Sensitivity on Two-Higgs Doublet Models from Higgs-Pair Production via $b\bar{b}b\bar{b}$ Final State

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2207..09602

Yonsei University 2022-7-27

References

- Chih-Ting Lu, Jung Chang, KC, Jae Sik Lee, An exploratory study of Higgs-boson pair production, JHEP 1508 (2015) 133
- Yi-Lun Chung, Shih-Chieh Hsu, Ben Nachman, Disentangling Boosted Higgs Boson Production Modes with Machine Learning, JINST, 2009.05930.
- K.C., Yi-Lun Chung, Shih-Chieh Hsu, Ben Nachman, Exploring the Universality of Hadronic Jet Classification, 2204.03812
- K.C., Yi-Lun Chung, Shih-Chieh Hsu, Sensitivity on Two-Higgs Doublet Models from Higgs-Pair Production via $b\bar{b}b\bar{b}$ Final State, 2207.09202.

Understand Higgs Interactions

- Basically the Higgs boson couples to massive particles, proportional to the mass.
- So the Higgs boson mainly interacts with W, Z bosons, top quark. Because they are heavy.

- $H \to WW, ZZ$: The couplings of H to WW and ZZ are

$$\mathcal{L} = g m_W \, H \, W^{+\,\mu} \, W^-_\mu + \frac{1}{2} g_z m_Z H \, Z \, Z$$

- $H \to f\bar{f}$: The decay into a fermion pair is given by

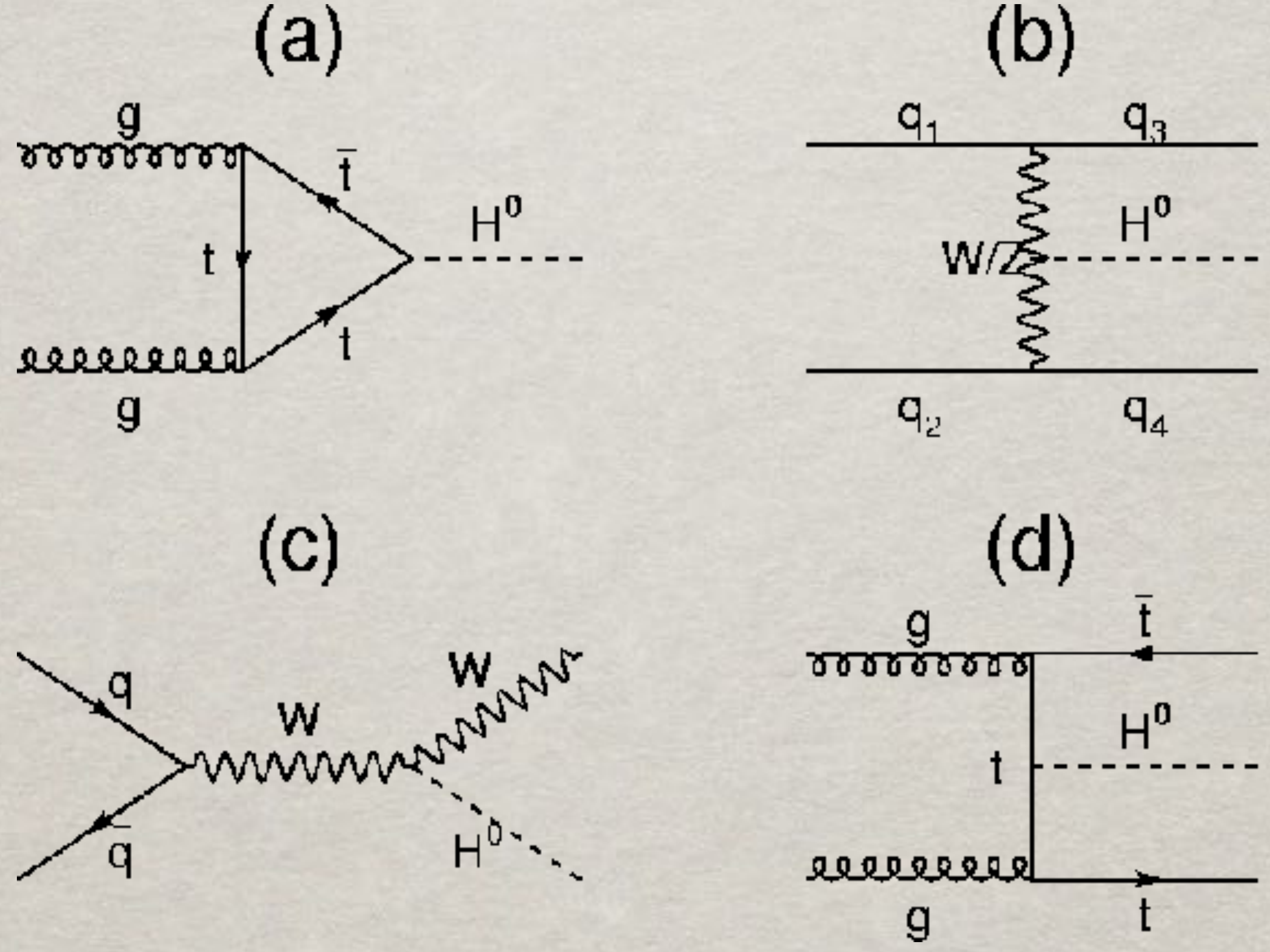
$$\mathcal{L} = -\frac{g m_f}{2 m_W} H \, \bar{f} \, f$$

- $H \to gg$: Higgs decays into a pair of gluons via a triangular loop described by an effective Lagrangian

$$\mathcal{L} = -\frac{g^2}{2 m_W} \frac{\alpha_s(m_H)}{12\pi} \; I \; G^a_{\mu\nu} \, G^{a\,\mu\nu} \; H$$

- $H \to \gamma\gamma, Z\gamma$:

Higgs Production Mechanisms

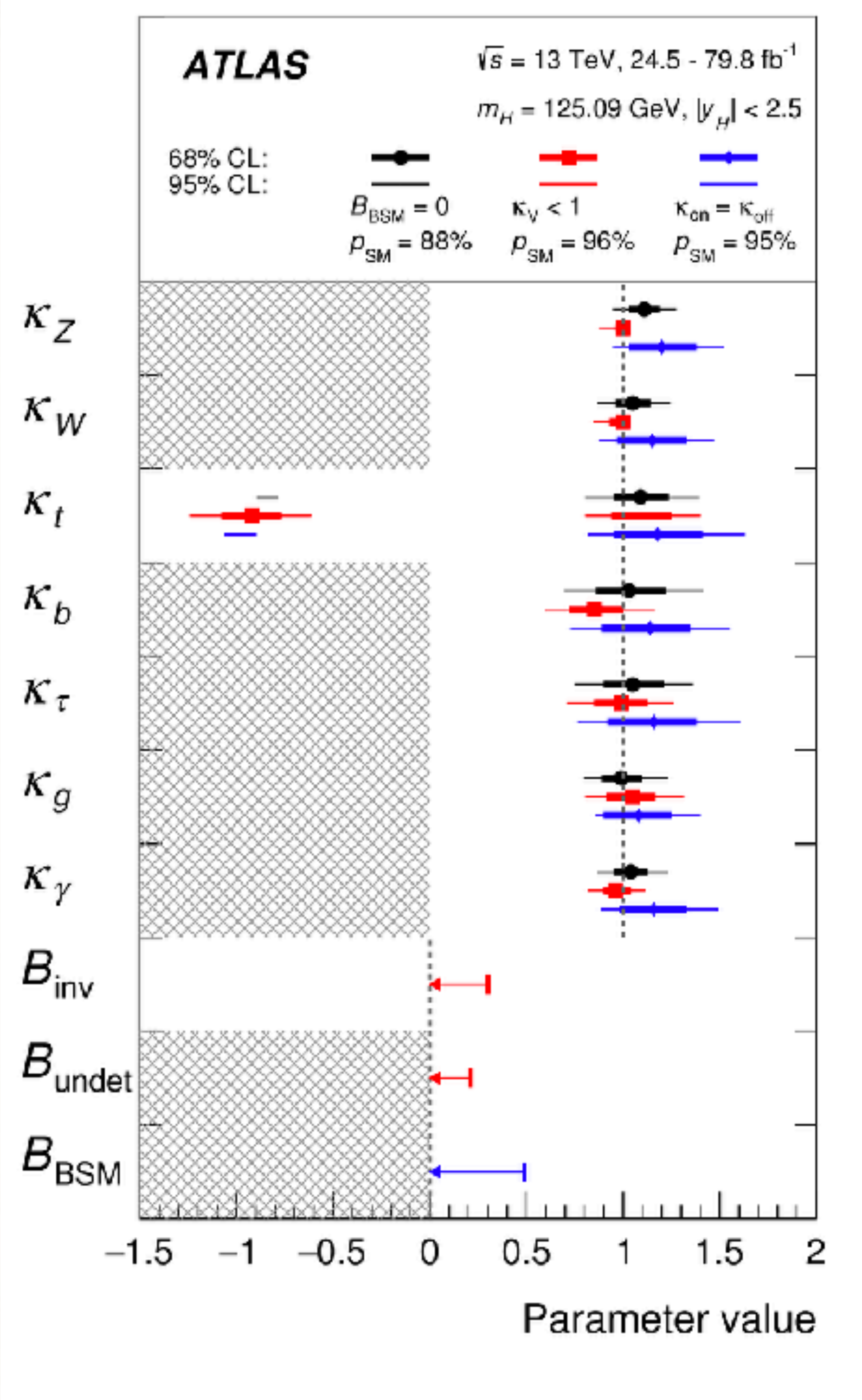


Summary by ATLAS

$B_{inv}=B_{undet}=0$ (black);

B_{inv} and B_{undet} included as free parameters, the conditions $\kappa_{W,Z} \leq 1$ (RED)

$B_{BSM}=B_{inv}+B_{undet}$ included as a free parameter (BLUE)



Higgs Sector Itself

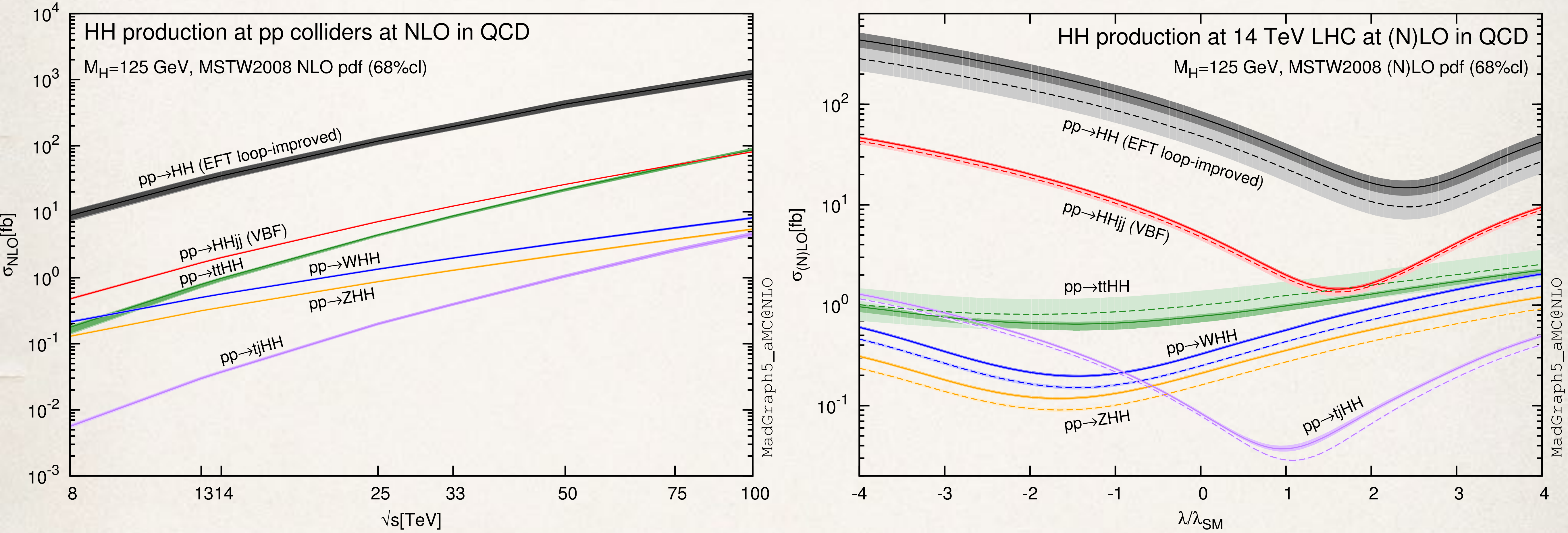
We have no information about $V(\Phi)$ except that it gives a nontrivial VEV. In the SM,

$$V(\phi) = -\frac{\lambda}{4}v^4 + \frac{1}{2}m_H^2 H^2 + \frac{m_H^2}{2v}H^3 + \frac{\lambda}{4}H^4$$

This is the simplest structure. The self couplings are fixed. But for extended Higgs sector it is not the case.

Probing self interactions of the Higgs boson becomes an important avenue to understand the Higgs sector.

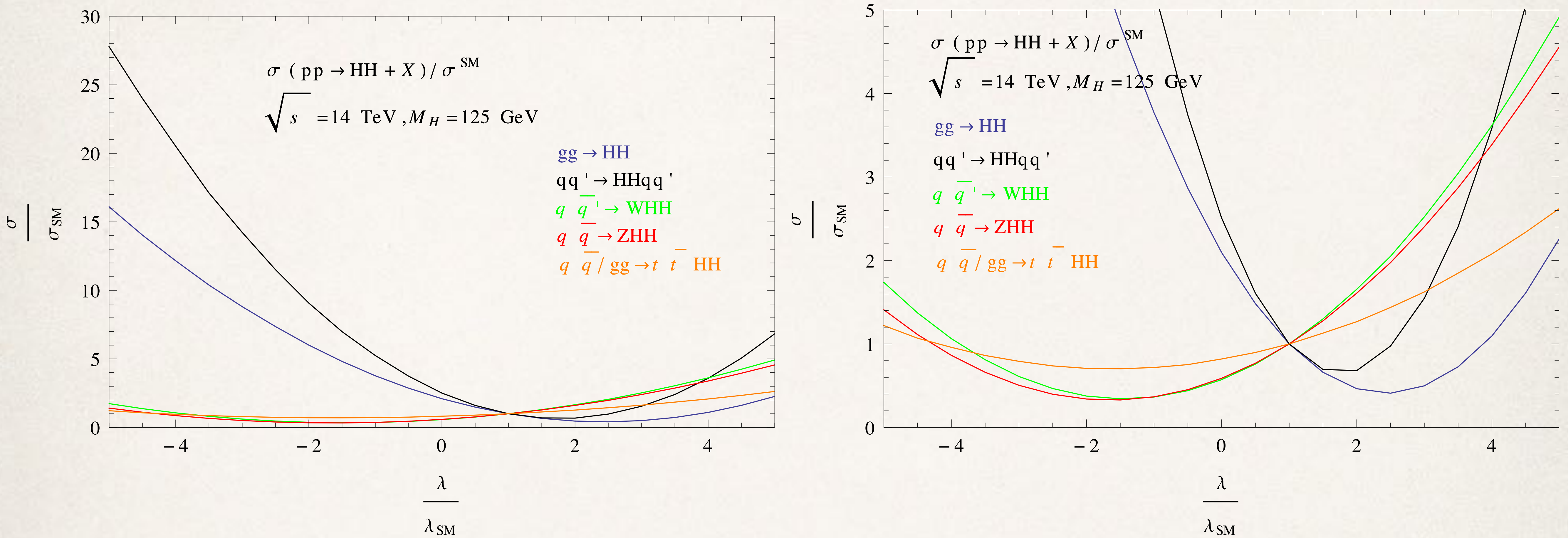
Channels for testing HHH coupling



Frederix et al. 1401.7340

SM Cross sections [4]

$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82



The ggF has the largest cross section, of order 10 - O(100) fb.

