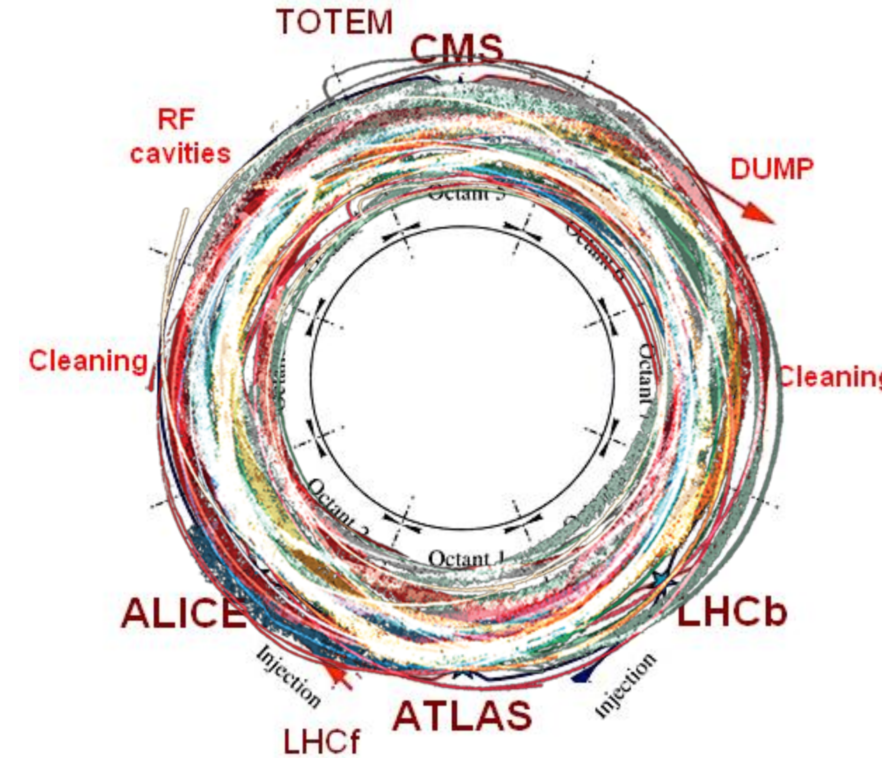
Portraying Double Higgs at



Myeonghun Park

서울과학기술대학교
SEOUL NATIONAL UNIV. OF SCIENCE & TECHNOLOGY
1910

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

2019, 6월 건국대학교 Di-Higgs Day

Higgs sector

"**Mexican Hat"** Higgs potential

↓

Spontaneous Symmetry Breaking

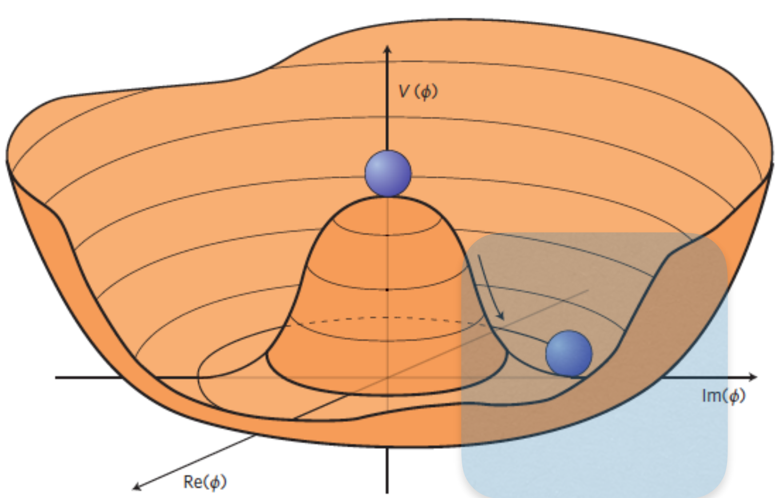
$$SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}$$

↓

Yukawa terms for massive fermions

Measuring Higgs potential

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



- From spontaneous symmetry breaking

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

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

Measuring Higgs potential

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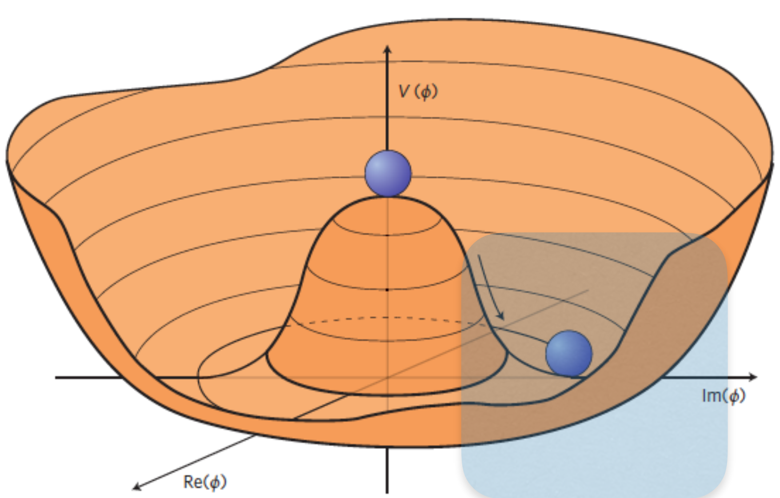

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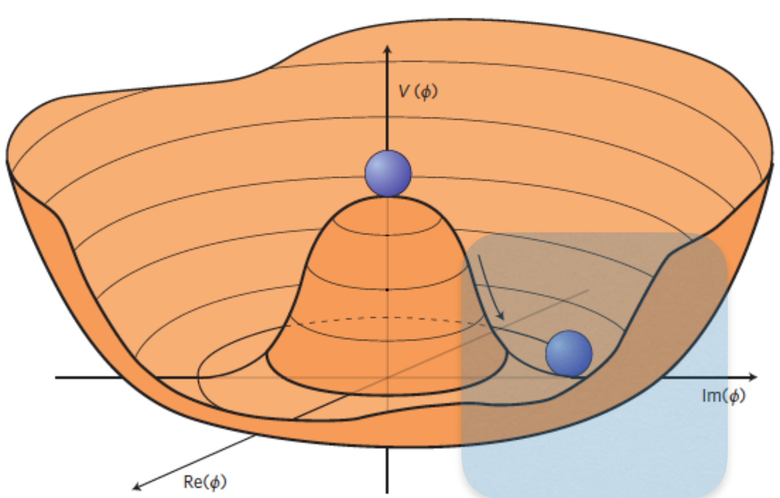
- The shape of a potential around EW scale is determined by h^2 term and h^3 term.

  - We know about the mass of Higgs from clean channels

Higgs Boson Pair
to measure Higgs potential

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



- From spontaneous symmetry breaking

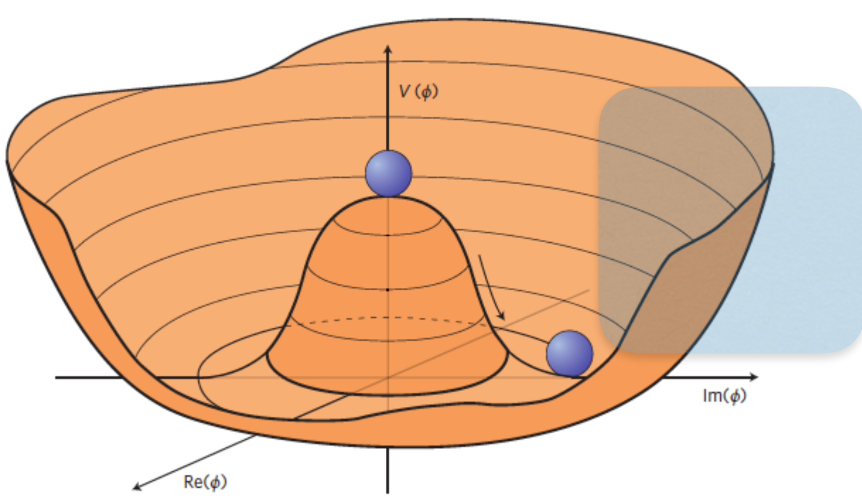
$$V_h^{\mathrm{SM}} = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$

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

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

Multi-Higgs
to measure Higgs potential

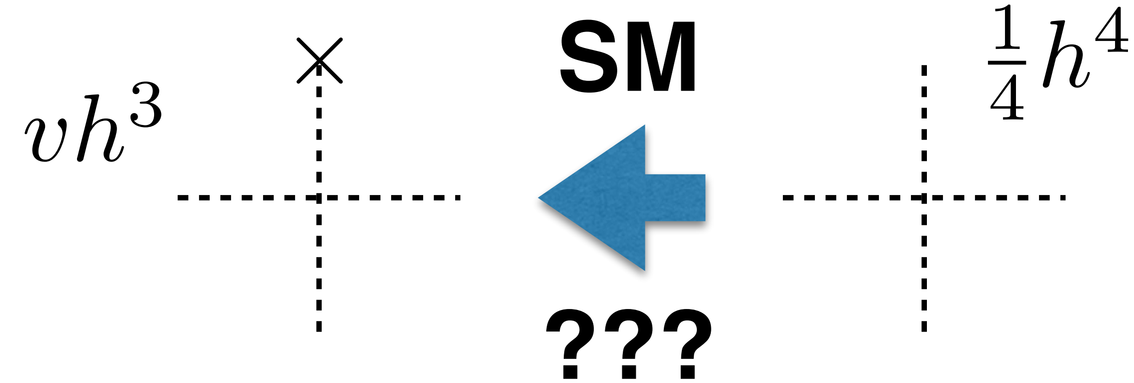
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



- From spontaneous symmetry breaking

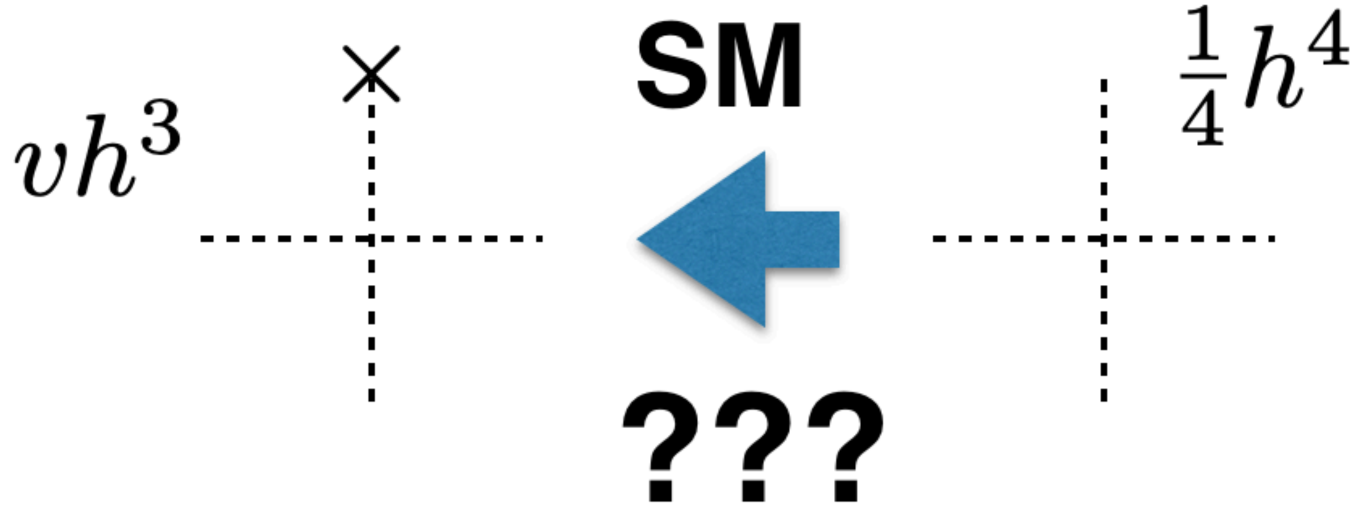
$$V_h^{\rm SM} = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$

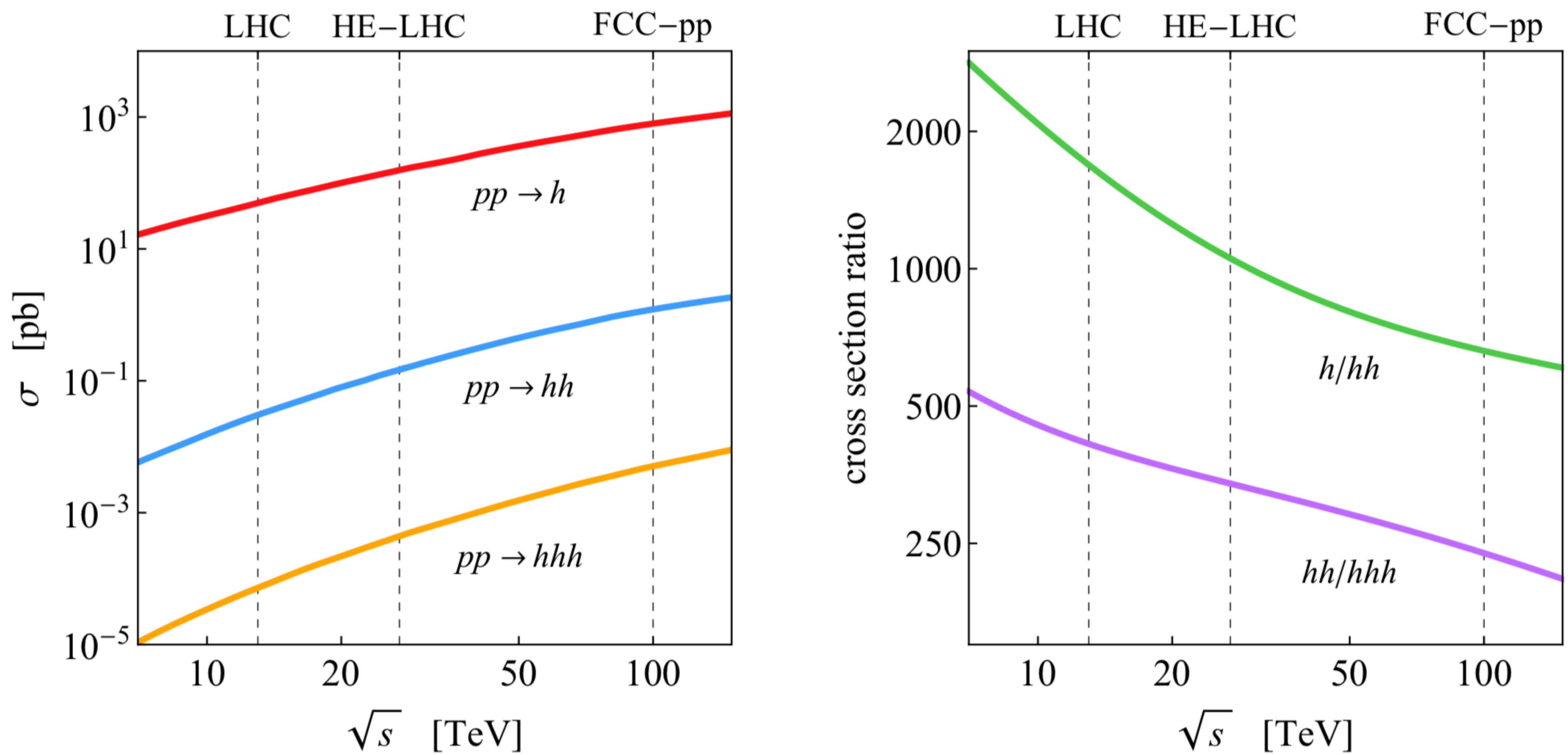
- check



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

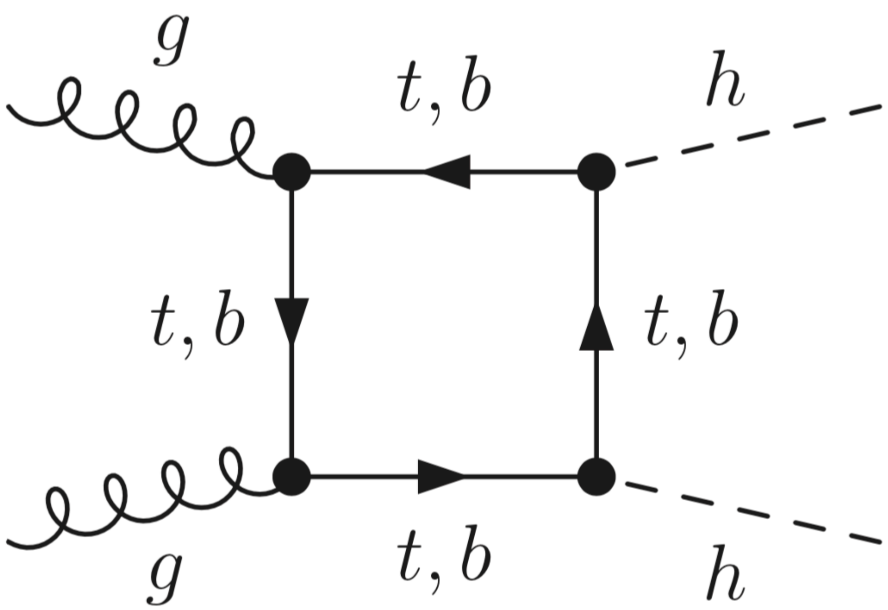
- Quartic Higgs coupling can be determined by $h \to h, h, h$

