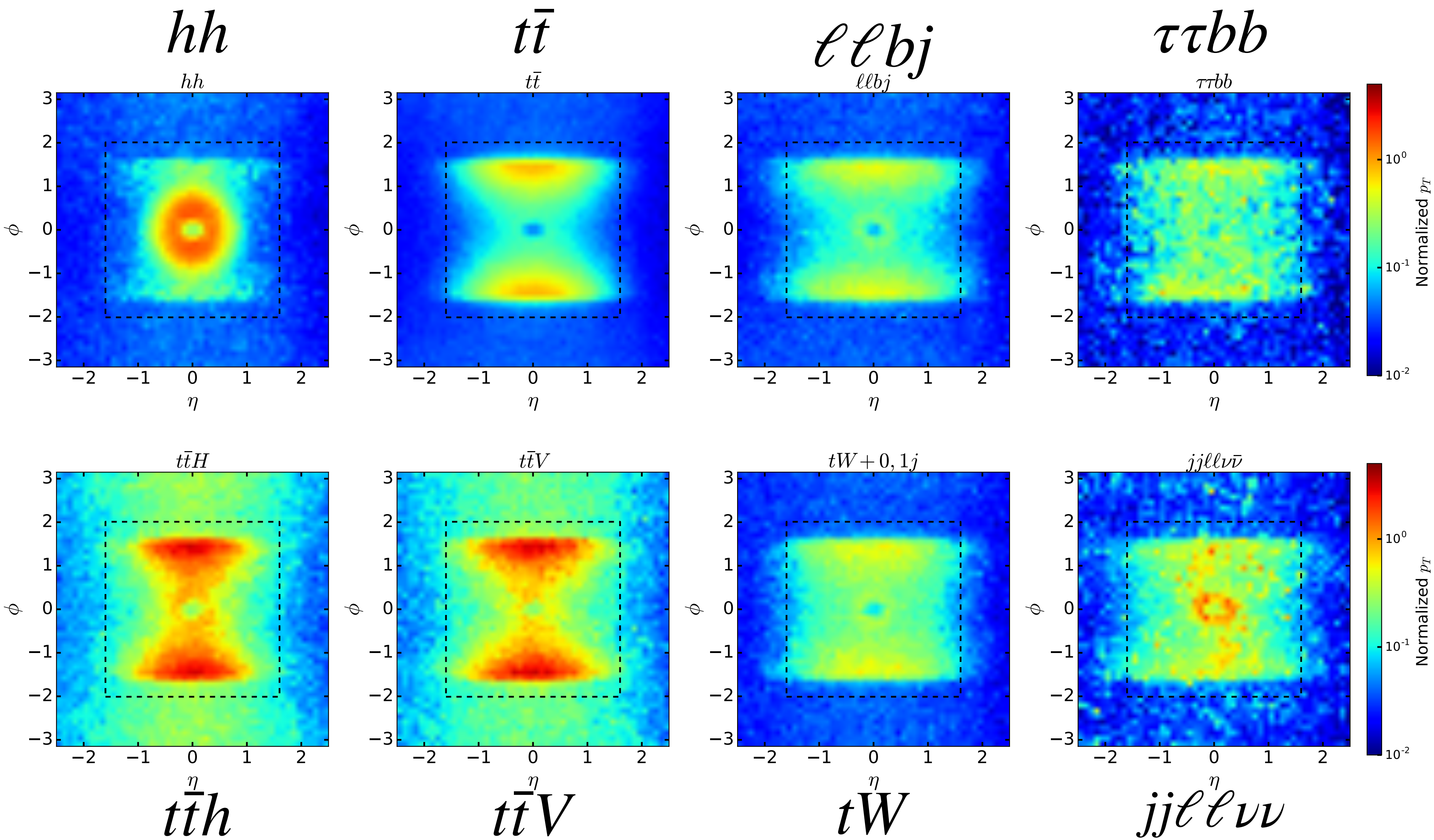
Sum of all events



Kim, Kong, Matchev, Park JHEP 2019

Jet images before baseline cuts

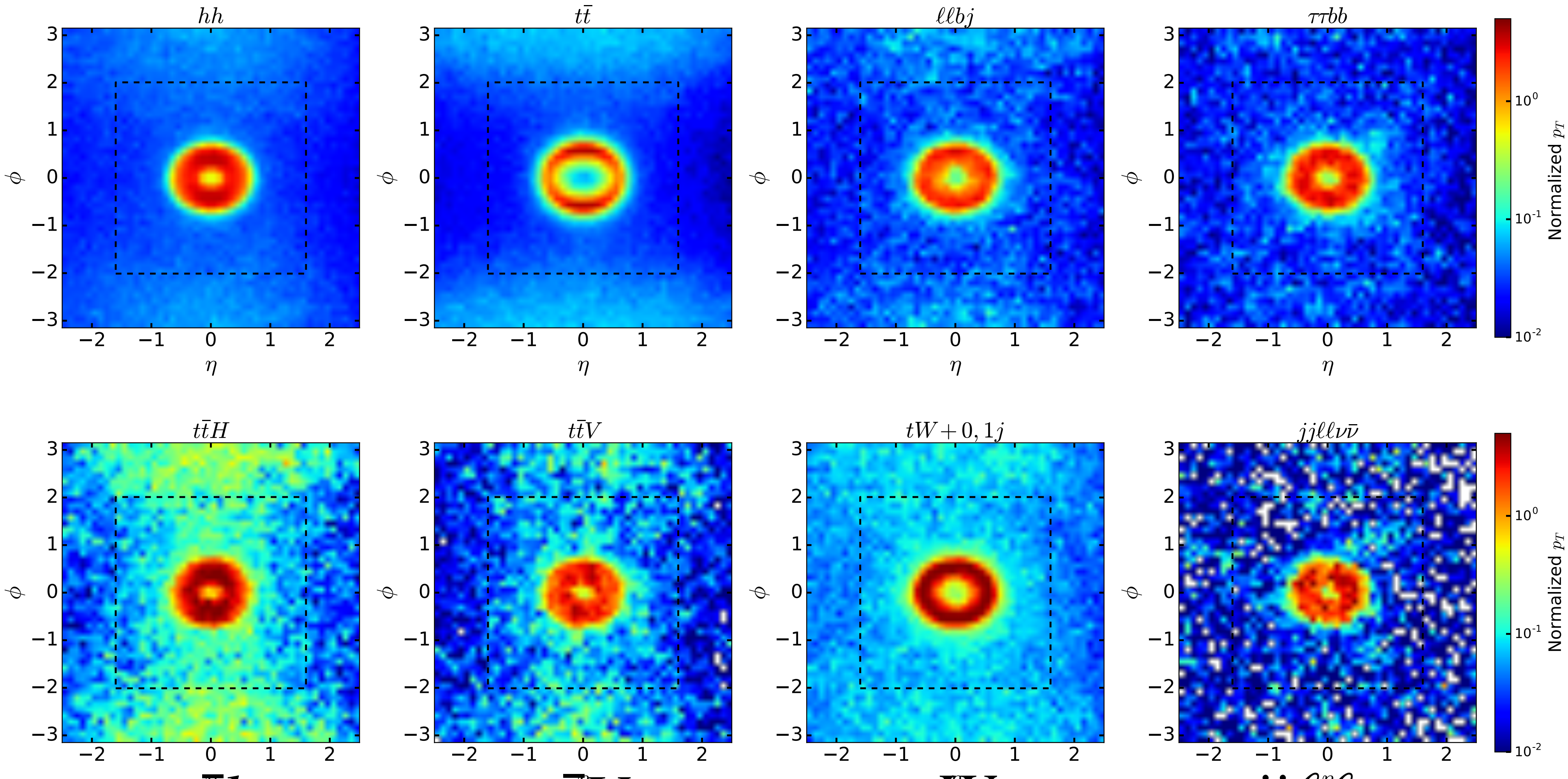
Kim, Kong, Matchev, Park JHEP 2019



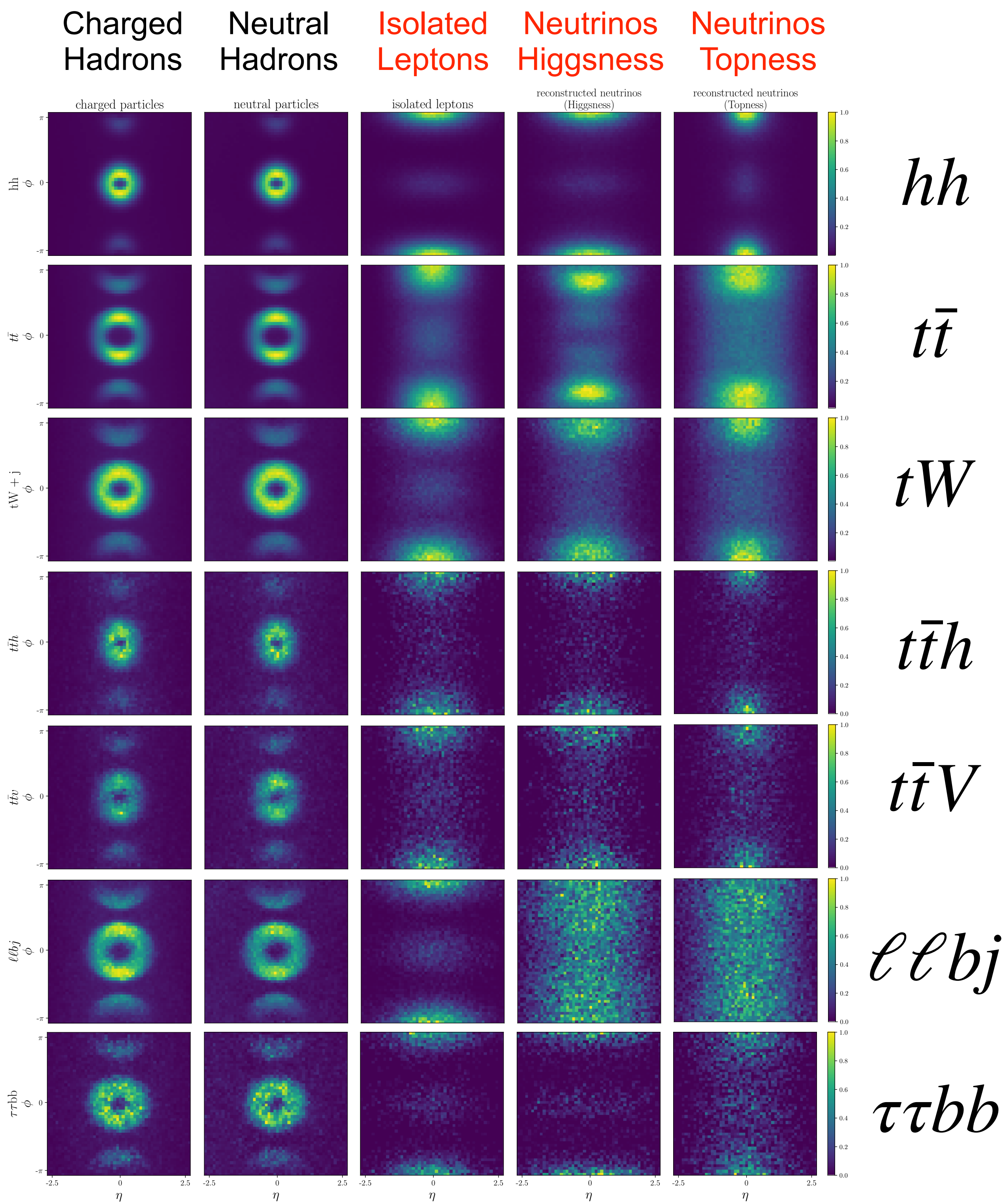
Jet images after baseline cuts

Kim, Kong, Matchev, Park JHEP 2019

hh $t\bar{t}$ $\ell\ell bj$ $\tau\tau bb$



$t\bar{t}h$ $t\bar{t}V$ tW $jj\ell\ell\nu\nu$



The Di-Higgs Photography

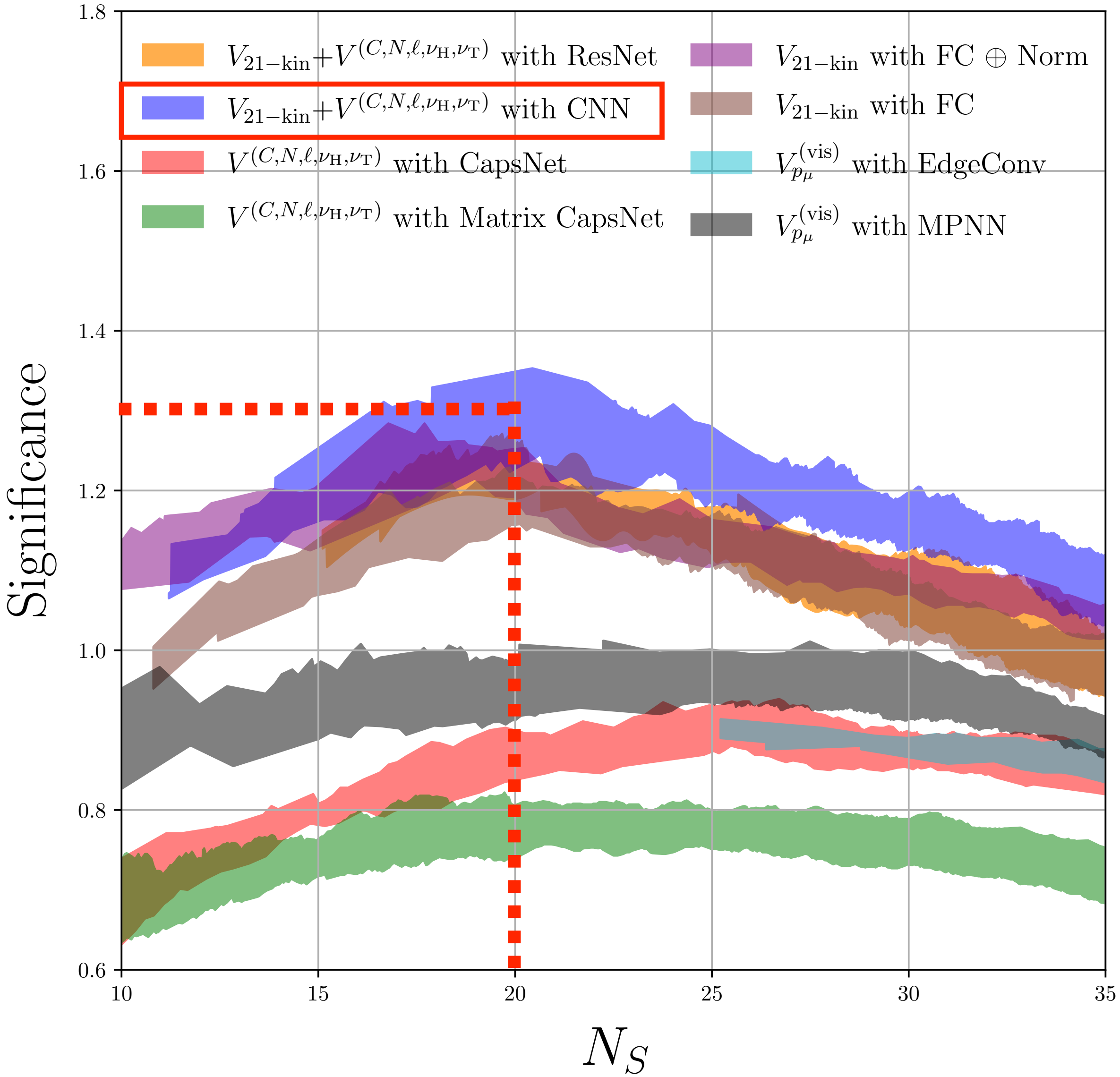
- Topness and Higgsness provide approximate neutrino momenta, which allow a complete reconstruction of the final state.
- From the W decay, we know that neutrino and lepton distributions must be similar.
- Use the additional lepton and neutrino images in NNs. Need enough training data and deep networks to catch correlation of all images.

$$V_{\rm image}^{(C,N,\ell,\nu_{\rm H},\nu_{\rm T})} = (5 \times 50 \times 50)$$

Huang, Kang, Kim, Kong, Pi, JHEP 2022

$$V_{\text{image}}^{(C,N,\ell,\nu_{\rm H},\nu_{\rm T})} = (5 \times 50 \times 50)$$

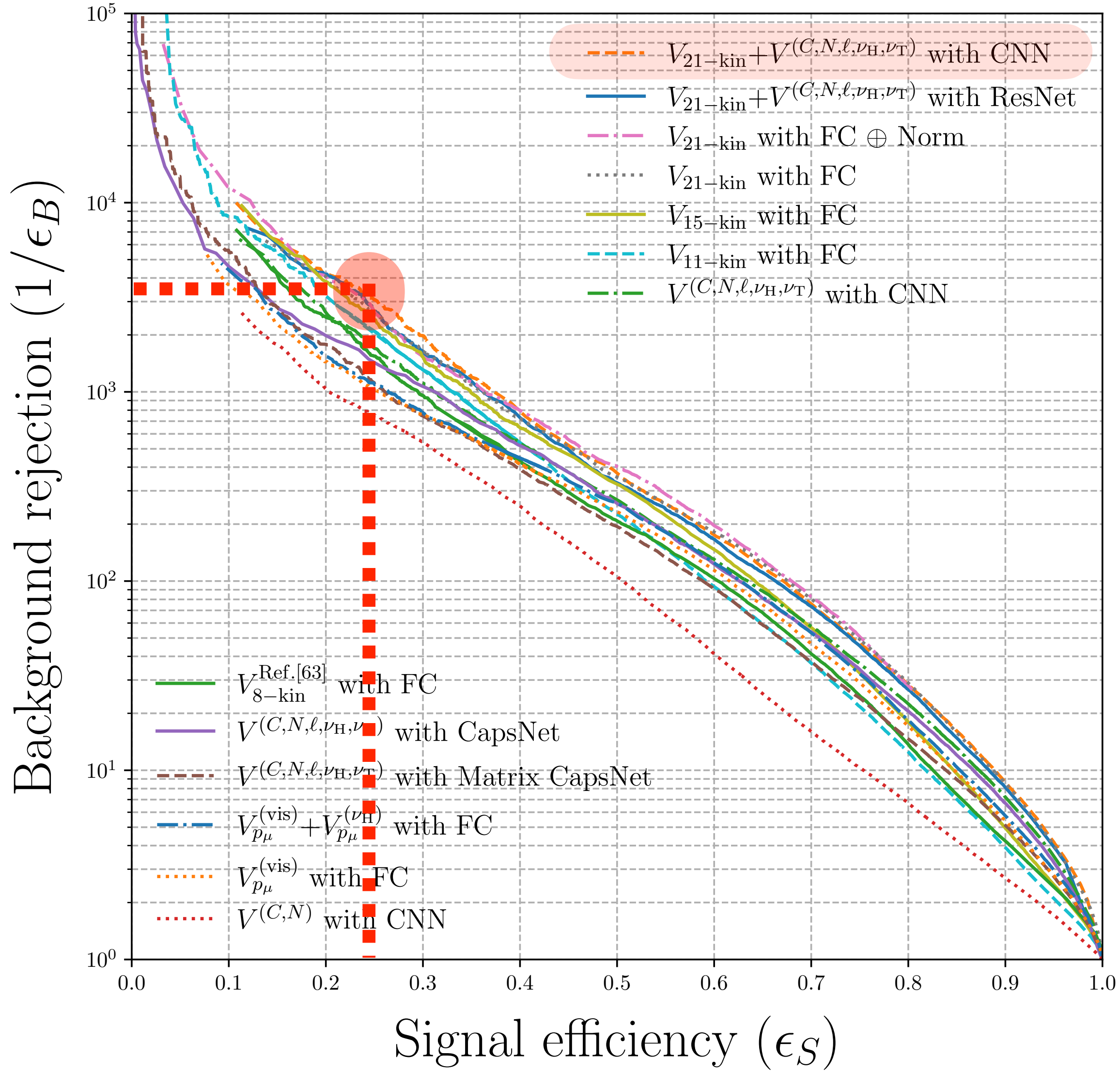
$$V_{\text{21-kin}} = \{\ p_T(\ell_1), p_T(\ell_2), p_{Tbb}, p_{T\ell\ell}, \not{P}_T, \Delta R_{bb}, \Delta R_{\ell\ell}, \Delta\phi_{bb,\ell\ell}, m_{\ell\ell}, m_{bb}, min[\Delta R_{b\ell}], \Delta R^{\rm H}_{\nu\nu}, m^{\rm H}_{\nu\nu}, \Delta R^{\rm T}_{\nu\nu}, m^{\rm T}_{\nu\nu}, \sqrt{\hat{s}}^{(bb\ell\ell)}_{\min}, \sqrt{\hat{s}}^{(\ell\ell)}_{\min}, M^{(b)}_{T2}, M^{(\ell)}_{T2}, {\rm H}, {\rm T}\ \}$$



- We have tried various NN architectures (DNN, CNN, ResNet, CapsNet, MPNN etc) with various combinations of input features (four momenta, kinematic variables, images).
