Probing electroweak symmetry breaking with Higgs pair production at the LHC

*Behr, Bortoletto, Frost, Issever, Hartland, JR, **arxiv:1512.08928***

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Oxford ATLAS Higgs Meeting
Oxford, 29/01/2015

Why Higgs couplings?

Higgs couplings may indicate new physics: a few percent precision is a good target

Higgs Snowmass report (arXiv:1310.8361)
Deviation from SM due to particles with M=1 TeV

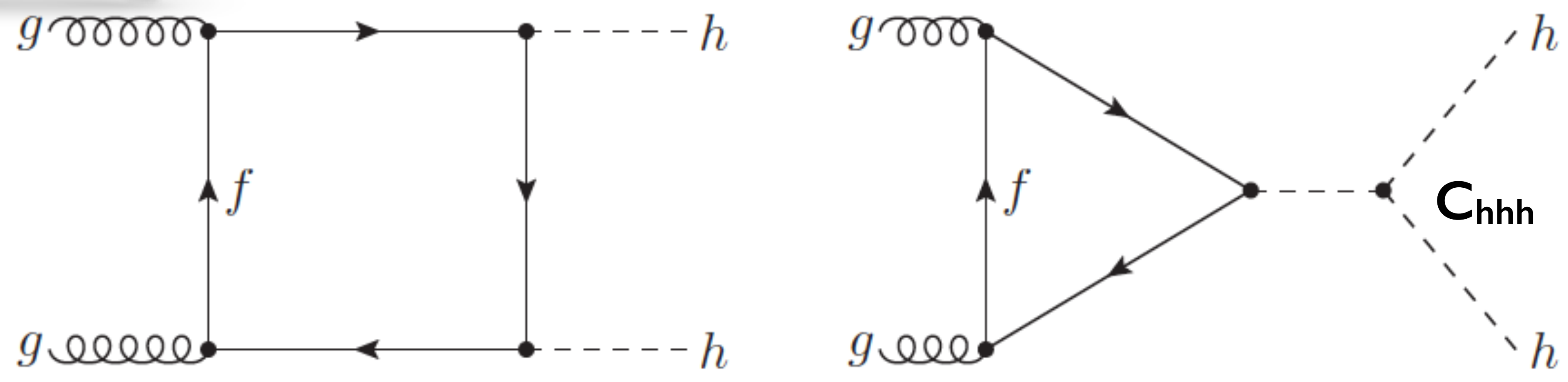
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Future LHC data: measure H couplings at 2-8% level (cf 20-50% today), and to access rare decays such as $H \rightarrow \mu\mu$

Higgs Pair Production at the LHC

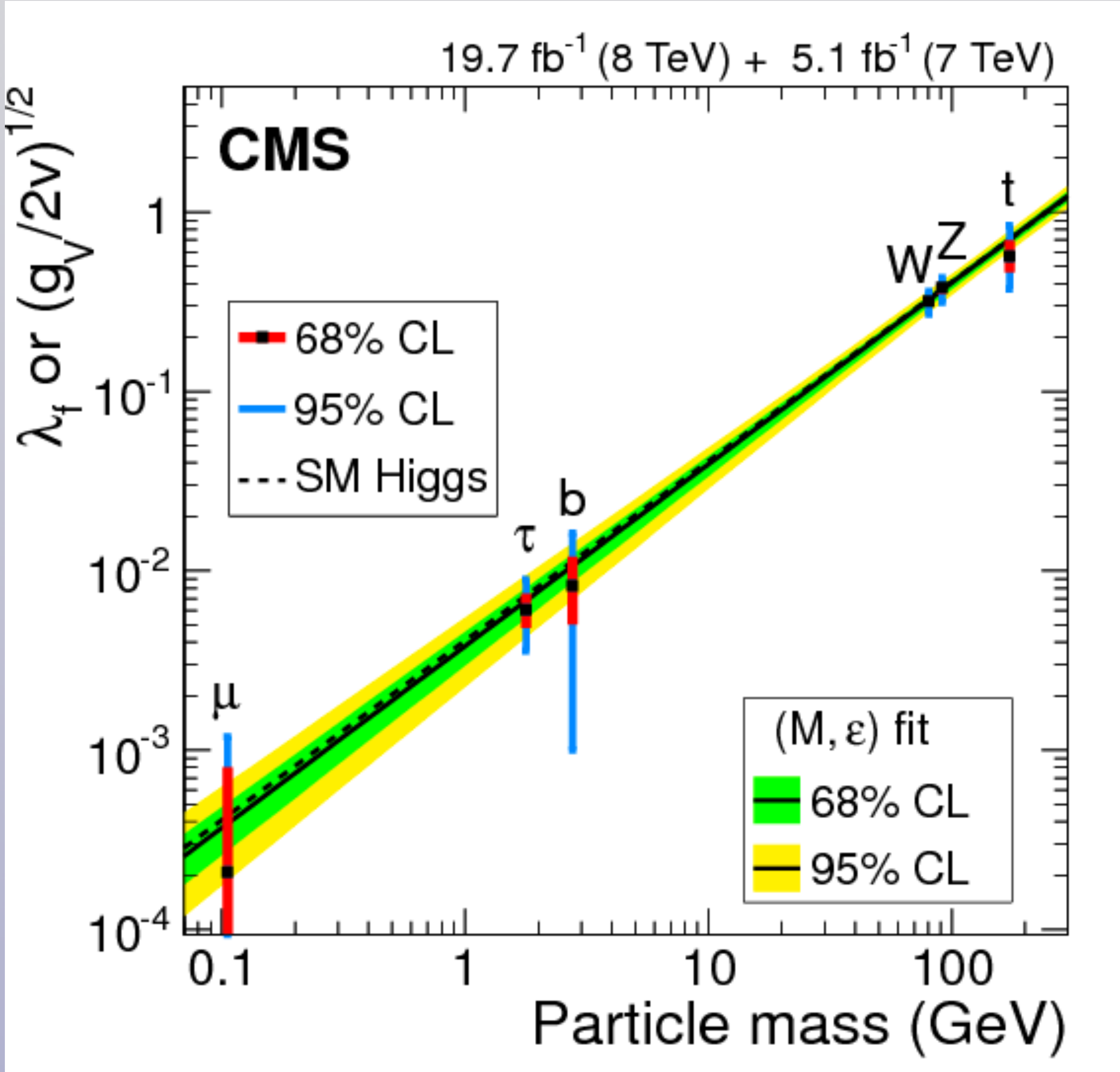
- **Double Higgs production** allows accessing crucial components of the Higgs sector:
  - ☑ Reconstruct the **full electroweak symmetry breaking potential**
  - ☑ Probe the **Higgs self-interaction**
  - ☑ Probe the **doublet nature** of the Higgs by means of the **hhVV coupling**
- In the SM, **hh rates are small:** in the leading gluon-fusion, mode, **cross-section at 14 TeV is 40 fb**
- Rates for double Higgs production **generically enhanced in BSM scenarios**, and **LHC searches** in various final states have already started at **Run I**

gg->hh



Interference between box and triangle complicates the extraction of the self-coupling

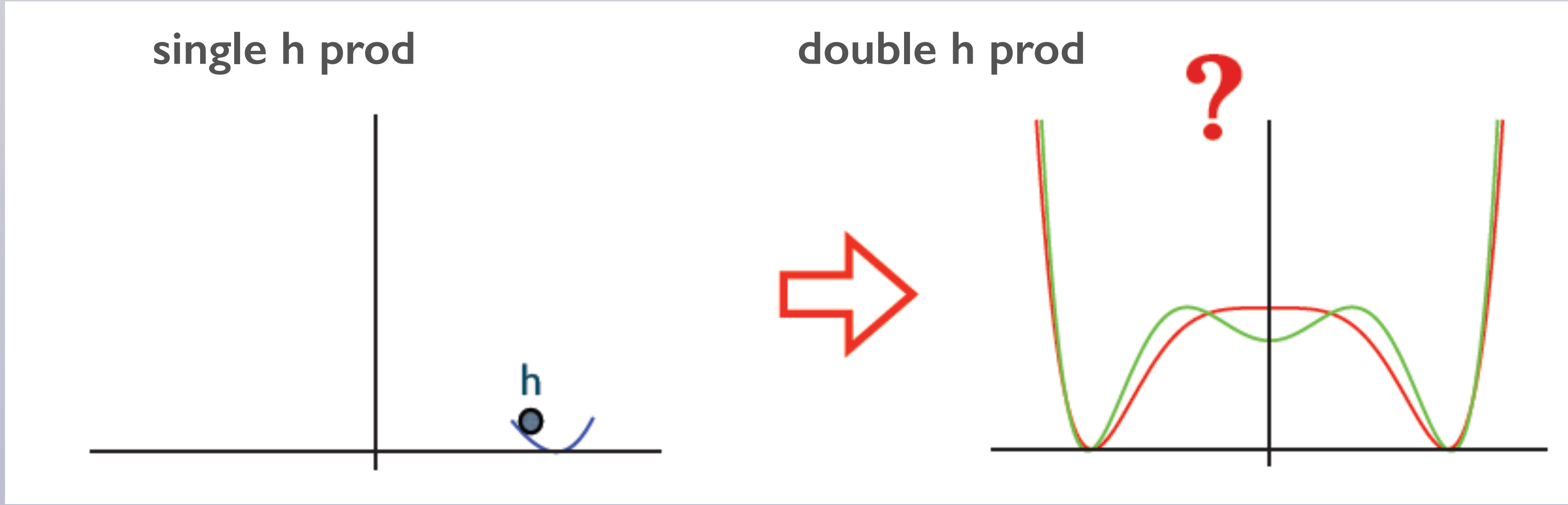
Probing Electroweak Symmetry breaking



- **Yukawa/Couplings** between Higgs and SM particles **proportional to mass**
- The Higgs boson is **responsible to break EW symmetry and give particles mass**
- However, we still lack understanding of **why and how** EWS is broken

Electroweak symmetry breaking

- **Current measurements** (couplings in single Higgs production) probe **Higgs potential close to minimum**
- Double Higgs production essential to **reconstruct the full Higgs potential** and clarify EWSB mechanism
- The Higgs potential is ad-hoc: **many other EWSB mechanisms conceivable**



