Probing electroweak symmetry breaking with Higgs pair production at the LHC

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Fingerprinting the Higgs sector

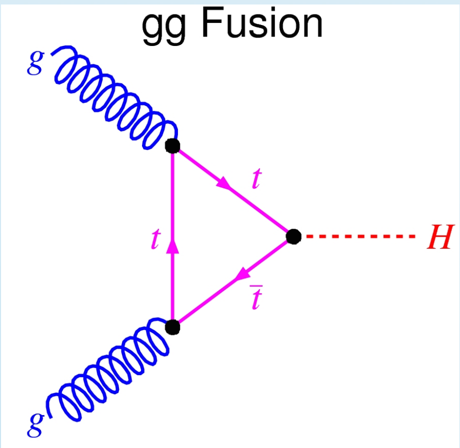
In the **Standard Model** the properties of the Higgs sector are **uniquely determined**

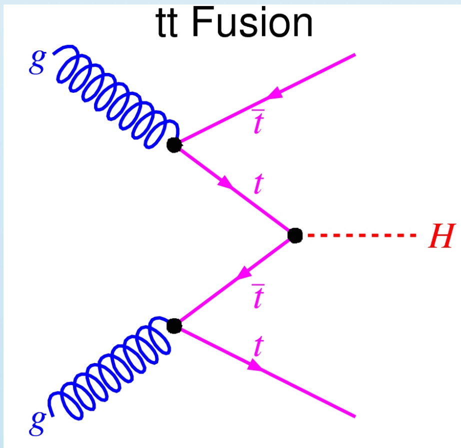
Any deviation from the tight SM predictions would be a **smoking gun for Physics beyond the SM**

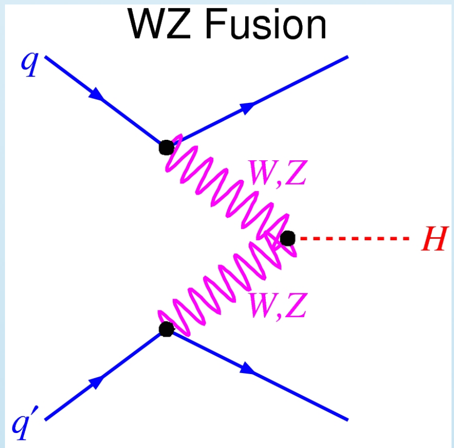
BSM model	Deviations in Higgs coupling to W, Z weak bosons	bottom quarks	photons
New heavy Higgs boson	6%	6%	6%
Two-Higgs Doublet model	1%	10%	1%
Composite Higgs	-3%	-9%	-9%
New heavy top-like quark	-2%	-2%	+2%

*A **precision of a few percent** in **Higgs couplings measurements** is the goal!*

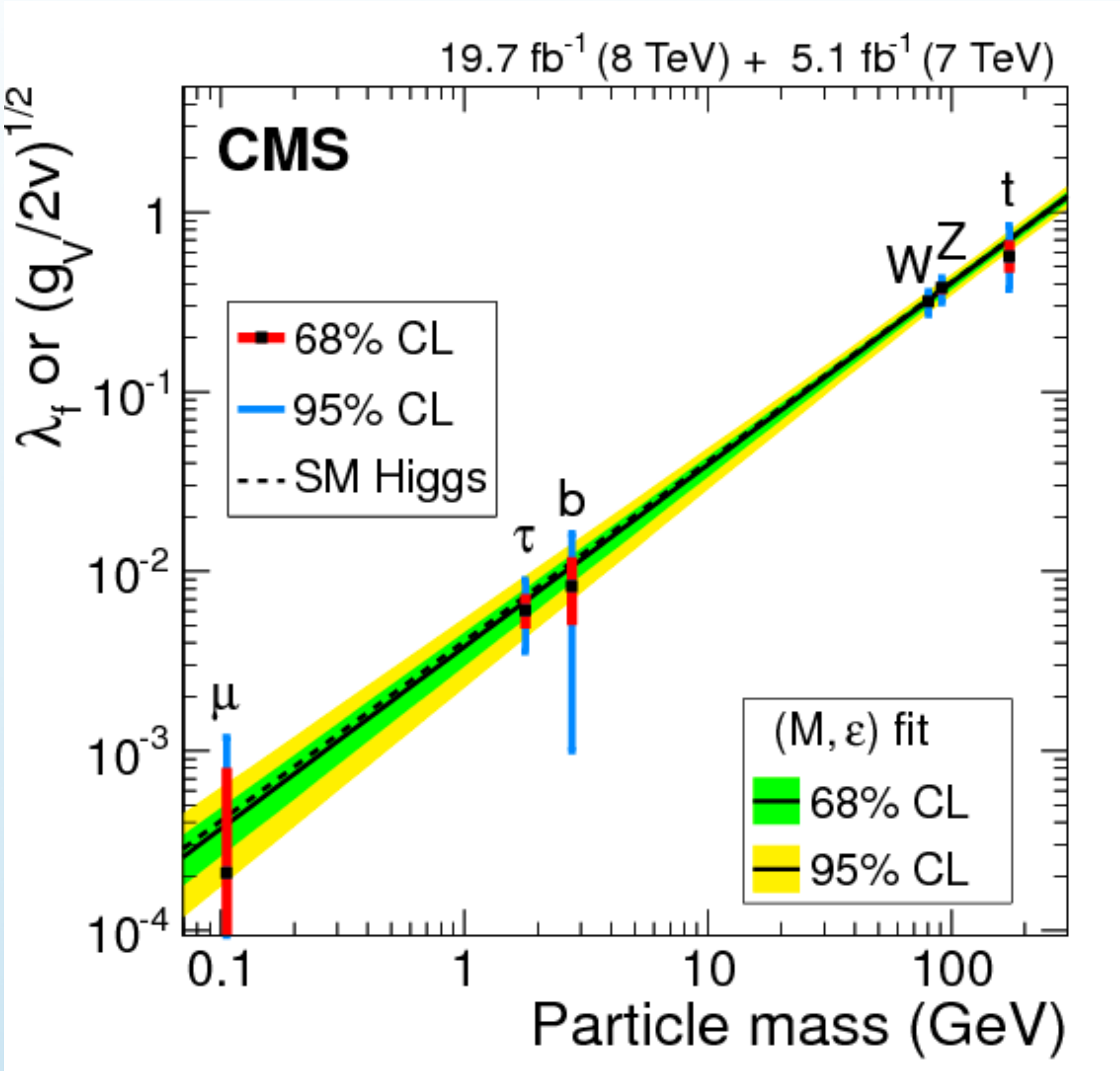
This precision required both in **experimental data** and in **theory calculations** of **Higgs production**







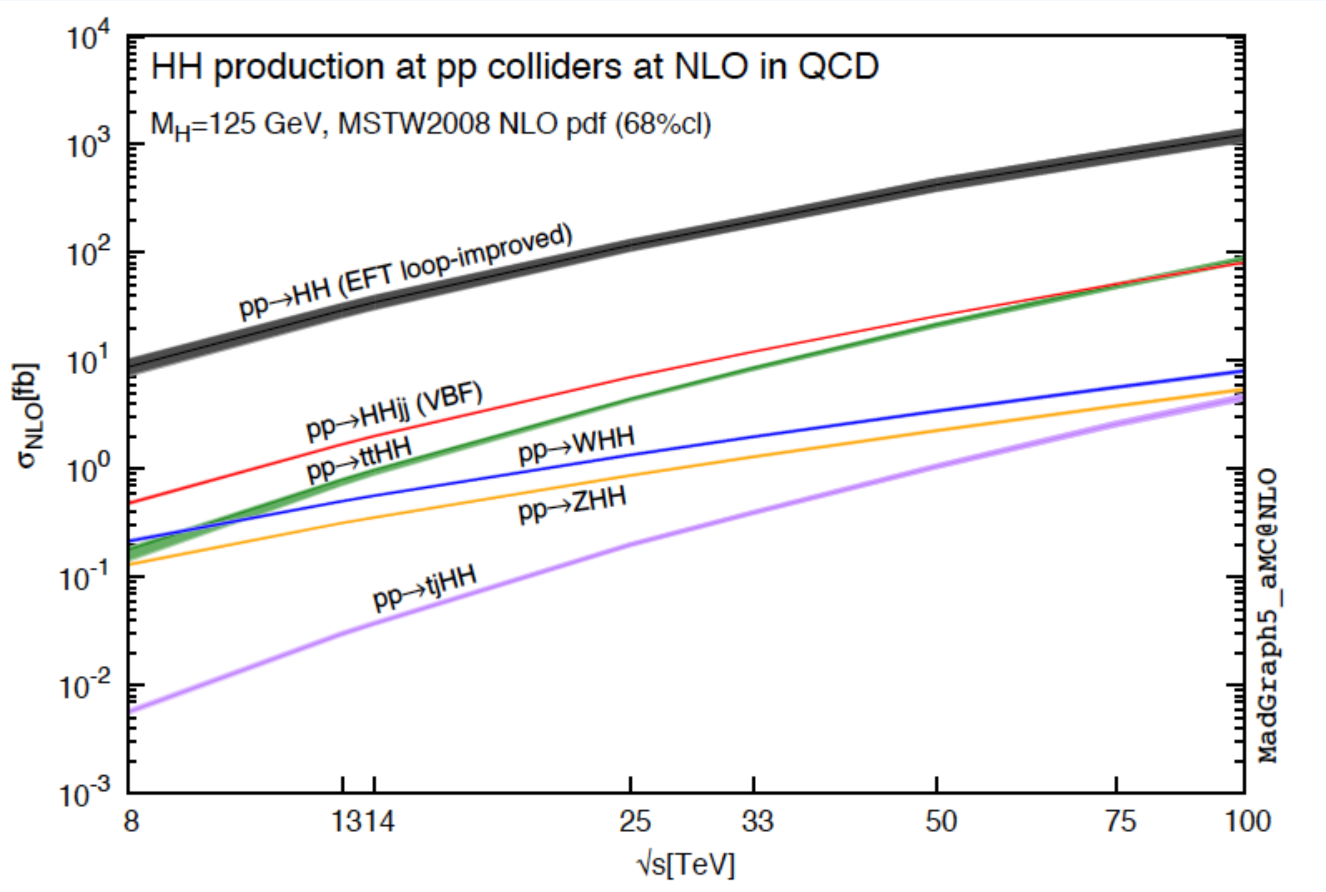
EW symmetry breaking: what do we know



- **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
- What are the **dynamics** underlying EW symmetry breaking?

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 production mode, the **cross-section at 14 TeV** is only **40 fb,** further suppressed by branching fractions



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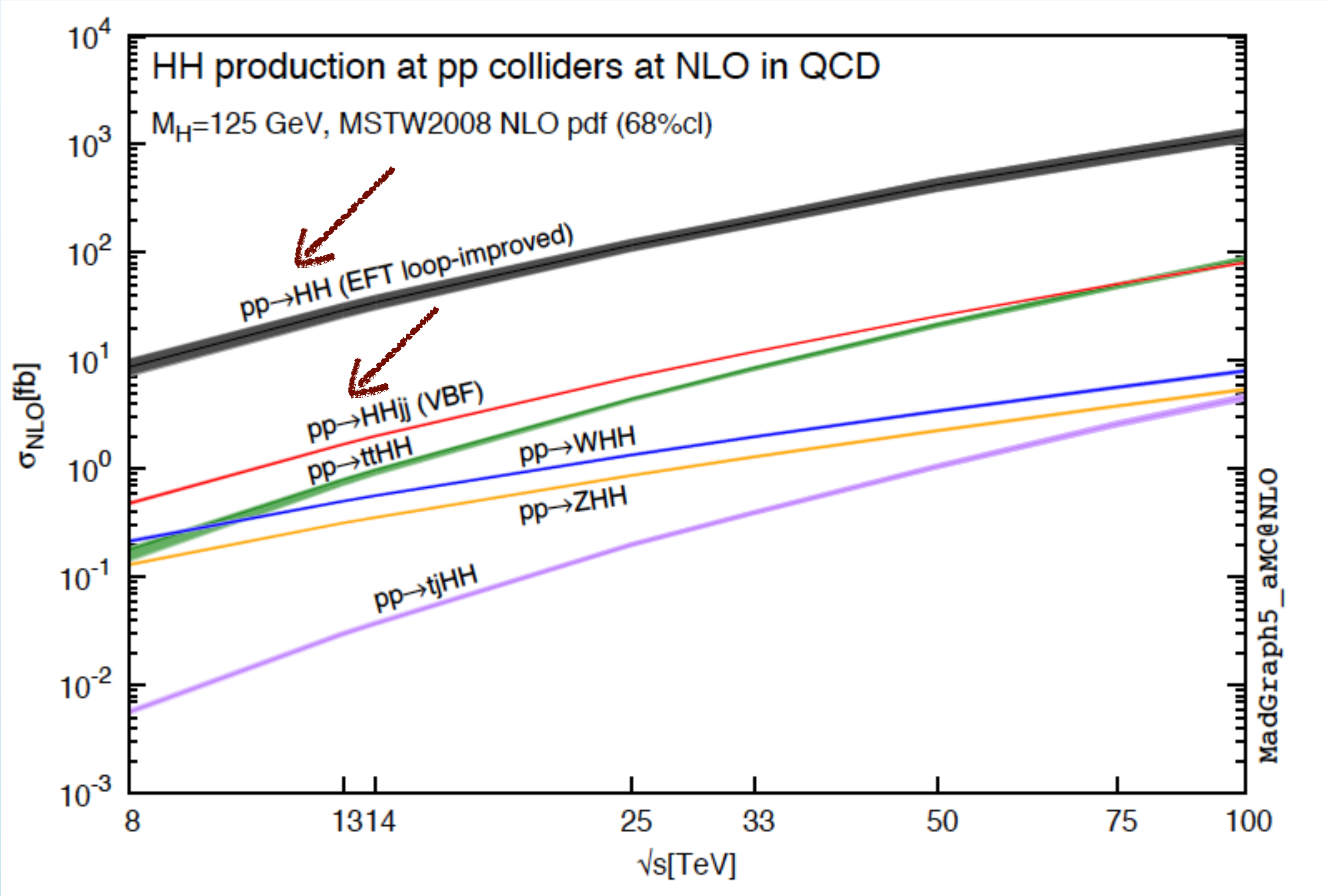
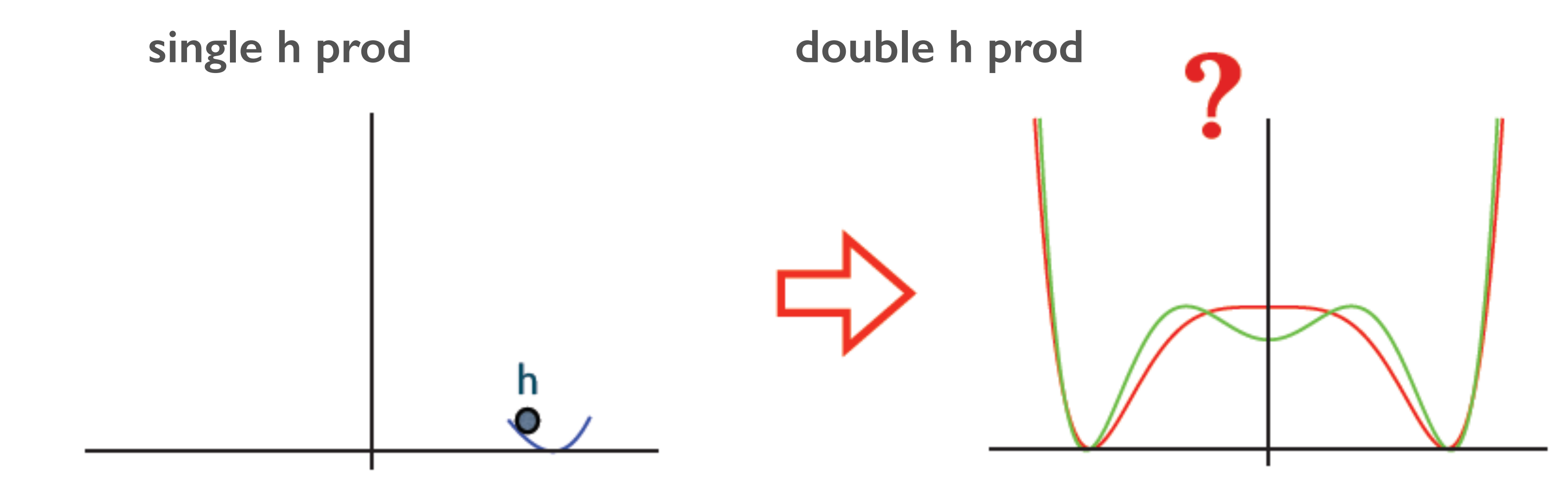