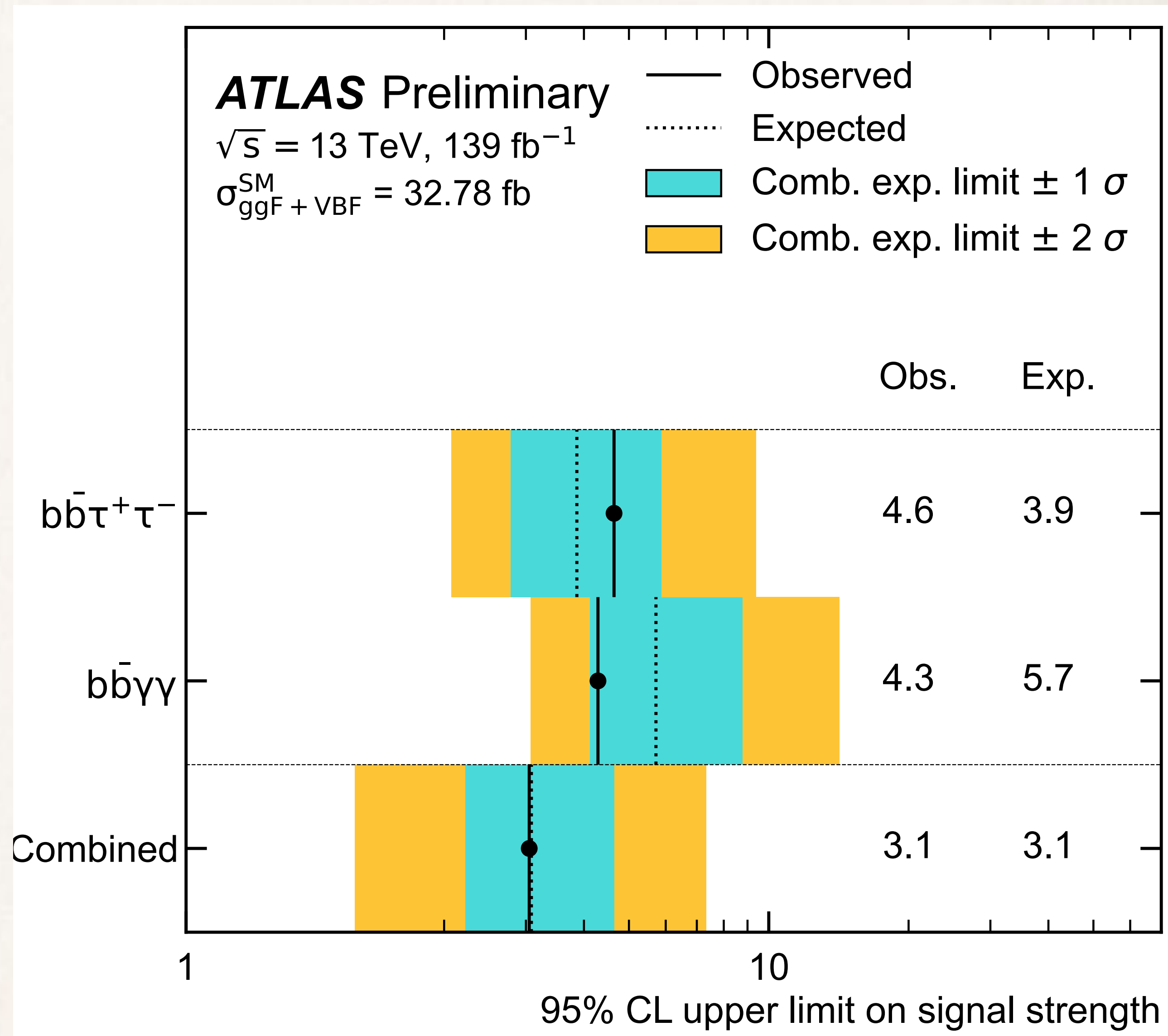
The VBF has the best sensitivity to Lambda_3H, but the cross section is one order smaller.

C.T. Lu, K.C., J. Chang, J.S. Lee, J.Park

A summary of HH production by ATLAS

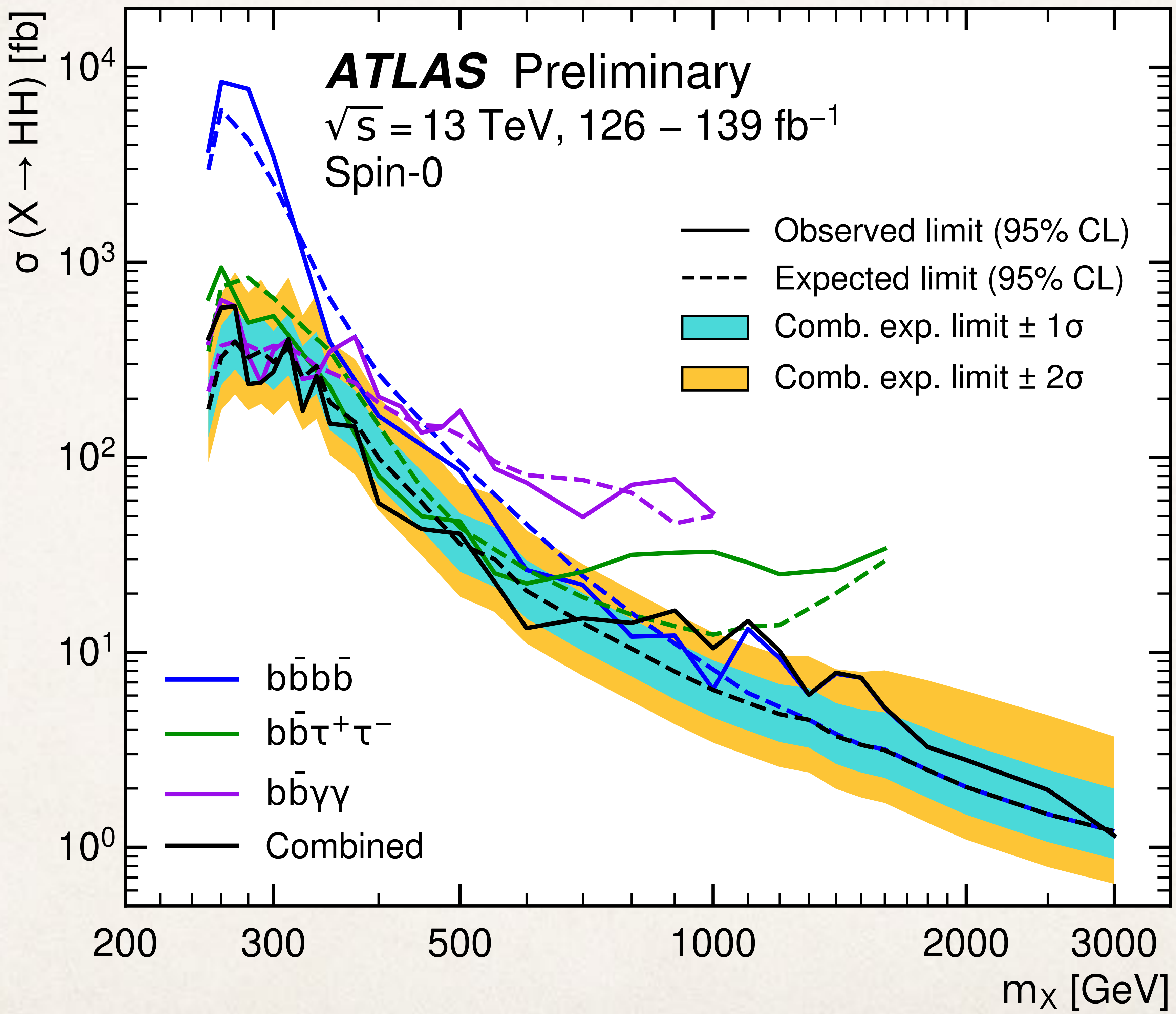
95% confidence level allowed ranges for κ_λ,

	Obs.	Exp.
$b\bar{b}\gamma\gamma$	$[-1.6, 6.7]$	$[-2.4, 7.7]$
$b\bar{b}\tau^+\tau^-$	$[-2.4, 9.2]$	$[-2.0, 9.0]$
Combined	$[-1.0, 6.6]$	$[-1.2, 7.2]$



Non-resonant HH Production

95% confidence level upper limits on $\sigma(X \to HH)$ for a spin-0 resonance

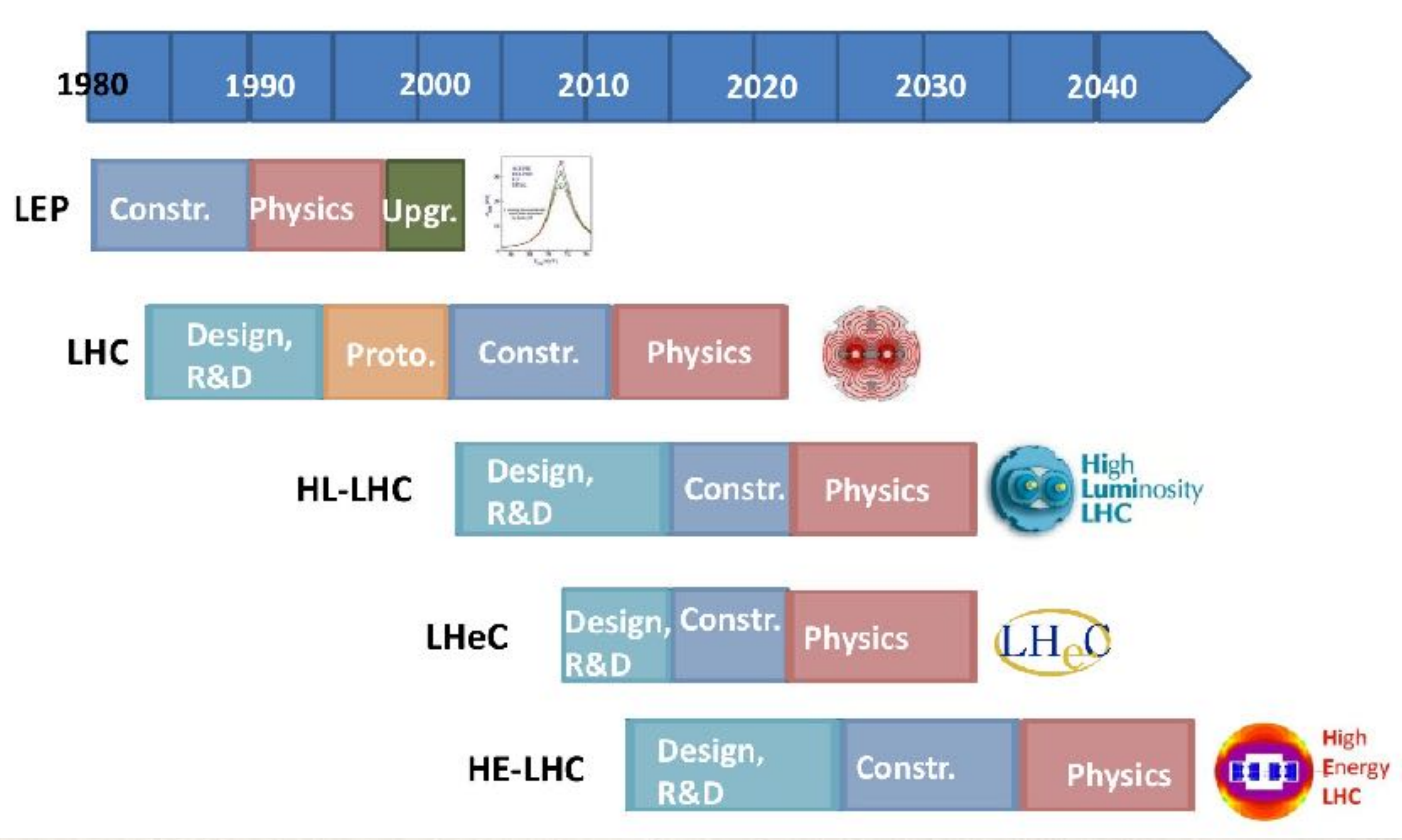


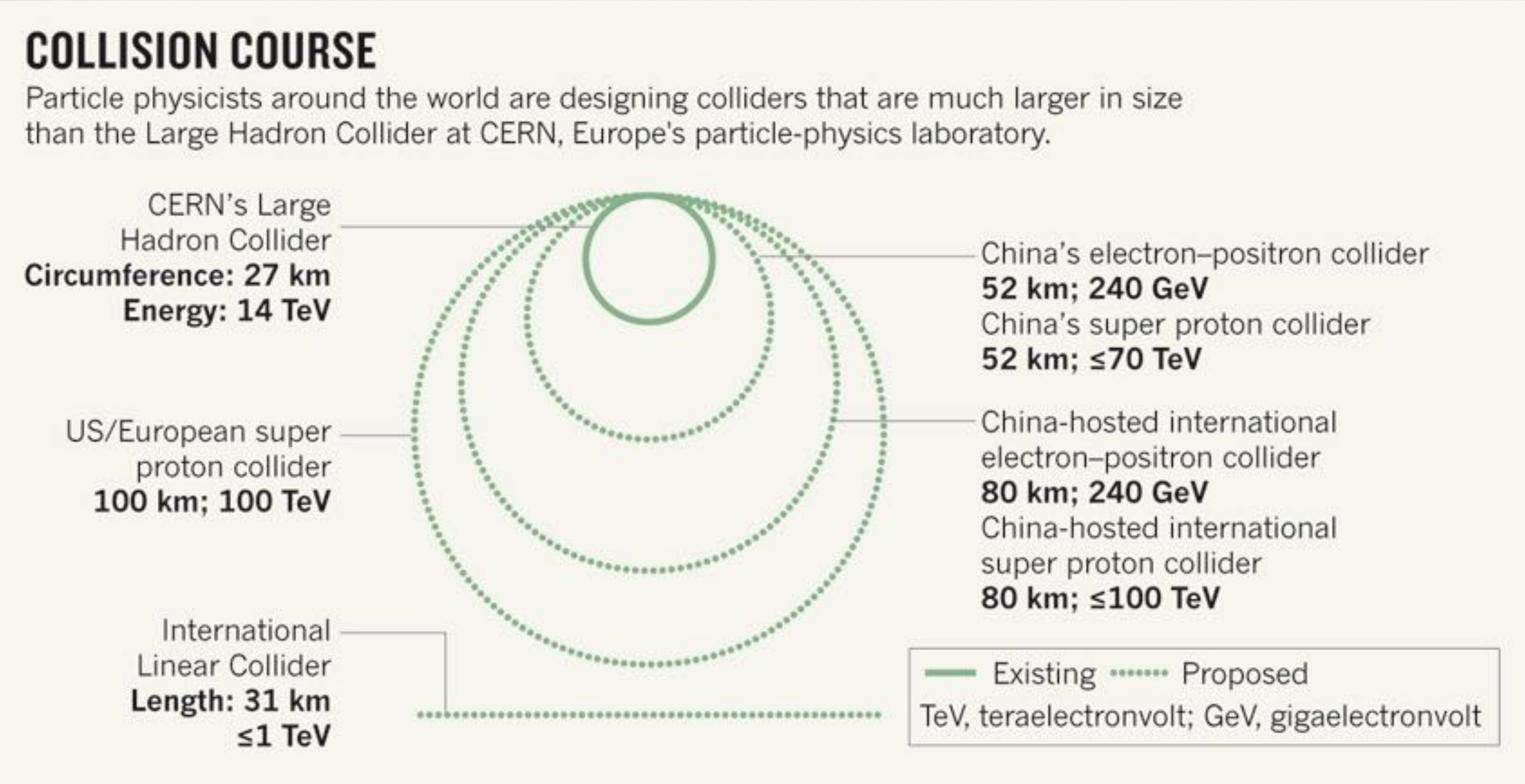
Resonant HH Production

Instead of investigating modified λ_{hhh}, we turn the focus to
resonance effects in Higgs pair production

HL-LHC

$\sqrt{s}$ = 14 TeV, L =3000 fb^{-1} Focus on $H(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$ **Analysis**





100 TeV pp Collider:

US/Europe vs China

Motivation

1. The SM Higgs boson cannot fix the gauge hierarchy problem. It requires unnatural cancellation for the bare and loop-corrected Higgs boson mass.

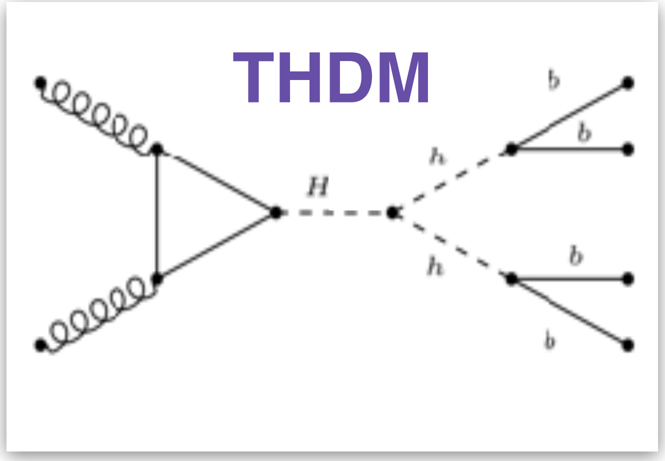
2. Many extensions of the EWSB sector consist of more Higgs fields
   - **Two-Higgs doublet models (2HDMs)**, MSSM, and any composite Higgs models

3. Probe the Higgs self-couplings is to probe the structure of the Higgs sector
   - Higgs-pair production via gluon-gluon fusion at the LHC

4. Study the signal process $pp \to hh \to b\bar{b}b\bar{b}$ via gluon fusion against the SM backgrounds at the High-Luminosity LHC via machine learning approach.

