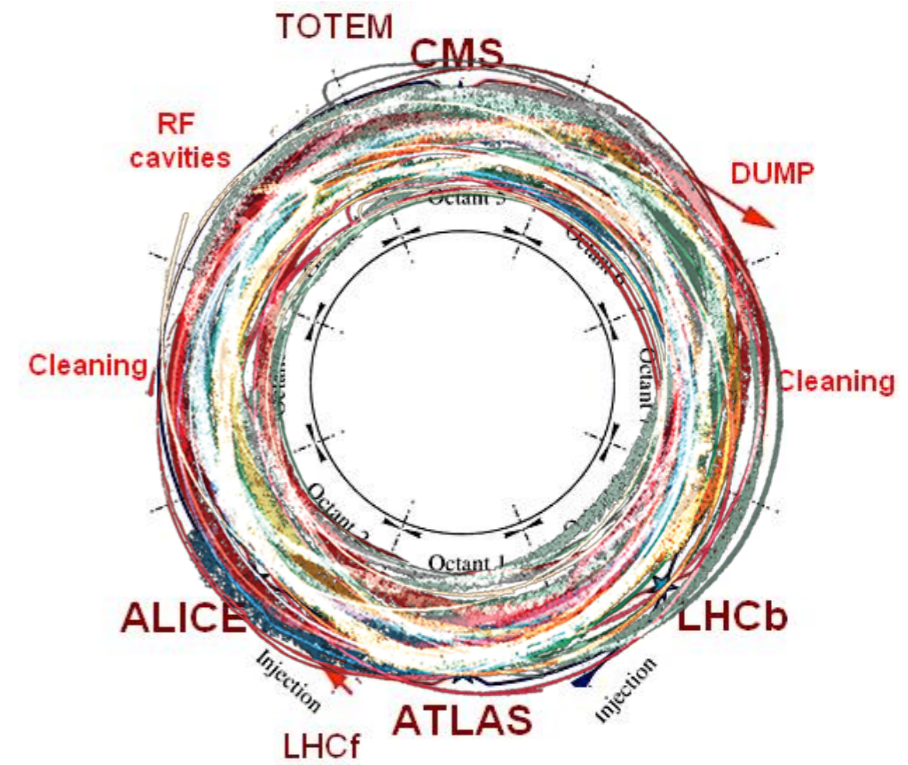


Triple Higgs



Myeonghun Park



based on arXiv:1807.11498 (PRL 2019), arXiv:1904.08549
with K. Matchev, KC Kong, Jeong Han Kim and Minho Kim

2019, 7. KAIST-KAIX

Higgs sector

"Mexican Hat" Higgs potential



Spontaneous Symmetry Breaking

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

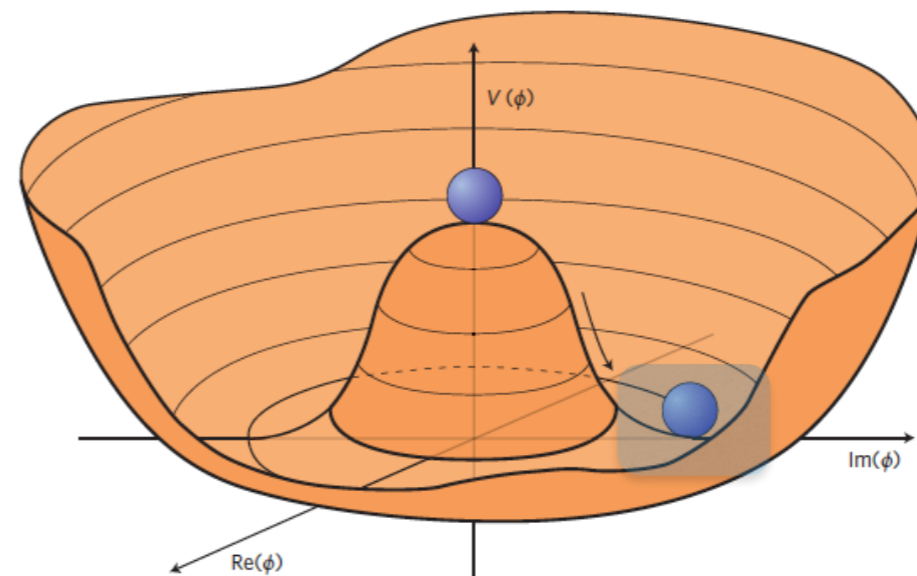
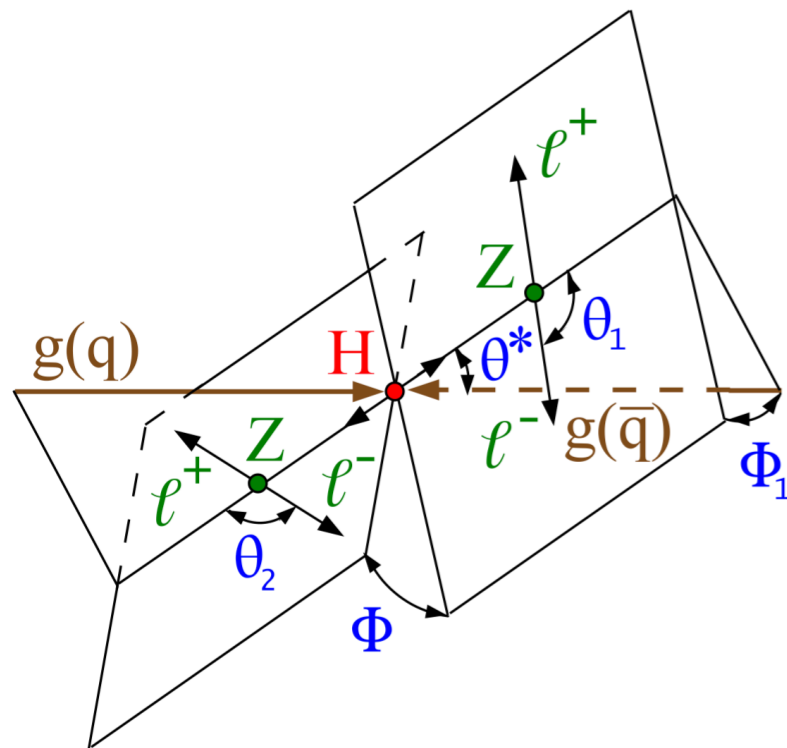


Yukawa terms for massive fermions

Electroweak Symmetry Breaking

- By measuring **interaction Lagrangian** in $H \rightarrow ZZ \rightarrow 4\ell$ channel, the **LHC identified a Higgs mechanism**

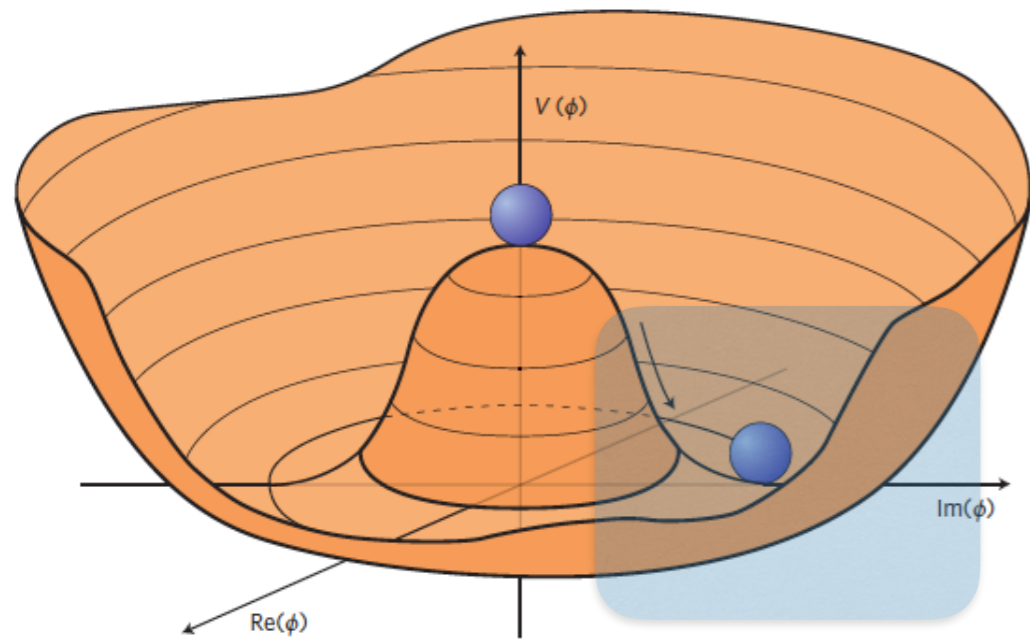
$$a_1 \frac{m_Z^2}{2} H Z^\mu Z_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 H Z_\mu \square Z^\mu - \frac{1}{2} a_2 H Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 H Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$



CMS PAS HIG-17-011

Parameter	Observed	Expected
$f_{a3} \cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21} [-0.45, 0.66]$	$0.000^{+0.017}_{-0.017} [-0.32, 0.32]$
$f_{a2} \cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04} [-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014} [-0.08, 0.29]$
$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$	$0.00^{+0.06}_{-0.33} [-0.92, 0.15]$	$0.000^{+0.014}_{-0.014} [-0.79, 0.15]$

Measuring **Higgs potential**



$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

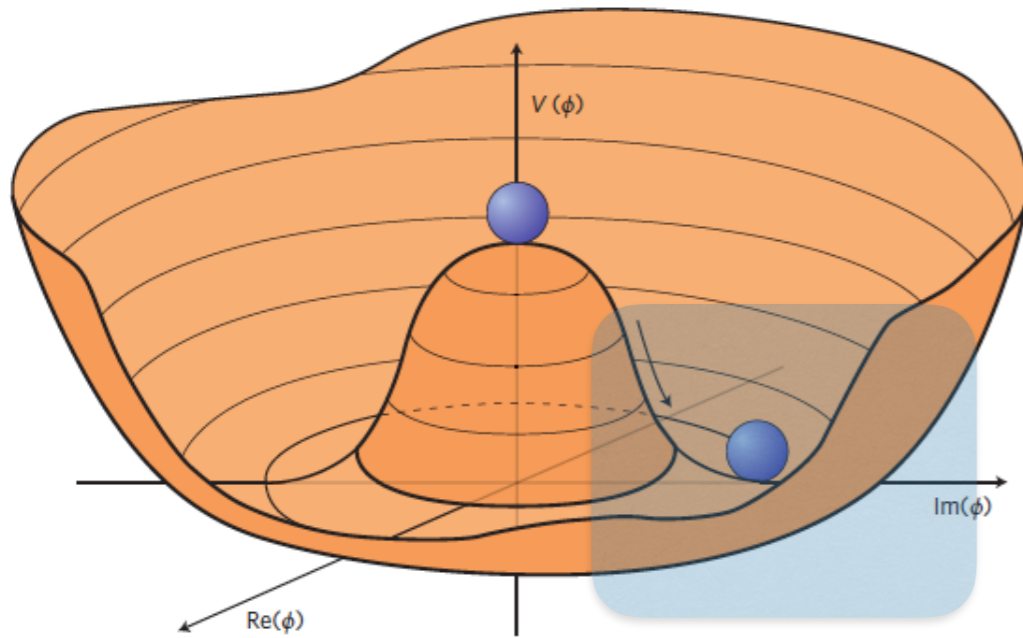
- From spontaneous symmetry breaking

$$V_h^{\text{SM}} = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$

- The shape of a potential around EW scale is determined by h^2 term and h^3 term.
 - We know about the mass of Higgs from clean channels

Higgs Boson Pair

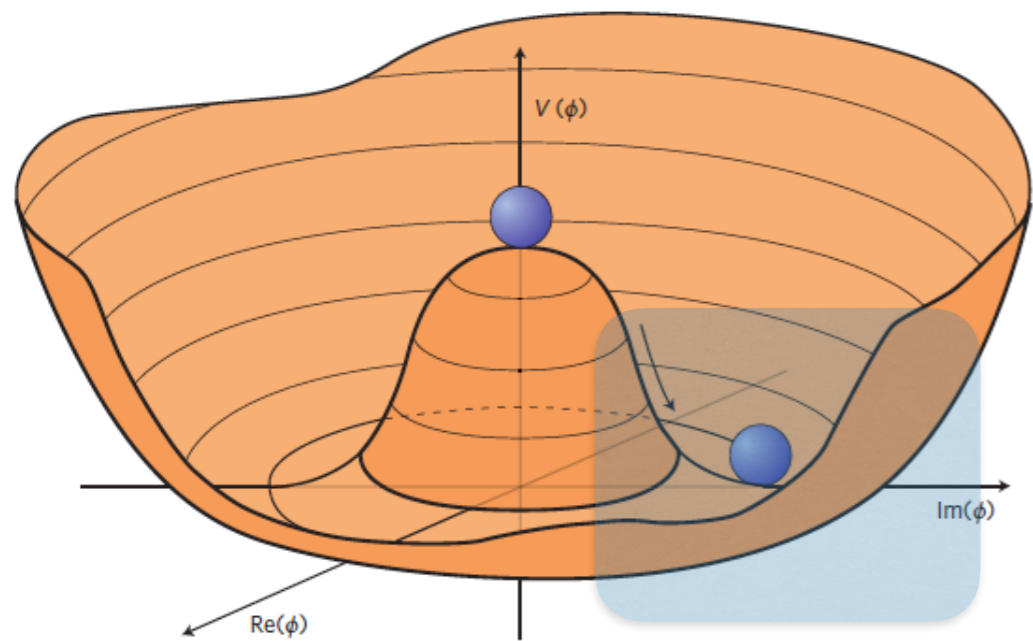
to measure Higgs potential



$$V_h^{\text{SM}} = \frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4$$

- The shape of a potential around EW scale is determined by h^2 term and h^3 term.

- This triple Higgs coupling can be determined by $h \rightarrow h, h$

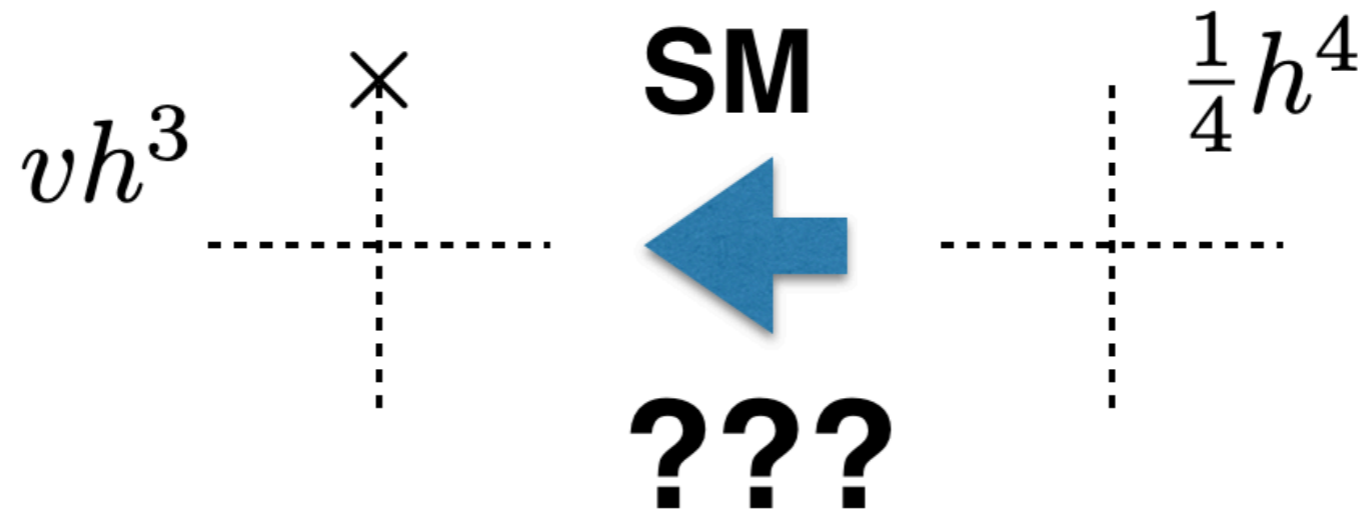


$$V_h^{\text{SM}} = \frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4$$

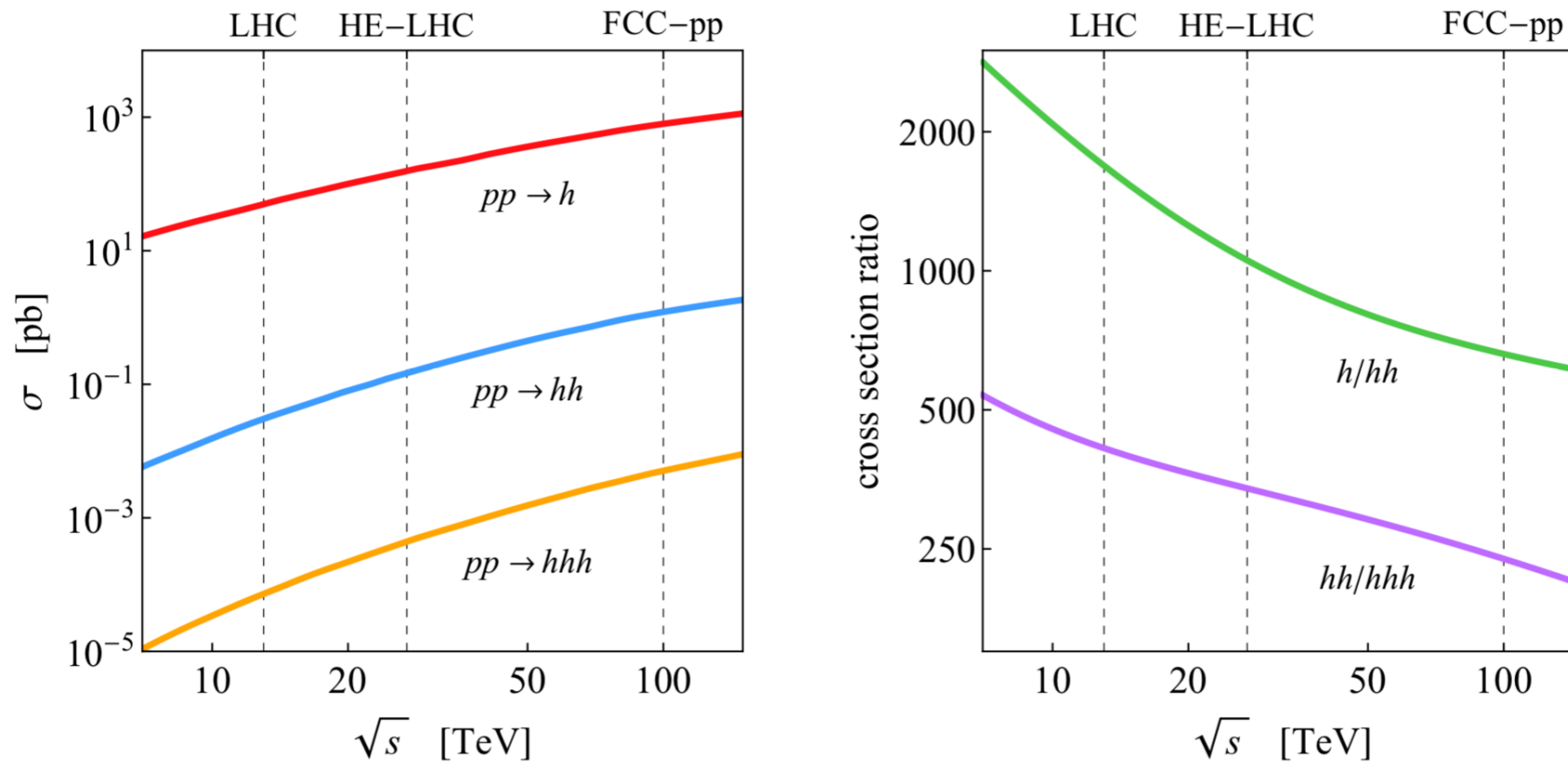
- check vh^3 \times **SM** \leftarrow $\frac{1}{4} h^4$
???

