Extending $hh \rightarrow b\bar{b}b\bar{b}$ 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

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EPS-HEP2021 conference

July 2021

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)
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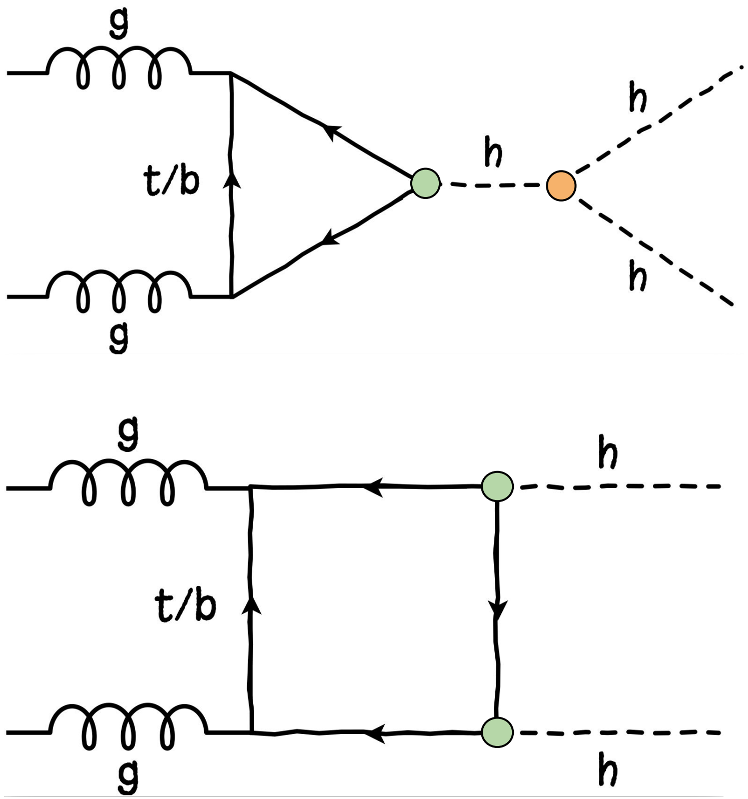
DOI:	10.1007/JHEP12(2020)115
Report number:	IPPP/20/11
Cite as:	arXiv:2004.04240 **[hep-ph]**
	(or arXiv:2004.04240v3 **[hep-ph]** for this version)

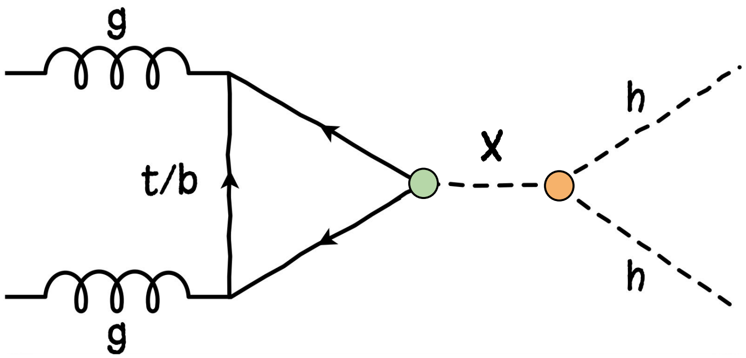
Introduction & Motivation

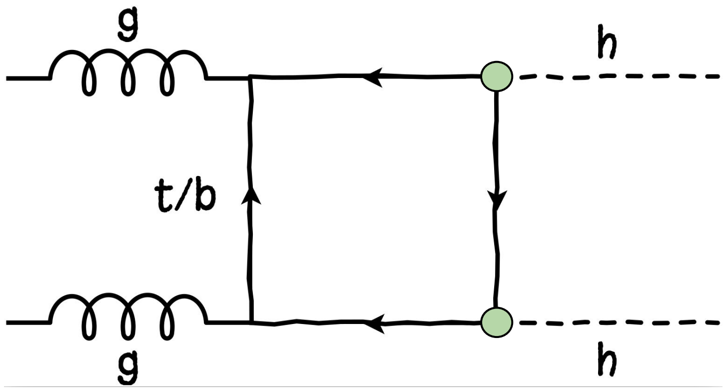
Why hh?



- 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?





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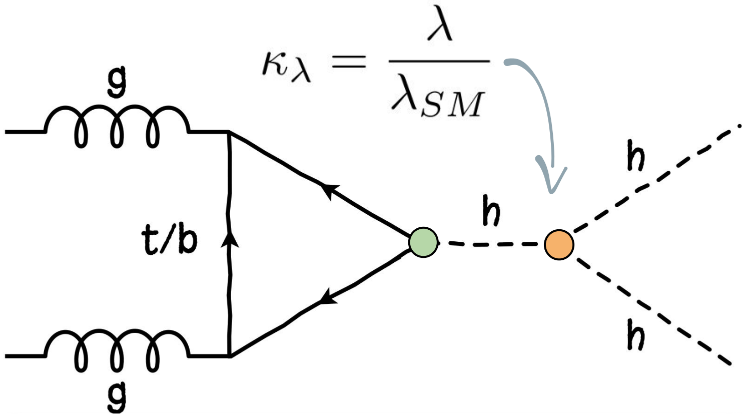
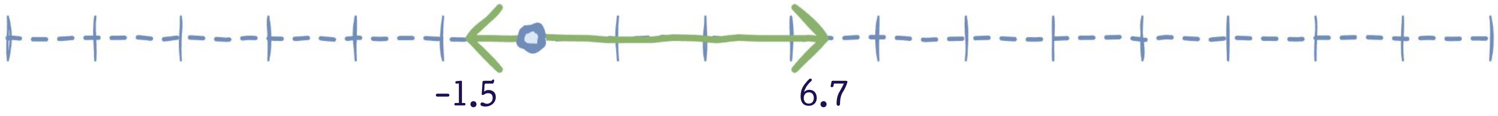


- **Key parameter** in the standard model
  - ↪ **Not only** for collider physics
- hh **the only way** to **directly** measure self-coupling!

