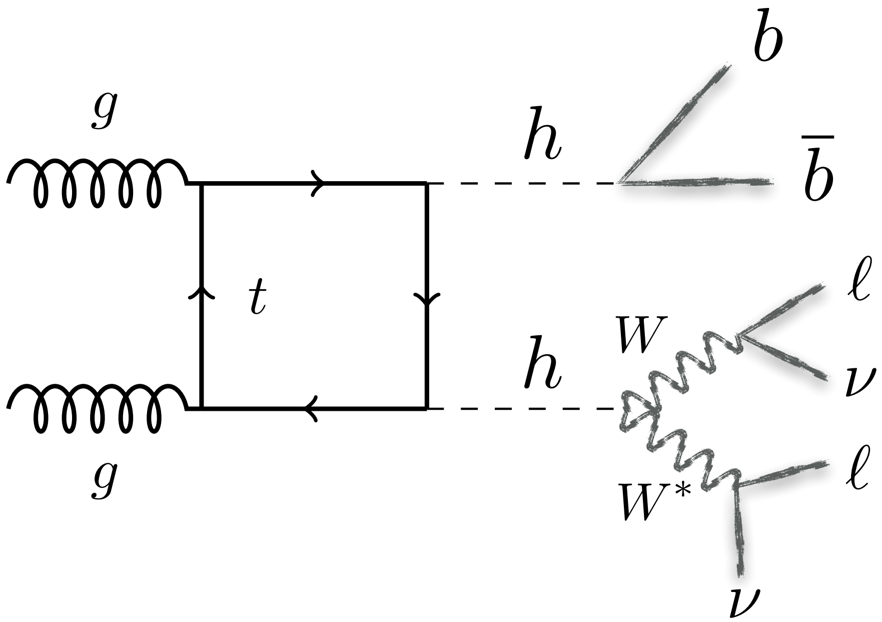
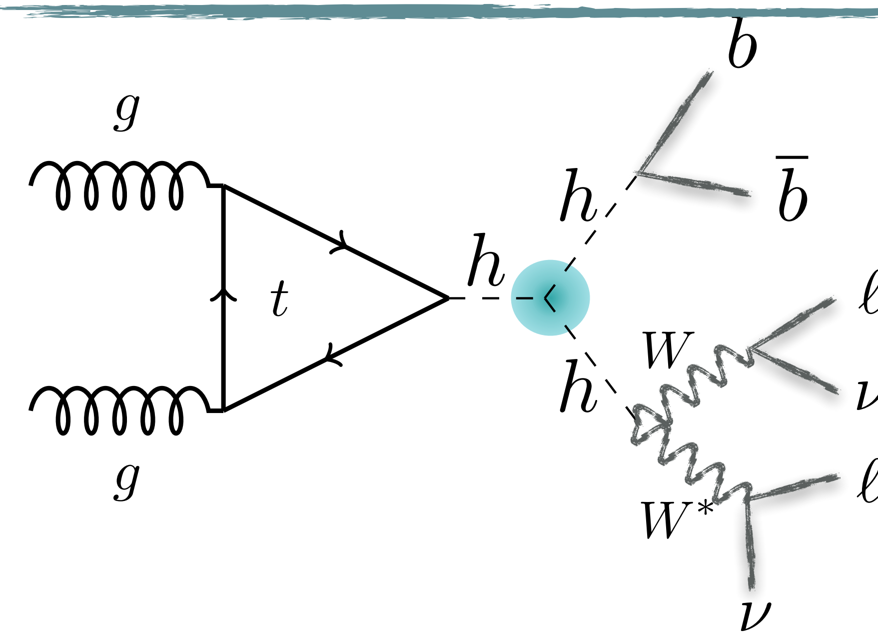
Why double Higgs (hh) ?



+



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

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

- We will focus on the triple Higgs self-coupling (c_3), with all other couplings set to their SM values.
- The knowledge of c_3 is crucial to reconstruct the Higgs potential for better understanding EWSB. Many BSM scenarios allow large deviations for c_3.
- The c_3 is sensitive at lower-energy bins where the backgrounds are large.
- That's why probing c_3 is notoriously difficult.

The *hh* faces experimental challenges

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

higher branching ratios

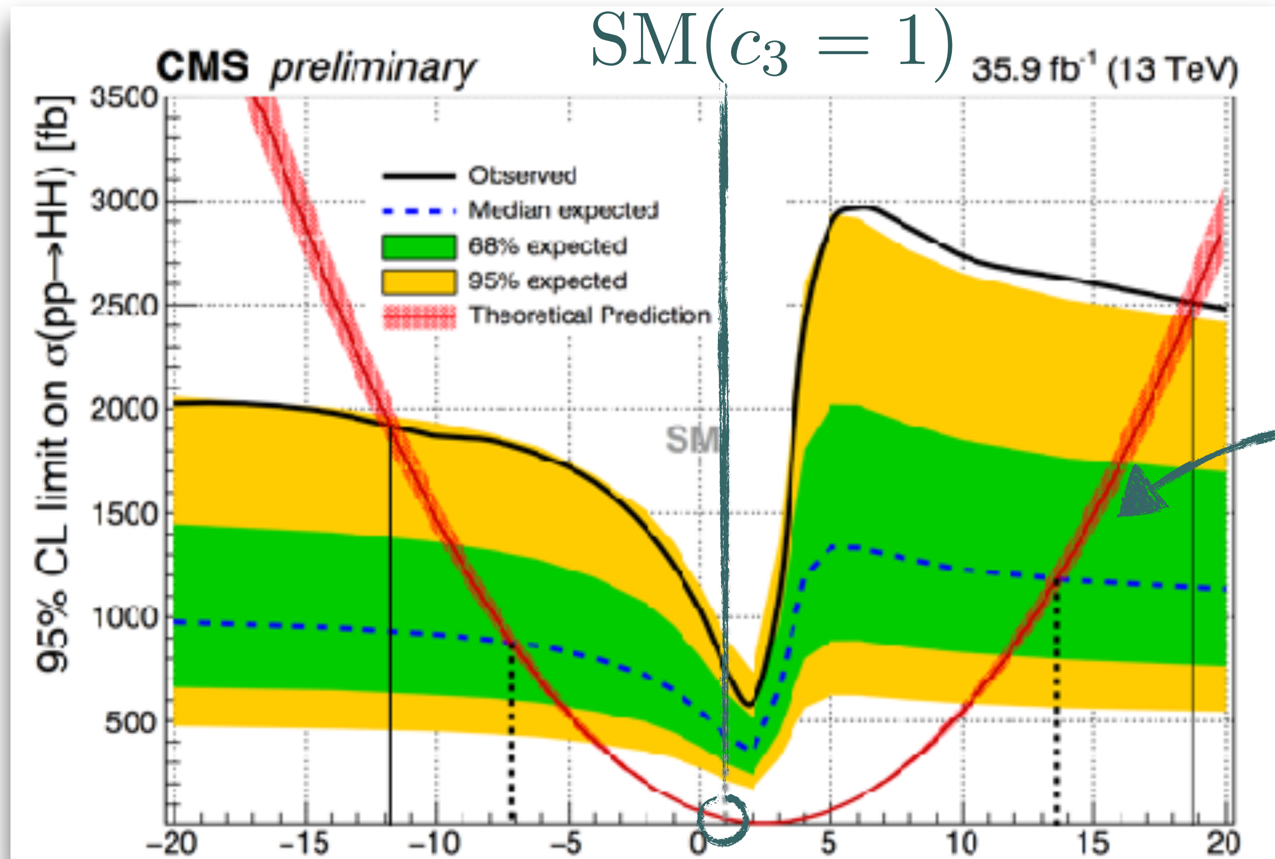
cleaner final state

	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%

- But, these measurements are challenged by a low σ (hh) and small branching ratios (BR).
- No single channel is expected to reach 5 sigma at HL-LHC.
- The combination of different channels is crucial.

Experimental status on c_3 @ LHC 13 TeV

CMS PAS HIG-17-030



- Allowed region of c_3.

$$-11.8 < c_3 < 18.8$$

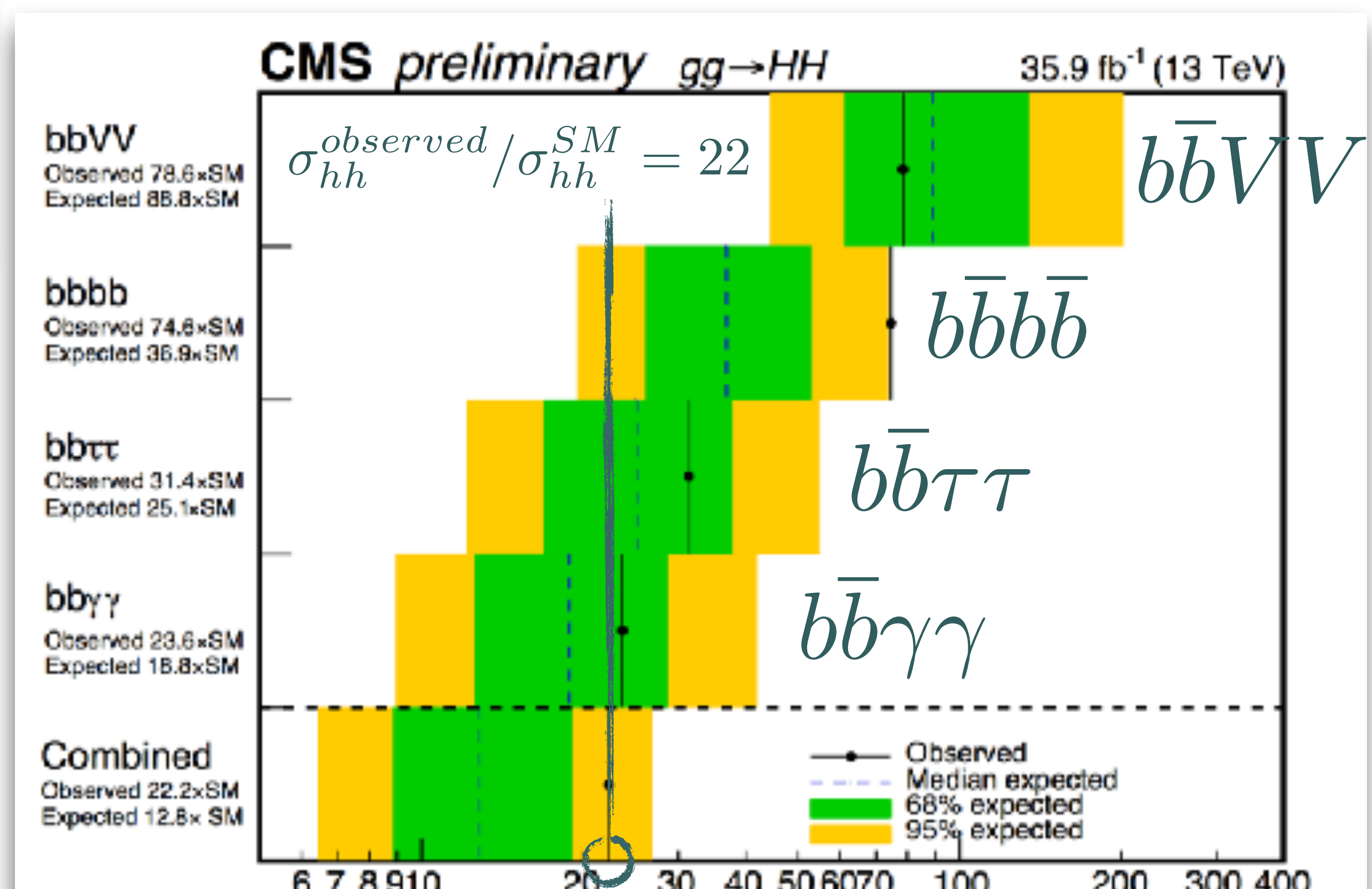
$$(b\bar{b}\gamma\gamma\ +\ b\bar{b}\tau\tau + \ b\bar{b}b\bar{b}\ +\ b\bar{b}VV)$$

$$\frac{\sigma}{\sigma_{SM}} = A_1\, c_t^4 + A_3\, c_t^2 c_3^2 + A_7\, c_t^3 c_3$$

- Allowed range of hh cross sections.

$$\sigma_{hh}^{observed}/\sigma_{hh}^{SM} = 22$$

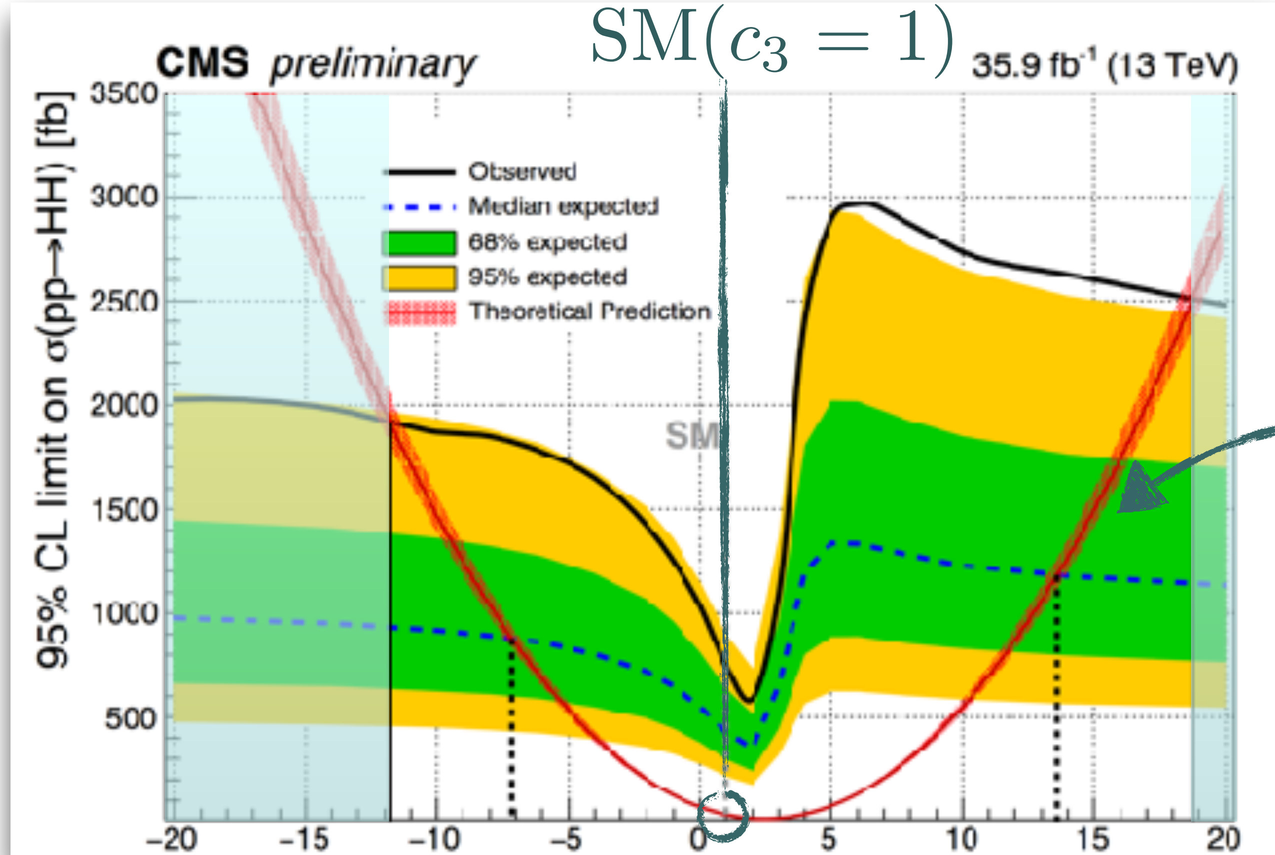
- The $bb\gamma\gamma$ and $bb\tau\tau$ are leading channels.



95% CL on $\sigma_{hh}/\sigma_{hh}^{SM}$

Experimental status on c_3 @ LHC 13 TeV

CMS PAS HIG-17-030



- Allowed region of c_3.

$$-11.8 < c_3 < 18.8$$

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$$\frac{\sigma}{\sigma_{SM}} = A_1\, c_t^4 + A_3\, c_t^2 c_3^2 + A_7\, c_t^3 c_3$$

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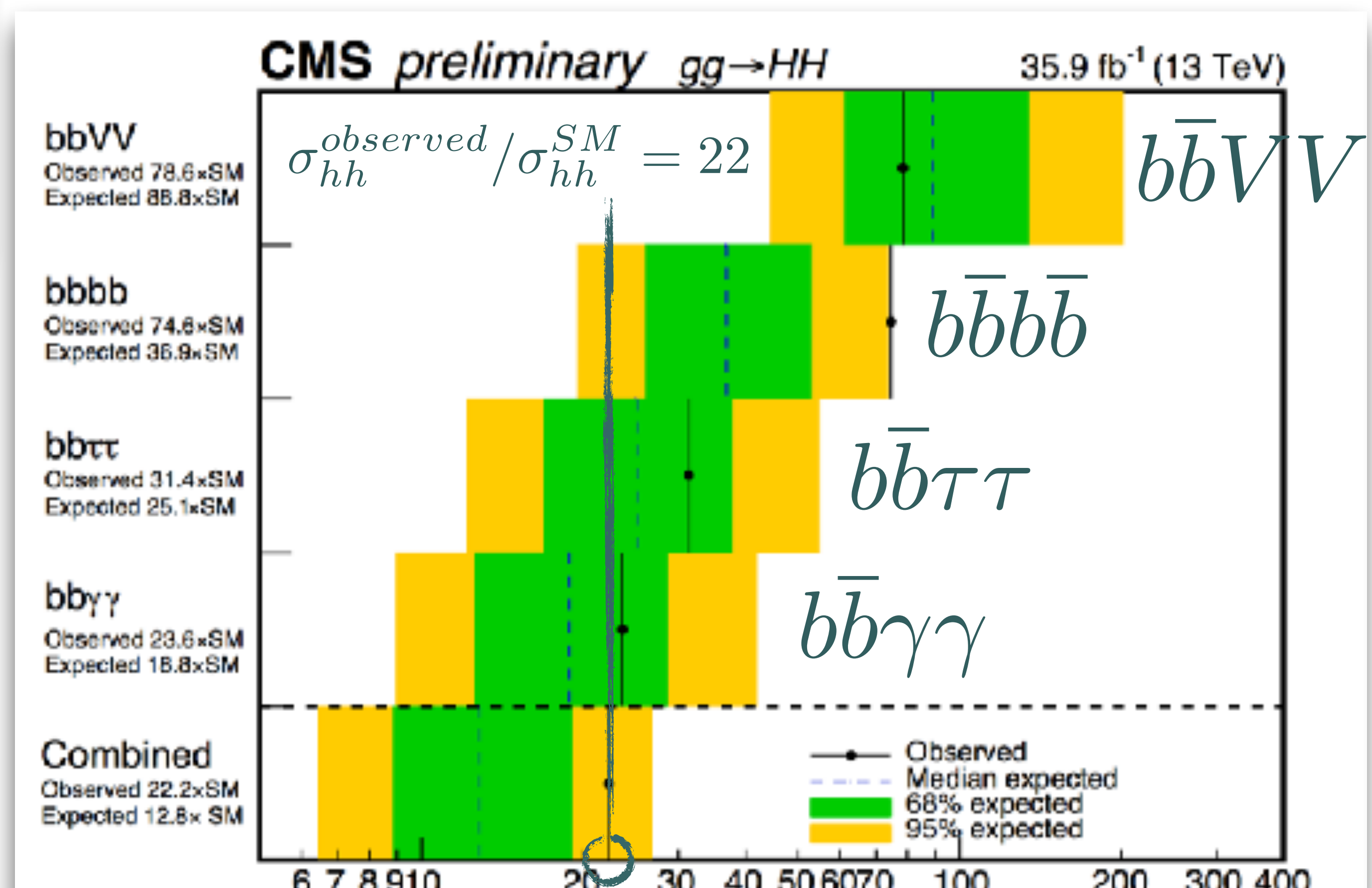
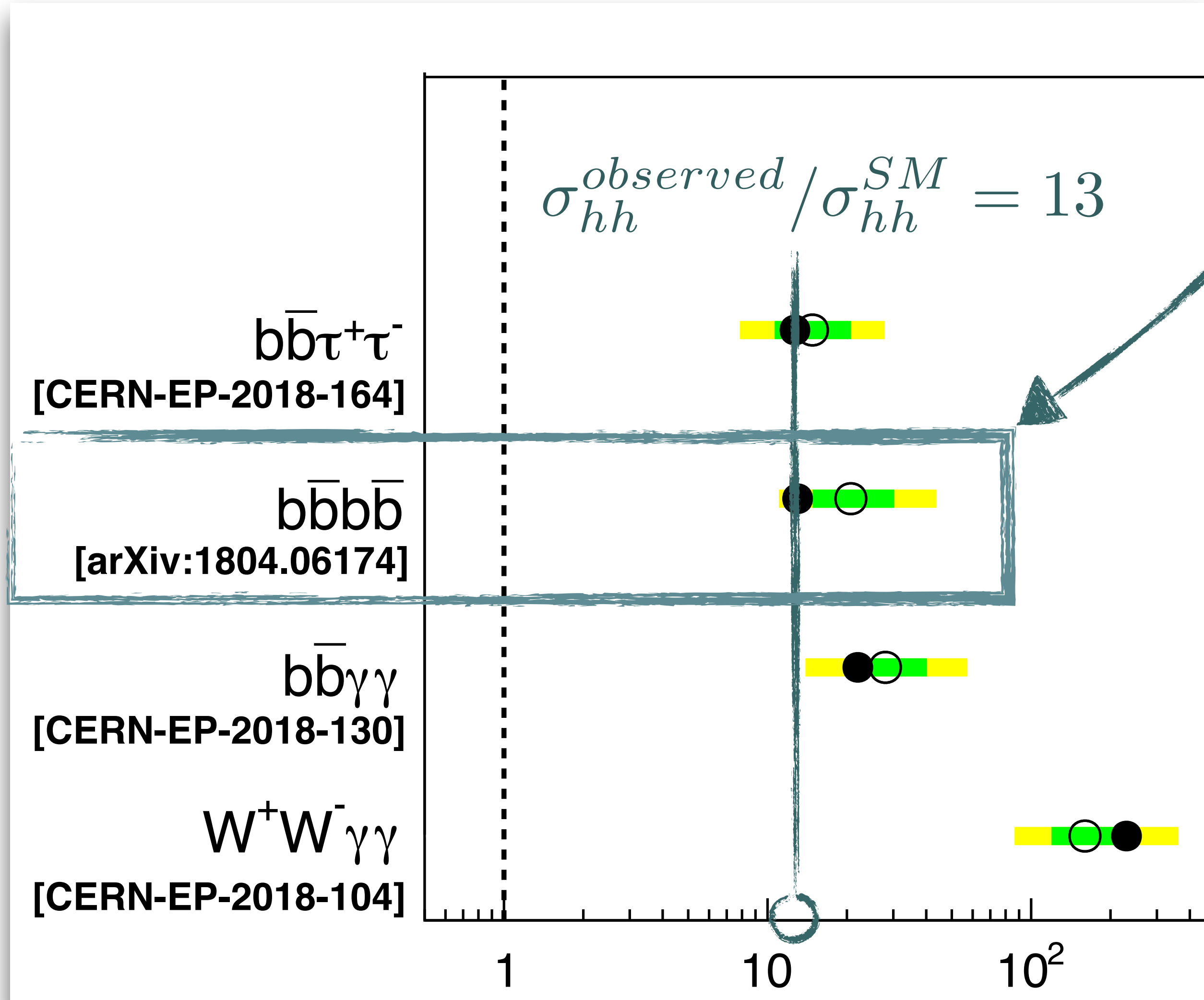


$95\%\ CL\ on\ \sigma_{hh}/\sigma_{hh}^{SM}$

Experimental status on c_3 @ LHC 13 TeV

$27.5 - 36.1\ \mathrm{fb}^{-1} (13\ \mathrm{TeV})$



$95\%\ CL\ on\ \sigma_{hh}/\sigma_{hh}^{SM}$

ATLAS, PRL 117 (2016) 079901

ATLAS, PRL 117 (2016) 012001

- The *bbbb* channel is significantly improved!
- Using an improved *b*-tagging algorithm (*MV2c10*)

$$\epsilon_b = 70\ \%$$
$$\epsilon_{c\to b} = 8.3 \sim 14.1\ \%$$
$$\epsilon_{j\to b} = 0.26 \sim 0.83\ \%$$

- Allowed region of c_3.

$$-8.2 \lesssim c_3 \lesssim 13.2 \quad (\text{Using only } b\bar{b}\gamma\gamma)$$

- The bound is weak… The situation at 300 fb^{-1} will be similarly bad…

Discovery potential of the *hh* at HL-LHC ?

	Channels	Significances	Combined	Combined
ATLAS ATL-PHYS-PUB-2018-053	$bb\gamma\gamma$	2.1	3.5	**4.5**
	$bb\tau\tau$ (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	
	$bb\tau\tau$ (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		

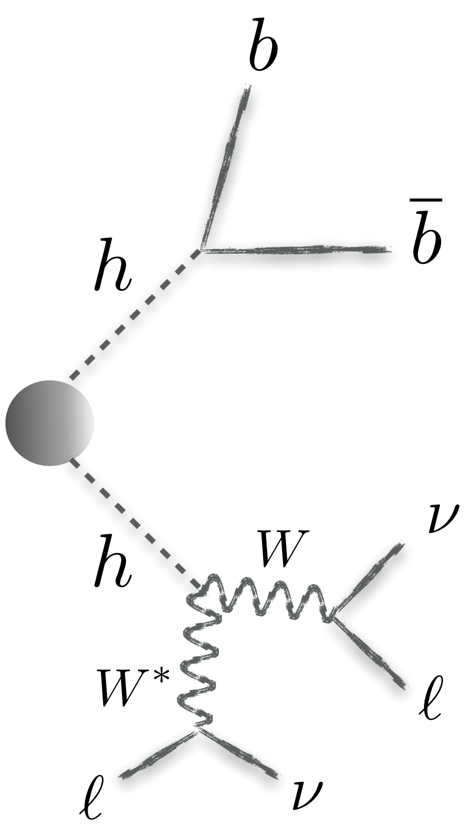
$3\ \mathrm{ab}^{-1}(14\ \mathrm{TeV})$

$c_3 = 1$

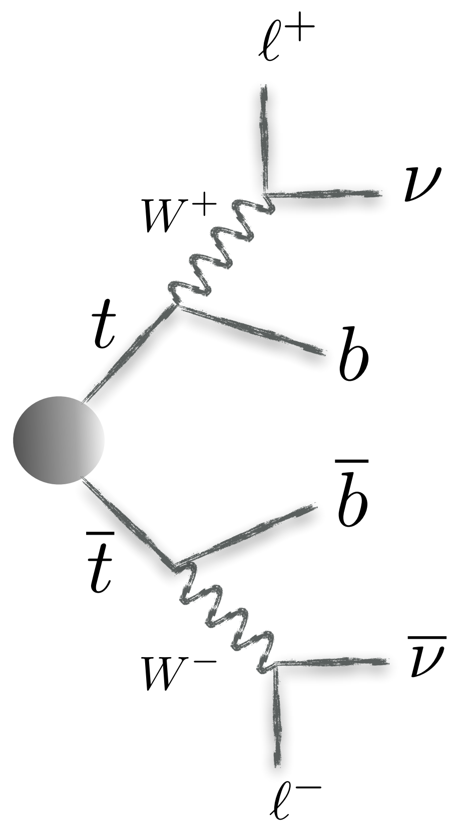
Previously overlooked and less studied

- In order to access c_3, we should observe the *hh* first.
- 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 $hh \to bbWW^*$



Signal



Major background

- $hh \to bbWW^*$ channel suffers for the large $t\bar{t}$ background where the final state is identical.
- The sensitivity of signal in the di-leptonic mode is very poor.

