Extending $hh \to b\bar{b}b\bar{b}$ searches into the HL-LHC era

Jacob Amacker, William Balunas, Lydia Beresford, Daniela Bortoletto, James Frost, Cigdem Issever, Jesse Liu, James McKee, Alessandro Micheli, **Santiago Paredes Saenz**, Michael Spannowsky, and Beojan Stanislaus
santiago.paredes@cern.ch

EOS be.h Equinox Meeting
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This Talk

- Introduction & **Motivation**
- **Signal & Background** Modelling
- Analysis **Strategies**
- **Self-Coupling** Constraints
- Conclusion

Based on arXiv:2004.04240

Cornell University

arXiv.org > hep-ph > arXiv:2004.04240

High Energy Physics – Phenomenology

[Submitted on 8 Apr 2020 (v1), last revised 12 Oct 2020 (this version, v3)]

Higgs self-coupling measurements using deep learning in the $b\bar{b}b\bar{b}$ final state

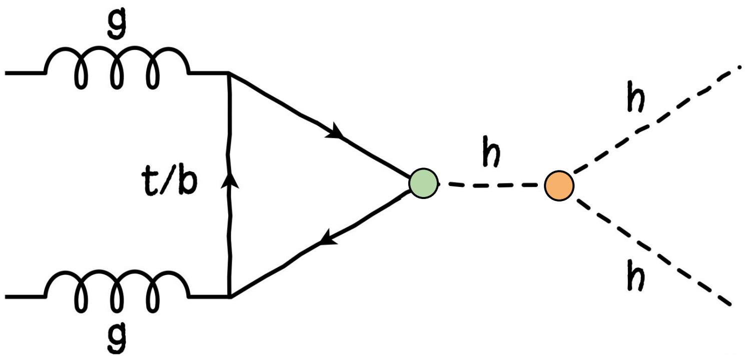
Jacob Amacker, William Balunas, Lydia Beresford, Daniela Bortoletto, James Frost, Cigdem Issever, Jesse Liu, James McKee, Alessandro Micheli, Santiago Paredes Saenz, Michael Spannowsky, Beojan Stanislaus

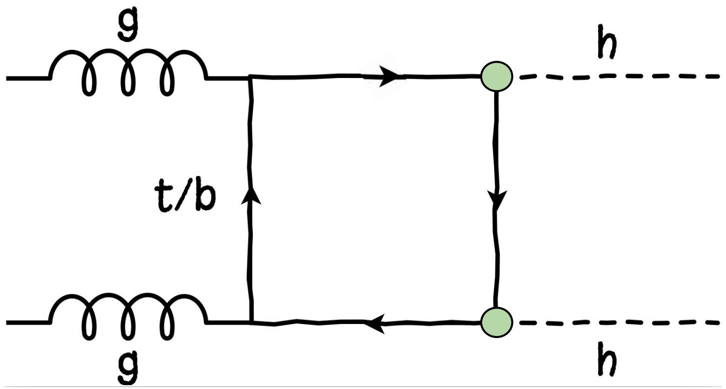
Measuring the Higgs trilinear self-coupling λ_{hhh} is experimentally demanding but fundamental for understanding the shape of the Higgs potential. We present a comprehensive analysis strategy for the HL-LHC using di-Higgs events in the four b-quark channel ($hh \to 4b$), extending current methods in several directions. We perform deep learning to suppress the formidable multijet background with dedicated optimisation for BSM λ_{hhh} scenarios. We compare the λ_{hhh} constraining power of events using different multiplicities of large radius jets with a two-prong structure that reconstruct boosted $h \to bb$ decays. We show that current uncertainties in the SM top Yukawa coupling y_t can modify λ_{hhh} constraints by $\sim 20\%$. For SM y_t, we find prospects of $-0.8 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 6.6$ at 68% CL under simplified assumptions for 3000~fb^{-1} of HL-LHC data. Our results provide a careful assessment of di-Higgs identification and machine learning techniques for all-hadronic measurements of the Higgs self-coupling and sharpens the requirements for future improvement.

Comments:	36 pages, 15 figures + bibliography and appendices
Subjects:	**High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex)
Journal reference:	JHEP 12 (2020) 115
DOI:	10.1007/JHEP12(2020)115
Report number:	IPPP/20/11
Cite as:	arXiv:2004.04240 **[hep-ph]**
	(or arXiv:2004.04240v3 **[hep-ph]** for this version)

Introduction & Motivation

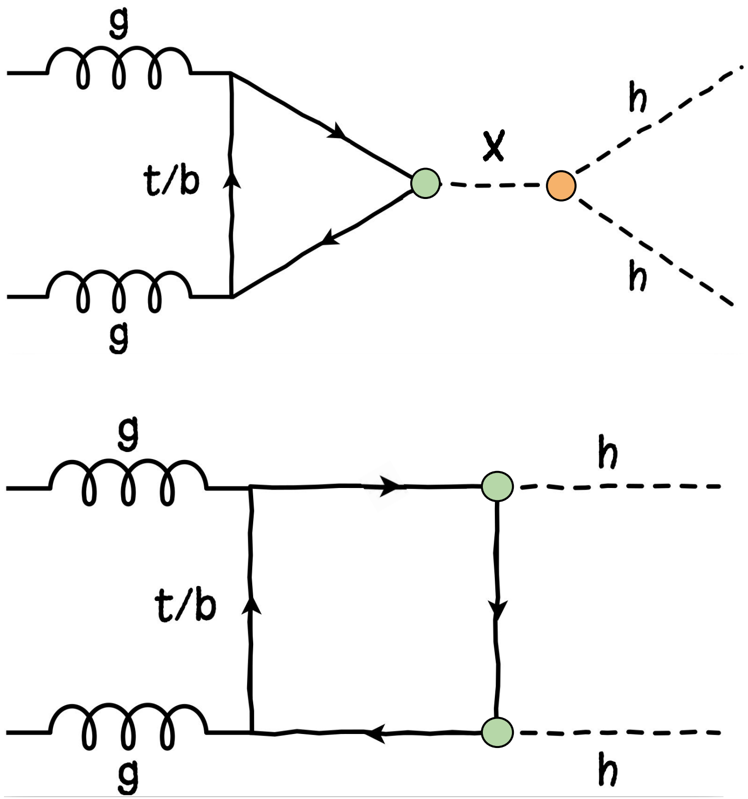
Why hh?





- Standard Model
  - ↪ Sensitive to the higgs **self-coupling**
  - ↪ Also to the **tth** vertex
- Beyond the SM
  - ↪ **New physics** effects in & loops
  - ↪ **Heavy resonances** (X) decaying to di-higgs

Why hh?



- Standard Model
  - ↪ Sensitive to the higgs **self-coupling** ●
  - ↪ Also to the **tth** ● vertex
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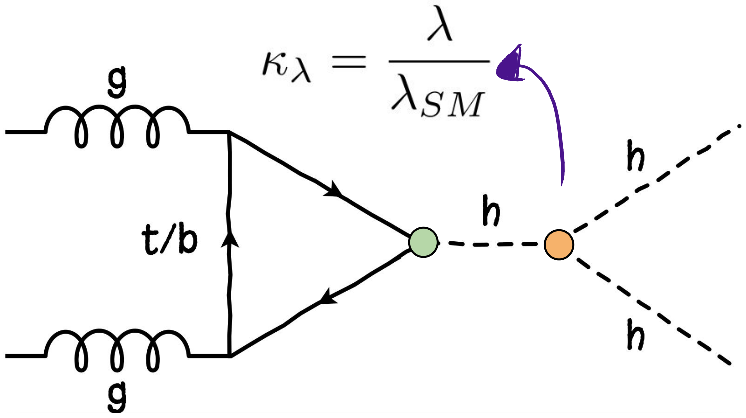
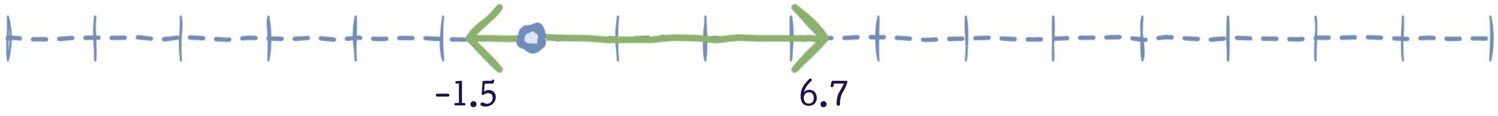


- **Key parameter** in the standard model
  - ↪ **Not only** for collider physics
- hh **the only way** to **directly** measure self-coupling!