full Run II data – **bbγγ** – **95% C.L. k_λ** constraints*

ATLAS EXPERIMENT



ATLAS-CONF -2021-016

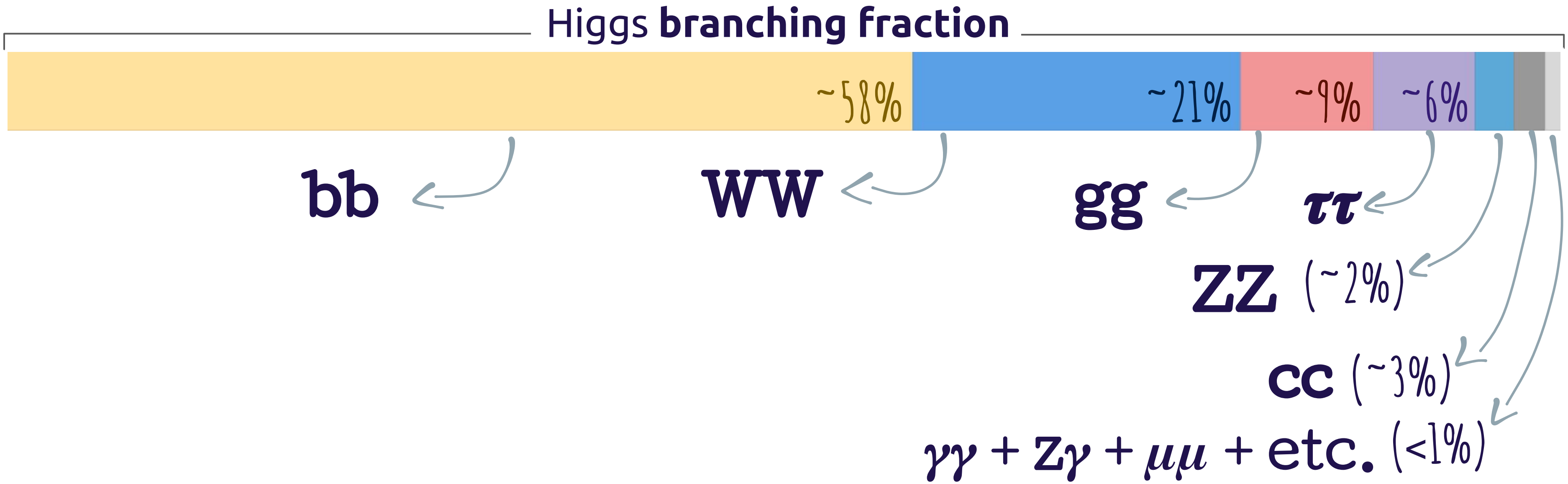
CMS

JHEP03(2021) 257

S. Paredes Saenz

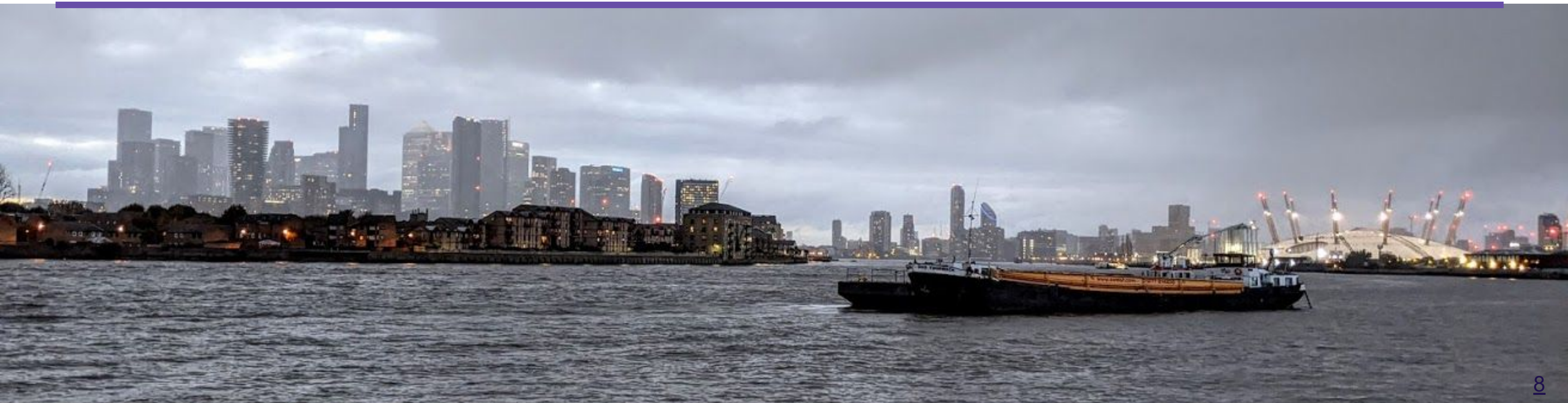
*Rough snapshot of our knowledge of k_λ today, with run II data. Other channels being worked on. Probably already outdated since a few talks.

Why hh → 4b?

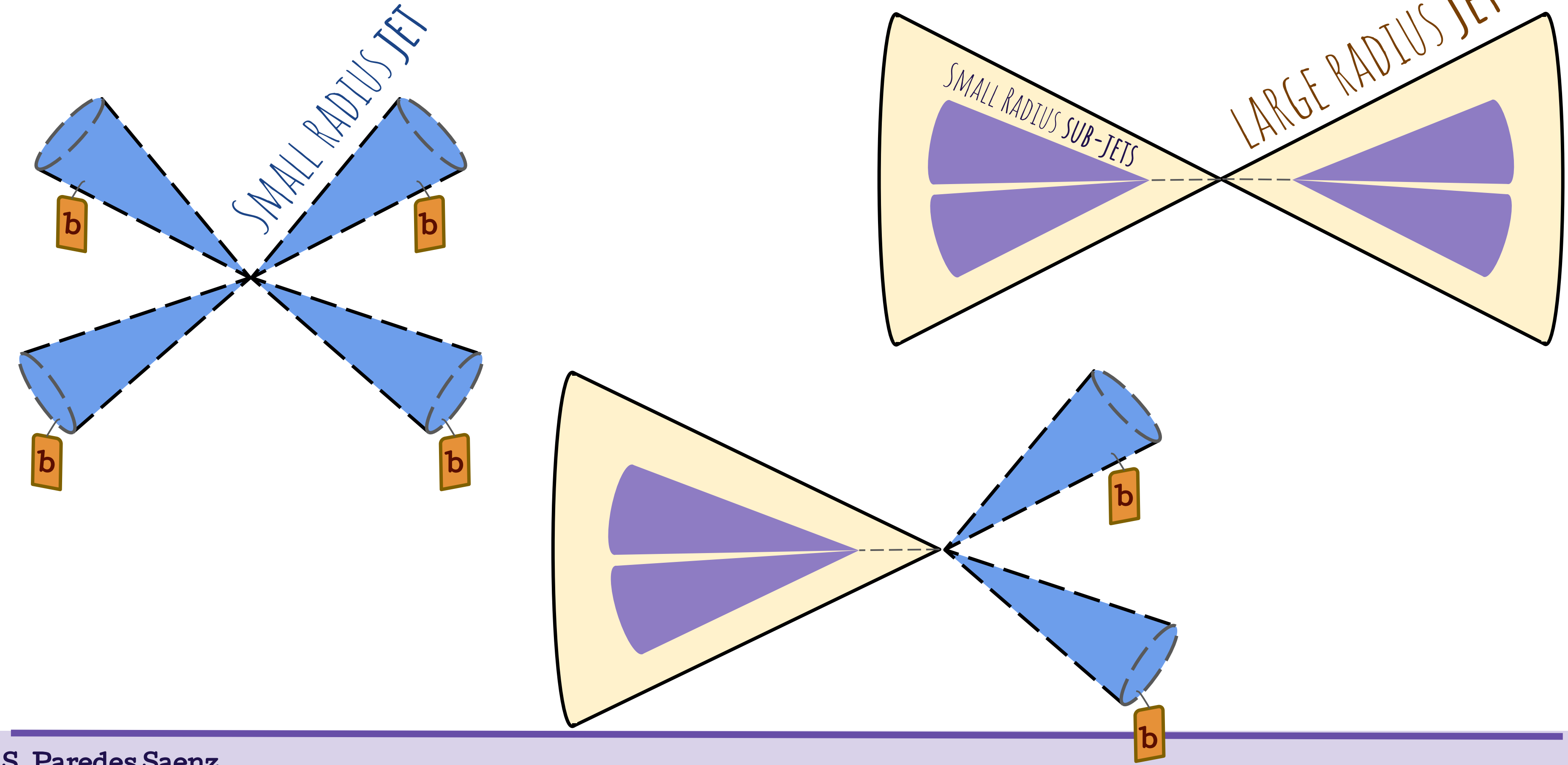


Higgs branching fraction
~58%
~21%
~9%
~6%
bb
WW
gg
ττ
ZZ (~2%)
cc (~3%)
γγ + Zγ + μμ + etc. (<1%)

