Testing the SM
(and searching beyond it)
in hh→4b events
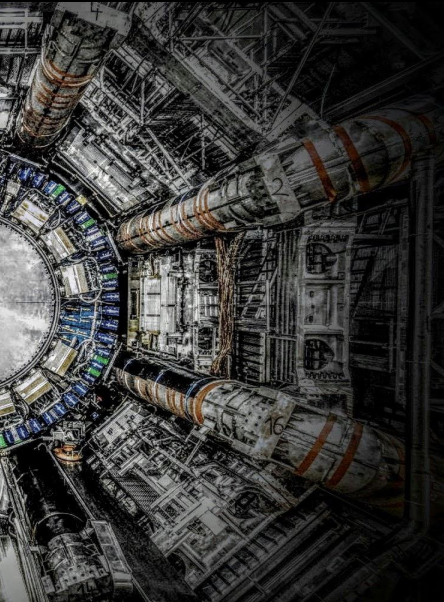
Santiago Paredes Sáenz
santiago.paredes@physics.ox.ac.uk

HEPHY Vienna

March 2020

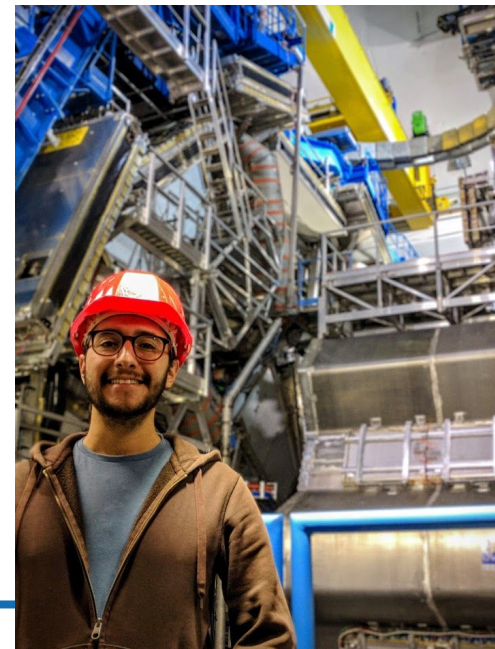# Overview

- **Motivation** for di-higgs to 4b searches
  ↳ Higgs **self-coupling**
- hh→4b **ATLAS** analysis
- **Future** of **hh** searches
- **Summary**

Overview

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My recent work

- **ATLAS**
  - ↳ **hh→4b analysis**
    - ○ Developed and maintained **boosted** analysis **software framework**
    - ○ Implemented use of **Variable Radius track jets**
    - ○ Tested **background reweighting** using **boosted decision trees**
    - ○ Performed **statistical analysis**, proposed **new result interpretation**
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    - ○ Developed **framework** for performance **monitoring plots**
    - ○ Evaluated and monitored **trigger performance** during **2017 run**
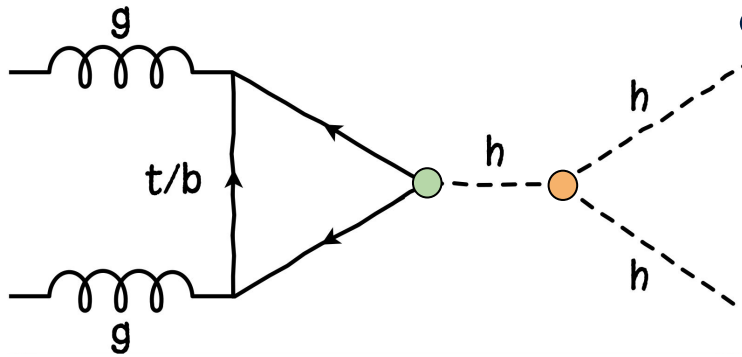- **hh→4b phenomenology study**
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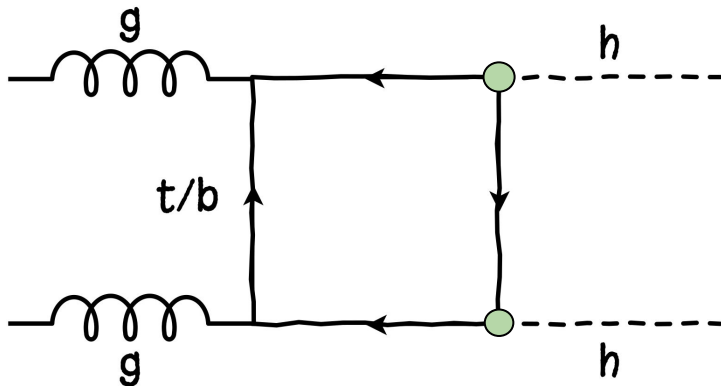IN THIS TALK

Motivation

Why **di-higgs**?

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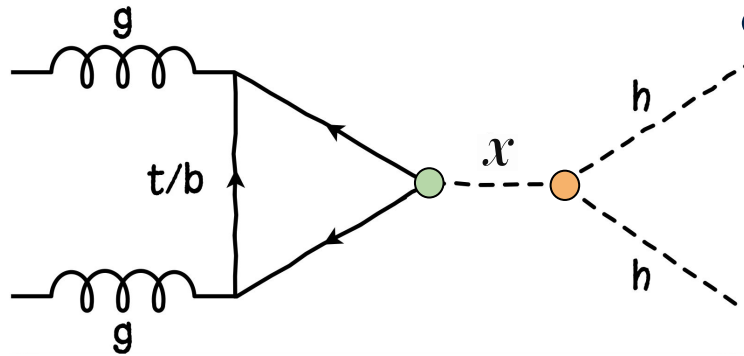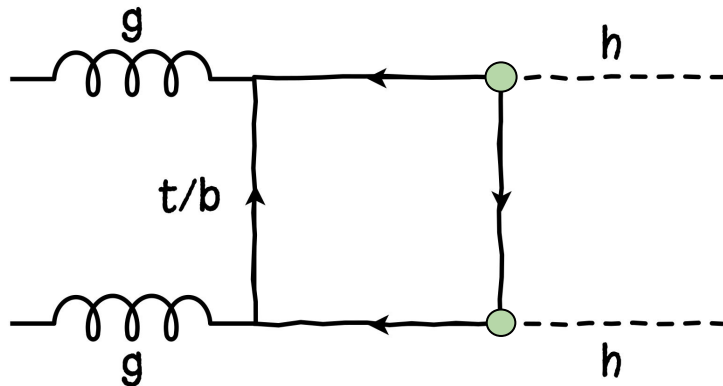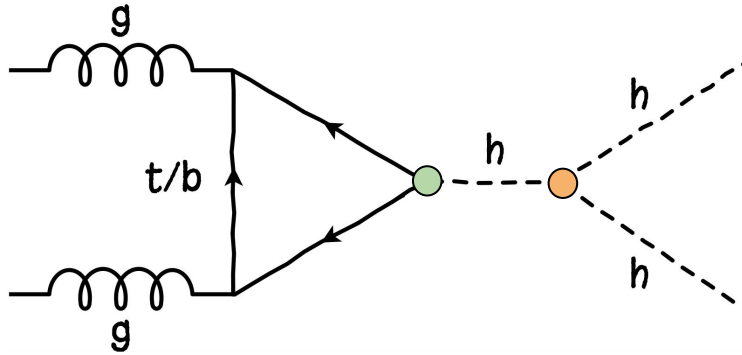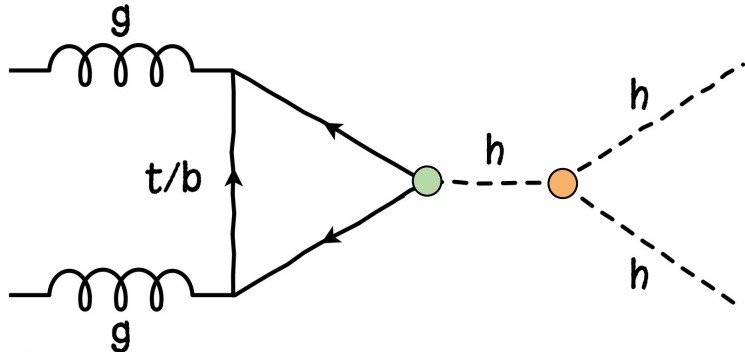 - ↳ Also to the **tth** ○ vertex
- Beyond the SM
  - ↳ **New physics** effects in ⦂ & loops
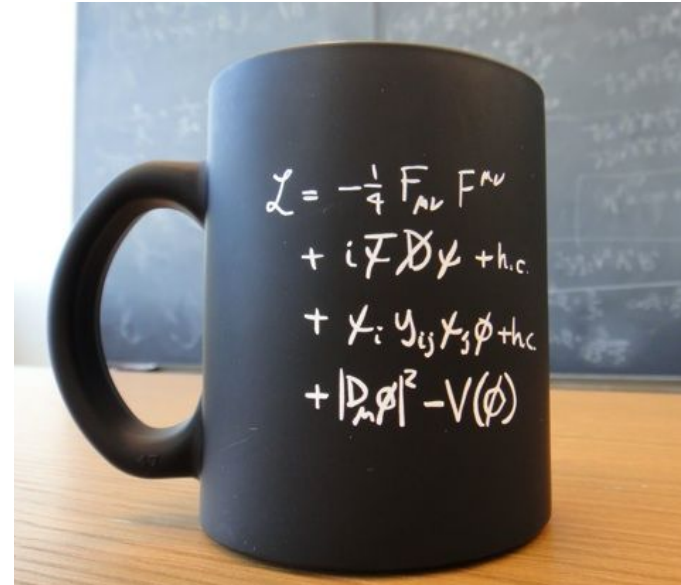 - ↳ **Heavy resonances** (x) decaying to di-higgs

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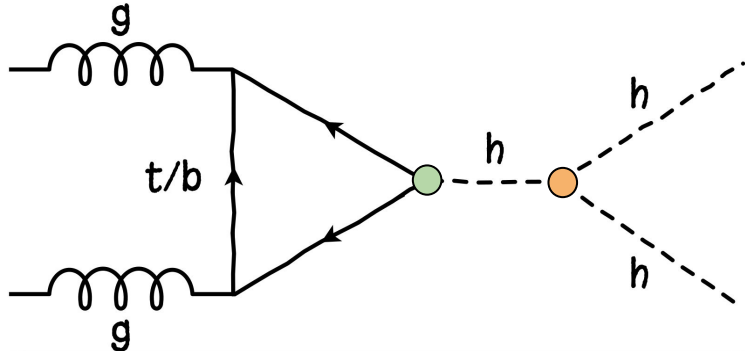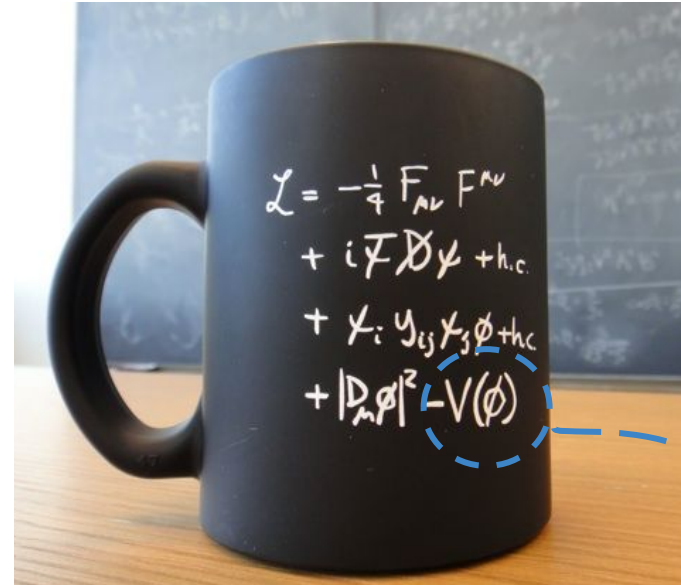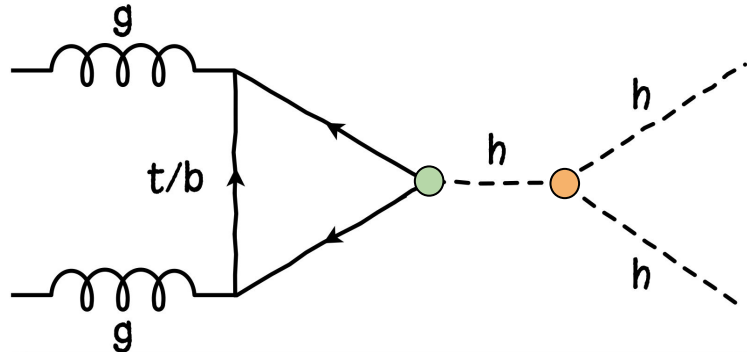 - ↳ **Heavy resonances** (x) decaying to di-higgs

Why **di-higgs**?

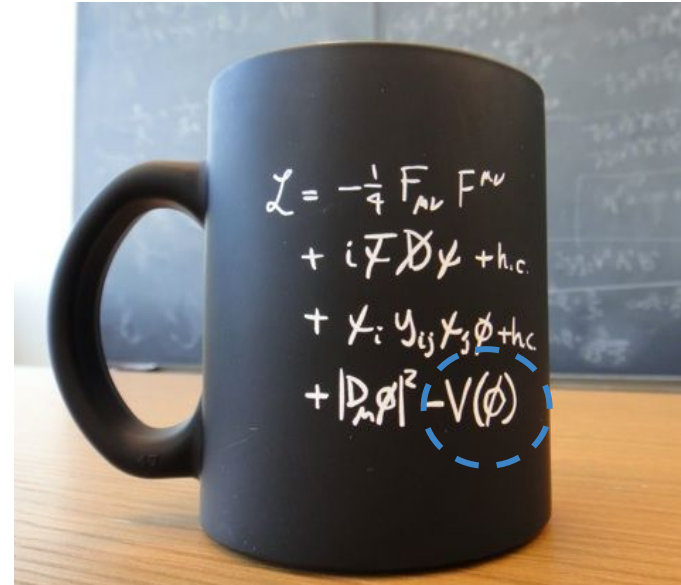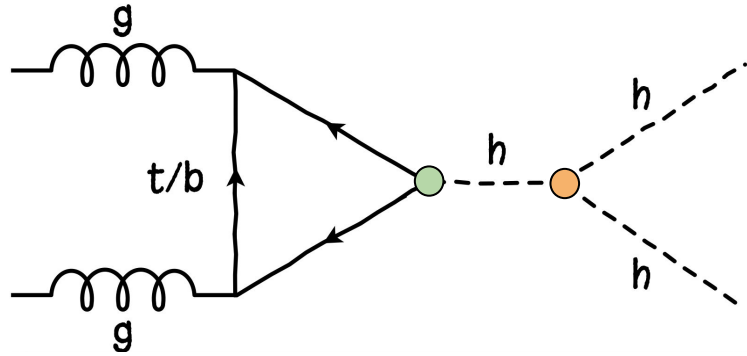# Why **di-higgs**?

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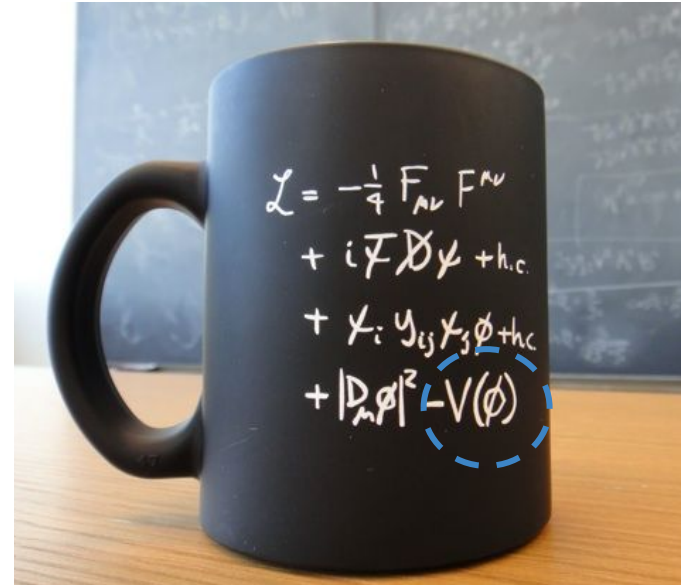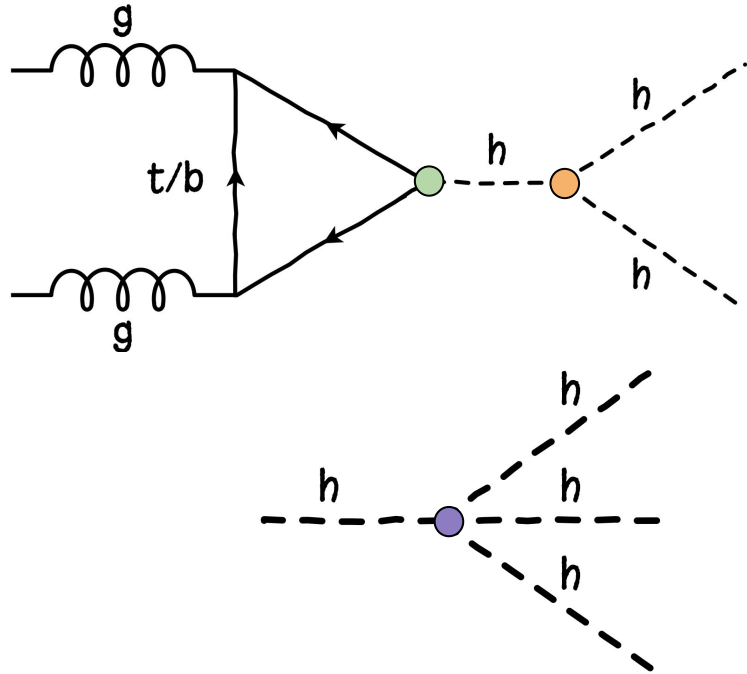

$$\lambda \nu^2 h^2 + \lambda \nu h^3 + \frac{\lambda}{4} h^4$$
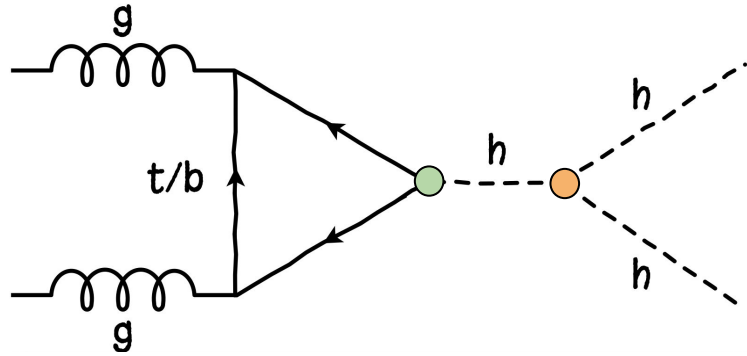
Why **di-higgs**?

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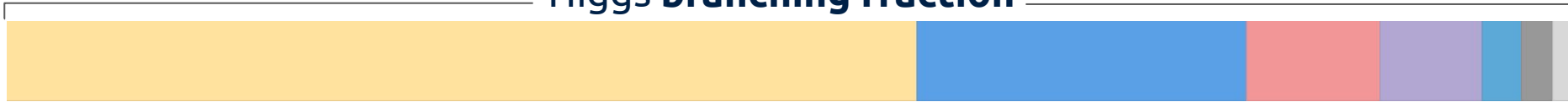
Why **di-higgs**?

- Key **missing** measurement in **SM**
- **Defines** Higgs **potential**
  - ↳ Evolution of **early universe**
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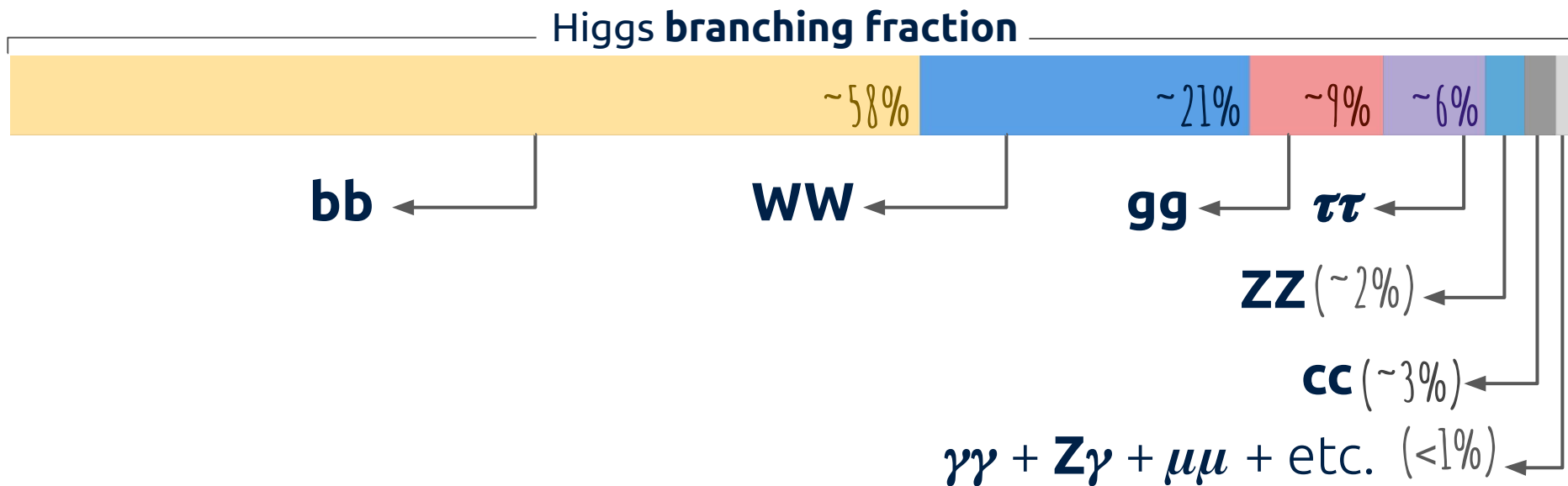- **hh** is the **only** way to **directly measure** self-coupling!

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

Which channels?

Higgs **branching fraction**

Which channels?