Higgs mechanism

$$V(h) = m_h^2 h^\dagger h + \frac{1}{2}\lambda(h^\dagger h)^2$$

Coleman-Weinberg mechanism

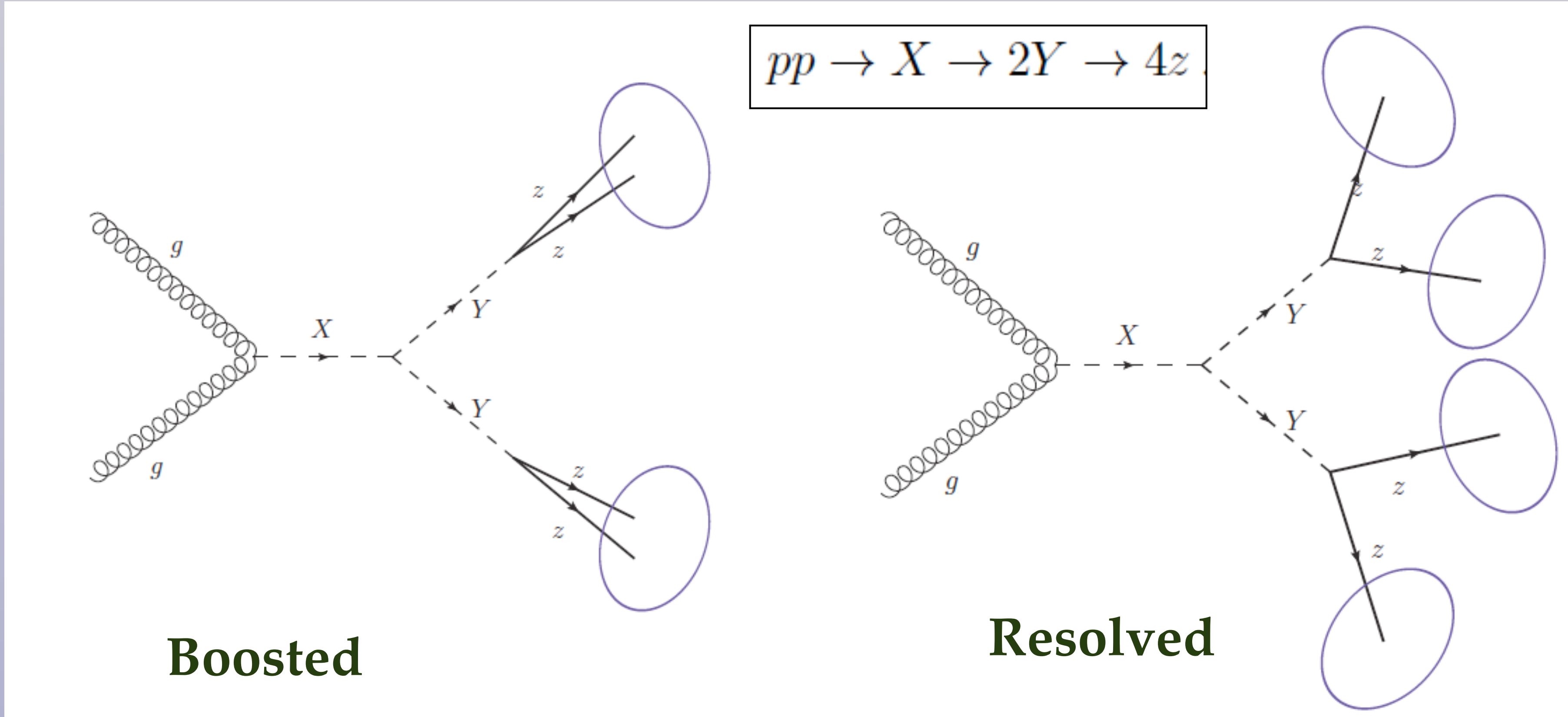
$$V(h) \to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

Each possibility associated to **completely different EWSB mechanism**, with crucial implications for the **hierarchy problem**, the structure of quantum field theory, and **New Physics at the EW scale**

Arkani-Hamed, Han, Mangano, Wang, arxiv:1511.06495

Higgs Pair Production at the LHC

- Focus on the **hh->4b final state:** largest rates, but **overwhelming QCD multijet background**
- Made competitive requiring the **di-Higgs system to be boosted** and exploiting kinematic differences between signal and QCD background with **jet substructure**
- Mandatory to optimize the **boosted b-tagging techniques,** impressive recent progress by ATLAS and CMS



Scale-invariant resonance tagging
Gouzevitch, Oliveira, Rojo, Rosenfeld, Salam and Sanz, arxiv:1303.6636

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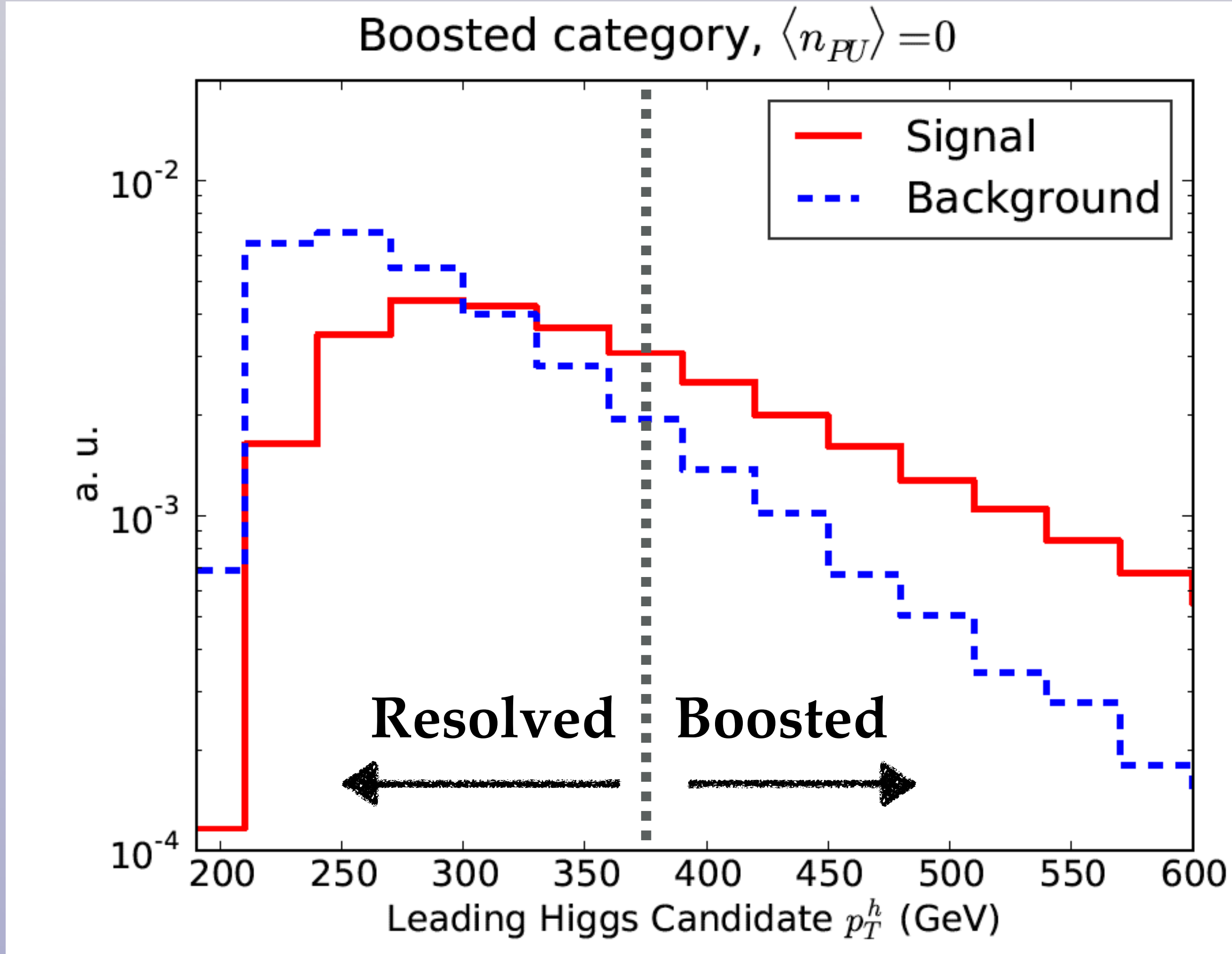

MC generation and pre-MVA analysis

Signal and background samples at LO, **normalized to higher-order calculation**

Process	Generator	N_{evt}	σ_{LO} (pb)	K-factor
$pp \to hh \to 4b$	`MadGraph5_aMC@NLO`	1M	$6.2 \cdot 10^{-3}$	2.4 (NNLO+NNLL [18, 19])
$pp \to b\bar{b}b\bar{b}$	`SHERPA`	3M	$1.1 \cdot 10^{3}$	1.6 (NLO [63])
$pp \to b\bar{b}jj$	`SHERPA`	3M	$2.7 \cdot 10^{5}$	1.3 (NLO [63])
$pp \to jjjj$	`SHERPA`	3M	$9.7 \cdot 10^{6}$	0.6 (NLO [77])
$pp \to t\bar{t} \to b\bar{b}jjjj$	`SHERPA`	3M	$2.5 \cdot 10^{3}$	1.4 (NNLO+NNLL [78])

Basic selection criteria different in the three categories: **boosted, resolved and intermediate**