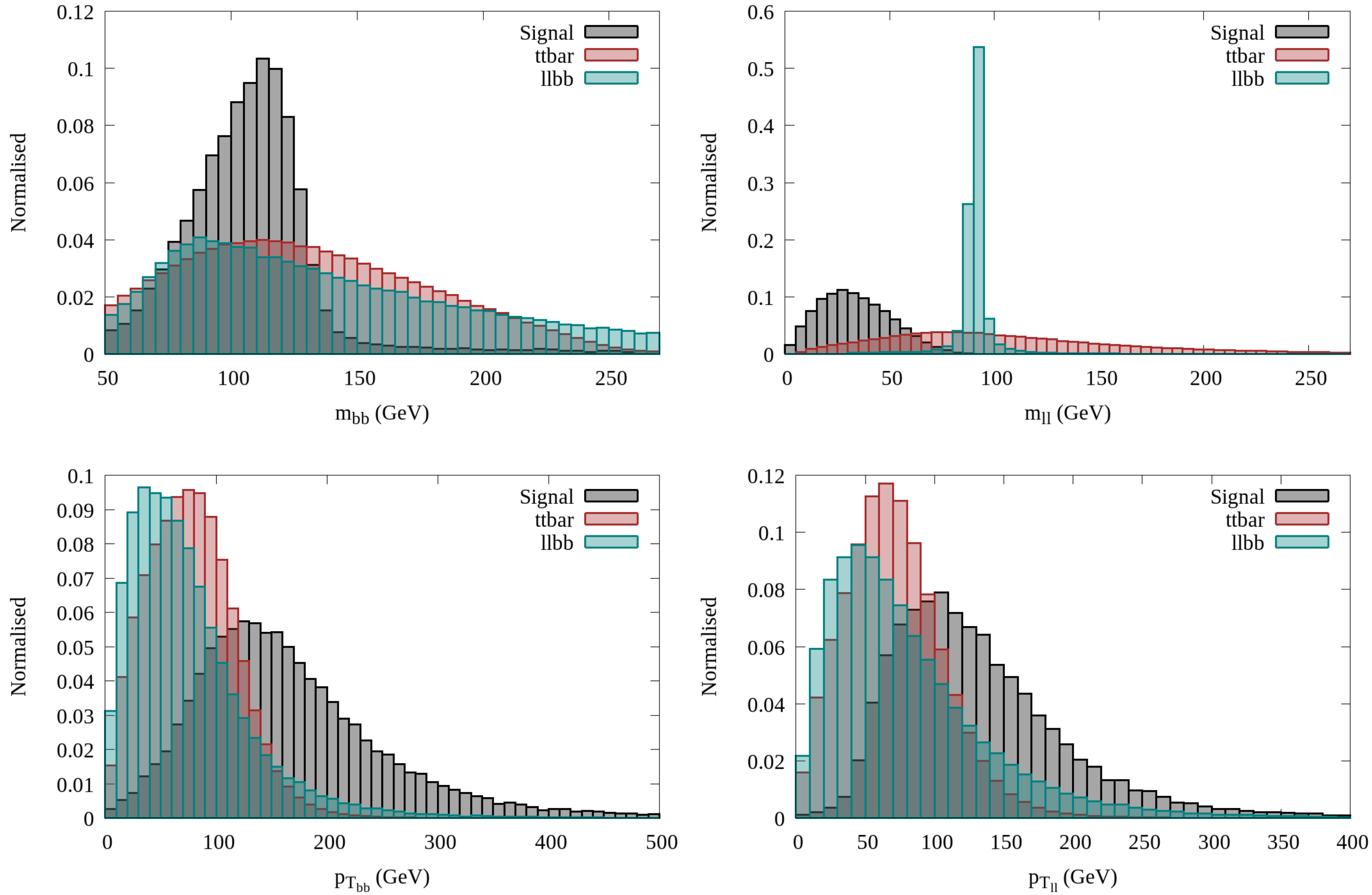
  CMS-FTR-15-002-PAS
- The situation in the semi-leptonic mode is even worse…

  Dolan, Englert, Spannowsky 2012

  Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

Seemingly it looks hopeless…

$hh \to bbWW^*$: dilepton channel



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

Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

$hh \to bbWW^*$: dilepton channel

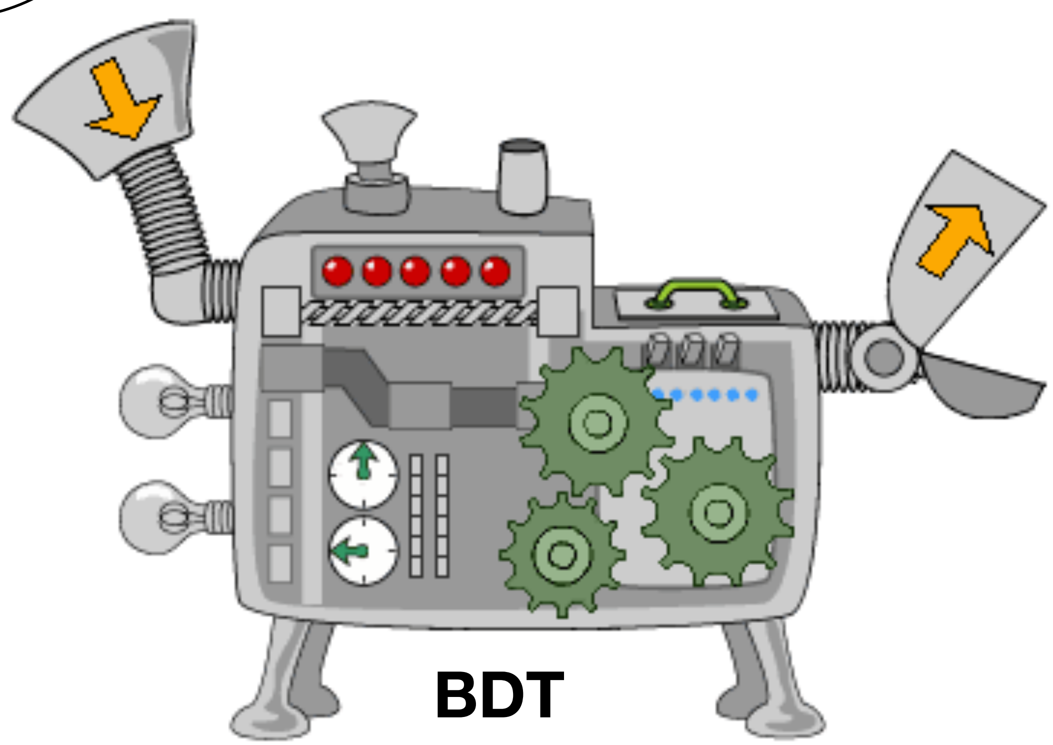
$\not{E}_T$

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

$\Delta R_{\ell\ell}$ ΔR_{bb}

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

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



Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

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

$\not{E}_T$

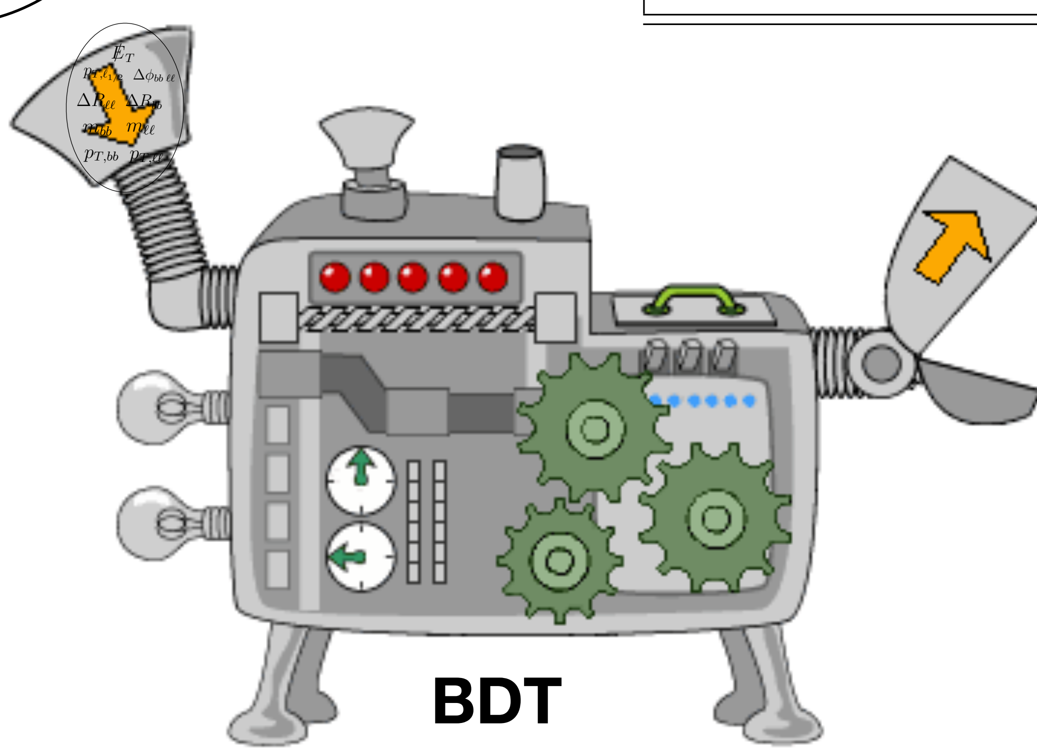
$p_{T,\ell_{1/2}}$ $\Delta\phi_{bb\,\ell\ell}$

$\Delta R_{\ell\ell}$ ΔR_{bb}

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

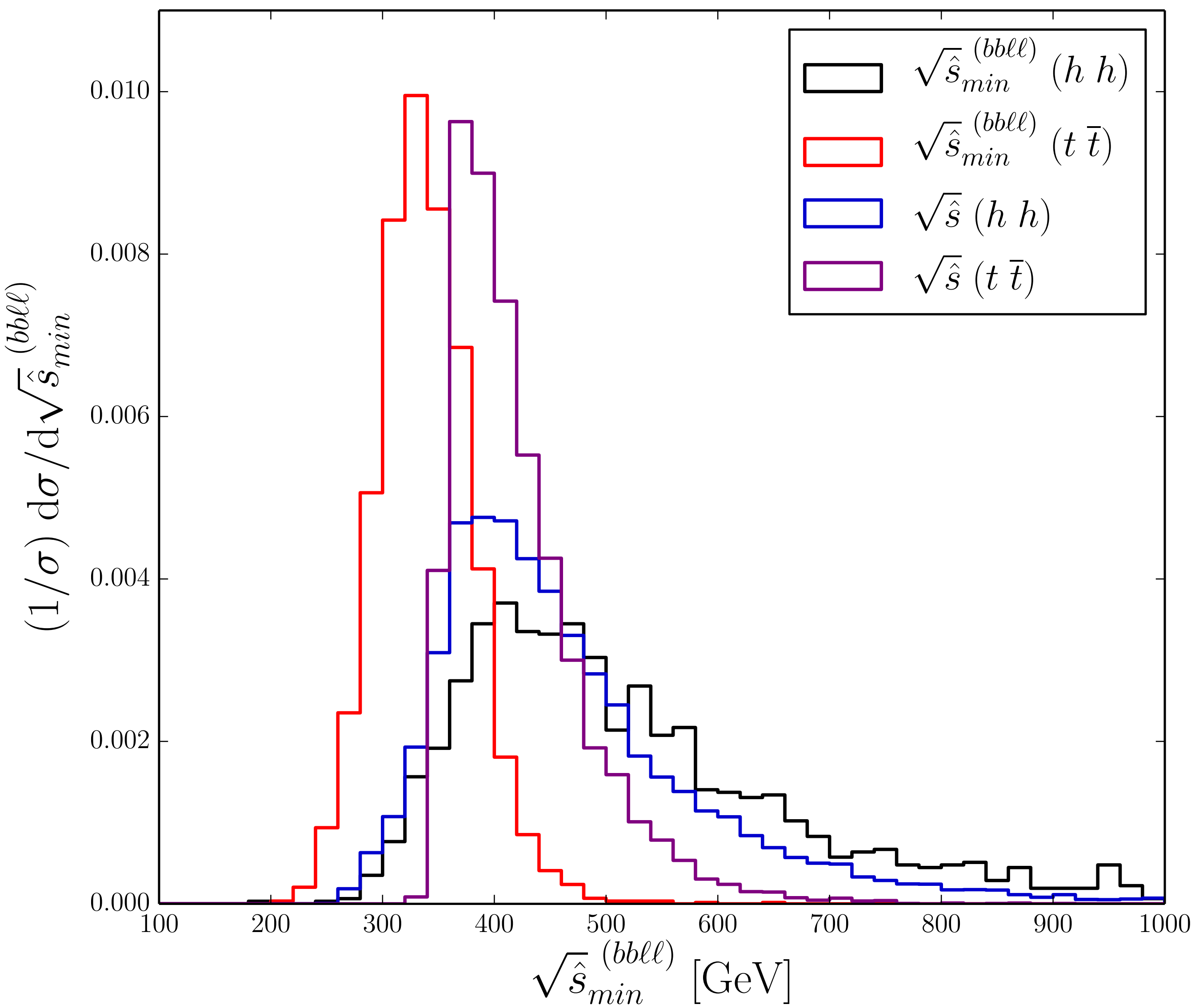
$p_{T,bb}$ $p_{T,\ell\ell}$

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



Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

Double Higgs vs top pair production



- Small signal cross section ~ 40 fb
- Large background
- TTbar ~ 950 pb

- MadGraph5_aMC@NLO v2.6, NNPDF2.3
- PYTHIA8235 for parton-shower and hadronization
- Delphes 3.41. for detector effects
- FastJet 3.3.1 for jet-reconstruction

$$\hat{s}_{min}^{(\mathrm{v})} = m_{\mathrm{v}}^2 + 2\left(\sqrt{|\vec{P}_T^{\mathrm{v}}|^2 + m_{\mathrm{v}}^2}\ |\vec{\not{P}}_T| - \vec{P}_T^{\mathrm{v}} \cdot \vec{\not{P}}_T\right)$$

$$\sqrt{s}\ =\ 14\ \mathrm{TeV}\ \ \mathrm{LHC}$$

Cross sections

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

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

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: $\mathrm{k}_{QCD\otimes QED}^{NNLO,DY} \approx 1$
- Irreducible jjllnunu: k_NLO = 2
- tWj: 0.51 pb (after cuts, including all relevant branching fractions)

Some modification

- Jets are clustered with the anti-k_T algorithm [65] with cone-size $\Delta R = 0.4$, where ΔR is the distance (2.1) in the (ϕ, η) space. Jets are also required to have $p_T > 30$ GeV and $|\eta| < 2.5$.

- For lepton isolation, we require $\frac{p_{T\ell}}{p_{T\ell}+\sum_i p_{Ti}} > 0.7$, where the sum is taken over the transverse momenta p_{Ti} of all final states particles i, $i \neq \ell$, with $|\eta_i| < 2.5$, $p_{Ti} > 0.5$ GeV and within $\Delta R_{i\ell} < 0.3$ of the lepton candidate ℓ.

- For photon isolation, we analogously require $\frac{\sum_i p_{Ti}}{p_{T\gamma}} < 0.12$ for particles within $\Delta R_{i\gamma} < 0.3$ of the photon candidate γ.

- The missing transverse momentum $\vec{\not{P}}_T$ is defined as the negative vector sum of the transverse momenta of the reconstructed jets, leptons and photons.

- We use the a flat b-tagging efficiency, $\epsilon_{b\to b} = 0.75$, and flat mis-tagging rates for non-b jets of $\epsilon_{c\to b} = 0.1$ and $\epsilon_{j\to b} = 0.01$ [66].

Cuts at event generation

$p_{Tj} > 20$ GeV, $p_{Tb} > 20$ GeV,

$p_{T\gamma} > 10$ GeV, $p_{T\ell} > 10$ GeV, $\eta_j < 5$, $\eta_b < 5$, $\eta_\gamma < 2.5$,

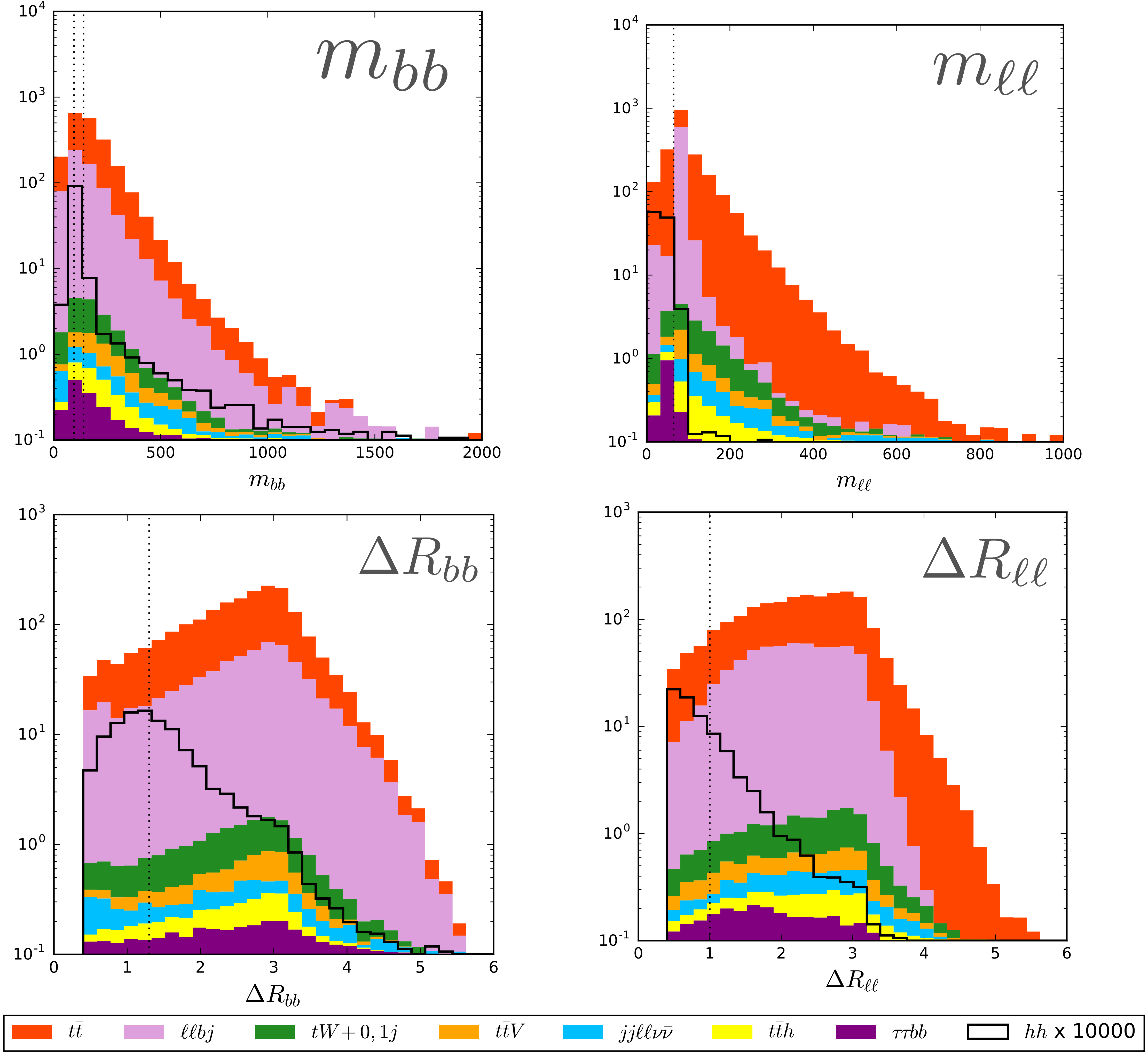
$\eta_\ell < 2.5$, $\Delta R_{bb} < 1.8$, $\Delta R_{\ell\ell} < 1.3$,

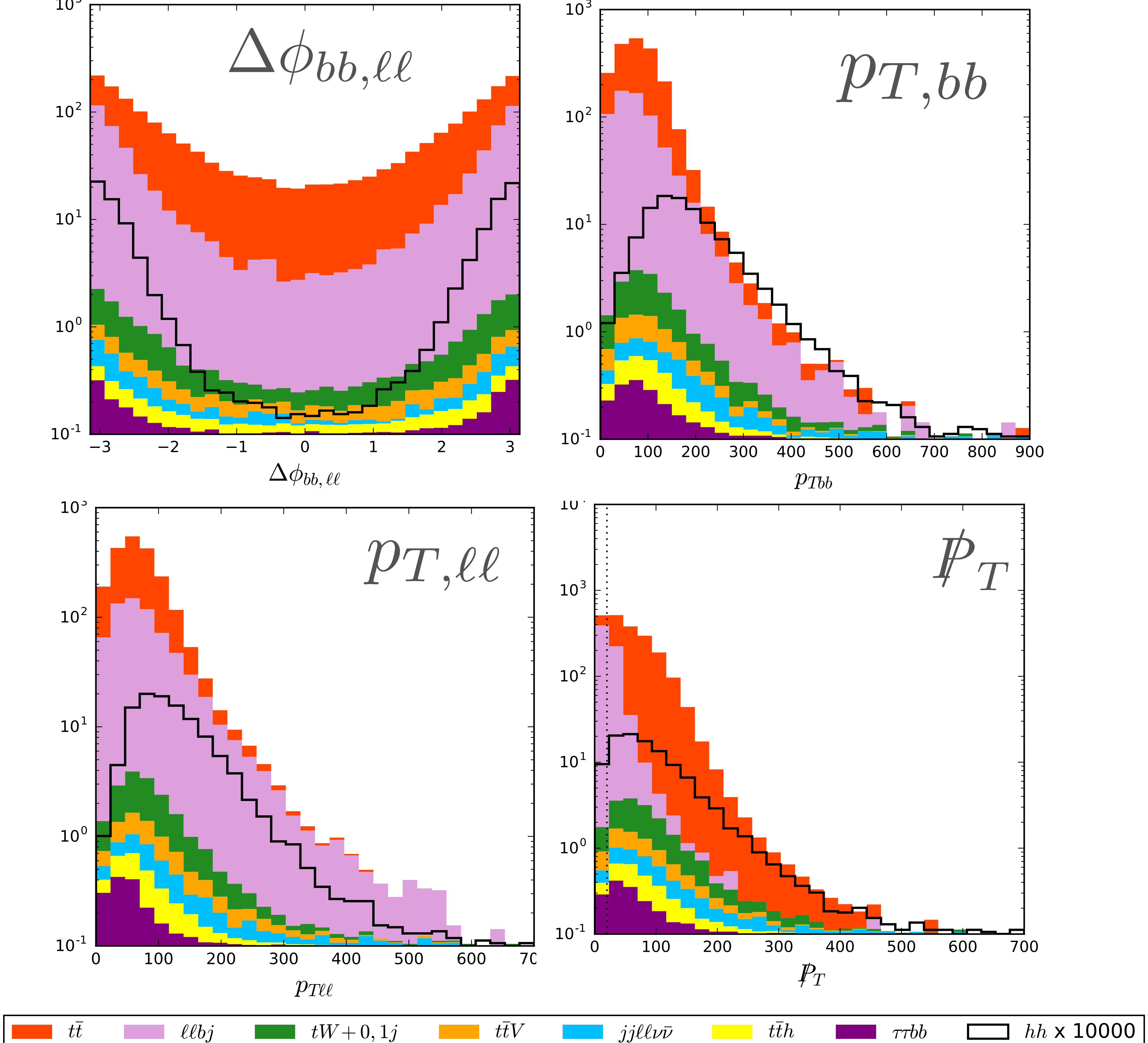
$70 \text{ GeV} < m_{jj}, m_{bb} < 160 \text{ GeV}$ and $m_{\ell\ell} < 75$ GeV

$5 \text{ GeV} < m_{\ell\ell} < 75 \text{ GeV}$ For $jj\ell\ell\nu\bar{\nu}$, $\ell\ell bj$ and $tW + j$ backgrounds,

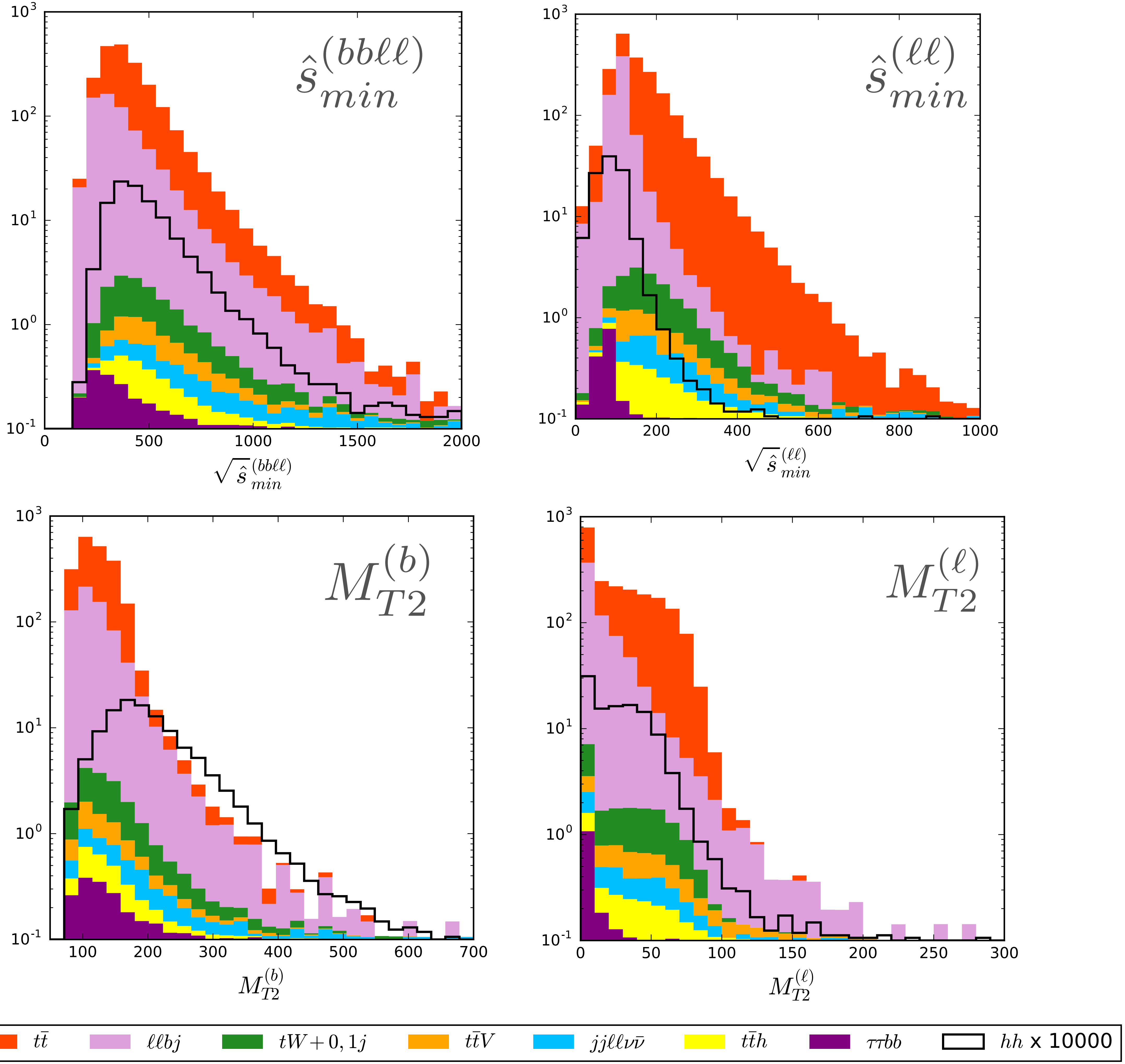
Baseline cuts

- the two leading jets must be b-tagged,
- exactly two isolated leptons of opposite sign, each with $p_{T\ell} > 20$ GeV,
- $\not{P}_T = |\vec{\not{P}}_T| > 20$ GeV for the reconstructed missing transverse momentum,
- proximity cut of $\Delta R_{\ell\ell} < 1.0$ for the two leptons,
- proximity cut of $\Delta R_{bb} < 1.3$ for the two b-tagged jets,
- $m_{\ell\ell} < 65$ GeV for the two leptons,
- 95 GeV $< m_{bb} <$ 140 GeV for the two b-tagged jets.