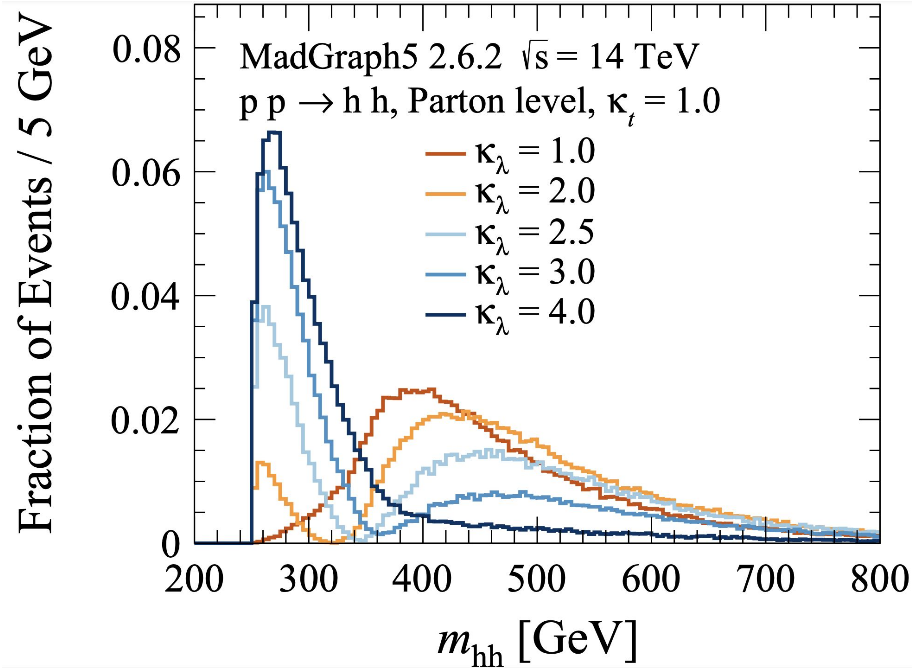
Signal & Background Modelling



Signal Topology



Signal Samples

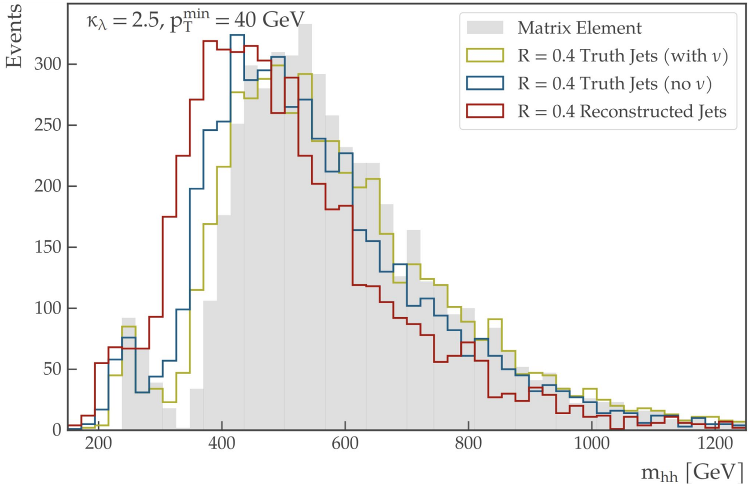


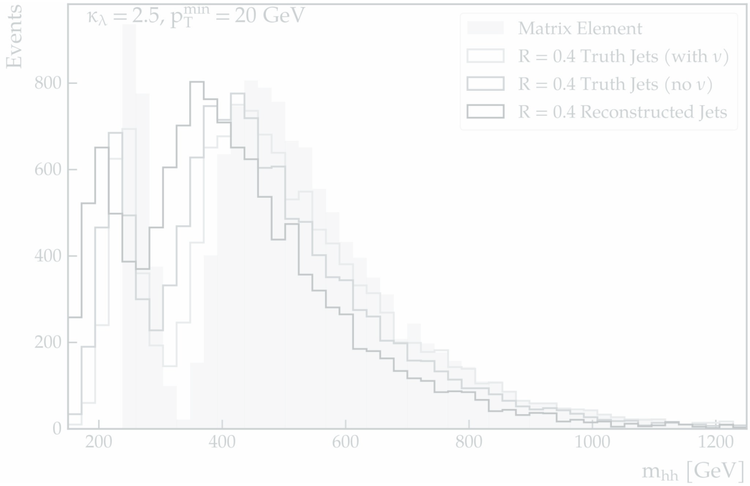
- gg→hh production
  - ↪ MadGraph 2.6.2
  - ↪ **Inclusive h decay**
- Decay, parton shower, hadronization, and underlying event ⟶ Pythia 8.230
- Points with **varied** coupling to **top** quark and **self couplings**
- Extra k_t=1 samples for **ML training**
  - ↪ **250k** events per point
  - ↪ Exclusive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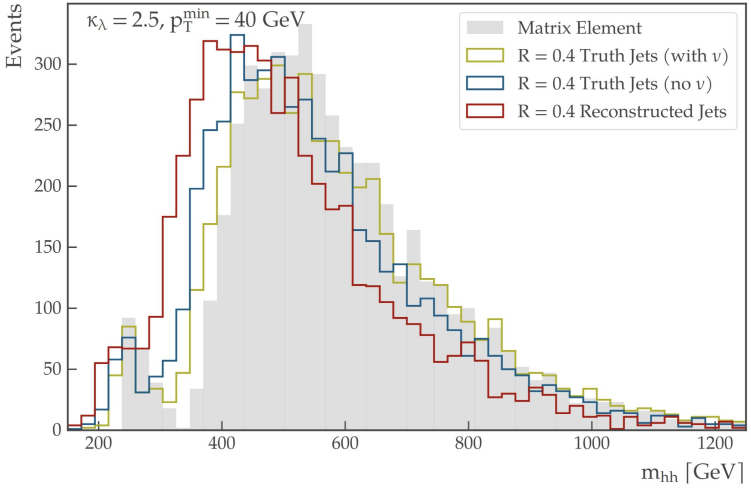

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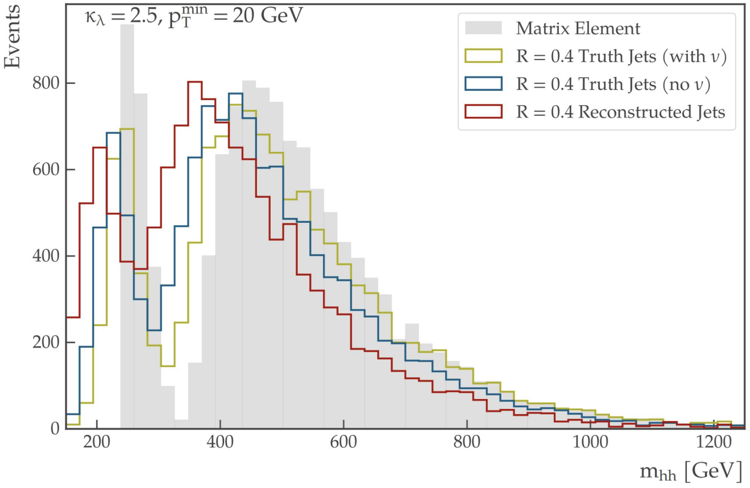
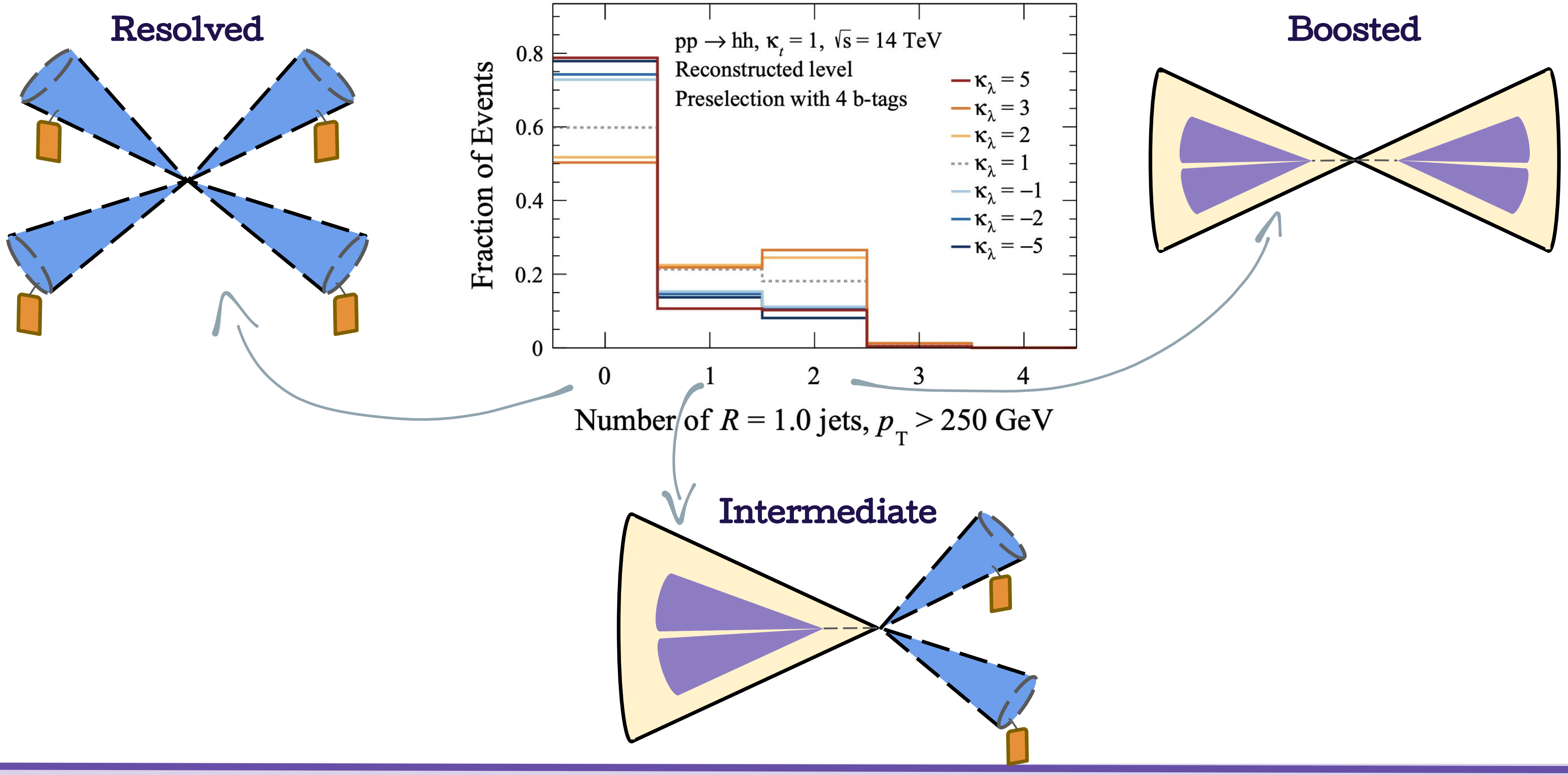


Background Samples

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

Analysis Strategies

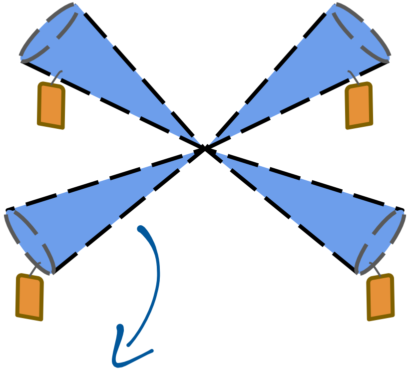
Channels



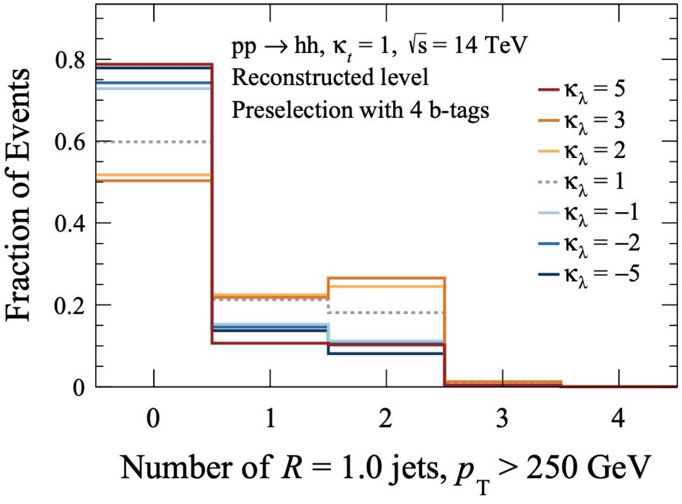
Resolved
Boosted
Intermediate
pp → hh, κ_t = 1, √s = 14 TeV
Reconstructed level
Preselection with 4 b-tags
κ_λ = 5
κ_λ = 3
κ_λ = 2
κ_λ = 1
κ_λ = −1
κ_λ = −2
κ_λ = −5
Fraction of Events
0.8
0.6
0.4
0.2
0
0
1
2
3
4
Number of R = 1.0 jets, p_T > 250 GeV