Higgs **branching fraction**

~58%   ~21%   ~9%   ~6%

bb   **WW**   **gg** $\tau\tau$

ZZ (~2%)

cc (~3%)

$\gamma\gamma$ + **Z**γ + $\mu\mu$ + etc. (<1%)

Why HH→**4b**?

bb

WW

gg

ττ

ZZ

cc

γγ + Zγ + μμ + etc.

~34%

~5%   ~24%

~1%

~8%

~1%

ττ gg **WW**   **bb**

Why HH→**4b**?

➔ **Public** results

bb

WW

gg

ττ

ZZ

cc

$\gamma\gamma$ + **Z**γ + $\mu\mu$ + etc.

ττ gg WW bb

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~5% ~24%

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* $\gamma\gamma$ only
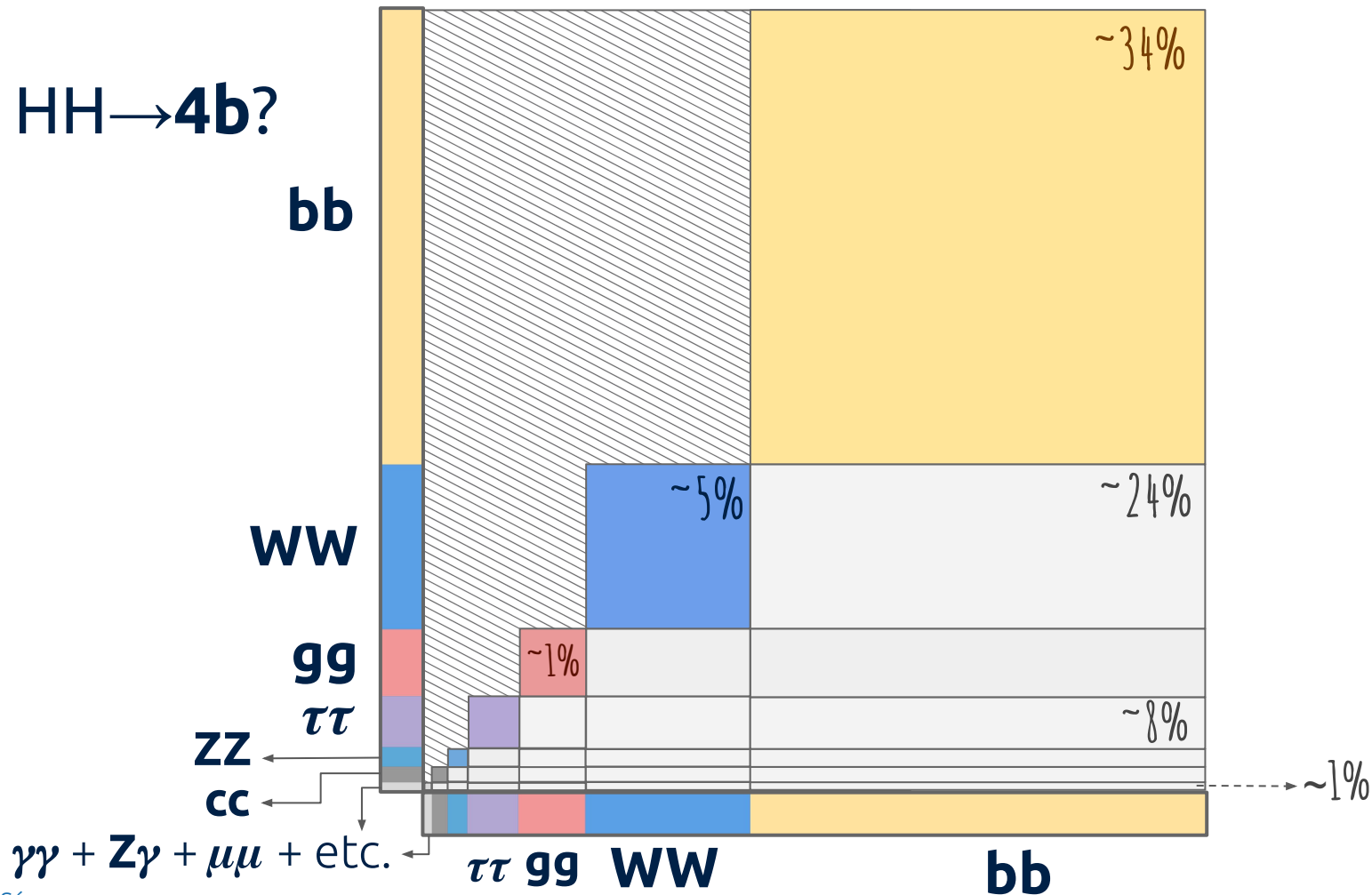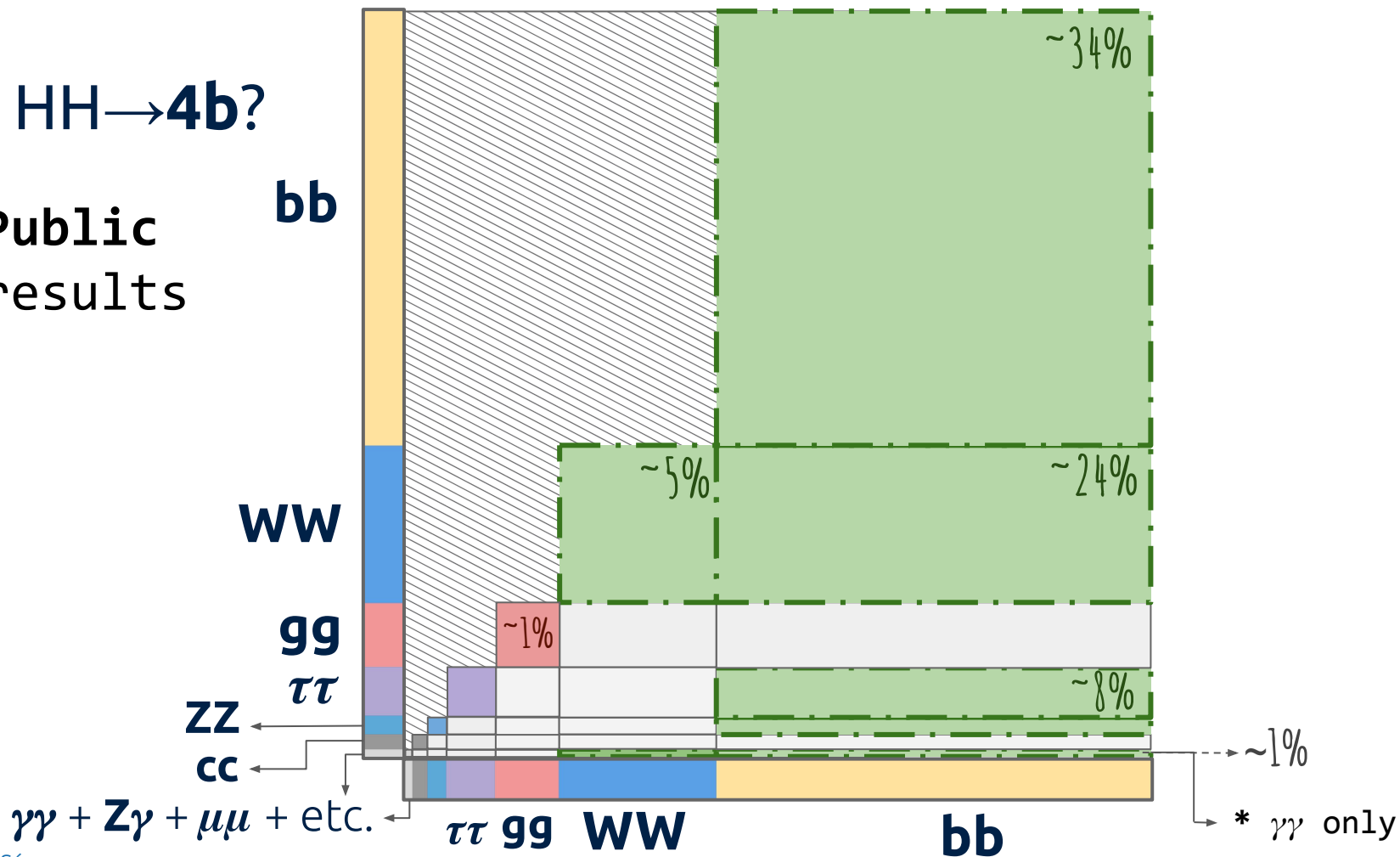
ATLAS
hh→4b
Analysis

HH → 4b: two regimes

Resolved
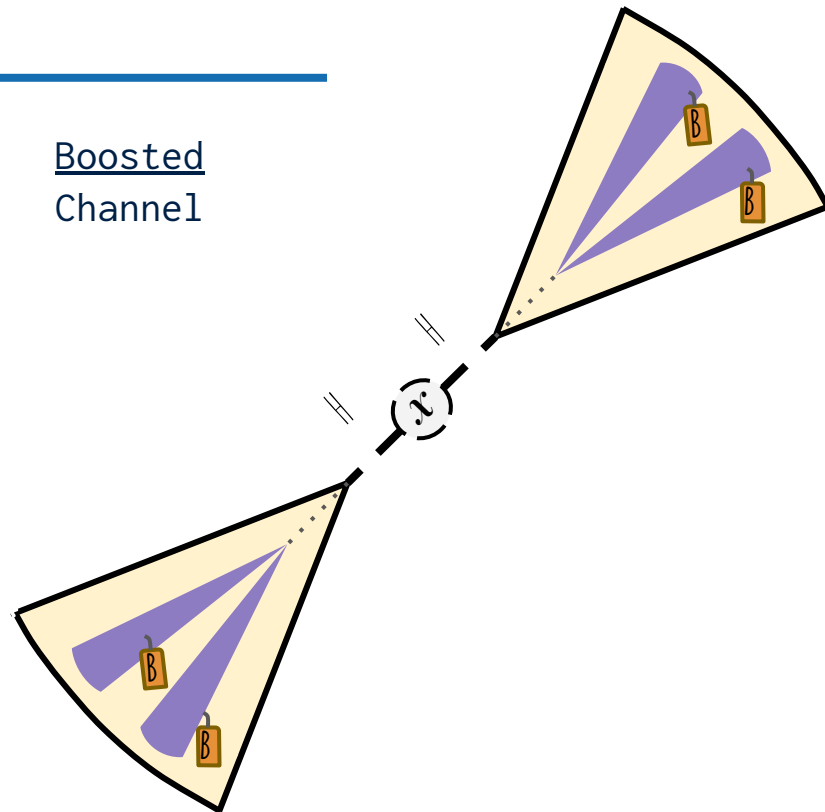Channel
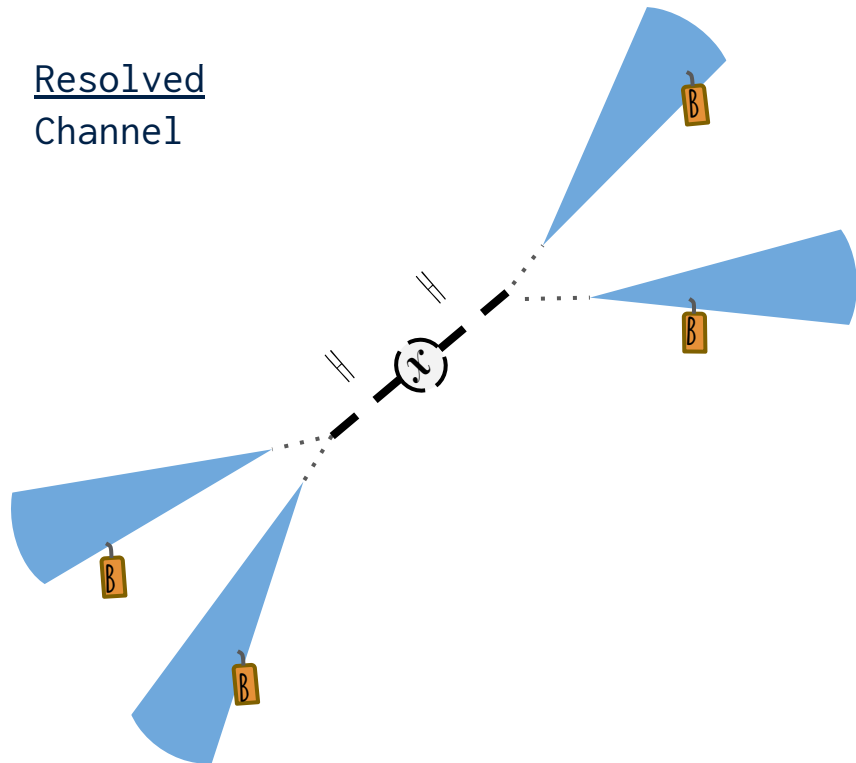
Boosted
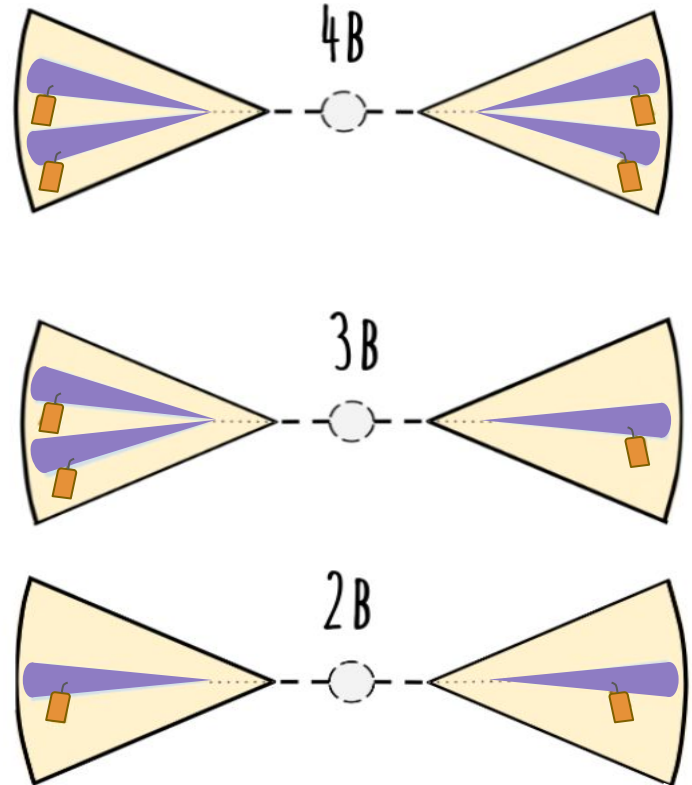Channel

Low higgs p_T

High higgs p_T

Boosted Signal Event Topology
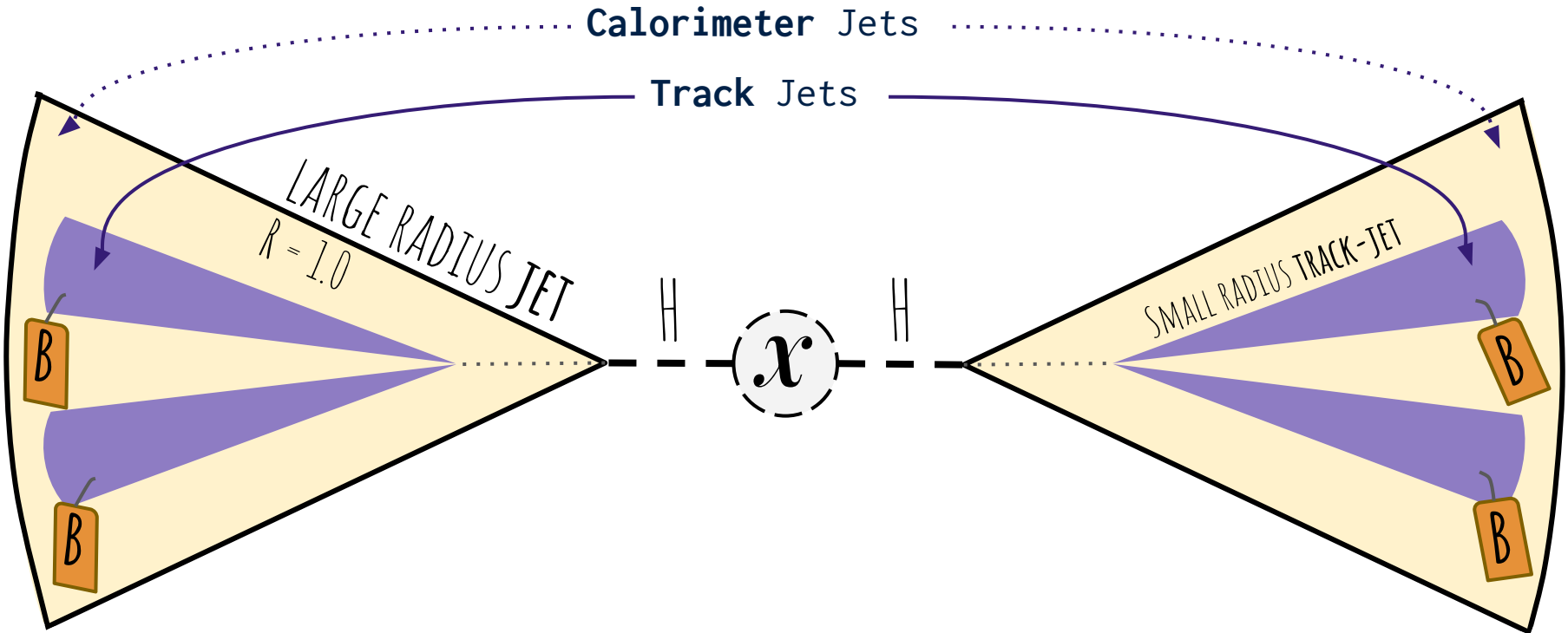
Separate signal regions

- **Boosted higgs** bosons

  ↳ Decay to **collimated b-jets**

    ↳ Jets start to **overlap**

      ⇒ **Three** search **regions**

Introduction of Variable Radius Track-Jets
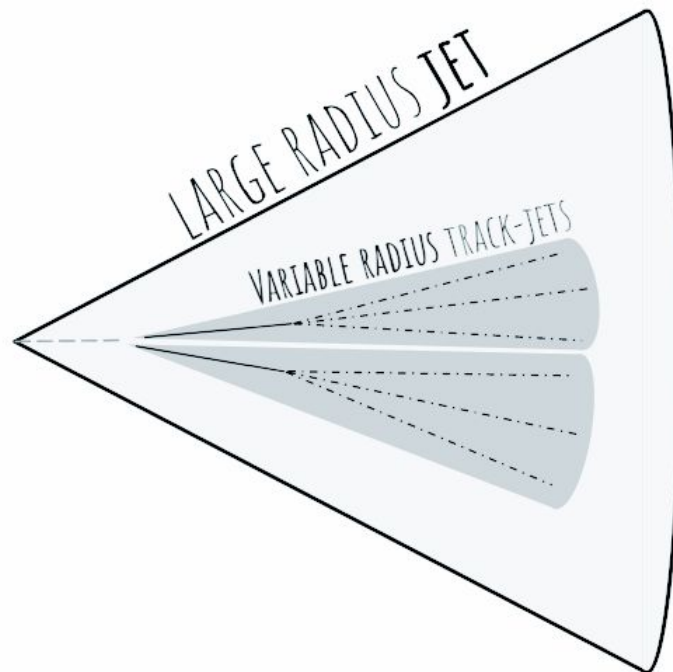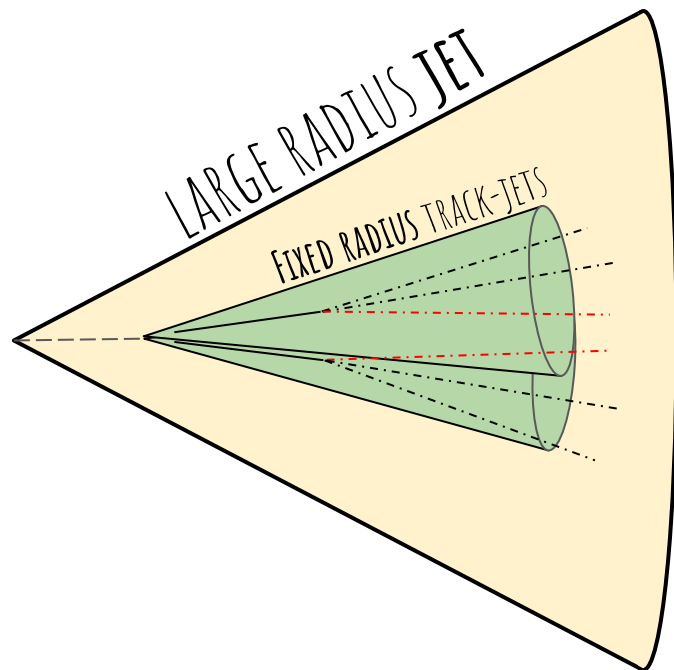
- How to **avoid overlapping** track jets **as p_T increases**?
  ↳ Let the **jet's** size **shrink**!