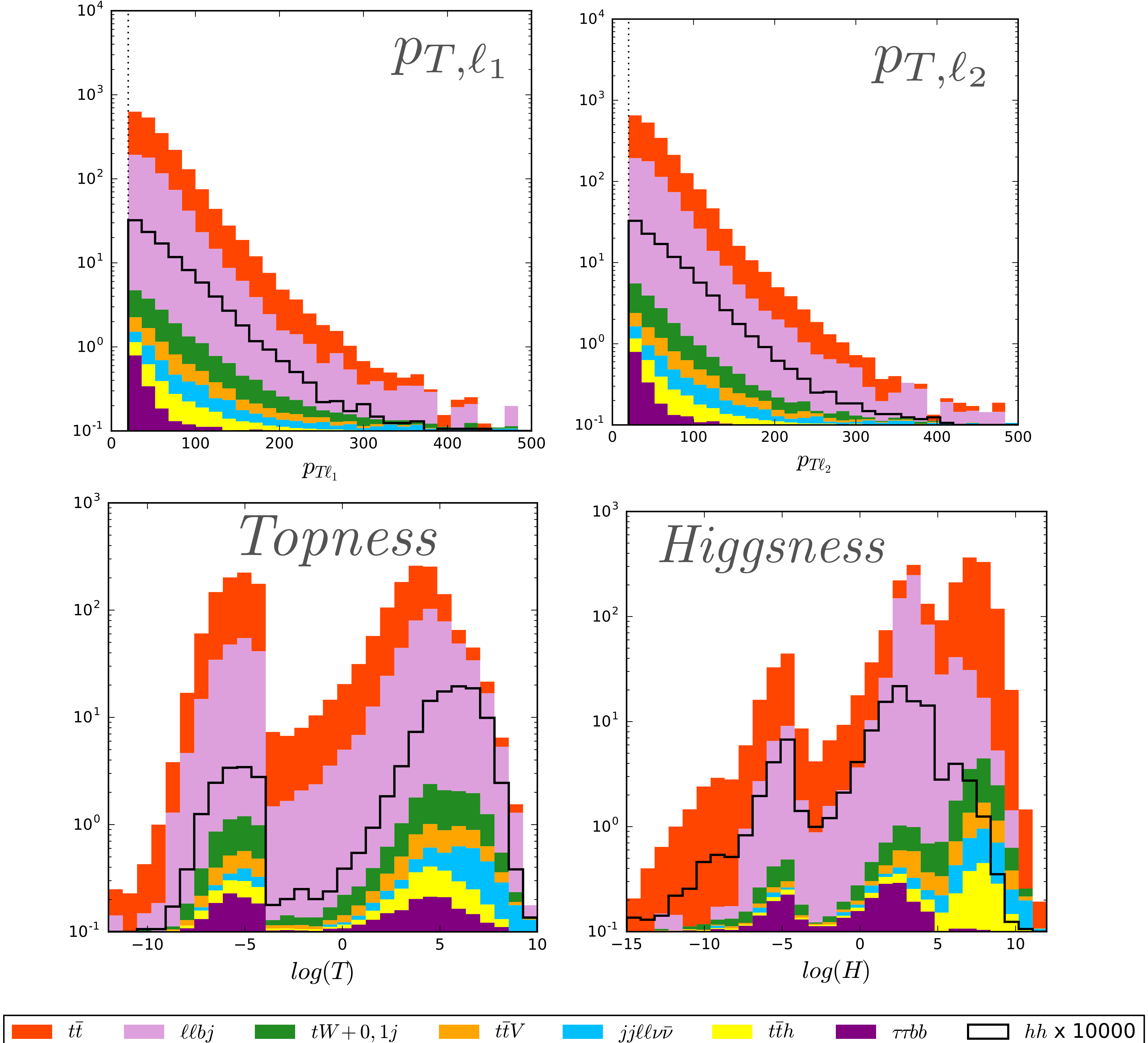

m_{bb}
$m_{\ell\ell}$
ΔR_{bb}
$\Delta R_{\ell\ell}$
$t\bar{t}$
$\ell\ell bj$
$tW+0,1j$
$t\bar{t}V$
$jj\ell\ell\nu\bar{\nu}$
$t\bar{t}h$
$\tau\tau bb$
hh x 10000



$\Delta\phi_{bb,\ell\ell}$
$p_{T,bb}$
$p_{T,\ell\ell}$
$\not{p}_T$
$\Delta\phi_{bb,\ell\ell}$
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

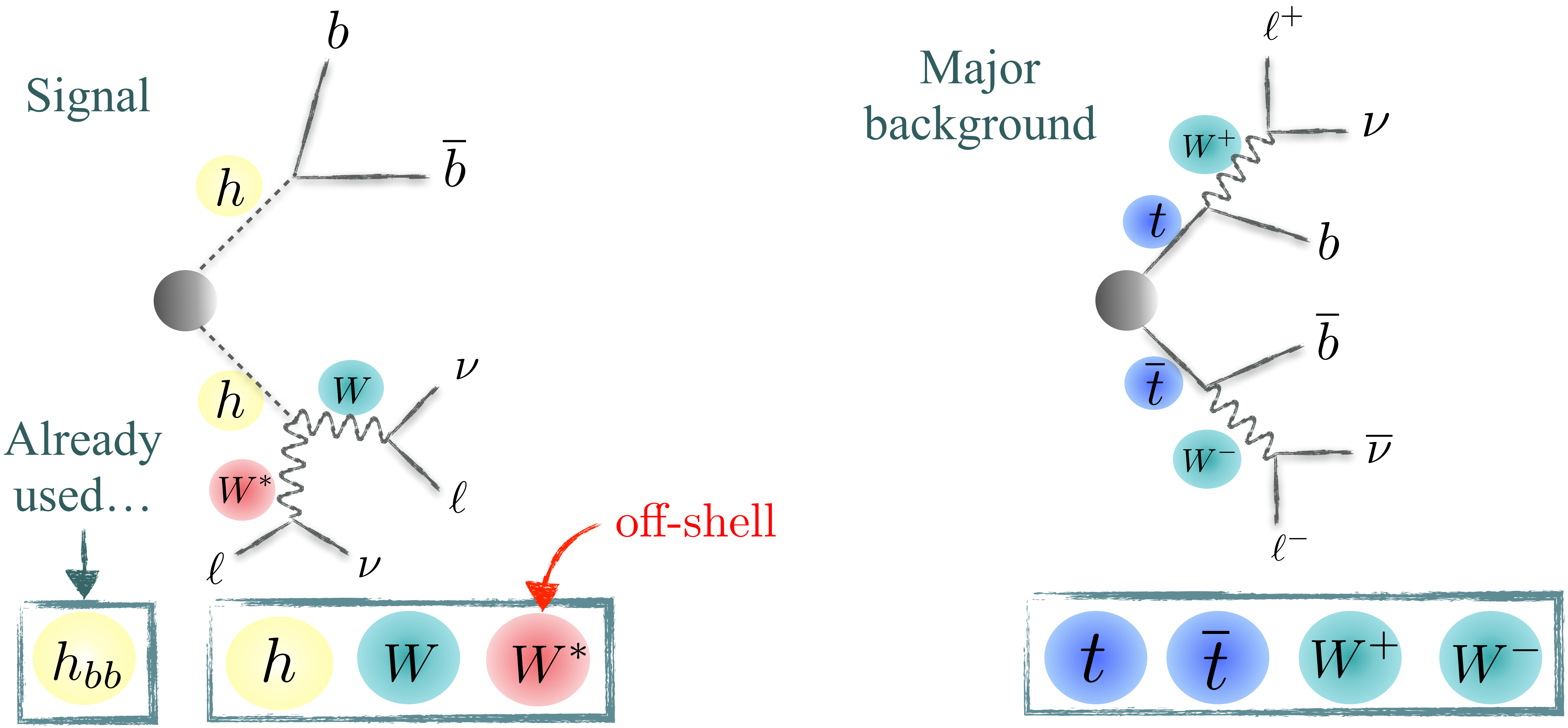


$\hat{s}_{min}^{(bb\ell\ell)}$
$\sqrt{\hat{s}}_{min}^{(bb\ell\ell)}$
$\hat{s}_{min}^{(\ell\ell)}$
$\sqrt{\hat{s}}_{min}^{(\ell\ell)}$
$M_{T2}^{(b)}$
$M_{T2}^{(\ell)}$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
0
500
1000
1500
2000
200
400
600
800
100
300
700
50
150
250
$t\bar{t}$
$\ell\ell bj$
$tW+0,1j$
$t\bar{t}V$
$jj\ell\ell\nu\bar{\nu}$
$t\bar{t}h$
$\tau\tau bb$
hh x 10000



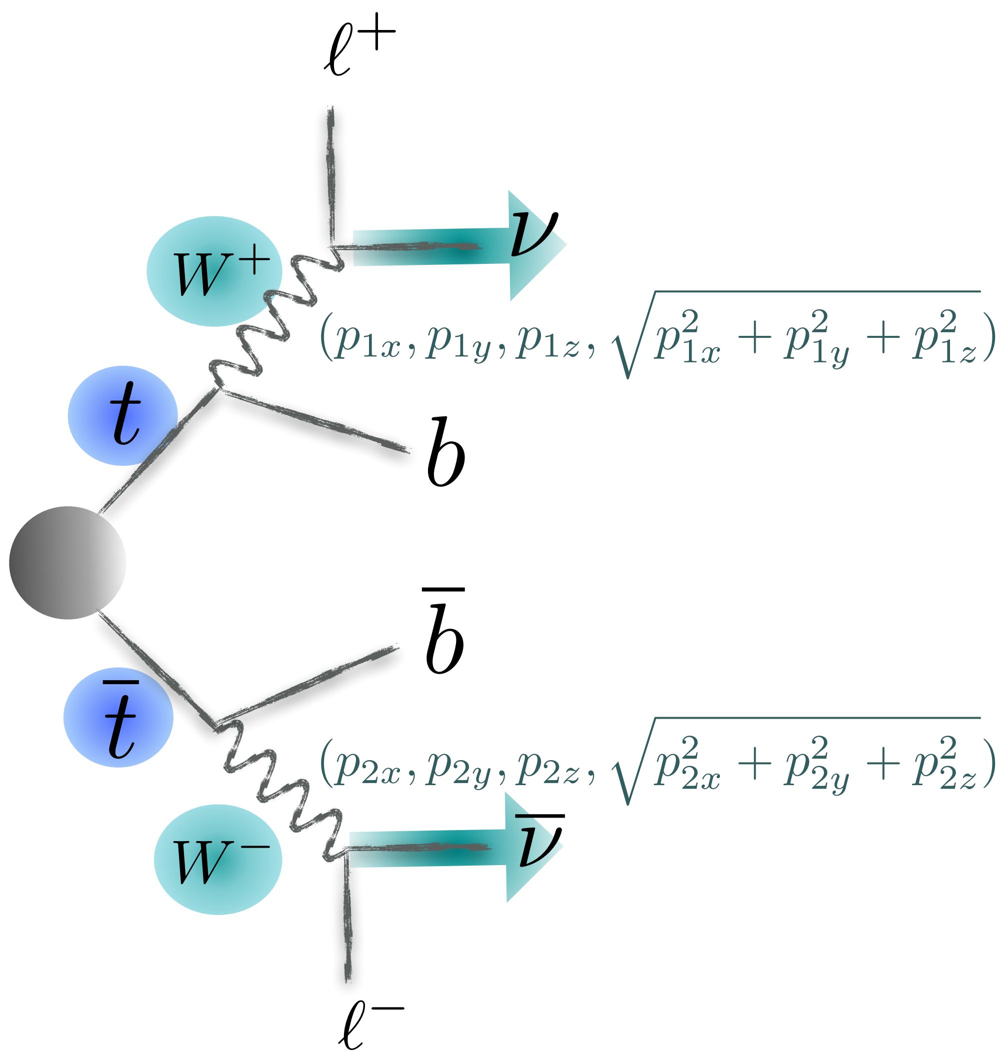
p_{T,ℓ_1}
$p_{T\ell_1}$
p_{T,ℓ_2}
$p_{T\ell_2}$
$Topness$
$log(T)$
$Higgsness$
$log(H)$
$t\bar{t}$
$\ell\ell bj$
$tW+0,1j$
$t\bar{t}V$
$jj\ell\ell\nu\bar{\nu}$
$t\bar{t}h$
$\tau\tau bb$
hh x 10000

Distinctive mass information



- We think this can be done with on-shell conditions of particles.
- This information is independent of how these particles are produced.
- Therefore less correlated with other kinematic variables.

Topness (T)



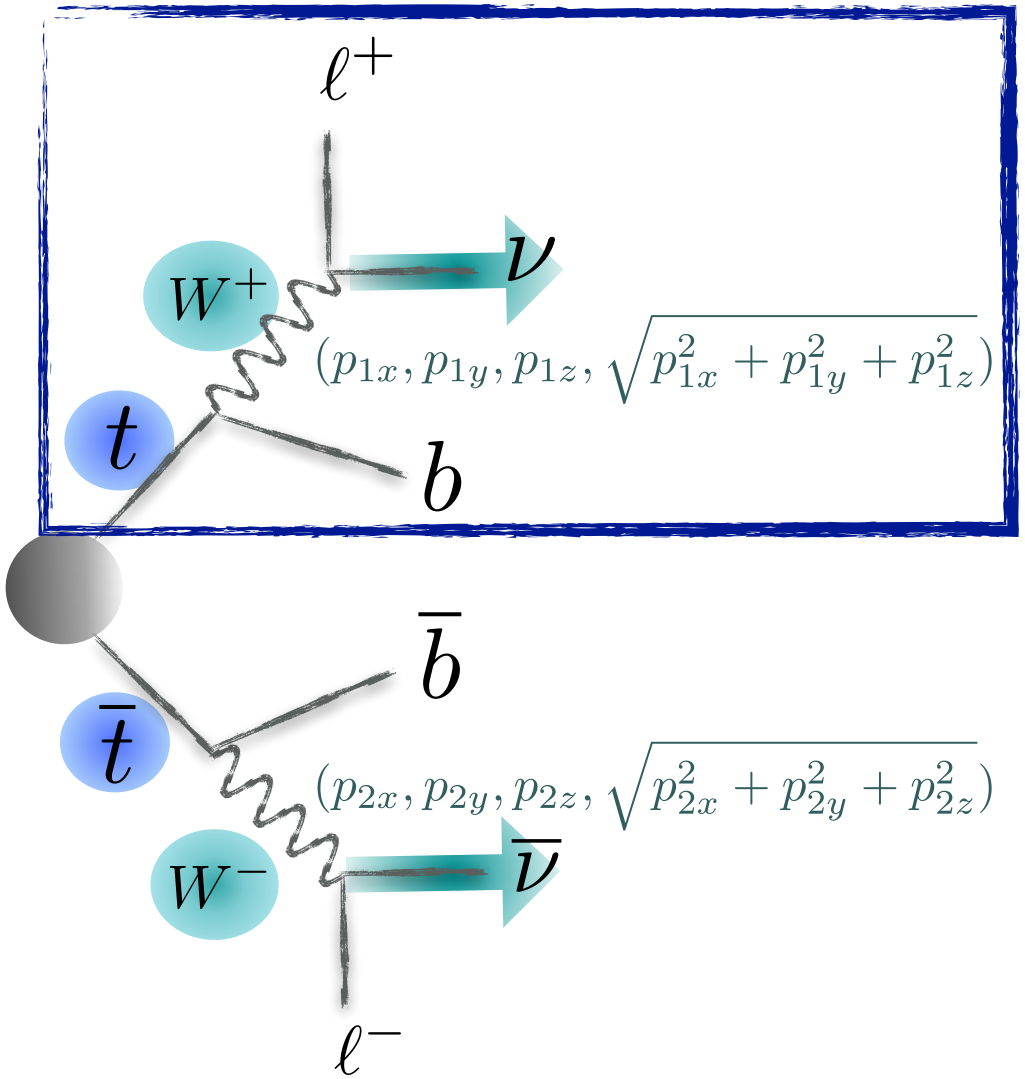
$$\chi^2_{ij} \equiv \min_{\vec{\not{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{b_i \ell^+ \nu} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^+ \nu} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{b_j \ell^- \bar{\nu}} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^- \bar{\nu}} - m_W^2\right)^2}{\sigma_W^4} \right]$$

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

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 a minimum of the likelihood function.

Topness (T)



$$\chi^2_{ij} \equiv \min_{\vec{\not{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{b_i \ell^+ \nu} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^+ \nu} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{b_j \ell^- \bar{\nu}} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^- \bar{\nu}} - m_W^2\right)^2}{\sigma_W^4} \right]$$

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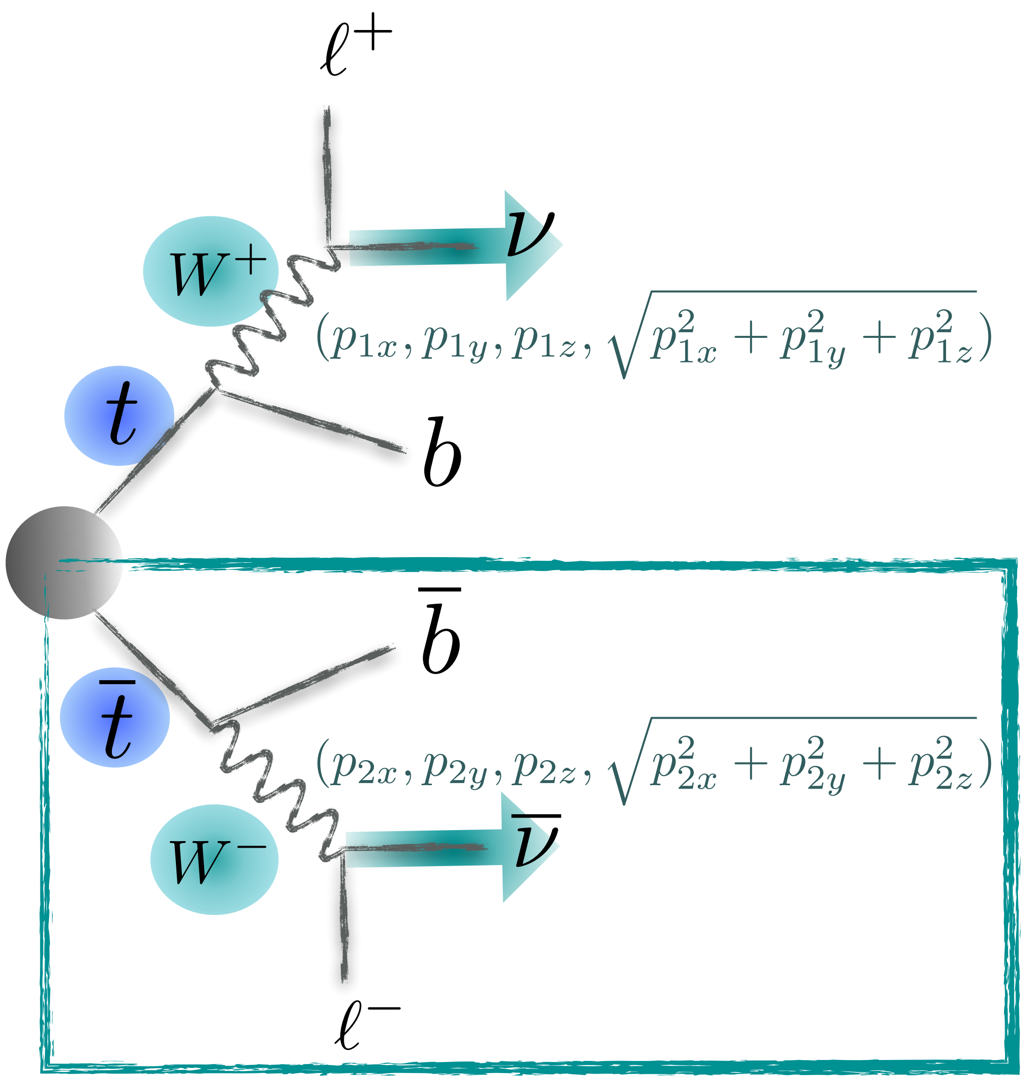
Topness (T)



$$\chi_{ij}^2 \equiv \min_{\vec{\not{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m_{b_i \ell^+ \nu}^2 - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m_{\ell^+ \nu}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{b_j \ell^- \bar{\nu}}^2 - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m_{\ell^- \bar{\nu}}^2 - m_W^2\right)^2}{\sigma_W^4} \right]$$

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

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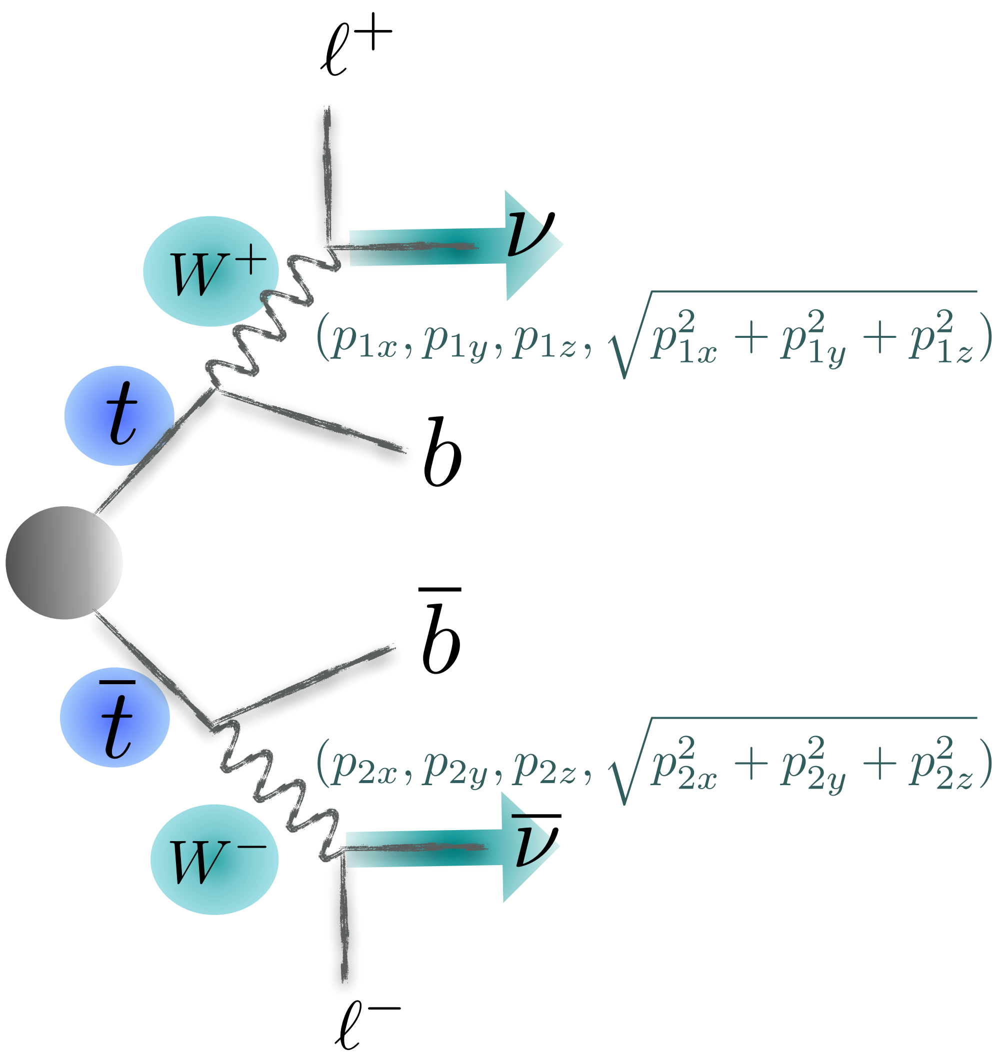
Topness (T)



$$\chi_{ij}^2 \equiv \min_{\vec{\not{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m_{b_i \ell^+ \nu}^2 - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m_{\ell^+ \nu}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{b_j \ell^- \bar{\nu}}^2 - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m_{\ell^- \bar{\nu}}^2 - m_W^2\right)^2}{\sigma_W^4} \right]$$

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two possible ways of paring b and ℓ

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- It scans over 6 unknowns of neutrino momenta with four on-shell masses and missing E_T constraints.
- And find a minimum of the likelihood function.

Hunting Asymmetric Stops

$$S(p_{Wx}, p_{Wy}, p_{Wz}, p_{\nu z}) = \frac{(m_W^2 - p_W^2)^2}{a_W^4} + \frac{(m_t^2 - (p_{b_1} + p_\ell + p_\nu)^2)^2}{a_t^4} + \frac{(m_t^2 - (p_{b_2} + p_W)^2)^2}{a_t^4} + \frac{(4m_t^2 - (\sum_i p_i)^2)^2}{a_{CM}^4}$$

$$t = \ln(\min S)$$

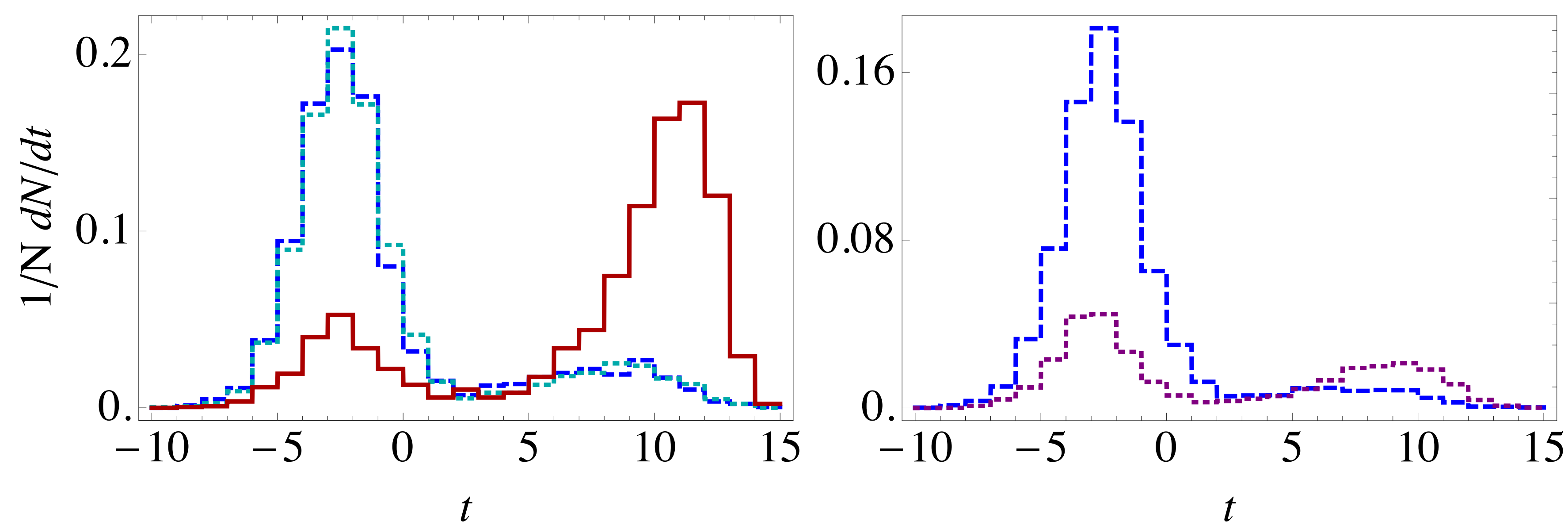
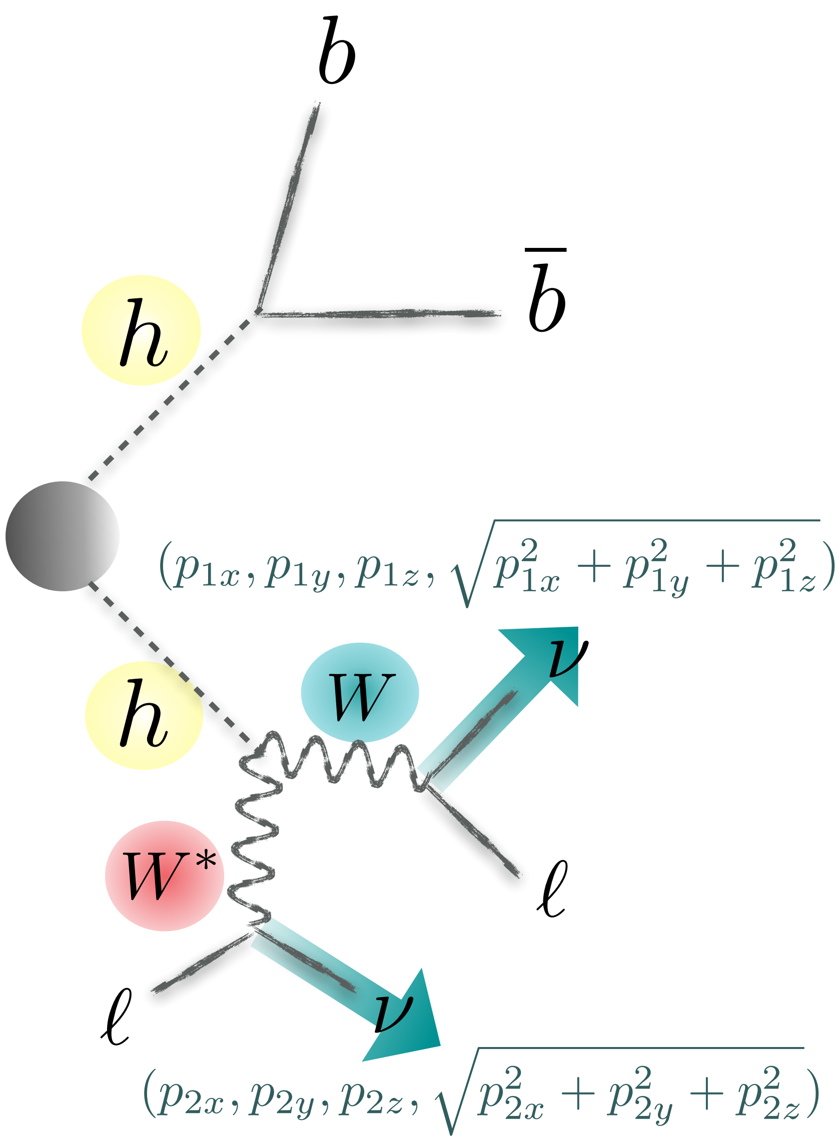


FIG. 2: Left: unit-normalized topness distributions for events passing preselection cuts as described in the text (signal, red, solid; dileptonic top, blue, dashed; one ℓ, one τ top, cyan, dotted). Right: topness distributions for the dileptonic background broken down into samples with two truth b jets (blue, dashed) and one truth b jet (purple, dotted).