Kinematics cuts deliberately loose: **optimization performed at the MVA level**

<table>
<tr><th></th><th>Boosted</th><th>Intermediate</th><th>Resolved</th></tr>
<tr><td rowspan="2">C1a</td><td>$N_{\mathrm{jets}}^{R10} \geq 2$</td><td>$N_{\mathrm{jets}}^{R04} \geq 2$, $N_{\mathrm{jets}}^{R10} = 1$</td><td>$N_{\mathrm{jets}}^{R04} \geq 4$</td></tr>
<tr><td colspan="3">$+p_T$ cuts and rapidity cuts</td></tr>
<tr><td>C1b</td><td>$+N_{\mathrm{MDT}} \geq 2$</td><td>$+N_{\mathrm{jets}}^{R10} = 1$ with MDT
+Higgs reconstruction</td><td>+Higgs reconstruction</td></tr>
<tr><td>C1c</td><td colspan="3">$+m_h$ window cut</td></tr>
<tr><td>C2</td><td colspan="3">$+b$-tagging</td></tr>
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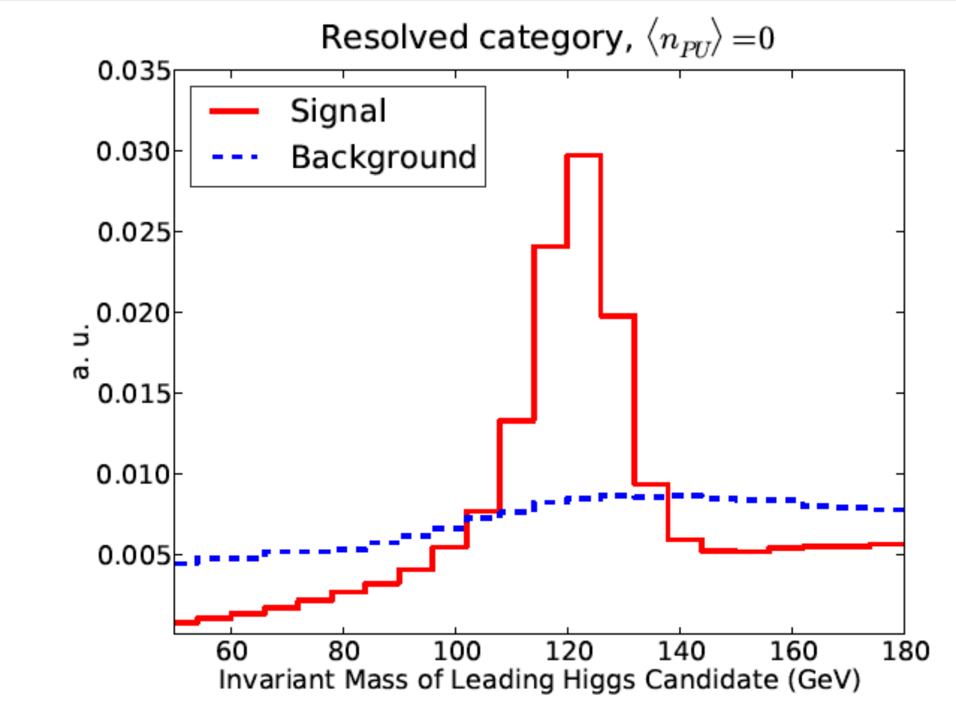
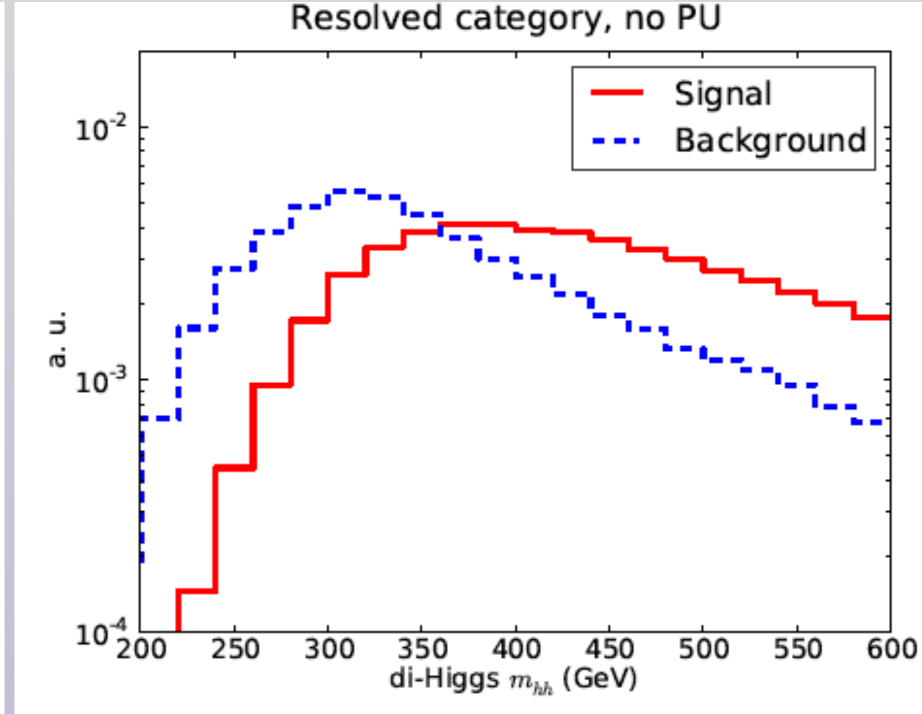
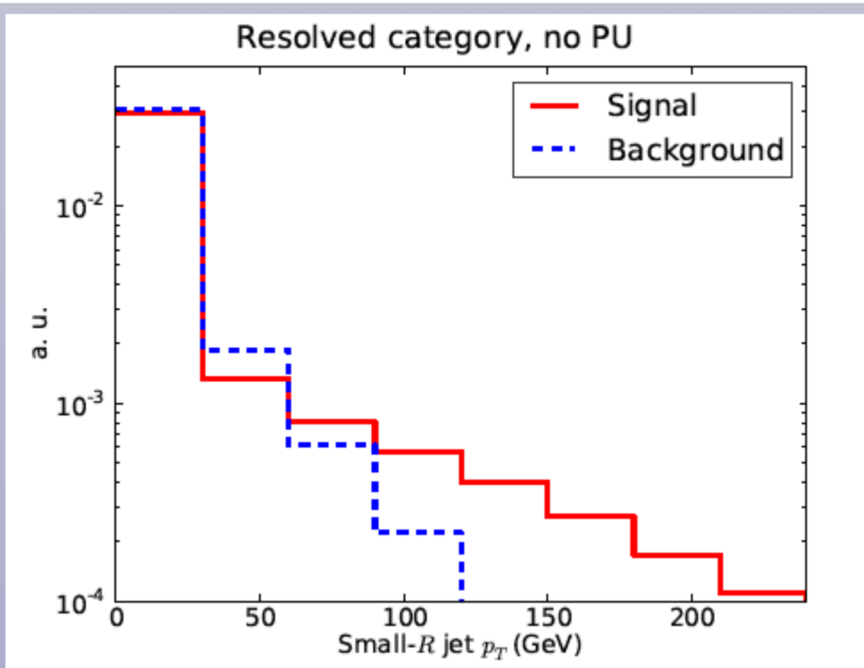
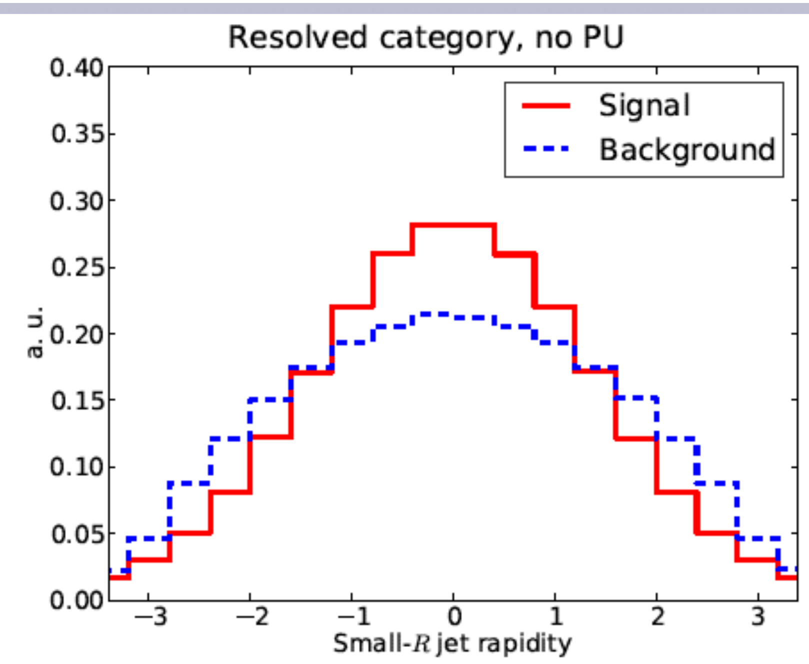
pre-MVA results









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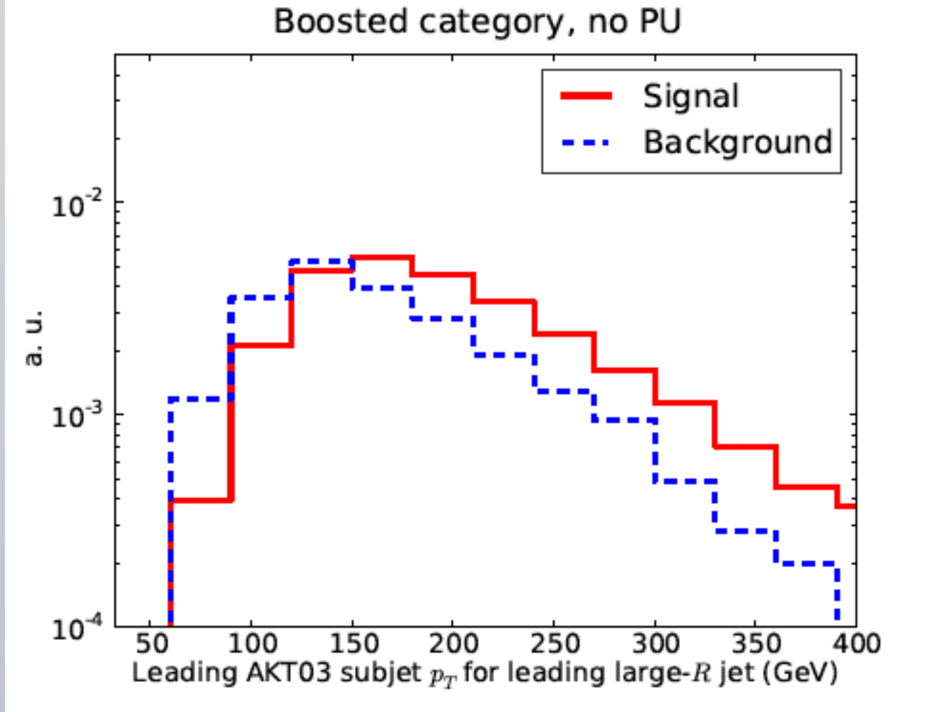
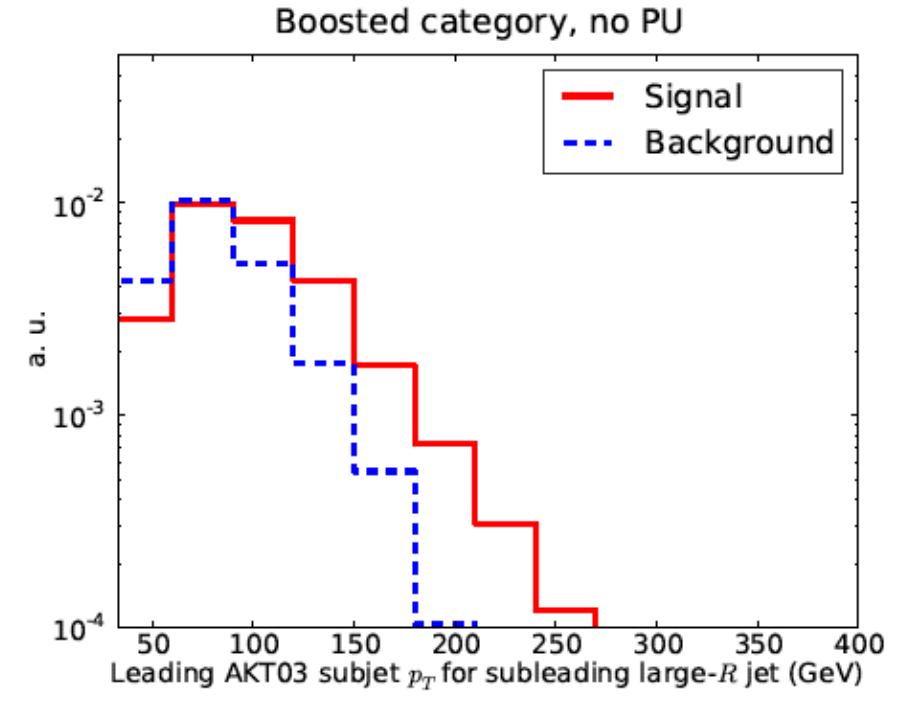
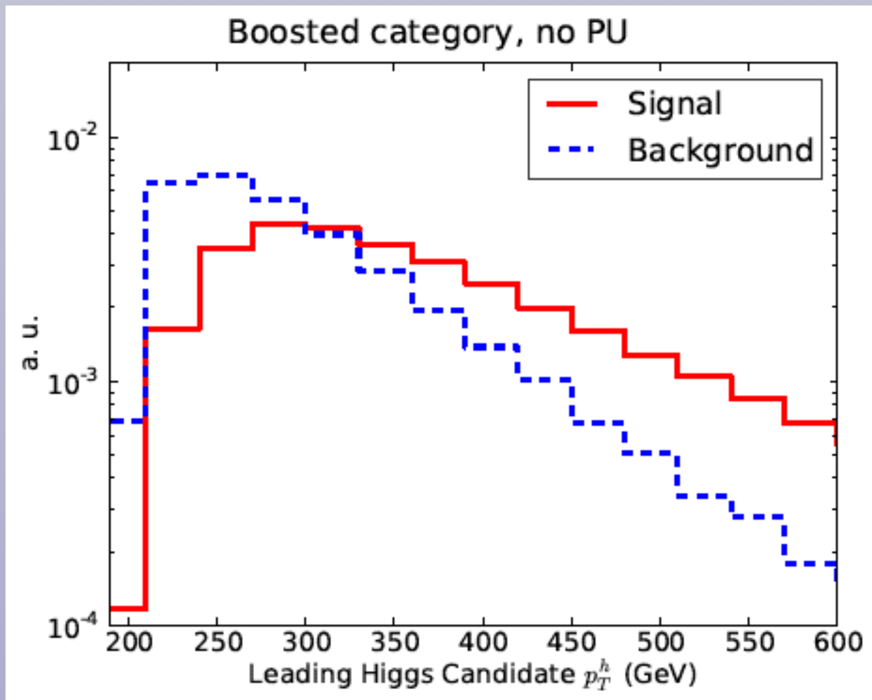
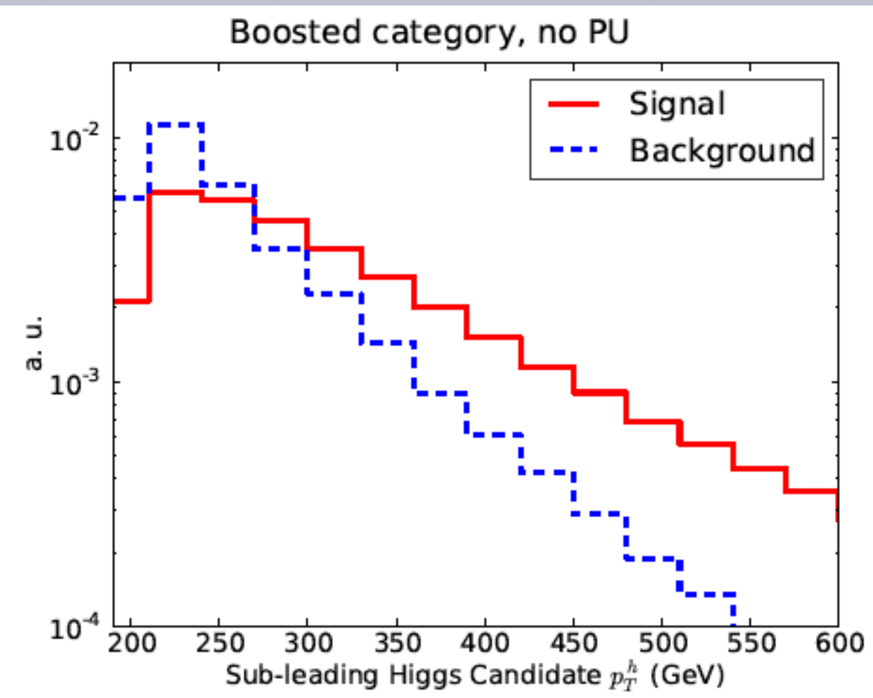






