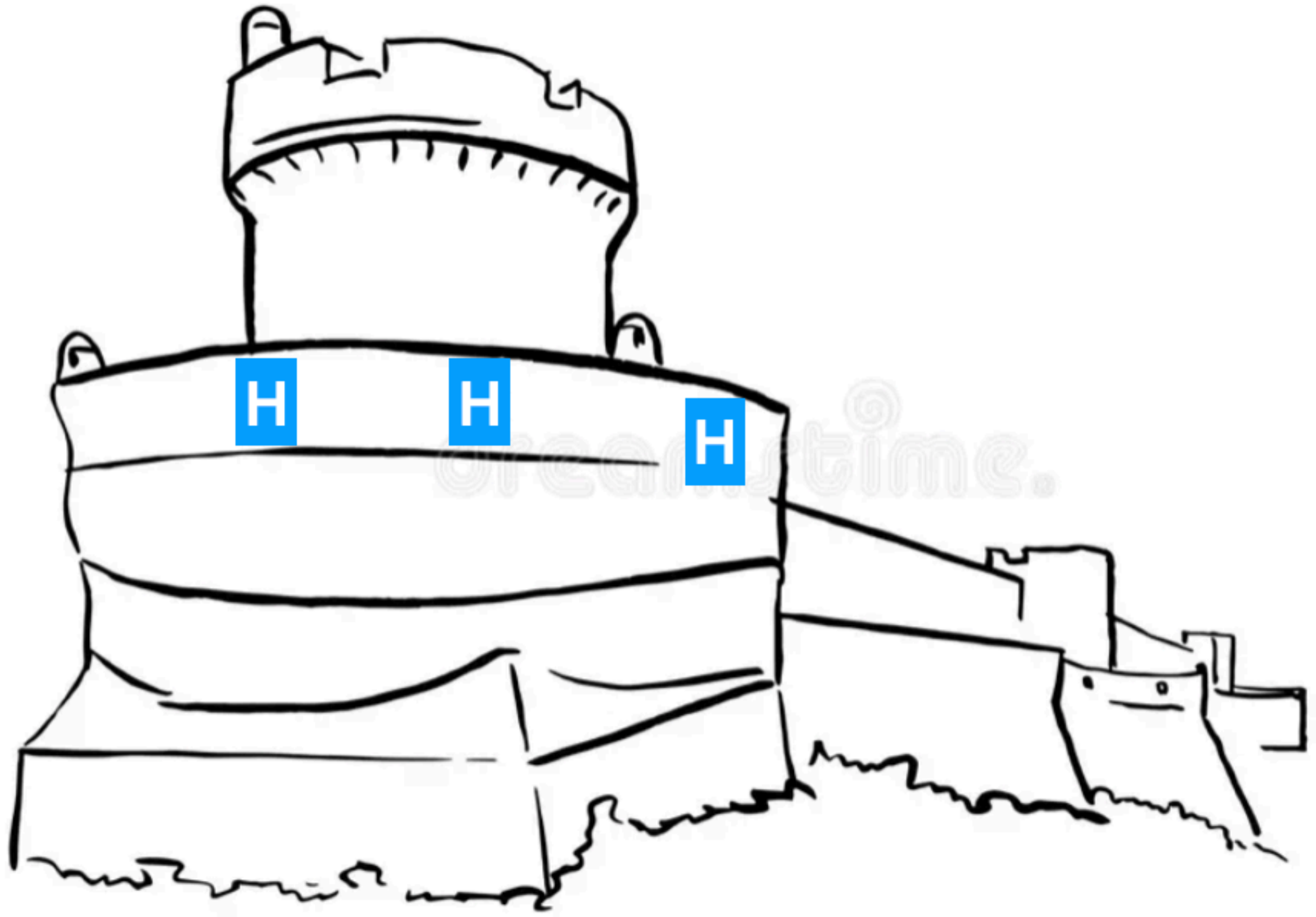
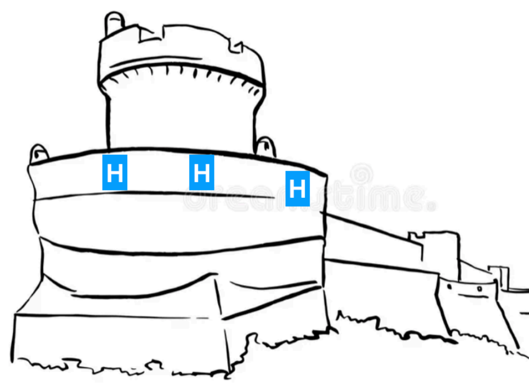
https://indico.cern.ch/event/1232581/

Selected Highlights



J. Konigsberg / Univ. of Florida

Preamble



Workshop

- Great idea for this workshop
- Thanks for the excellent organization !

Some caveats about this talk

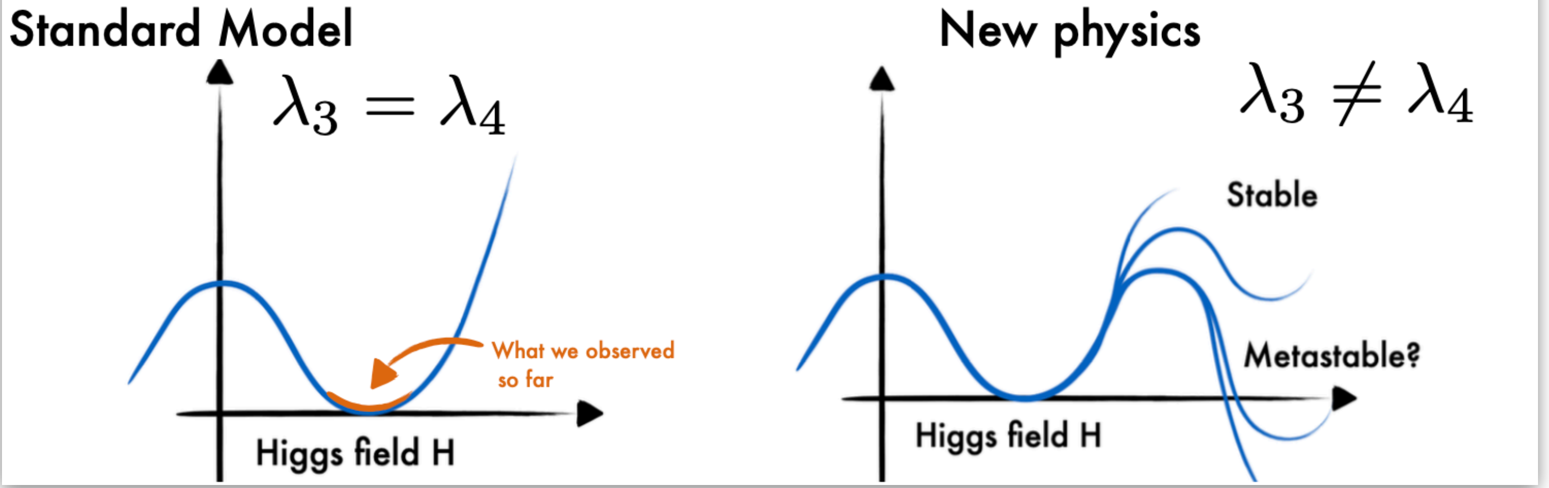
- High level filter talk on excellent, detailed, presentations
  - Filter based on myNN convoluted with memory retention, understanding, and saturation thresholds + apparently some form of adversarial training
- Mixed and matched from most talks
  - So credit goes to to all presenters & discussions :)
  - Far from comprehensive
- Apologies for omissions, misunderstandings, over-simplifications
  - Lots to digest in ~real time

Multiple Higgs production

Fuks/Moser/Stamenkovic

- **Critical probe of the Higgs potential**
  - Introduced ad-hoc to the SM
  - No fundamental explanation to its shape
  - Sensitive to new physics

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$



In SM:

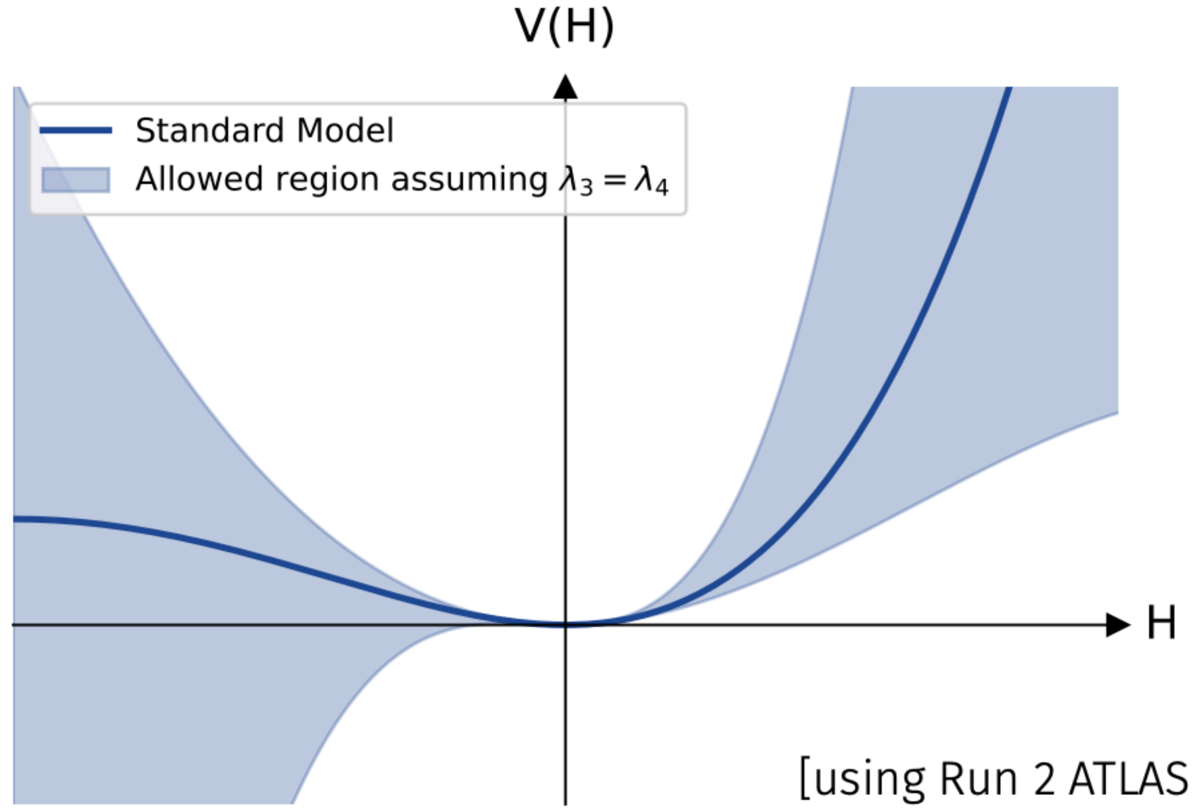
$$\lambda_3 = \lambda_4 = \lambda = \frac{m_H}{2v^2} \sim \frac{1}{8}$$

Parameterize:

$$\kappa_3 = \frac{\lambda_3}{\lambda_3^{SM}}$$

$$\kappa_4 = \frac{\lambda_4}{\lambda_4^{SM}}$$

Assuming 1 free parameter $\lambda_3 = \lambda_4 = \lambda$



Very weak constraints

[using Run 2 ATLAS constraints from Phys. Lett. B 843 (2023) 137745]

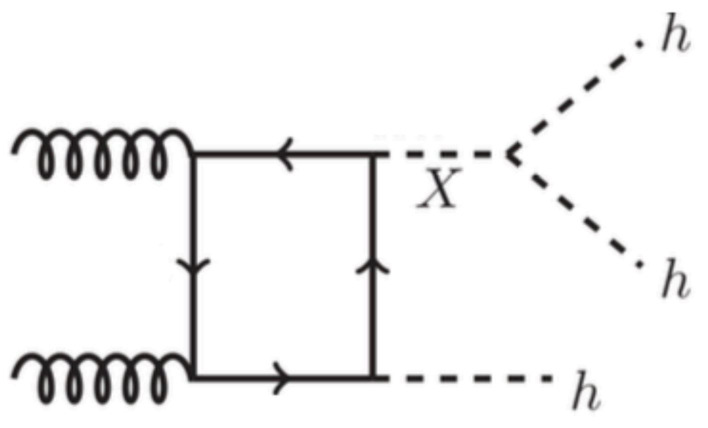
Simplest new physics parameterisation

- **SM coupling modifiers**

$$V_h = \frac{1}{2}m_h^2 h^2 + (1+\kappa_3)\lambda_{hhh} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh} h^4$$

More involved parameterisation

- **Extended scalar sector**
  → xSM, 2HDM, 3HDM, *etc.*
- **Resonant enhancement in multi-Higgs production**



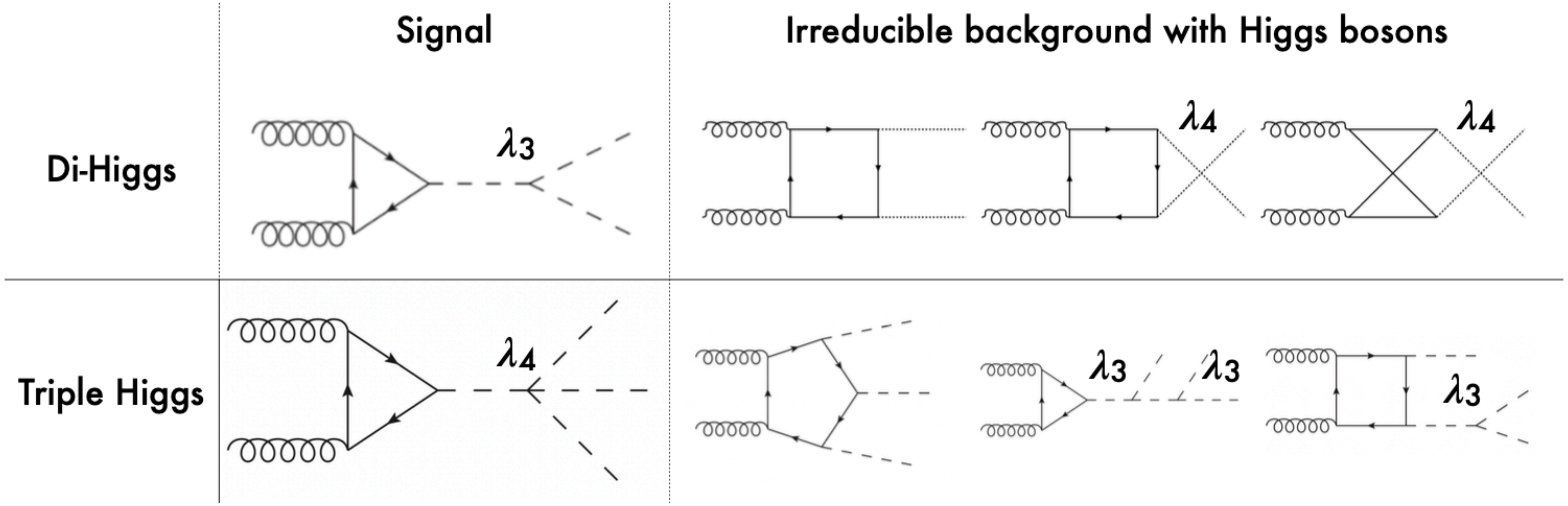
$$\begin{aligned} V_0(\phi_1,\phi_2,\phi_3) \;=\; & \mu_1^2\left(\phi_1^\dagger\phi_1\right) + \mu_2^2\left(\phi_2^\dagger\phi_2\right) + \mu_3^2\left(\phi_3^\dagger\phi_3\right) + \lambda_1\left(\phi_1^\dagger\phi_1\right)^2 \\ & + \lambda_2\left(\phi_2^\dagger\phi_2\right)^2 + \lambda_3\left(\phi_3^\dagger\phi_3\right)^2 + \lambda_4\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_5\left(\phi_1^\dagger\phi_1\right)\left(\phi_3^\dagger\phi_3\right) \\ & + \lambda_6\left(\phi_2^\dagger\phi_2\right)\left(\phi_3^\dagger\phi_3\right) + \lambda_7\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) \\ & + \lambda_8\left(\phi_1^\dagger\phi_3\right)\left(\phi_3^\dagger\phi_1\right) + \lambda_9\left(\phi_2^\dagger\phi_3\right)\left(\phi_3^\dagger\phi_2\right) \end{aligned}$$

See talks by Pasechnik, Papaefstathiou & Robens

Multiple Higgs production

Stamenkovic/Stylianou

Probing self-interaction di-Higgs and triple Higgs



Probing the Higgs self-coupling possible through di-Higgs and triple Higgs measurements:

- Di-Higgs: nearly exclusively sensitive to λ_3 coupling (very small contribution from λ_4)
- Triple Higgs: sensitive to both λ_3 and λ_4 coupling

  → Full determination of the Higgs potential only possible through combined measurement!

Sensitivity:

- Di-Higgs: current sensitivity < 2.5 x SM @ 95% CL → expect evidences at HL-LHC
- Triple Higgs: considered impossible to measure at LHC → No estimated results so far!

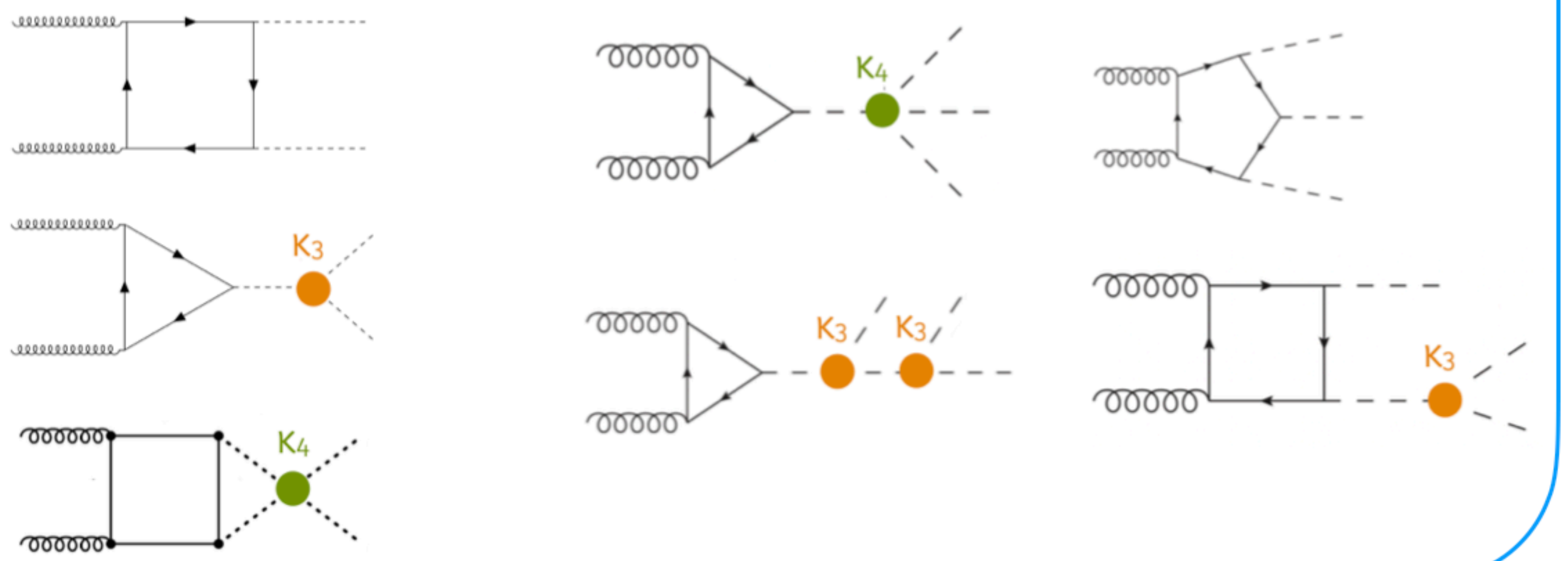
M. Stamenkovic, 14th of July 2023, HHH workshop, Dubrovnik 5