Channels

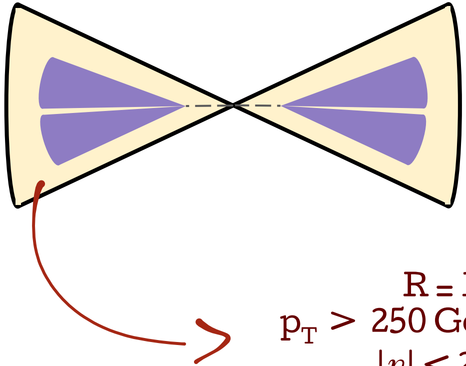
Resolved



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



Boosted

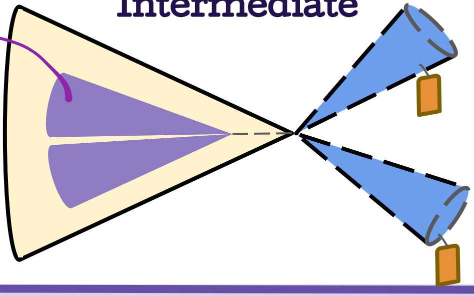


$R = 1.0$
$p_T > 250$ GeV | j_L
$|\eta| < 2.0$

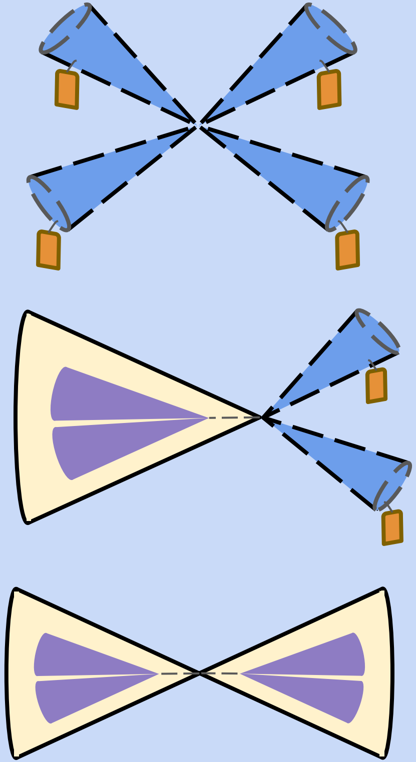
Intermediate

j_T

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

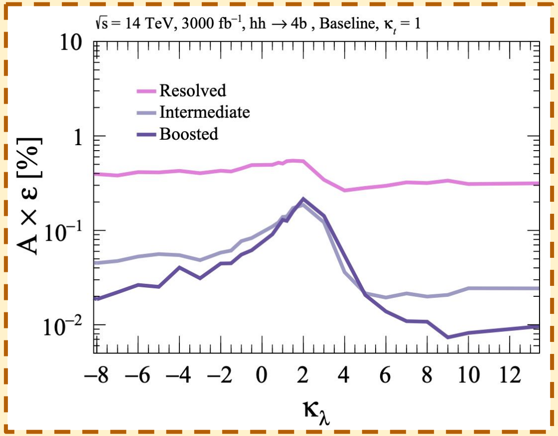


Analysis Strategy



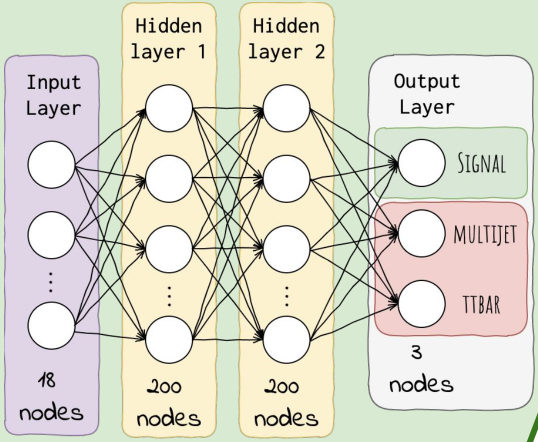
Baseline Analysis

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



DNN Analysis

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



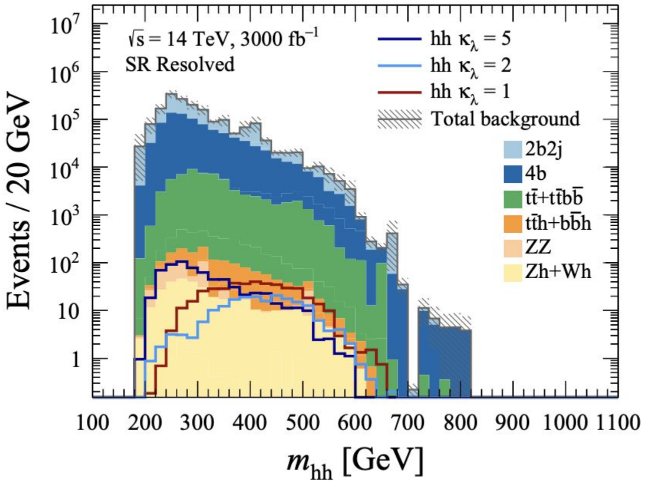
Baseline Analysis

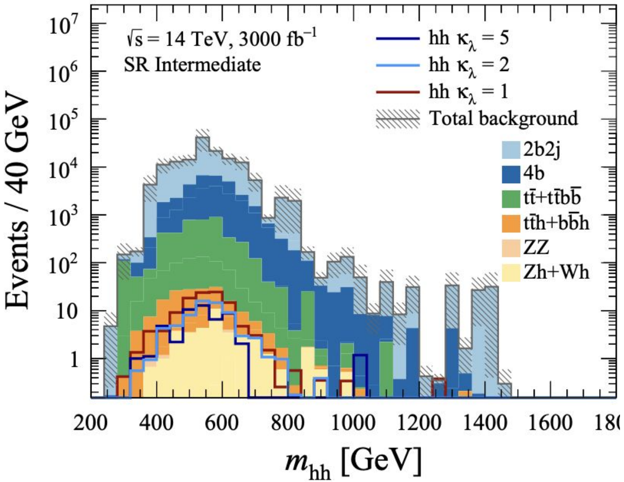
- **Analysis-specific** cuts ⇒ define Signal Region (**SR**) in m_{hh}

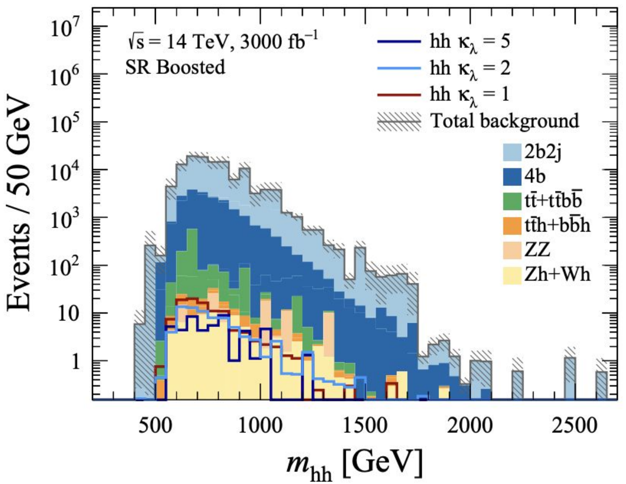
↪ $N(j_L) = 0$
↪ $N(j_S) \geq 4$
↪ Lepton, MET veto
↪ 4 b-tags
↪ $\Delta R(j_S^1, j_S^2)$ cut

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

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







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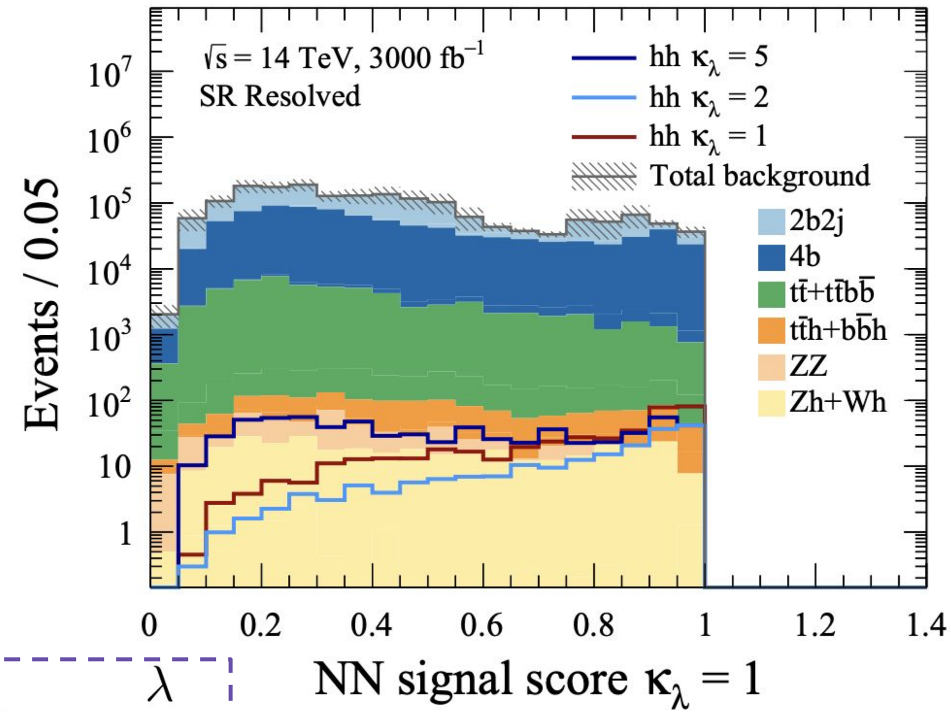