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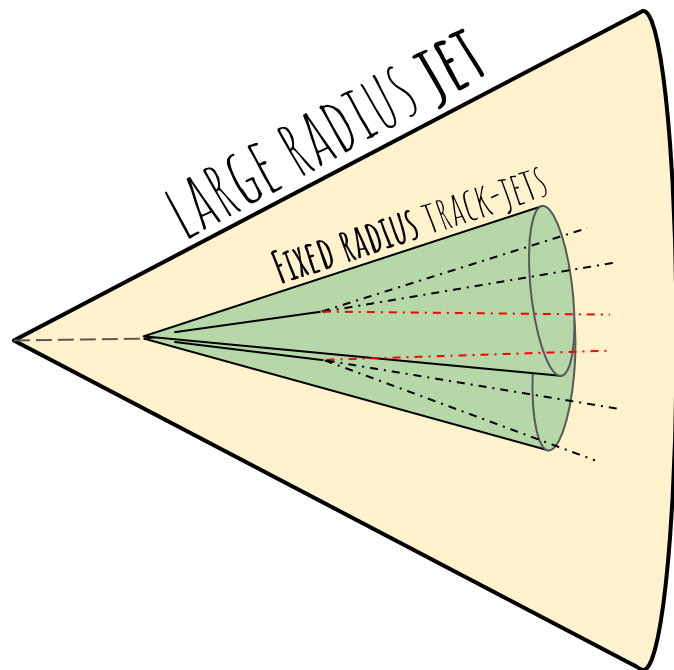
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Acceptance Gain in the 4b Region

- **Expected** migration of events **from 2b**, **3b**, **to 4b**

Acceptance ~~Gain~~ Loss in the 4b Region
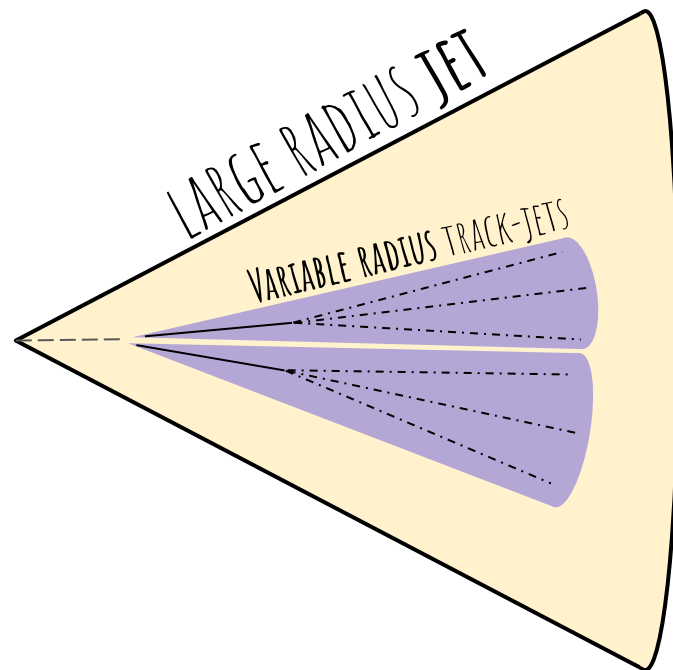
- **Expected** migration of events **from 2b**, **3b**, **to 4b**
- **Unexpected** drop in efficiency in the **4b** region
  - ↳ Events **migrated** to the **2b** region
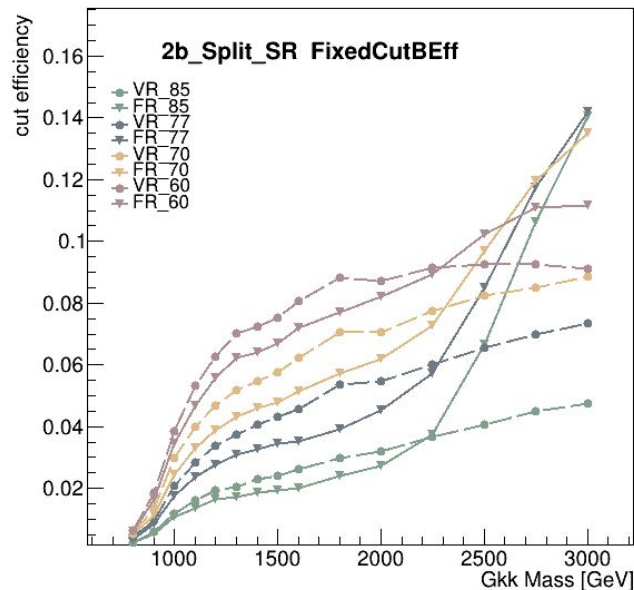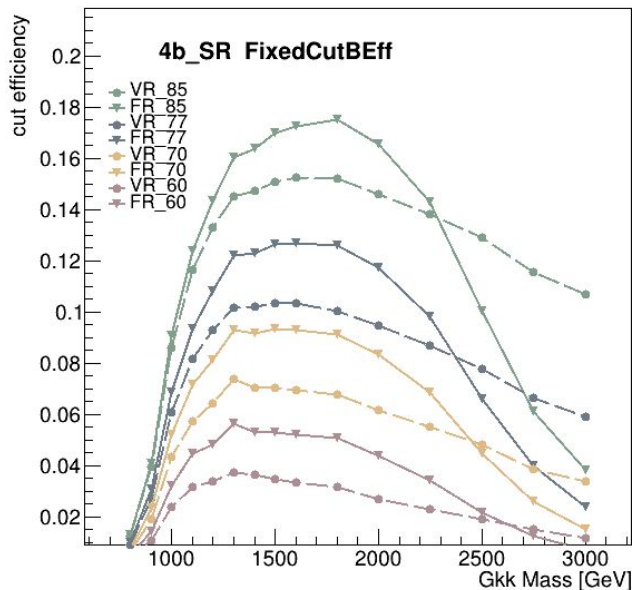
Traced down the problem...

- Working with the **flavour tagging group**
  - ↳ **Issue** was **traced** down to a **small inefficiency** in the b-tagger
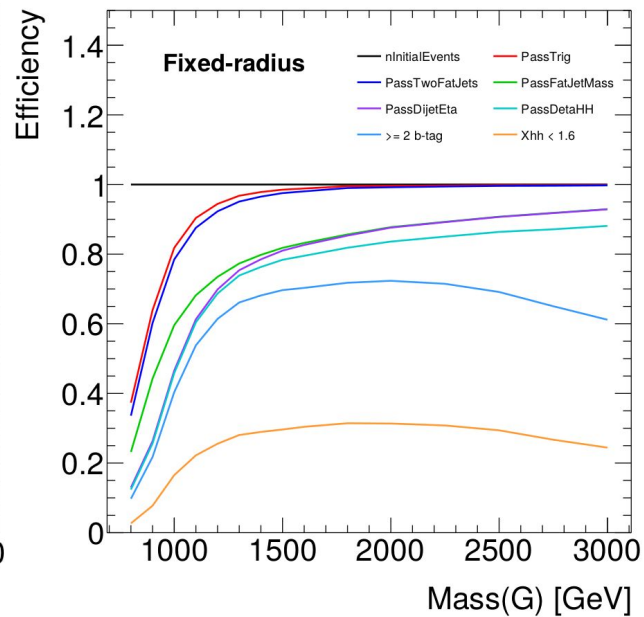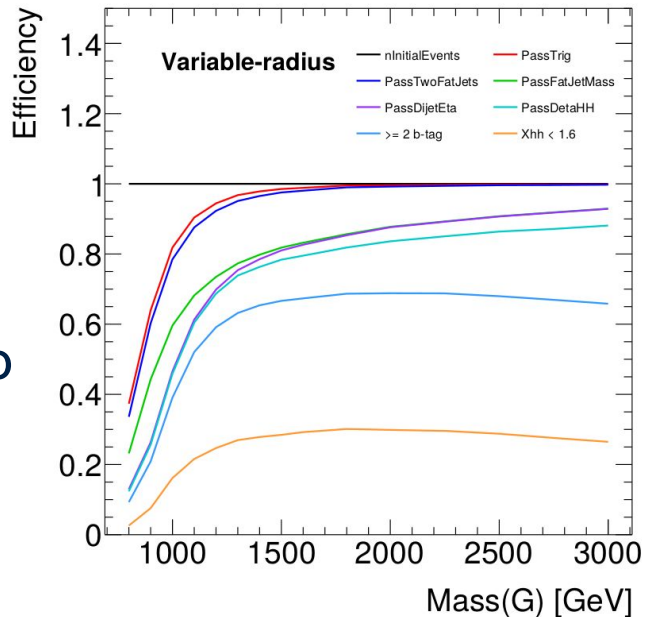
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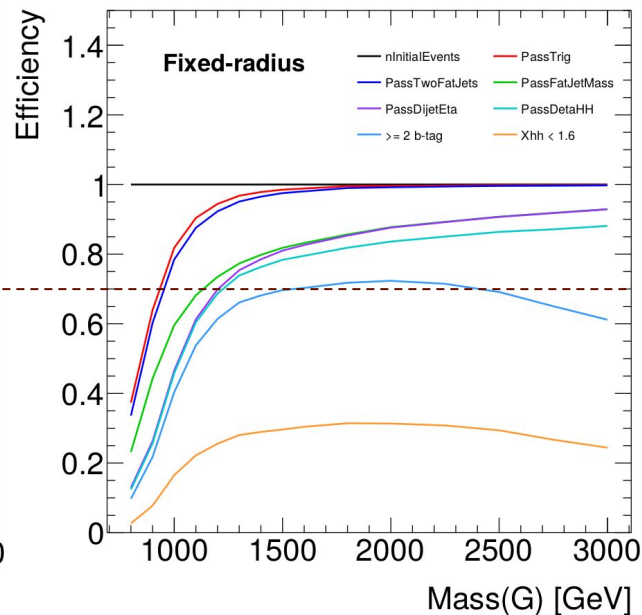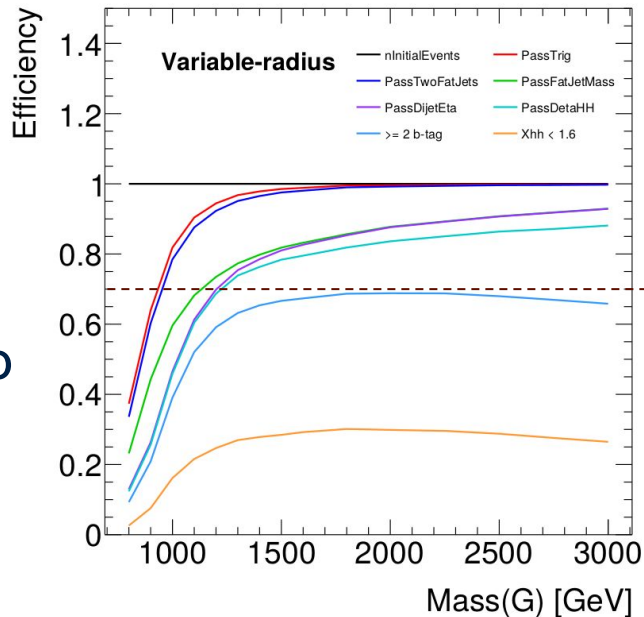
Impact on the Expected Limit

- **VR track jets** were **implemented** to the analysis
  - ↳ **Improvements** even with b-tagging issue!
- Input from our search **prompted** a re-training of btagging
  - ↳ Expected soon
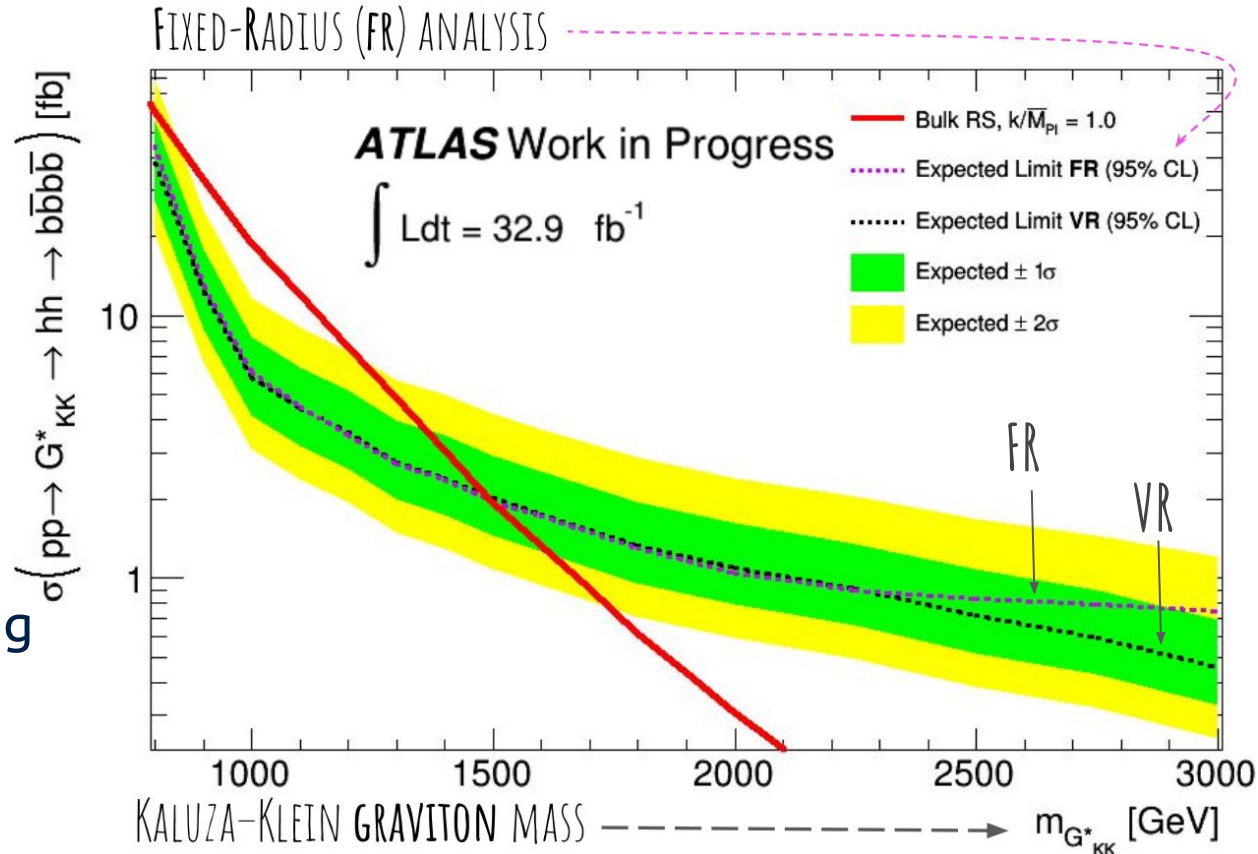
Future of
hh searches
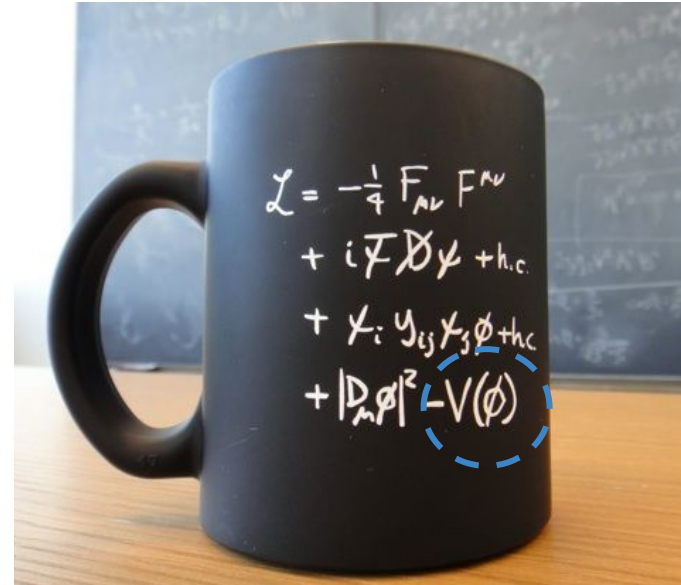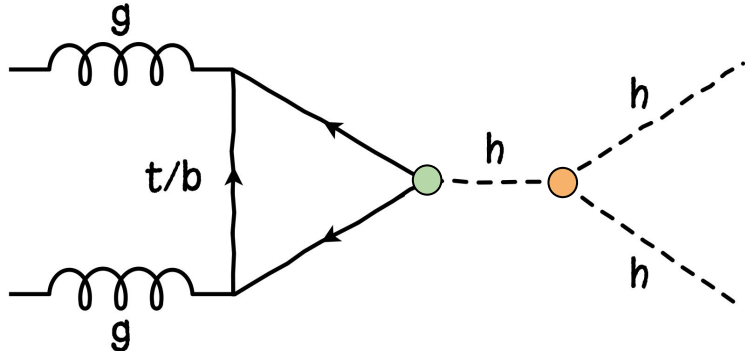
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  ↳ Baryon **asymmetry**
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$$\lambda v^2 h^2 + \boxed{\lambda v h^3} + \frac{\lambda}{4} h^4$$

Future & Prospects

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

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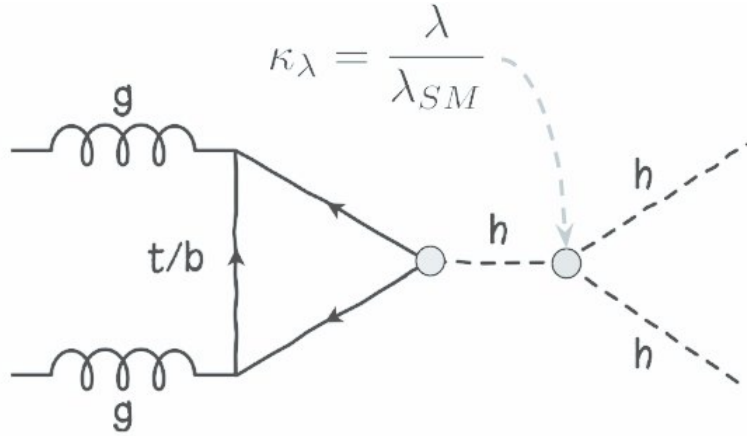
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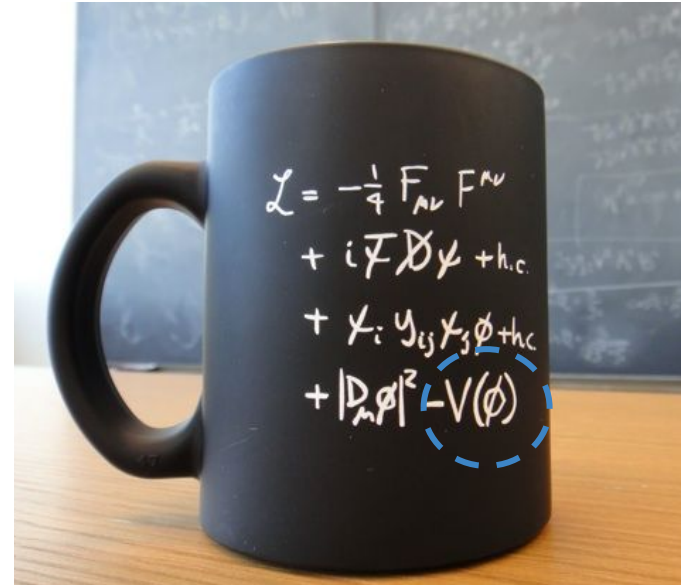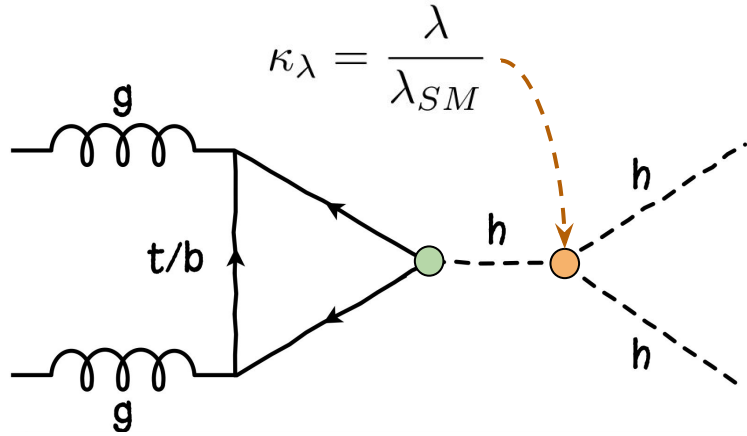- **hh** is the **only** way to **directly measure** self-coupling!