- CNN with 21 kinematic variables + 5 images gives the best significance of ~1.3 for NS=20.
- We have repeated the same runs with 10 different random initializations, which give similar results.
- Images with leptons and neutrinos improve the results slightly.

Huang, Kang, Kim, Kong, Pi, JHEP 2022

Huang, Kang, Kim, Kong, Pi, JHEP 2022



Cross section after baseline cuts
(Before cutting on NN score)

	Cross sections [fb]	
$hh\ (\kappa_3 = 1)$	2.81×10^{-2}	
$t\bar{t}$	2.52×10^{2}	~97%
$tW + j$	5.73	~2%
$t\bar{t}h$	2.53×10^{-1}	
$t\bar{t}V$	3.18×10^{-1}	
$\ell\ell bj$	1.61	
$\tau\tau bb$	1.49×10^{-2}	

$$\sigma_{bknd}/\sigma_{hh} \approx 9250$$

After cutting on NN score
for CNN with 21 variables + 5 images

background rejection $= 1/\epsilon_B = 3{,}500$

signal efficiency $= \epsilon_S = 0.23$

NS=20 and NB=220

$\sigma_{bknd}/\sigma_{hh} \approx 11$

$t\bar{t}$: 44 %

$t\bar{t}h + t\bar{t}V$: 22 %

tW : 24 %

$\ell\ell bj + \tau\tau bb$: 10 %

Combination of various channels

$\sigma(hh)^{NNLO}_{SM} \simeq 40.7 \text{ fb} \quad (\ 14 \text{ TeV}\ )$

higher branching ratios

cleaner final state

	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%

1902.00134	Statistical-only		Statistical + Systematic	
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$HH \to b\bar{b}VV\,(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ\,(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

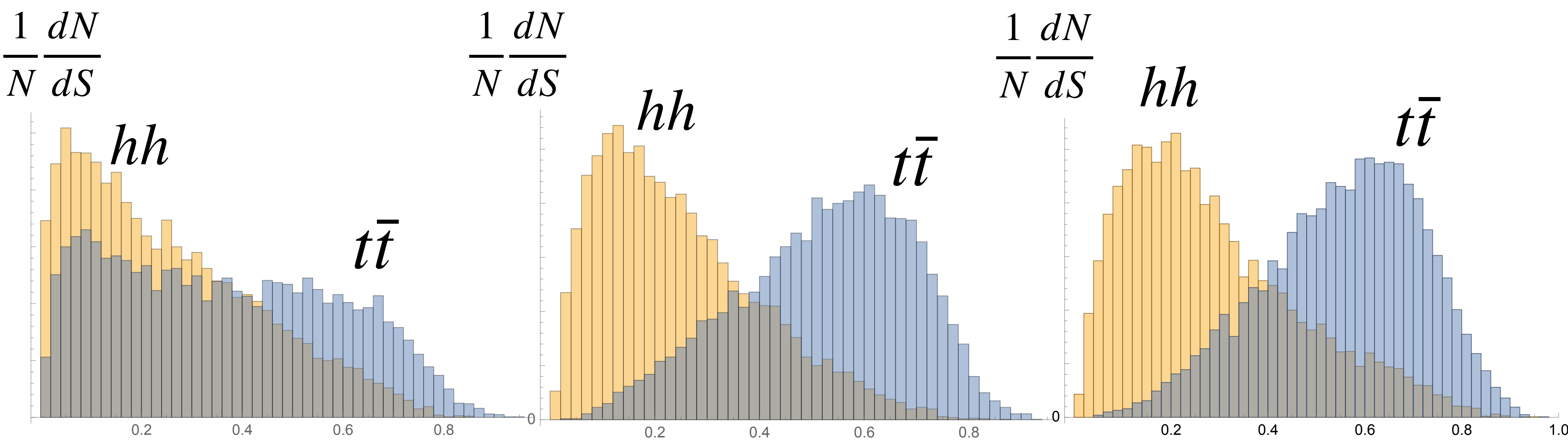
4σ expected for ATLAS+CMS!

- These measurements are challenged by a low σ (hh) and small branching ratios (BR).
- No single channel is expected to reach 3 sigma at HL-LHC.
- The combination of different channels is crucial. bbWW has good potential for further improvement.