EW symmetry breaking: what we don't know

- **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

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

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

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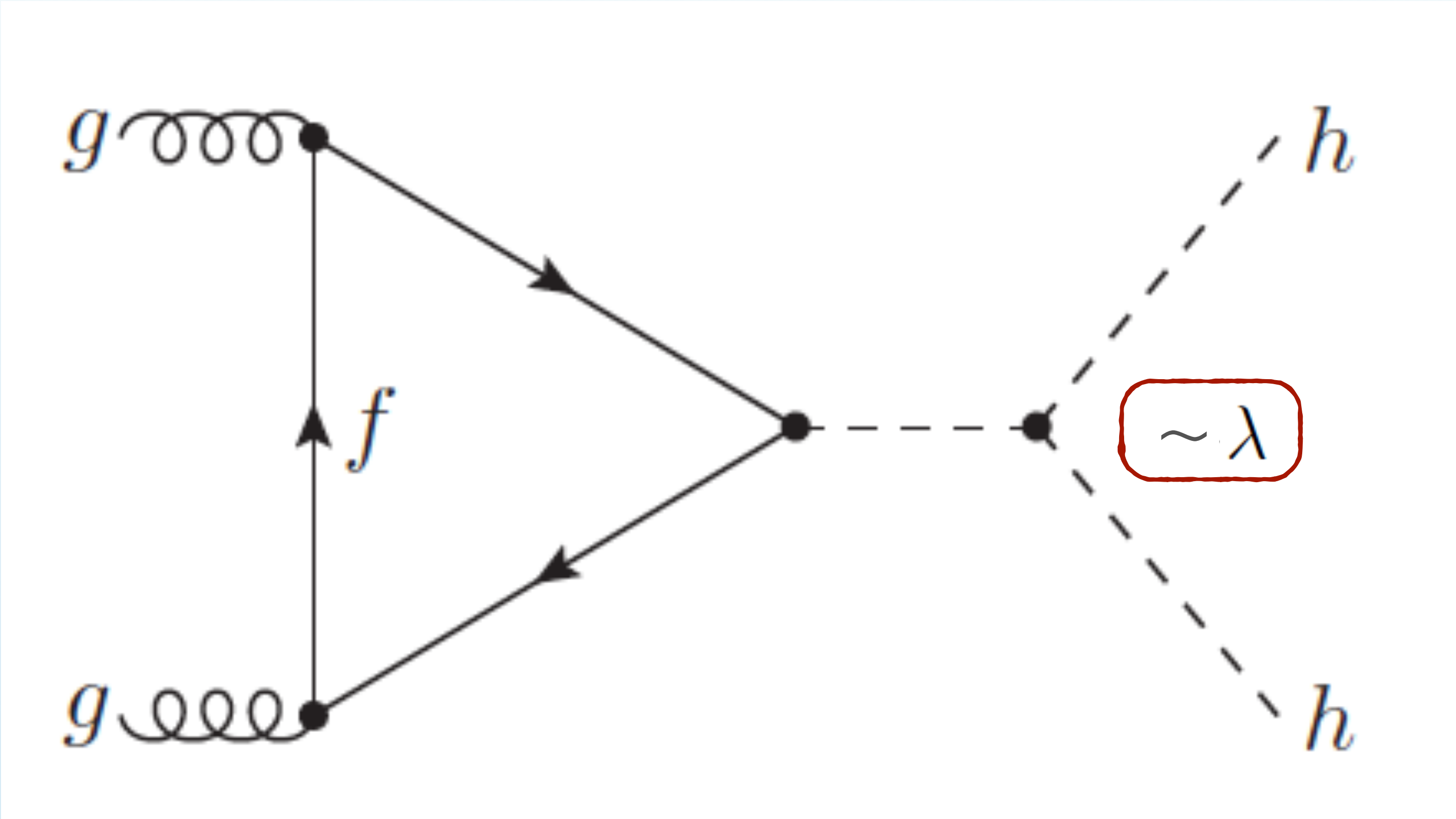

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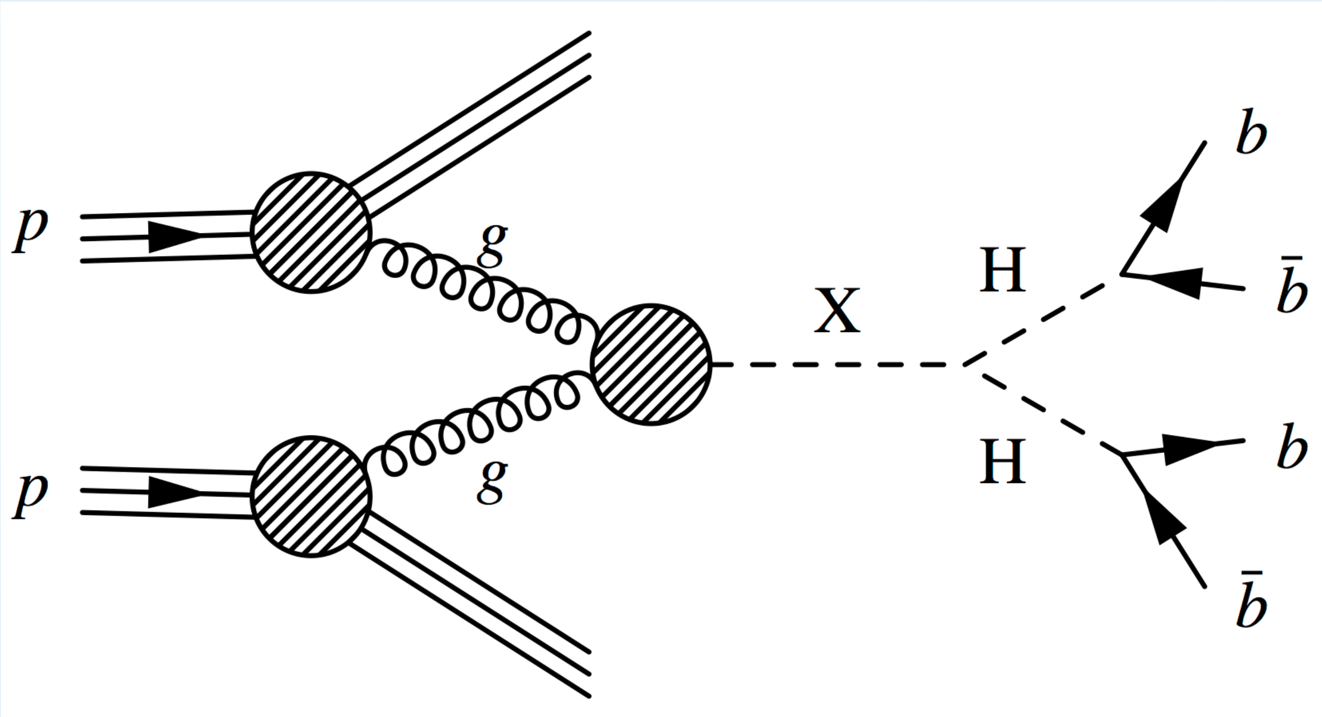

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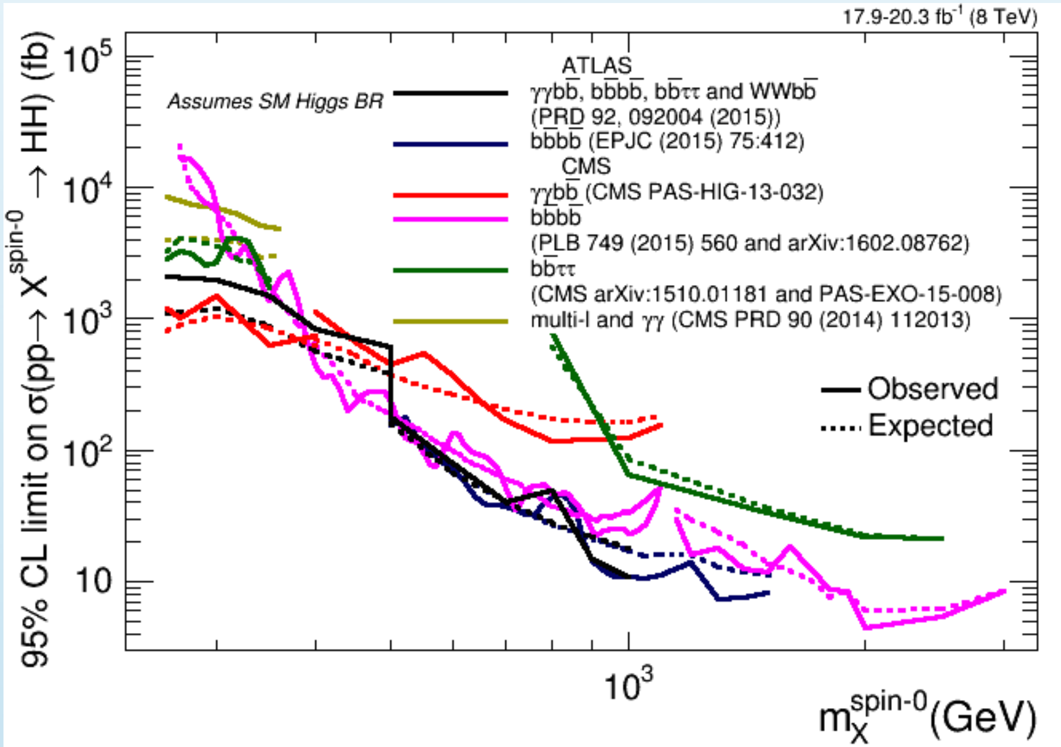
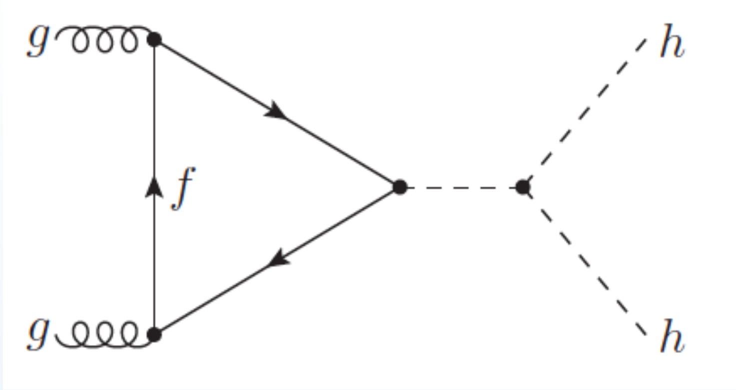
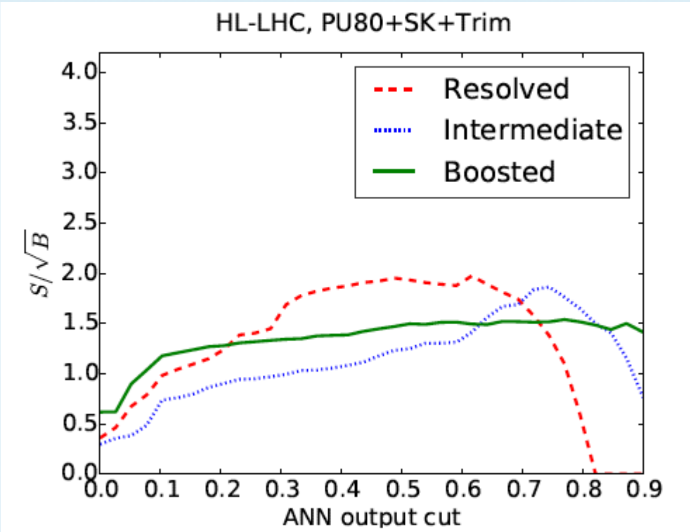


Important contributions to this plot from the CP3 CMS group!