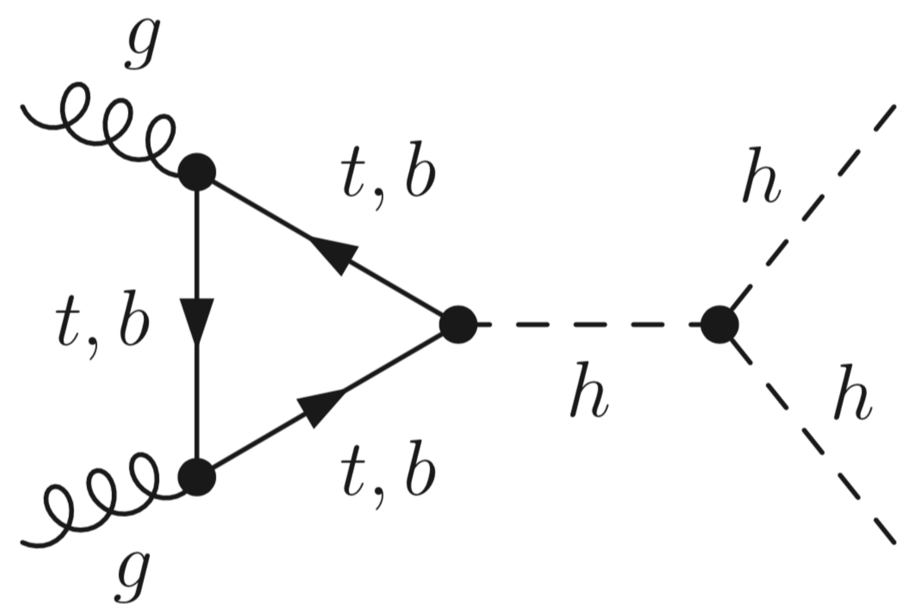


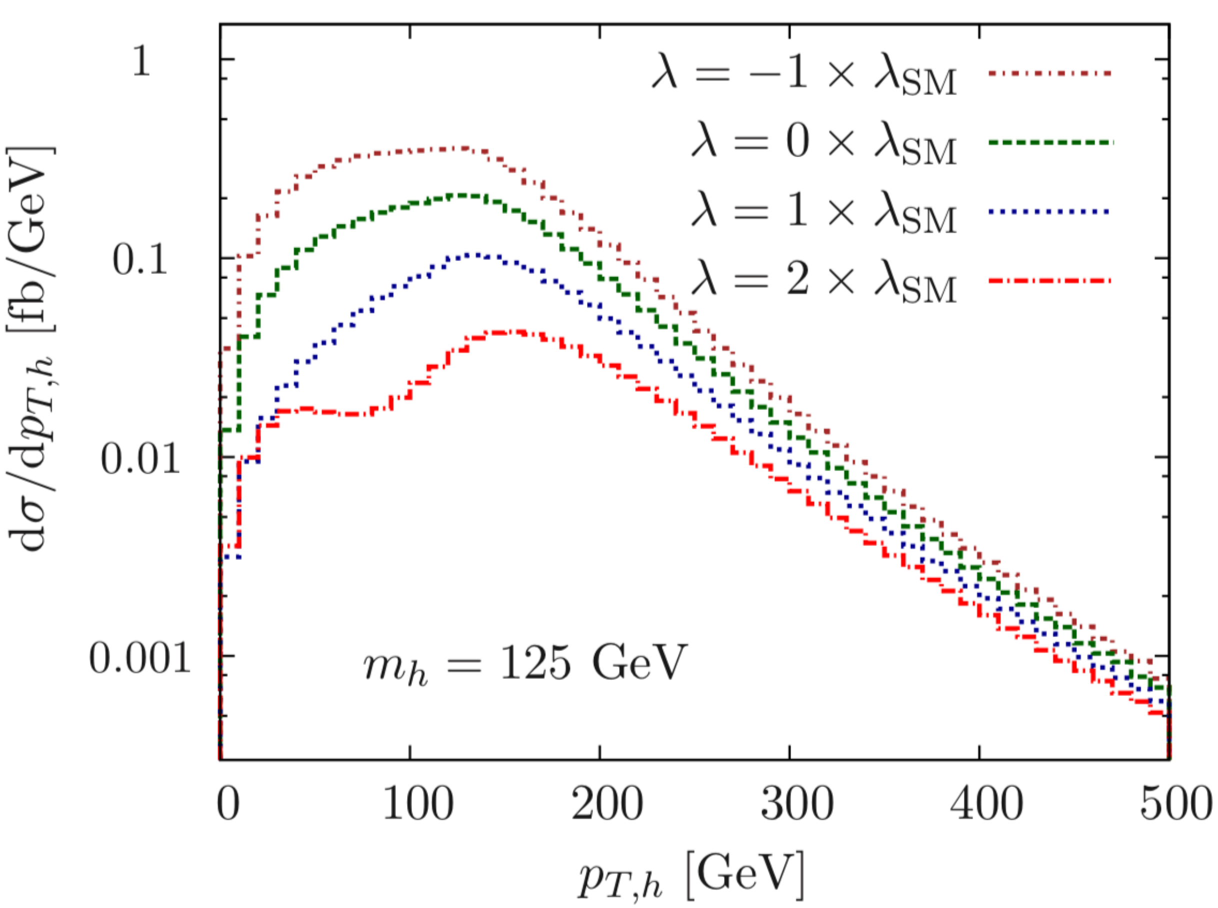


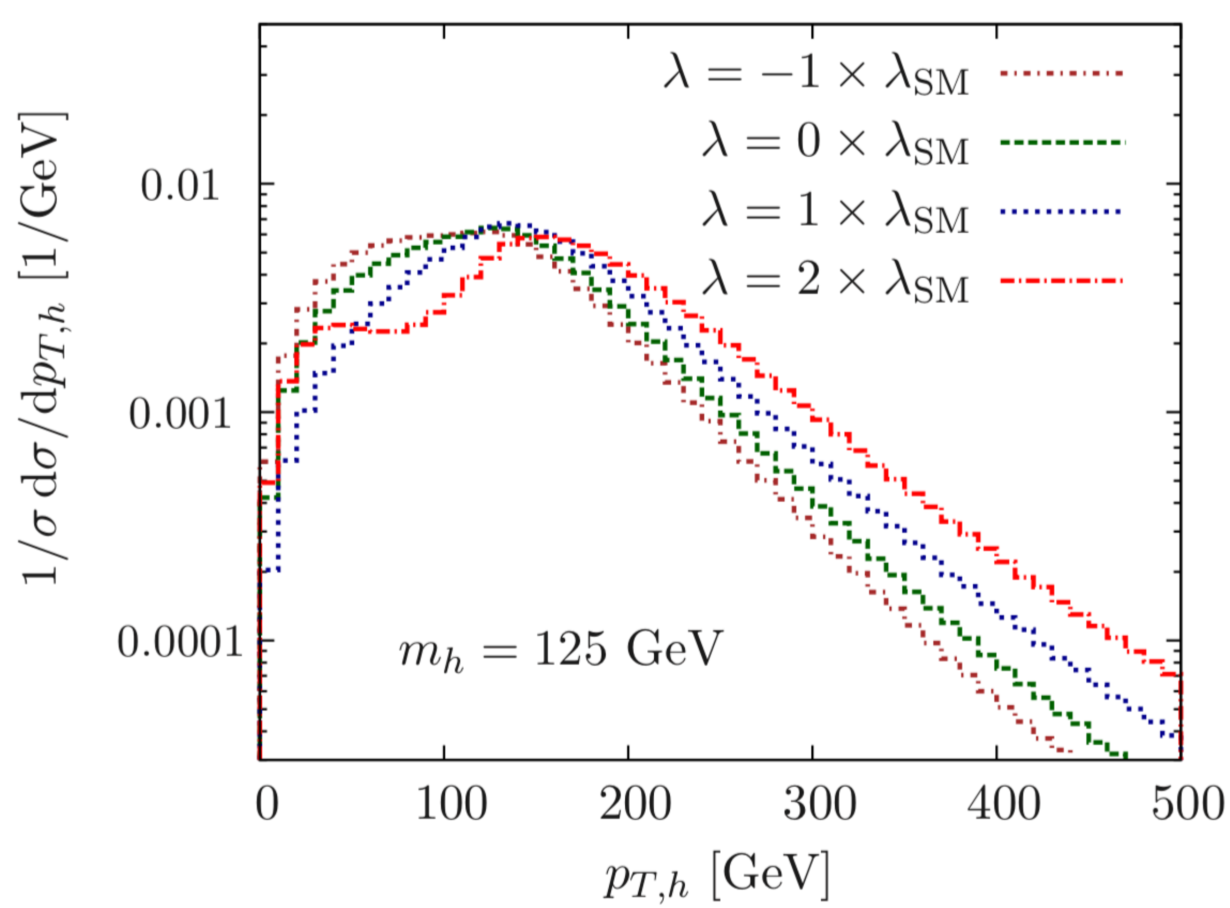
- So, let's focus on "**precise measurement** of" triple Higgs coupling at the LHC

