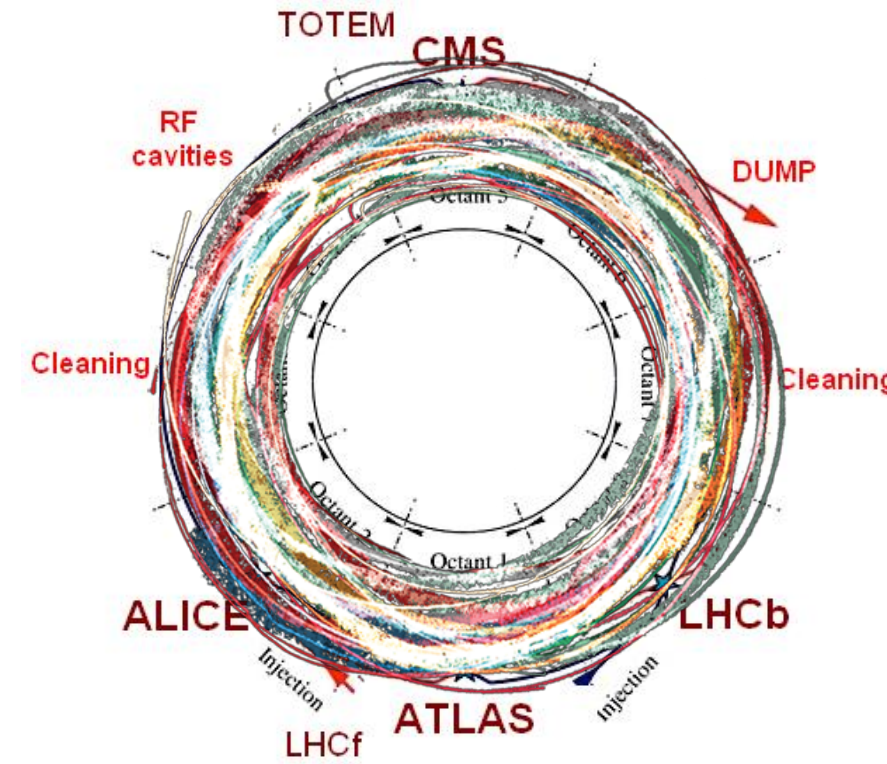
Precision **Higgs** at



Myeonghun Park

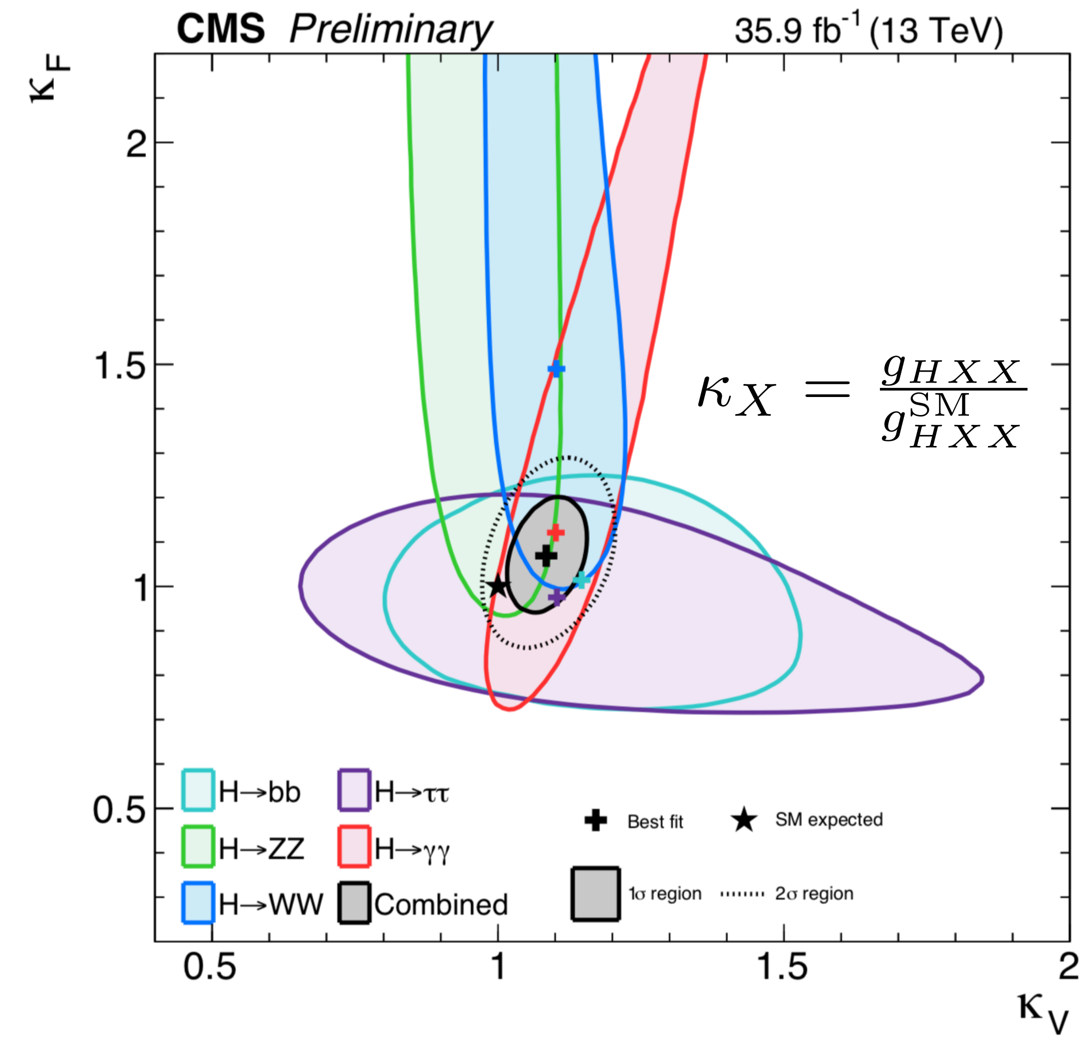
based on arXiv:1812.02679
with **Zhuoni Qian** and SJ Lee

based on arXiv:1807.11498 (PRL 2019), arXiv:1903(4?).XXXX
with K. Matchev, KC Kong, **Jeong Han Kim and Minho Kim,**

YuCHE 2019

Precision for Higgs

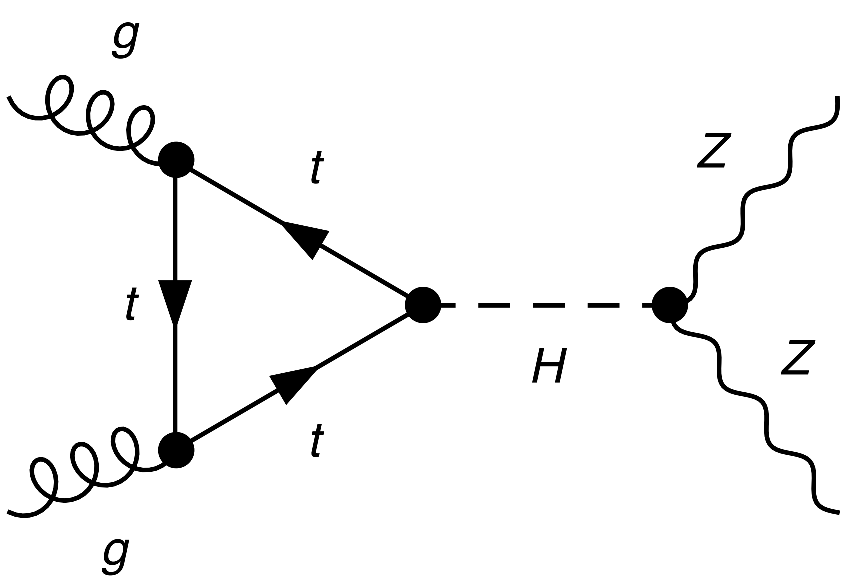
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

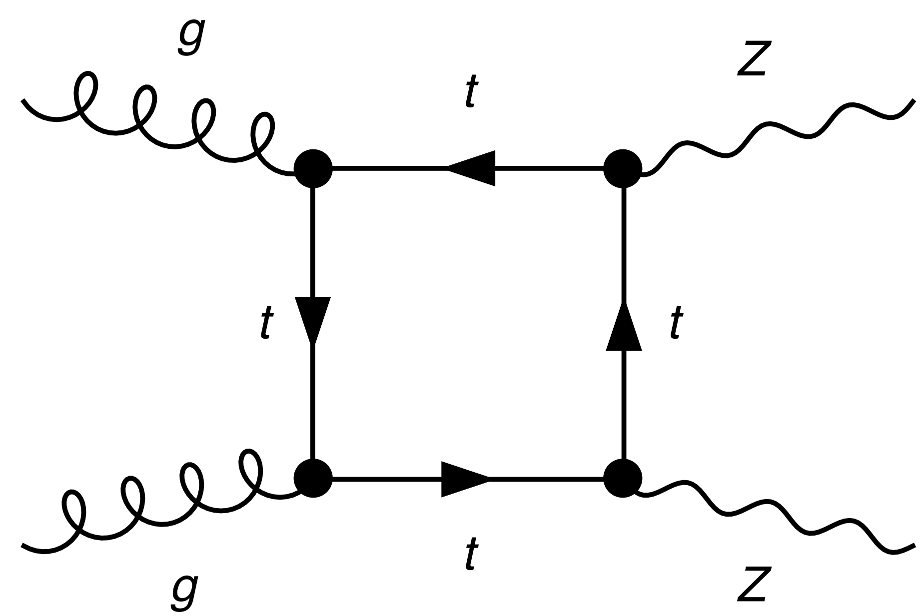


$$\kappa_X = \frac{g_{HXX}}{g_{HXX}^{\rm SM}}$$

- A singlet S, (for example Higgs portal Dark Matter Model)
- Two Higgs Doublet Model : Enlarged Higgs family
- MSSM, a decoupling limit for SM-like Higgs. Suppressed stop effect for a loop.
- Composite Higgs Model: Higgs as a pseudo-NGB, just like a pion.
- Top Partner, (for Naturalness...)

Precision for Higgs beyond the Onshell





$$\mathcal{A}_{\triangle} \to \frac{m_t^2}{\hat{s}} \frac{1}{2} \log^2\left(\frac{m_t^2}{\hat{s}}\right)\left(\frac{\sqrt{\hat{s}}}{m_Z}\right)^2$$

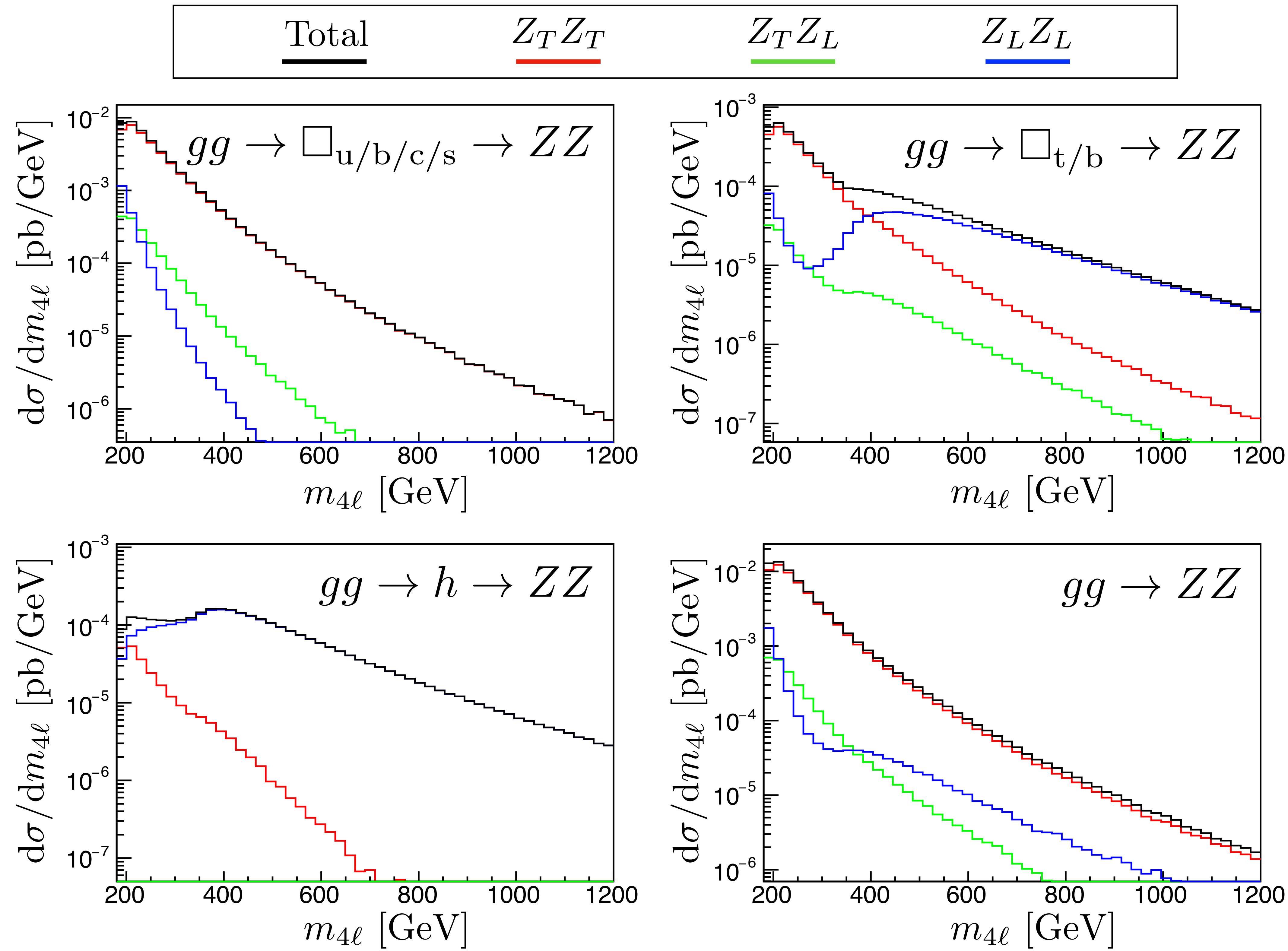
$$= \frac{m_t^2}{2m_Z^2} \log^2\left(\frac{\hat{s}}{m_t^2}\right)$$

$$\mathcal{A}_{\Box} \to -8C_A^2 \frac{m_t^2}{\hat{s}} \left(\frac{\hat{s}}{m_Z^2}\right) \log^2\left(\frac{\hat{s}}{m_t^2}\right)$$

$$= -\frac{m_t^2}{2m_Z^2} \log^2\left(\frac{\hat{s}}{m_t^2}\right)$$

in the limit $\sqrt{\hat{s}} \gg m_t$

Precision for Higgs beyond the Onshell



A new physics which ...

- **A**: A Higgs portal light scalar

$$\mathcal{L} \ni \mathcal{L}_{\rm SM} + \partial_\mu S \partial^\mu S^* - \mu^2 |S|^2 - \kappa |S|^2 |\Phi|^2$$

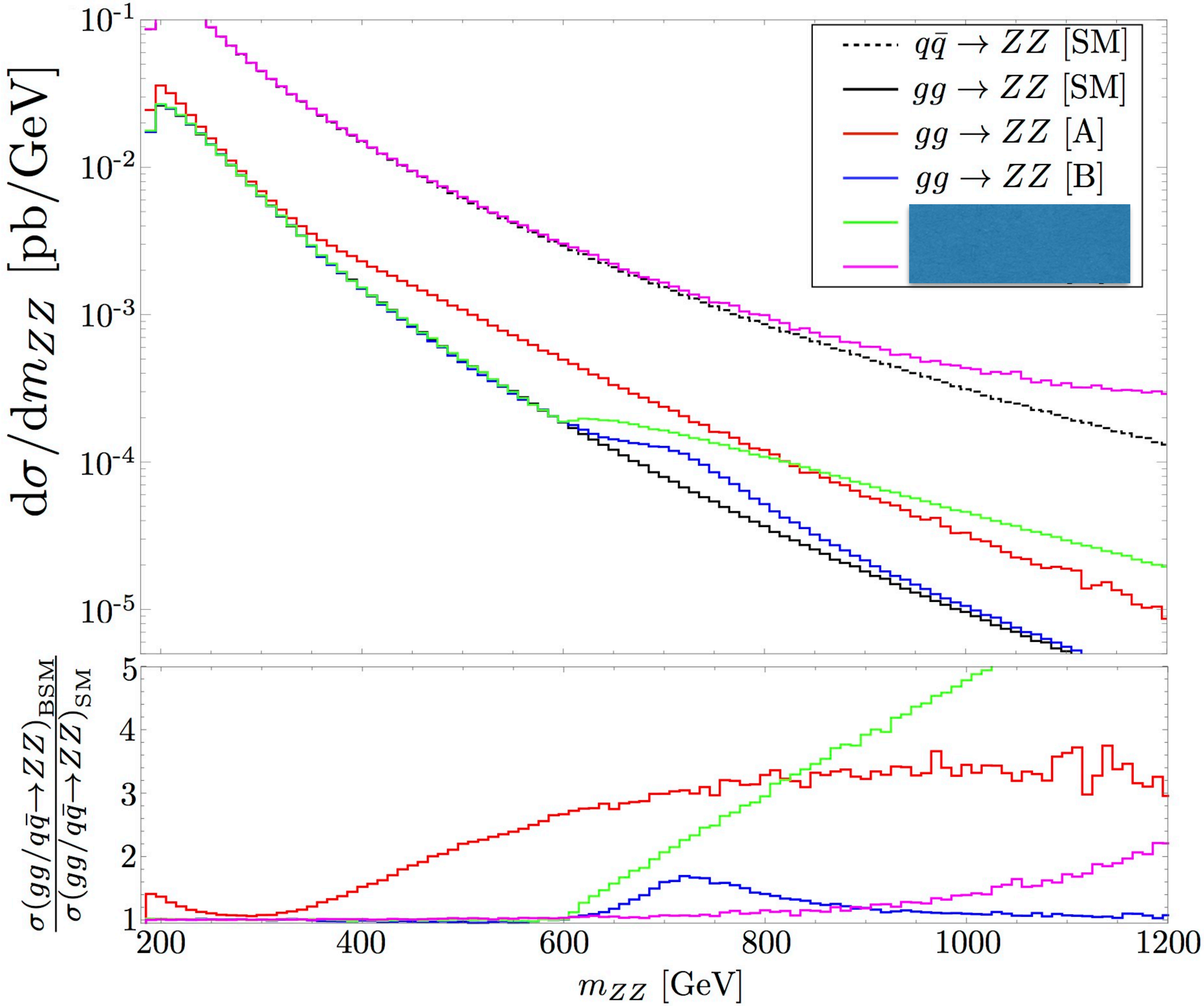
$$m_S = 80 \text{ GeV with } \kappa = 9$$