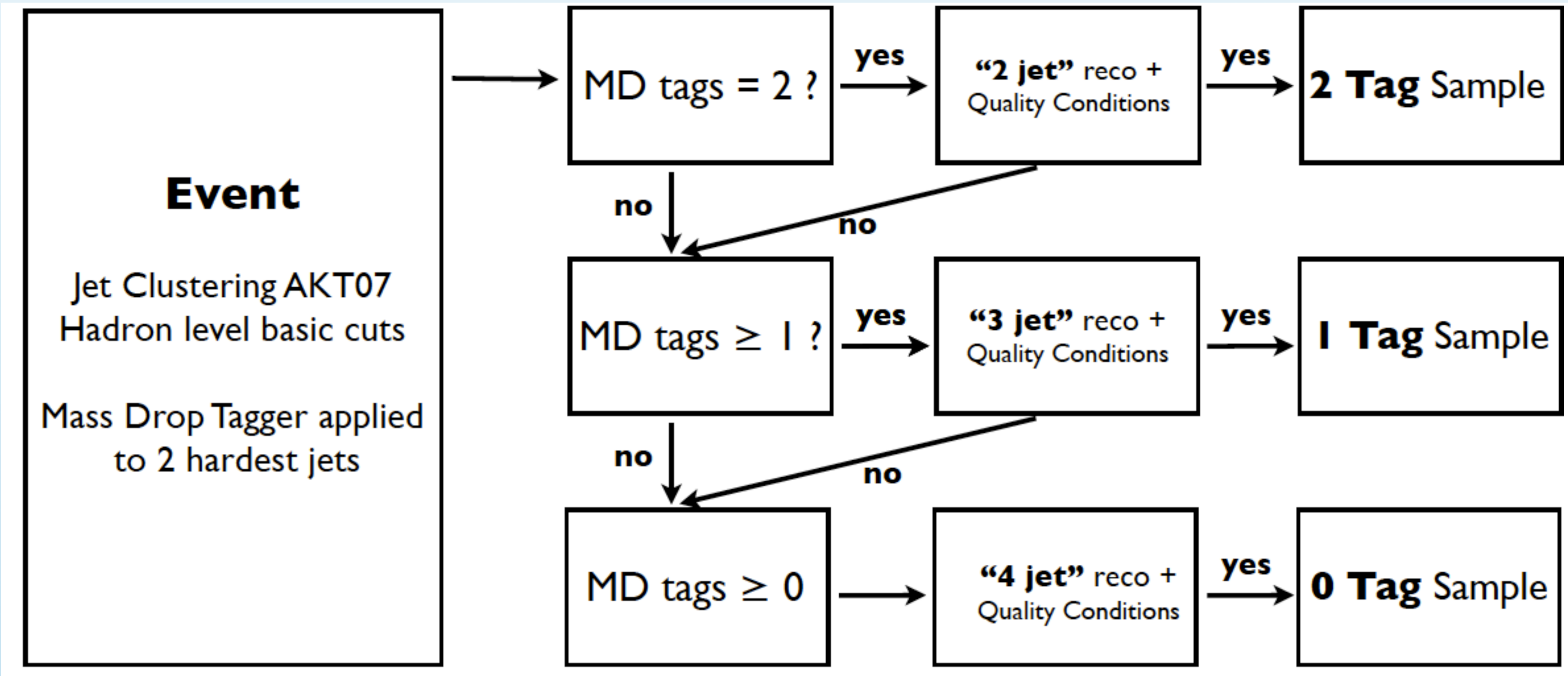
Higgs pair production by gluon-fusion in the 4b final state



- *M. Gouzevitch, A. Oliveira, J. Rojo, R. Rosenfeld, G. P. Salam and V. Sanz, JHEP 1307, 148 (2013), arXiv:1303.6636*
- *J. K. Behr, D. Bortoletto, J. A. Frost, N. P. Hartland, C. Issever and J. Rojo, EPJC76, no. 7, 386 (2016), arXiv:1512.08928*

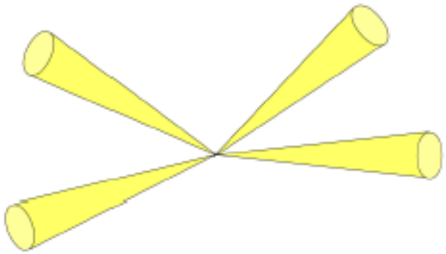
Higgs pair production in the 4b channel

- Focus on the **hh->4b final state:** largest rates, but **overwhelming QCD multijet backgrounds**
- 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,** recent progress by ATLAS and CMS
- **Boosted b-tagging** by ghost-associating mass-drop tagged large-*R* jets with b-tagged small-*R* jets
- **Tagging these events** is changeling due to the very high rate of QCD multijets, but doable
- **Scale-invariant tagging:** event-by-event classification depending on final state topology



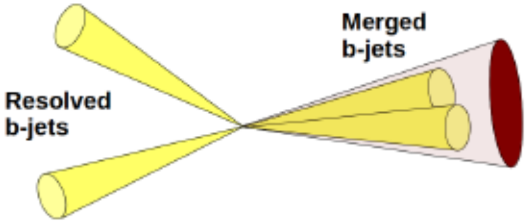
Selection strategy

Resolved



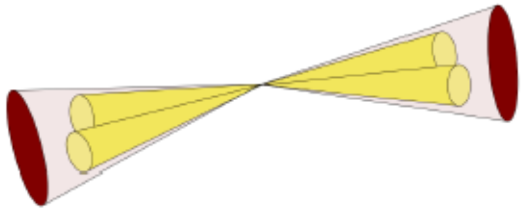
- ≥ 4 b-tagged small-R jets
- Higgs reconstruction from leading 4 jets
- Choice that minimises mass difference between dijet systems

Intermediate



- $= 1$ large-R jet (Higgs-tagged + b-tagged) (leading Higgs)
- ≥ 2 b-tagged small-R jets
- $\Delta R > 1.2$ w.r.t. large-R jet
- Higgs reconstruction from leading 2 small-R jets
- Choice that minimises mass difference of dijet system and large-R jet

Boosted



- ≥ 2 large-R jets (Higgs-tagged + b-tagged)
- Leading two jets taken as Higgs candidates

+ **Loose Higgs mass window cut**: $|m_{h,j} - 125\ \mathrm{GeV}| < 40\ \mathrm{GeV}\ ,\ j = 1, 2$
+ **Rank categories** by $S/\sqrt{B}$ to make them **exclusive**: boosted > intermediate > resolved

Higgs pair production in the 4b channel

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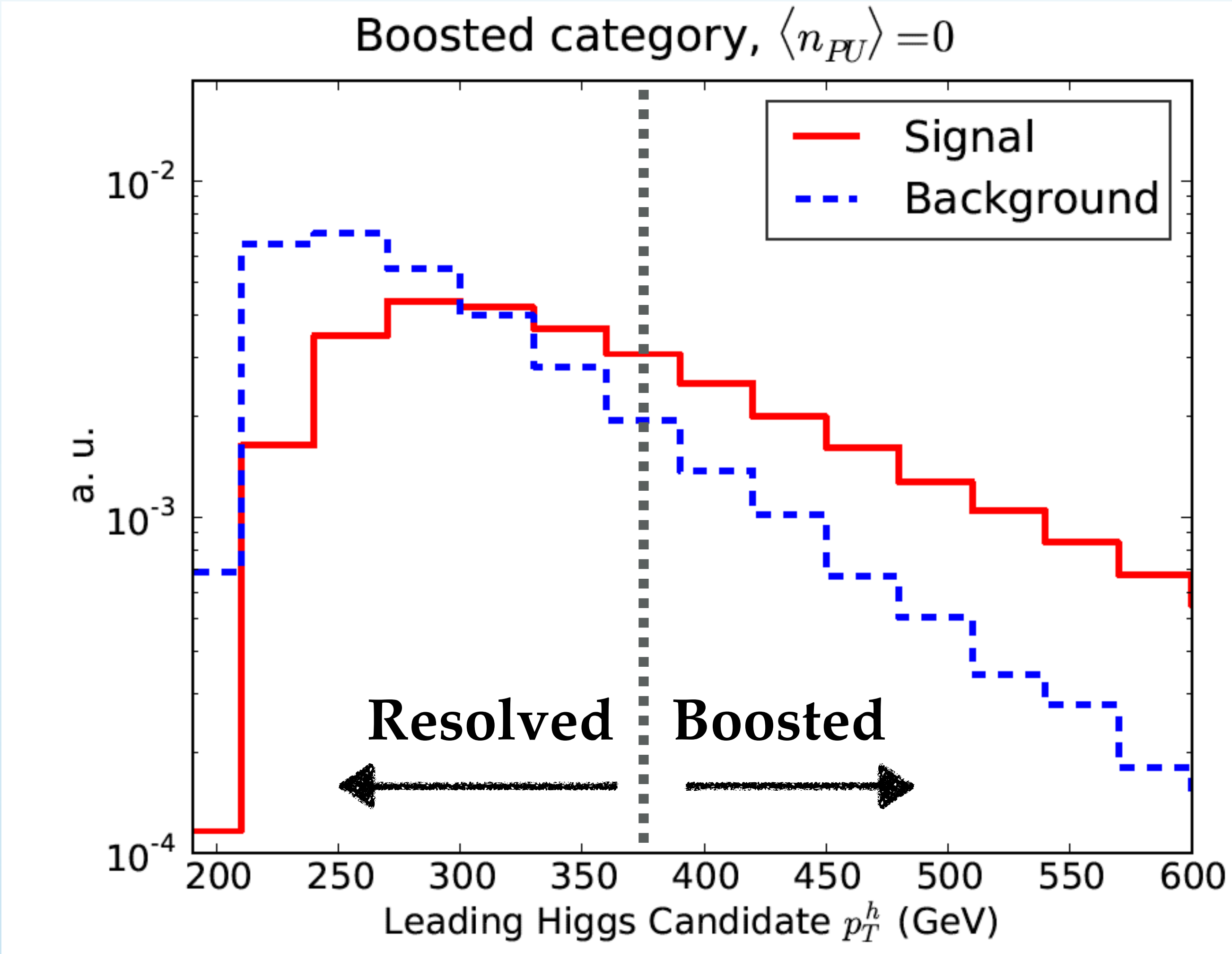
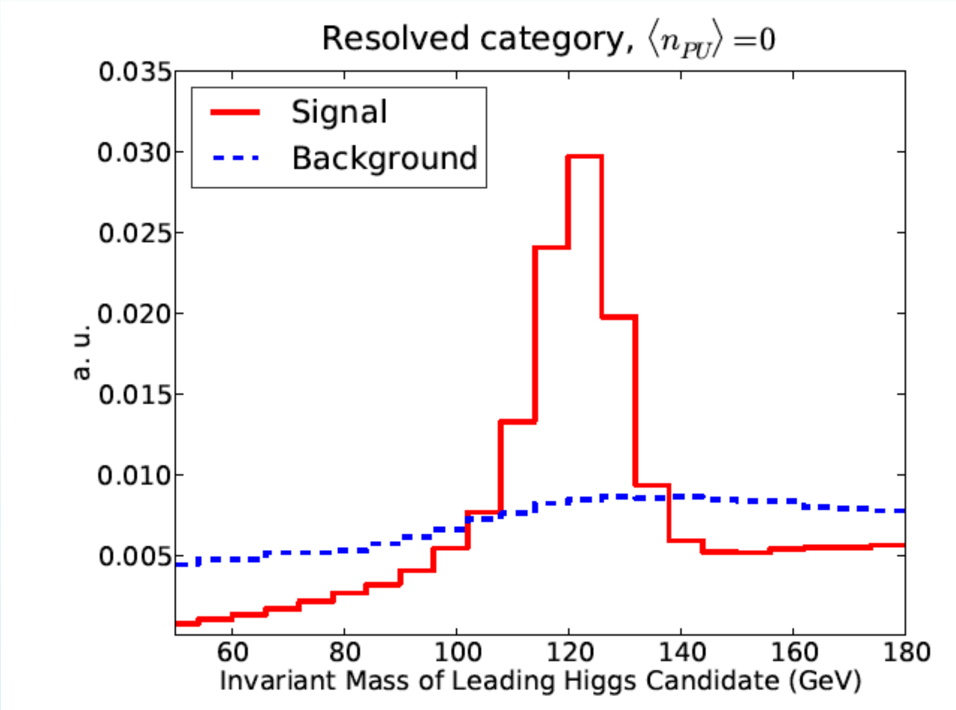
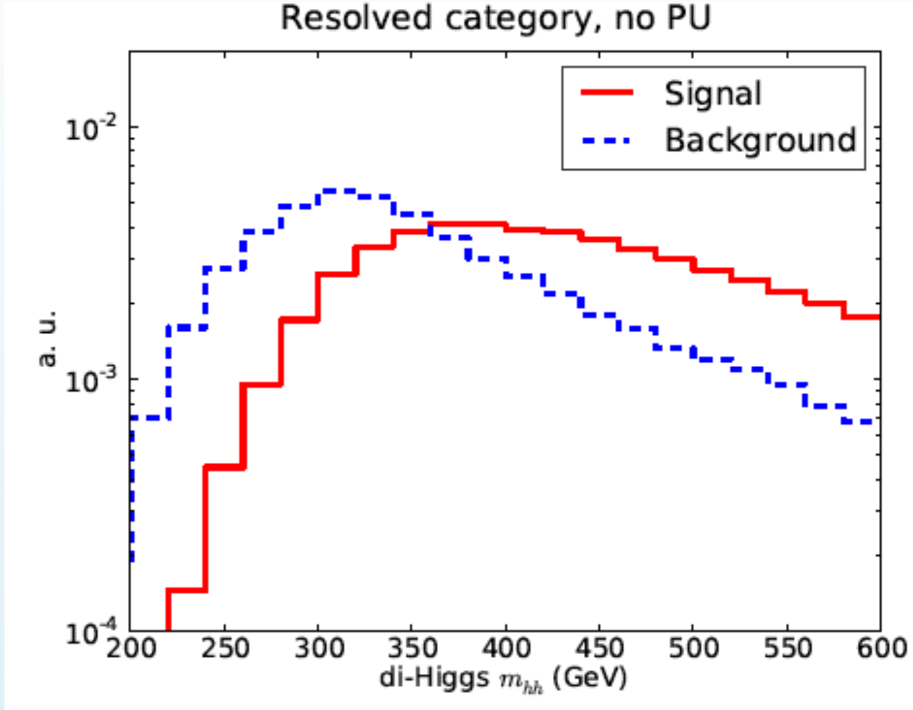
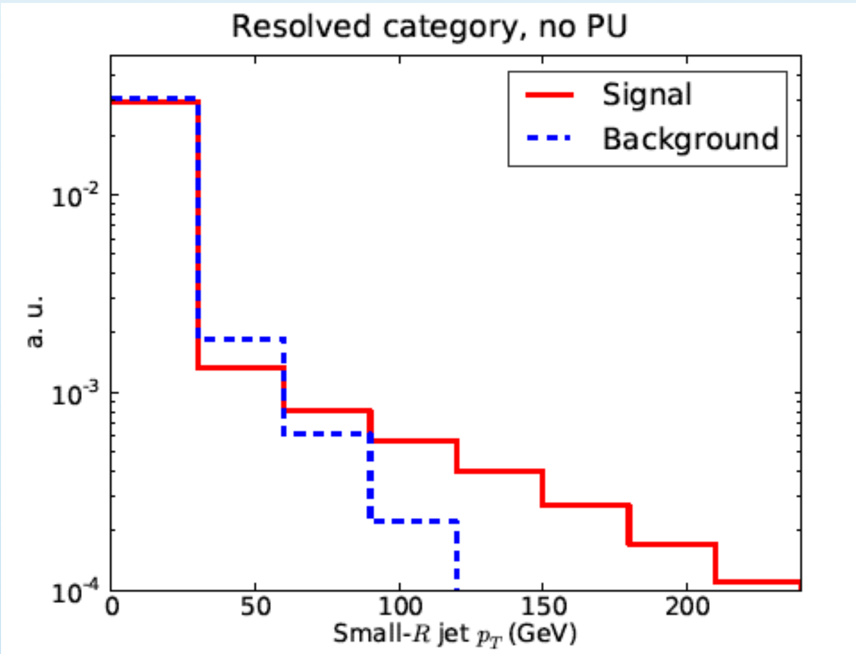
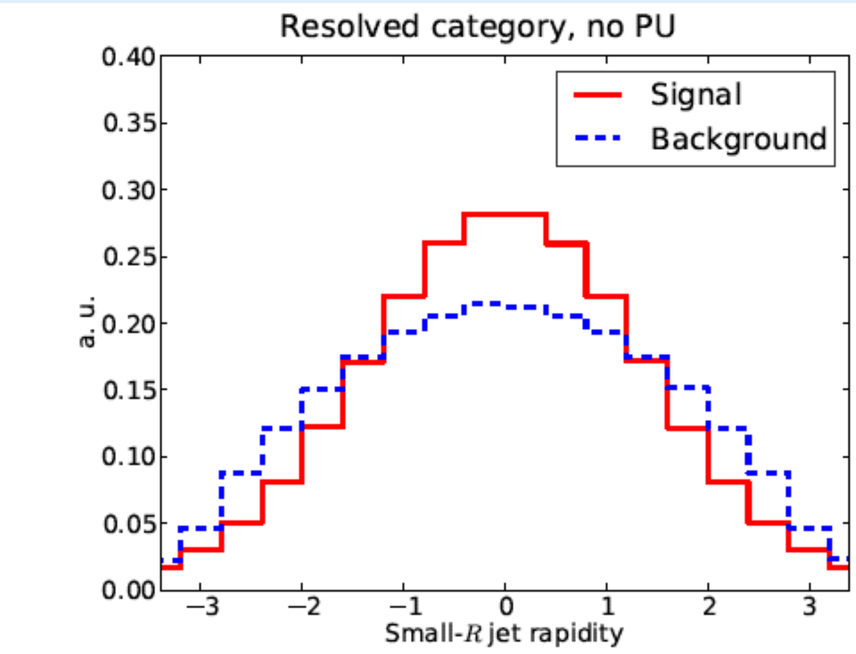


