WHHHere are we now?
HHHow Far can we go?

Summary of the HHH conference – Dubrovnik Sept. 2025

WHHHere are we now?

I was not certain.

So I do what we all do → Rely on the expert!

Vuko!

We are HHHere:

According to Vuko

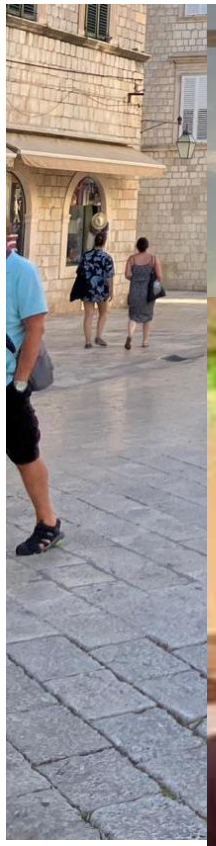
We are HHHere:

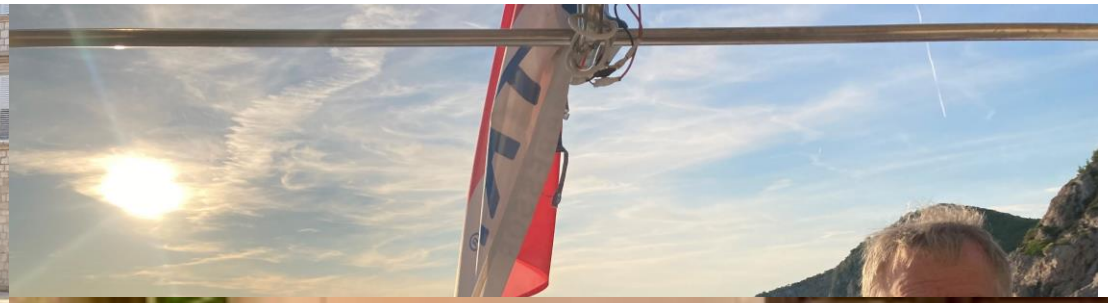
According to Vuko

And we all owe him,

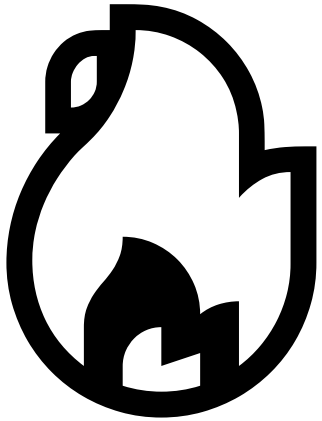
And the IUC staff

Our Gratitude!





The Fire Brigade



The ‘S’ in Science Stands for “Safety”!

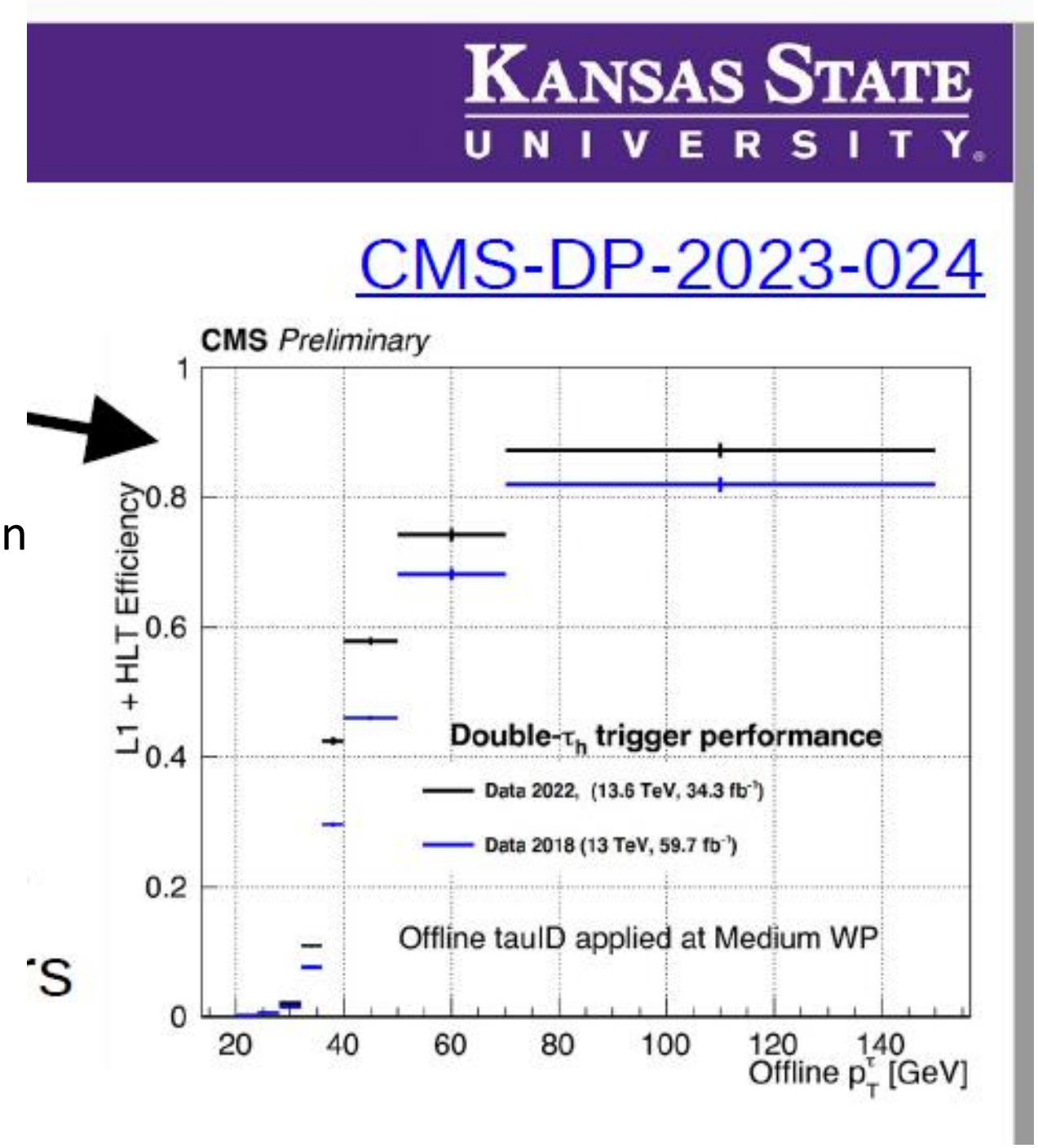
How Many Higgs does it take to screw in a light bulb?

Deep Tau - CMS

From D. Roy's talk

From 2024 – new triggers available operating on 4 jets

Useful for any Higgs → ττ signature.



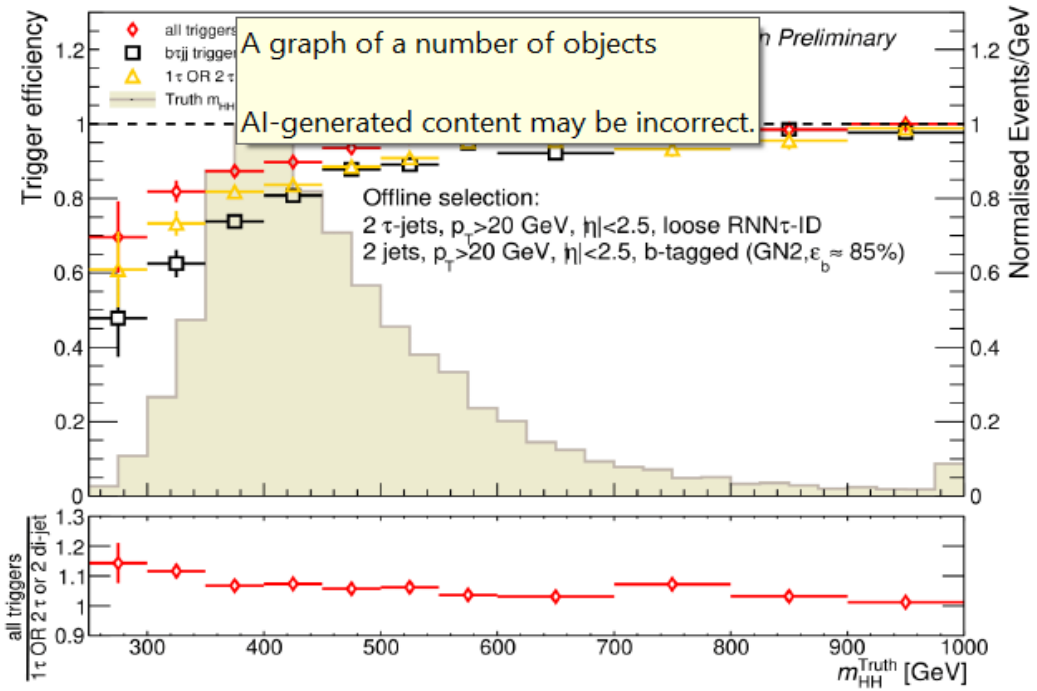
Roshan Joshi (aka – “The Shirt”)

ATLAS flavour tagging advances

Not to be outdone – ATLAS adding τ triggers as well

Improving the trigger strategy: b+tau triggers

- New b+tau trigger added for 2024:
  - 1b + 1τ + 2j: 4 jets with p_T > 65, 40, 25, 20 GeV, requiring 1 b-tagged (GN1/GN2) jet, and 1τ (RNN) with p_T > 25 .
- Gain of 5% in HH signal efficiency when compared to using the previous tau/jet triggers.
- To be checked where this trigger would fall in a possible trigger bucket strategy.



A graph of a number of objects

AI-generated content may be incorrect.

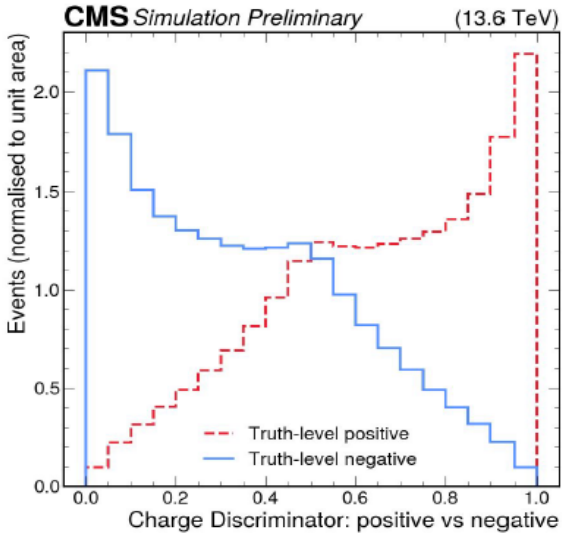
ATLAS Tau Trigger Public Results

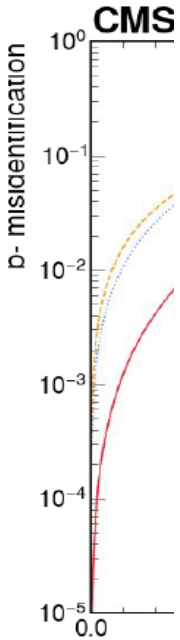
More on this tomorrow in Roshan's talk!

Jet Charge tagging (Clara R.)

Binary classification fo

- Take the classifier as binary: **Positive vs Negative**
- Negative vs Positive shows the same performance
- Good discrimination between both classes **AUC ≃ 0.8**
- The Charge Tagger shows **a 20% better performance** than the traditional cut-based method.





Comparing with LEP:
DELPHI NN to distinguish b vs $\bar{b}$:

- AUC ~ 0.75 Eur.Phys.J.C40:1-25.2005
- We achieve similar performance as in the LEP environment!

$$\text{Positive vs Negative} = \frac{Out(}{Out(\text{positive})}$$

But Seriously – **WHHHere are we?**

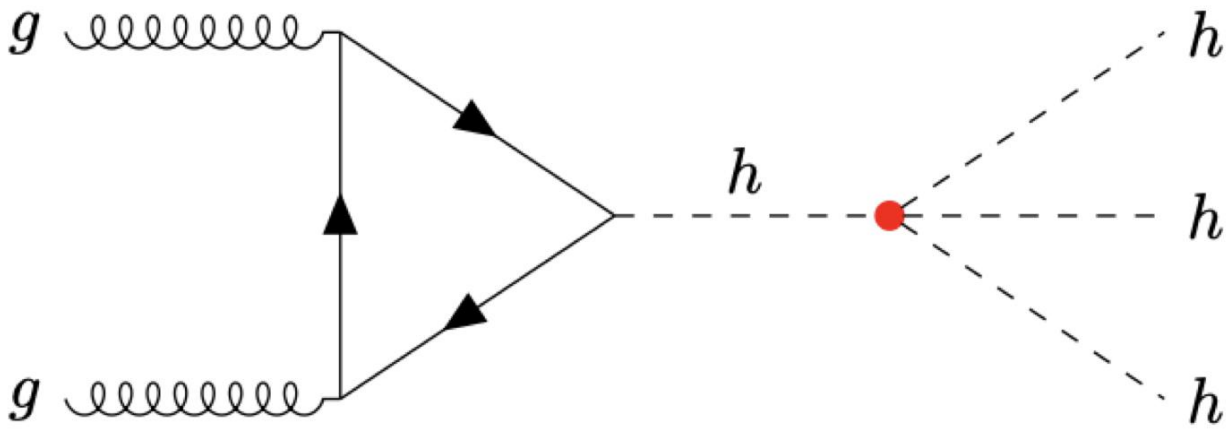
LEARN MORE ABOUT THE Higgs potential?