full Run II data - **bbγγ - 95% C.L. k**$_\lambda$ constraints*



ATLAS-CONF-2021-016

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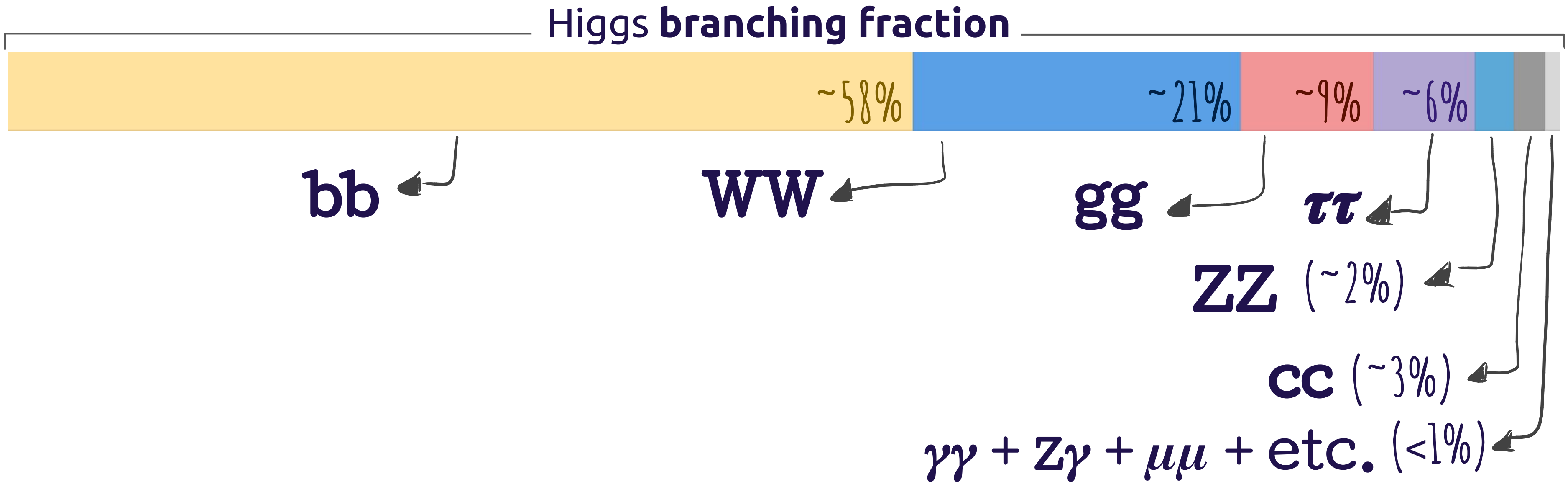
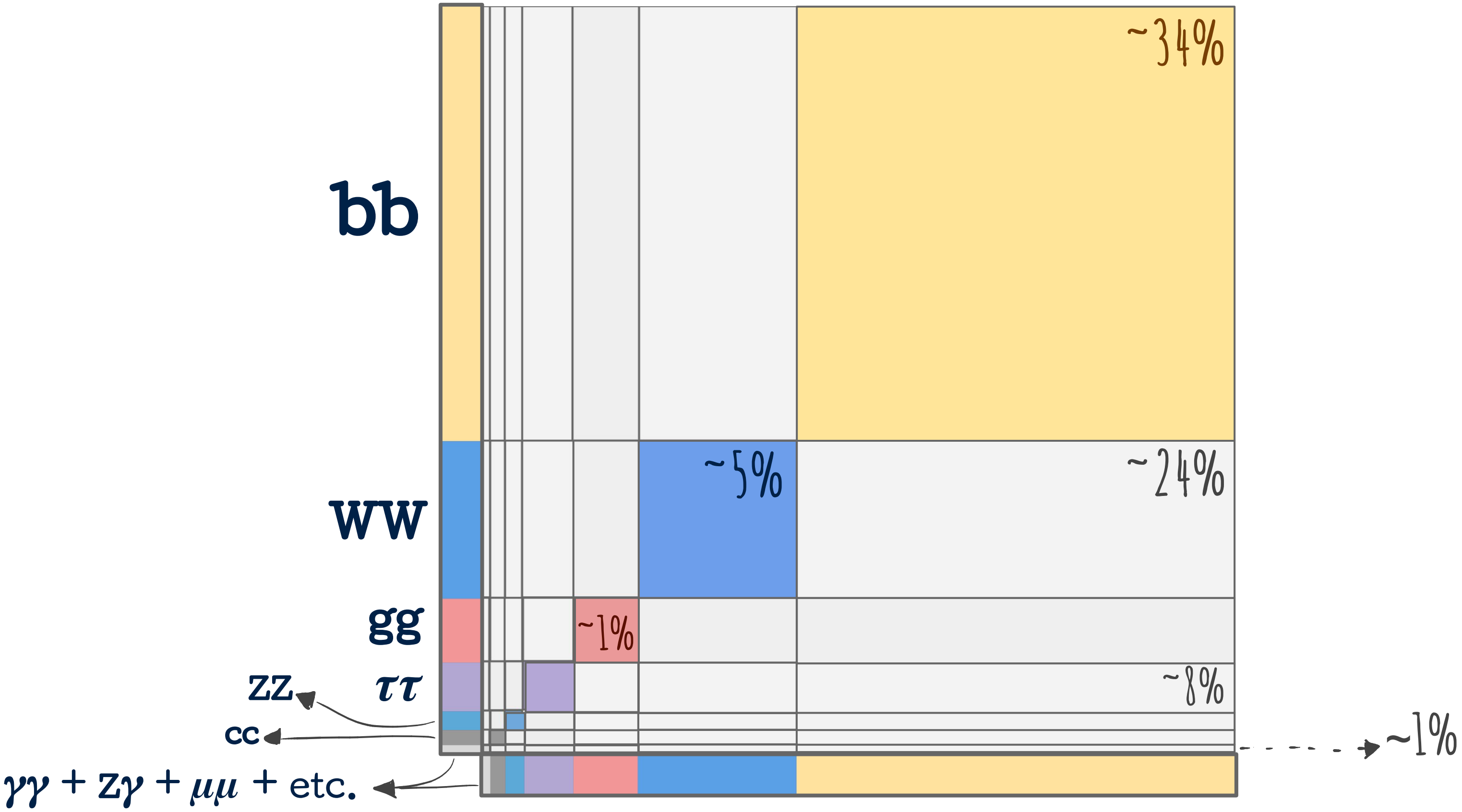
*Rough snapshot of our knowledge of k$_\lambda$ today, with run II data. Other channels being worked on. Probably already outdated since a few talks.

Why hh → 4b?

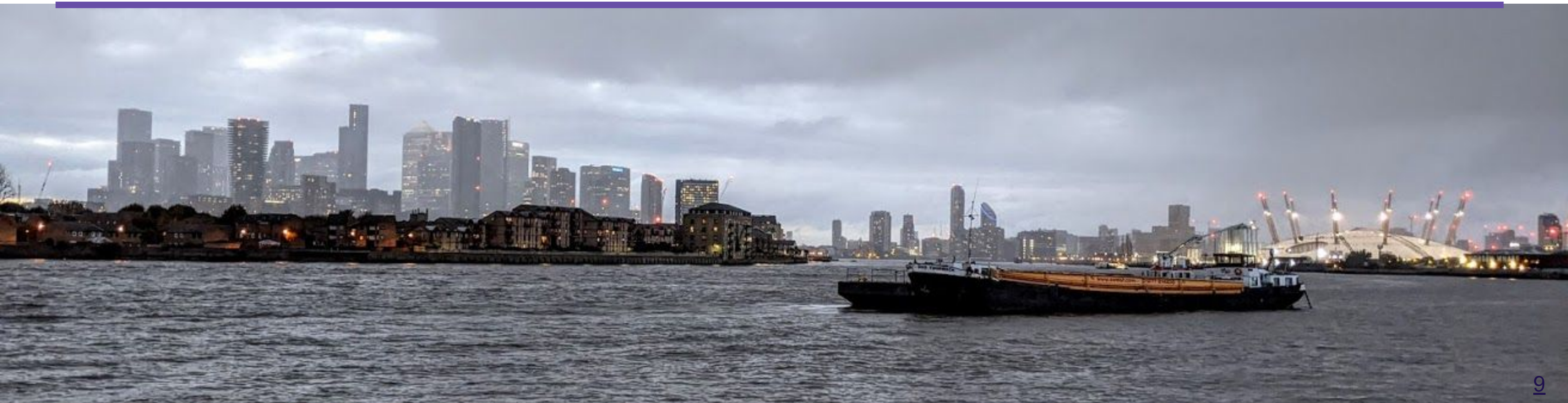


Higgs **branching fraction**
~58%
~21%
~9%
~6%
bb
WW
gg
ττ
ZZ (~2%)
cc (~3%)
γγ + Zγ + μμ + etc. (<1%)

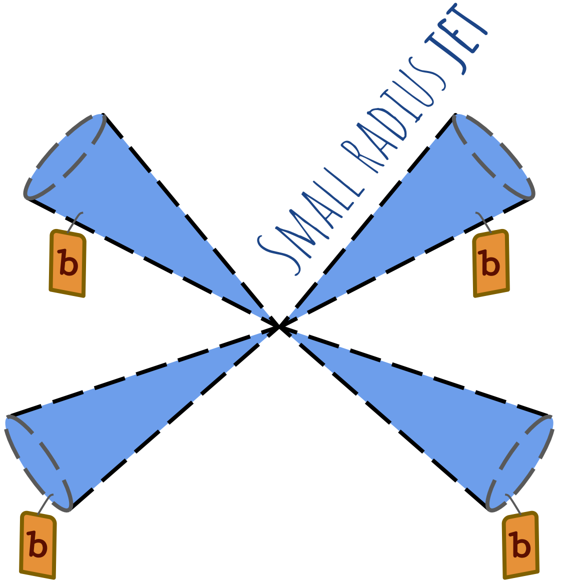
Why hh $\rightarrow$ 4b?