Multiple Higgs production

Moser/Stylianau

- Multi Higgs boson production rates are extremely low compared to single Higgs production, which itself is already low [h/hh ~ 1800, hh/hhh ~ 450 @ LHC]
- To add to the complexity, the connection between final state multiplicity and contributing coupling modifiers is not trivial

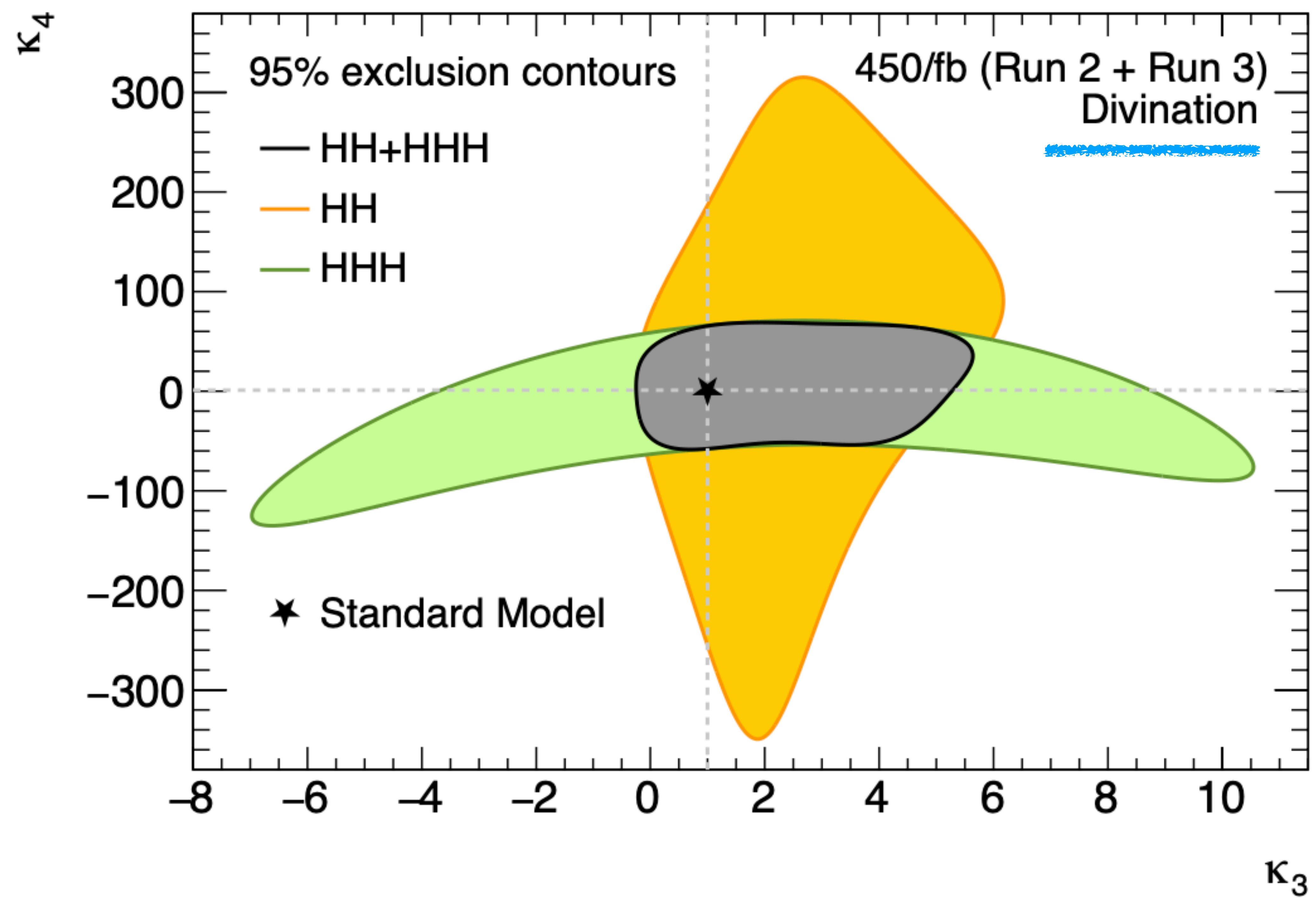
pp→HH: pp→HHH:



