



Probing electroweak symmetry breaking with Higgs pair production at the LHC

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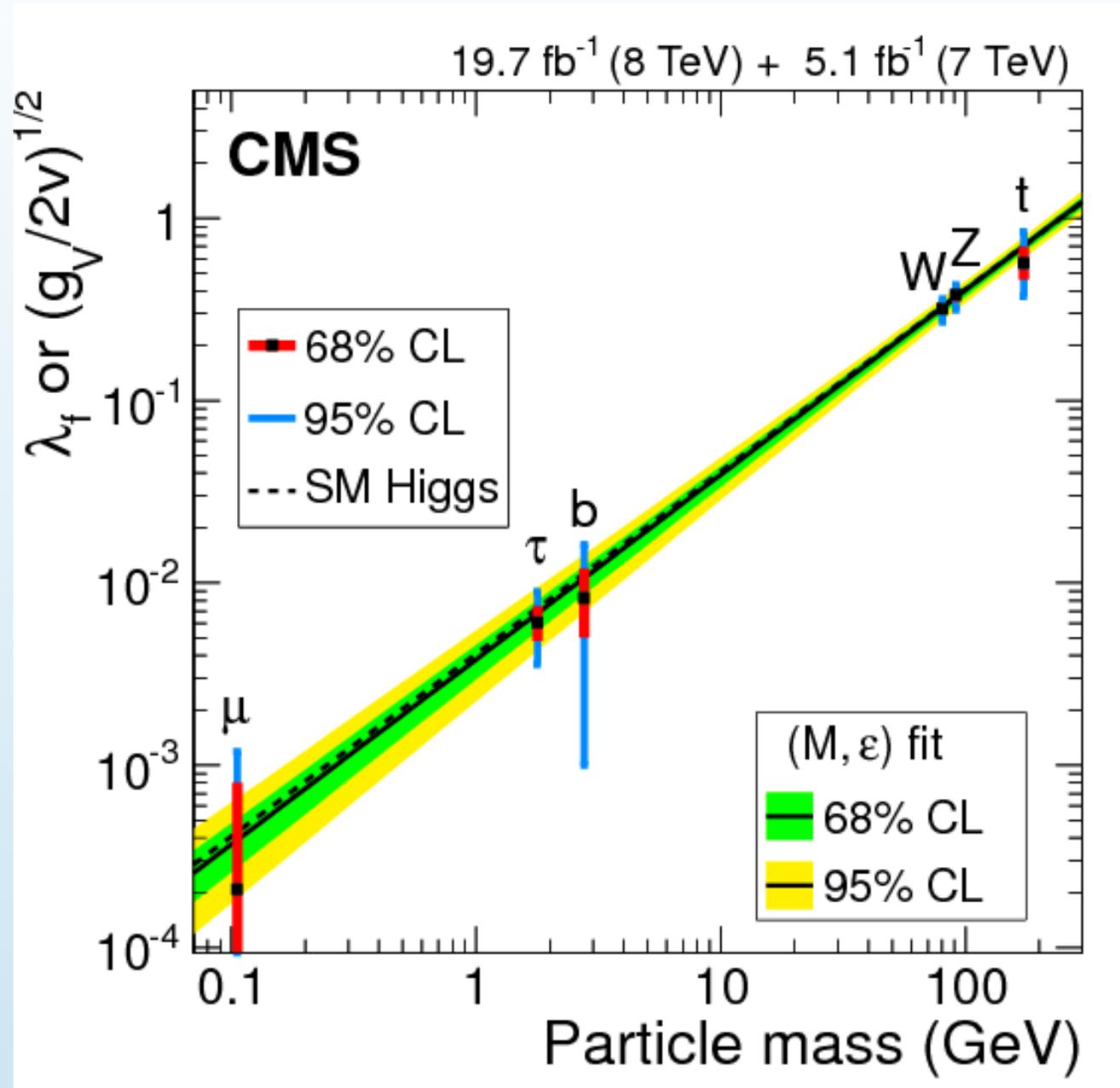
Particle Theory Seminar

High Energy Physics Group

Center for the Fundamental Laws of Nature

Harvard, 29/11/2016

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

Fingerprinting the Higgs sector

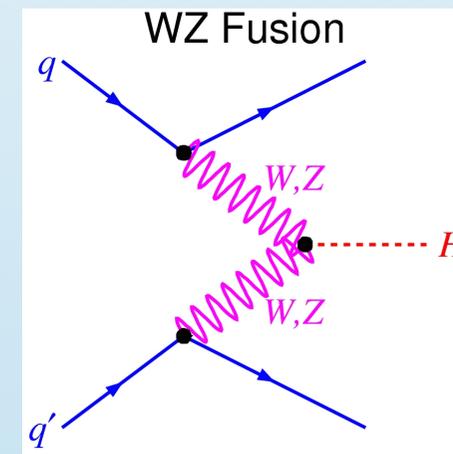
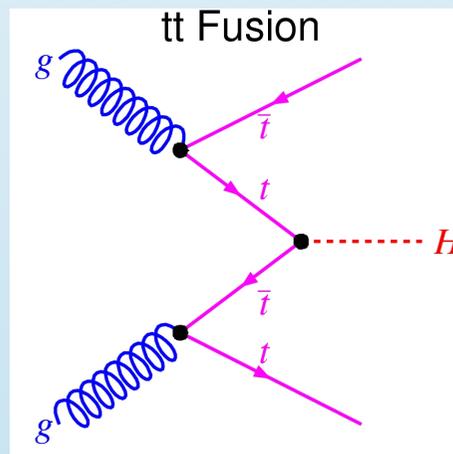
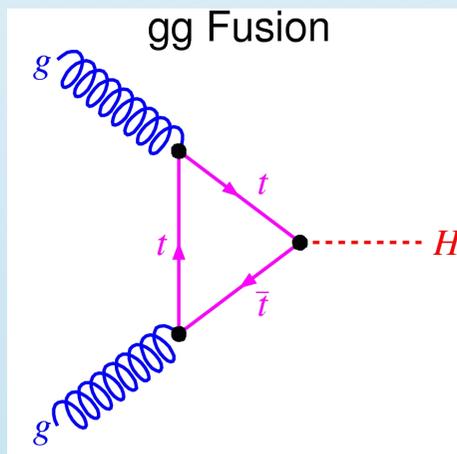
In the **Standard Model** the properties of the Higgs sector are **uniquely determined**

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%

In single Higgs production, a precision of a few percent in couplings measurements is the goal!

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



Higgs Pair Production at the LHC

📌 **Double Higgs production** allows accessing **crucial components of the Higgs sector**:

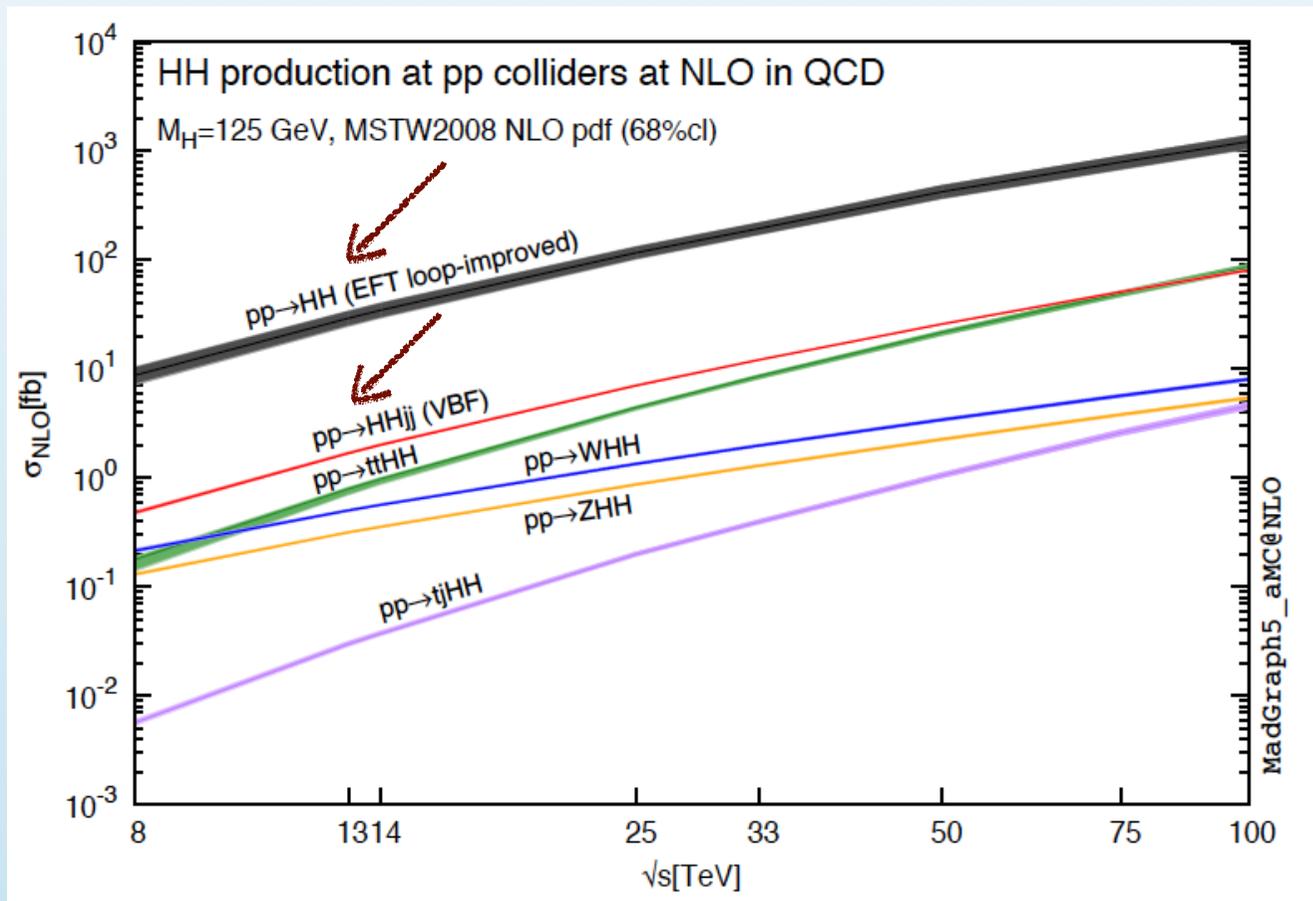
- ☑ Testing the **electroweak symmetry breaking potential** beyond the VEV region
- ☑ Probe directly the **Higgs self-interaction** (first ever fundamental scalar)
- ☑ Probe the **doublet nature** of the Higgs by means of the **hhVV coupling**

Higgs Pair Production at the LHC

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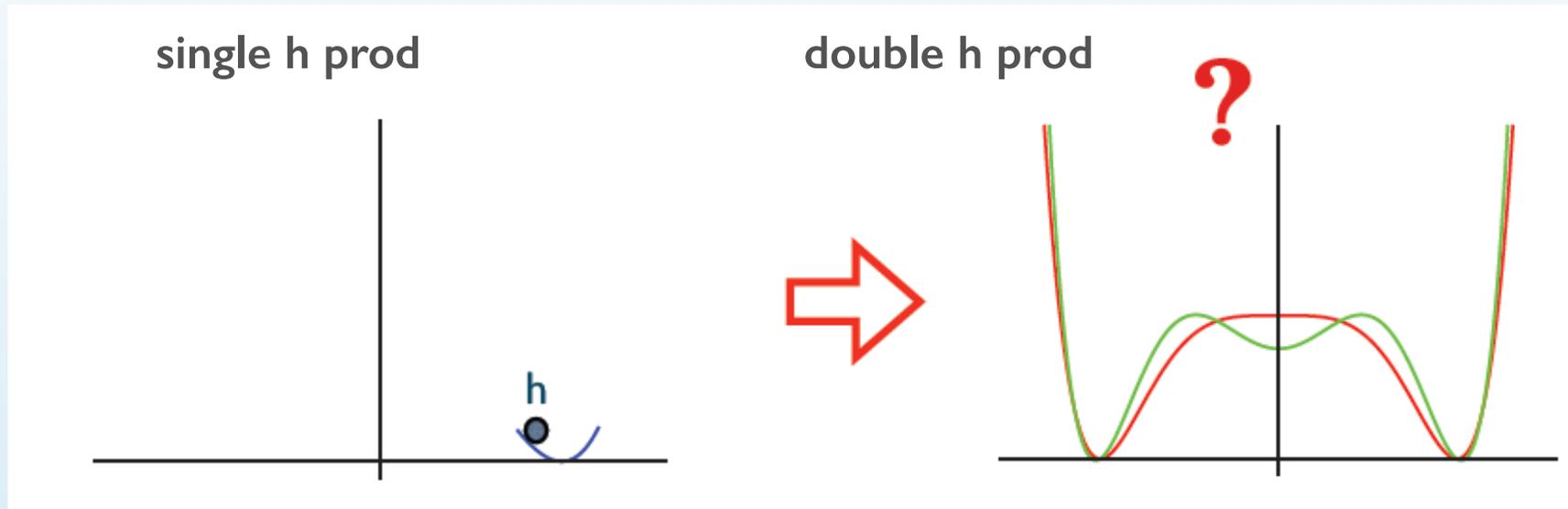
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📌 In the SM, **di-Higgs rates are small**: in the leading gluon-fusion production mode, the **cross-section at 14 TeV** is only **40 fb**, further suppressed by branching fractions



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 **test the full Higgs sector potential** and clarify EWSB mechanism
- 📍 The Higgs potential is the only *ad-hoc* ingredient of the SM: **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