10 year Higgs discovery at Nikhef

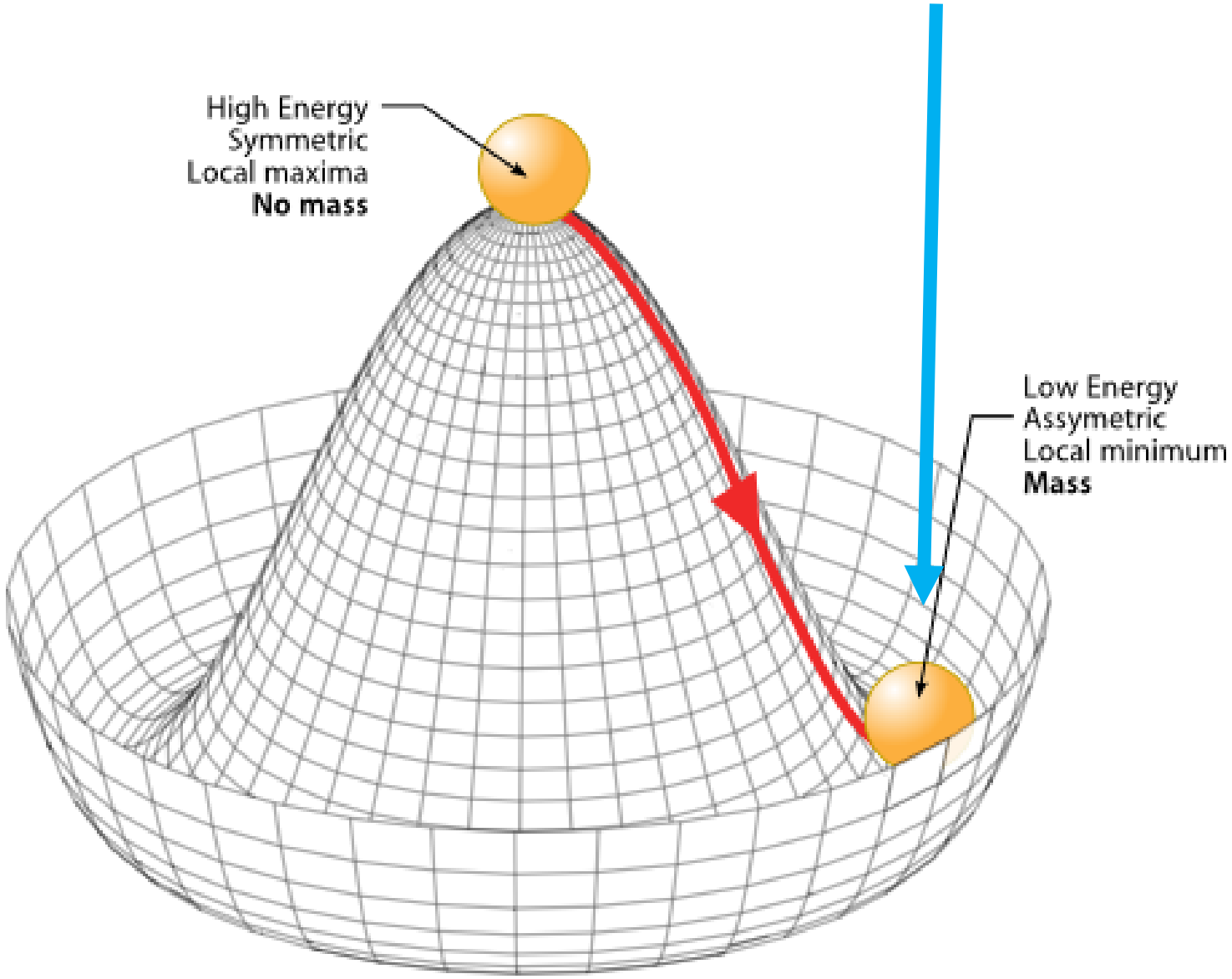
4 July 2022

O.Karkout

$$V(\Phi) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda\nu H^3 + \frac{1}{4}\lambda H^4$$



We are here:

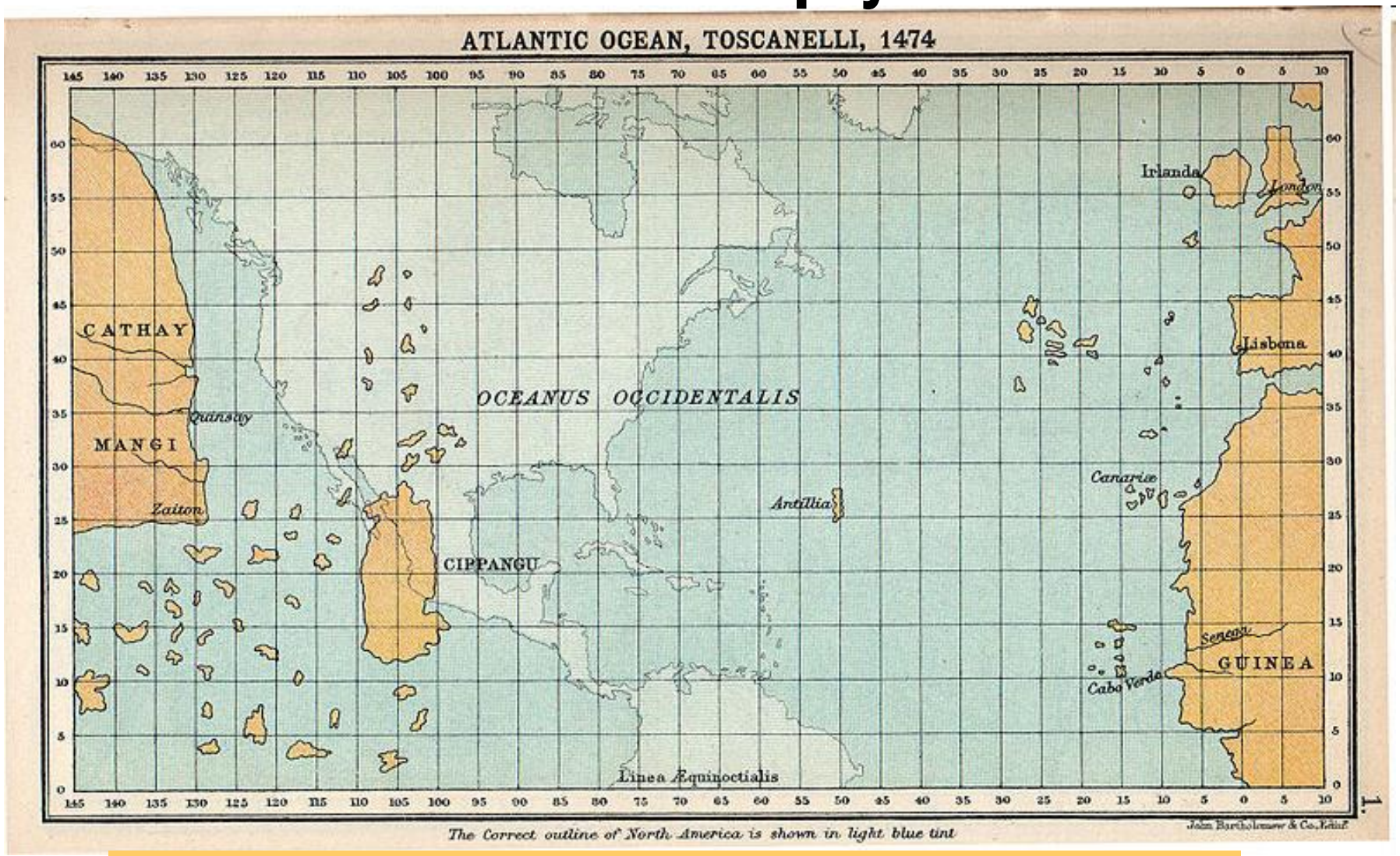

High Energy
Symmetric
Local maxima
No mass
Low Energy
Assymetric
Local minimum
Mass

Let’s turn to theory

There are many models.

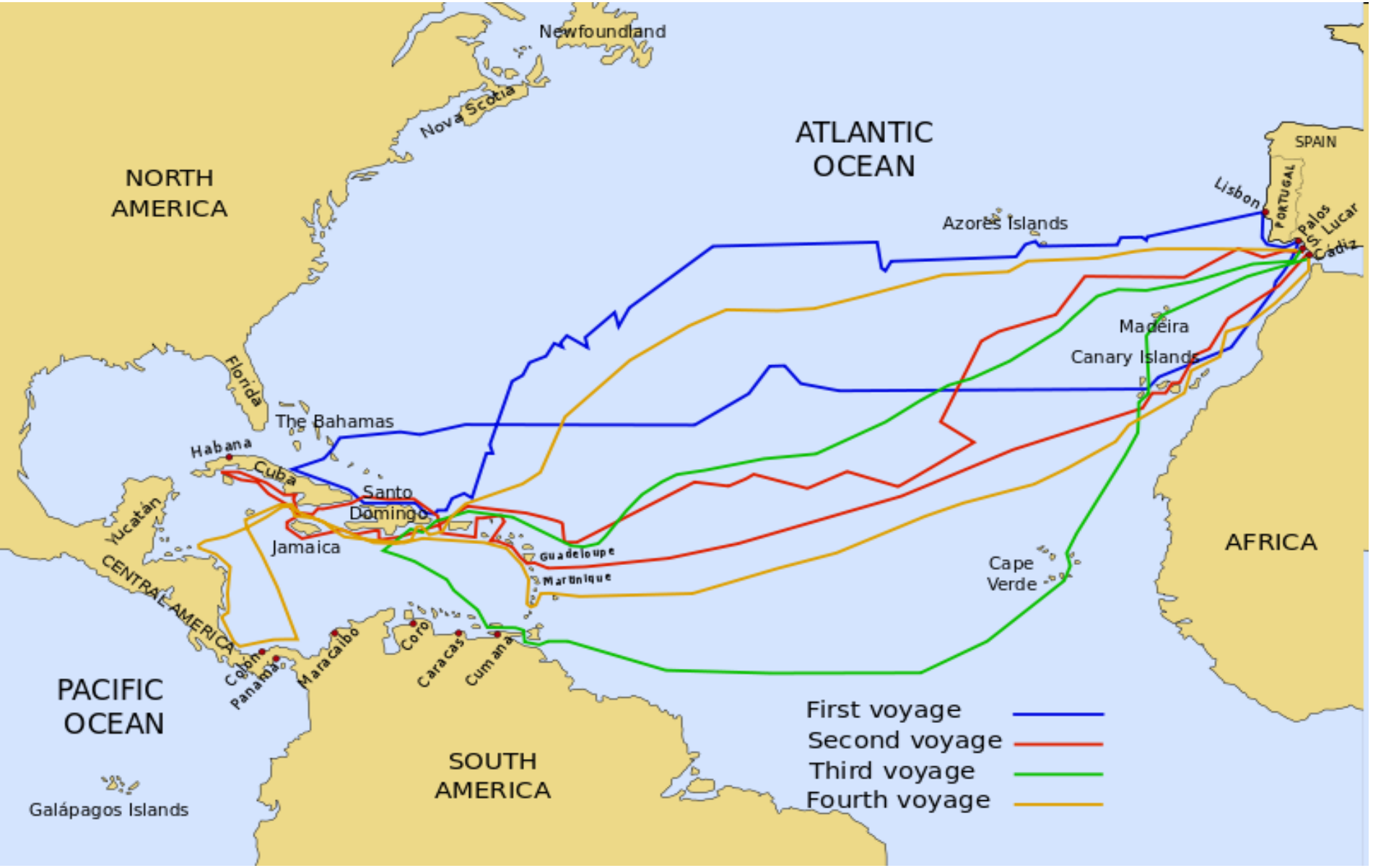
What to make of it all?

The Role of Models in Exotic physics Searches



Toscanelli's model of the geography of the Atlantic Ocean, which directly influenced Columbus's plans