- Triple Higgs coupling can be determined by $h \rightarrow h, h$

- Quartic Higgs coupling can be determined by $h \rightarrow h, h, h$

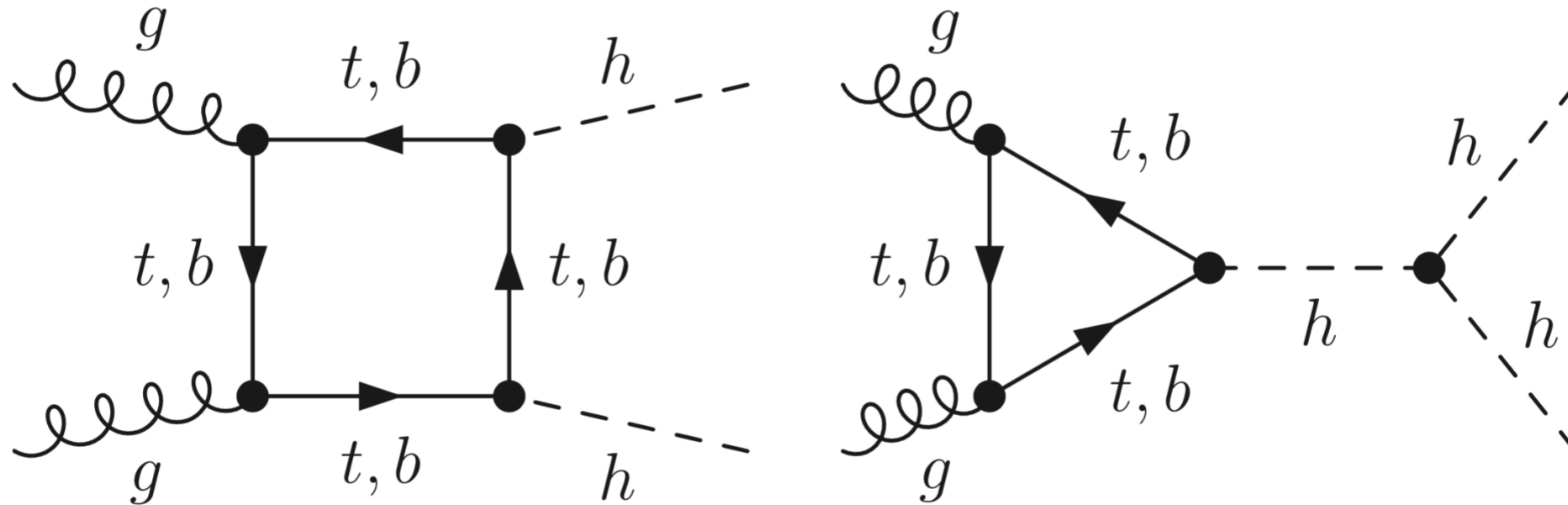


by Ulrich Haisch et.al (arXiv:1810.04665)

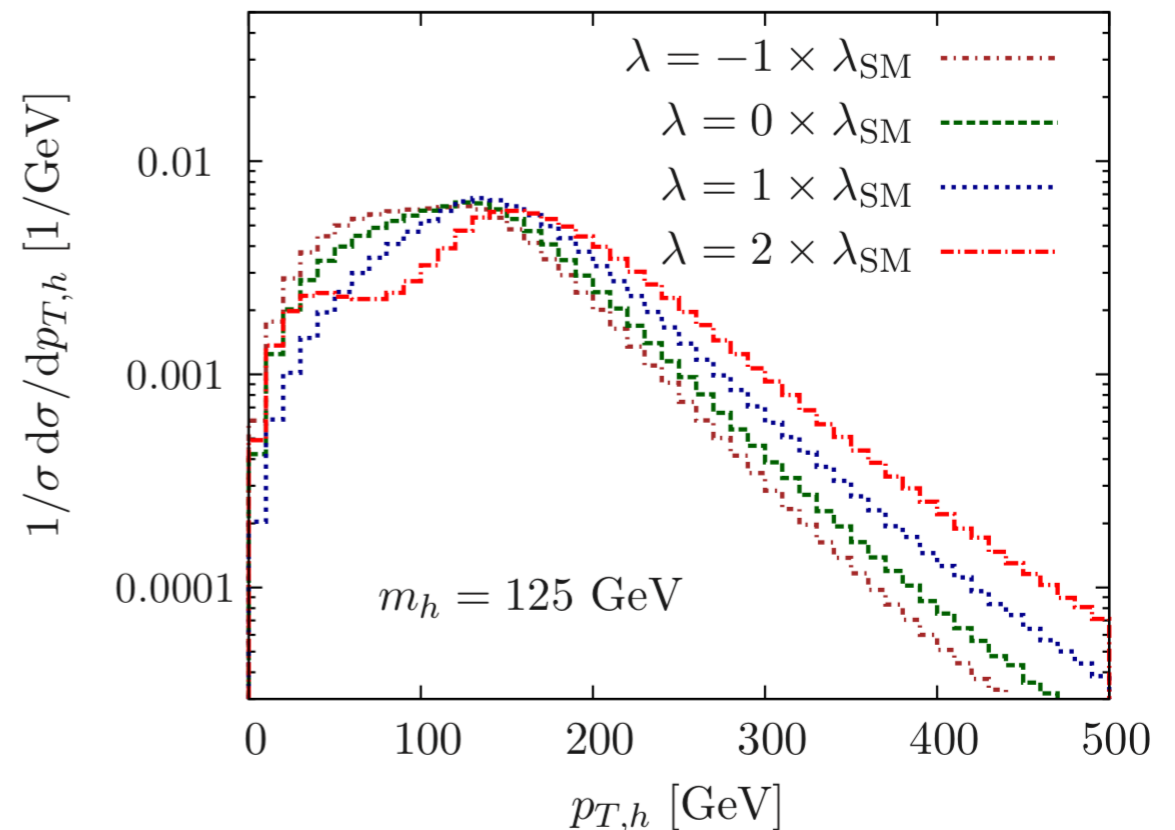
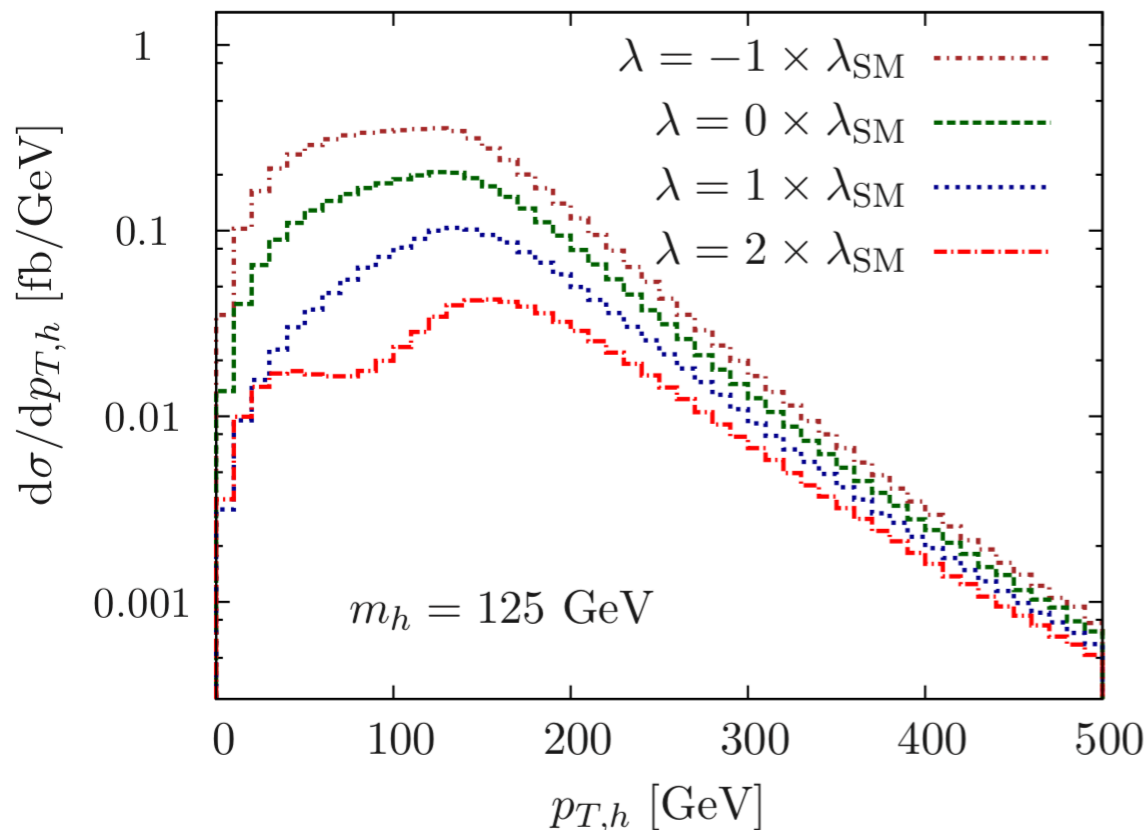


- So, let's focus on "**precise measurement**" of triple Higgs coupling at the LHC

Higgs Boson Pair @LHC



by Matthew J. Dolan et.al (arXiv:1206.5001)

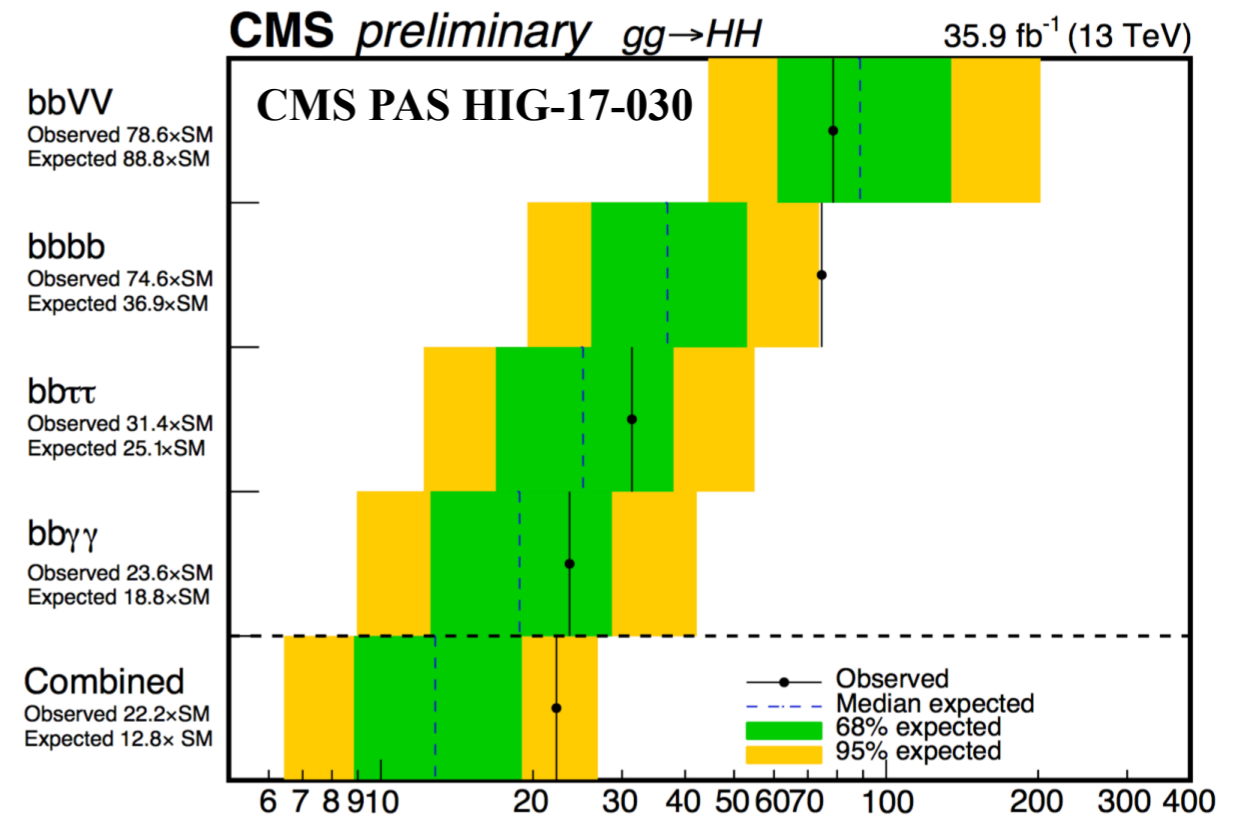


Higgs Boson Pair @LHC

- Current status from various channels

$h \rightarrow XX$

$XX \leftarrow h$	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%

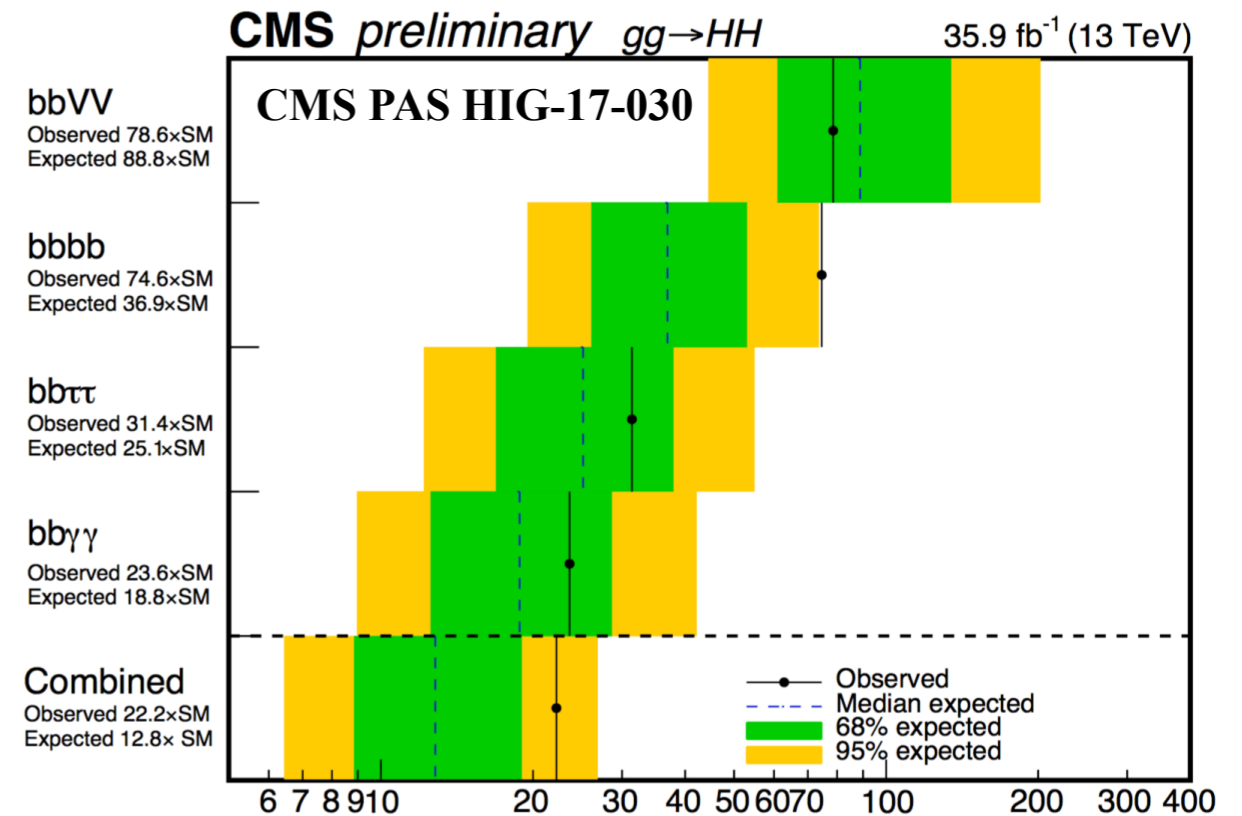


- The driven channel is the "compromised" clean channel.

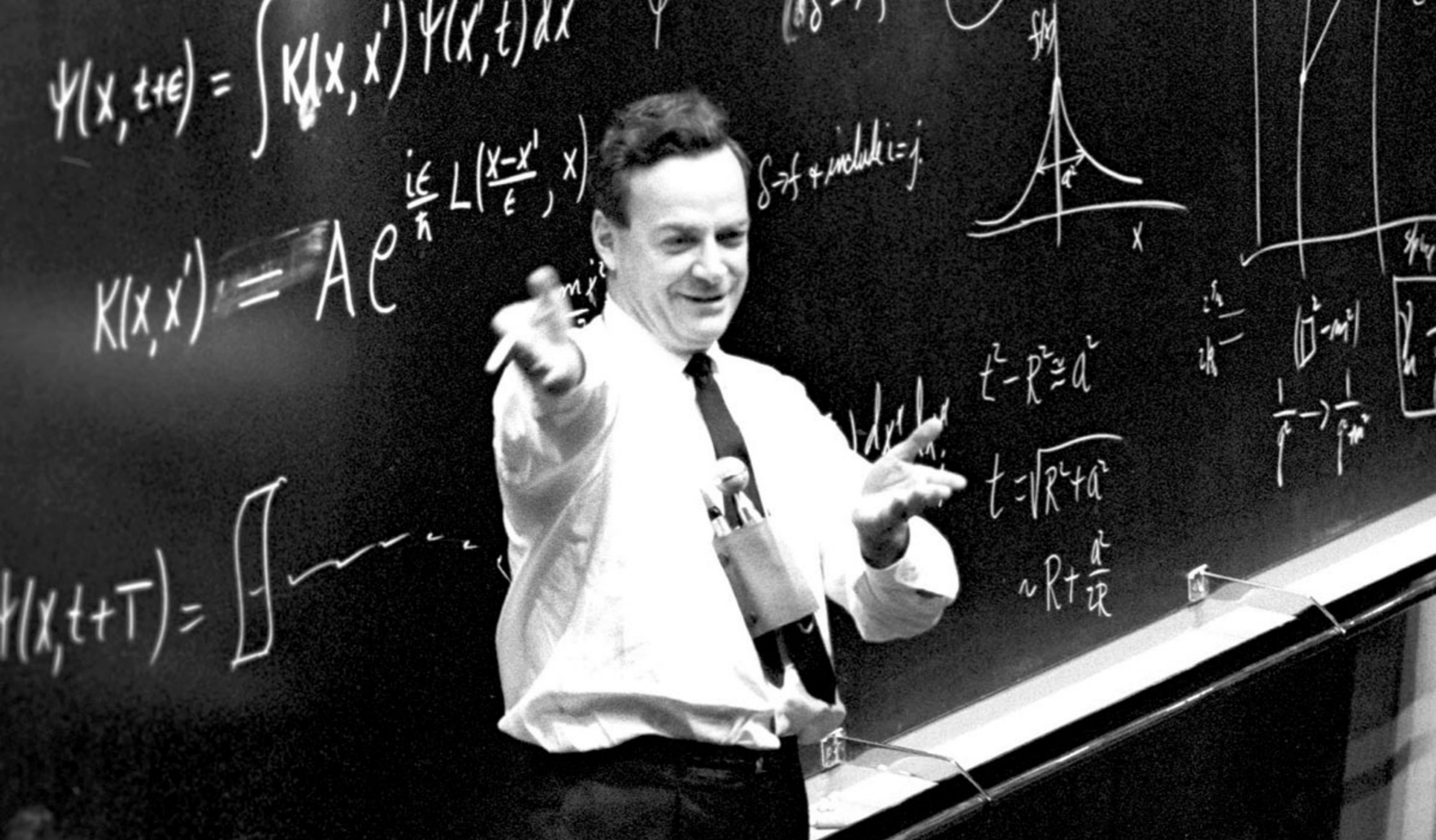
Higgs Boson Pair @LHC

- Current status from various channels

		$N(hh)_{SM}$	N_{BKG}	
<i>ATLAS</i>	$bb\gamma\gamma$	8.4	47.1	1.2
<i>CMS</i>	$bb\gamma\gamma$	9	26.9	1.7
	$bb\tau\tau$ (fully-hadronic)	4.9	30.3	0.89
	$bb\tau\tau$ (semi-leptonic)	6.1	122	0.55
	$bbWW^*$ (di-leptonic)	37.1	3875	0.60