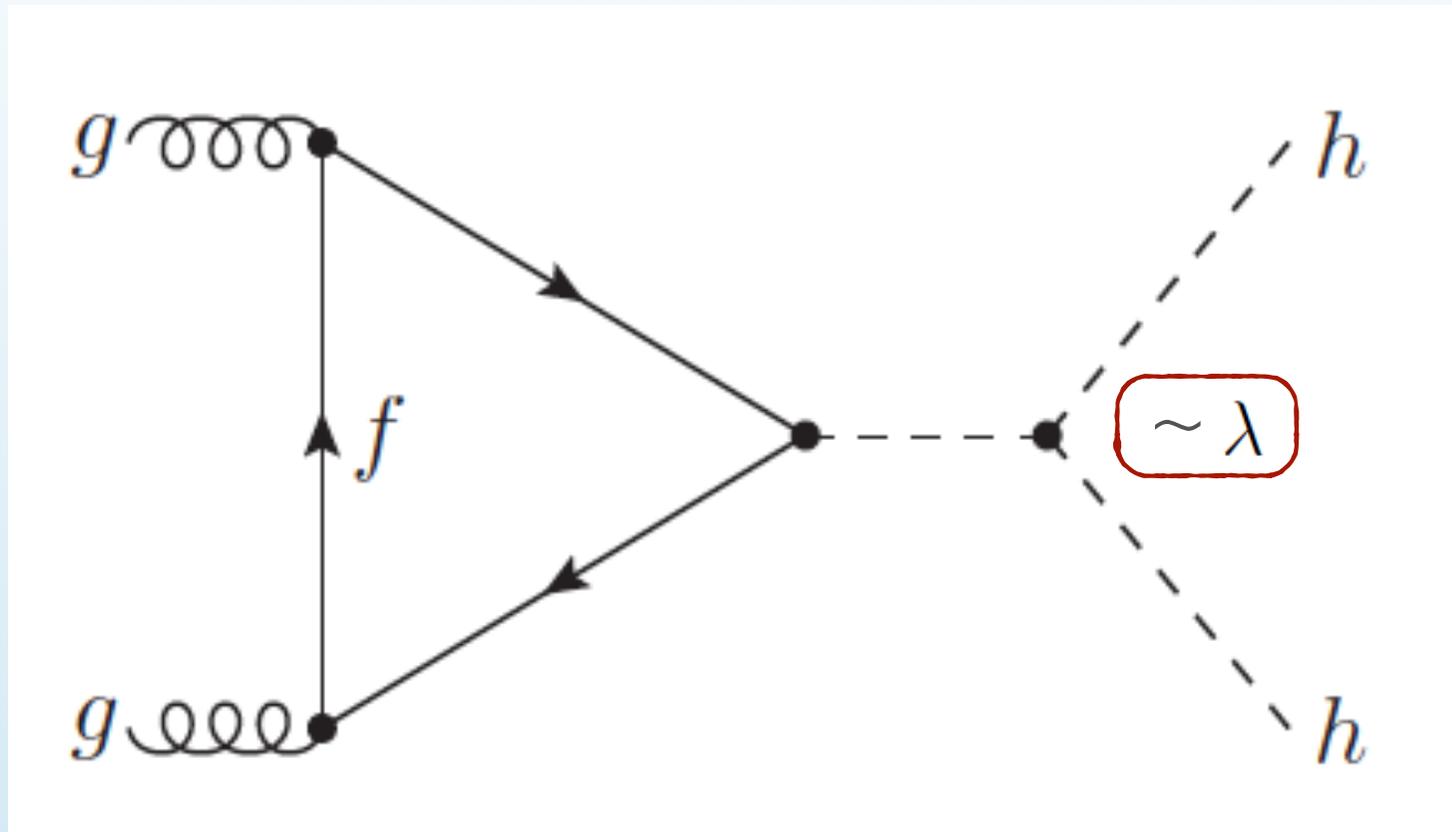
$$V(h) \rightarrow \frac{1}{2} \lambda (h^\dagger h)^2 \log \left[\frac{(h^\dagger h)}{m^2} \right]$$

Each possibility associated to **different EWSB mechanism**, with 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

EW symmetry breaking: what we don't know

Higgs pair production is a crucial ingredient in our understanding of the EWSB mechanism



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

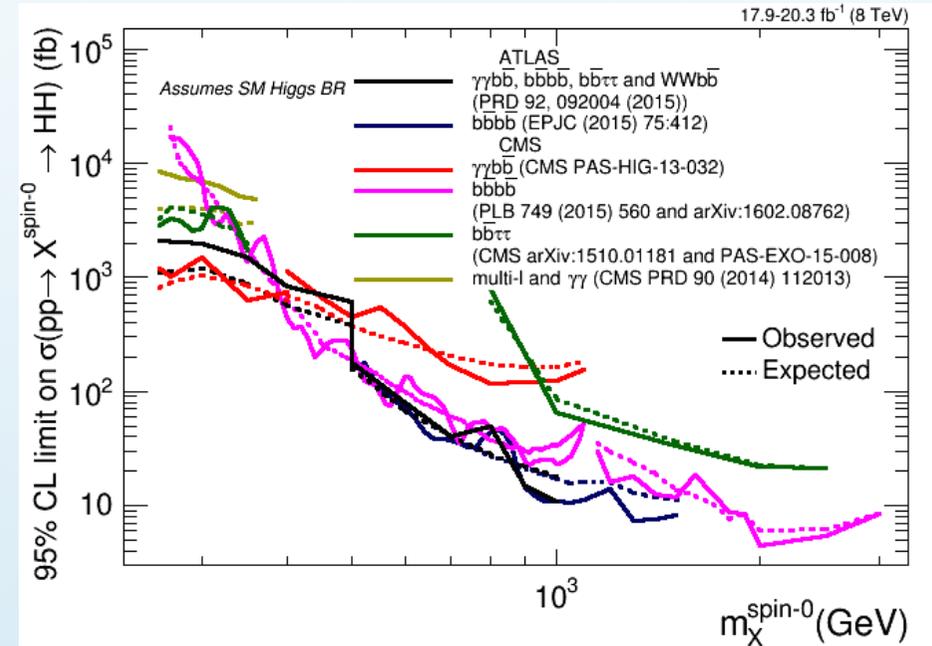
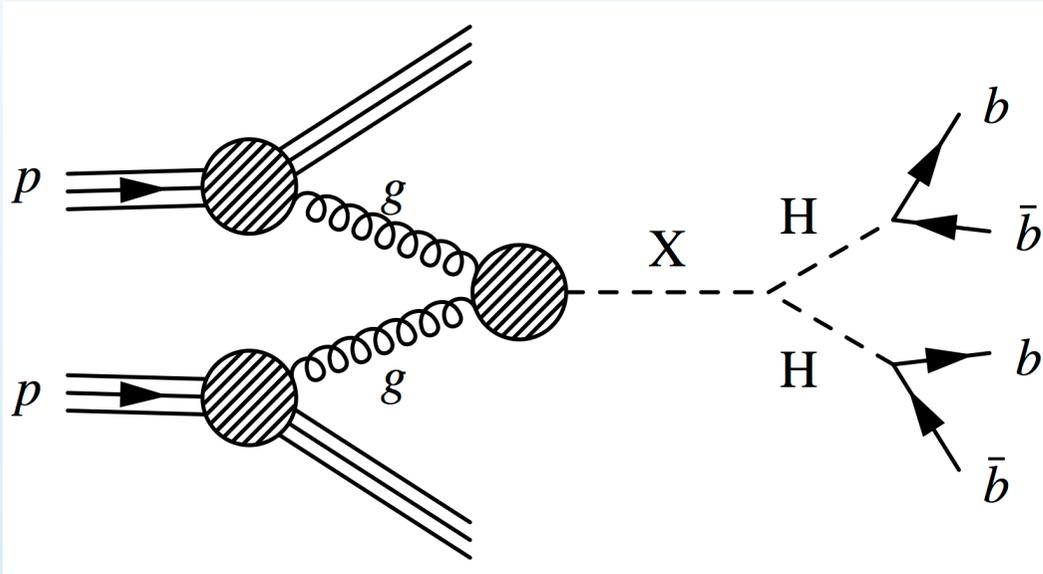
Higgs self-coupling can also be constrained indirectly via loop effects in single-Higgs production, i.e.

Degrassi et al, arXiv:1607.04251

Bizon et al. arXiv:1610.05771

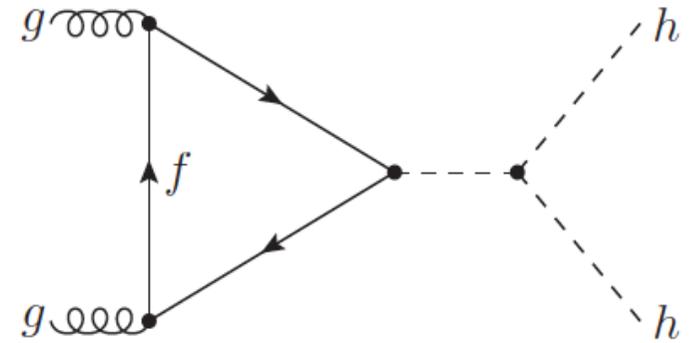
BSM Higgs Pair Production

- Rates for double Higgs production **generically enhanced in BSM scenarios**
- LHC searches** in various final states have already started based on Run I and Run II data

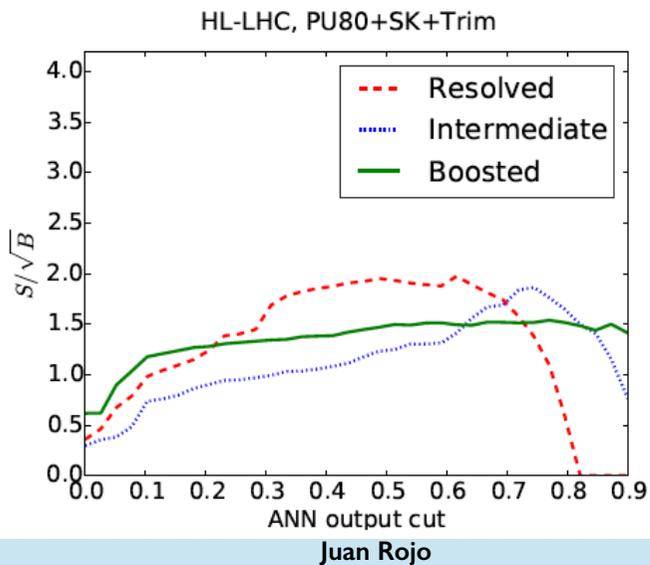


Current bounds still very loose, *i.e.*, from the **ATLAS 13 TeV search for di-Higgs in 4b final state**:

$$\sigma(hh) / \sigma_{\text{SM}}(hh) \lesssim 27$$



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



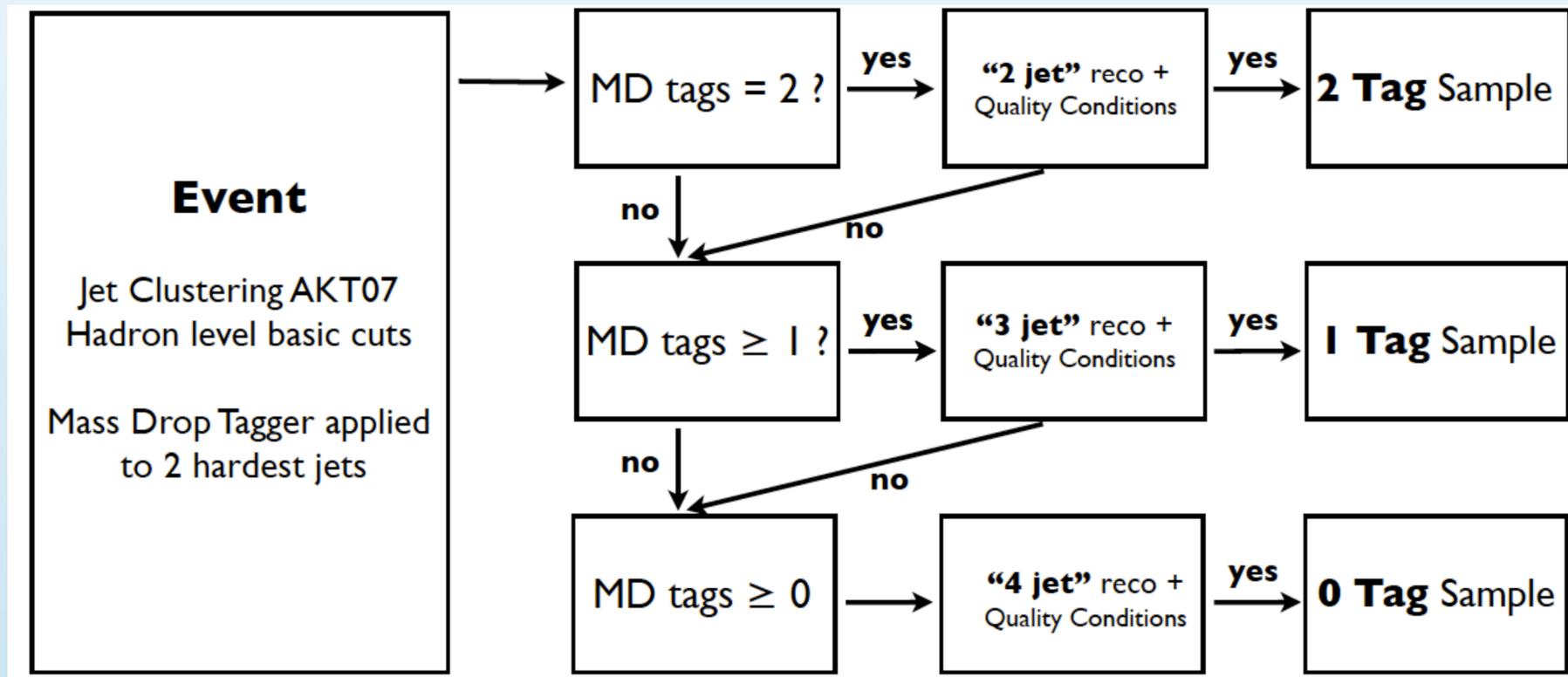
✓ *M. Gouzevitch, A. Oliveira, J. Rojo, R. Rosenfeld, G. P. Salam and V. Sanz, JHEP 1307, 148 (2013), arXiv:1303.6636*

✓ *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

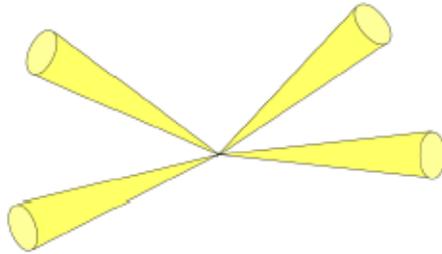
- Focus on the **hh->4b final state**: largest rates, but **overwhelming QCD multijet backgrounds**
- Made competitive requiring the **di-Higgs system to be boosted** and exploiting kinematic differences between signal and QCD background with **jet substructure**
- Boosted b-tagging** by *ghost-associating* mass-drop tagged large-*R* jets with b-tagged small-*R* jets
- Triggering these events** is challenging due to the very high rate of QCD multijets, but not impossible!