5. The boosted hadronic Higgs jet can help to against the background

hadronic jet tagger



Outline

- Universality of hadronic jet classification
- Disentangling of Boosted Higgs production modes
- Apply the boosted Higgs jet tagging to

$$gg \to H \to hh \to b\bar{b}b\bar{b}$$

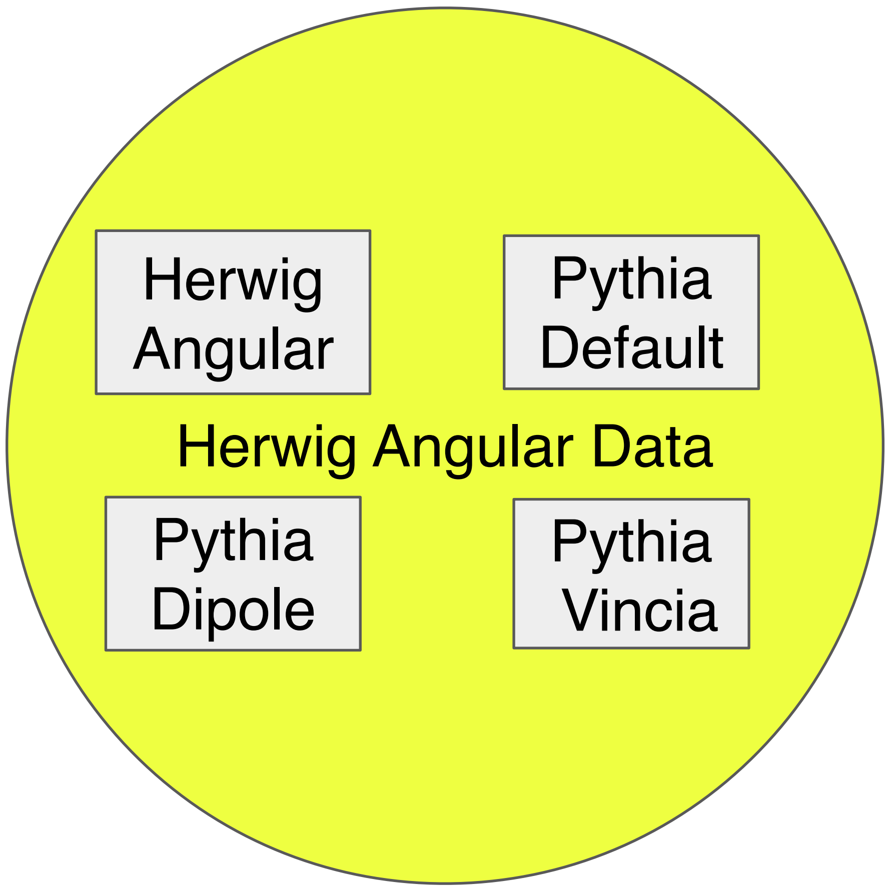
- Sensitivity to the 2HDM parameter space

Universality of Hadronic Jet Classification

1. Two-point uncertainty
   - fragmentation modeling
   - between each generator

2. Study precision of NN model
   - fix test sample
   - vary trained NN models

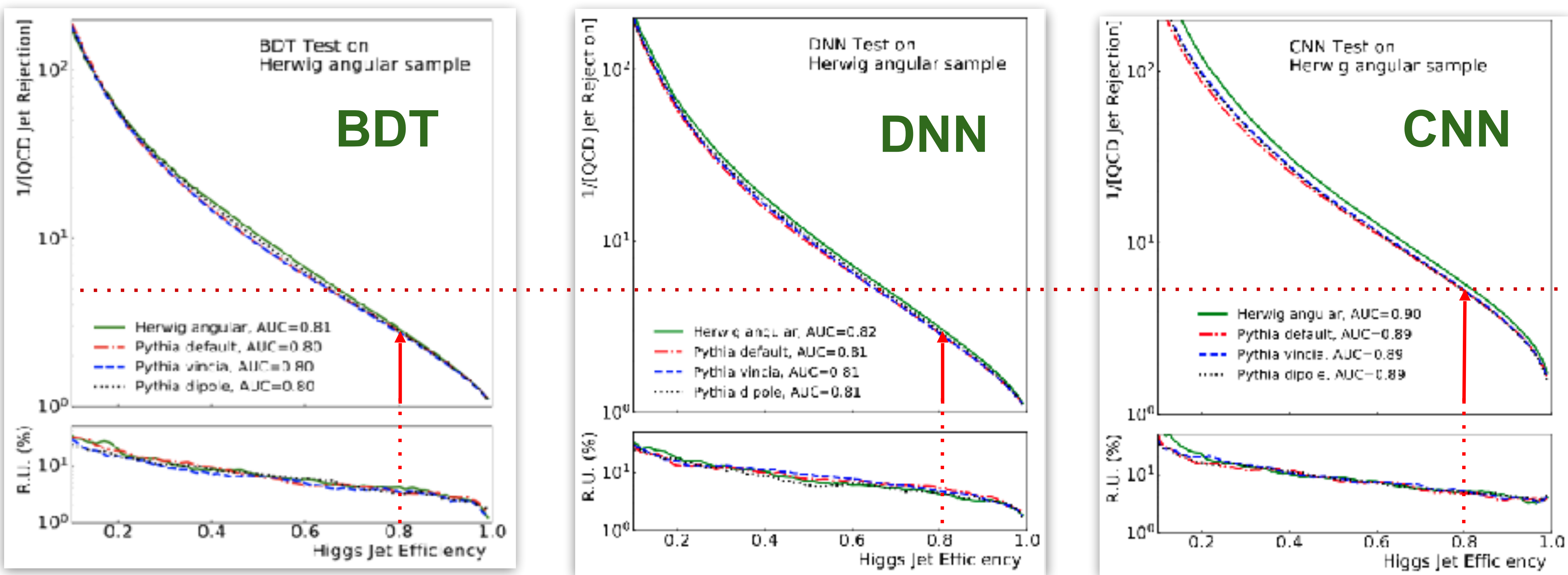
Precision



KC, Y.L. Chung, S.H. Hsu, B. Nachman, 2204.03812

Results of Exploring the Universality of Hadronic Jet Classification

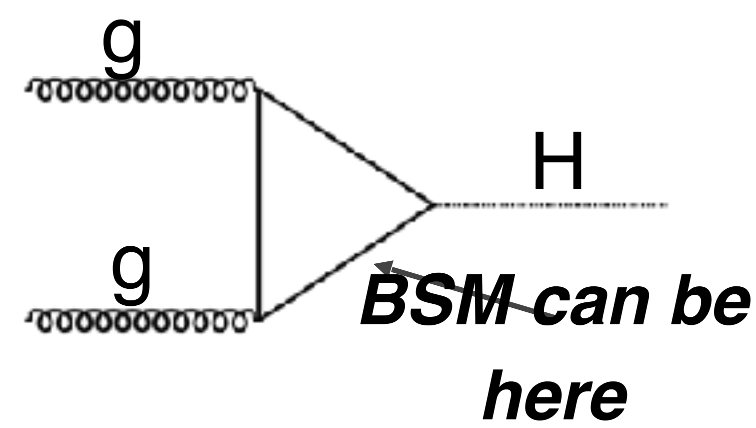
1. ROC curves of BDT, DNN and CNN models
2. Networks trained on low-level inputs can outperform networks trained on high-level features
3. These results suggest that **NNs** can learn universal properties of hadronic jets and be **insensitive to fragmentation models**.

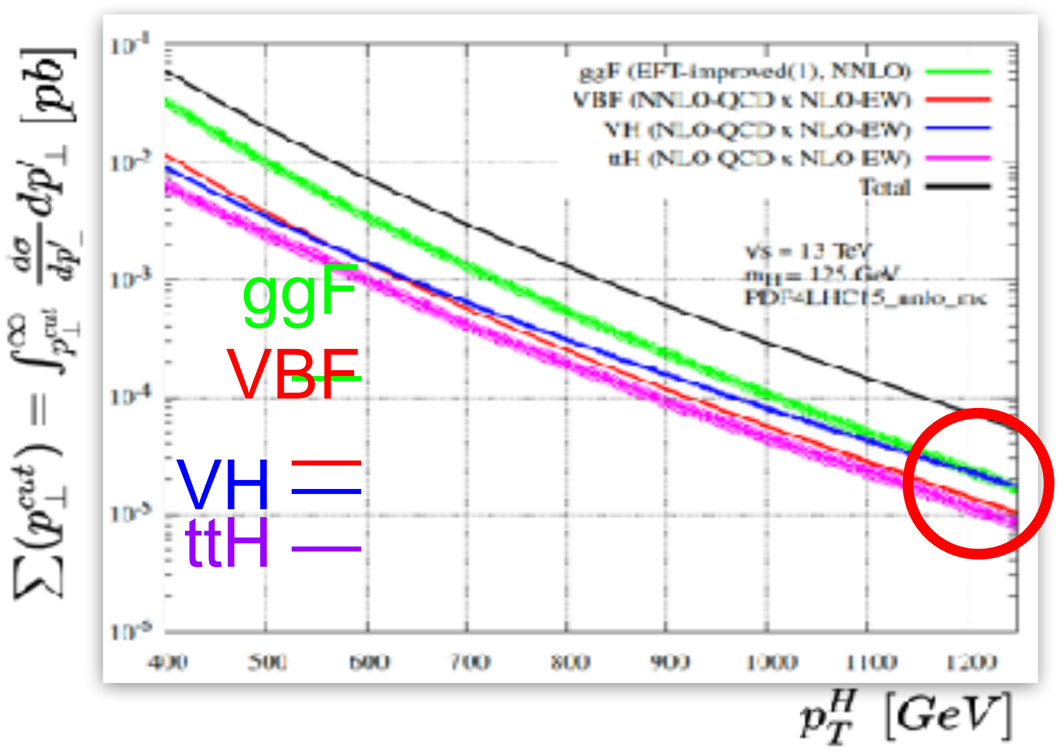


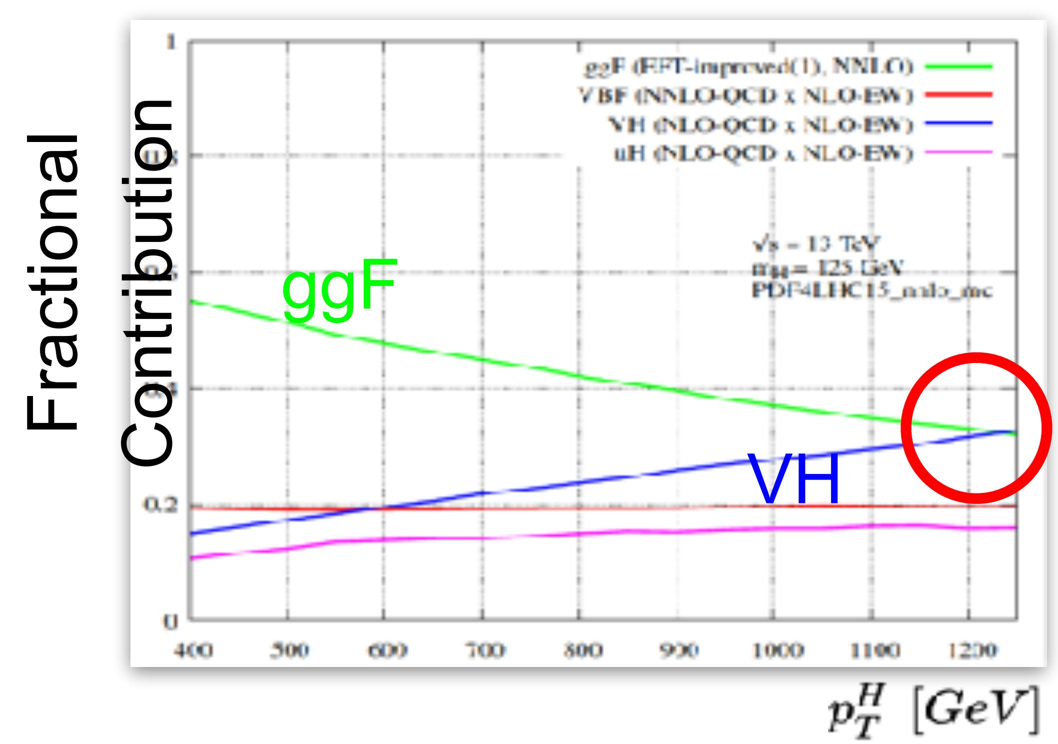
Disentangling Boosted Higgs Boson Production Modes with Machine Learning

Journal of Instrumentation, Volume 16, July 2021

1. High pT Higgs from
   - the SM Higgs, e.g. ggF
   - Beyond the Standard Model
2. Many Higgs productions other than ggF could be substantial in the boosted region. [K. Becker et al, arXiv:2005.07762]



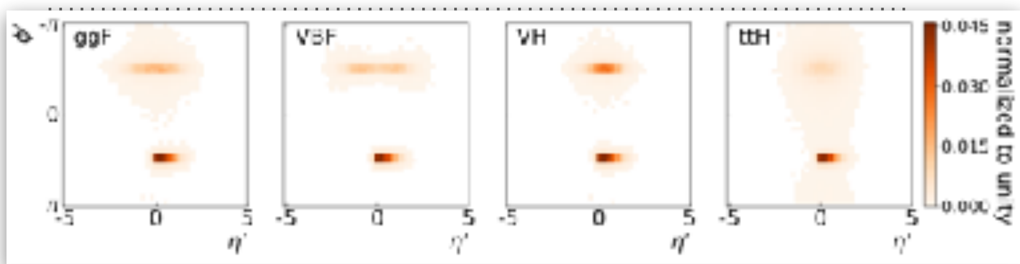




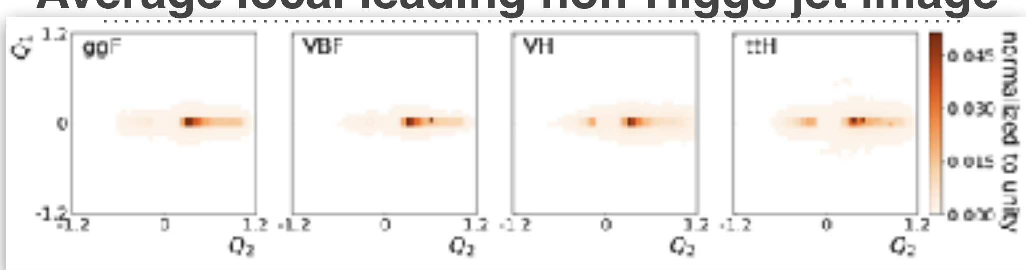
Machine Learning Method for Disentangling

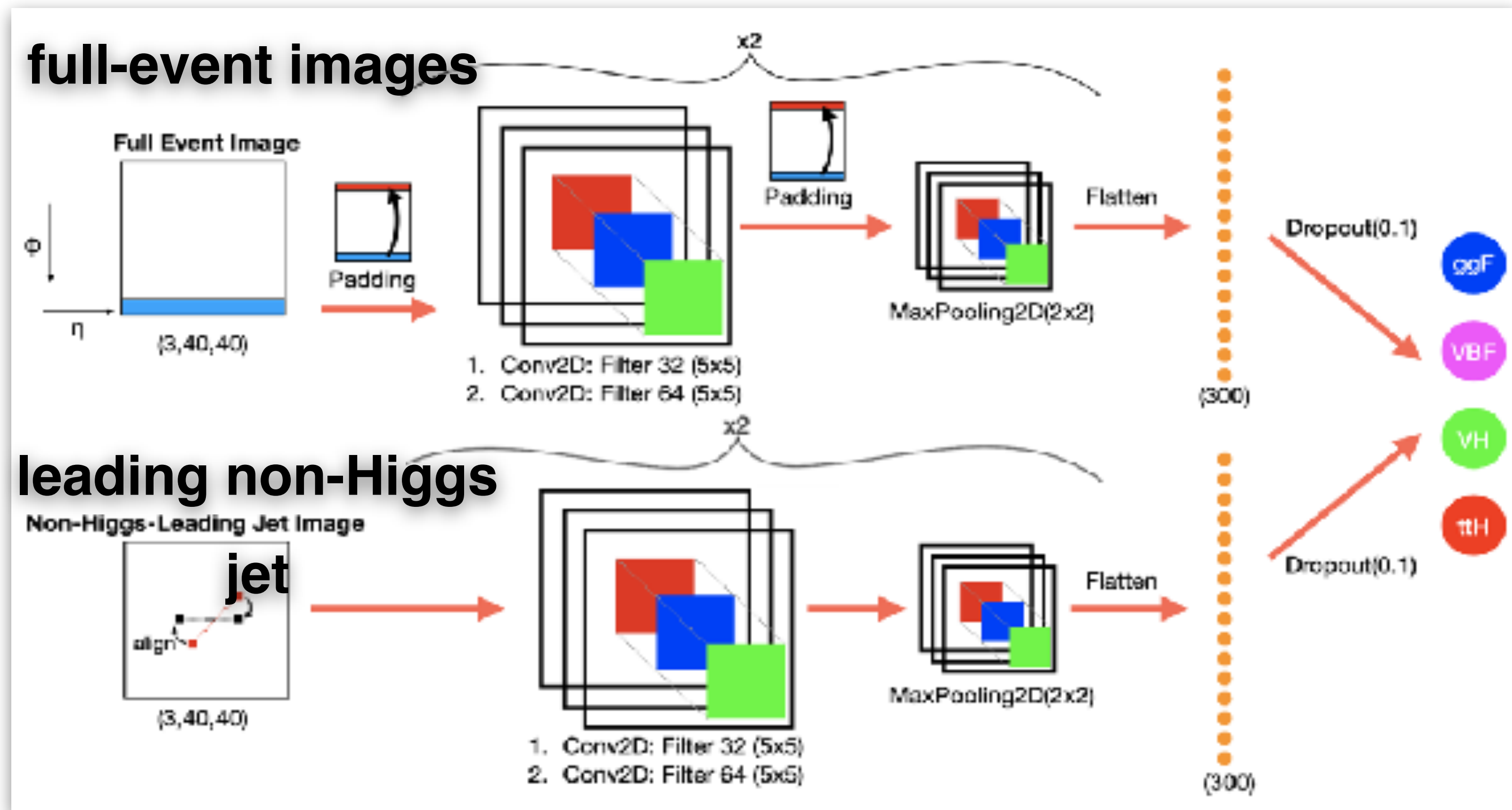
1. Ghosted-association method for Higgs jet tagging
2. First stream acting on global information
3. Second stream acting on local information