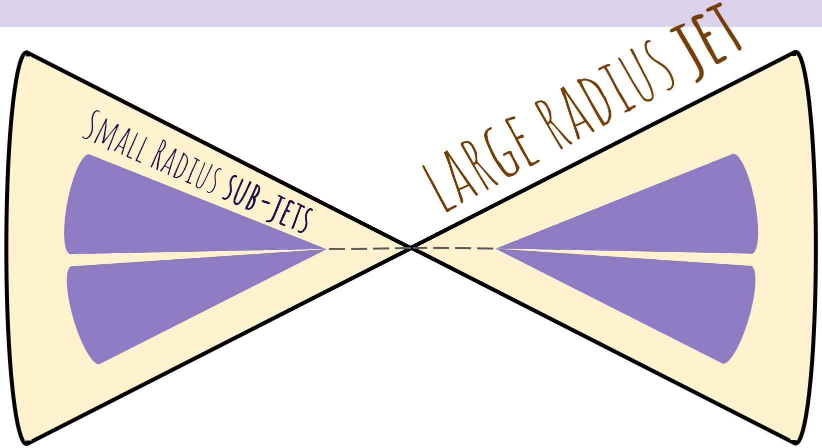


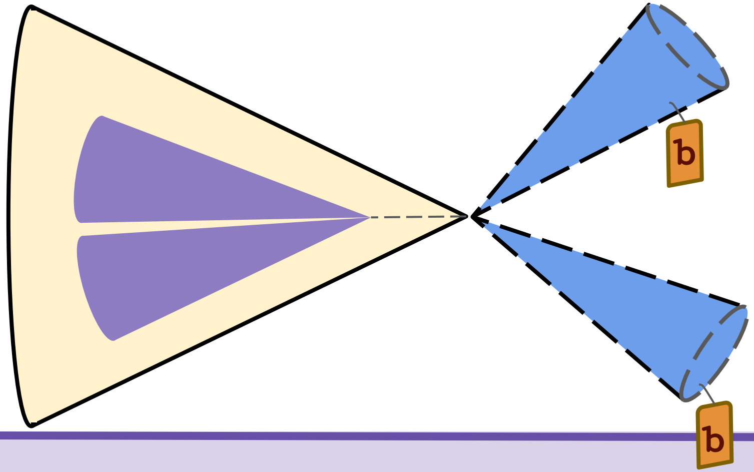
Signal & Background Modelling



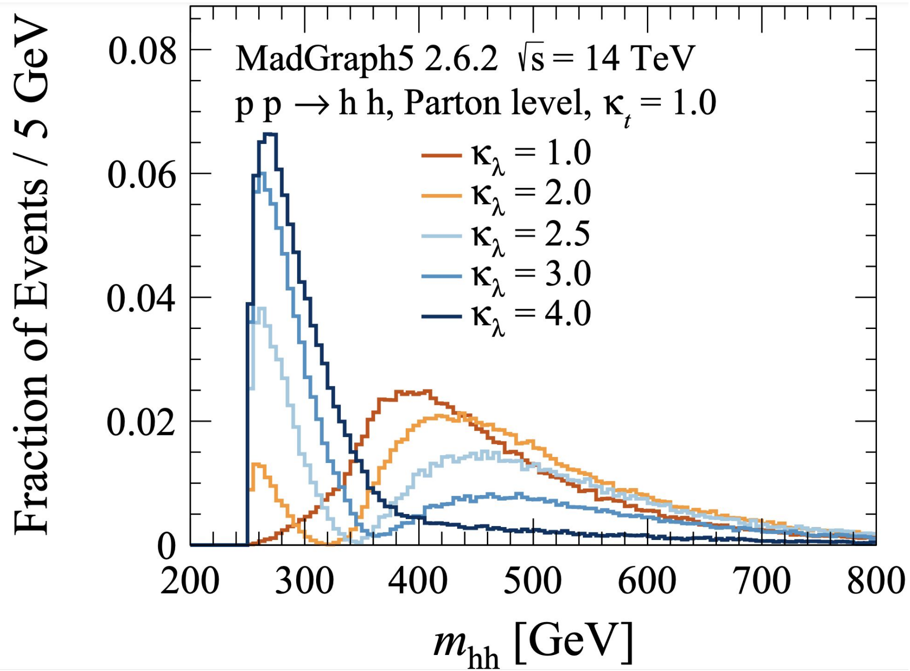
Signal Topology







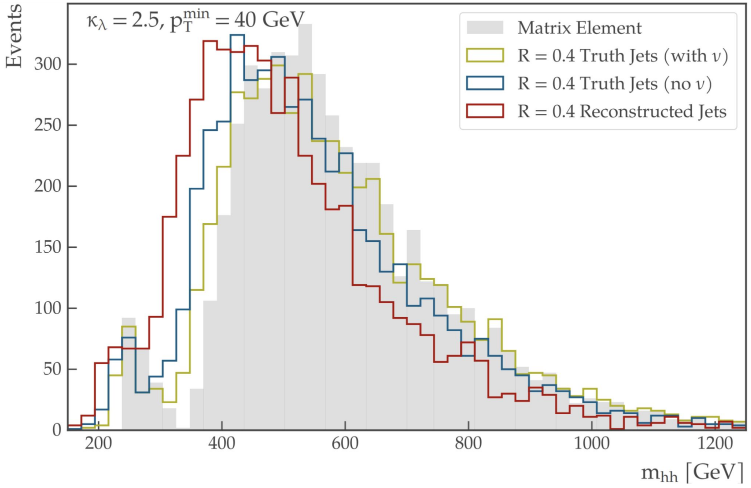
Signal Samples



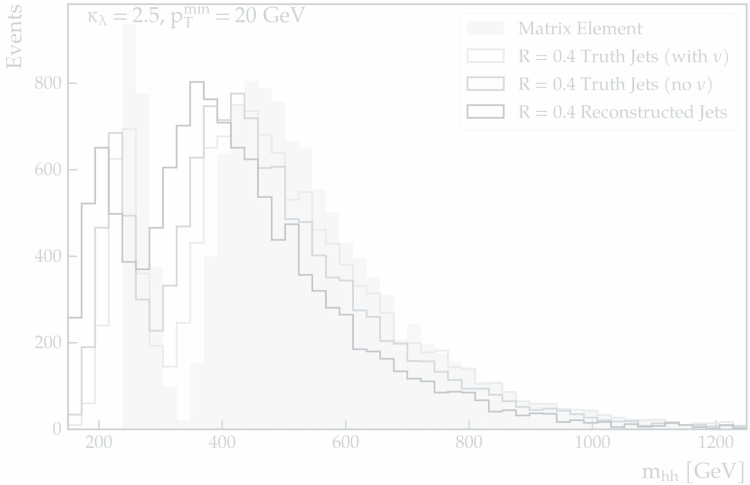
- gg→**hh** production
  - ↪ **Inclusive h decay**
- Points with **varied** coupling to **top** quark and **self couplings**
- Extra k_t=1 samples for **training**
  - ↪ **More** events per point
  - ↪ **Exclusive** decay **h→bb**

Parentheses - m_{hh} shape degradation

- m_{hh} spectrum, various jets
  - ↪ $p_T >$ **40 GeV** → Same as analysis
  - ↪ $k_\lambda = 2.5$ → Max. interference
- **Double-peak** is **degraded**



- Same plot, except:
  - ↪ $p_T >$ **20** GeV
- **Recover** double **peak**



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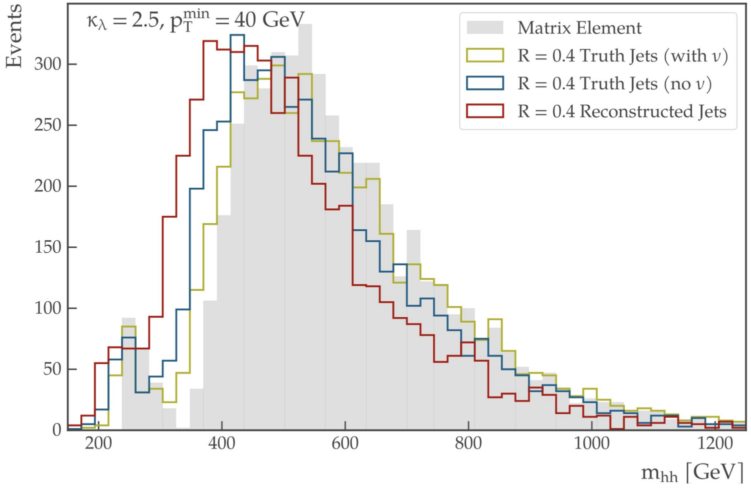

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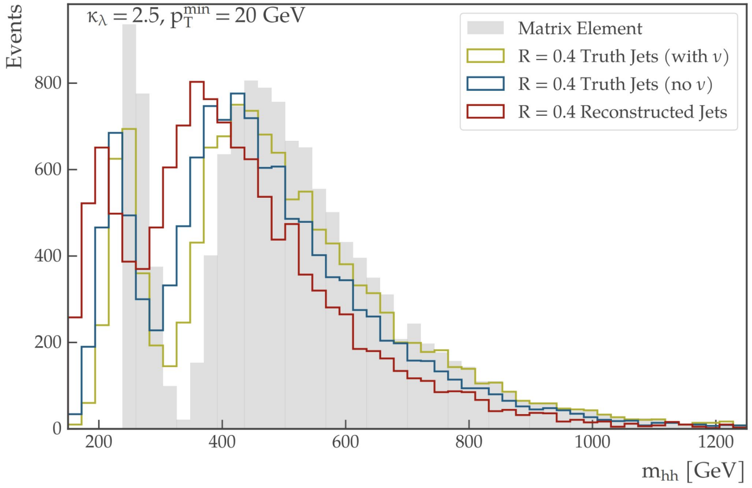


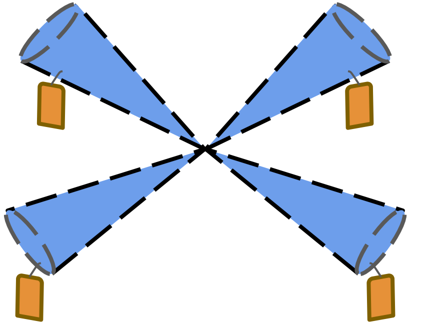
Background Samples

- Similar generation process to signals
- **Main** backgrounds:
  - ↪ **Multijet**$\longrightarrow$ $4b$ and $2b$-$2j$
  - ↪ **Top** quark **backgrounds**$\longrightarrow$ $t\bar{t}$ $(+b\bar{b})$ and $t\bar{t}h$
- Other backgrounds:
  - ↪ $b\bar{b}h$
  - ↪ ZZ
  - ↪ Zh
  - ↪ Wh

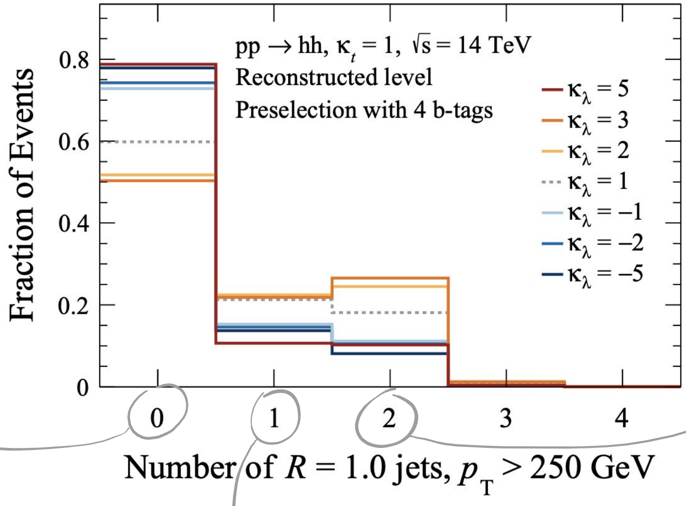
Analysis Strategies

Channels

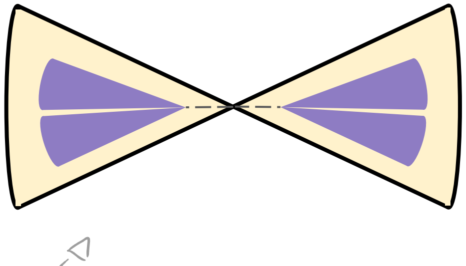
Resolved



j_S | $R = 0.4$
$p_T > 40$ GeV
$|\eta| < 2.5$

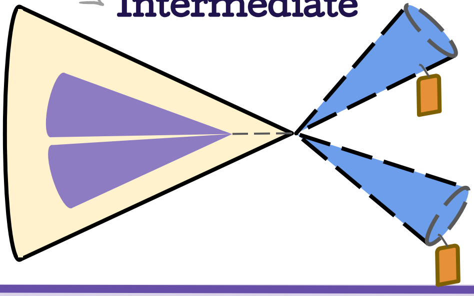


Boosted



$R = 1.0$
$p_T > 250$ GeV | j_L
$|\eta| < 2.0$

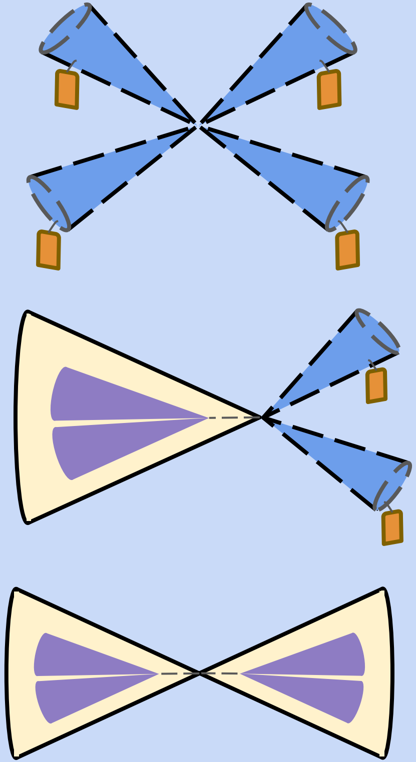
Intermediate



j_T

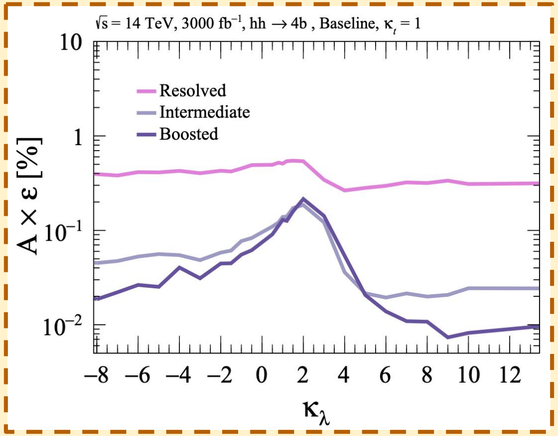
$R = 0.2$
$p_T > 20$ GeV
$|\eta| < 2.5$
$\Delta R(,) < 1.0$

Analysis Strategy



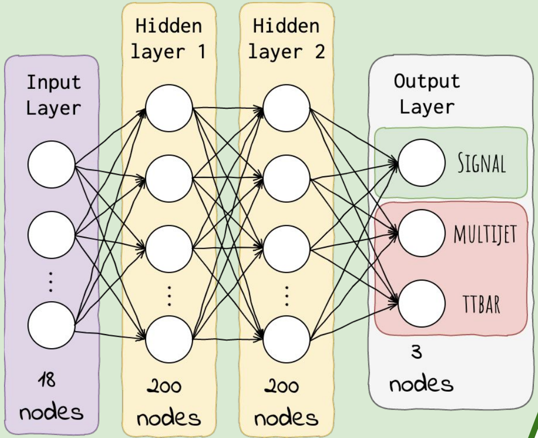
Baseline Analysis

- **Cut** Based
- ATLAS/CMS-**inspired**



DNN Analysis

- Trained NN **classifier**
- **Cut** on **NN score**



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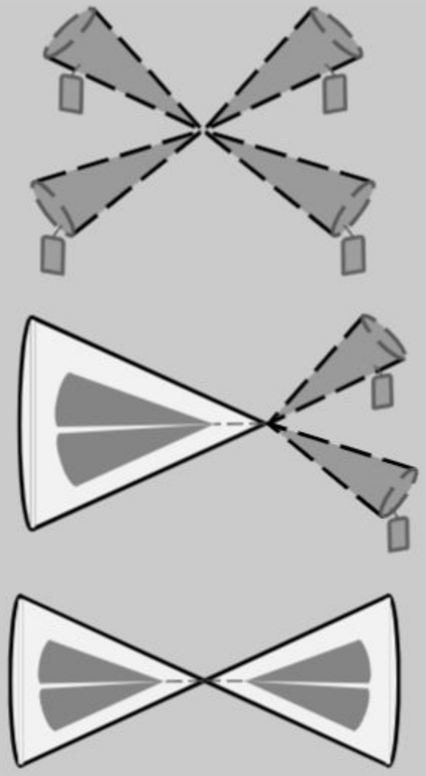