Brian Moser

Higgs potential shape from HH and HHH

HH based on Run 2 sensitivities
HHH based on the Pheno 100 TeV scaled down

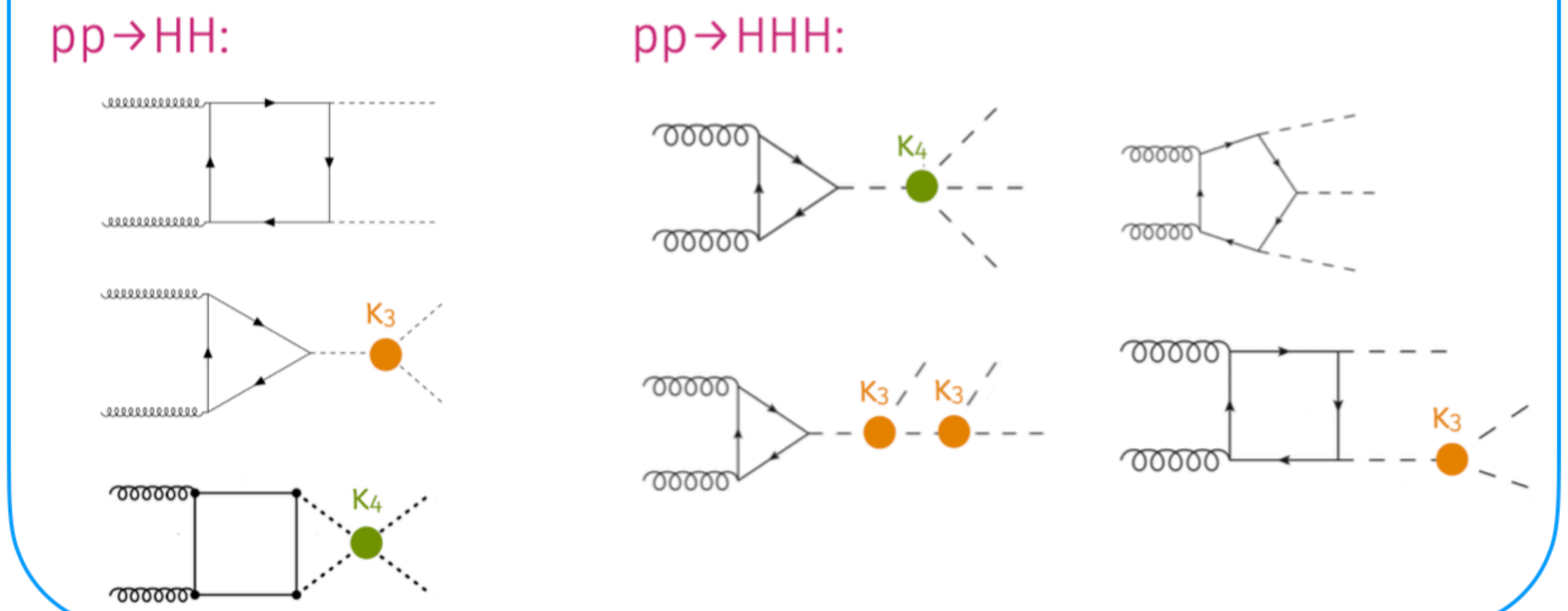


- HH and HHH Constraints on k3 and k4 are complementary

Multiple Higgs production

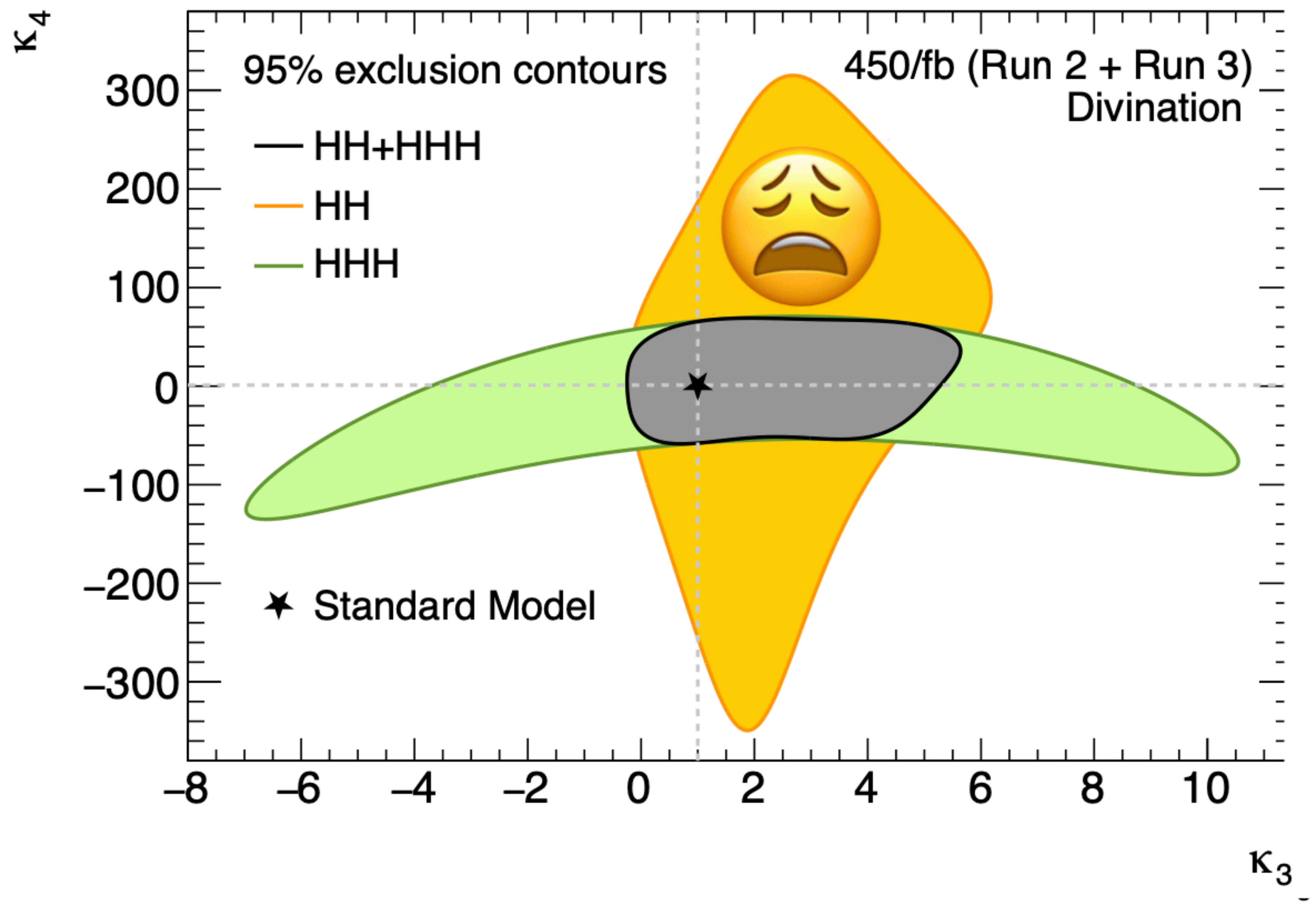
Moser/Stylianau

- Multi Higgs boson production rates are extremely low compared to single Higgs production, which itself is already low [h/hh ~ 1800, hh/hhh ~ 450 @ LHC]
- To add to the complexity, the connection between final state multiplicity and contributing coupling modifiers is not trivial



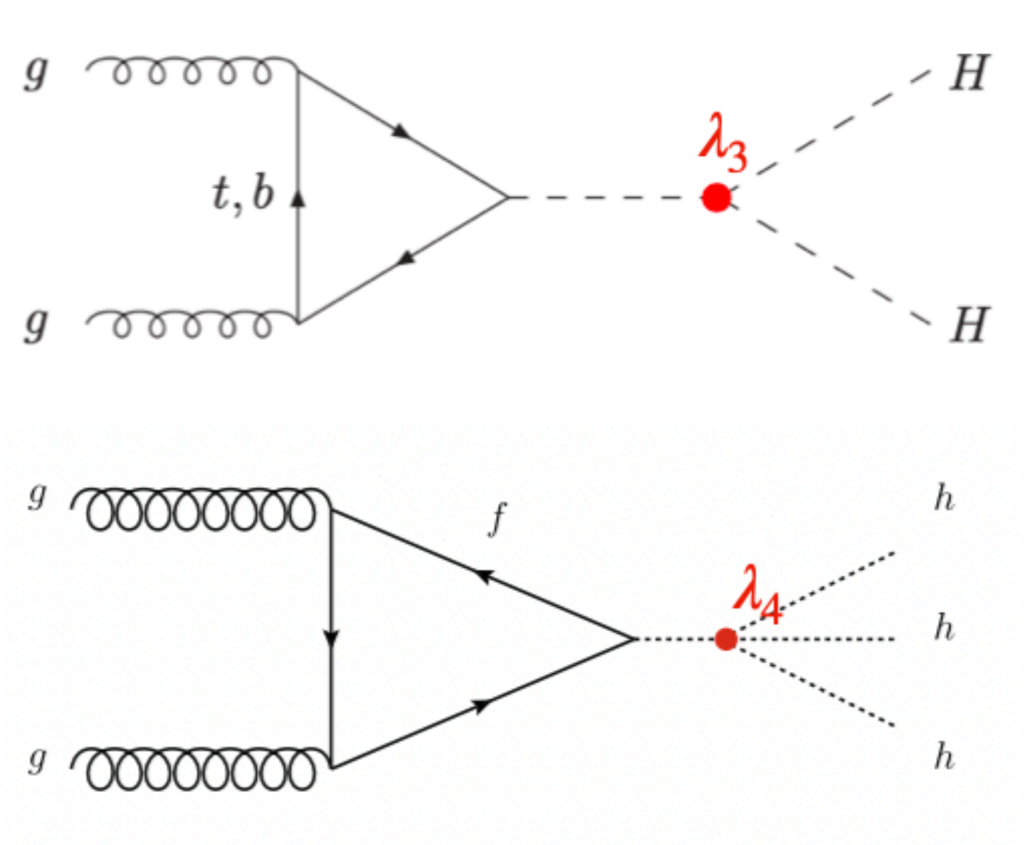
Brian Moser   Higgs potential shape from HH and HHH

- **The difference is obvious:**



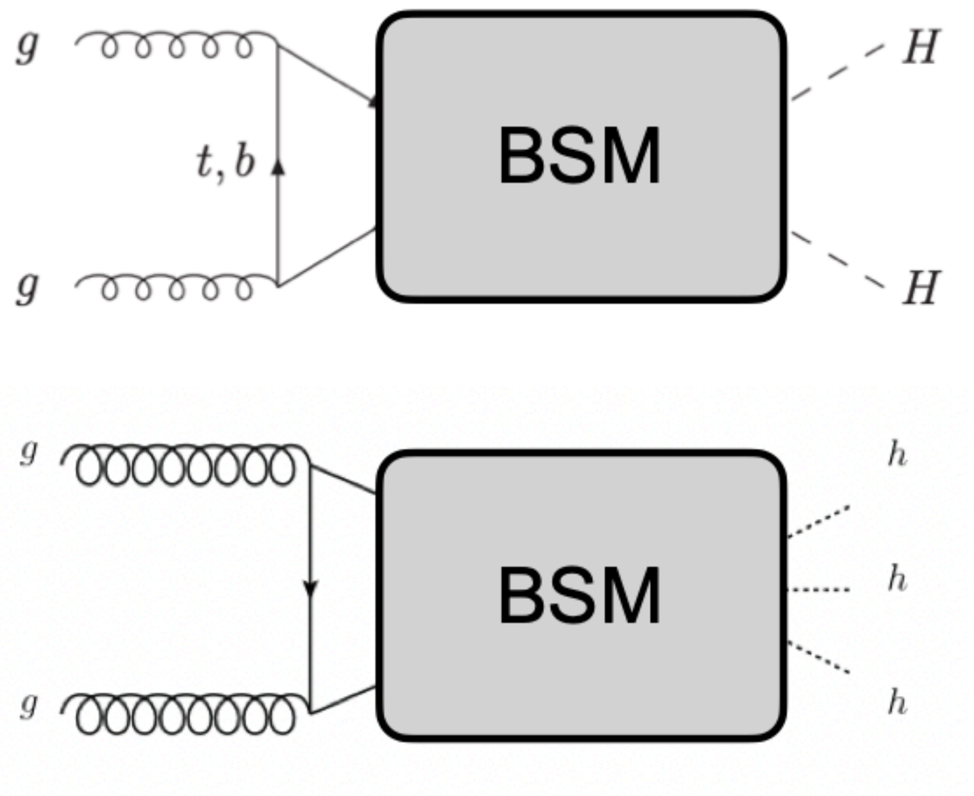
HH and HHH Constraints on k3 and k4 are complementary

SM predicts HH and HHH production



BSM can appear in HH and HHH production

As modification of λ_3 and λ_4



$$V(h,?) = \frac{1}{2}m_h^2 h^2 + \ldots ?$$

BSM model predicting large HHH: TRSM.