- **B**: Broad-width heavy scalar

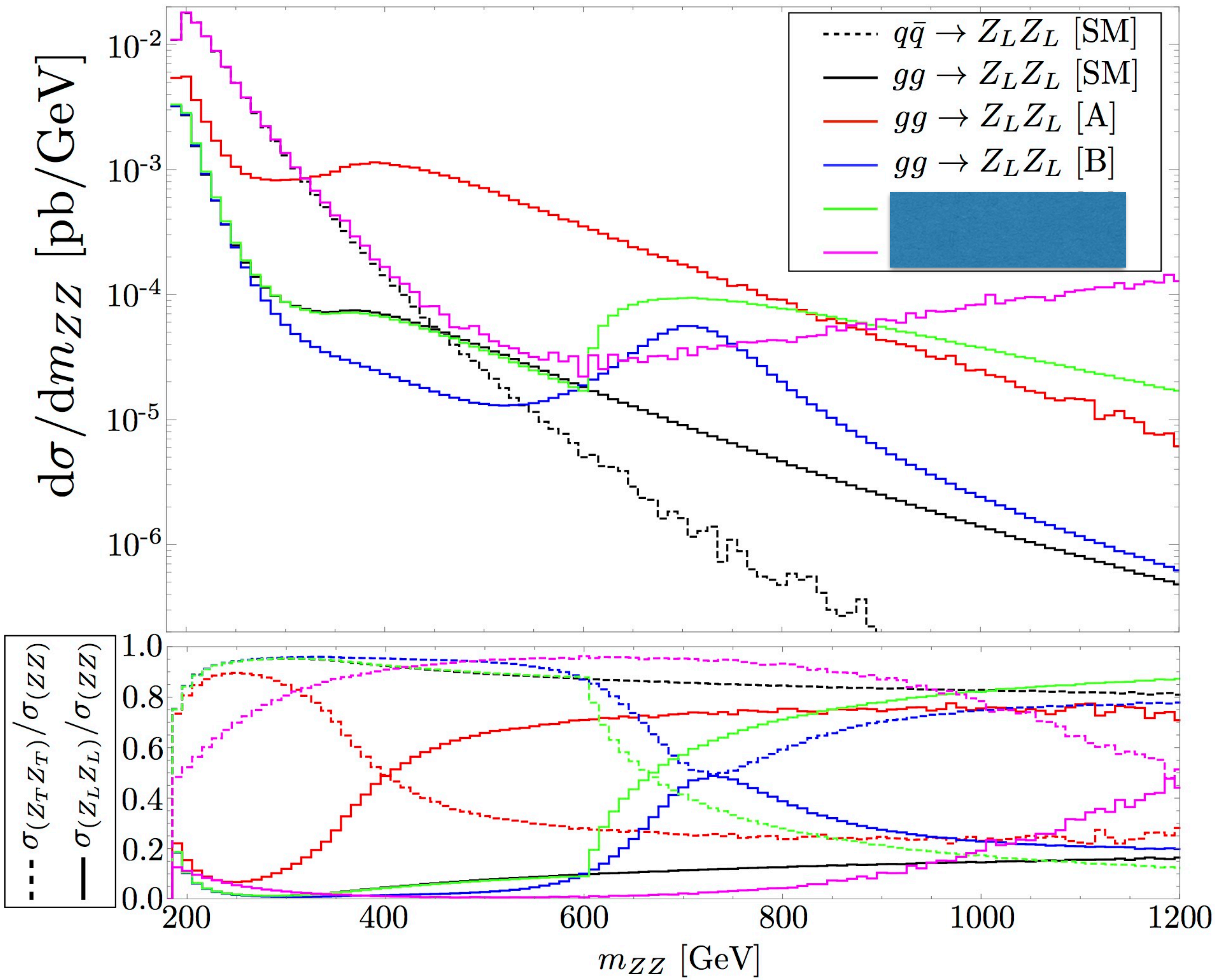
$$\mathcal{L} \ni \mathcal{L}_{\rm SM} - \mu_S S |\Phi|^2$$

$$M_S = 700 \text{ GeV with } \Gamma_S = 20\%$$

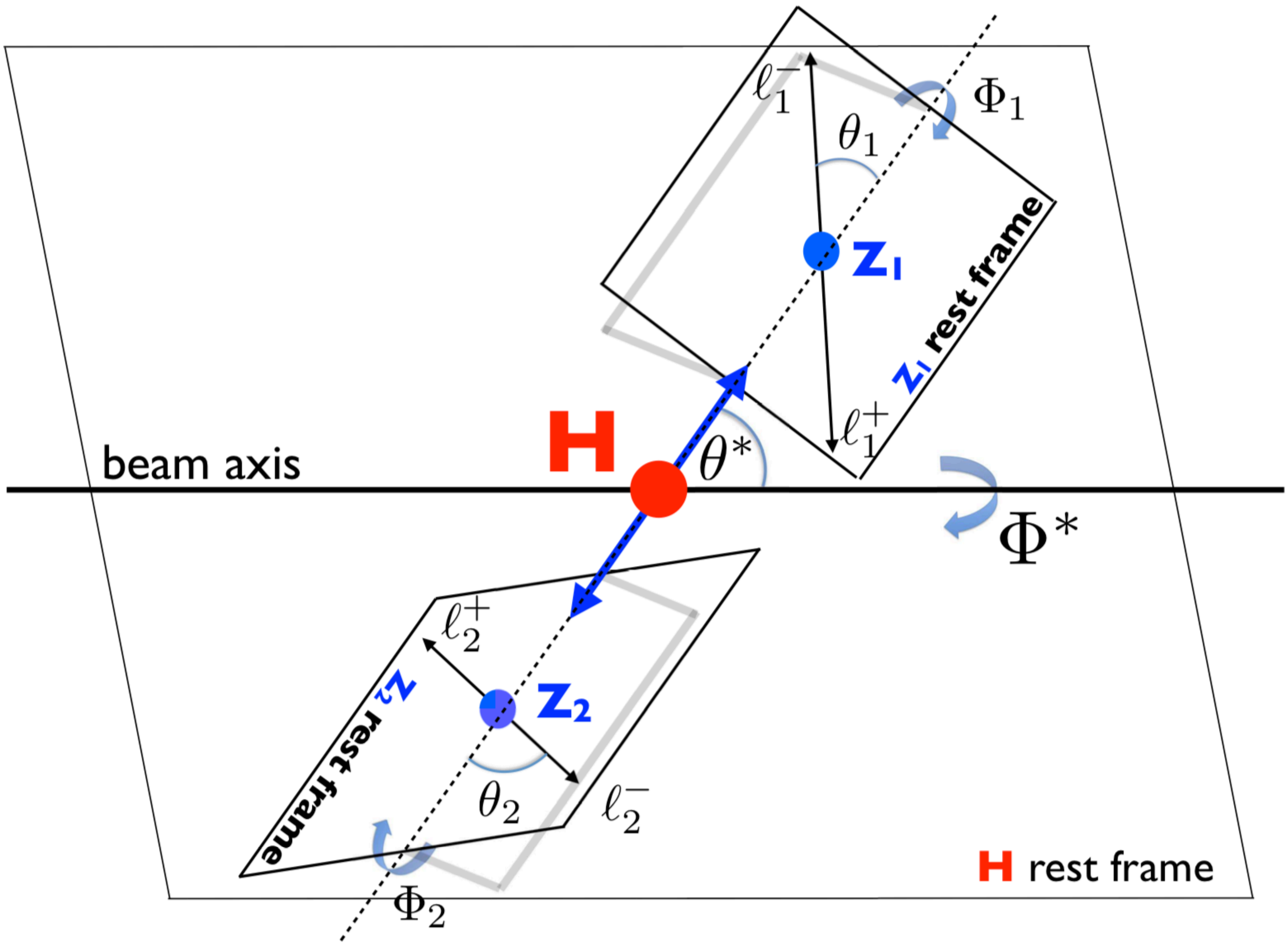
Precision for Higgs beyond the Onshell



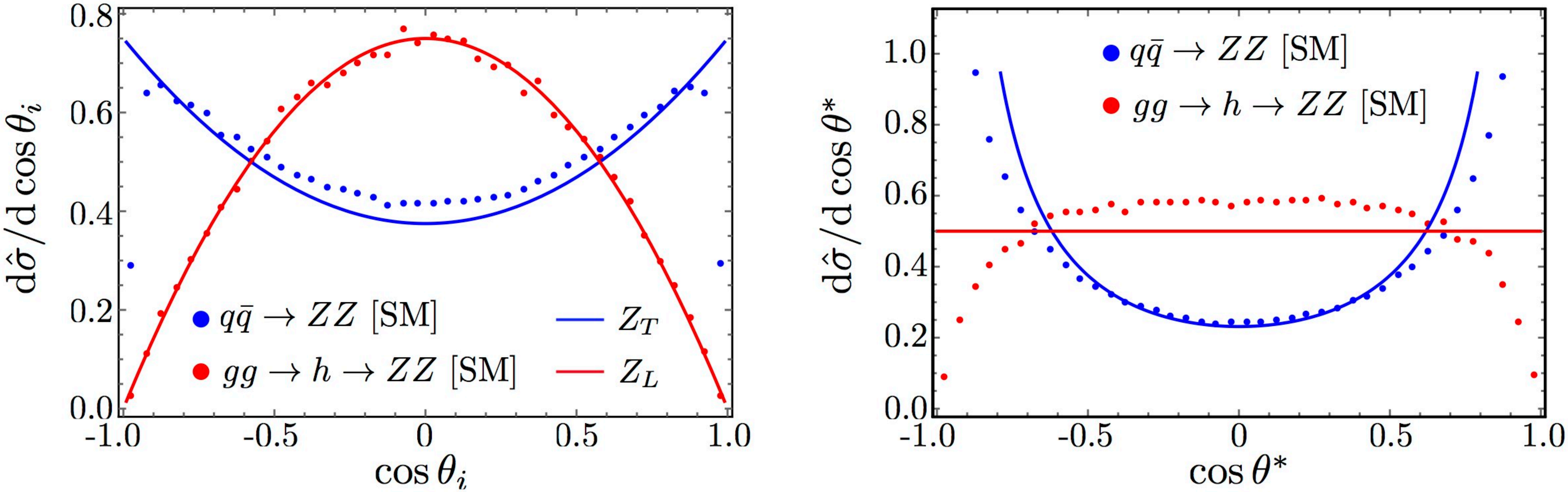
Precision for Higgs beyond the Onshell



Simple variables to utilize polarization



Simple variables to utilize polarization



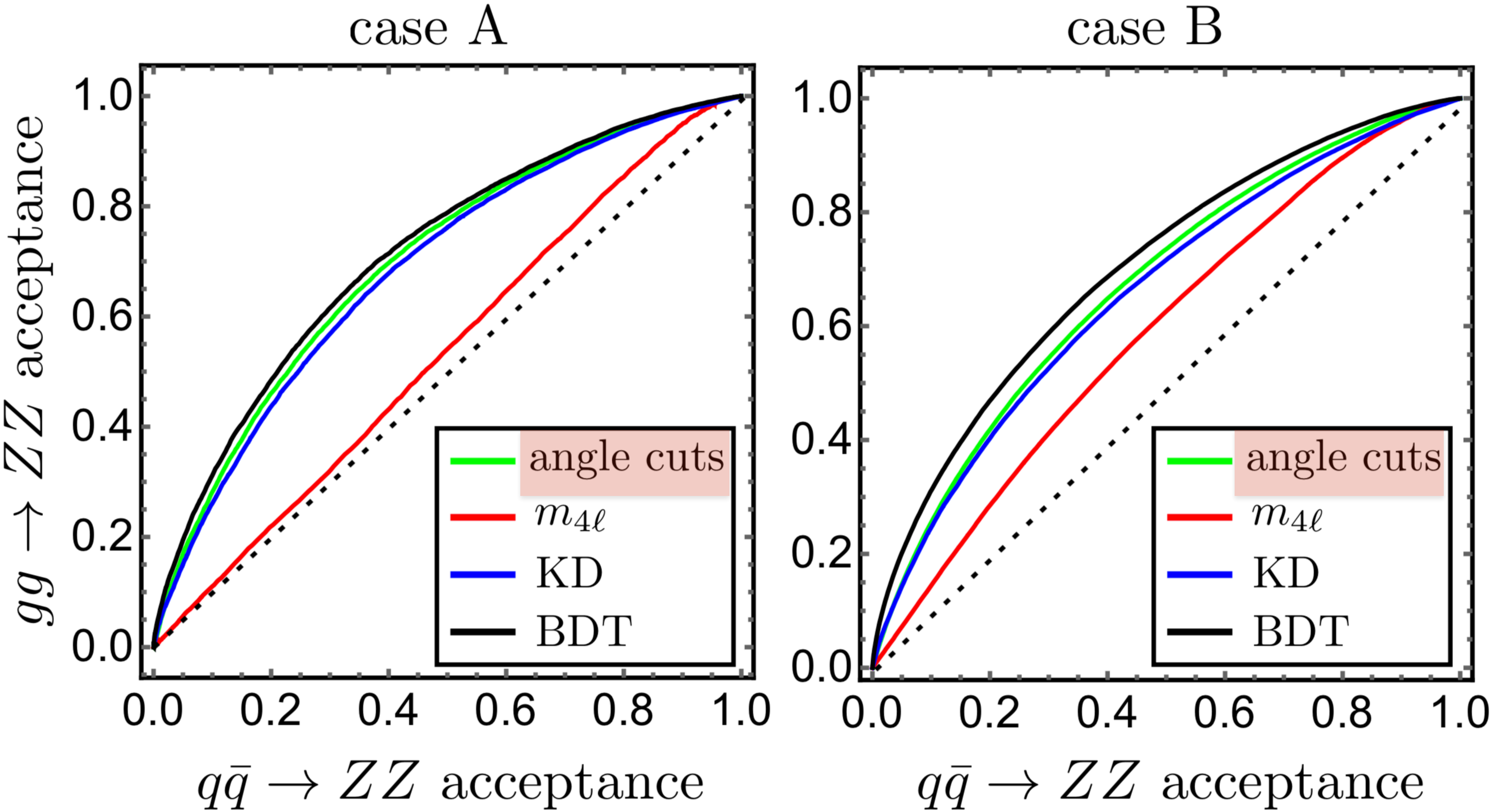
Simple angle cuts: $|\cos\theta^*| < 0.7, \quad |\cos\theta_1| < 0.68$

Conventional $m_{4\ell}$ cut: $m_{4\ell} > 700\text{GeV}$

Matrix Element Method: $\mathrm{KD} = \ln\left(\frac{f_g(x_1)f_g(x_2)|\mathcal{M}(gg \to h^* \to 4\ell)|^2}{\sum f_q(x_1)f_{\bar{q}}(x_2)|\mathcal{M}(q\bar{q} \to 4\ell)|^2}\right)$

we set $m_{h^*} = m_{4\ell}$ for a generic case

Simple variables to utilize polarization



The Higgs Sector

"**Mexican Hat"** Higgs potential

↓

Spontaneous Symmetry Breaking

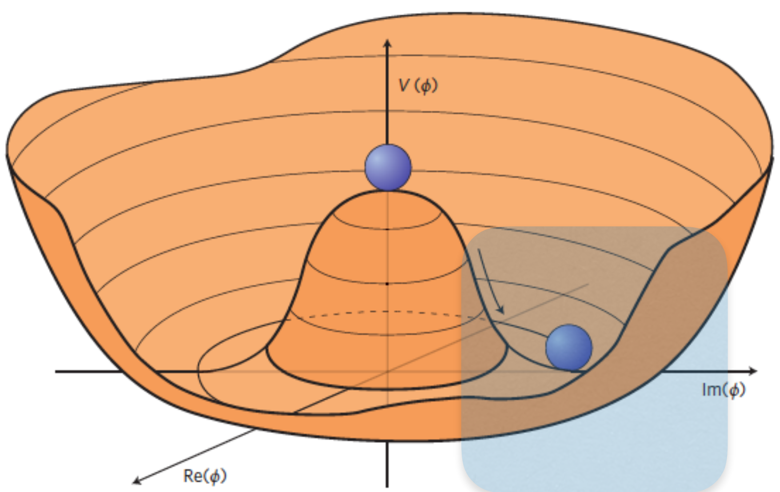
$$SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$$

↓

Yukawa terms for massive fermions

Measuring Higgs potential

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



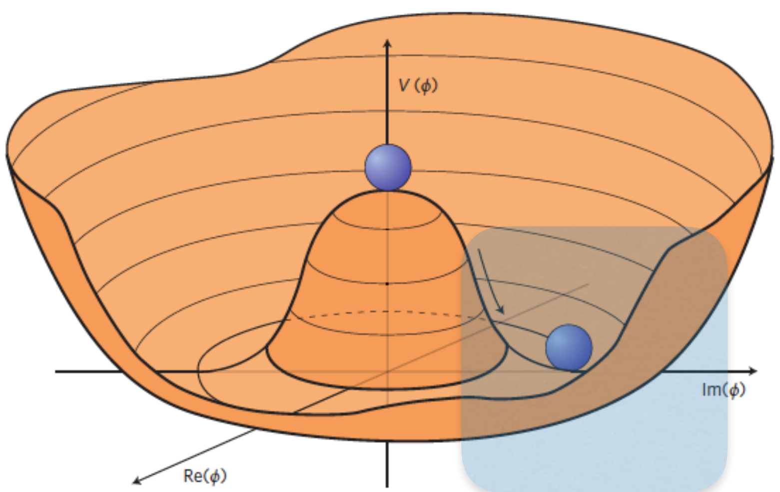
- From spontaneous symmetry breaking

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

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

Measuring Higgs potential

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



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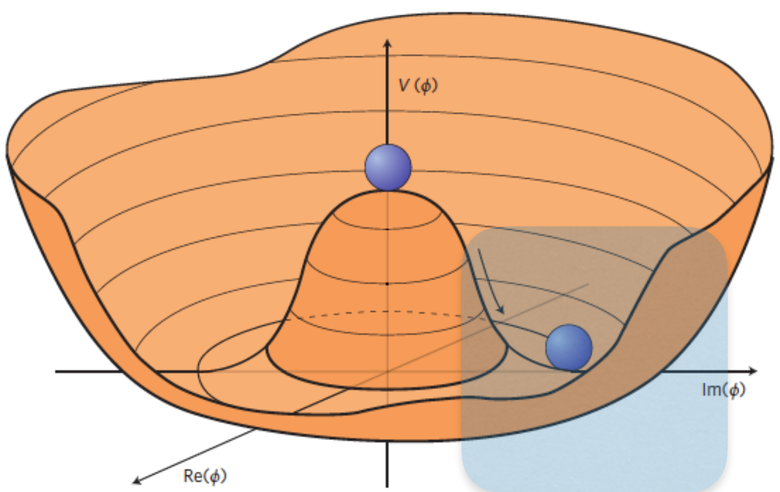
- The shape of a potential around EW scale is determined by h^2 term and h^3 term.