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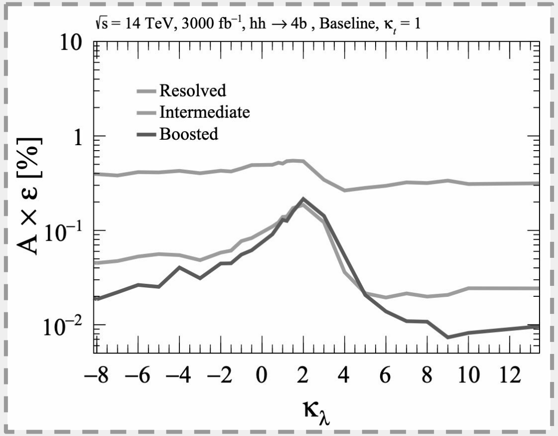

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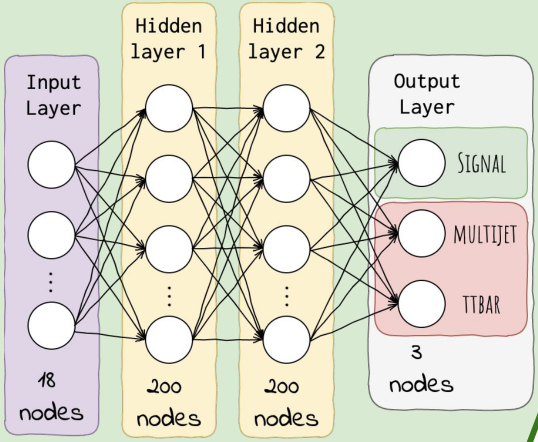
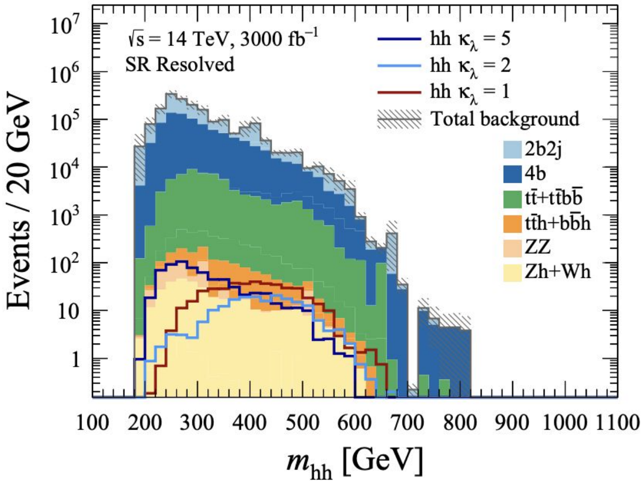
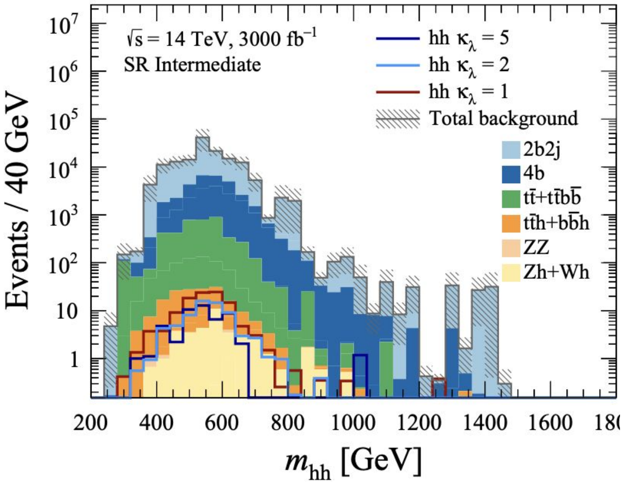


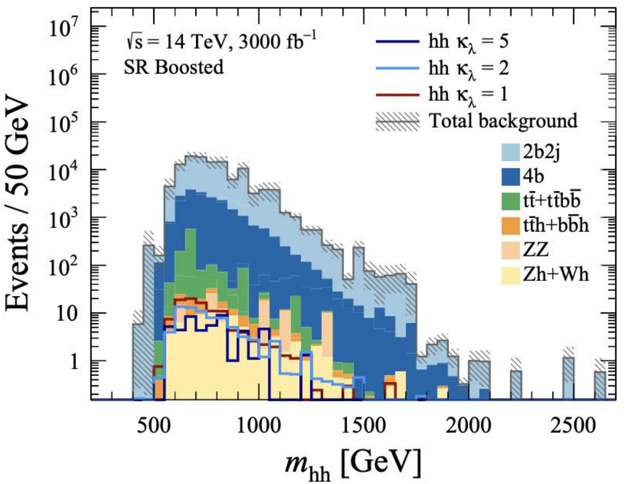
Baseline Analysis

- **Analysis-specific** cuts ⇒ define Signal Region (**SR**) in m_{hh}

↪ $N(j_L) = 0$	↪ $N(j_L) = 1$	↪ $N(j_L) = 2$
↪ $N(j_S) \geq 4$	↪ $N(j_S) \geq 2$	↪ $N(j_S) \geq 0$
↪ Lepton, MET veto	↪ Lepton, MET veto	↪ Lepton, MET veto
↪ 4 b-tags	↪ 4 b-tags	↪ 4 b-tags
↪ $\Delta R(j_S^1, j_S^2)$ cut		







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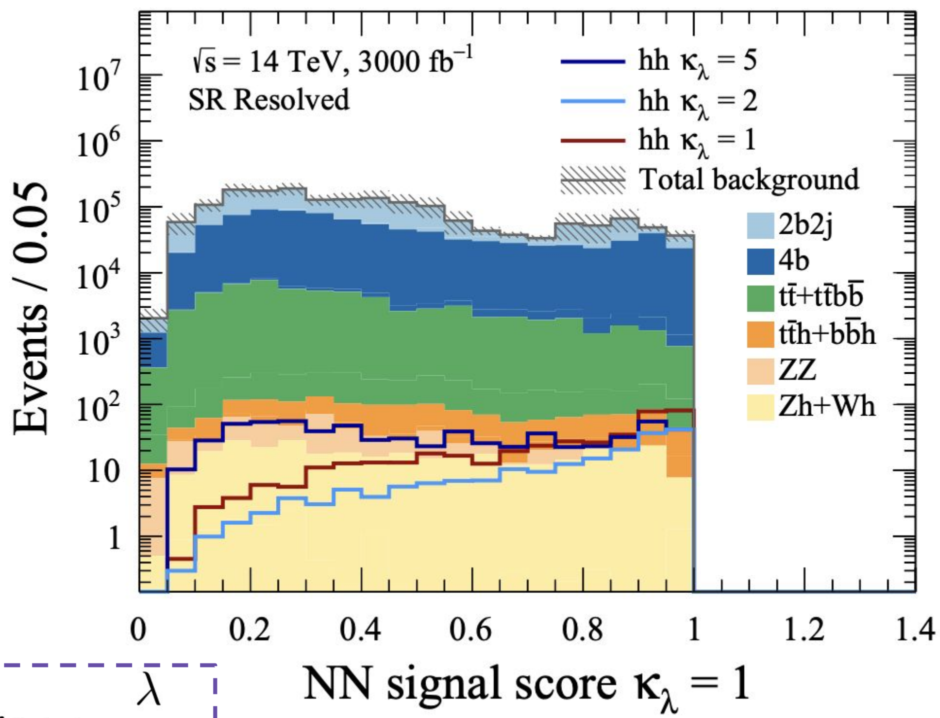


$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

- **Muli-class** classifier
  - ↪ Signal vs multijet vs $t\bar{t}$

Training Variables

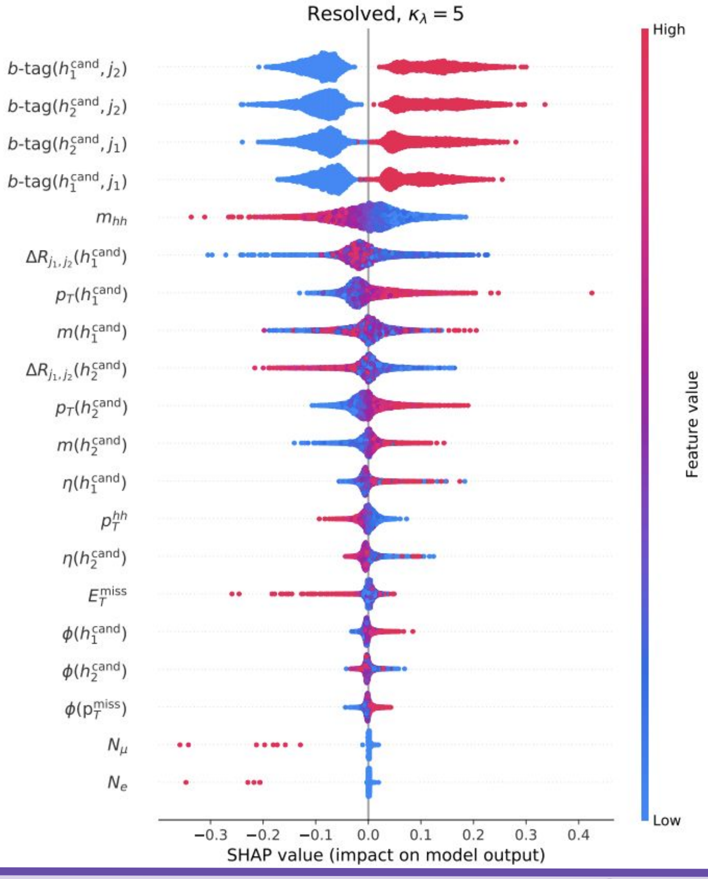
➳ p_T^{HH}	➳ MET	➳ Sub-jet η
➳ M^{HH}	➳ MET ϕ	➳ Sub-jet ϕ
➳ #Muons	➳ Sub-jet mass	➳ Sub-jets ΔR
➳ #Elec	➳ Sub-jet p_T	➳ Sub-jets b-tag

- Cut ⇒ NN signal **score > 0.75**
- Trained with **multiple k_λ** signals
  - ↪ **Use $k_\lambda = 5$** network

Parentheses - What did our machine learn?

NN variables

Ranked by impact on NN score



- SHAP value framework
  - ↪ **Shapley** values for ML **interpretability**

SHAP value | More signal-like impact on score

Parentheses - What did our machine learn?