SM + two singlets coupling to the Higgs doublet.

$$V = \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2 .$$

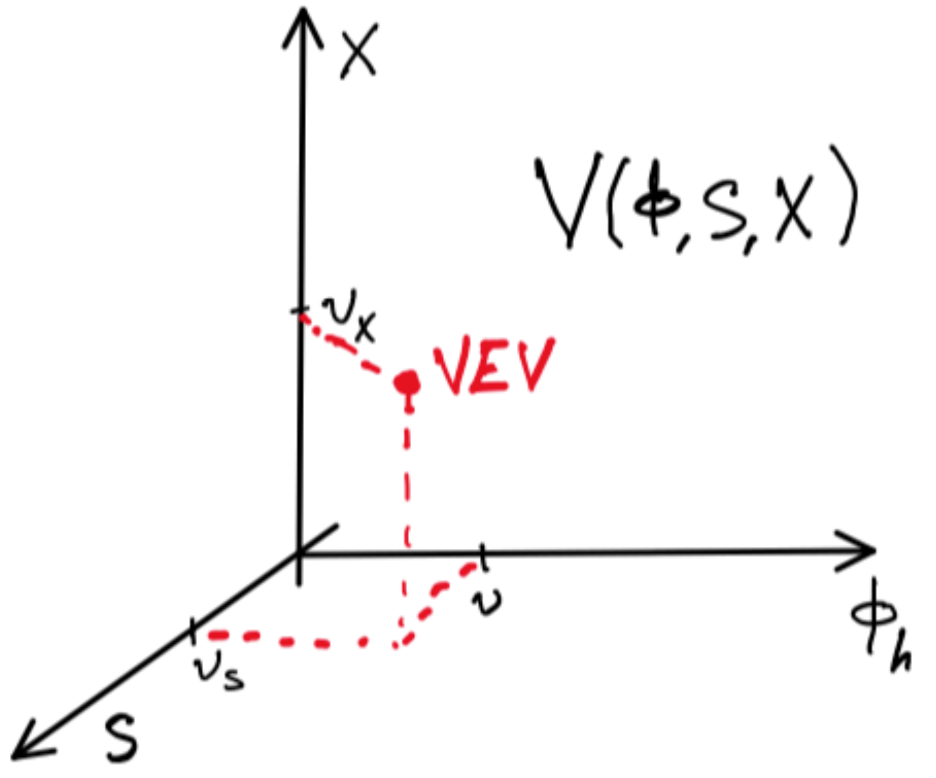
Mixing:

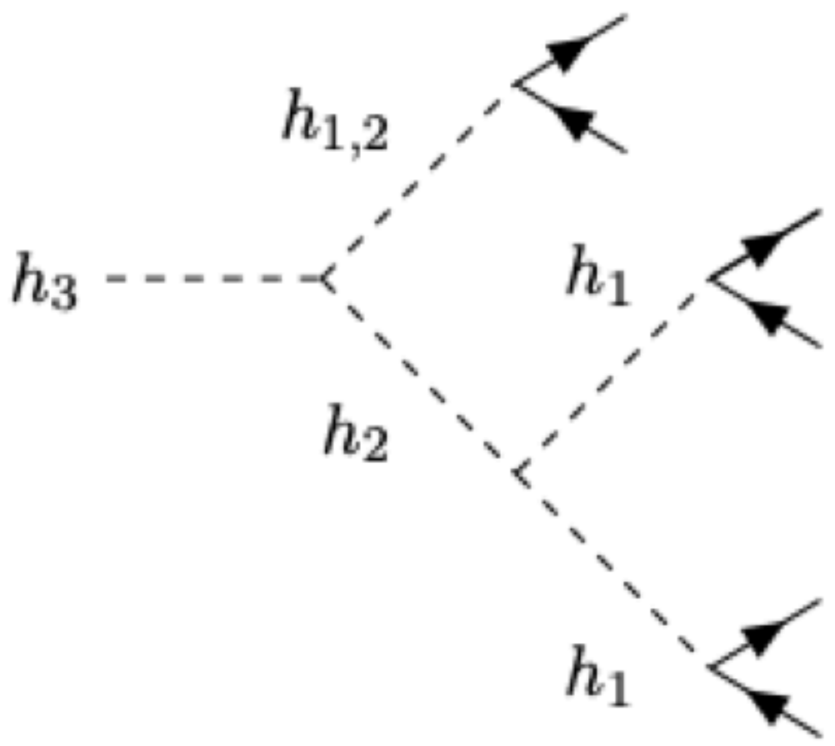
$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi_h + v}{\sqrt{2}} \end{pmatrix}, \quad S = \frac{\phi_S + v_S}{\sqrt{2}}, \quad X = \frac{\phi_X + v_X}{\sqrt{2}}$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_h \\ \phi_S \\ \phi_X \end{pmatrix}$$

h1 can be our scalar particle of 125 GeV

Tania Robens,[1,*] Tim Stefaniak,[2,†] and Jonas Wittbrodt[2,‡]





Example: TRSM can predict large HHH

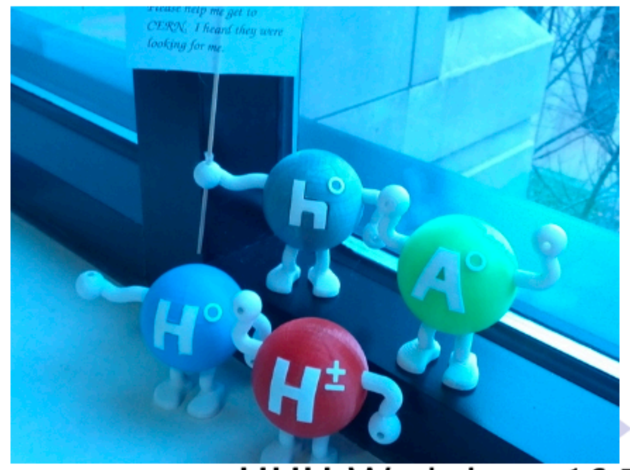
BSM additional scalars/resonances

Papaefstathiou/Pasechnik/Robens/++

- additional scalars offers way to resolve some of the long-standing issues of the SM framework
- multi-scalar models offer rich phenomenology at colliders, in neutrino physics and in cosmology
- flavour and high-CP symmetries enable to generate very specific patterns in mass, mixing and FCNC hierarchies
- search for suitable UV complete theories giving rise to such models is under way

- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at** $\sim 125\,\mathrm{GeV}$
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add ons:**
  - can **push vacuum breakdown to higher scales**
  - can **explain additional features**, e.g. dark matter, or hierarchies in quark mass sector
  - ...
- Multitude of models out there
- adding ew gauge singlets/ doublets/ triplets...

  $\Rightarrow$ **new scalar states** $\Leftarrow$

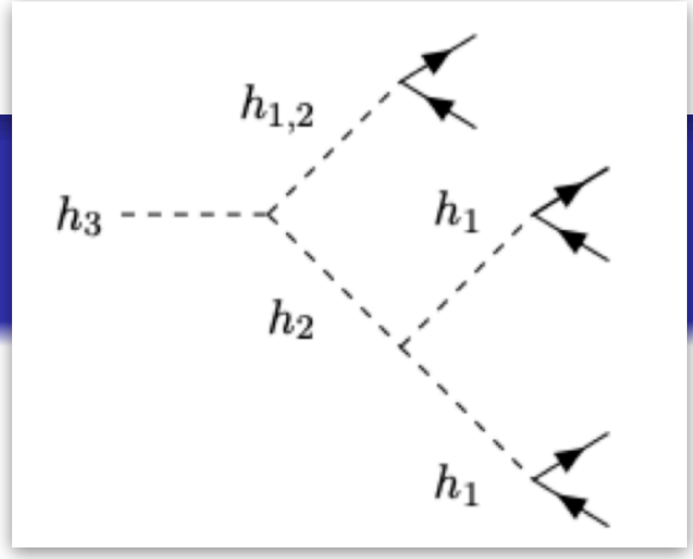


Tania Robens BSM: HH, HHH HHH Workshop, 16.7.23

TRSM

SM + Two Real Singlet Scalars [= TRSM]

BP3: $h_3 \to h_1 h_2$ $(h_1 = h_{125})$ [up to 0.3 pb]



ADDING TWO REAL SCALAR SINGLETS

Scalar potential (Φ: $SU(2)_L$ doublet, S, X: $SU(2)_L$ singlets)

$$\mathcal{V} = \mu_\Phi^2 \Phi^\dagger\Phi + \mu_S^2 S^2 + \mu_X^2 X^2 + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \lambda_S S^4 + +\lambda_X X^4 + \lambda_{\Phi S}\Phi^\dagger\Phi S^2 + \lambda_{\Phi X}\Phi^\dagger\Phi X^2 + \lambda_{SX} S^2 X^2.$$

Imposed $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetry, which is spontaneously broken by singlet vevs.

⇒ three $\mathcal{CP}$-even neutral Higgs bosons: h_1, h_2, h_3

Two interesting cases:

Case (a): $\langle S\rangle \neq 0, \langle X\rangle = 0 \Rightarrow X$ is DM candidate;
Case (b): $\langle S\rangle \neq 0, \langle X\rangle \neq 0 \Rightarrow$ all scalar fields mix.

Again, Higgs couplings to SM fermions and bosons are *universally reduced by mixing*.