Higgs Boson Pair @LHC

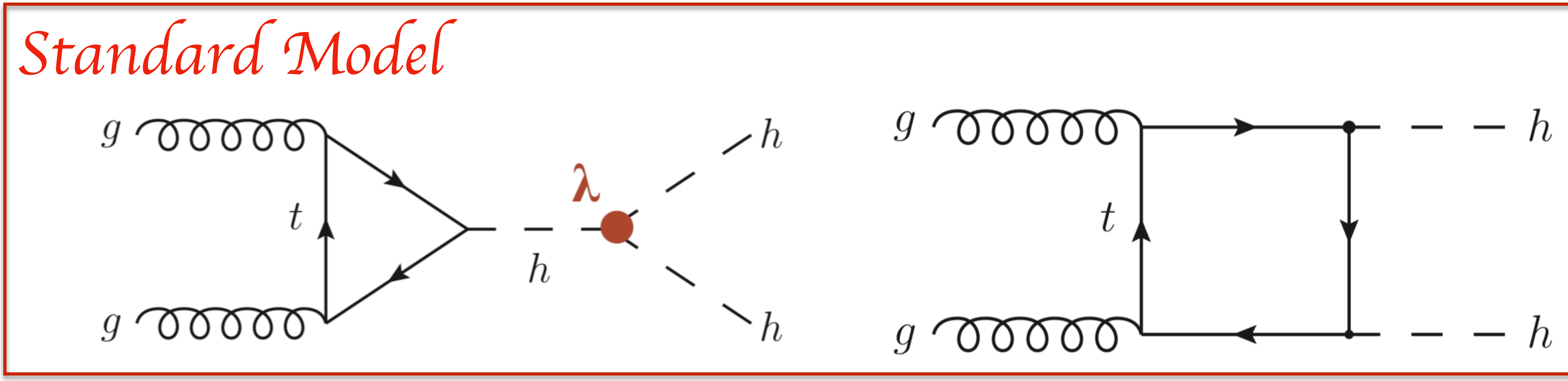




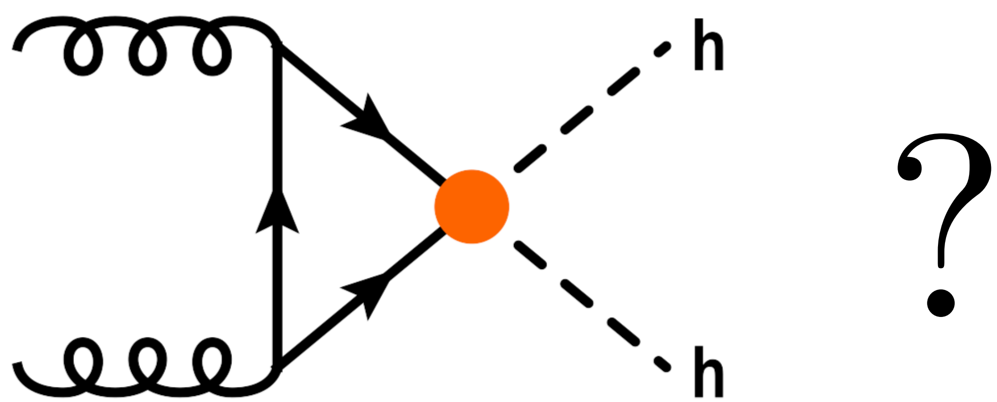




- This triple Higgs coupling can be determined by $h \to h, h$



$+$



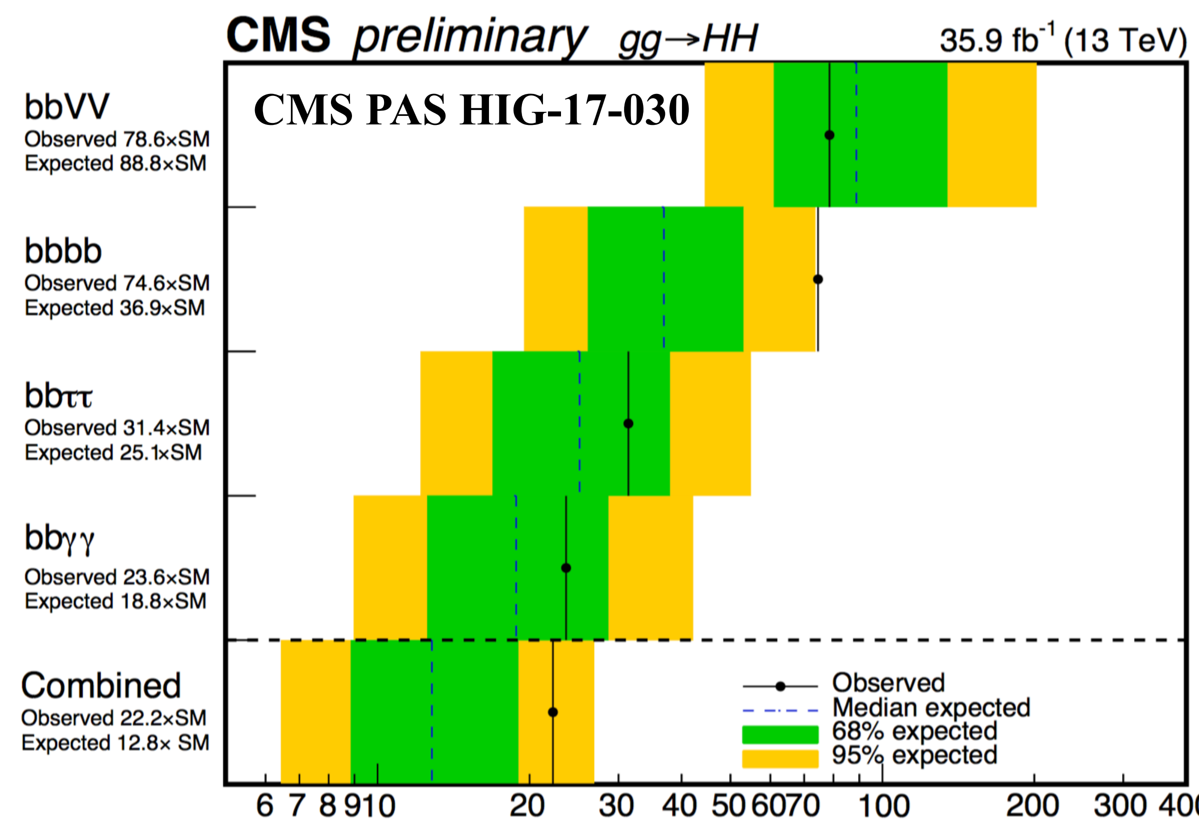
Non-resonant di-Higgs: can be probed

Higgs Boson Pair @LHC

- Current status from various channels

$h \to XX$

$XX \leftarrow h$	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%

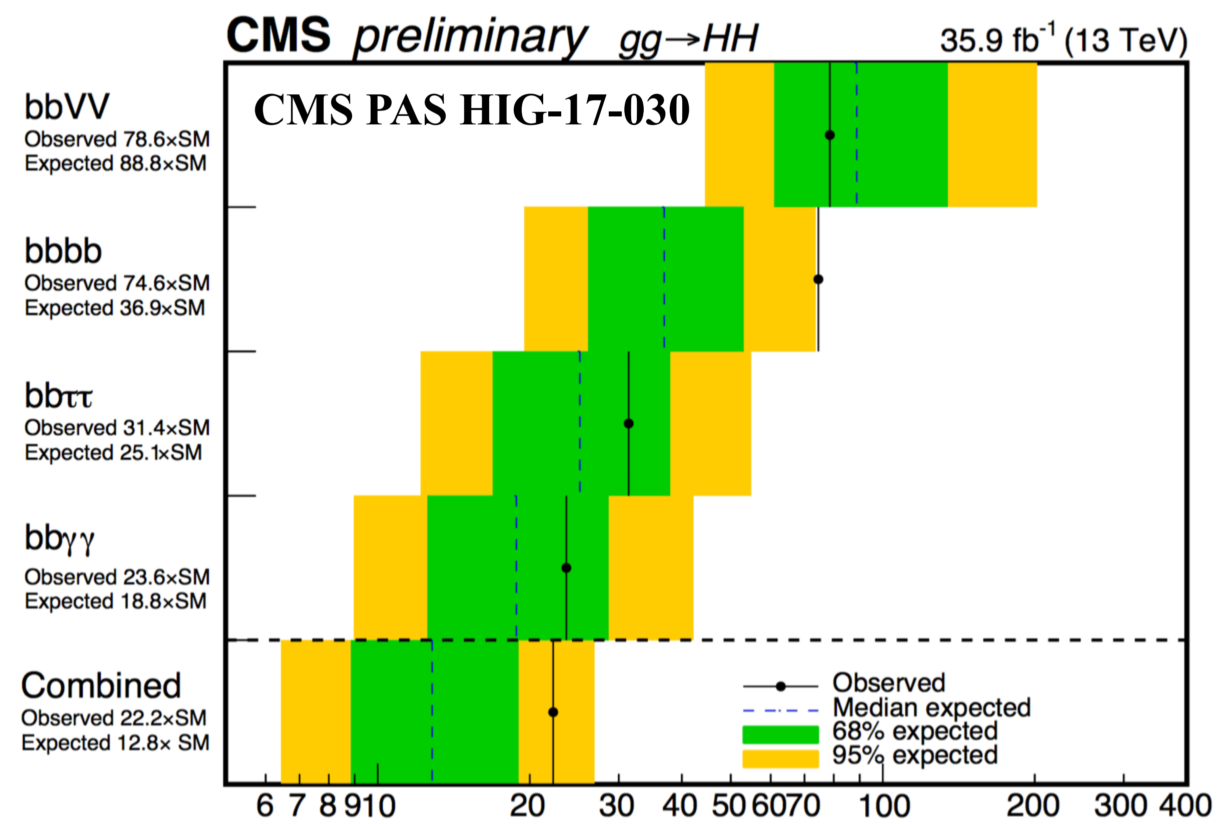


- The driven channel is the "compromised" clean channel.

Higgs Boson Pair @LHC

- Current status from various channels

		$N(hh)_{SM}$	N_{BKG}	
ATLAS	$bb\gamma\gamma$	8.4	47.1	1.2
CMS	$bb\gamma\gamma$	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

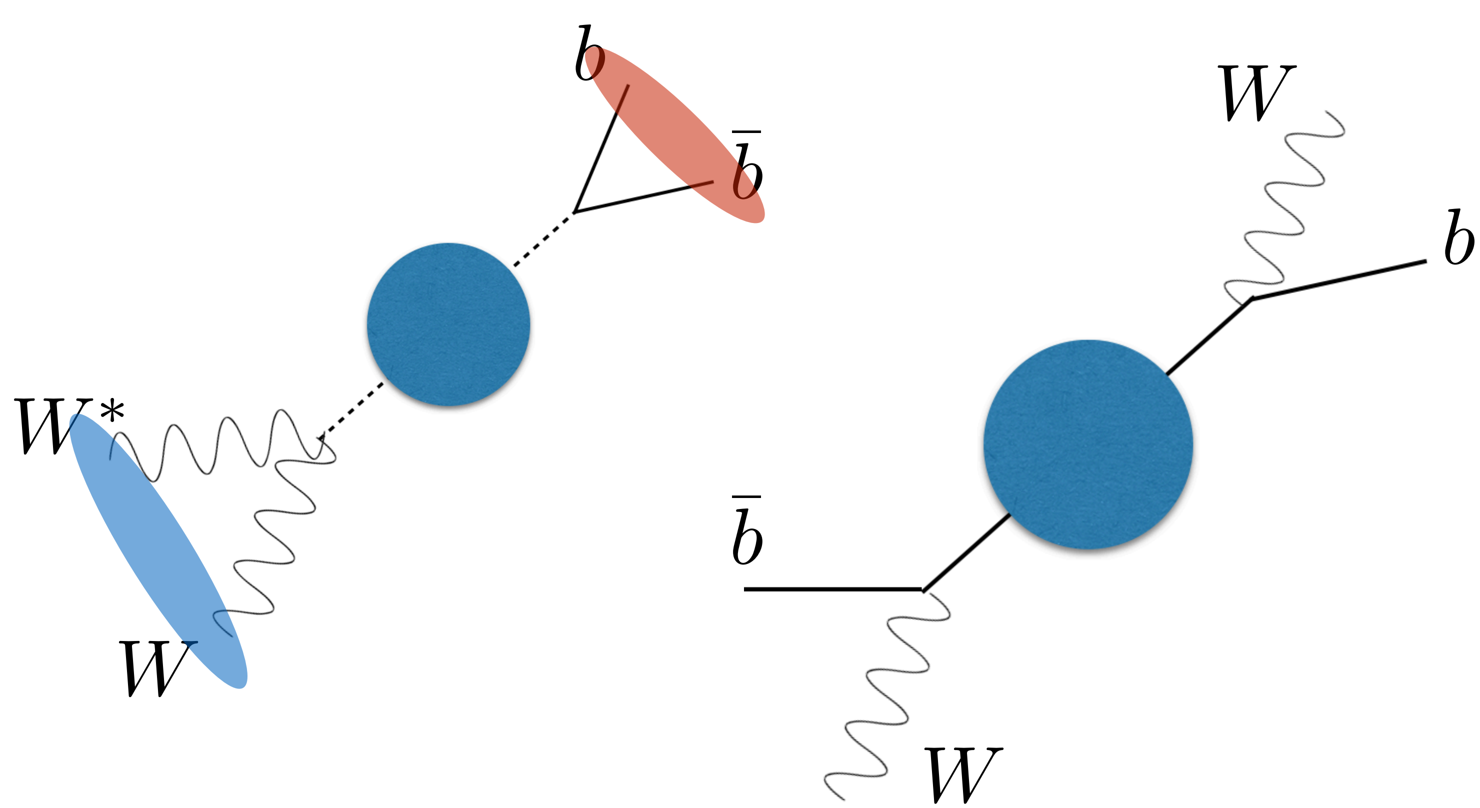


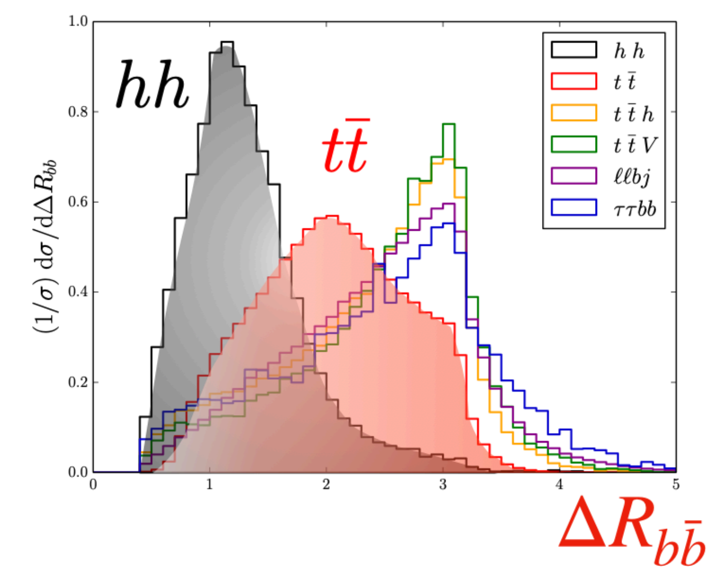
- **Why** is $bbVV$ **bad** ? **how** can one **improve** ?

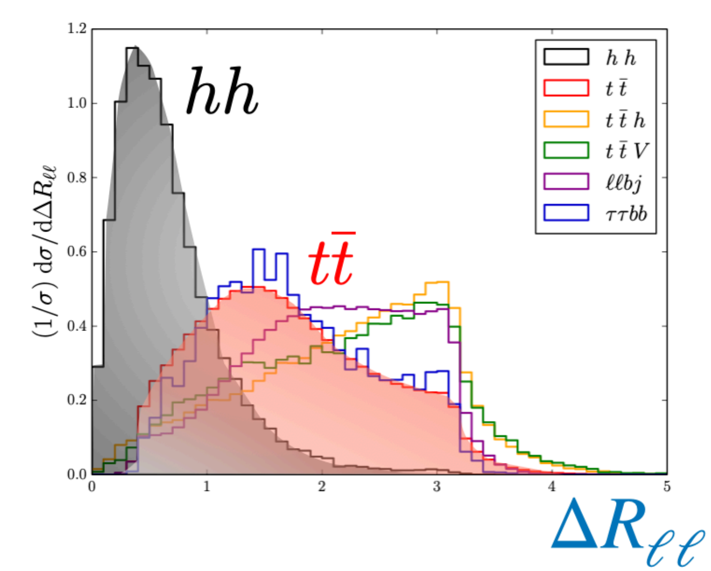
- **Why** is $bbVV$ **bad** ? LHC is the **Top-factory**

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

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







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

Baseline selections: $\not{E}_T > 20$ GeV, $p_T^\ell > 20$ GeV, $\Delta R_{\ell\ell} < 1.0$, $m_{\ell\ell} < 65$ GeV, $\Delta R_{bb} < 1.3$, $95 < m_{bb} < 140$ GeV

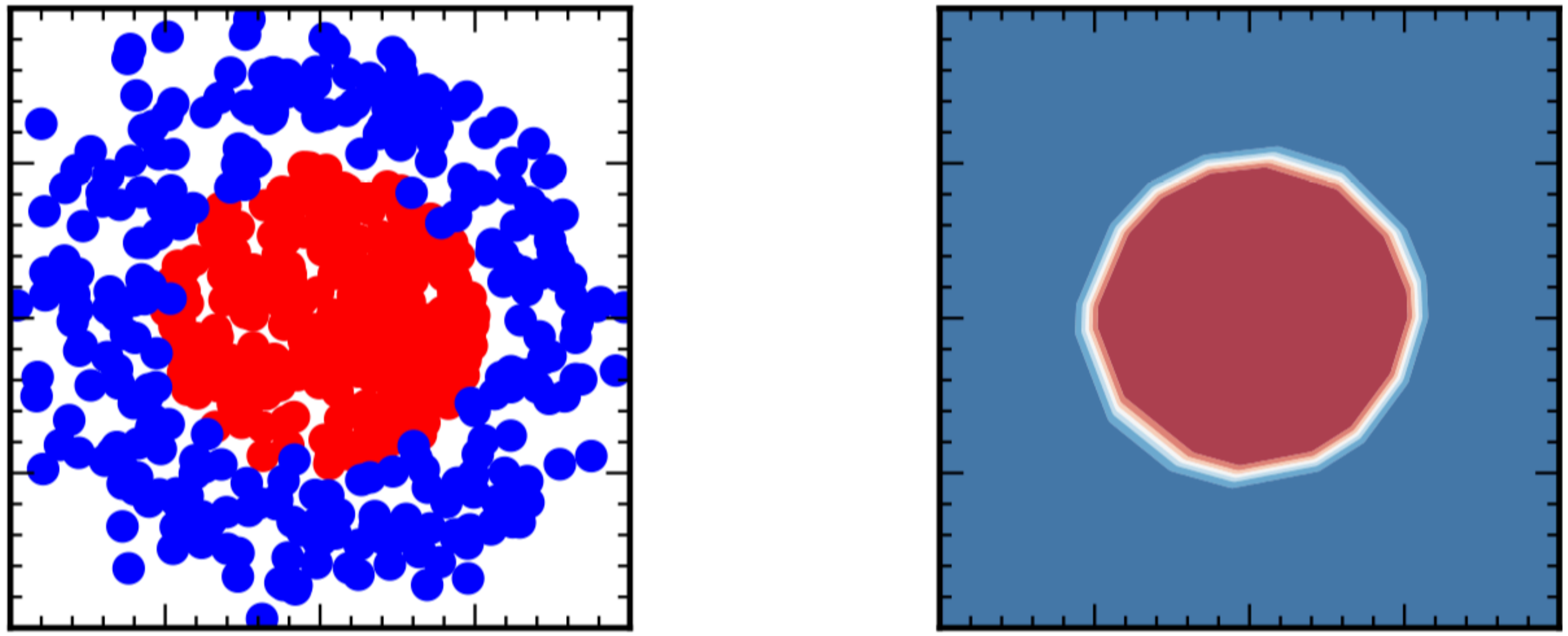
Signal	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}V$	$\ell\ell bj$	$\tau\tau bb$	others	σ	N_{sig}^{SM}/N_{bknd}
0.0124	1.1724	0.0297	0.0246	0.0158	0.0379	0.00590	0.60	0.00964

$jj\ell\ell\nu\bar{\nu}$ 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** in that case.

what if we know BKG very well

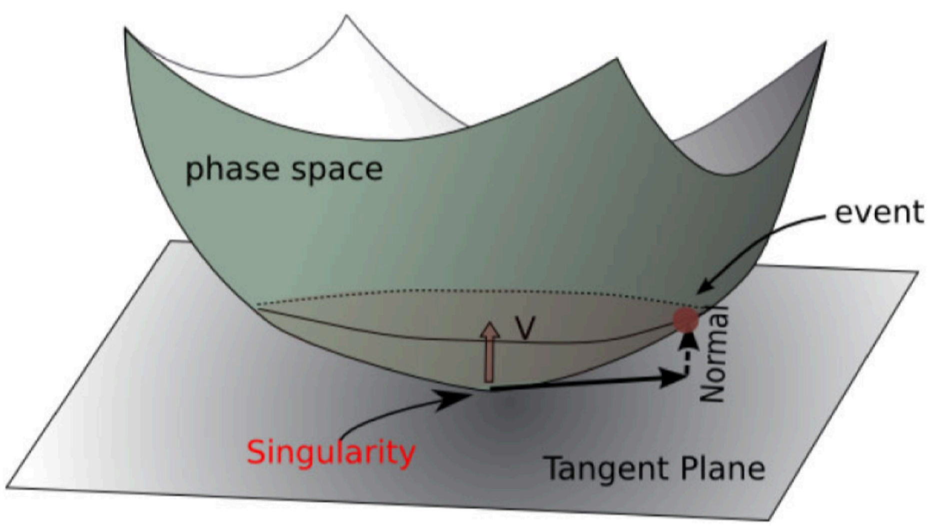


A cartoon is from a paper by Spencer Chang, Timothy Cohen and Bryan Ostdiek, Phys. Rev. D 97, 056009 (2018)

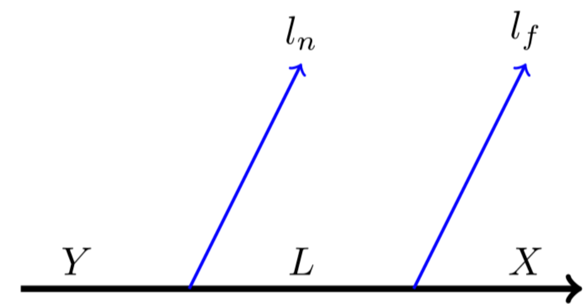
- If we know BKG is a circle, we can take BKG out very easily with **input variables which characterizes** BKG events

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

- Considering "**high-level** " kinematic cuts based on event-topology
- What are the "**high-level** " kinematic variables?