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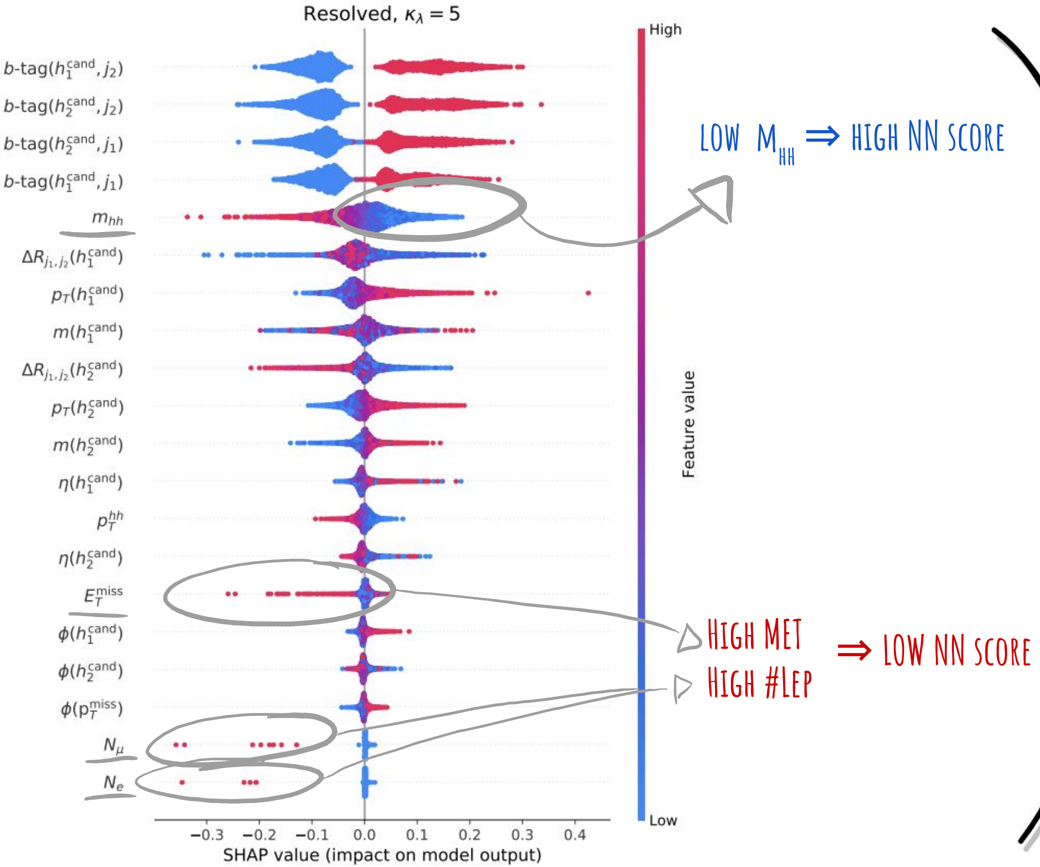
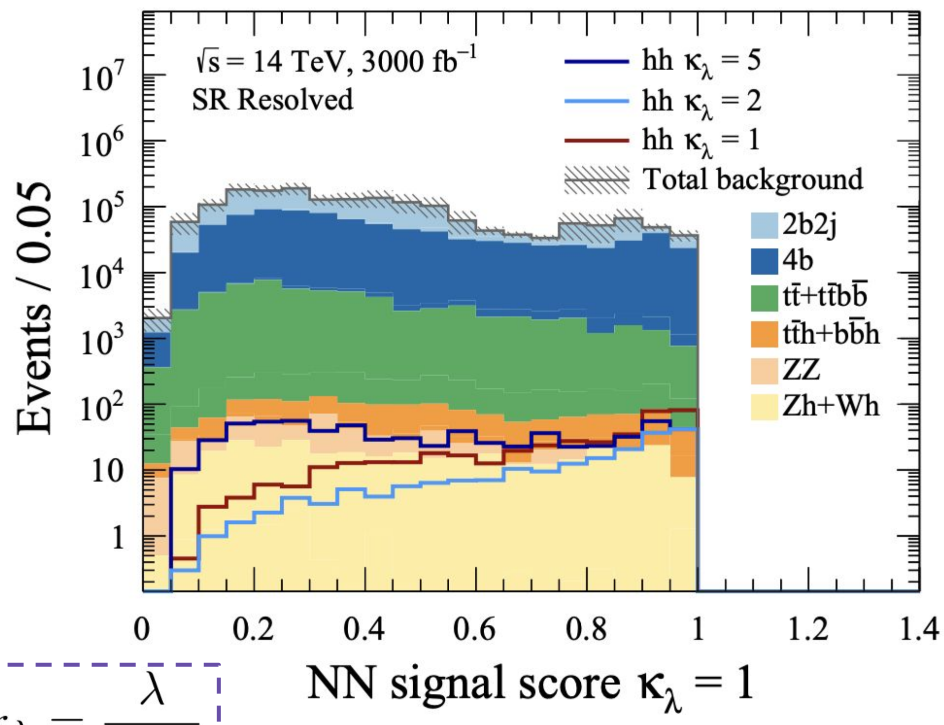


SHAP value
More signal-like impact on score

DNN Analysis



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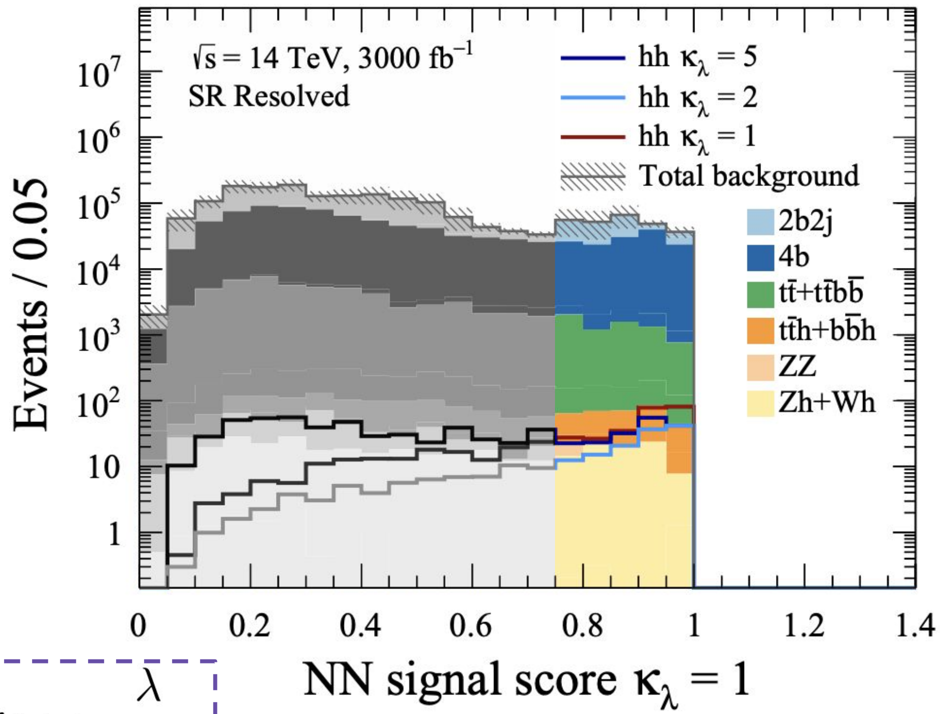

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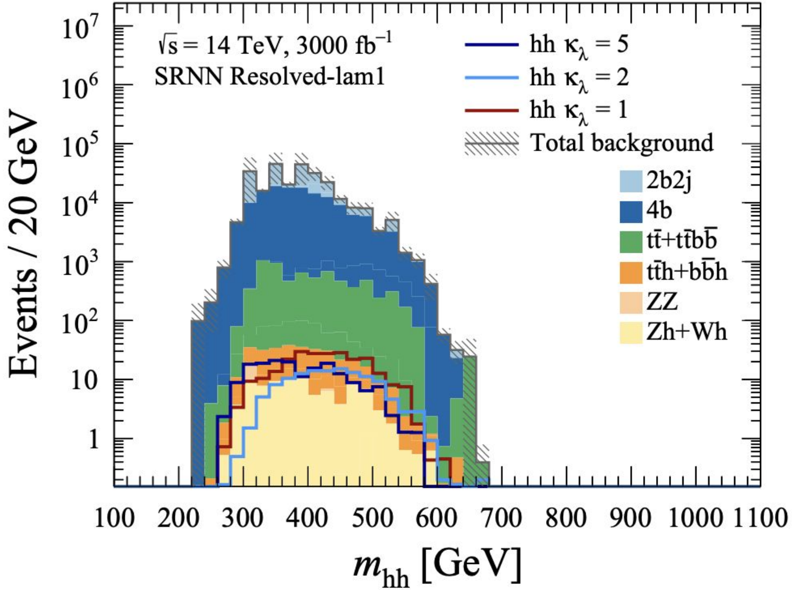
Parentheses - BSM k_λ training

$k_\lambda = 1$ NN cut

- **Background** rejection ✓
- Signal **characterization** ✗



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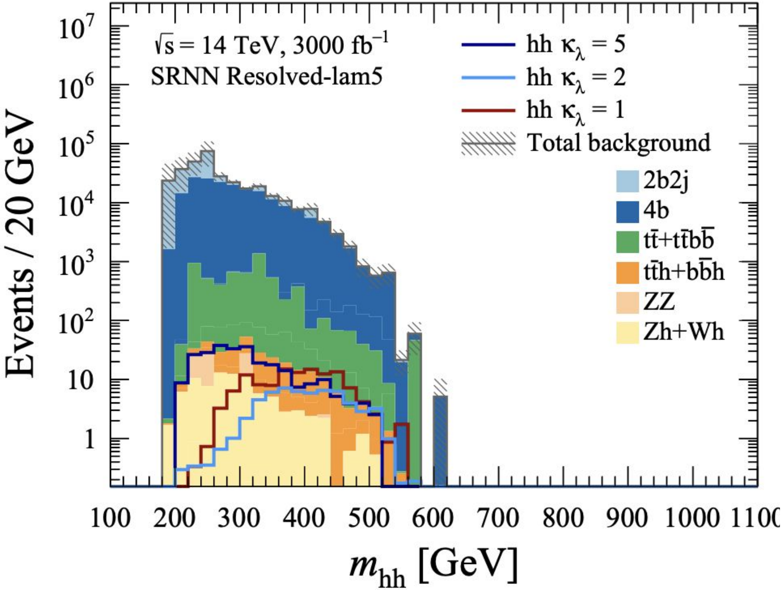

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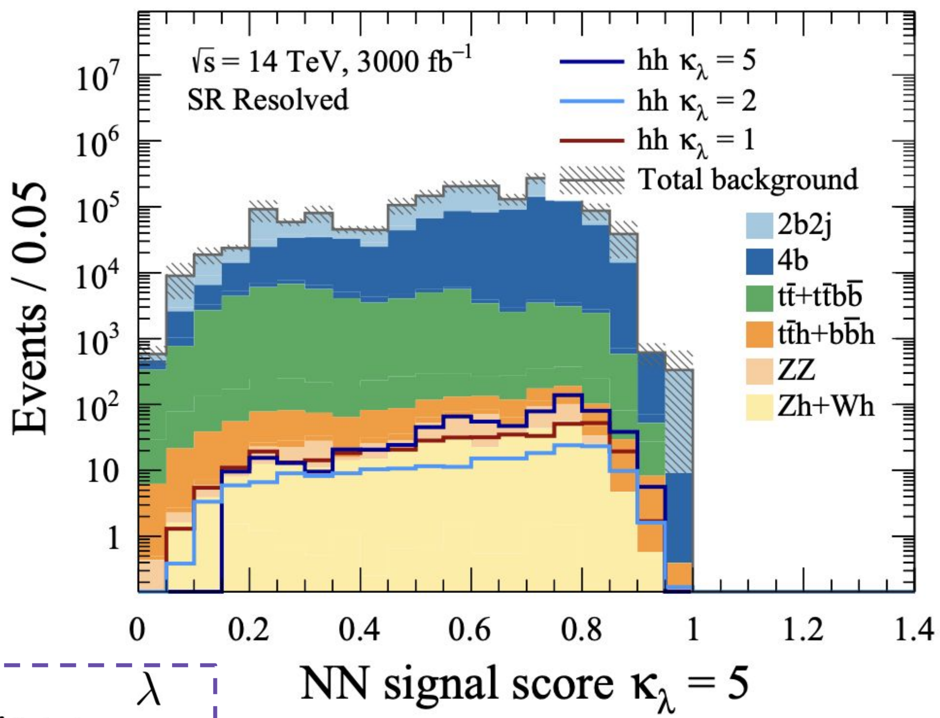