Cut-based analysis - resolved category

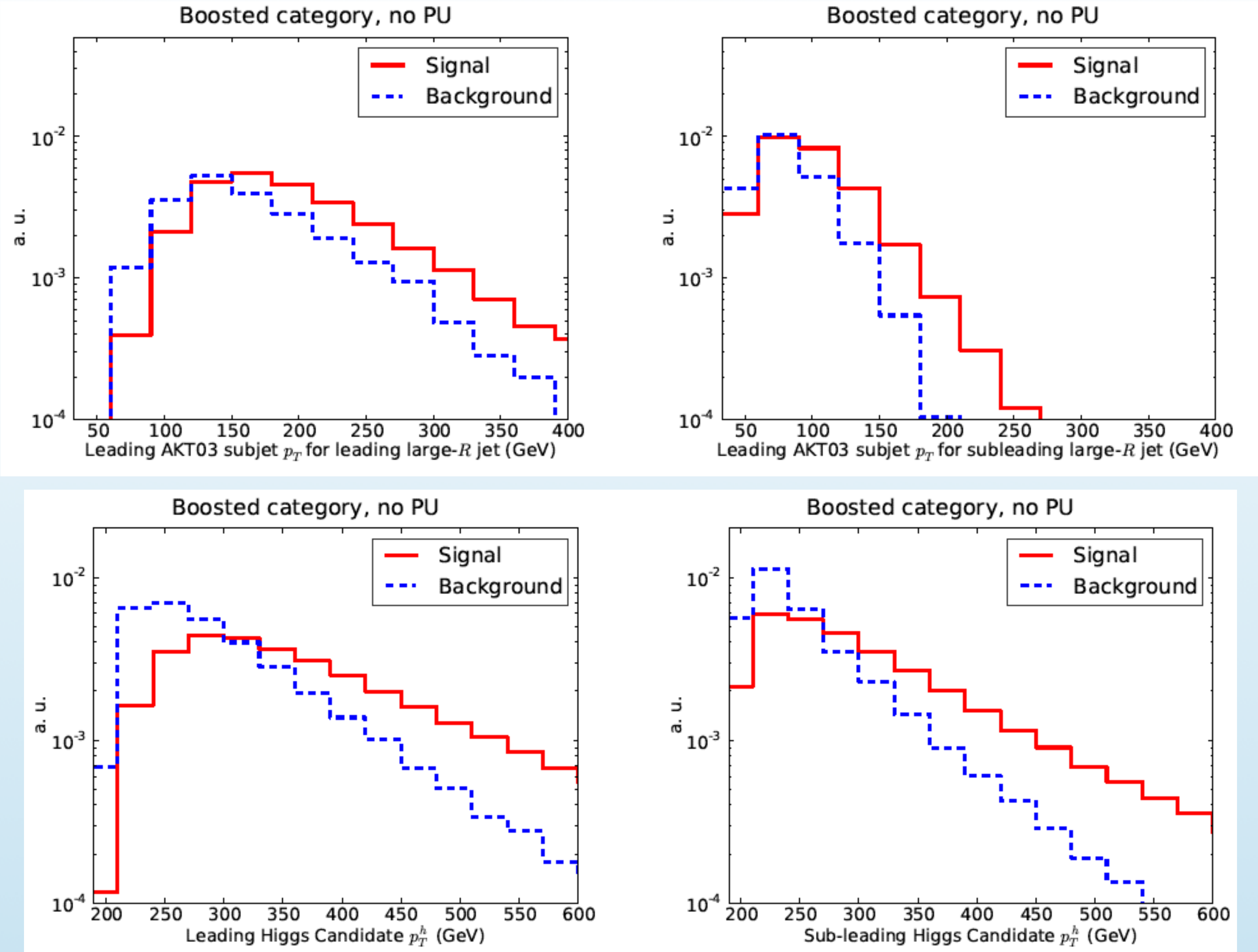








Cut-based analysis - boosted category



Cut-based analysis results

- Assume **HL-LHC integrated luminosity of L=3000 fb^{-1}**
- At the end of the cut-based analysis (level **C2**) **backgrounds still still overwhelmingly larger than the signal**, and signal significances very low
- Use **MVA to fully exploit the kinematic discrimination power** between signal and background events

HL-LHC, Resolved category, no PU										
	Cross-section [fb]						S/B		$S/\sqrt{B}$	
	$hh4b$	total bkg	$4b$	$2b2j$	$4j$	$t\bar{t}$	tot	$4b$	tot	$4b$
C1a	9	$2.2\cdot10^8$	$6.9\cdot10^4$	$1.5\cdot10^7$	$2.0\cdot10^8$	$2.1\cdot10^5$	$4.0\cdot10^{-8}$	$1.3\cdot10^{-4}$	0.03	1.9
C1b	9	$2.2\cdot10^8$	$6.9\cdot10^4$	$1.5\cdot10^7$	$2.0\cdot10^8$	$2.1\cdot10^5$	$4.0\cdot10^{-8}$	$1.3\cdot10^{-4}$	0.03	1.9
C1c	2.6	$4.4\cdot10^7$	$1.6\cdot10^4$	$3.2\cdot10^6$	$4.1\cdot10^7$	$8.8\cdot10^4$	$6.1\cdot10^{-8}$	$1.6\cdot10^{-4}$	0.02	1.1
C2	0.5	$4.9\cdot10^3$	$1.7\cdot10^3$	$2.9\cdot10^3$	$2.1\cdot10^2$	47	$1.1\cdot10^{-4}$	$2.9\cdot10^{-4}$	0.4	0.6

HL-LHC, Boosted category, no PU										
	Cross-section [fb]						S/B		$S/\sqrt{B}$	
	$hh4b$	total bkg	$4b$	$2b2j$	$4j$	$t\bar{t}$	tot	$4b$	tot	$4b$
C1a	3.9	$4.6\cdot10^7$	$1.1\cdot10^4$	$2.9\cdot10^6$	$4.3\cdot10^7$	$2.4\cdot10^4$	$8.2\cdot10^{-8}$	$3.4\cdot10^{-4}$	0.03	2.0
C1b	2.7	$3.7\cdot10^7$	$7.5\cdot10^3$	$2.1\cdot10^6$	$3.5\cdot10^7$	$2.2\cdot10^4$	$7.4\cdot10^{-8}$	$3.7\cdot10^{-4}$	0.03	1.7
C1c	1.0	$3.9\cdot10^6$	$8.0\cdot10^2$	$2.3\cdot10^5$	$3.7\cdot10^6$	$7.1\cdot10^3$	$2.6\cdot10^{-7}$	$1.3\cdot10^{-3}$	0.03	2.0
C2	0.16	$2.5\cdot10^2$	53	$1.9\cdot10^2$	13	1.6	$5.7\cdot10^{-4}$	$2.7\cdot10^{-3}$	0.5	1.1

- Accurate treatment of **b-jet fakes from light and charm jets** crucial for this final state

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

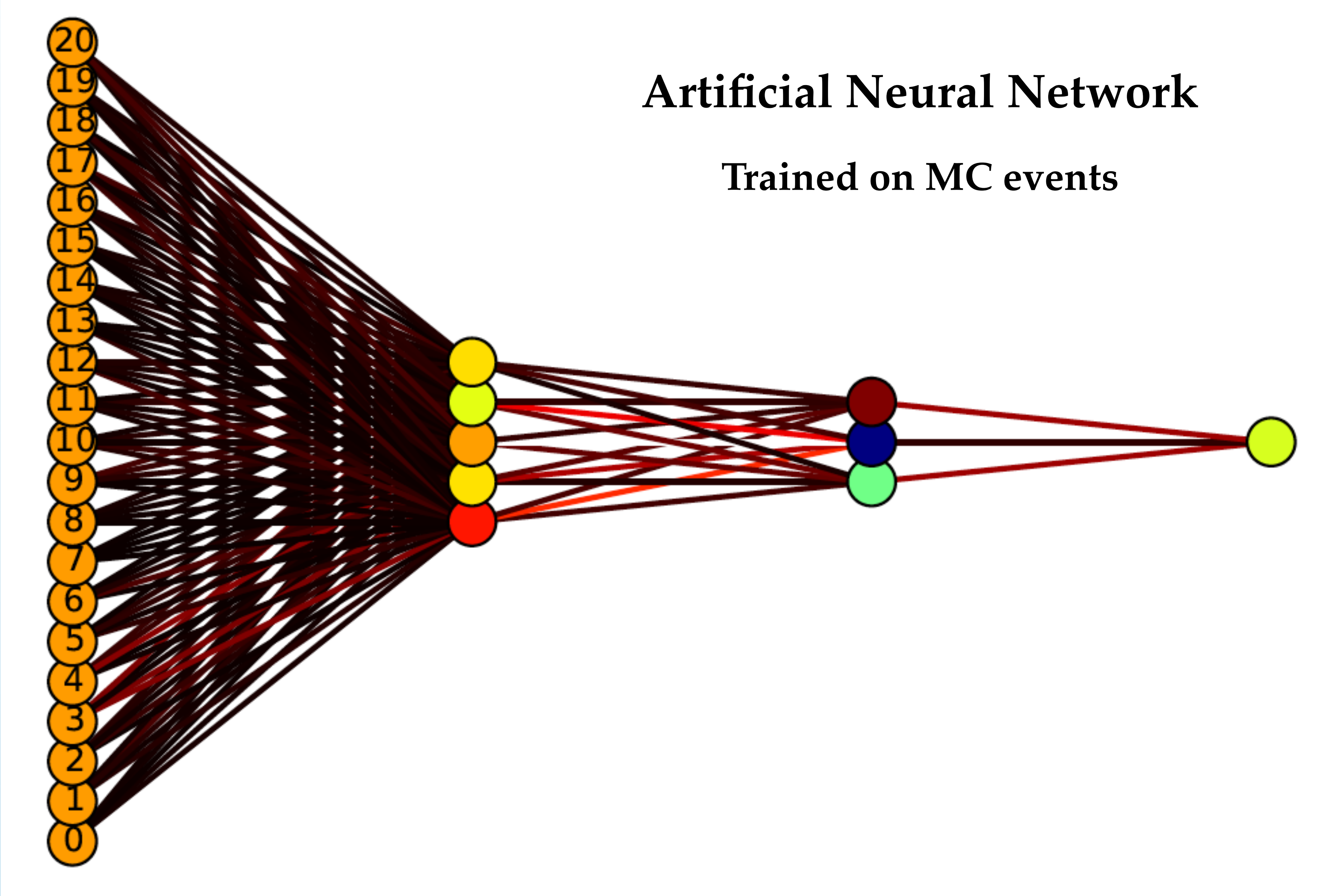
di-Higgs m

ECF

τ_{12}

Subjet pT

.....



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**

Jet substructure variables

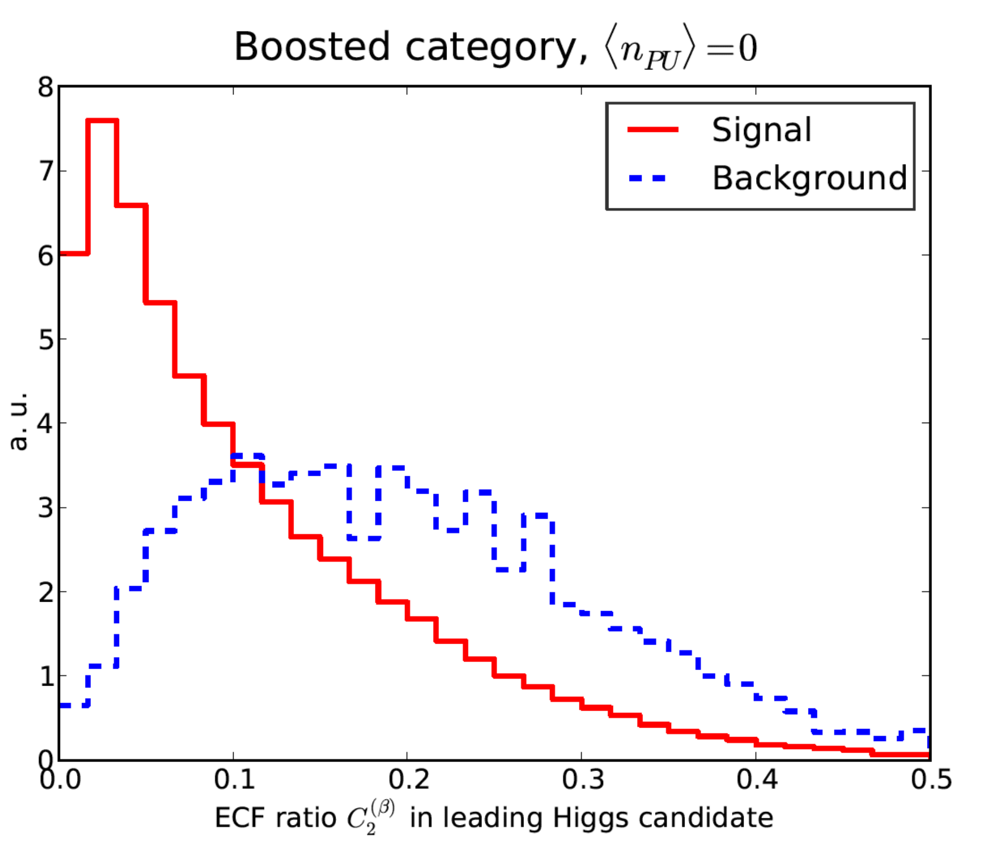
- **Substructure variables** quantify differences in internal structure between **QCD jets** and **jets from the decay of heavy resonances**
- QCD radiation tends to be **soft** and **collinear,** while decay products of resonances **share momentum evenly**