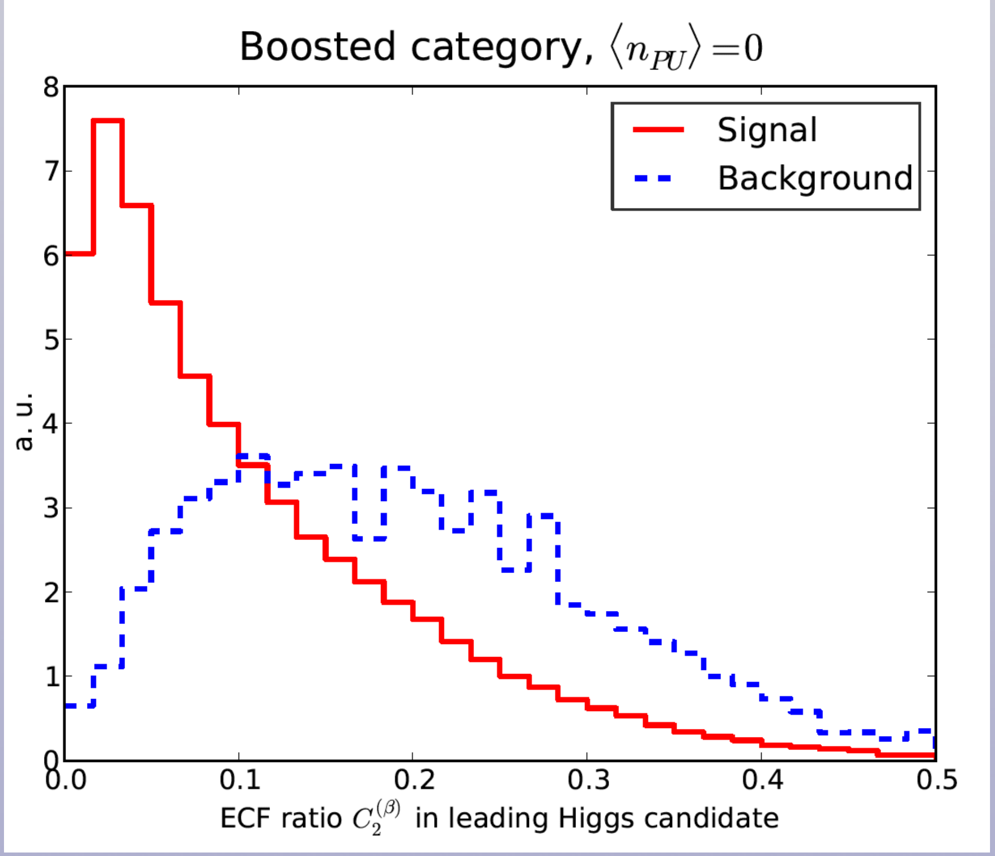


Jet substructure variables

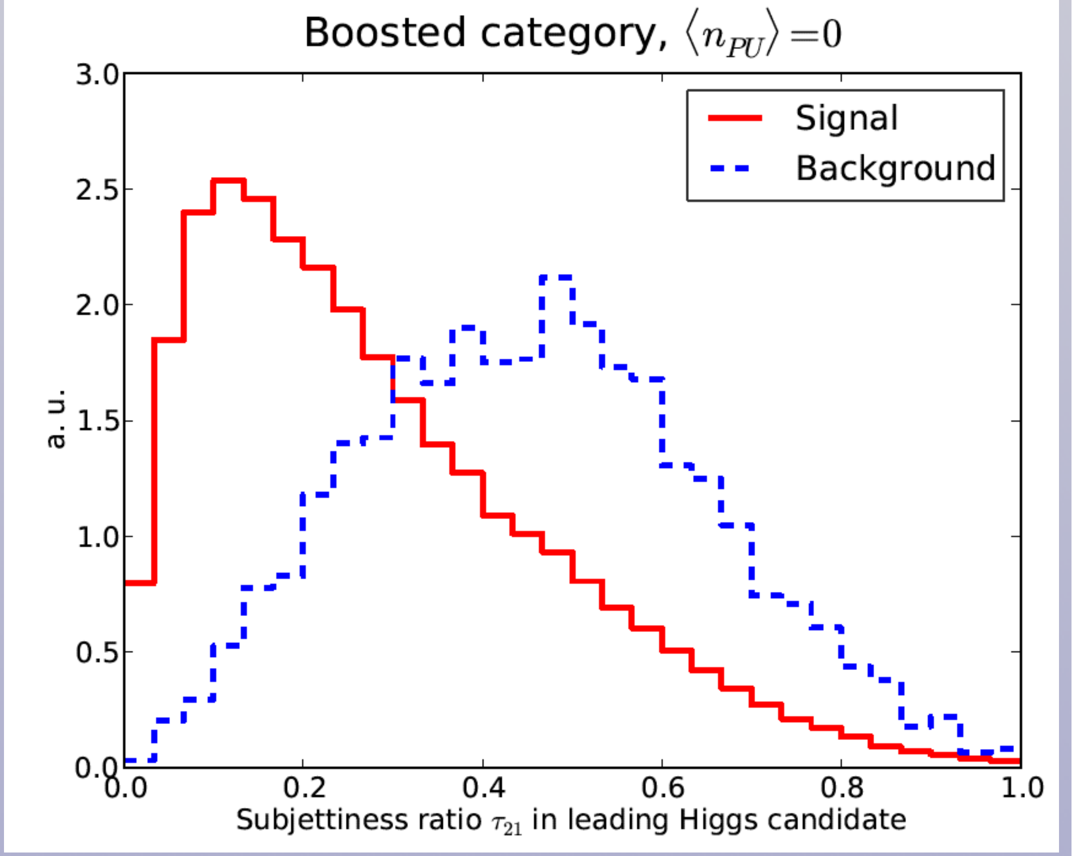
- **Substructure variables** quantify differences in internal structure between **QCD jets** and **jets from the decay of heavy resonances**

- QCD radiation tends to be **soft** and **collinear,** while decay products of resonances **share momentum evenly**