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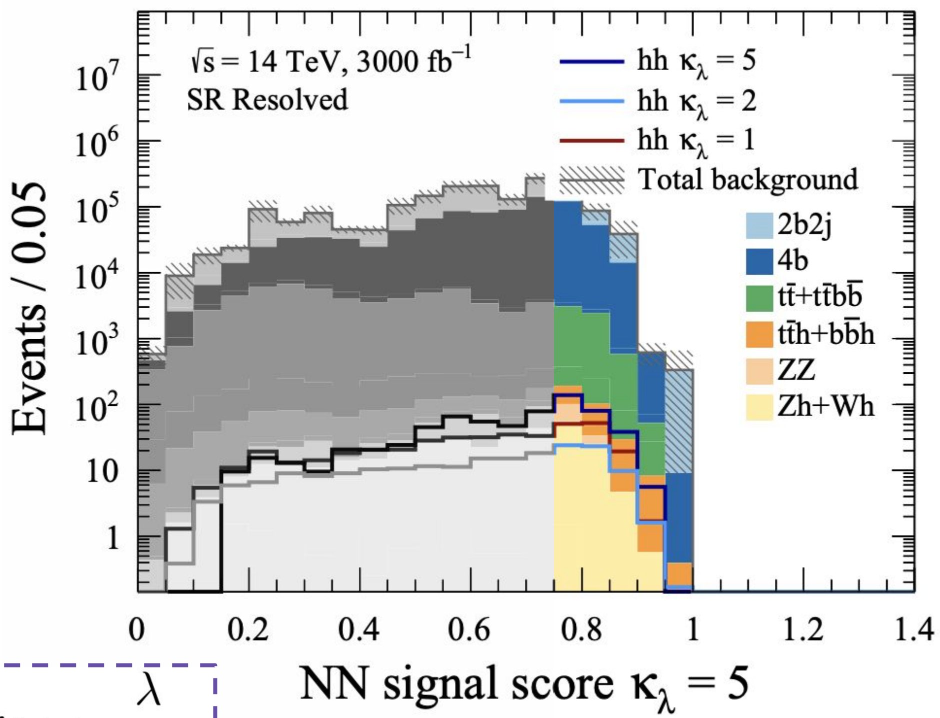

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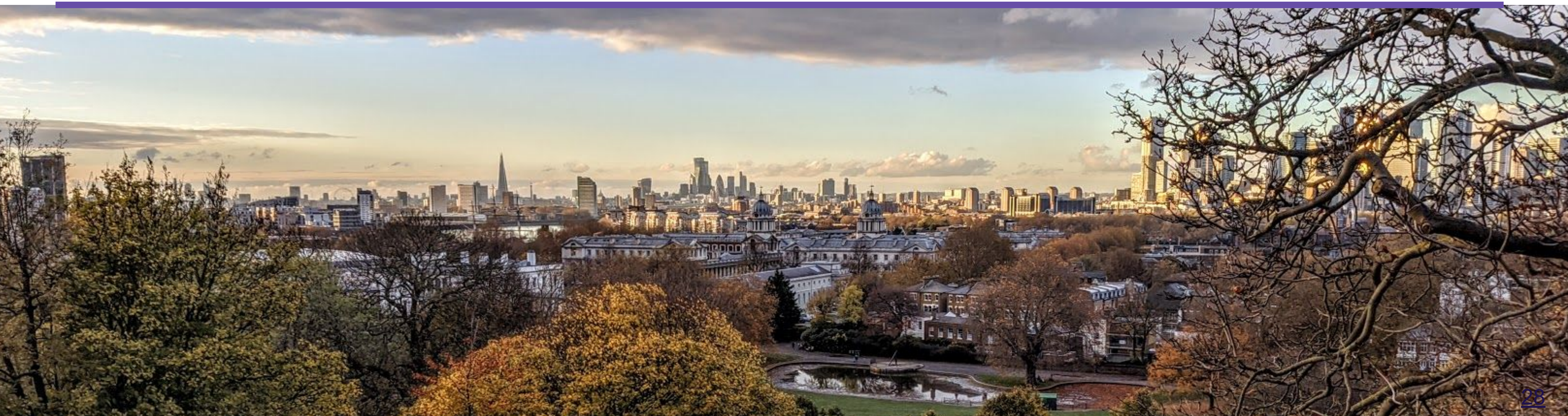
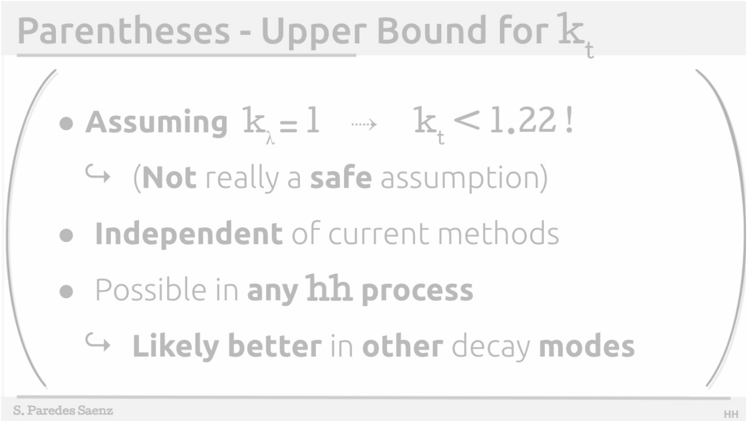
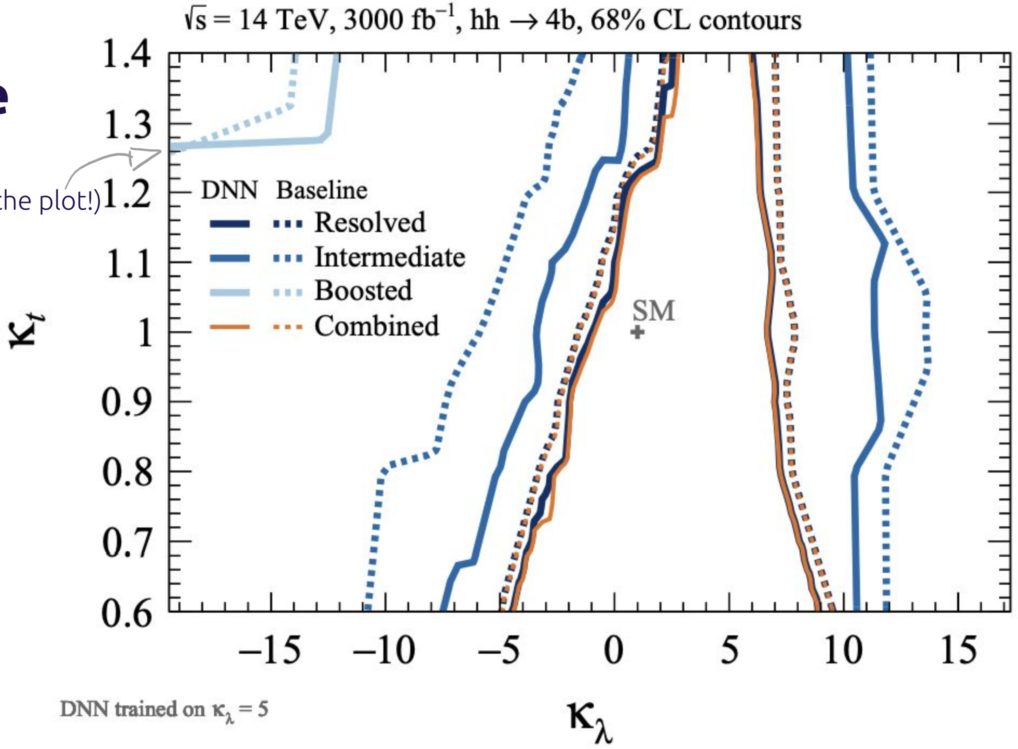
Self-Coupling Constraints



Constraints on k_λ - k_t Plane

- Resolved ⇢ **most powerful**
  - ↪ Intermediate ⇢ **non-negligible**
  - ↪ Boosted ⇢ **negligible***(but made it in the plot!)
- **Strong dependence** on k_t





*Note that this does not necessarily apply to analyses optimized for discovery of SM hh production – only those aiming to constrain k_λ.

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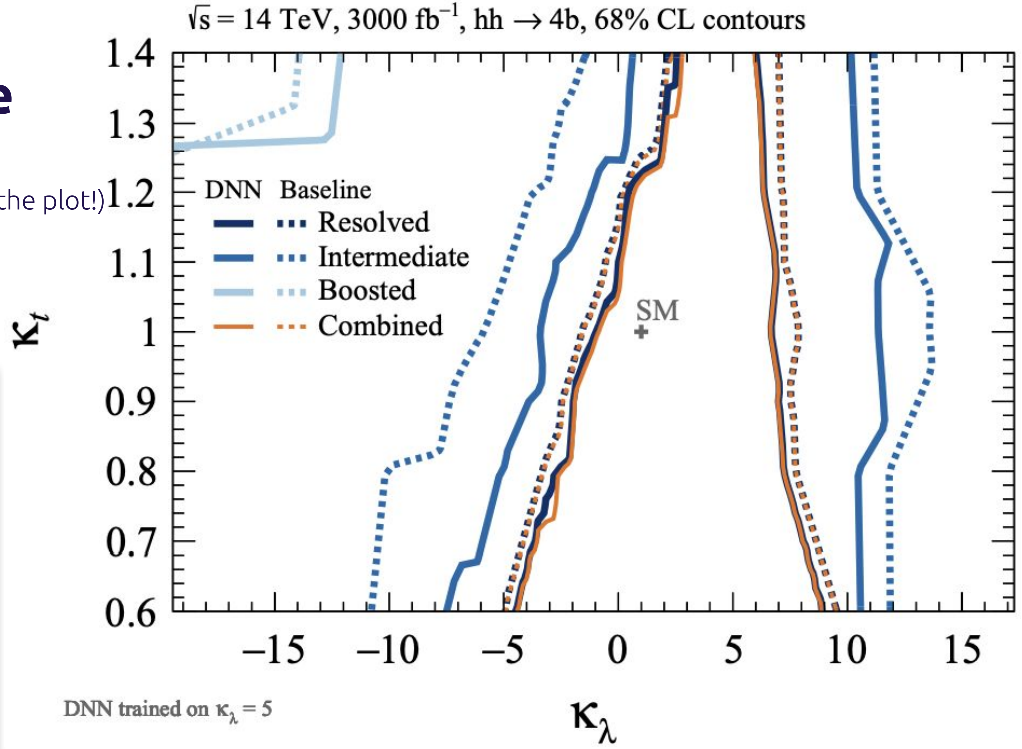

Parentheses - Upper Bound for k_t

- **Assuming** $k_\lambda = 1$ ⇢ $k_t < 1.22$!
  - ↪ (**Not** really a **safe** assumption)
- **Independent** of current methods
- Possible in **any hh process**
  - ↪ **Likely better** in **other** decay **modes**

S. Paredes Saenz HH

*Note that this does not necessarily apply to analyses optimized for discovery of SM hh production – only those aiming to constrain k_λ.