Scale-invariant tagging: event-by-event classification depending on final state topology

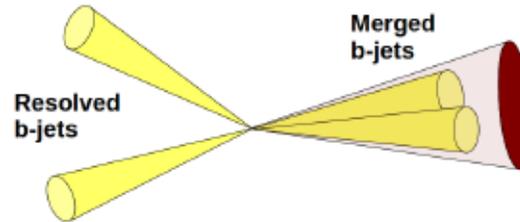


Selection strategy

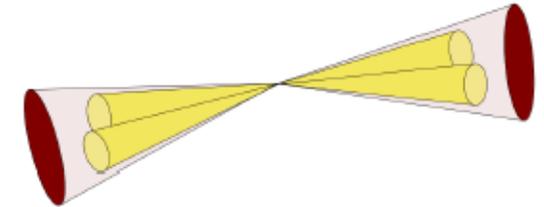
Resolved



Intermediate



Boosted



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

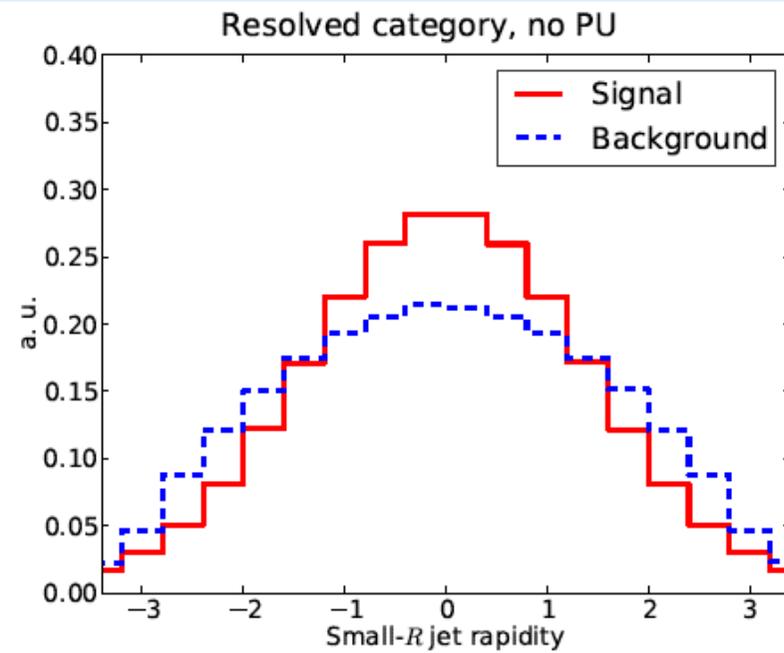
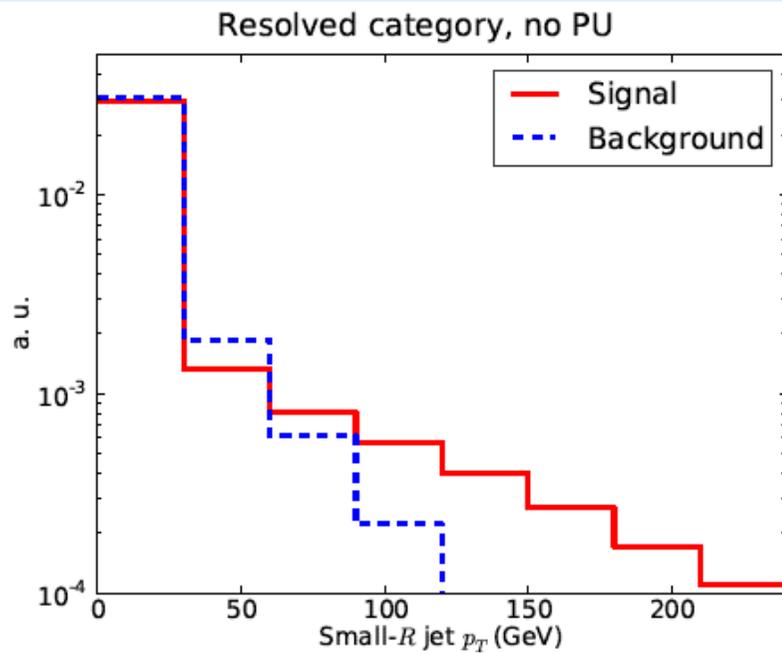
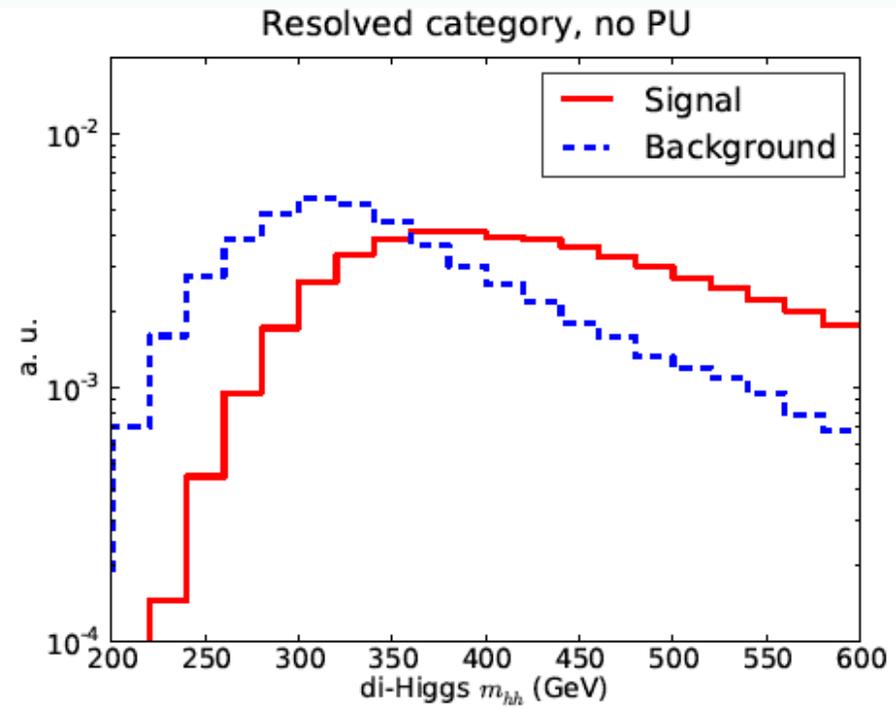
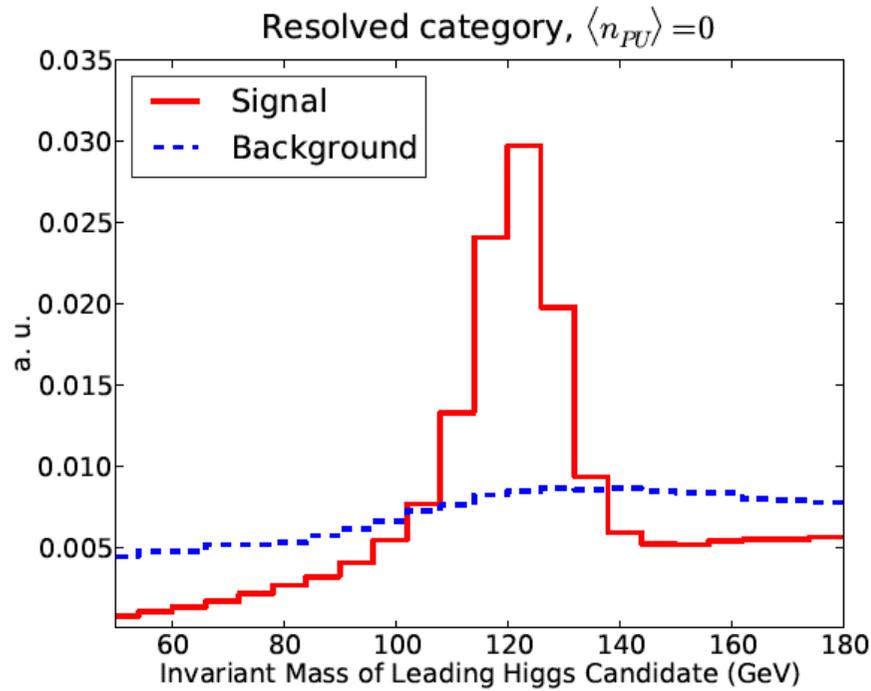
- = 1 large- R jet (Higgs-tagged + b -tagged) (leading Higgs)
- ≥ 2 b -tagged small- R jets
- $\Delta R > 1.2$ w.r.t. large- R jet
- Higgs reconstruction from leading 2 small- R jets
- Choice that minimises mass difference of dijet system and large- R jet

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

+ **Loose Higgs mass window cut:** $|m_{h,j} - 125 \text{ GeV}| < 40 \text{ GeV}$, $j = 1, 2$

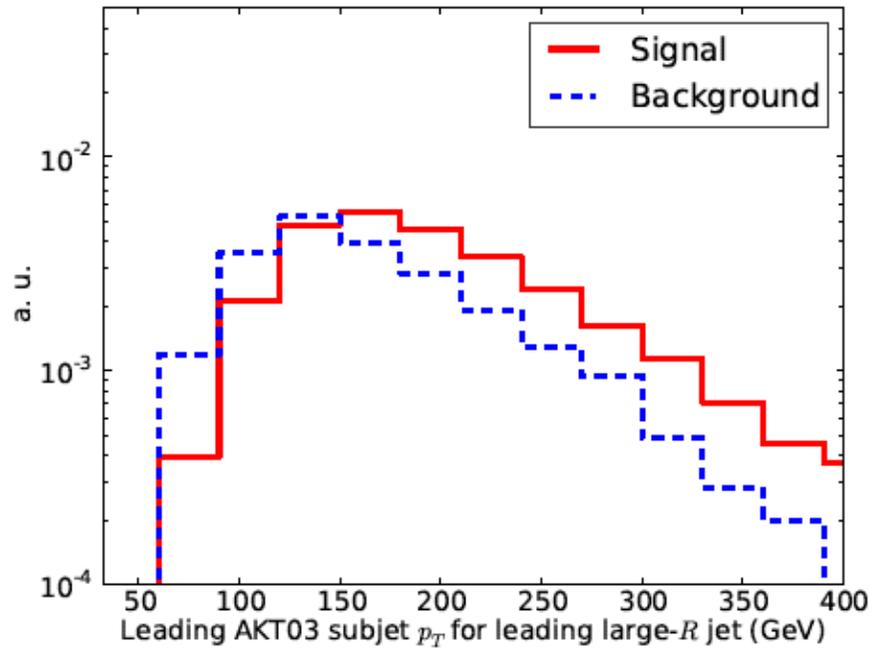
+ **Rank categories** by S/\sqrt{B} to make them **exclusive**: boosted $>$ intermediate $>$ resolved

Cut-based analysis - resolved category

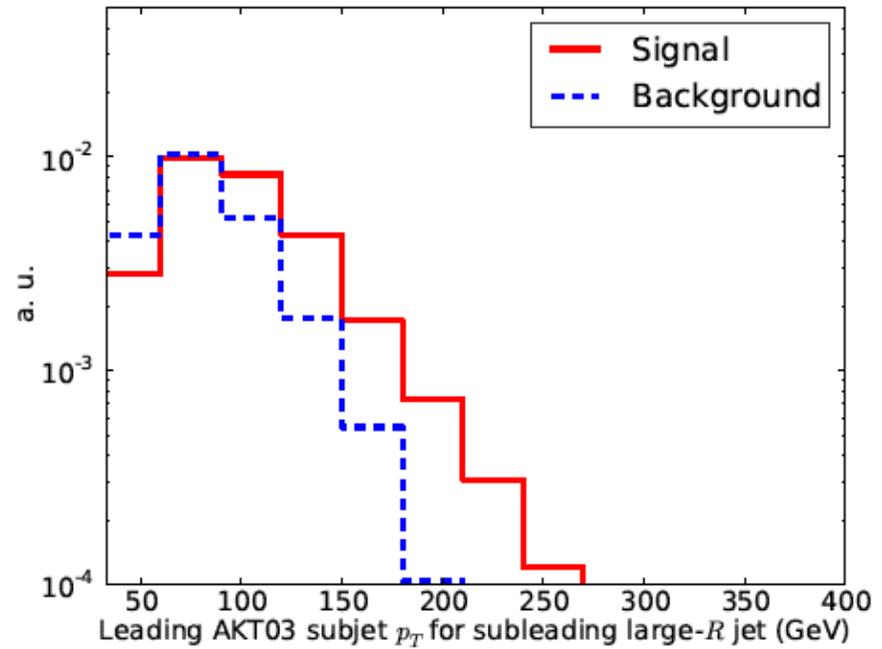


Cut-based analysis - boosted category

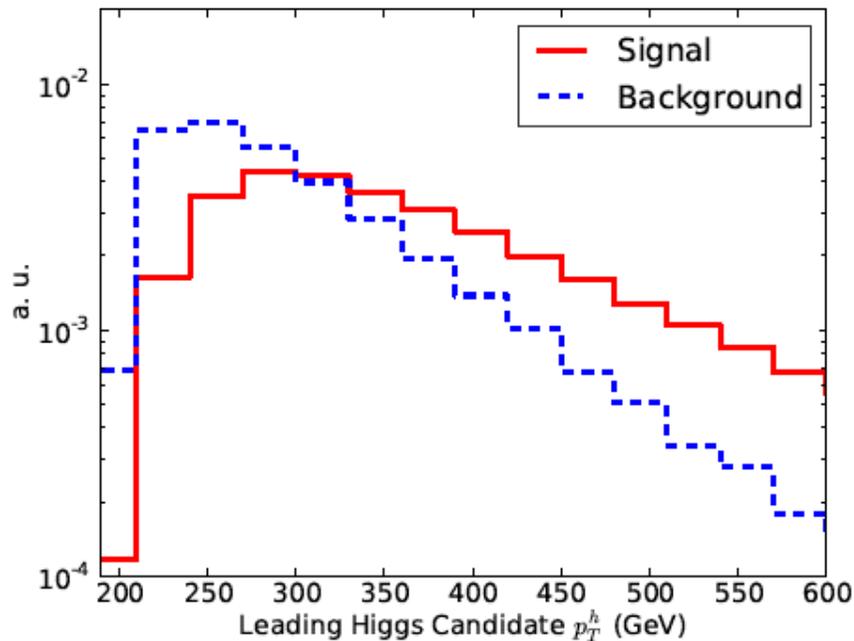
Boosted category, no PU



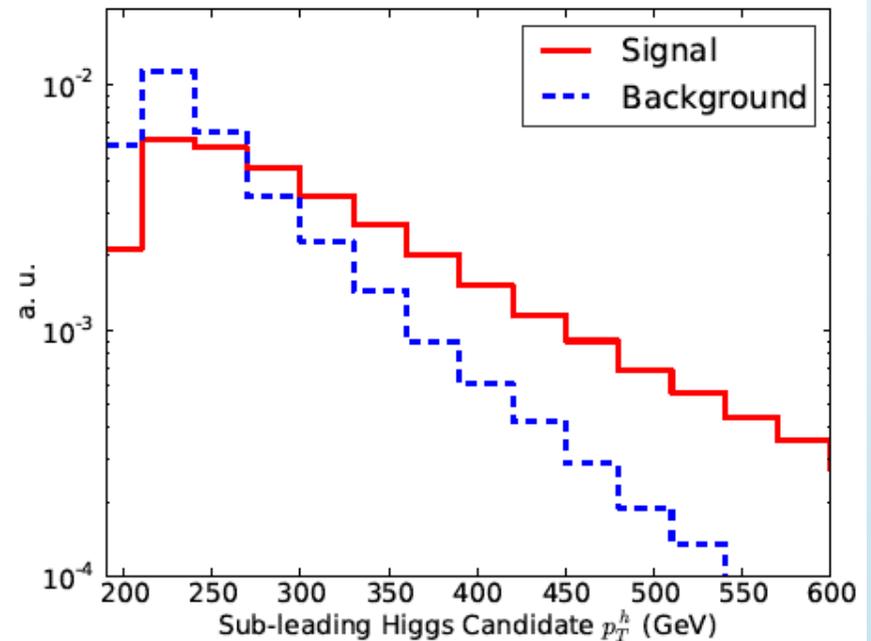
Boosted category, no PU



Boosted category, no PU



Boosted category, no PU



Cut-based analysis results

- At the end of the cut-based analysis (level C2) **backgrounds still overwhelmingly larger than signal**, and signal significances low even for $L=3000 \text{ fb}^{-1}$
- Small S/B** also problematic, since requires **unfeasibly small systematic uncertainties** in the measurement
- Contribution of mis-identified b-jets **from light and charm jets** comparable to irreducible 4b background