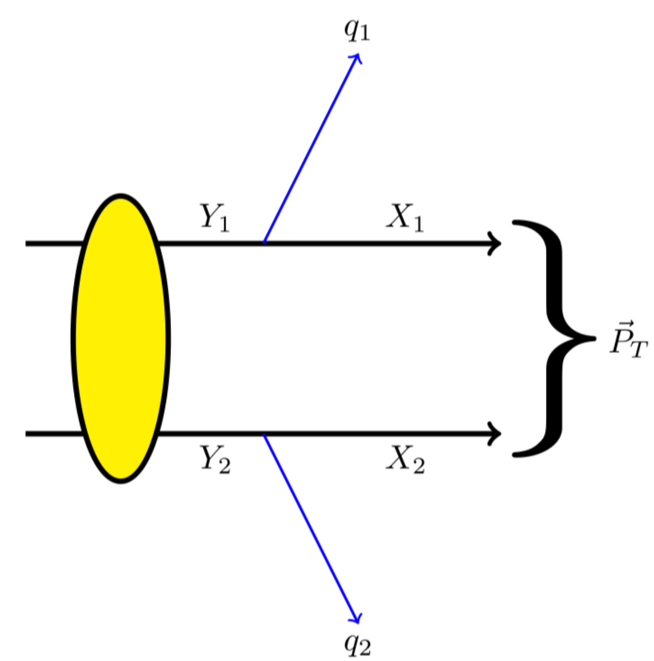


invariant mass



when one considers only visibles

transverse mass

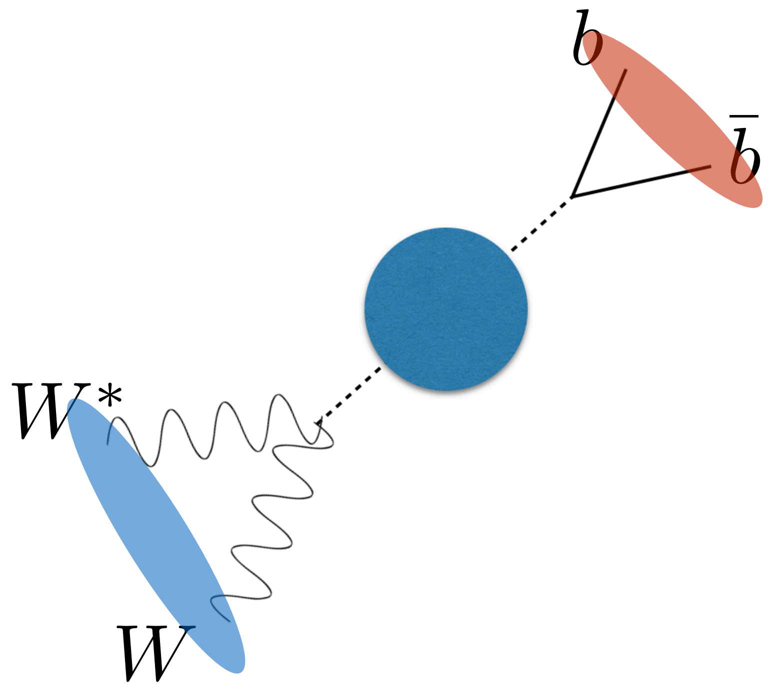


when one considers visibles+invisbles

Ian-Woo Kim, 2010

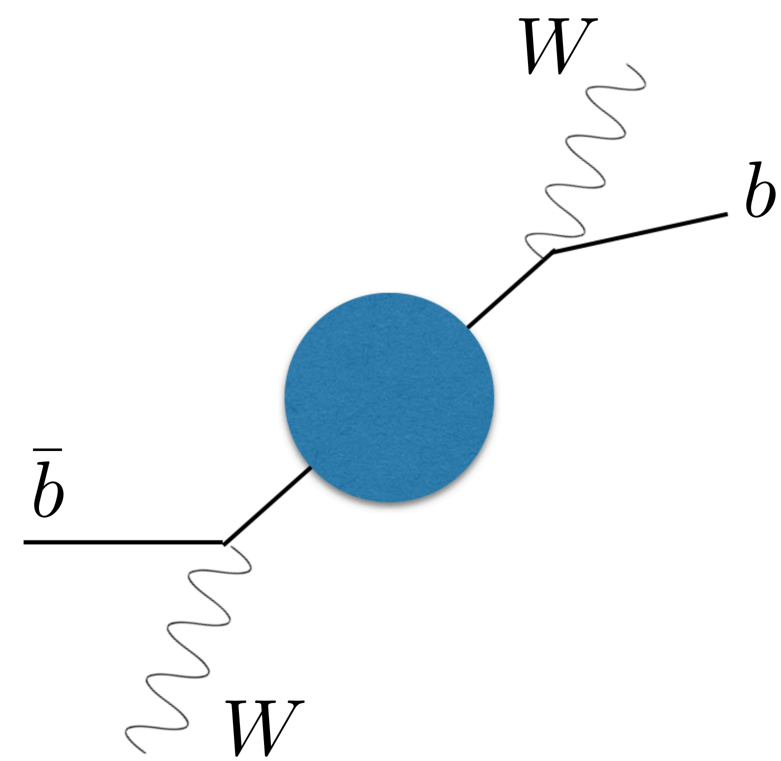
- Considering "**high-level** " kinematic cuts based on event-topology

Hypothesis test: invariant mass



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

Higgs(to WW*), W, and off-shell W

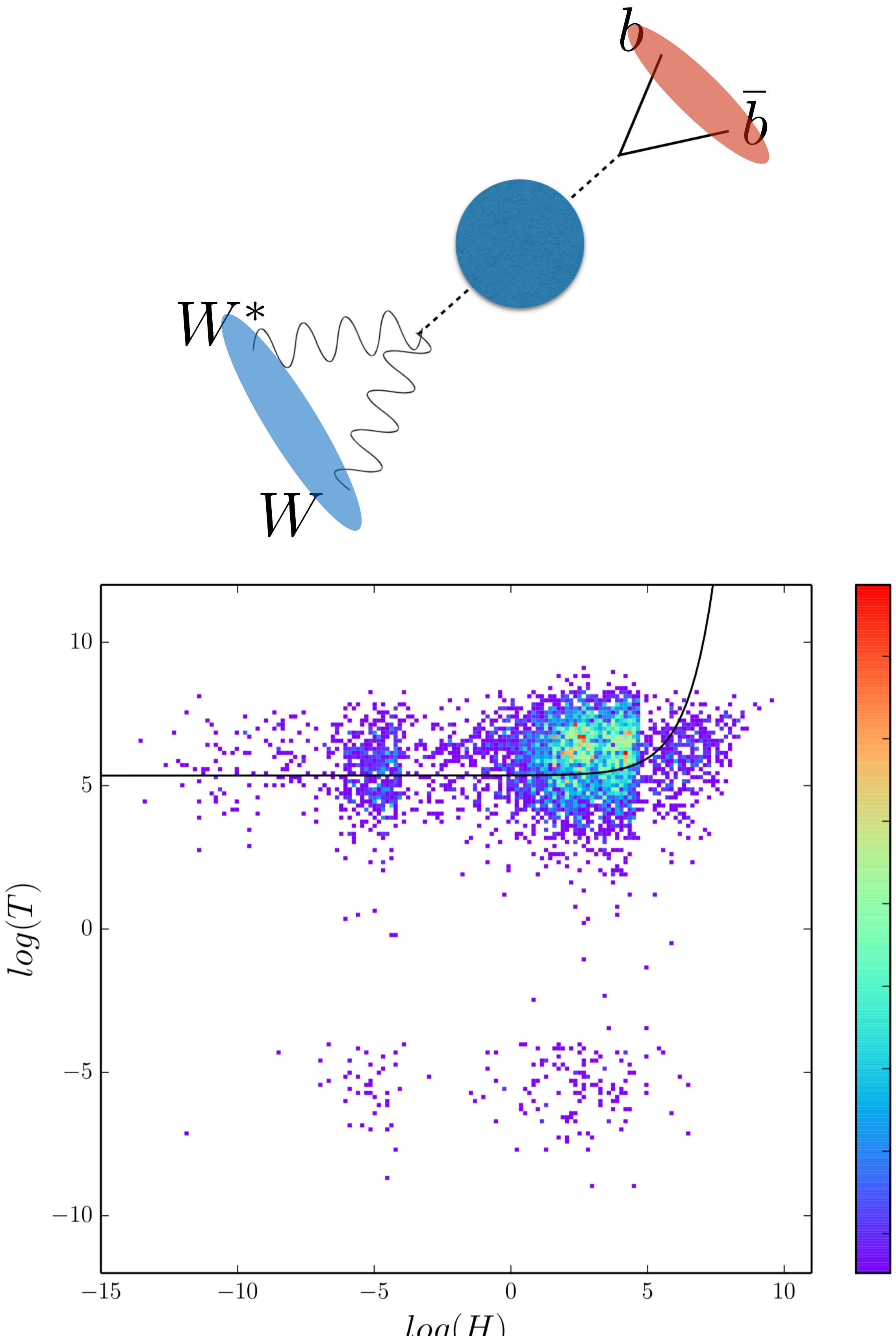


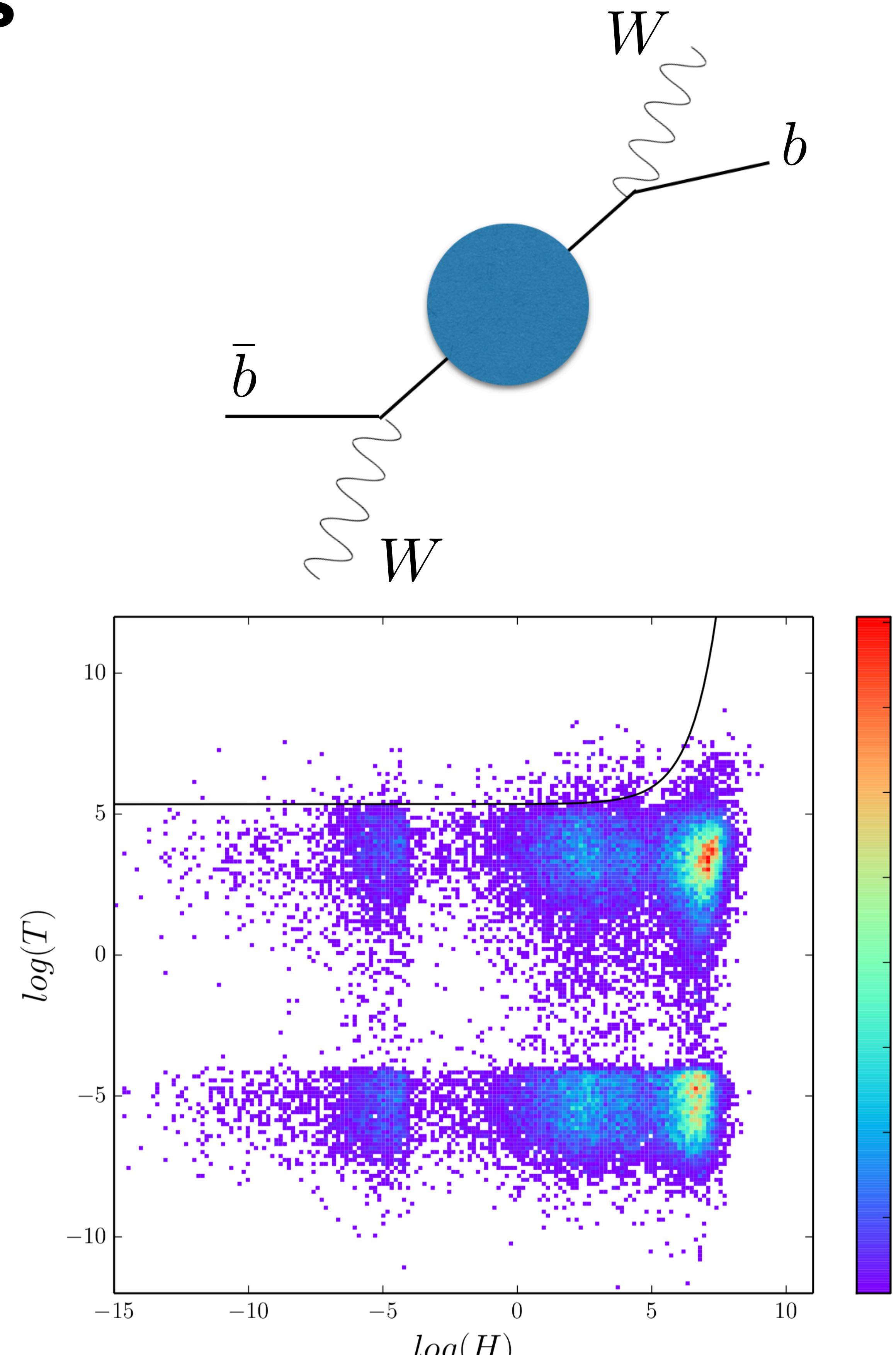
$$\chi^2_{ij} \equiv \min_{\vec{p}\!\!/_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{b_i\ell^+\nu} - m^2_t\right)^2}{\sigma^4_t} + \frac{\left(m^2_{\ell^+\nu} - m^2_W\right)^2}{\sigma^4_W}\right.$$
$$\left. + \frac{\left(m^2_{b_j\ell^-\bar{\nu}} - m^2_t\right)^2}{\sigma^4_t} +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