Conclusion

Conclusions

- **First detailed comparison** of λ_{hhh} **constraints** in $hh \to 4b$ resolved, intermediate and boosted channels, in the context of HL-LHC.

  ↪ **Resolved most constraining**, then intermediate and then boosted
- A basic **DNN analysis** provided **noticeable improvement** over the cut based baseline analysis
- Best constraints came from NN trained on BSM signal

  ↪ $hh \to 4b$ analyses **optimized** for **discovery of SM hh** may be **suboptimal**

Conclusions

- **Experimental limitations**, triggering and jet reconstruction, **affect** the reconstruction of the **main discriminating variable m_{hh}**
- **Uncertainty** on k_t has a strong impact on sensitivity to k_λ
  - ↪ Same applies for **uncertainty multijet BKG estimates**
- This $hh \to 4b$ search has **some sensitivity** to constrain k_t despite no dedicated optimization
- **4b** is a **challenging** hh channel for λ_{hhh} constraints, but can provide important **independent information** for statistical **combinations**

iihe
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Thanks!

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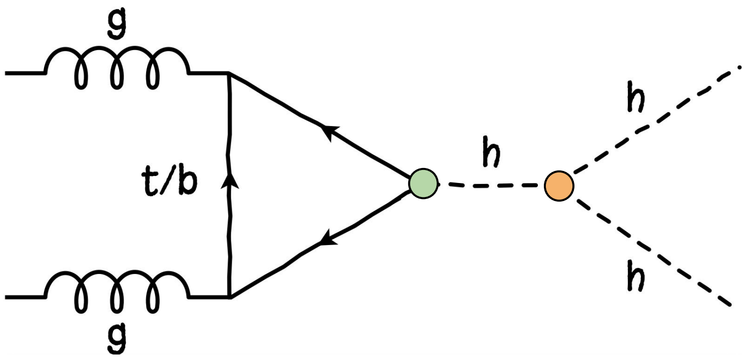
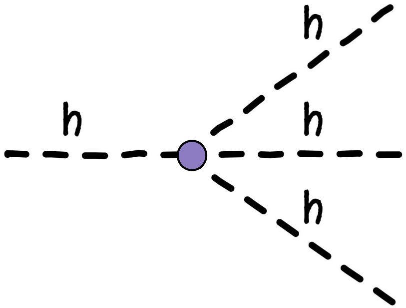
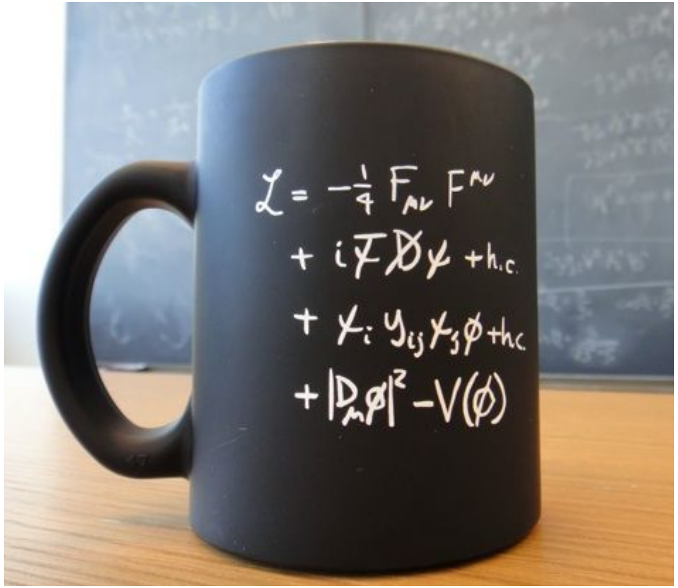
santiago.paredes@cern.ch

EOS be.h Equinox Meeting
September 2021

Why di-higgs?

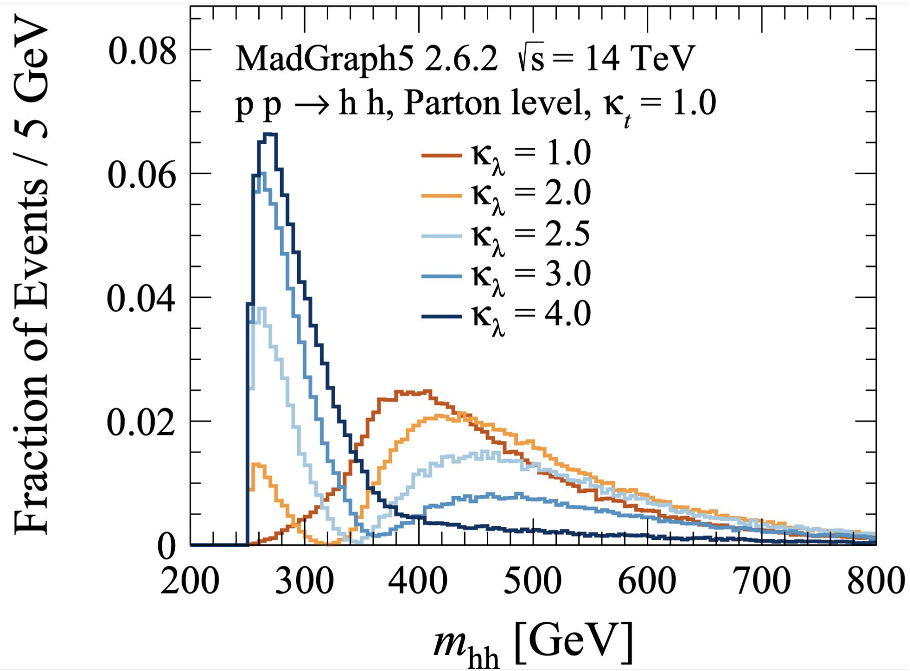






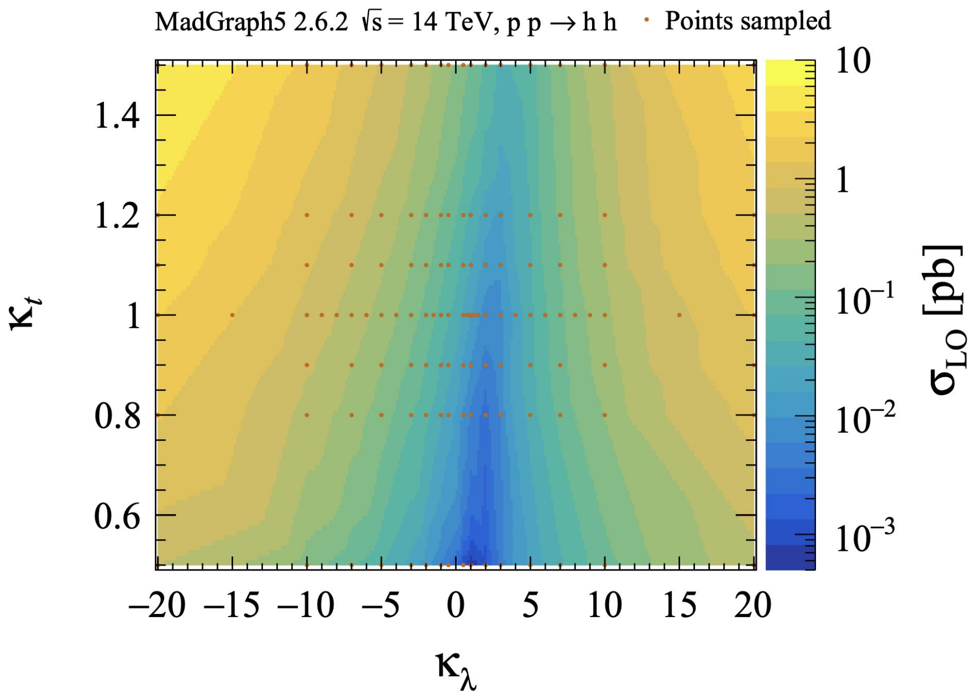
$$\lambda\nu^2 h^2 + \boxed{\lambda\nu h^3} + \boxed{\frac{\lambda}{4} h^4}$$

Signal Samples



- gg→hh production
  - ↪ **100k events** per point
  - ↪ MadGraph 2.6.2
  - ↪ **Inclusive** h **decay**
- Decay, parton shower, hadronization, and underlying event ⟶ Pythia 8.230
- **Varied** coupling to **top** quark and **self couplings**
  - ↪ All **BSM couplings** set to **0**
- Extra k_t=1 samples for **ML training**
  - ↪ **250k** events per point
  - ↪ Exclusive decay h→bb

Signal Samples



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Event and Object Selection

Observable	Preselection		
Large jet j_L	$R = 1.0, p_{\mathrm{T}} > 250$ GeV, $\lvert\eta\rvert < 2.0$		
Small jet j_S	$R = 0.4, p_{\mathrm{T}} > 40$ GeV, $\lvert\eta\rvert < 2.5$		
Track jet j_T	$R = 0.2, p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.5$		
$j_T \in j_L$	$\Delta R(j_T, j_L) < 1.0$		
	Resolved	Intermediate	Boosted
$N(j_L)$	$= 0$	$= 1$	$= 2$
$N(j_S)$	≥ 4	≥ 2	≥ 0
h_1^{cand}	$j_S^{(i)}$ pair	j_L	$j_L^{(1)}$
h_2^{cand}	$j_S^{(i)}$ pair	$j_S^{(i)}$ pair, $\Delta R(j_S^{(i)}, j_L) > 1.2$	$j_L^{(2)}$
ΔR_{jj}	See Eqs. 3.2, 3.3	—	—

Signal region definitions

	Signal region		
$j_T \in h_1^{\text{cand}}$	—	≥ 2	≥ 2
$j_T \in h_2^{\text{cand}}$	—	—	≥ 2
b-tagging	Two b-tags for each h_i^{cand}		
$\lvert\Delta\eta(h_1, h_2)\rvert$	< 1.5		
$E_{\text{T}}^{\text{miss}}$	< 150 GeV		
$p_{\text{T}}^{\ell}, \lvert\eta_\ell\rvert$	> 10 GeV, < 2.5		
N_ℓ	$= 0$		
$p_{\text{signal}}^{\text{DNN}}$	> 0.75 (*neural network analysis* only)		
	Resolved	Intermediate	Boosted
$m(h_1)$ [GeV]	[90, 140]	[90, 140]	[90, 140]
$m(h_2)$ [GeV]	[90, 140]	[90, 140]	[90, 140]
	Lower bin edges for m_{hh} binning [GeV]		
Resolved	$[200, 250, 300, 350, 400, 500]$		
Intermediate	$[200, 500, 600]$		
Boosted	$[500, 800]$		

Fixed k_t=1

BSM k_λ yield

SM k_λ yield

Category	Systematic ζ_b
Resolved	0.3%
Intermediate	1%
Boosted	5%

$$\chi^2 = \sum_i \left[\frac{(S - S_{\mathrm{SM}})^2}{S + B + (\zeta_b B)^2 + (\zeta_s S)^2} \right]_i$$