  - 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

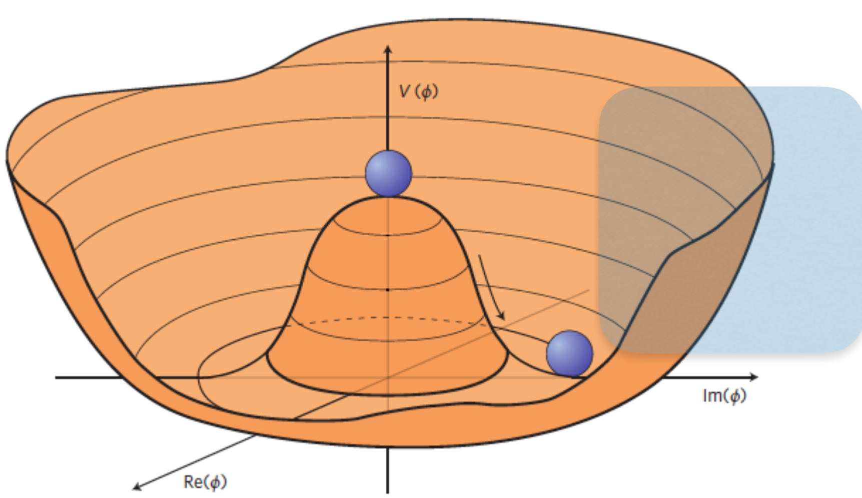
$$V_h^{\rm SM} = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$

- 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

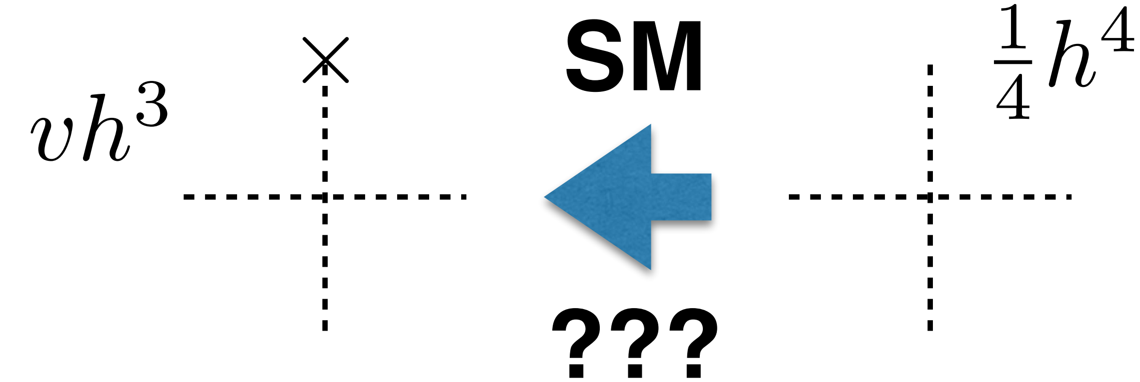
$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$



- From spontaneous symmetry breaking

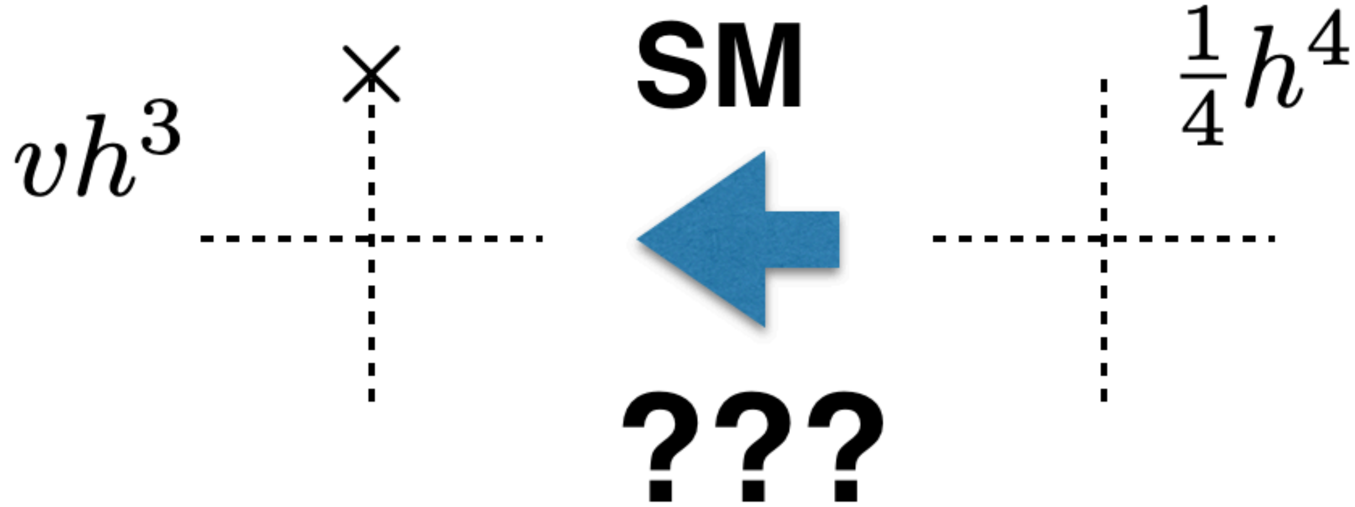
$$V_h^{\rm SM} = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$

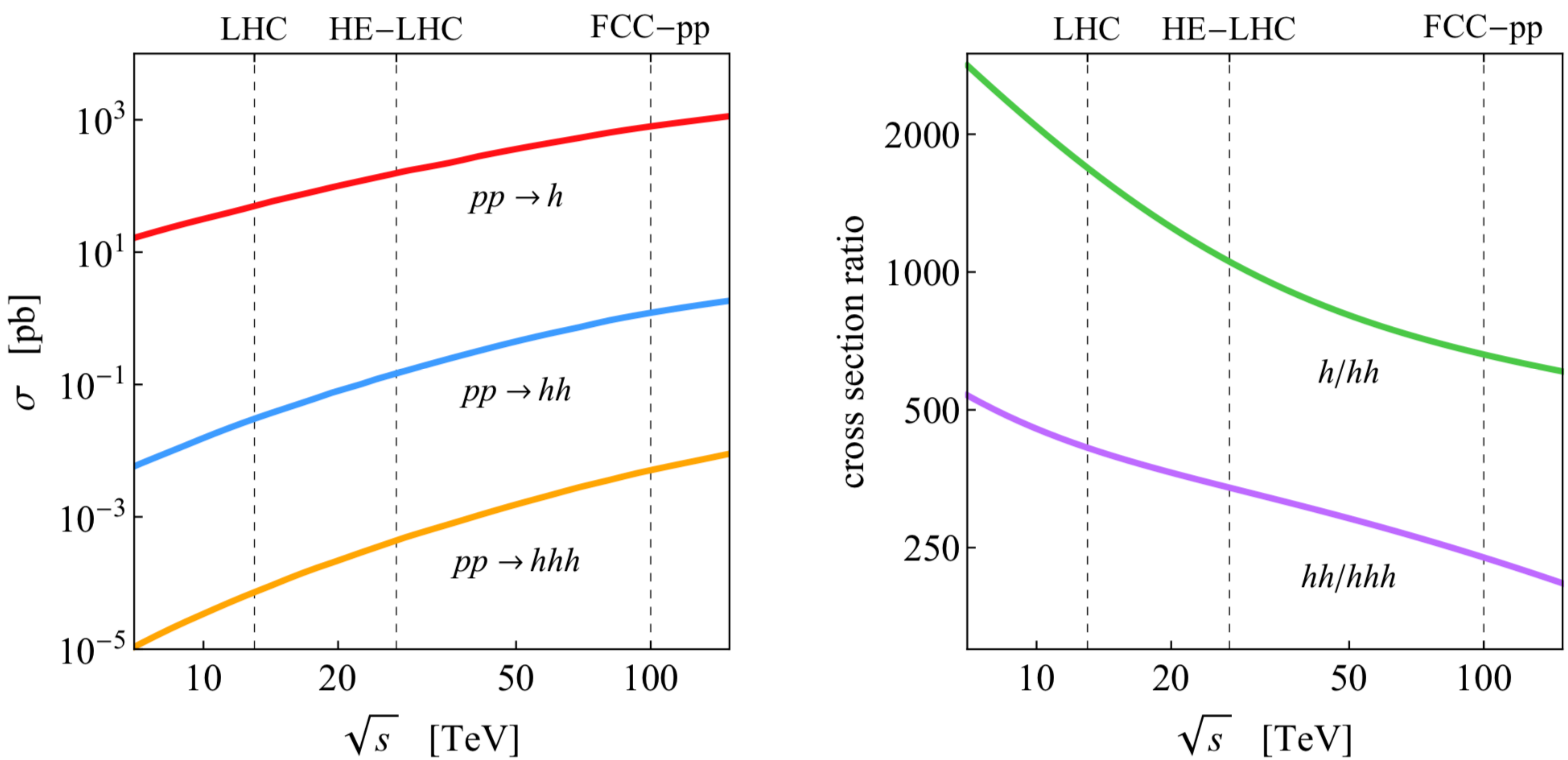
- check



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

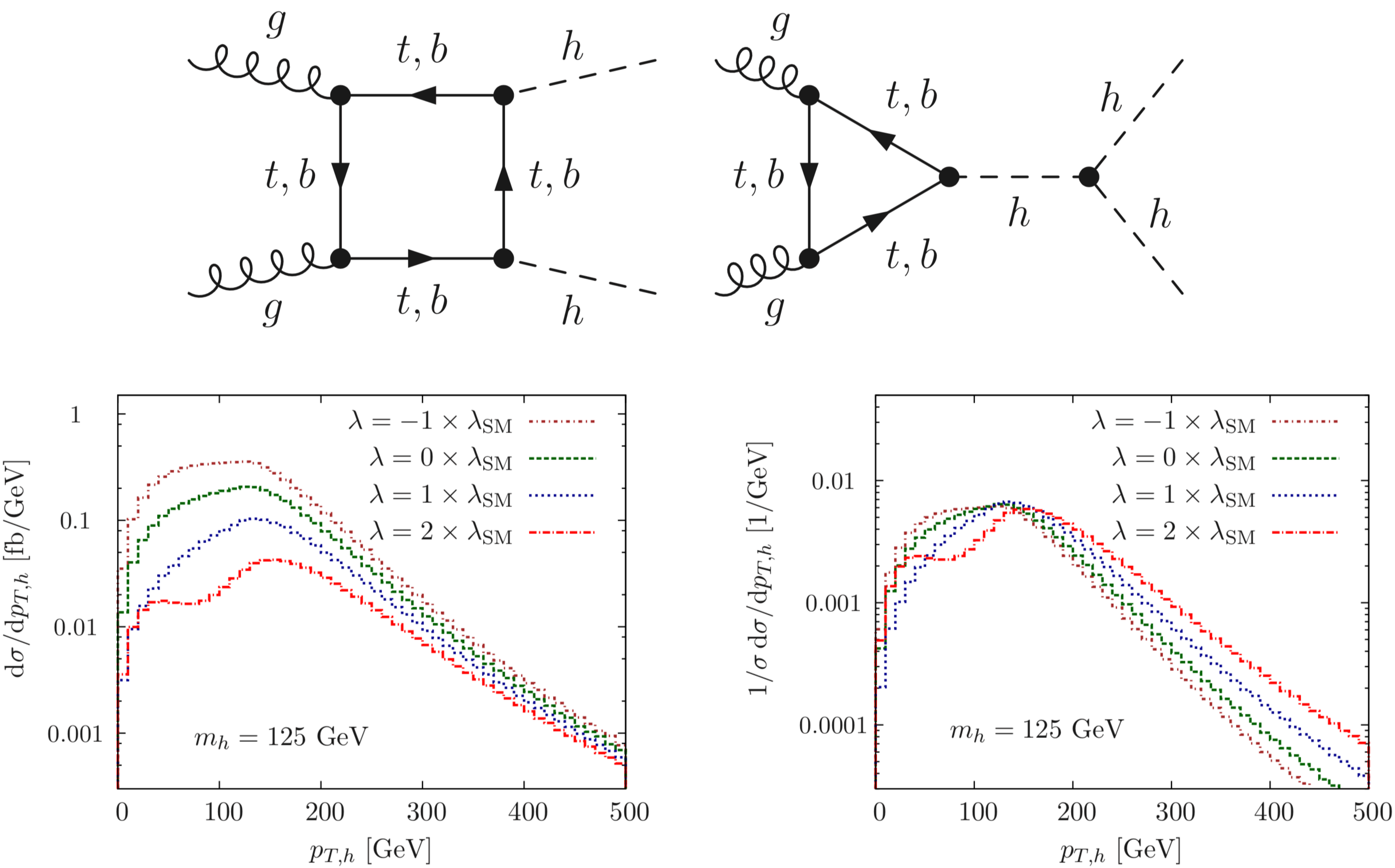
- Quartic Higgs coupling can be determined by $h \to h, h, h$



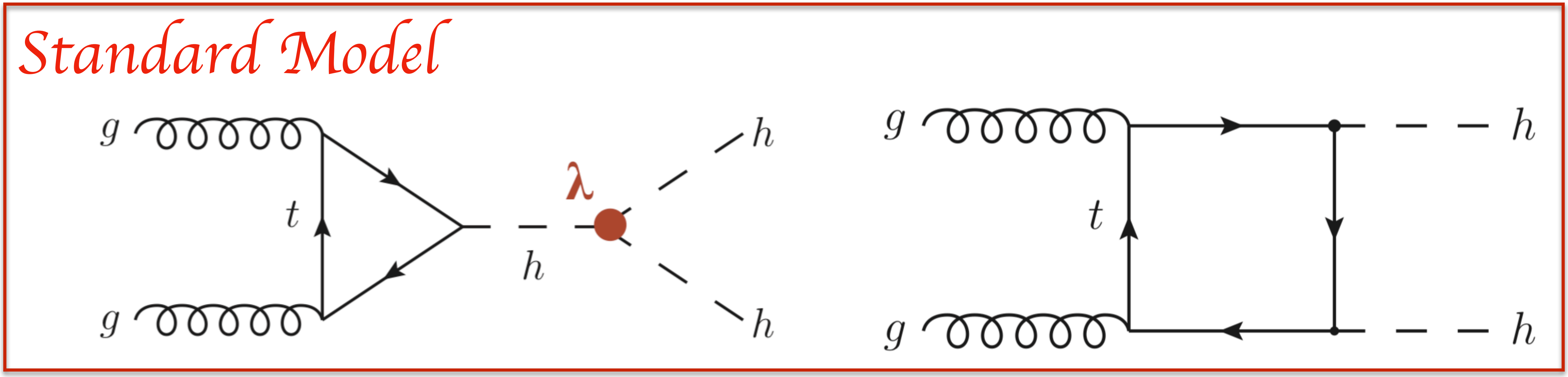


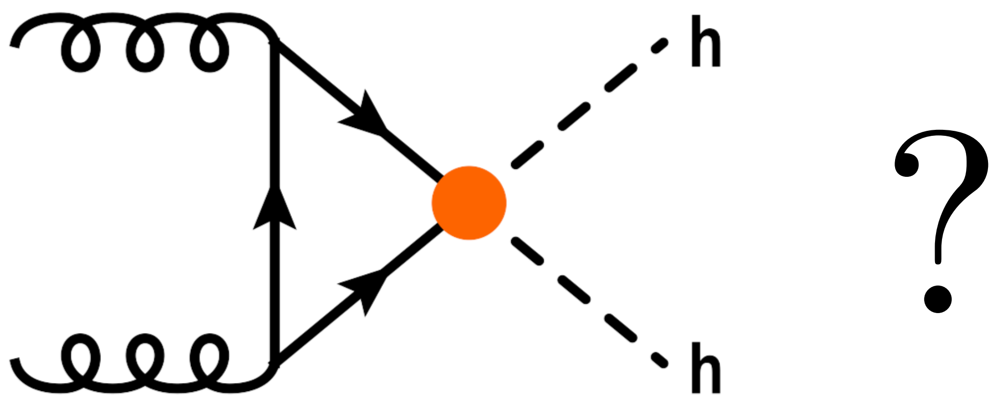
- So, let's focus on "**precise measurement** of" triple Higgs coupling at the LHC