$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

- **Muli-class** classifier
  - ↪ Signal vs multijet vs $t\bar{t}$
- Trained with **multiple k_λ** signals
  - ↪ **Use $k_\lambda = 5$** network
- Cut ⇒ NN signal **score > 0.75**

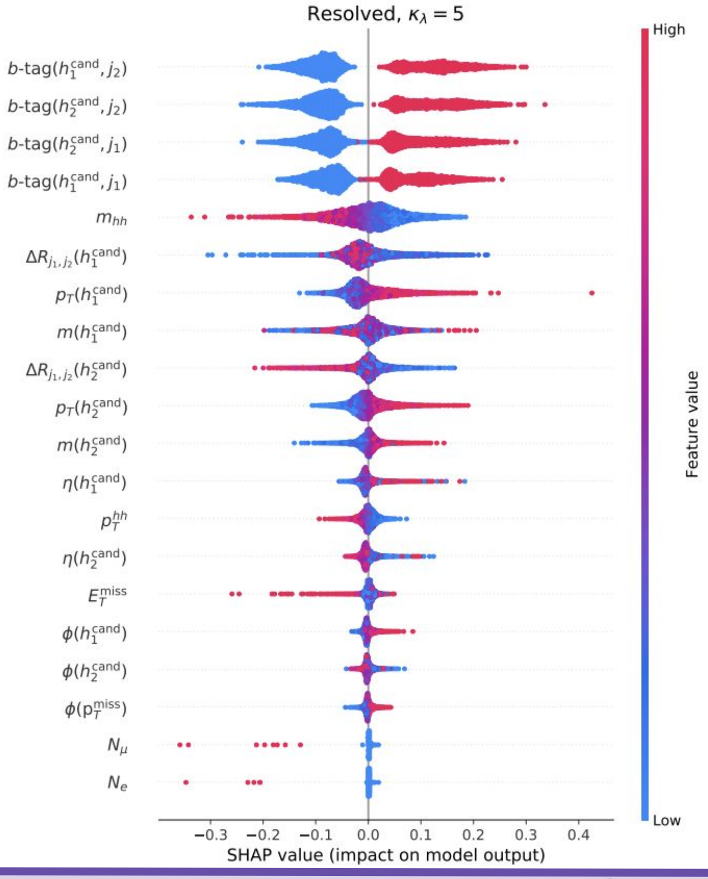
Training Variables

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

Parentheses - What did our machine learn?

NN variables

Ranked by impact on NN score



- SHAP value framework
  - ↪ ML **interpretability**

SHAP value | More signal-like impact on score

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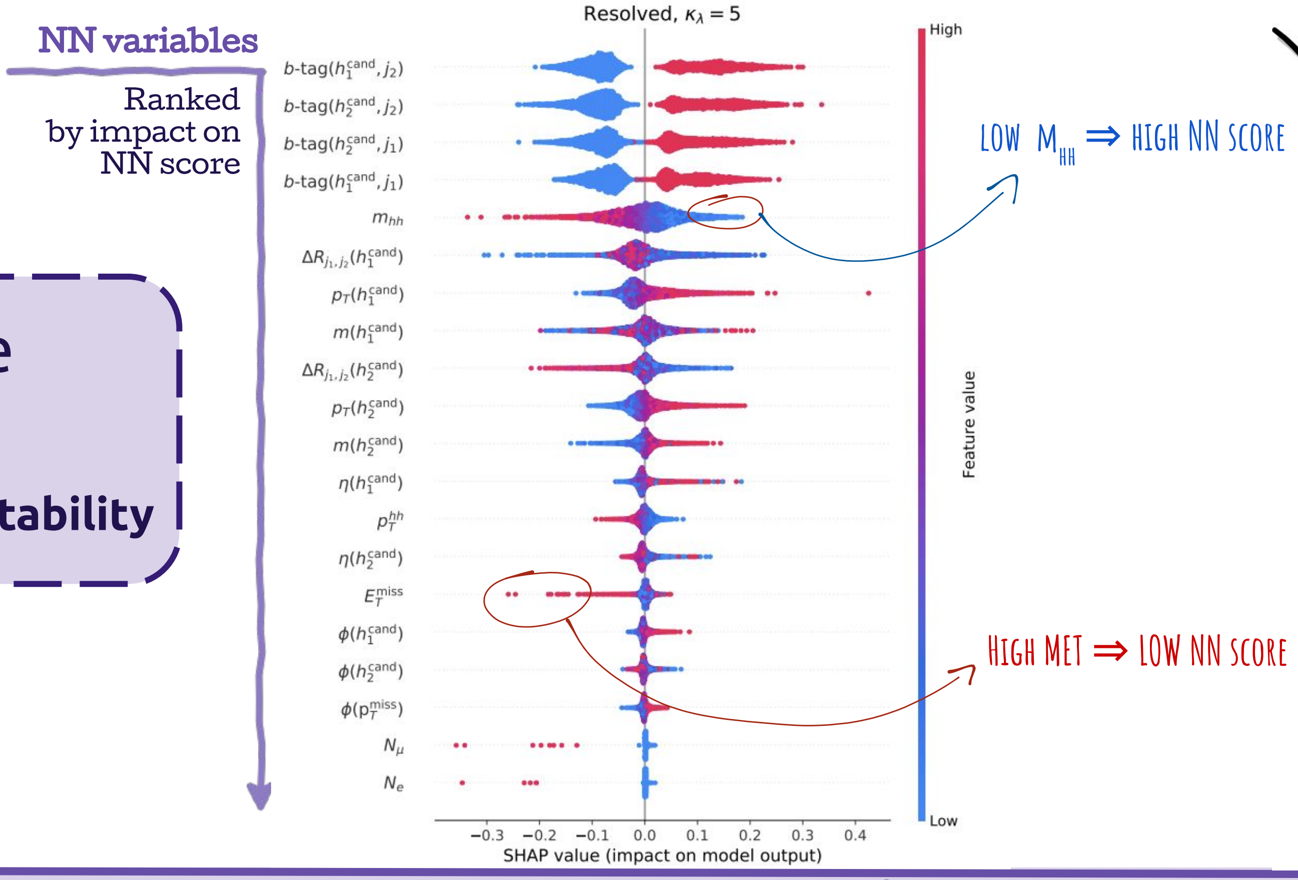
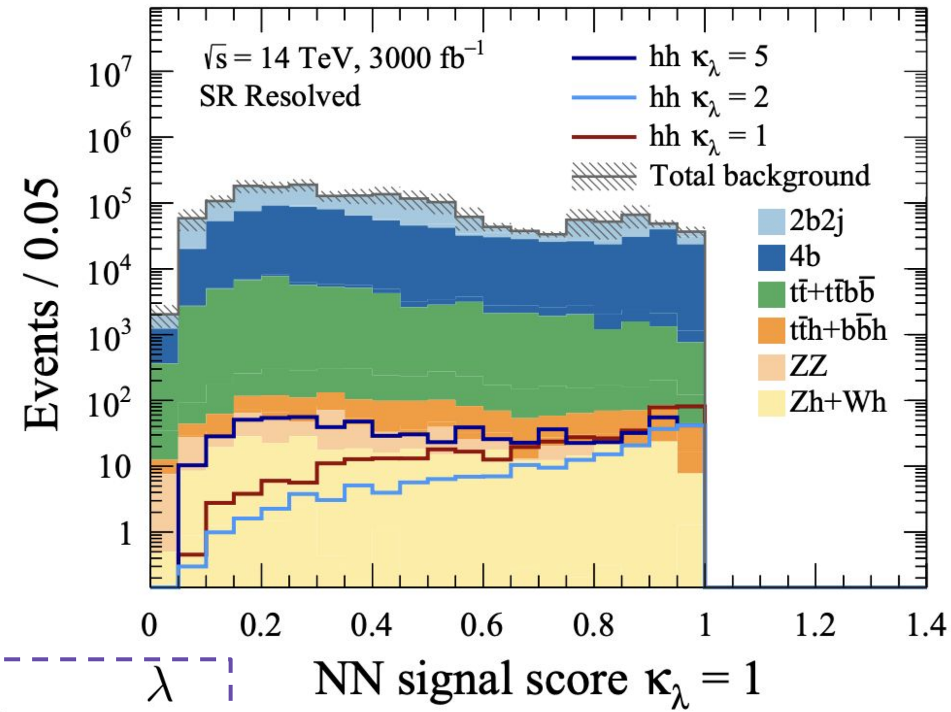