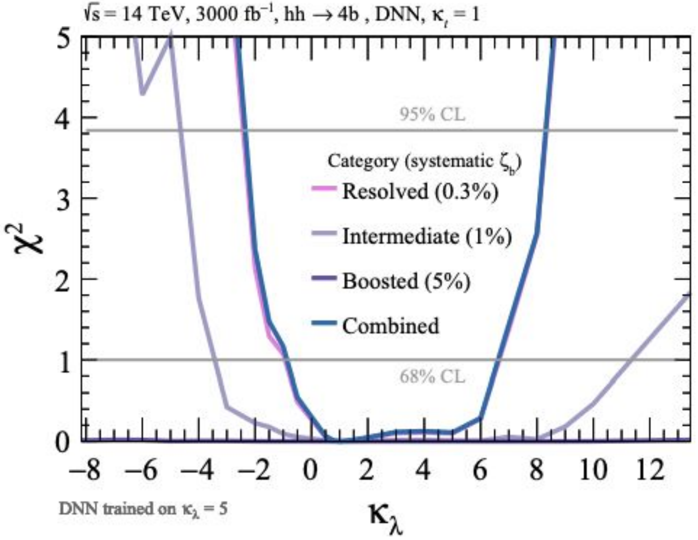
m_{hh} bins

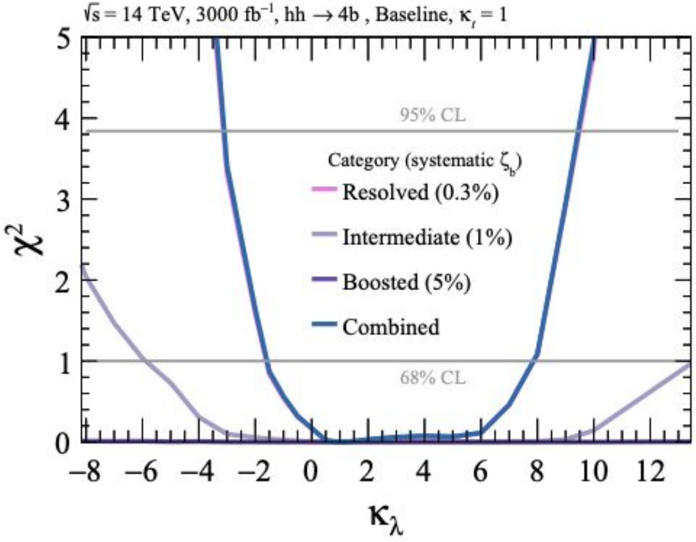
background uncertainty

signal uncertainty

Constraints on k_λ - Fixed k_t=1

- Resolved ⇢ **most powerful**
  - ↪ Intermediate ⇢ **non-negligible**
  - ↪ Boosted ⇢ **negligible***
- **Basic DNN** analysis **improved sensitivity**

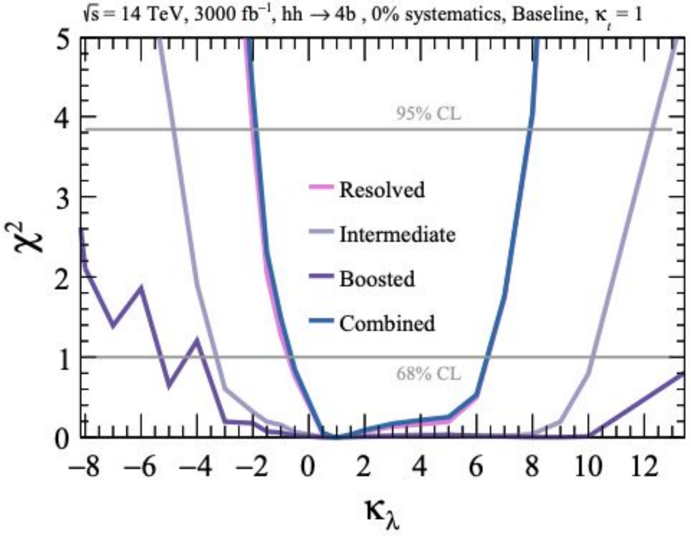


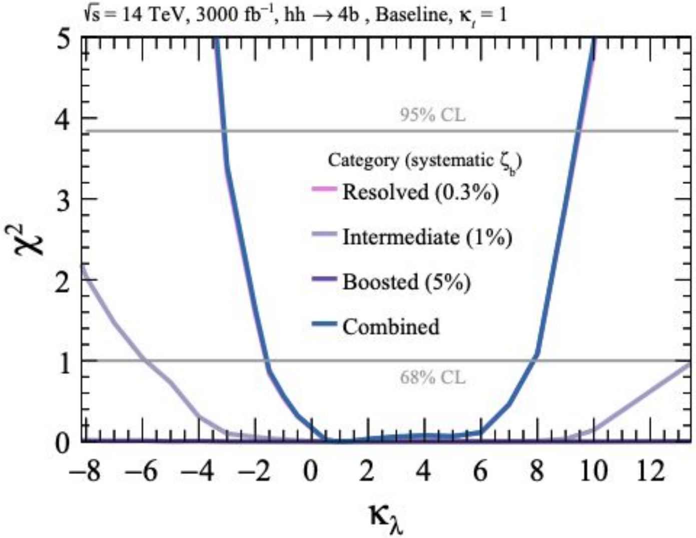


*Note that this does not necessarily apply to analyses optimized for discovery of SM hh production - only those aiming to constrain k_λ.

Parentheses - Impact of BKG Uncertainty

- **Background uncertainty** has **large impact** on sensitivity
  - ↪ **Often** a **large uncertainty** in $hh \to 4b$ searches



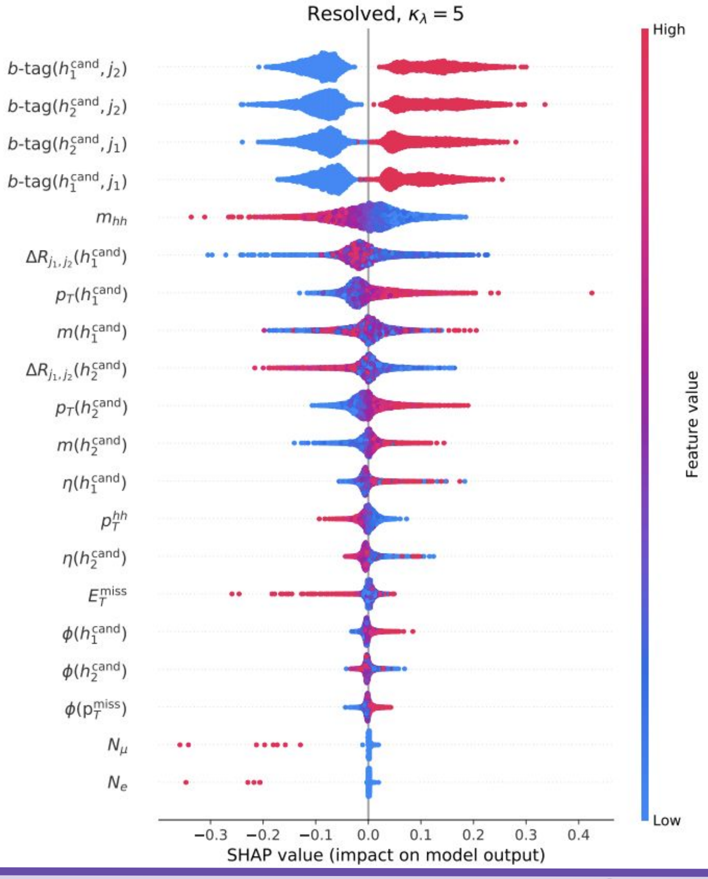


Parentheses - What did our machine learn?

NN variables

Ranked by impact on NN score

- [SHAP](#) value framework
  - ↪ **Shapley** values for ML **interpretability**



Parentheses - What did our machine learn?

Resolved, $\kappa_\lambda = 5$

Parentheses - Shapley Values

−0.3 −0.2 −0.1 0.0 0.1 0.2 0.3 0.4

SHAP value (impact on model output)

Parentheses - What did our machine learn?

Resolved, $\kappa_\lambda = 5$

Parentheses - Shapley Values

−0.3 −0.2 −0.1 0.0 0.1 0.2 0.3 0.4

SHAP value (impact on model output)

SHAP value | More signal-like impact on score

Parentheses - What did our machine learn?

Resolved, $\kappa_\lambda = 5$

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−0.3 −0.2 −0.1 0.0 0.1 0.2 0.3 0.4

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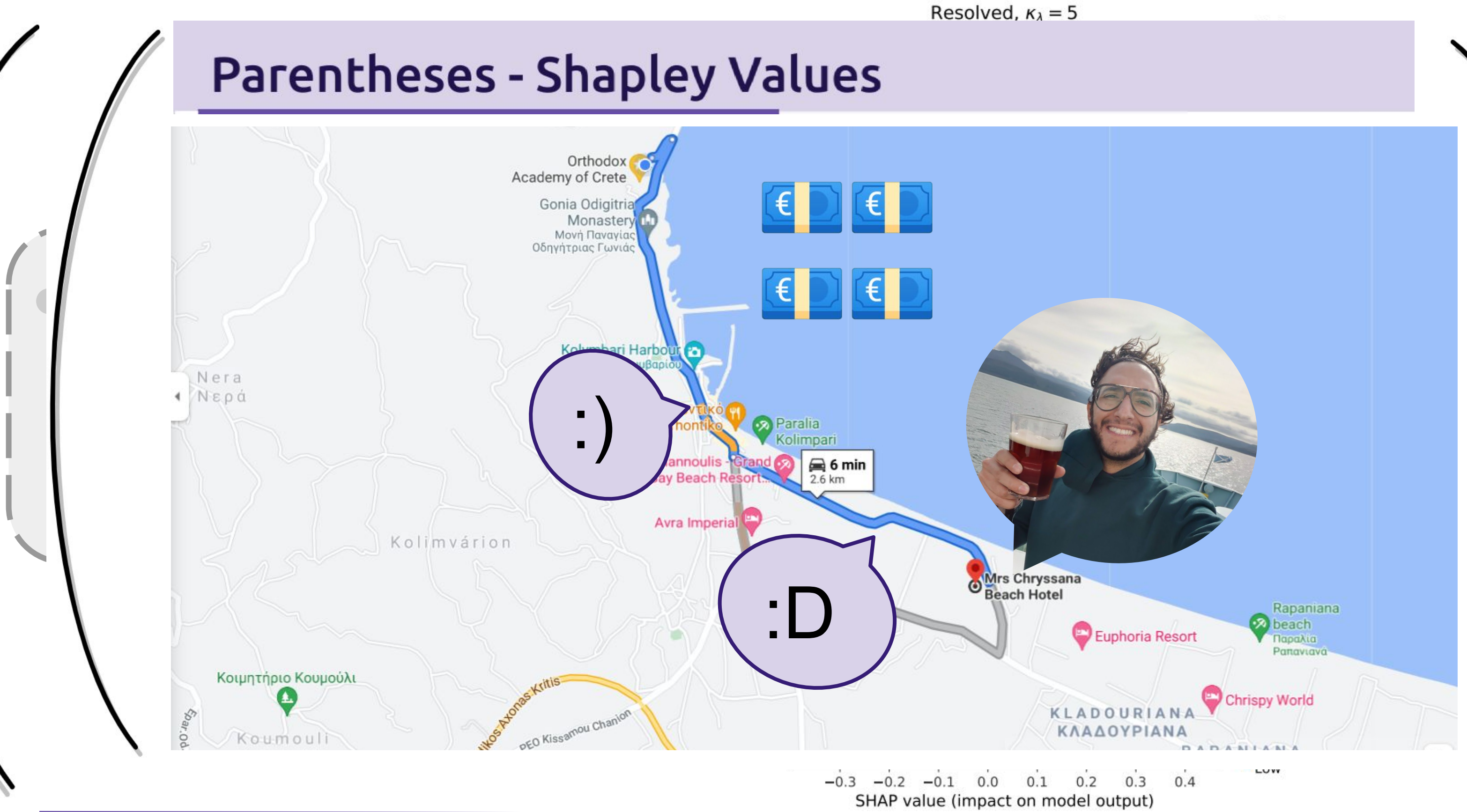

SHAP value | More signal-like impact on score