Higgs Boson Pair @LHC



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





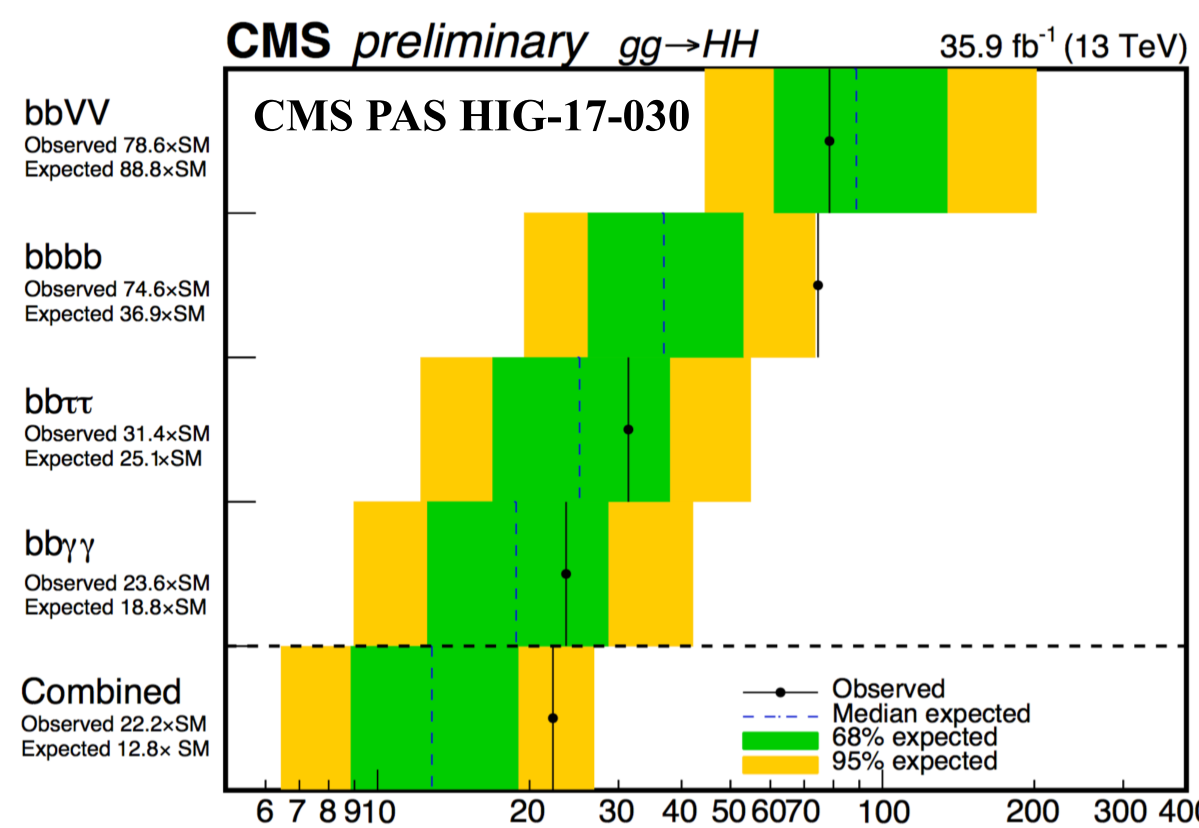
Non-resonant di-Higgs: can be probed

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%

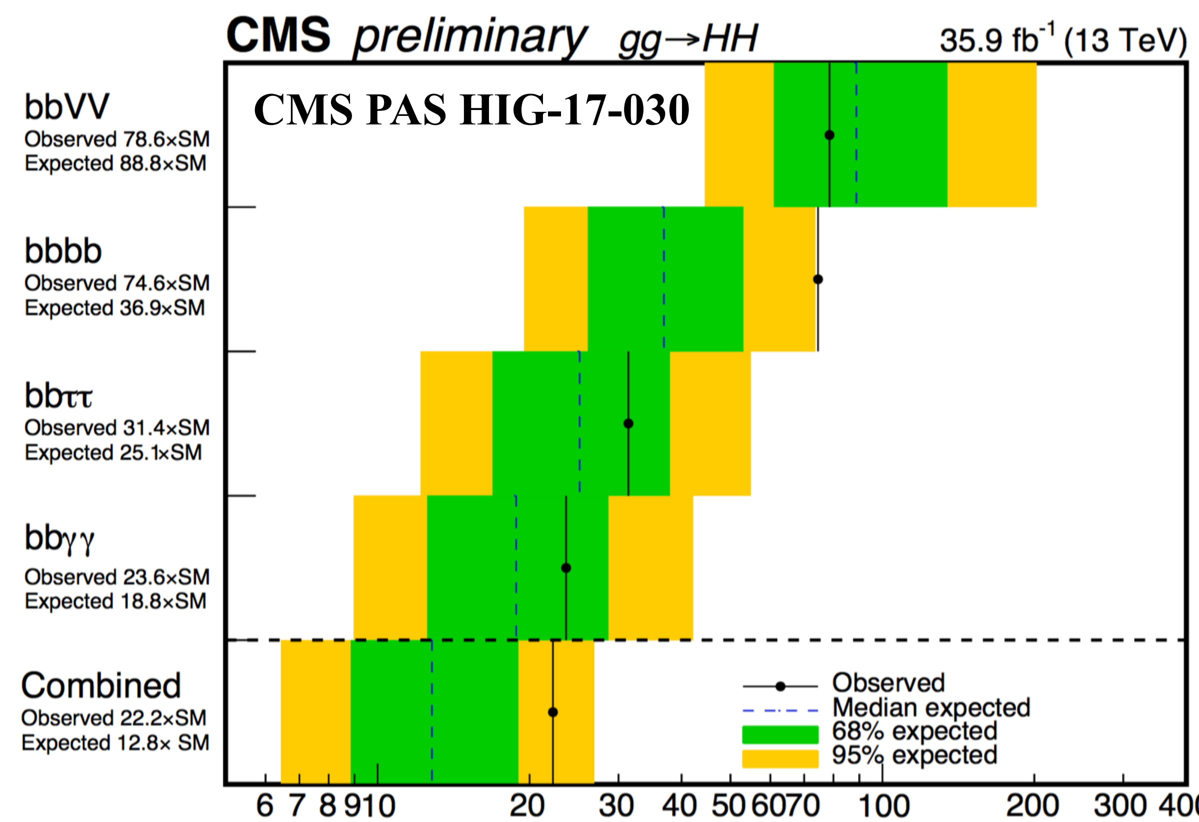


- The driven channel is the "compromised" clean channel.

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

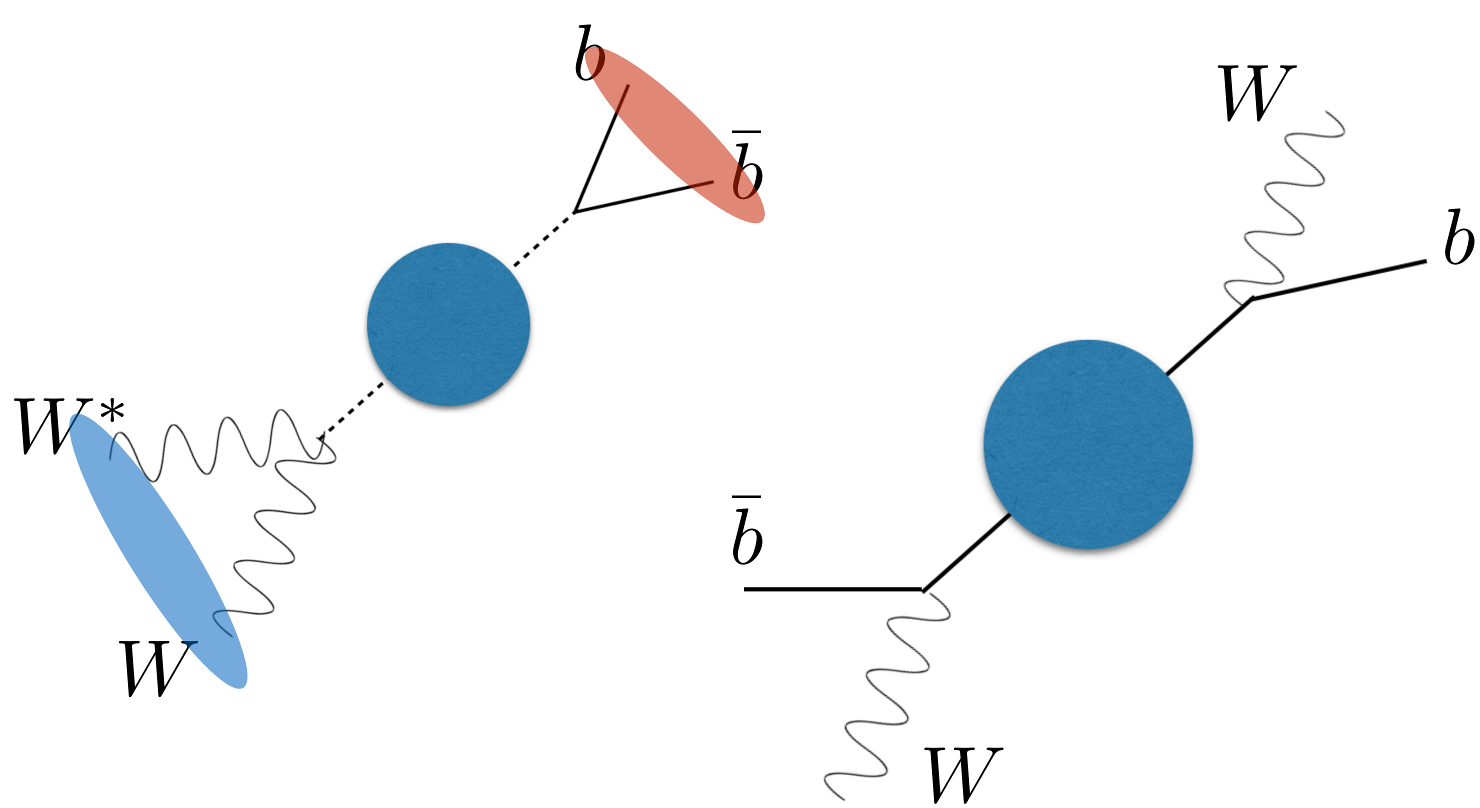


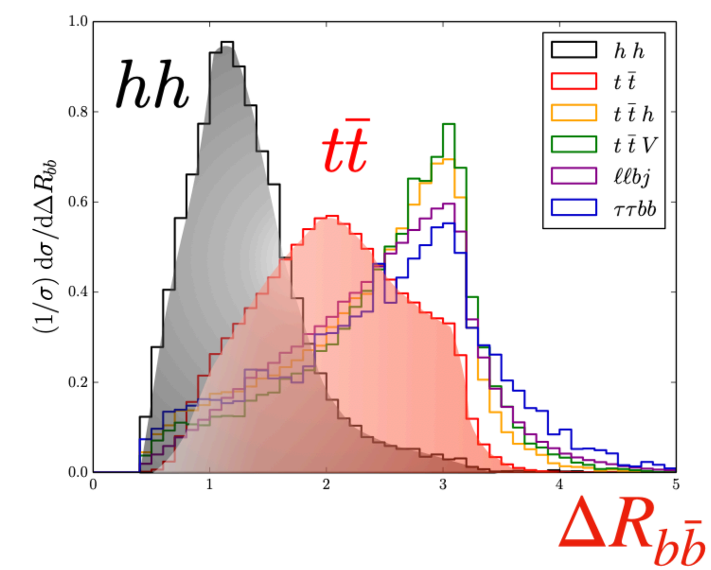
- **Why** is $bbVV$ **bad** ? **how** can one **improve** ?

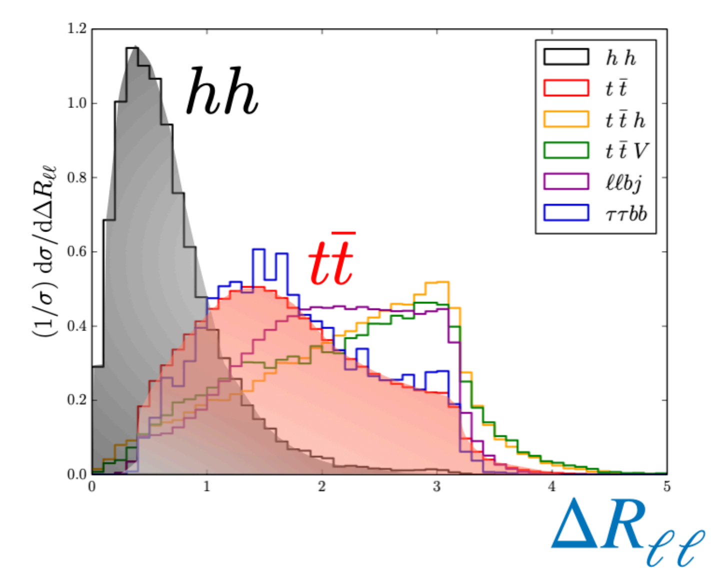
- **Why** is $bbVV$ **bad** ? LHC is the **Top-factory**

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

- 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

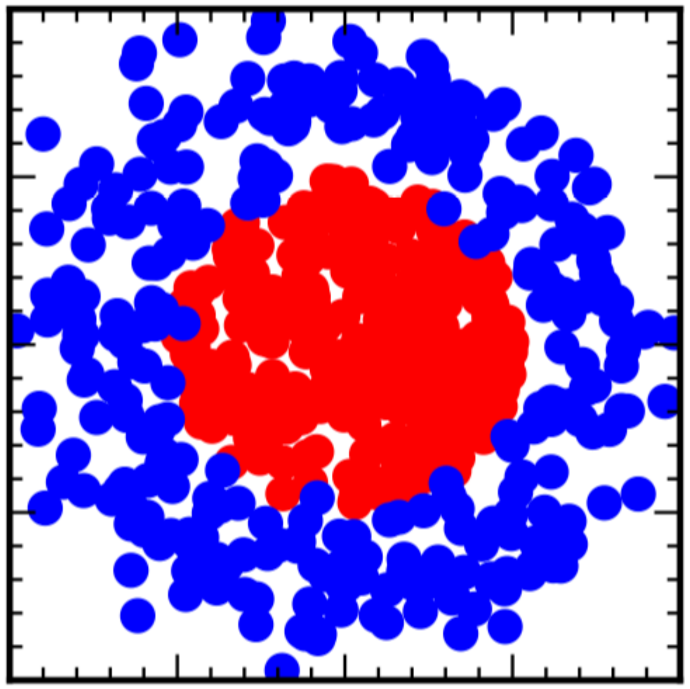
Signal	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}V$	$\ell\ell bj$	$\tau\tau bb$	others	σ	N_{sig}^{SM}/N_{bknd}
0.0124	1.1724	0.0297	0.0246	0.0158	0.0379	0.00590	0.60	0.00964

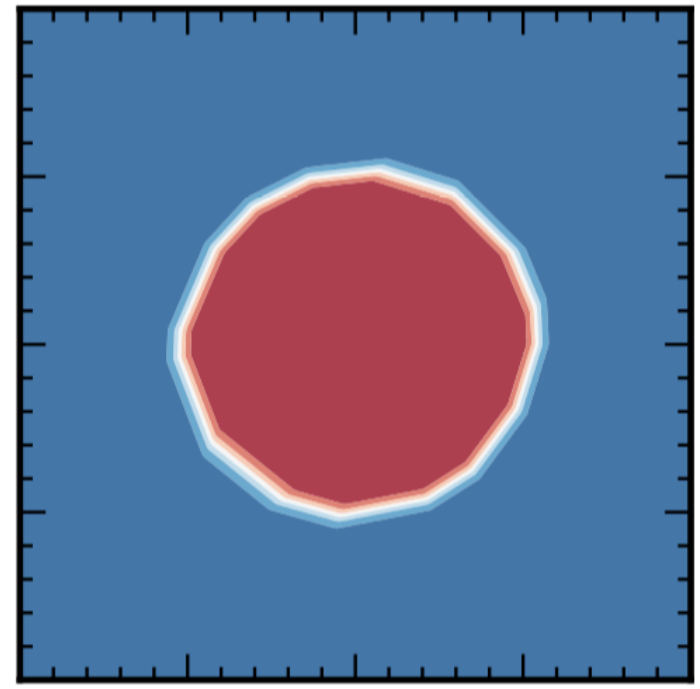
$jj\ell\ell\nu\bar{\nu}$ backgrounds from QCD+EW

- 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



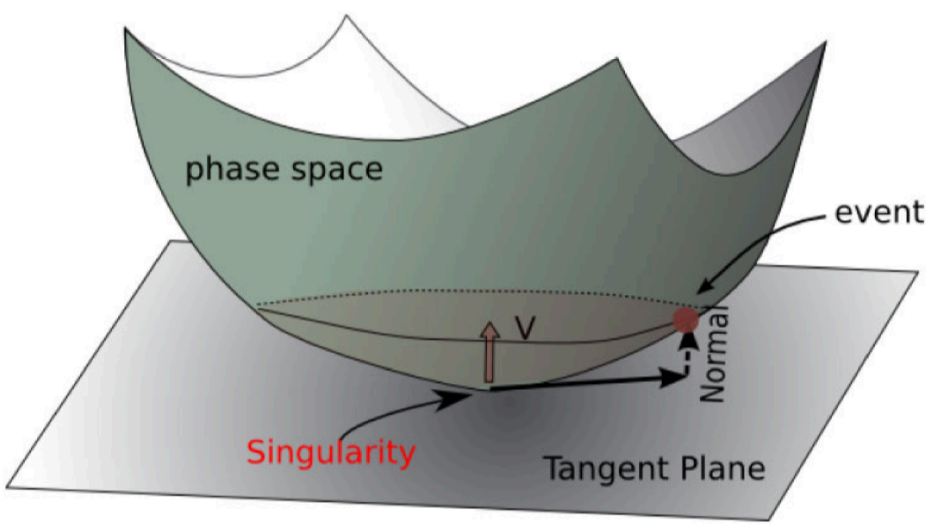


A cartoon is from a paper by Spencer Chang, Timothy Cohen and Bryan Ostdiek, Phys. Rev. D 97, 056009 (2018)

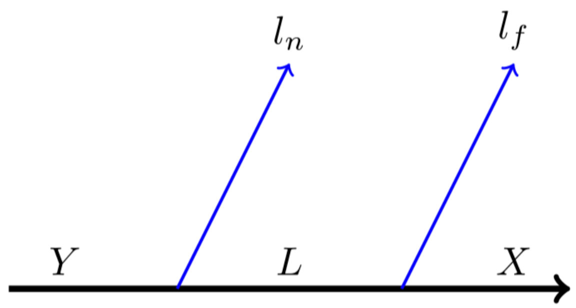
- If we know BKG is a circle, we can take BKG out very easily with **input variables which characterizes** BKG events

  (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?