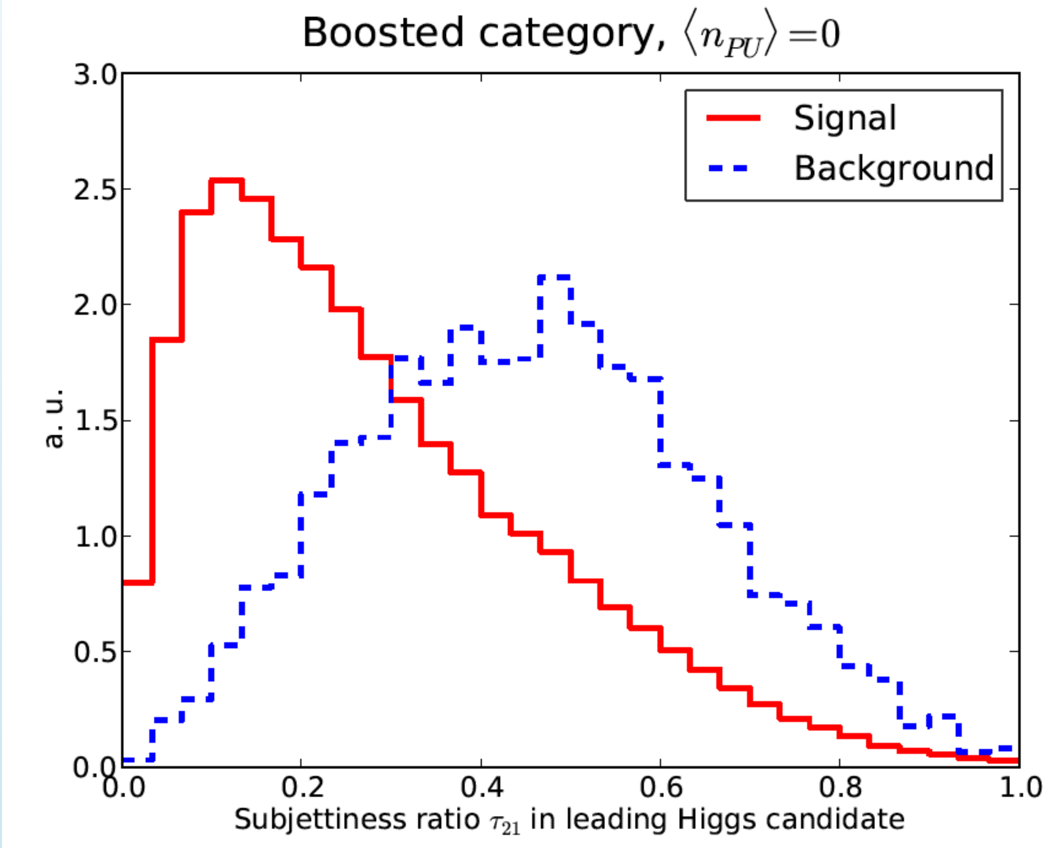
$$C_2^{(\beta)} \equiv \frac{\mathrm{ECF}(3,\beta)\mathrm{ECF}(1,\beta)}{[\mathrm{ECF}(2,\beta)]^2}$$

$$\tau_N \equiv \frac{1}{d_0} \sum_k p_{T,k} \cdot \min\left(\delta R_{1k}, \ldots, \delta R_{Nk}\right)$$

Energy Correlation Functions ratio

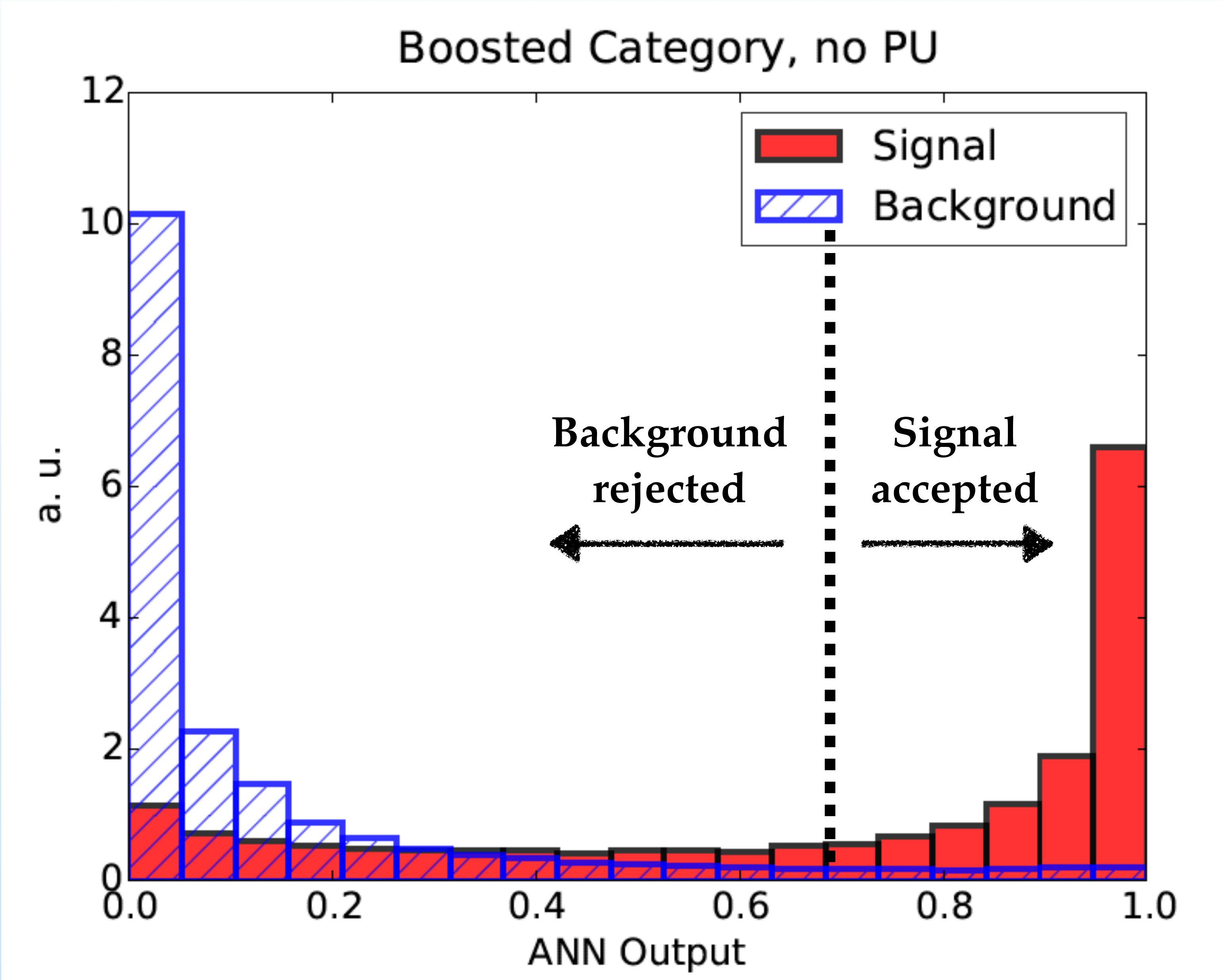
τ_{21}: 2-to-1 Subjettiness ratio





Multivariate techniques

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

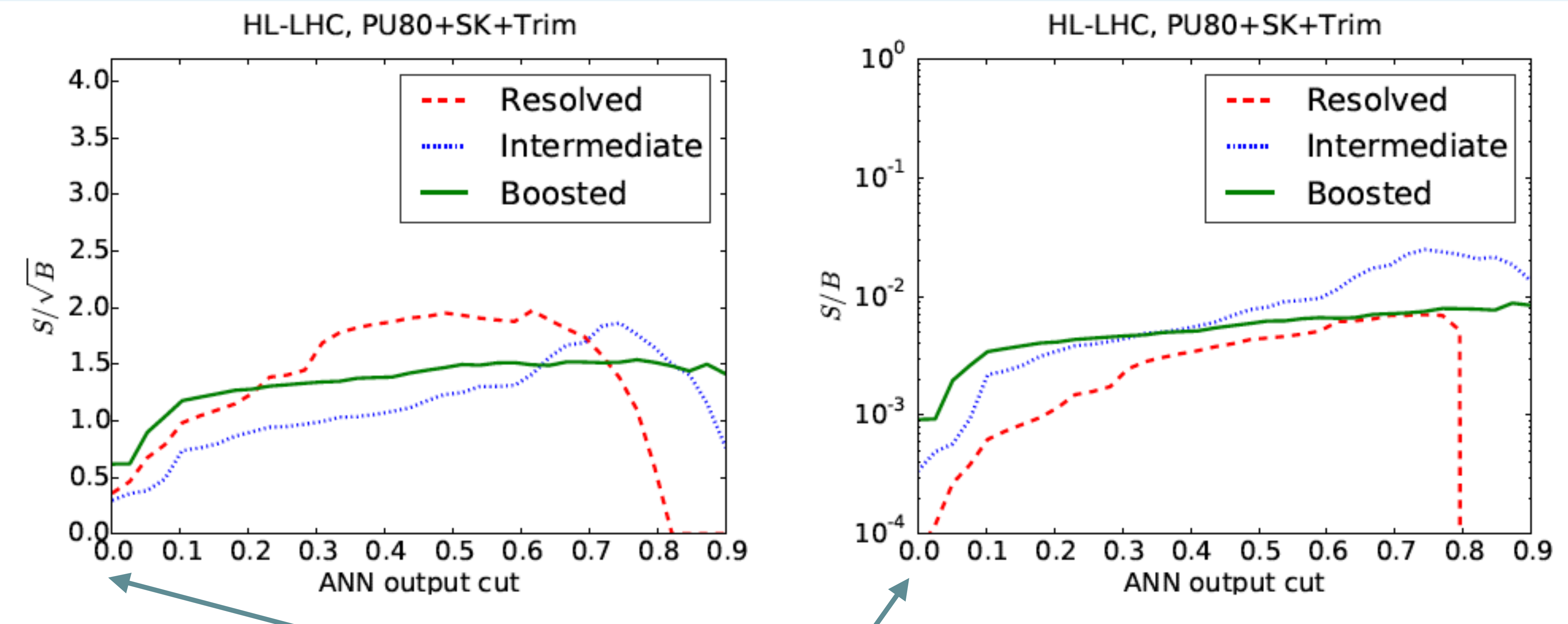


Signal significance

- 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. Substantial improvement if reducible backgrounds (fakes) can be eliminated

$$\left(\frac{S}{\sqrt{B}}\right)_{\rm tot} \simeq 3.1\ (1.0)\,, \quad \mathcal{L} = 3000\ (300)\ {\rm fb}^{-1}$$

$$\left(\frac{S}{\sqrt{B_{4b}}}\right)_{\rm tot} \simeq 4.7\ (1.5)\,, \quad \mathcal{L} = 3000\ (300)\ {\rm fb}^{-1}$$



Pre-MVA result

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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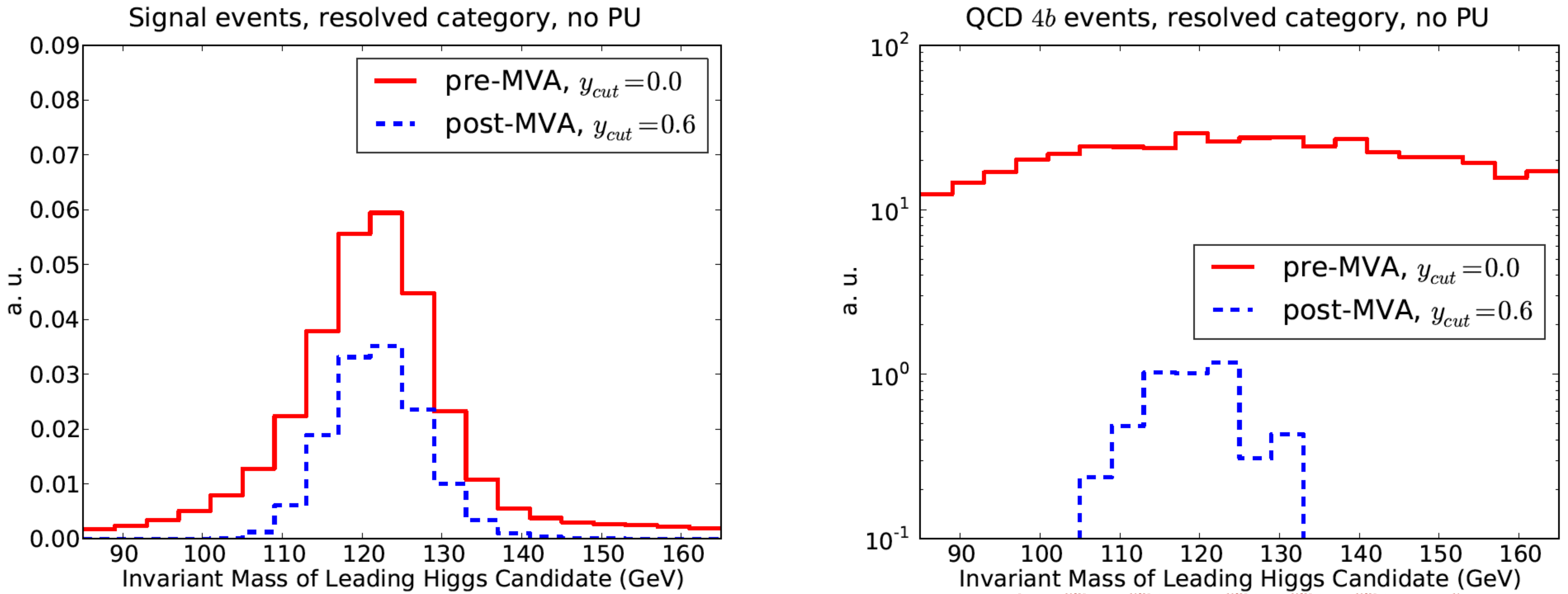


The background "Higgs mass peak" now mimics the signal one!