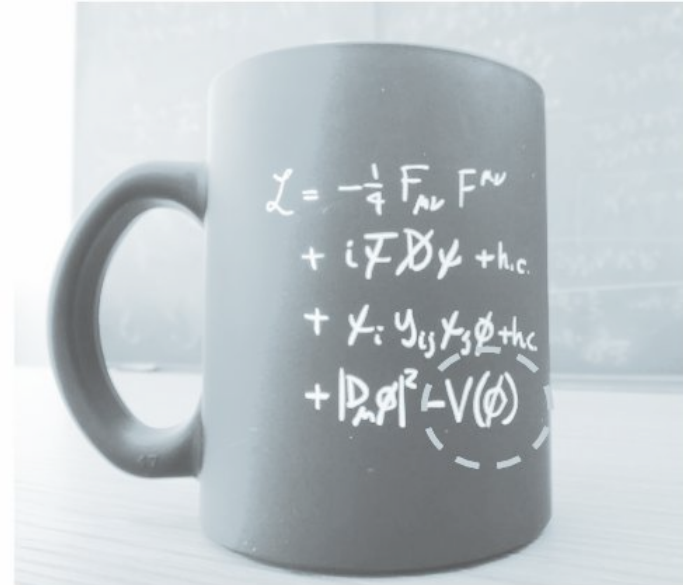$$\lambda v^2 h^2 + \boxed{\lambda v h^3} + \frac{\lambda}{4} h^4$$

Future & Prospects

- **Multiple** channels making promising **progress**!
  ↳ bb$\gamma\gamma$, **bb$\tau\tau$**, and bbbb
- **HL-LHC** projections (yellow report)
  ↳ **~3σ** sensitivity for **hh** discovery
  ↳ **~50%** precision on κ_λ

- Key **missing** ...
- **Defines** Higgs potential
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$\kappa_\lambda = \dfrac{\lambda}{\lambda_{SM}}$

Phenomenology Studies of Di-Higgs→4b

- **Study** the hh→4b process in **HL-LHC** conditions
  - ↳ Explore how to **optimize for** κ_λ precision
  - ↳ Explore **new techniques** to overcome difficulties

Higgs self-coupling measurements using deep learning and jet substructure

William Balunas,[a] Lydia Beresford,[a] Daniela Bortoletto,[a] James Frost,[a] Cigdem Issever,[a,b,c] Jesse Liu,[d] Santiago Paredes Saenz,[a] Michael Spannowsky,[e] and Beojan Stanislaus[a]

[a]Department of Physics, University of Oxford, 1 Keble Road, Oxford OX1 3RH, UK
[b]Humboldt-Universität zu Berlin, Institut für Physik, Newtonstraße 15, 12489 Berlin, Germany
[c]DESY, Platanenallee 6, D-15738 Zeuthen, Germany
[d]Department of Physics, University of Chicago, 933 E 56th St, Chicago IL 60637, USA
[e]Institute of Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK

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DRAFT

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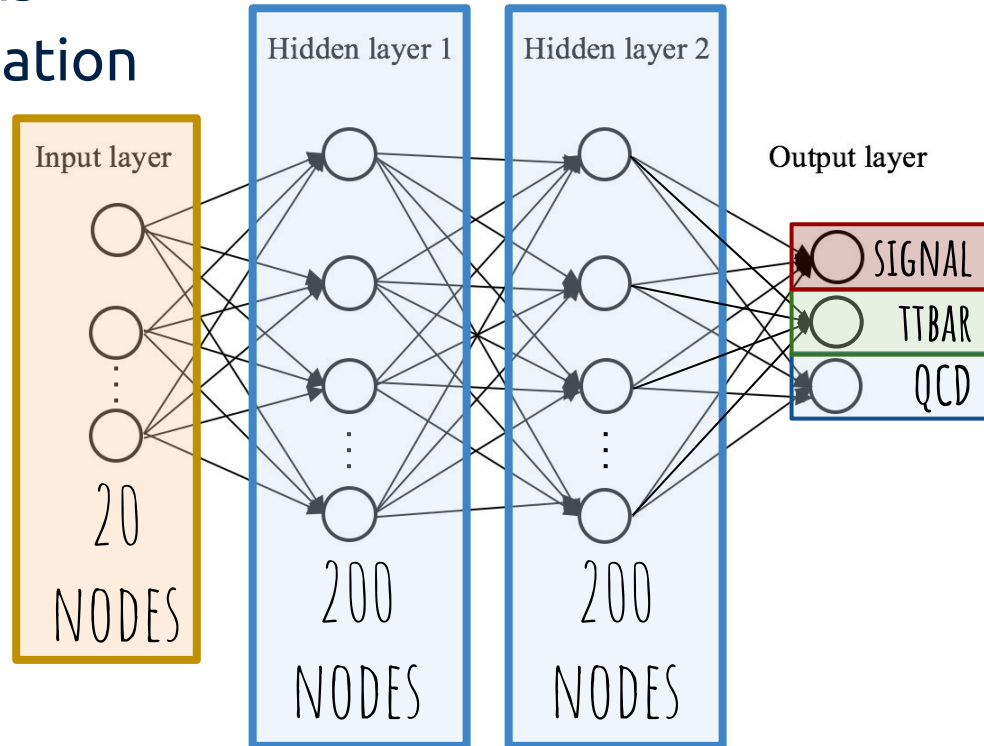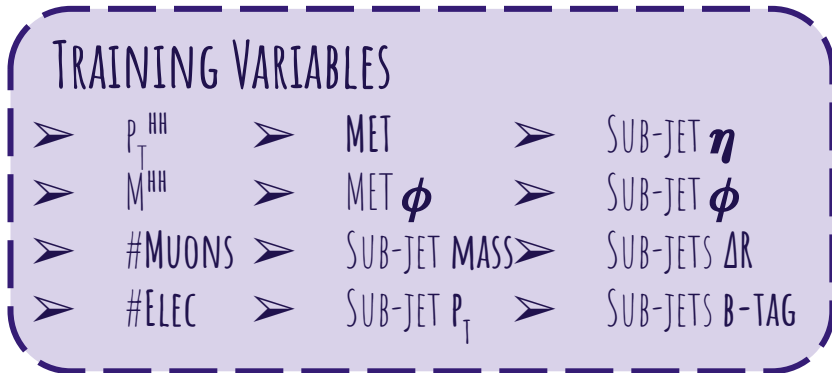[c] DESY, Platanenallee 6, D-15738 Zeuthen, Germany
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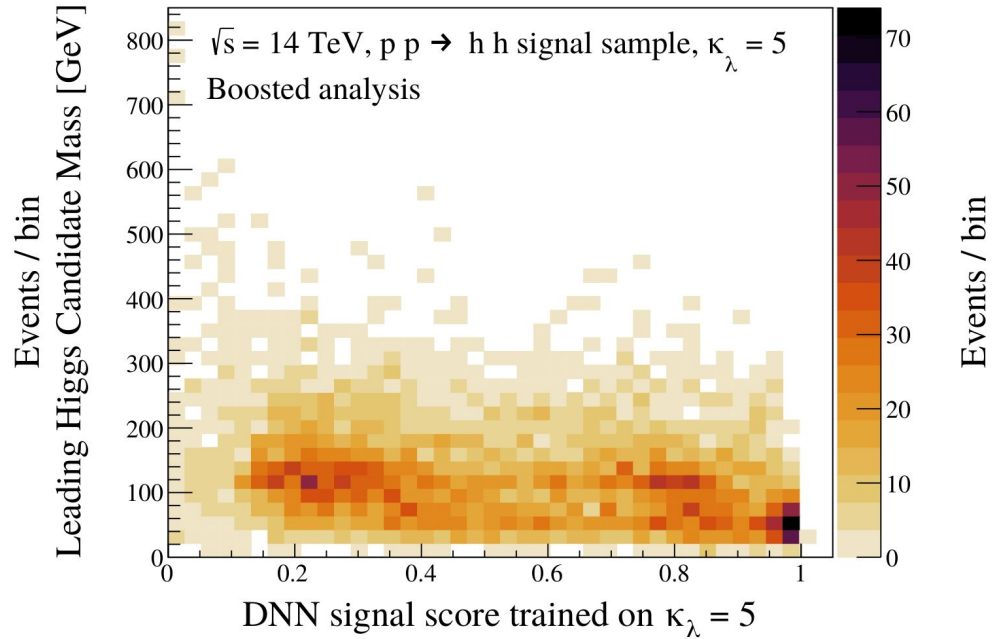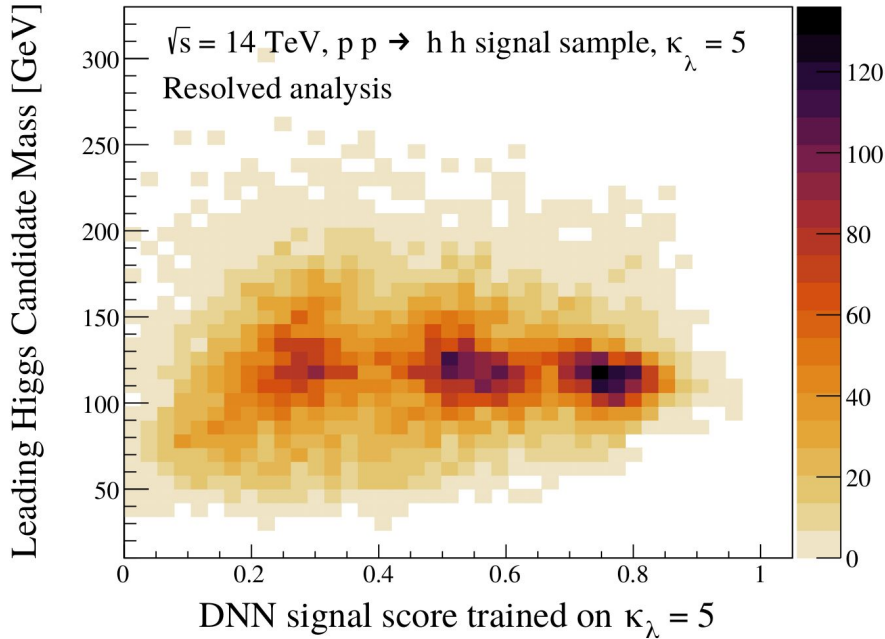[e] Institute of Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK

Neural Networks Analysis

- One of the **main challenges** is **signal-background** discrimination
 - ↳ Trained **neural networks** to improve separation

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

Input layer

20 NODES

Hidden layer 1

200 NODES

Hidden layer 2

200 NODES

Output layer

SIGNAL
TTBAR
QCD

NN Validation: Signal Sample

- ## Correlation plots made to validate NN training
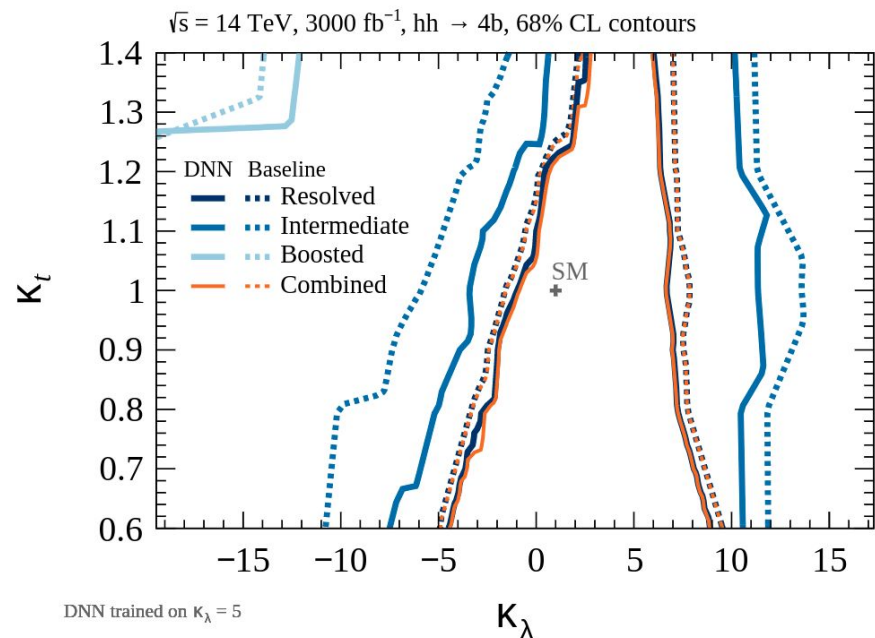
NN Feature impact: SHAP values

- [SHAP](#):
  - ↳ **SH**apley **A**dditive
    ex**P**lanations
  - ↳ **Combines** several feature
    importance **methods**
- **Impact** on **signal score** of each
  of the **input variables**
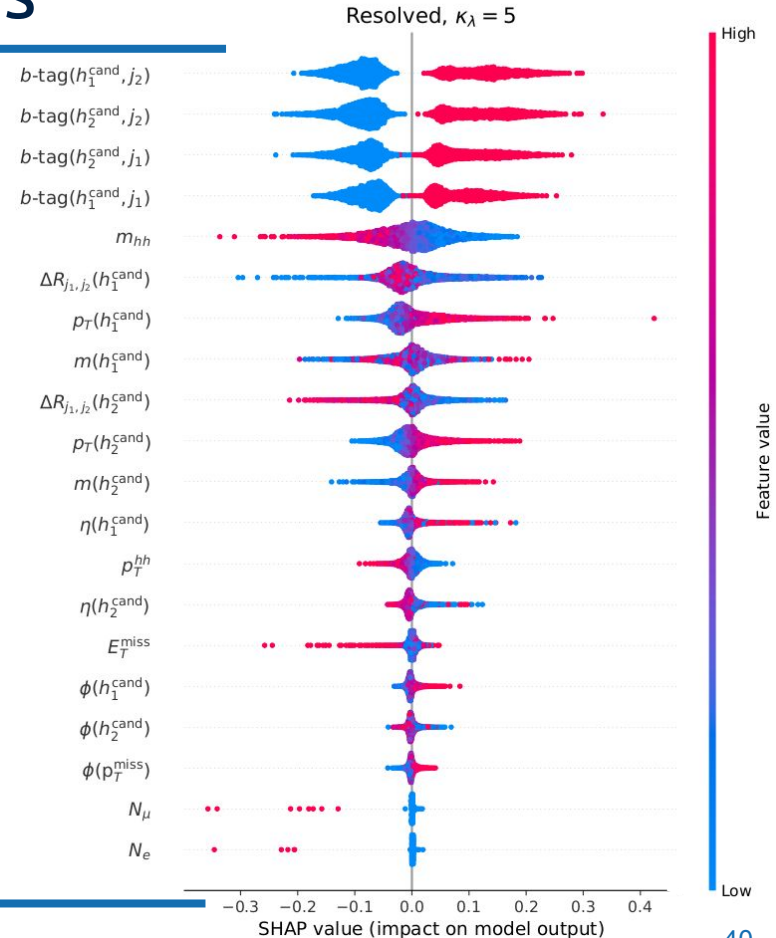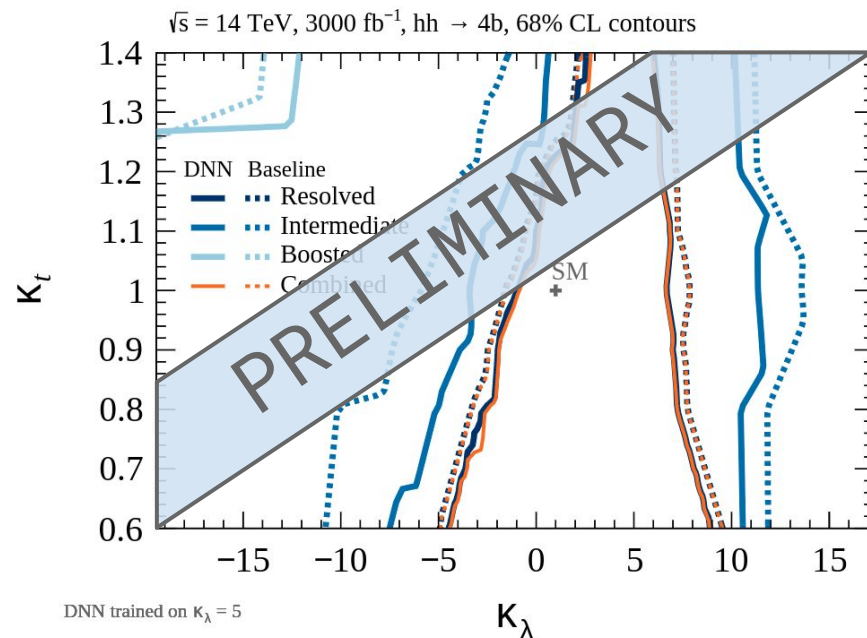

Resolved, $\kappa_\lambda = 5$

Neural Network Improvements

- Cuts on **neural network signal score** were set in the analysis
  - ↳ Significant **improvements**, even with proof-of-concept
    - ↳ **Room to expand** in the future

$\sqrt{s}$ = 14 TeV, 3000 fb^{-1}, hh → 4b, 68% CL contours

DNN   Baseline
Resolved
Intermediate
Boosted
Combined

SM

DNN trained on $\kappa_\lambda = 5$

κ_λ

κ_t

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SM

κ_t

κ_λ

DNN trained on $\kappa_\lambda = 5$

PRELIMINARY

Summary

Summary & Conclusions

- A variety of **di-Higgs** searches are doing good progress towards **discovery** and **constraining** λ_{hhh}
  - ↳ **hh→4b** and **hh→bb**$\tau\tau$ two **most sensitive** channels in ATLAS
- **Di-higgs** is a **rich area** for both **SM** and **BSM** searches
  - ↳ **Promising** results expected for **run III** and **HL-LHC**
  - ↳ With **new approaches** and **novel techniques** these **expectations** could even be **exceeded**!

Latest ATLAS hh4b paper
Latest ATLAS bbtautau paper
h+hh self-coupling constraints

Thanks!

Santiago Paredes Sáenz
santiago.paredes@physics.ox.ac.uk
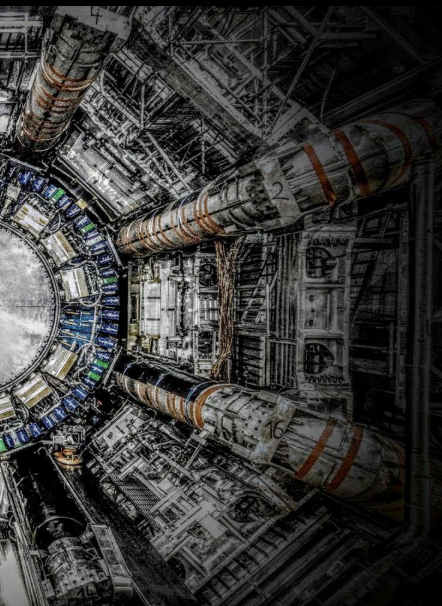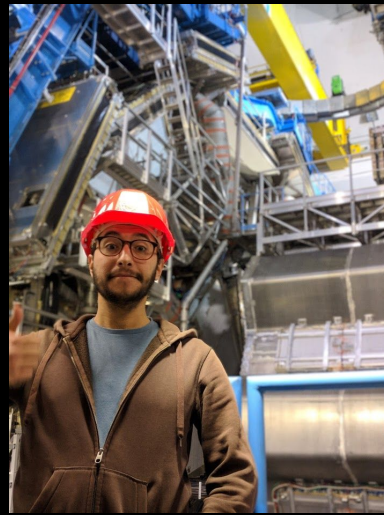
HEPHY Vienna
March 2020

Thanks!

Santiago Paredes Sáenz
santiago.paredes@physics.ox.ac.uk
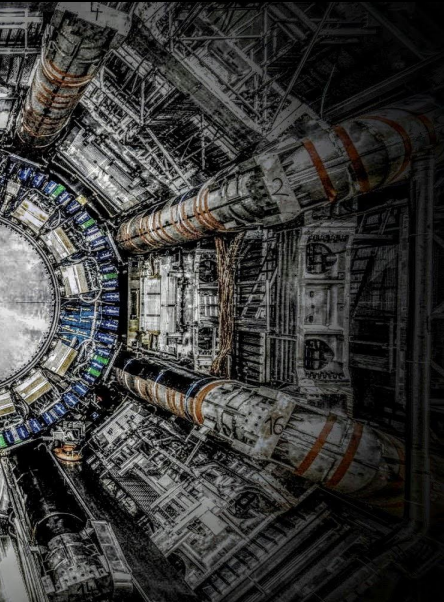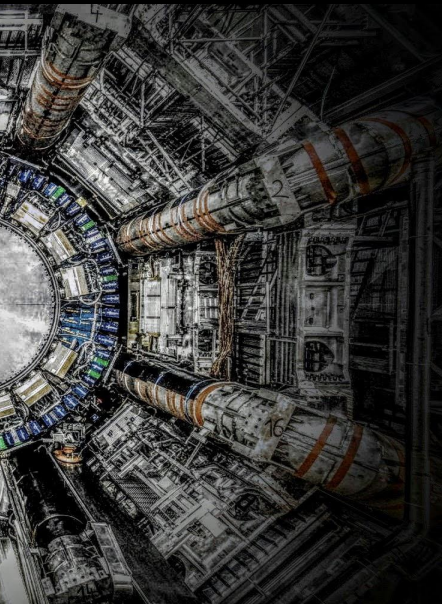
HEPHY Vienna
March 2020
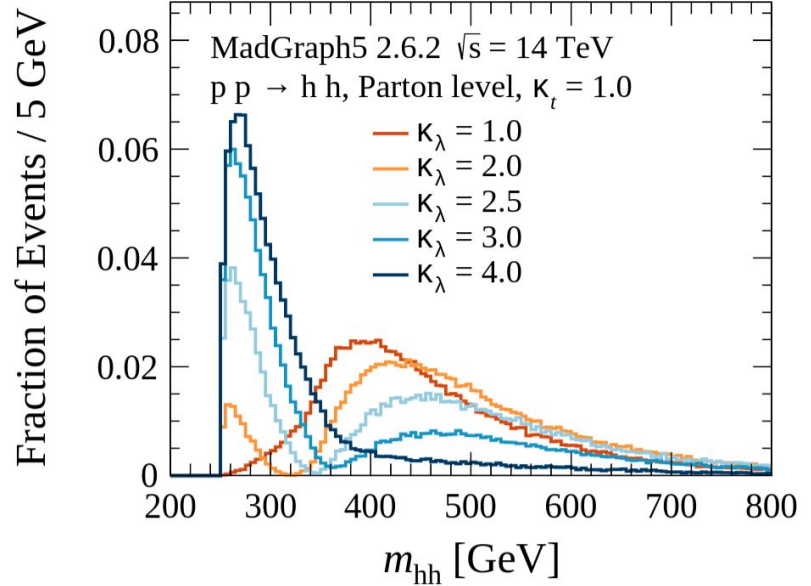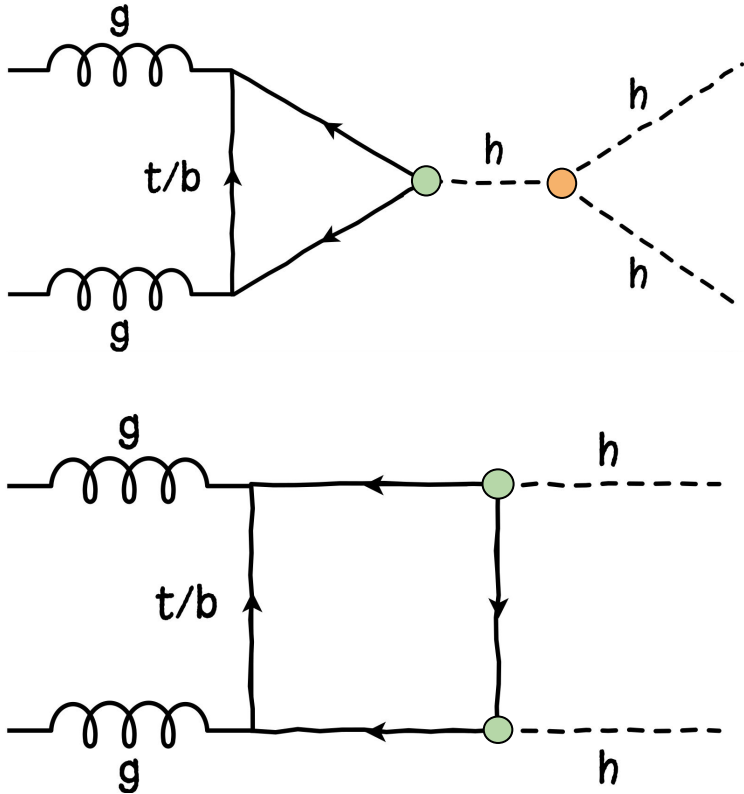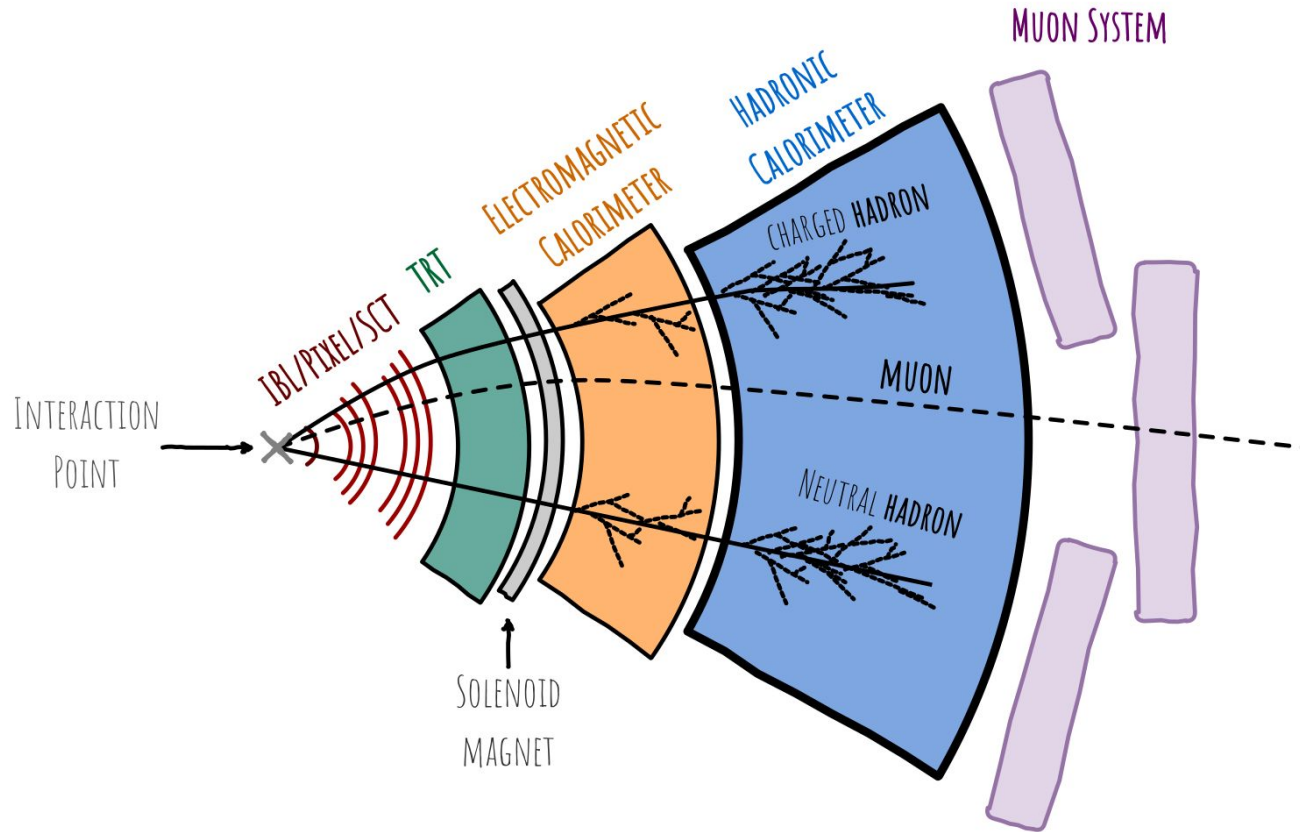
Additional Slides