Tim Stefaniak (DESY) | BSM Higgs physics | ALPS 2019 | 27 April 2019 10

AS **BP1: $h_3 \to h_1 h_2$ $(h_3 = h_{125})$**

SM-like decays for both scalars: $\sim$ 3 pb; h_1^3 final states: $\sim$ 3pb

AS **BP2: $h_3 \to h_1 h_2$ $(h_2 = h_{125})$**

SM-like decays for both scalars: $\sim$ 0.6 pb

AS **BP3: $h_3 \to h_1 h_2$ $(h_1 = h_{125})$**

(a) SM-like decays for both scalars $\sim$ 0.3 pb; **(b) h_1^3 final states: $\sim$ 0.14 p**

S **BP4: $h_2 \to h_1 h_1$ $(h_3 = h_{125})$**

up to 60 pb

S **BP5: $h_3 \to h_1 h_1$ $(h_2 = h_{125})$**

up to 2.5 pb

S **BP6: $h_3 \to h_2 h_2$ $(h_1 = h_{125})$**

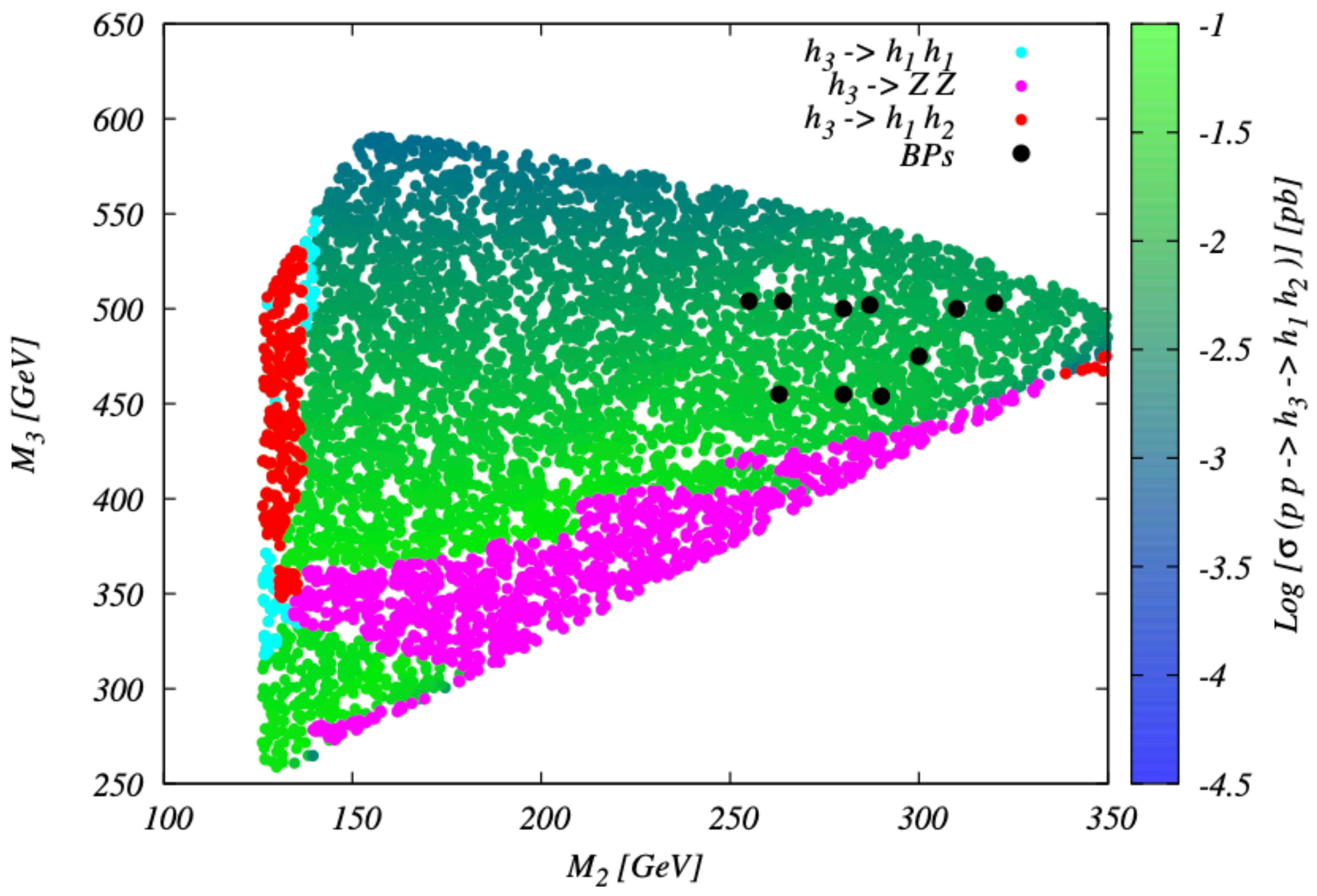
SM-like decays: up to 0.5 pb; **h_1^4 final states: around 14 fb**

BP3

$\sigma(pp \to h_3) \simeq 0.06 \cdot \sigma(pp \to h_{SM})|_{m=M_3}$
$\mathrm{BR}(h_3 \to h_{125} h_2)$ mostly $\sim 50\%$.
if $M_2 < 250\,\mathrm{GeV}$: $\Rightarrow h_2 \to$ SM particles.
if $M_2 > 250\,\mathrm{GeV}$:
$\Rightarrow \mathrm{BR}(h_2 \to h_{125} h_{125}) \sim 70\%$,

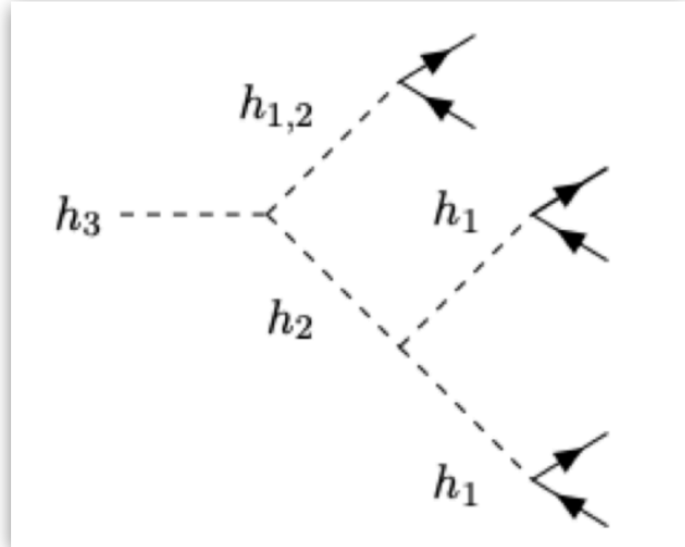
⇒ spectacular triple-Higgs signature

[up to 140 fb; maximal close to thresholds]



$[\kappa_3 = 0.24]$ $[\Gamma_3/M_3 \leq 0.05]$

bounds from $p\,p \to h_3 \to h_1\,h_2$ [CMS, Run II, JHEP 11 (2021) 057]



Analysis @ LHC & HL-LHC

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

⇒ **select points** on BP3 which might be **accessible at HL-LHC**

⇒ perform detailed analysis including SM background, hadronization, ...

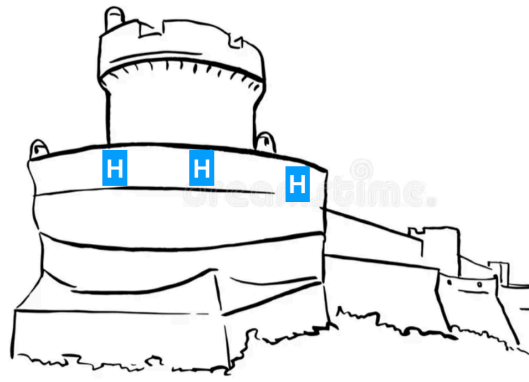
- tools: implementation using **full** t, b **mass dependence, leading order** [UFO/ Madgraph/ Herwig] [analysis: use K-factors]

(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [fb]	$\text{sig}\vert_{300\text{fb}^{-1}}$	$\text{sig}\vert_{3000\text{fb}^{-1}}$
(255, 504)	32.40	6.40	2.92	9.23
(263, 455)	50.36	9.95	4.78	15.11
(287, 502)	39.61	7.82	4.01	12.68
(290, 454)	49.00	9.68	5.02	15.86
(320, 503)	35.88	7.09	3.76	11.88
(264, 504)	37.67	7.44	3.56	11.27
(280, 455)	51.00	10.07	5.18	16.39
(300, 475)	43.92	8.68	4.64	14.68
(310, 500)	37.90	7.49	4.09	12.94
(280, 500)	40.26	7.95	4.00	12.65

discovery, exclusion

⇒ at HL-LHC, all points within reach ⇐

Multi-higgs <=> Multi-theories



Fuks, Papaefstathiou, Pasechnik ++++

D=6-Inspired Anomalous Couplings

- Add **higher-dimensional operators** to the SM Lagrangian!
  - → To capture the **effects of new particles at scales ≫ collision energies**.