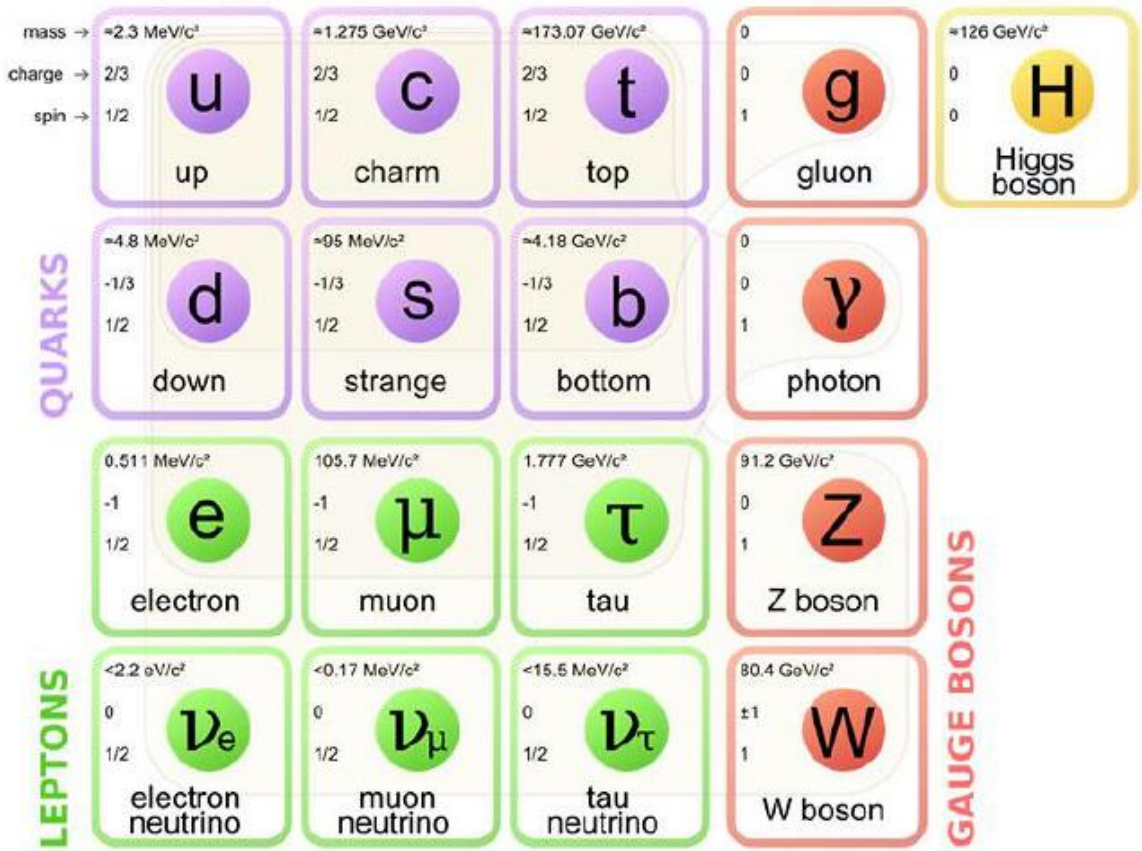
The Role of Models in “most” Searches



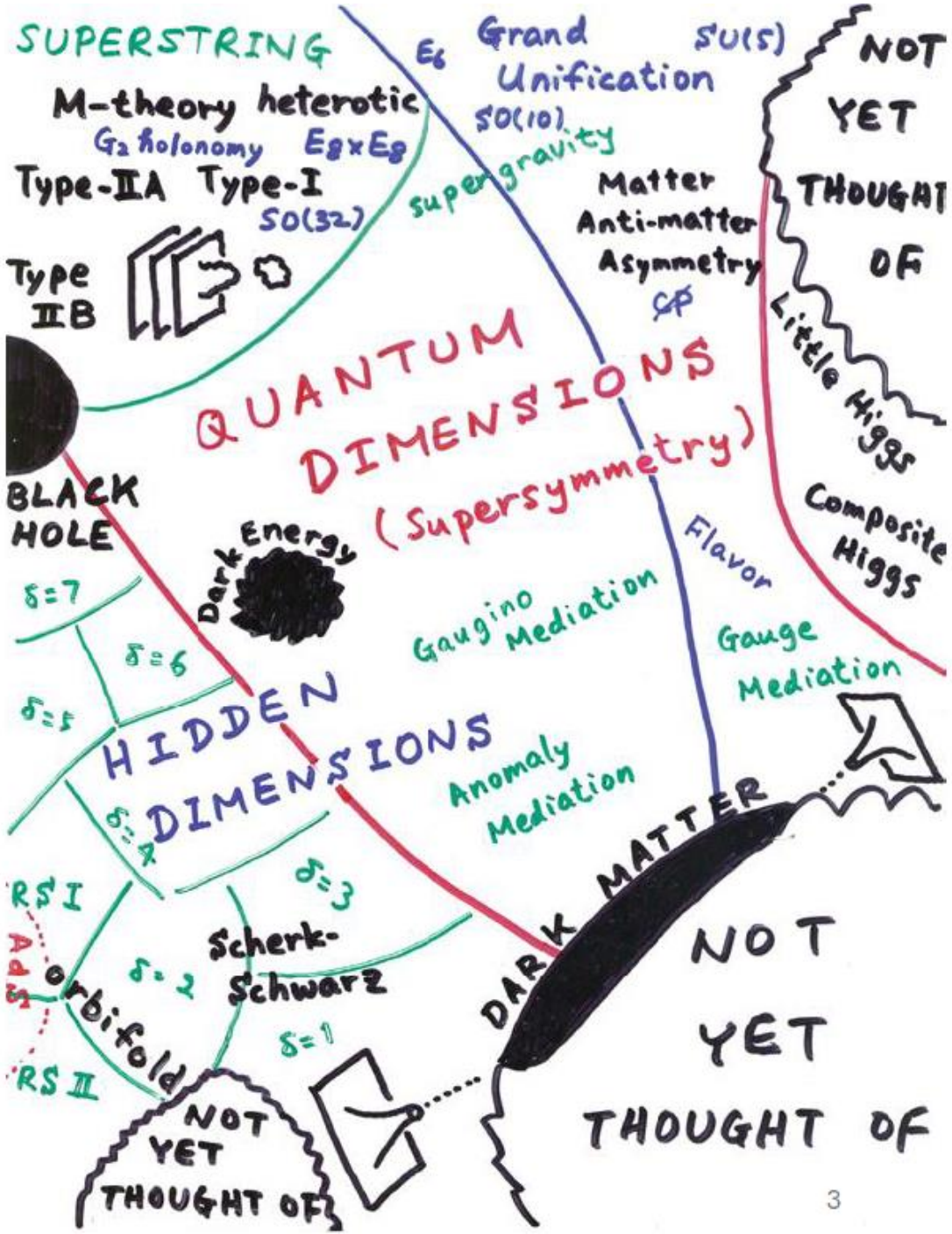
Columbus’ Voyages

Lesson from this:

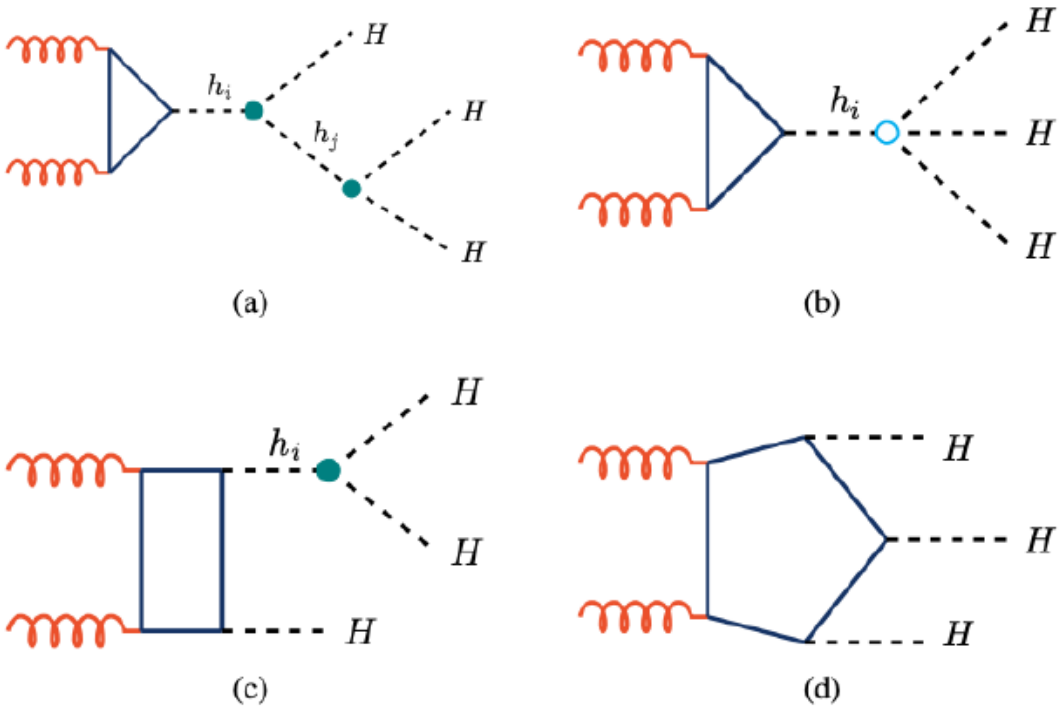
It is good to be right
But it is not necessary


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

?


SUPERSTRING
E6
Grand Unification
SU(5)
NOT YET THOUGHT OF
M-theory heterotic
G2 holonomy
E8xE8
SO(10)
Type-IIA
Type-I
SO(32)
supergravity
Matter Anti-matter Asymmetry
CP
Type IIB
QUANTUM DIMENSIONS (Supersymmetry)
Little Higgs
BLACK HOLE
Dark Energy
Composite Higgs
Flavor
δ=7
δ=6
δ=5
δ=4
δ=3
δ=2
δ=1
Gaugino Mediation
Gauge Mediation
HIDDEN DIMENSIONS
Anomaly Mediation
DARK MATTER
RS I
ADD
orbifold
RS II
Scherk-Schwarz
NOT YET THOUGHT OF
NOT YET THOUGHT OF

HHH 6b analysis: SM & BSM



○ is λ_4

● is λ_3

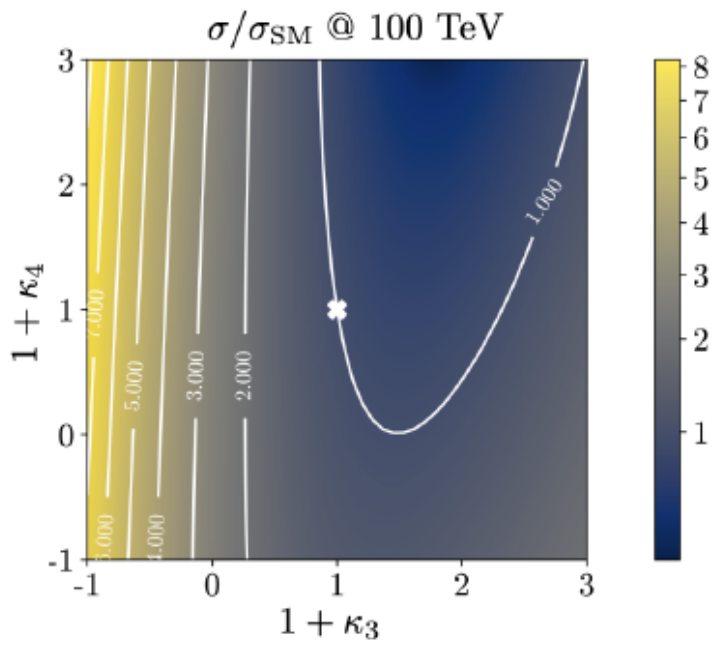
h_i, h_j are TRSM particles

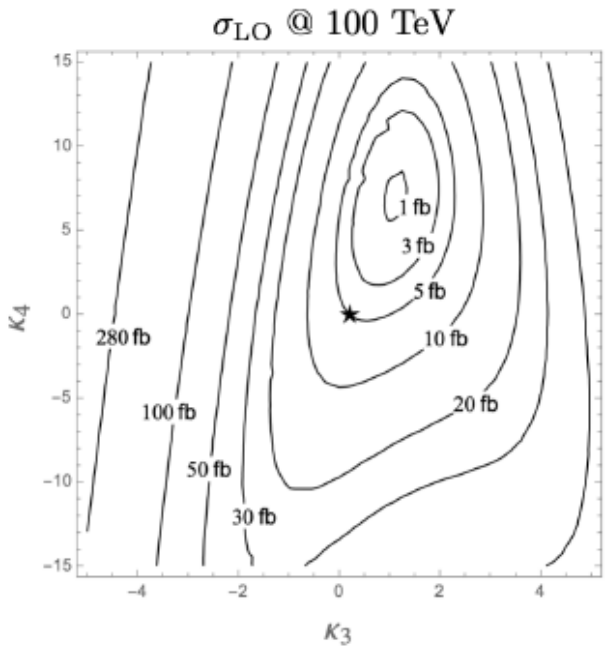
non-resonant + resonant + heavy resonant

(SM-like + TRSM) (TRSM + DM-CPV) Generic (narrow+wide)

Current state of the art

- SM prediction: $0.103\text{fb}^{+5\%}_{-8\%}$ ($5.56\,\text{fb}^{+5\%}_{-6\%}$) **at 14 (100) TeV, NNLO** [D. de Florian ea, JHEP, 03:155, 2020]
- **negative interference between different contributions in SM scenario** [see e.g. Plehn, Rauch, Phys.Rev.D 72 (2005) 053008]
- away from SM, and **at 100 TeV: better prospects**





left: D. De Florian ea, JHEP, 03:155, 2020, NNLO, heavy top limit

right: B. Fuks ea, Phys. Rev. D, 93(3):035026, 2016, leading order, top mass dependence

Problem:

SM XS is really small

Not what I'd call huge even at FCC

But some theories are easier to parse than others.

Extensions to SM –
like TRSM

Can enhance crossections

Worth a look.

Even in CMS and ATLAS

Exploration of $h_1 h_1 h_1$ final state at HL-LHC

[A. Papaefstathiou, TR, G. Tetlalmatzi-Xolocotzi, JHEP 05 (2021) 193]

- Model: **TRSM, 2 real scalar extension**

  (Eur.Phys.J.C 80 (2020) 2, 151; Symmetry 15 (2023) 27)

- **3 scalar states h_1, h_2, h_3 that mix**

concentrate on

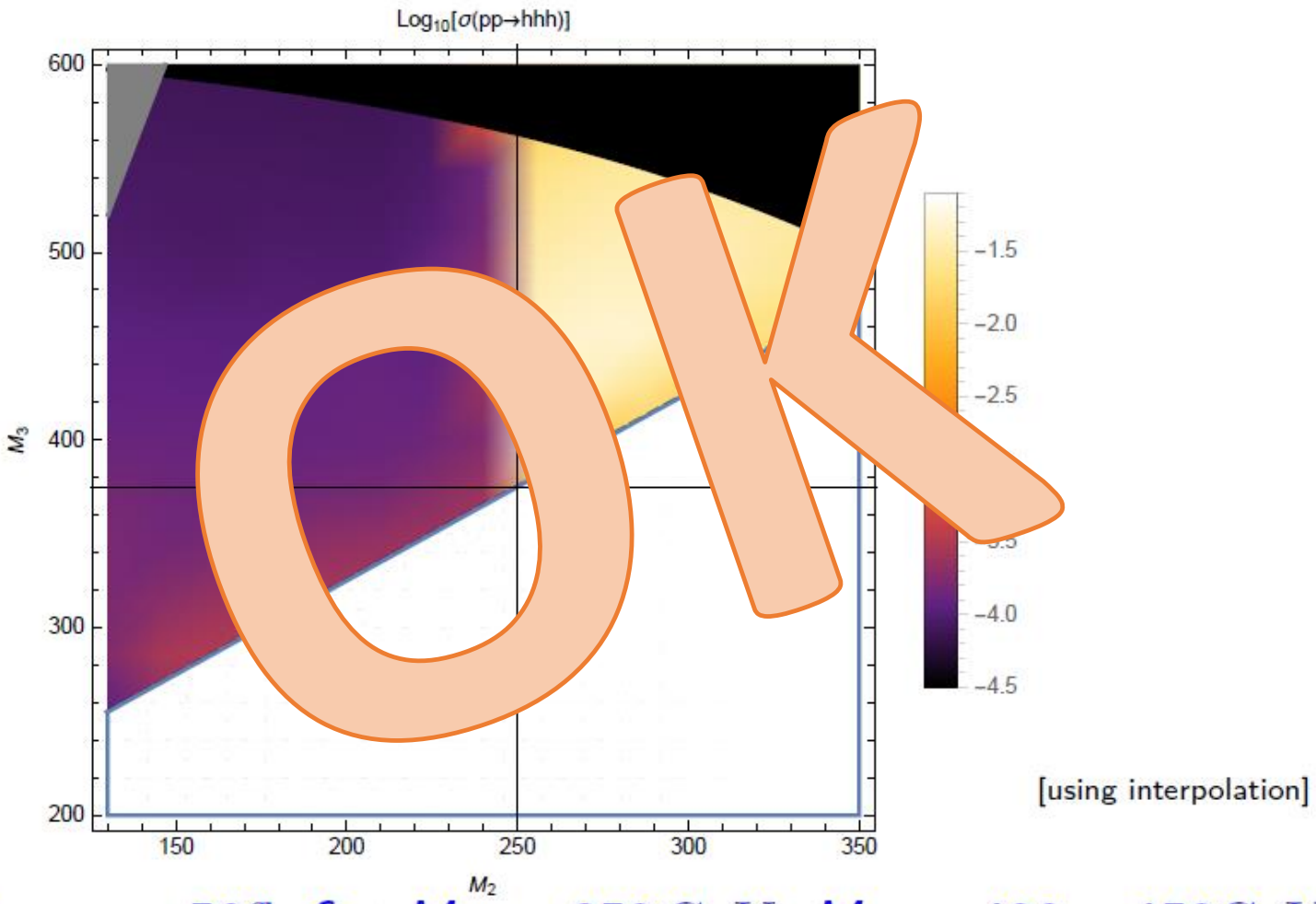
$$p\,p \to h_3 \to h_2\,h_1 \to h_1\,h_1\,h_1 \to b\,\bar{b}\,b\,\bar{b}\,b\,\bar{b}$$

$\Rightarrow$ **select points** on BP3 which might be **accessible at HL-LHC**

$\Rightarrow$ perform detailed analysis including SM background, hadronization, ...