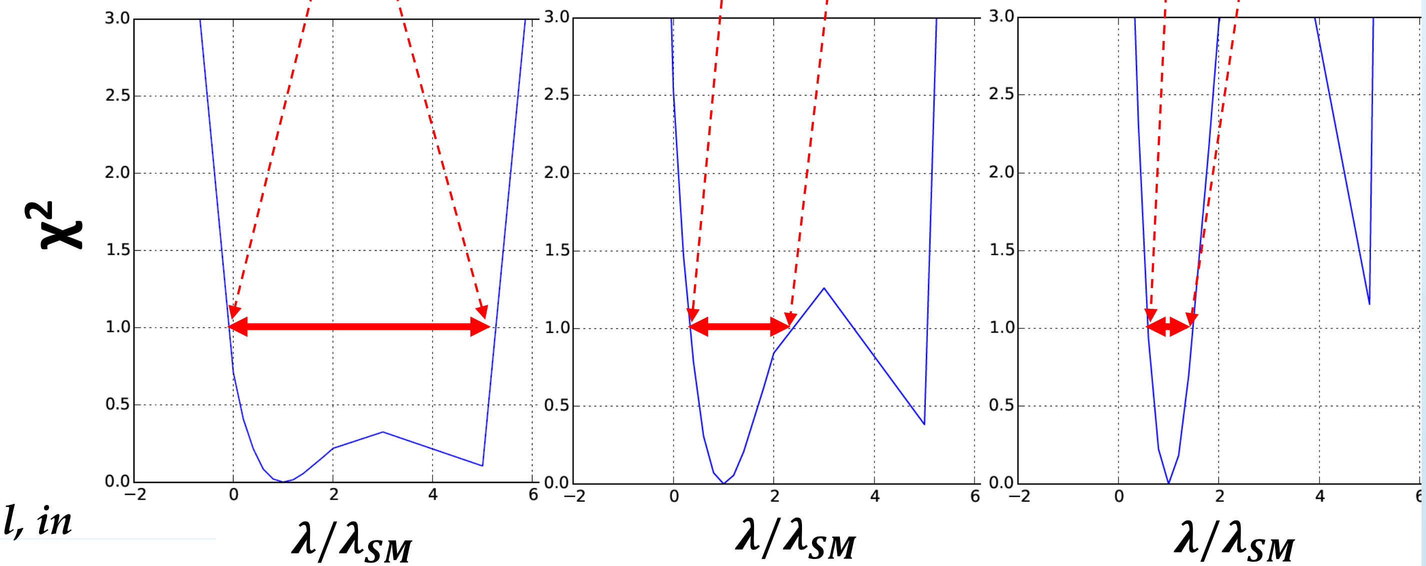
Towards a measurement of λ

- 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**

- Need to carefully estimate the **systematic uncertainties** that affect the **measurement of the fiducial cross-section**, which ultimately determines **how precisely the self-coupling can be determined**

Expected Sensitivity for the case $\lambda/\lambda_{SM} = 1$ with S/B = 5%, 230 fb^{-1}

Syst. Error on Background	5%	2.5%	1.25%
$\lambda \in$	$[0, 5] * \lambda_{SM}$	$[0.4, 2.3] * \lambda_{SM}$	$[0.5, 1.5] * \lambda_{SM}$



Behr et al, in preparation

LHC 13 TeV, Resolved Category

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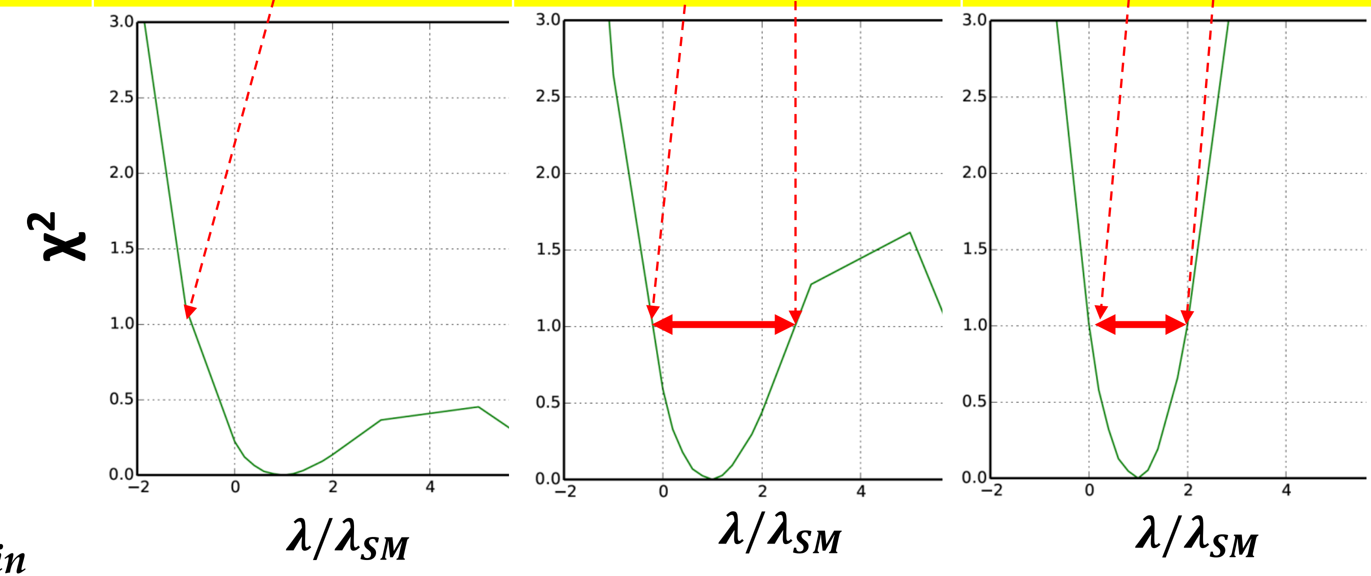

Behr et al, in preparation

LHC 13 TeV, Boosted Category

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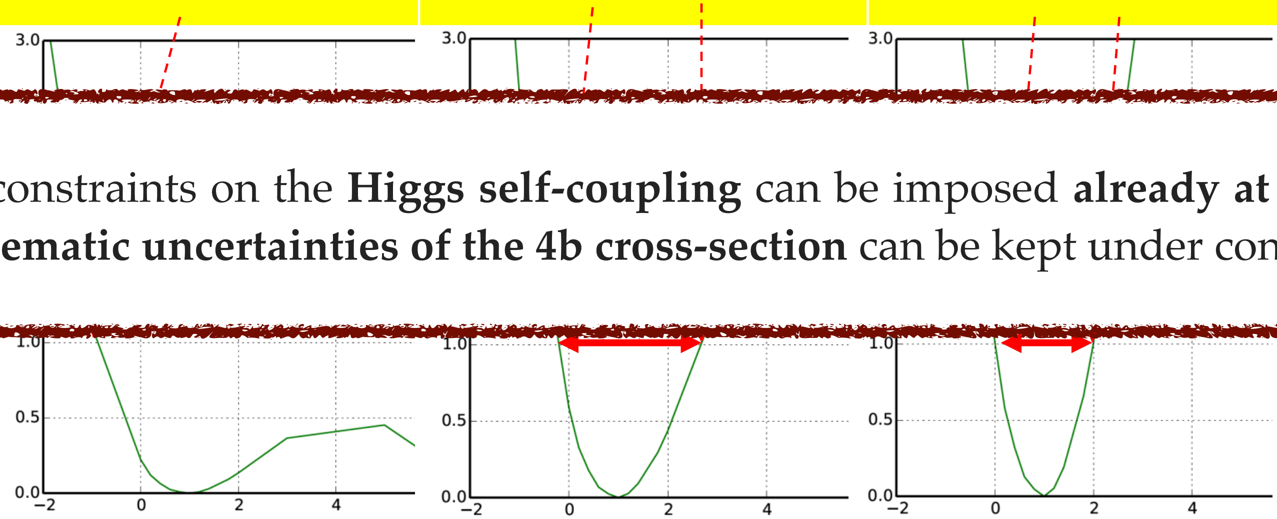
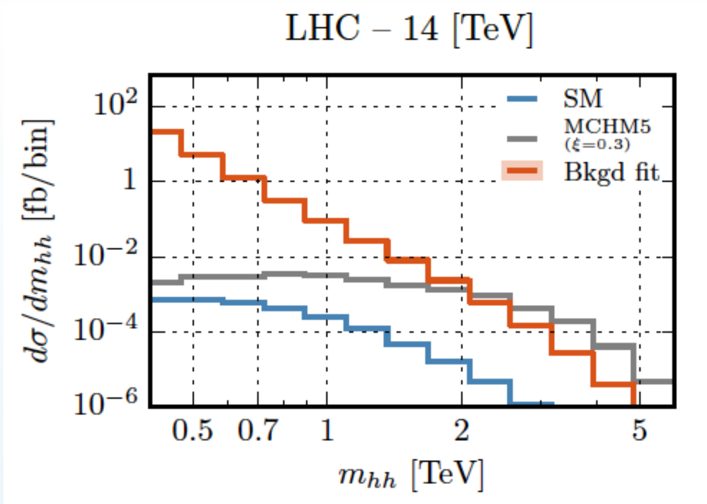


λ/λ_{SM} λ/λ_{SM} λ/λ_{SM}

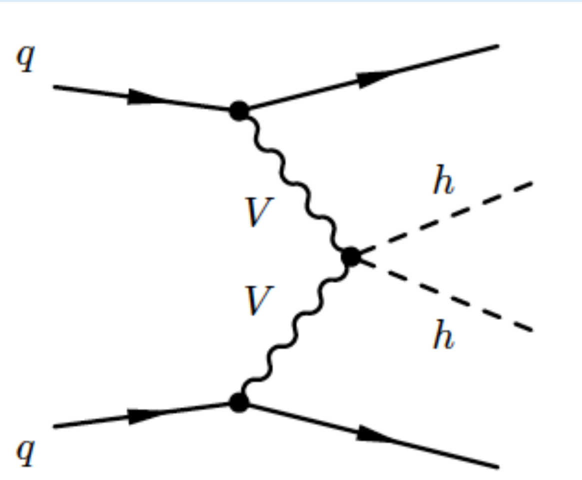
Take-away message

Competitive constraints on the **Higgs self-coupling** can be imposed **already at Run II**, provided **systematic uncertainties of the 4b cross-section** can be kept under control

Behr et al, in preparation



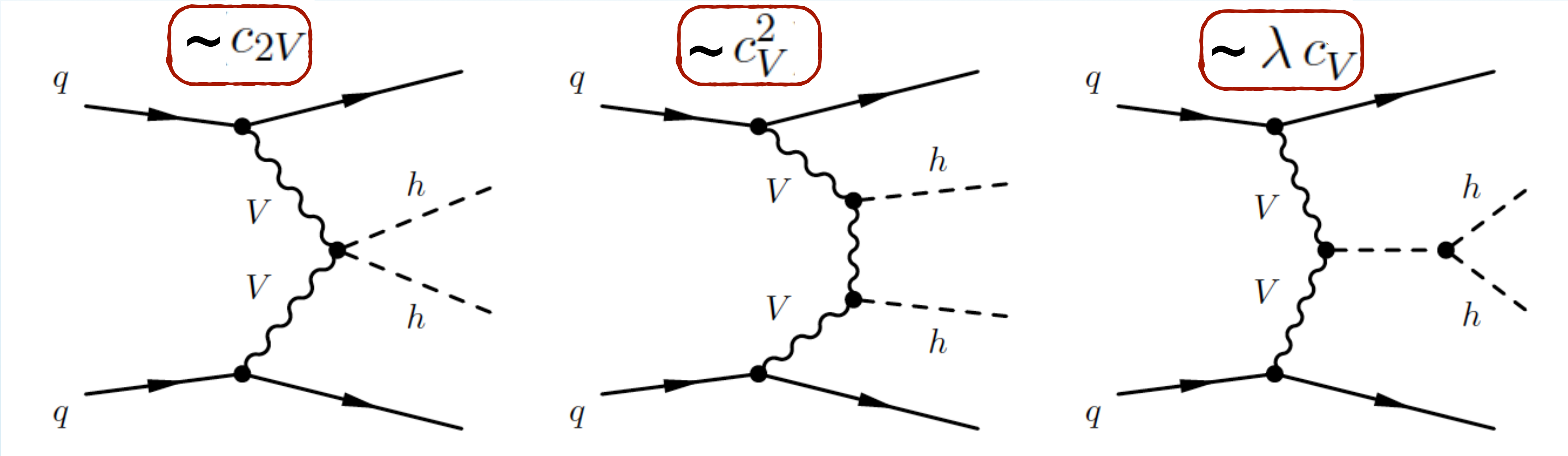
Higgs pair production by vector-boson fusion in the 4b final state



☑ *F. Bishara, R. Contino and J. Rojo, arxiv:1611.03860*

EW symmetry breaking: what we don't know

- In the absence of the Higgs boson, the amplitude for **vector-boson scattering** (VBS) **grows** with the partonic center-of-mass energy, until eventually **unitarity is violated**
- In the SM, the Higgs boson **unitarizes the high-energy behaviour** of VBS amplitudes



at high energies

$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)\,,$$

Is this **cancellation exact** (as in SM, $c_{2V} = c_V^2$) or only **approximate (BSM, $c_{2V} \neq c_V^2$)?**

No model-independent information on c_{2V} available so far at the LHC

Even for small deviation of the SM couplings, **striking signals within the reach of Run II!**

EW symmetry breaking: what we don't know

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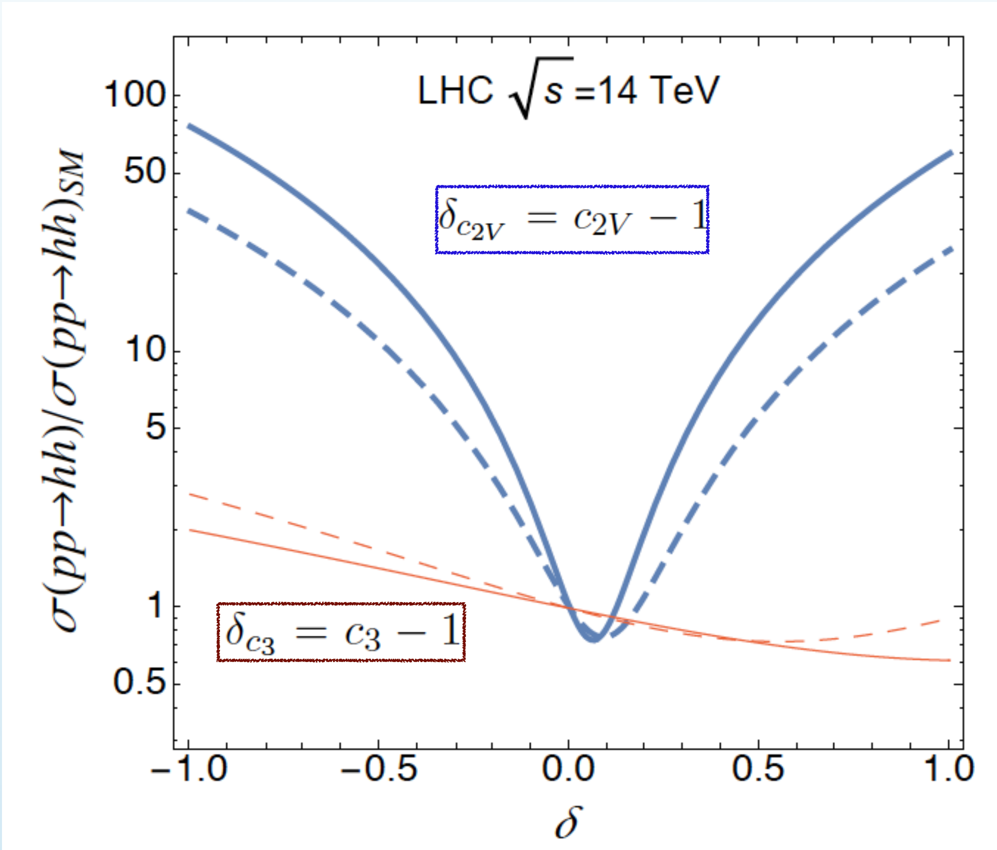


On the other hand, VBF production has **very little sensitivity to the Higgs self-coupling ...**

at high energies

$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)\,,$$

Exploiting the VBF channel for di-Higgs

- Signal generation with **MadGraph5** using customized UFO model
- **Event rates** can increase by **up to a factor 30** as compared to SM if new physics is present
- At a 100 TeV collider, **10^5 events before cuts** even for SM couplings

Signal: VBF $hh \to b\bar{b}b\bar{b}$					
$\{c_V, c_{2V}, c_3\}$		LHC 14 TeV		FCC 100 TeV	
		σ (fb)	$N_{ev}(\mathcal{L} = 3\,\text{ab}^{-1})$	σ (fb)	$N_{ev}(\mathcal{L} = 10\,\text{ab}^{-1})$
{1,1,1}	SM	0.26	780	14.8	$1.5 \cdot 10^5$
{1,0,1}		4.4	$1.3 \cdot 10^4$	593	$5.9 \cdot 10^6$
{1,2,1}		2.5	$7.5 \cdot 10^3$	471	$4.7 \cdot 10^6$
{1,0,0}		5.8	$1.7 \cdot 10^4$	656	$6.6 \cdot 10^6$
{1,0,-1}		7.5	$2.3 \cdot 10^4$	731	$7.3 \cdot 10^6$
{1,1,0}		0.64	$1.9 \cdot 10^3$	29.8	$3.0 \cdot 10^5$
{0.84,0.40,0.48}	MCHM5 $\xi = 0.3$	0.78	$2.3 \cdot 10^3$	75.7	$7.6 \cdot 10^5$

Exploiting the VBF channel for di-Higgs

- Generation of **QCD multijet backgrounds** highly CPU time-intensive
- Generated at LO with **Sherpa** (weighted and unweighted events), **cross-checked with ALGEN**
- **Gluon-fusion di-Higgs** production now background to VBF production
- The **irreducible 4b multijet background** is **seven orders of magnitude larger than the SM signal** at the generation level. How to overcome this huge difference?