two top quarks and two W

- Considering "**high-level** " kinematic cuts based on event-topology

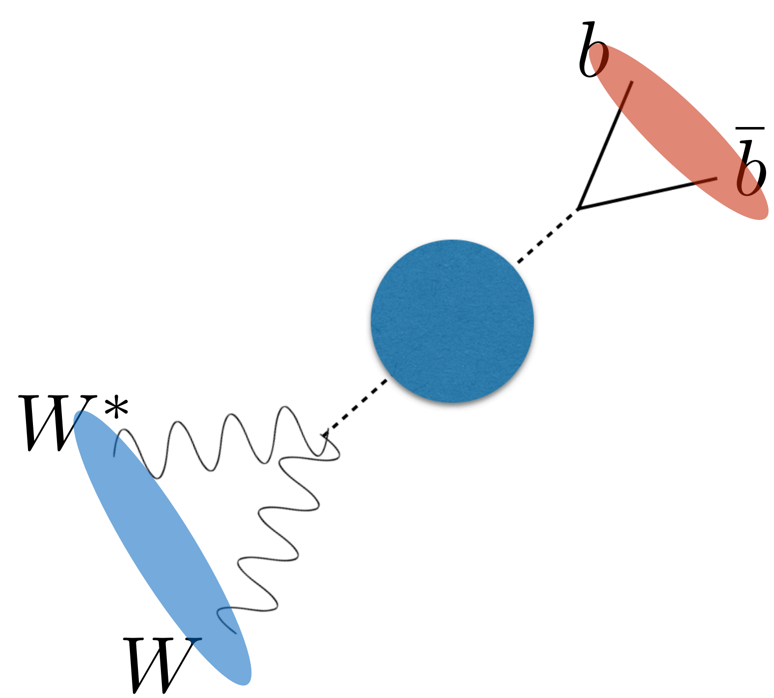
Hypothesis test: invariant mass

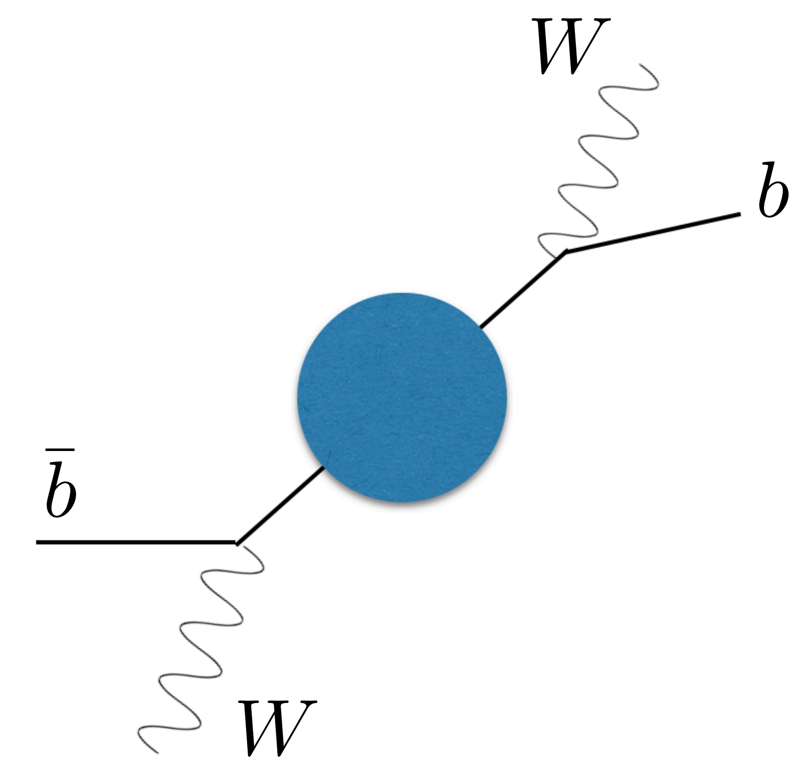


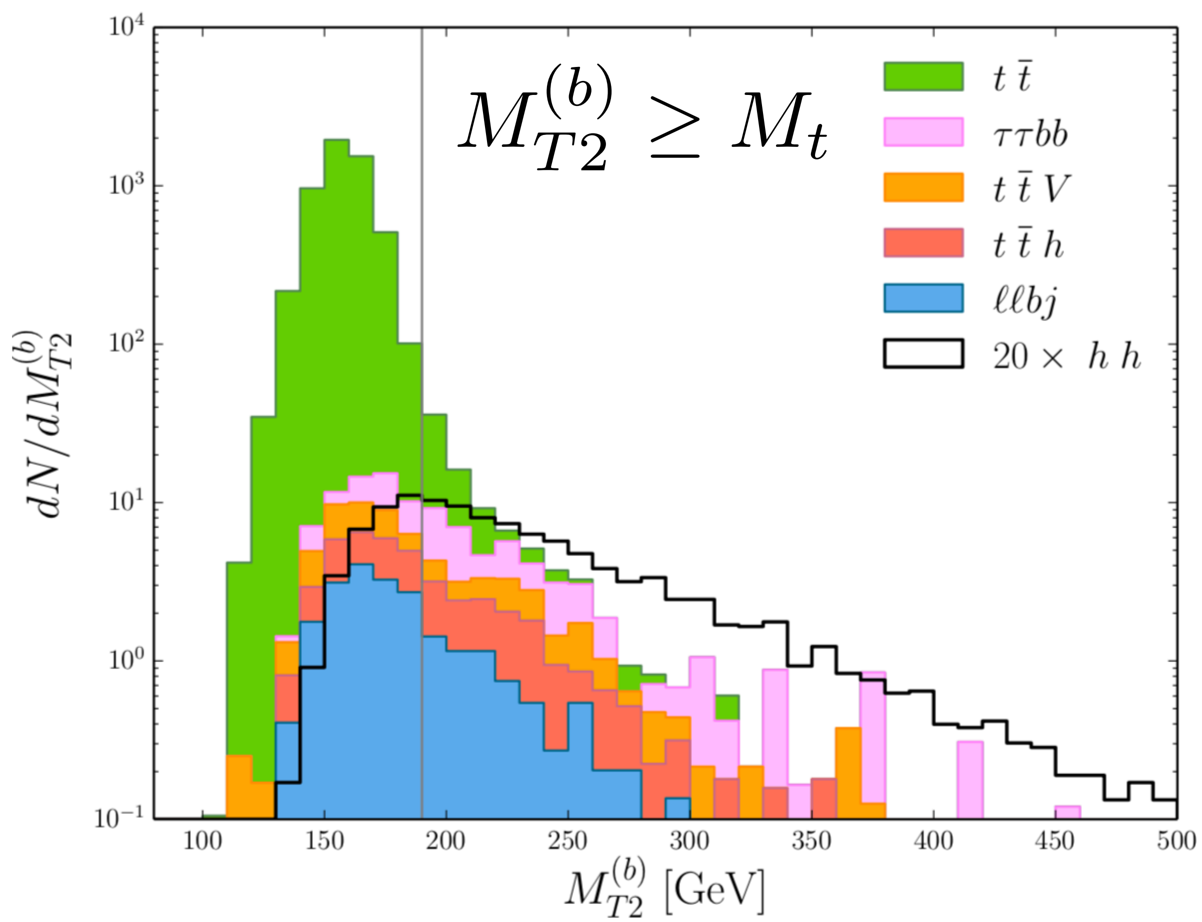


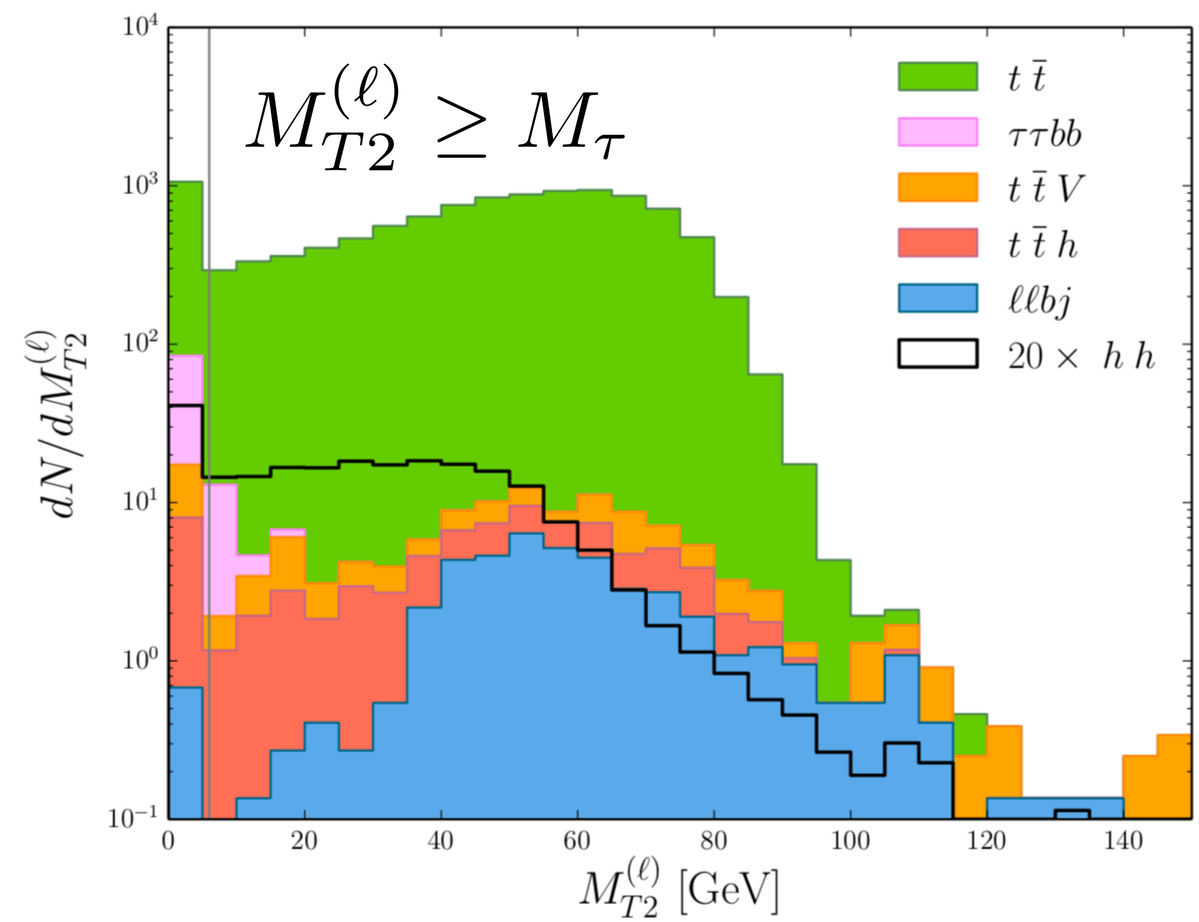
- Considering "**high-level** " kinematic cuts based on event-topology

Transverse mass

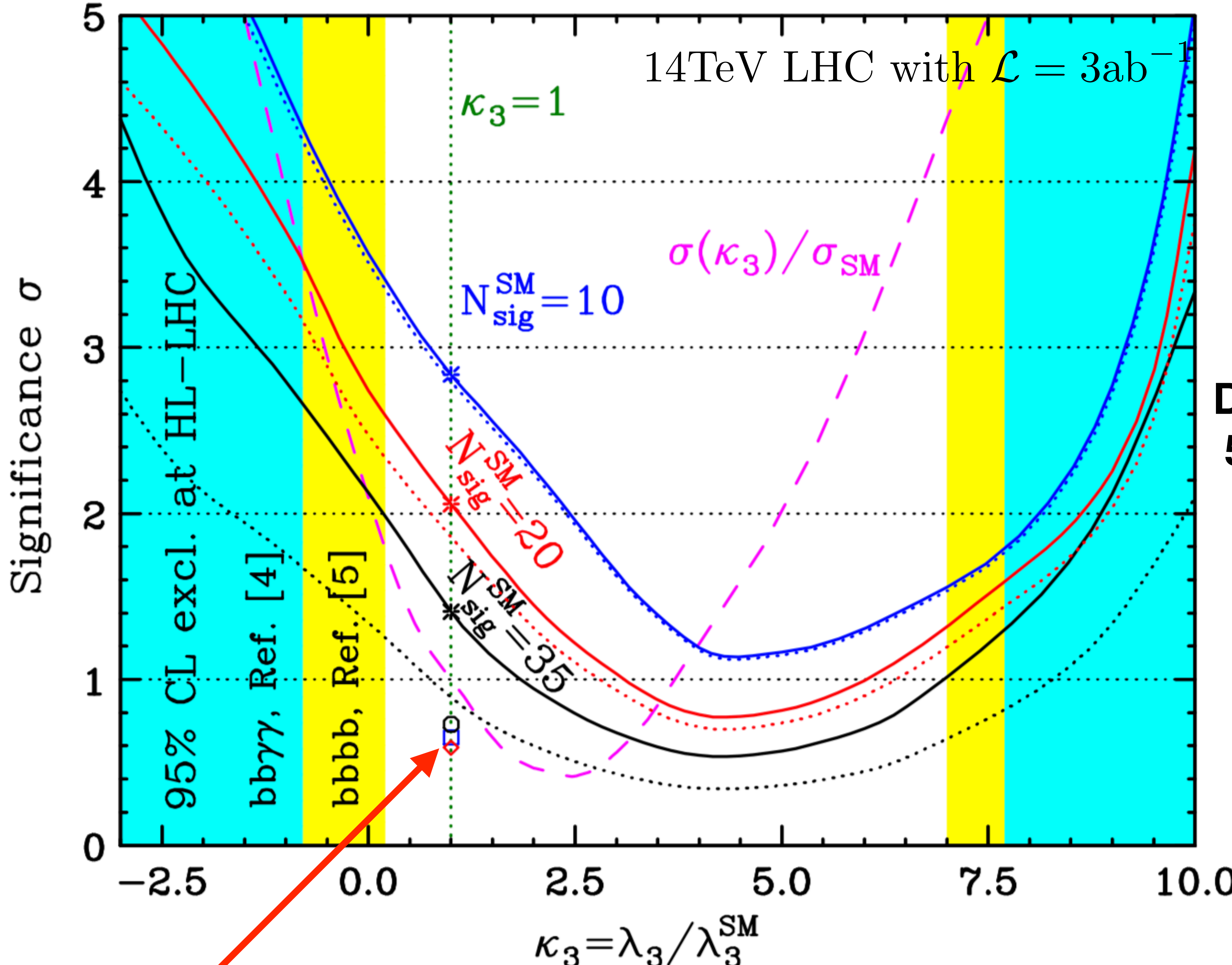








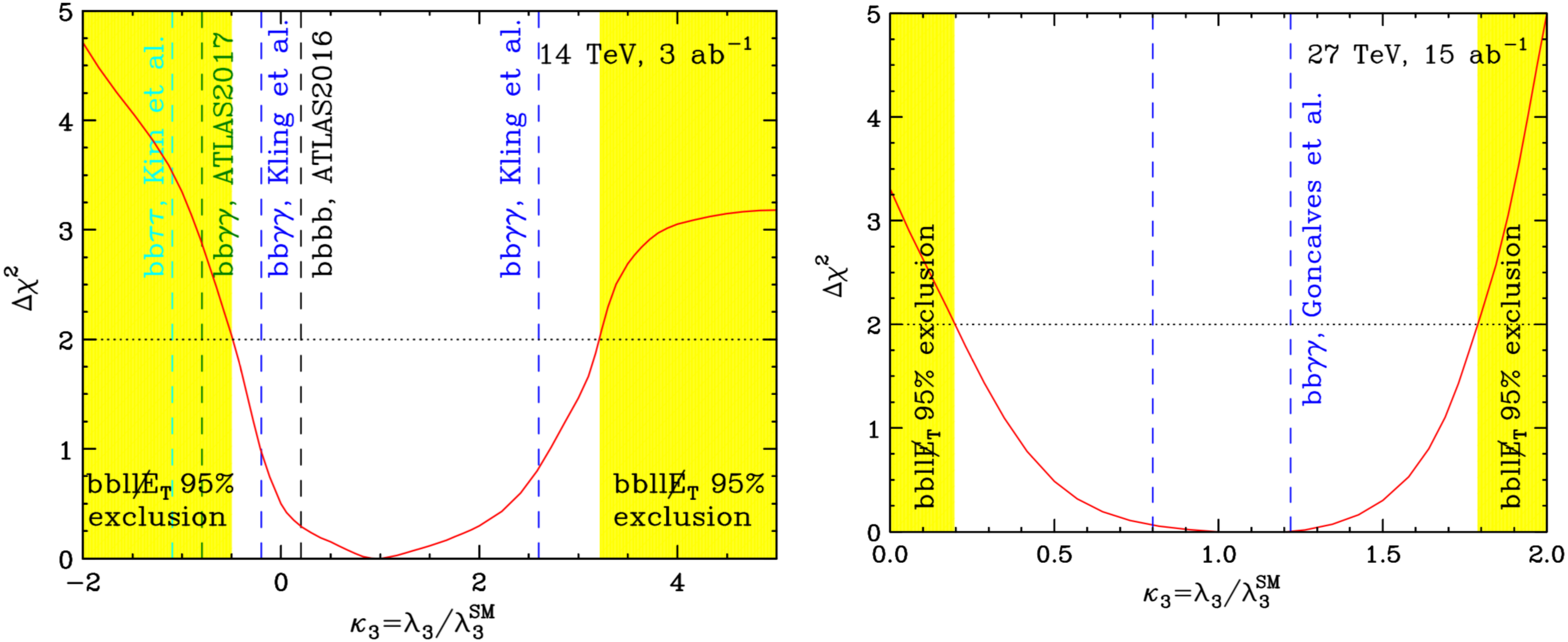
- Discovery chance for triple Higgs coupling
  - Optimization for cut is set for SM case