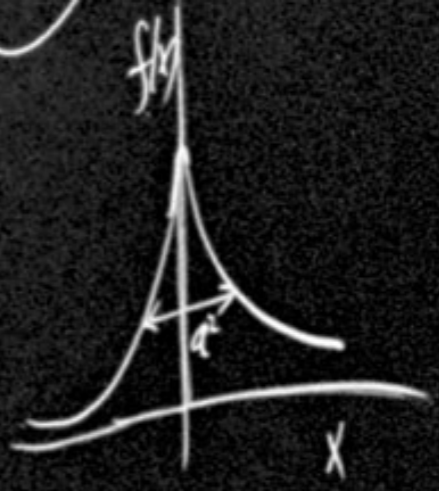


- Why** is $bbVV$ **bad** ? **how** can one **improve** ?



$$\psi(x, t+\epsilon) = \int K(x, x') \psi(x', t) dx'$$

$$K(x, x') = A e^{\frac{i\epsilon}{\hbar} L\left(\frac{x-x'}{\epsilon}, x\right)}$$



$$t^2 - R^2 = a^2$$

$$t = \sqrt{R^2 + a^2}$$

$$\sim R + \frac{a^2}{2R}$$

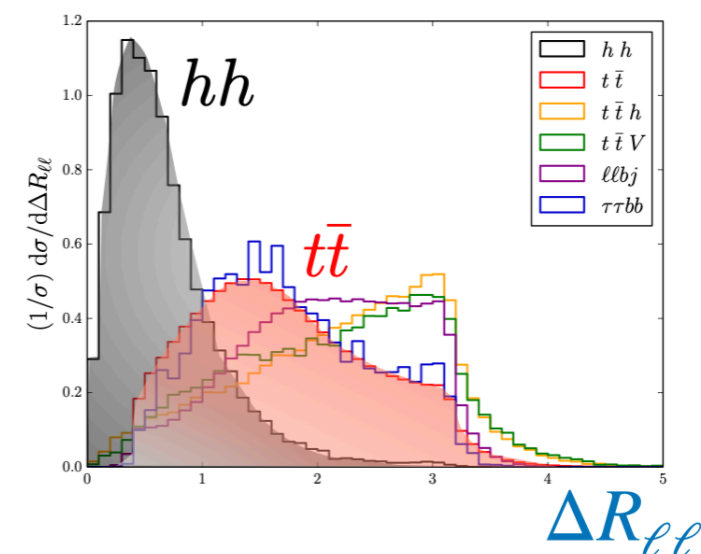
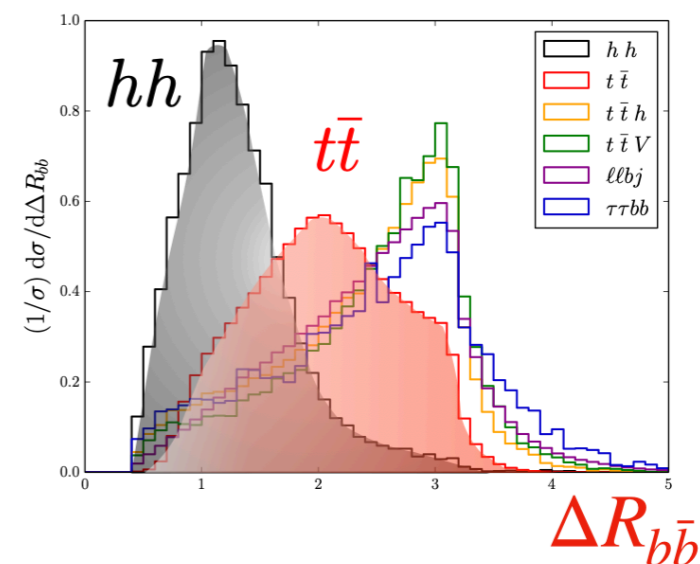
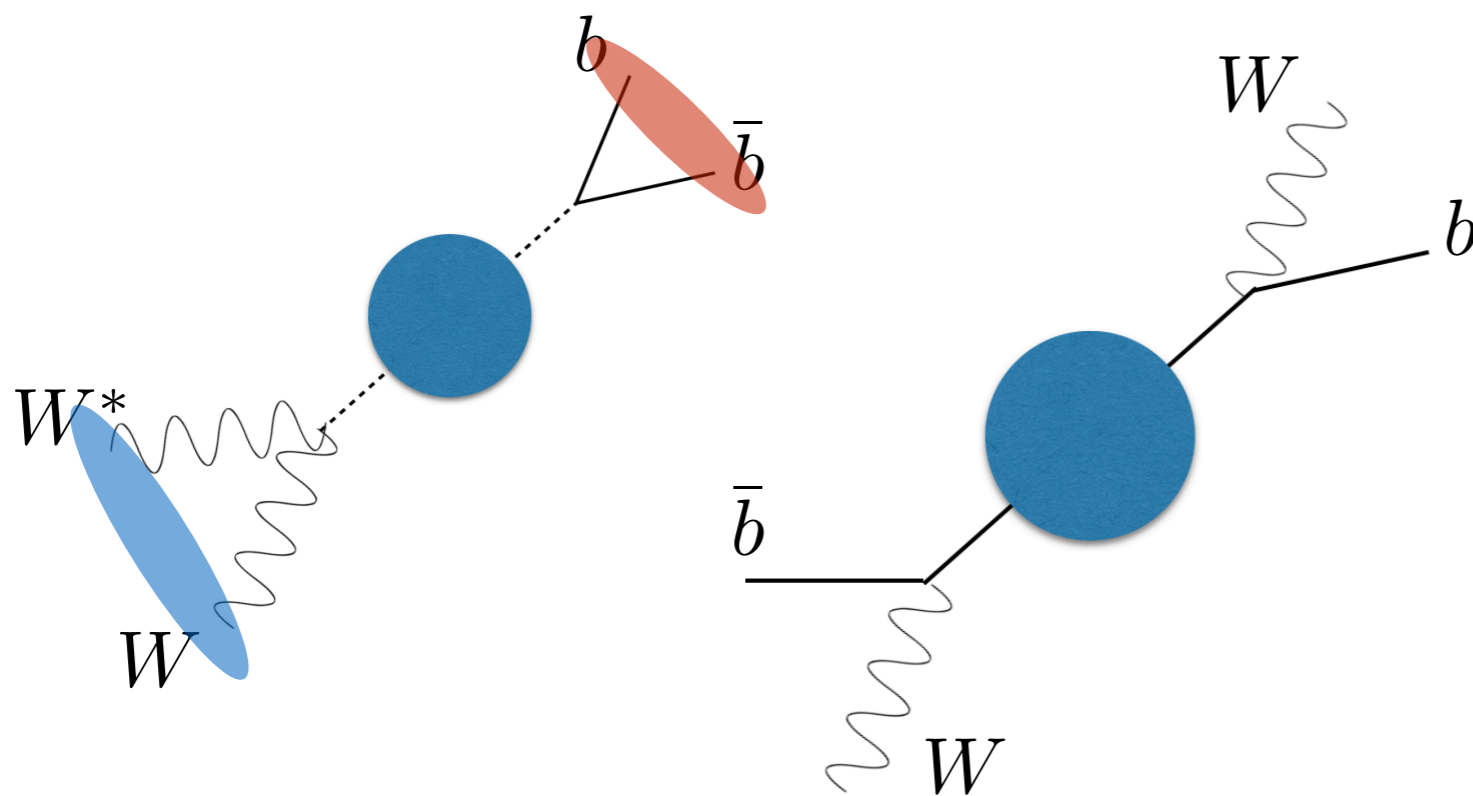
$$\psi(x, t+\tau) = \int \dots$$

How can **theorists contribute** to the battle of the LHC?

- **Why is $bbVV$ bad ?** LHC is the **Top-factory**

$$\frac{\sigma(pp \rightarrow hh \rightarrow b\bar{b}VV^*)}{\sigma(pp \rightarrow t\bar{t} \rightarrow b\bar{b}VV)} \Bigg|_{13\text{TeV}} \simeq \frac{31\text{fb}*(25\%)}{215\text{pb}} \simeq \mathcal{O}(10^{-5})$$

- Applying "**low-level**" kinematic cuts based on event-topology



- Applying "**low-level**" kinematic cuts based on event-topology

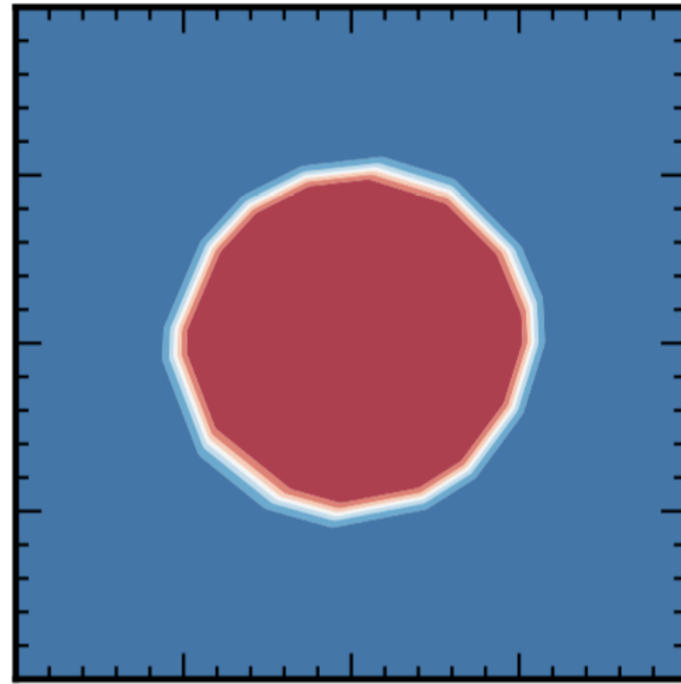
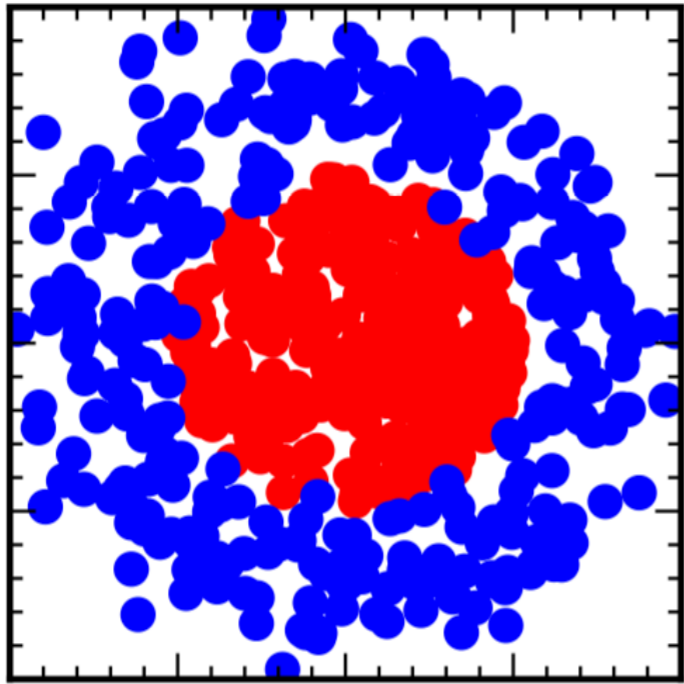
Baseline selections: $\cancel{E}_T > 20 \text{ GeV}$,
 $p_T^\ell > 20 \text{ GeV}$, $\Delta R_{\ell\ell} < 1.0$, $m_{\ell\ell} < 65 \text{ GeV}$,
 $\Delta R_{bb} < 1.3$, $95 < m_{bb} < 140 \text{ GeV}$

Signal	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}V$	$llbj$	$\tau\tau bb$	others	σ	$N_{\text{sig}}^{\text{SM}} / N_{\text{bknd}}$
0.0124	1.1724	0.0297	0.0246	0.0158	0.0379	0.00590	0.60	0.00964

jjllνν̄ backgrounds from QCD+EW

- We may apply the advanced statistical tools to see correlations among "low-level" kinematic variables.
- But the **efficiency based on "low-level cuts" is NOT GOOD**

what if we know BKG very well



A cartoon is from a paper by Spencer Chang, Timothy Cohen and Bryan Ostdiek, Phys. Rev. D 97, 056009 (2018)

- If we know BKG is a circle, we can take BKG out very easily with **input variables which characterizes** BKG events

(for a circle, variables are; a location of center, radius)

Hypothesis test: Is the event from top production?

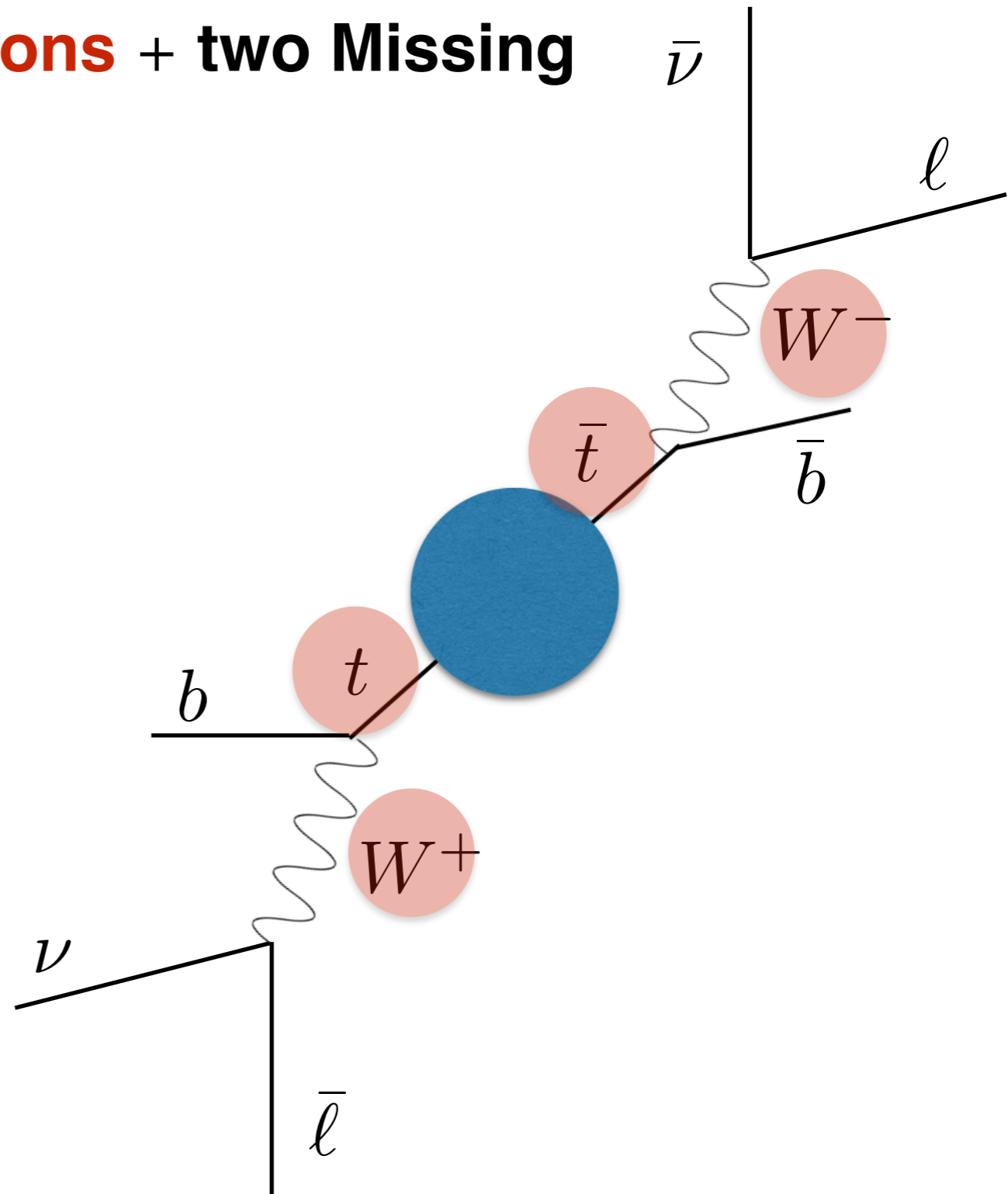
- We have **six unknowns** for two neutrino momentums.
- We have **four mass-shell conditions** + **two Missing Transverse Energy conditions**

$$(p_{\bar{\nu}} + p_{\ell})^2 = m_W^2$$

$$(p_{\bar{\nu}} + p_{\ell} + p_{\bar{b}})^2 = m_{\bar{t}}^2$$

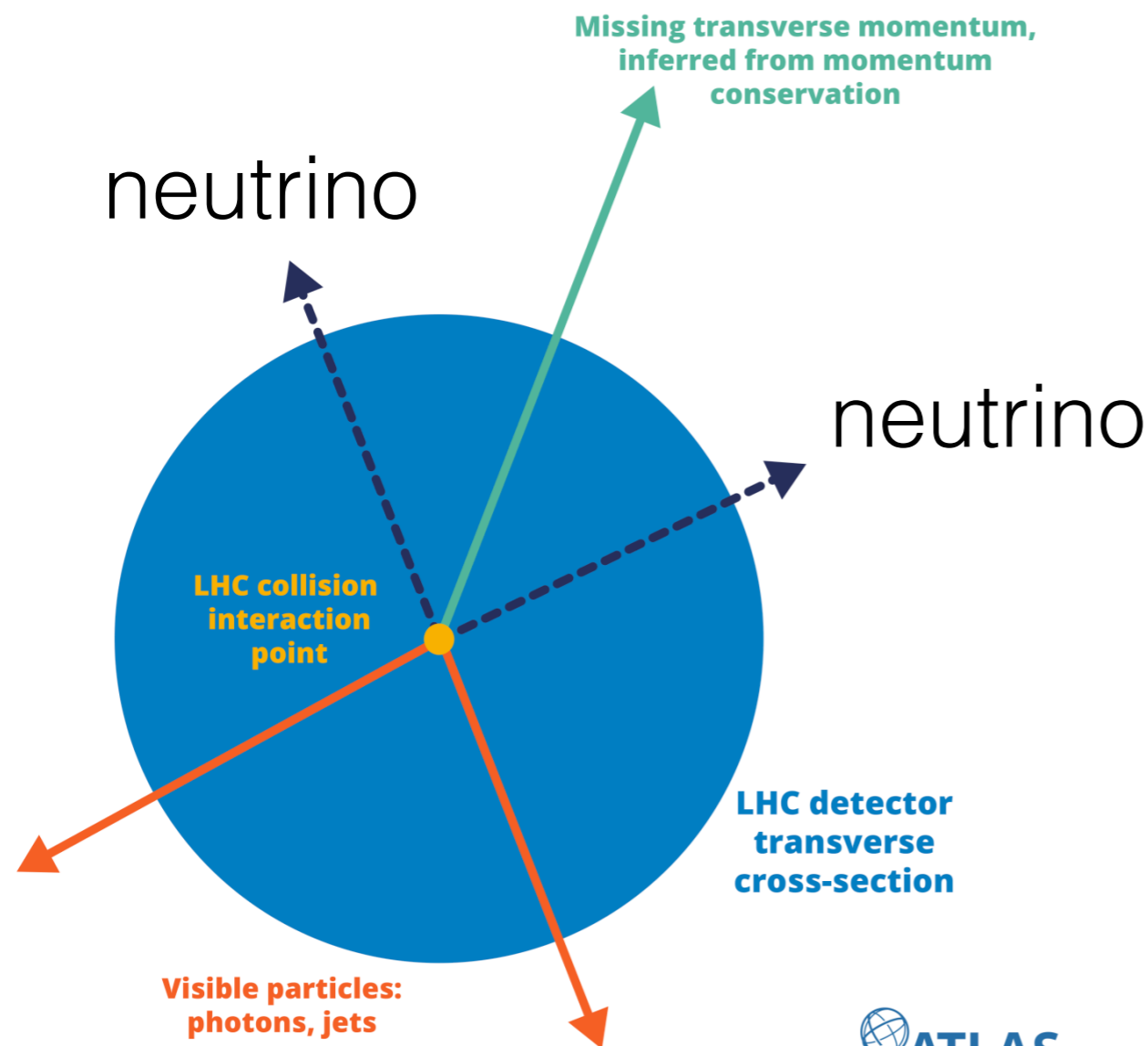
$$(p_{\nu} + p_{\bar{\ell}})^2 = m_W^2$$