1212.4495 Graesser, Shelton

Higgsness (H)



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

$\sim m_h - m_W$

off-shell

- Higgsness provides a degree of consistency to dileptonic $h \rightarrow WW^*$ system.
- The off-shell W also has an end-point near m_h - m_W.
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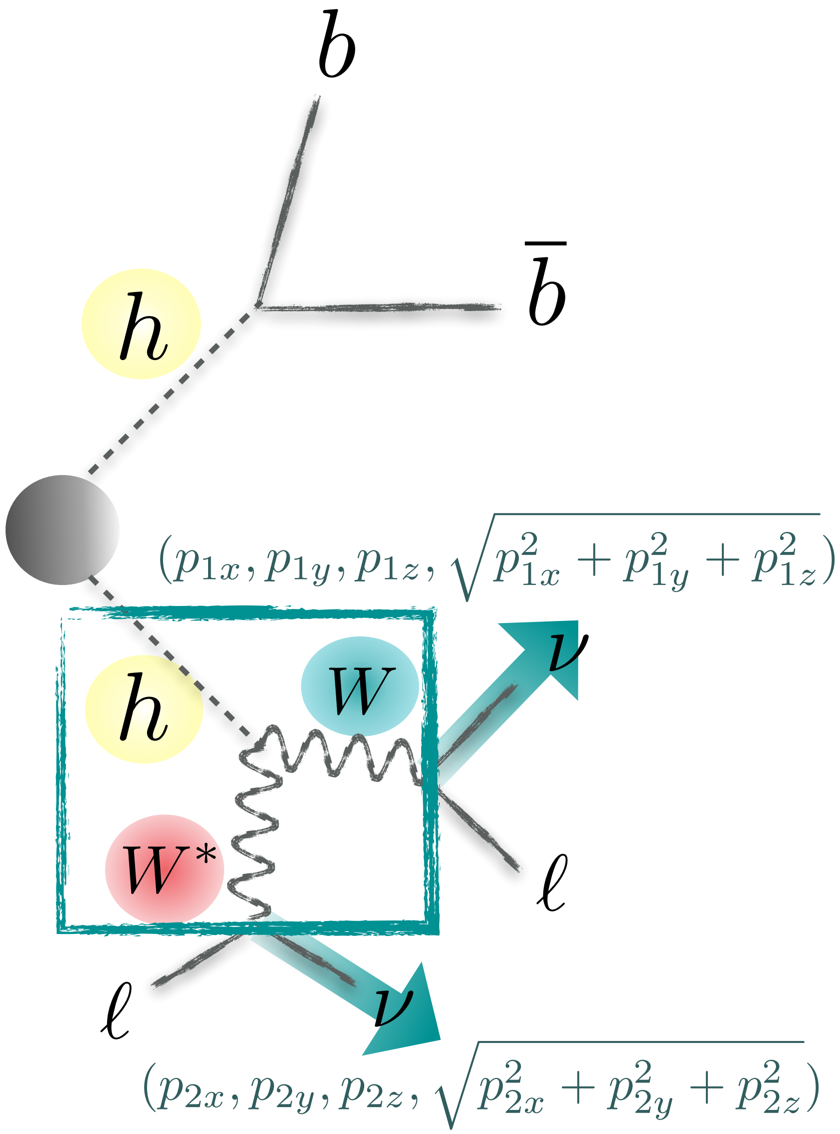

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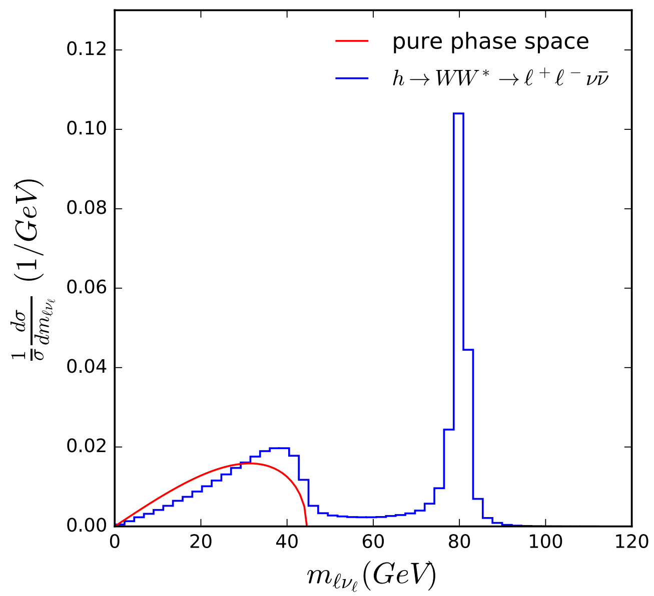


$$m_{W^*}^{peak} = \frac{1}{\sqrt{3}}\sqrt{2\left(m_h^2 + m_W^2\right) - \sqrt{m_h^4 + 14 m_h^2 m_W^2 + m_W^4}}$$

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

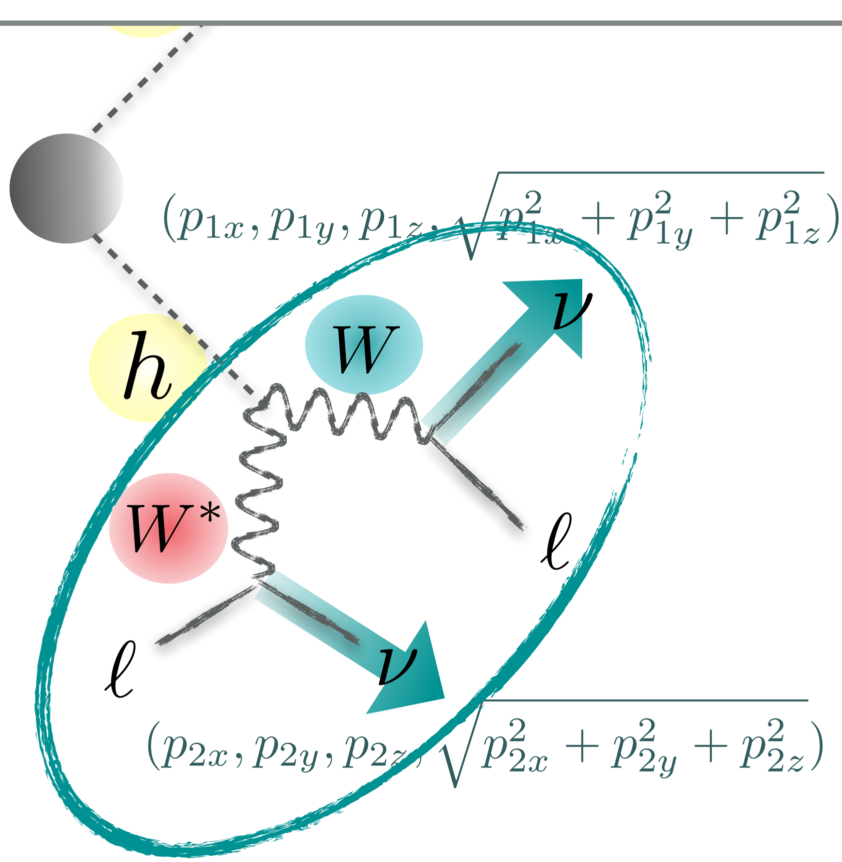
$$\cosh\eta = \left(\frac{m_h^2 - m_W^2 - m_{W^*}^2}{2 m_W m_{W^*}}\right)$$

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

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

$\sim m_h - m_W$

off-shell



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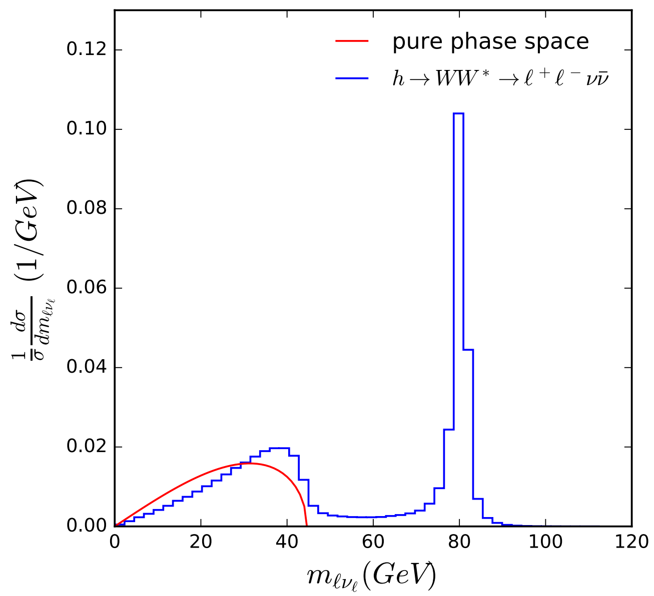

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$$\left.\frac{\left(m_{\ell^-\bar{\nu}}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{\ell^+\nu}^2 - m_{W^*,peak}^2\right)^2}{\sigma_{W_*}^4}\right)\Bigg]\,,$$

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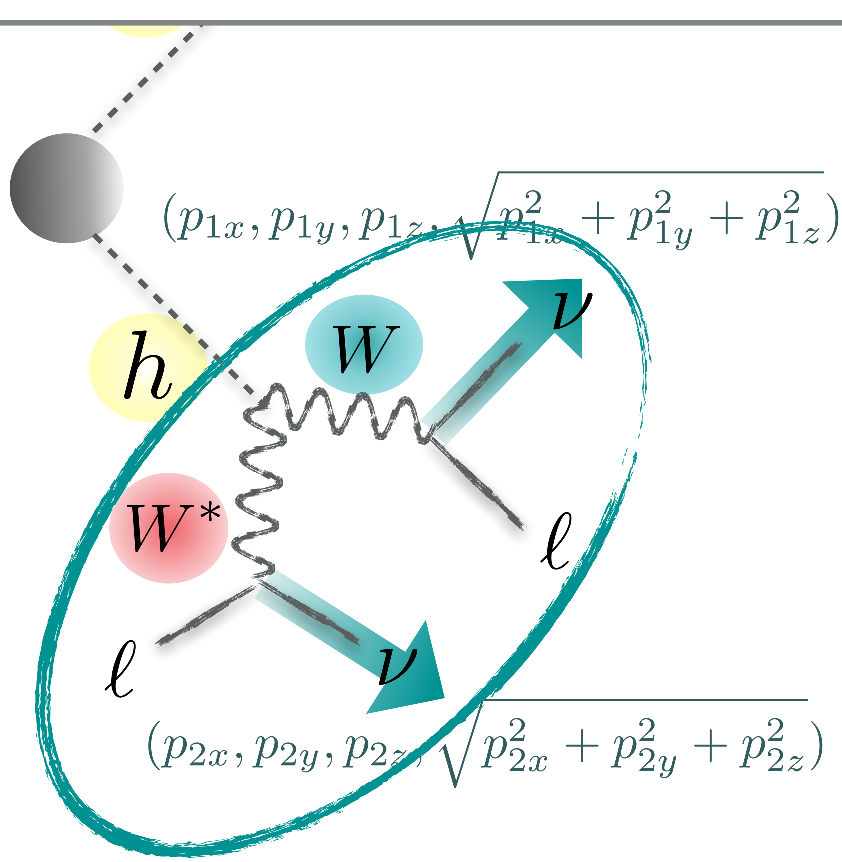
off-shell



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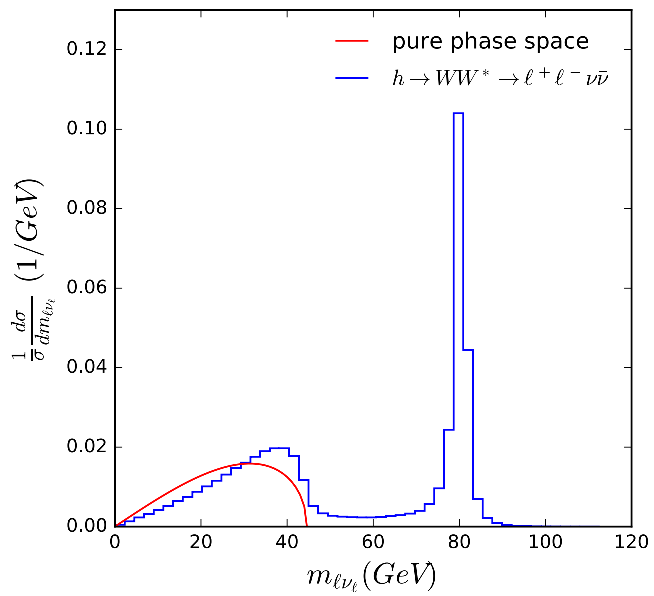

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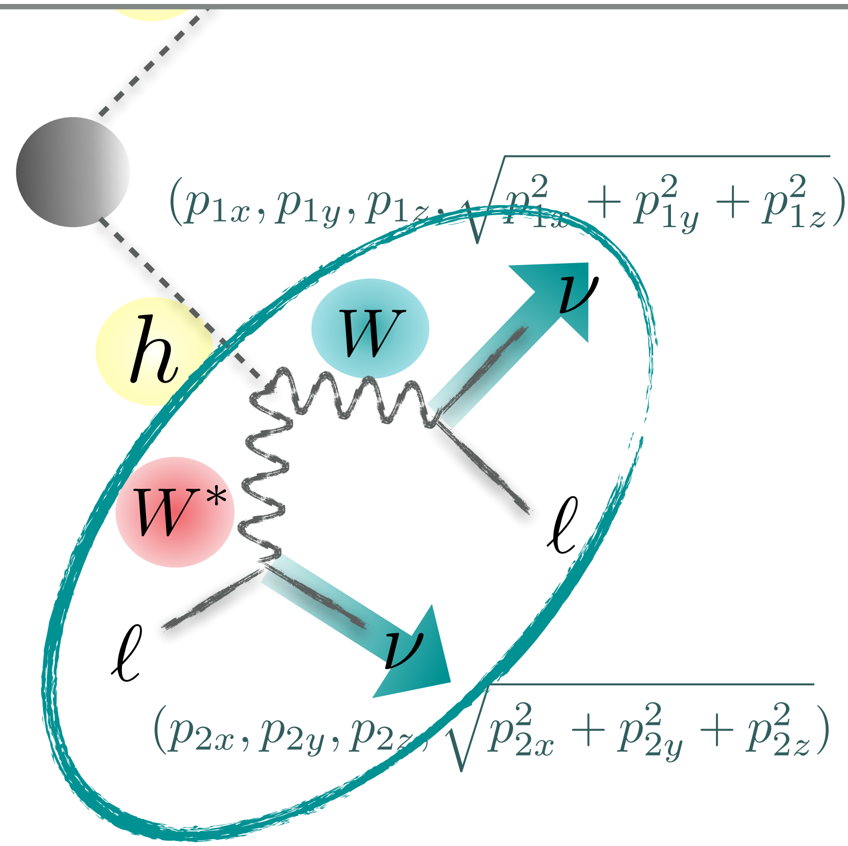

two possible ways of paring ν and ℓ

$\sim m_h - m_W$
off-shell

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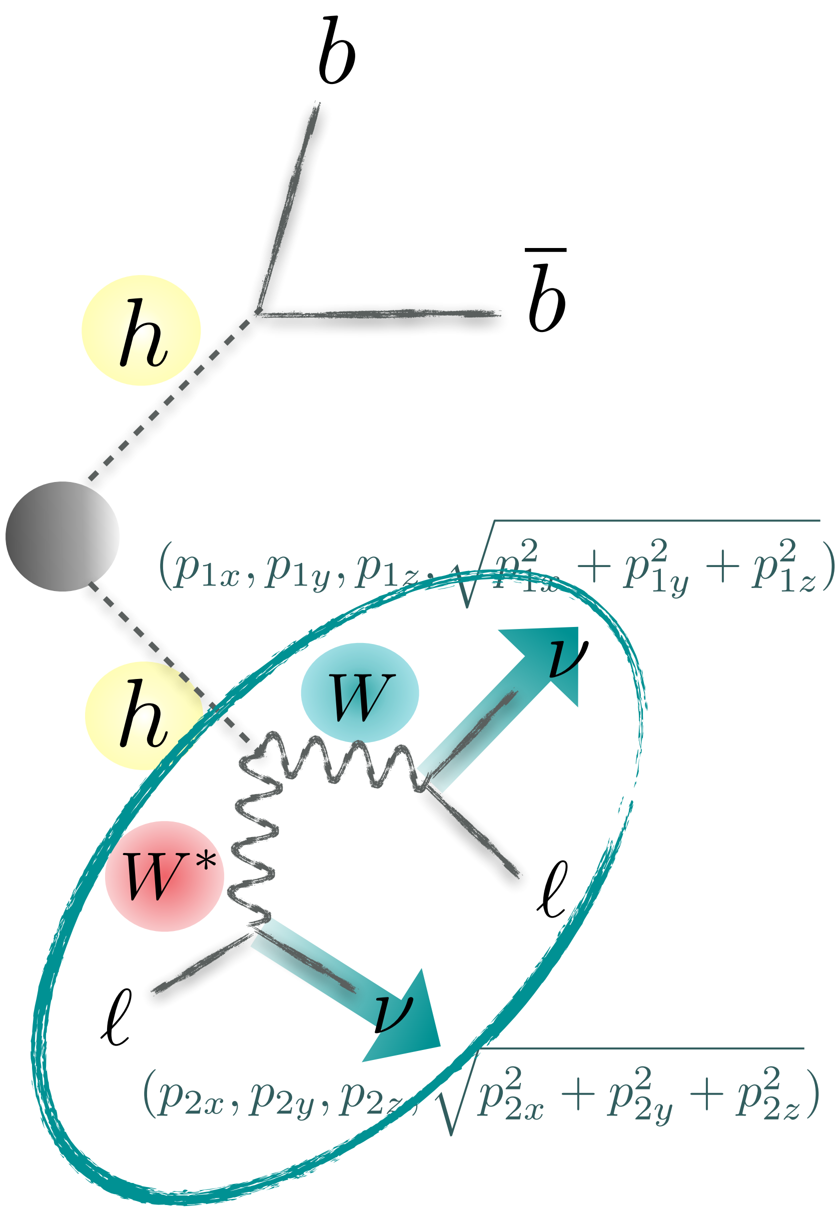

$$H \equiv \min_{\vec{\not p}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{\ell^+\ell^-\nu\bar{\nu}} - m_h^2\right)^2}{\sigma^4_{h_\ell}} + \frac{\left(m^2_{\nu\bar{\nu}} - m^2_{\nu\bar{\nu},peak}\right)^2}{\sigma^4_\nu} \right.$$

$$\left. + min\left(\frac{\left(m^2_{\ell^+\nu} - m_W^2\right)^2}{\sigma^4_W} + \frac{\left(m^2_{\ell^-\bar{\nu}} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}}, \frac{\left(m^2_{\ell^-\bar{\nu}} - m_W^2\right)^2}{\sigma^4_W} + \frac{\left(m^2_{\ell^+\nu} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}} \right) \right],$$

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Higgsness (*H*)

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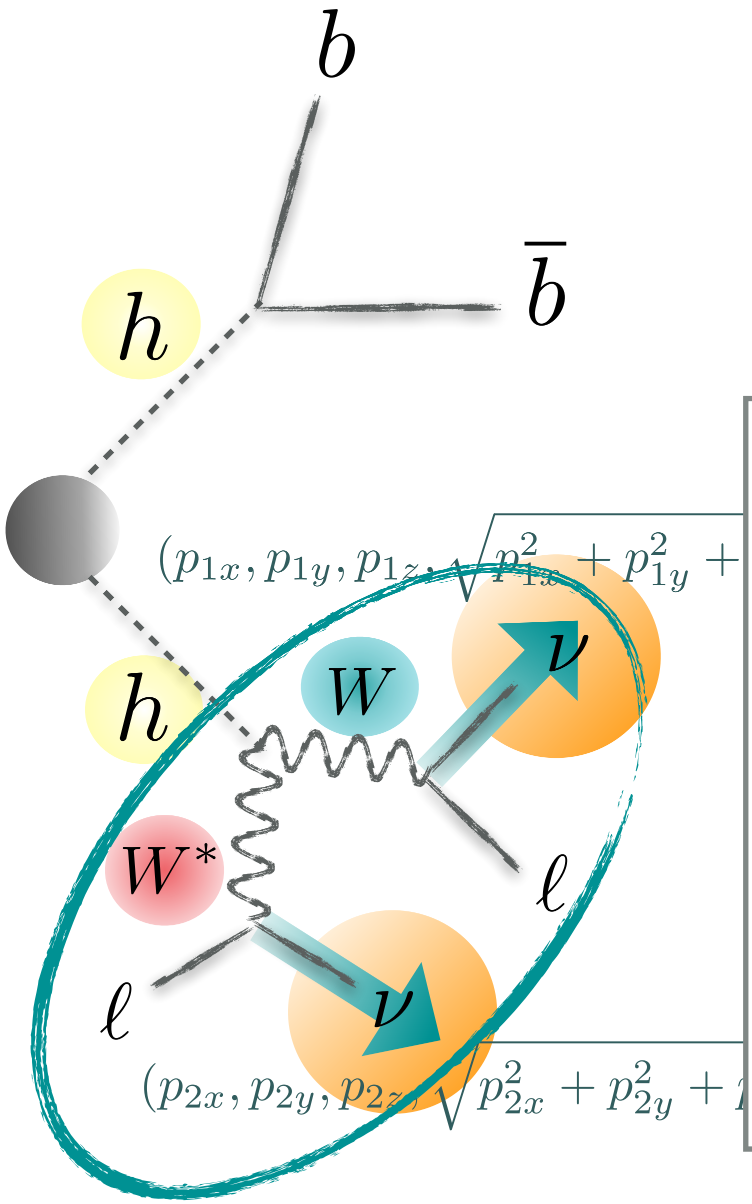

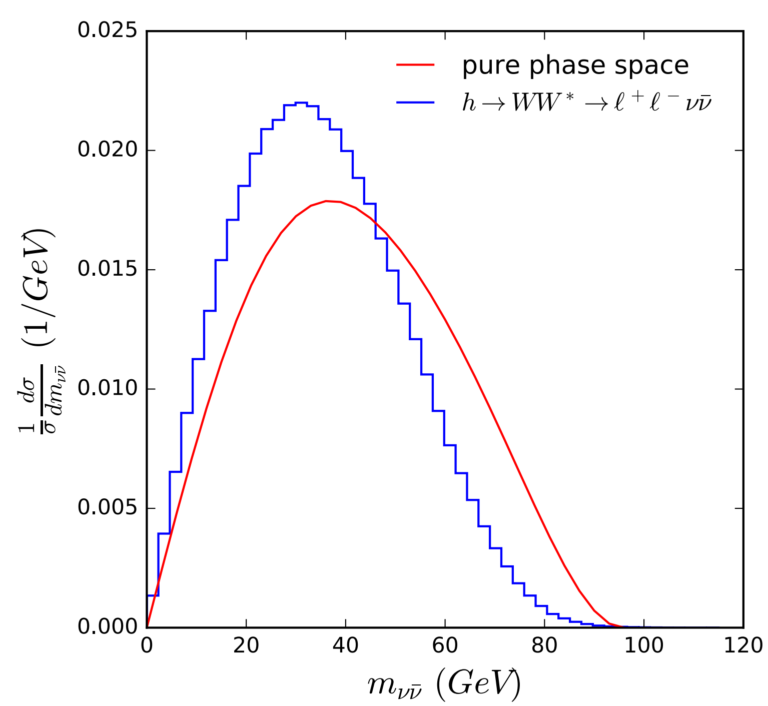

$$\frac{d\sigma}{dm_{\nu\bar{\nu}}} \propto \int dm^2_{W^*} \lambda^{1/2}(m_h^2, m_W^2, m_{W^*}^2) f(m_{\nu\bar{\nu}})$$

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

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

pairing $\bar{\nu}$ and ℓ

off-shell

- Higgsness provides a degree of consistency to dileptonic $h \to WW^*$ system.
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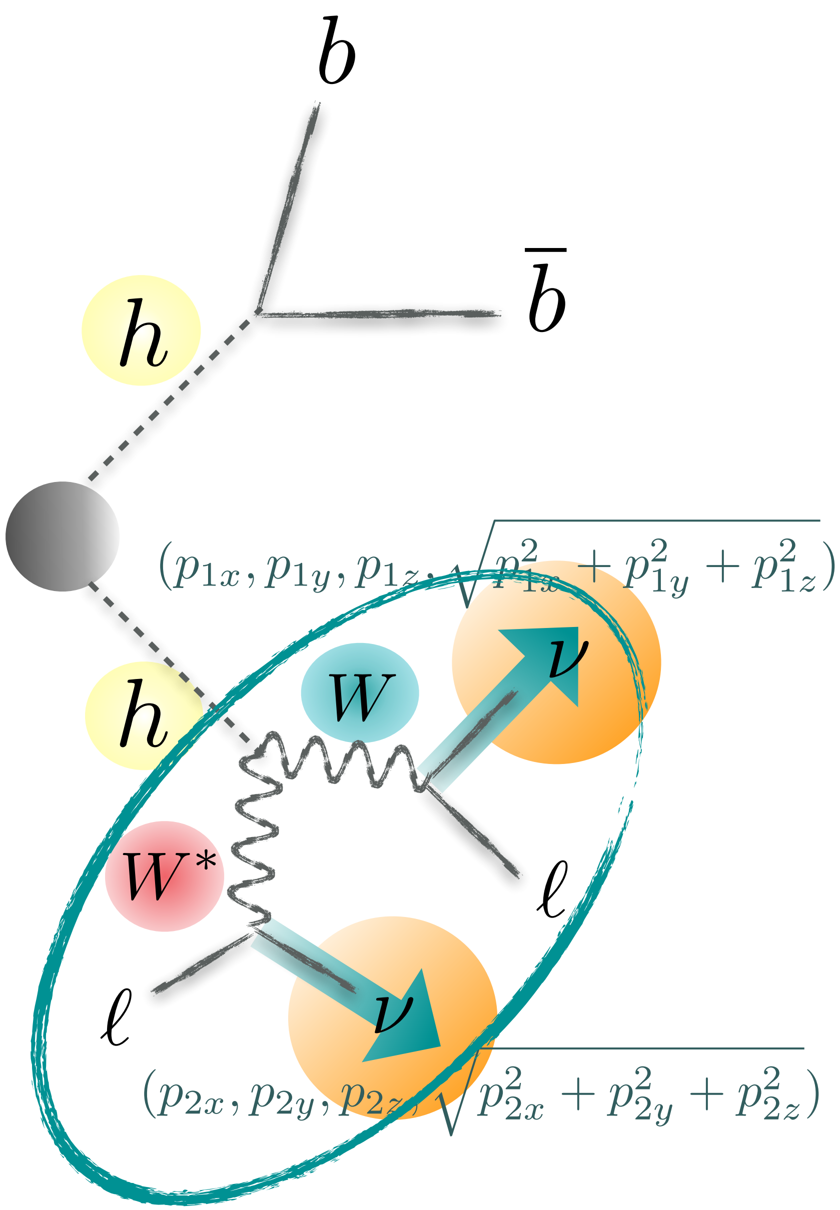