Dotted lines with 5% systematics

CMS-NN, CMS-BDT, BDT with basic observables

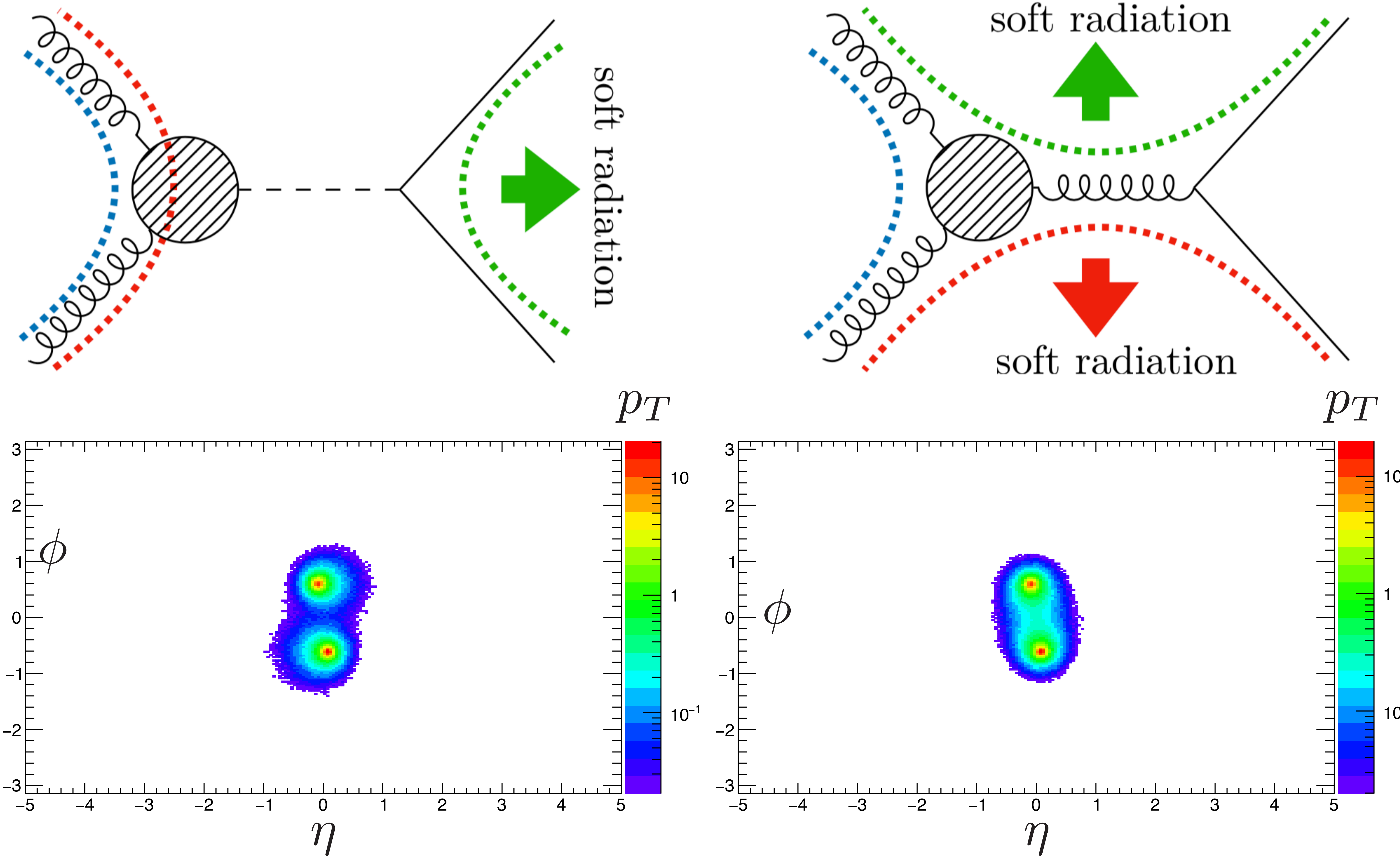
- Significance for observing "**anomalous**" Higgs triple coupling



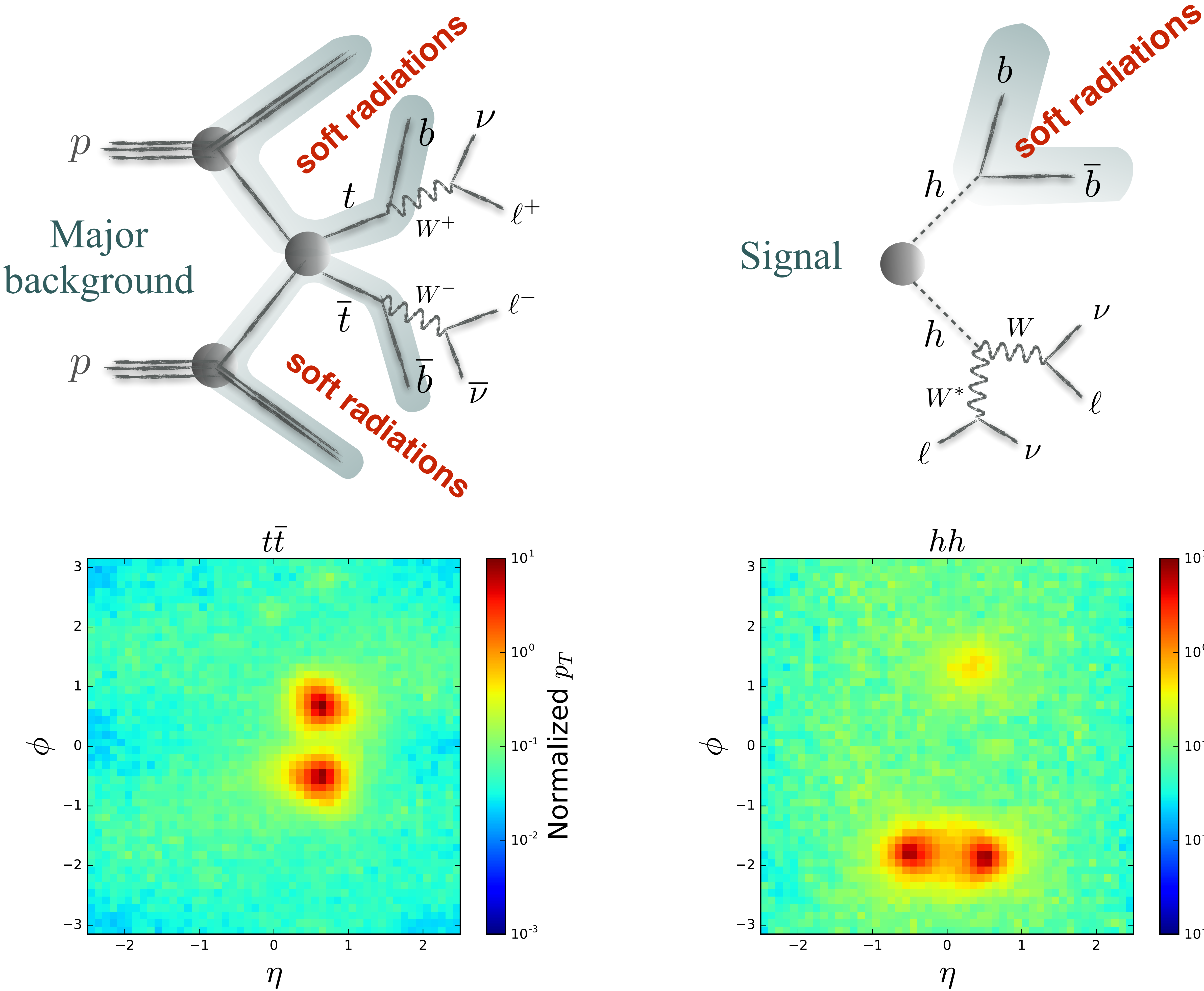
- Here the hypothesis is SM Higgs (triple coupling = SM case)

Can we do
more than this?

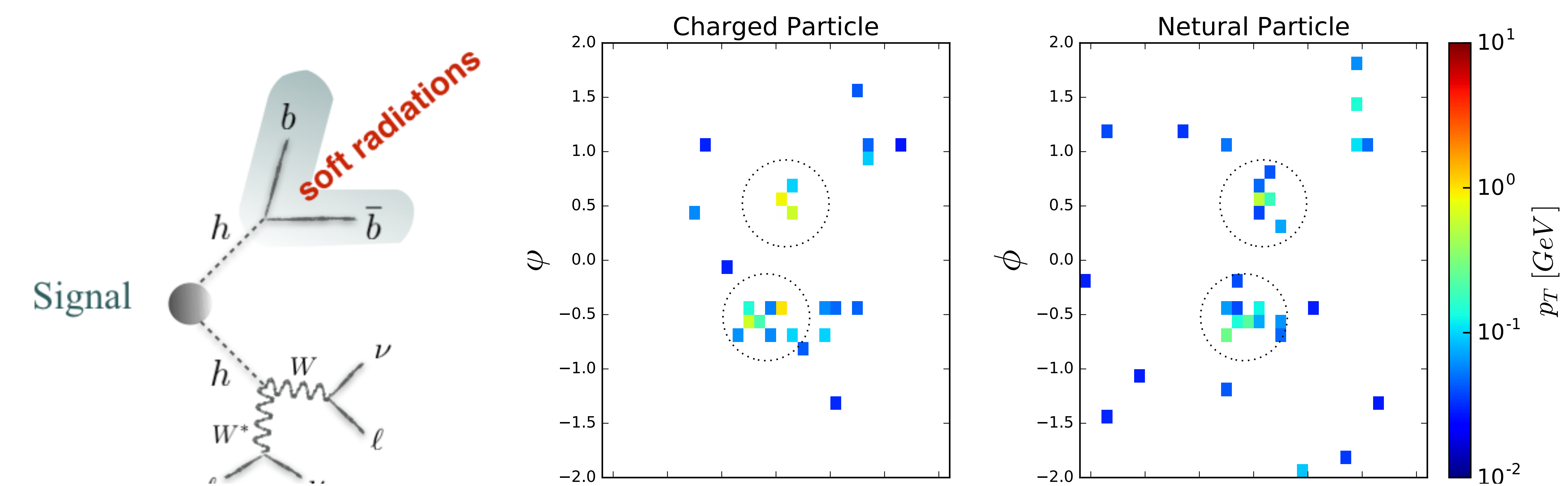
- Consider "**orthogonal**" method to kinematics; **QCD Color-flow**



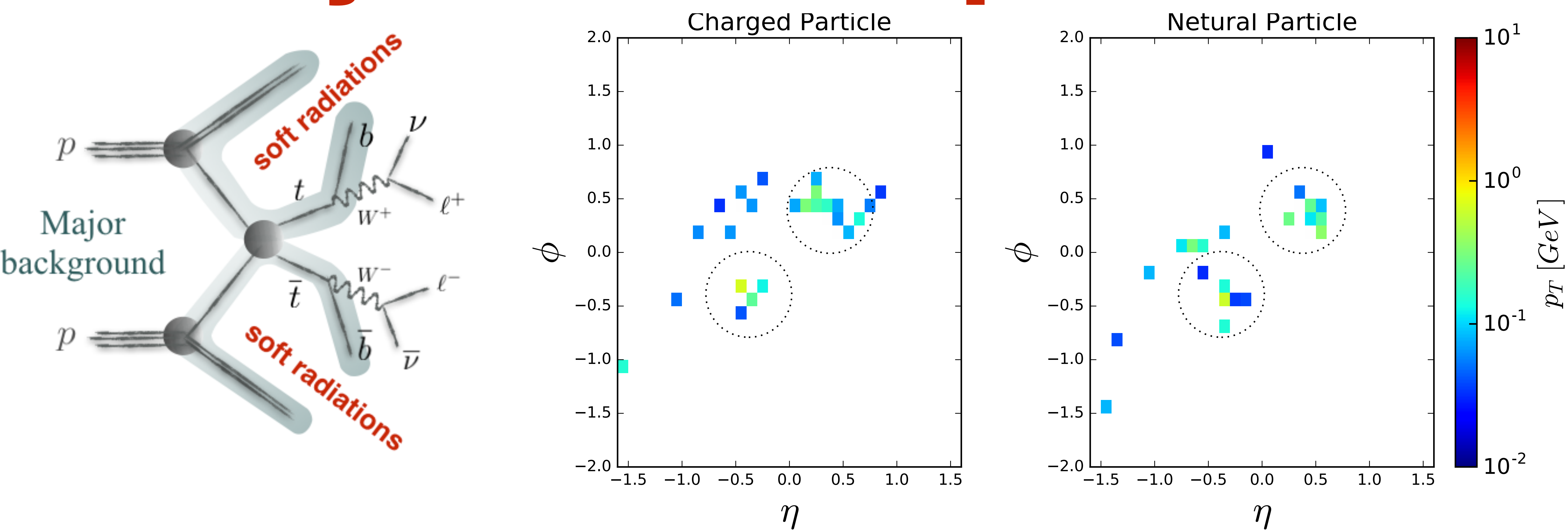
Energy deposits



Major background
soft radiations
soft radiations
p
p
t
$\bar{t}$
b
$\bar{b}$
W^+
W^-
ν
$\bar{\nu}$
ℓ^+
ℓ^-
Signal
soft radiations
h
h
b
$\bar{b}$
W
W^*
ν
ν
ℓ
ℓ
$t\bar{t}$
hh
η
ϕ
Normalized p_T
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}

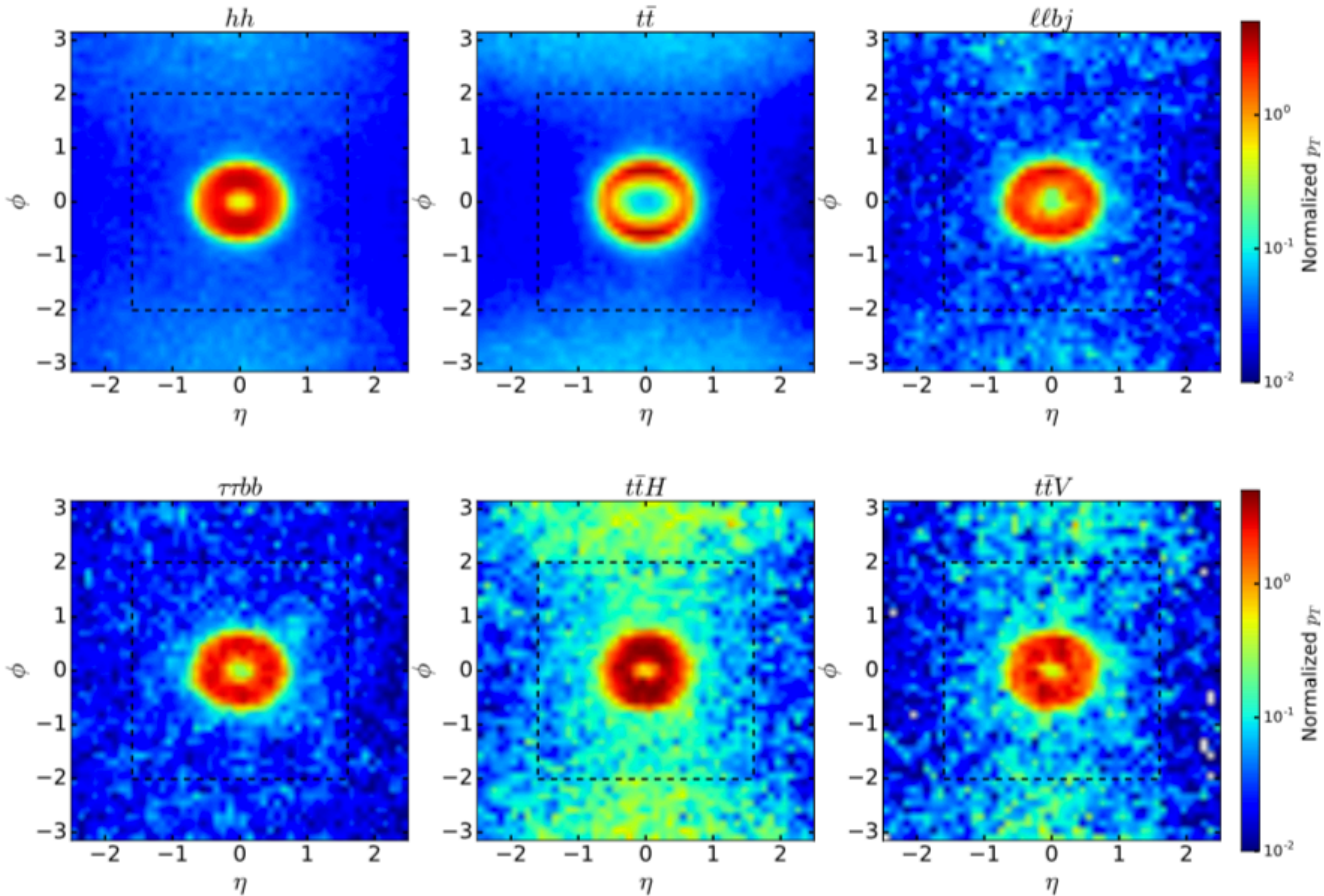


Can you see a pattern?