Average global full-event image

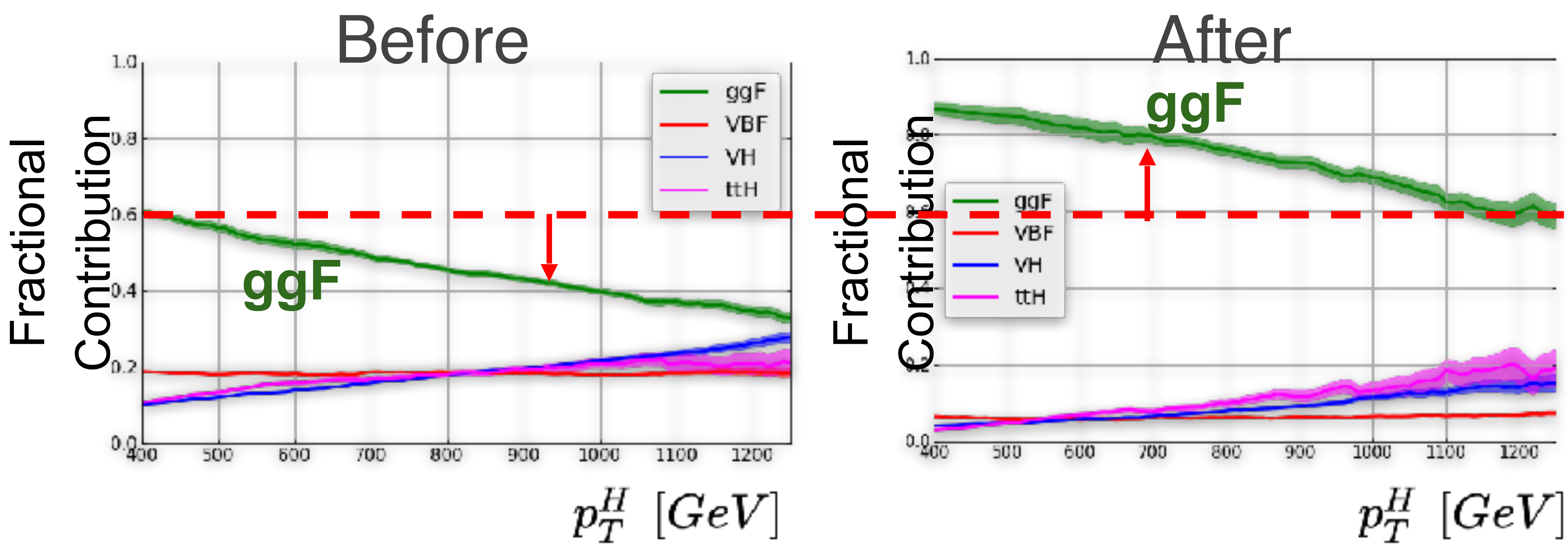


Average local leading non-Higgs jet image





Results of Disentangling Boosted Higgs Boson Production Modes



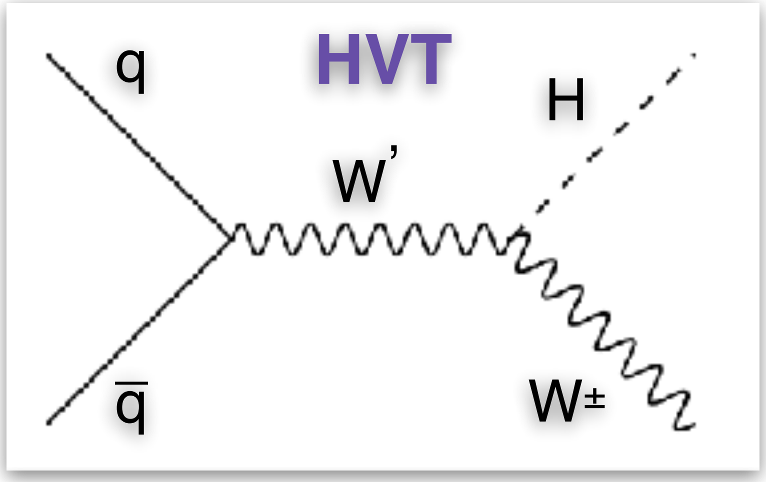
These two plots are passed preselection and included decay branching ratio

The 2CNN highly increases the ggF fraction in whole pT range!

Benefit of Disentangling Boosted Higgs Boson Production Modes

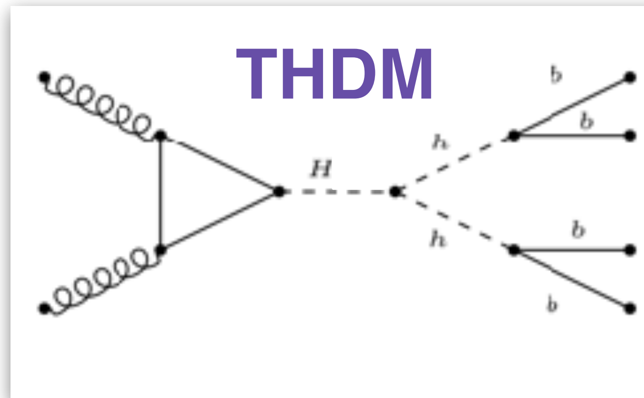
1. By using 2CNN method, we can provide exceptionally clear separation for boosted Higgs bosons produced via ggF at the LHC.

2. The approach in this study additionally has the potential to **improve the precision for other Higgs production modes** in extreme regions of phase space.
   - VBF and VH fractional contributions reach 77% and 78% with p^H_T threshold = 400 GeV
     - probe Heavy Vector Triplet (VH)
       - top quark Yukawa coupling in the Higgs precision measurement (ttH)

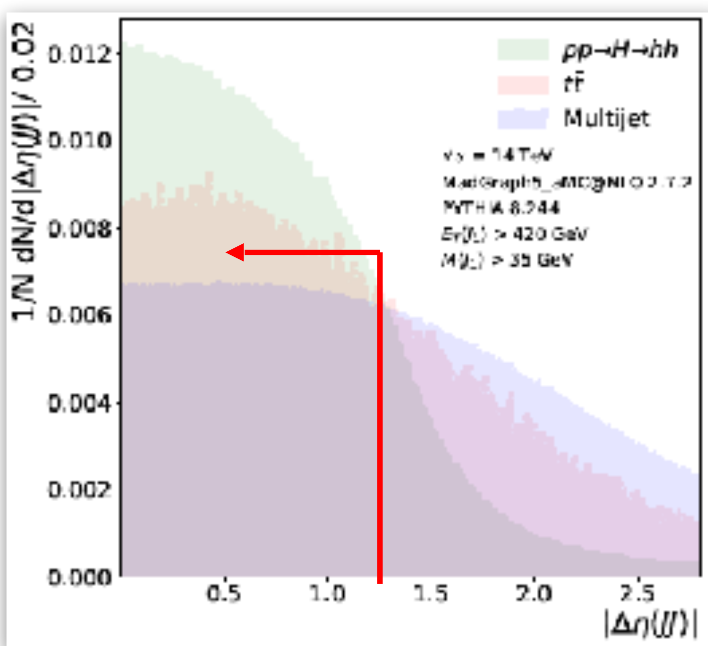


$pp \to hh \to b\bar{b}b\bar{b}$ via gluon-gluon fusion in THDMs at the High-Luminosity LHC

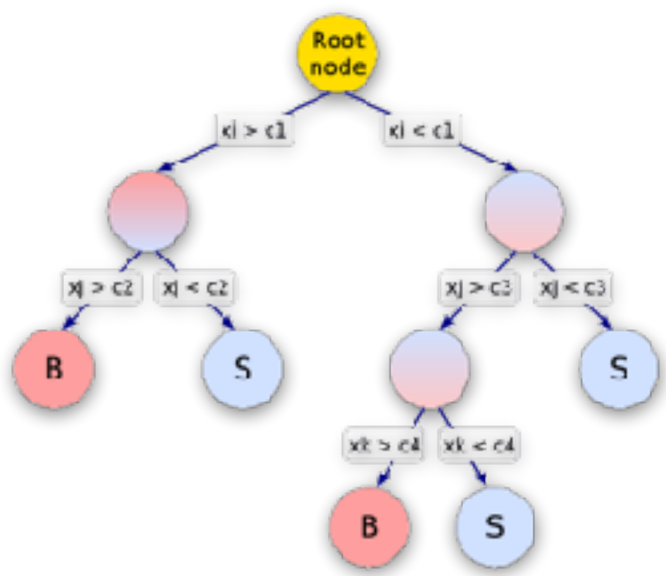
- Three approaches to study Higgs-pair production



the conventional cut-based approach

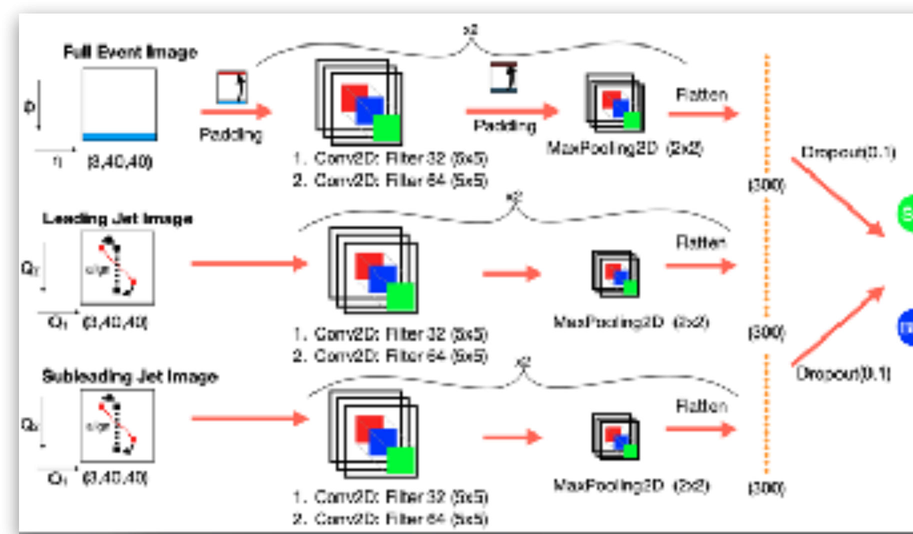


boosted decision tree BDT



[A. Hoecker et al, arXiv:physics/0703039]()

three-stream convolutional neural network



Two-Higgs Doublet Models

General Higgs potential:

Mayumi Aoki et al, Phys.Rev.D, arXiv:0902.4665

$$V^{\rm THDM} = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_3^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

	up-type	down-type	charged leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton Specific(Type III)	Φ_2	Φ_2	Φ_1
Flipped(Type IV)	Φ_2	Φ_1	Φ_2

The Yukawa interactions:

$$\mathcal{L}_{\rm yukawa}^{\rm THDM} = -\sum_{f=u,d,\ell}\left(\frac{m_f}{v}\xi_h^f\overline{f}fh + \frac{m_f}{v}\xi_H^f\overline{f}fH - i\frac{m_f}{v}\xi_A^f\overline{f}\gamma_5 fA\right)$$
$$-\left\{\frac{\sqrt{2}V_{ud}}{v}\overline{u}\left(m_u\xi_A^u{\rm P}_L + m_d\xi_A^d{\rm P}_R\right)dH^+ + \frac{\sqrt{2}m_\ell\xi_A^\ell}{v}\overline{\nu_L}\ell_R H^+ + {\rm H.c.}\right\}$$

The modifier in Yukawa interactions:

	ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

*$\tan(\beta) = v_2 / v_1$

Calculation of Current Constraints

- Combine 3CNN analysis with the current constraints
- Calculate from the public code
  - HiggsBounds-v5.10.2 arxiv:2006.06007 HiggsBounds GitLab
    - direct searches at high energy colliders
    - include all processes at LEP, Tevatron, and LHC
    - provide most sensitive channel and whether the point is still allowed or not at the 95% CL
  - HiggsSignals-v2.6.2 arxiv:2012.0917 HiggsSignals GitLab
    - the Higgs-signal strengths obtained at the LHC
    - gives the χ^2 output for 111 Higgs observables
    - require that the p-value is larger than 0.05, corresponding to 2σ level
- Regard the overlapping regions as the currently allowed parameter space

Currently Allowed Region

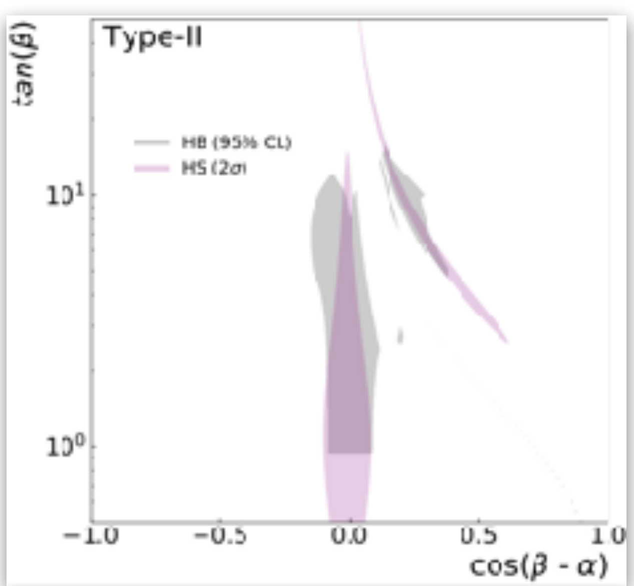
- **Gray area** is the currently allowed region from **HiggsBounds at the 95% CL**
  - direct searches at high energy colliders
  - include all processes at LEP, Tevatron, and LHC

[Philip Bechtle et al, Eur.Phys.J.C, arxiv:2006.06007](#) [HiggsBounds GitLab](#)

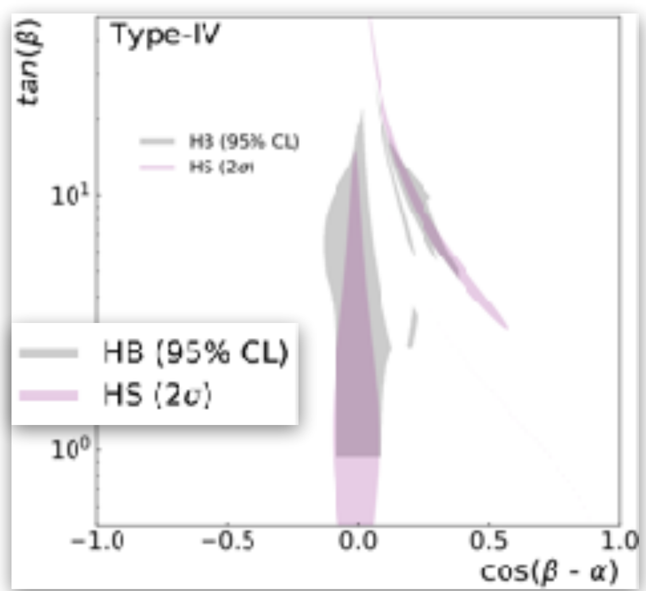
- **Purple area** is the allowed region from **HiggsSignals at 2 σ level**
  - the Higgs-signal strengths obtained at the LHCs
  - gives the χ^2 output for 111 Higgs observables
  - require that the p-value is larger than 0.05, corresponding to 2σ level

[Philip Bechtle et al, Eur.Phys.J.C, arxiv:2012.0917](#) [HiggsSignals GitLab](#)