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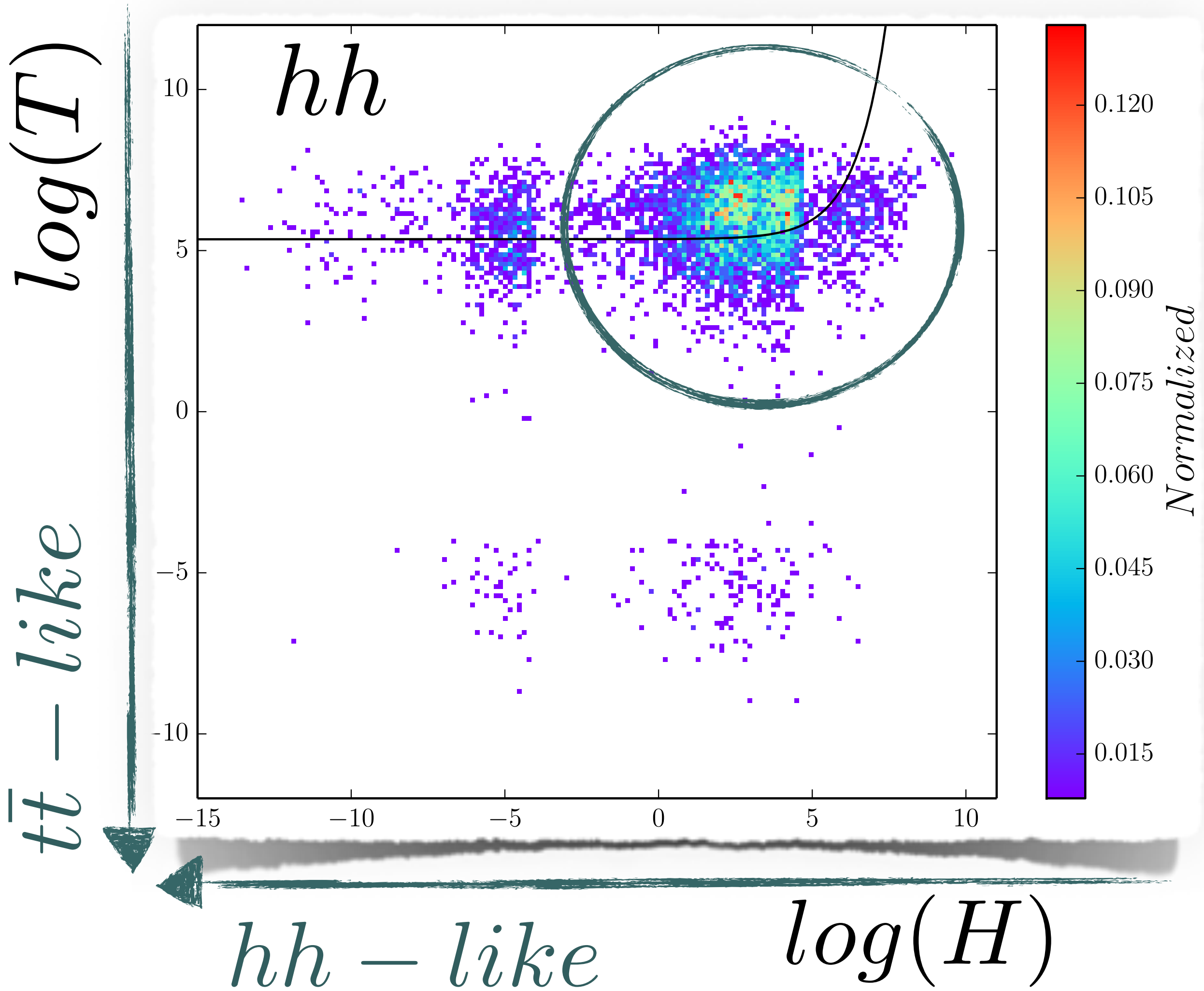
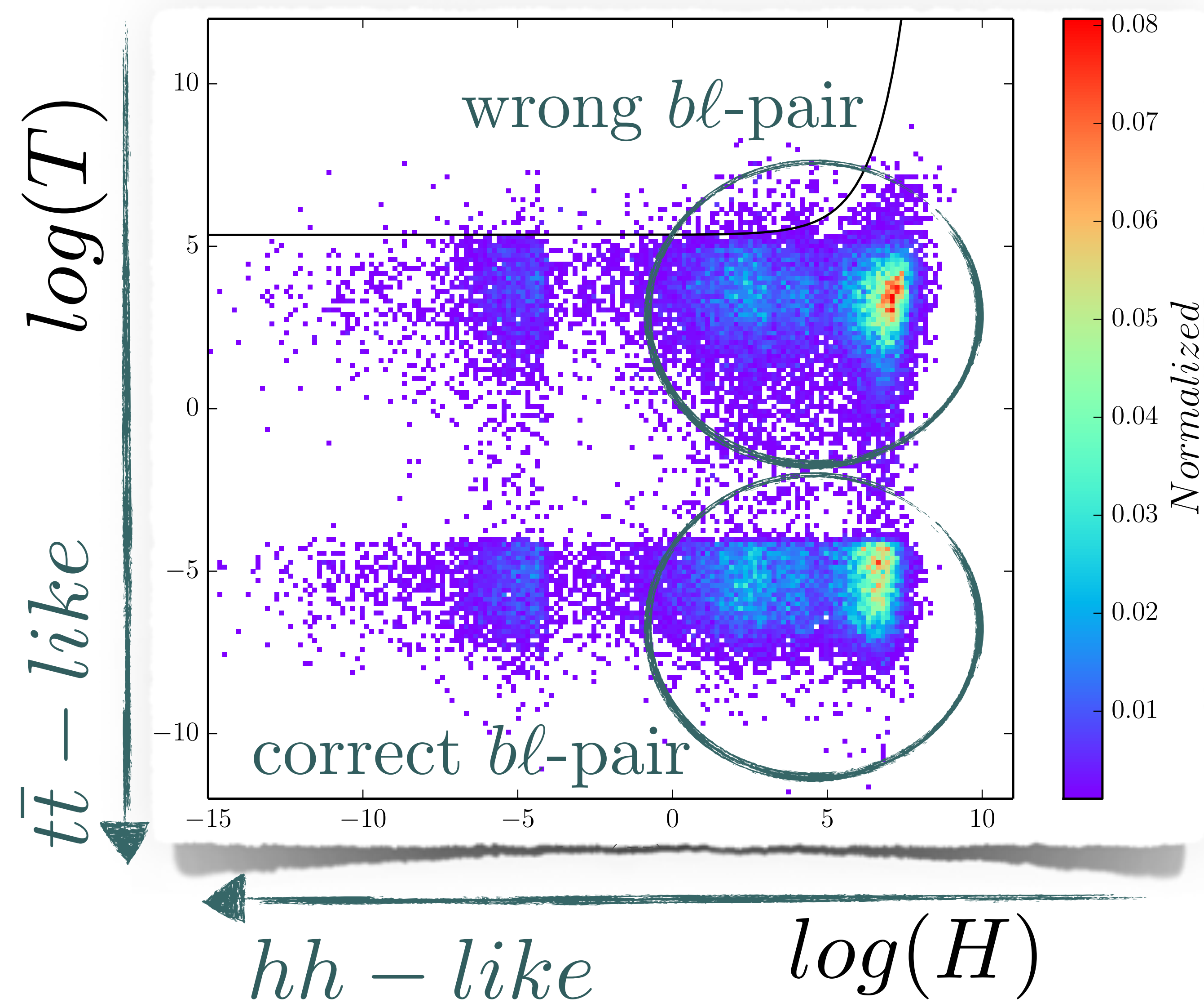
Distributions of (*log H* , *log T*) after baseline selection cuts



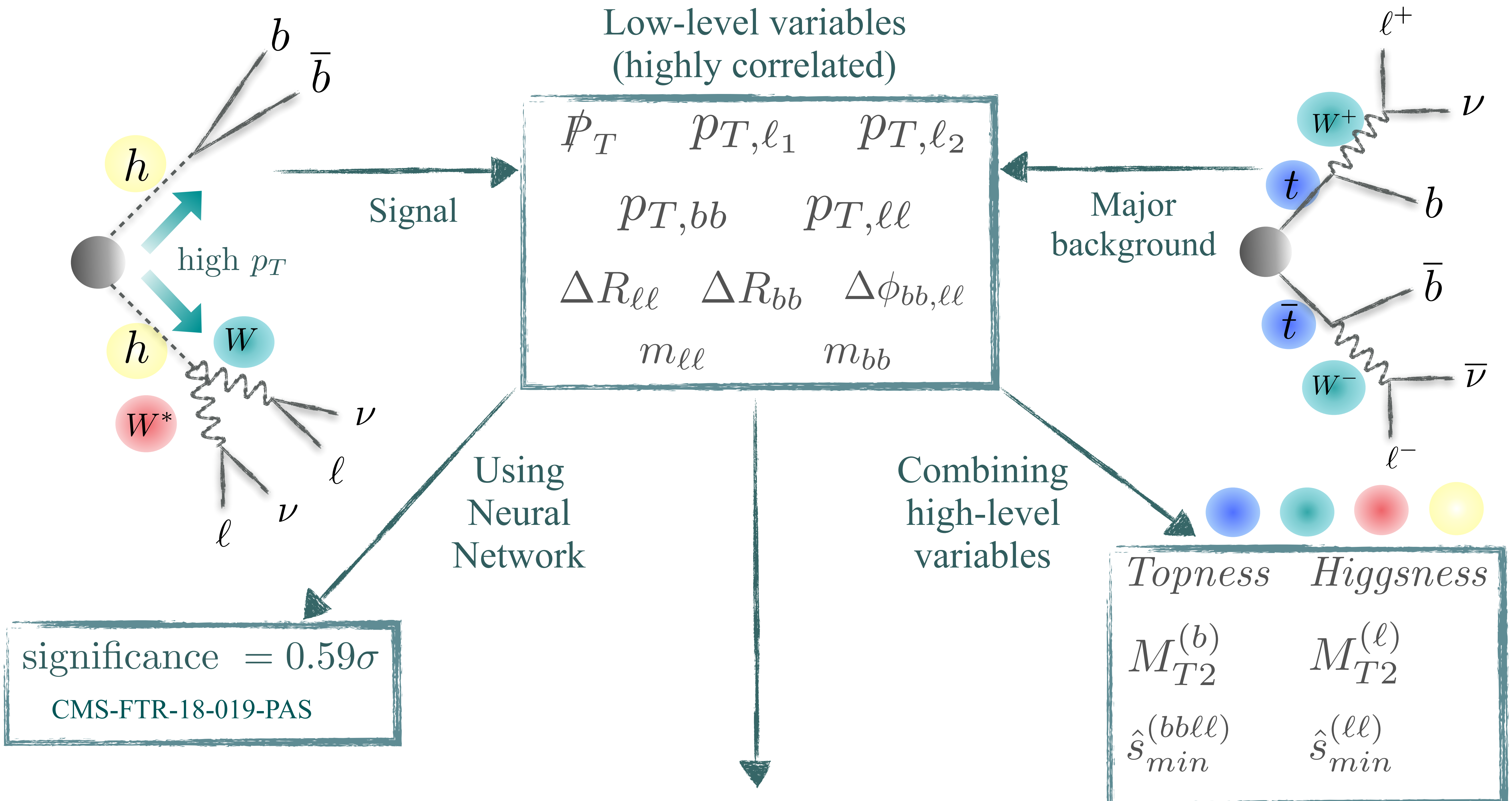
- A clear separation between *hh* and backgrounds ($t\bar{t}$ is dominant)

All backgrounds



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

How to rescue $bbWW^*$?



We utilize jet images, and let the machine deal with correlations.

J. H. Kim, K. C. Kong, K. T. Matchev, M. Park [2018]

Different Color flows

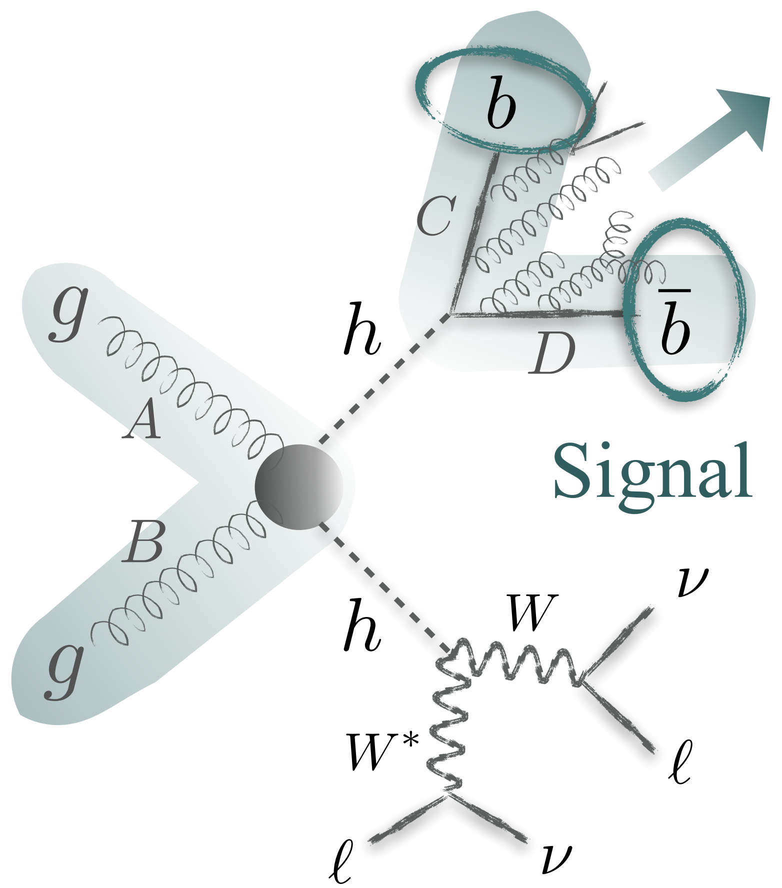
J. Gallicchio and M. D. Schwartz [2010]

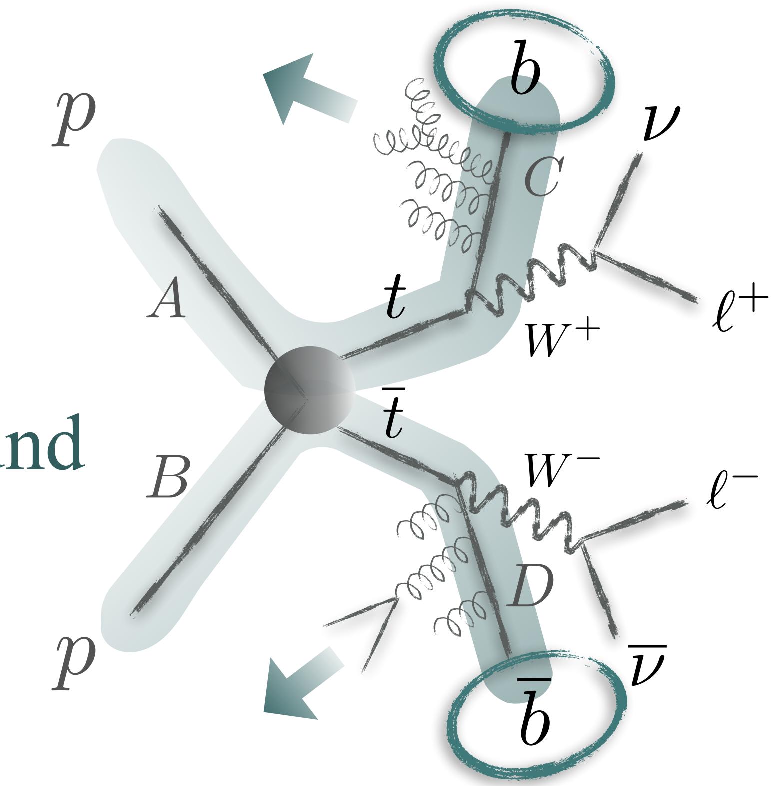
L. Oliveira, M. Kagan, L. Mackey, B. Nachman, A. Schwarzman [2017]

J. Lin, M. Freytsis, I. Moult, B. Nachman [2018]

See also P. T. Komiske, E. M. Metodiev, J. Thaler [2019]

J. H. Kim, M. Kim, K. C. Kong, K. T. Matchev, M. Park [2019]





- The advantage of using jet images is that we can better capture color-flow effects.
- Since the Higgs is a color-singlet, two b jets are color-connected with each other.
- However, two b jets from $t\bar{t}$ are color-connected with initial states.
- Parton showering dominantly occurs in the direction of color string.

Different Color flows

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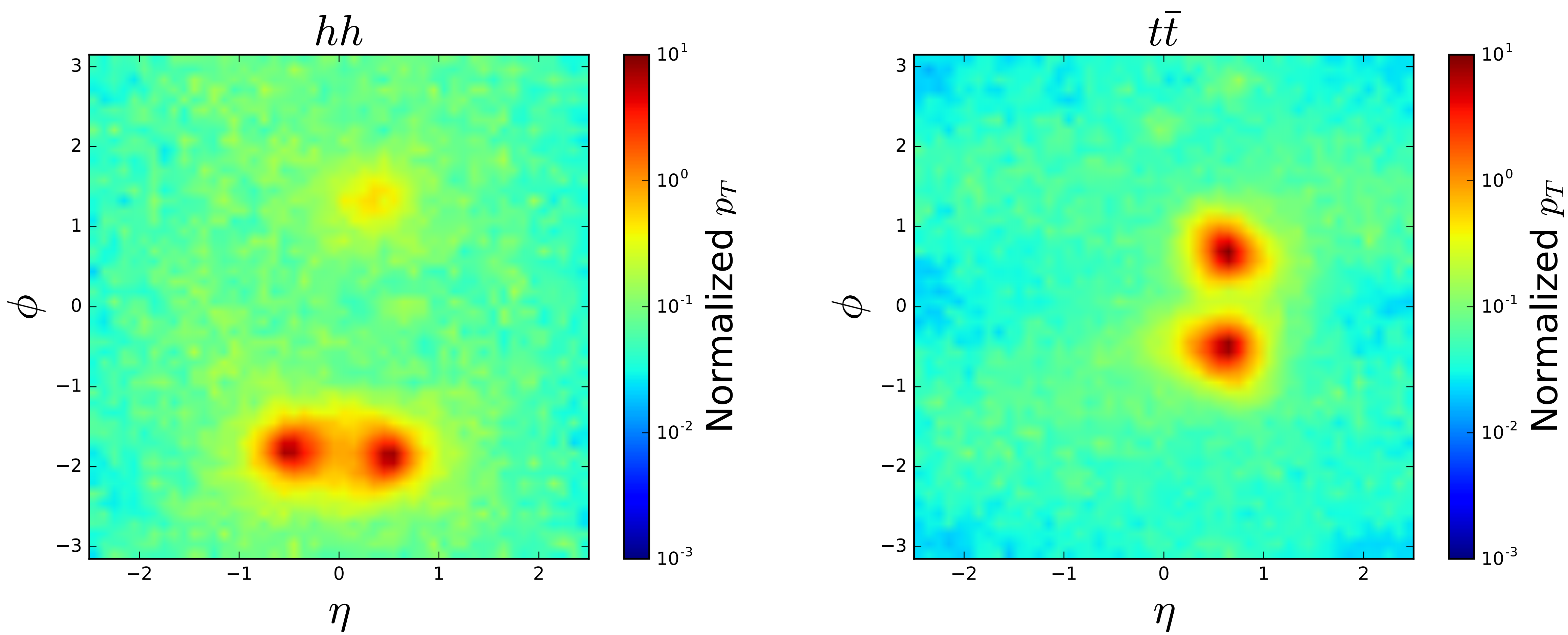
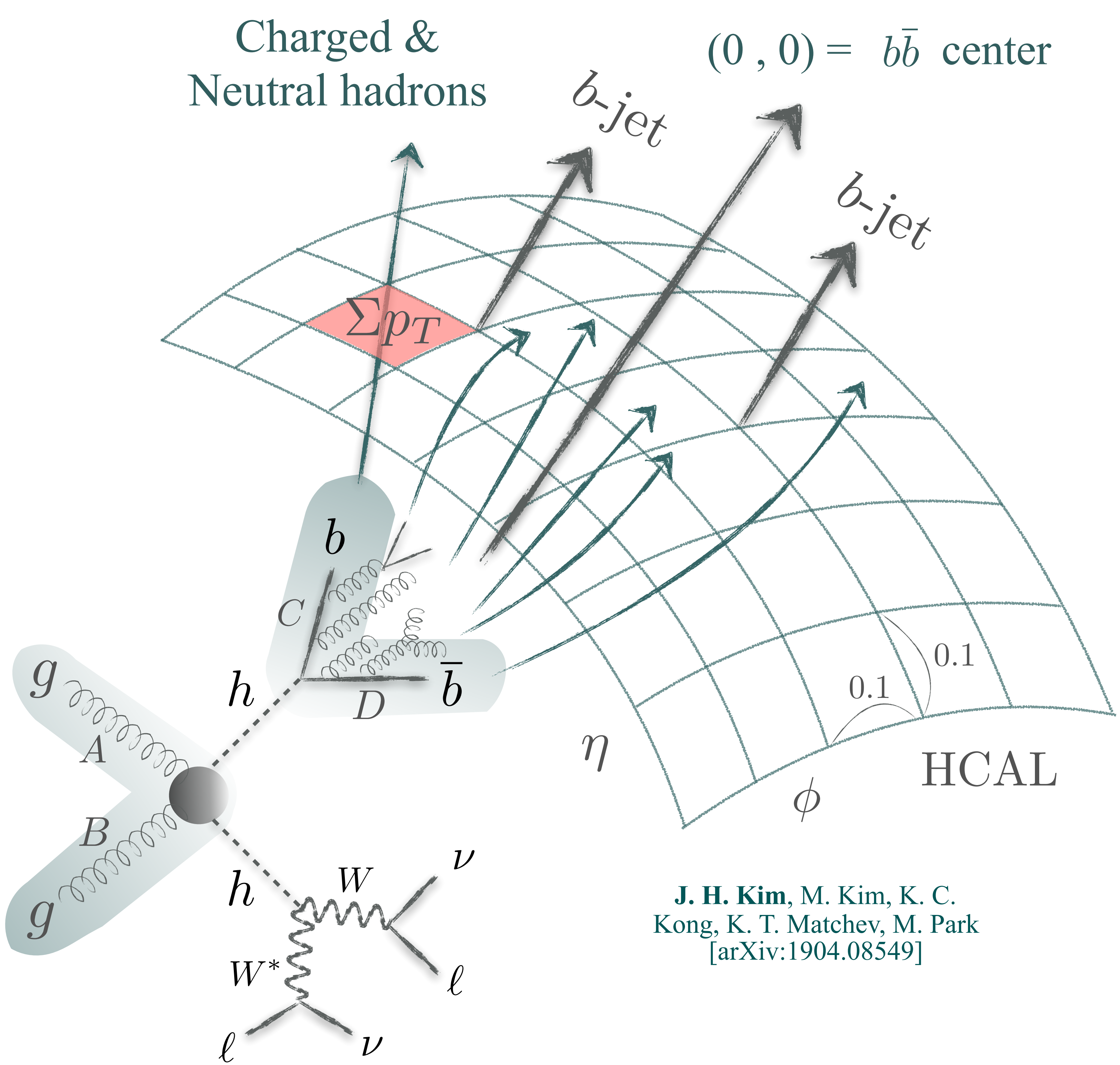


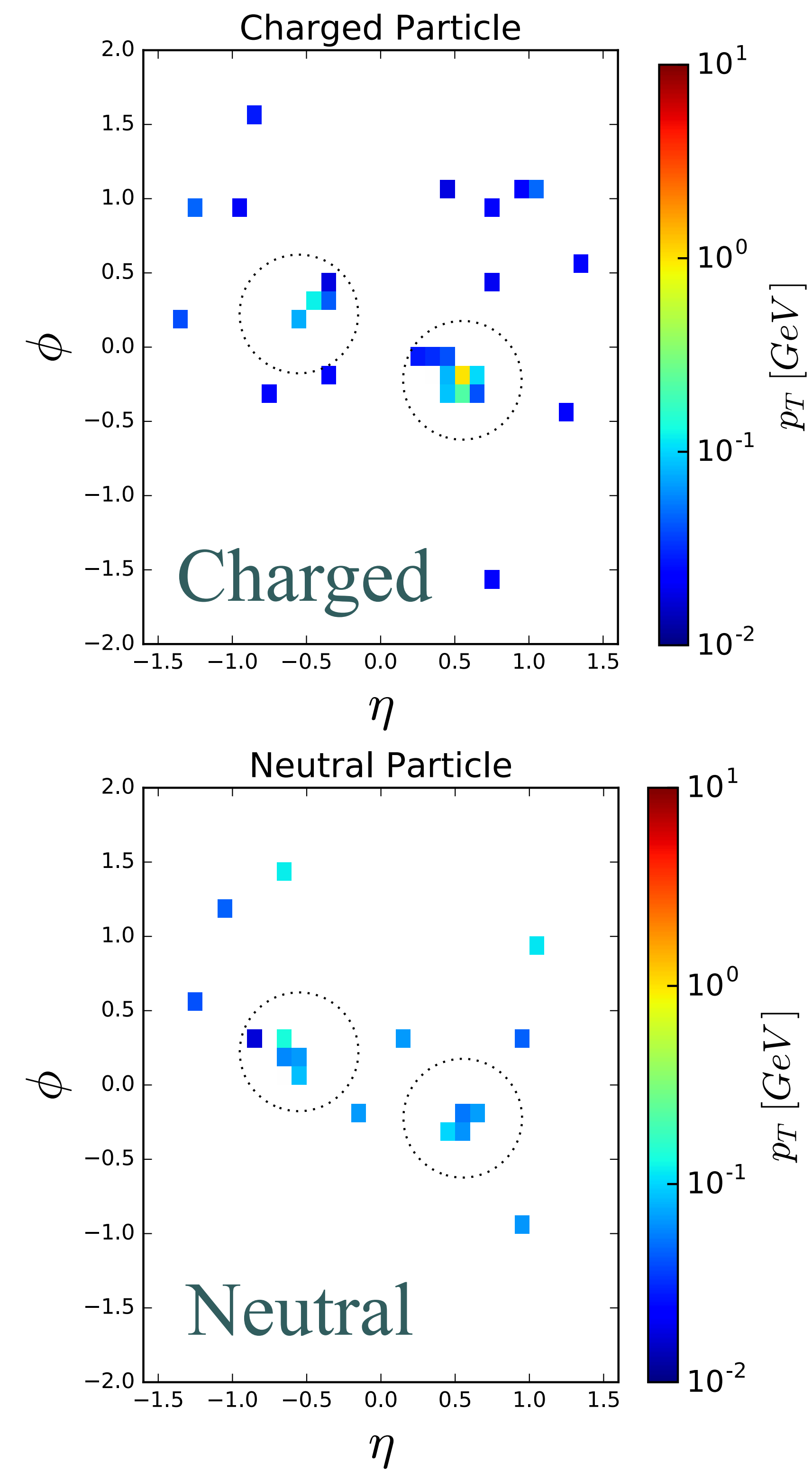
Figure 5. Cumulative p_T distributions resulting from showering 10,000 times a single partonic event for the signal (left) and $t\bar{t}$ production (right). The two b quarks from $h \to b\bar{b}$ are color-connected to each other and the soft radiation tends to fill in the region between them (left panel), while the two b quarks from $t\bar{t}$ production are not color-connected and the two clusters from their hadronization tend to be more isolated (right panel).