Channel	Statistical only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$hh \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$hh \to b\bar{b}\tau^+\tau^-$	2.5	1.6	2.1	1.4
$hh \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$hh \to b\bar{b}VV(\ell\ell\nu\nu)$	-	0.59	-	0.56
$hh \to b\bar{b}ZZ(4\ell)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	combined 4.5		combined 4.0	
combined with the new results on $hh \to b\bar{b}VV(\ell\ell\nu\nu)$ in this study	**3.8**	**3.0**	**3.2**	**2.8**
	combined **4.8**		combined **4.2**	

- We roughly reproduce all significances in the other channels following 1902.00134, and combine the new/updated result from $bb\ell\ell$ channel.
- The significances are added in quadrature, and the channels are treated as uncorrelated, assuming that the systematic uncertainties such as the theory uncertainties and the luminosity uncertainty, have little impact on the individual results.
- We assume 10% reduction in the signal significance, to take into account the systematics in the $bb\ell\ell$ channel,

Shape variables



Parton-level Sphericity in lab frame assuming perfect neutrino reconstruction

Parton-level Sphericity in CM frame assuming perfect neutrino reconstruction

Delphes-level Sphericity in CM frame using Higgsness for reconstruction

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i \mid p_i \mid^2}, \quad \lambda_1 + \lambda_2 + \lambda_3 = 1$$

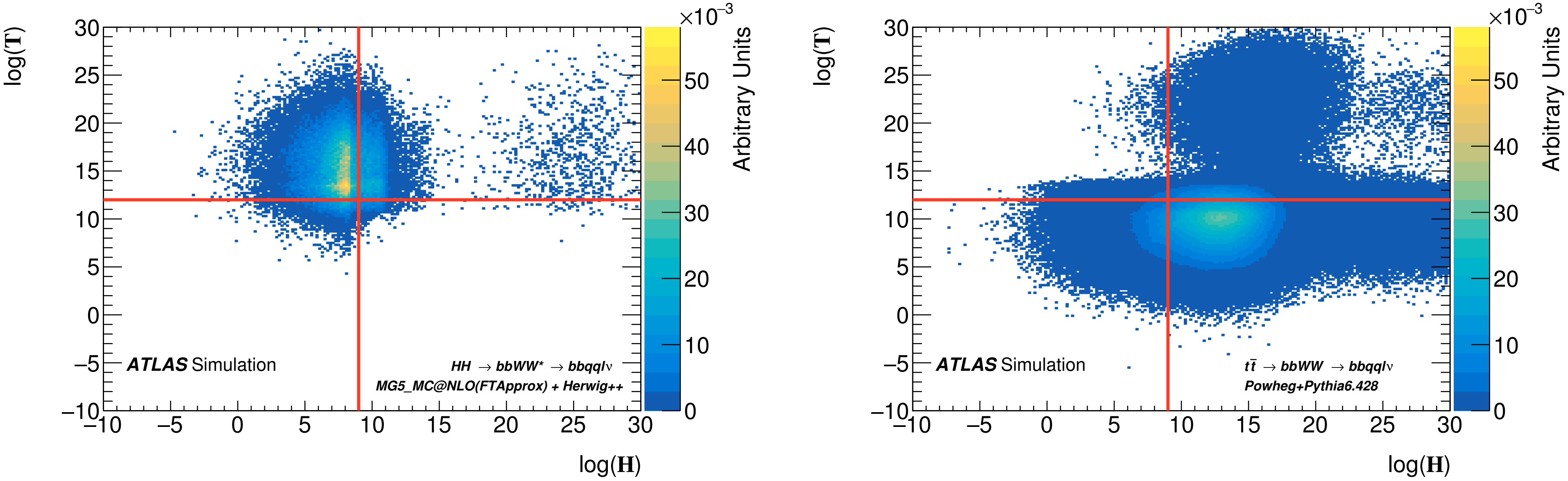
$$\lambda_1 \geq \lambda_2 \geq \lambda_3$$

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

- S -> 0: pencil-like event
- S -> 1: isotropic event
- Results using Topness are similar.

Huang, Kang, Kim, Kong, Pi, JHEP 2022

HH: semi-leptonic channel



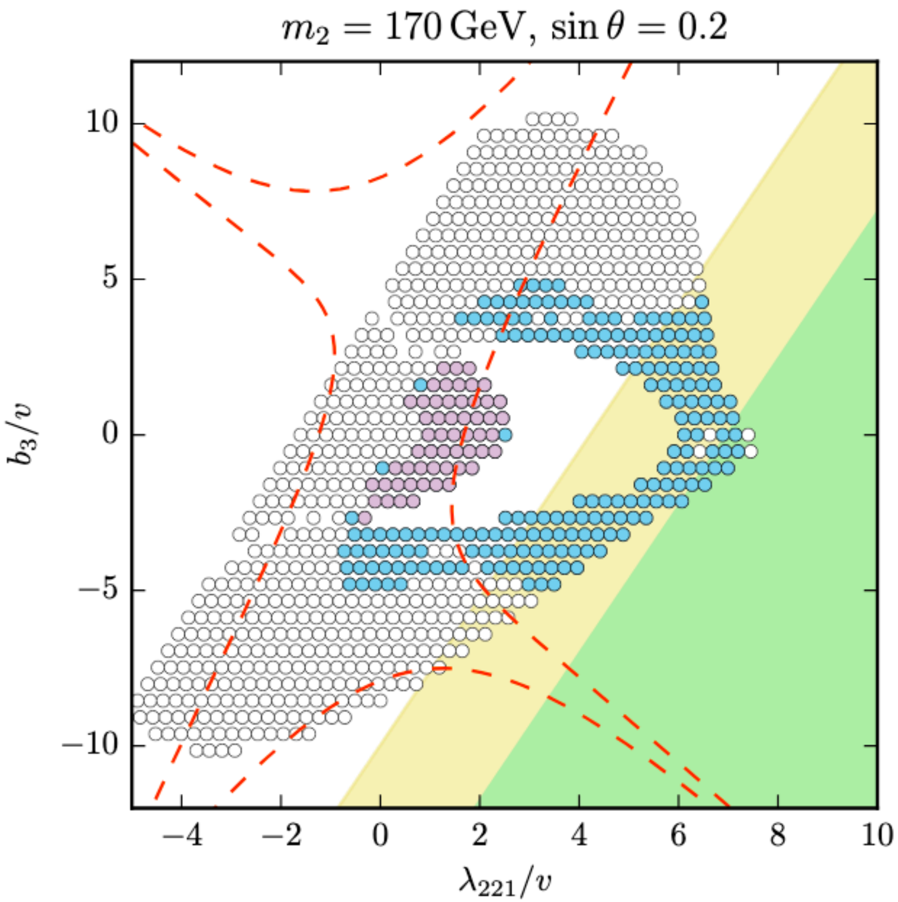
(a) (b)

Figure 2: Distribution of Higgsness and Topness in a two-dimensional plane ($log(\mathbf{H})$, $log(\mathbf{T})$) for simulated signal $HH \to bbWW^* \to bbqql\nu$ (a) and background $t\bar{t} \to bbWW \to bbqql\nu$ (b) events without selection requirements. The signal sample is generated with MG5_MC@NLO(FTApprox) + Herwig++, while the background sample is generated with Powheg + Pythia6.428. The distributions are normalised to unit area. Red lines are drawn to give a visible reference for a possible separation between signal and background.

ATL-PHYS-PUB-2019-040

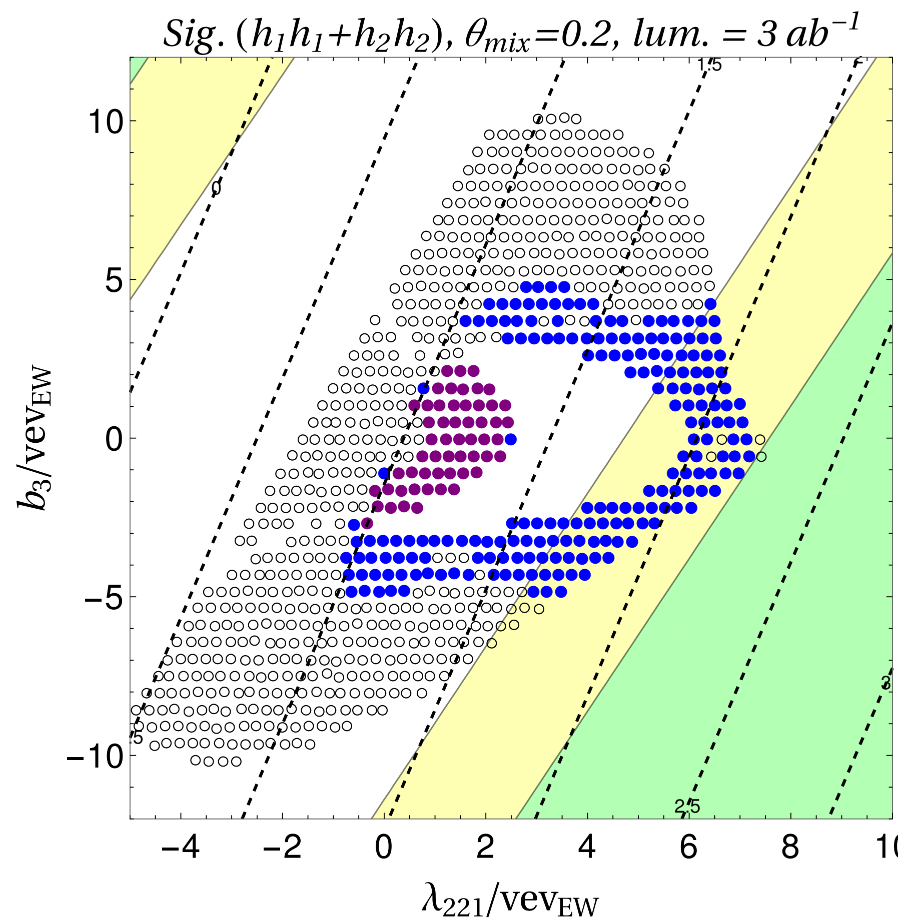
Chen, Kozaczuk, Lewis, 1704.05844, Non-resonant Collider Signatures of a Singlet-Driven Electroweak Phase Transition

Exclusion (yellow) and discovery reach (green) in h2 h2 -> 2j 3l + met channel at the HL-LHC.



Alhazmi, Kim, Kong, Lewis, preliminary

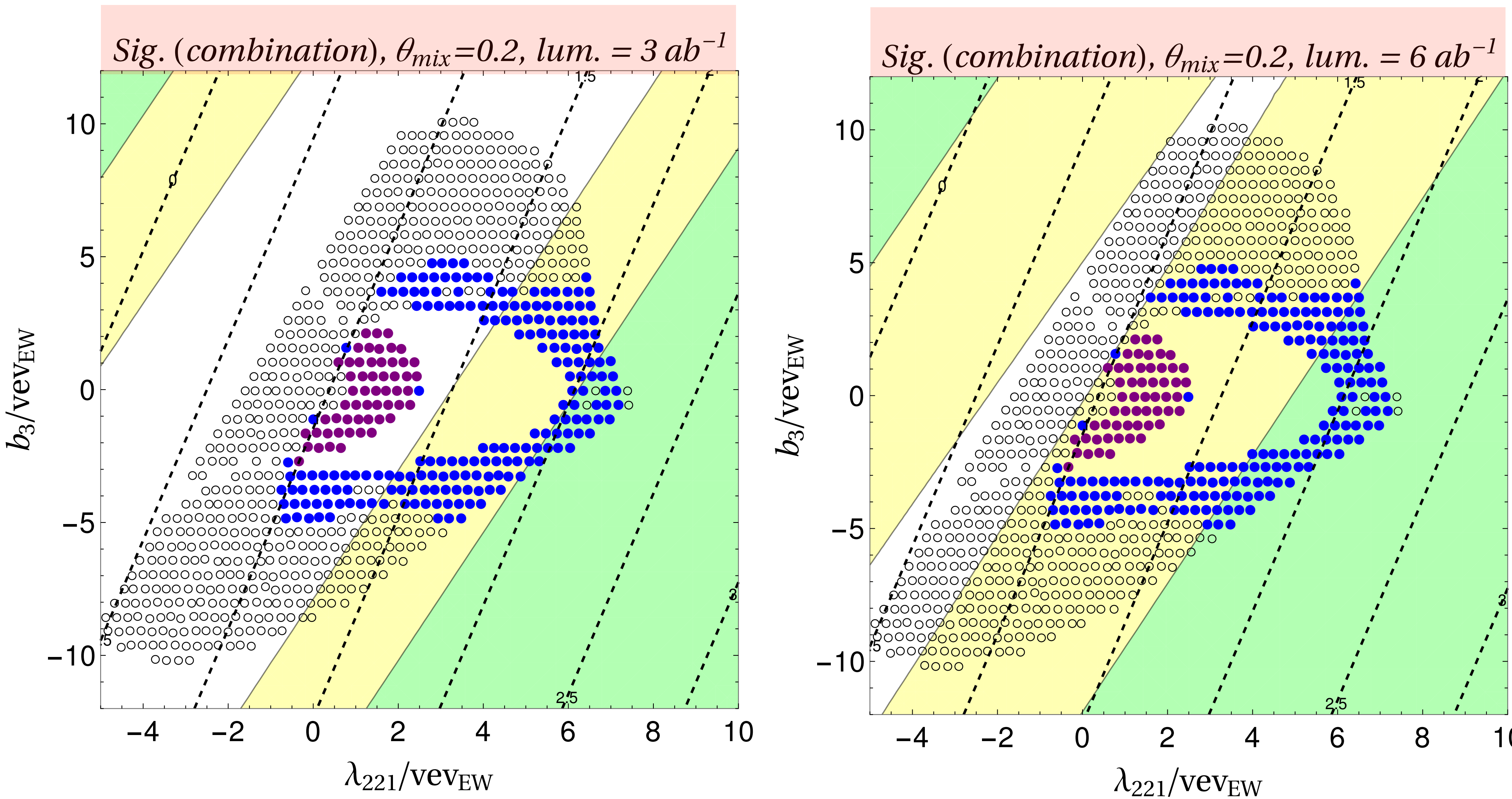
Exclusion (yellow) and discovery reach (green) in h1 h2 + h1 h1 -> bb 2l + met channel at the HL-LHC.