HL-LHC, Resolved category, no PU										
	<i>hh4b</i>	total bkg	Cross-section [fb]				<i>S/B</i>		<i>S/√B</i>	
			4b	2b2j	4j	$t\bar{t}$	tot	4b	tot	4b
C1a	9	$2.2 \cdot 10^8$	$6.9 \cdot 10^4$	$1.5 \cdot 10^7$	$2.0 \cdot 10^8$	$2.1 \cdot 10^5$	$4.0 \cdot 10^{-8}$	$1.3 \cdot 10^{-4}$	0.03	1.9
C1b	9	$2.2 \cdot 10^8$	$6.9 \cdot 10^4$	$1.5 \cdot 10^7$	$2.0 \cdot 10^8$	$2.1 \cdot 10^5$	$4.0 \cdot 10^{-8}$	$1.3 \cdot 10^{-4}$	0.03	1.9
C1c	2.6	$4.4 \cdot 10^7$	$1.6 \cdot 10^4$	$3.2 \cdot 10^6$	$4.1 \cdot 10^7$	$8.8 \cdot 10^4$	$6.1 \cdot 10^{-8}$	$1.6 \cdot 10^{-4}$	0.02	1.1
C2	0.5	$4.9 \cdot 10^3$	$1.7 \cdot 10^3$	$2.9 \cdot 10^3$	$2.1 \cdot 10^2$	47	$1.1 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$	0.4	0.6

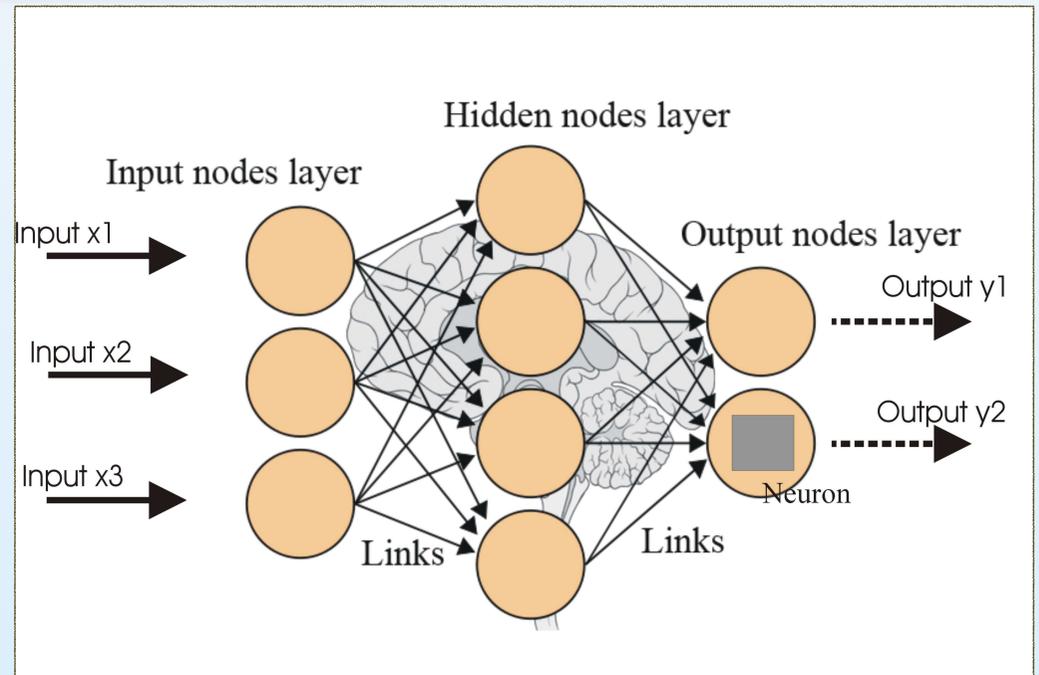
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			4b	2b2j	4j	$t\bar{t}$	tot	4b	tot	4b
C1a	3.9	$4.6 \cdot 10^7$	$1.1 \cdot 10^4$	$2.9 \cdot 10^6$	$4.3 \cdot 10^7$	$2.4 \cdot 10^4$	$8.2 \cdot 10^{-8}$	$3.4 \cdot 10^{-4}$	0.03	2.0
C1b	2.7	$3.7 \cdot 10^7$	$7.5 \cdot 10^3$	$2.1 \cdot 10^6$	$3.5 \cdot 10^7$	$2.2 \cdot 10^4$	$7.4 \cdot 10^{-8}$	$3.7 \cdot 10^{-4}$	0.03	1.7
C1c	1.0	$3.9 \cdot 10^6$	$8.0 \cdot 10^2$	$2.3 \cdot 10^5$	$3.7 \cdot 10^6$	$7.1 \cdot 10^3$	$2.6 \cdot 10^{-7}$	$1.3 \cdot 10^{-3}$	0.03	2.0
C2	0.16	$2.5 \cdot 10^2$	53	$1.9 \cdot 10^2$	13	1.6	$5.7 \cdot 10^{-4}$	$2.7 \cdot 10^{-3}$	0.5	1.1

Use MVAs to fully exploit the kinematic discrimination power between signal and background events

Artificial Neural Networks

Inspired by **biological brain models**, **Artificial Neural Networks** are **mathematical algorithms** widely used in a wide range of applications, from **high energy physics** to **targeted marketing** and **finance forecasting**

From Biological to Artificial Neural Networks



Artificial neural networks aim to excel in the same domains as their biological counterparts: **pattern recognition**, **forecasting**, **classification**, where our **evolution-driven biology** outperforms traditional algorithms

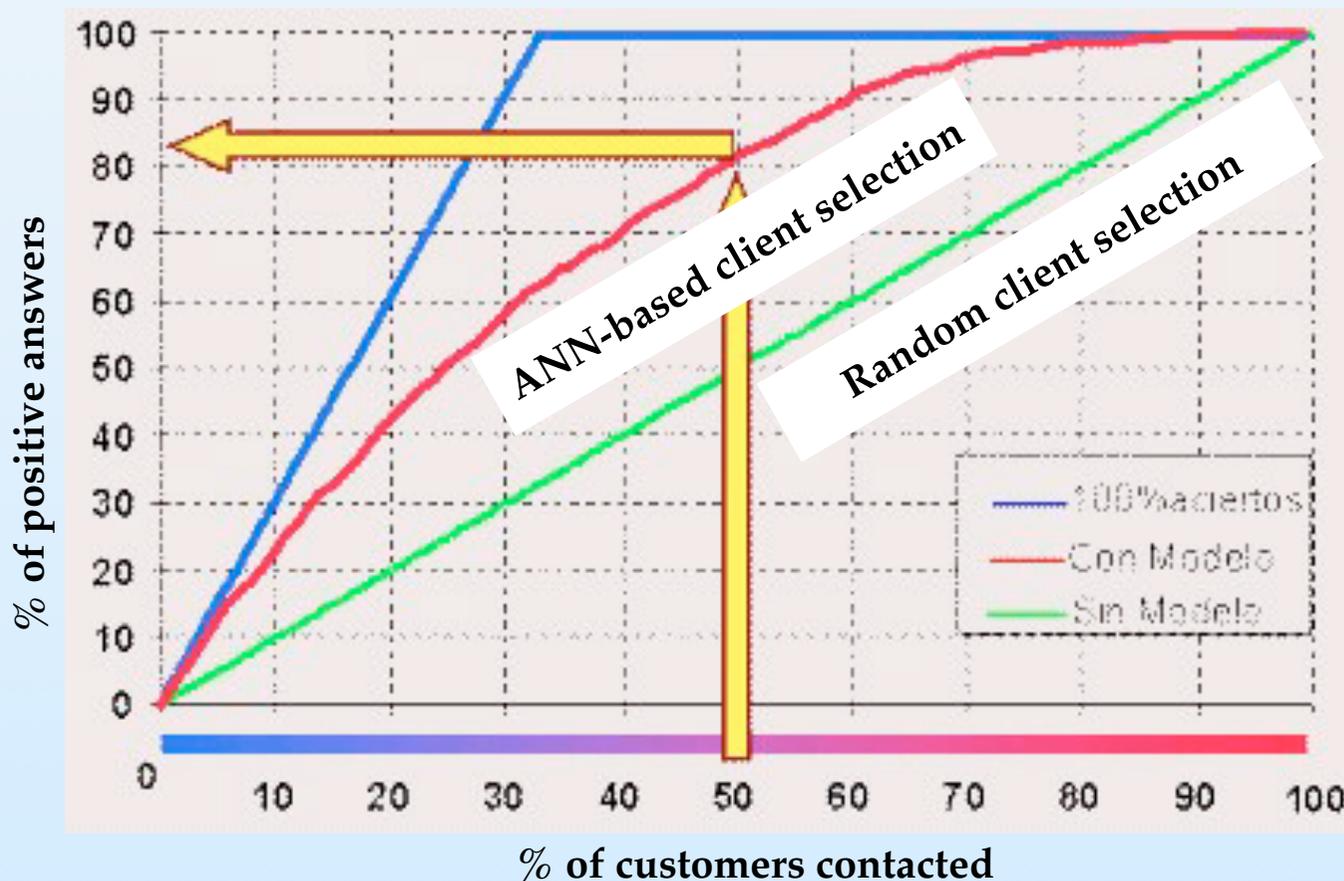
Artificial Neural Networks

Application in Marketing

A bank wants to offer a new credit card to their clients. Two possible strategies:

- 📌 **Contact all customers:** slow and costly
- 📌 Contact 5% of the customers, **train a ANN with their input** (gender, income, loans) and **their output** (yes/no) and use the information to **contact only clients likely to accept the product**

Cost-effective method to improve marketing performance

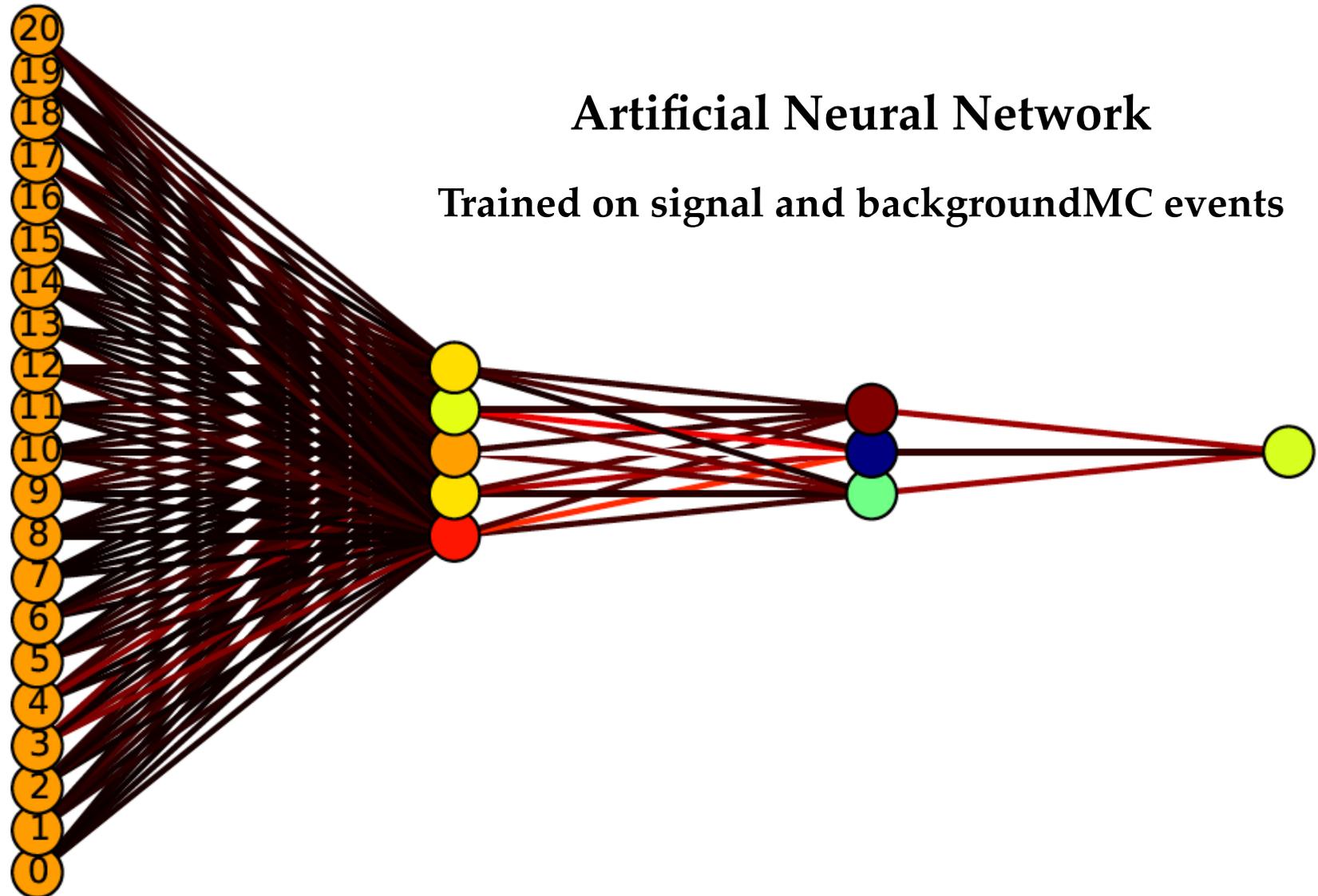


Multivariate techniques

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 p_T
Higgs m
di-Higgs m
ECF
 τ_{12}
Subjet p_T
.....