$$(p_{\nu} + p_{\bar{\ell}} + p_b)^2 = m_t^2$$

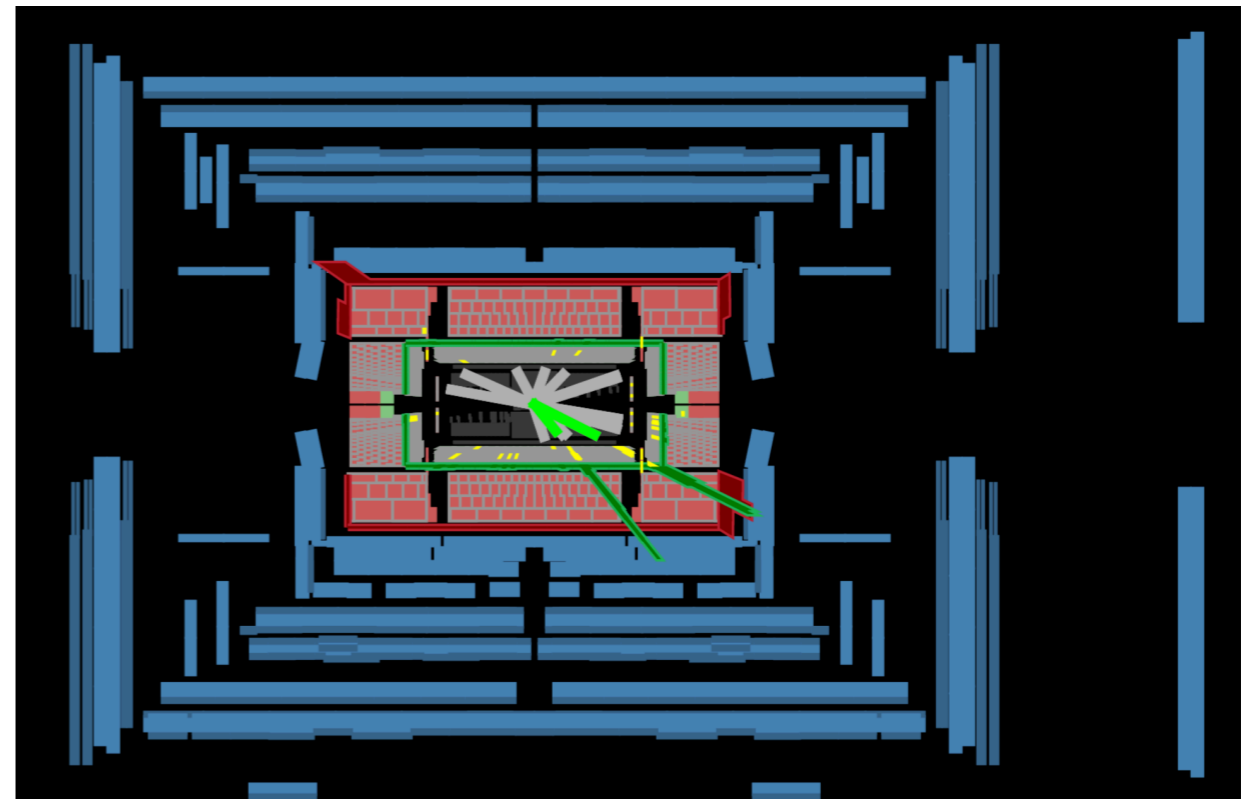


Hypothesis test: Is the event from top production?

- We have **six unknowns** for two neutrino momentums.
- We have **four mass-shell conditions** + **two Missing Transverse Energy conditions**



$$\left(\sum_{\text{visible particles}} \vec{P}_T \right) + \left(\sum_{\text{neutrinos}} \vec{P}_T \right) = 0$$

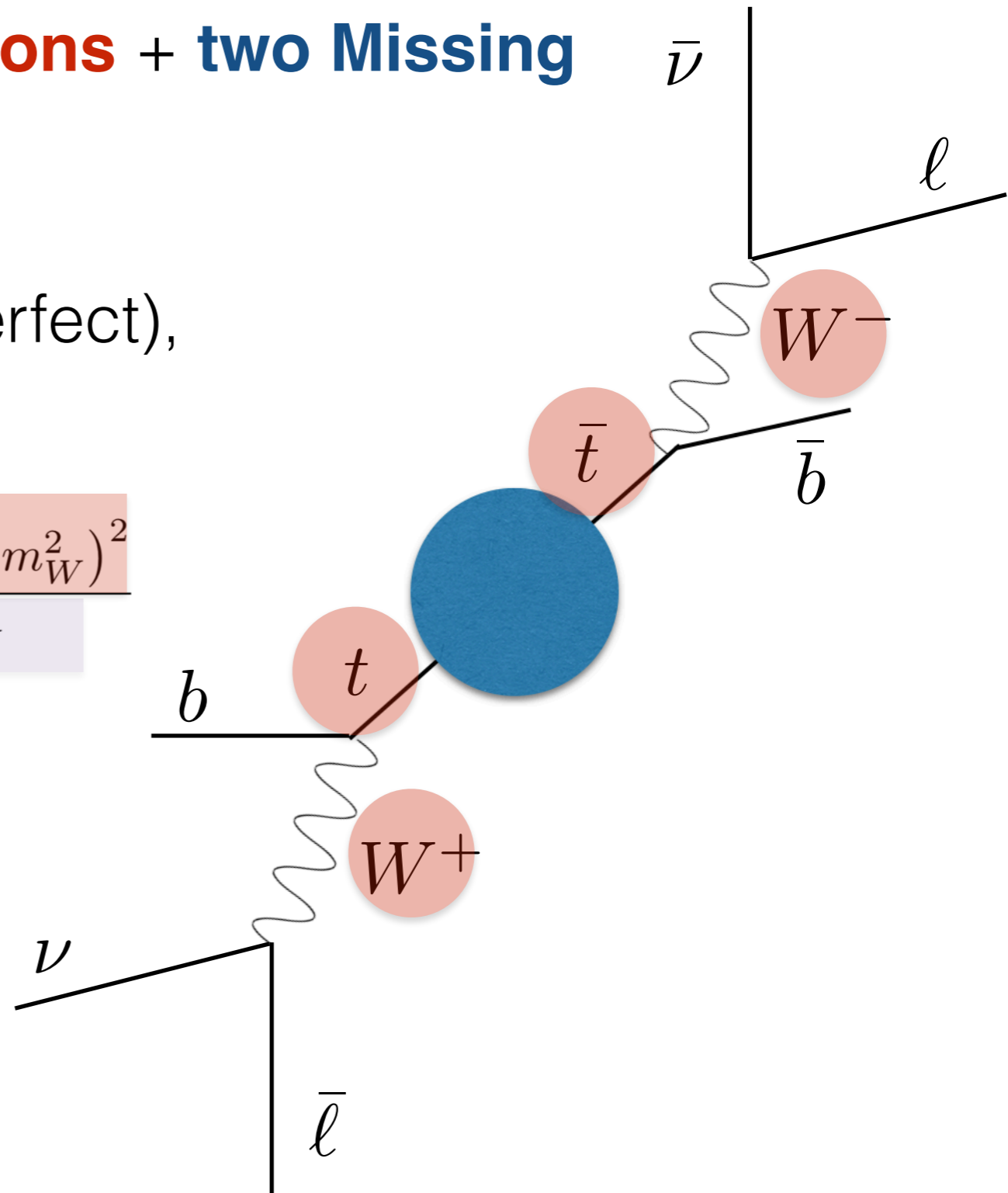


Hypothesis test: Is the event from top production?

- We have **six unknowns** for two neutrino momentums.
- We have **four mass-shell conditions** + **two Missing Transverse Energy conditions**
- In a reality (as a detector is not perfect), we allow some "**smearing**" effects

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

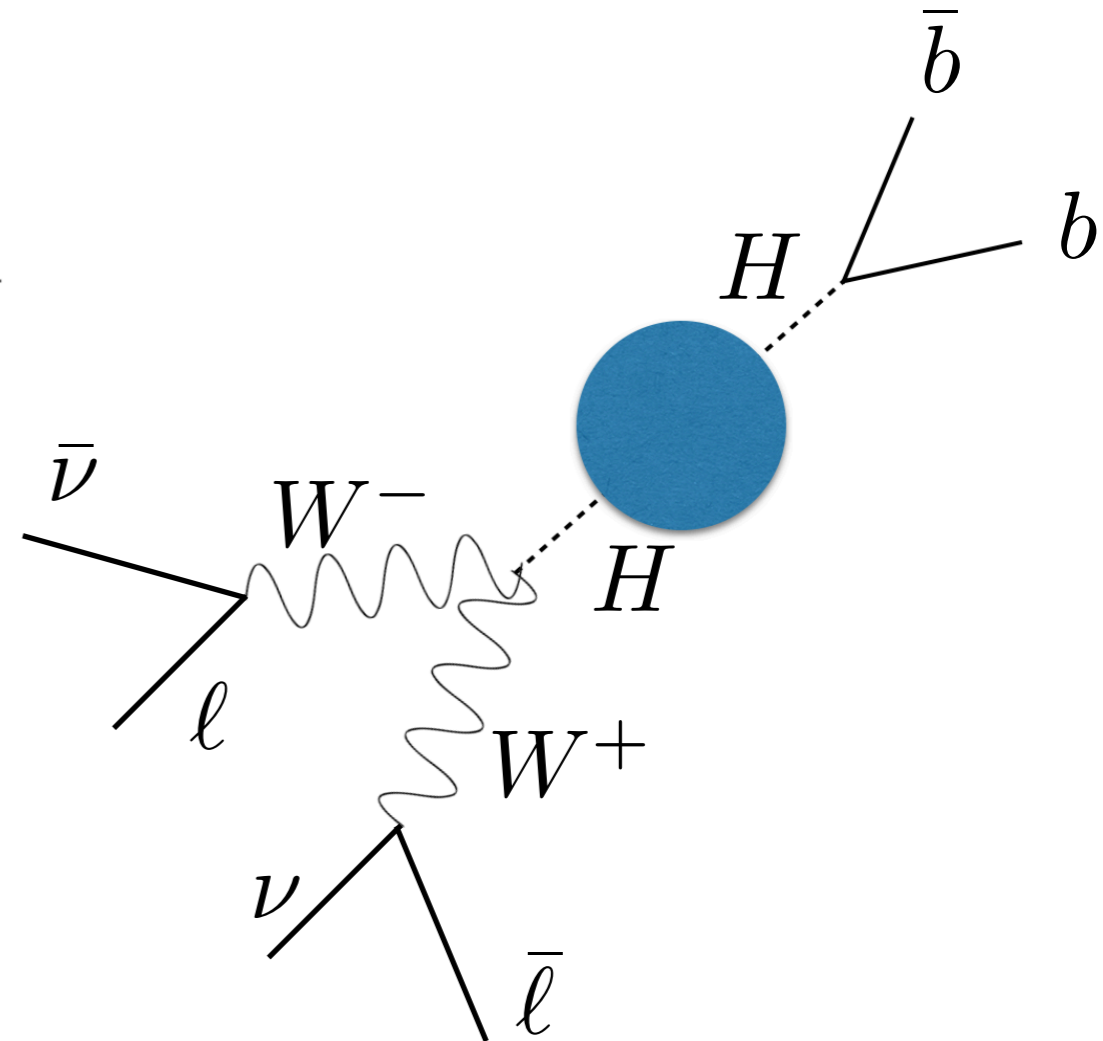
$$T \equiv \min(\chi_{12}^2, \chi_{21}^2)$$



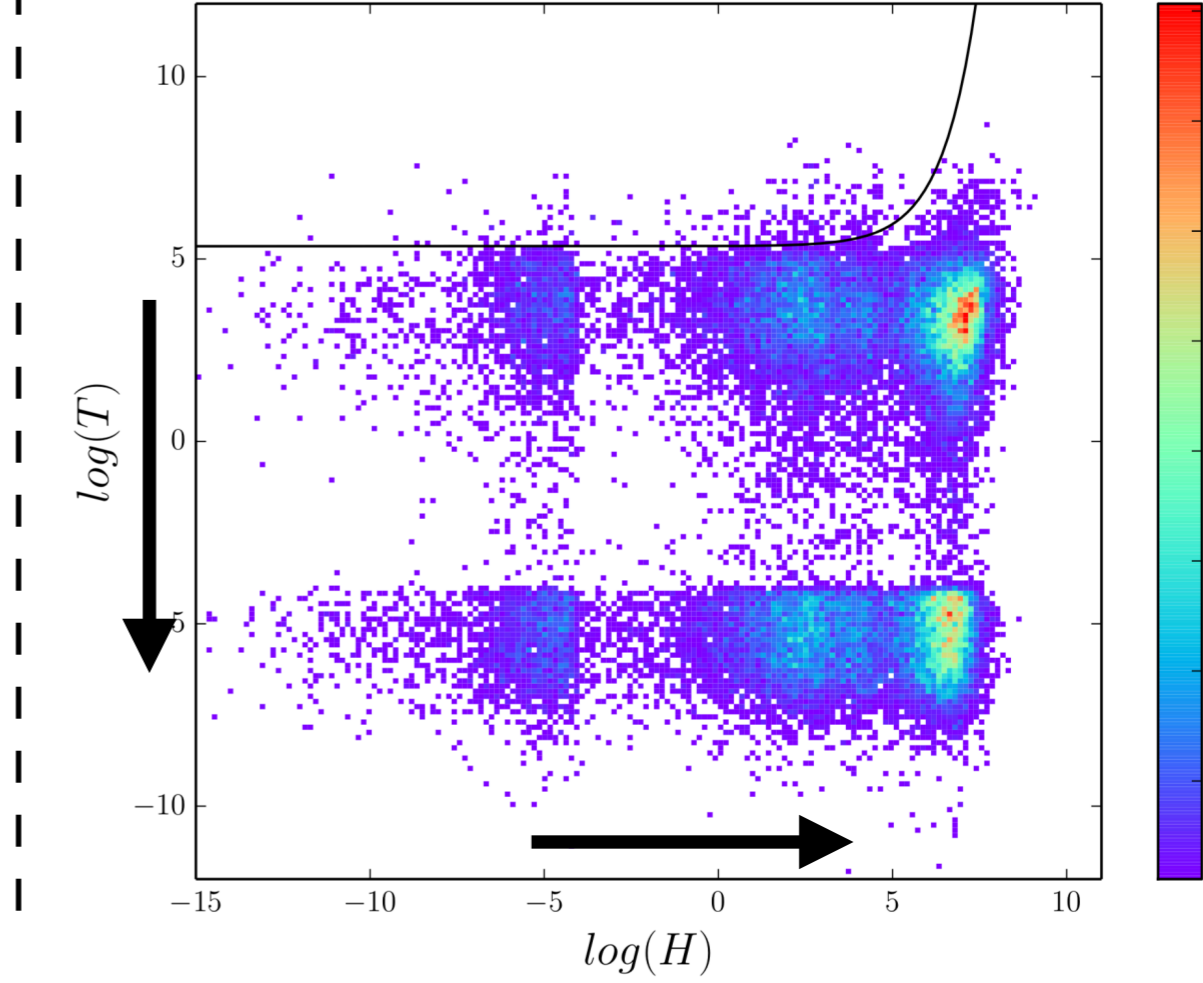
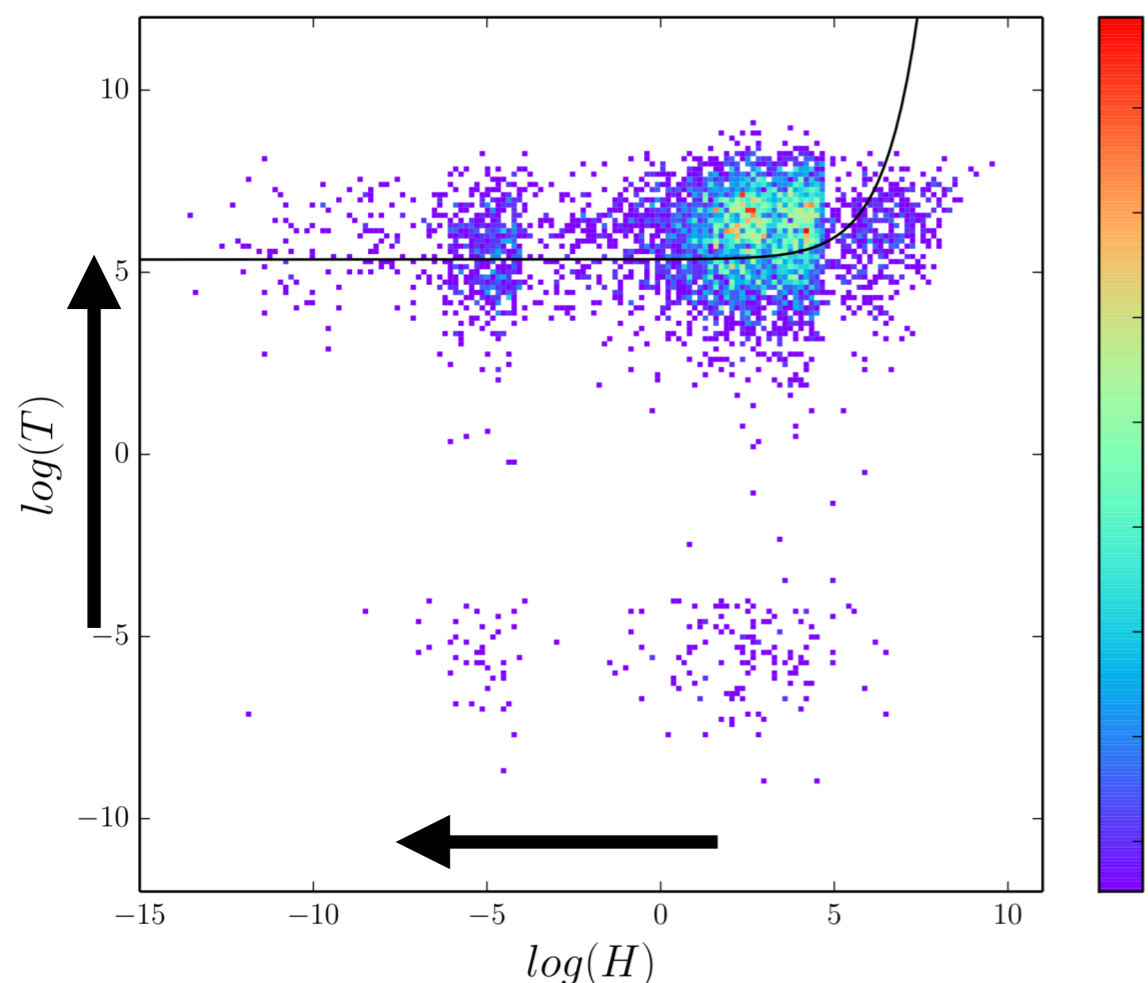
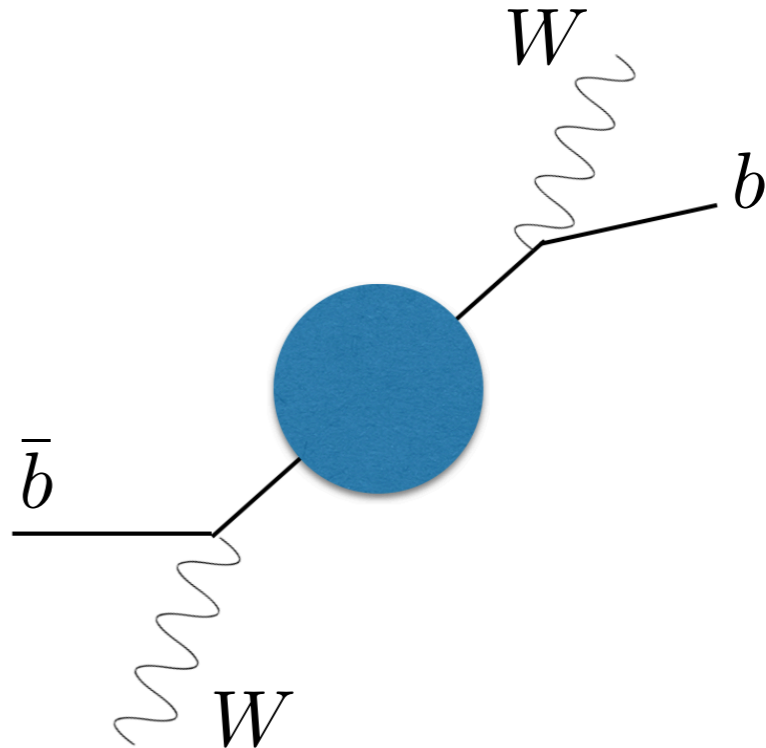
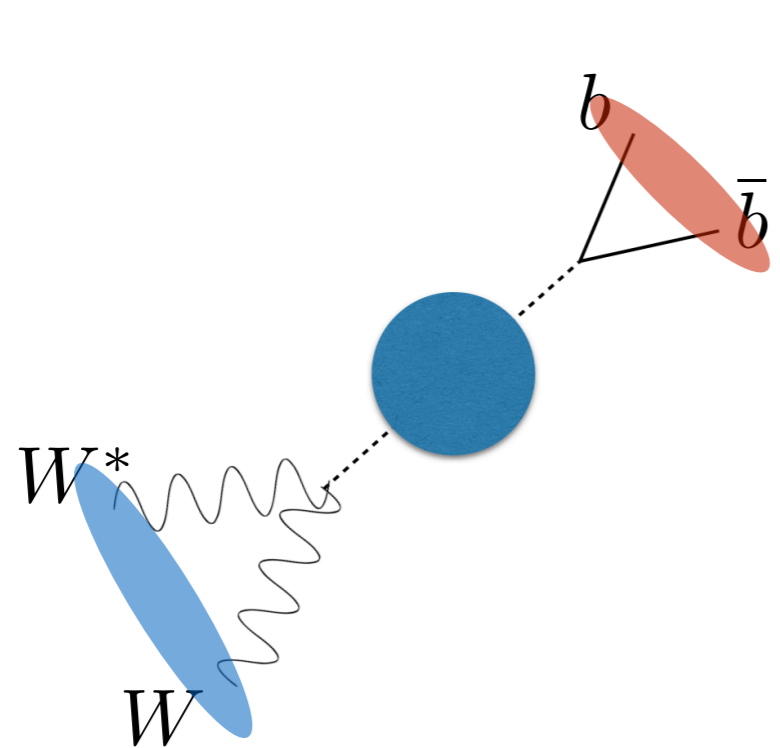
Hypothesis test: Is the event from signal ?