$hh \to bbWW^*$ meets jet-images

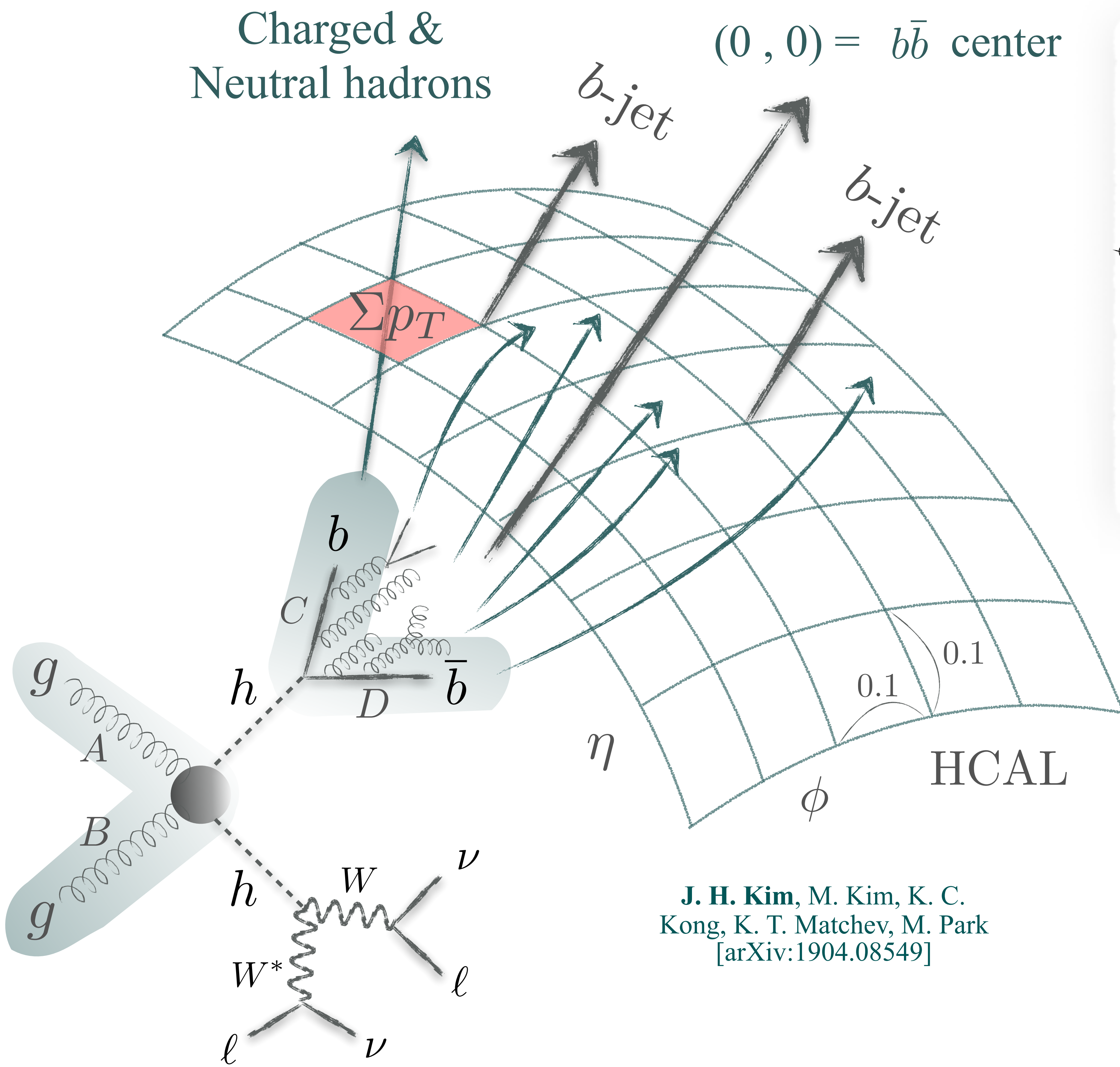


J. H. Kim, M. Kim, K. C. Kong, K. T. Matchev, M. Park [arXiv:1904.08549]

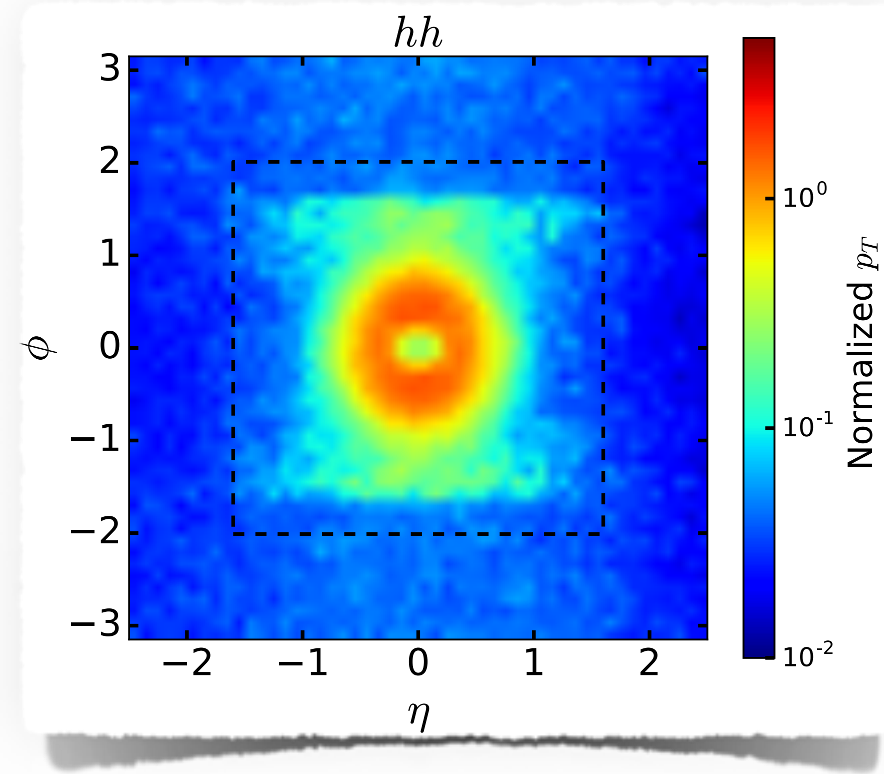
Each event



$hh \to bbWW^*$ meets jet-images



Sum of all events



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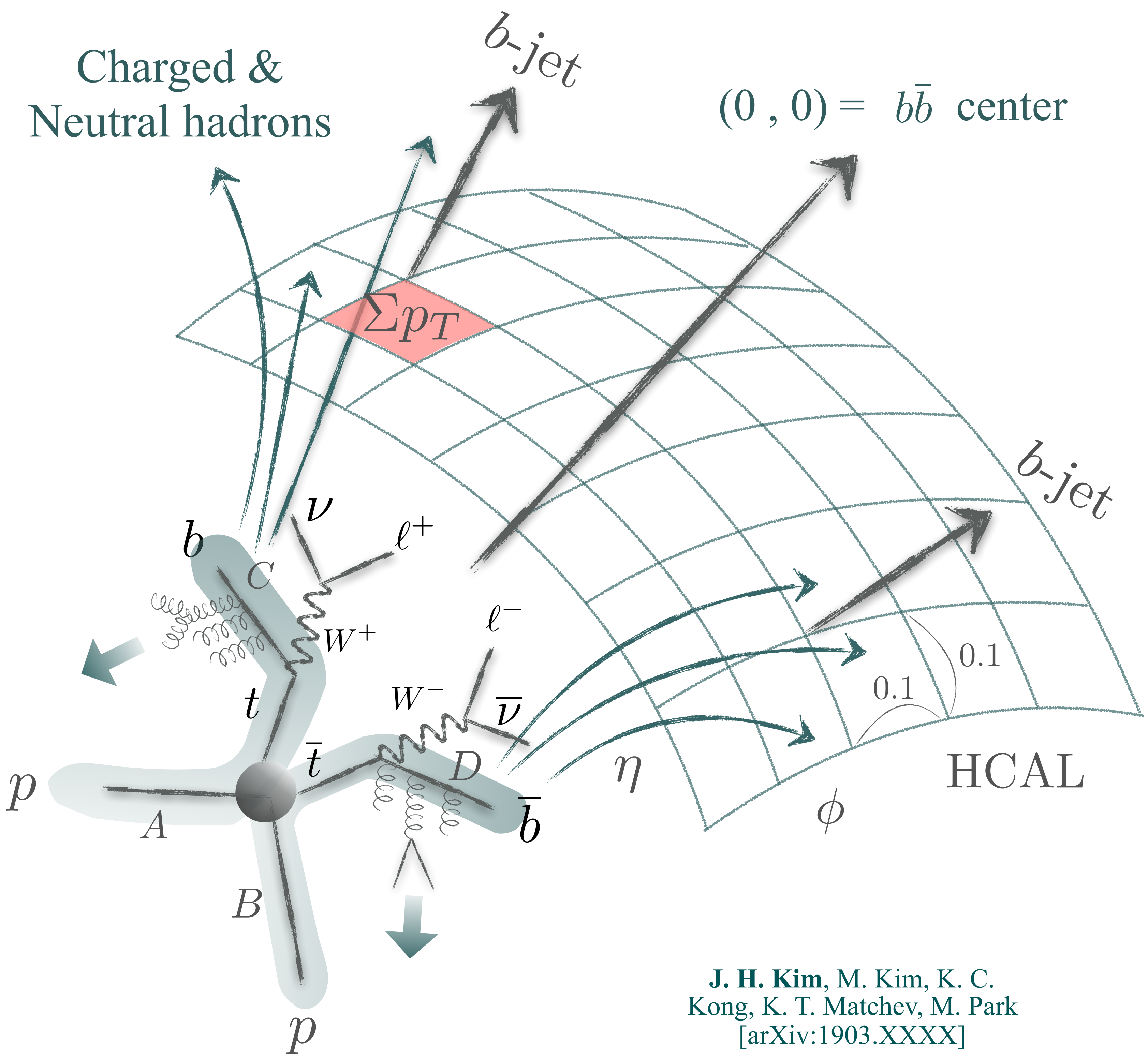
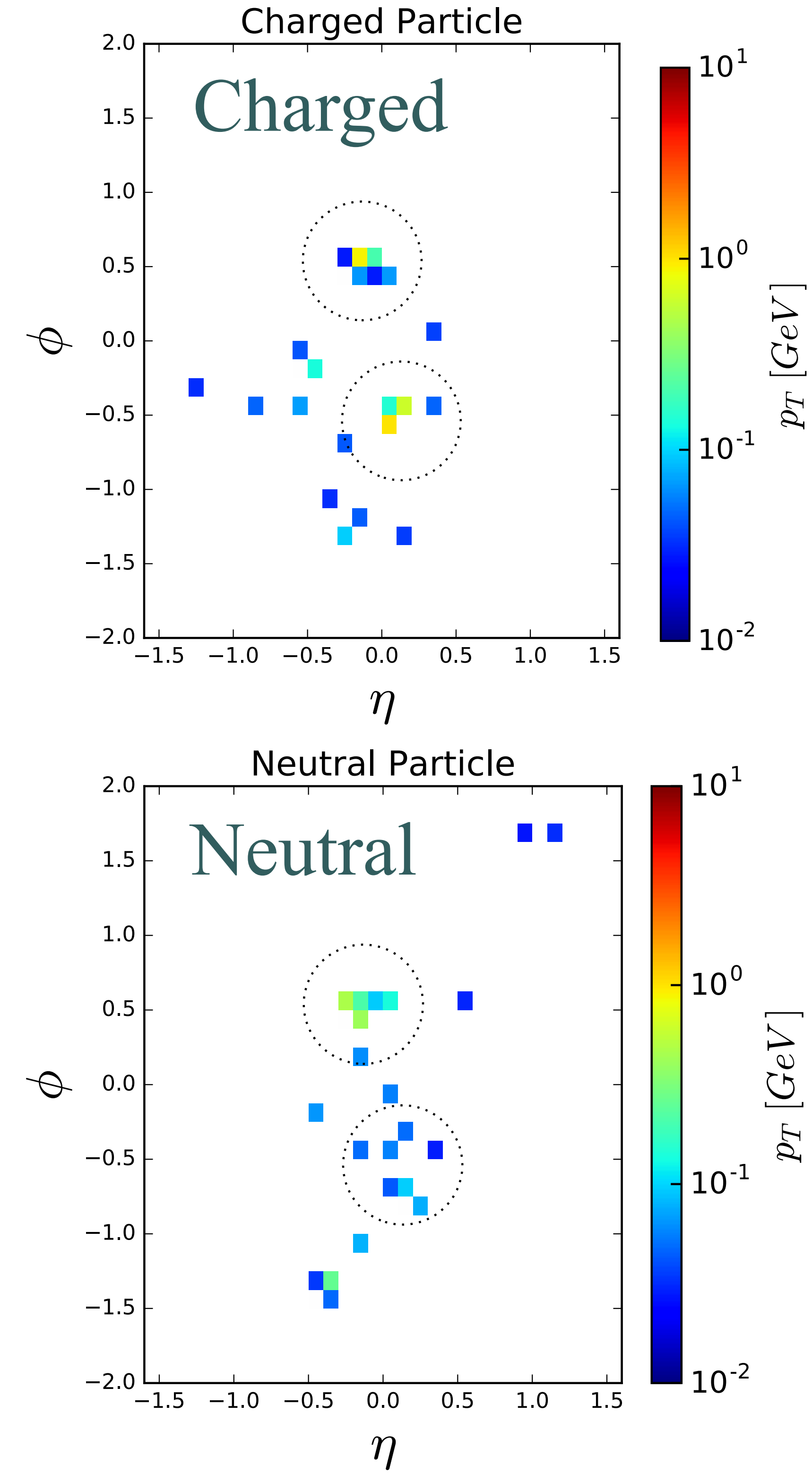
$hh \to bbWW^*$ meets jet-images

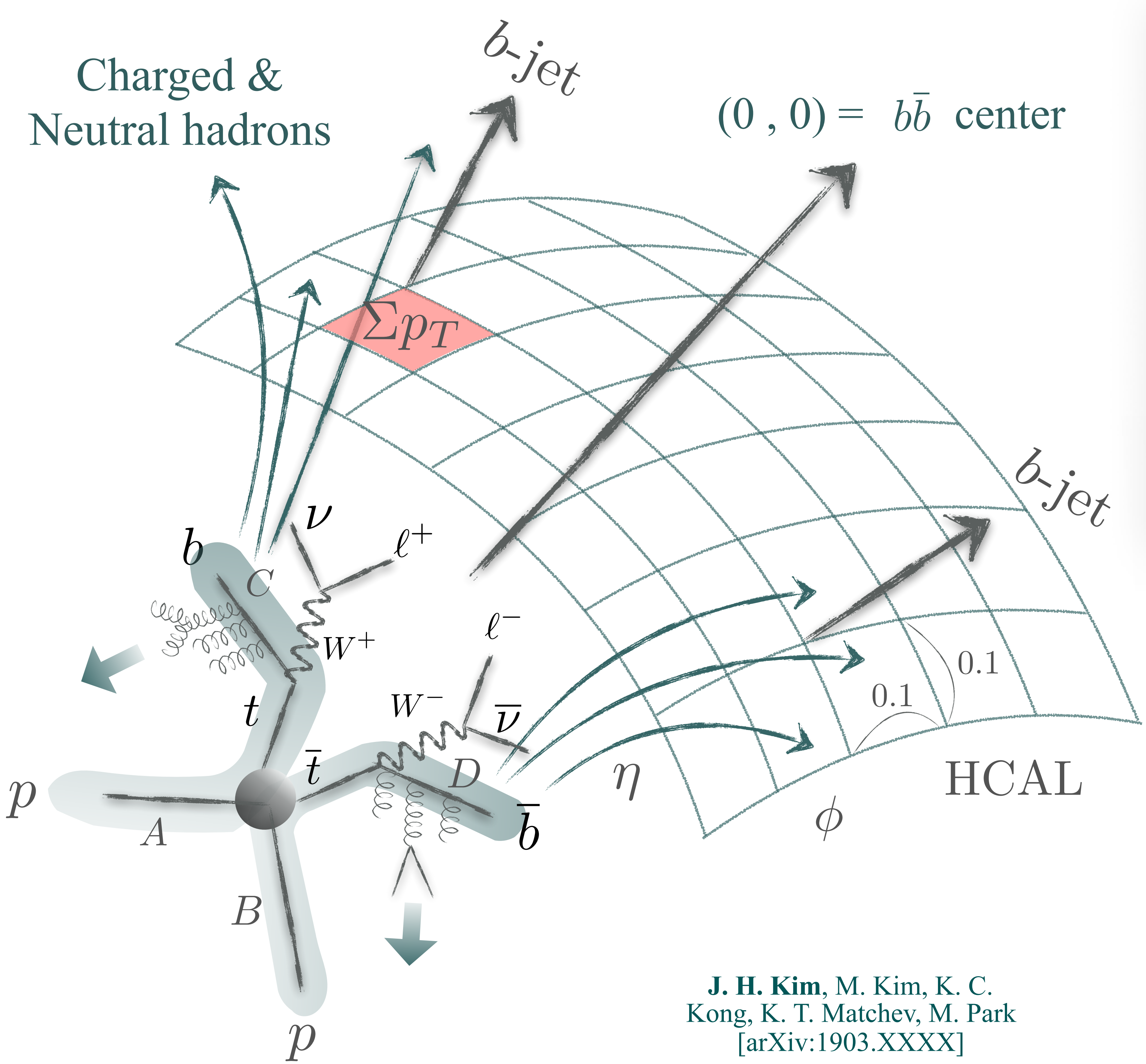


Each event

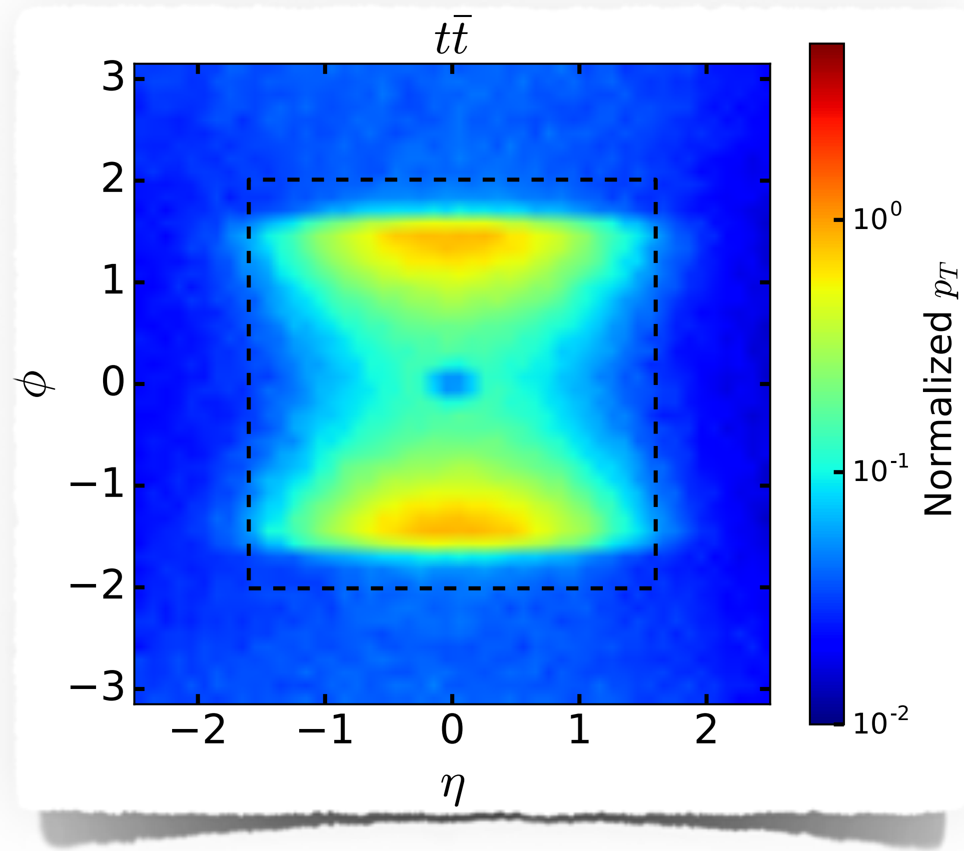


J. H. Kim, M. Kim, K. C. Kong, K. T. Matchev, M. Park
[arXiv:1903.XXXX]

$hh \to bbWW^*$ meets jet-images

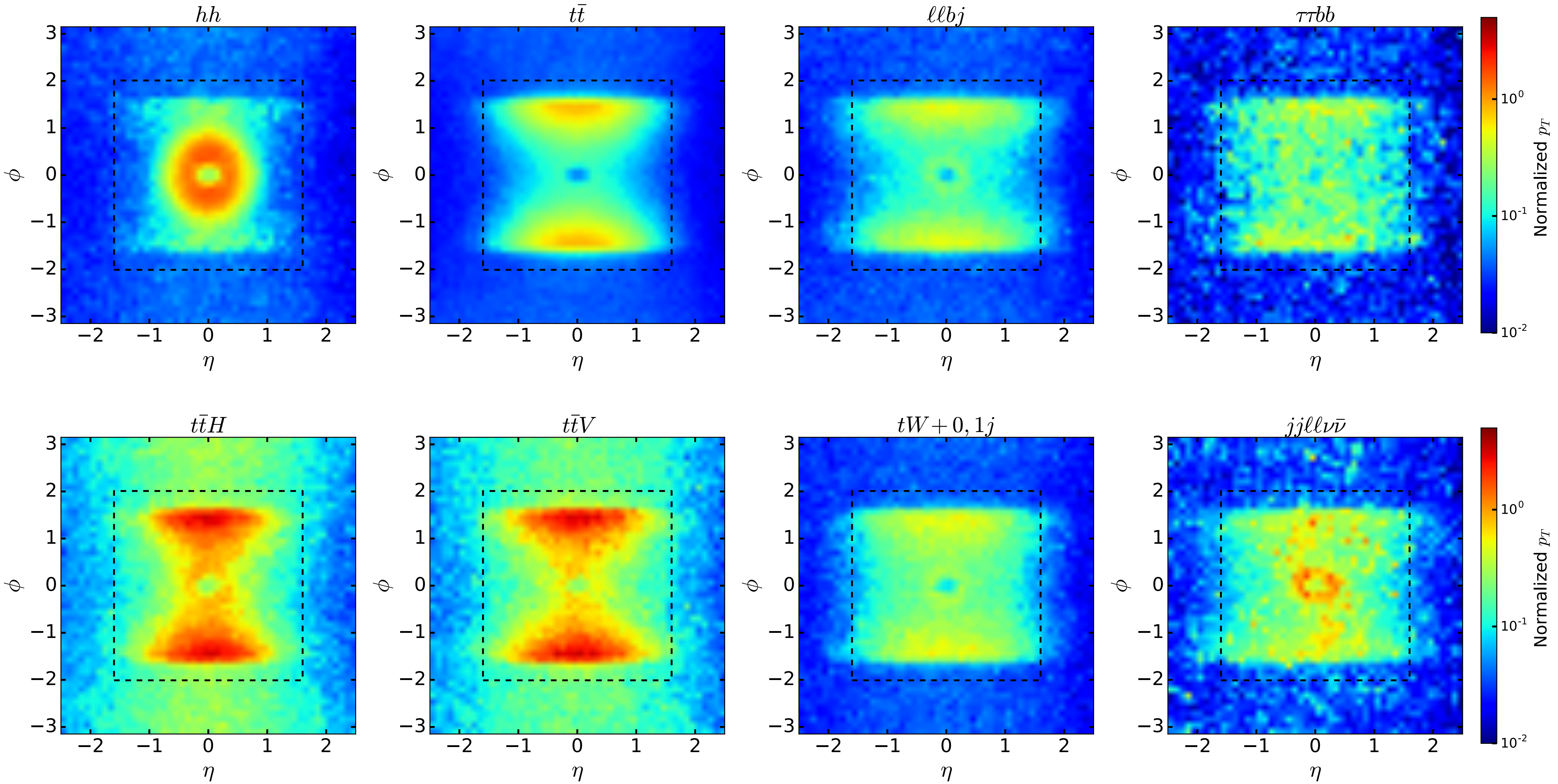


Sum of all events



J. H. Kim, M. Kim, K. C. Kong, K. T. Matchev, M. Park
[arXiv:1903.XXXX]

Jet images before baseline cuts



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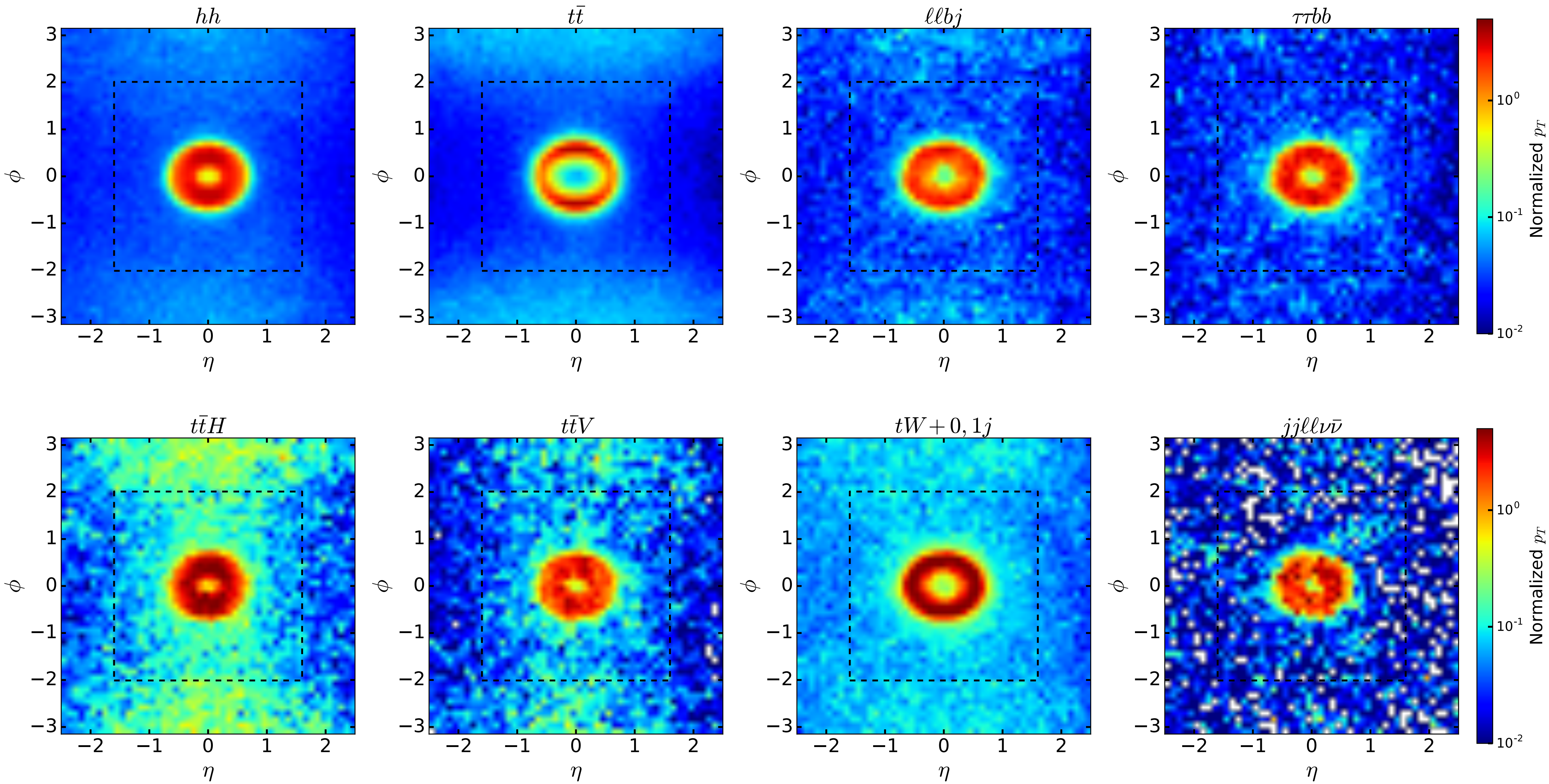
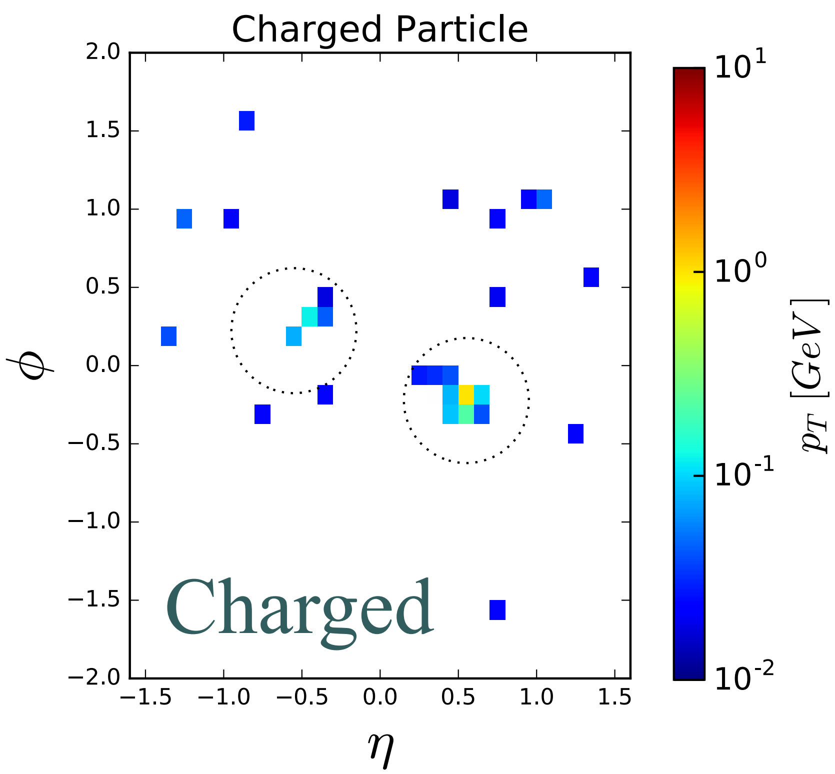
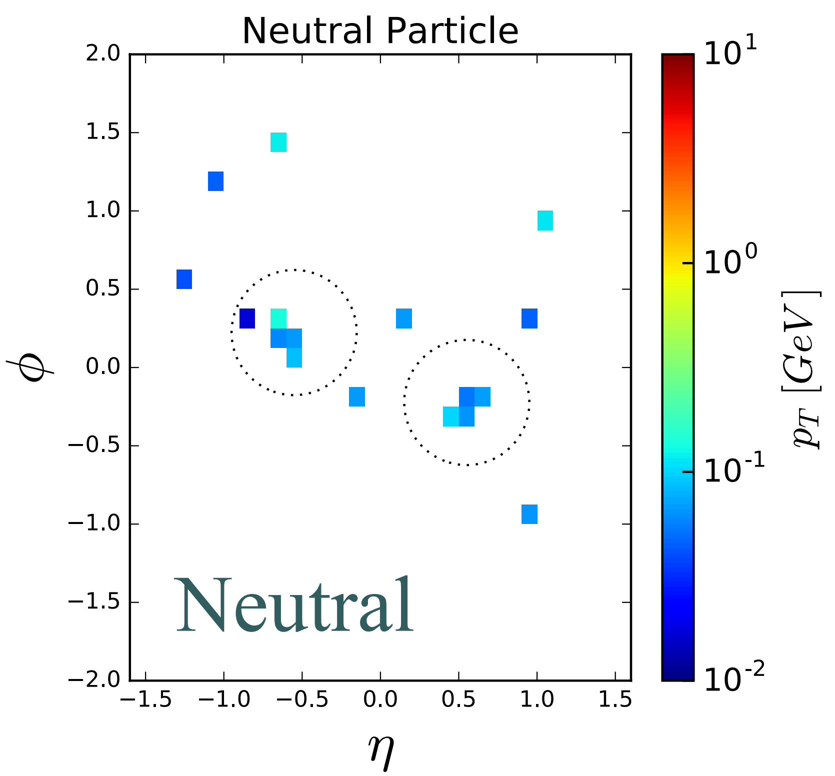