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**:

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

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

Jet substructure variables

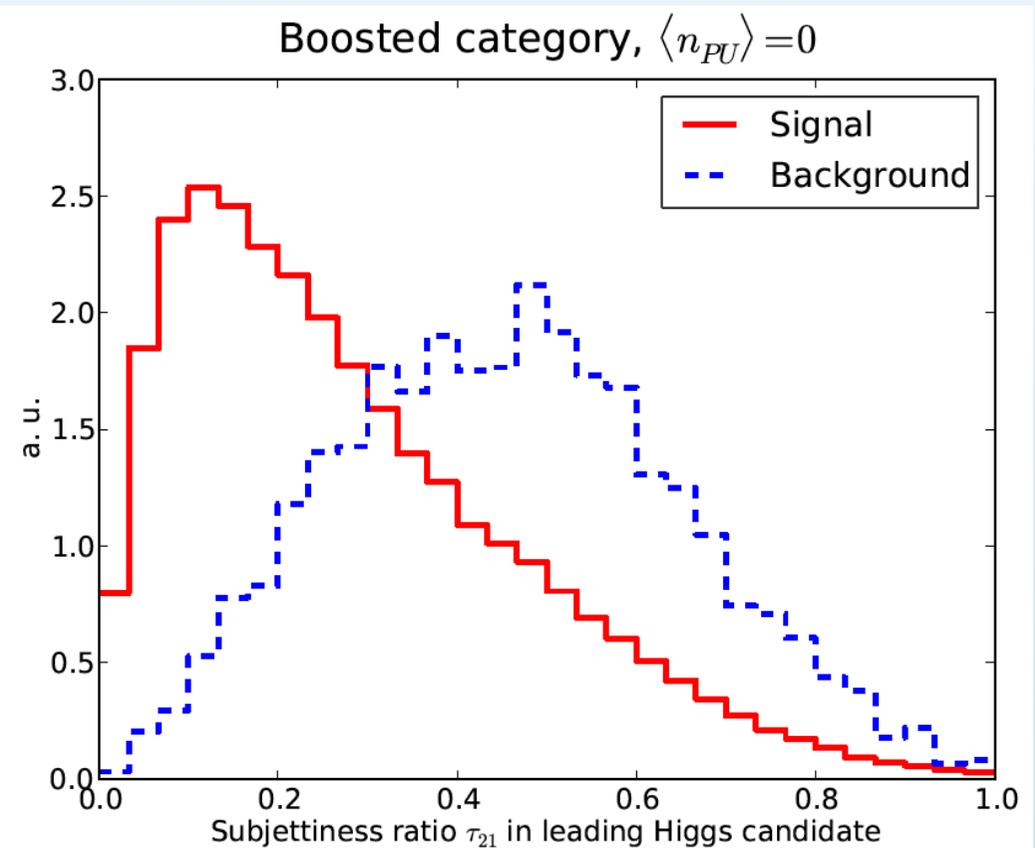
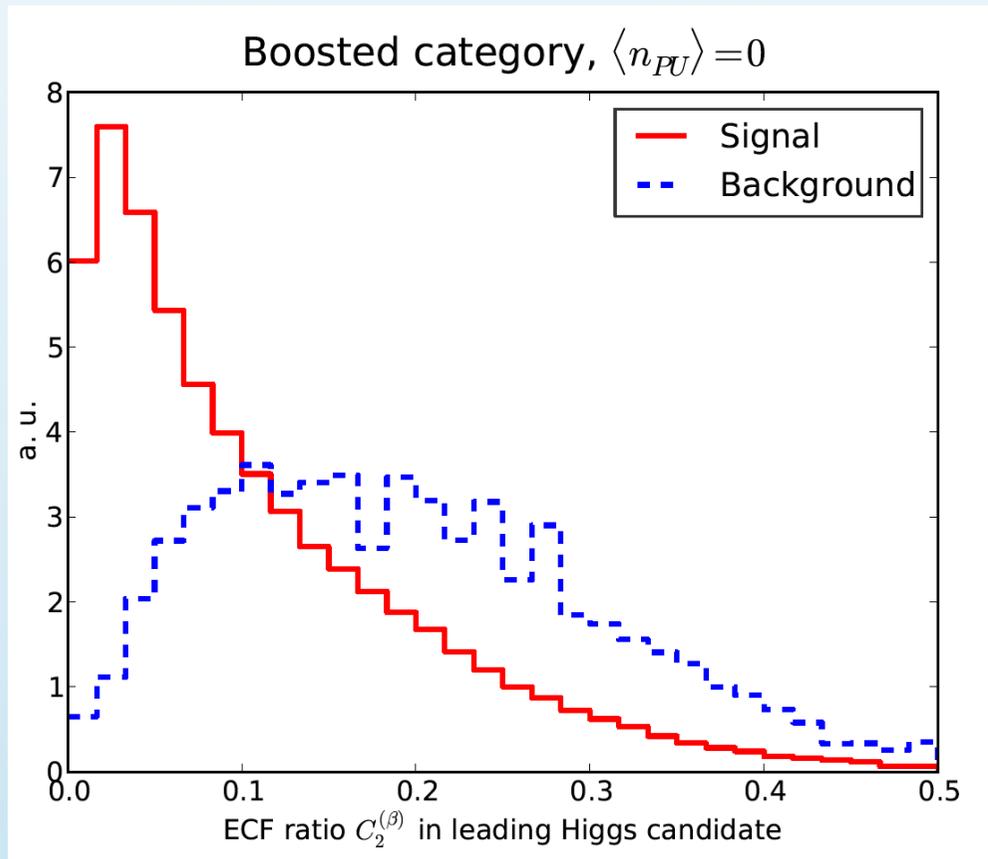
- **Substructure variables** quantify differences in internal structure between QCD jets and jets from the decay of heavy resonances
- QCD radiation tends to be **soft** and **collinear**, while decay products of resonances **share momentum evenly**

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

Energy Correlation Functions ratio

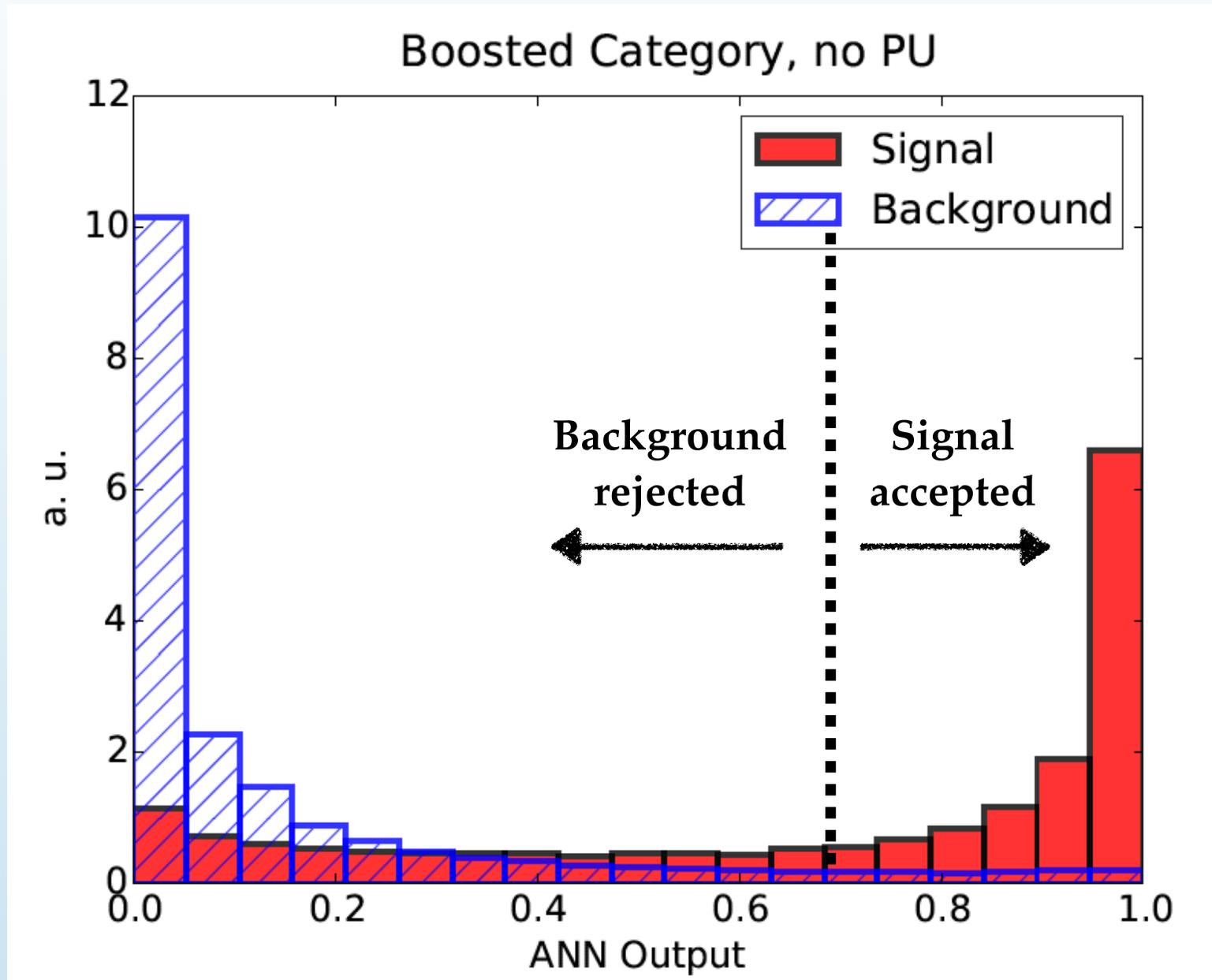
$$\tau_N \equiv \frac{1}{d_0} \sum_k p_{T,k} \cdot \min(\delta R_{1k}, \dots, \delta R_{Nk})$$

τ_{21} : 2-to-1 Subjettiness ratio



Multivariate techniques

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

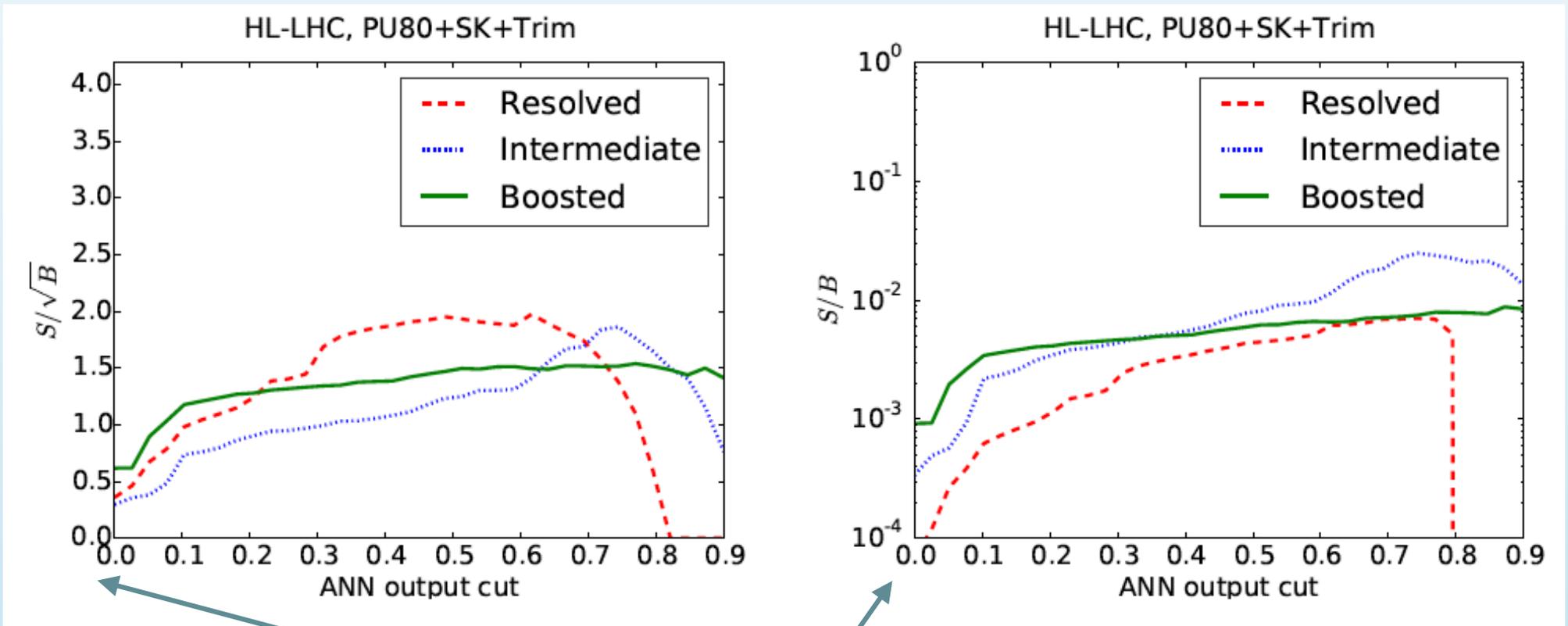


Signal significance

- Use of **multivariate techniques** allows to **substantially improve the signal significance** for this process
- 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 minimised