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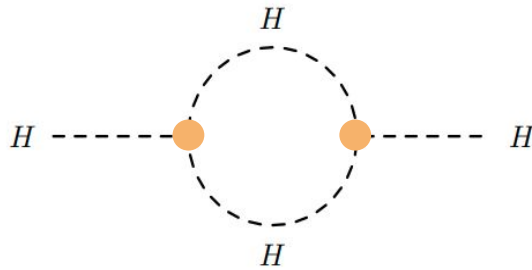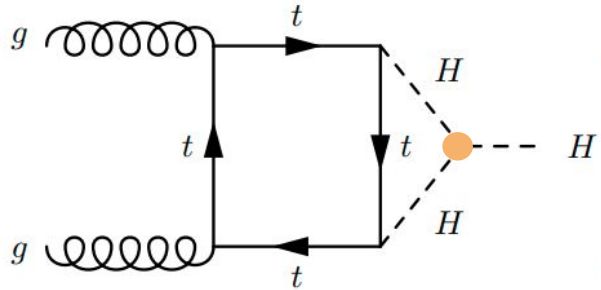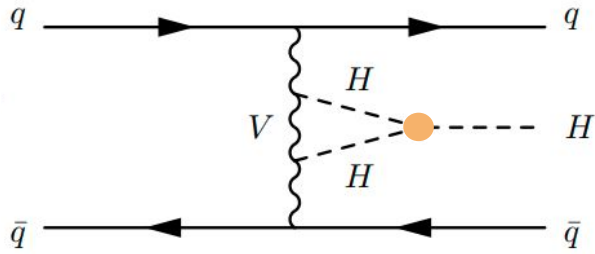HEPHY Vienna
March 2020

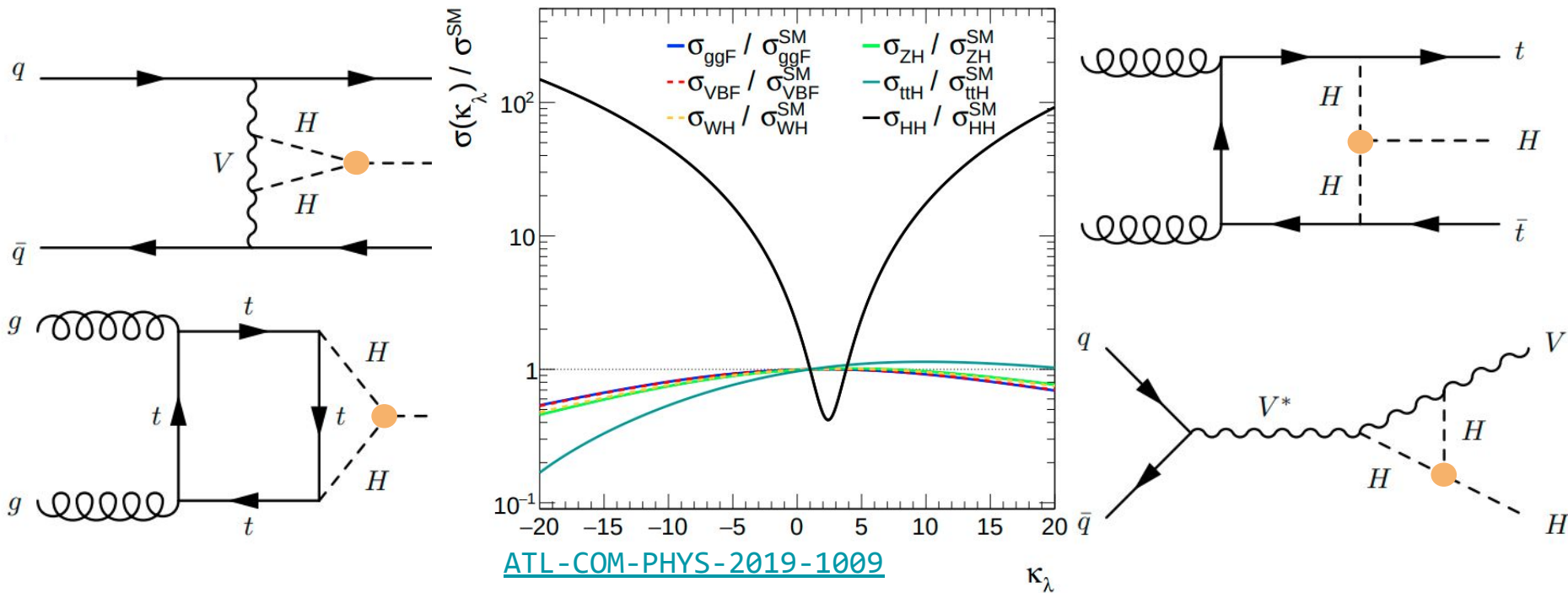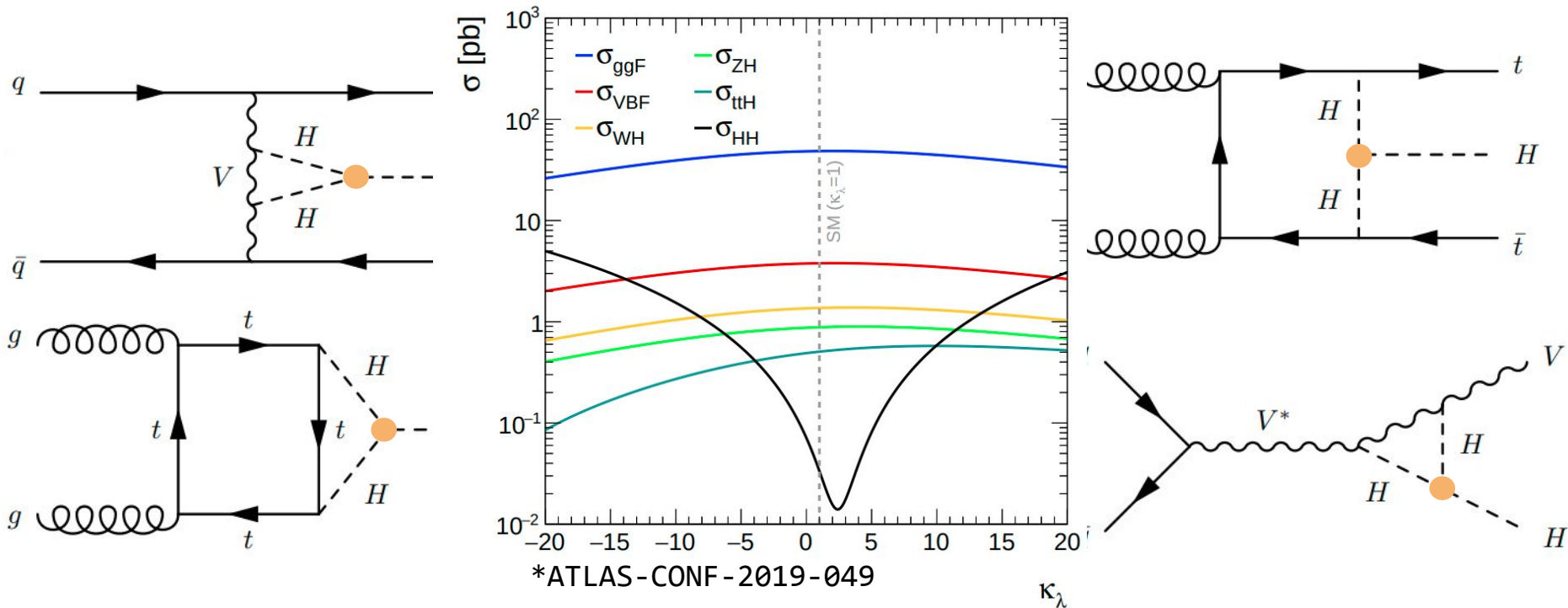# Di-Higgs Diagram Interference

ATLAS Detector

Self-Coupling from Single Higgs Production
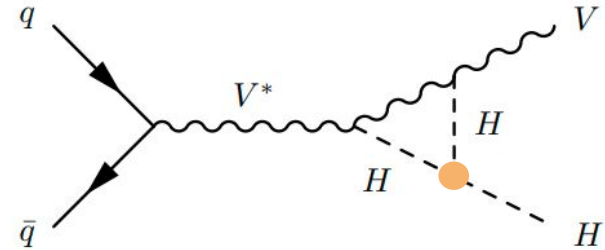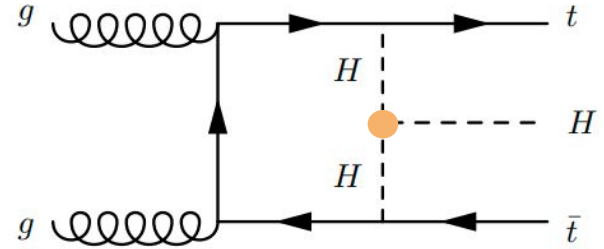
- **Single Higgs** also (indirectly) depends on λ_{hhh} !

Self-Coupling from Single Higgs Production

- **Single Higgs** also (indirectly) depends on λ_{hhh} !

ATL-COM-PHYS-2019-1009

Self-Coupling from Single Higgs Production

- **Single Higgs** also (indirectly) depends on λ_{hhh} !

*ATLAS-CONF-2019-049

The Idea

- **Combine** existing **H and HH** analyses for **improved constraints**

Single Higgs
36.1 fb^{-1} - 79.8 fb^{-1}

$$H \to \gamma\gamma$$
$$H \to ZZ^* \to 4\ell$$
$$H \to WW^* \to e\nu\mu\nu$$
$$H \to \tau^+\tau^-$$
$$VH, H \to b\bar{b}$$
$$t\bar{t}H, H \to b\bar{b}$$
$$t\bar{t}H, H \to \text{multilepton}$$

Double Higgs
27.5 fb^{-1} - 36.1 fb^{-1}

$$HH \to b\bar{b}b\bar{b}$$
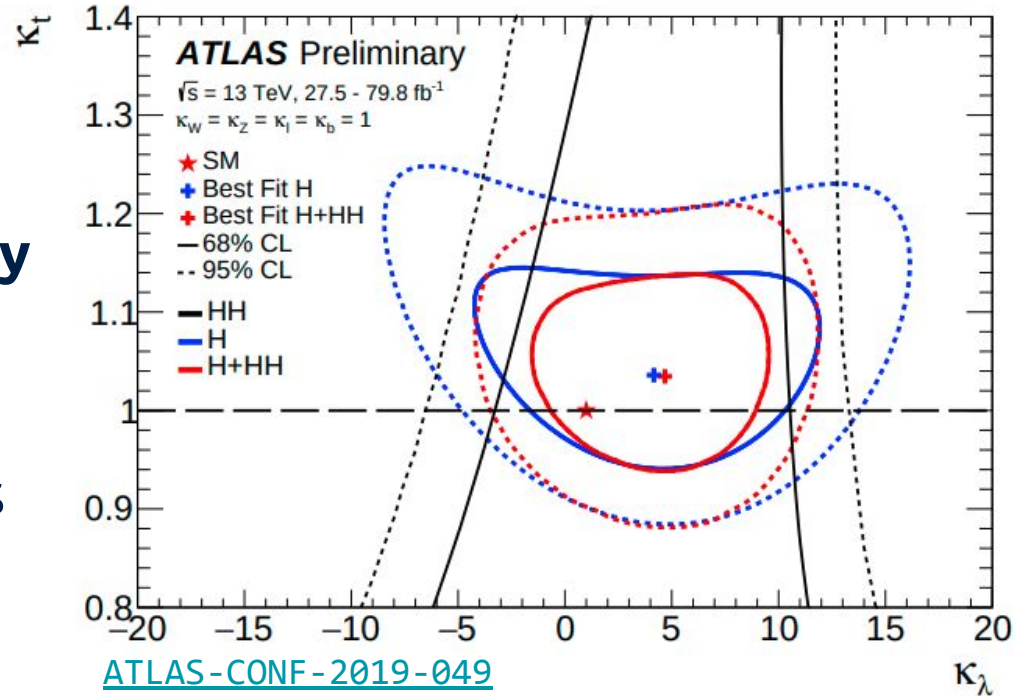$$HH \to b\bar{b}\tau^+\tau^-$$
$$HH \to b\bar{b}\gamma\gamma$$

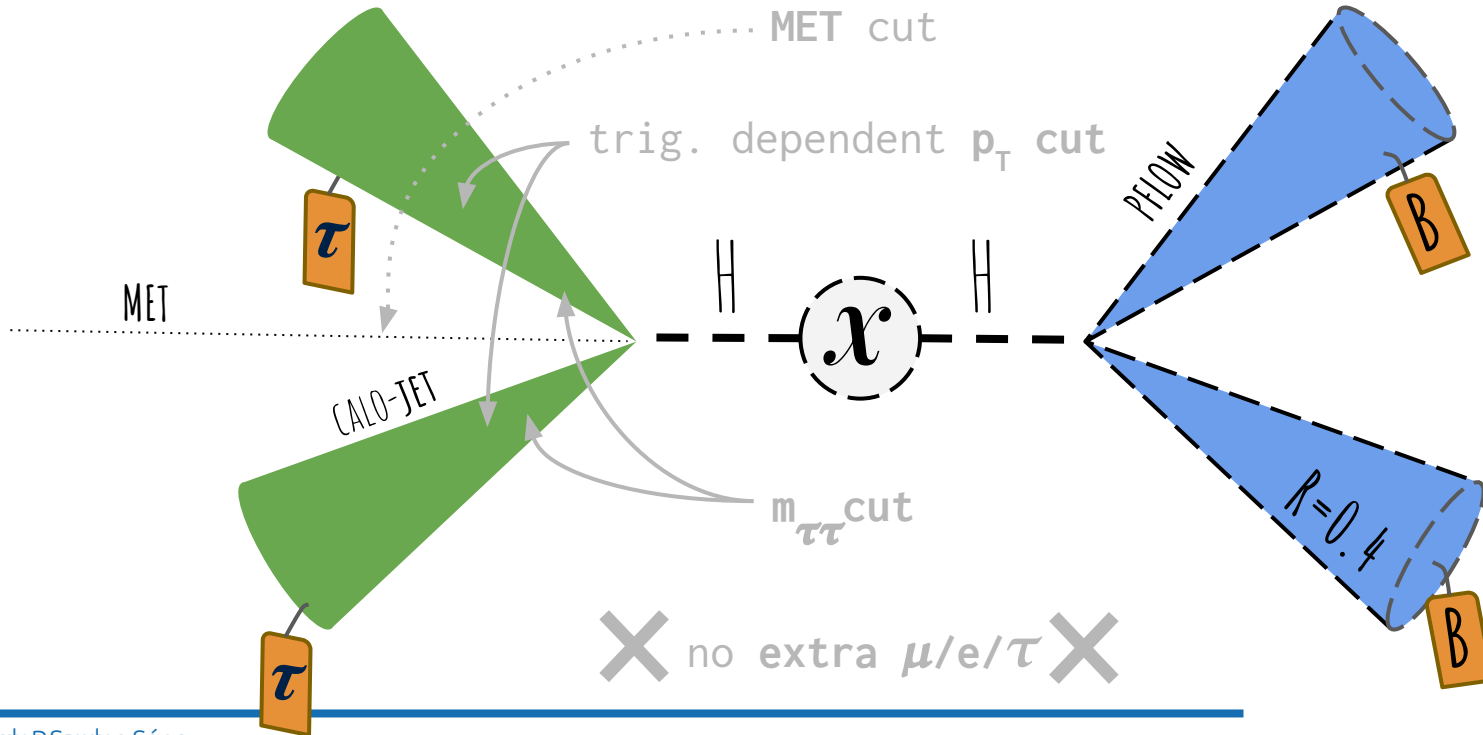*Caveat: **Overlap** between **H** and **HH** analyses carefully considered

Improved Constraints!

- **Constraints** improved by combining **H** and **HH**
- **Various results** presented:
  - ↳ Varying **self-coupling only**
  - ↳ Vary **self-coupling** and **coupling to top**
  - ↳ **Generic model** (couplings to V, top, b, lep. may vary)

ATLAS-CONF-2019-049

Resolved bbττ (had-had) Event Topology

⚠ **single** or **di-τ** trigger ⚠

MET cut

trig. dependent p_T **cut**

PFLOW

τ

MET

𝒳

H   H

B

CALO-JET

$m_{ττ}$ cut

R=0.4

τ

✖ no **extra** **μ/e/τ** ✖

B

× **μ/e** vetoes ×

MET cut

at least **1 di - τ**

R = 1.0

R = R(P_T)