SHAP value → More signal-like impact on score

DNN Analysis



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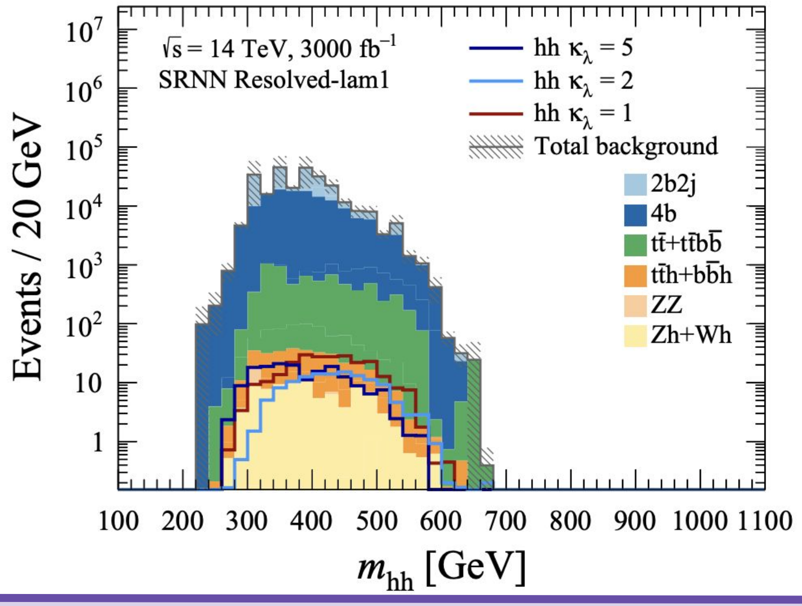
➢ M^{HH}	➢ MET ϕ	➢ Sub-jet ϕ
➢ #Muons	➢ Sub-jet mass	➢ Sub-jets ΔR
➢ #Elec	➢ Sub-jet p_T	➢ Sub-jets b-tag

Parentheses - BSM k_λ training

$k_\lambda = 1$ NN cut

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



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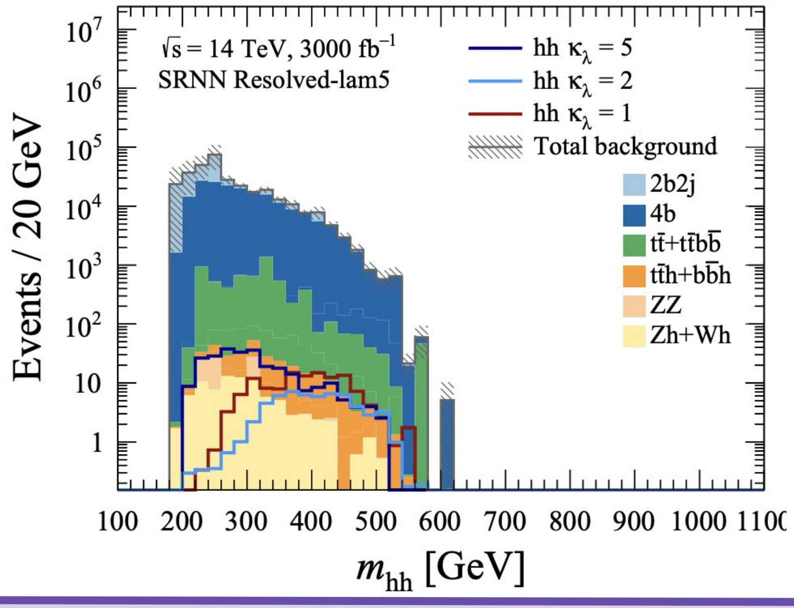
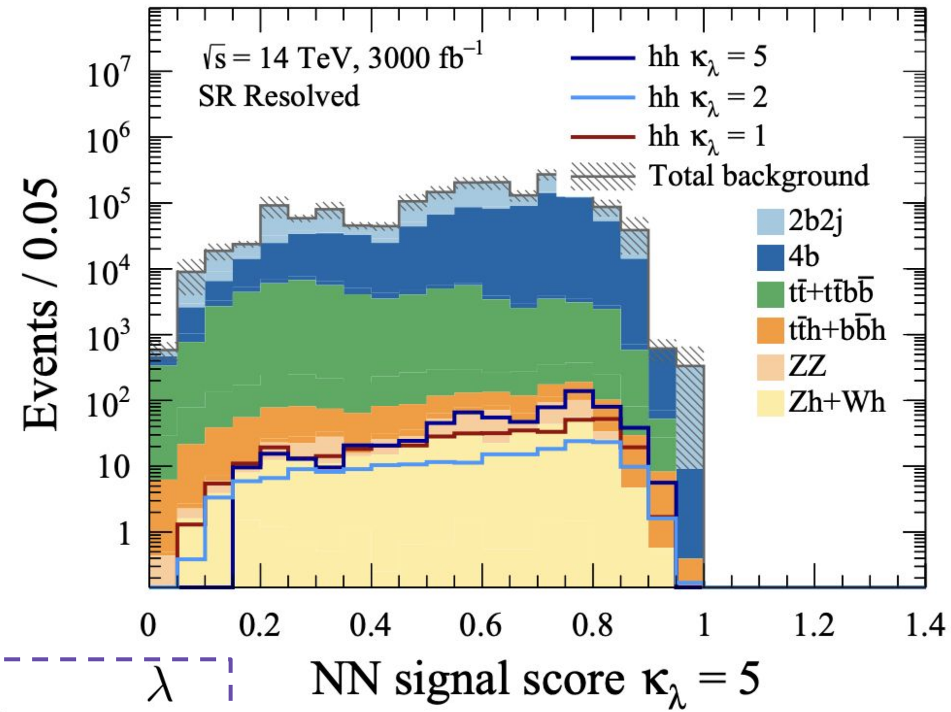
- Signal **characterization** ✓



DNN Analysis



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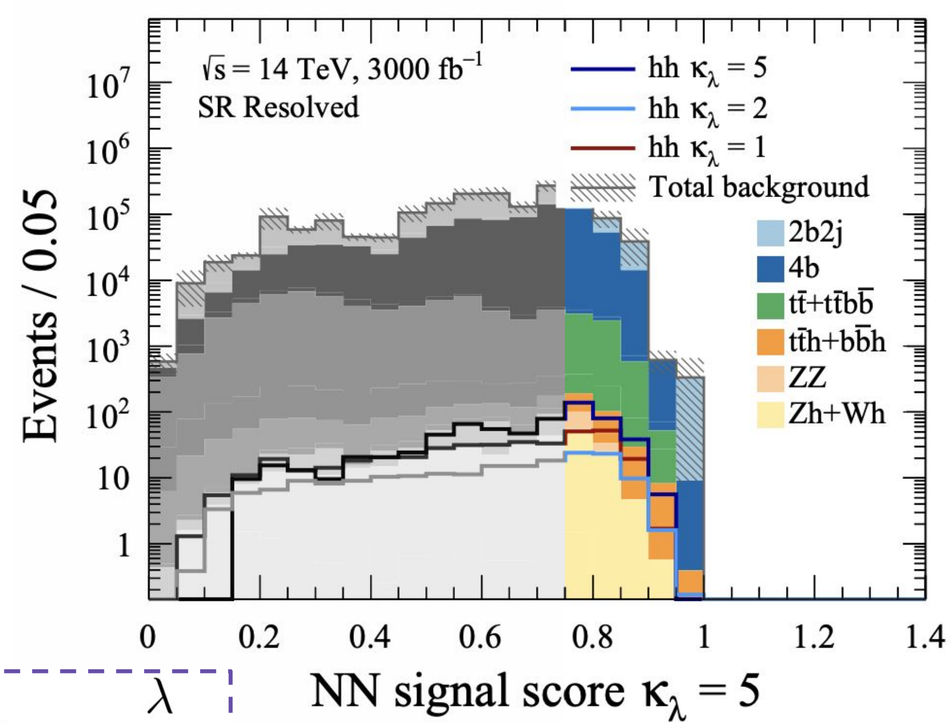

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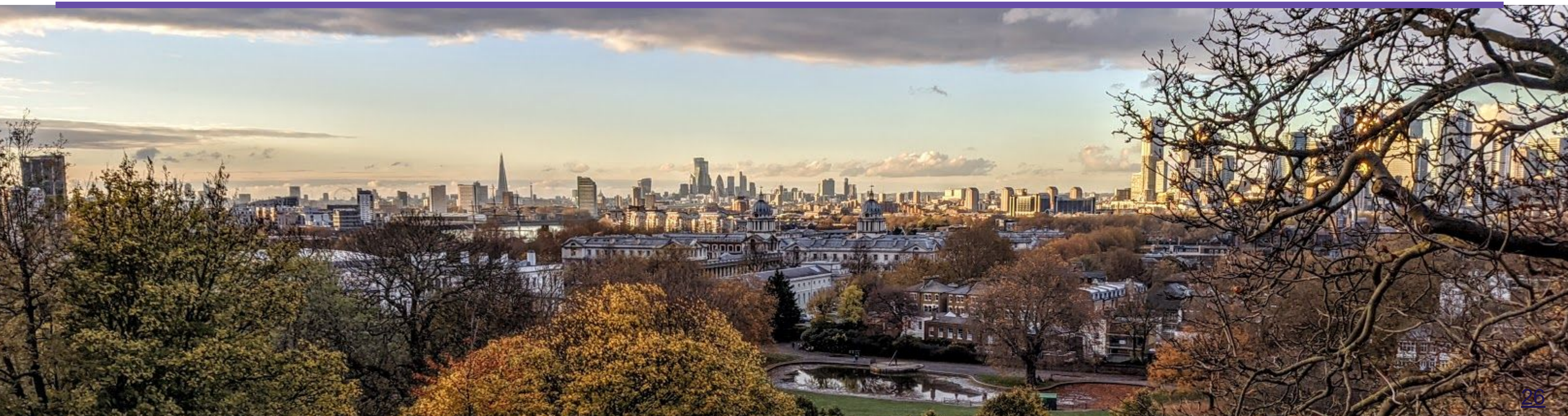
Self-Coupling Constraints