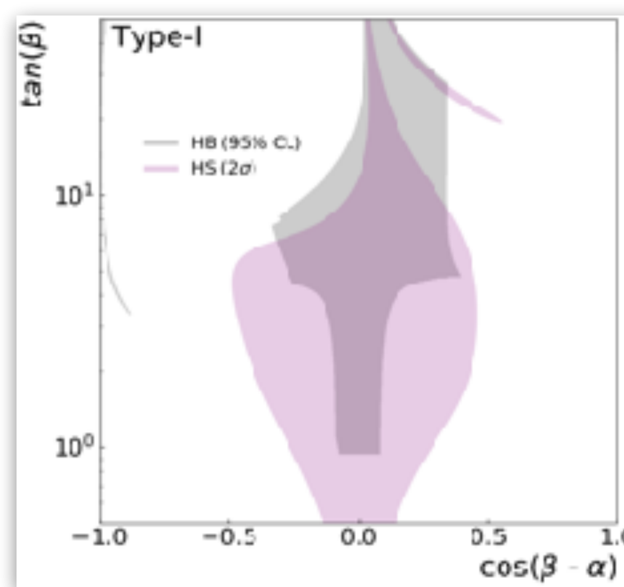
Type II



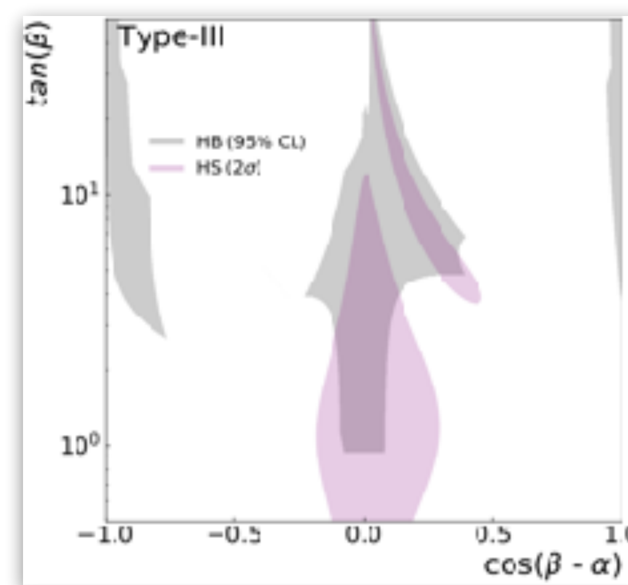
Type IV



Type I



Type III



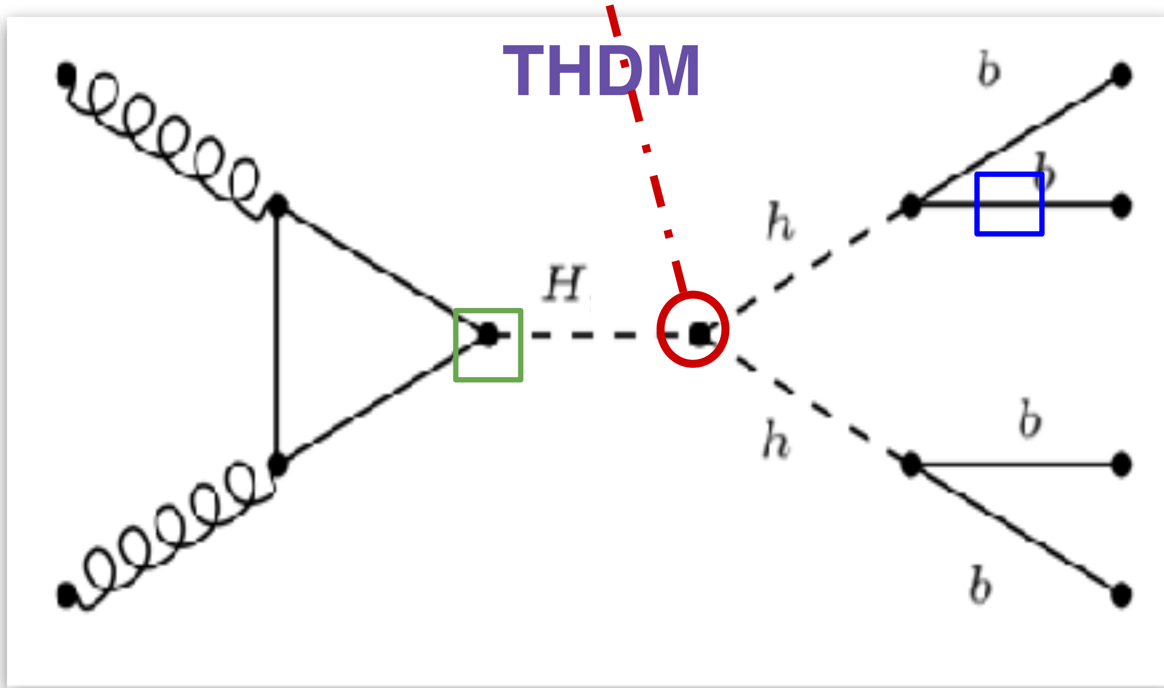
* at m_{12}^2 = 400000 GeV^2, $\cos(\beta-\alpha)$ = 0.08 and $m_A = m_H = m_{H\pm}$ = 1000 GeV

Higgs-pair Production in THDMs

Triple Higgs self–interaction:

$$\lambda_{h^0 h^0 H^0} : \frac{\cos(\beta-\alpha)}{\sin 2\beta}\left[\sin 2\alpha\,(2m_{h^0}^2 + m_{H^0}^2) - \frac{2m_{12}^2}{\sin 2\beta}(3\sin 2\alpha - \sin 2\beta)\right]$$

Benoit Hespel et al, JHEP, arxiv:1407.0281



Parametrized as a shift from the SM:

	Type II
$1+\Delta_t^{h^0}$	$\frac{\cos\alpha}{\sin\beta} = 1 + \xi/\tan\beta - \xi^2/2 + \mathcal{O}(\xi^3)$
$1+\Delta_b^{h^0}$	$-\frac{\sin\alpha}{\cos\beta} = 1 - \xi\,\tan\beta - \xi^2/2 + \mathcal{O}(\xi^3)$
$1+\Delta_t^{H^0}$	$\frac{\sin\alpha}{\sin\beta} = -1/\tan\beta + \xi + \xi^2/(2\tan\beta) + \mathcal{O}(\xi^3)$
$1+\Delta_b^{H^0}$	$\frac{\cos\alpha}{\cos\beta} = \tan\beta + \xi - \xi^2/2\,\tan\beta + \mathcal{O}(\xi^3)$

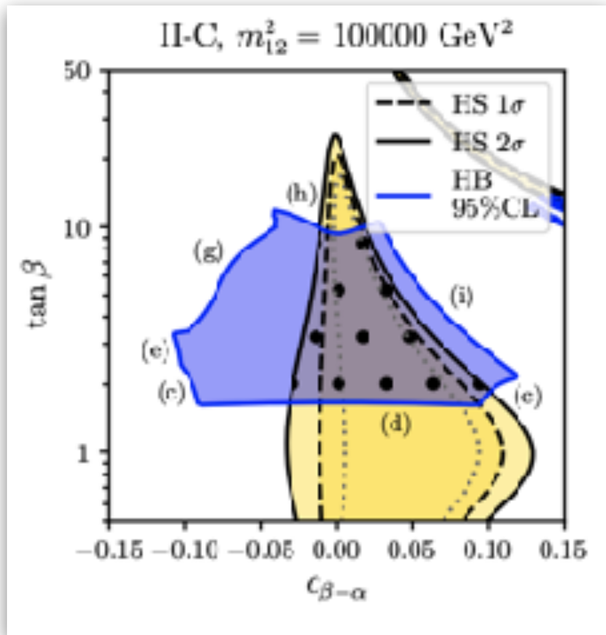
$^*\xi = \cos(\beta-\alpha)$

Benoit Hespel et al, JHEP, arxiv:1407.0281

- **Fix m^2_{12}, m_h, m_H, scan ($\cos(\beta-\alpha)$, $\tan(\beta)$) plane**
- **Fix $\tan(\beta)$, m_h, m_H, scan ($\cos(\beta-\alpha)$, m^2_{12}) plane**

Current Bounds - λ_{hhH}

type II

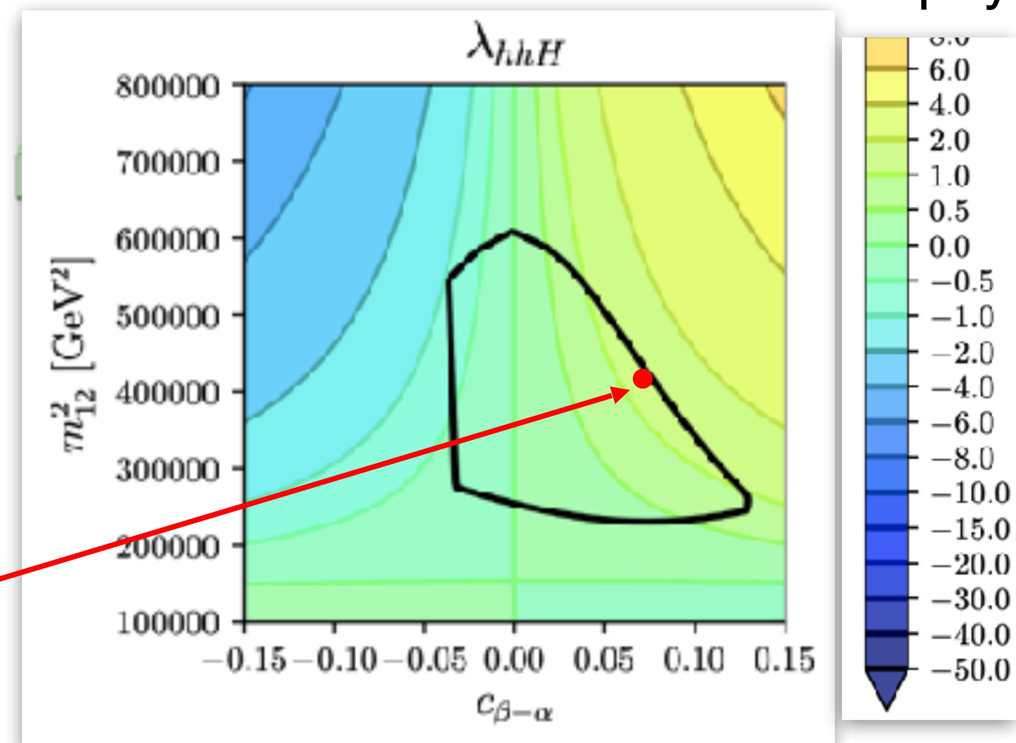


LHC Run 2 data

(a) $pp \to H \to hh \to (b\bar{b})(\tau^+\tau^-)$ [18],
(b) $pp \to H \to hh \to (b\bar{b})(b\bar{b}/\tau^+\tau^-/W^+W^-/\gamma\gamma)$
(c) $pp \to H \to VV$ [20],
(d) $pp \to H^{\pm}tb \to (tb)tb$ [21],
(e) $gg \to A \to Zh \to (l^+l^-)(b\bar{b})$ [22],
(f) $pp \to hX \to \gamma\gamma X$ [23],
(g) $pp \to H \to hh \to (b\bar{b})(b\bar{b})$ [24],
(h) $pp \to H \to \tau^+\tau^-$ [25],
(i) $pp \to h \to ZZ \to (l^+l^-)(l^+l^-)$ [26]

F. Arco et al, Eur.Phys.J.C, arxiv:2005.10576

Combine colliders and flavor physics



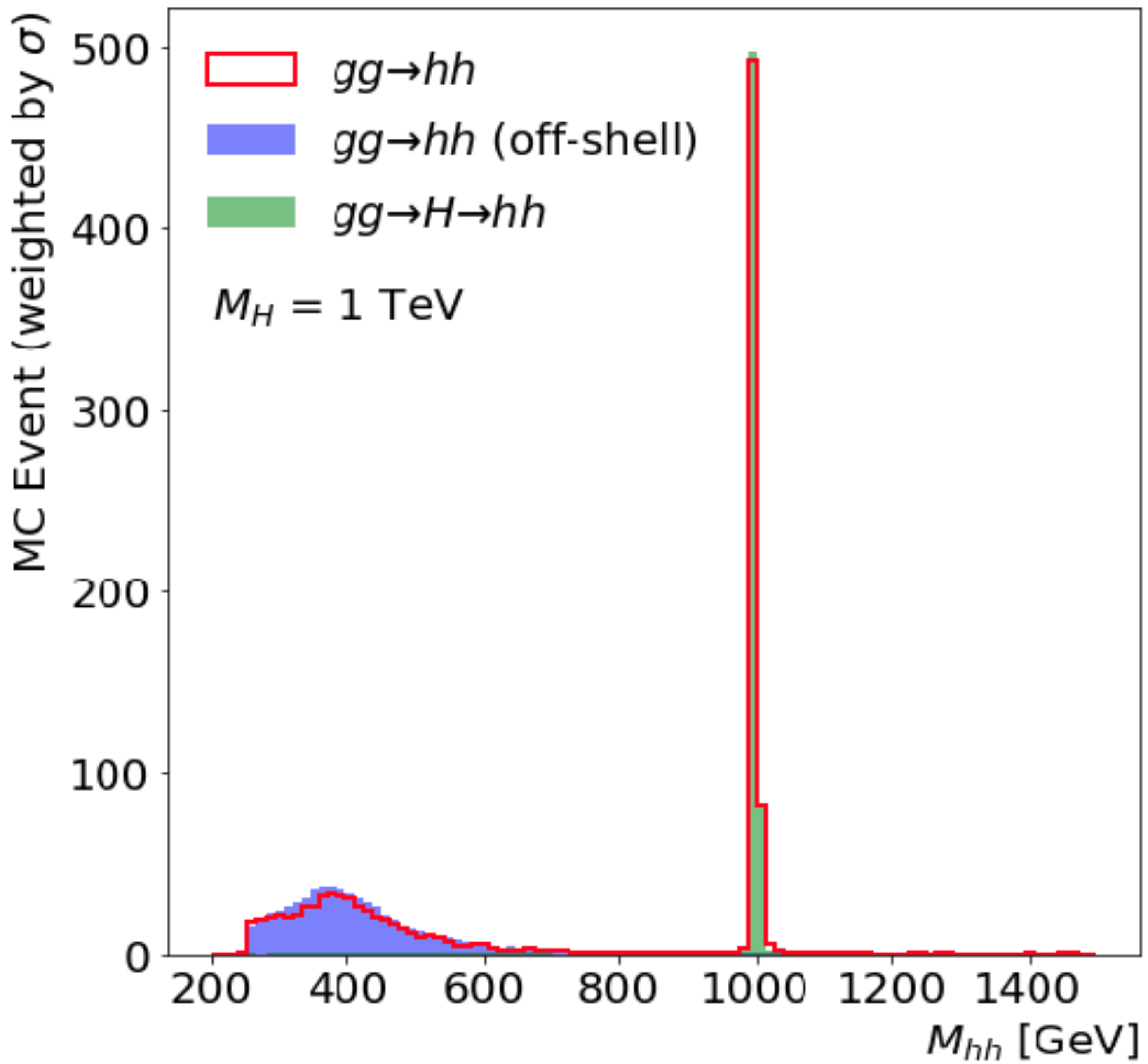
1. Maximun λ_{hhH} ~ 1.4 at m_{12}^2 ~ 400000 GeV², cos(β-α) = 0.08
   *m_A=m_H=$m_{H\pm}$=1100GeV and tan(β)=0.9

   F. Arco et al, Eur.Phys.J.C, arxiv:2005.10576

2. Benchmark Point:
   - tan(β) = 5 and m_{12}^2 = 400000 GeV², cos(β-α) = 0.01
   - m_A=$m_{H\pm}$= 1001 GeV, m_H= 1000 GeV
   - the branching ratio of H → h h (*BR*(H → h h) = 0.28, BR(h —>bb)=0.59

Resonance Against the Continuum

- Resonance is dominate around M_{hh} = 1 TeV



*tan(β)=5, m_{12}^2 = 400000 GeV^2, cos(β-α) = 0.01 and m_H=1000 GeV, m_A= $m_{H\pm}$= 1001 GeV in Type II

Higgs-Jet-Tagging Method

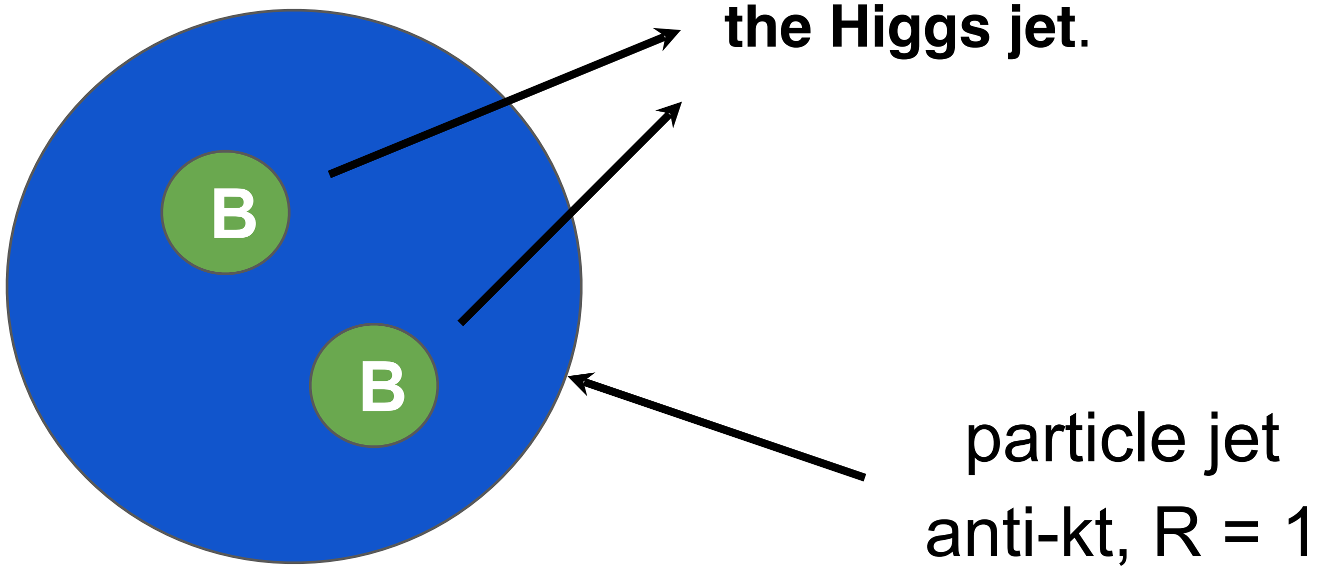
Higgs jet is recognized by double b-tagging due to the hardronic Higgs decay.

arXiv:1507.00508

Double-B Hadrons-tagging via **ghost-association** method is used to do double b-tagging in this study.

arXiv:1507.00508

1. Multiply infinitesimal value to B hadrons, it is **ghosted B hadrons**.
2. Adding this ghosted B hadrons into the final state list and cluster the jets
3. **If large R(=1) jet contains two ghost-associated B hadrons, it will be tagged to the Higgs jet**.