- We have **six unknowns** for two neutrino momentums.
- We have **two mass-shell conditions** + **two "mass" constraints** + **two Missing Transverse Energy conditions**

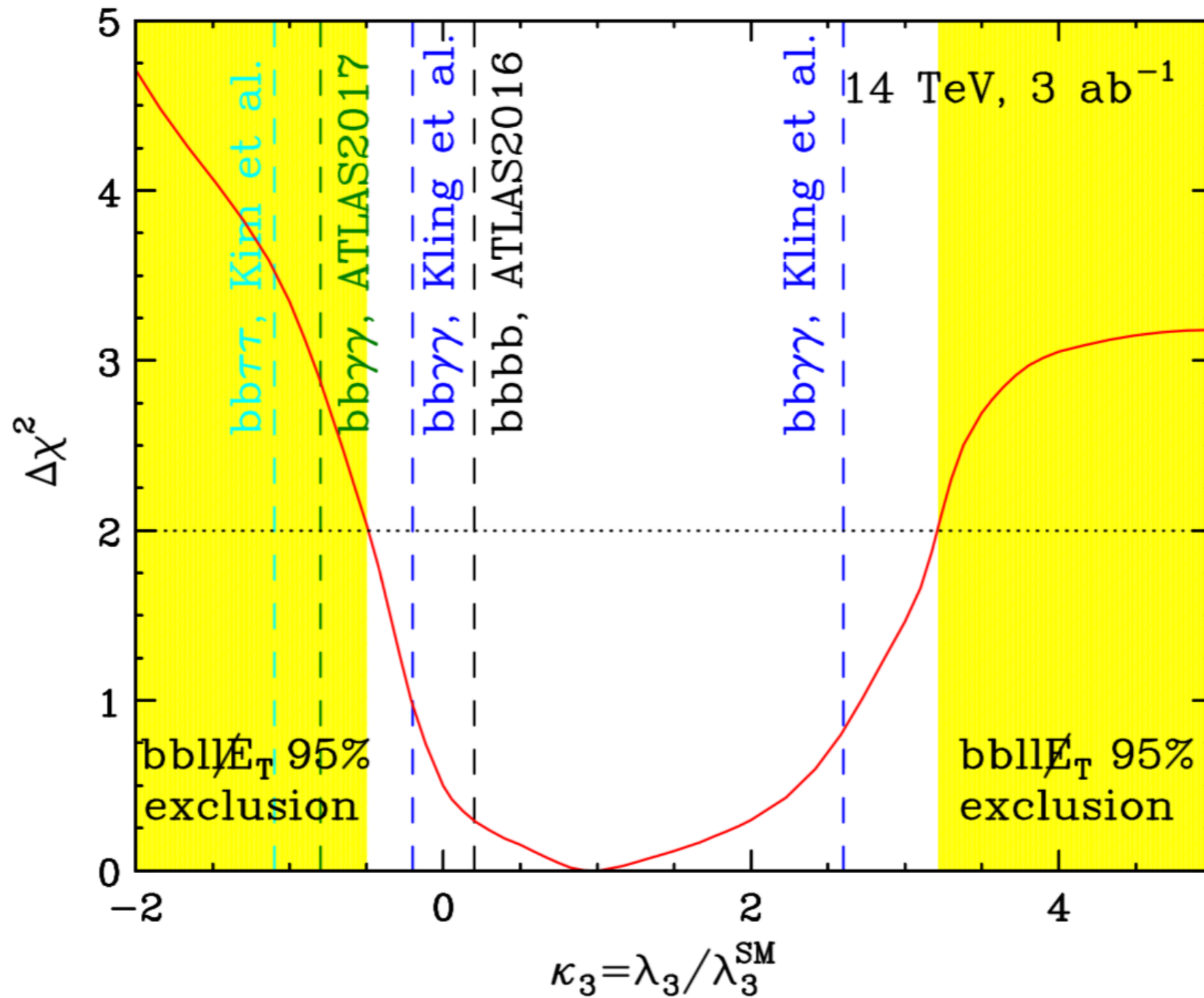
$$\begin{aligned}
 H \equiv \min & \left[\frac{(m_{\ell^+\ell^-\nu\bar{\nu}}^2 - m_h^2)^2}{\sigma_{h_\ell}^4} + \frac{(m_{\nu\bar{\nu}}^2 - m_{\nu\bar{\nu},peak}^2)^2}{\sigma_\nu^4} \right. \\
 & + \min \left(\frac{(m_{\ell^+\nu}^2 - m_W^2)^2}{\sigma_W^4} + \frac{(m_{\ell^-\bar{\nu}}^2 - m_{W^*,peak}^2)^2}{\sigma_{W^*}^4} \right. \\
 & \left. \left. \frac{(m_{\ell^-\bar{\nu}}^2 - m_W^2)^2}{\sigma_W^4} + \frac{(m_{\ell^+\nu}^2 - m_{W^*,peak}^2)^2}{\sigma_{W^*}^4} \right) \right]
 \end{aligned}$$



- Signal events = Low H-ness, High T-ness
background events = High T-ness, Low H-ness



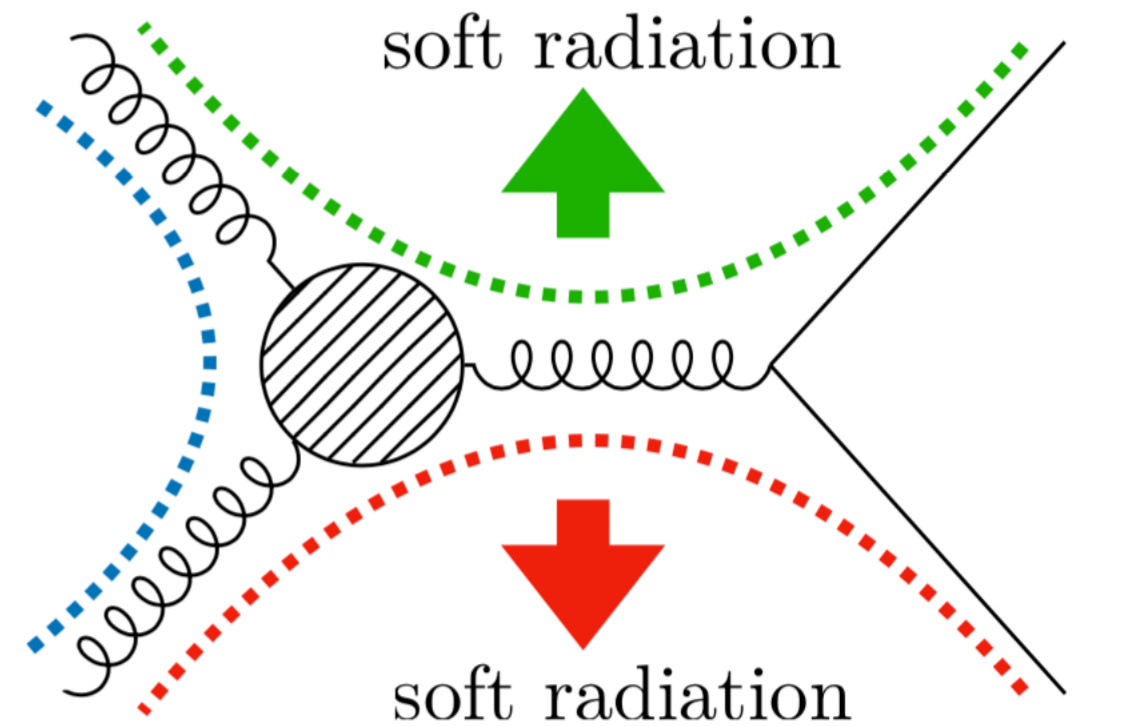
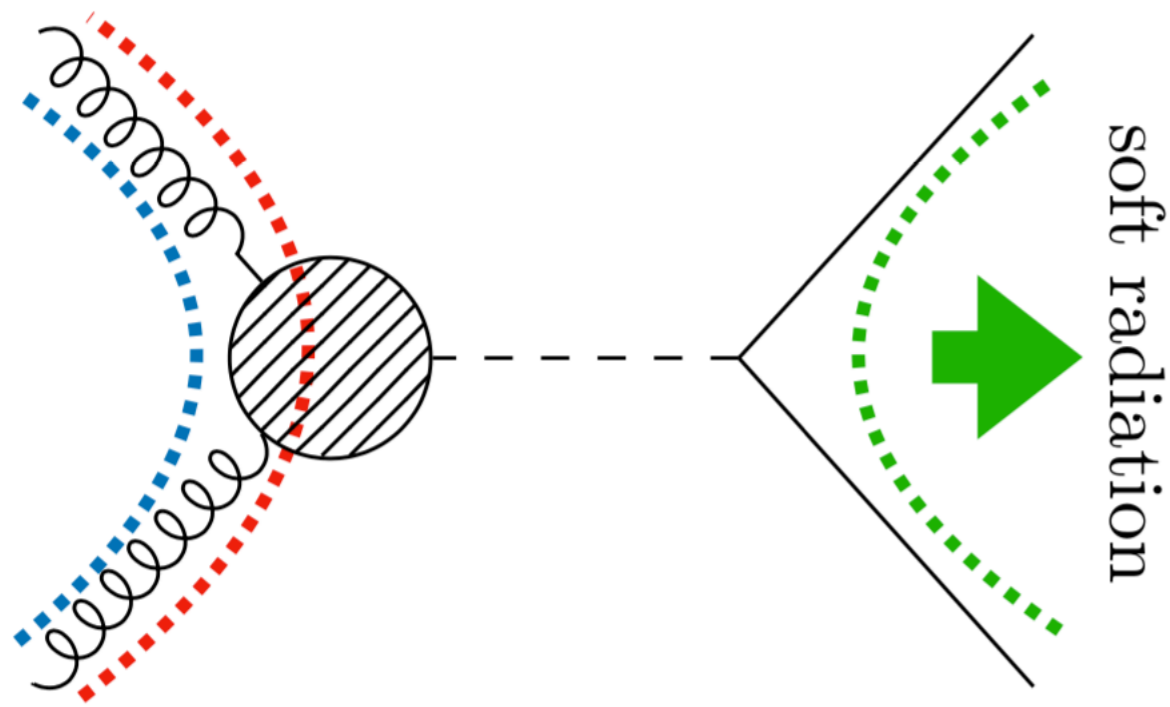
- Significance for constraining anomalous Higgs triple coupling



How can **young generations**
contribute to the battle of the LHC?

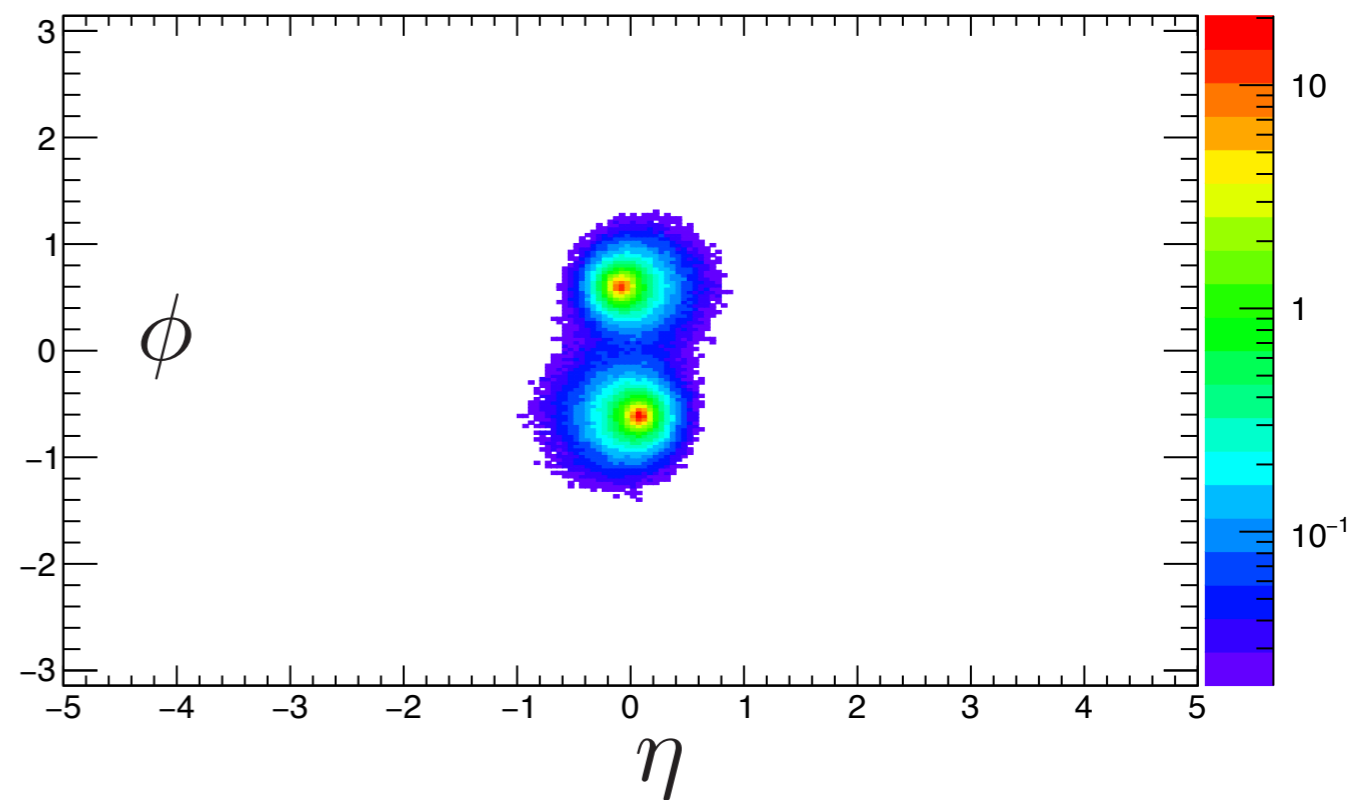
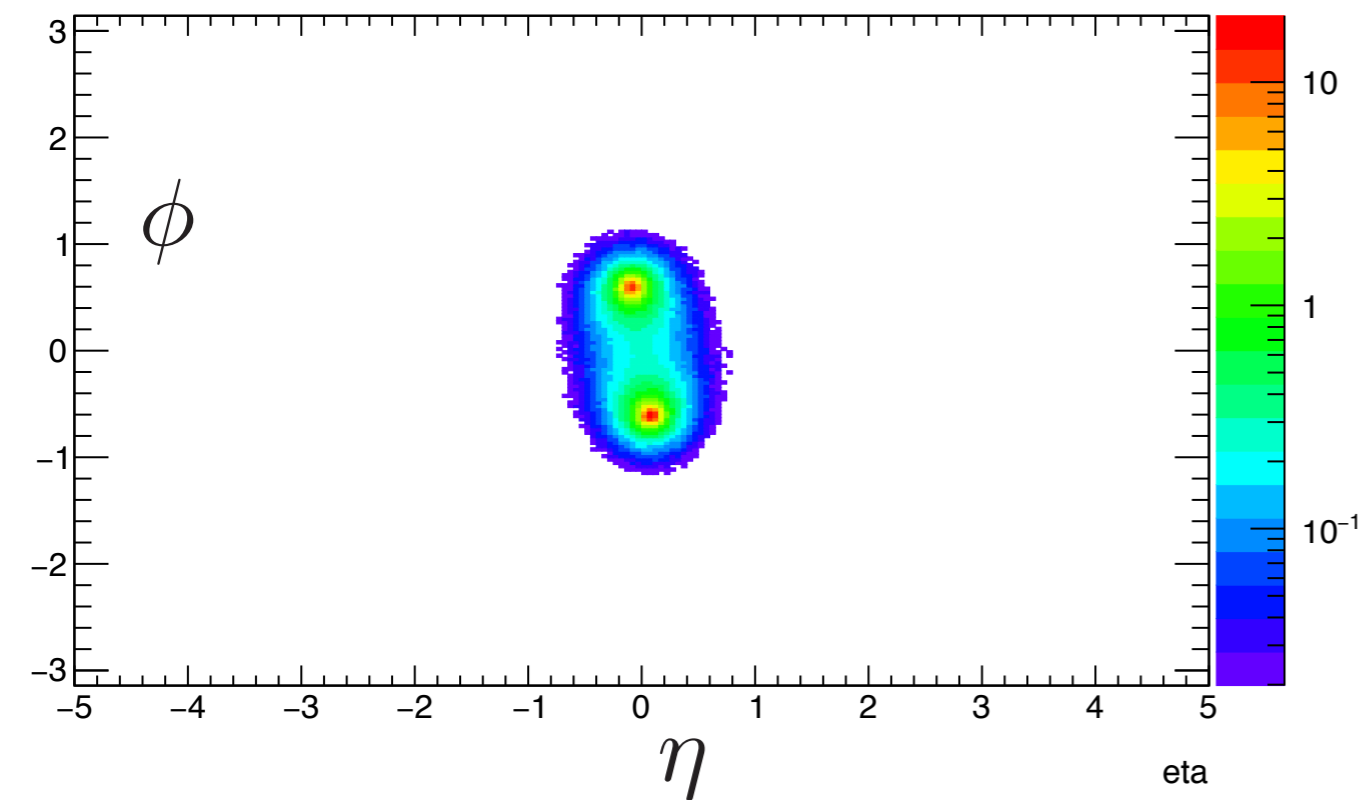
- Minho Kim, Jeong Han Kim