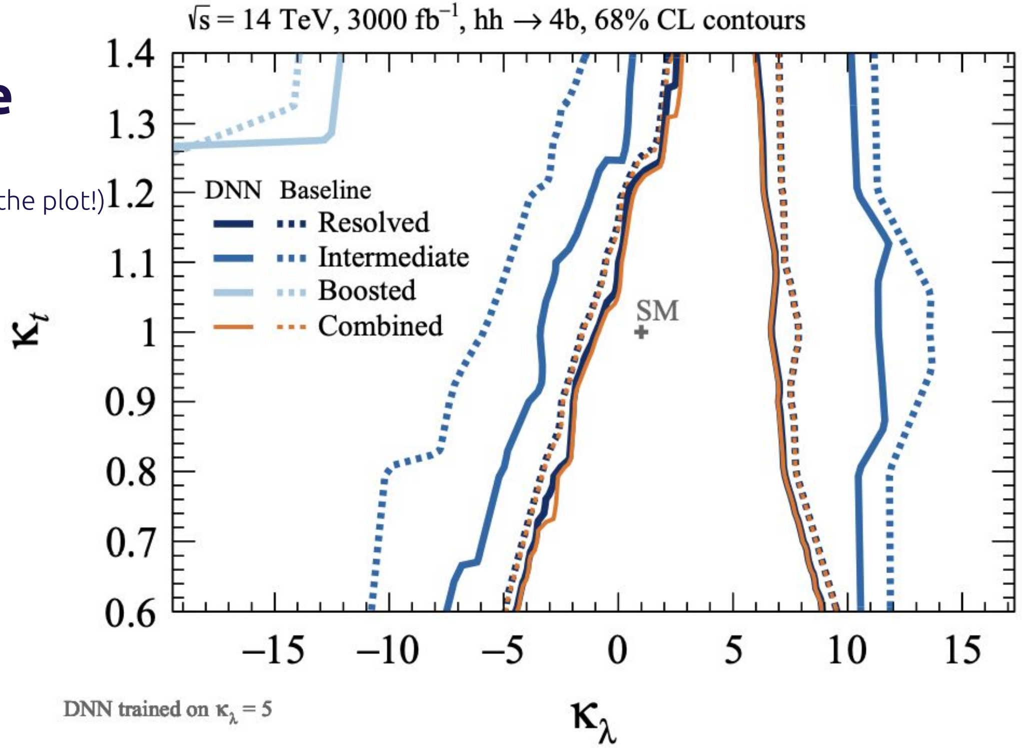
Constraints on k_λ - k_t Plane

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

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.

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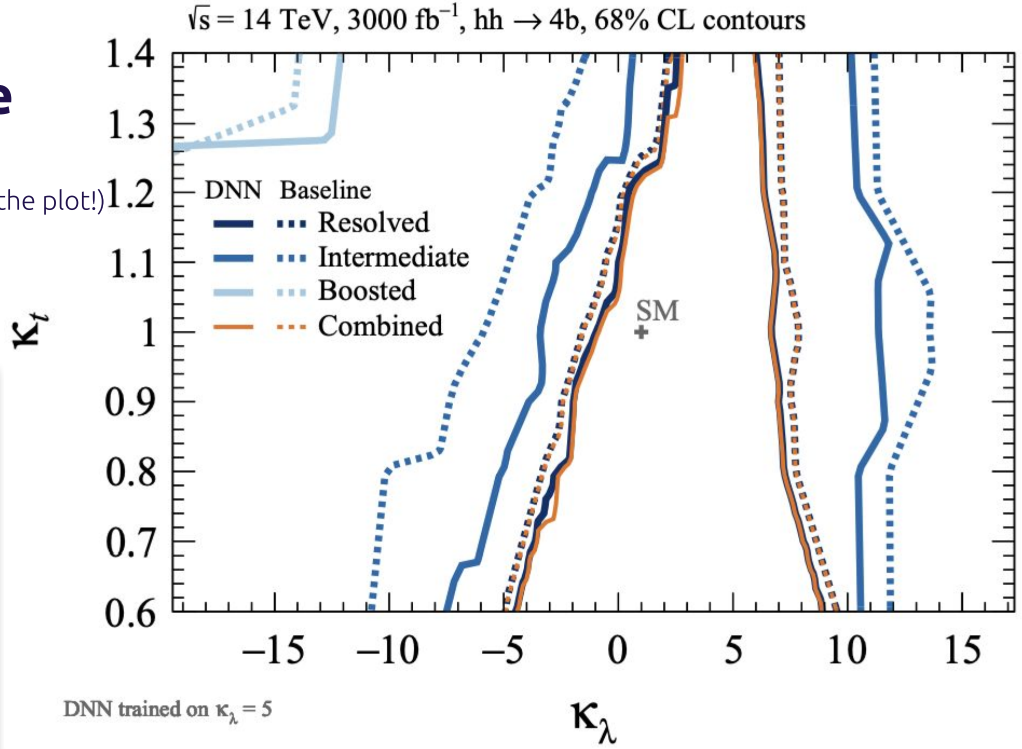

DNN trained on $\kappa_\lambda = 5$

*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 $hh \rightarrow 4b$ 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
  ↪ $hh \rightarrow 4b$ 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 $hh \rightarrow 4b$ 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**

Thanks!

Jacob Amacker, William Balunas, Lydia Beresford, Daniela Bortoletto,
James Frost, Cigdem Issever, Jesse Liu, James McKee, Alessandro Micheli,
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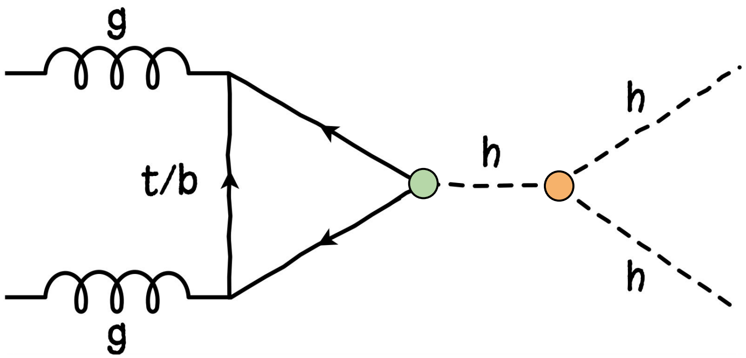
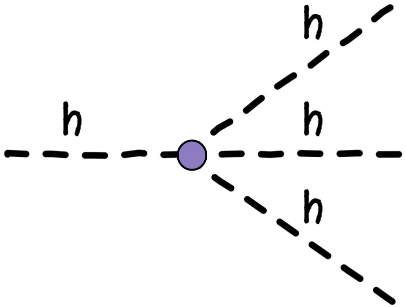
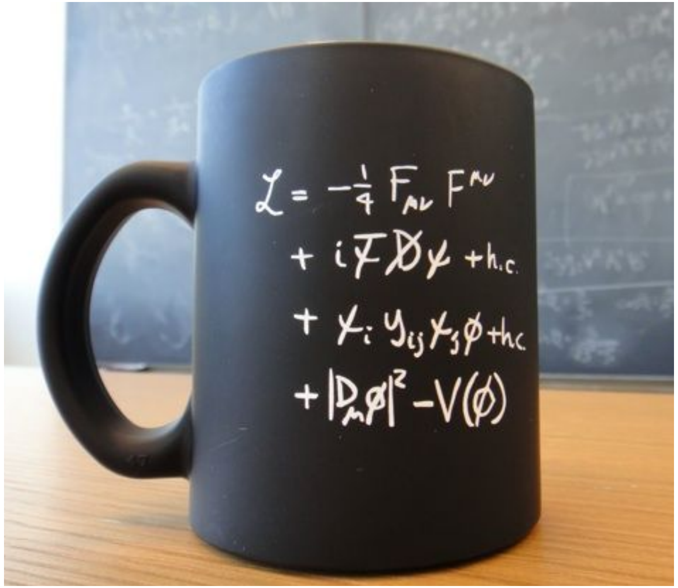
EPS-HEP2021 conference
July 2021

Why di-higgs?