- tools: implementation using **full t, b mass dependence, leading order** [UFO/ Madgraph/ Herwig] [analysis: use K-factors]

$h_1 h_1 h_1$ production cross sections, leading order [pb], BP3

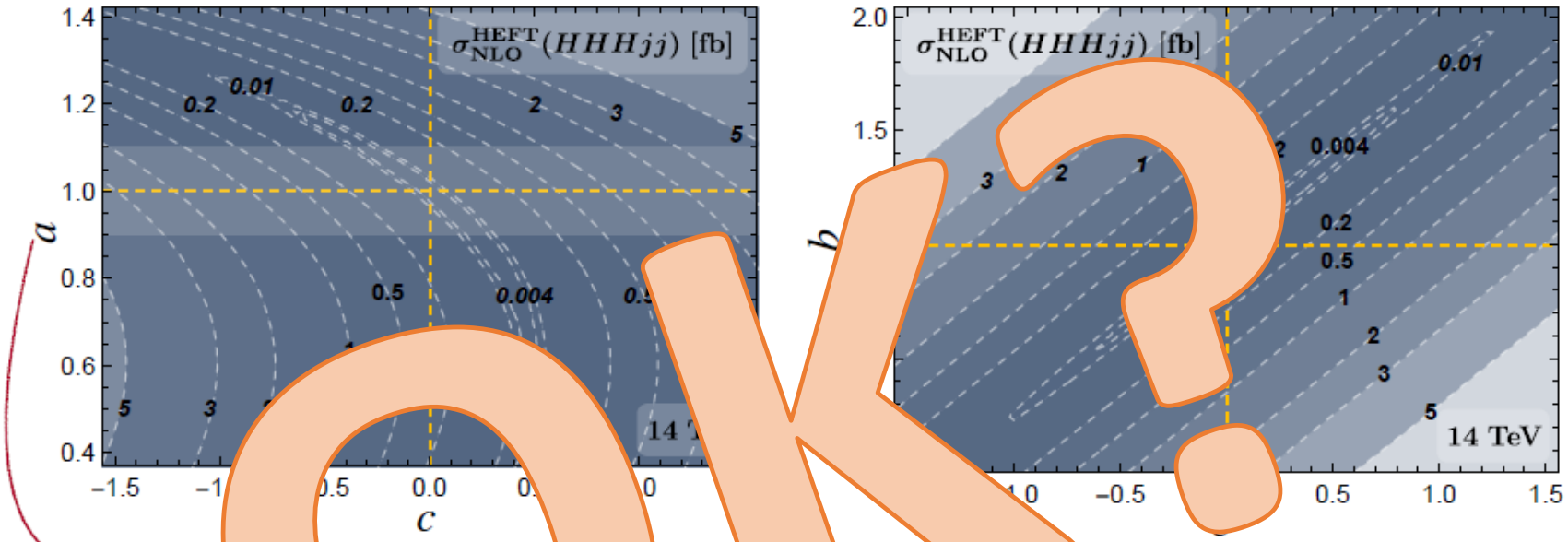


[using interpolation]

highest values: $\sim 50\mathrm{fb}$ **for** $M_2 \sim 250\,\mathrm{GeV}$, $M_3 \sim 400 - 450\mathrm{GeV}$

Correlations between HEFT parameters

$\mu_F = \mu_R = Q$



OK?

- HL-LHC ... e Higgs limits
  $a \in [-$ ... $]$

- Correlatio ... vs the high ... gy behaviour of the amplitudes $s \gg m_W^2, m_H^2$ following Goldstone e ...

$$\mathcal{M}(W_L^+ W_L^- \to HHH) \sim \frac{3g^3}{2m_{\rm W}} \left(c - \frac{4}{3} a(b - a^2) \right) \frac{s}{4m_{\rm W}^2}$$

Ambrosio et al 2204.01763 Delgado et al 2311.04280

- $c \neq 0$ leads to $\sigma(pp \to HHHjj)$ enhancements.

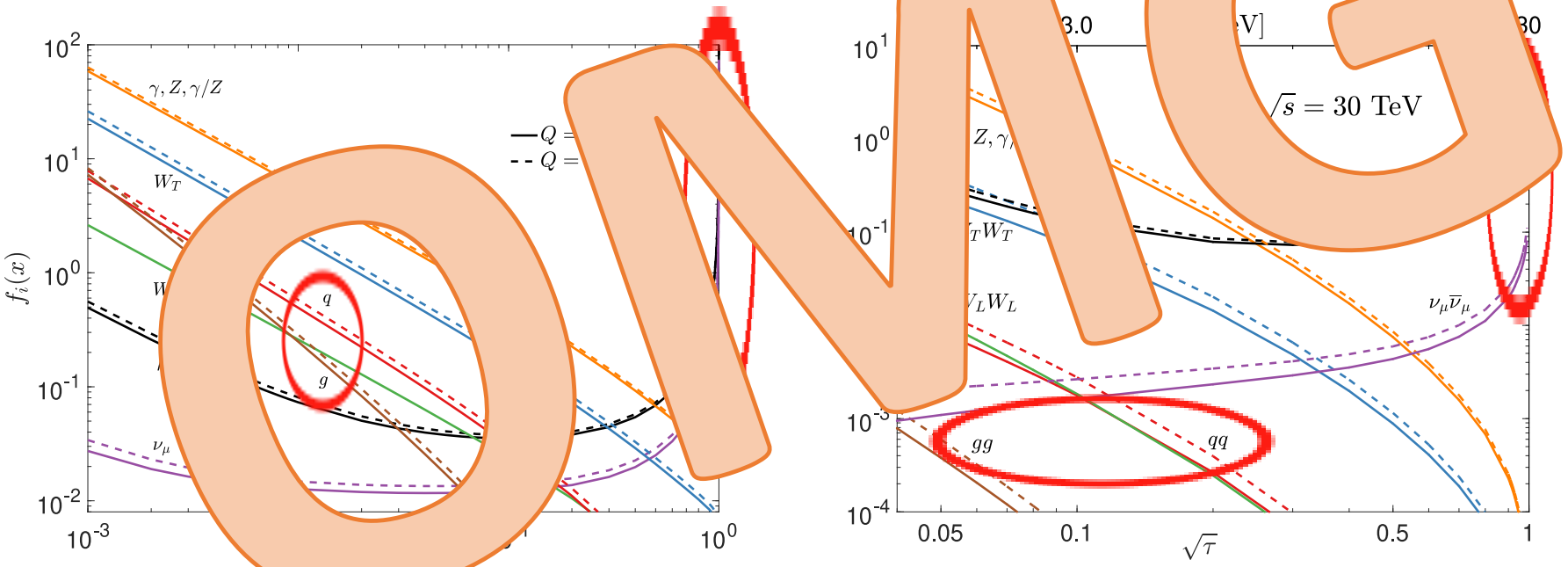
EW PDFs @ a Muon Collider

TH, Yang Ma, Keping Xie, arXiv:2007.14300

DGLAP evolution in full SM:

$$\begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix} = \frac{\mathrm{d}}{\mathrm{d}\log Q^2} \begin{pmatrix} P_{\ell\ell} & 0 & 0 & 2N_\ell P_{\ell\gamma} & 0 \\ 0 & P_{uu} & 0 & 2N_u P_{u\gamma} & 2N_u P_{ug} \\ 0 & 0 & P_{dd} & 2N_d P_{d\gamma} & 2N_d P_{dg} \\ P_{\gamma\ell} & P_{\gamma u} & P_{\gamma d} & P_{\gamma\gamma} & 0 \\ 0 & P_{gu} & P_{gd} & 0 & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \end{pmatrix}$$

Take into account two scales: $\mu_{QCD} \sim \Lambda_{QCD}$, $\mu_{EW} \sim v$



OMG

$\mu^\pm$, ν_μ : the valance. ℓ_R, ℓ_L, ν_L and $B, W^{\pm,3}$: LO sea.

Quarks: NLO; gluons: NNLO.

Iterated Pole Subtraction

(i.e. geometry at codimension greater than one)

GDL, Maître ('19)
GDL, Page ('22)
Chawdhry ('23)
Xia, Yang ('25)

- Let's go back to our example

$$\hat{d}^{++}_{12\times 3\times 4} = \frac{\mathcal{N} \leftarrow \text{2794 free parameters}}{\langle 12\rangle^2 \langle 1|\mathbf{5}|\mathbf{4}|\mathbf{3}|2]\langle 2|\mathbf{3}|\mathbf{4}|\mathbf{5}|1]\Delta}$$

- We can prove $\langle 1|\mathbf{5}|\mathbf{4}|\mathbf{3}|2], \langle 2|\mathbf{3}|\mathbf{4}|\mathbf{5}|1]$ can be separated, their primary de[illegible]position reads

$$\langle\langle 1|\mathbf{5}|\mathbf{4}|\mathbf{3}|2], \langle 2|\mathbf{3}|\mathbf{4}|\mathbf{5}|1]\rangle = \langle\langle 1|[illegible]|\mathbf{4}|\mathbf{3}|2], \langle 2|\mathbf{3}|\mathbf{4}|[illegible]|1], \mathrm{tr}_5\rangle \cap \langle\langle 1|\mathbf{5}|[illegible], \langle 2|\mathbf{3}|\mathbf{4}|\mathbf{5}|1], s_{23}, s_{15}\rangle$$

Generate two phase space p[illegible]nts, one for each branch [illegible]nd verify [illegible]umerator vanishes.

- Similarly, with four evalua[illegible]ons we [illegible]n prove $\langle 1|\mathbf{5}|\mathbf{4}|\mathbf{3}|2[illegible]\Delta_{12|\mathbf{3}|\mathbf{4}|\mathbf{5}}$ ca[illegible]eparated,

$$\langle\langle 1|\mathbf{5}|\mathbf{4}|\mathbf{3}|2], \Delta_{12|\mathbf{3}|\mathbf{4}|\mathbf{5}}\rangle = \langle M_H[illegible]\mathbf{5}_{\alpha\dot{\alpha}}\mathbf{4}^{\dot{\alpha}\beta}\rangle \cap \langle[illegible]_H,\ \mathbf{4}^{\dot{\alpha}\alpha}\mathbf{3}_{\alpha\dot{\beta}}\rangle \cap \langle\langle 1|\mathbf{3}|2],\ \langle 1|\mathbf{4}|2],\ \langle 1|\mathbf{3}|\mathbf{4}|1\rangle, [2|\mathbf{3}|\mathbf{4}|2]\rangle \cap \langle ???\rangle$$

Although we don't have a comp[illegible]te set of generato[illegible] for the last branch, we can still sample it.

- Fit $\langle 1|\mathbf{5}|\mathbf{4}|\mathbf{3}|2]$ residue by sampling in limit $\langle 1|\mathbf{5}|\mathbf{4}|\mathbf{3}|2] \to 0$

$$\hat{d}^{++}_{12\times 3\times 4} = \frac{\mathcal{N} \leftarrow \text{112 free parameters}}{\langle 12\rangle^2 \langle 1|\mathbf{5}|\mathbf{4}|\mathbf{3}|2]} + \mathcal{O}(\langle 1|\mathbf{5}|\mathbf{4}|\mathbf{3}|2]^0)$$

Signal strengths for single-Higgs processes

Including the process-dependent and universal O(λ) one-loop corrections, along with two-loop O(λ²) contributions from Higgs WFR

$$\mu_i^f \simeq 1 + \delta\sigma_i + \delta\mathrm{BR}_f$$

$$\delta\sigma_i \simeq C_1^{\sigma_i}(\kappa_3 - 1) - 1.536 \cdot 10^{-3}(\kappa_3 - 1) - 5.49 \cdot 10^{-6}(1 - 1.333L)(\kappa_4^2 - 1)$$
$$- 4.180 \cdot 10^{-6}(1 - L)(\kappa_3 - 1) - 8.517 \cdot 10^{-6}(1 - 1.767L)(\kappa_3^2\kappa_4 - 1)$$
$$- 1.726 \cdot 10^{-5}(1 + 1.307L)(\kappa_3^4 - 1)$$

$$\delta\mathrm{BR}_f \simeq \frac{(\kappa_3 - 1)\left(C_1^{\Gamma_f} - C_1^{\Gamma_h}\right)}{1 + (\kappa_3 - 1)\, C_1^{\Gamma_h}}$$