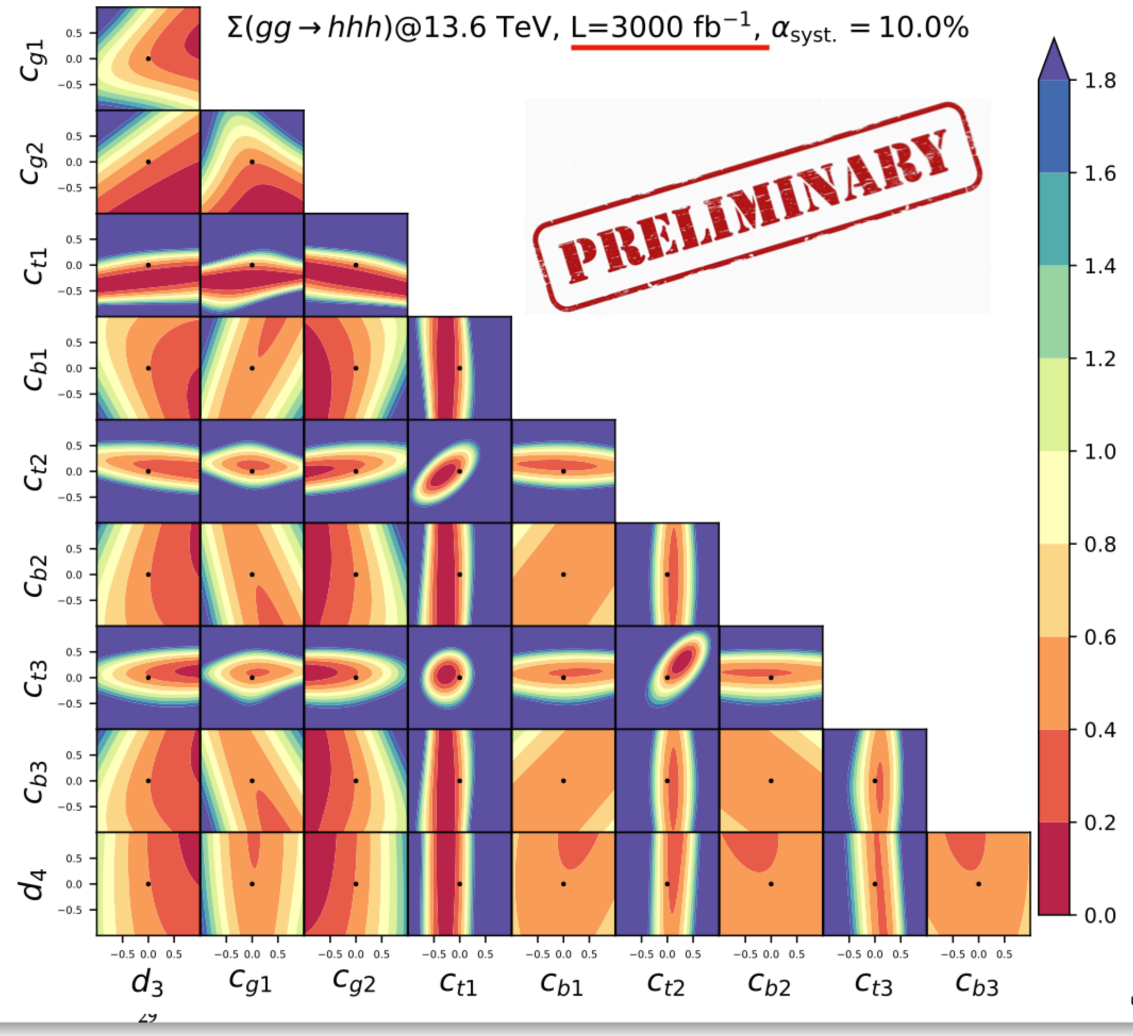
★ e.g. Add D=6 operators **relevant to multi-Higgs boson production**, of the form $\frac{\mathcal{O}_6}{\Lambda^2}$:

$$\mathscr{L}_{h^n} = -\mu^2|H|^2 - \lambda|H|^4 - \left(y_t\bar{Q}_L H^c t_R + y_b \bar{Q}_L H b_R + \mathrm{h.c.}\right)$$
$$+\frac{c_H}{2\Lambda^2}(\partial^\mu|H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda_{\mathrm{SM}}|H|^6 + \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu}G^{\mu\nu}_a$$
$$-\left(\frac{c_t}{\Lambda^2}y_t|H|^2\bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2}y_b|H|^2\bar{Q}_L H b_R + \mathrm{h.c.}\right)$$

Andreas

Anomalous Couplings @ LHC 13.6 TeV w/ 3000 fb^{-1}

- Dark blue regions excluded @ ≥ 2σ.
- Similar conclusions at 3000 fb^{-1}!
- TO-DO:
  - What about higher energies, e.g. 100 TeV?
  - Comparison to SMEFT? e.g. using "SMEFT@NLO" [C. Degrande, G. Durieu, Fabio Maltoni, K. Mimasu, E. Vryonidou, C. Zhang, arXiv:1607.04251]