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

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



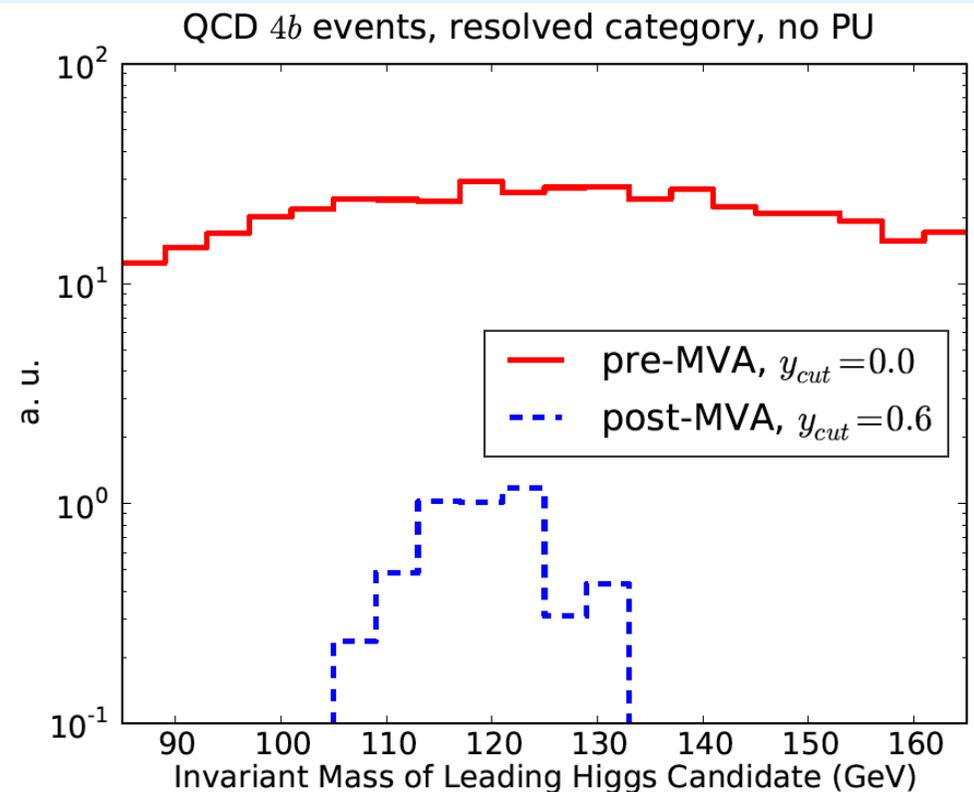
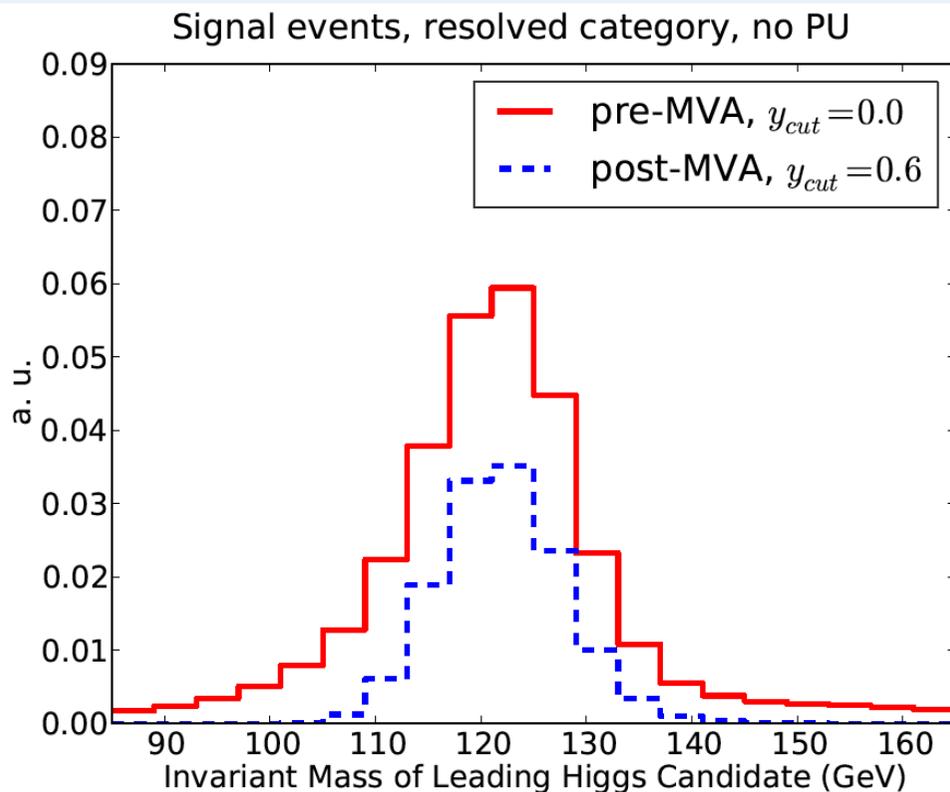
Pre-MVA result

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

Opening the Black Box

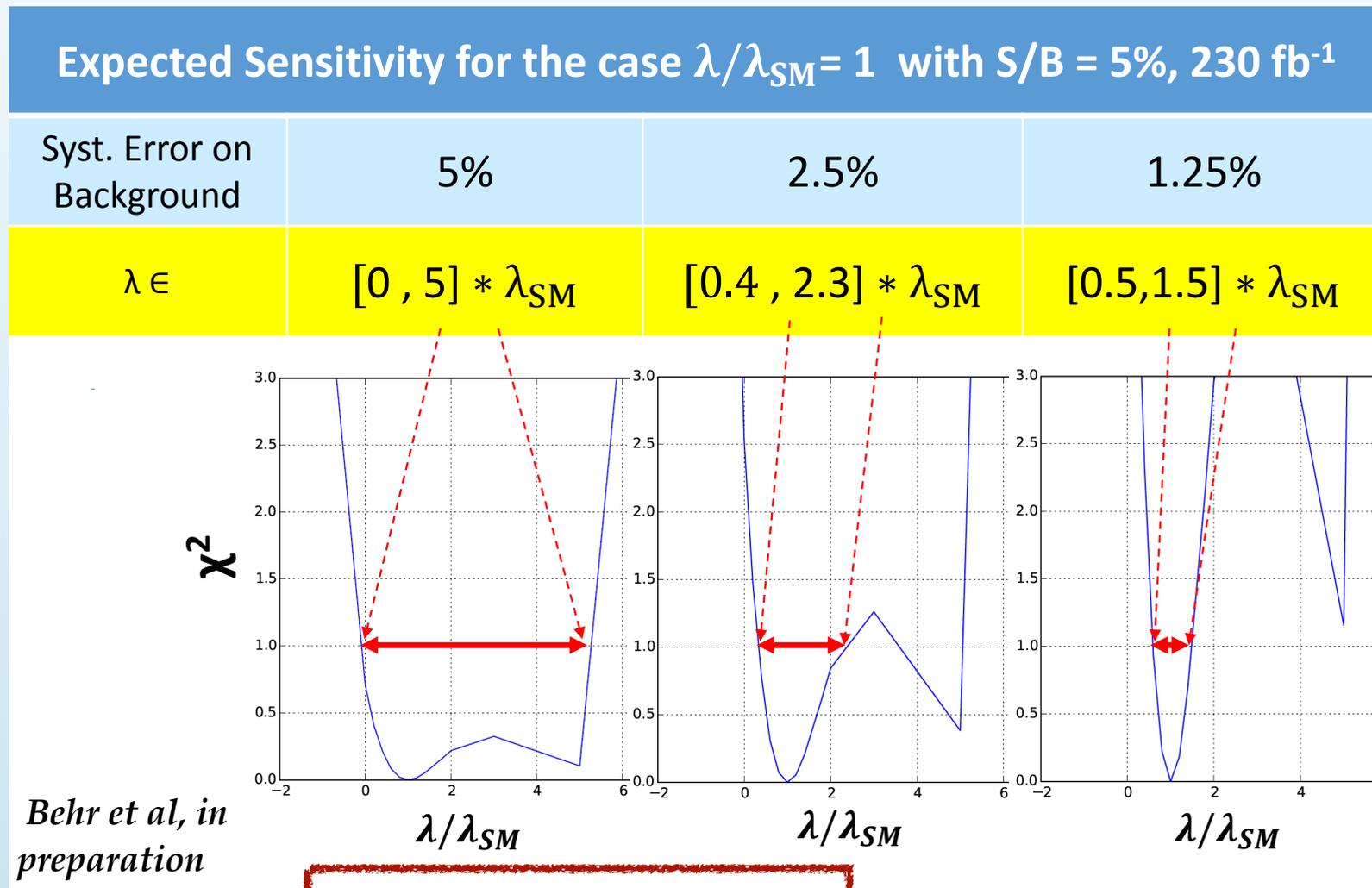
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- This info should be enough to **perform a cut-based analysis** and achieve similar signal significance



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**



LHC 13 TeV, Resolved Category

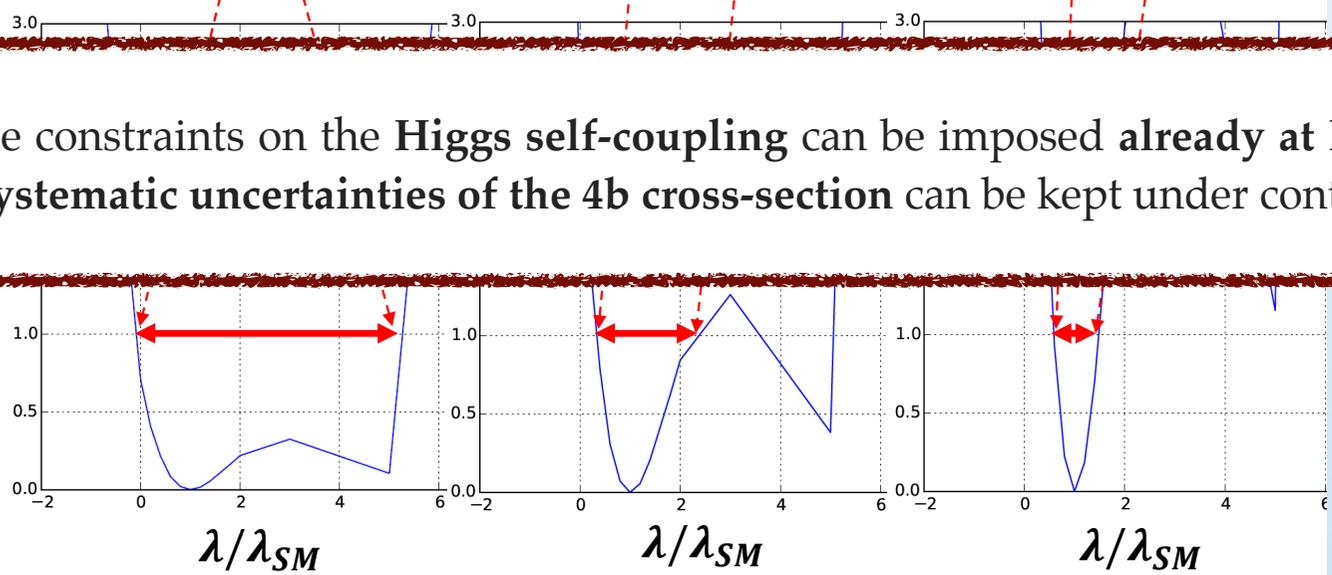
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Expected Sensitivity for the case $\lambda/\lambda_{SM} = 1$ with $S/B = 5\%$, 230 fb^{-1}			
Syst. Error on Background	5%	2.5%	1.25%
$\lambda \in$	$[0, 5] * \lambda_{SM}$	$[0.4, 2.3] * \lambda_{SM}$	$[0.5, 1.5] * \lambda_{SM}$

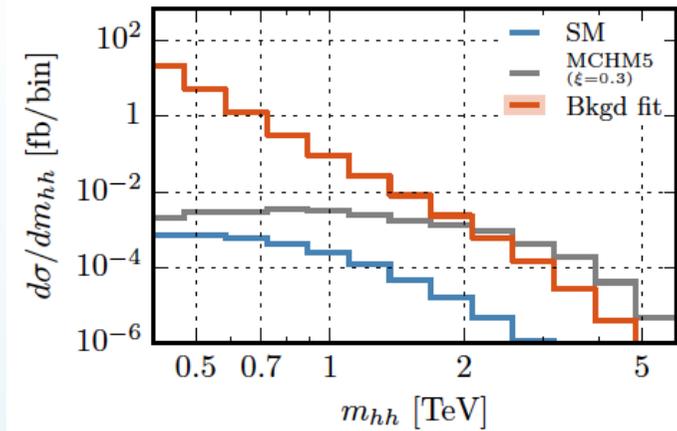
Take-away message

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

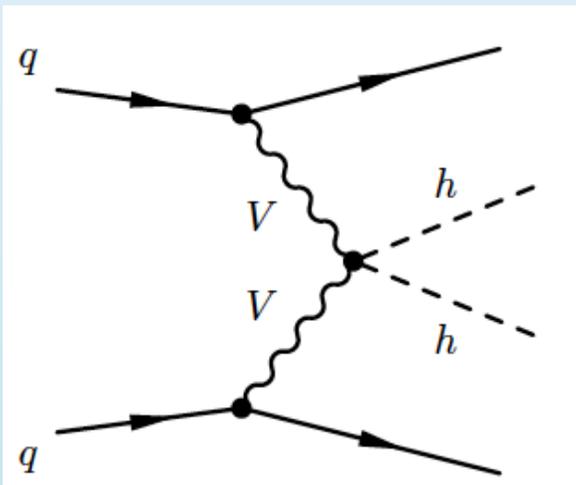


Behr et al, in preparation

LHC 13 TeV, Resolved Category



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

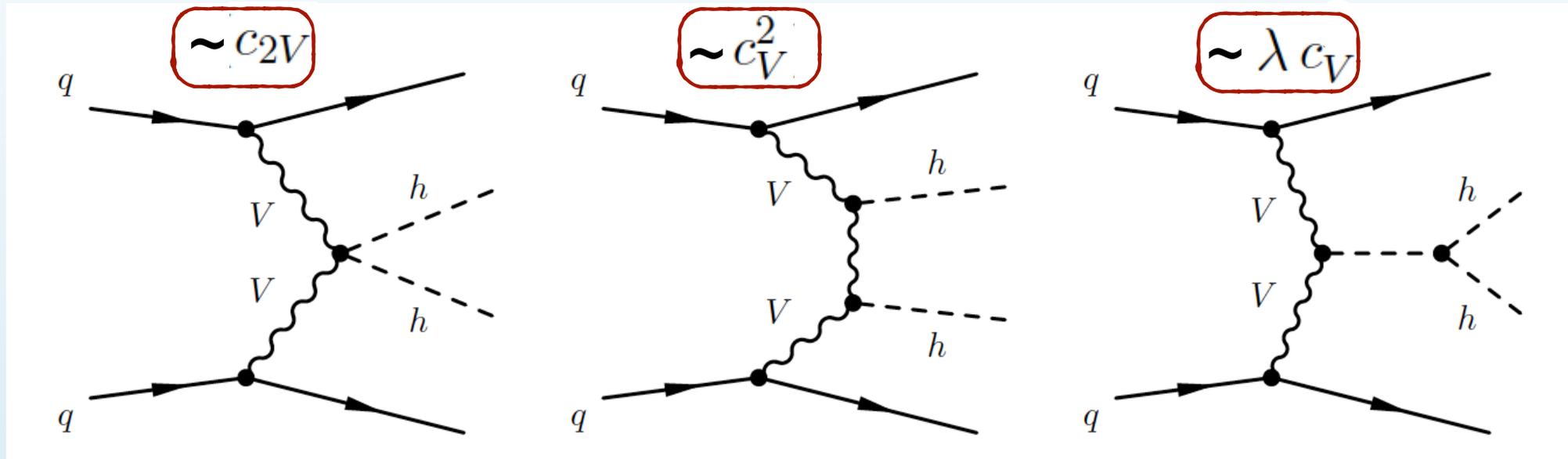


Juan Rojo

✓ 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 **unitarises the high-energy behaviour** of VBS amplitudes