Analysis Workflow

1. Sample Preparation (MadGraph5_aMC@NLO v2.7.2):
   Signal($\sqrt{s}$ = 14TeV) :
   - p p > H *with THMD model (mH = 1000 GeV) [σ(pp -> H)=2.55 fb]
   - H > h h, (h > b b) *Decay heavy Higgs and light Higgs in MadSpin
     [BR(H -> h h)=0.28, **BR(h -> b b)=100%**]

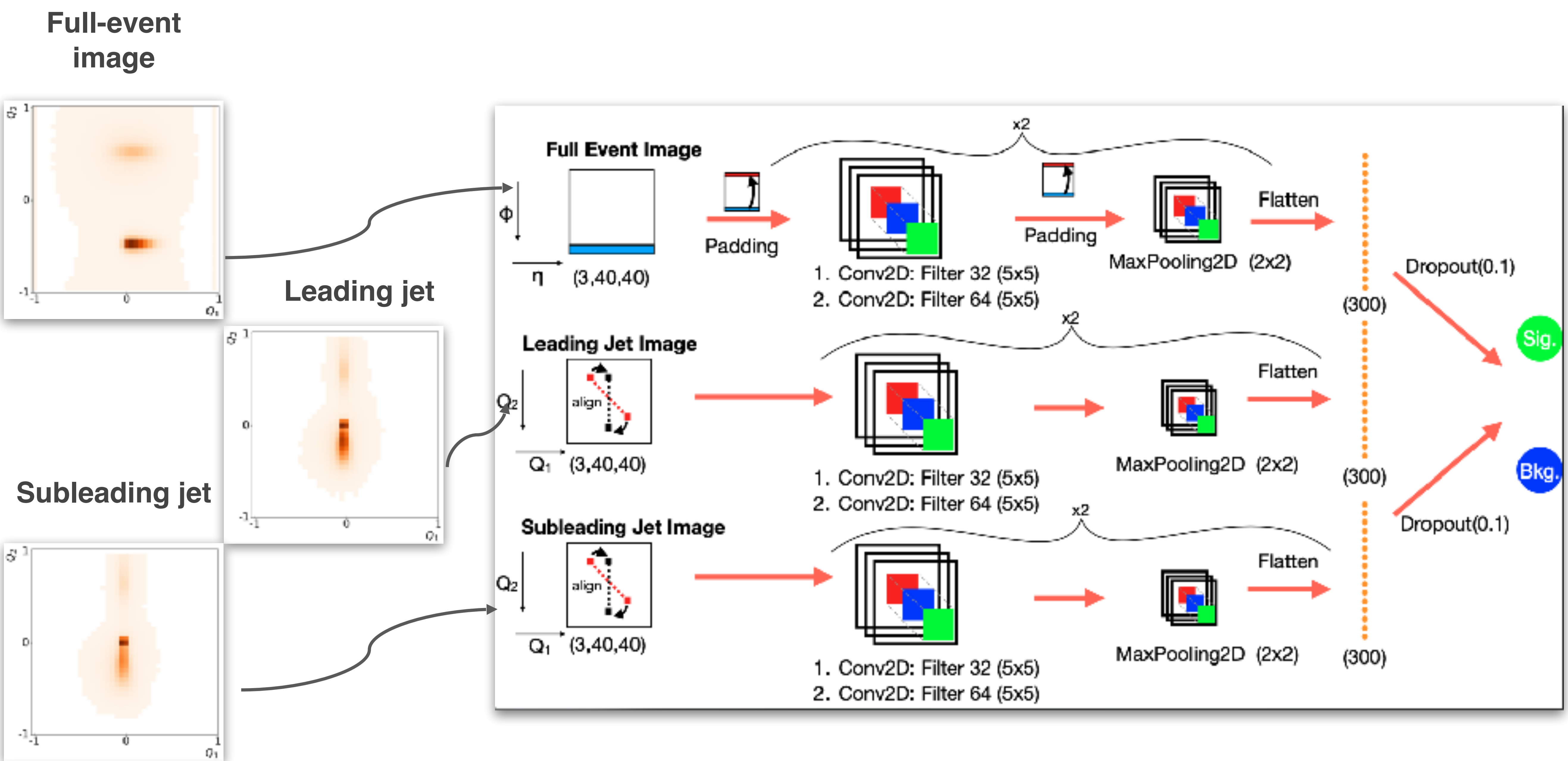
   Background($\sqrt{s}$ = 14TeV) :
   - QCD Multijet (flavor-inclusive) [σ(pp -> jjjj) = 11087.84 pb]
   - tt + n j [σ(ttbar + nj) = 260.36 pb]
2. Analysis (similar to ATLAS Collaboration, Phys.Rev.D, arxiv:2202.07288):
   - Large-R jet: for the boosted object, jet cone size R = 1.0
   - Using the ghost-associated method to define Higgs candidate (an approach similar to subjet b-tagging in ATLAS) ATLAS Collaboration, JHEP, arxiv:1805.01845
   - Jet trimming (k_T algorithm with R = 0.2 for subjets and remove thershold is 5%)
   - For leading jet E_T > 420 GeV and M_J > 35 GeV — Joshua Lin et al, JHEP, arxiv:1807.10768
   - At least two large-R jets with p_T > 450 GeV and p_T > 250 GeV
   - M_J > 50 GeV and $|\eta_J| < 2$

   Preselection (the three cuts above)

   - **High-level Features**: Cut-based method (similar to ATLAS analysis) and BDT method
   - **Low-level Features**: Event, leading jet and sub-leading jet images for a 3CNN classifier
3. Statistics:
   - sensitive region at 95% CL with an integrated luminosity $\mathscr{L}$ = 3000 fb^{-1}

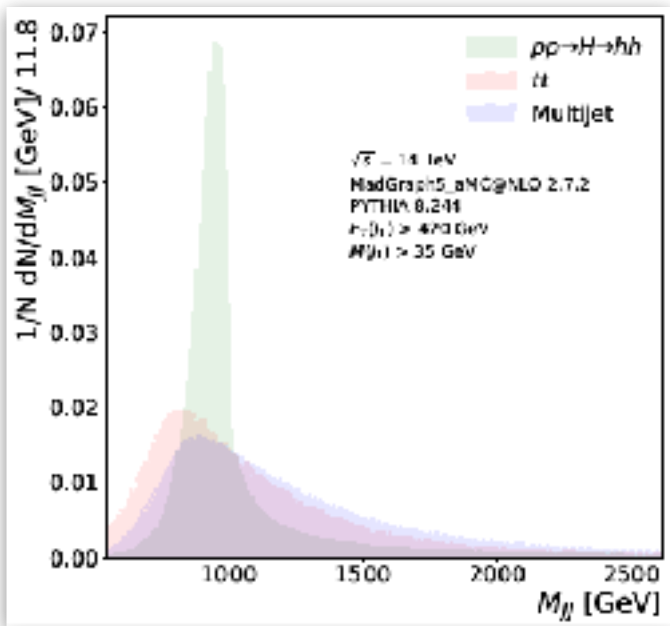
3CNN Architecture

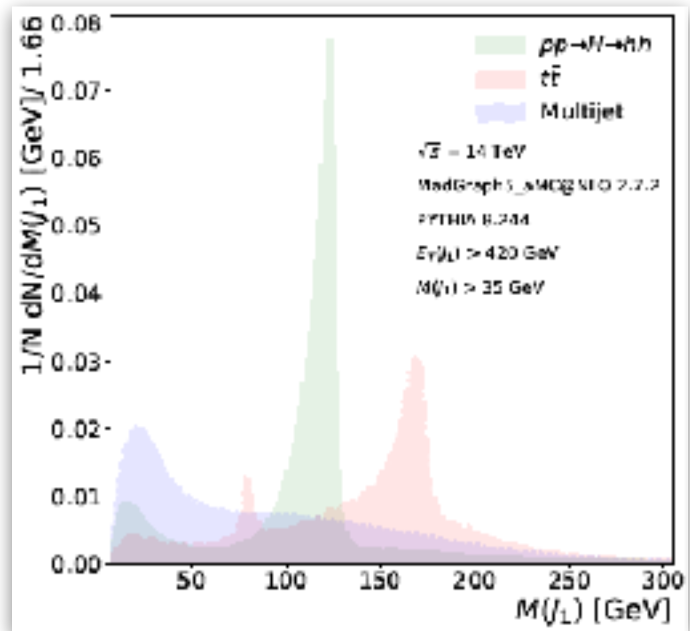
- Inspired by works [Joshua Lin et al, JHEP, arxiv:1807.10768](#) [Yi-Lun Chung et al, JINST, arxiv:2009.05930](#)

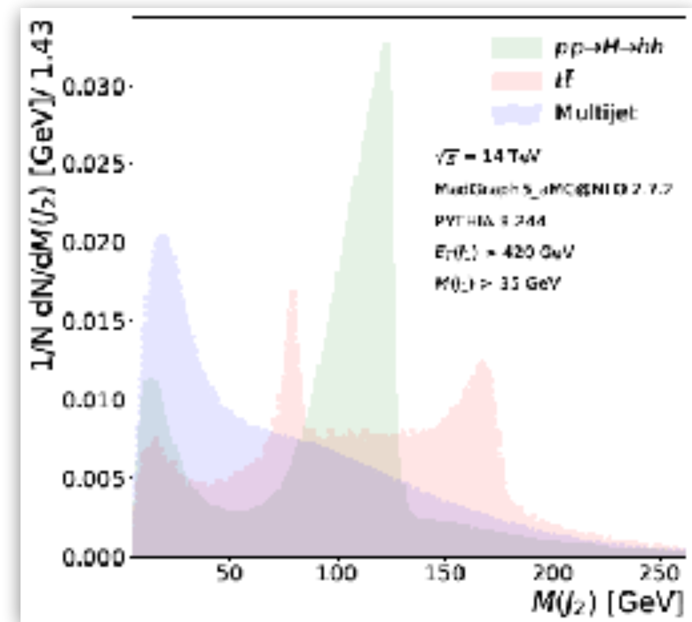


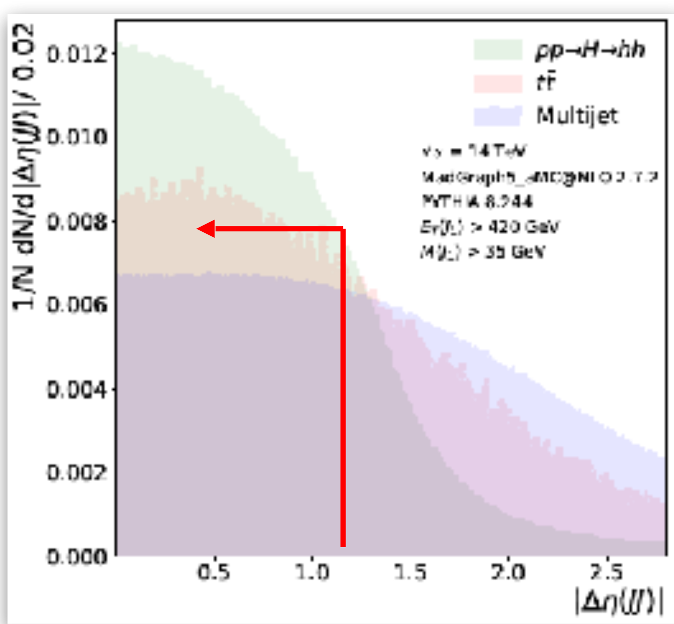
$$X_{HH} = \sqrt{\left(\frac{m(H_1) - 124\ \text{GeV}}{0.1 \times m(H_1)}\right)^2 + \left(\frac{m(H_2) - 115\ \text{GeV}}{0.1 \times m(H_2)}\right)^2}.$$

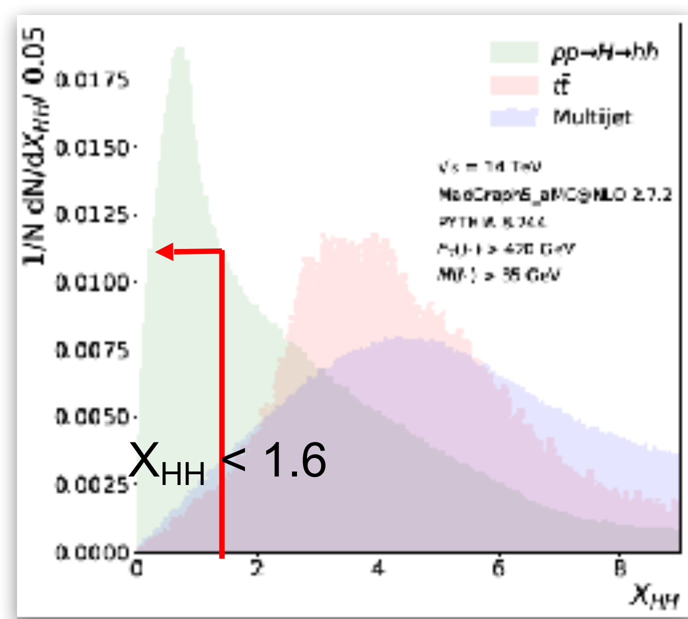
High-Level Features - Kinematic Features