Jet Image: Pattern Recognition with DL

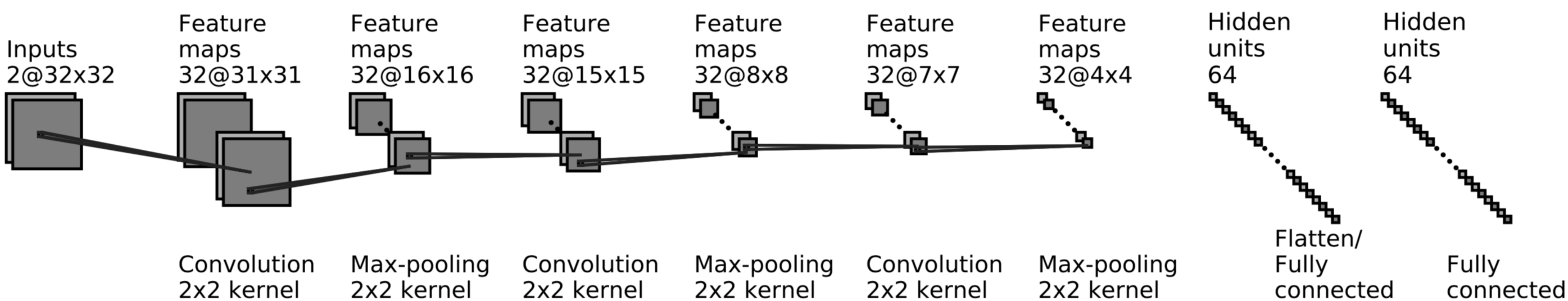
- Whole events with bbar (fat-jet) axis as a center

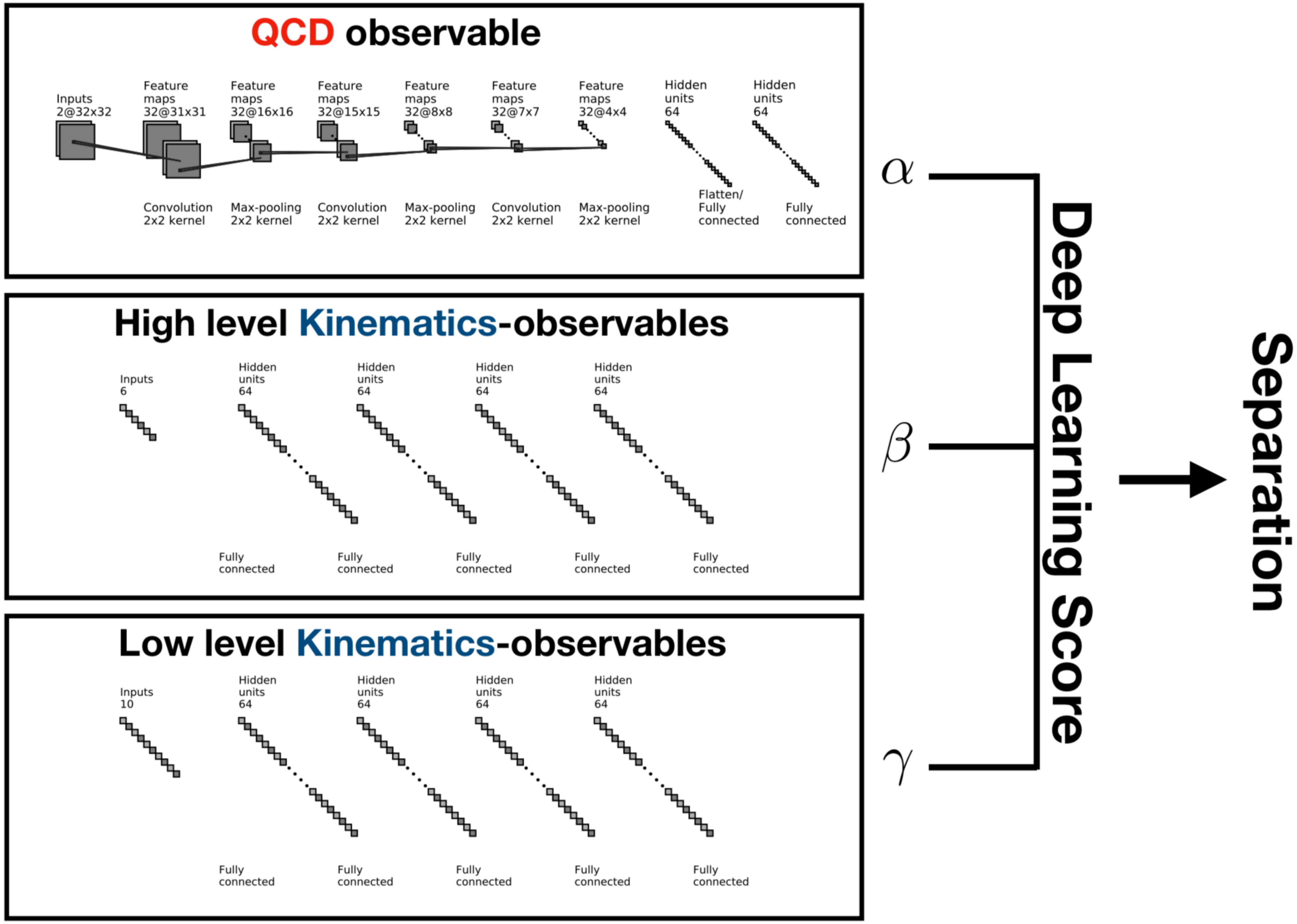


Maximizing information with Deep Neural Network

- 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



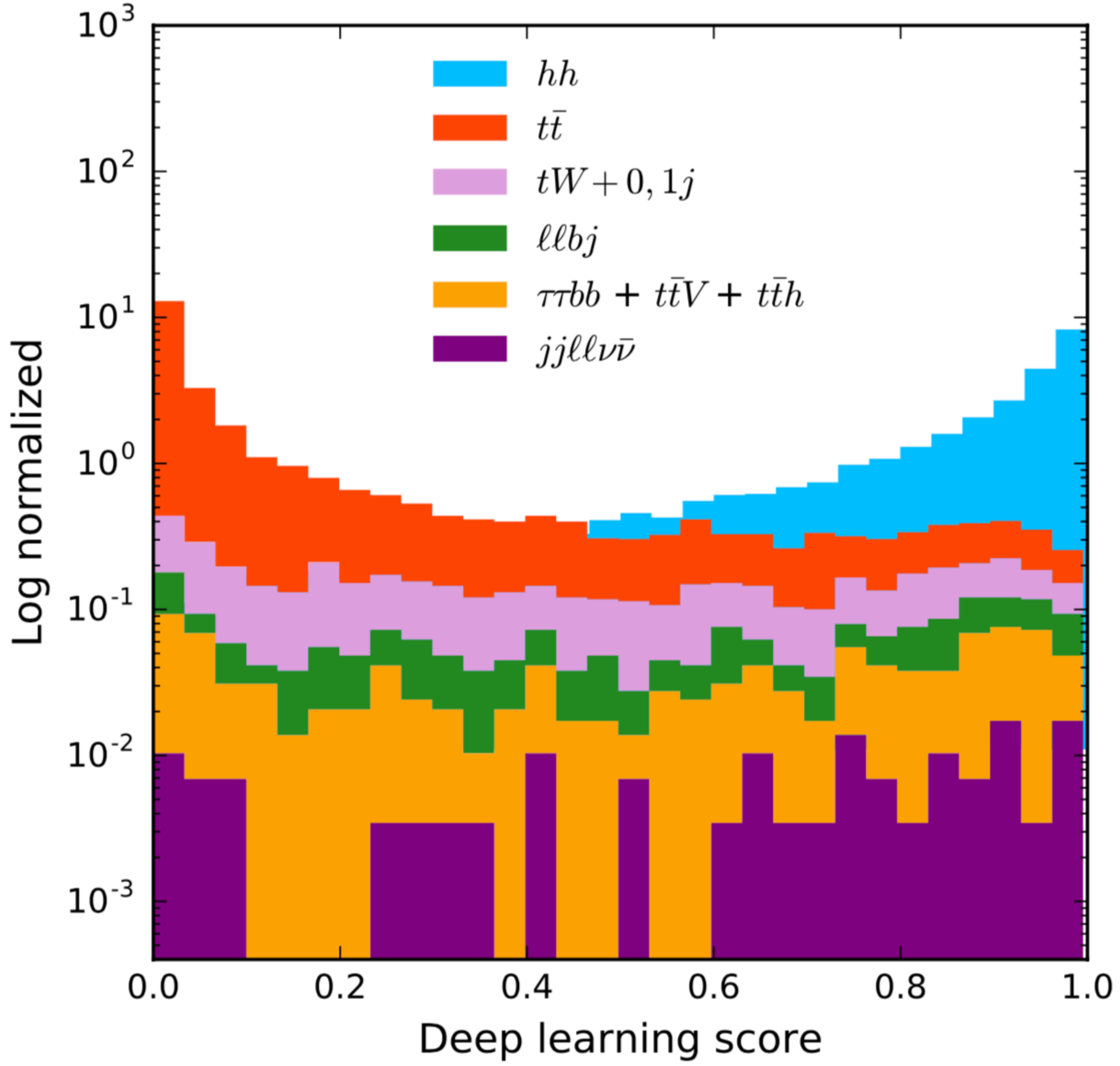


6 High Level Variables

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

10 Low Level Variables

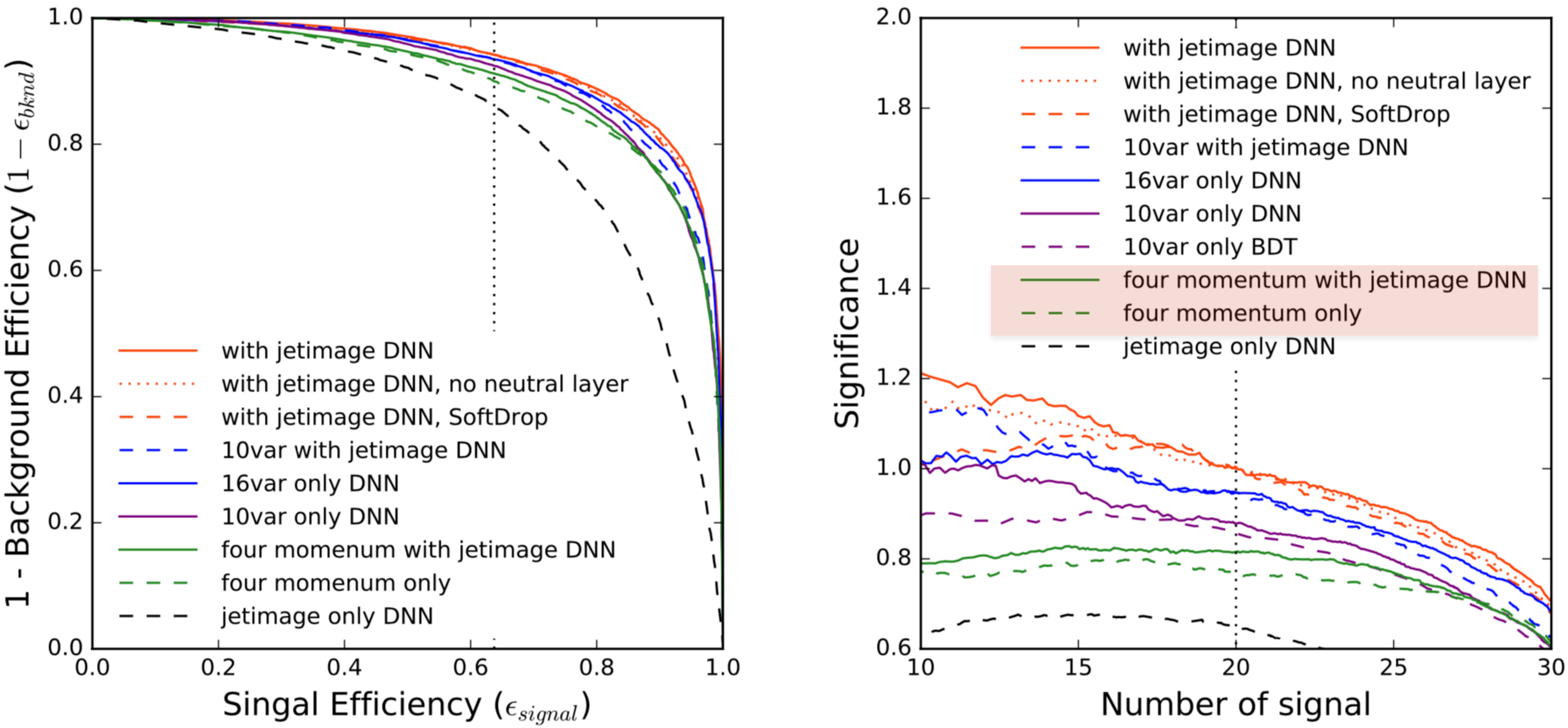
Input data: MET $p^t_{\bar{\ell}}$ p^t_{ℓ} $\Delta R_{(\bar{\ell},\ell)}$ $M_{(\bar{b},b)}$ $p^t_{(\bar{b},b)}$ $\Delta R_{(\bar{b},b)}$ $M_{(\bar{\ell},\ell)}$ $p^t_{(\bar{\ell},\ell)}$, $\Delta\phi_{\{(\bar{\ell},\ell),(\bar{b},b)\}}$



"Backgrounds as stacked Histogram"

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

  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)

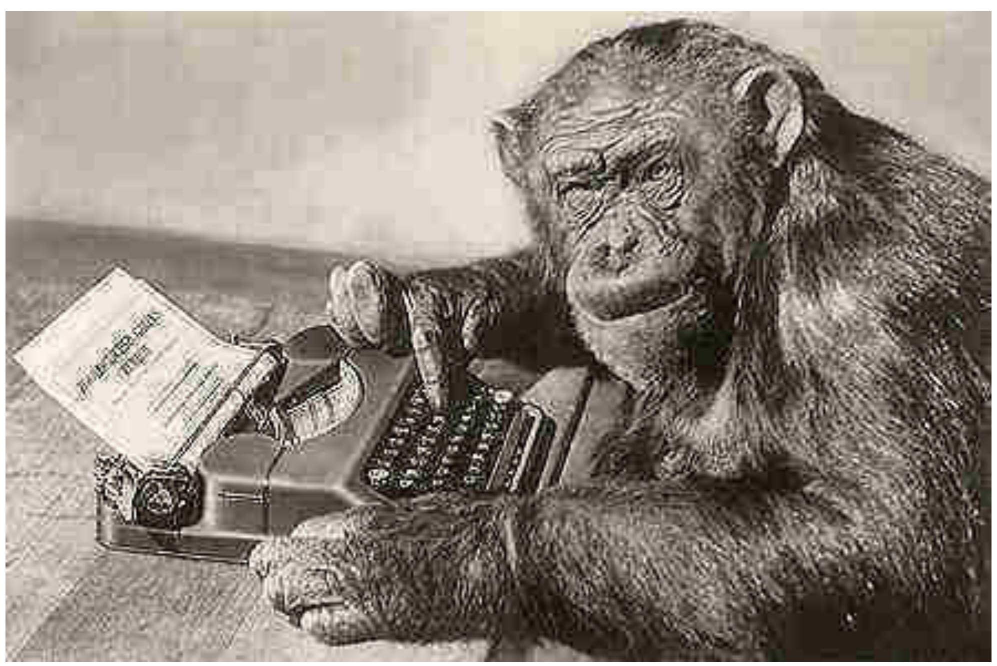


If DL is so smart,
why do we bother
to invent high-level observables?

V.S.

Sorry, Sedol Lee!