LARGE RADIUS JETS

VARIABLE-RADIUS **TRACK-JETS**
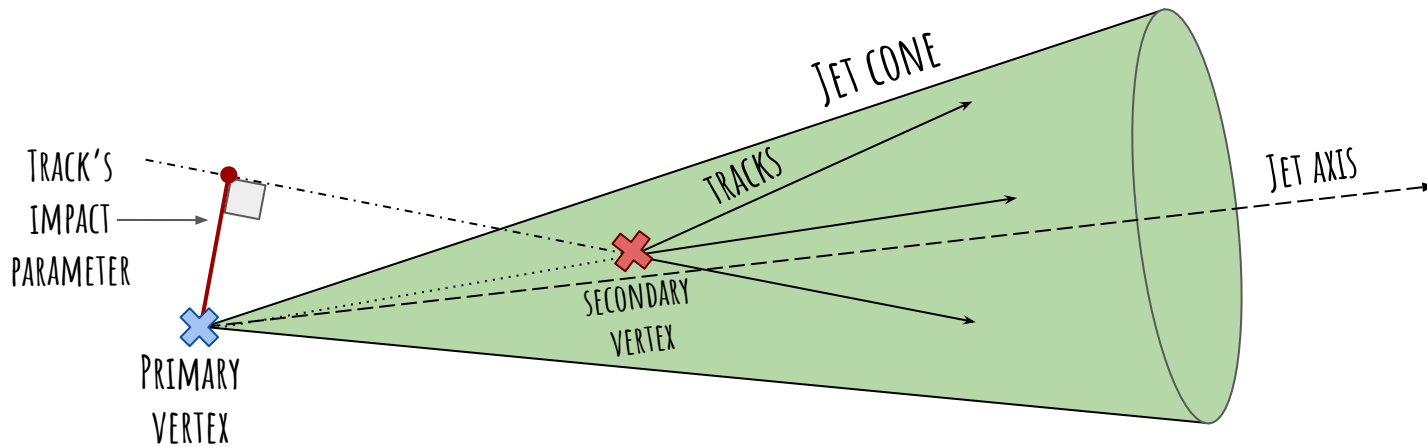
B

B

H   **x**   H

CALO-JET

R = 0.2

τ

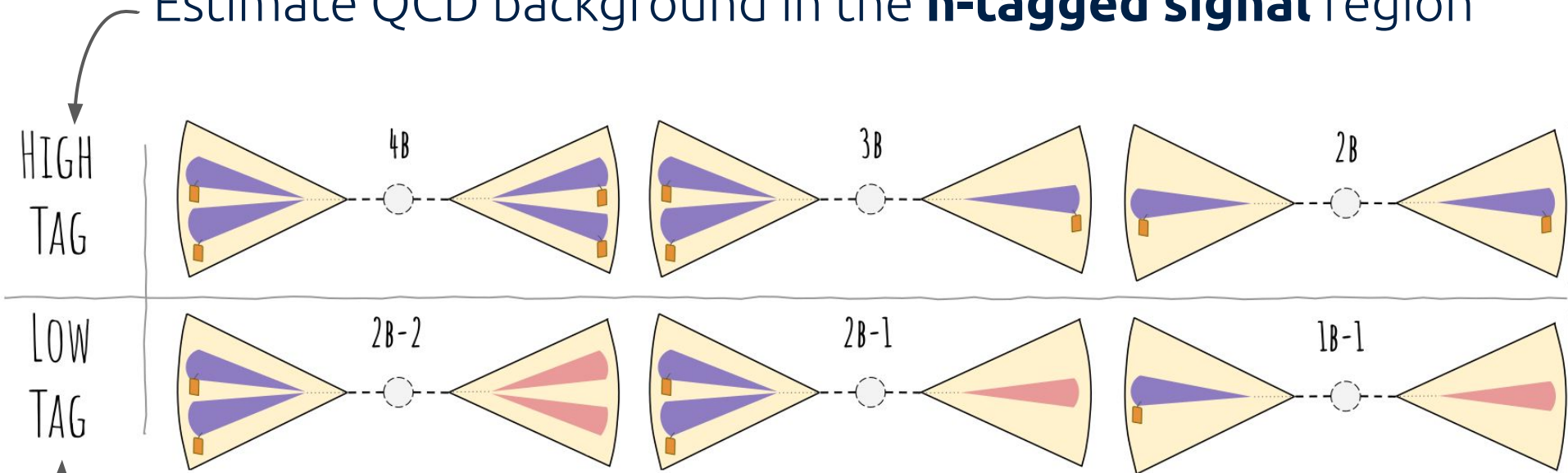τ

MET

LR **jet kinematic** cuts
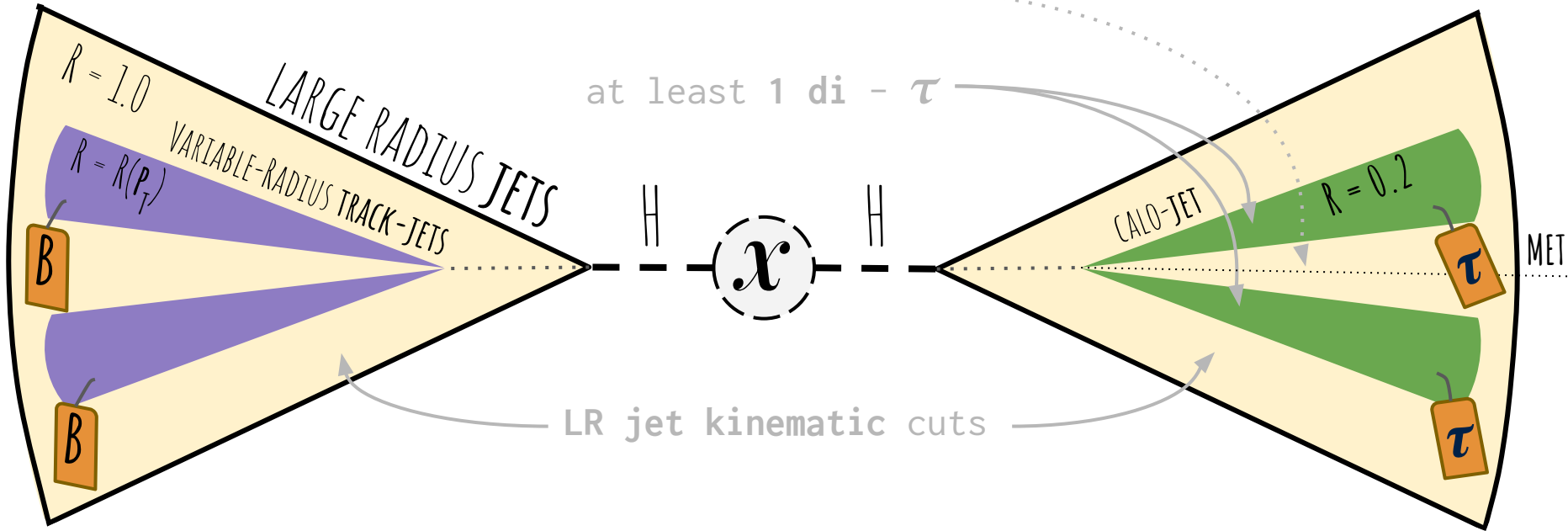
BTagging relevant variables
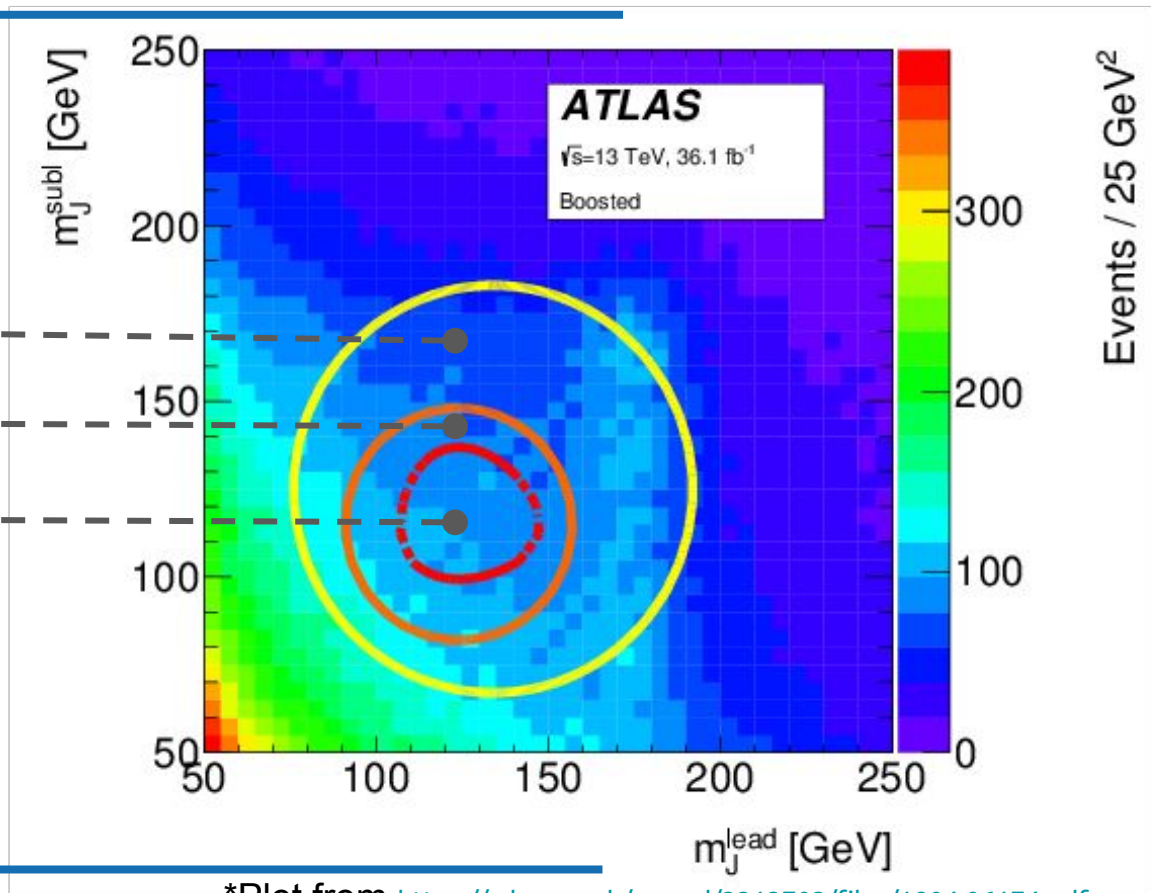
QCD Background Estimation

Estimate QCD background in the **n-tagged signal** region
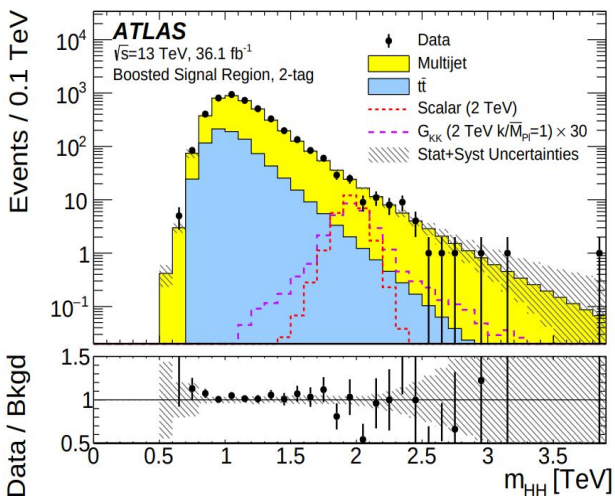

By using the **corresponding low-tag** sample

Mass Plane Region Definition

- Control
- Validation
- Signal
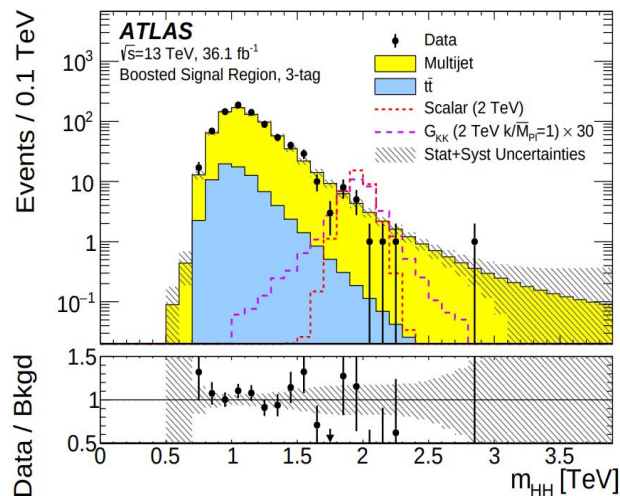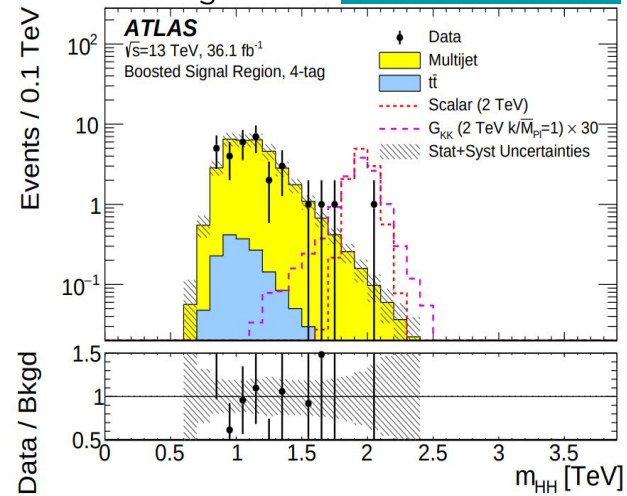
*Plot from https://cds.cern.ch/record/2313703/files/1804.06174.pdf

Backgrounds

- Main backgrounds: **ttbar** + **multijet**
  ↳ **Multijet** is **dominant**
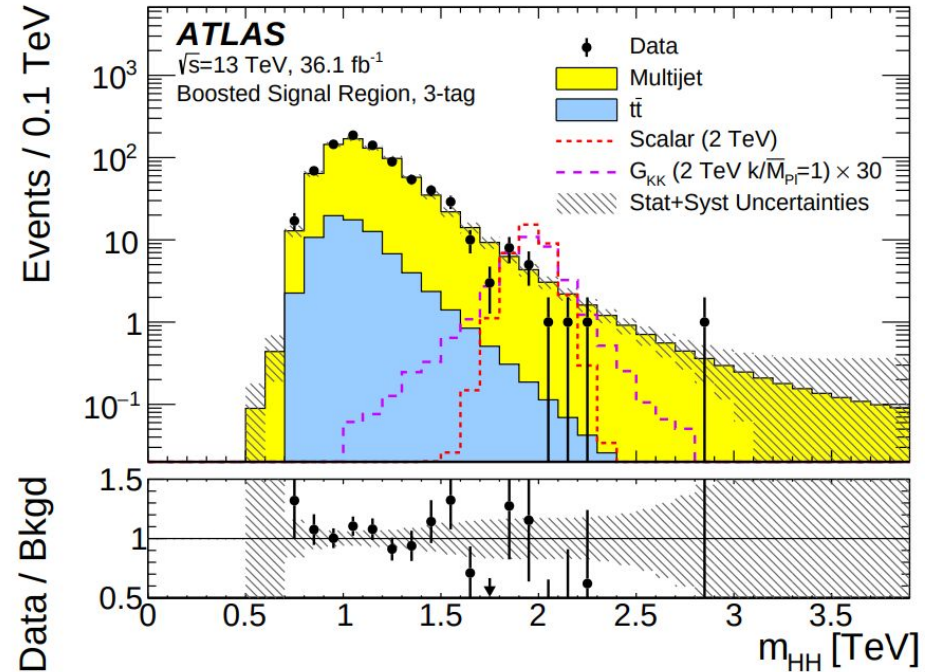- **Estimated separately** for each signal region

Figure 8 in arXiv:1804.06174

(a) Two-tag (b) Three-tag (c) Four-tag

Background Estimation

- QCD multi-jet 🟨

  ↳ Estimated using **data**

  ↳ **Biggest** contribution

- ttbar 🟦

  ↳ **Shape** from Monte Carlo

  ↳ **Normalized** with data
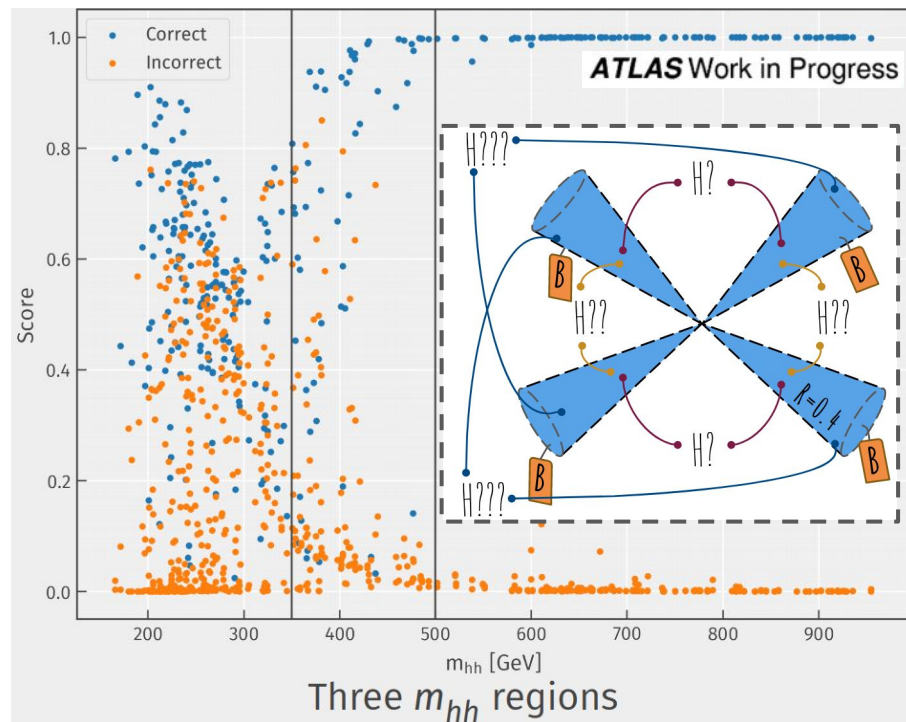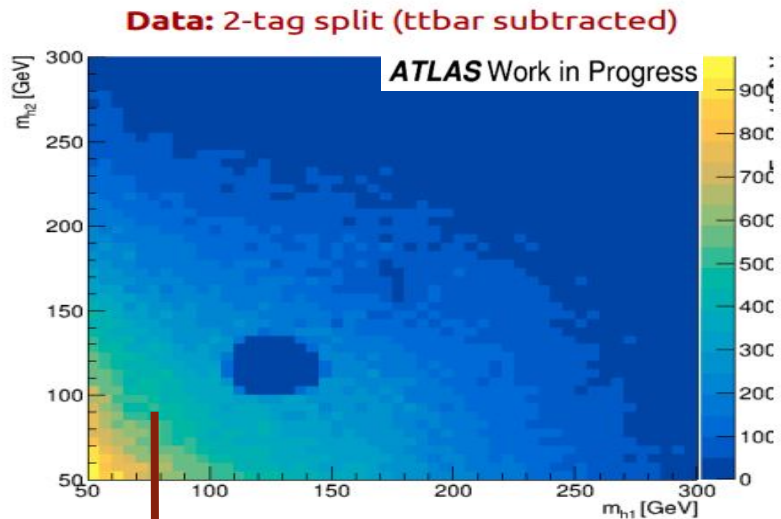

(b) Three-tag

Resolved hh4b analysis

- **One of the main challenges is jet pairing**
- **Different approaches**
  - Using dR between jets
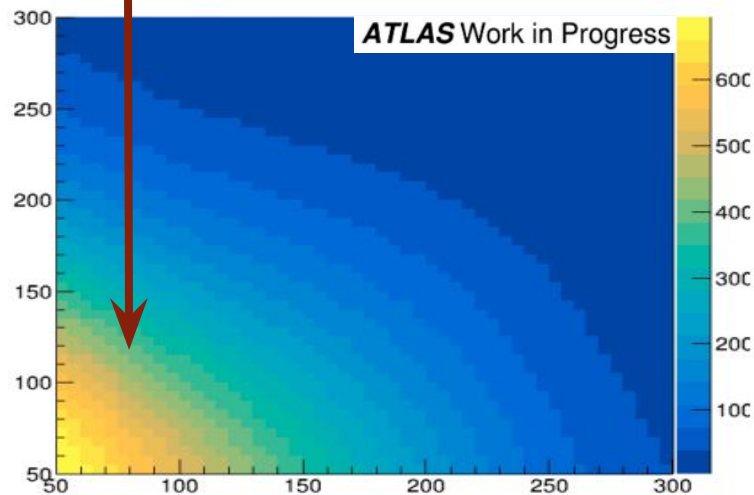 - Use a BDT to discriminate right/wrong pairs

Boosted hh4b background

- **New idea:**
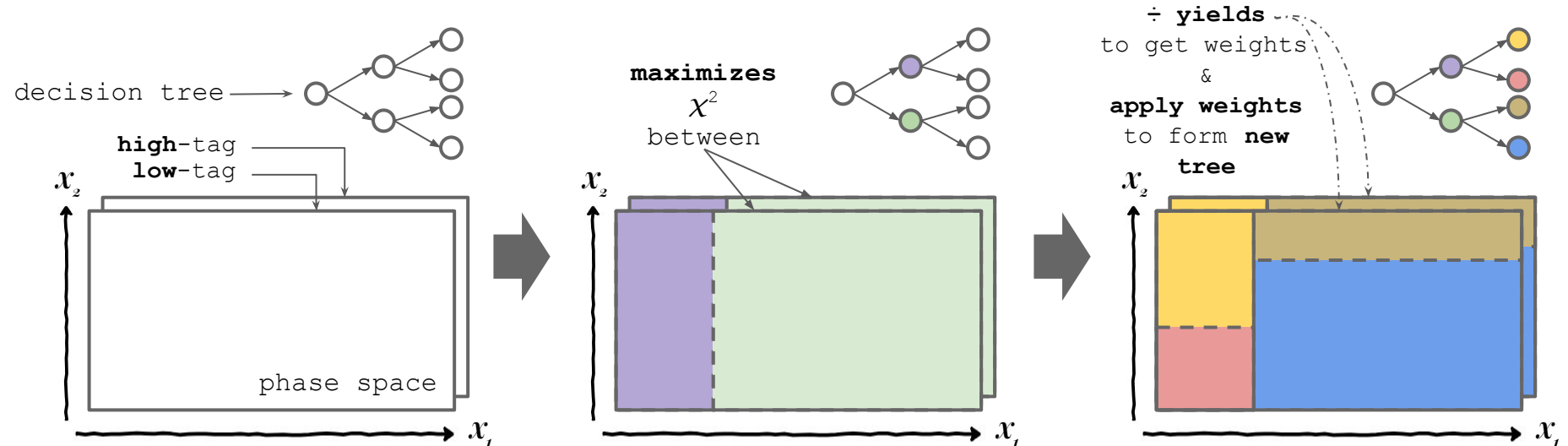 - **Gaussian processes** regression for **background estimation + systematics**

Data: 2-tag split (ttbar subtracted)