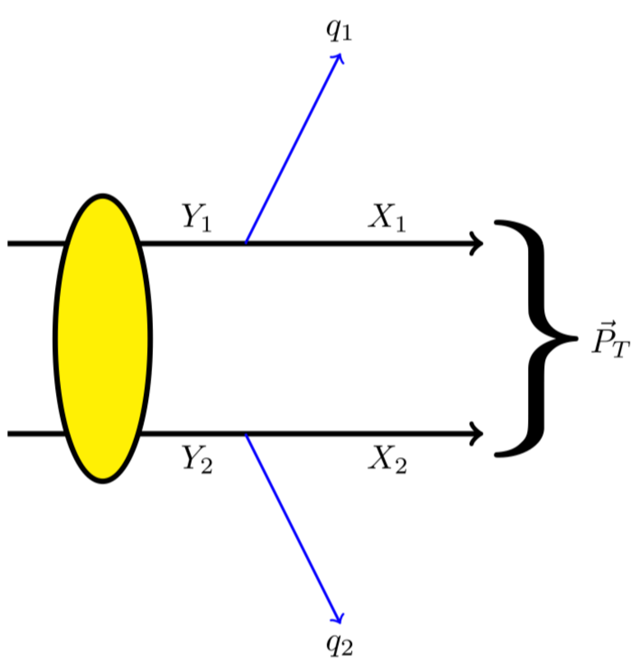


invariant mass



when one considers only visibles

transverse mass

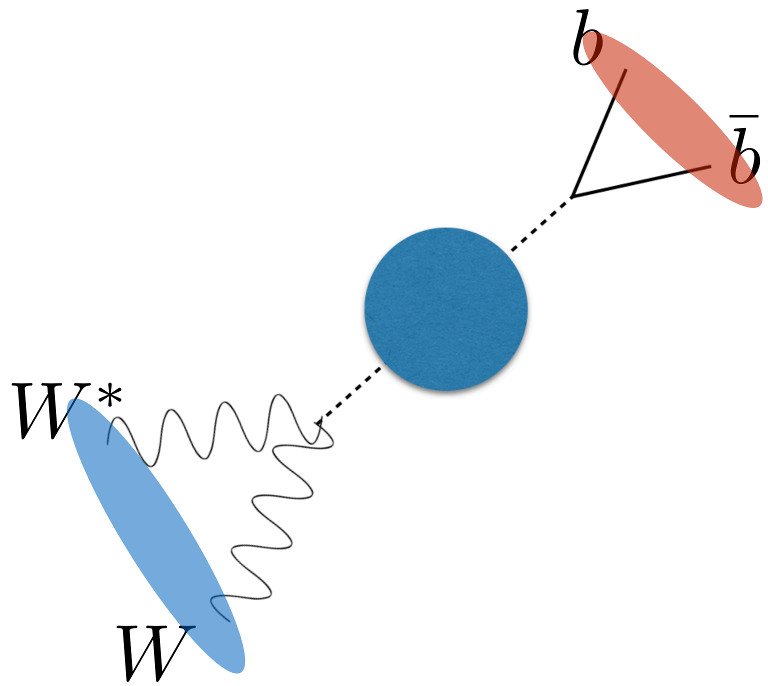


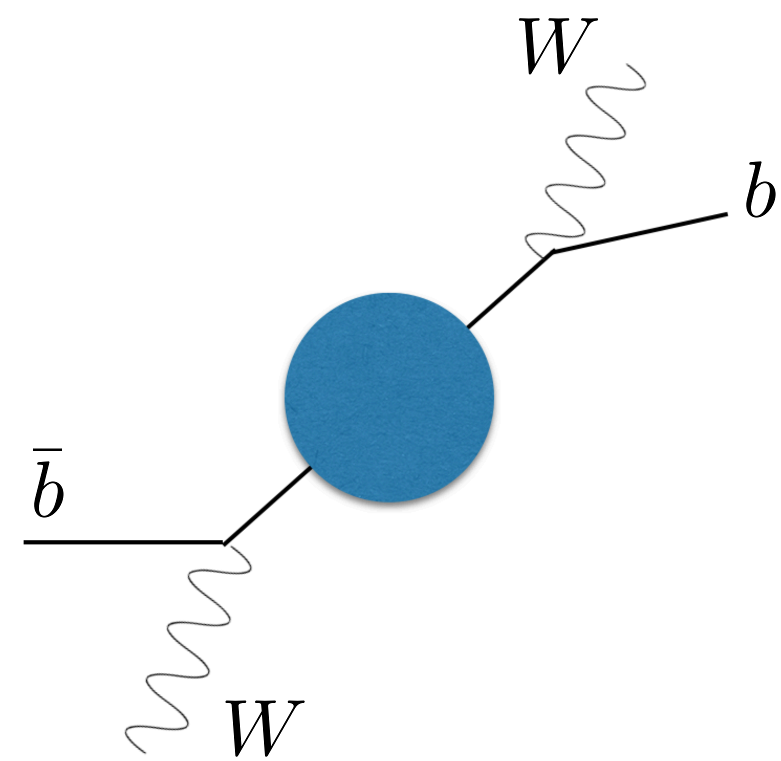
when one considers visibles+invisbles

Ian-Woo Kim, 2010

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

invariant mass





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

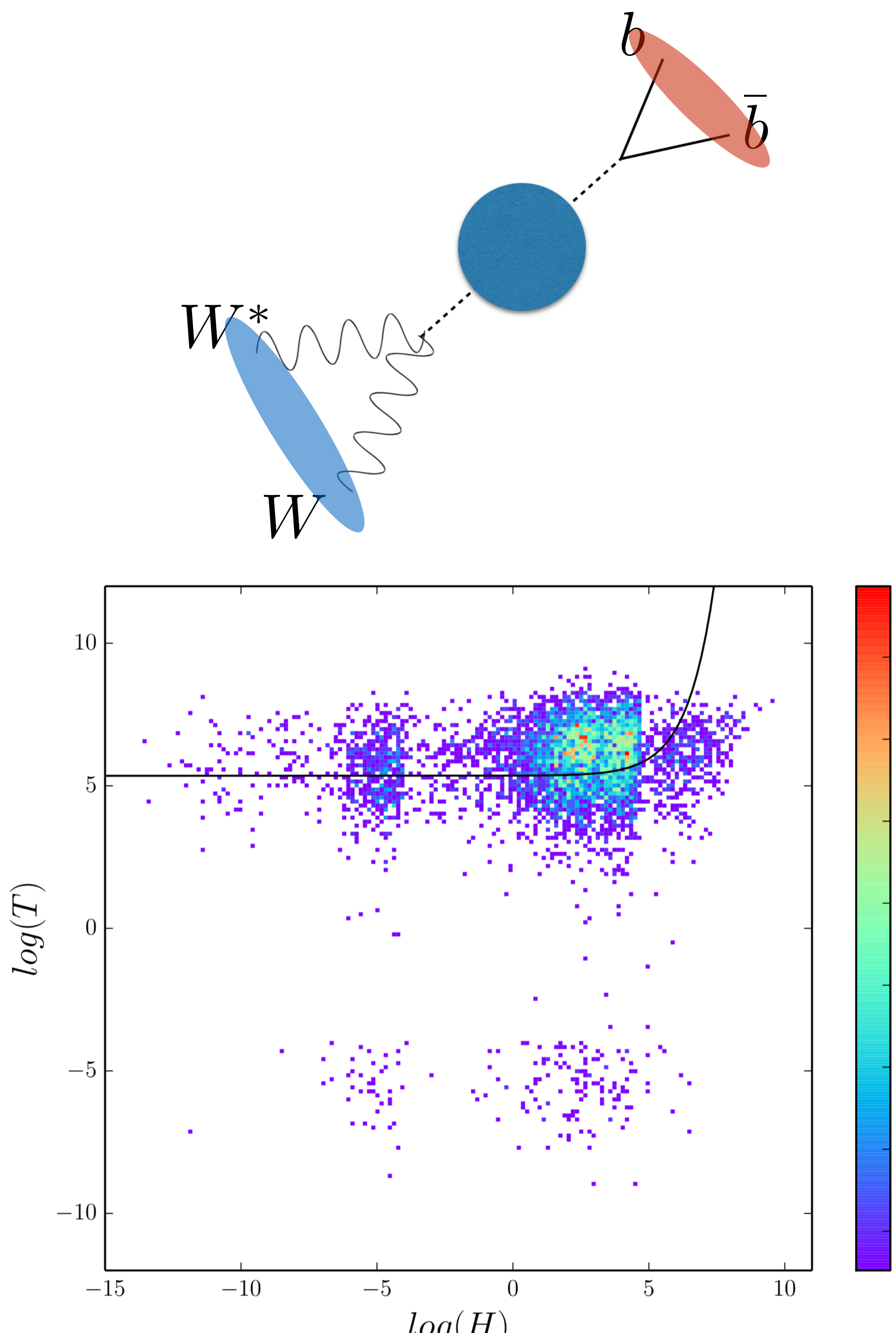
Higgs(to WW*), W, and off-shell W

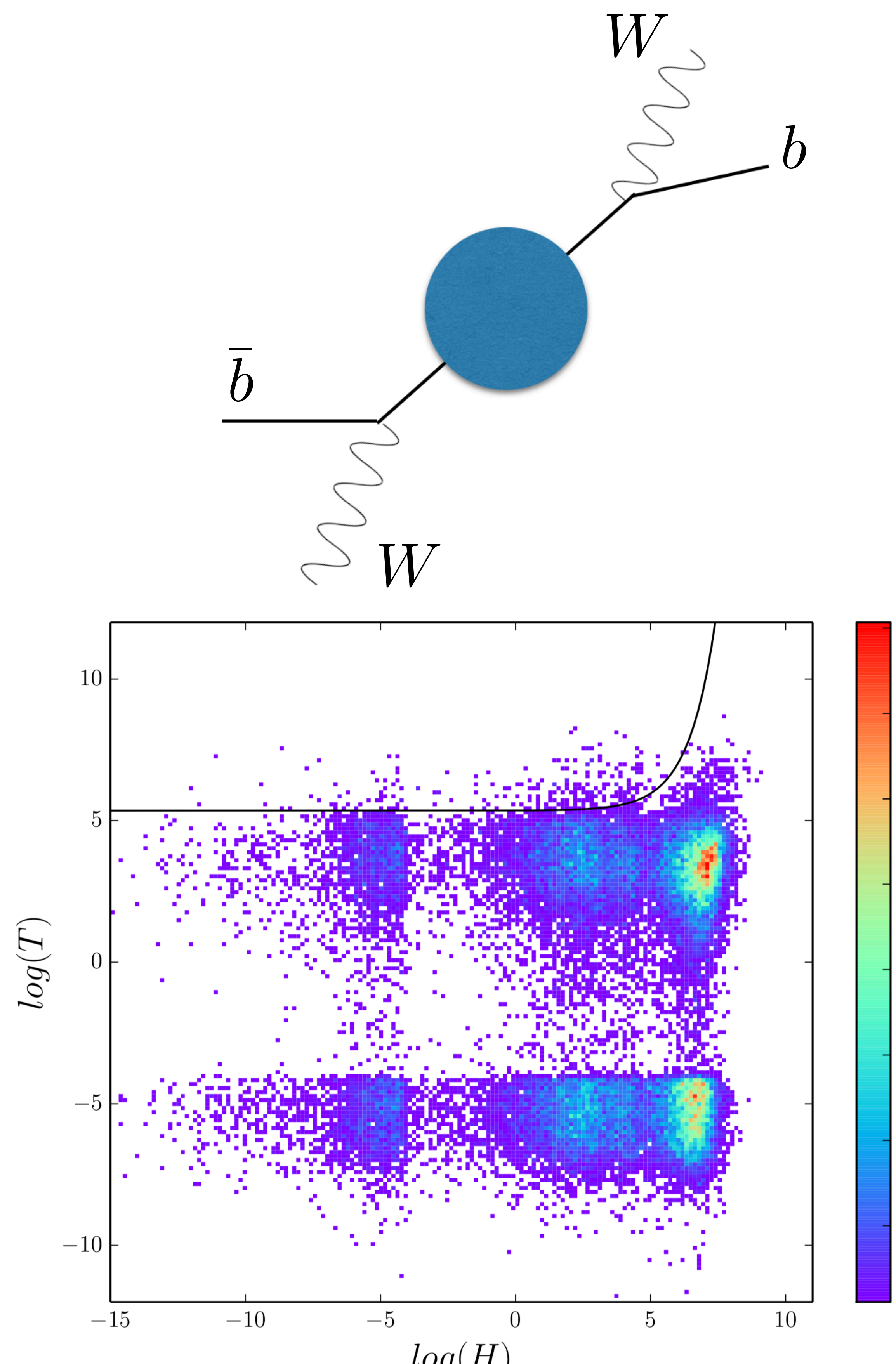
$$\chi^2_{ij} \equiv \min_{\not{\vec{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}}\left[\frac{\left(m^2_{b_i\ell^+\nu} - m^2_t\right)^2}{\sigma^4_t} + \frac{\left(m^2_{\ell^+\nu} - m^2_W\right)^2}{\sigma^4_W} + \frac{\left(m^2_{b_j\ell^-\bar{\nu}} - m^2_t\right)^2}{\sigma^4_t} + \frac{\left(m^2_{\ell^-\bar{\nu}}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