Background processes						
Process	Program	Generation	$\sigma_{\rm LO}$ (fb) LHC14	$\sigma_{\rm LO}$ (fb) FCC100	K–factor LHC14	K–factor FCC100
$4b$	Sherpa2.2	$N_{\rm ev}=50$M weighted	$1.1\cdot10^6$	$1.6\cdot10^7$	1.7	1.7
$2b2j$	Sherpa2.2	$N_{\rm ev}=50$M weighted	$2.6\cdot10^8$	$3.8\cdot10^9$	1.3	1.3
$t\bar{t}jj$	Sherpa2.2	$N_{\rm ev}=10$M weighted	$1.9\cdot10^4$	$1.6\cdot10^6$	1.6	1.6
$4b2j$	ALPGEN	$N_{\rm ev}=6$M(2M) unweighted	$5.4\cdot10^4$	$2.4\cdot10^6$	1.7	1.7
$2b4j$	ALPGEN	$N_{\rm ev}=260$k unweighted	10^7	$5.2\cdot10^8$	1.3	1.3
$gg\to hh\to b\bar{b}b\bar{b}$	aMC@NLO	$N_{\rm ev}=1$M unweighted	6.2	272	2.4	2.2

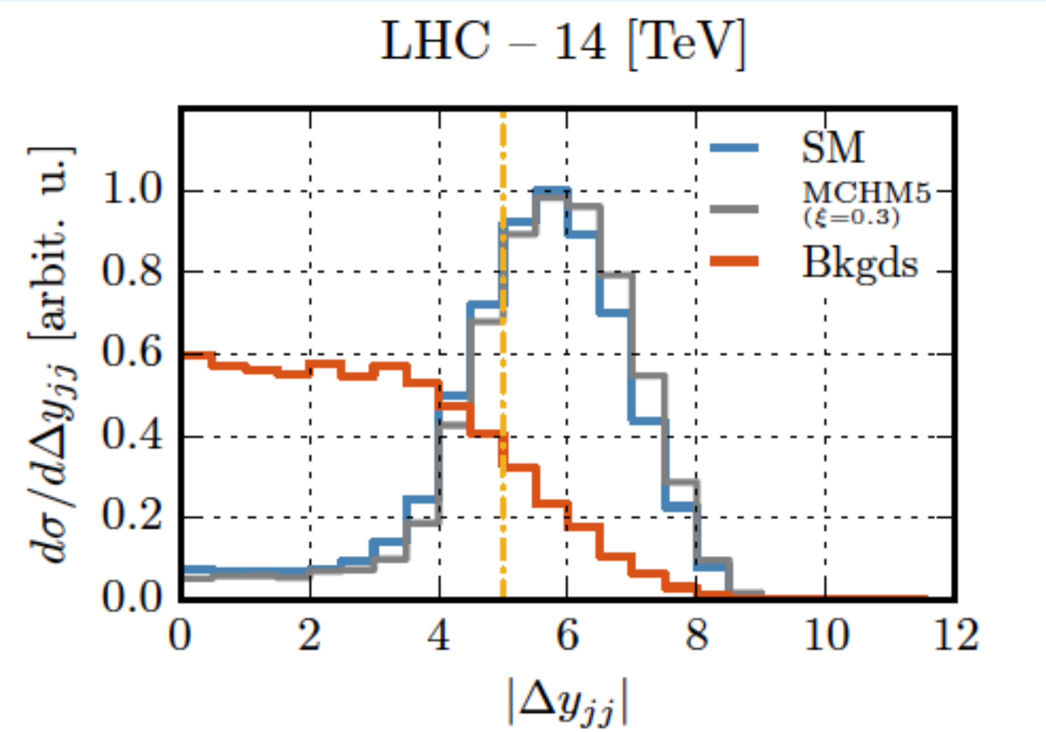
Killing backgrounds with VBF topology

The huge QCD jet backgrounds can be **reduced by exploiting the VBF topology**

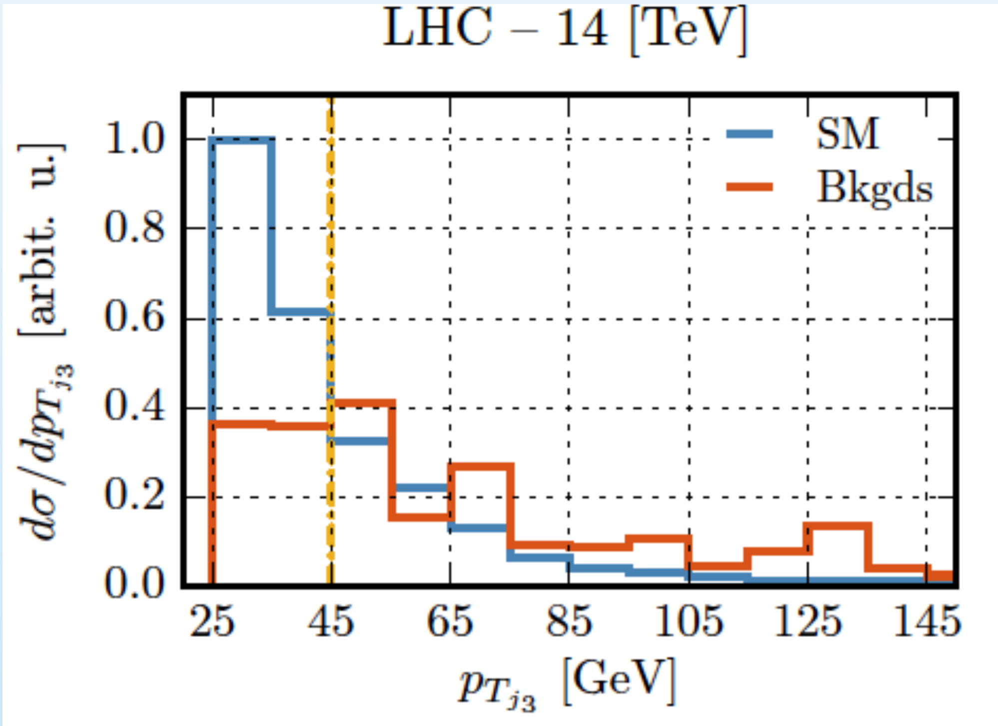
Require **two forward jets, separated in rapidity**, plus a **veto in hadronic activity** in the central region

Additional cuts in the r**econstructed Higgs invariant mass** and the **di-Higgs invariant mass m_{hh}** further reduce the QCD multijet cross-sections

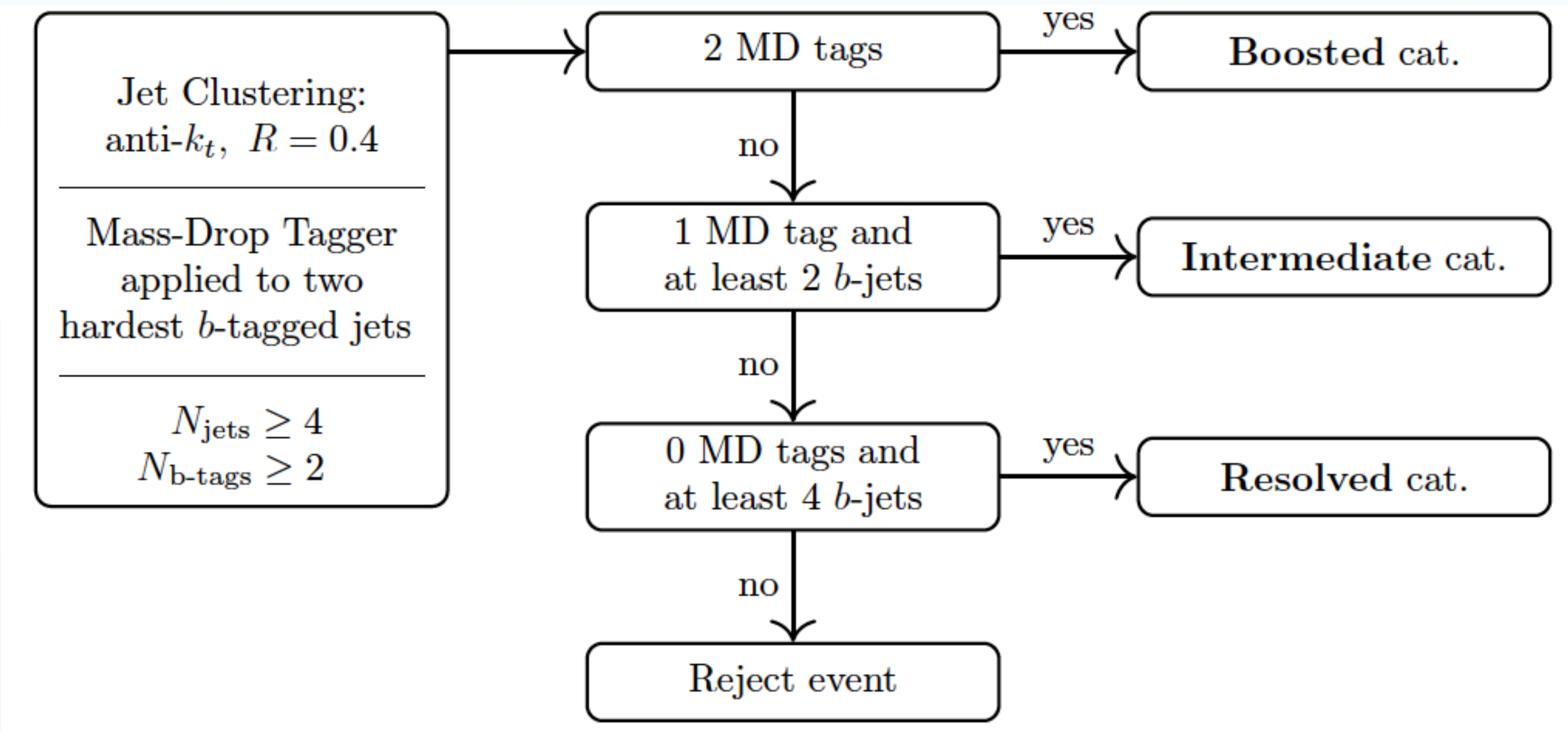
Dijet rapidity separation cut



Central jet veto cut



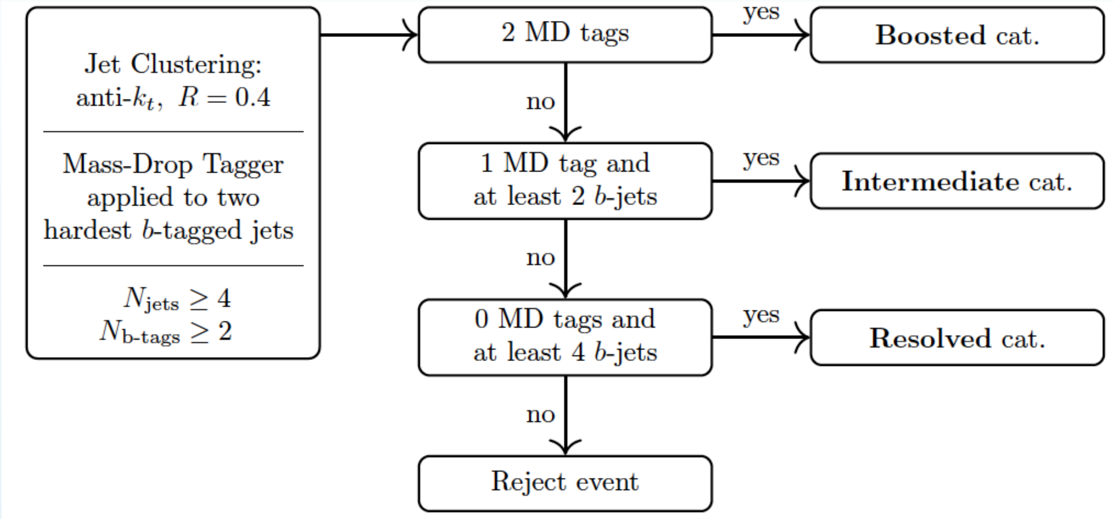
Scale-invariant Tagging



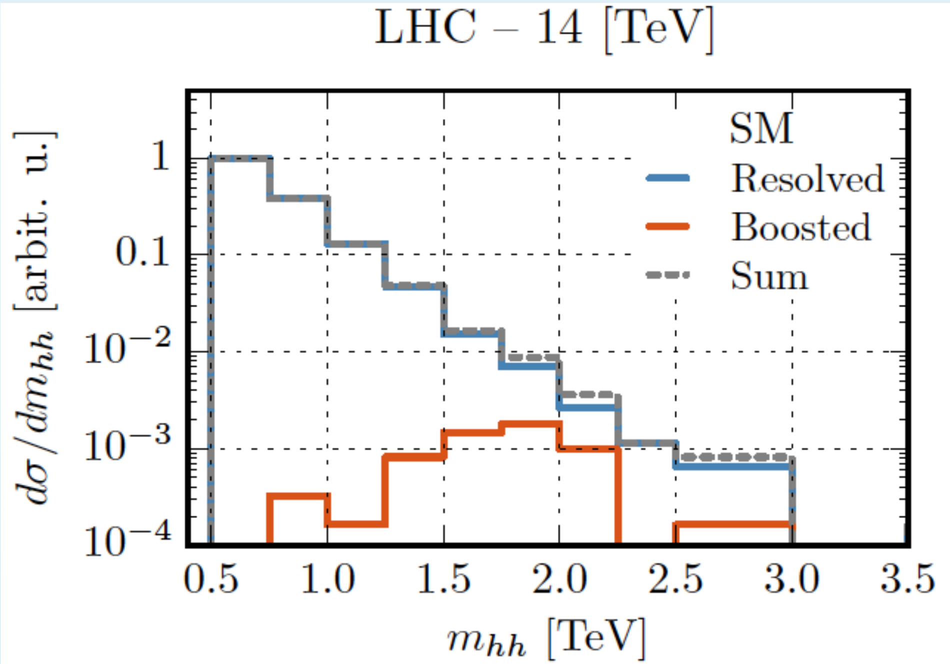
Same strategy as that used for the **analysis of the gluon-fusion channel**