- Consider "**orthogonal**" method to kinematics; **QCD Color-flow**



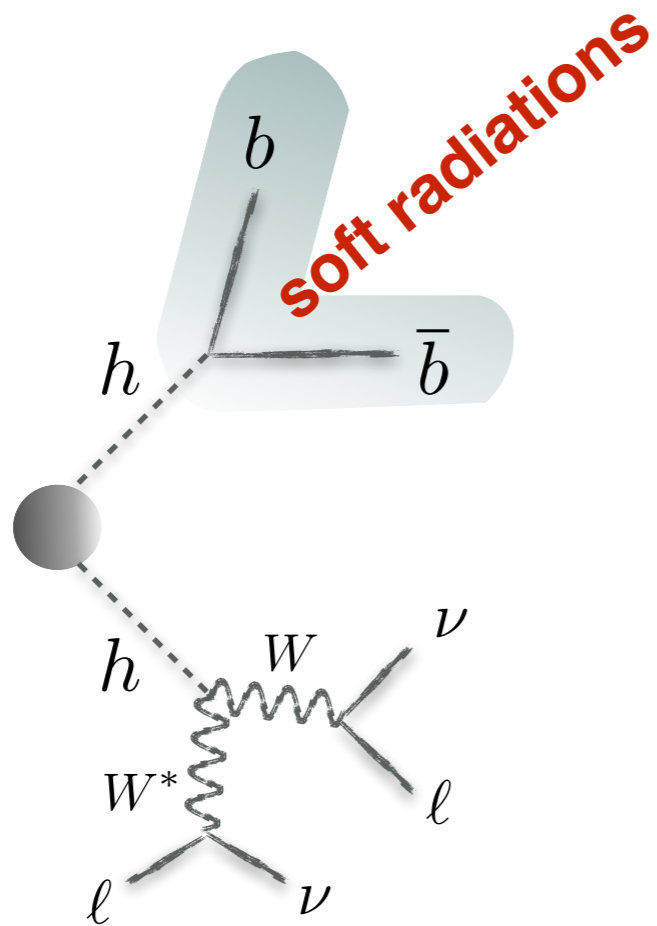
p_T

p_T

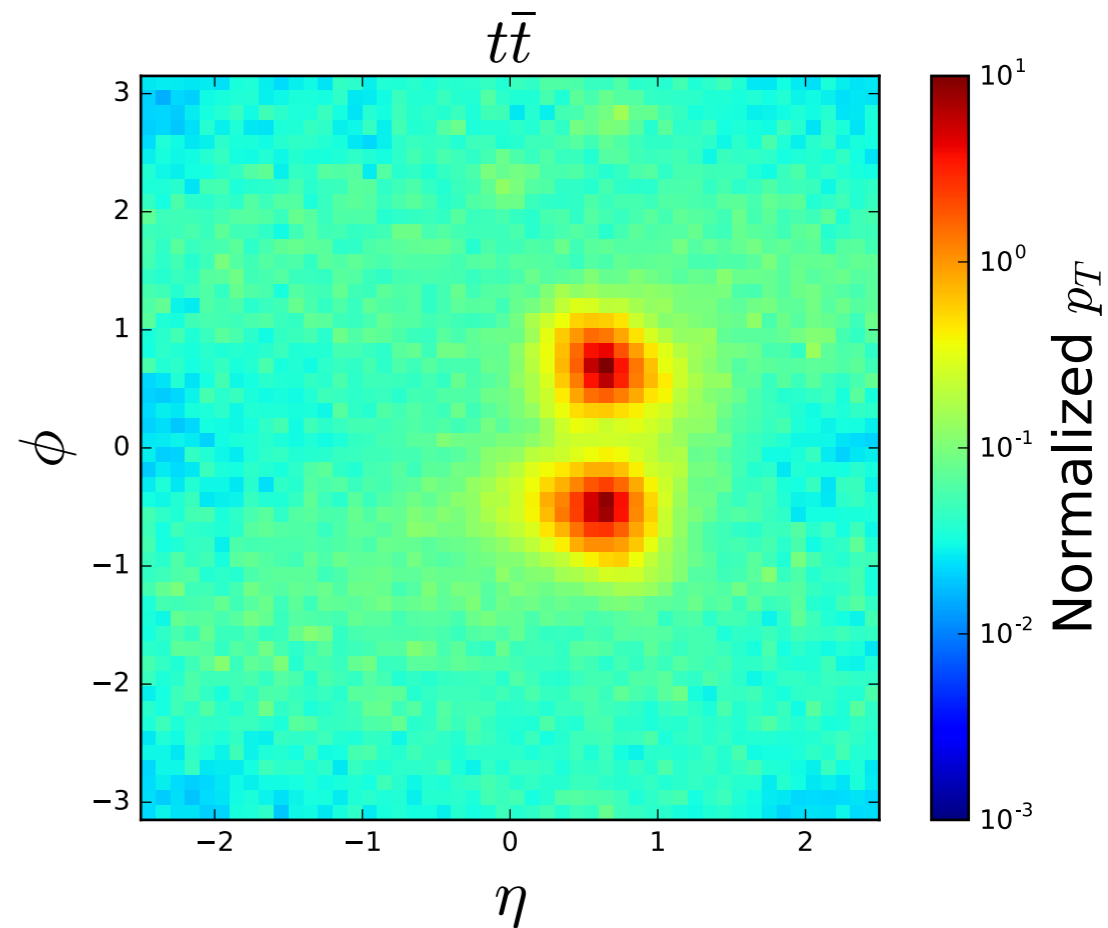
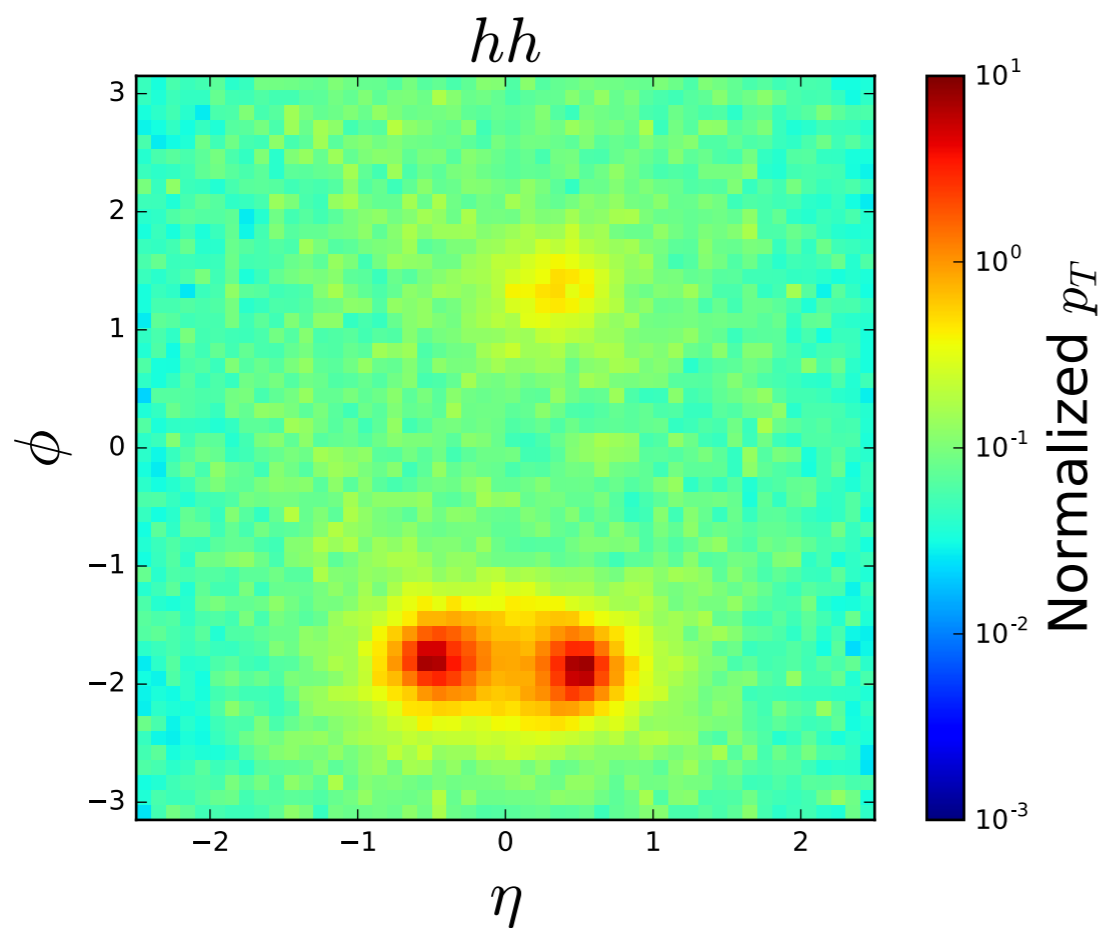
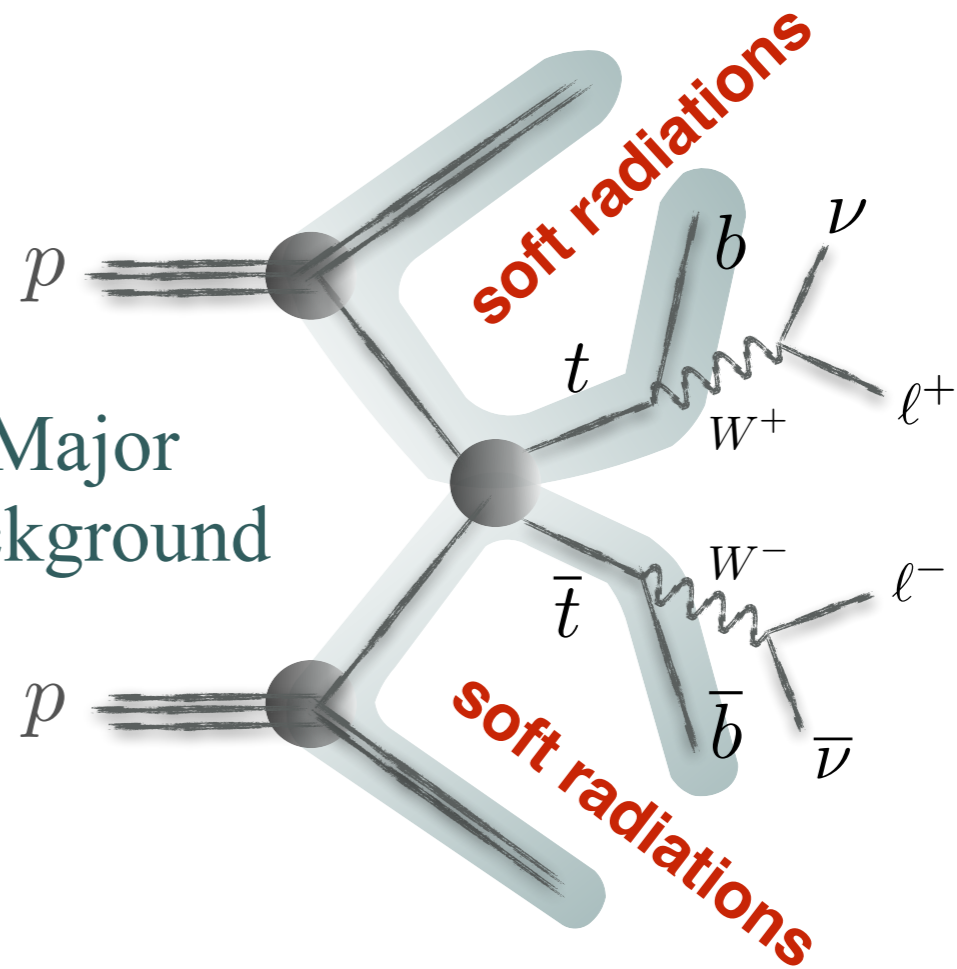


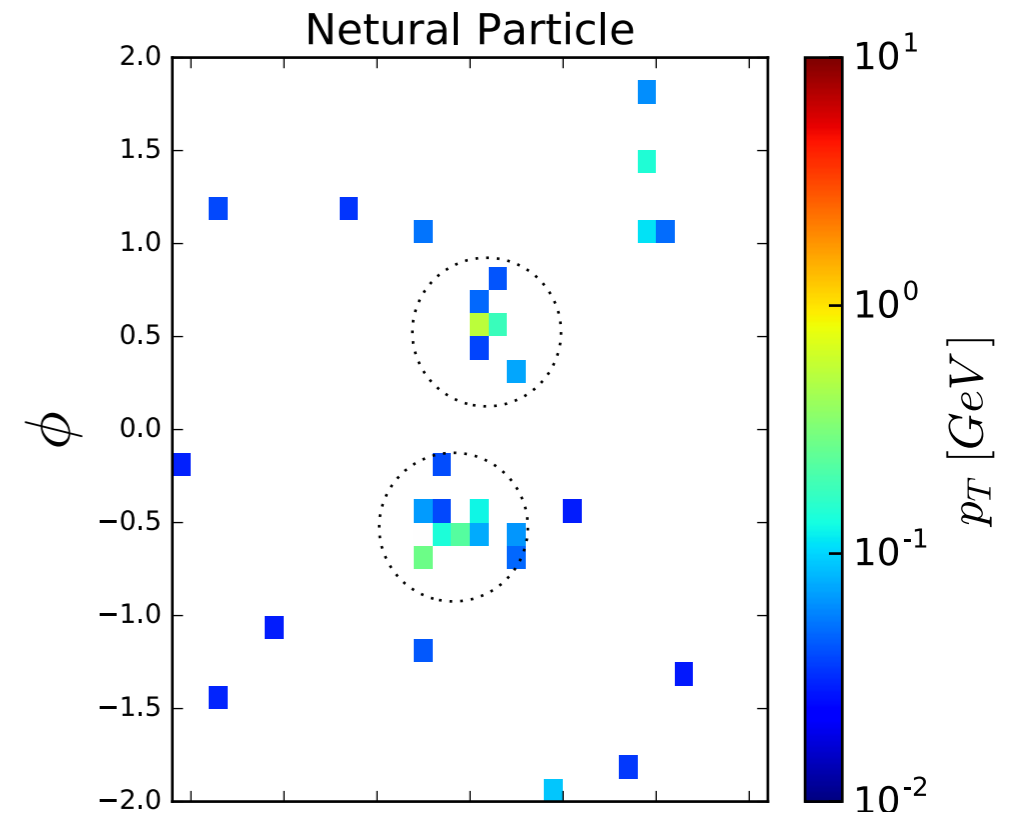
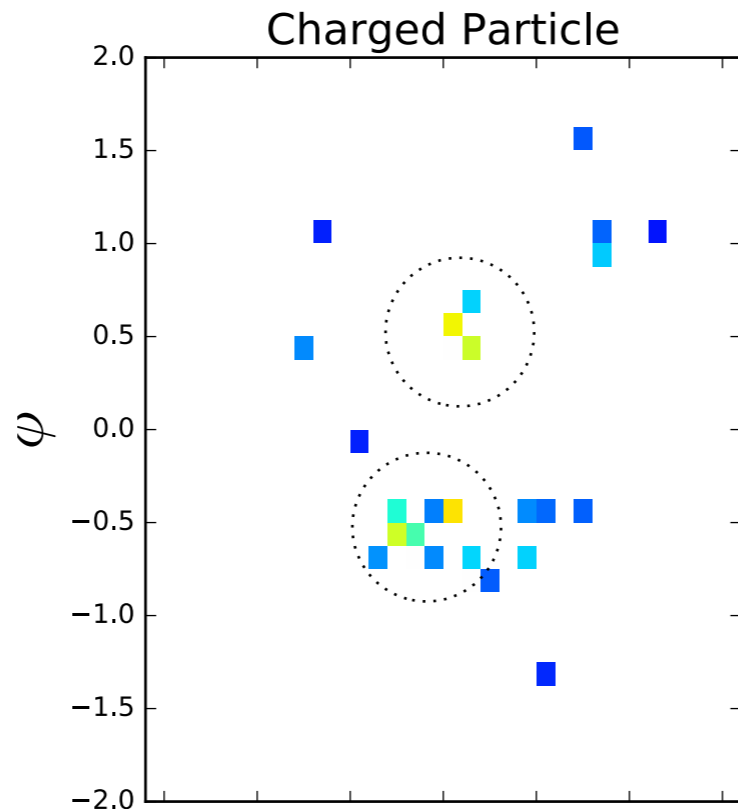
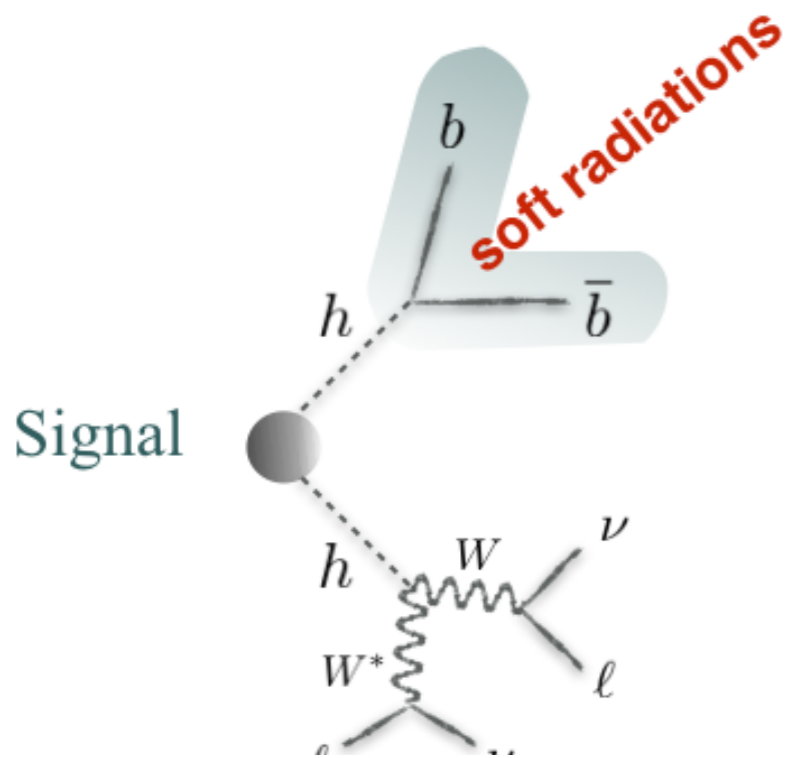
Energy deposits