Blue points feature an EWPT with $\phi_h(T_c)/T_c \geq 1$ for some value of $b_4 > 0.01$ utilizing the one-loop daisy-resummed thermal effective potential. Purple points additionally feature a strong first-order electroweak phase transition as predicted by the gauge-invariant high-T approximation (which drops the Coleman-Weinberg potential and is thus only applied to regions with tree-level vacuum stability). Strong electroweak phase transitions are typically correlated with sizable values of λ_{221}.

Exclusion (yellow) and discovery reach (green) for combining h2 h2 -> 2j 3l + met and h1 h2 + h1 h1 -> bb 2l + met channel at the HL-LHC.

(Mixing angle=0.2 and mH=170 GeV)



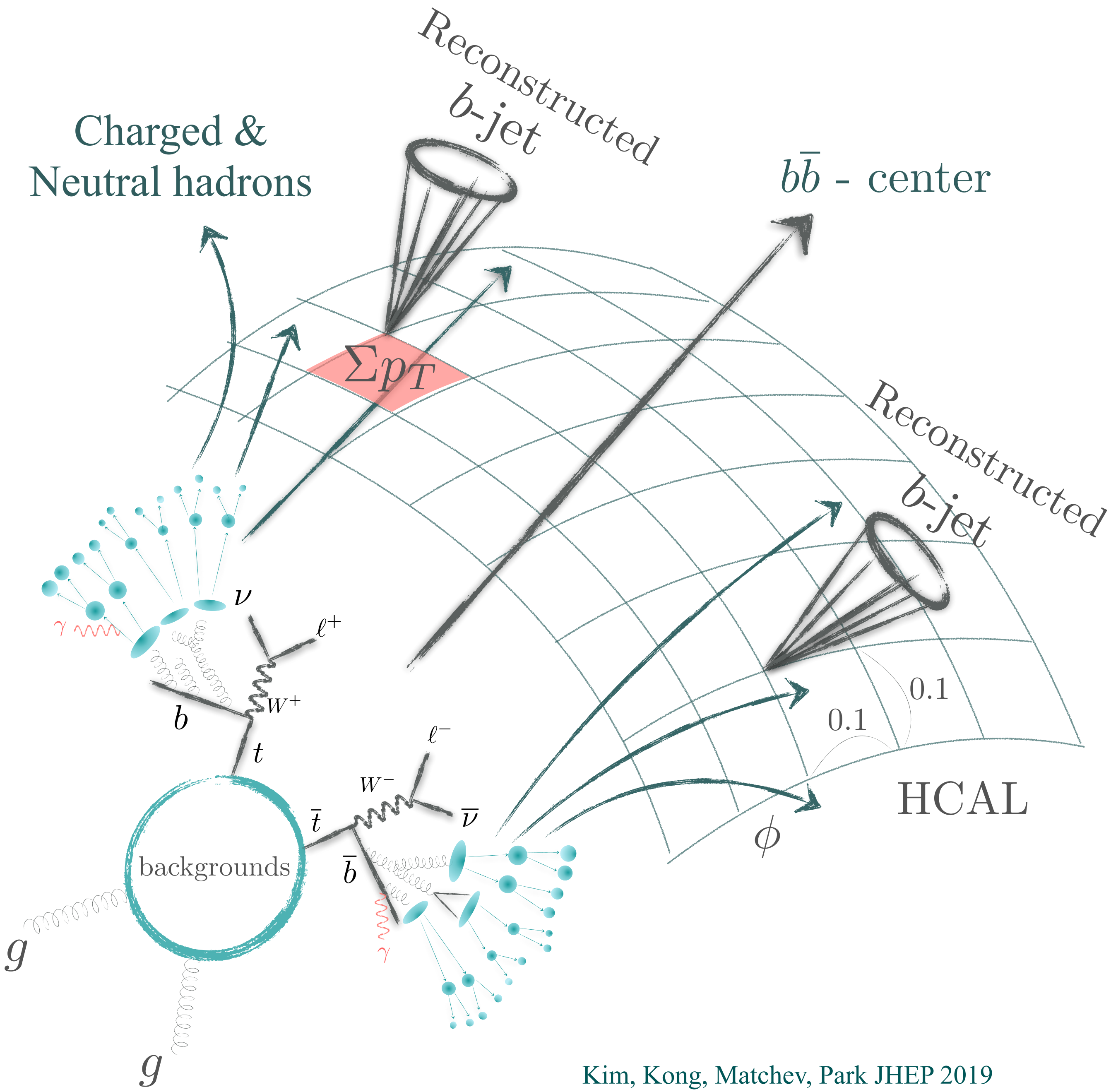
Alhazmi, Kim, Kong, Lewis, preliminary

Summary

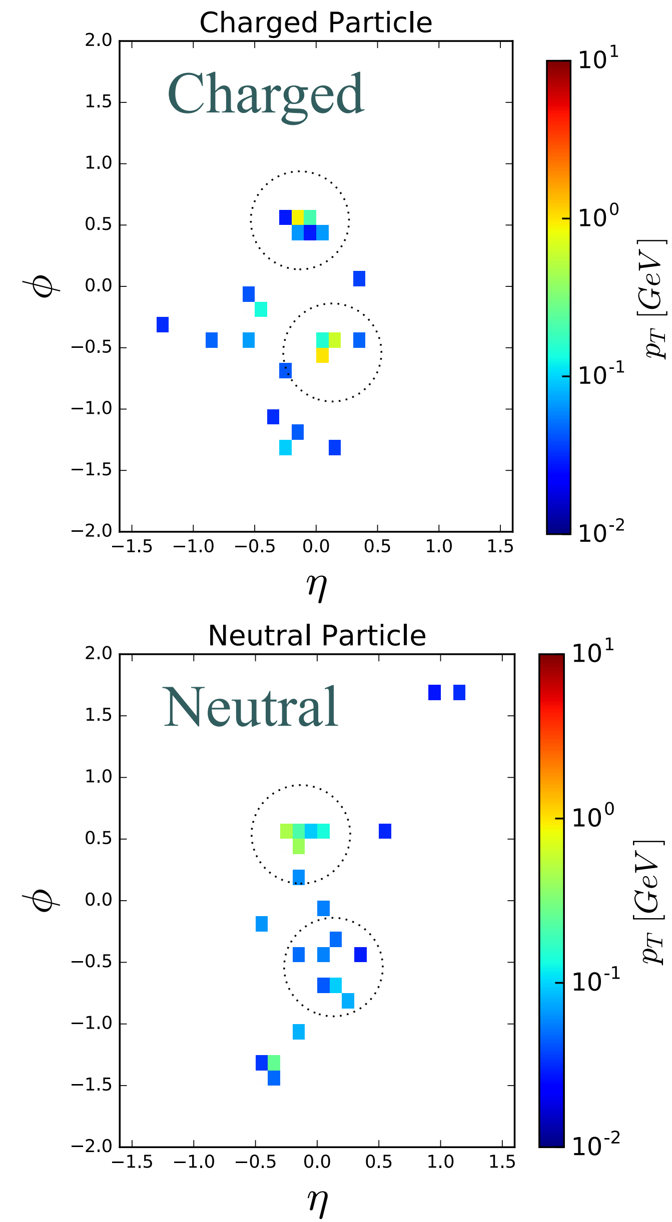
- Higgs self couplings are important to understand the nature of electroweak symmetry breaking. The HL-LHC will have a sensitivity to the measurement of the triple Higgs coupling via double Higgs production.
- Double Higgs production is challenging due to small signal cross section / large SM backgrounds, which requires combination of multiple channels.
- bbWW dilepton channel is one of difficult channels due to strong correlation among many kinematic variables.
- Multivariate analysis could benefit from deep neural networks using jet images and sophisticated kinematic variables such as Topness / Higgsness with mass information. Further improvement may be possible by optimizing network structure (ResNets, CapsNets)
- Topness/Higgsness provide approximate momenta of the missing neutrinos.
- bbWW channel could make a significant contribution in the combination of multiple channels for the triple Higgs coupling measurement.
- Application in the semi-leptonic channel, and non-resonant HH production in the singlet extension of SM.

Additional slides

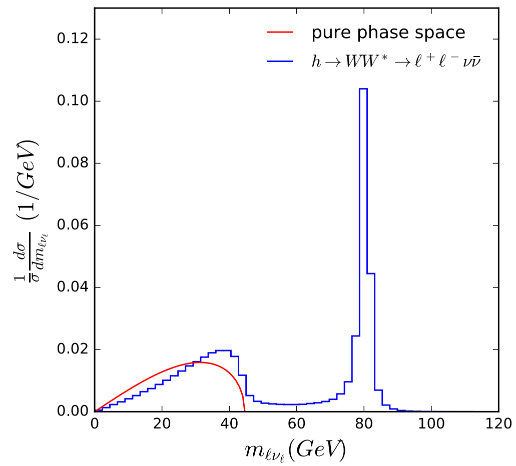
Processing Hadron Images (tt)



Each event



Kim, Kong, Matchev, Park JHEP 2019



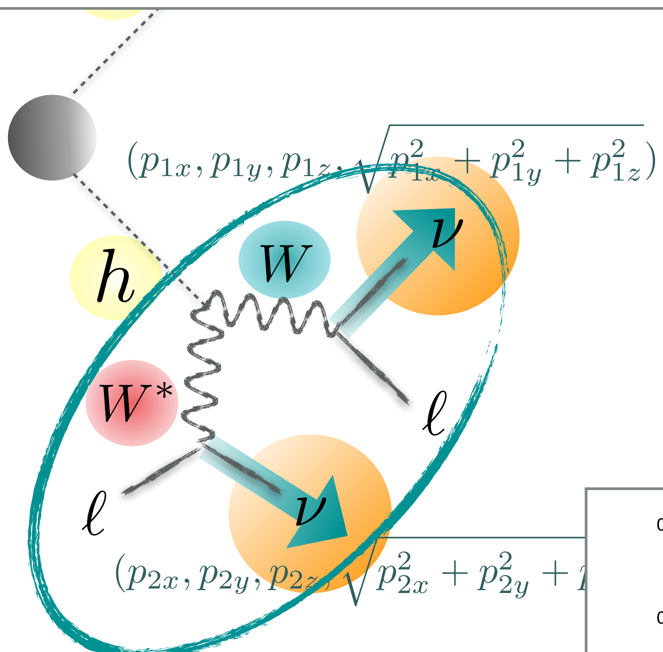
$$m_{W^*}^{peak} = \frac{1}{\sqrt{3}}\sqrt{2\left(m_h^2 + m_W^2\right) - \sqrt{m_h^4 + 14m_h^2 m_W^2 + m_W^4}}$$

$$E = \sqrt{m_W m_{W^*}\, e^{\eta}}\,,$$

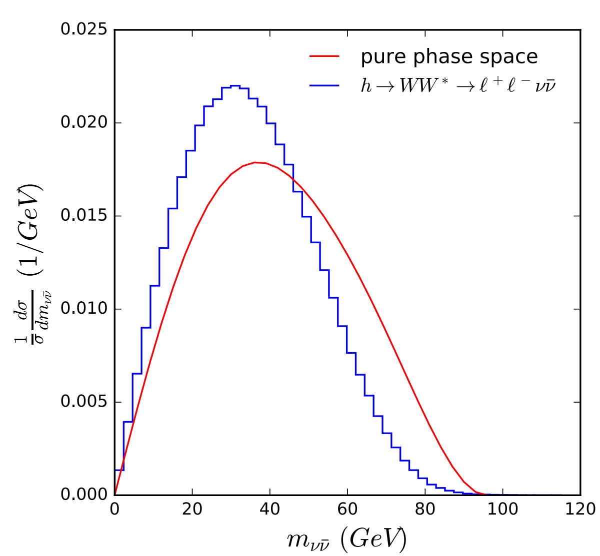
$$\cosh\eta = \left(\frac{m_h^2 - m_W^2 - m_{W^*}^2}{2m_W m_{W^*}}\right)$$

$$\ldots h^2)^2 + \frac{\left(m_{\nu\bar{\nu}}^2 - m_{\nu\bar{\nu},peak}^2\right)^2}{\sigma_\nu^4}$$

$$+min\left(\frac{\left(m_{\ell^+\nu}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{\ell^-\bar{\nu}}^2 - m_{W^*,peak}^2\right)^2}{\sigma_{W_*}^4},\ \frac{\left(m_{\ell^-\bar{\nu}}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{\ell^+\nu}^2 - m_{W^*,peak}^2\right)^2}{\sigma_{W_*}^4}\right)\Bigg],$$