ATLAS Work in Progress

Background Model

ATLAS Work in Progress

New idea: BDT re-weighting

- Use a boosted decision tree to find the optimal **multi-dimensional binning** to re-weight low-tag to estimate the background in signal region
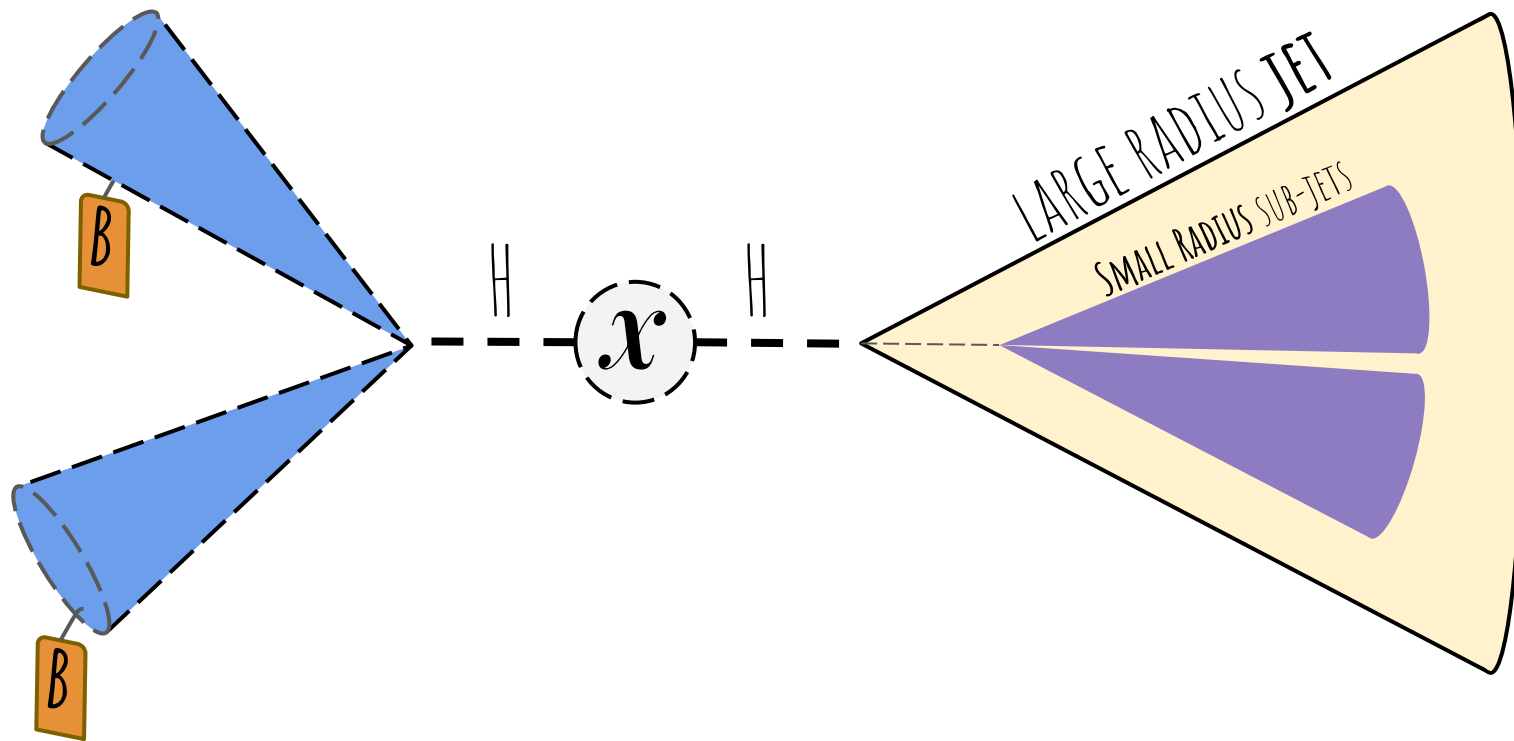
BDT re-weighting
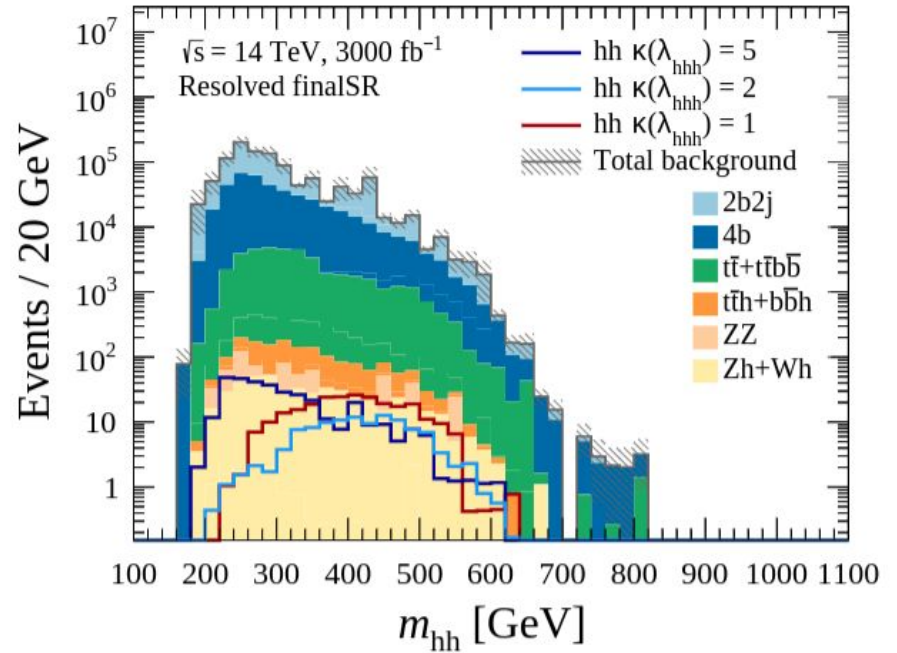
- Re-weighting variables, control region used for training
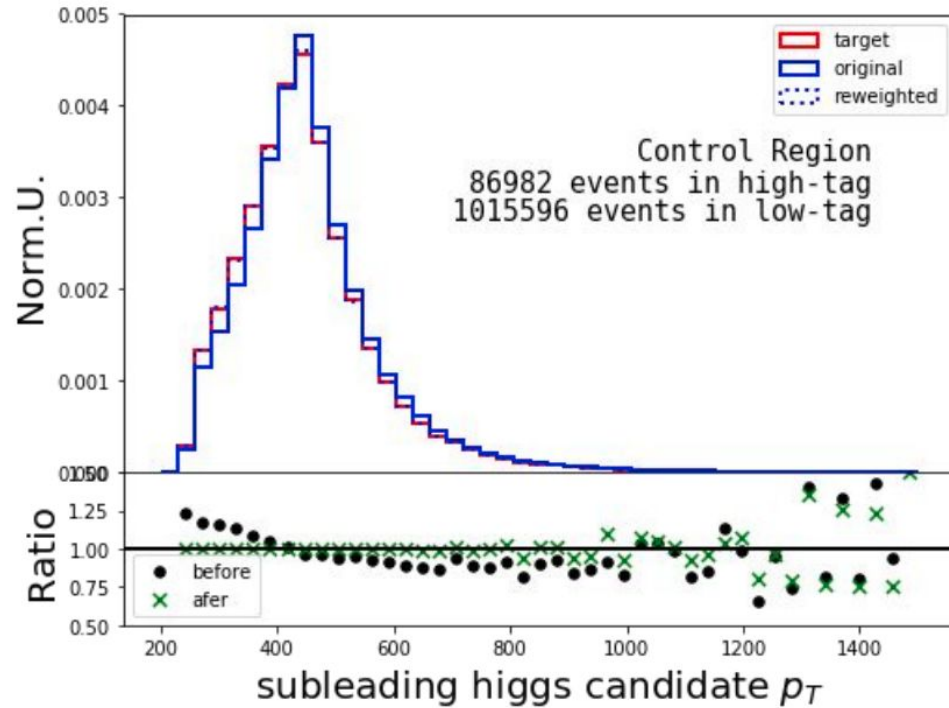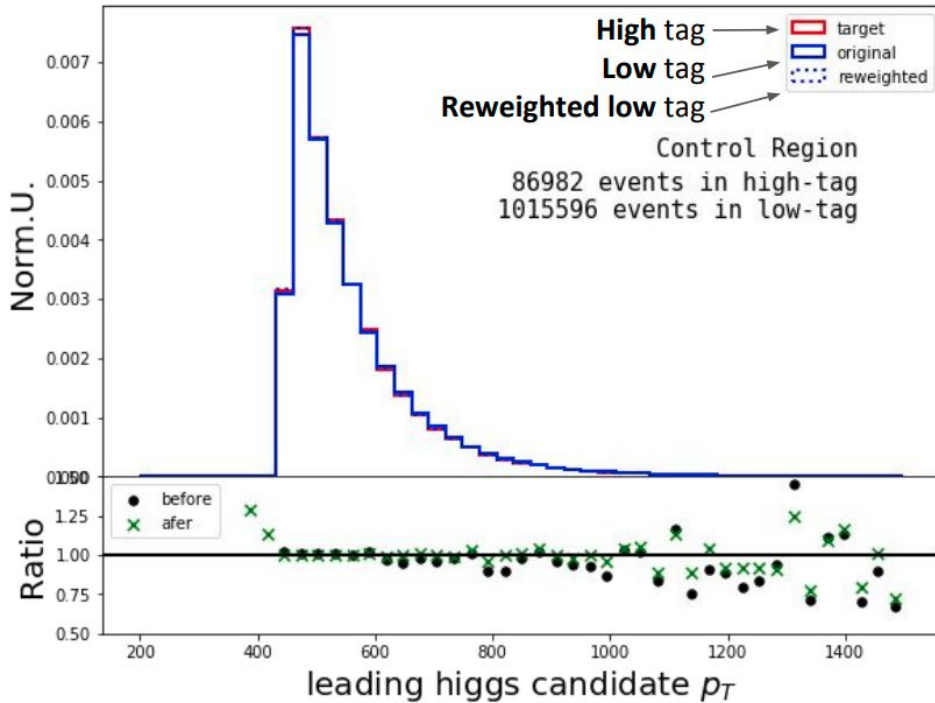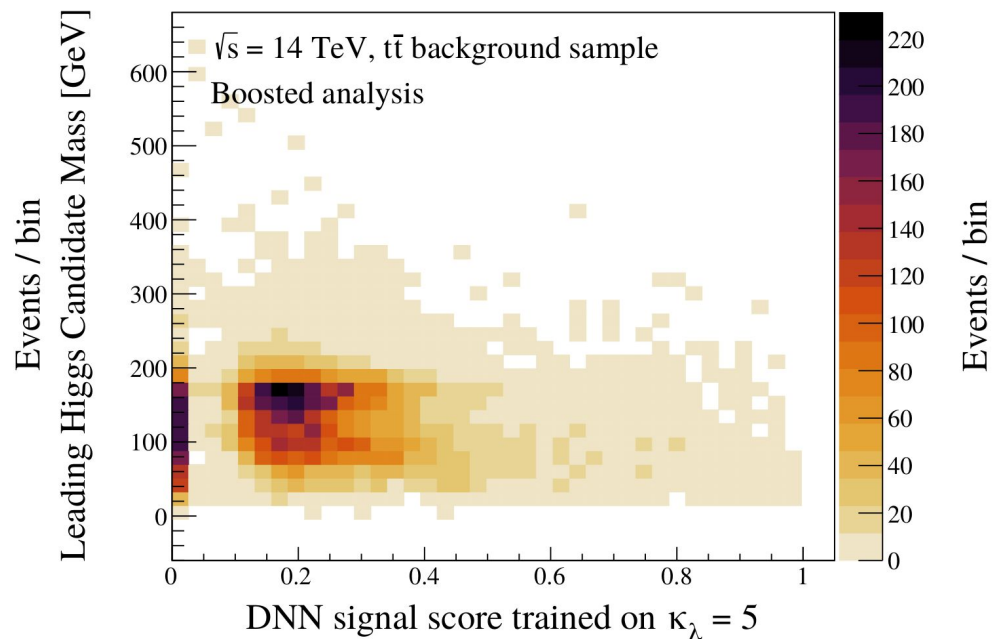
Intermediate Signal Event Topology

Datasets

- **Generated MC samples:**
  - ↳ QCD **multijet**
    - ↳ **2 b**-jets + **2 j**ets
    - ↳ **4 b**-jets
  - ↳ **ttbar**
  - ↳ ZZ, Zh, Wh + other bkg
  - ↳ hh→4b **signal**
    - ↳ 15 variations of κ_λ

$\sqrt{s} = 14$ TeV, 3000 fb^{-1}
Resolved finalSR

hh $\kappa(\lambda_{hhh}) = 5$
hh $\kappa(\lambda_{hhh}) = 2$
hh $\kappa(\lambda_{hhh}) = 1$
Total background
2b2j
4b
$t\bar{t}+t\bar{t}b\bar{b}$
$t\bar{t}h+b\bar{b}h$
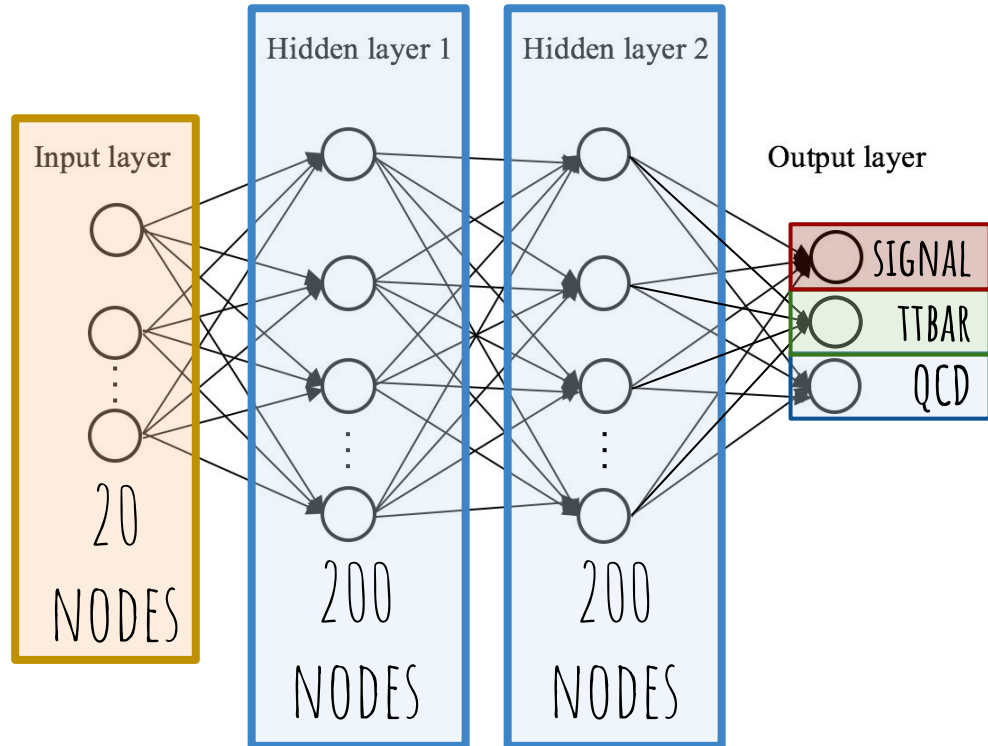ZZ
Zh+Wh

Events / 20 GeV

m_{hh} [GeV]

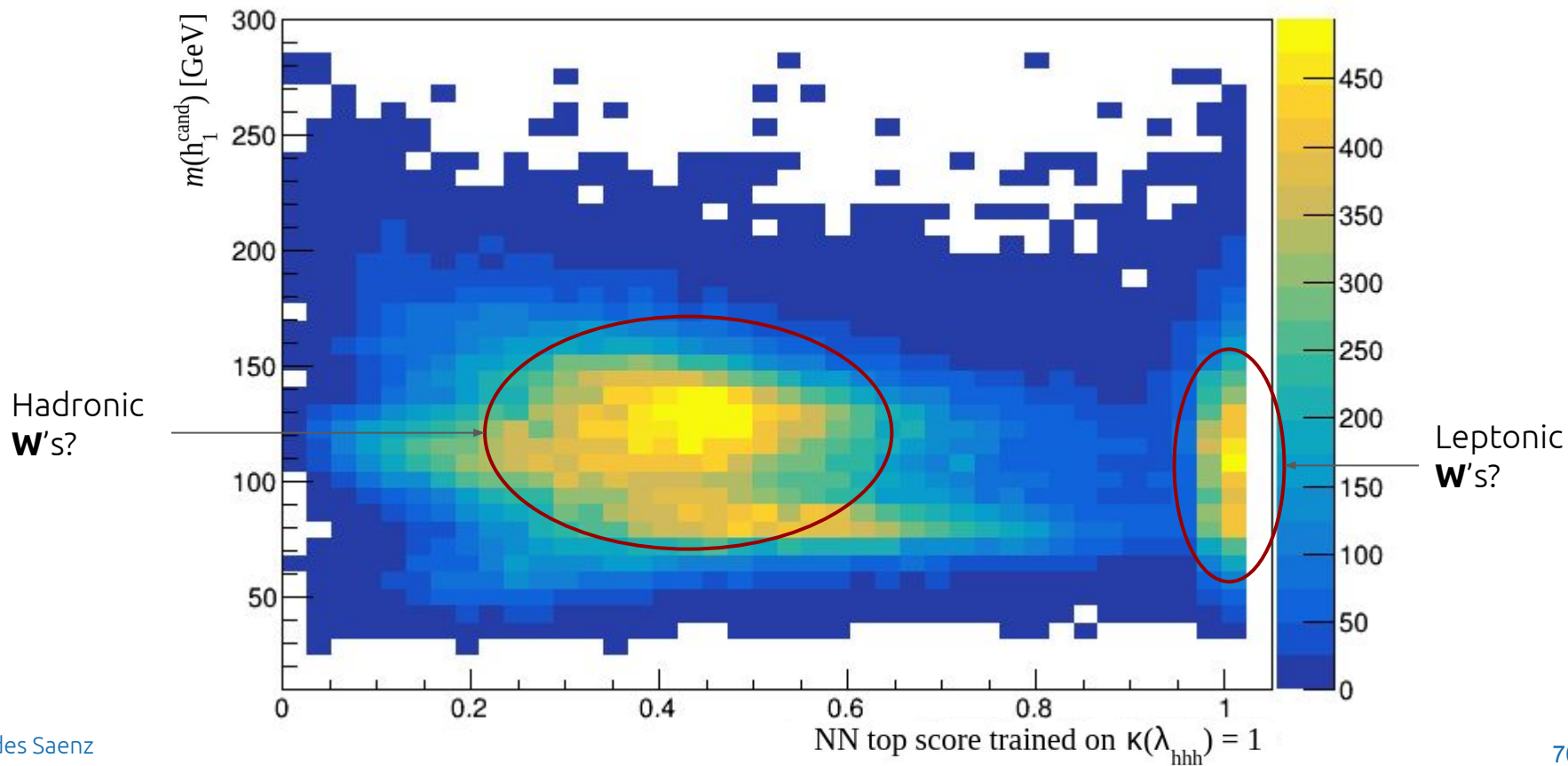# NN Validation: ttbar Sample
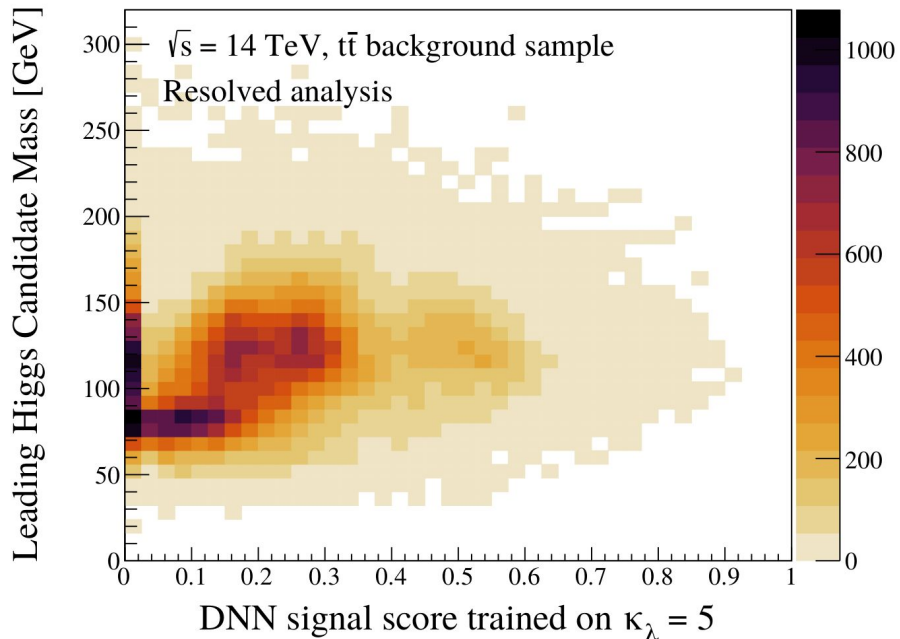
● Correlation plots made to validate NN training