$hh \to bbWW^*$ meets jet-images

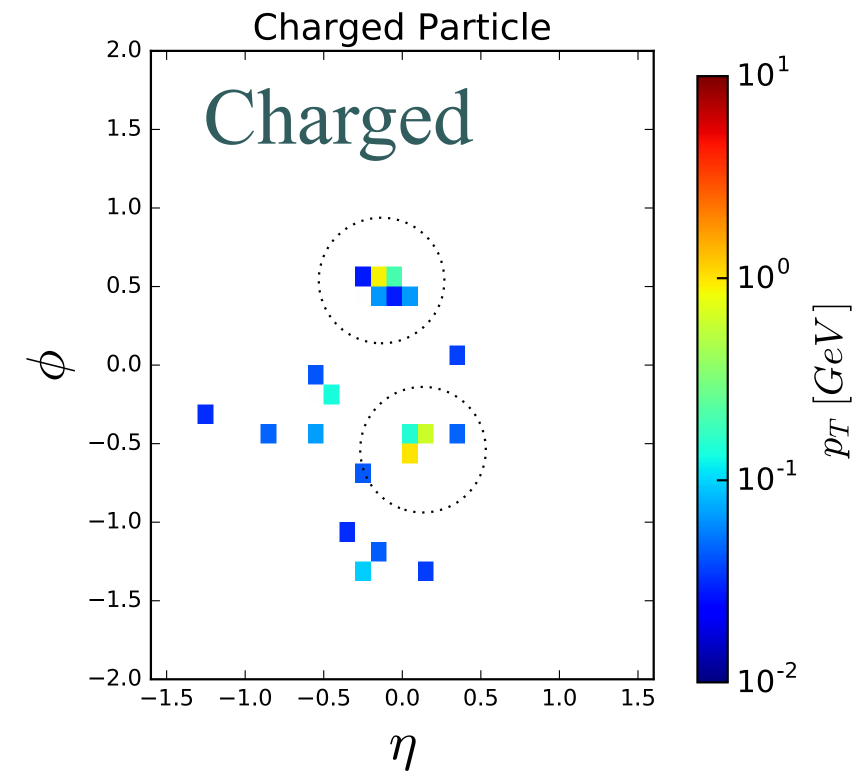
Each *hh* event

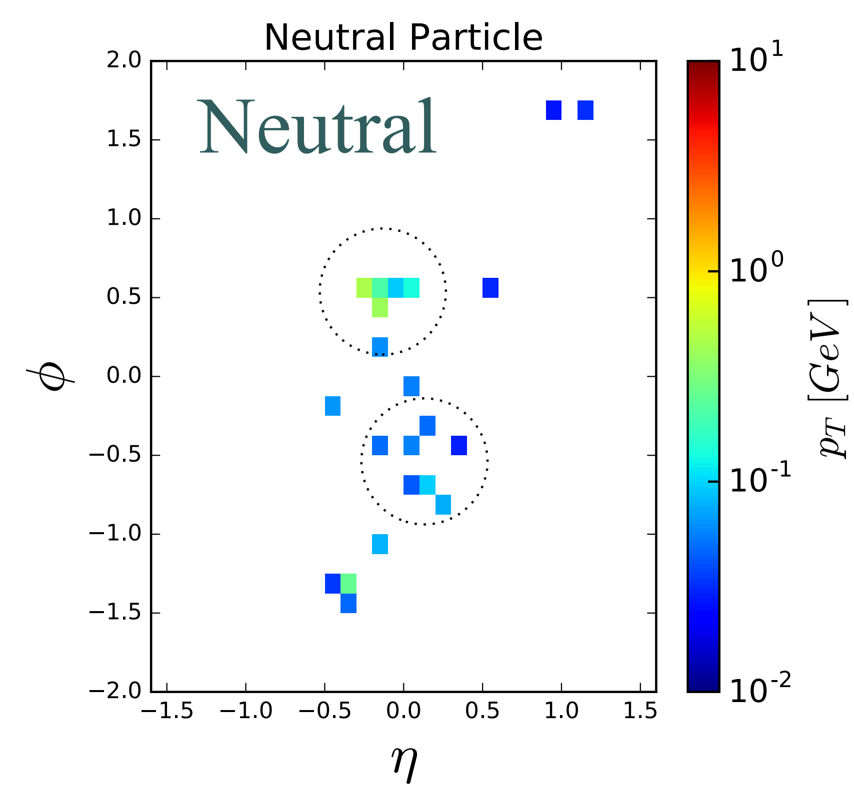




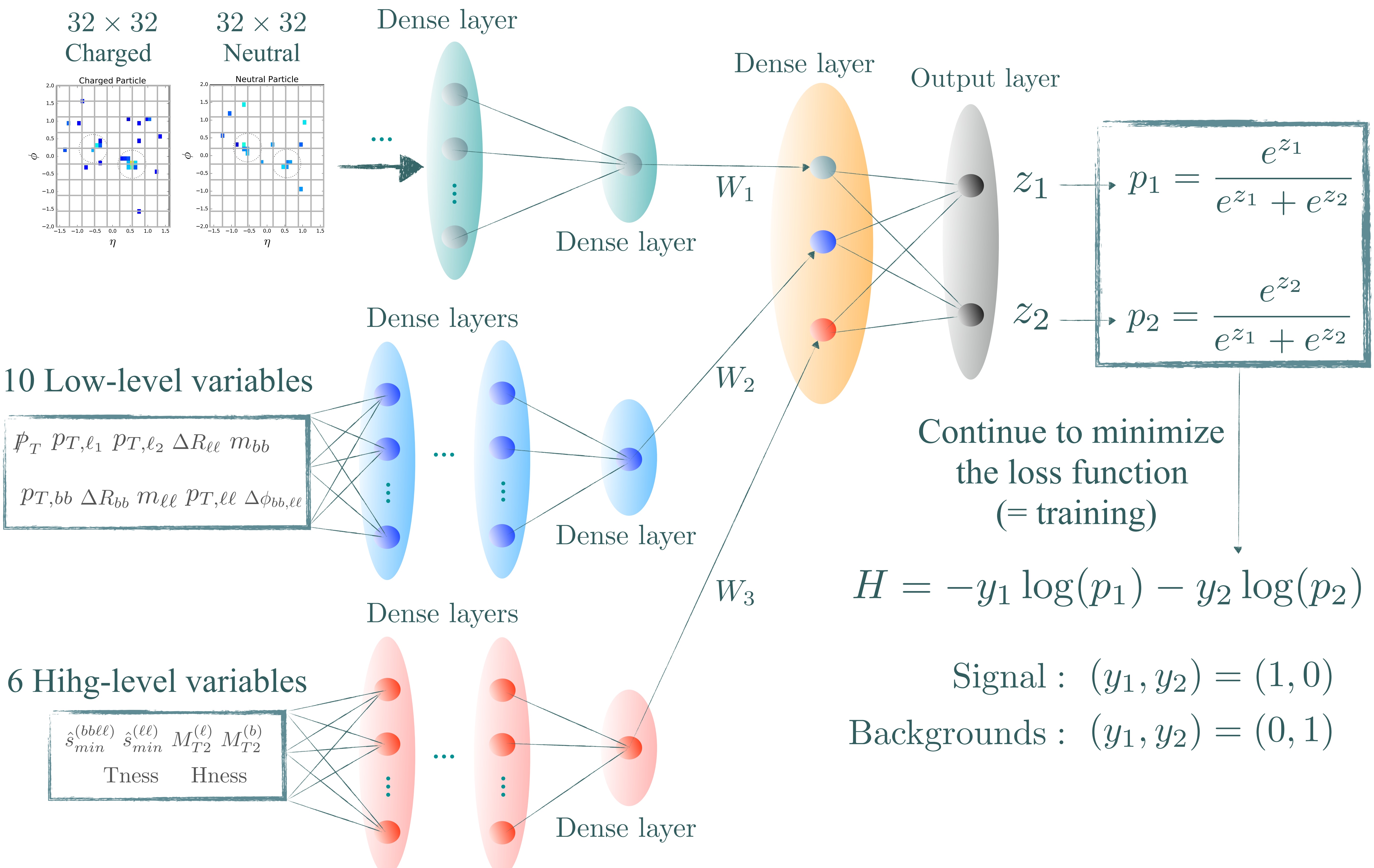
- It is difficult to distinguish them using the cut-and-count method…
- We train the machine using Deep Neural Network (DNN) architecture.

Each *tt* event

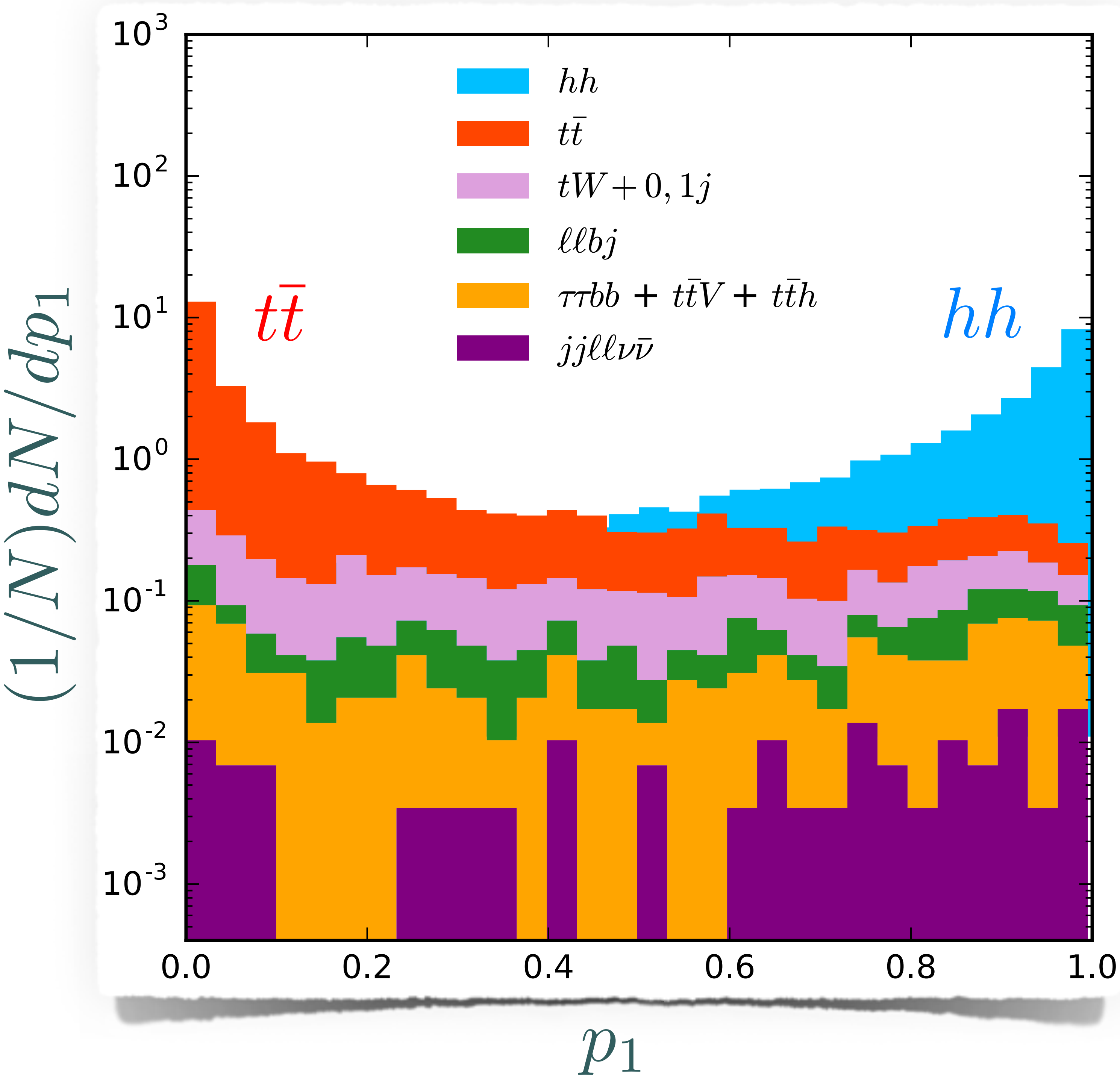




Combining dense neural networks

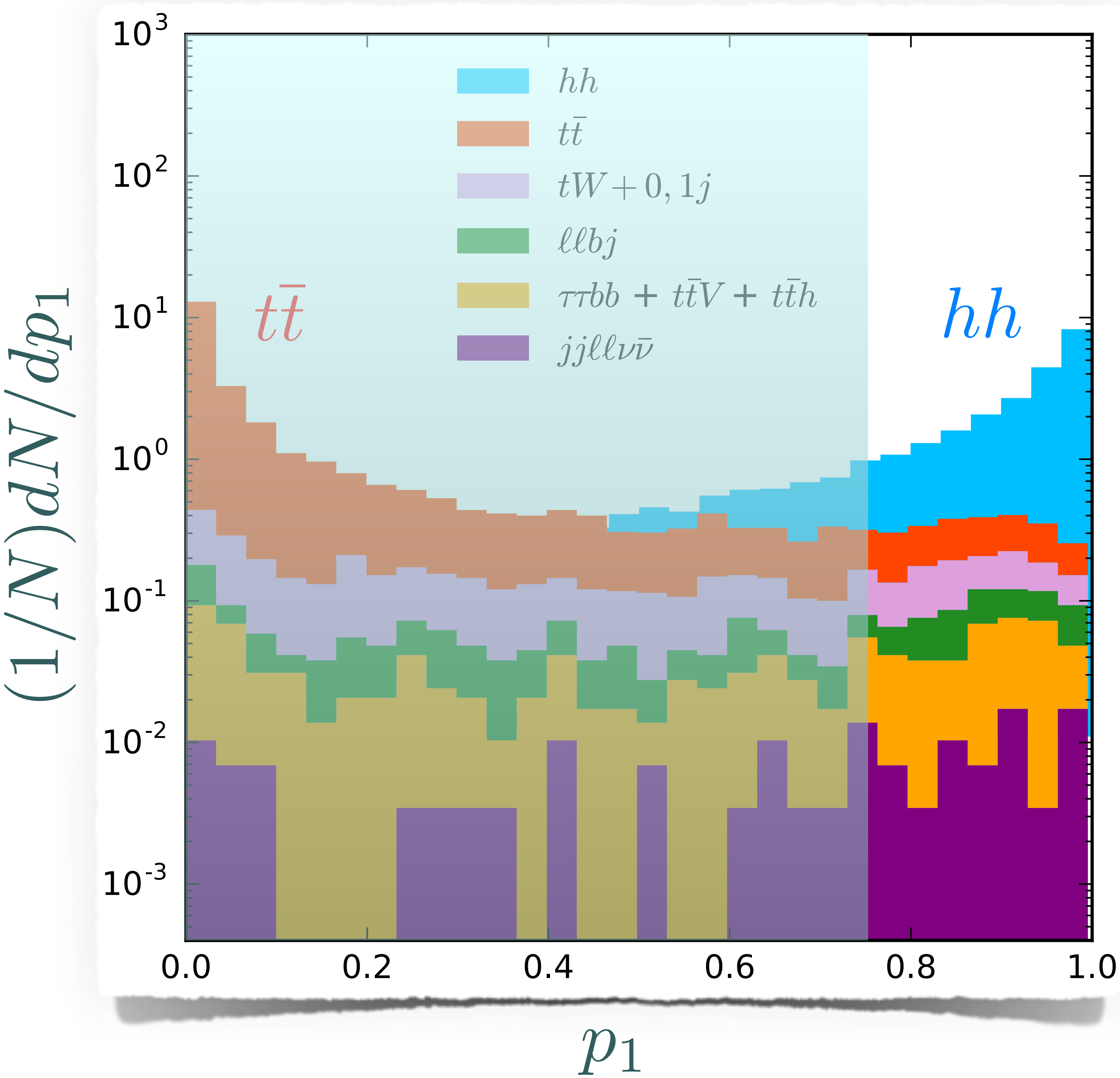


DNN results



- Once the training is complete, we compute the probability (p_1) that a given event is classified as *hh*.
- Most of backgrounds are unlikely to be classified as *hh*.
- We place a cut on p_1 to disentangle the backgrounds.

DNN results



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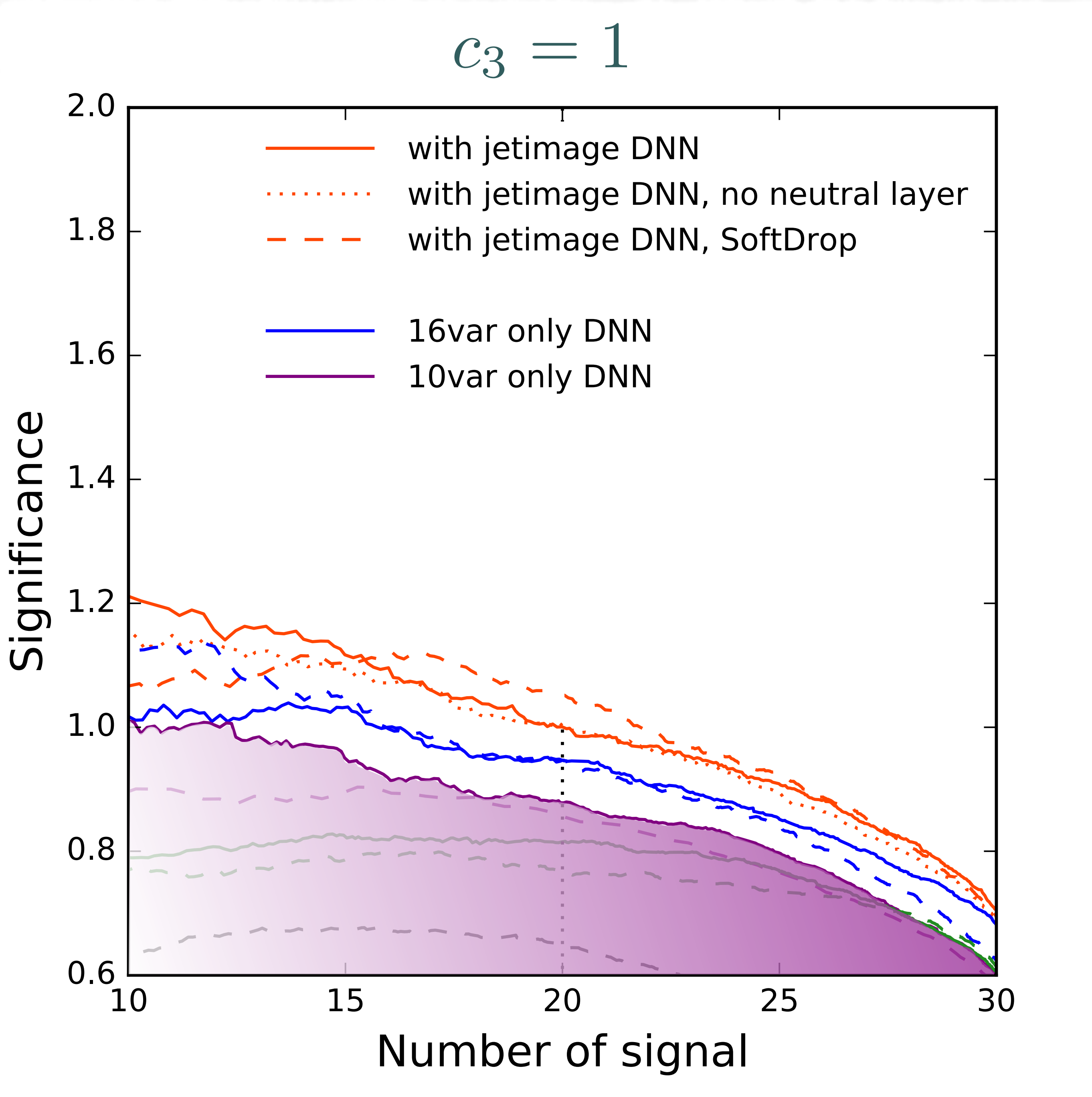
$hh \rightarrow bbWW^*$ discovery sigfinicance

Using Delphes $3\ \text{ab}^{-1} (14\ \text{TeV})$



- We can see a relative improvement in each layer of information.
- The DNN with jet images and high-level variables improves the final significance.

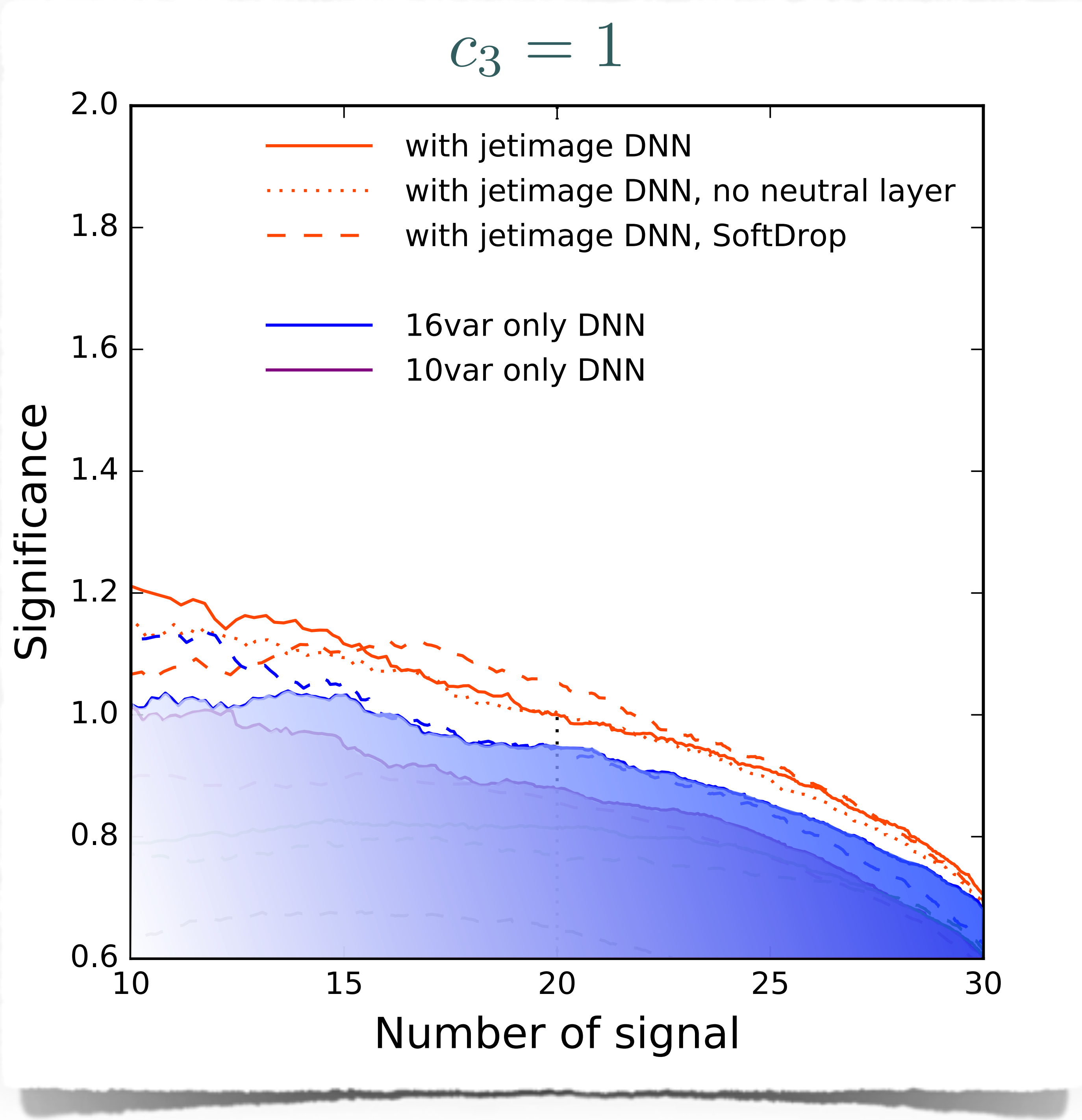
10 Low-level variables

$\not{p}_T\ p_{T,\ell_1}\ p_{T,\ell_2}\ \Delta R_{\ell\ell}\ m_{bb}$

$p_{T,bb}\ \Delta R_{bb}\ m_{\ell\ell}\ p_{T,\ell\ell}\ \Delta\phi_{bb,\ell\ell}$

$hh \to bbWW^*$ discovery sigfinicance

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



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- The DNN with jet images and high-level variables improves the final significance.

6 Hihg-level variables

$\hat{s}^{(bb\ell\ell)}_{min}\ \hat{s}^{(\ell\ell)}_{min}\ M^{(\ell)}_{T2}\ M^{(b)}_{T2}$ Tness Hness

$+$

10 Low-level variables

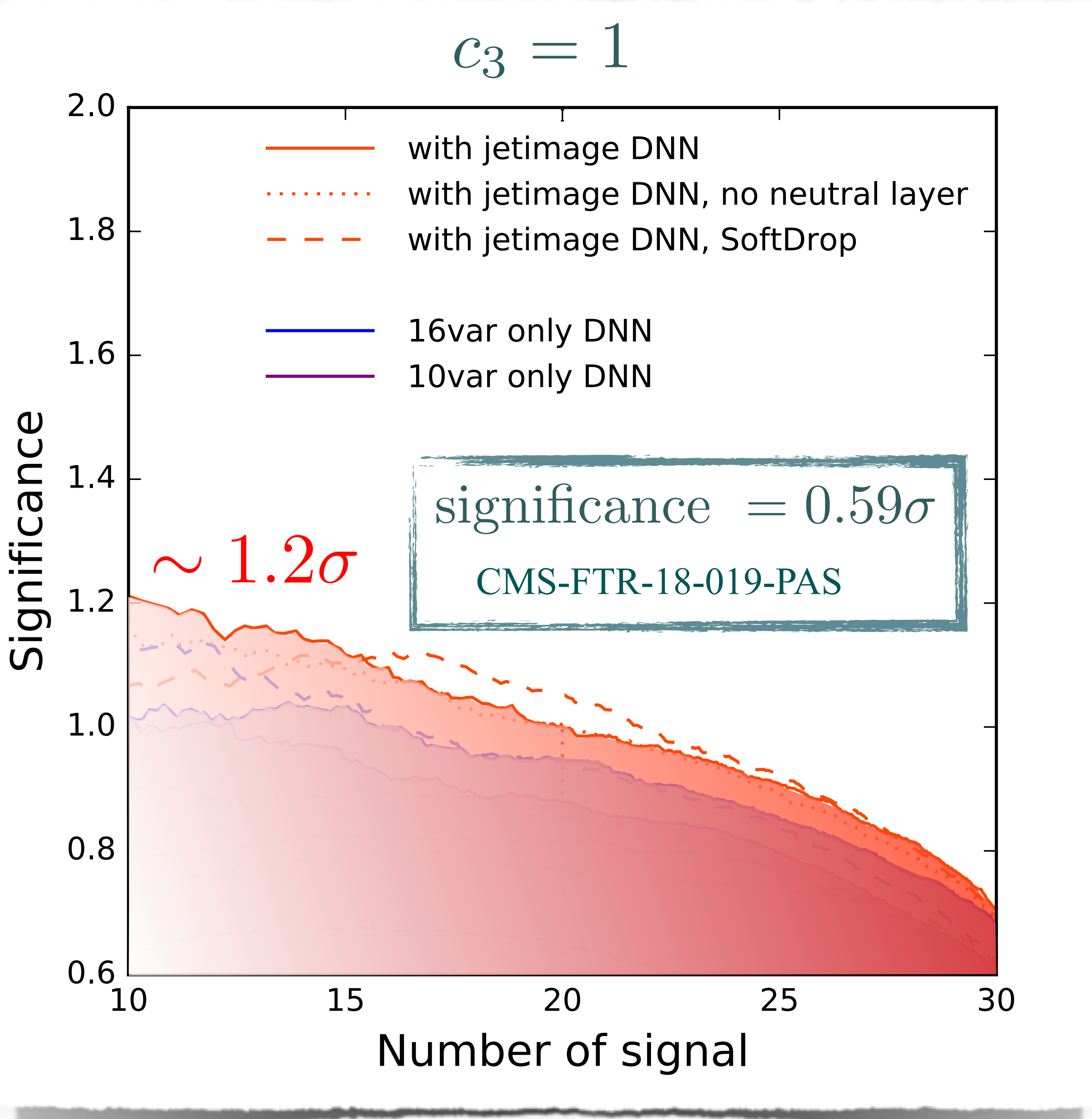
$\not{p}_T\ p_{T,\ell_1}\ p_{T,\ell_2}\ \Delta R_{\ell\ell}\ m_{bb}$

$p_{T,bb}\ \Delta R_{bb}\ m_{\ell\ell}\ p_{T,\ell\ell}\ \Delta\phi_{bb,\ell\ell}$

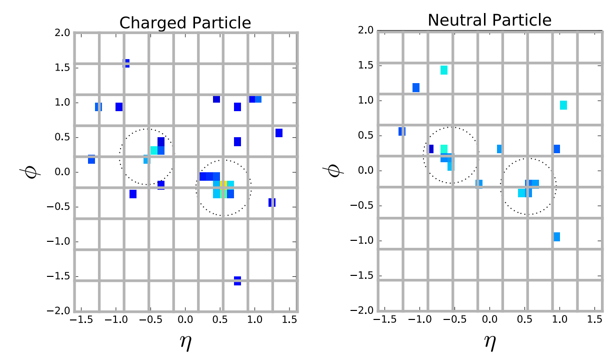
$hh \to bbWW^*$ discovery sigfinicance

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

$c_3 = 1$



- We can see a relative improvement in each layer of information.
- The DNN with jet images and high-level variables improves the final significance.