at high energies \longrightarrow

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

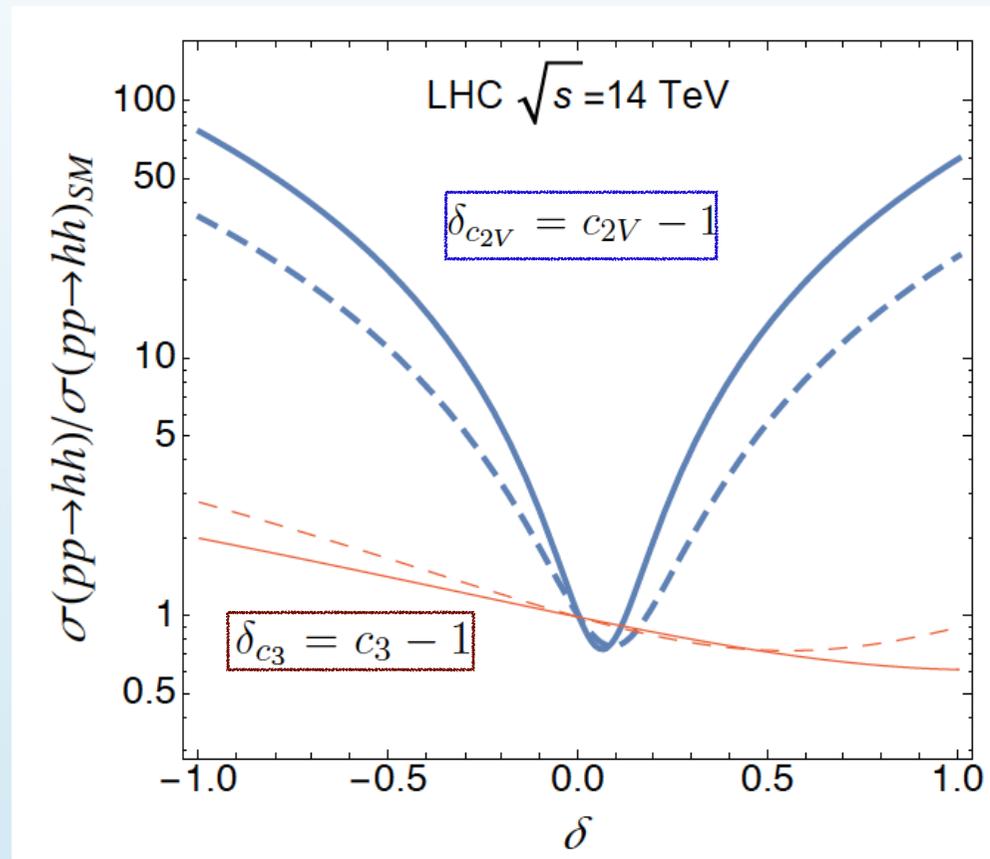
Is this **cancellation exact** (as in SM, $c_{2V} = c_V^2$) or only **approximate (BSM, $c_{2V} \neq c_V^2$)**?

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

- 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 **unitarises the high-energy behaviour** of VBS amplitudes



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

at high energies \longrightarrow

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

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 $hh \rightarrow b\bar{b}b\bar{b}$					
$\{c_V, c_{2V}, c_3\}$		LHC 14 TeV		FCC 100 TeV	
		σ (fb)	$N_{\text{ev}}(\mathcal{L} = 3 \text{ ab}^{-1})$	σ (fb)	$N_{\text{ev}}(\mathcal{L} = 10 \text{ ab}^{-1})$
$\{1,1,1\}$	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	σ_{LO} (fb)		K -factor	
			LHC14	FCC100	LHC14	FCC100
$4b$	Sherpa2.2	$N_{\text{ev}} = 50\text{M}$ weighted	$1.1 \cdot 10^6$	$1.6 \cdot 10^7$	1.7	1.7
$2b2j$	Sherpa2.2	$N_{\text{ev}} = 50\text{M}$ weighted	$2.6 \cdot 10^8$	$3.8 \cdot 10^9$	1.3	1.3
$t\bar{t}jj$	Sherpa2.2	$N_{\text{ev}} = 10\text{M}$ weighted	$1.9 \cdot 10^4$	$1.6 \cdot 10^6$	1.6	1.6
$4b2j$	ALPGEN	$N_{\text{ev}} = 6\text{M}(2\text{M})$ unweighted	$5.4 \cdot 10^4$	$2.4 \cdot 10^6$	1.7	1.7
$2b4j$	ALPGEN	$N_{\text{ev}} = 260\text{k}$ unweighted	10^7	$5.2 \cdot 10^8$	1.3	1.3
$gg \rightarrow hh \rightarrow b\bar{b}b\bar{b}$	aMC@NLO	$N_{\text{ev}} = 1\text{M}$ unweighted	6.2	272	2.4	2.2

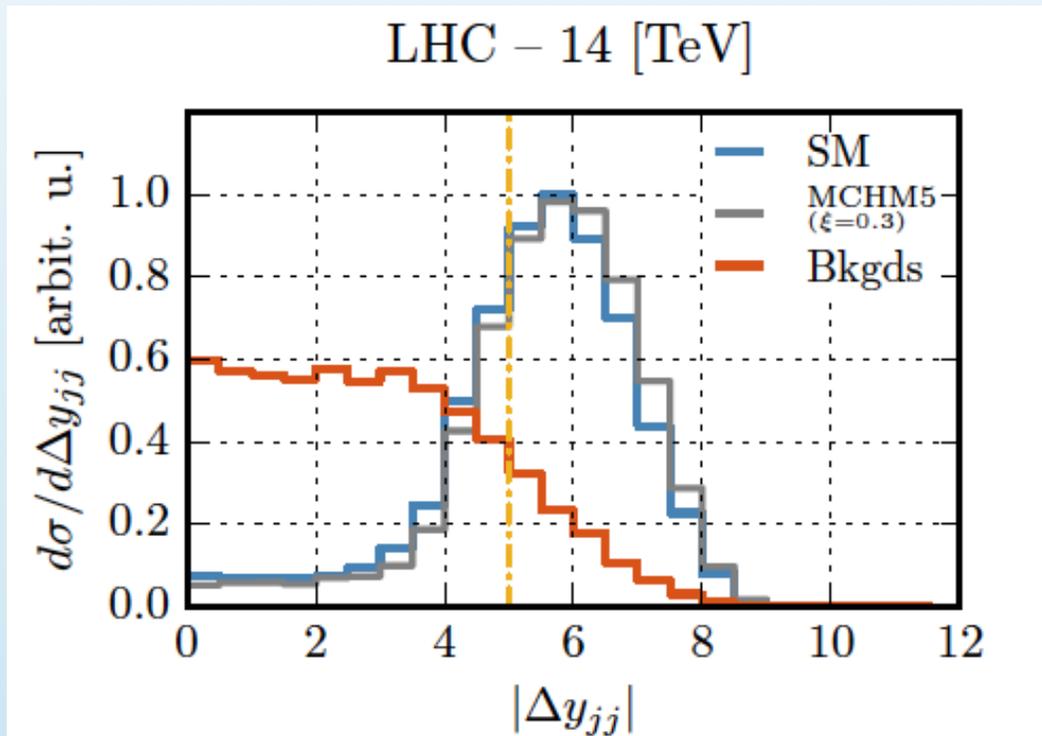
Killing backgrounds with VBF topology

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

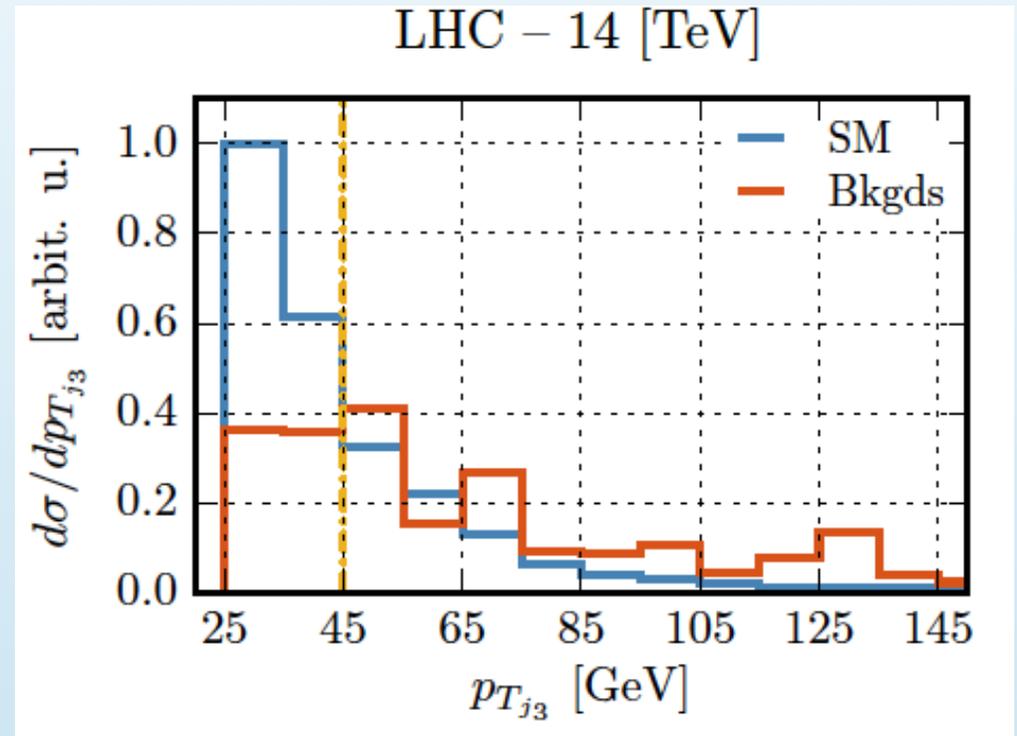
Require **two forward jets, separated in rapidity**, plus a **veto in hadronic activity** in the central region