- Higgsness provides a de…
- The off-shell W also has…
- Its distribution is wide,…



$$\frac{d\sigma}{dm_{\nu\bar{\nu}}} \propto \int dm_{W^*}^2 \lambda^{1/2}(m_h^2, m_W^2, m_{W^*}^2) f(m_{\nu\bar{\nu}})$$

$$f(m) \sim \begin{cases} \eta\, m\,, & 0 \le m \le e^{-\eta}E, \\ m\ln(E/m)\,, & e^{-\eta}E \le m \le E, \end{cases}$$

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$$

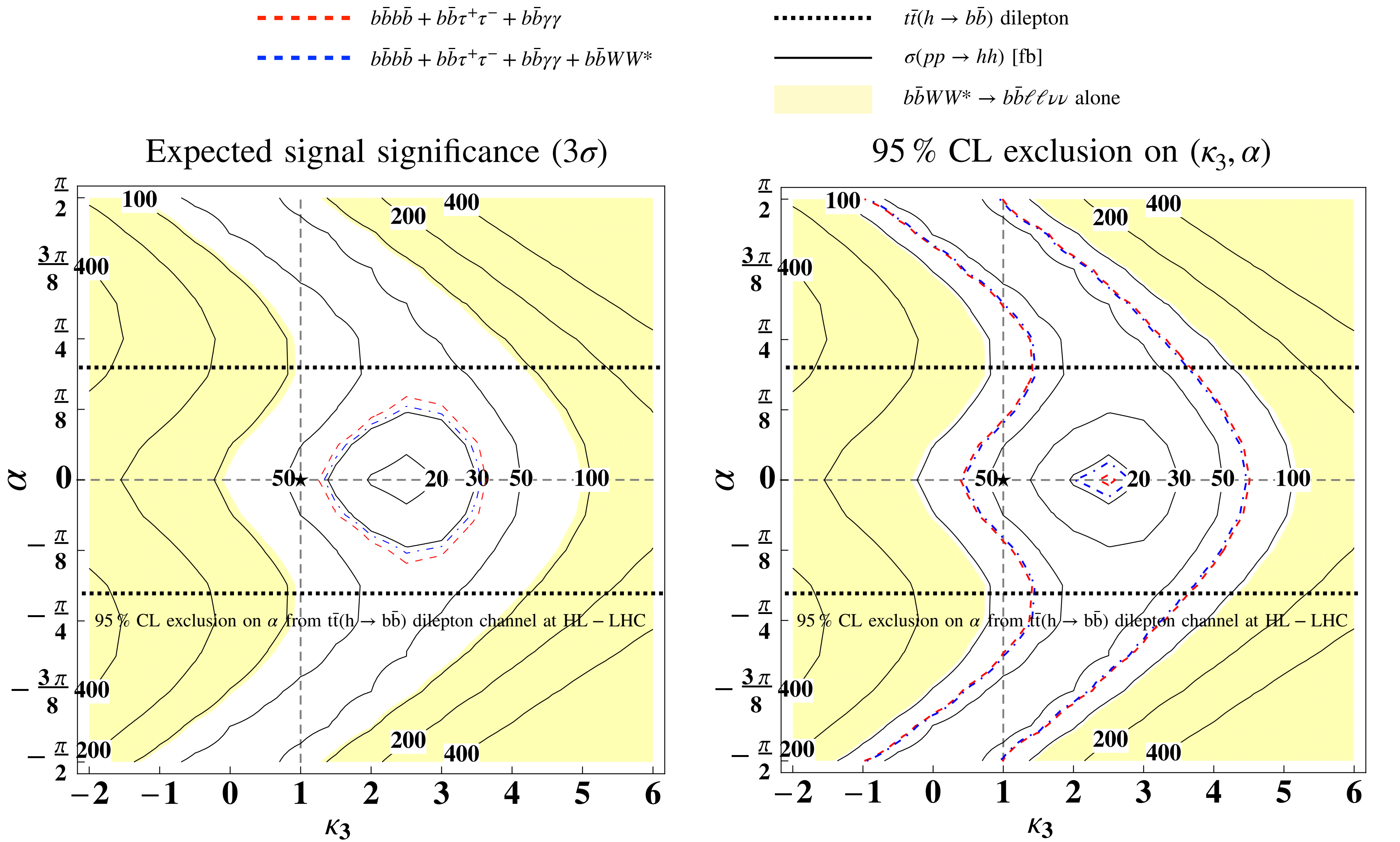


Figure 15. Expected 3σ significance of observing Higgs boson pair production (left) and 95% C.L. exclusion (right) in the (κ_3, α) plane at the HL-LHC with 3 ab^{-1}. We used the binned log-likelihood analysis with statistical uncertainties only, assuming the same efficiencies for all (κ_3, α) values as one for $(\kappa_3, \alpha) = (1, 0)$ (SM point denoted by $\star$). Contours of the double Higgs production cross section (in fb) are shown in black-solid curves. The yellow shaded region is obtained using results in this study for the dilepton channel ($hh \to b\bar{W}W^* \to b\bar{b}\ell\nu\bar{\nu}$). The red dashed curve is obtained combining three channels, $b\bar{b}b\bar{b} + b\bar{b}\tau^+\tau^- + b\bar{\gamma}\gamma$ following Ref. [45], while the blue dashed curve includes all four channels. The horizontal-black dotted line represents a sample 95% exclusion on the CP angle from the dilepton channel of $t\bar{t}h$ production with $h \to b\bar{b}$ [103], $|\alpha| \lesssim 35°$.

Pile-up

- Soft Drop method: a powerful pile-up mitigation technique
- Tried without neural layers (for which pile up effect would be worse)
- We adopt the definition for a missing transverse momentum from ATLAS, which excludes contributions from soft neutral particles

$$\vec{\not{p}}_T = -\left(\sum \vec{p}_{T\ell} + \sum \vec{p}_{T\gamma} + \sum \vec{p}_{Tj} + \sum \vec{p}_{T(\mathrm{track})}\right)$$

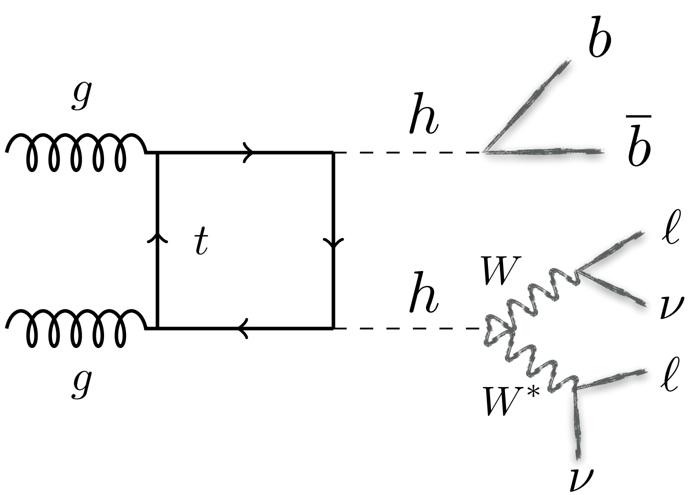
Here the last term is added to consider unused soft tracks. These tracks are required to have $p_T > 0.4$ GeV, $|\eta| < 2.5$ and transverse (longitudinal) impact parameter $|d_0| < 1.5\,\mathrm{mm}$ ($|z_0 \sin\theta| < 1.5\,\mathrm{mm}$). To reduce effects from pile-up, we only use particles which have track information.

Pile-up

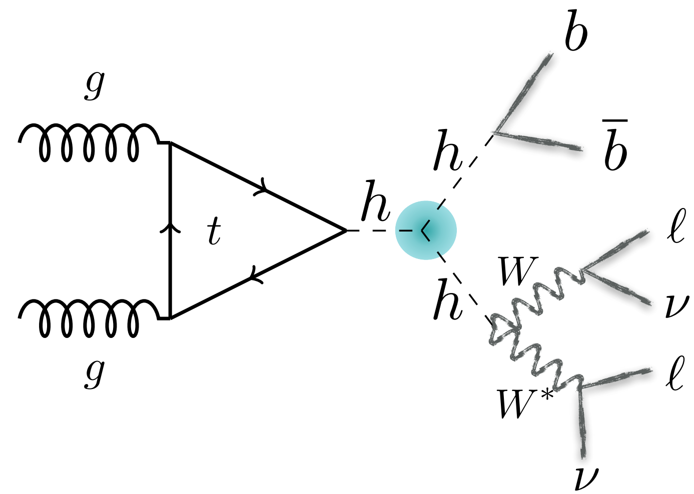
$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

In order to examine the effects of pile-up, we use several methods as follows. In the first method, we use the Soft Drop algorithm [58] to remove soft jet activity which is exacerbated by pile-up. We set $\beta = 0$ and $z_{\text{cut}} = 0.1$ with $R = 1.2$ anti-k_T clustered fatjets. Then we select the closest fatjet to the $b\bar{b}$ momentum in the η-ϕ plane and replace the particle flow data with the charged and neutral jet constituents of the selected fatjet. Soft Drop does not affect the jet images and retains the same shapes as in Fig. 8. In second method, we remove the neutral jet image layer in the analysis. Unlike charged particles, which can be cleaned up from pile-up relatively easily by checking the longitudinal vertex information [106], neutral particles cannot be treated the same way and suffer from non-removable pile-up effects. The corresponding results with these two pile-up mitigation methods are also shown in Fig. 11 with the red dotted line labelled "16var with jetimage DNN, SoftDrop" and the red, dashed line labelled "16var with jetimage DNN, no neutral layer", respectively.

Why double Higgs (*hh*) ?



+



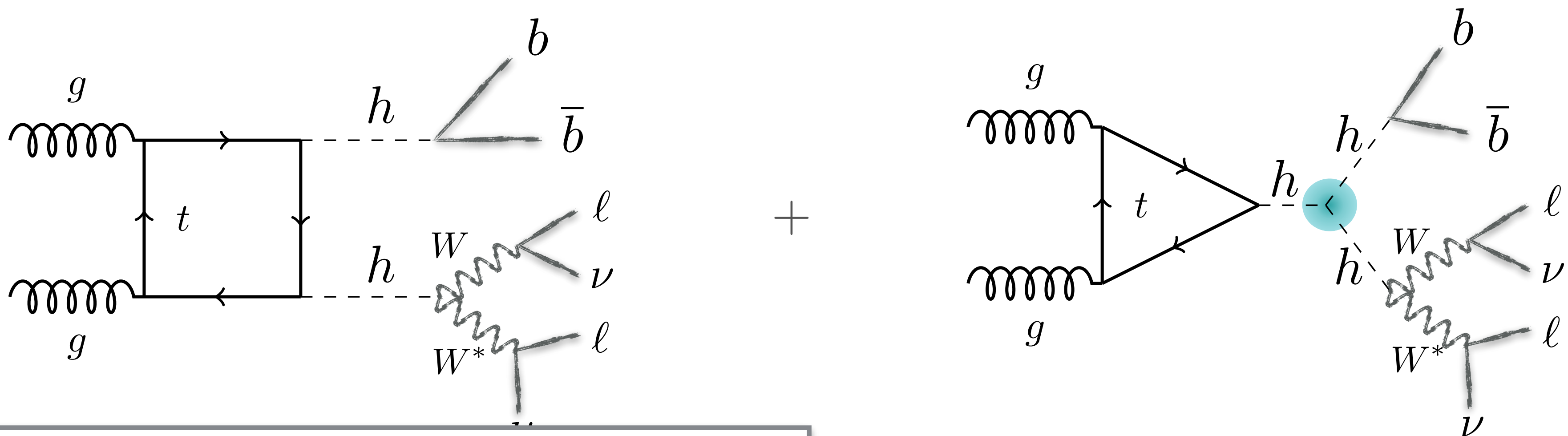
$$V_h = \frac{m_h^2}{2}h^2 + c_3\frac{m_h^2}{2v}h^3 + c_4\frac{m_h^2}{8v^2}h^4$$

$$\sim c_3 y_t^2 \frac{\alpha_S}{4\pi}\frac{m_h^2}{\hat{s}}\left(log\frac{m_t^2}{\hat{s}} + i\pi\right)^2$$