two top quarks and two W

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

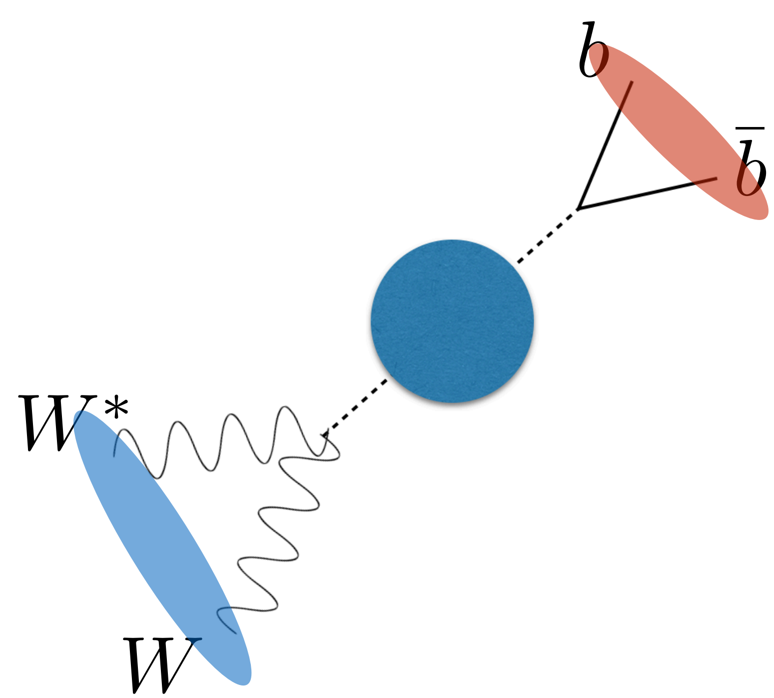
invariant mass

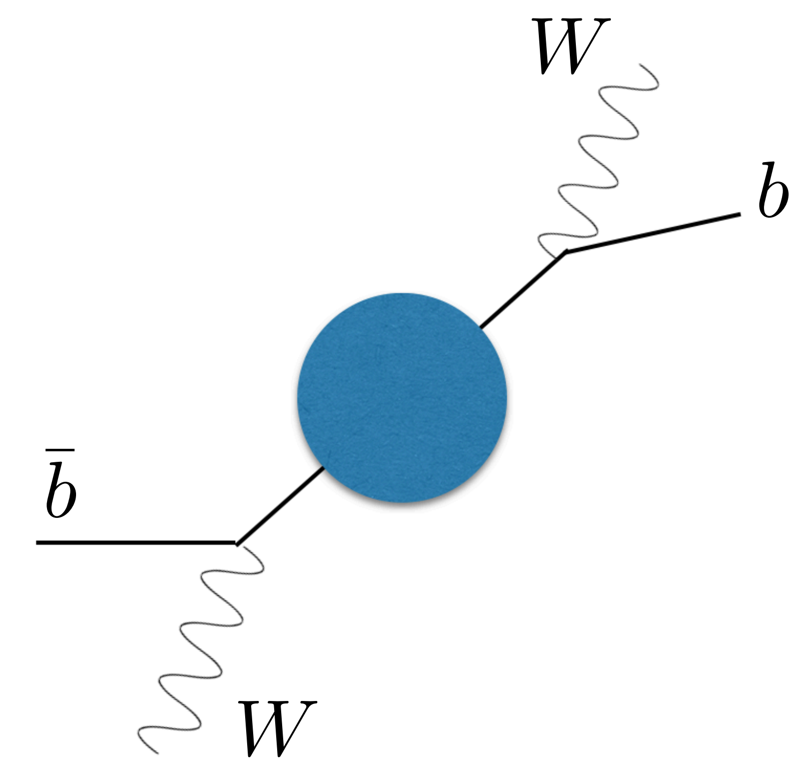


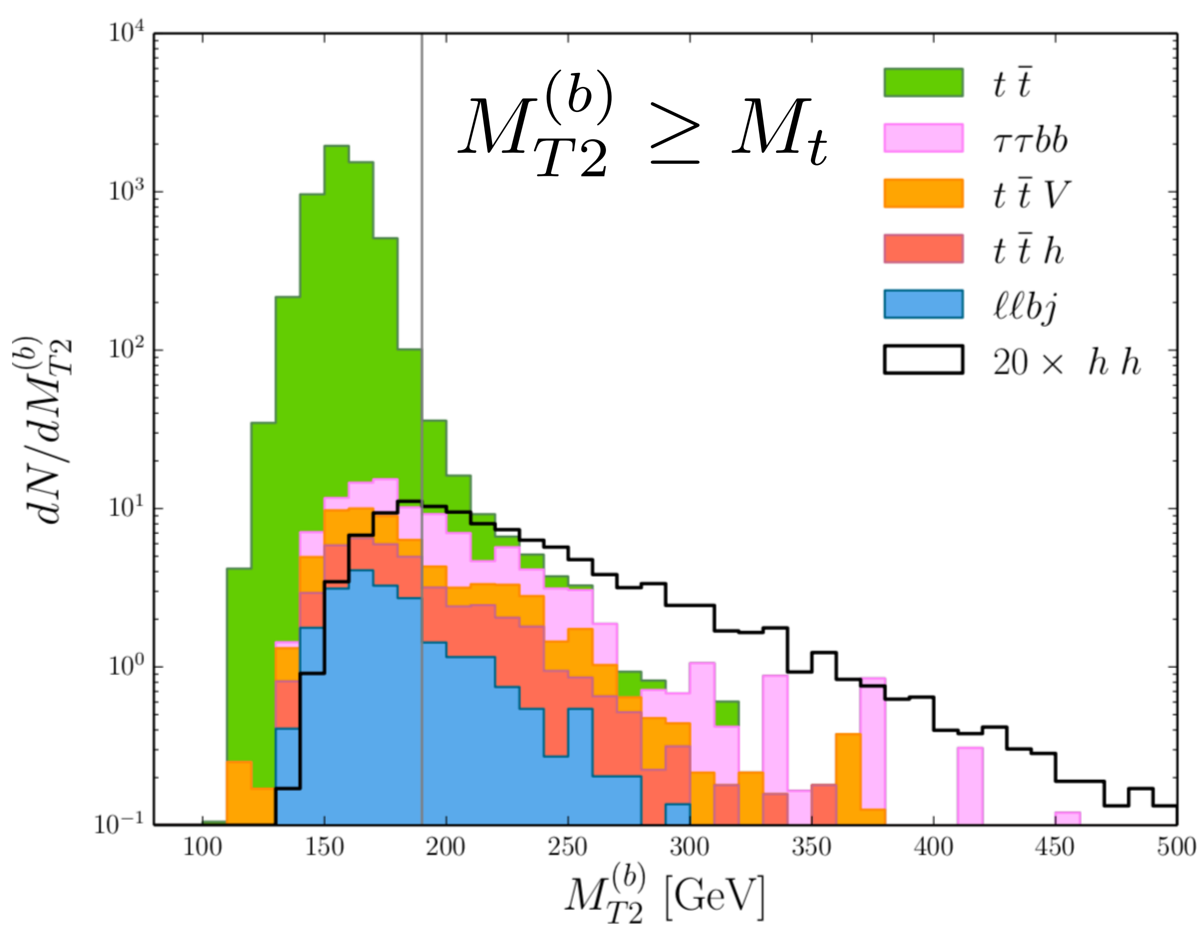


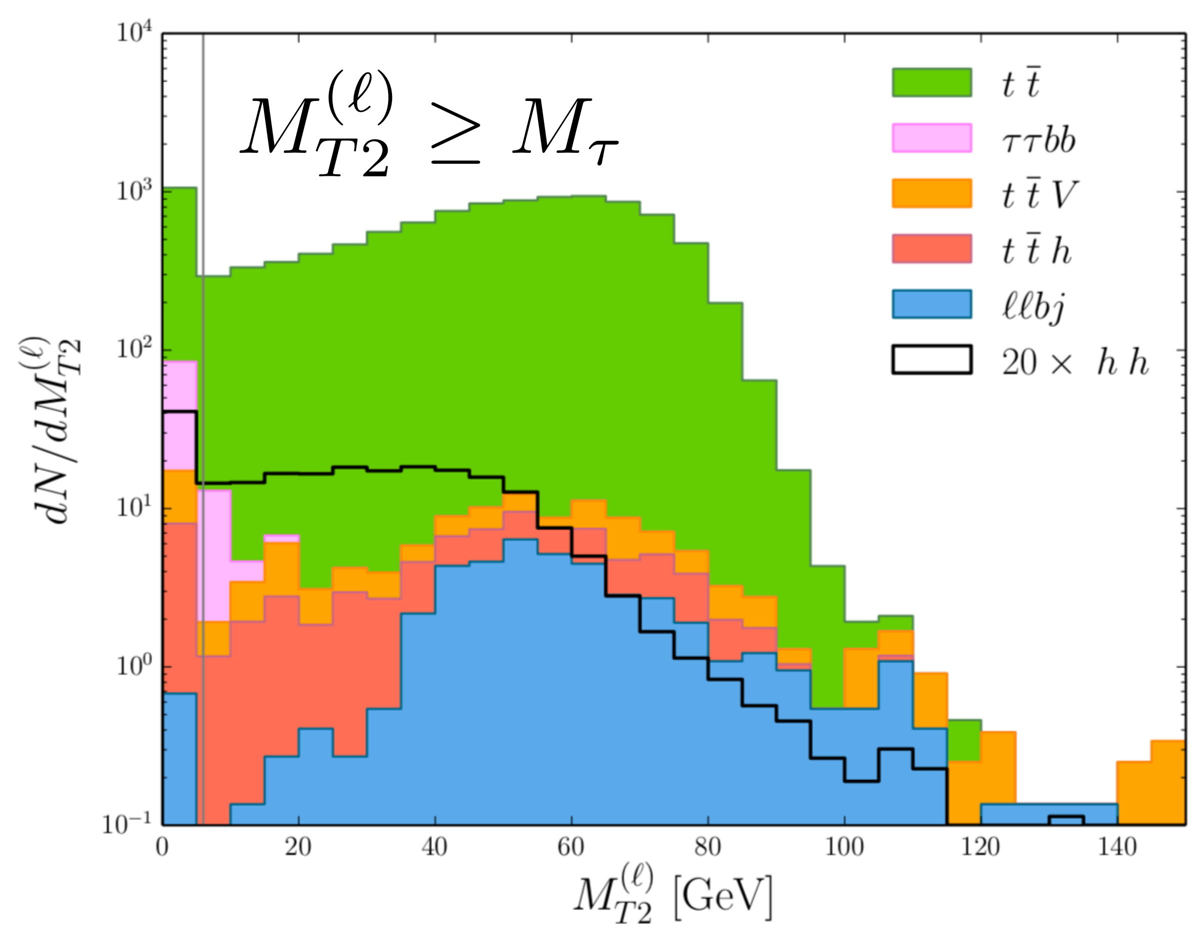
- Considering "**high-level** " kinematic cuts based on event-topology

Transverse mass

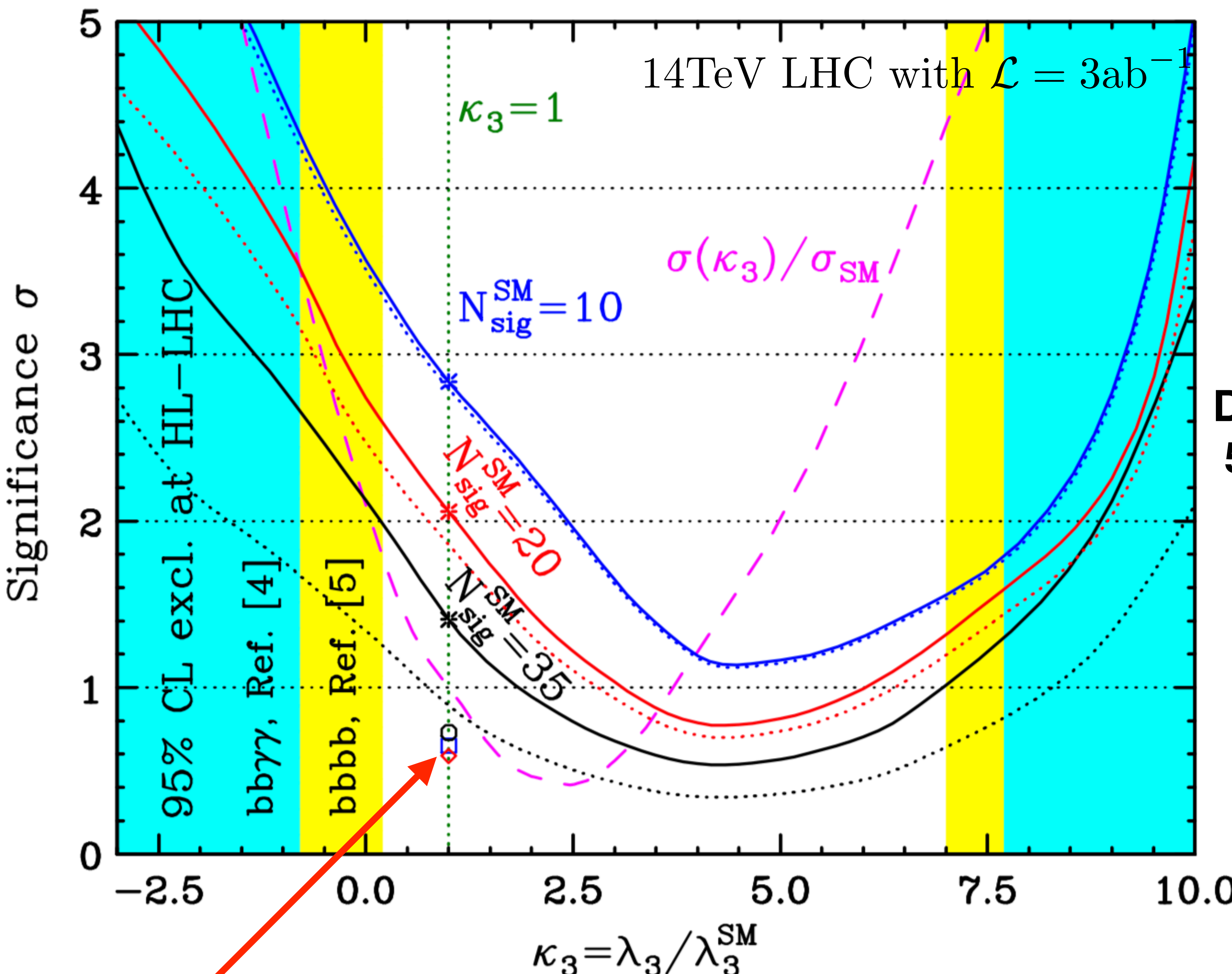








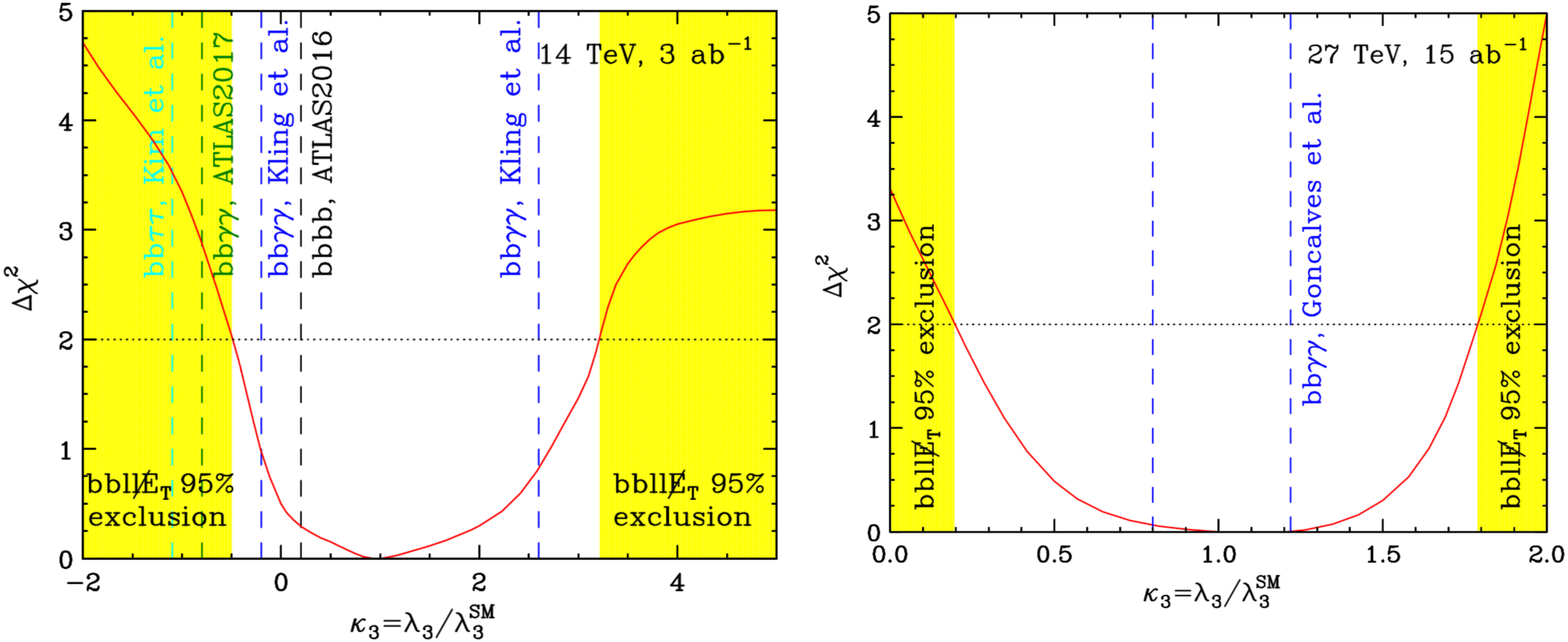
- Discovery chance for triple Higgs coupling
  - Optimization for cut is set for SM case



Dotted lines with 5% systematics

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

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

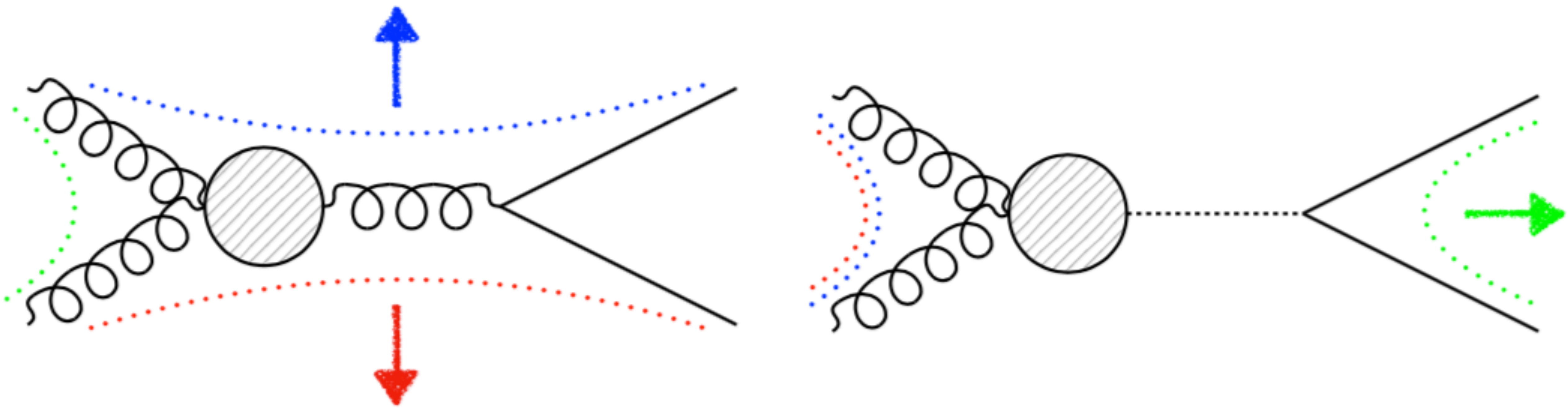


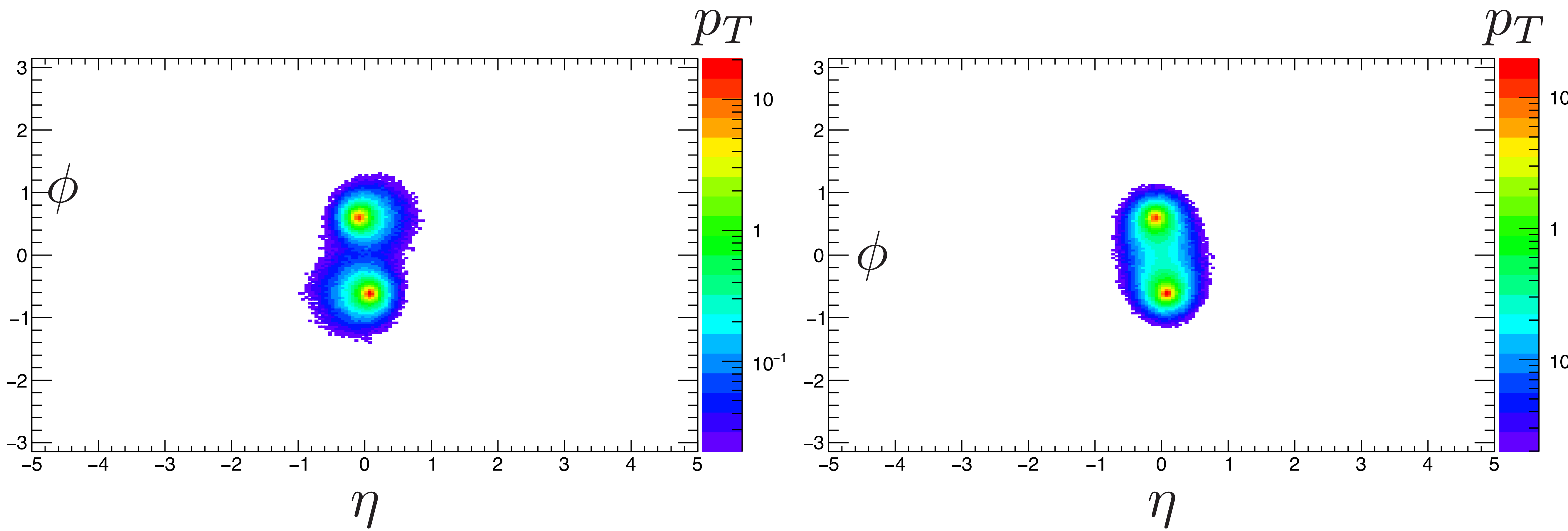
- Here the hypothesis is SM Higgs (triple coupling = SM case)