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

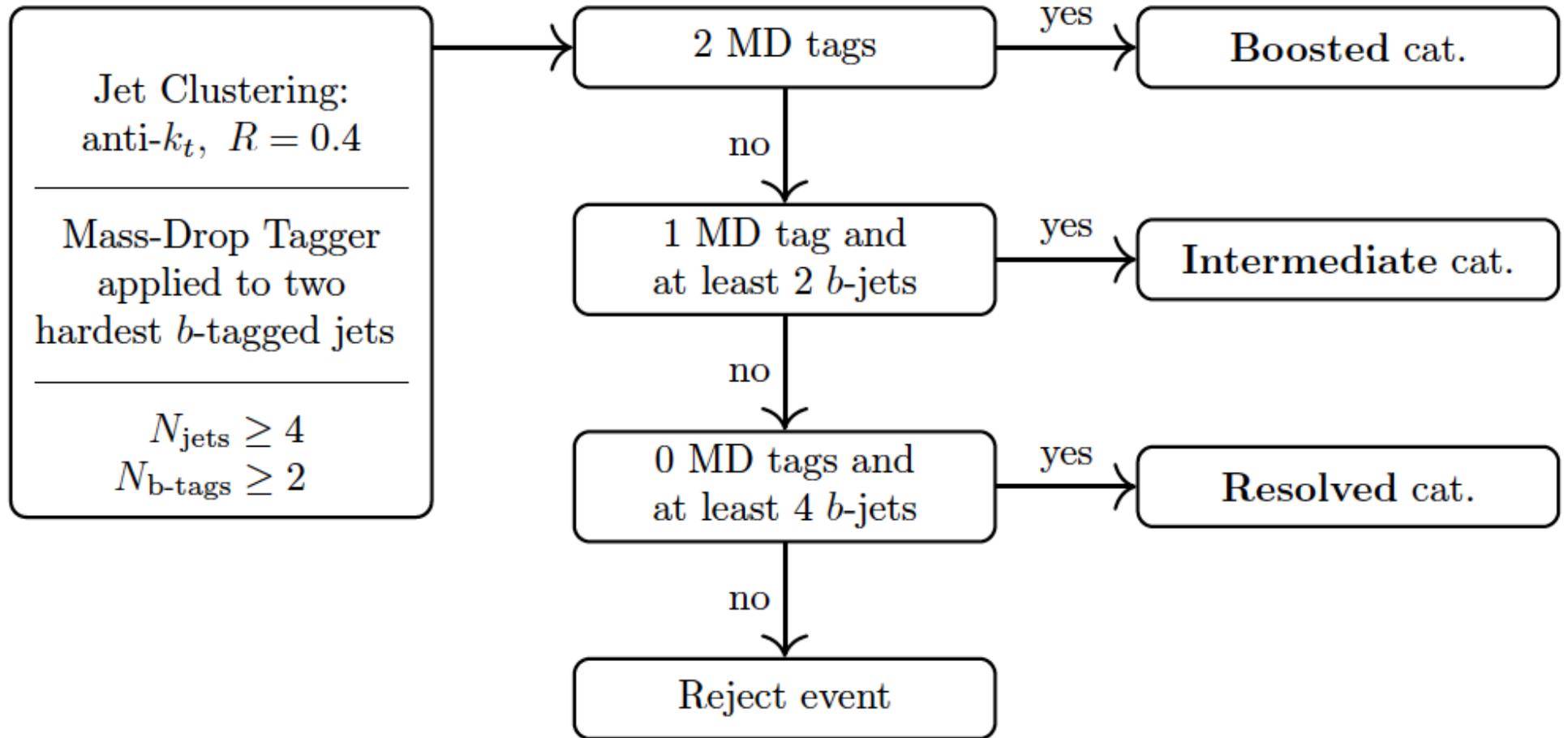
Dijet rapidity separation cut



Central jet veto cut



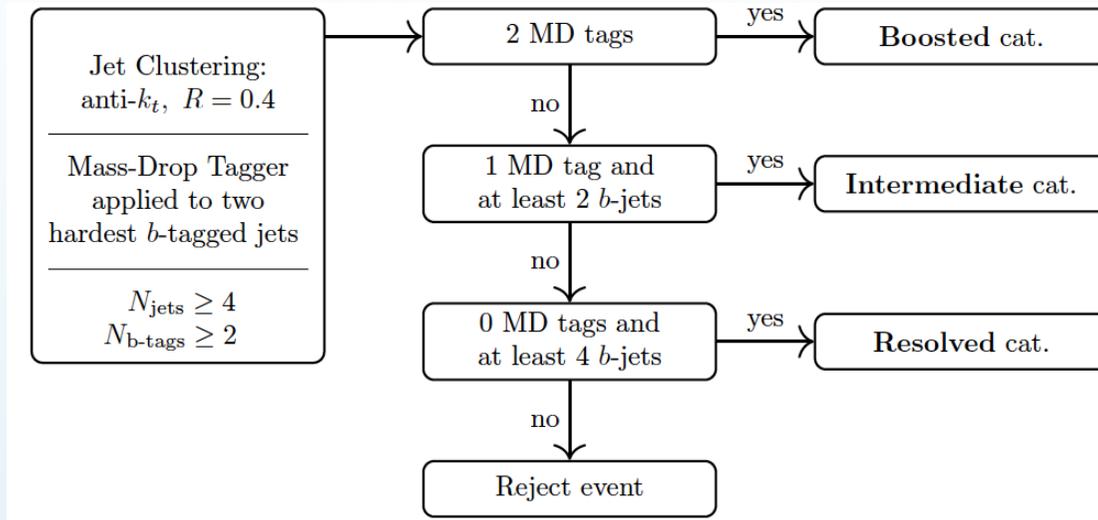
Scale-invariant Tagging



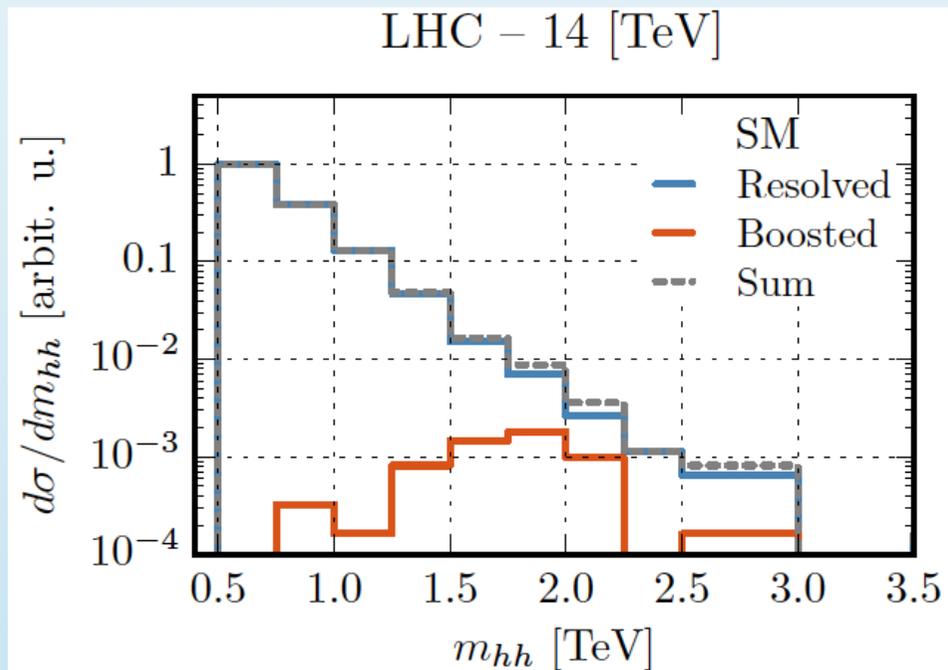
Same strategy as that used for the **analysis of the gluon-fusion channel**

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

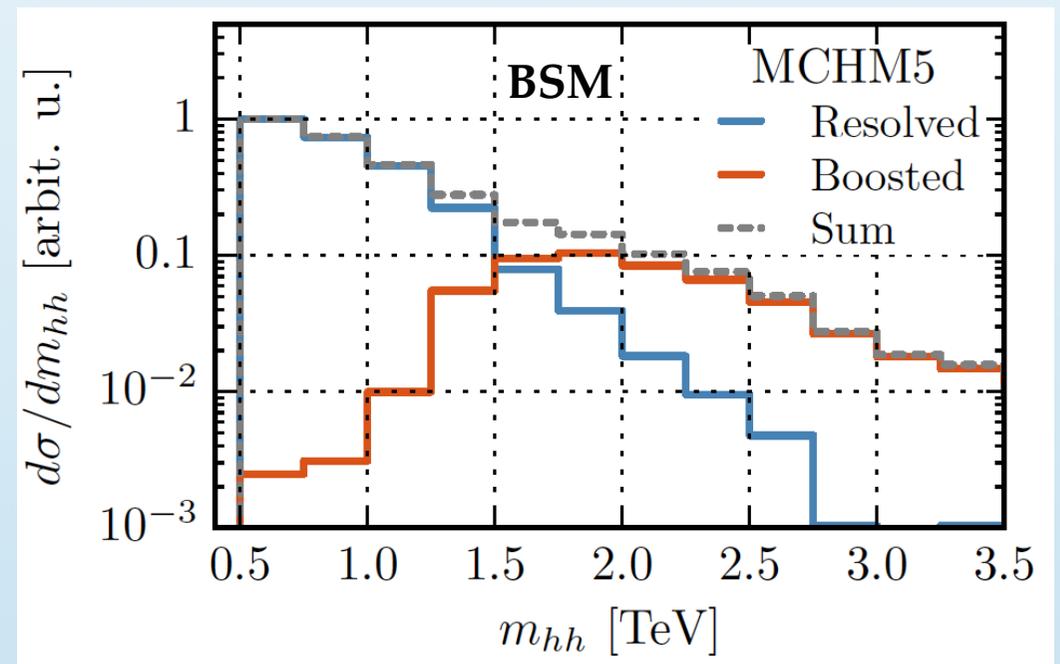
Scale-invariant Tagging



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



Juan Rojo



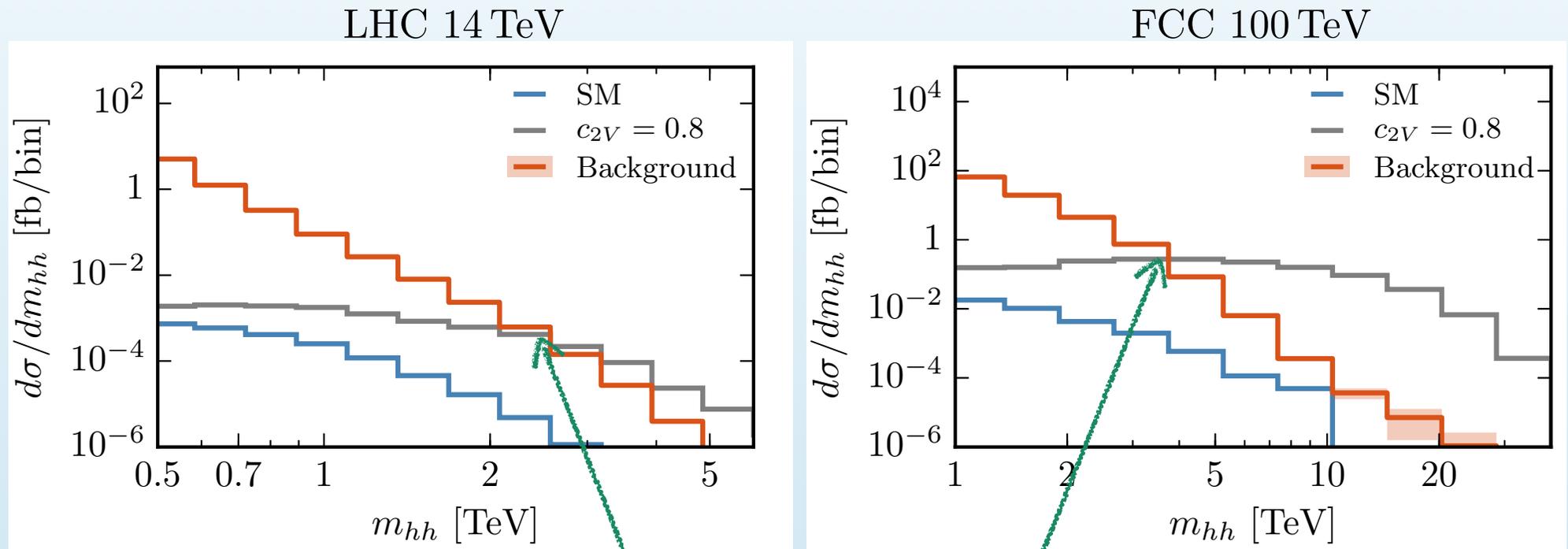
Particle Theory Seminar, Harvard, 29/11/2016

Probing the high-energy regime

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

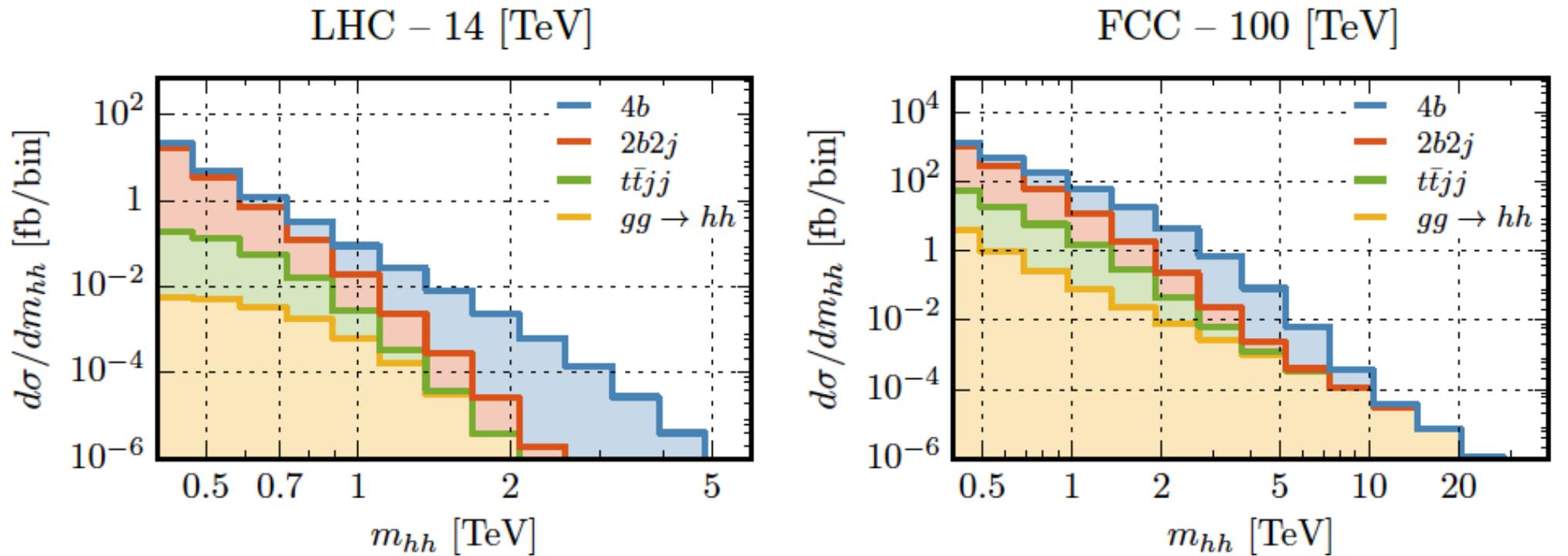
For BSM couplings, the ratio of cross-sections **between BSM and SM increases dramatically** as we probe the regions of **large m_{hh}** , eventually dominating over backgrounds

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



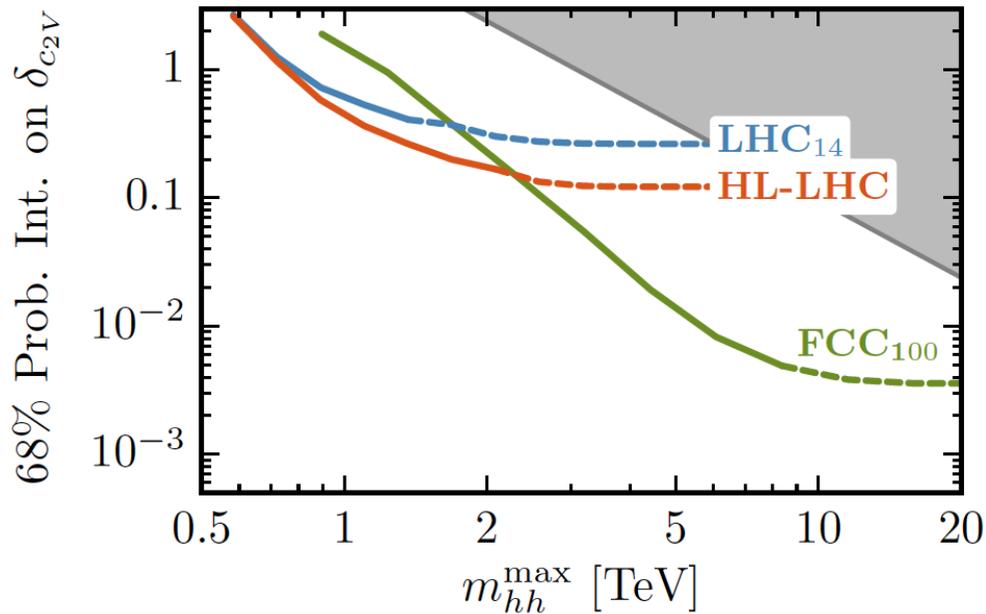
BSM signal ($c_{2V}=0.8$ benchmark) dominates over background

Background decomposition



- At 14 TeV, contribution from **reducible $2b2j$ multijet** backgrounds (mistagged light jets) dominate up to $m_{hh} \sim 800$ GeV, when the **irreducible $4b$ background** becomes the most important
- Same trend at 100 TeV, with now **$gg \rightarrow hh$ becoming dominant** at highest invariant masses, $m_{hh} \sim 8$ 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 $\delta_{c_{2V}}$	
	$1 \times \sigma_{\text{bkg}}$	$3 \times \sigma_{\text{bkg}}$
LHC ₁₄	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC ₁₀₀	$[0, 0.01]$	$[-0.01, 0.01]$

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

In absence of new resonances, c_{2V} can be measured 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 c_{2V}
- For such complex final states like 4b, the **ultimate signal optimisation** 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!

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 **discriminative constraints on the self-coupling** can be imposed **already at Run II**, provided **the systematic uncertainties of the 4b cross-section** can be kept under control
- In the **VBF channel**, the **steep rise of the cross-section at high Higgs invariant mass in the case of deviations from the SM** can be exploited to improve the **sensitivity of this process to c_{2V}**
- For such complex analyses, **advanced signal optimization** of the extraction of the Higgs coupling is required, including **machine learning methods** such as **Multivariate Analysis**

Thanks for your attention!

Take-away
message

Higgs pair production holds unique potential
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