Energy Correlation Functions ratio

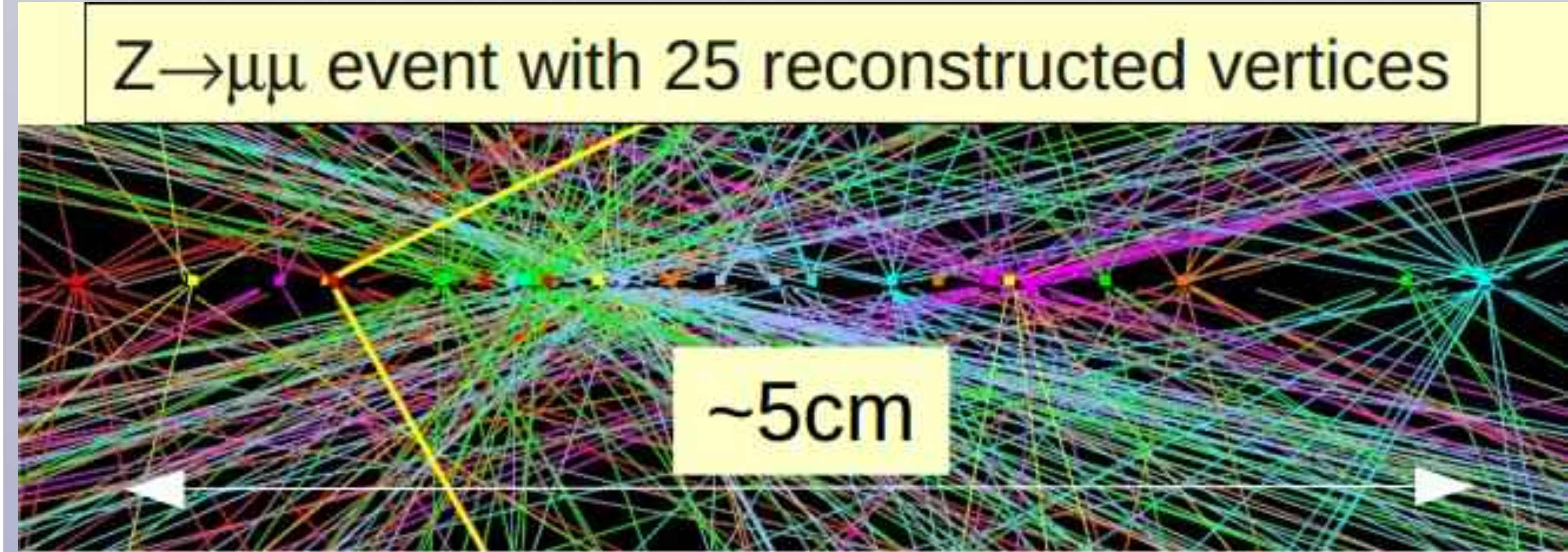


τ_{21}: 2-to-1 Subjettiness ratio



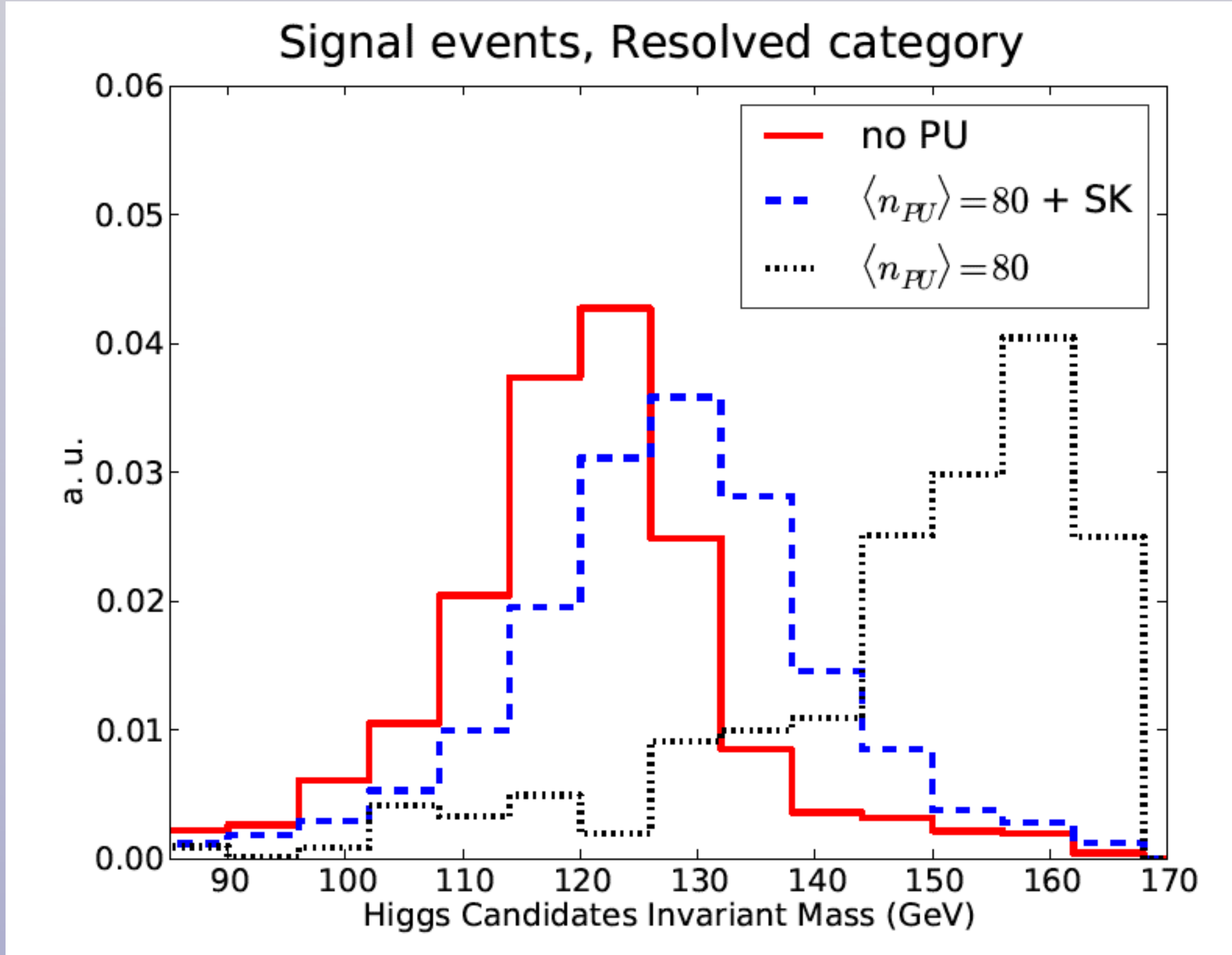
Pile-up at the HL-LHC

- **Pile-up (PU)**: multiple interactions between different pairs of protons in the same **bunch crossing**
- At the **high luminosities** of the HL-LHC, PU will be the **major contamination** in most analysis
- **$<n_{PU}>=150$** corresponds to **embedding each hard event into 150 minimum bias events**



Pile-up at the HL-LHC

- Recent development of **PU subtraction methods** allows to overcome these limitations
- Use **SoftKiller (SK)** to **subtract PU contamination** and maintain most of the signal/background discrimination power of the no-PU scenario   SoftKiller: Cacciari, Salam and Soyez, arxiv:1407.0408
- In addition, **jet trimming** is also performed on the **large-*R* jets**



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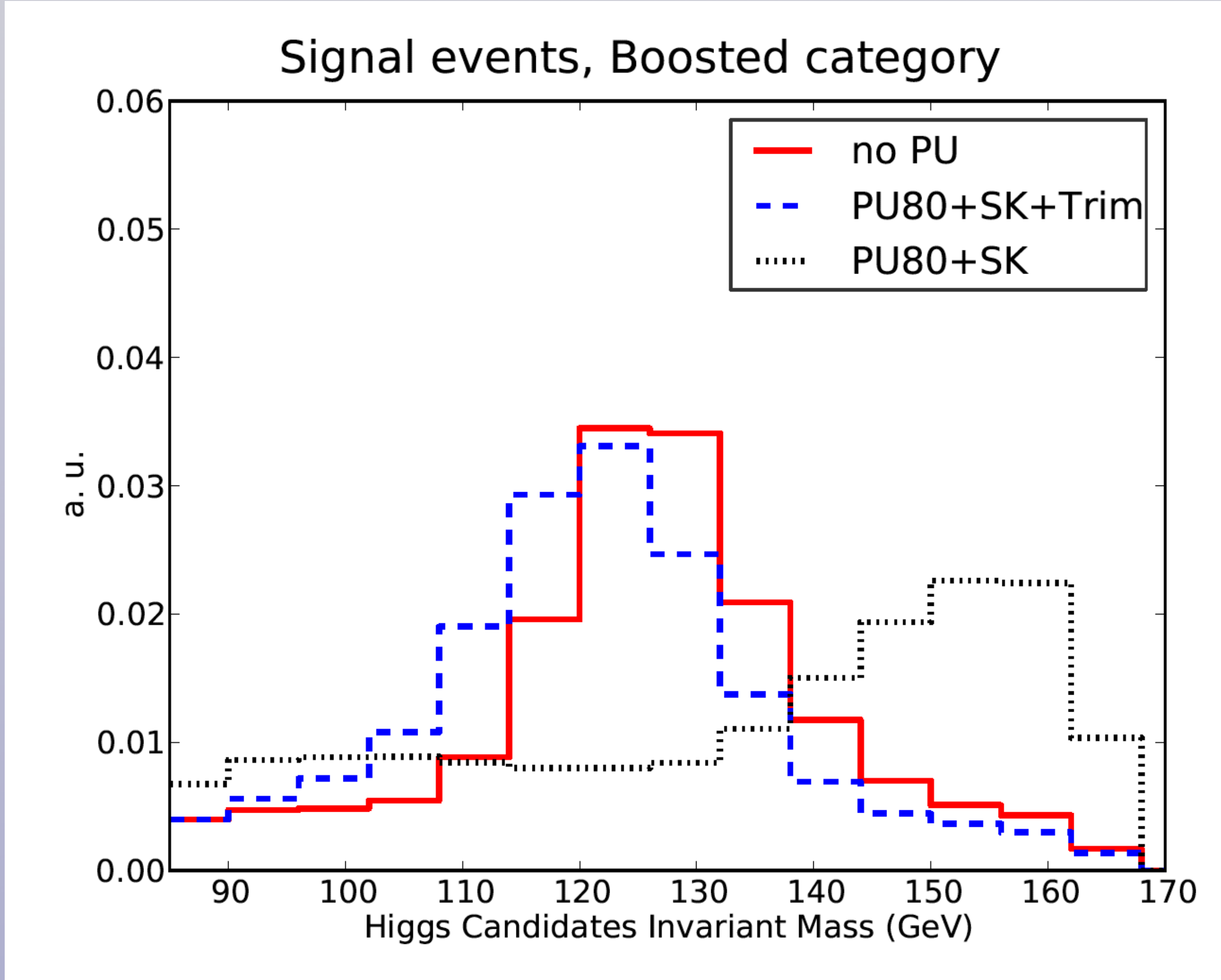


Multivariate techniques

Large number of kinematic variables to disentangle signal and background, **how to combine them?**

Multivariate techniques: Identify automatically kinematical variables with most discrimination power