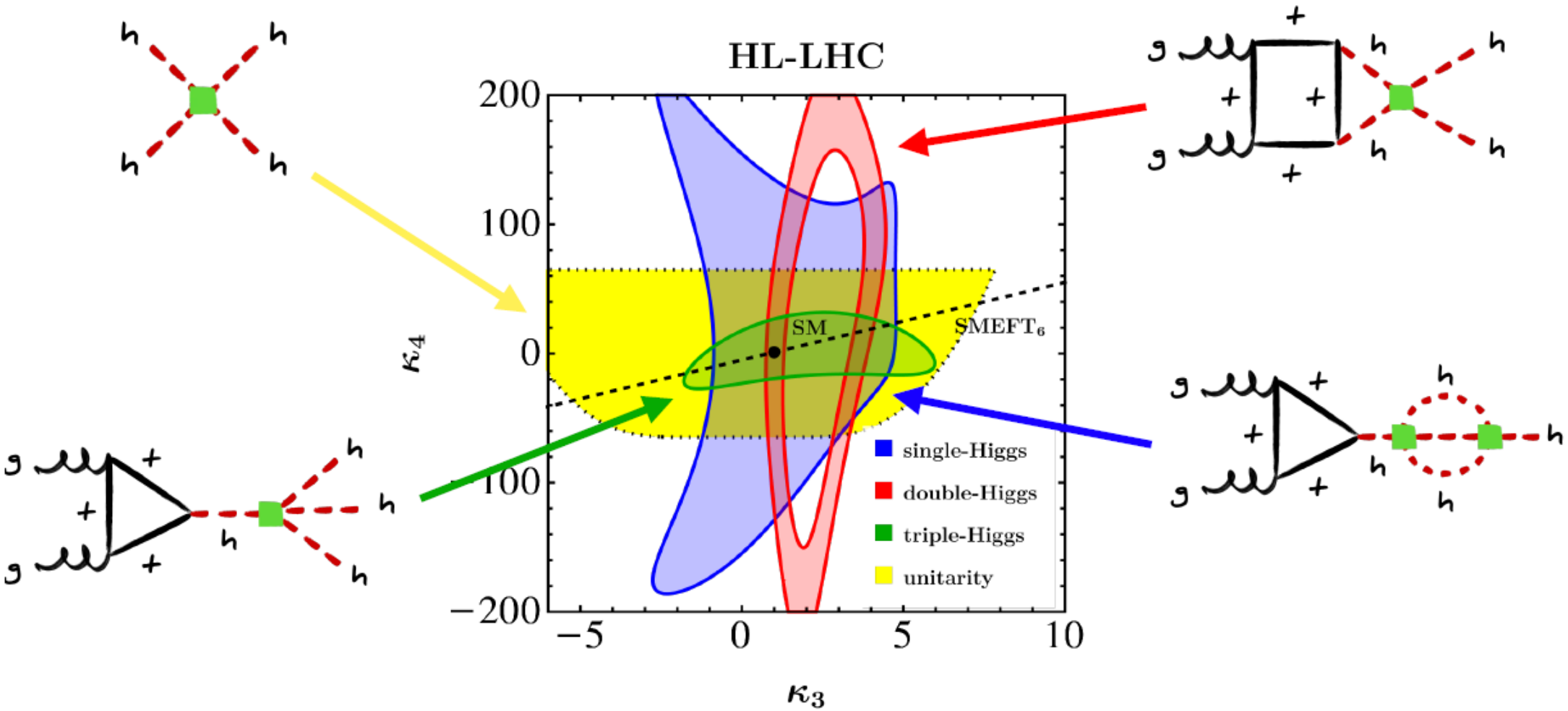
= process-dependent corrections

Includes all two-loop contributions proportional to κ_4^2, $\kappa_3\,\kappa_5$, $\kappa_3^2\,\kappa_4$ & κ_3^4

[see Haisch, Sankar & Zanderighi, 2505.20463 & references therein]

<face Palm>

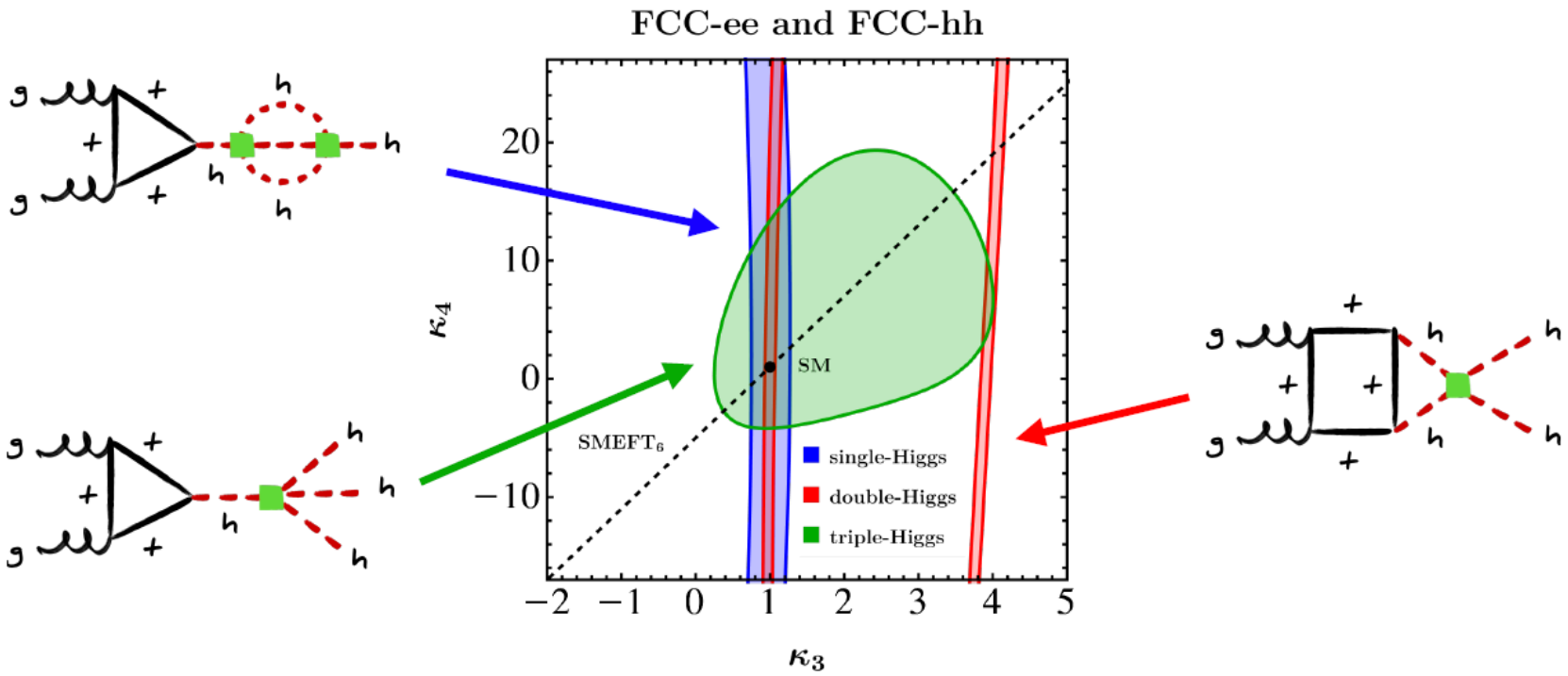
Giulia Z. Projections to the future of HHH



[Haisch, Sankar & Zanderighi, 2505.20463; double- & triple-Higgs bound from ATL-PHYS-PUB-2022-005 & Brigljevic et al., 2407.03015]

The far future of HHH limits. Including SMEFT

FCC analysis



[Haisch, Sankar & Zanderighi, 2505.20463; double- & triple-Higgs bounds from Mangano et al., 1607.01831]

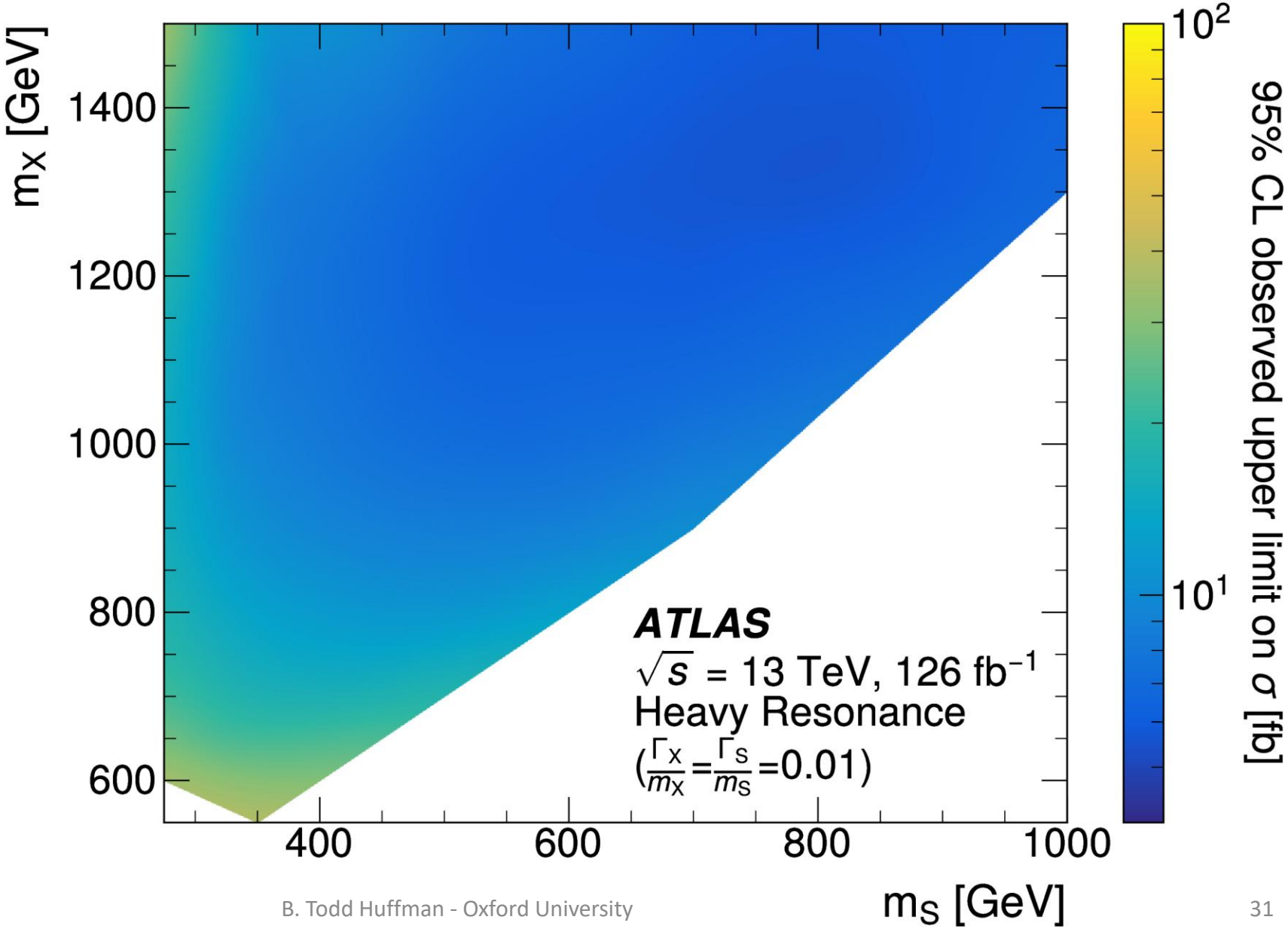
In HHH Experimentally much progress!

- ATLAS – First HHH limits in K3 vs K4 in the 6b channel
  - Also limits in TRSM and a general search for high-mass resonances
  - Published in Feb. this year

- CMS – Very recent K3 vs K4 limits in two channels
  - 4byy – low background, but even more rare
  - 6b in mixed boosted and resolved jet signatures

A TRSM Money plot

Published in
[Phys. Rev. D]



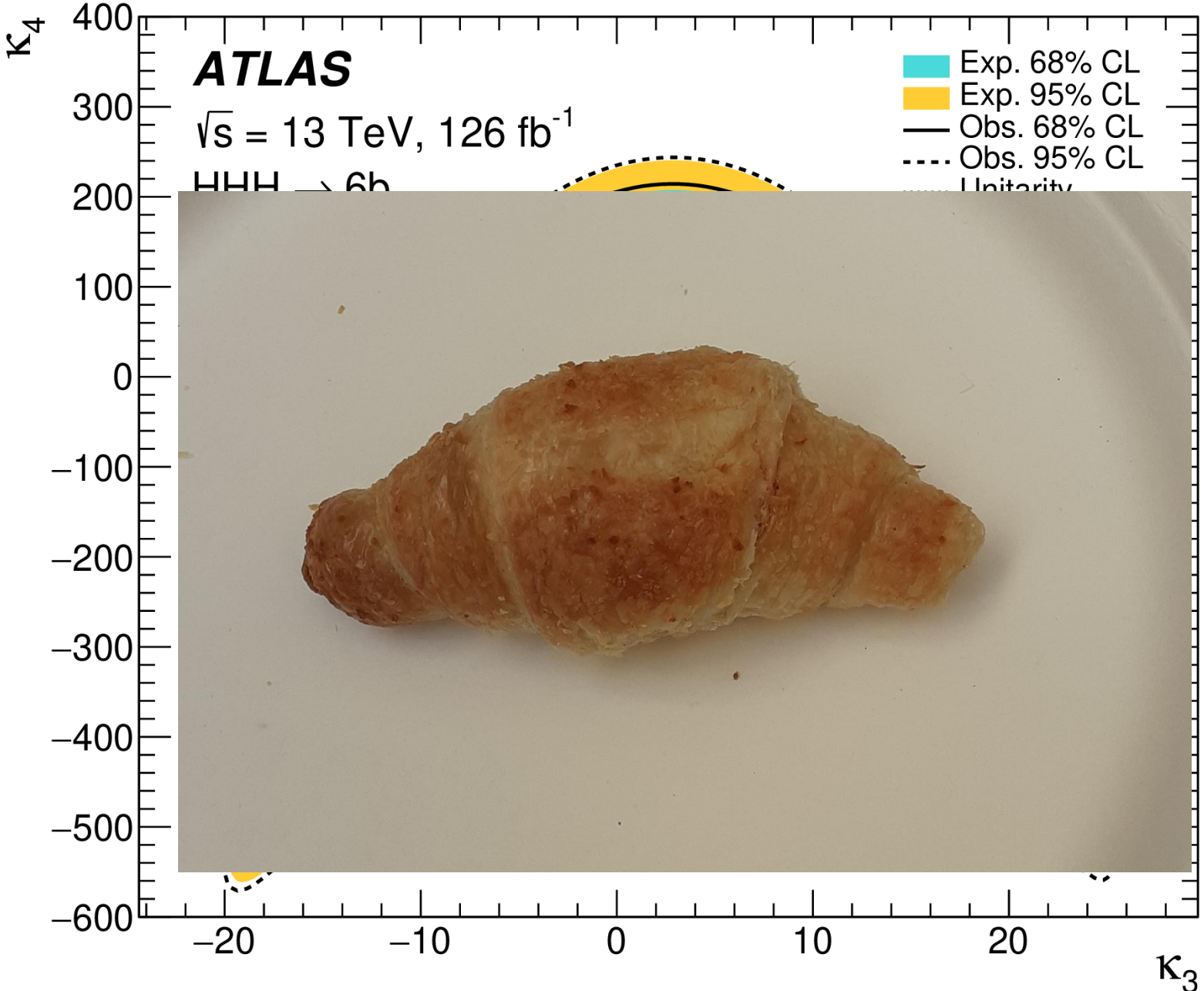
Used DNN scores in 4b/5b ratio and low score 5b/6b from data to fix backgrounds