Signal

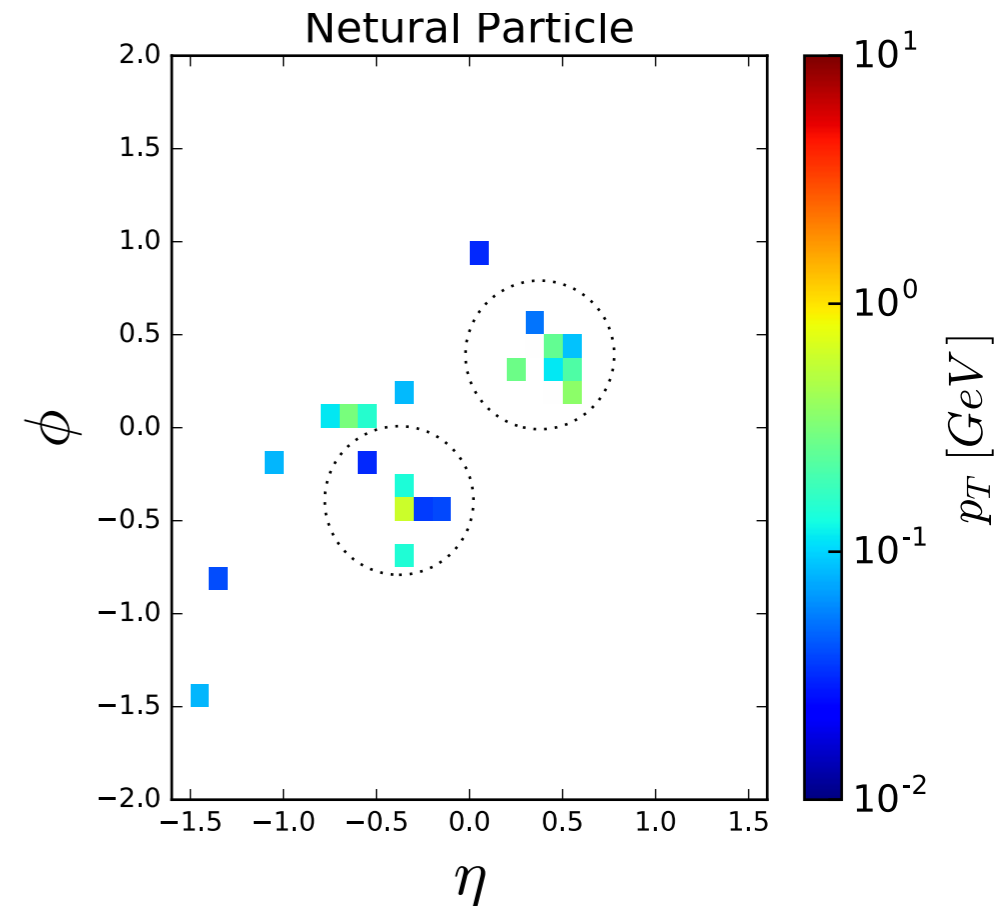
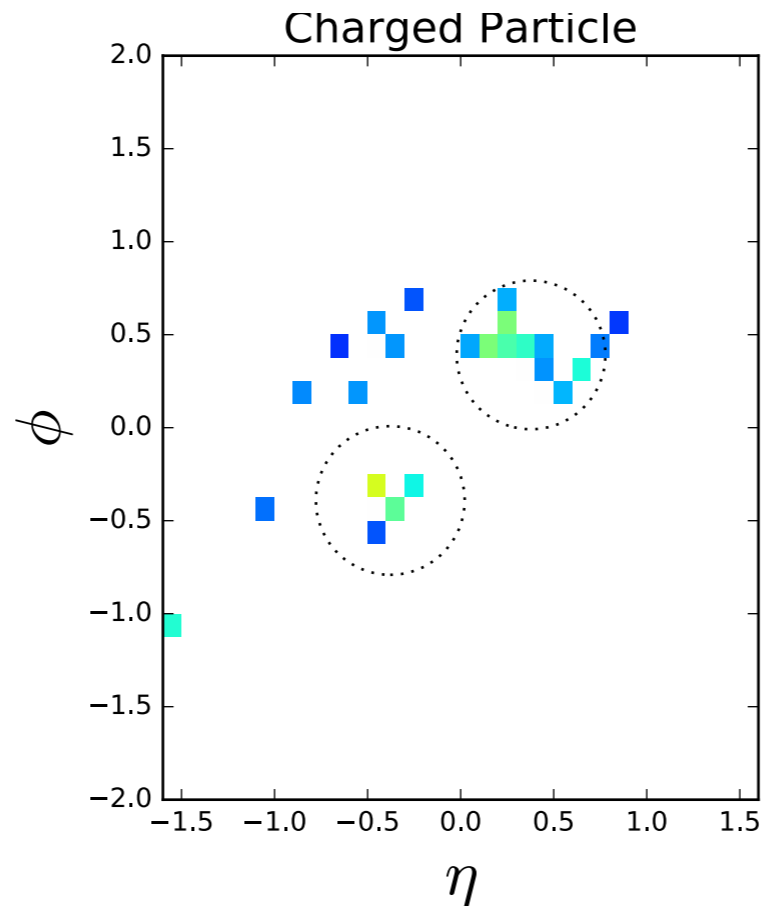
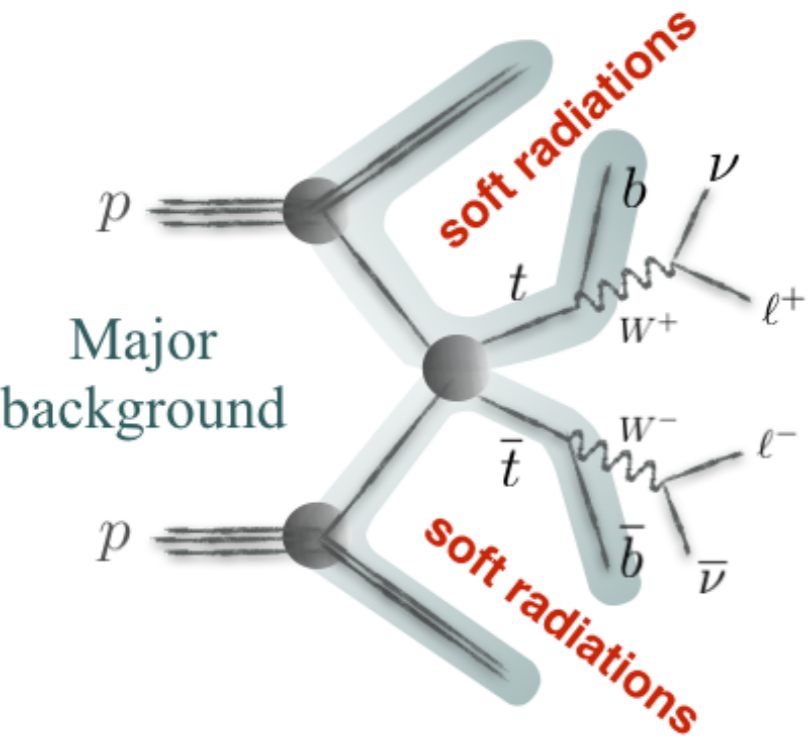


Major background



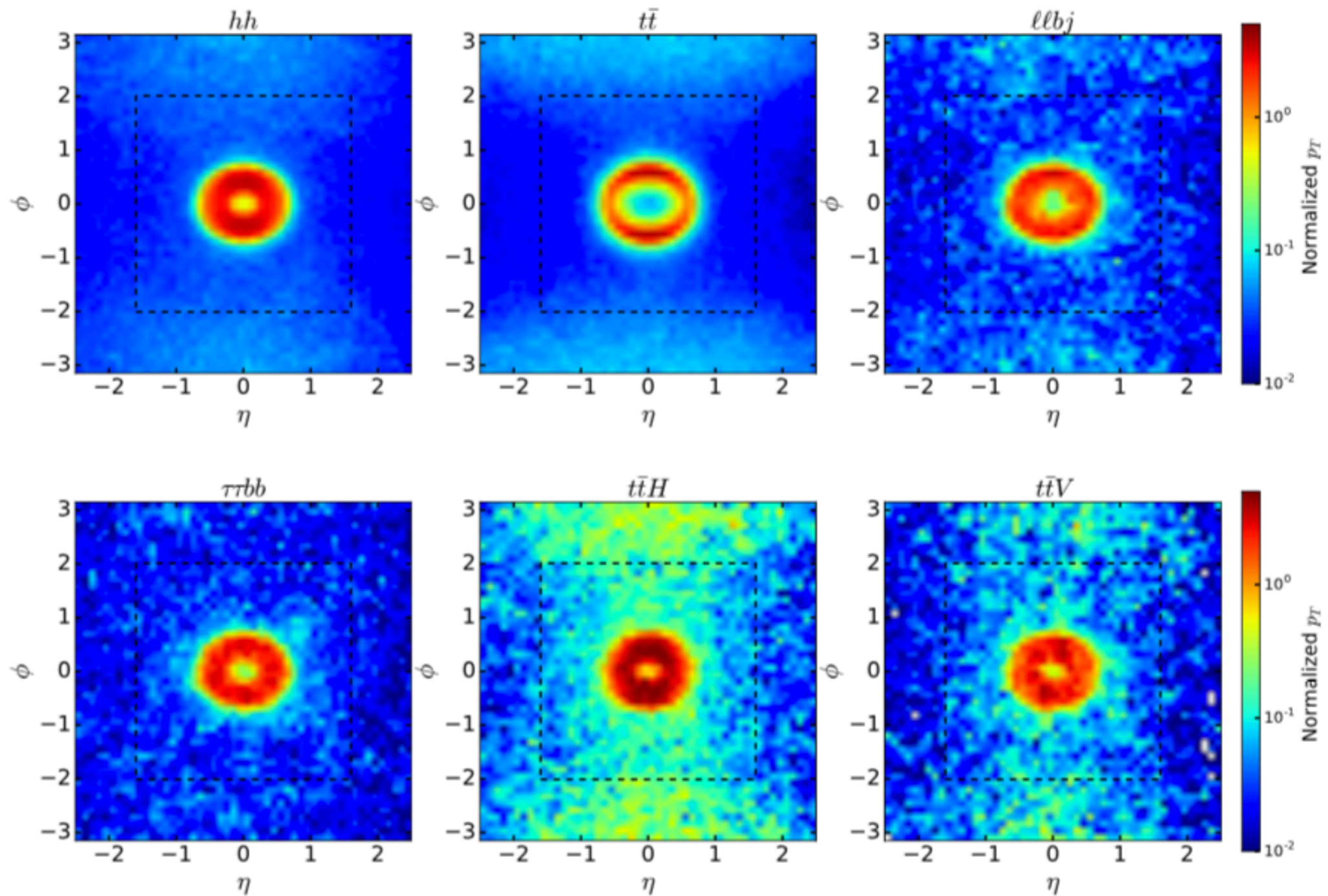


Can you see a pattern?



Jet Image: Pattern Recognition with DL

- Whole events with $b\bar{b}$ (fat-jet) axis as a center

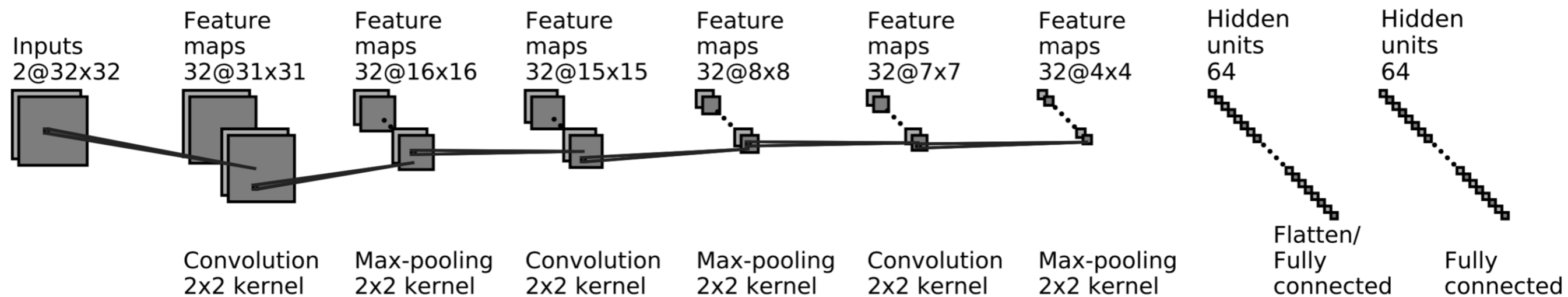


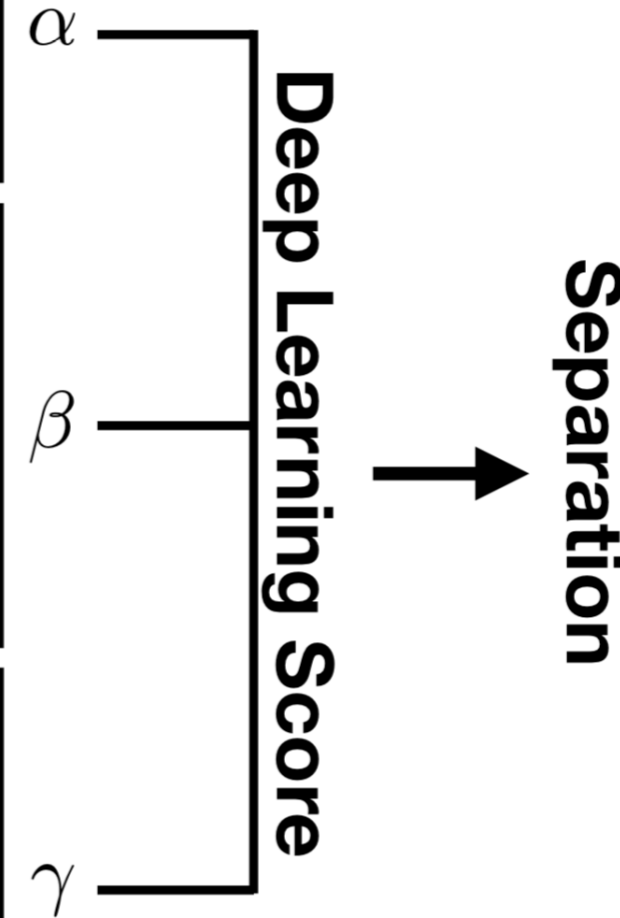
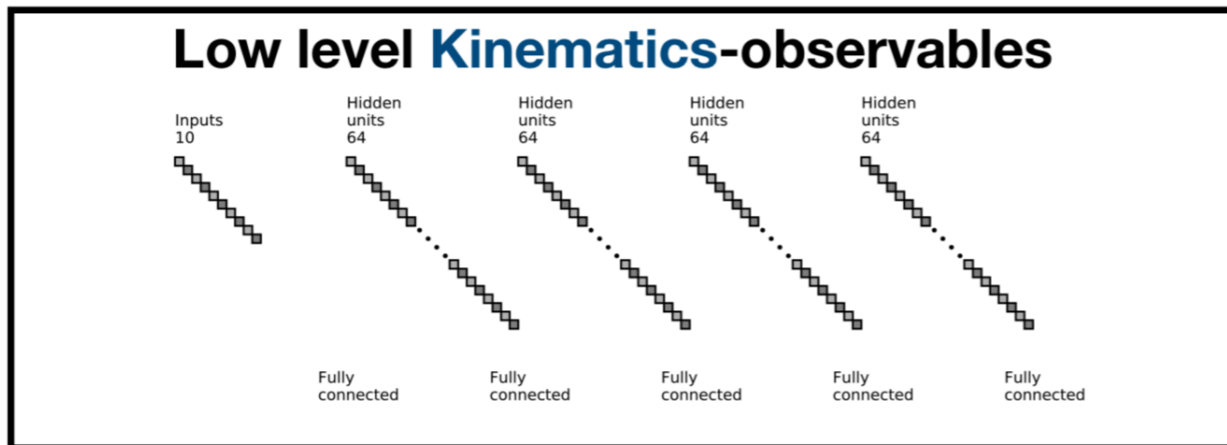
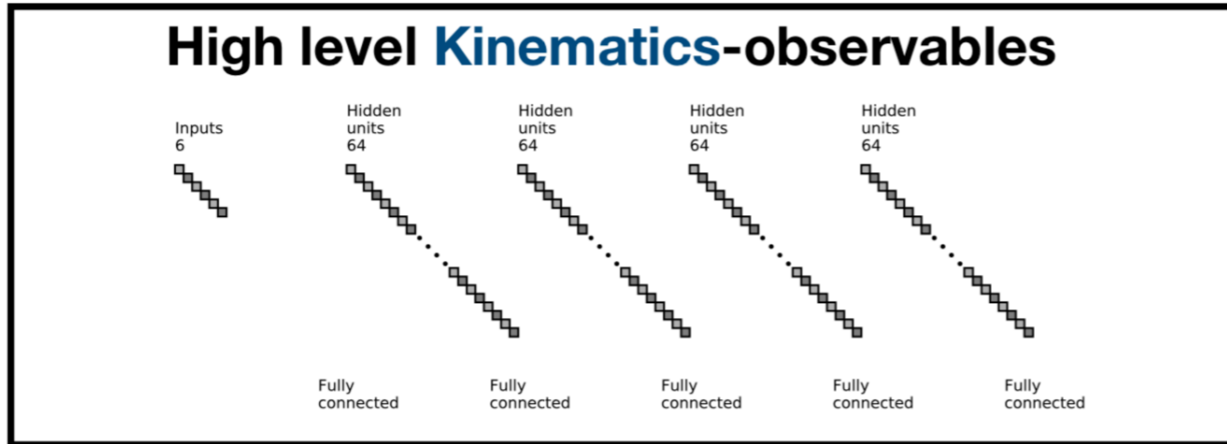
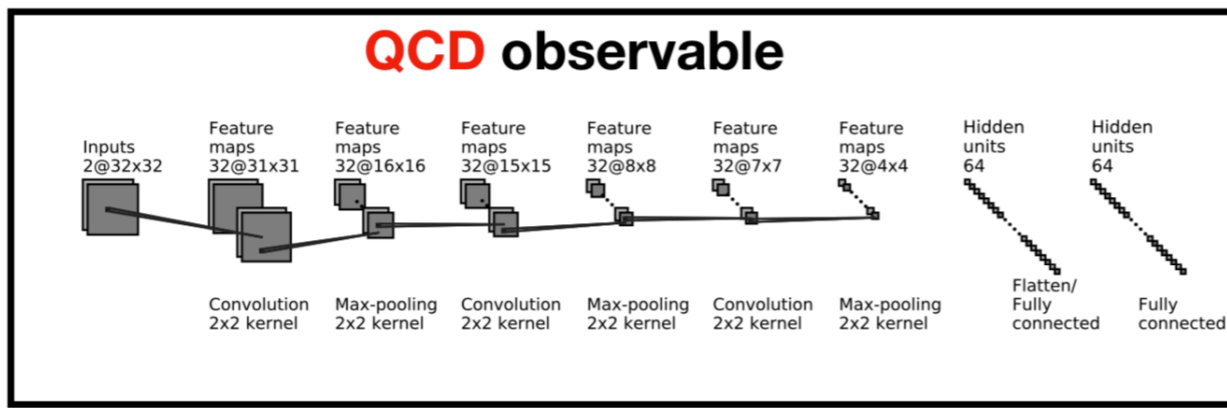
Maximizing information with Deep Neural Network

- For **jet-image**, we use 32x32 pixels for $-2.5 < \eta < 2.5$, $-\pi < \phi < \pi$.