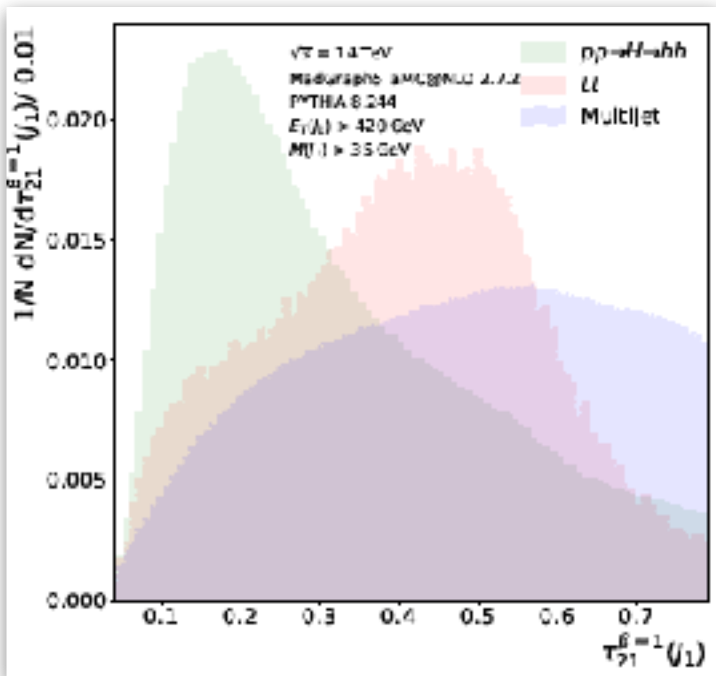


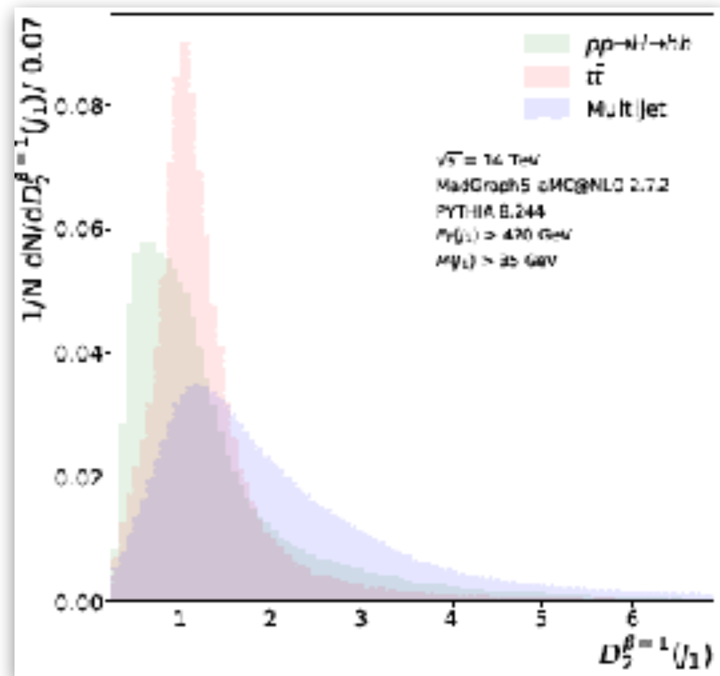


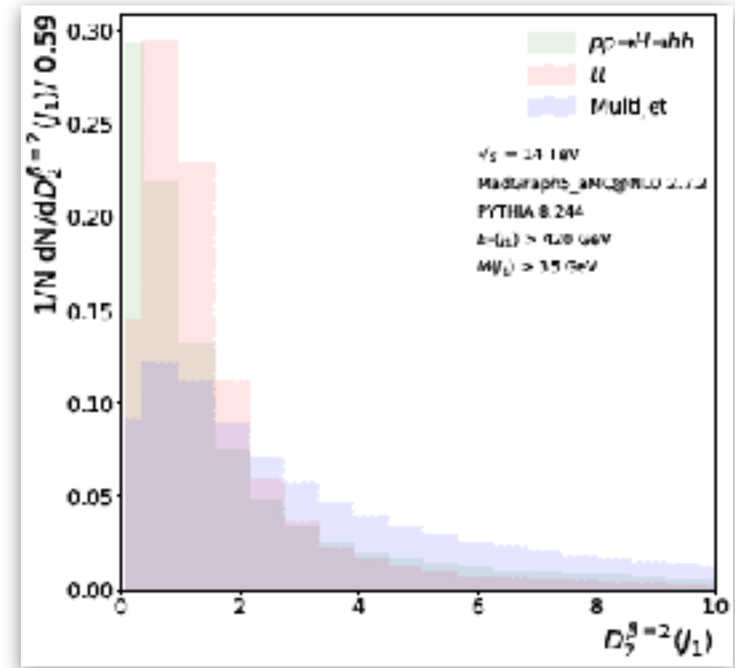


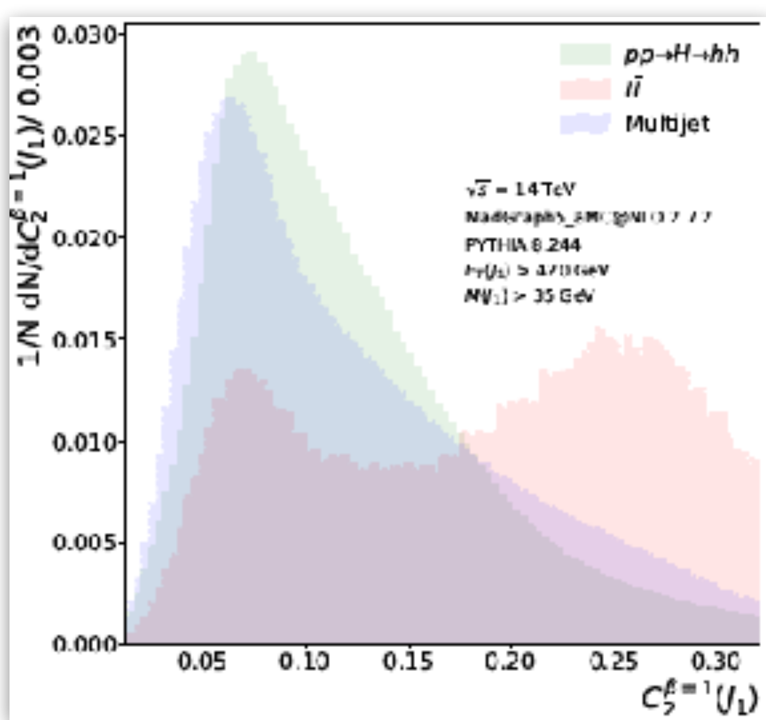
| Δ[η(J1) , η(J2)] | < 1.3

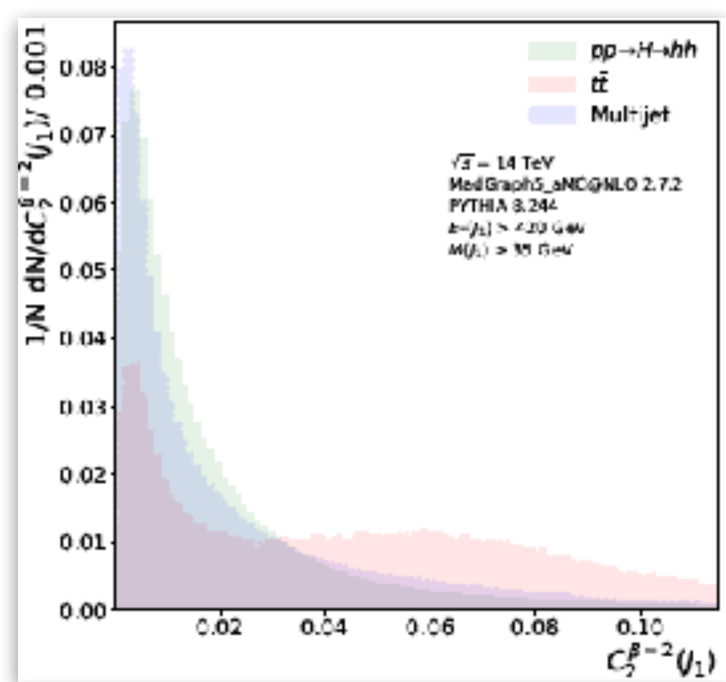
High-Level Features - Jet Substructures











Low-Level Features

1. The leading and subleading trimmed jet

2. Rotated full-event images

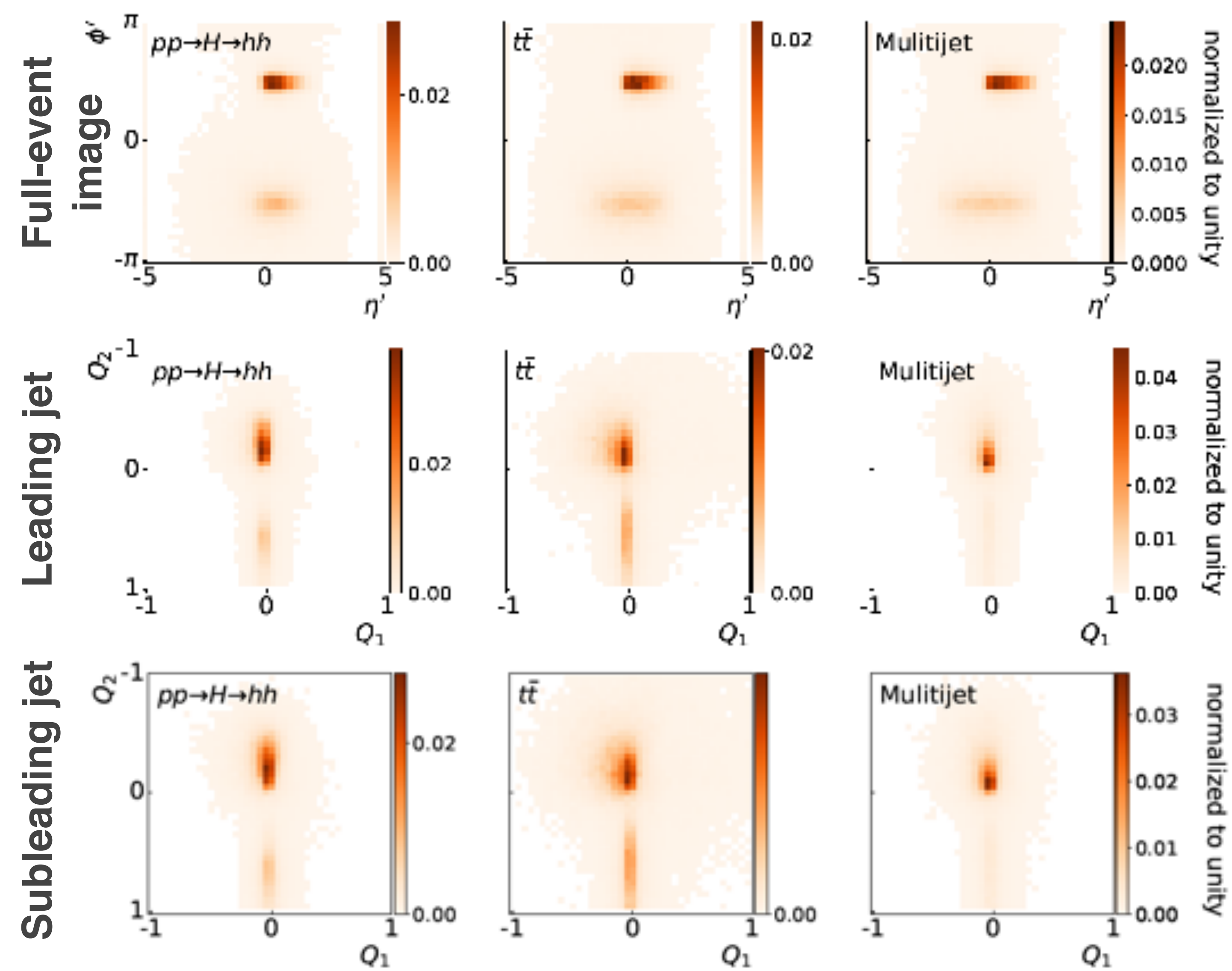
3. Deposit intensities into 40X40 pixels
 (1RX1R -> 40X40 pixels)

- charged pt
- neutral pt
- charged multiplicity (analogy RGB)

4. Rotation and Reflection:
 - put the leading subjet at the origin
 - subleading subjet directly below the leading subjet
 - put the third-leading subjet on the right-hand side

1. Normalized: sum of intensity is unity
2. Standardization: mean zero and unit variance

The average of 10000 images



* Q_1 and Q_2 are new axes for the jet's axis

Selection Table (at 14TeV with $\mathscr{L}$ = 3000 fb^{-1})

- The 3CNN analysis outperforms the BDT and the baseline analysis based on the conventaional cut-based method

Selection Flow Table					
		$pp \to H \to hh \to b\bar{b}b\bar{b}$ **(Type II)**	$t\bar{t}$	**Mulitijet**	**Total Backgrounds**
preselection		8.02×10^1	9.23×10^5	2.76×10^7	2.86×10^7
900 GeV $< M_{JJ} <$ **1100 GeV**		5.29×10^1	2.77×10^5	6.92×10^6	7.20×10^6
2 Higgs jets		4.74×10^1	1.05×10^3	2.34×10^4	2.45×10^4
Baseline	$\lvert\Delta\eta(JJ)\rvert <$ **1.3**	4.68×10^1	9.99×10^2	2.18×10^4	2.28×10^4
	$X_{HH} <$ **1.6**	2.82×10^1	2.13×10^1	1.37×10^3	1.39×10^3
BDT score $>$ **0.964**		2.56×10^1	5.33	1.37×10^2	1.42×10^2
3CNN score $>$ **0.99**		2.56×10^1	2.93×10^1	2.74×10^1	5.67×10^1

* include B-hadron tagging eff. = 0.77

* For signal: σ(pp->H->hh) =0.71 fb, Br(h->bb) = 0.594 at tan(β)=5, m_{12}^2 = 400000 GeV^2, cos(β-α) = 0.01 and m_A=$m_{H\pm}$= 1001 GeV, m_H=1000 GeV in Type II

Comparisons for 4-Types of 2HDM

- Significance of 4 types in 3 analyses

$\mathscr{L}$ = 3000 fb^{-1}	Type I	Type II	Type III	Type IV
σ(pp->H) (fb)	0.9864	0.81186	0.98173	0.83234
Br(H->hh)	0.88221	0.87147	0.88087	0.87279
Br(h->bb)	0.62102	0.35596	0.64835	0.32968
Cut-based Method (sig. eff. = 0.1059, # of bkg = 1392.67)				
Survival Events	**37.48**	**10.01**	**40.60**	**8.82**
S/√B	**1.00**	**0.27**	**1.09**	**0.24**
BDT Method (sig. eff. =, # of bkg = 142.46)				
Survival Events	**33.98**	**9.08**	**36.80**	**7.99**
S/√B	**2.85**	**0.76**	**3.08**	**0.67**
3CNN Method (sig. eff. = 0.0961, # of bkg = 56.73)				
Survival Events	**33.98**	**9.08**	**36.81**	**7.99**
S/√B	**4.51**	**1.21**	**4.89**	**1.06**

* include B-hadron tagging eff. = 0.77

* For signal: tan(β)=5, m_{12}^2 = 400000 GeV^2, cos(β-α) = 0.08 and m_A=m_H=$m_{H\pm}$= 1000 GeV

Scanning Method

1. Scan **tan(β)** and **cos(β-α)**
   - fix m_H=125 GeV, m_A=m_H=$m_{H\pm}$=1000GeV and m12^2=400000
     Feed them into 2HDMC to get coulpings and branching ratio BR(H->hh) and BR(h->bb)

2. Put coulpings and branching ratio into MG5 to calculate σ(gg -> H)

3. Calculate siginificance for each point
   - # of sig. : σ(gg -> H) x BR(H->hh) x BR(h->bb) x BR(h->bb) x $\mathscr{L}$ x selection efficiency x (B-hadron tagging efficiency)^4
   - siginificance Z = √(2*((**s**+**b**)xln(1+**s**/**b**)-**s**)), where **s** is number of signal and **b** is number of total background

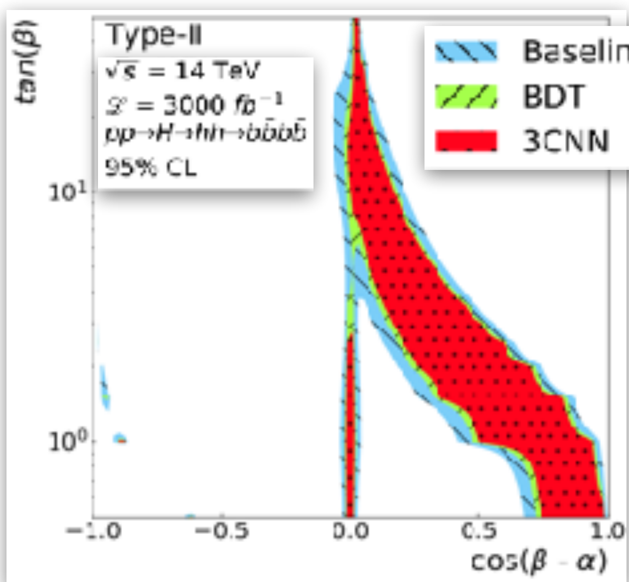
5. Find siginificance Z ≤ 2 to make plots

6. Currently, the grid size is 100X100

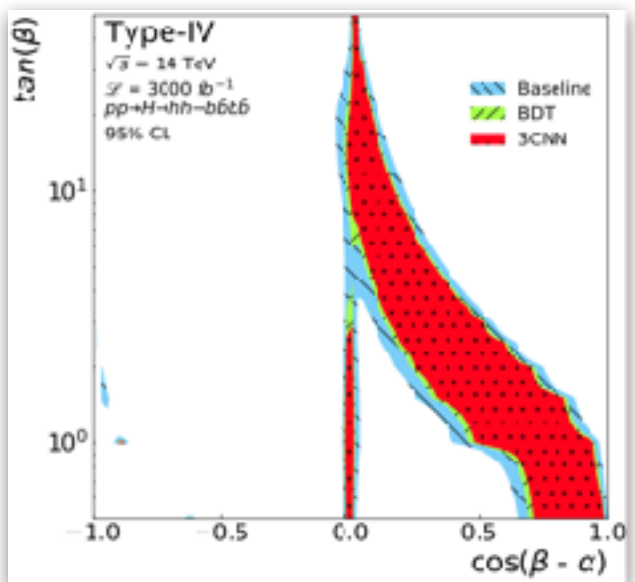
Interpretation at (cos(β-α), tan(β)) plane

- Results are shown in allowed region at 95% CL (the significance ≤ 2)
- The smallest region is red area
- The 3CNN analysis provides stonger constraints for four-types of 2HDMs