Higgs pT

Higgs m

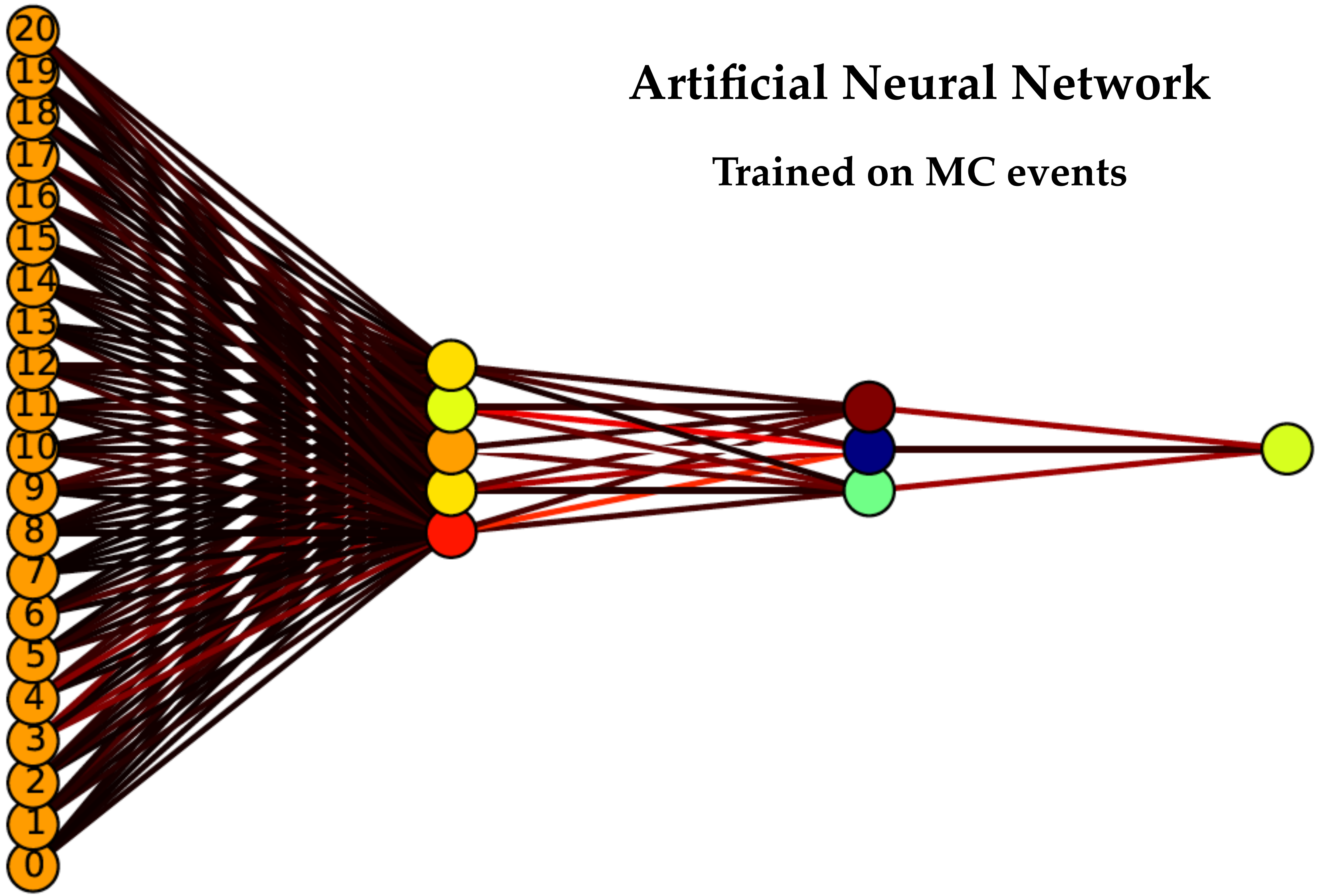
di-Higgs m

ECF

τ_{12}

Subjet pT

…..



Artificial Neural Network

Trained on MC events

Multivariate techniques

Given a set of N_{var} kinematic variables $\{k_i\}$ associated to MC event i, and a set of ANN weight parameters $\{\omega\}$, the ANN output y_i interpreted as **probability that this event originates from signal process**

$$y_i = P(y'_i = 1|\{k\}_i, \{\omega\}) ,$$

With y'_i the true MC classification: $y'_i=1$ for signal, $y'_i=0$ for background

The **general classification probability** including background events is

$$P(y'_i|\{k\}_i, \{\omega\}) = y_i^{y'_i}(1-y_i)^{1-y'_i}$$

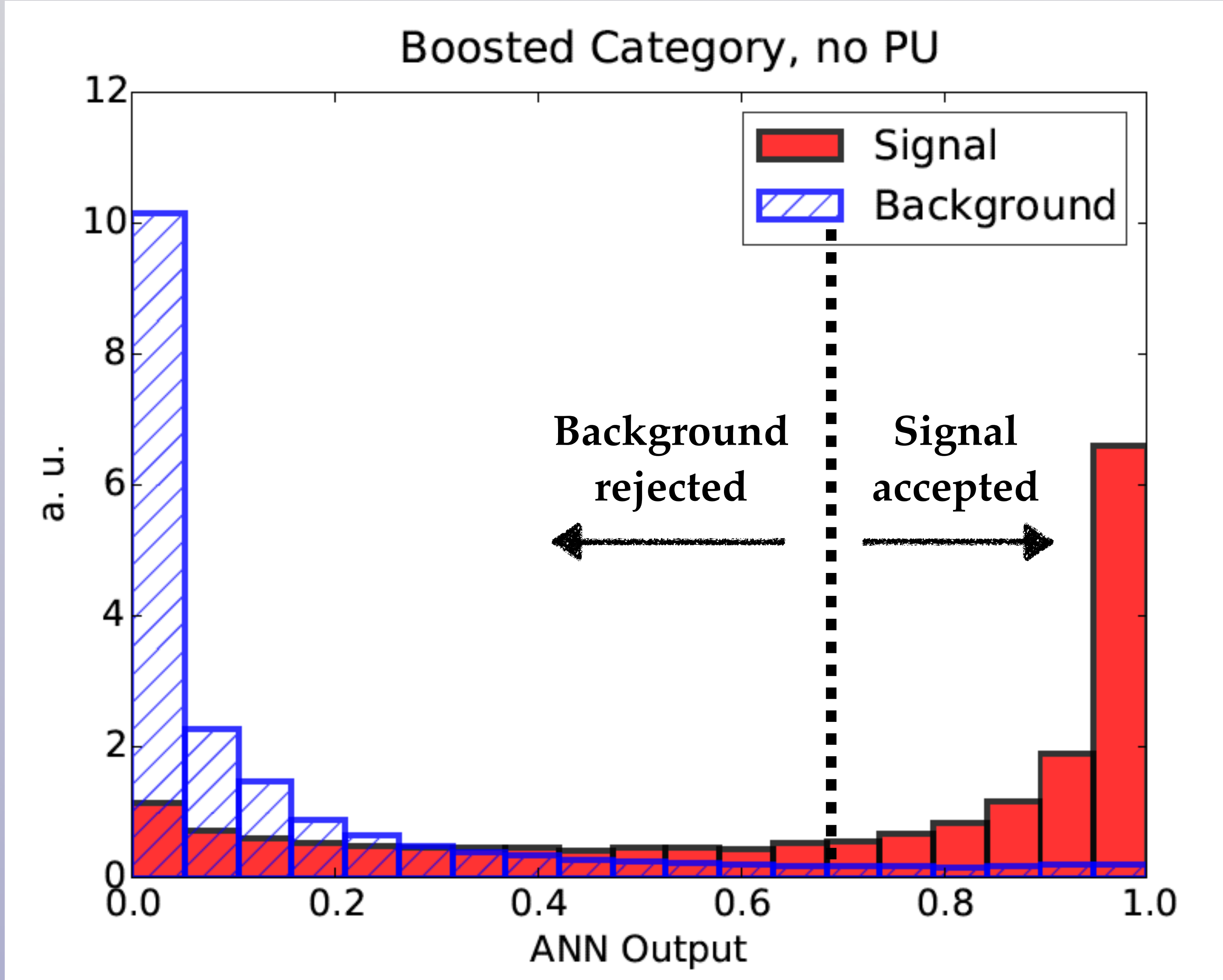
Thus the **error function to be minimised during the training** is the cross-entropy:

$$E(\{\omega\}) \equiv -\log\left(\prod_i^{N_{\rm ev}} P(y'_i|\{k\}_i, \{\omega\})\right)$$
$$= \sum_i^{N_{\rm ev}} \left[y'_i \log y_i + (1-y'_i)\log(1-y_i)\right]$$

ANN training performed with **Genetic Algorithms** using **cross-validation stopping**

Multivariate techniques

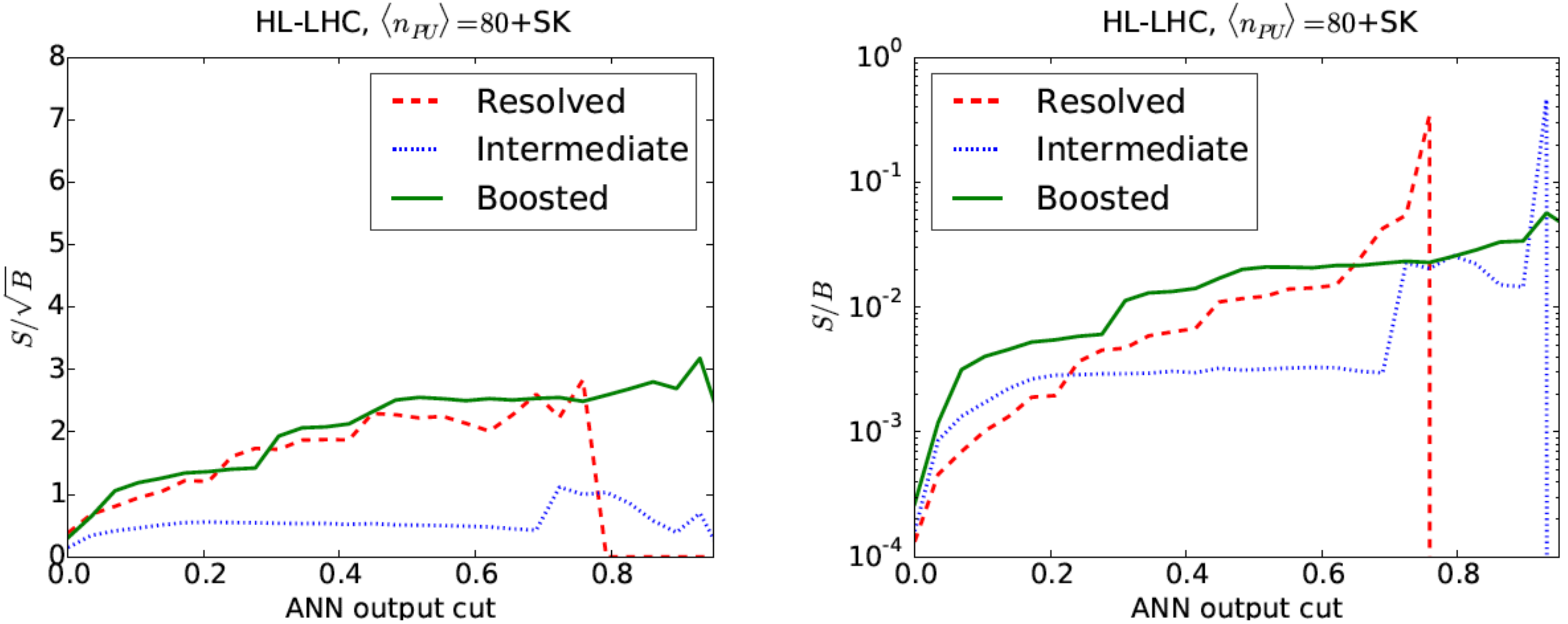
Combining information from all kinematic variables in MVA: **excellent signal/background discrimination**