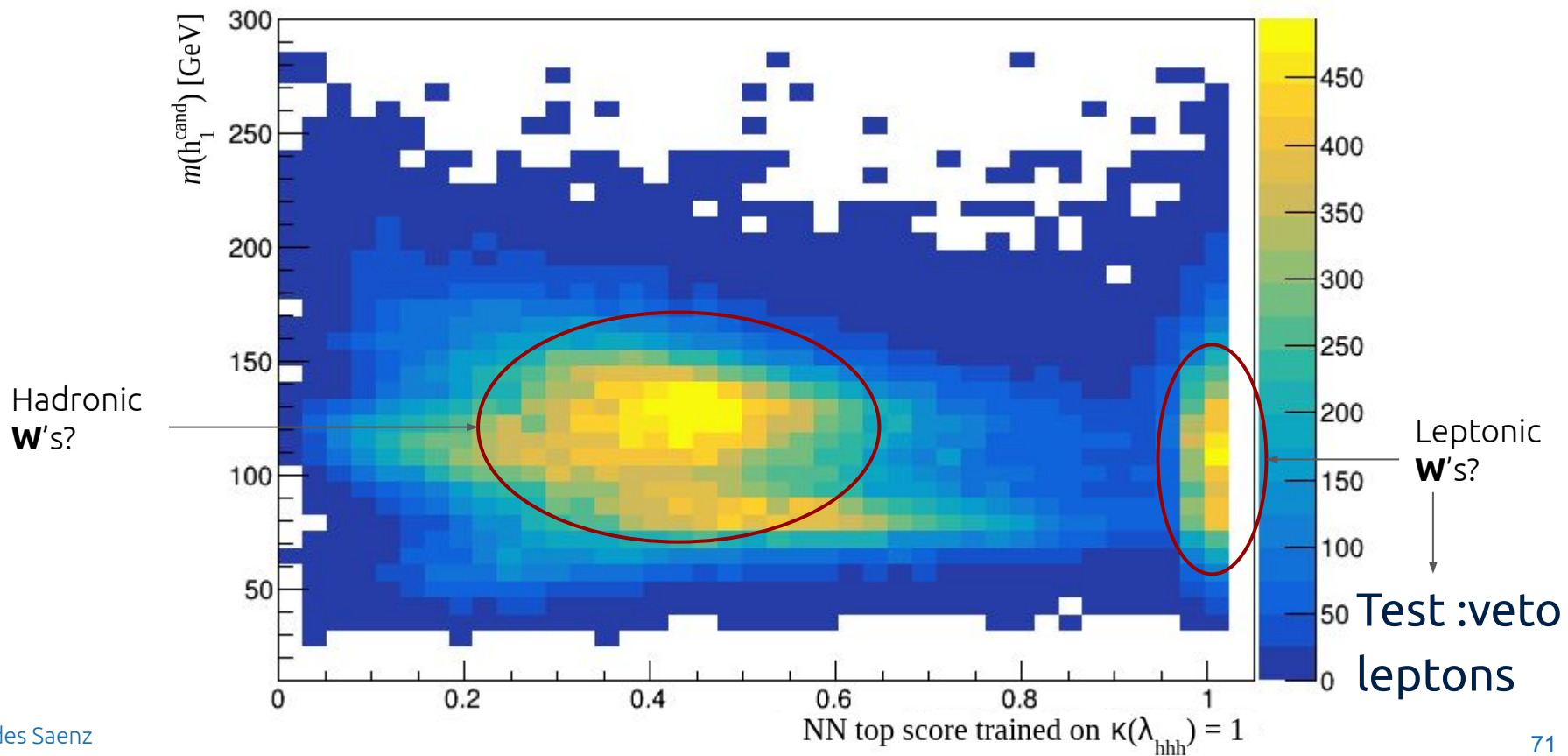# Neural networks and structure

- Loss
  - ↳ `categorical_crossentropy`
- Activations
  - ↳ Hidden layers
    - ↳ `ReLU`
  - ↳ Output layer
    - ↳ `softmax`
- Adamax optimizer
- Learning rate, drop-out and batch size optimized using random search
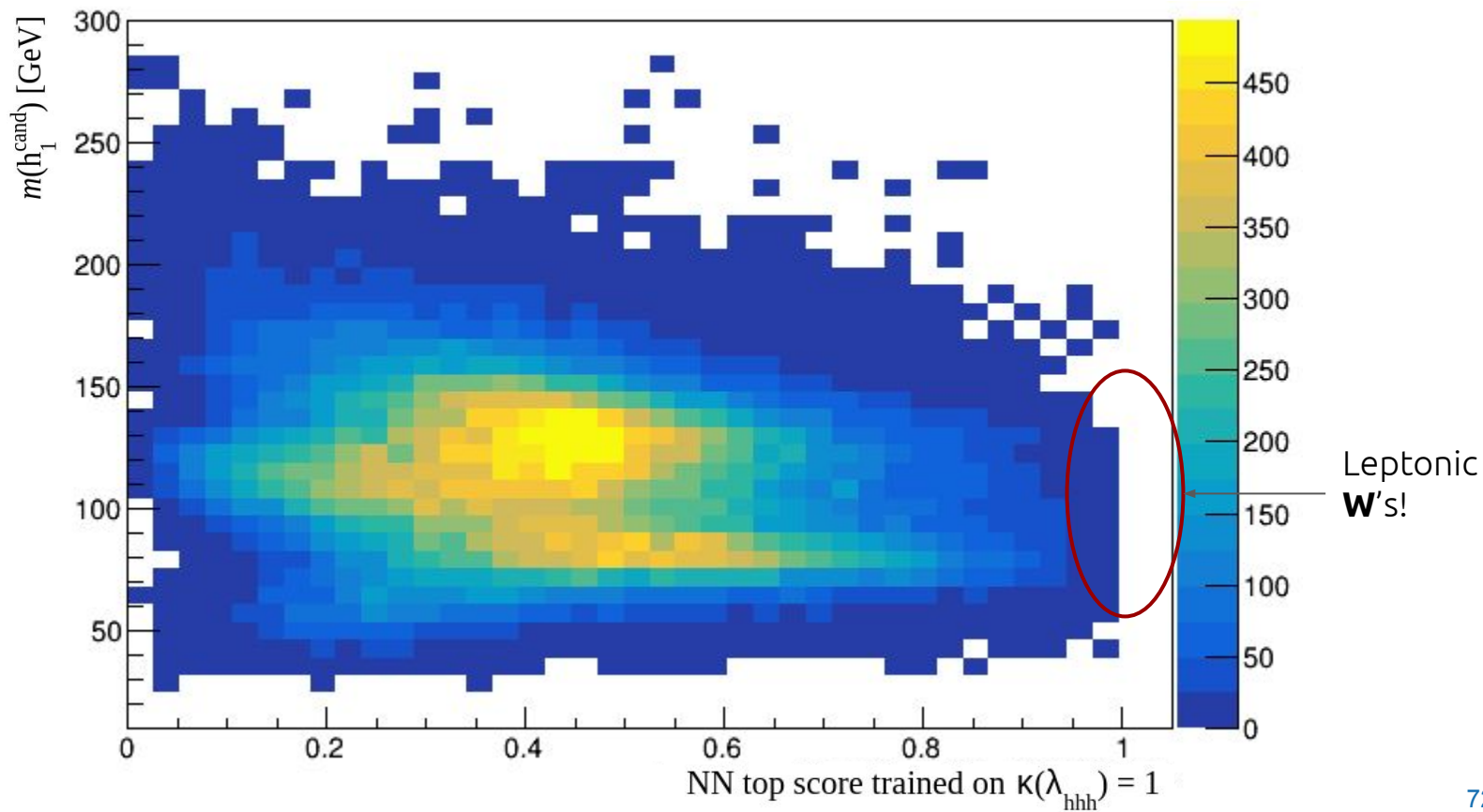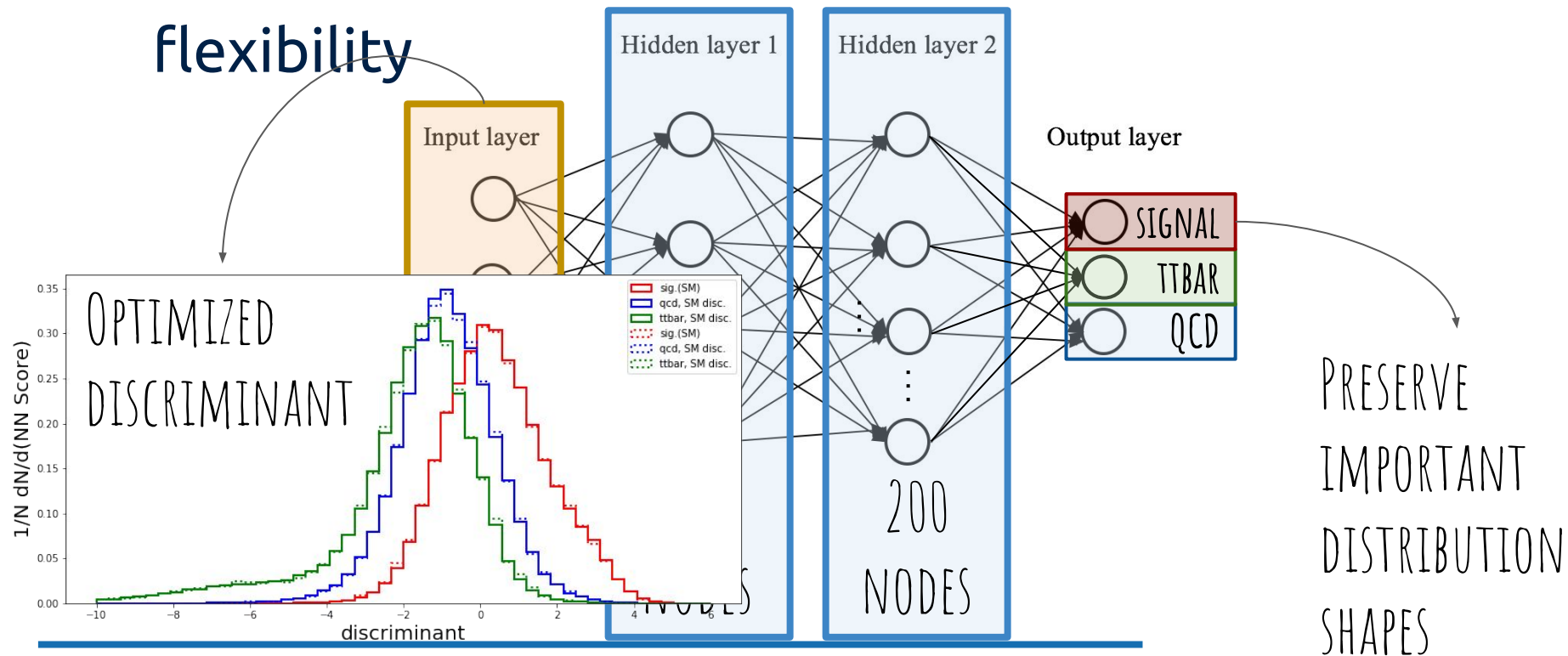
Validation: **ttbar** Sample

Hadronic **W**'s?

Leptonic **W**'s?

Validation: **ttbar** Sample

Hadronic **W**'s?

Leptonic **W**'s?

Test :veto leptons

Validation: **ttbar** Sample

Leptonic **W**'s!

- **This approach allows for extensions and more flexibility**

Input layer

Hidden layer 1

Hidden layer 2

Output layer

200 NODES

SIGNAL

TTBAR

QCD

OPTIMIZED DISCRIMINANT

PRESERVE IMPORTANT DISTRIBUTION SHAPES

sig.(SM)
qcd, SM disc.
ttbar, SM disc.
sig.(SM)
qcd, SM disc.
ttbar, SM disc.

1/N dN/d(NN Score)

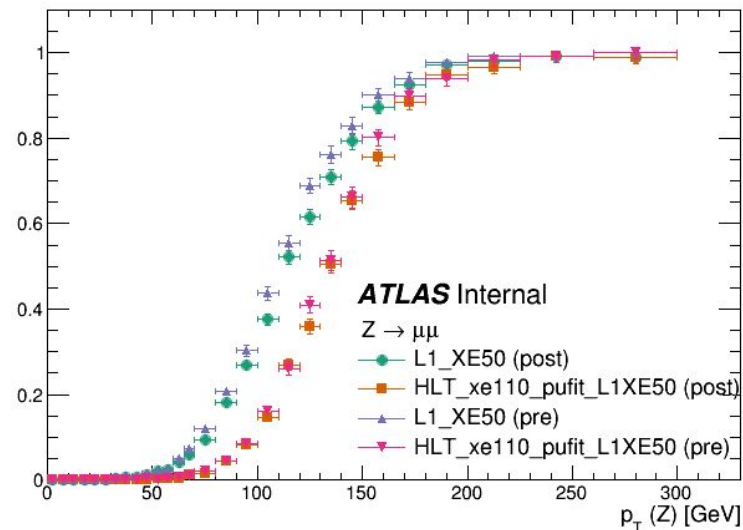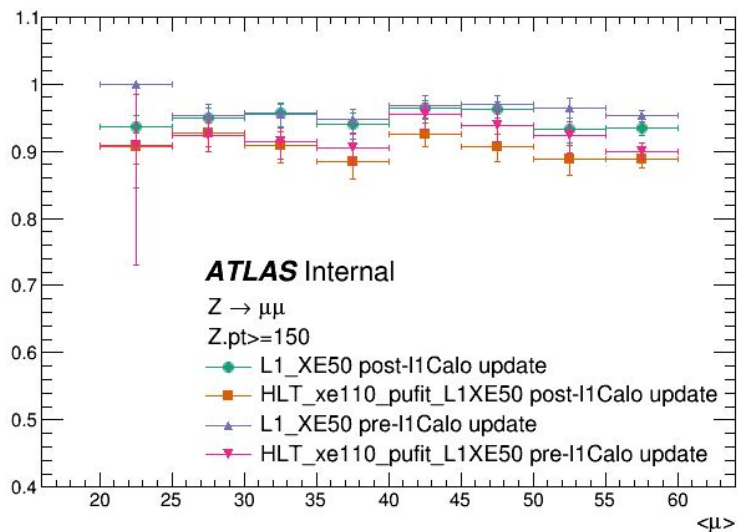discriminant

Feature impact: SHAP values

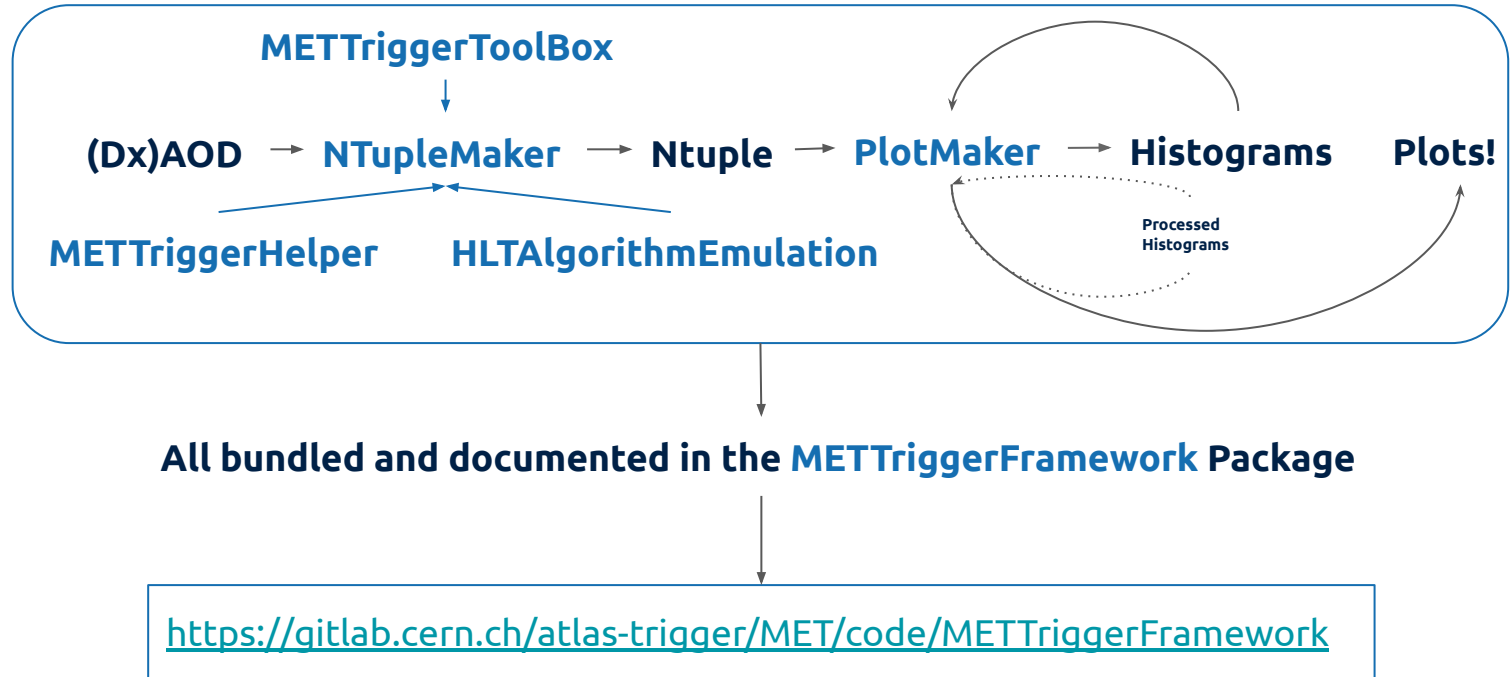- Can also **study correlations** this way
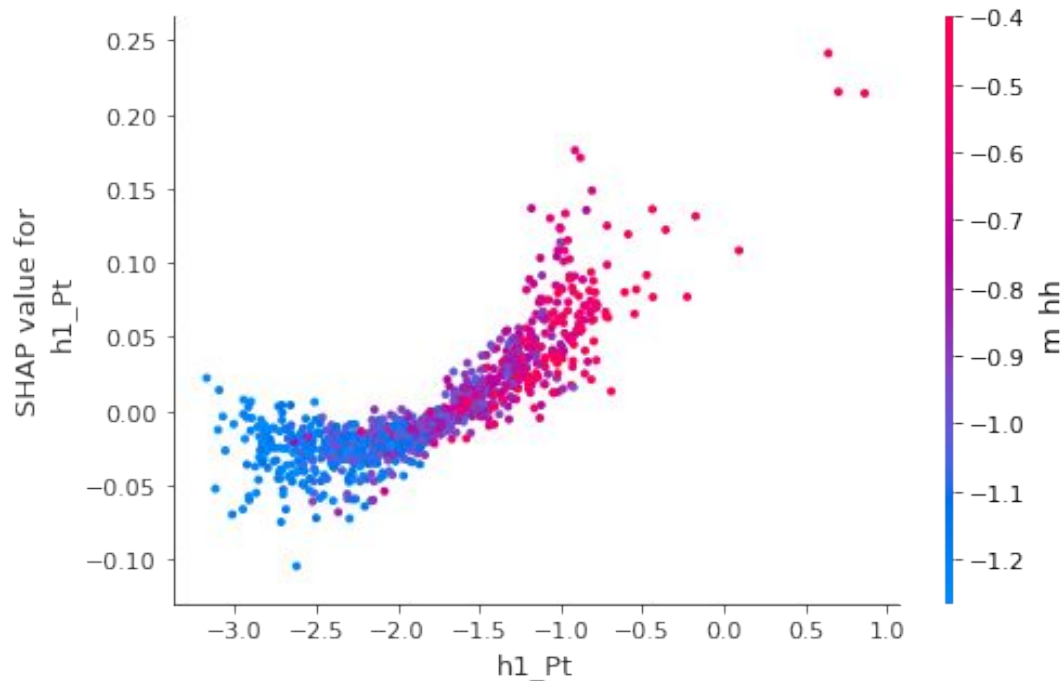
L1Calo Changes

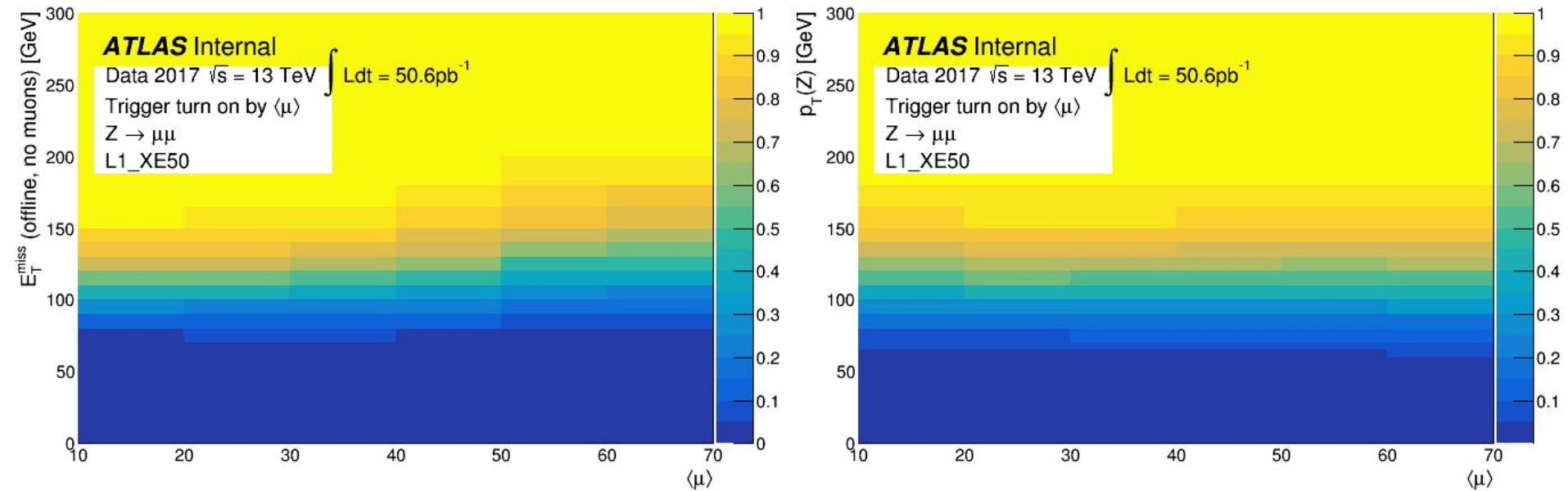L1Calo updated its filter and noise cut coefficients, starting with run 339037

- Expect positive effect on rates
  - ↳ Needed to check the impact on MET trigger performance
- Comparing to the previous run 338987

MET Trigger SW Framework Layout

METTriggerToolBox

(Dx)AOD → NTupleMaker → Ntuple → PlotMaker → Histograms → Plots!

METTriggerHelper   HLTAlgorithmEmulation

Processed Histograms

All bundled and documented in the METTriggerFramework Package

https://gitlab.cern.ch/atlas-trigger/MET/code/METTriggerFramework

Trigger turn-on by pileup

Trigger turn-on, run-by-run, $W \rightarrow \mu\nu$

efficiency of L1_XE50 by run number
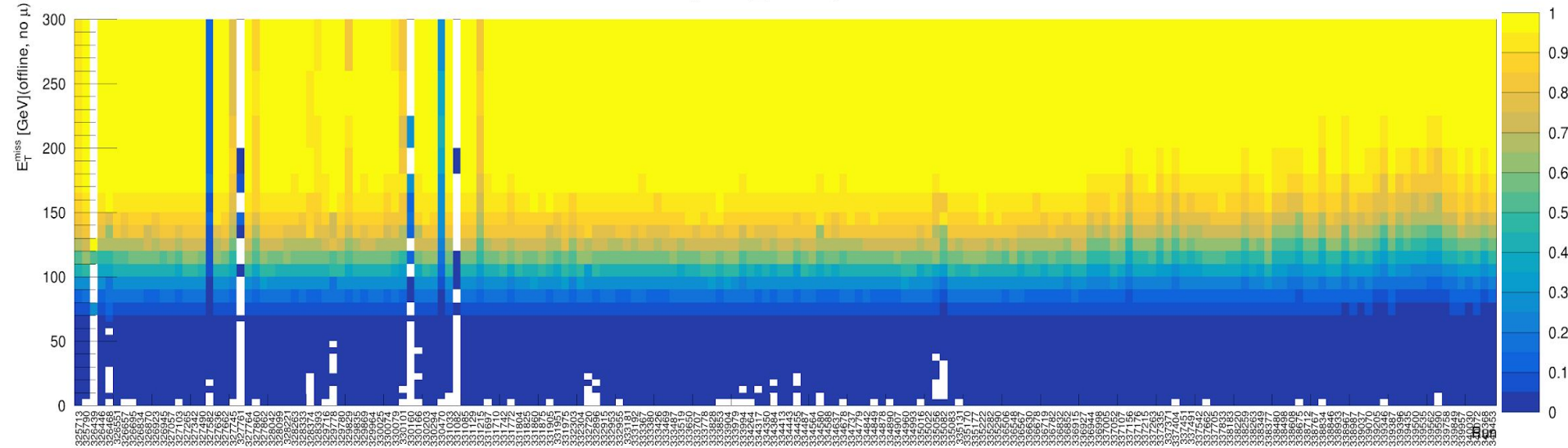
Trigger turn-on, run-by-run, checks