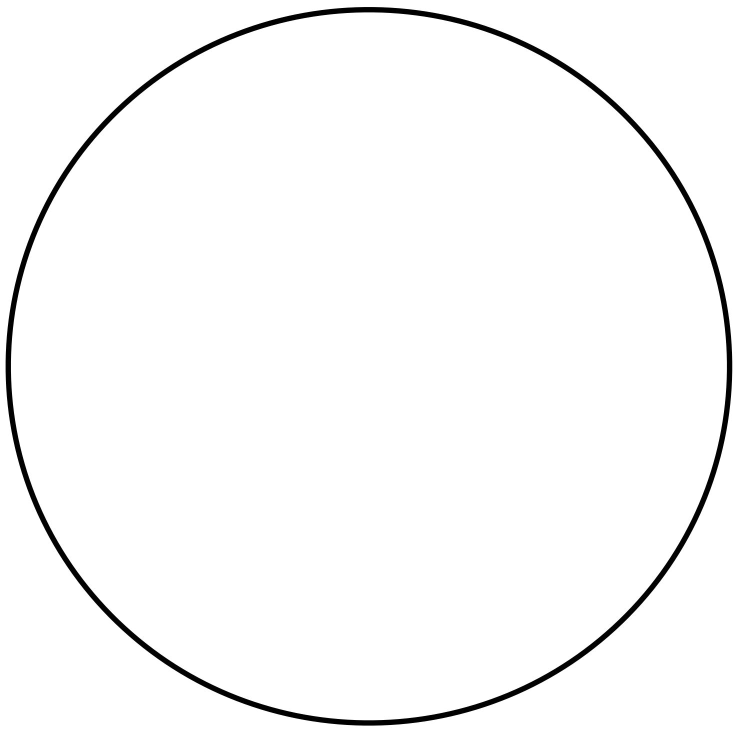
Is DL really smart ???
Or
Typing Monkey (with **seamless efforts**)



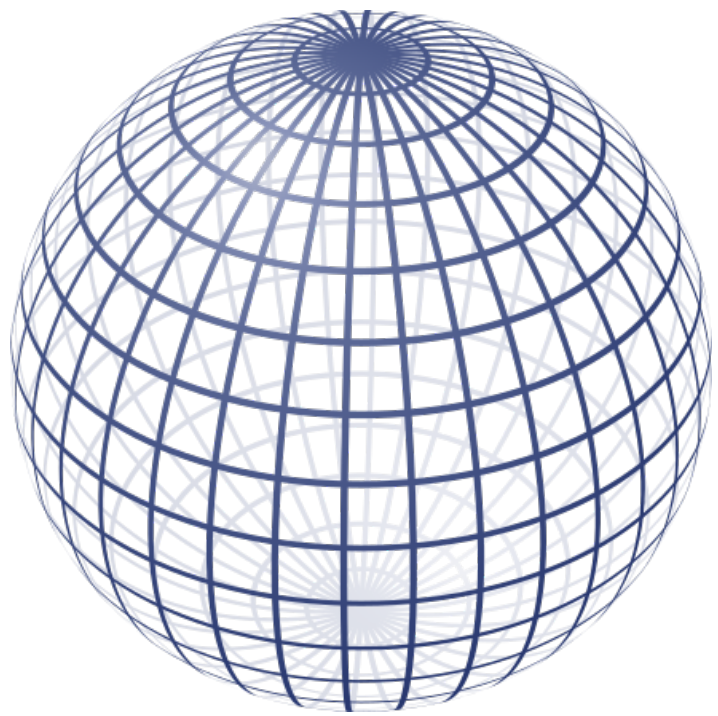
Sorry, Sedol Lee!

V.S.

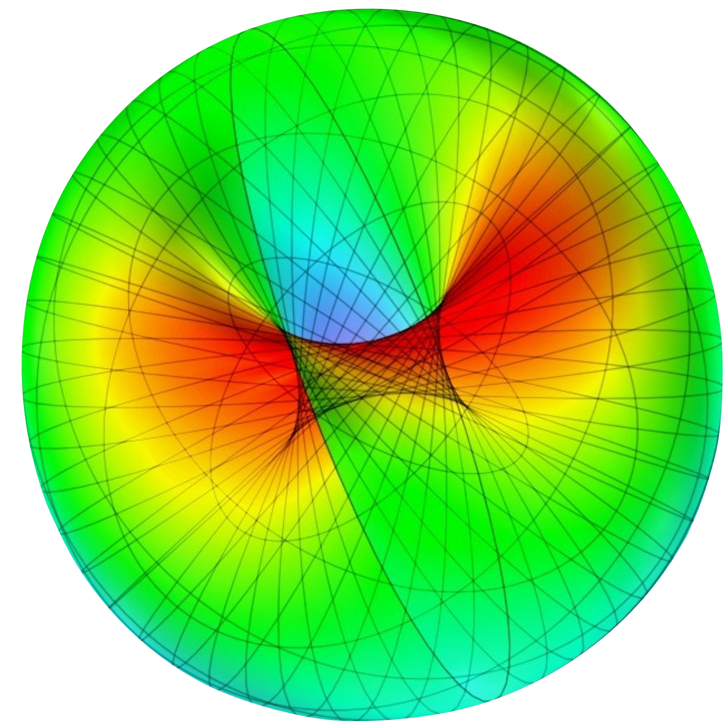
Curse of Dimensionality



S^1



S^2

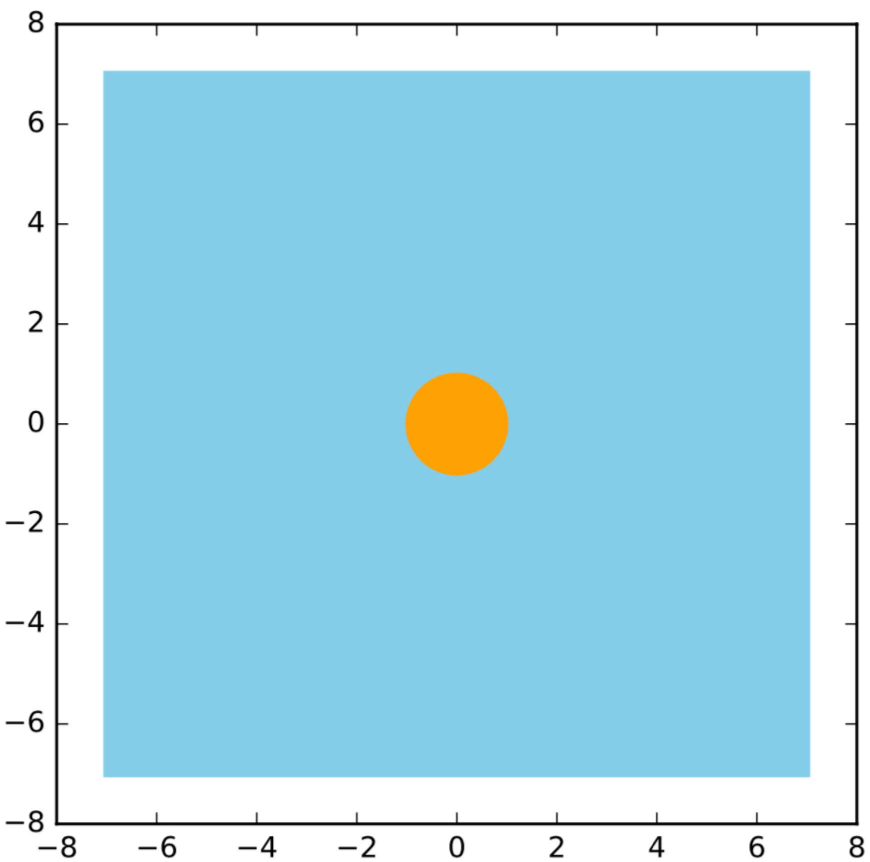


Projection of S^3 into R^3

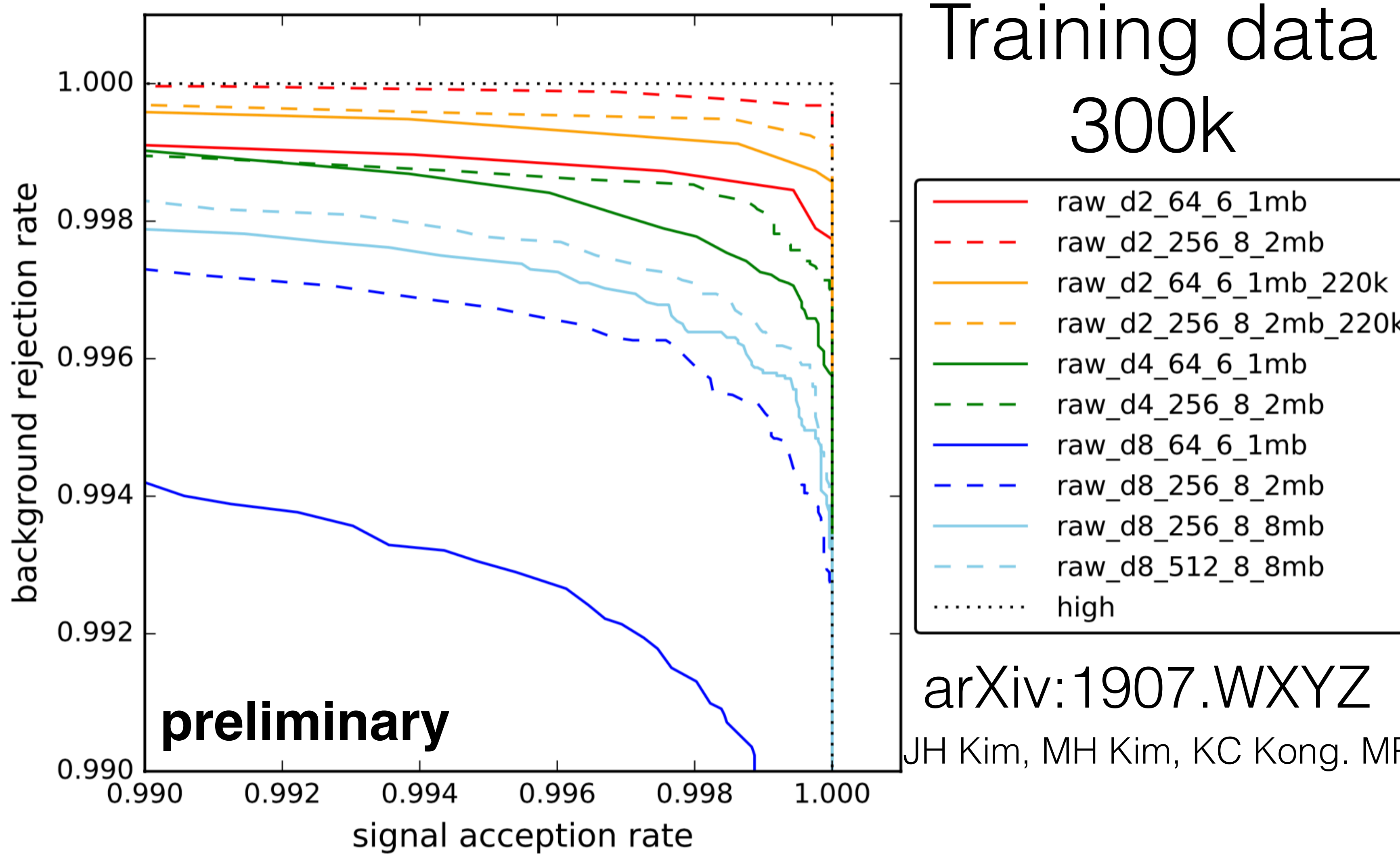
…

- Inside n-sphere: Signal events
  Outside n-sphere: Backgrounds.

Curse of Dimensionality



Training data
300k



arXiv:1907.WXYZ
JH Kim, MH Kim, KC Kong. MP

- SIG : BKG = $V(S^8)$: $V(B^8) - V(S^8)$ = $\frac{\pi^{\frac{8}{2}}}{\Gamma(\frac{8}{2}+1)} : \left[2^8 - \frac{\pi^{\frac{8}{2}}}{\Gamma(\frac{8}{2}+1)}\right] \simeq 1 : 252$
- Higher-level observable: Radius.
  Raw observable: coordinate

Curse of MC SIZE

$\sigma(\text{fb})$	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	0.648	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

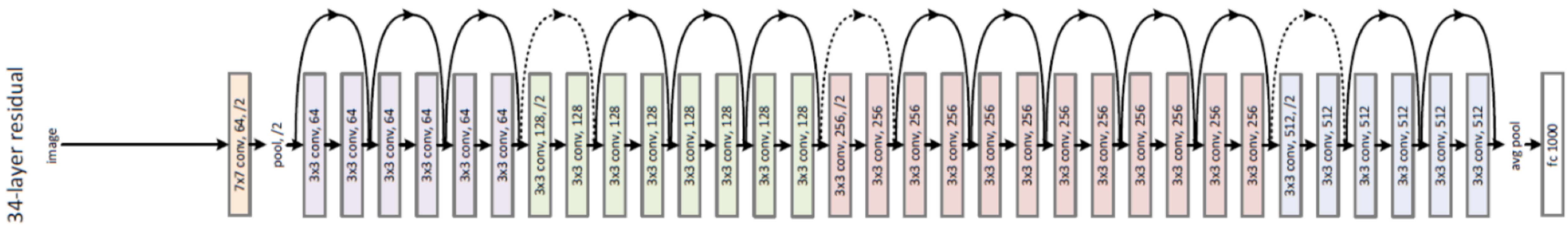
- To generate backgrounds properly, we need to make HUGE Monte Carlo samples
- Preparing "Good enough" MC samples for testing is **NOT EASY.**
- Thus, we should find very good features (High-level observables)

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
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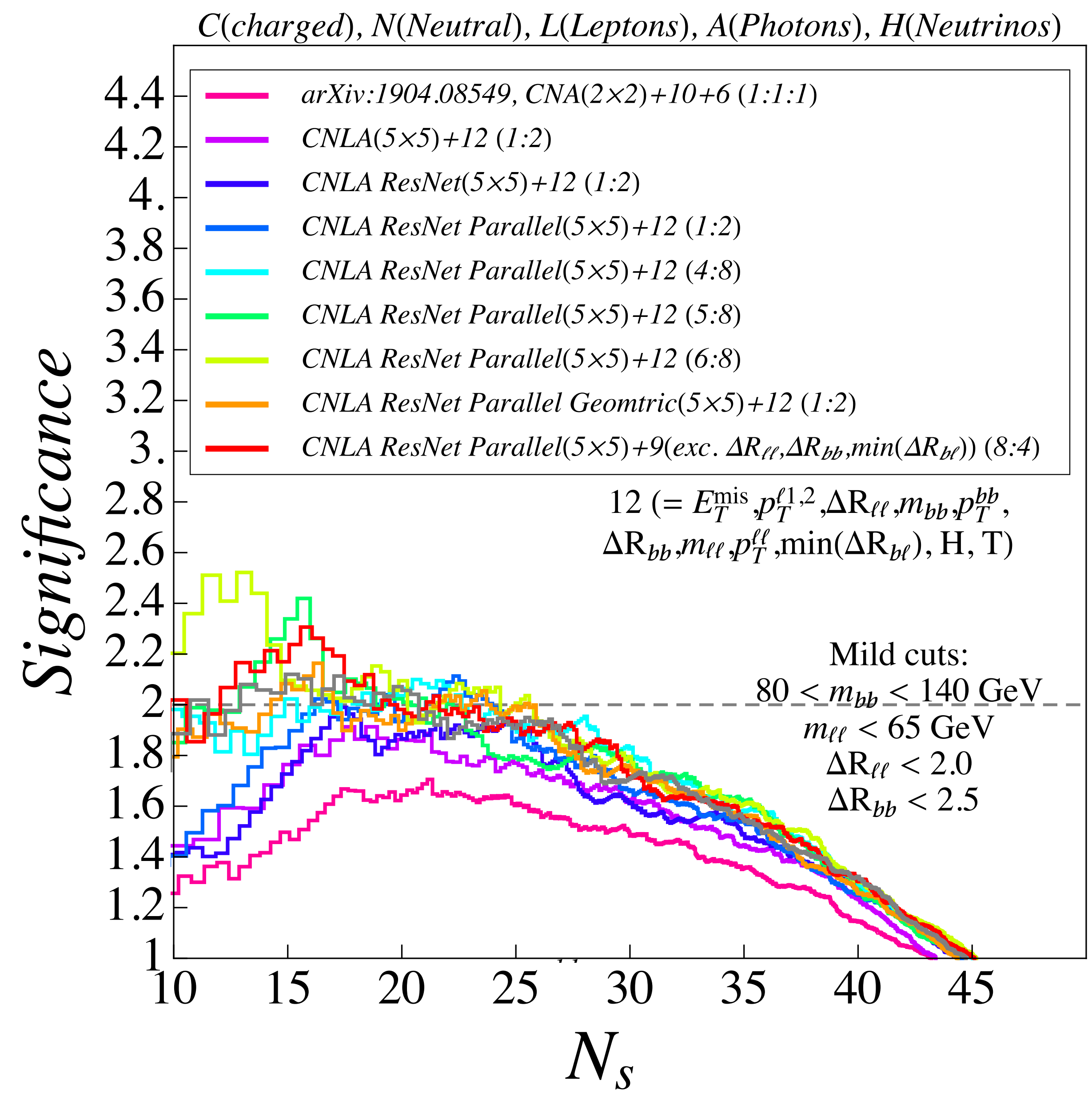

Conclusions

- For HL-LHC, Offshell Higgs can be a good probe for BSM.
- High Precision and maximization of **background rejection** are required.
- For a new computational tool, there are things that we need to look into and "**design**" analysis methods.
  - High level kinematical variables is introduced.