Input channels for **CNN** are divided into two with particle flow:

- Neutral particles
- Charged particles



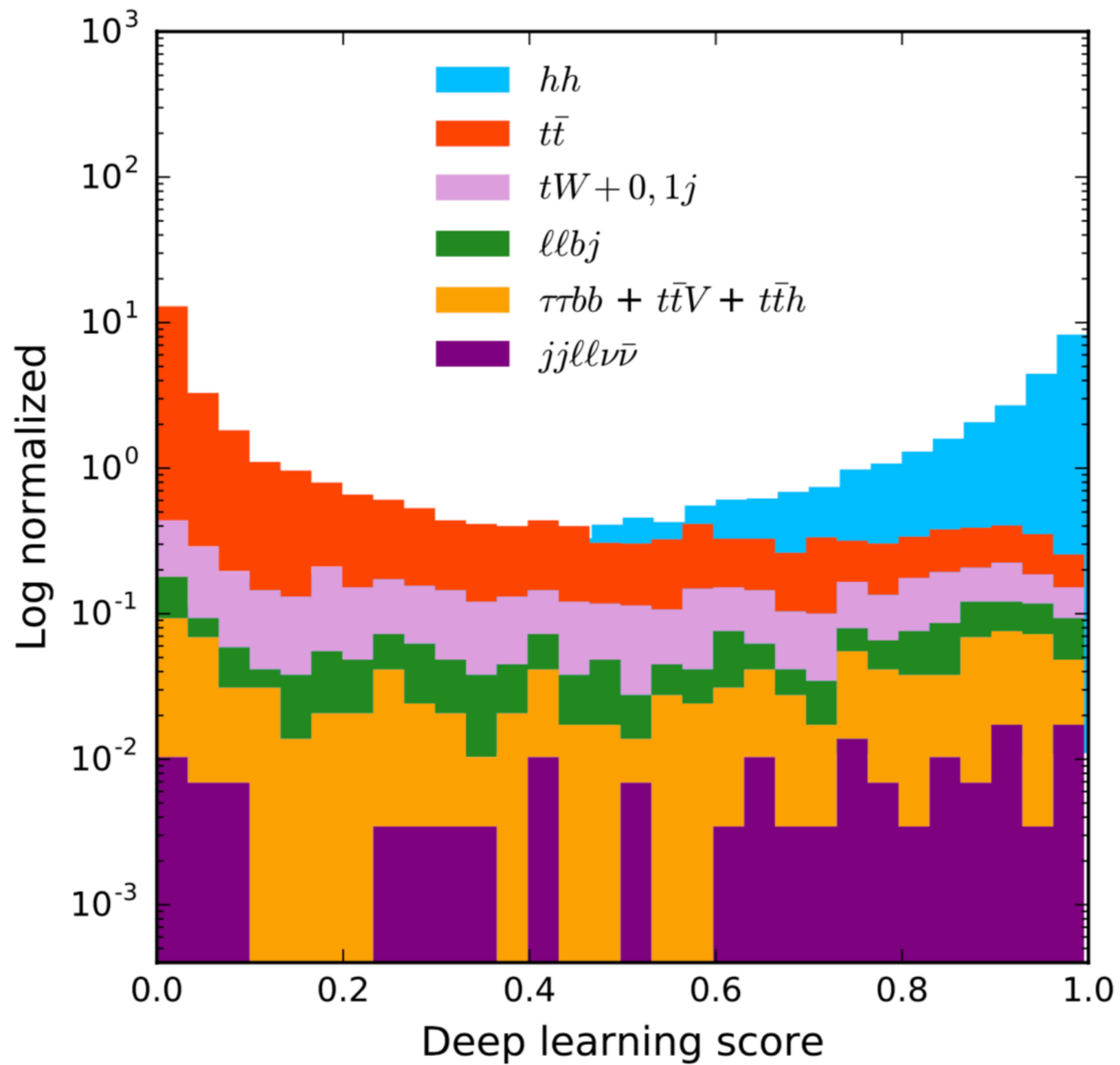


6 High Level Variables

Input data: $\sqrt{\hat{s}}_{\min}^{(\bar{b}, b, \bar{\ell}, \ell)}$ $\sqrt{\hat{s}}_{\min}^{(\bar{\ell}, \ell)}$ M_{T2}^b M_{T2}^{ℓ} Higgsness, Topness (featured variables)

10 Low Level Variables

Input data: MET $p_{\bar{\ell}}^t$ p_{ℓ}^t $\Delta R_{(\bar{\ell}, \ell)}$ $M_{(\bar{b}, b)}$ $p_{(\bar{b}, b)}^t$ $\Delta R_{(\bar{b}, b)}$ $M_{(\bar{\ell}, \ell)}$ $p_{(\bar{\ell}, \ell)}^t$, $\Delta\phi_{\{(\bar{\ell}, \ell), (\bar{b}, b)\}}$



"Backgrounds as stacked Histogram"

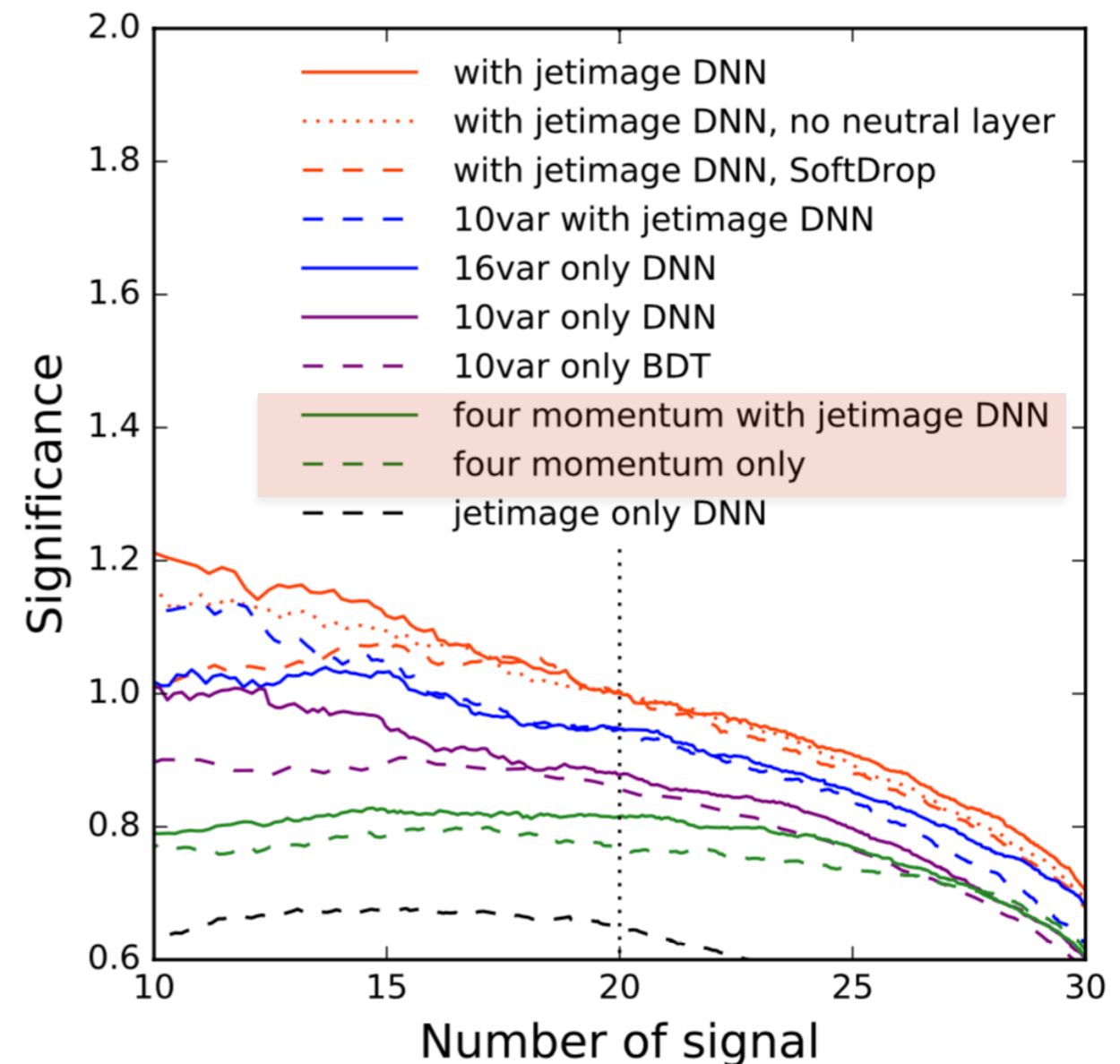
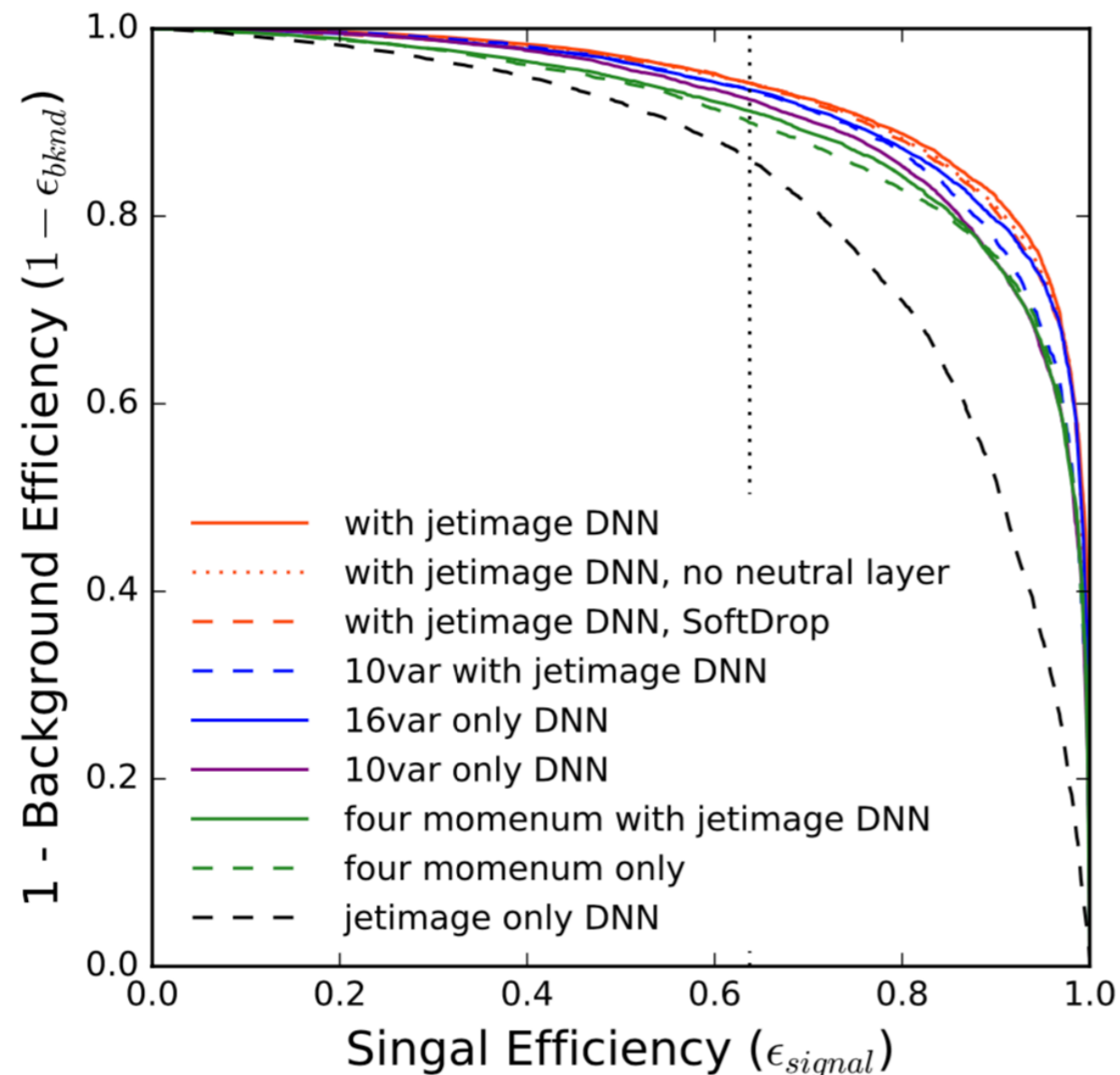
- To estimate effects from **pileup** removal (important in using QCD info),

0. No additional processes.

1. we apply SoftDrop to a fat-jet ($R= 1.2$ anti-Kt)

2. we use "charged layer only"

(Various pile-up removers use "longitudinal vertex information through tracking")

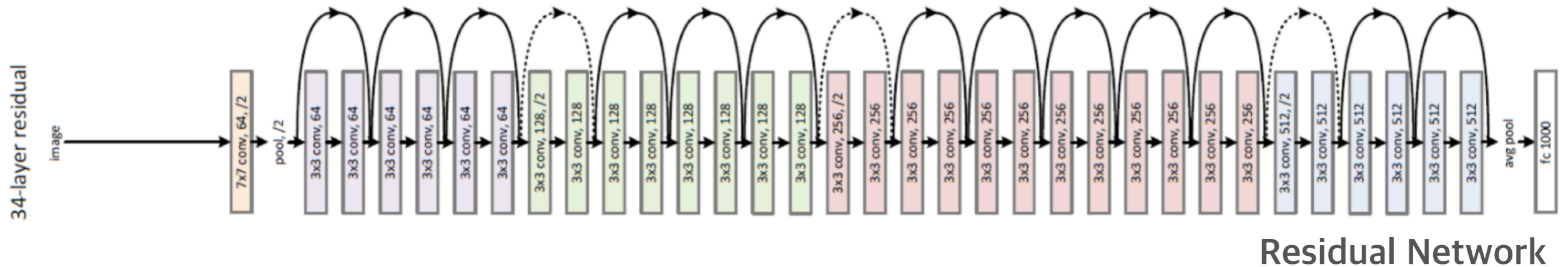


Additional improvements

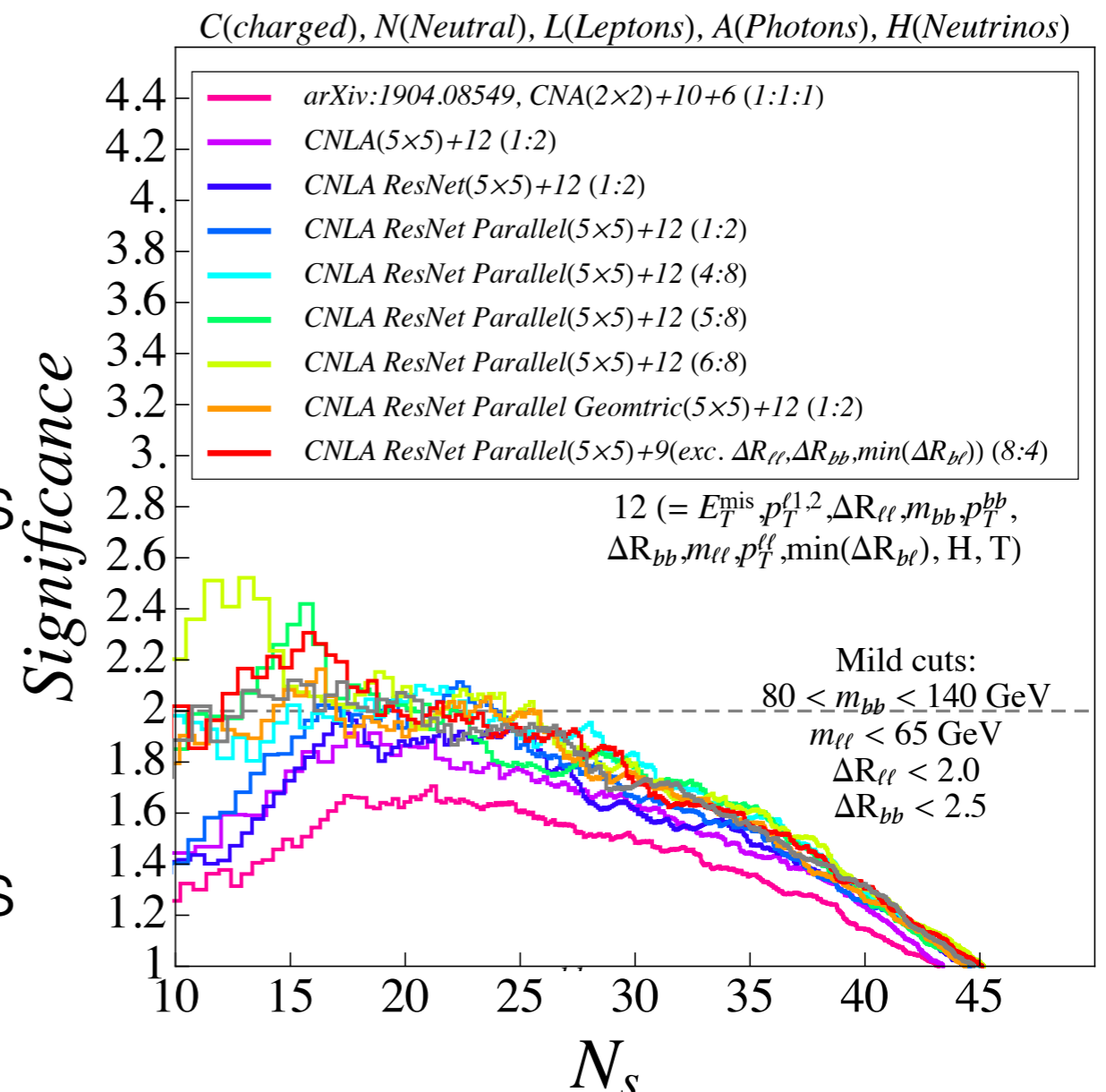
arXiv:1908(?).WXYZ

JH Kim, MH Kim, KC Kong, Matchev, MP

Improved DL architecture



- Deeper Layer structure would capture more features
- As we have deeper layers, information propagation becomes inefficient
- As we have deeper layers, information propagation becomes inefficient



Conclusions

- Theorists can contribute to the LHC game.
- (Armed with New technologies)
Young generations can win the battle of the LHC.
- For HL-LHC, Offshell Higgs can be a good probe for BSM.
- High Precision and maximization of **background rejection** are required.



Behinds...

Difficulties in preparing data

$\sigma(\text{fb})$	Signal	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}V$	$l\bar{l}bj$	$\tau\tau bb$	$tw + j$	$jjll\nu\nu$	σ	S/B
Baseline cuts: $p_T > 20$ 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	0.648	953.6 $\times 10^3$	611.3	1.71 $\times 10^3$	71.17 $\times 10^3$	3.289 $\times 10^3$	5.107 $\times 10^3$	8.819 $\times 10^3$		
	0.01046	1.8855	0.0269	0.0179	0.0697	0.0250	0.2209	0.0113	0.38	0.0046
jet-image DL	0.00667	0.1817	0.0133	0.00793	0.0245	0.0129	0.0671	0.00854	0.65	0.021
10 low-level variables DL	0.00668	0.0806	0.00897	0.00435	0.0163	0.00876	0.0462	0.00578	0.88	0.039
16 variables DL	0.00667	0.0662	0.00948	0.00358	0.0170	0.00747	0.0387	0.00402	0.95	0.046
10 variables + jet-image DL	0.00667	0.0693	0.00897	0.00435	0.0178	0.00722	0.0359	0.00352	0.95	0.045
16 variables + jet-image DL	0.00668	0.0607	0.00769	0.00281	0.0173	0.00799	0.0317	0.00402	1.0	0.051

- To generate backgrounds properly, we need to make HUGE Monte Carlo samples
- Preparing "Good enough" MC samples for testing is **NOT EASY**.
- Thus, we should find very good features (High-level observables)