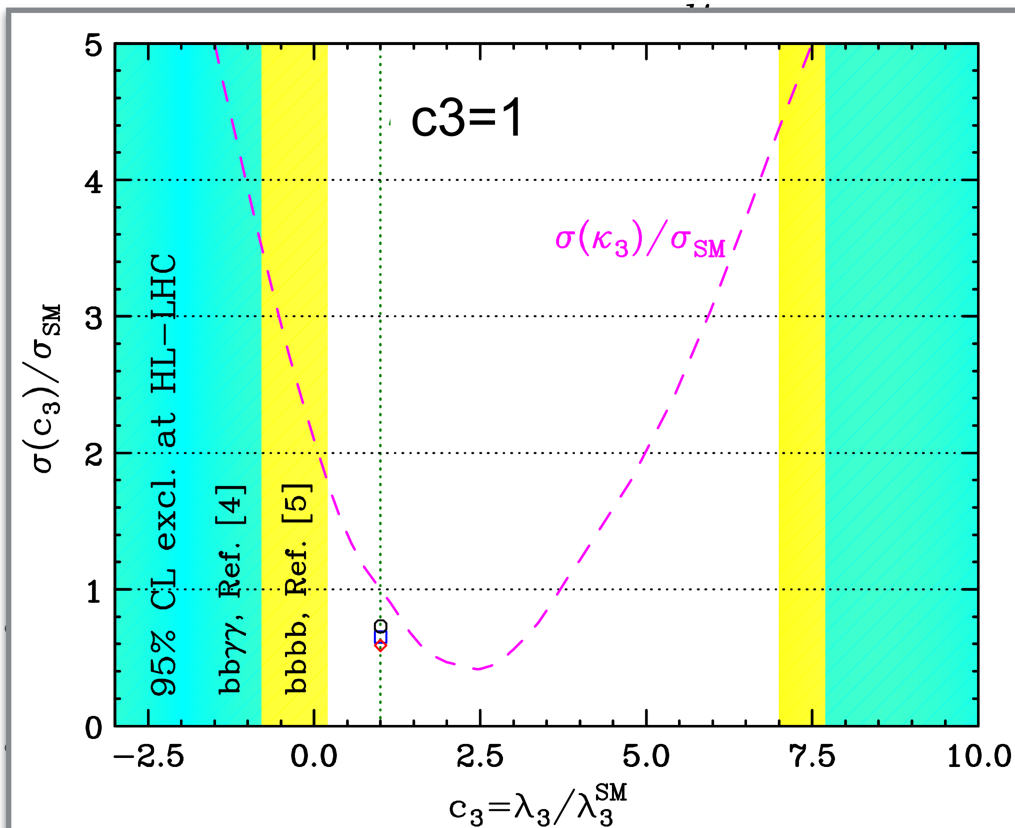
- Measurement of triple and quartic couplings provides crucial input to confirm SM prediction. The knowledge of c3 and c4 is crucial to reconstruct the Higgs potential for better understanding of EWSB. Any deviation will lead to new physics beyond SM. The HL-LHC will have opportunity to probe triple Higgs self-coupling (c_3), while we will need a new machine to probe quartic coupling (c4).
- The c_3 is sensitive at lower-energy bins where the backgrounds are large.
- Destructive interference between two diagrams in SM makes it difficult to probe c3.

For Higgs EFT, see talks by Adam Martin and Andrea Sciandra.

Why double Higgs (hh) ?



$$\sim c_3 y_t^2 \frac{\alpha_S}{4\pi} \frac{m_h^2}{\hat{s}} \left(log \frac{m_t^2}{\hat{s}} + i\pi \right)^2$$



des crucial input to confirm SM prediction. The
e Higgs potential for better understanding of EWSB.
M. The HL-LHC will have opportunity to probe triple
machine to probe quartic coupling (c4).

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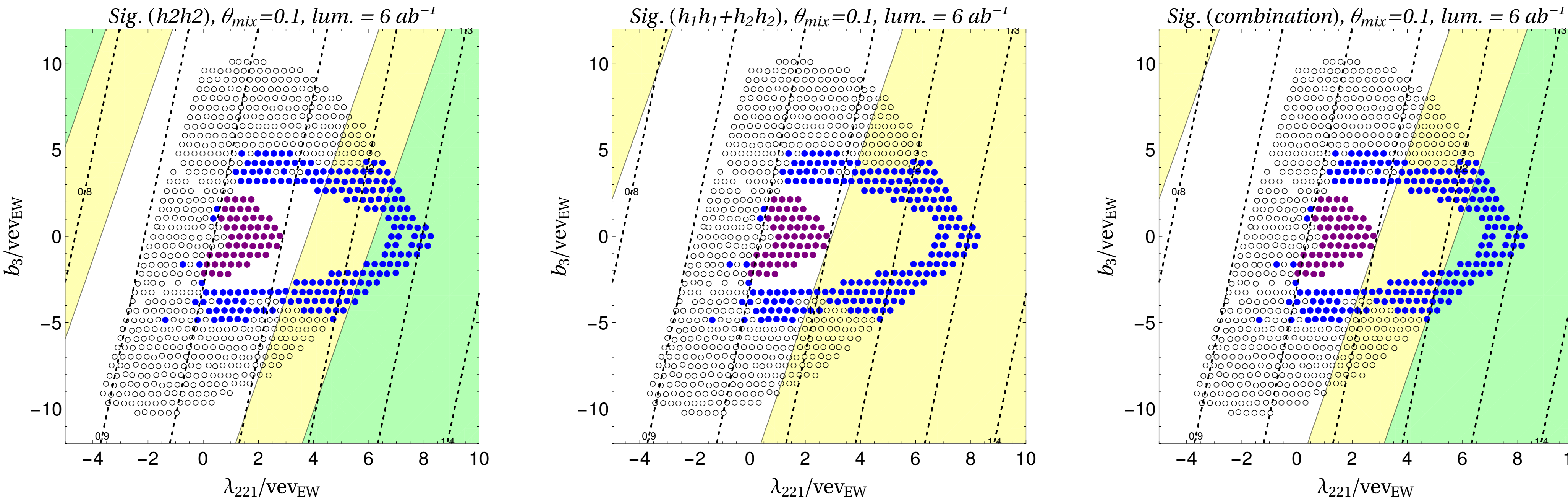
ms in SM makes it difficult to probe c3.

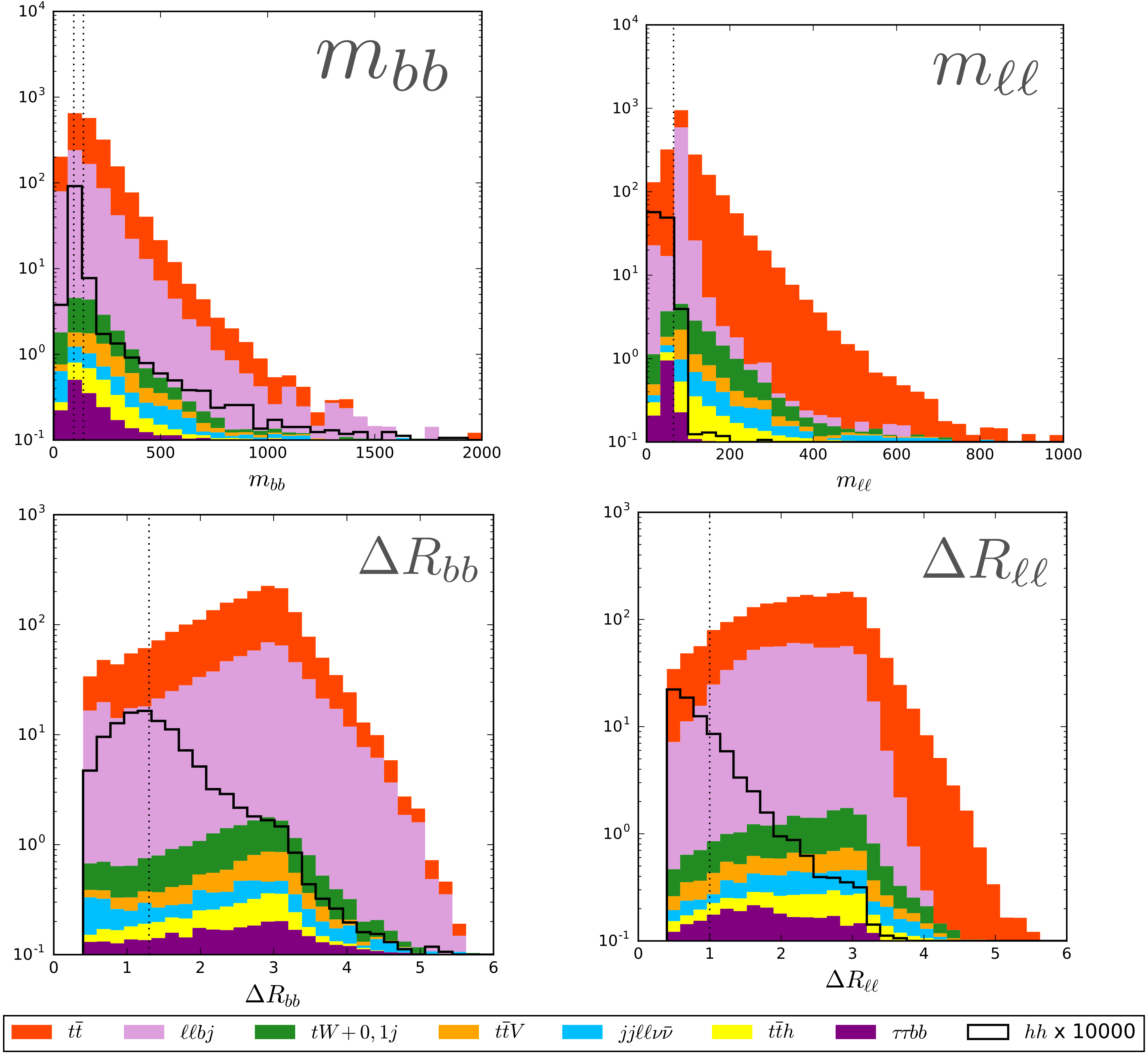
Exclusion (yellow) reach for combining h2 h2 -> 2j 3l + met and h1 h2 + h1 h1 -> bb 2l + met channel at the HL-LHC.

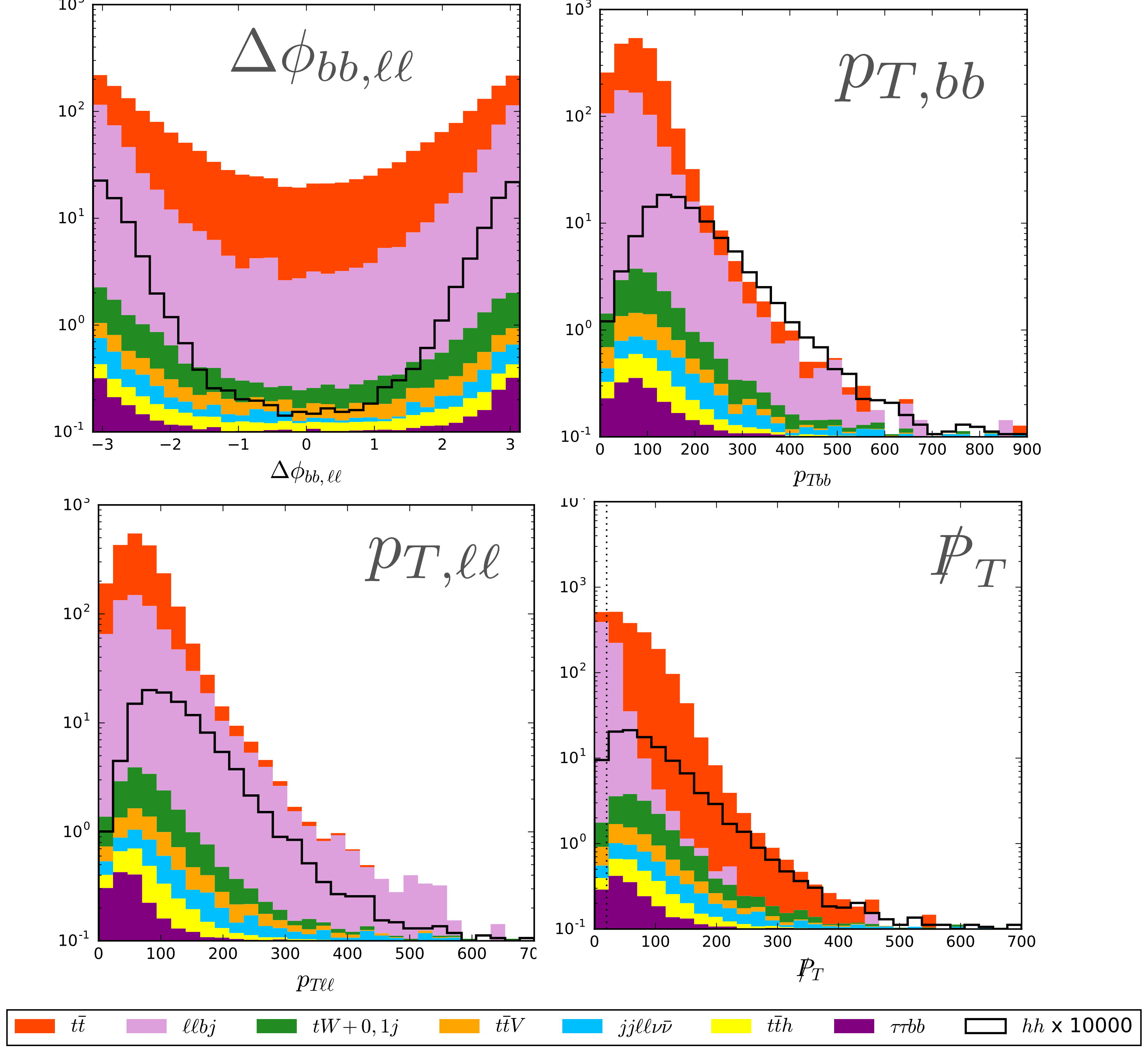
(Mixing angle=0.1 and mH=170 GeV)