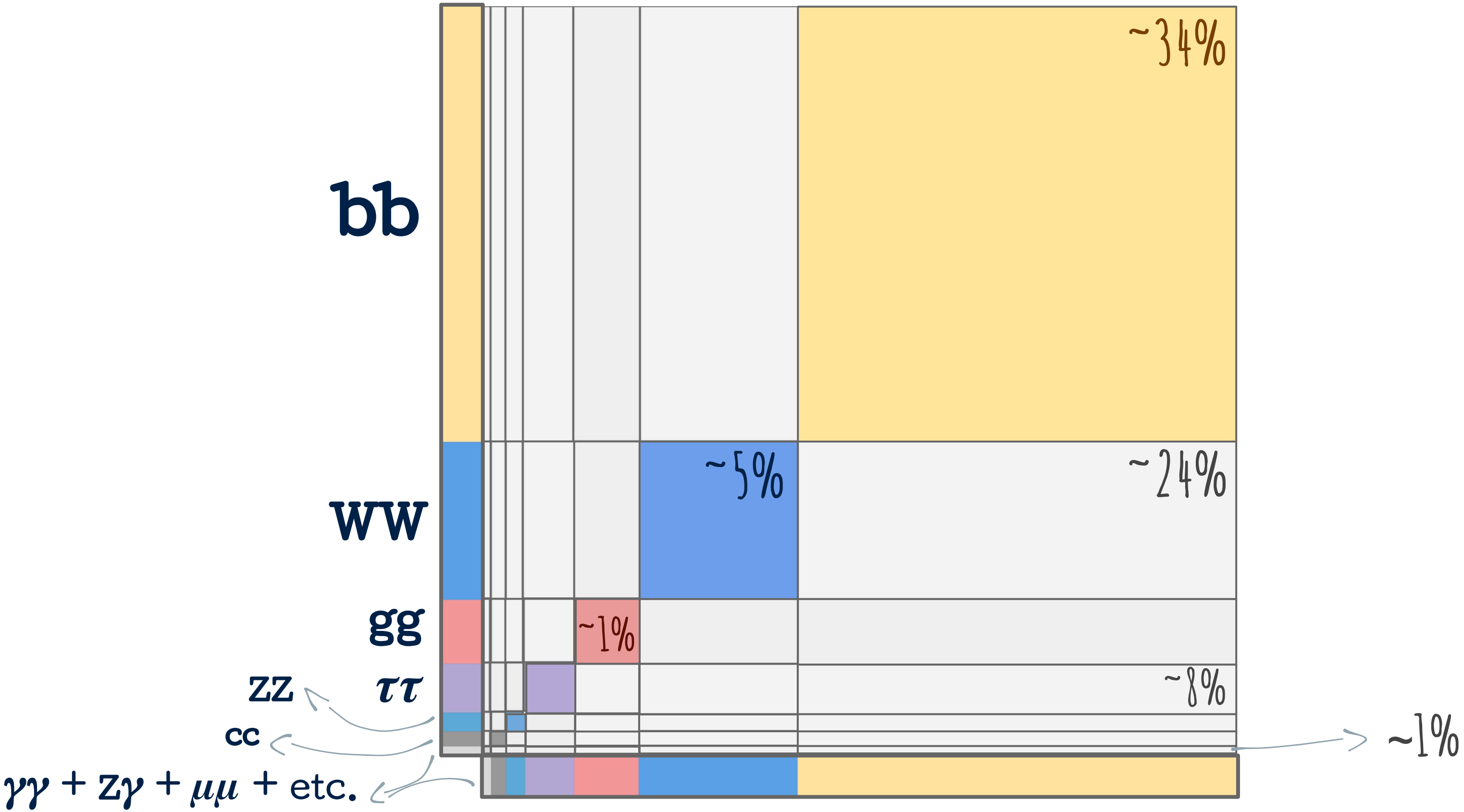




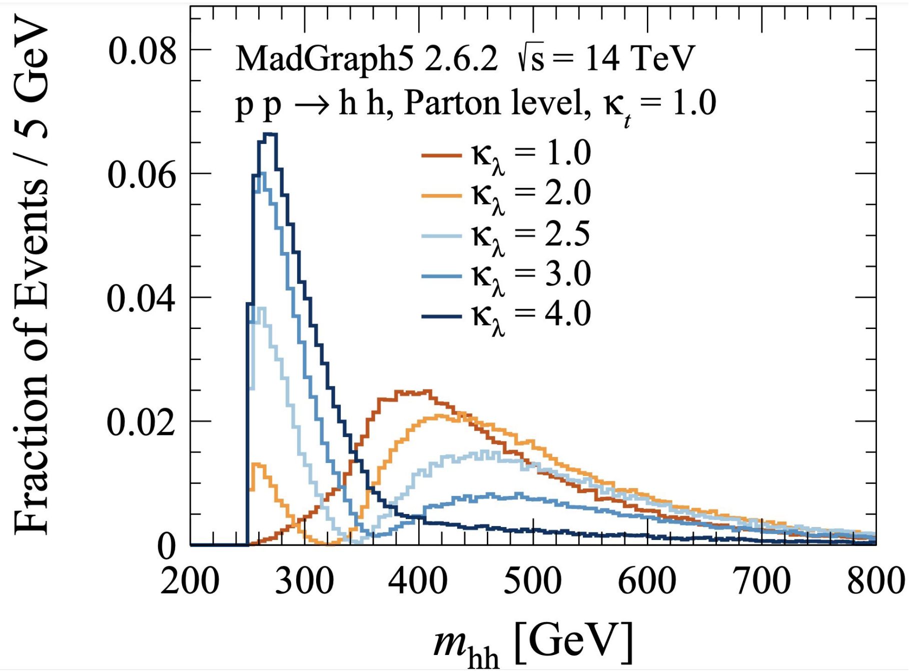


$$\lambda\nu^2 h^2 + \lambda\nu h^3 + \frac{\lambda}{4} h^4$$

Why hh → 4b?

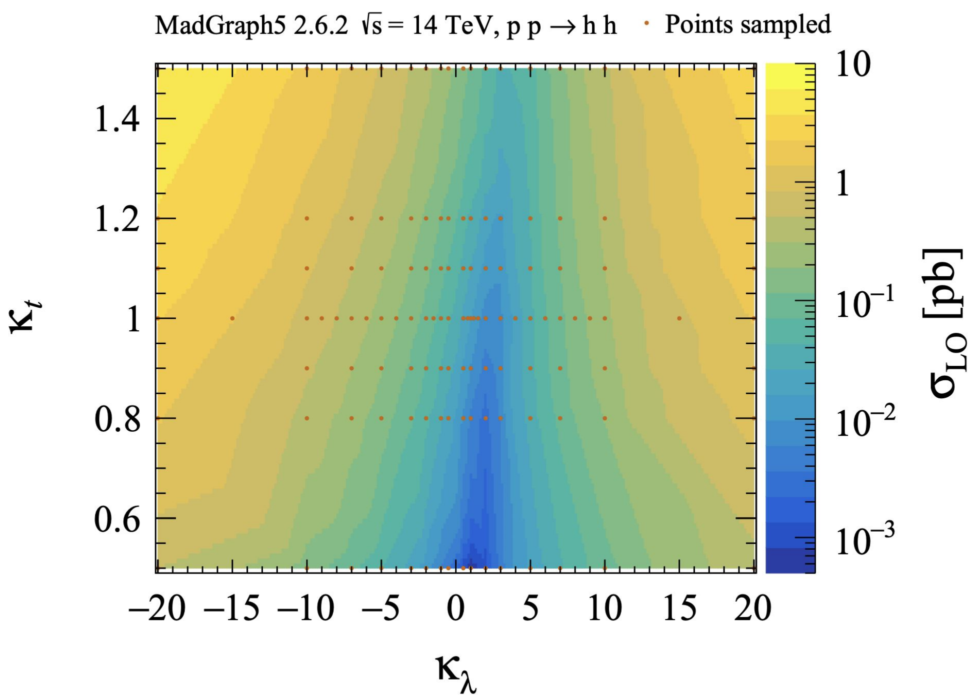


Signal Samples



- 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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  - ↪ **100k events** per point
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  - ↪ Exclusive decay h→bb

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

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

BSM k_λ yield

SM k_λ yield

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

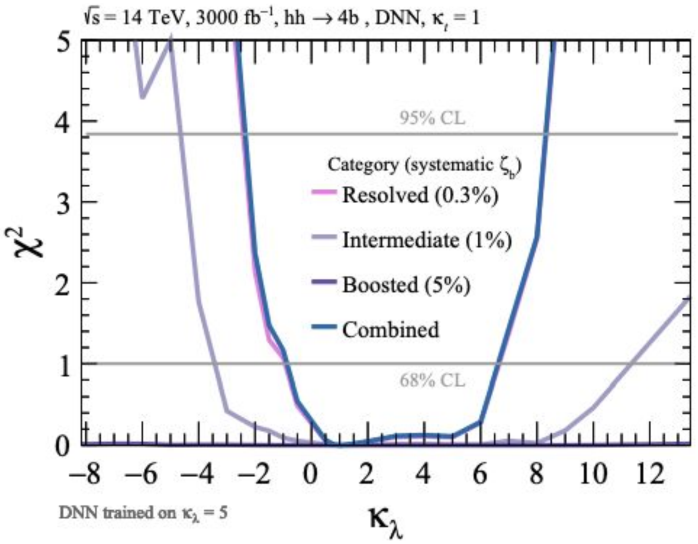
m_{hh} bins

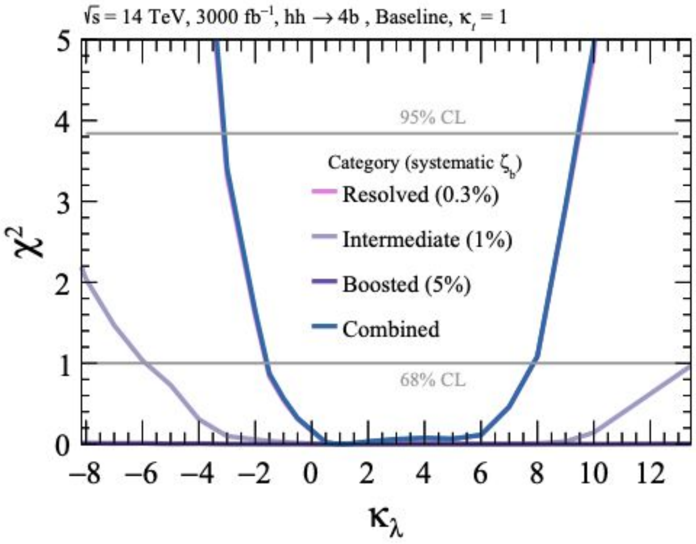
background uncertainty

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