Can we do

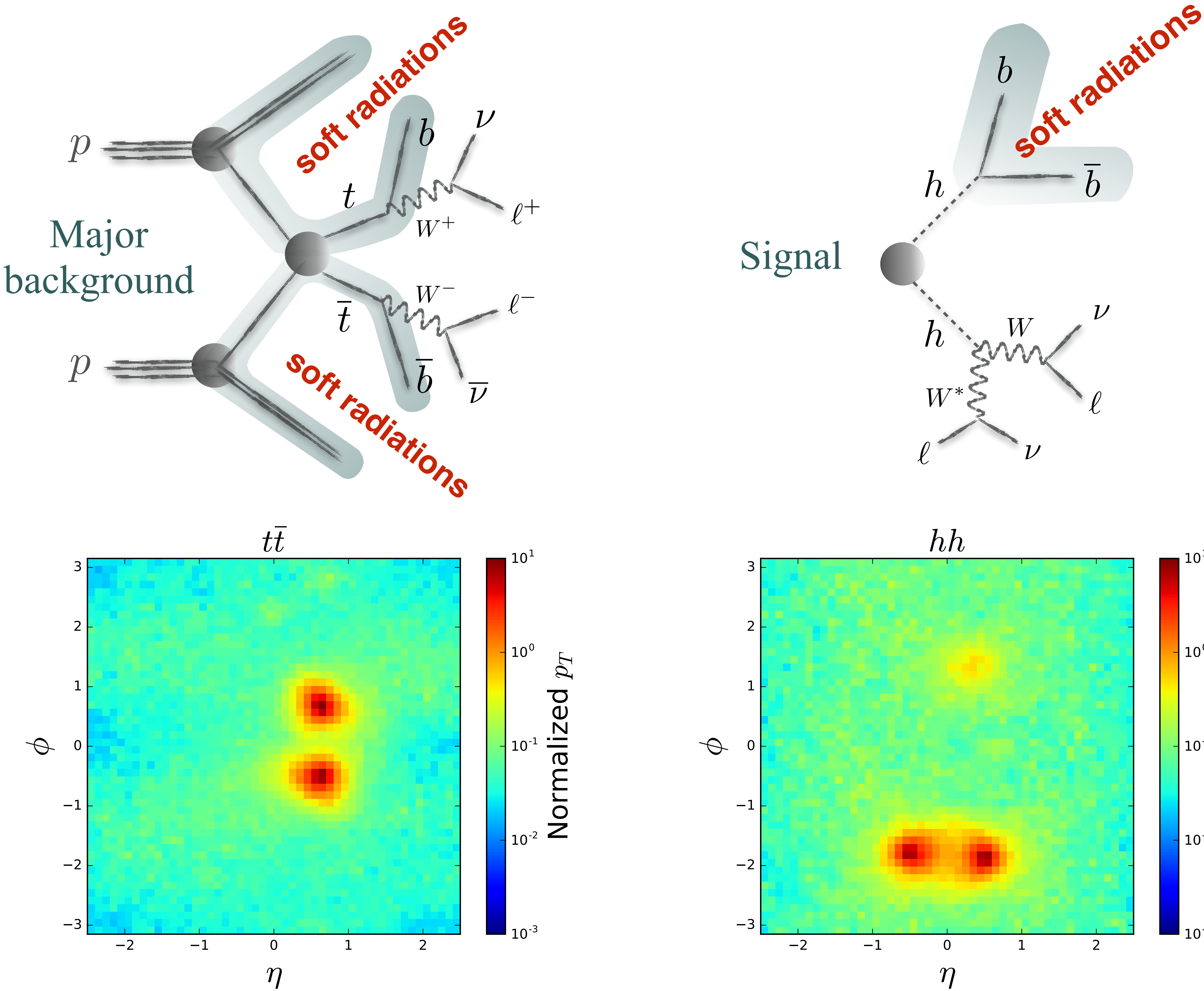
more than this?

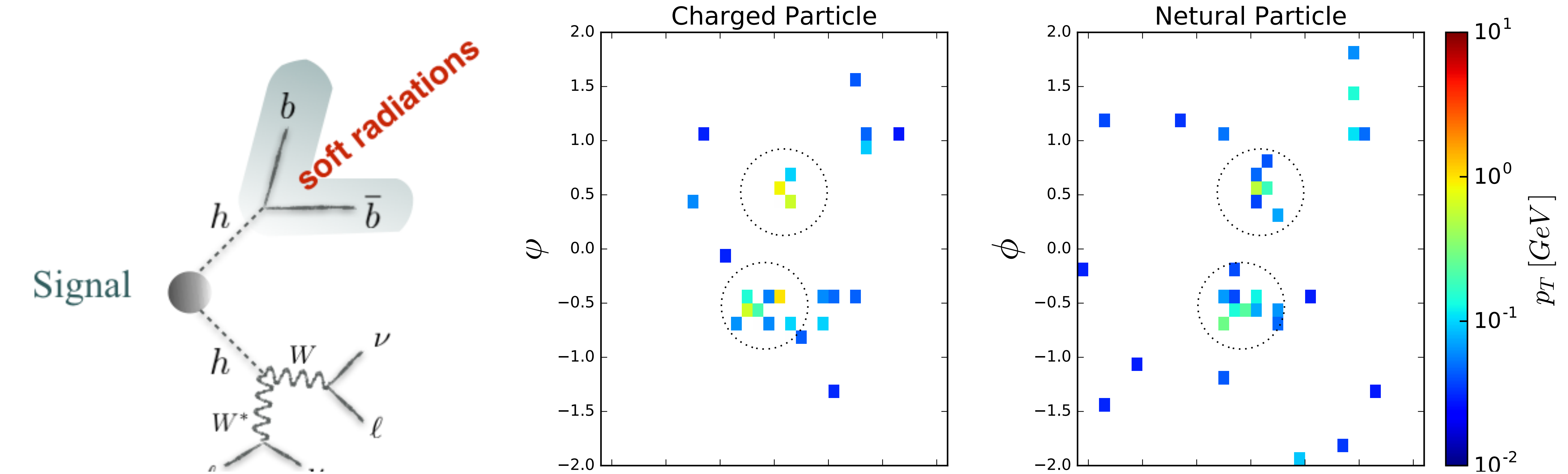
- Consider "**orthogonal**" method to kinematics; **Color-flow**



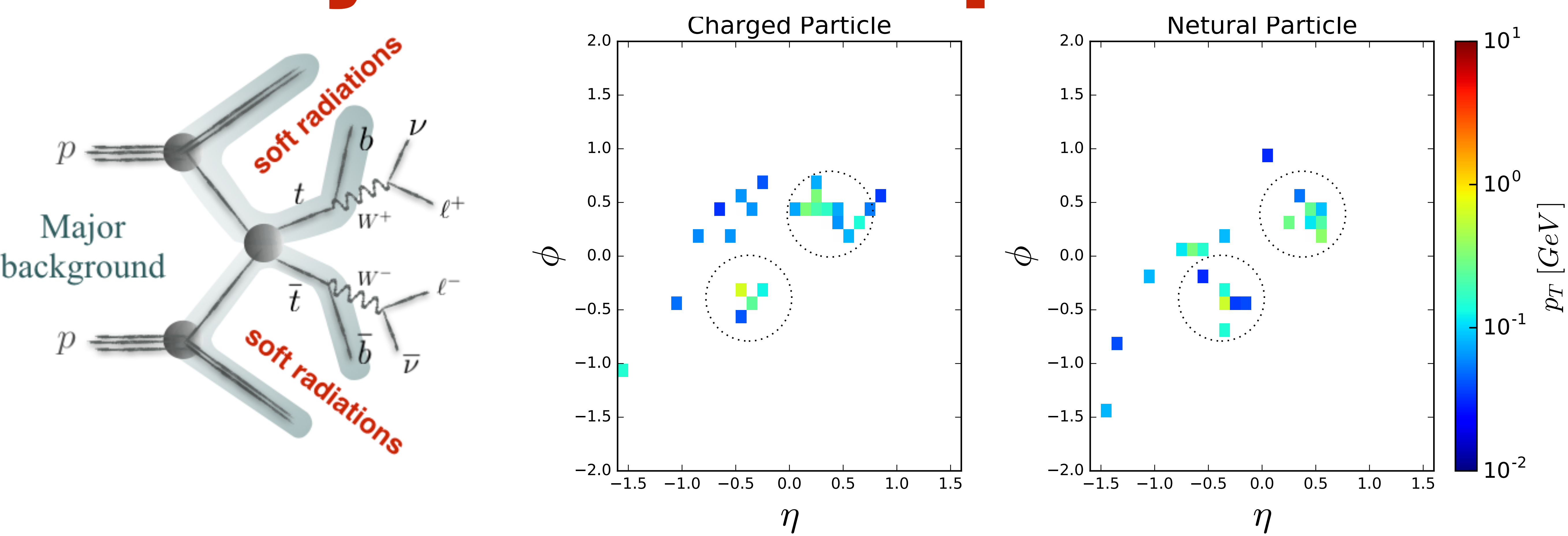


Energy deposits

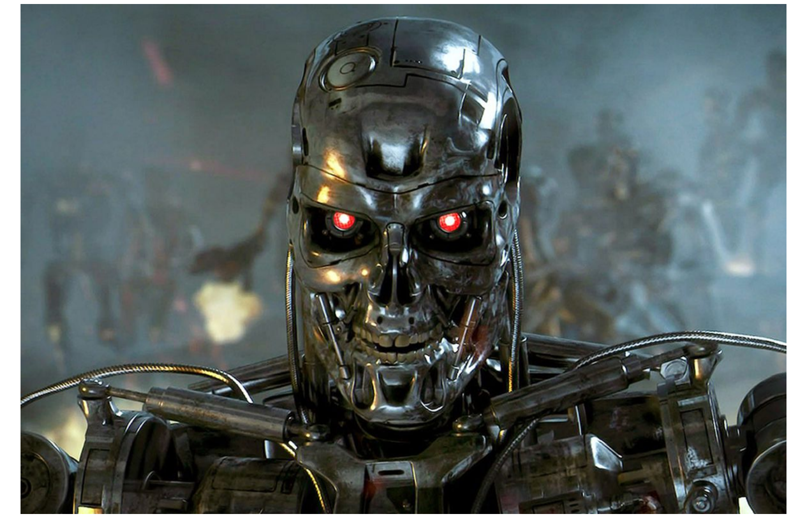

Major background
p
p
soft radiations
soft radiations
t
$\bar{t}$
b
$\bar{b}$
W^+
W^-
ν
$\bar{\nu}$
ℓ^+
ℓ^-
Signal
h
h
b
$\bar{b}$
soft radiations
W
W^*
ν
ℓ
ℓ
ν
$t\bar{t}$
hh
η
φ
Normalized p_T
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}



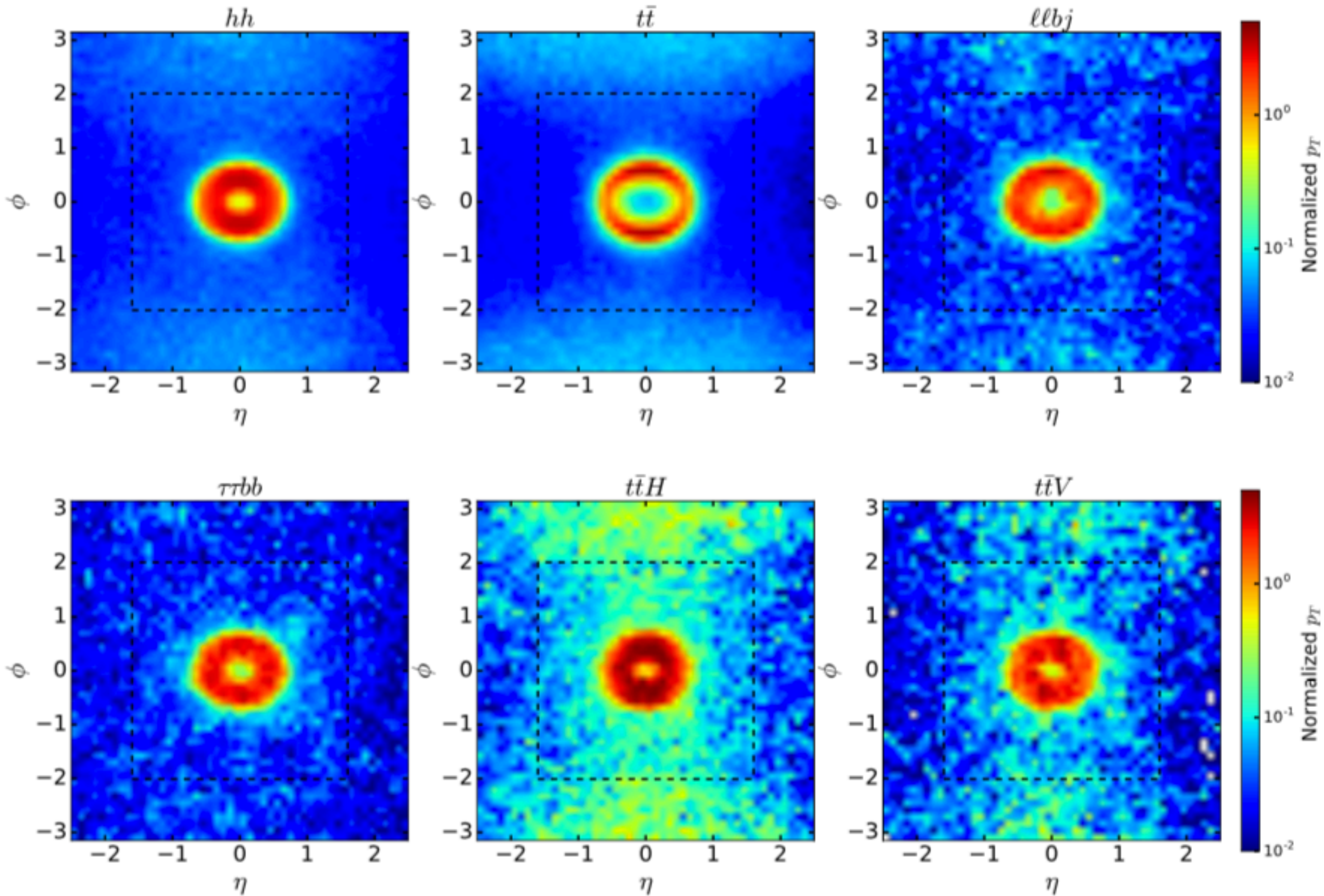
Can you see a pattern?



Let's leave **simple and mundane jobs** to a **machine**



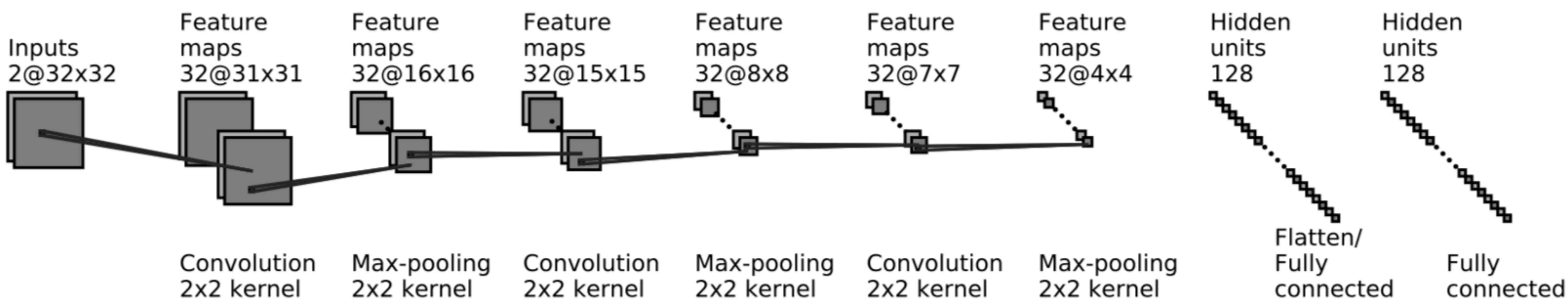
- Whole events with bbar (fat-jet) axis as a center