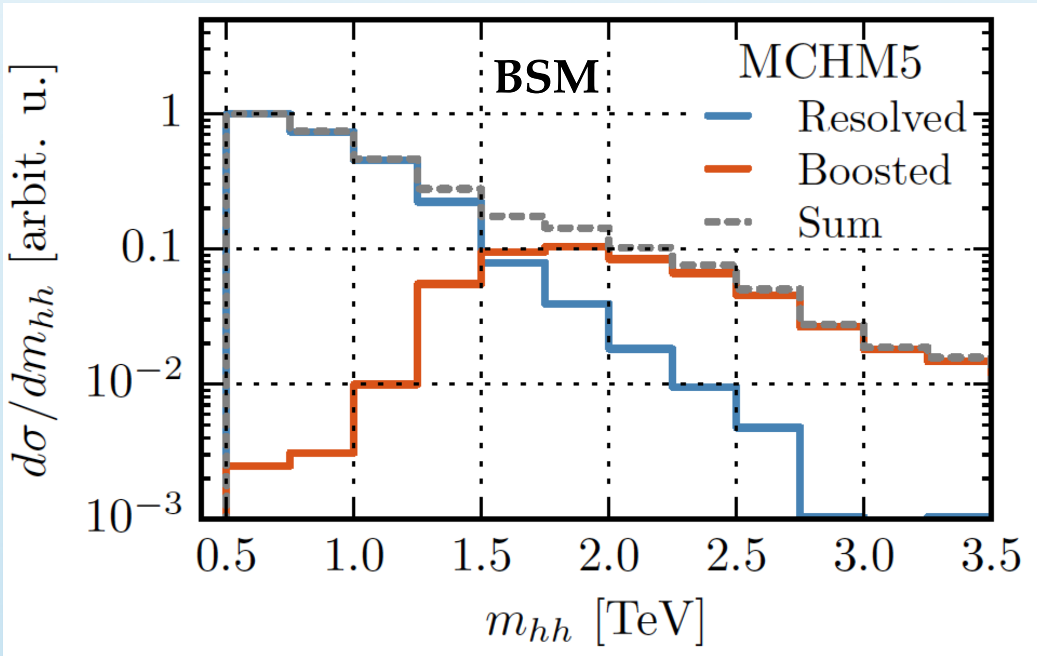
Determine, **event-by-event**, degree of **boost of di-Higgs system** and optimise selection accordingly

Scale-invariant Tagging



In the **SM, resolved selection** dominates, but for **BSM couplings**, **boosted topology** important



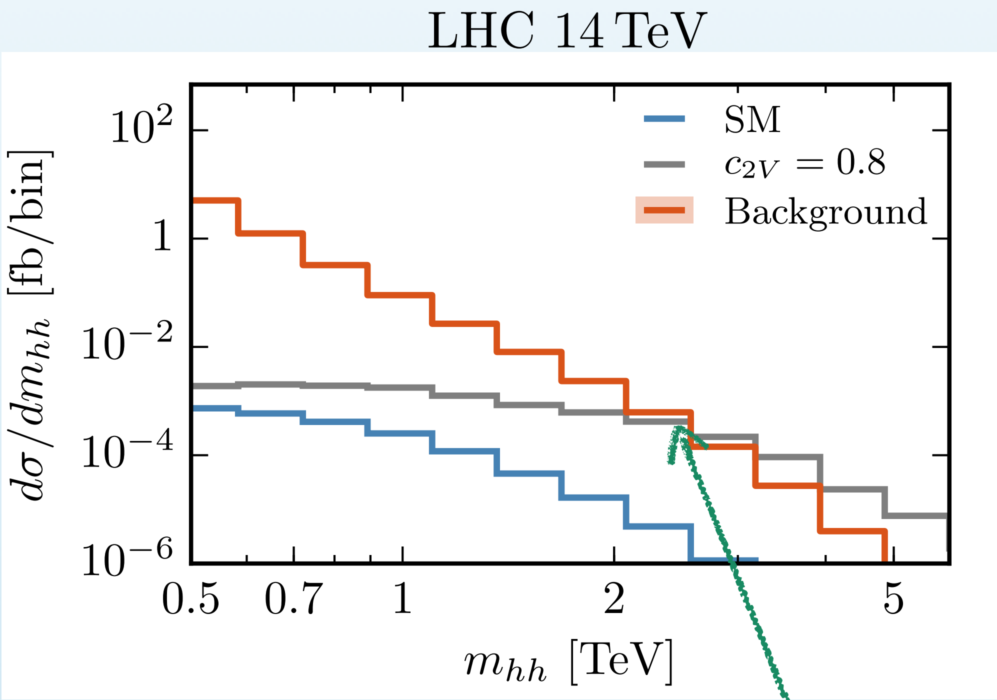


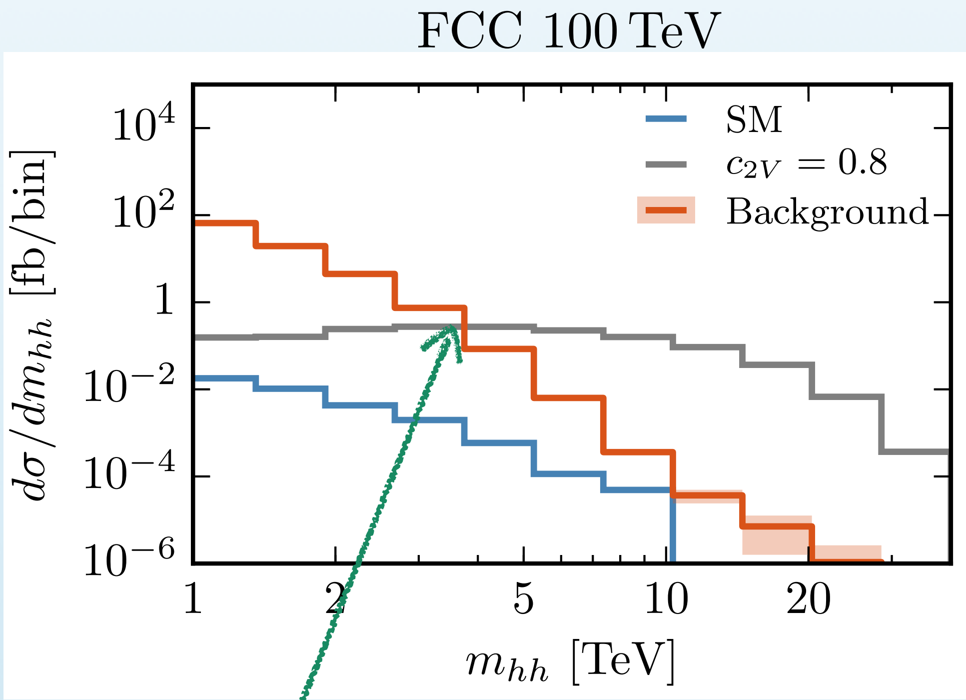
Probing the high-energy regime

After selection and analysis cuts, backgrounds are still **overwhelmingly large for m_{hh} close to threshold**

For BSM couplings, the ratio of cross-sections **between BSM and SM increases dramatically** as we probe the regions of **large m_{hh},** eventually dominating over backgrounds

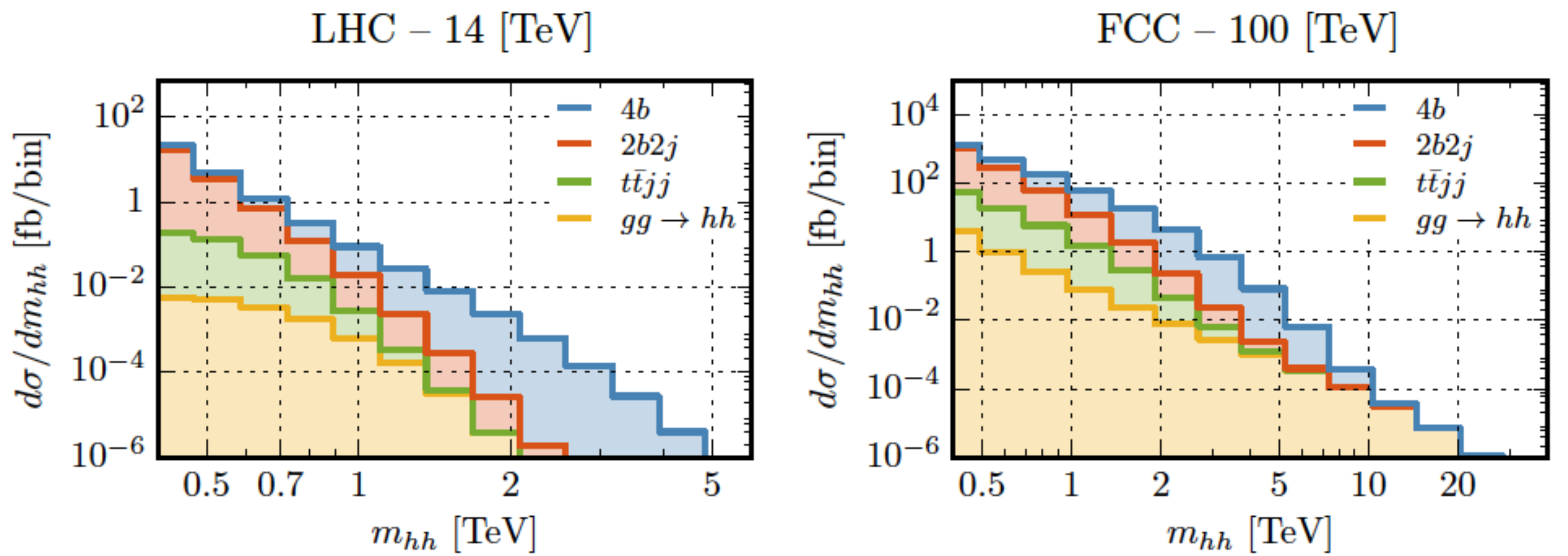
This is the key of **the sensitivity to c_{2V}** despite the tiny SM cross-sections





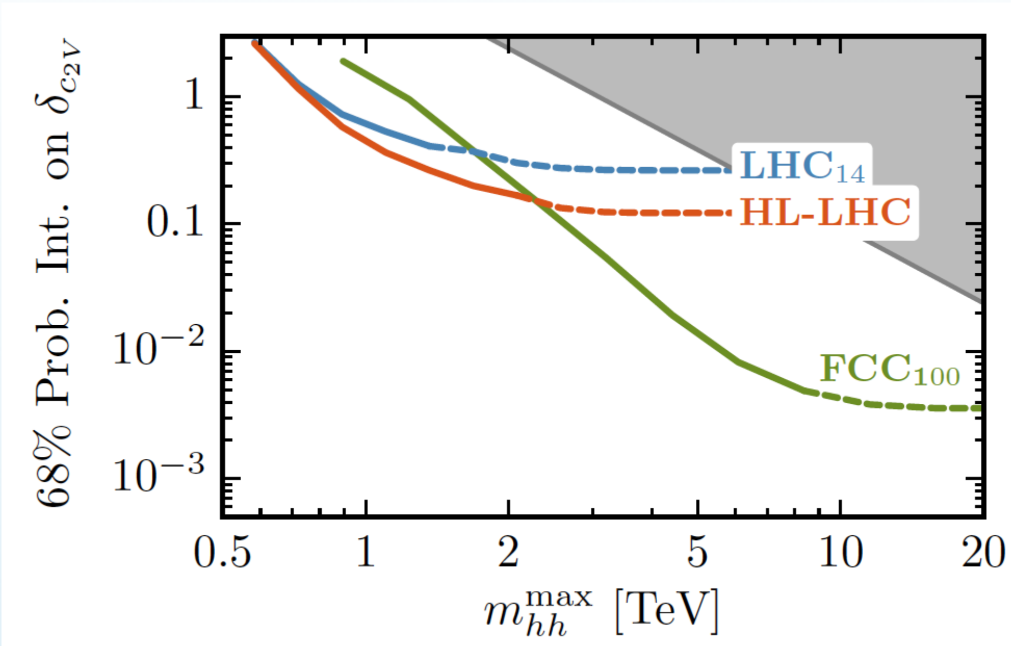
BSM signal (c_{2V}=0.8 benchmark point) dominates over background

Background decomposition



- At 14 TeV, contribution from **reducible 2b2j multijet** backgrounds (mistagged light jets) dominate up to **m_{hh} ~800 GeV**, when the **irreducible 4b background** becomes the most important
- Same trend at 100 TeV, with now **gg>hh becoming dominant** at highest invariant masses, **m_{hh} ~8 TeV**
- Reliability of QCD multijet background estimation has been carefully validated with **two independent MC generators, Sherpa and ALPGEN**

Sensitivity to the hhVV coupling



	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{\mathrm{bkg}}$	$3 \times \sigma_{\mathrm{bkg}}$
LHC_{14}	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC_{100}	$[0, 0.01]$	$[-0.01, 0.01]$

The **sensitivity to c_{2V}** improves significantly the **higher the values of m_{hh} that can be probed**

In the absence of new resonances, **c_{2V}** can be constrained **down to 45% (20%) of its SM value at the 1-sigma level** at the LHC (HL-LHC), assuming SM couplings

Take-away message

Searches for **di-Higgs production in the vector-boson-fusion channel** should start already during **Run II**, without waiting for the HL-LHC!

The di-Higgs frontier at the LHC

- Higgs pair production is a **cornerstone of the LHC program** for the coming years, allowing us to reconstruct the **EWSB potential** and to test the nature of the **EWSB mechanism**
- The **4b final state** offers the highest yields, but requires **clever analysis techniques** for taming the **overwhelming QCD background**, both theoretically and experimentally
- In the **gluon-fusion channel, discovery is guaranteed at the HL-LHC,** and competitive constraints on the **self-coupling** can be imposed **already at Run II**, provided **systematic uncertainties of the 4b cross-section** can be kept under control
- In the VBF channel, the **steep rise of the cross-section with the di-Higgs invariant mass in the case of deviations from the SM couplings** is the key for the high sensitivity of this process to $\mathbf{c_{2V}}$
- For such complex final sates like 4b, the **ultimate signal optimization** of the extraction of the Higgs couplings requires the use of **machine learning methods** such as **Multivariate Analysis**

Take-away message

Higgs pair production holds unique potential
to uncover BSM dynamics at the LHC!

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Thanks for your attention!

Take-away message

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