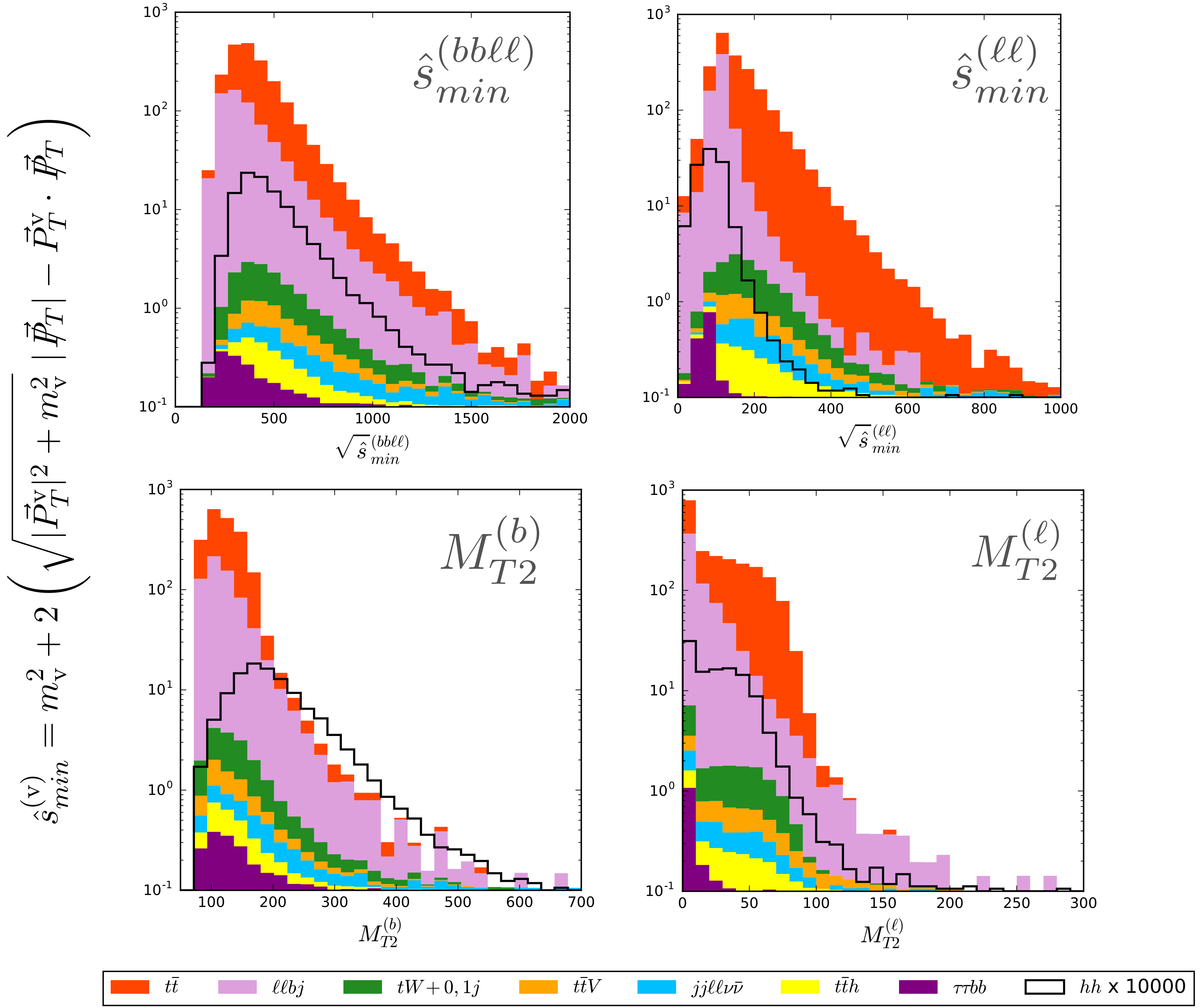


Alhazmi, Kim, Kong, Lewis, preliminary

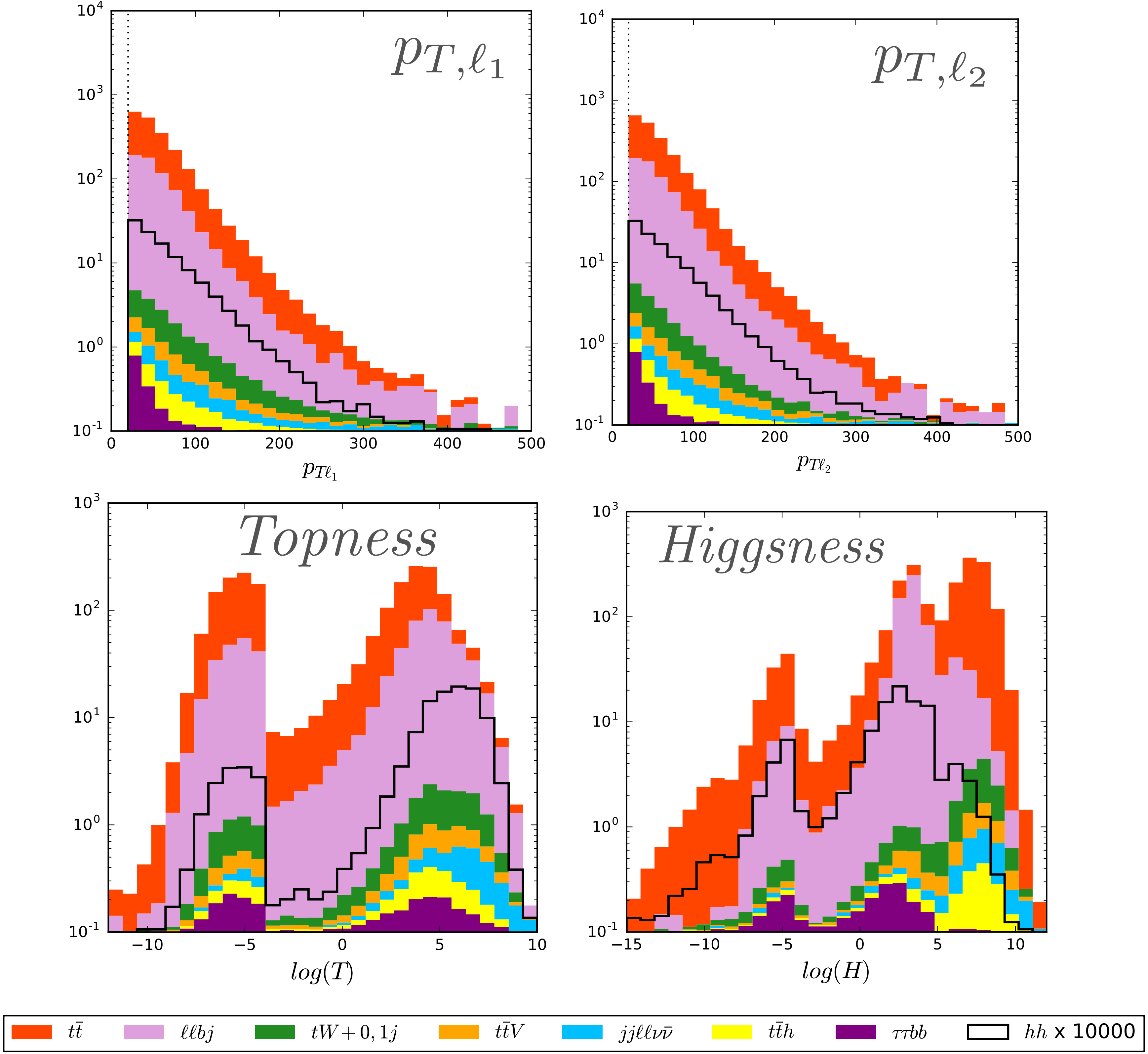
Dotted lines are baseline cuts.



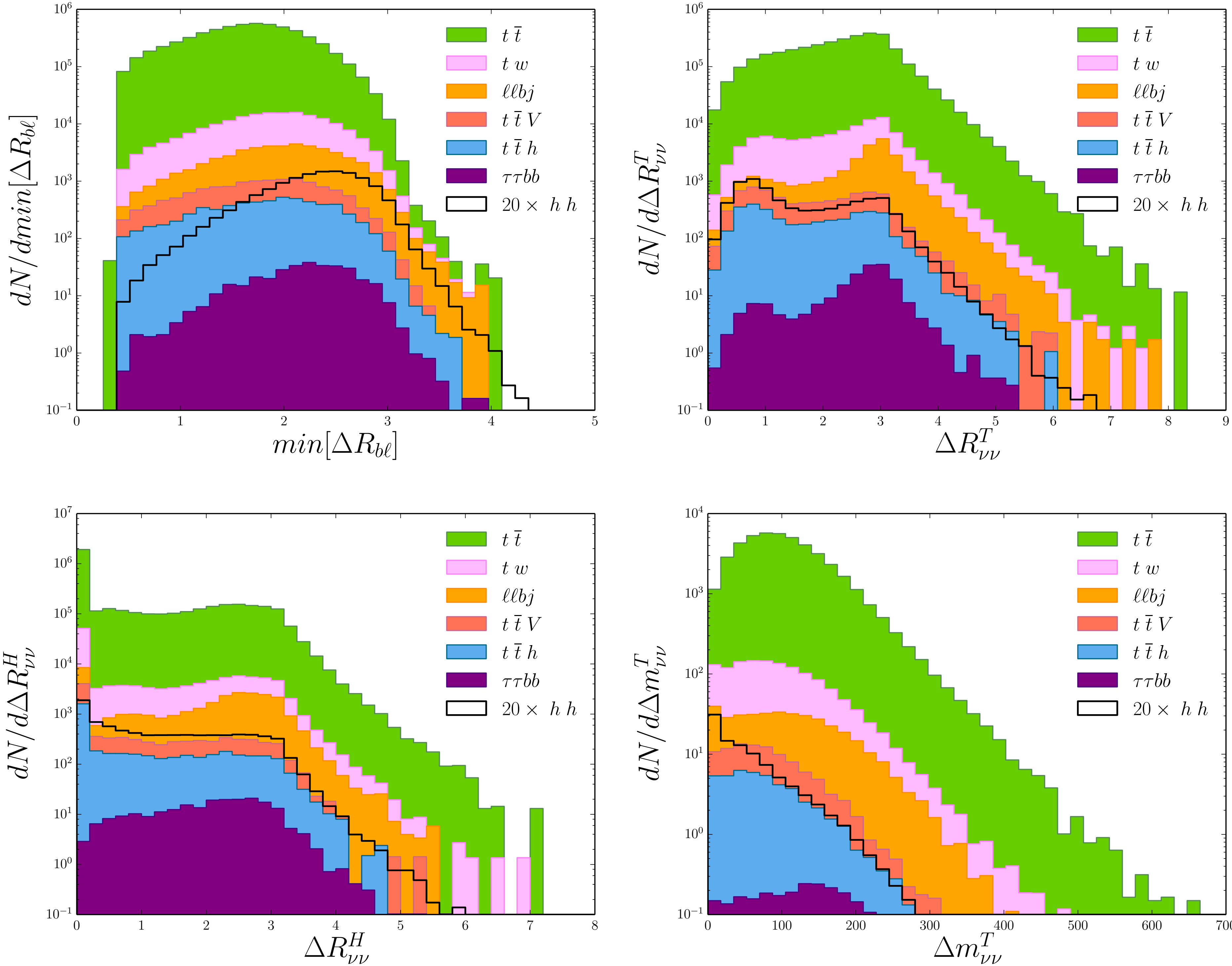

$\Delta\phi_{bb,\ell\ell}$
$p_{T,bb}$
$p_{T,\ell\ell}$
$\not{p}_T$
$\Delta\phi_{bb,\ell\ell}$
p_{Tbb}
$p_{T\ell\ell}$
$\not{p}_T$
$t\bar{t}$
$\ell\ell bj$
$tW+0,1j$
$t\bar{t}V$
$jj\ell\ell\nu\bar{\nu}$
$t\bar{t}h$
$\tau\tau bb$
hh x 10000