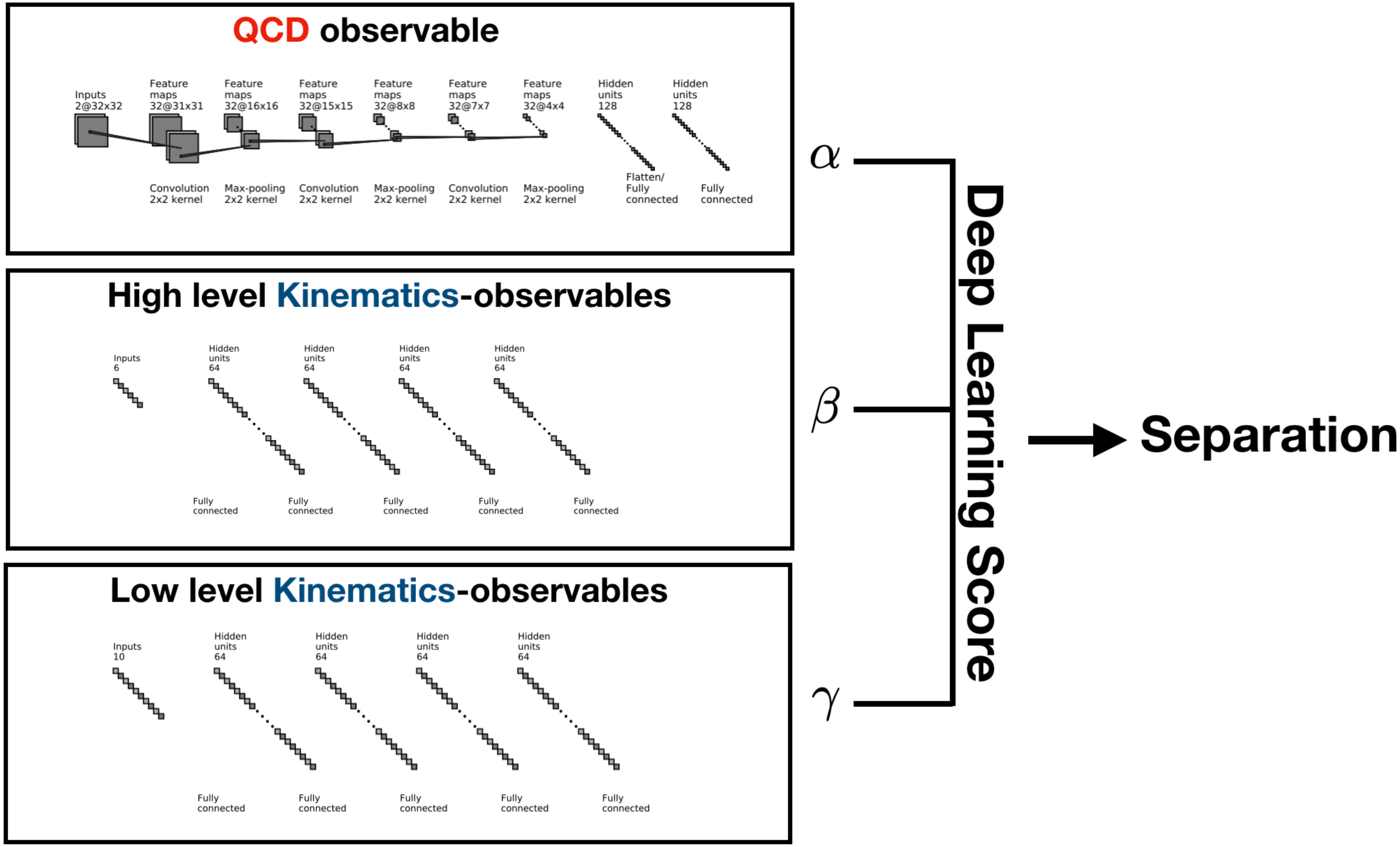
Maximizing information with Deep Neural Network

- 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



For technical details about DNN, please contact **Minho Kim** (kmhmon@postech.ac.kr)

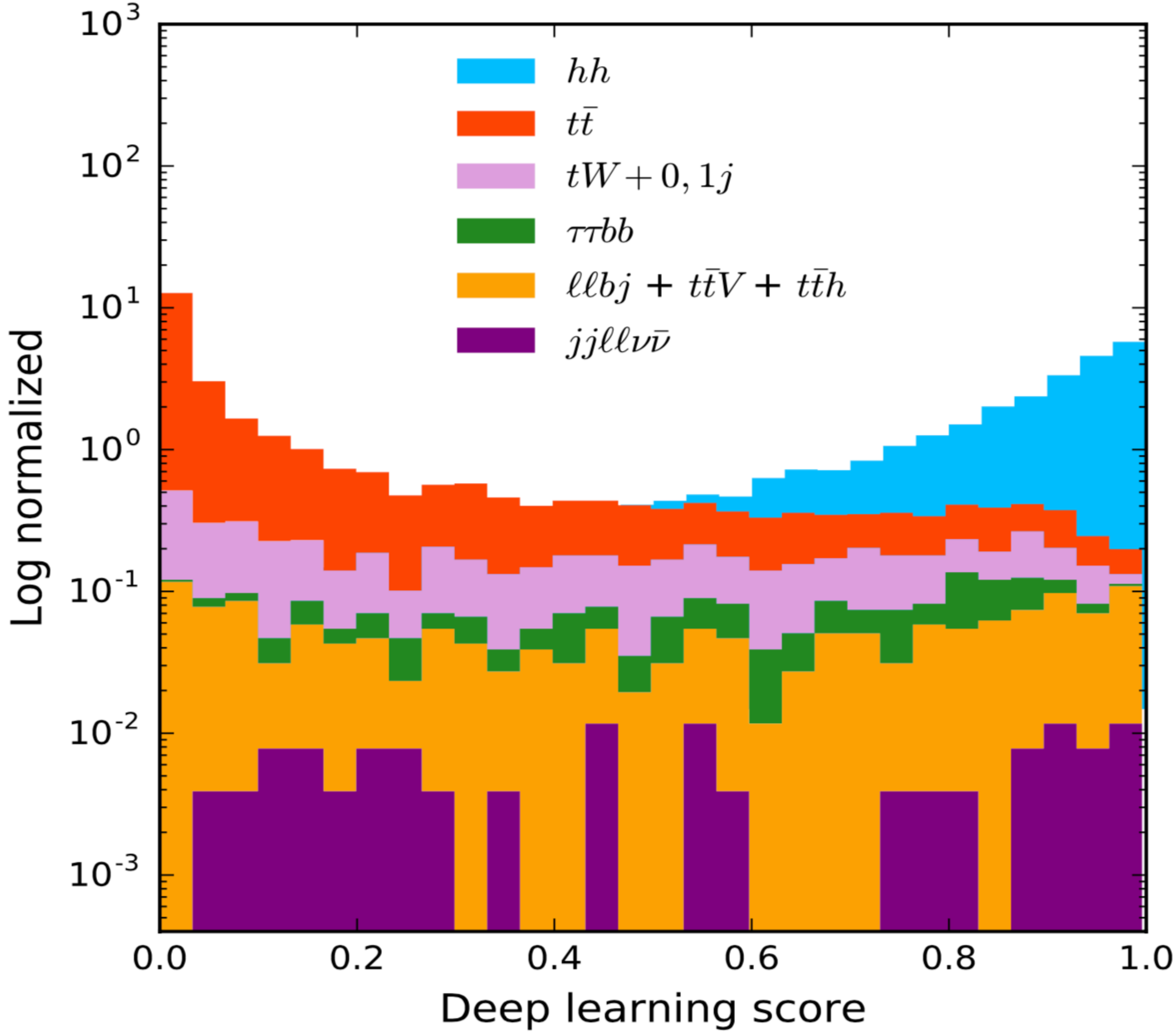


6 High Level Variables

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

10 Low Level Variables

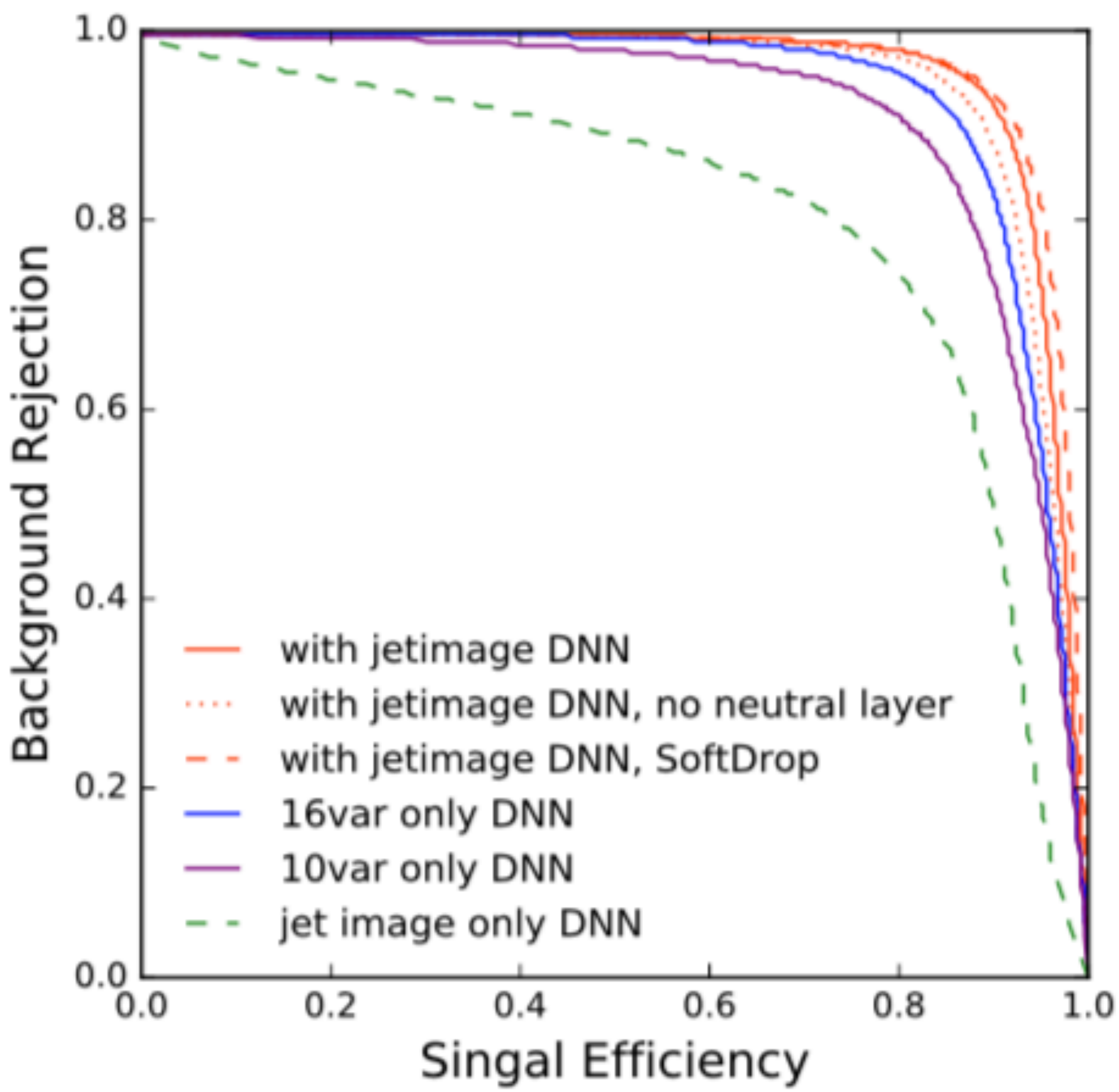
Input data: MET $p^t_{\bar{\ell}}$ p^t_{ℓ} $\Delta R_{(\bar{\ell},\ell)}$ $M_{(\bar{b},b)}$ $p^t_{(\bar{b},b)}$ $\Delta R_{(\bar{b},b)}$ $M_{(\bar{\ell},\ell)}$ $p^t_{(\bar{\ell},\ell)}$, $\Delta\phi_{\{(\bar{\ell},\ell),(\bar{b},b)\}}$

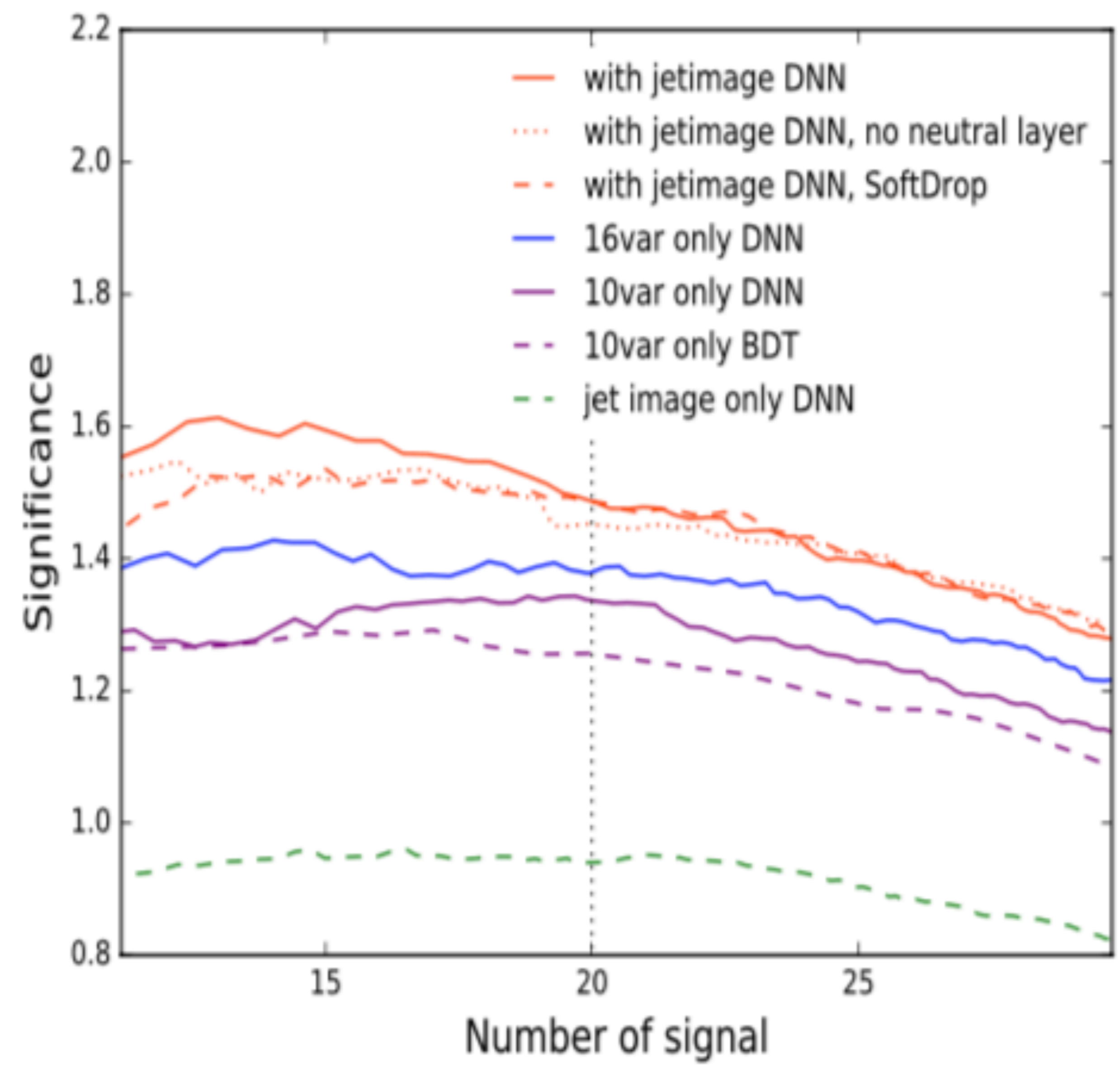


"Backgrounds as stacked Histogram"

- To estimate effects from **pileup** removal,

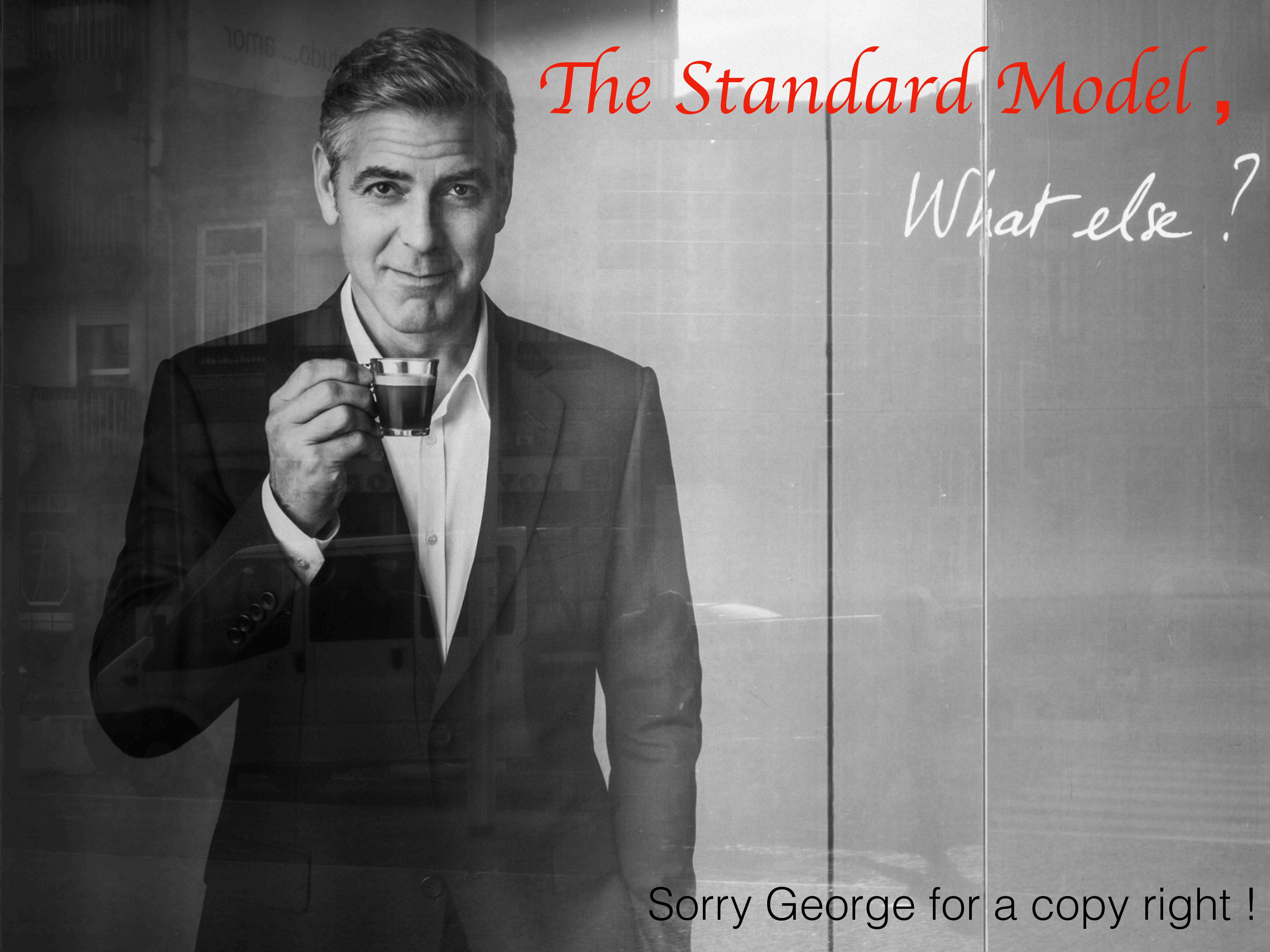
0. No additional processes.
1. we apply SoftDrop to a fat-jet (R= 1.2 anti-Kt)
2. we use only charged layer





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.


The Standard Model ,
What else ?
Sorry George for a copy right !

Really George?

Precision to a New Physics!!!