$+$

6 Hihg-level variables

$\hat{s}^{(bb\ell\ell)}_{min}$ $\hat{s}^{(\ell\ell)}_{min}$ $M^{(\ell)}_{T2}$ $M^{(b)}_{T2}$ Tness Hness

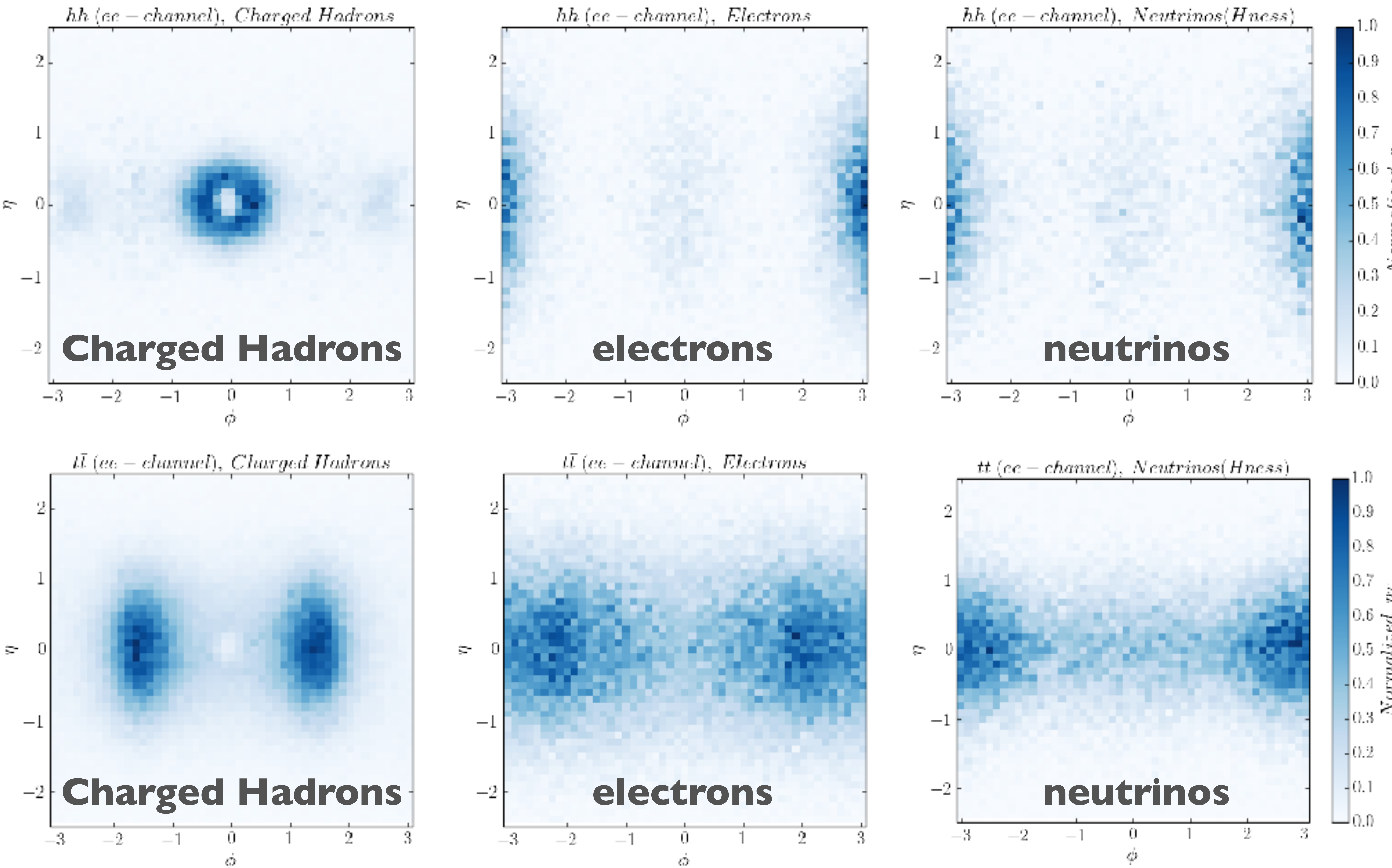
$+$

10 Low-level variables

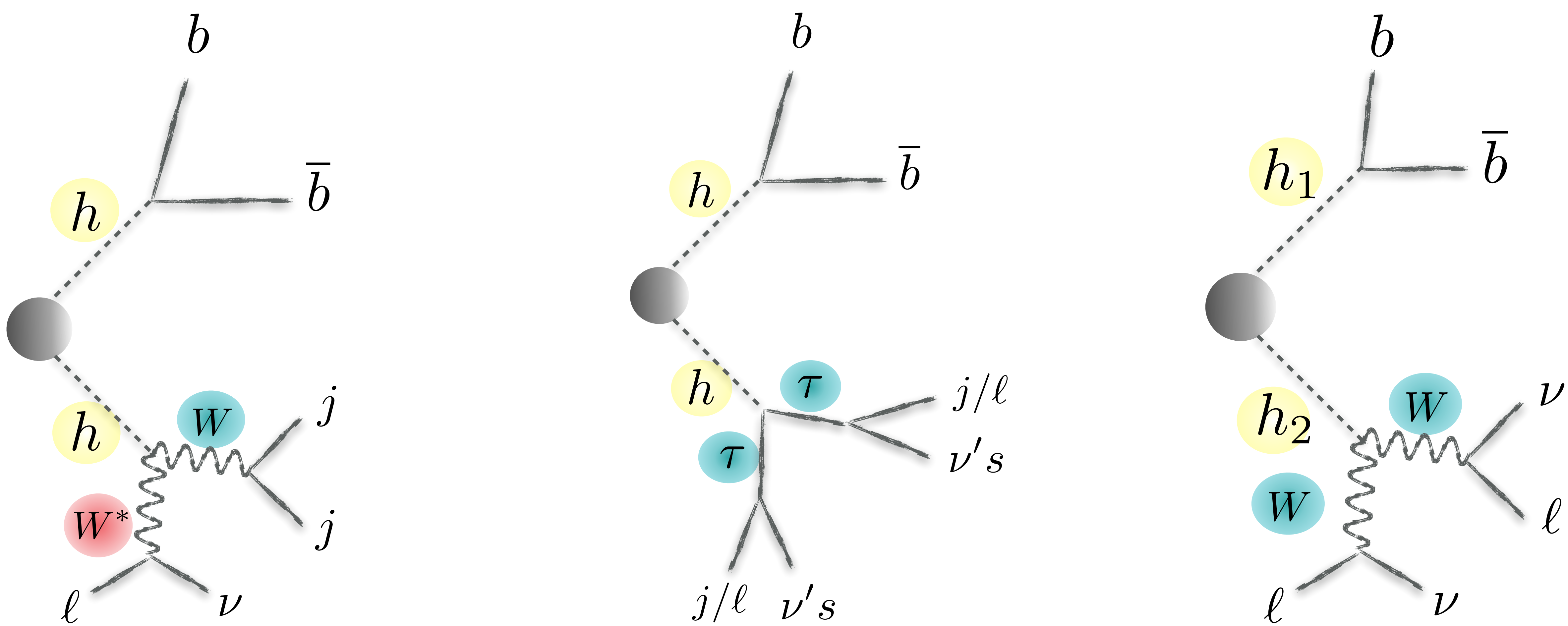
$\not{p}_T$ p_{T,ℓ_1} p_{T,ℓ_2} $\Delta R_{\ell\ell}$ m_{bb}

$p_{T,bb}$ ΔR_{bb} $m_{\ell\ell}$ $p_{T,\ell\ell}$ $\Delta\phi_{bb,\ell\ell}$

What about other images?

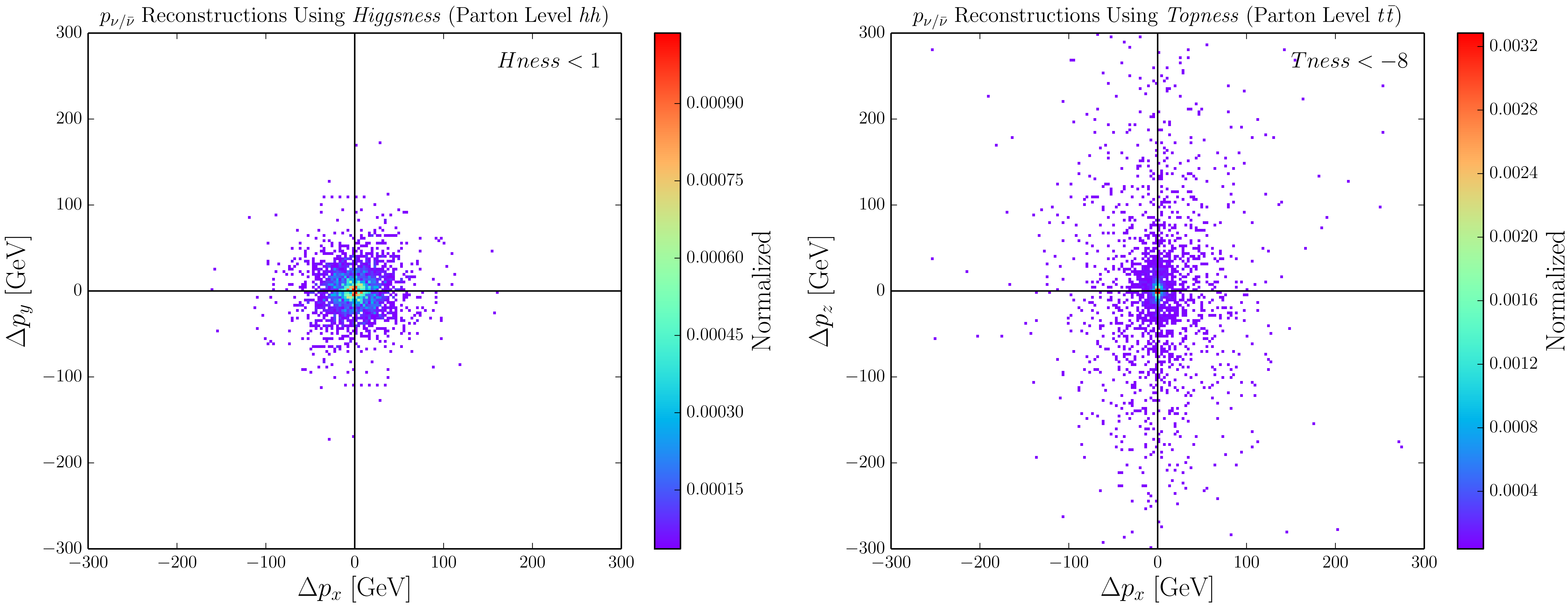


Future & On-going directions



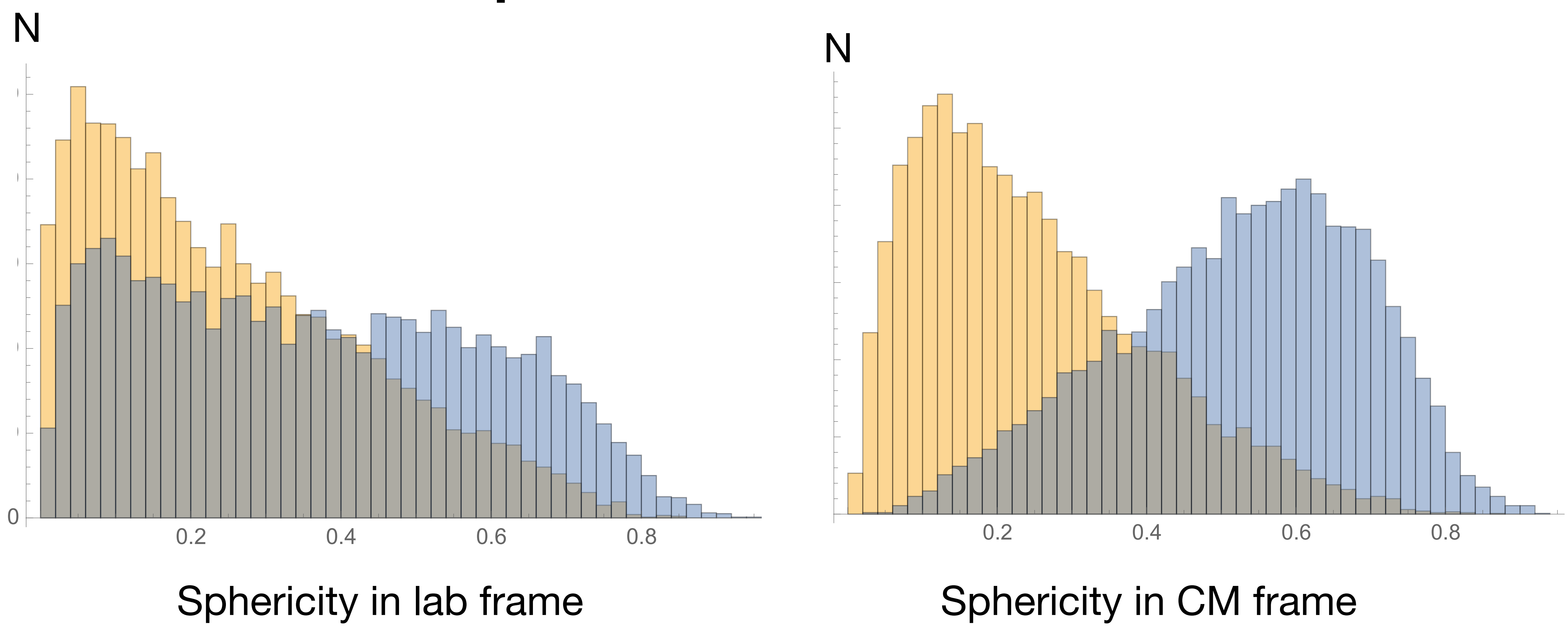
- Our method has a wide applicability to improve other channels.
- The semi-leptonic $hh \to bbWW^*$ channel.
- The $hh \to bb\tau\tau$ channel.
- The BSM Higgs searches $h_1\, h_2 \to bbWW$

Neutrino momenta (parton-level)



- Just like MT2, Higgsness and Topness provide momentum of neutrinos.
- They can be used to study other quantities.

Shape variables



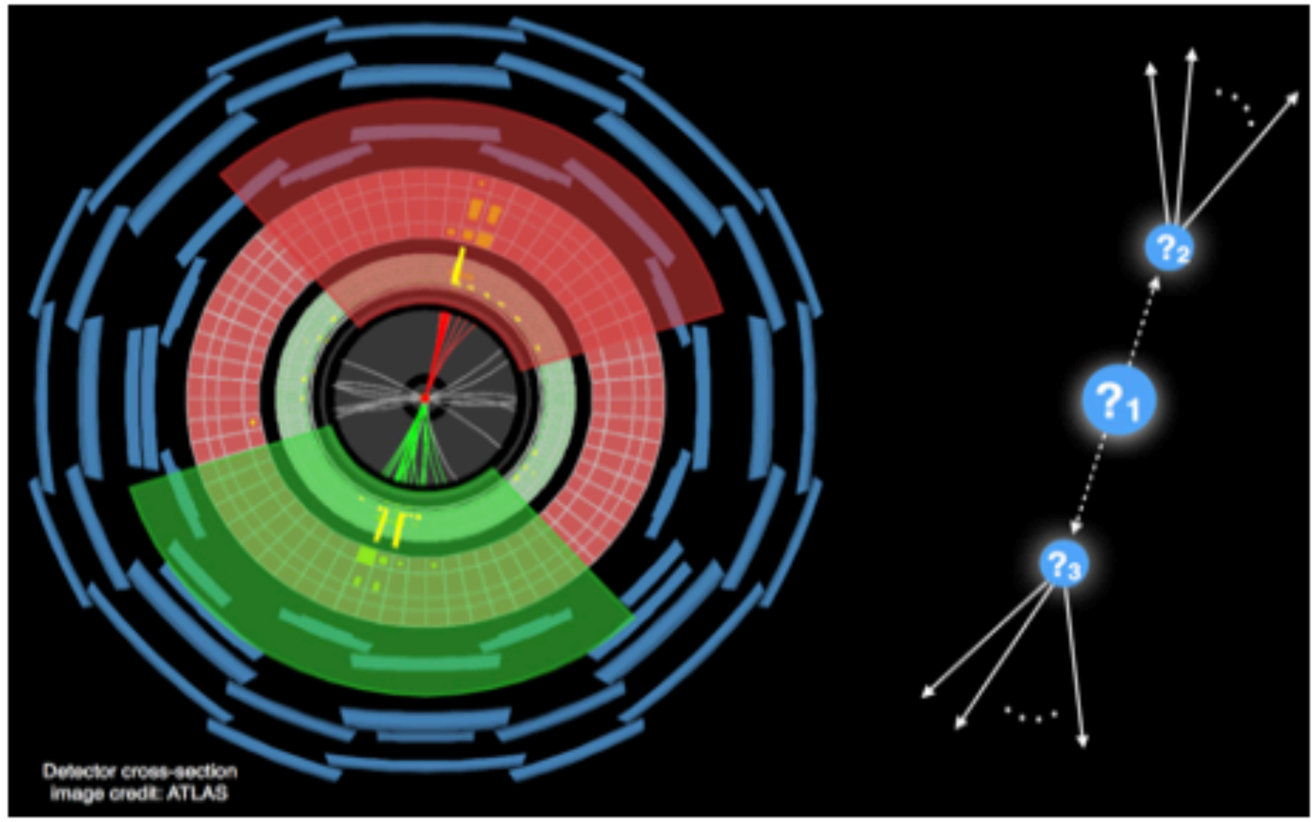
$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i \mid p_i \mid^2}, \quad \lambda_1 + \lambda_2 + \lambda_3 = 1$$

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

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

- S -> 0: pencil-like event
- S -> 1: isotropic event

LHCOlympics2020 https://indico.cern.ch/event/809820/page/16782-lhcolympics2020



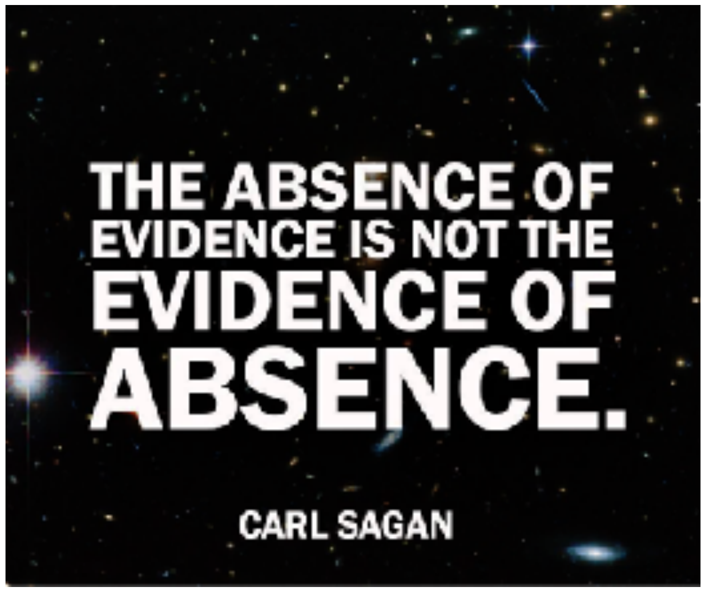
Despite an impressive and extensive effort by the LHC collaborations, there is currently no convincing evidence for new particles produced in high-energy collisions. At the same time, there has been a growing interest in machine learning techniques to enhance potential signals using all of the available information.

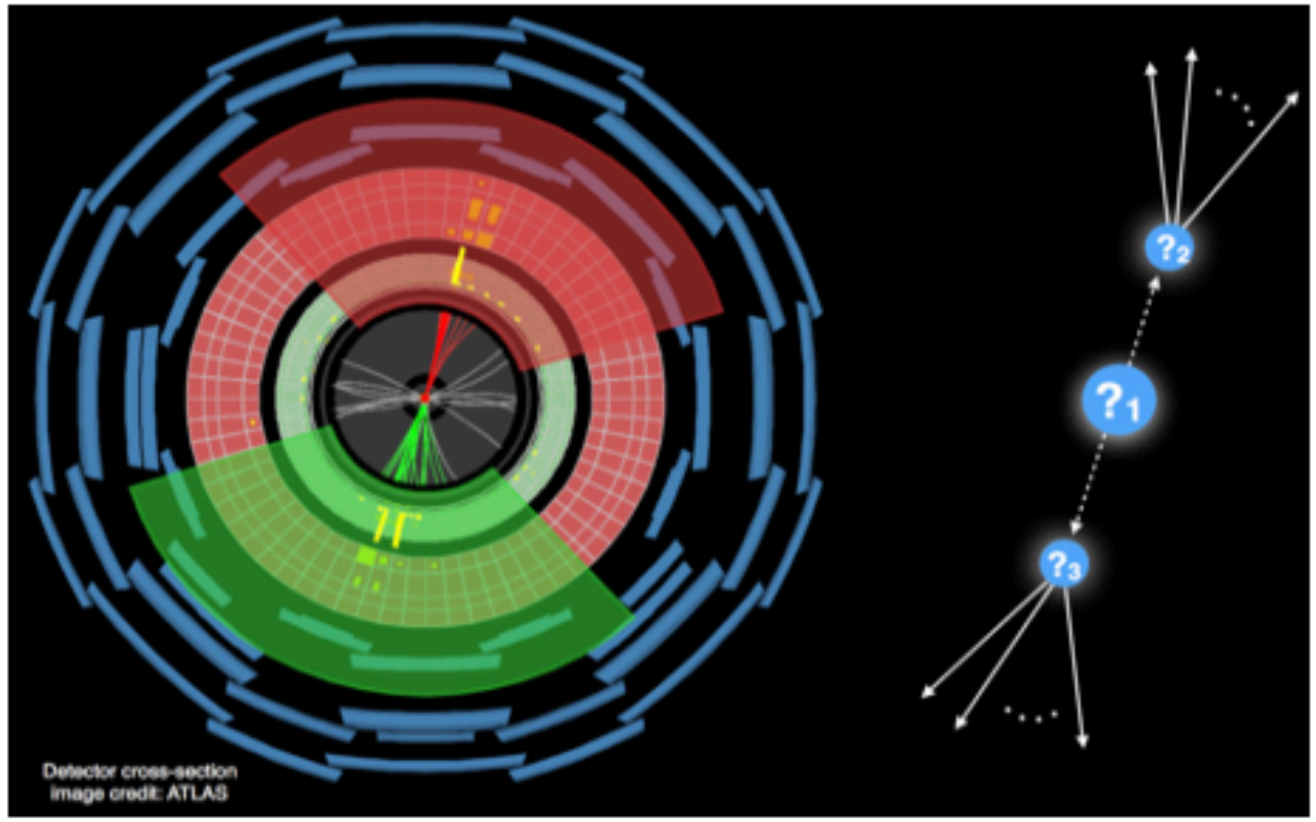
In the spirit of the first LHC Olympics (circa 2005-2006) [1st, 2nd, 3rd, 4th], we are organizing the 2020 LHC Olympics. Our goal is to ensure that the LHC search program is sufficiently well-rounded to capture "all" rare and complex signals. The final state for this olympics will be focused (generic dijet events) but the observable phase space and potential BSM parameter space(s) are large: all hadrons in the event can be used for learning (be it "cuts", supervised machine learning, or unsupervised machine learning).

For setting up, developing, and validating your methods, we provide background events and a benchmark signal model. You can download these from this page. To help get you started, we have also prepared simple python scripts to read in the data and do some basic processing.

The final test will happen 2 weeks before the ML4Jets2020 workshop. We will release a new dataset where the "background" will be similar to but not identical to the one in the development set (as is true in real data!). The goal of the challenge is to see who can "best" identify BSM (yes/no, what mass, what cross-section) in the dataset. There are many ways to quantify "best" and we will use all of the submissions to explore the pros/cons of the various approaches

LHCOlympics2020 https://indico.cern.ch/event/809820/page/16782-lhcolympics2020





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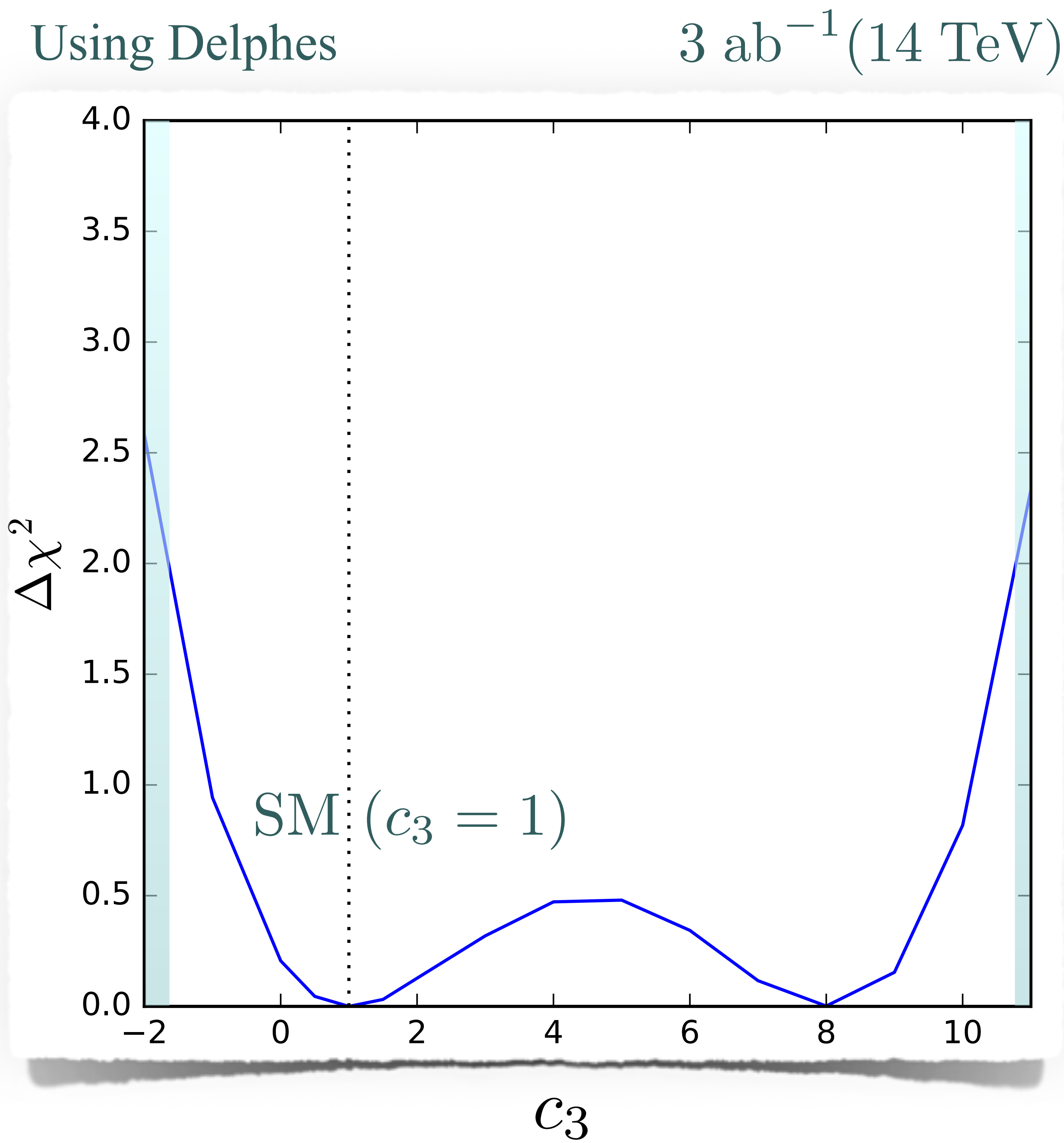
How well can we distinguish c_3=1 vs c_3≠1?



- Now our null hypothesis includes the SM backgounds + *hh* (@SM).
- We ask how well we can distinguish the SM c_3 and anomalous c_3.
- We can see that there would not be a significant impact on improving the precision of c_3 coupling.
- Nevertheless $hh \to bbWW^*$ can be useful to discover *hh*, when combining all channels.