Set K3 limit independent of HH (which CMS showed can strengthen limits)

(κ_3, κ_4) interpretation

$-11 < \kappa_3 < 17$

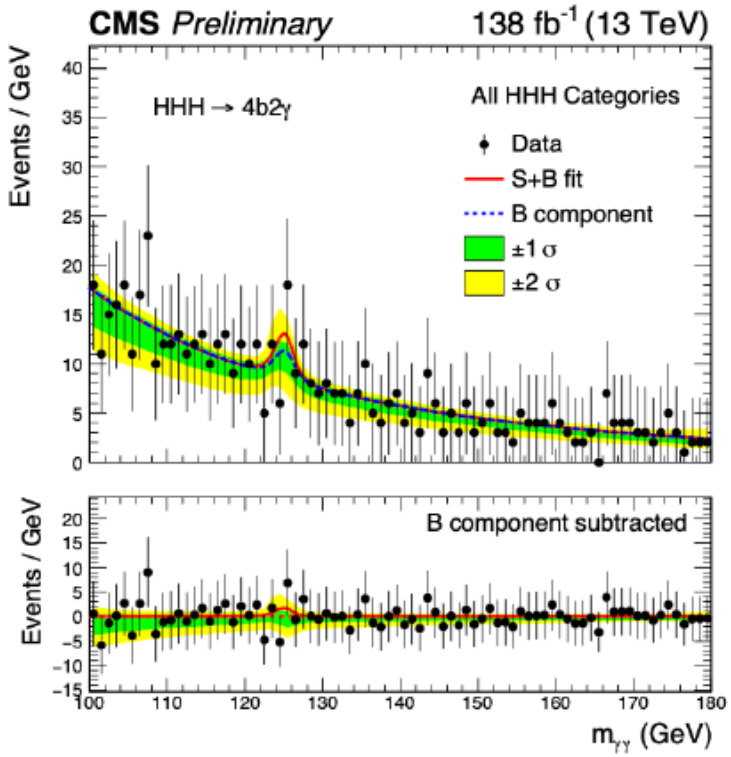
$-230 < \kappa_4 < 240$



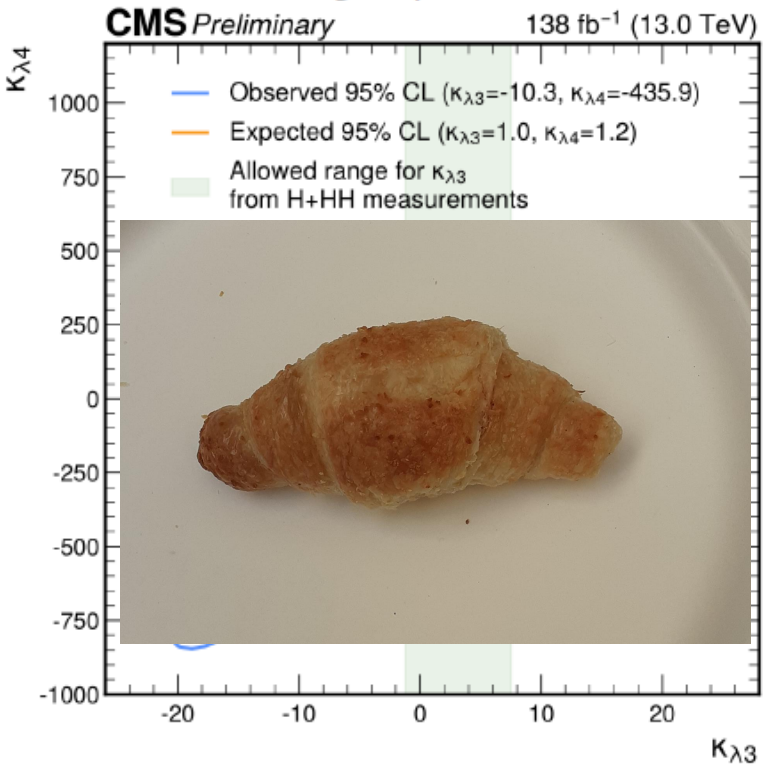
Non-resonant $HHH \to 4b2\gamma$

CMS-PAS-HIG-24-015

Fit to the data



(κ_3, κ_4) scan



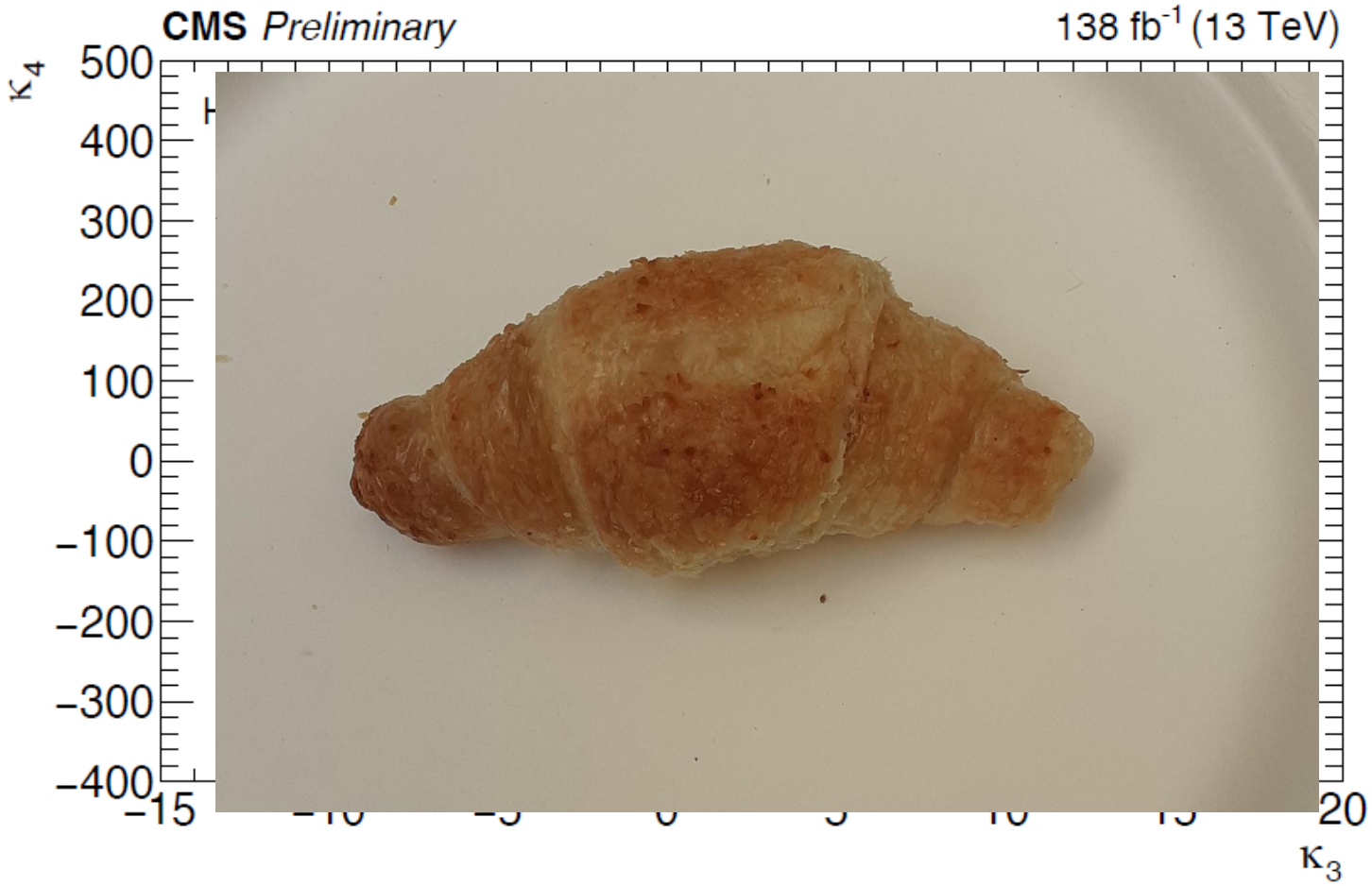
Observed (expected) limit on the signal strength: $\mu < 3400\ (2086)$ x SM at 95% CL

- Slight excess observed in data (within 1 sigma)
- Challenging channel, large background and low cross-section
- Selection acceptance, trigger, pairing, tagging, ...

Interpretation: 1D: $-16 < \kappa_3 < 20$ and $-397 < \kappa_4 < 405$ as well as 2D scan

Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012

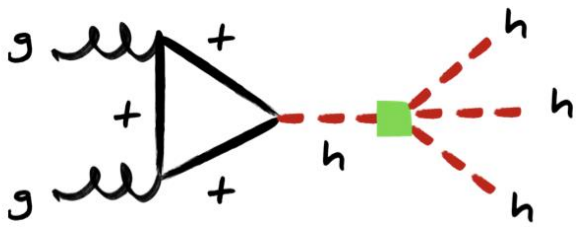


Interpretation: normalization effects of κ_3 and κ_4 on HHH and κ_3 on HH

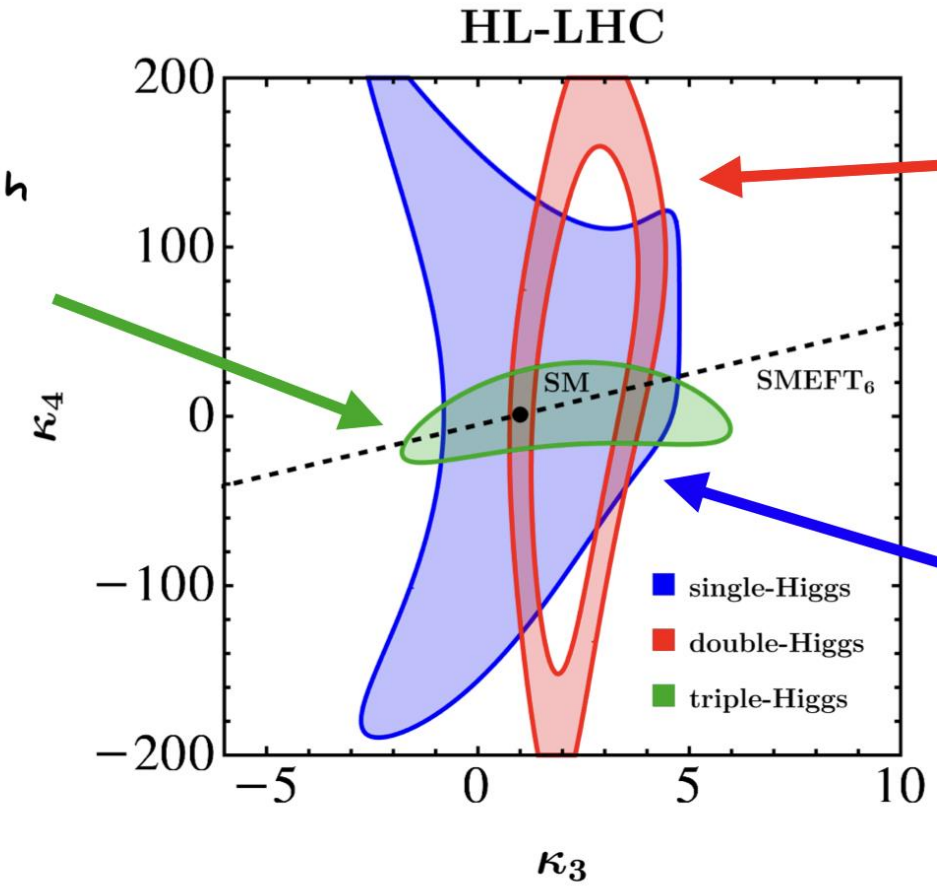
First exclusion of (κ_3, κ_4) at 95% CL in region allowed by perturbative unitarity bounds!