Signal significance

- Use of **multivariate techniques** allows to **substantially improve the signal significance** for this process as compared to a **traditional cut -based analysis**
- The total combined significance is enough to **observe Higgs pair production in the 4b final state** at the HL-LHC.

$$\left(\frac{S}{\sqrt{B}}\right)_{\rm tot} \simeq 4.0\ (1.3)\,, \quad \mathcal{L} = 3000\ (300)\ {\rm fb}^{-1}\,,$$



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HL-LHC, PU80+SK+Trim					
Category		$N_{\rm ev}$ signal	$N_{\rm ev}$ back	$S/\sqrt{B}$	S/B
Boosted	$y_{\rm cut} = 0$	410	$4.5 \cdot 10^5$	0.6	10^{-3}
	$y_{\rm cut} = 0.8$	290	$3.7 \cdot 10^4$	1.5	0.01
Intermediate	$y_{\rm cut} = 0$	260	$7.7 \cdot 10^5$	0.3	$3 \cdot 10^{-4}$
	$y_{\rm cut} = 0.75$	140	$5.6 \cdot 10^3$	1.9	0.03
Resolved	$y_{\rm cut} = 0$	1800	$2.7 \cdot 10^7$	0.4	$7 \cdot 10^{-5}$
	$y_{\rm cut} = 0.60$	640	$1.0 \cdot 10^5$	2.0	0.01

The MVA achieves a **substantial background reduction** with **high signal efficiency**

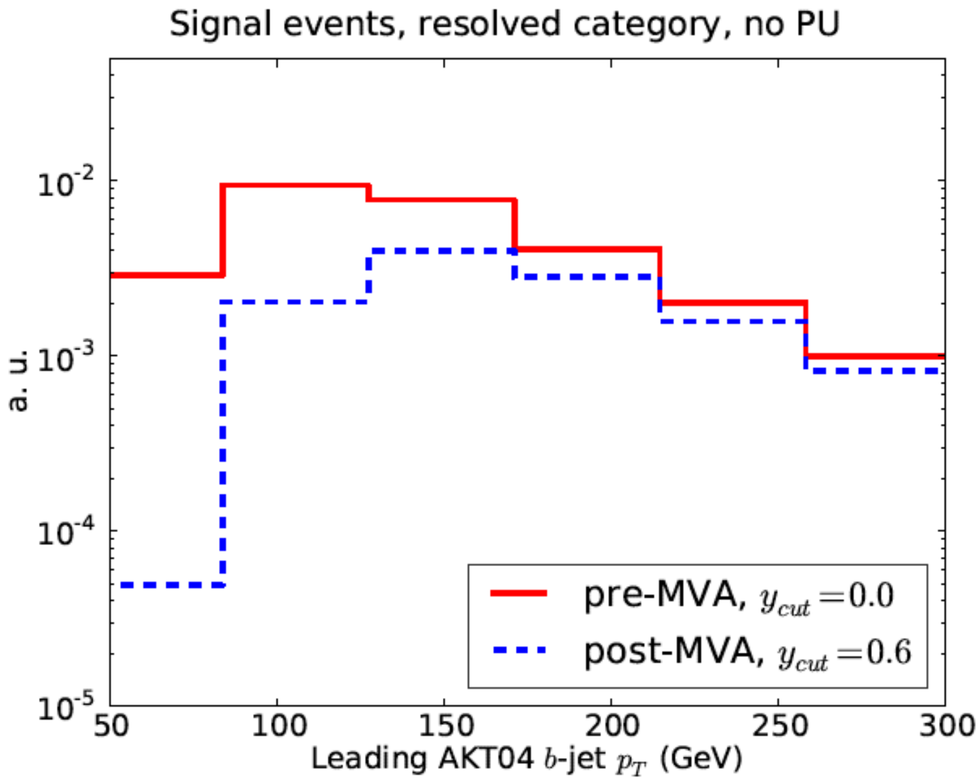
Signal significance

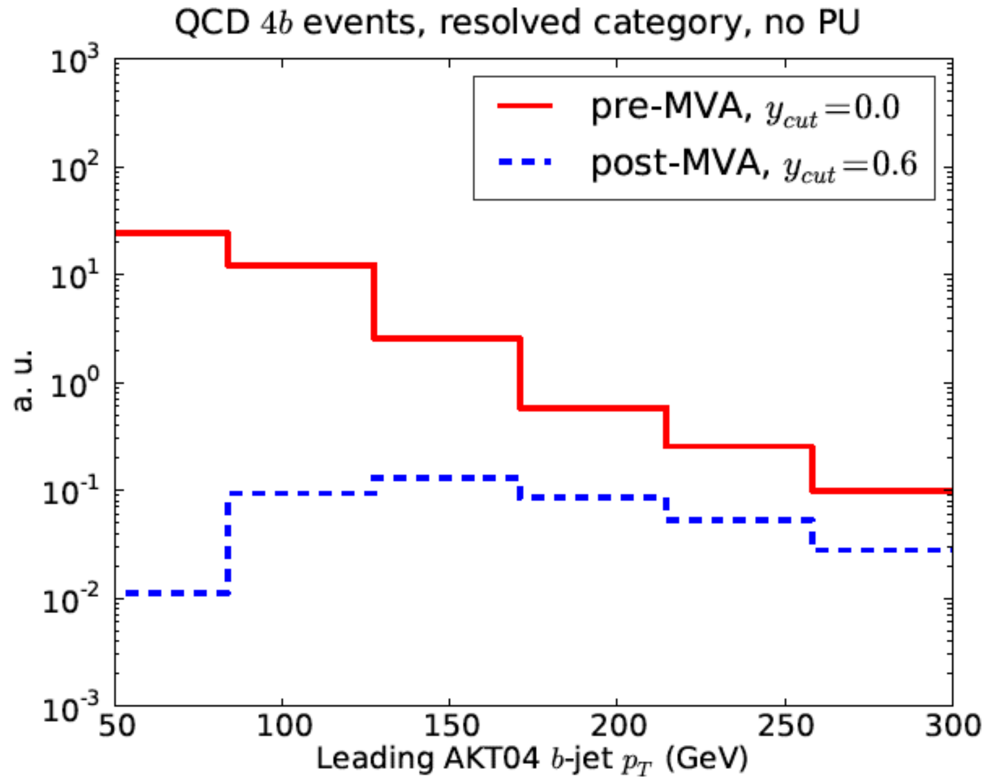
Category		signal N_{ev}	background N_{ev}^{tot}	N_{ev}^{4b}	$S/\sqrt{B_{tot}}$	$S/\sqrt{B_{4b}}$	S/B_{tot}	S/B_{4b}
Boosted	no PU	290	$1.2 \cdot 10^4$	$8.0 \cdot 10^3$	2.7	3.2	0.03	0.04
	PU80+SK+Trim	290	$3.7 \cdot 10^4$	$1.2 \cdot 10^4$	1.5	2.7	0.01	0.02
Intermediate	no PU	130	$3.1 \cdot 10^3$	$1.5 \cdot 10^3$	2.3	3.3	0.04	0.08
	PU80+SK+Trim	140	$5.6 \cdot 10^3$	$2.4 \cdot 10^3$	1.9	2.9	0.03	0.06
Resolved	no PU	630	$1.1 \cdot 10^5$	$5.8 \cdot 10^4$	1.9	2.7	0.01	0.01
	PU80+SK	640	$1.0 \cdot 10^5$	$7.0 \cdot 10^4$	2.0	2.6	0.01	0.01
Combined	no PU				4.0	5.3		
	PU80+SK+Trim				3.1	4.7		

- If we can reduce the **contamination from b-jet mistags**, the signal significance at the HL-LHC would increase up to **almost discovery level**
- **Role of light and charm jet mistags** not considered in previous HH->4b feasibility studies
- Optimisation of **PU subtraction strategy** also important to increase signal significance

Opening the Black Box

- ANNs are sometimes criticised by acting as **black boxes**, with little control/understanding of what is happening inside them
- But ANNs are simply a **set of combined kinematical cuts**, nothing mysterious in them
- To verify this, plot kin distributions **after and before the ANN cut**: we can then determine the **effective kinematic cuts** are being optimised by the MVA
- This info should be enough to perform a cut-based analysis and achieve similar signal significance





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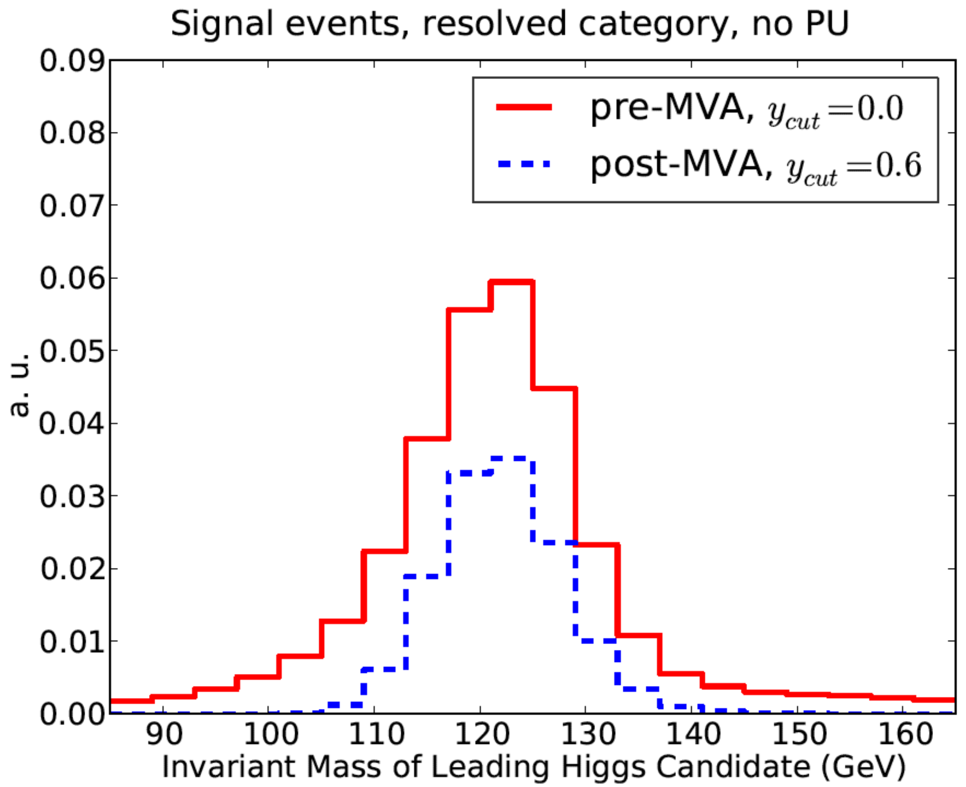
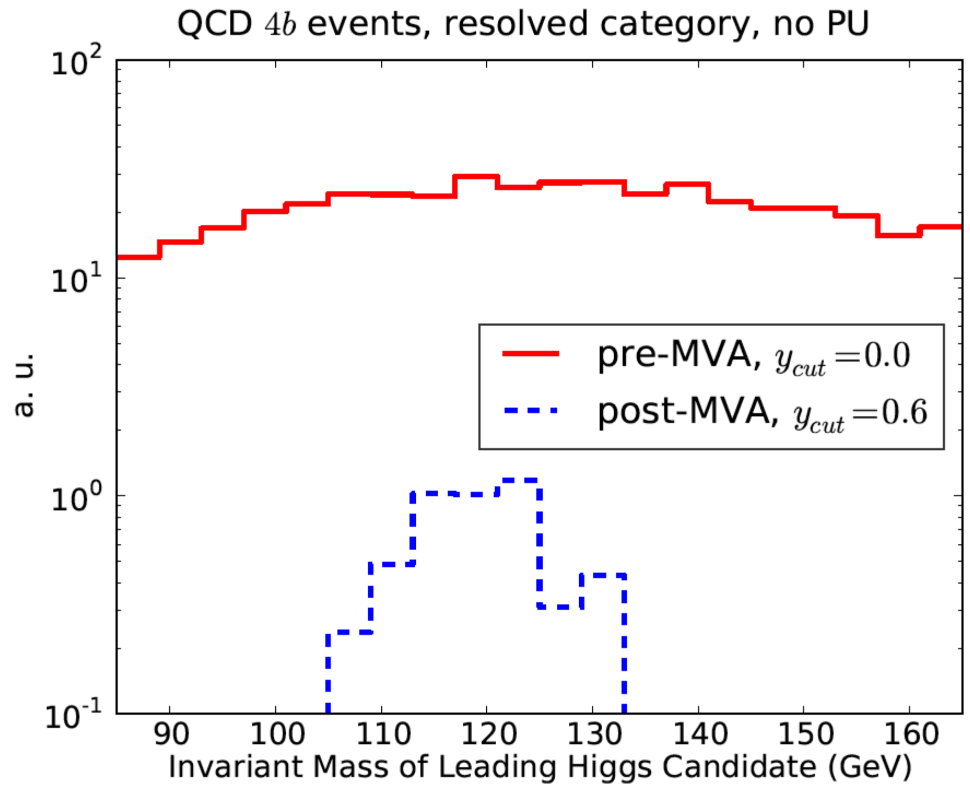