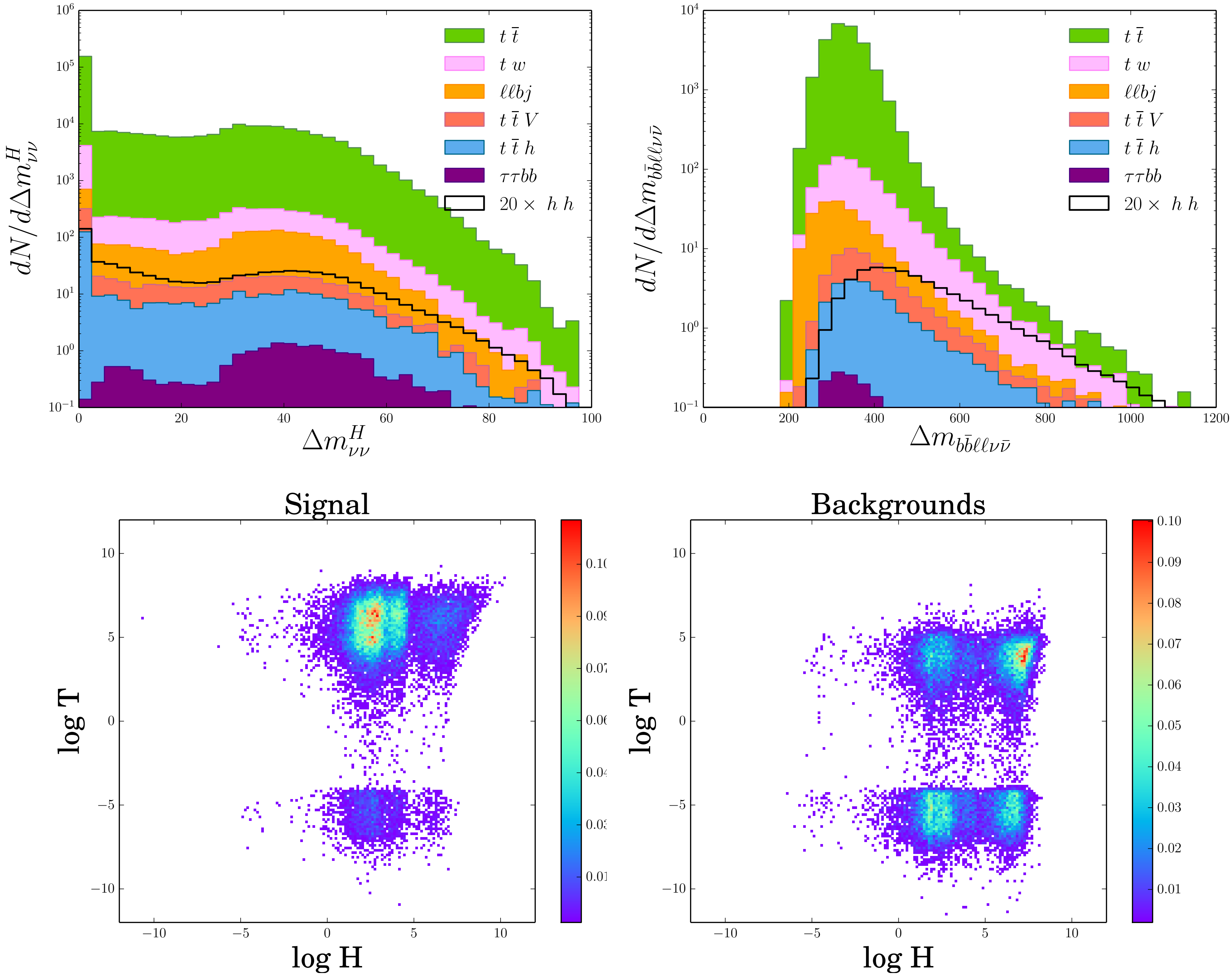
$\hat{s}_{min}^{(\mathrm{v})} = m_{\mathrm{v}}^2 + 2\left(\sqrt{|\vec{P}_T^{\mathrm{v}}|^2 + m_{\mathrm{v}}^2}\ |\vec{\not{P}}_T| - \vec{P}_T^{\mathrm{v}} \cdot \vec{\not{P}}_T\right)$
$\hat{s}_{min}^{(bb\ell\ell)}$
$\sqrt{\hat{s}}_{min}^{(bb\ell\ell)}$
$\hat{s}_{min}^{(\ell\ell)}$
$\sqrt{\hat{s}}_{min}^{(\ell\ell)}$
$M_{T2}^{(b)}$
$M_{T2}^{(\ell)}$
$t\bar{t}$
$\ell\ell bj$
$tW+0,1j$
$t\bar{t}V$
$jj\ell\ell\nu\bar{\nu}$
$t\bar{t}h$
$\tau\tau bb$
hh x 10000



p_{T,ℓ_1}
$p_{T\ell_1}$
p_{T,ℓ_2}
$p_{T\ell_2}$
Topness
$log(T)$
Higgsness
$log(H)$
$t\bar{t}$
$\ell\ell bj$
$tW+0,1j$
$t\bar{t}V$
$jj\ell\ell\nu\bar{\nu}$
$t\bar{t}h$
$\tau\tau bb$
hh x 10000



$dN/dmin[\Delta R_{b\ell}]$
$min[\Delta R_{b\ell}]$
$t\,\bar{t}$
$t\,w$
$\ell\ell bj$
$t\,\bar{t}\,V$
$t\,\bar{t}\,h$
$\tau\tau bb$
$20\times\ h\,h$
$dN/d\Delta R^T_{\nu\nu}$
$\Delta R^T_{\nu\nu}$
$t\,\bar{t}$
$t\,w$
$\ell\ell bj$
$t\,\bar{t}\,V$
$t\,\bar{t}\,h$
$\tau\tau bb$
$20\times\ h\,h$
$dN/d\Delta R^H_{\nu\nu}$
$\Delta R^H_{\nu\nu}$
$t\,\bar{t}$
$t\,w$
$\ell\ell bj$
$t\,\bar{t}\,V$
$t\,\bar{t}\,h$
$\tau\tau bb$
$20\times\ h\,h$
$dN/d\Delta m^T_{\nu\nu}$
$\Delta m^T_{\nu\nu}$
$t\,\bar{t}$
$t\,w$
$\ell\ell bj$
$t\,\bar{t}\,V$
$t\,\bar{t}\,h$
$\tau\tau bb$
$20\times\ h\,h$


$t\,\bar{t}$
$t\,w$
$\ell\ell bj$
$t\,\bar{t}\,V$
$t\,\bar{t}\,h$
$\tau\tau bb$
$20\times\ h\,h$
$dN/d\Delta m^{H}_{\nu\nu}$
$\Delta m^{H}_{\nu\nu}$
$dN/d\Delta m_{b\bar{b}\ell\ell\nu\bar{\nu}}$
$\Delta m_{b\bar{b}\ell\ell\nu\bar{\nu}}$
Signal
Backgrounds
log T
log H

Cross sections @14 TeV LHC

$\sigma_{hh} = 40.7$ fb (NNLO)

Kim, Kong, Matchev, Park, PRL 2019
Kim, Kim, Kong, Matchev, Park, JHEP 2019

$\sigma_{hh} \cdot 2 \cdot \mathrm{BR}(h \to b\bar{b}) \cdot \mathrm{BR}(h \to WW^* \to \ell^+\ell^-\nu\bar{\nu}) = 0.648\,\mathrm{fb}$

ℓ denotes an electron or a muon, including leptons from tau decays.

- tt: 953.6 pb (NNLO)
- tth: 611.3 fb (NLO)
- ttV (V=W, Z): 1.71 pb (NLO)
- DY: $\mathrm{k}^{NNLO,DY}_{QCD\otimes QED} \approx 1$
- Irreducible jjllnunu: k_NLO = 2
- tWj: 0.51 pb (after cuts, including all relevant branching fractions)

$\sigma_{bknd} \sim 10^5 \sigma_{hh}$

	Signal	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}V$	$\ell\ell bj$	$\tau\tau bb$	$tw+j$	$jj\ell\ell\nu\nu$	σ	S/B
Baseline cuts: $\not{p}_T > 20$ GeV, $p_{T,\ell} > 20$ GeV, $\Delta R_{\ell\ell} < 1.0$, $p_{T,b} > 30$ GeV, $\Delta R_{bb} < 1.3$, $m_{\ell\ell} < 65$ GeV, $95 < m_{bb} < 140$ GeV	0.01046	1.8855	0.0269	0.0179	0.0697	0.0250	0.2209	0.0113	0.38	0.0046

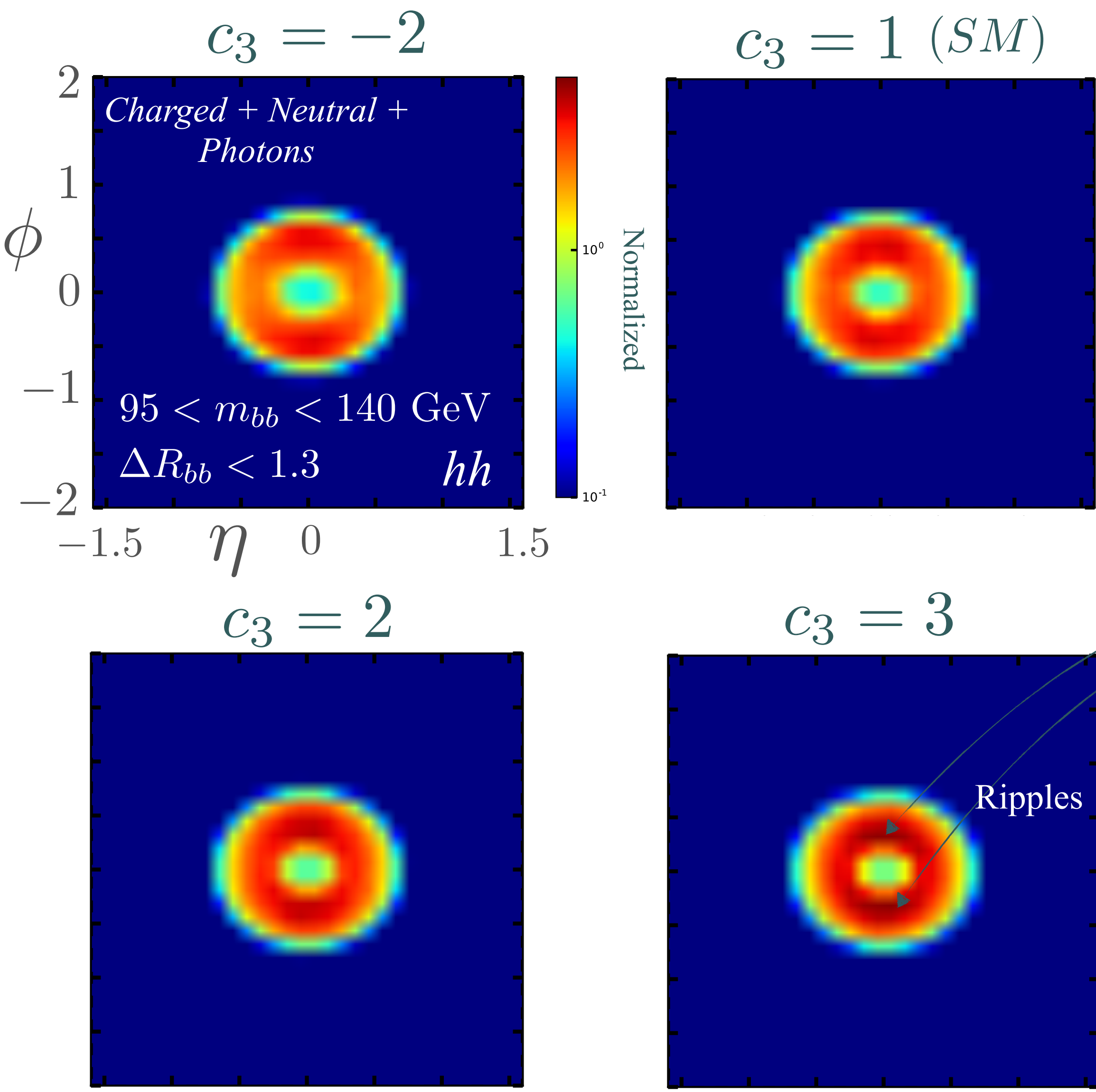
cross section in fb

tt: 84% tW: 9.8% DY+jets: 3.1% tth: 1.2% tautau + bb: 1.1% ttV: 0.8%

Shifting the Higgs triple coupling c_3

- How does the *hh* image vary by shifting the Higgs triple coupling c_3 ?

$$\mathcal{L} \supset -c_3 \frac{m_h^2}{2v} h^3$$



- Interestingly, the gradient of images change as moving into the region of a destructive interference.
- We are working on how much neural network can be sensitive to this change (we don't know yet, sorry).