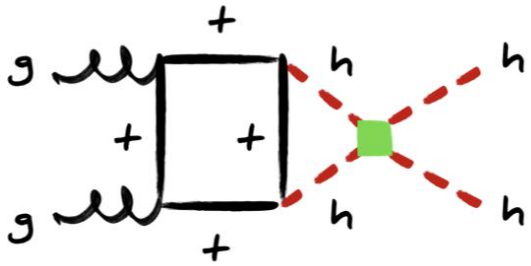
THE ULTIMATE COMBINATION: H + HH + HHH

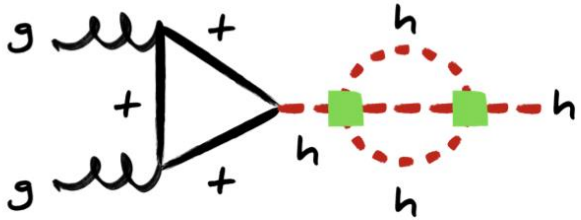
See G.Zanderighi arXiv:2505.20463



Ilustration by U.Haisch







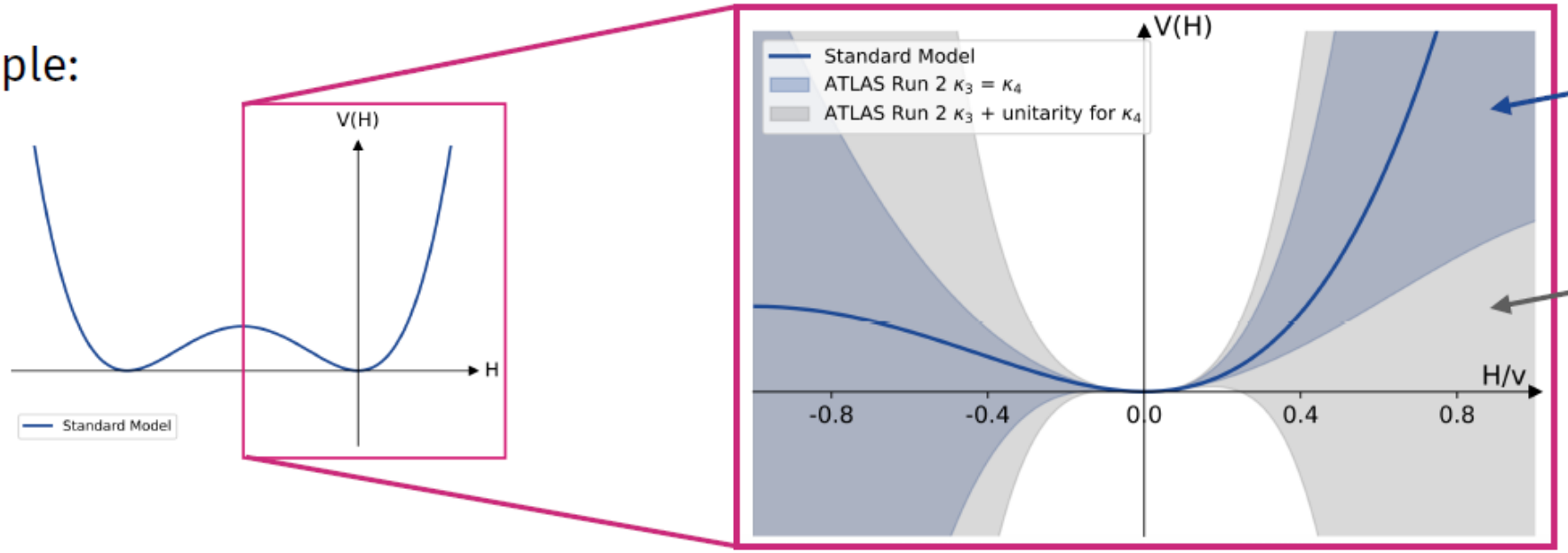
Concluding remarks

Remarkable progress has been made in our searches for resonant and non-resonant HH production with the ATLAS experiment since the last HHH workshop
→ continue exploring the Higgs sector of the SM

In terms of methodology and underlying physics all (multi-)Higgs analyses are connected

Should strive to combine H+HH+HHH measurements/searches to get the most complete picture with the least assumptions

Example:



$\kappa_3 = \kappa_4 = \kappa_\lambda$

$\kappa_3 \neq \kappa_4$

$-0.4 < \kappa_3 < 6.3$

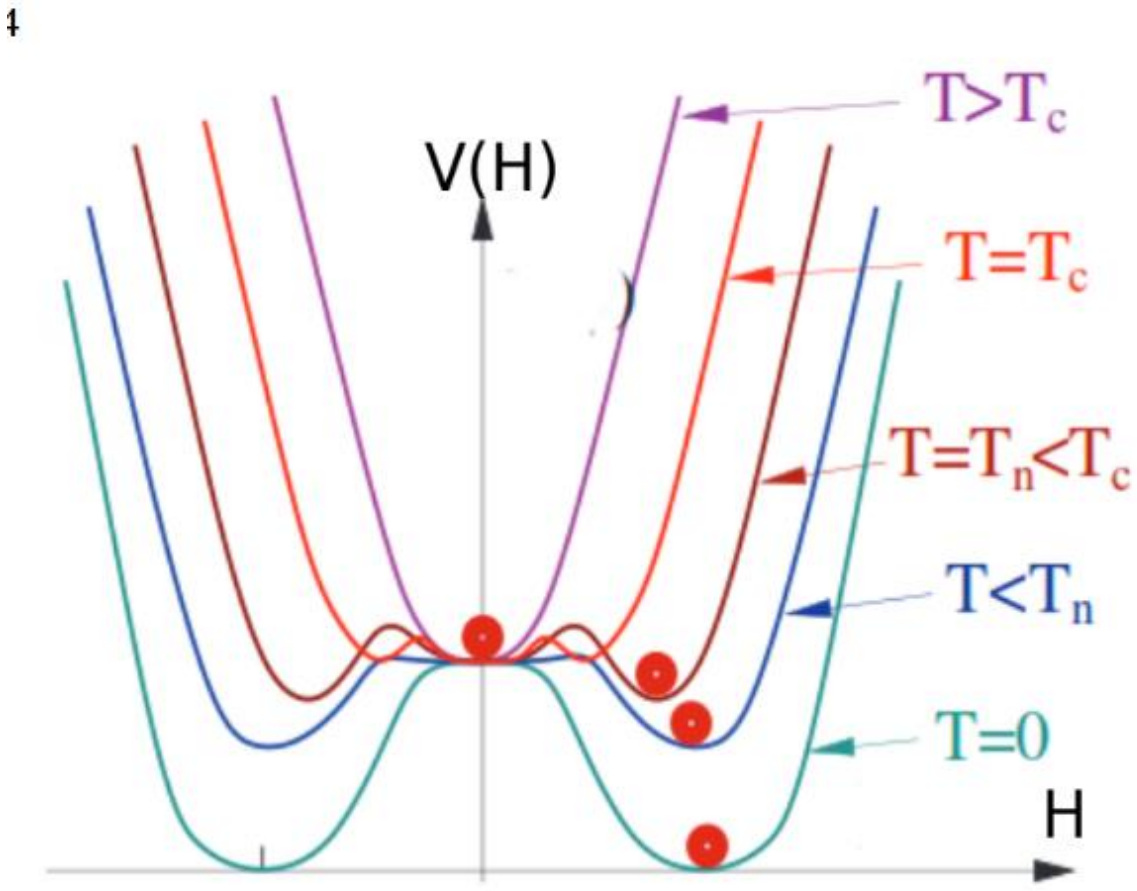
$-60 < \kappa_4 < 60$

Ultimate Goal (unless we find a resonance)

- The K3 and K4 parameters are key to the shape of the Higgs potential.

- We are only just beginning to explore this.
- Was there a phase transisiton in the early Universe?
- Will there be another?!

- **I would love to find out!**



T_n = temperature of bubble nucleation

WHHHere are we going?

I am not certain.

But I am more confident than I was!
For in the future →

Surely we are going back to….

Welcome to the
Inter University Centre Dubrovnik
and its amazing staff:
Nada, Nikolina, Tomi, …

My Poster Entry! 2027

Symbolic

Up-hill struggle of HHH physics

Hard climb – the top is not visible.

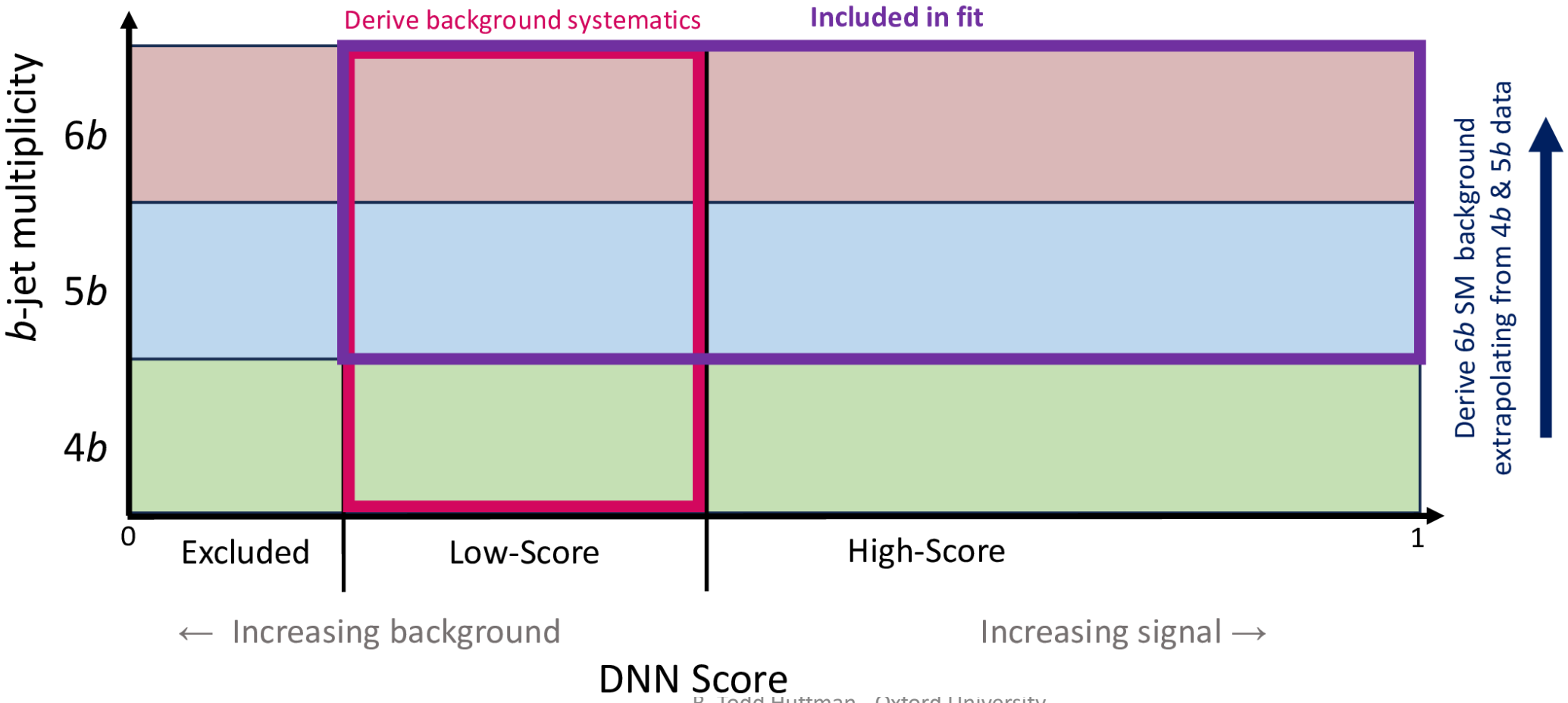
Fabulous rewards at the end…..