The background "Higgs mass peak" now mimics the signal one

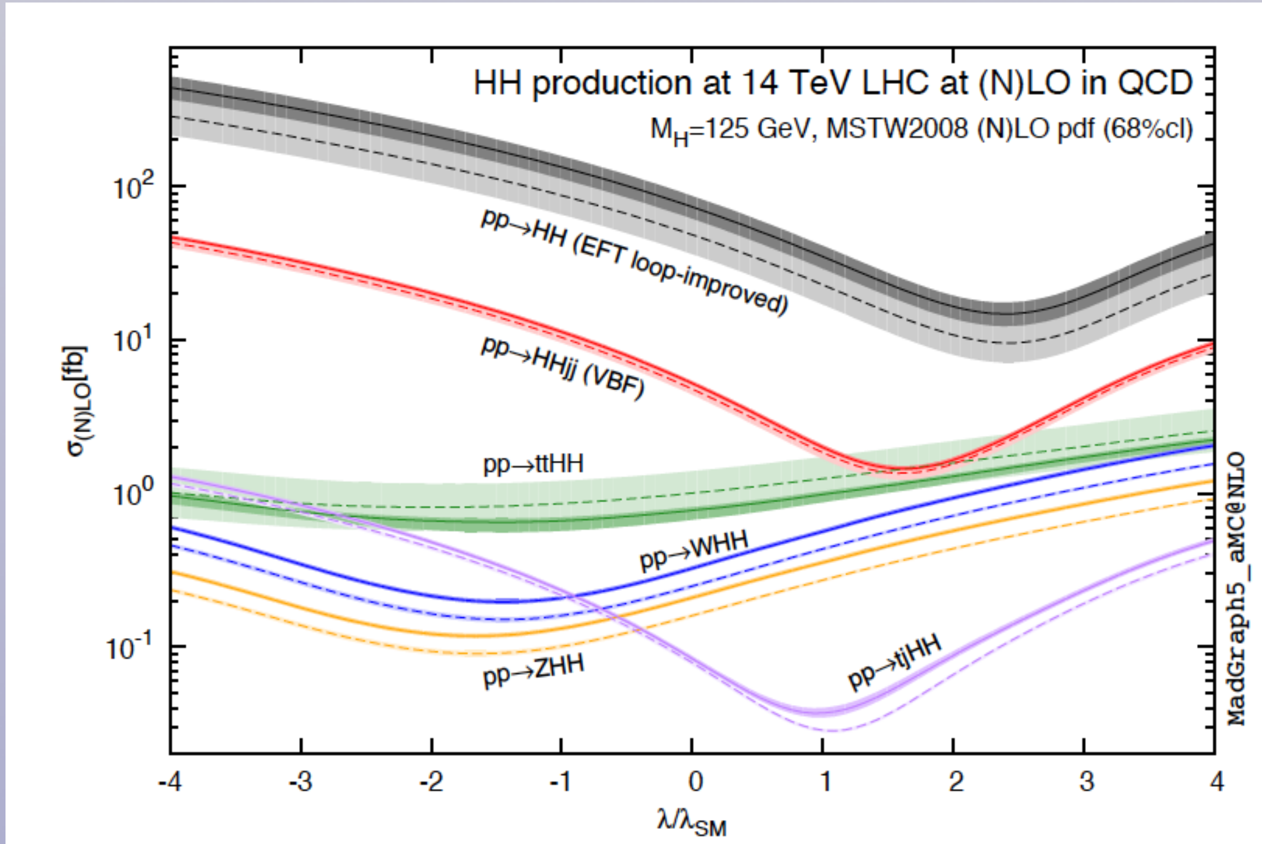
Next steps

- Now working on estimating the accuracy on the **extraction of the Higgs self-coupling** that can be achieved at the **LHC Run II**, the **HL-LHC** and at a **100 TeV FCC**

- **The optimization of the extraction of the Higgs self-coupling might require the use of an additional MVA** (different learning task than signal/background classification)

- Crucial the estimate of the impact of **experimental systematic uncertainties** that in real measurement

- We train with MC samples, a measurement the **MVA should be trained on LHC data** in control regions



Frixione et al, 1401.7340

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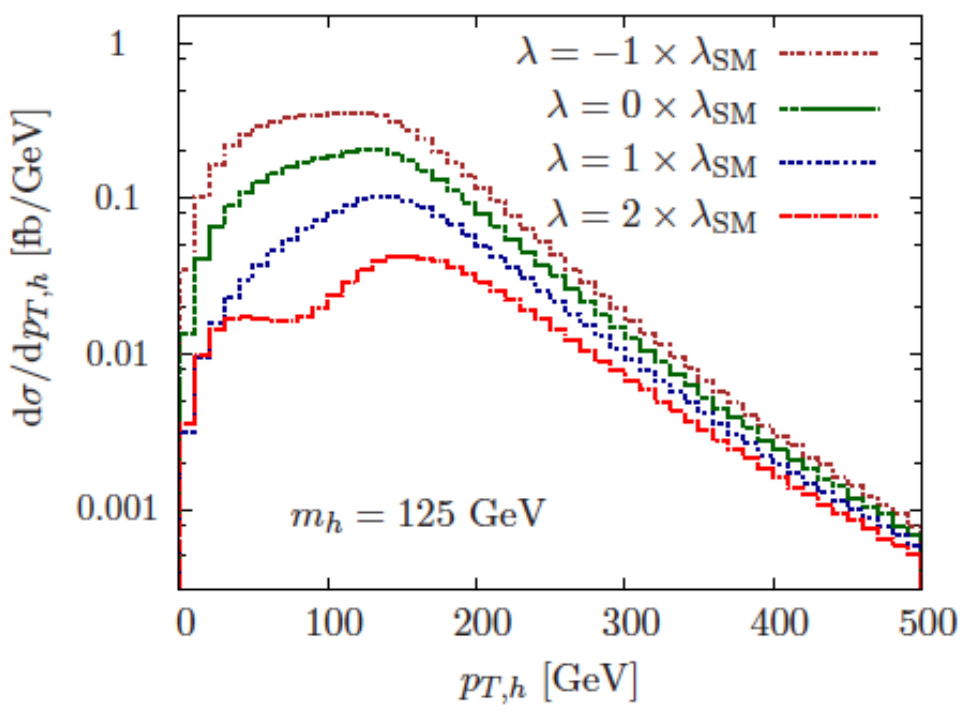

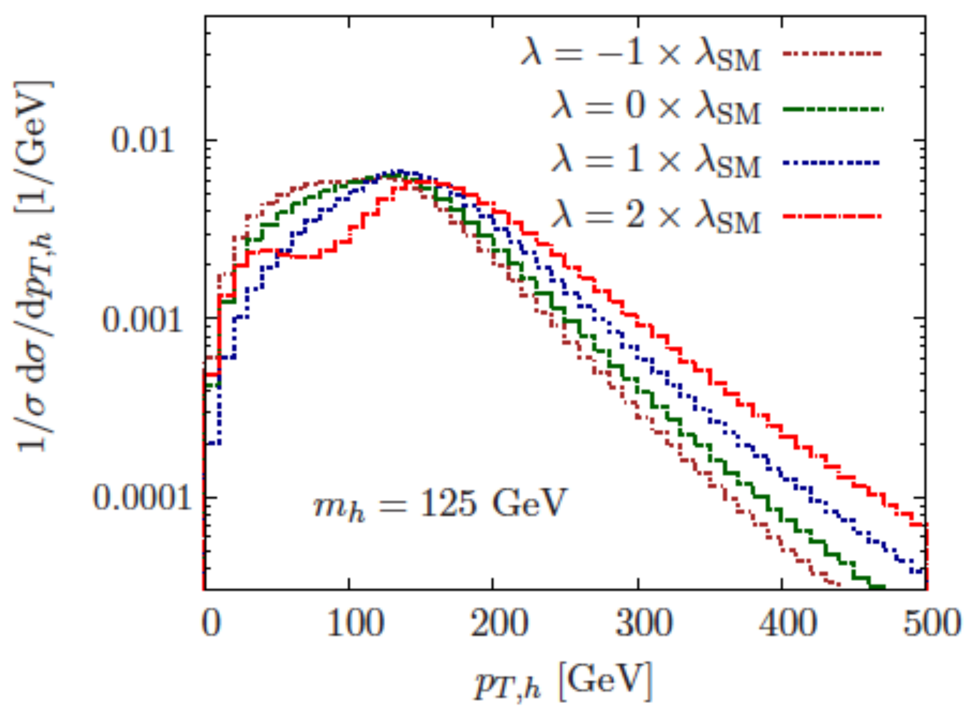

Englert, Dolan, Spannowsky, arXiv:1206.5001