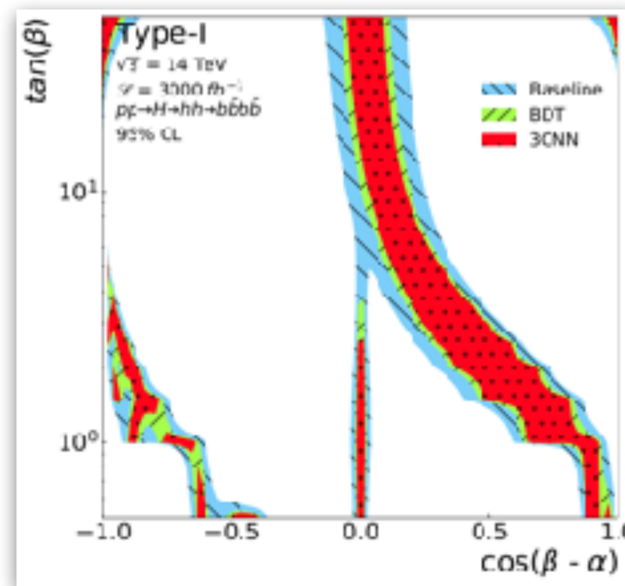
Type II



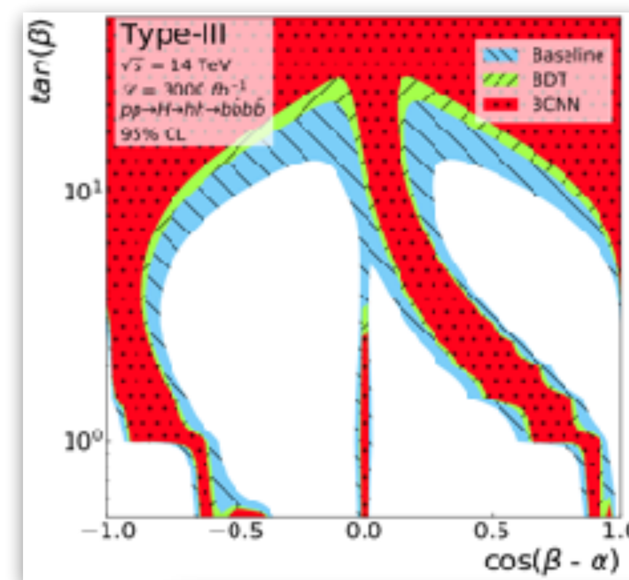
Type IV



Type I



Type III



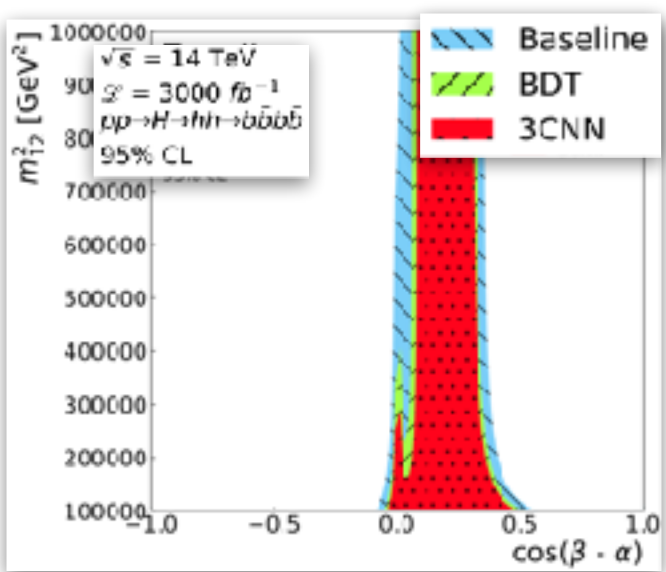
* m_{12}^2 = 400000 GeV^2 and m_A=m_H=$m_{H\pm}$= 1000 GeV

* siginificance Z = √(2*((s+b)xln(1+s/b)-s)), where s is number of signal and b is number of total background

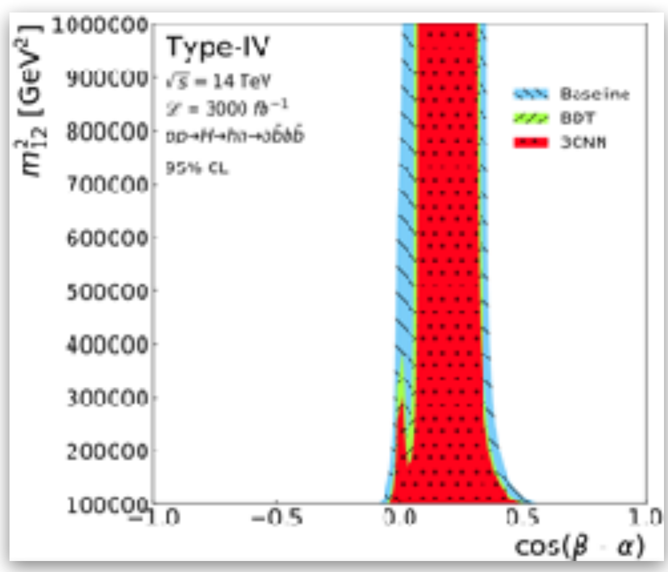
Interpretation at (cos(β-α), m_{12}^2) plane

- Results are shown in allowed region at 95% CL (the significance ≤ 2)
- The smallest region is red area
- The 3CNN analysis provides stonger constraints for four-types of 2HDMs

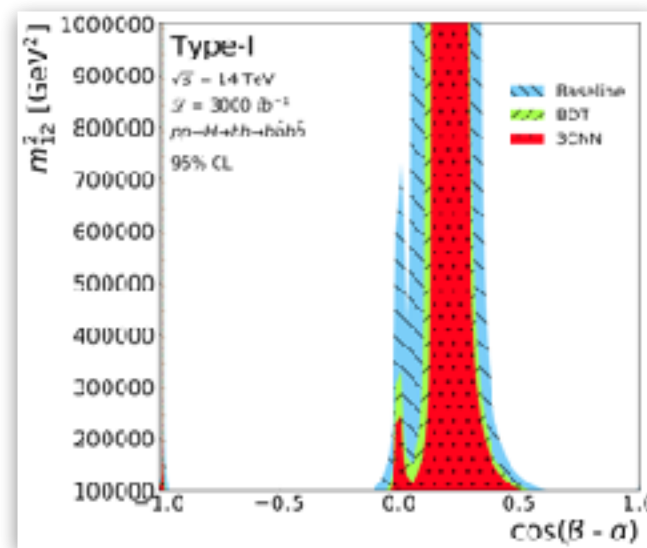
Type II



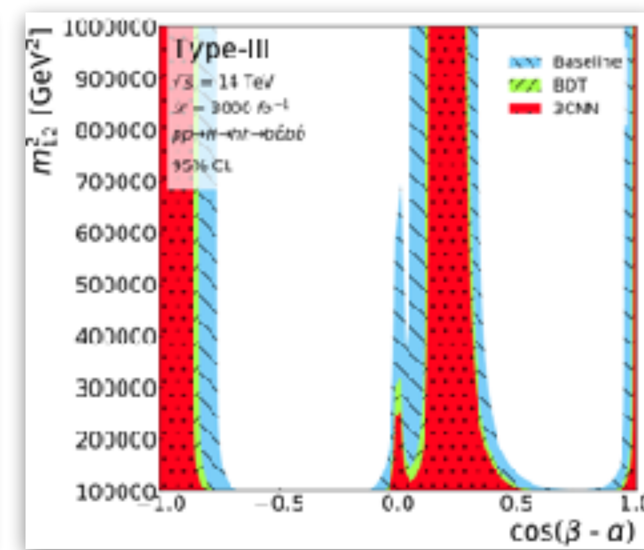
Type IV



Type I



Type III

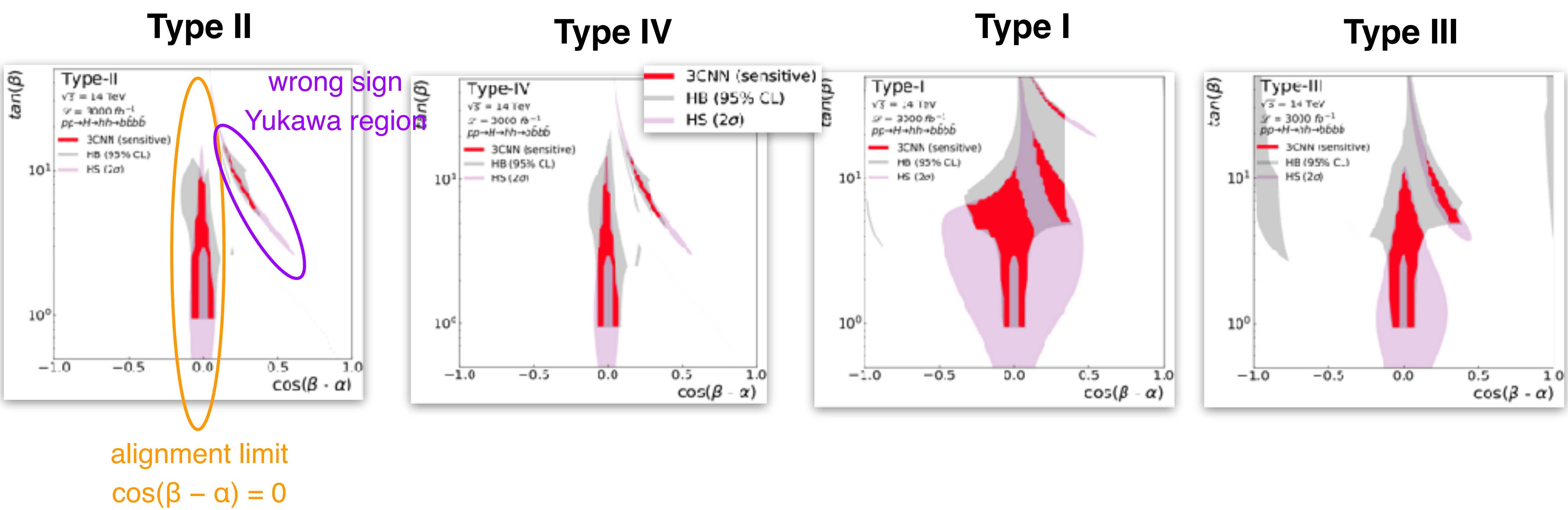


* m_{12}^2 = 400000 GeV² and $m_A = m_H = m_{H\pm}$ = 1000 GeV

* siginificance Z = √(2*((s+b)xln(1+s/b)-s)), where s is number of signal and b is number of total background

Allowed Sensitivity Region Under Current Constraints at 14 TeV HL-LHC

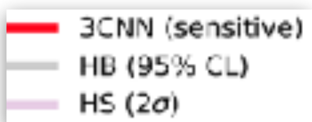
- **Red area** is the **sensitive region at 95% CL** (where the significance > 2)
- **Gray area** is the currently allowed region from **HiggsBounds at the 95% CL**
- **Purple area** is the allowed region from **HiggsSignals at 2 σ level**
- The 3CNN can cover a large area of the overlapping region in all 4 types of 2HDMs



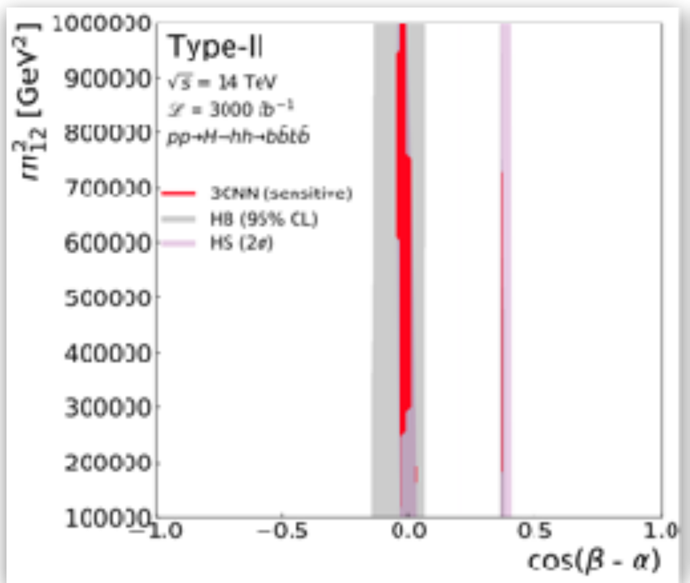
* m_{12}^2 = 400000 GeV^2 and m_A=m_H=$m_{H\pm}$= 1000 GeV

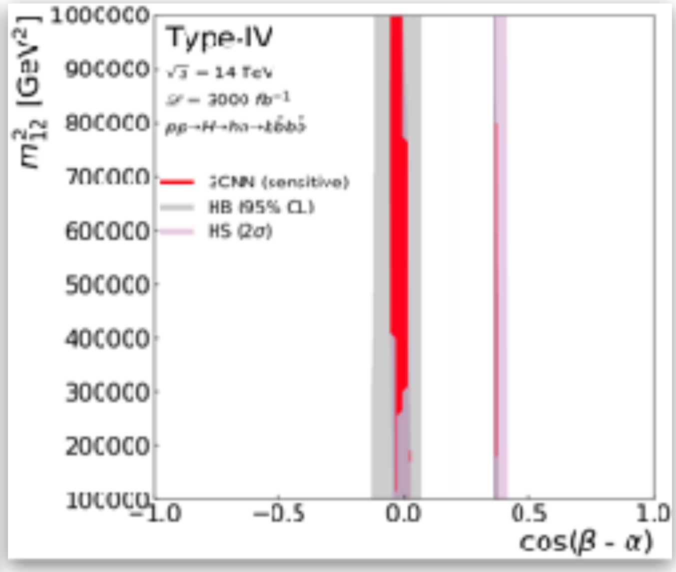
* siginificance $Z = \sqrt{(2*((s+b)x\ln(1+s/b)-s))}$, where s is number of signal and b is number of total background

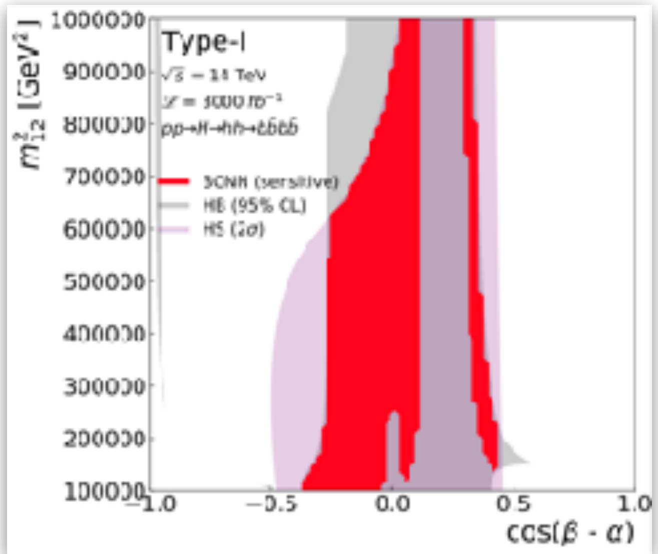
Allowed Sensitivity Region Under Current Constraints at 14 TeV HL-LHC

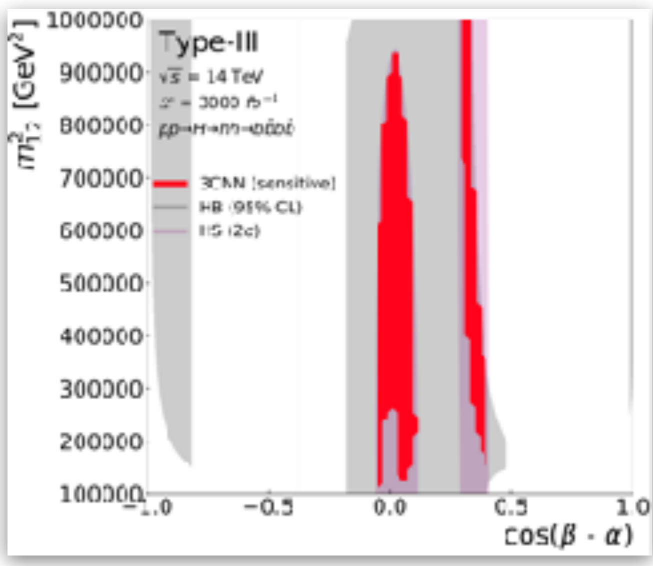


Type II **Type IV** **Type I** **Type III**









* m_{12}^2 = 400000 GeV^2 and $m_A = m_H = m_{H\pm}$ = 1000 GeV

* significance $Z = \sqrt{(2*((s+b)x\ln(1+s/b)-s))}$, where s is number of signal and b is number of total background

Conclusions

1. By using 3CNN approach, we can **significantly enhance the signal-background ratio** for Higgs-pair production produced via gluon-gluon fusion at the 14 TeV HL-LHC
2. This architecture has 2-class outputs and contains one stream **acting on global event information**, and other streams **acting on local information** from leading and subleading jets.
3. The 3CNN can significantly **enhance the significance of the signal** at HL-LHC
4. It allows us to probe **sizeable sensitive parameter space** in the currently allowed region in the Types I to IV of 2HDM.
5. This work is **flexible** to implement in **other Higgs-pair production channels with hadronic or semi-hadronic final state with boosted boson** and may be able to **enrich the sensitivity of the signal at the HL-LHC**

Thank You