Maybe

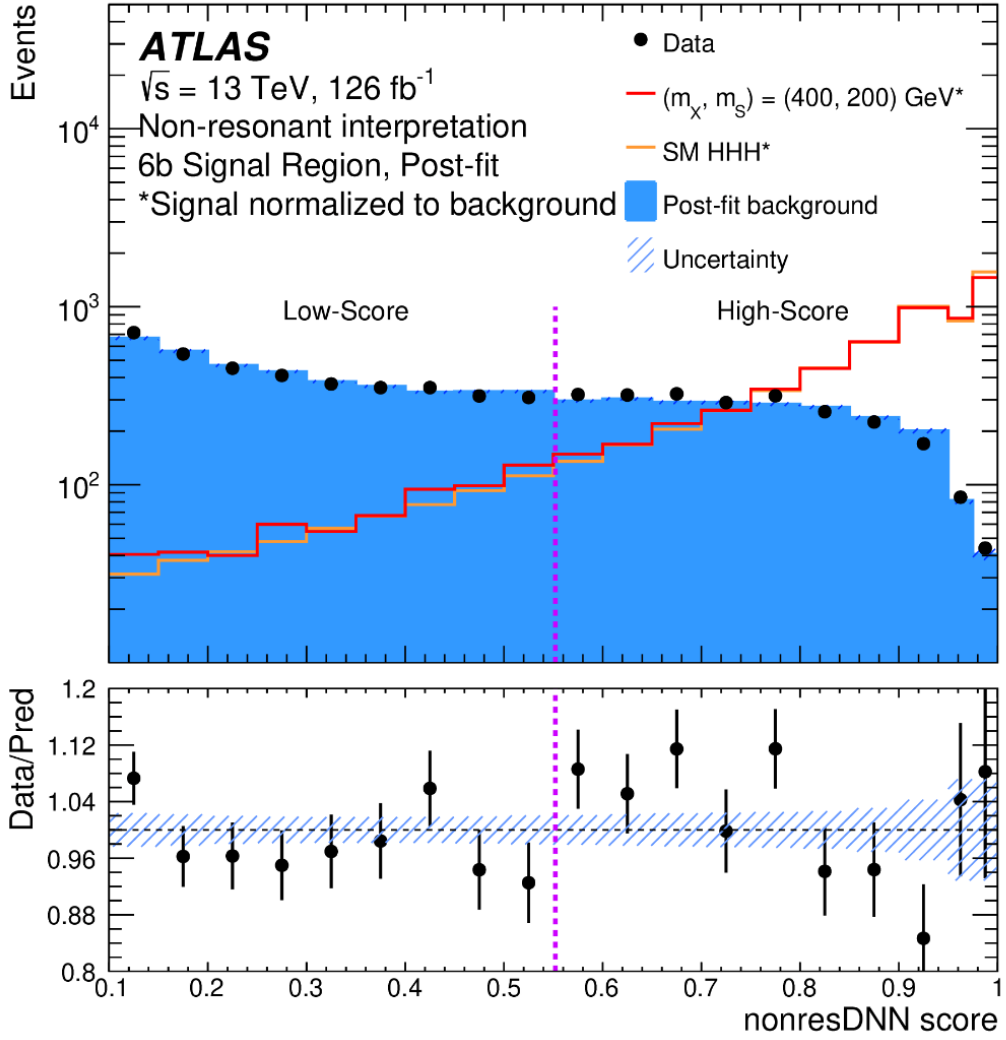
End and maybe Backup slides

BKG estimation Procedure

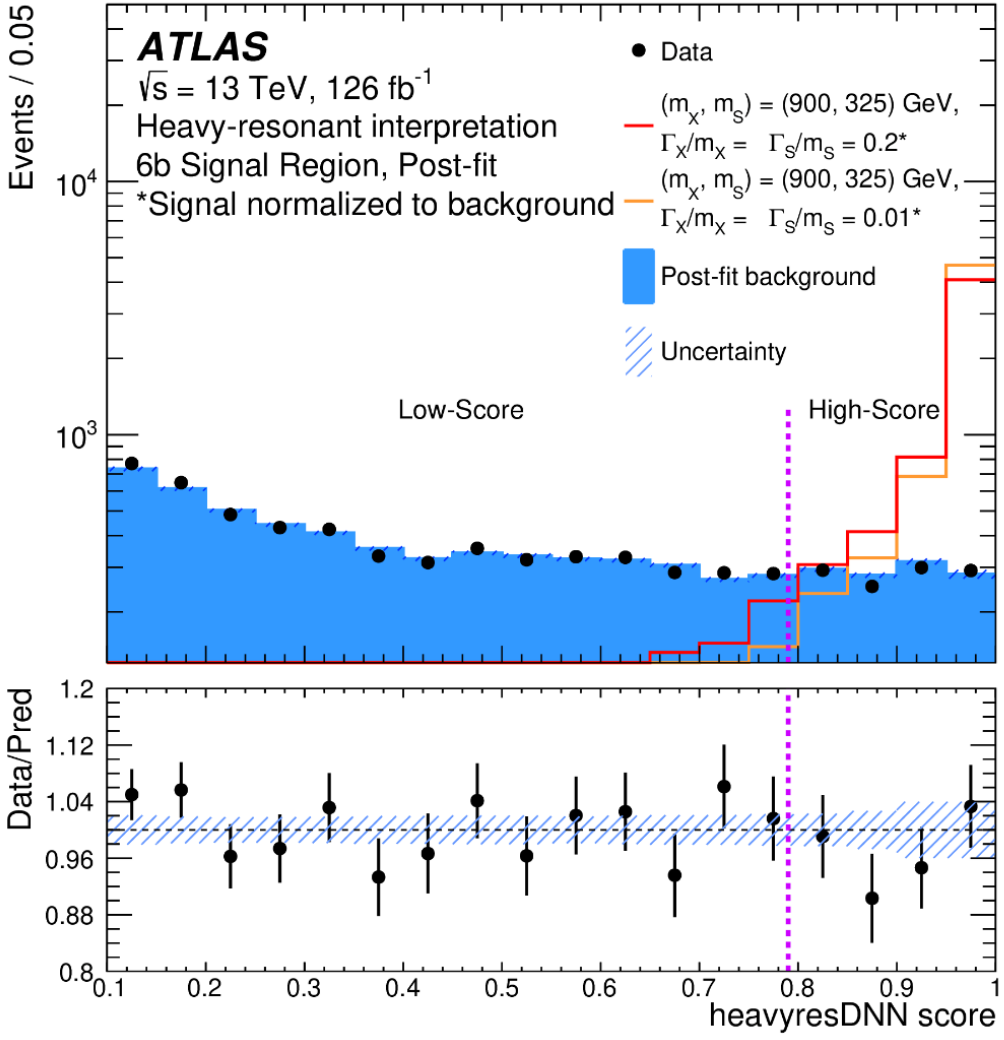
- Look at 4 and 5 tagged b-jets to get background
- Best to show you with an example.



Unblinded DNN score plots



K3 – k4 → Higgs couplings search

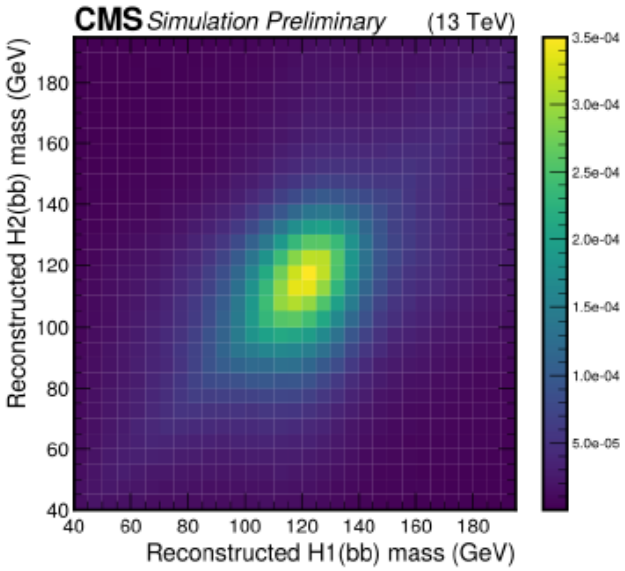


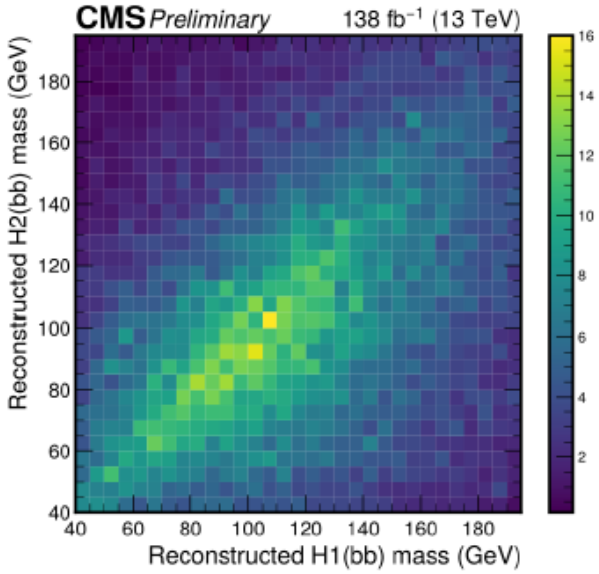
Resonant ‘X’ and ‘S’
exotic particle search

Non-resonant $HHH \to 4b2\gamma$

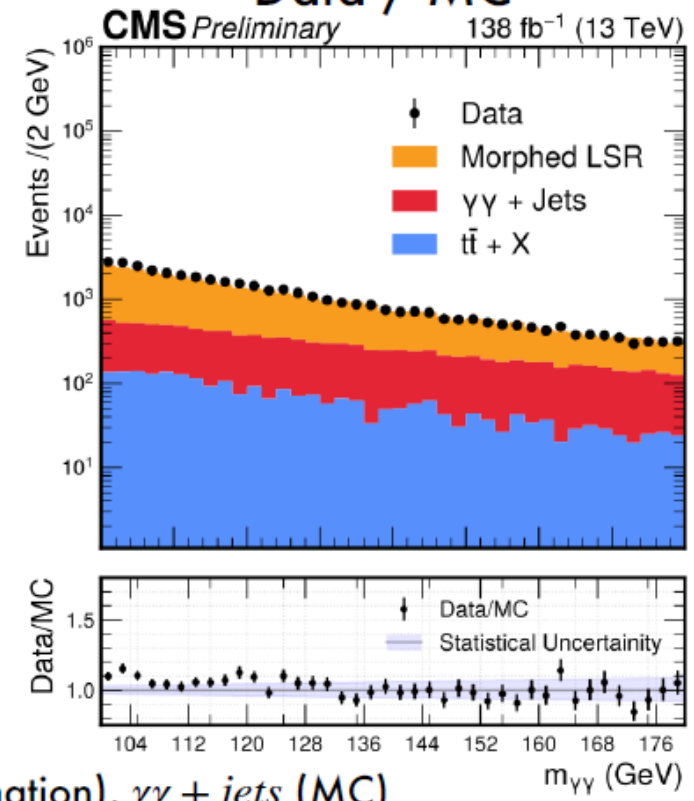
CMS-PAS-HIG-24-015

Pairing algorithms for 4b





Data / MC



Trigger: di-photon trigger developed for $H \to \gamma\gamma$, about 70% acceptance

- Non-resonant: $\gamma + jets$ and QCD (faking photons, modeled with data-driven estimation), $\gamma\gamma + jets$ (MC)
- Resonant: H+X using MC

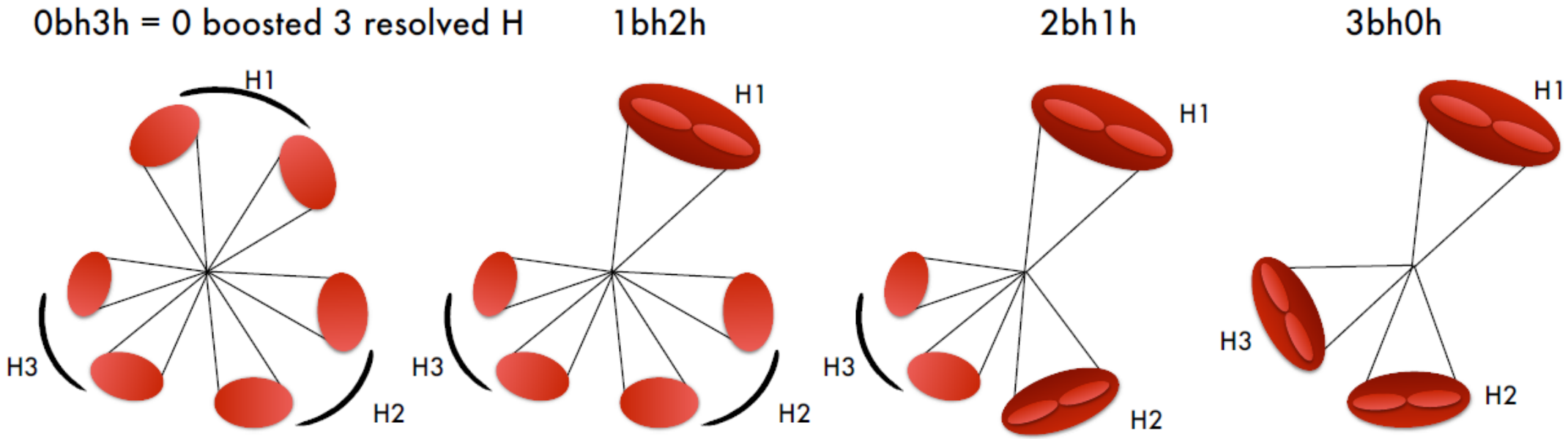
Focus on fully resolved analysis, pairing of the 4b candidates: exploiting HH4b methods minimizing $D_{HH} = |m_{H_1} - 1.05 \times m_{H_2}|$

- Accuracy, about 75% (softer Higgs kinematic than in HH4b)

Overall, signal efficiency is about 60% before machine learning optimization

Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012



HHH6b: rich experimental topology

- Resolved Higgs: reconstructed from 2 small-radius jets
- Boosted Higgs: reconstructed from one large-radius jets
- Complex mixing, dependent on momentum of the Higgs candidates

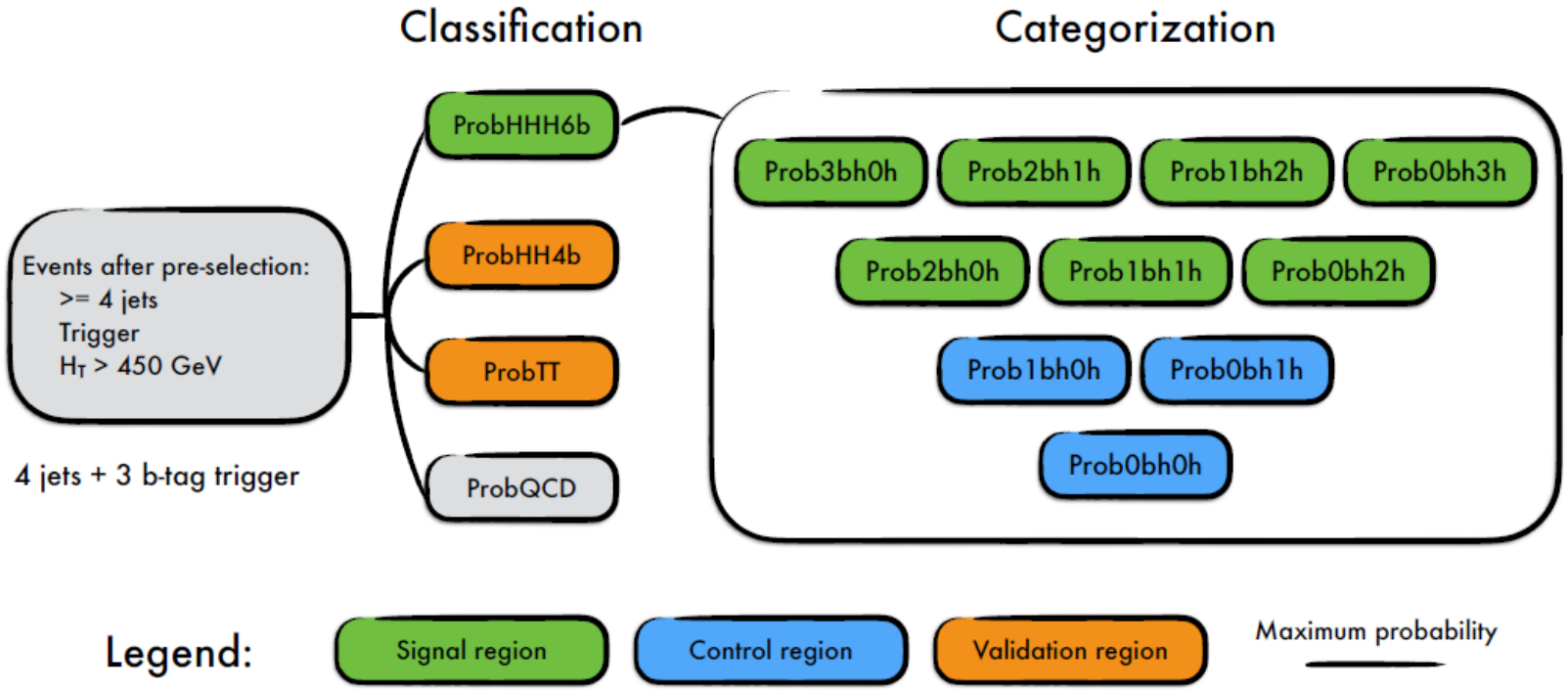
Perfect problem for state-of-the-art machine learning: **symmetry preserving attention networks**

- Permutation symmetry of indistinguishable objects (= jets in this case)
- Input order invariance and assignment symmetry: two b's can be exchanged

CMS - Split Data into regions of background, validation, and signal regions

Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012



Dominant background: QCD (95%) and ttbar (5%)

Train two networks using SPANET

- Multi-classifier: **HHH6b** vs **HH4b** vs **QCD** vs **ttbar** → Effectively vetoing HH4b events
  - Use HH4b-like events to validate background model, use ttbar node to validate Data / MC
- Multi-categorization: trained on HHH6b and HH4b **predict categories** based on truth matching

Many other models can enhance σ .

- 2HDM, 3HDM

- Extensions to these – N2HDM and NMSSM
  - Start from 2 Higgs models and then add further extensions
    - Don't ask me – See Tania Robens' talk

⇒ **large number of models e.g. implemented in ScannerS**
[M. Muhlleitner ea, Eur.Phys.J.C 82 (2022) 3, 198]