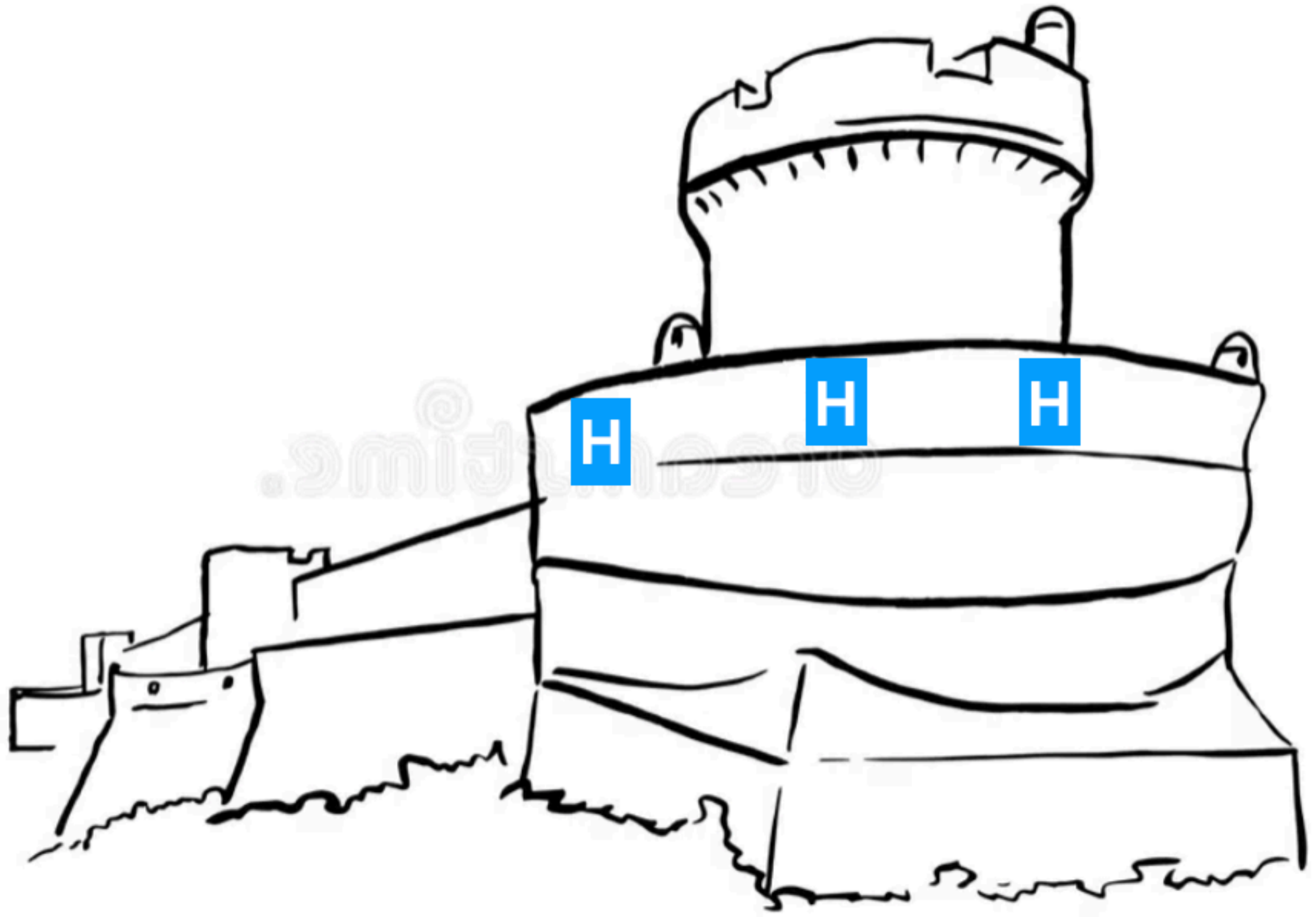


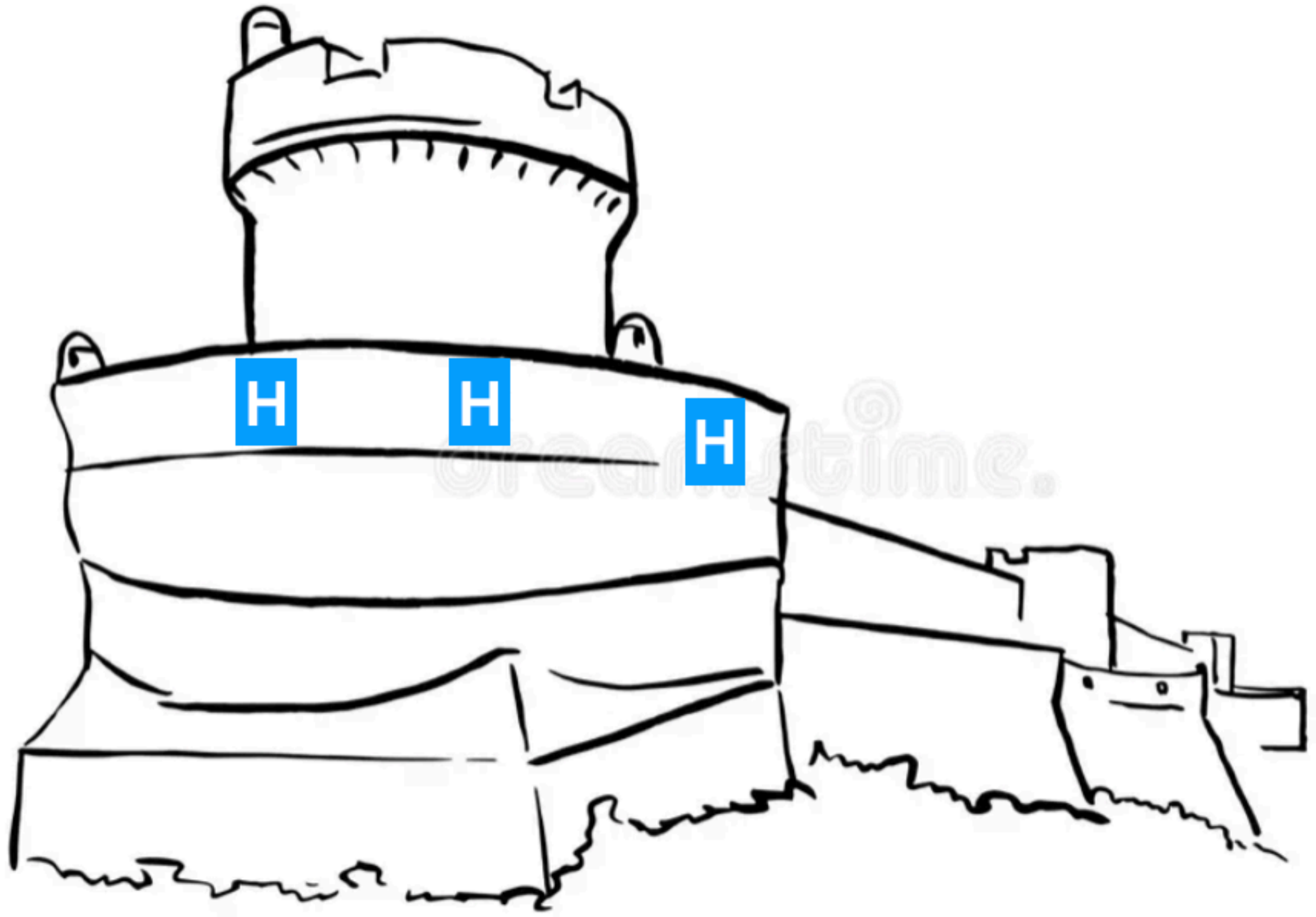
efstathiou

Summary & Outlook

- **hhh** is one of the few ways to probe the Higgs quartic coupling @pp colliders; **extremely rare** within the SM → a 100 TeV SM measurement.
- Nevertheless, **hhh may be enhanced by new phenomena.**
- Measurement of **hhh** within models with **extra scalars** possible at the LHC:
  - an avenue for **solving the inverse problem** in case of discovery
  - and perhaps understanding **electro-weak baryogenesis**.
- **Anomalous couplings can also modify hhh**: some constraints can be obtained at the LHC! What are the possibilities at **higher energies?**

HHH Experimental view

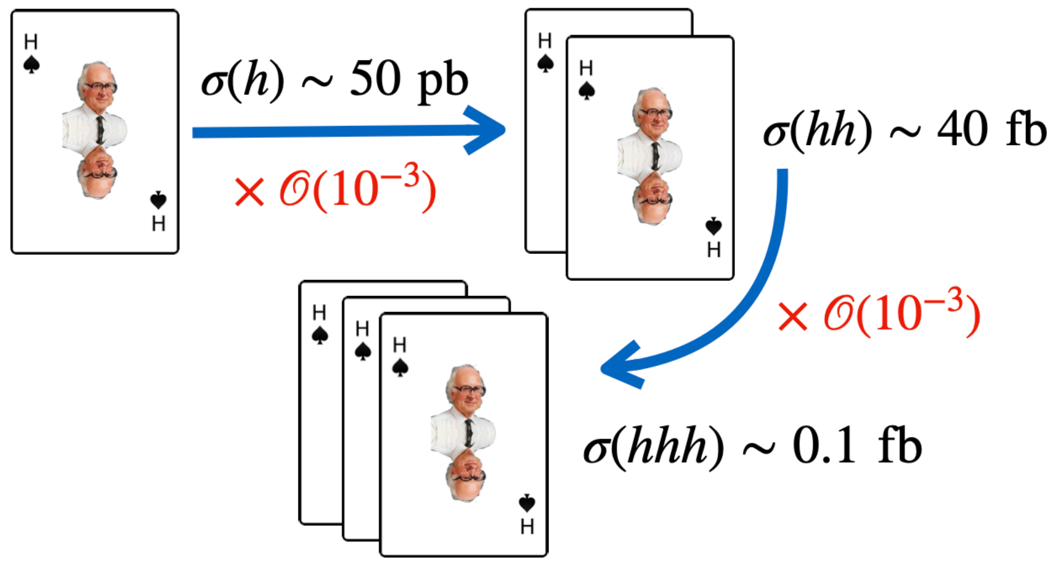




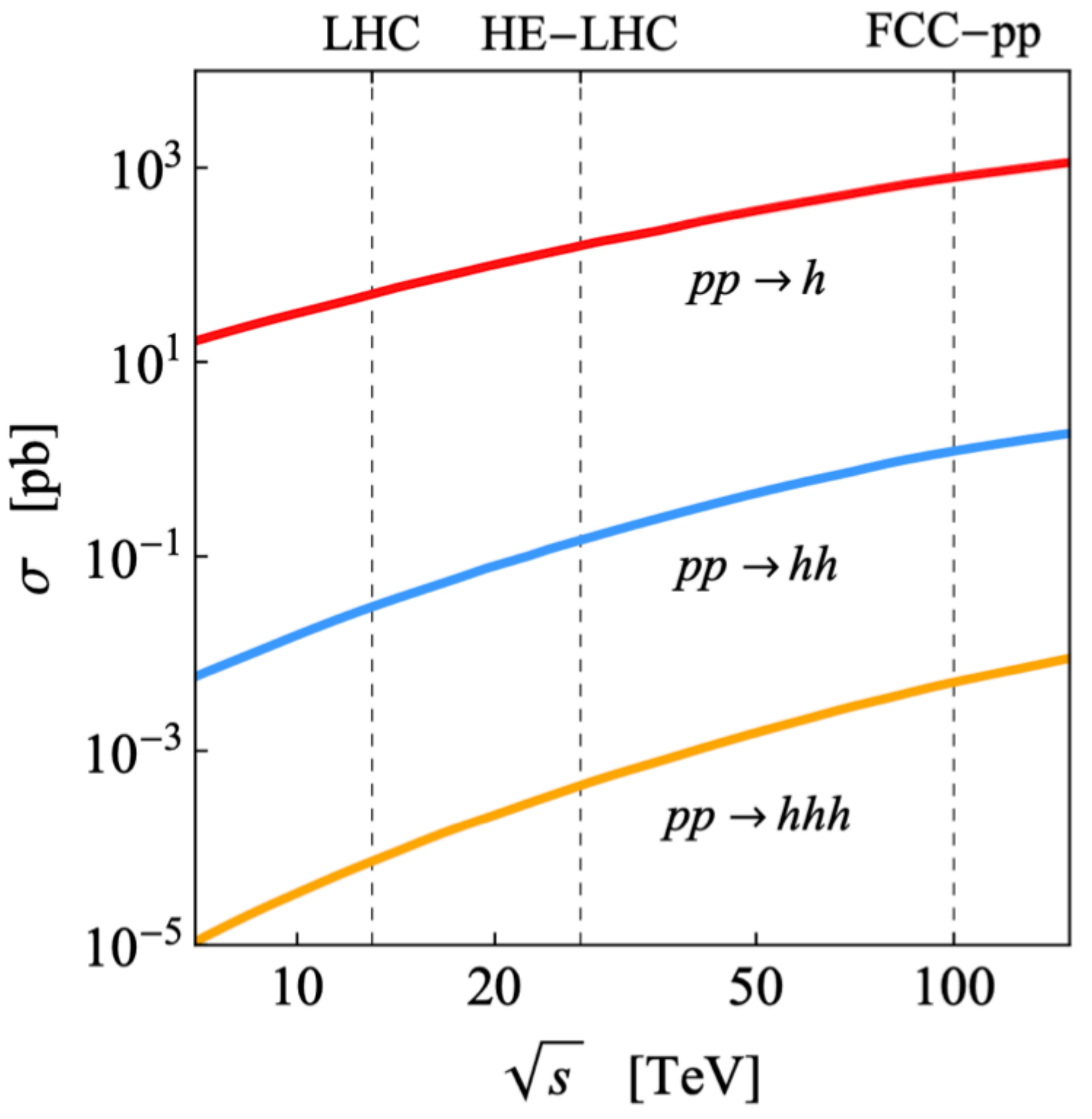
Some SM HHH numerology

Moser/Landsberg/Papaefstathiou

Production rates / branching fractions



[Bizon, Haisch, Rottoli JHEP 10 (2019) 2



Run 2 expected yields:

pp→HH: ~ 4500 events

pp→HHH: ~ 13 events

Branching Fractions

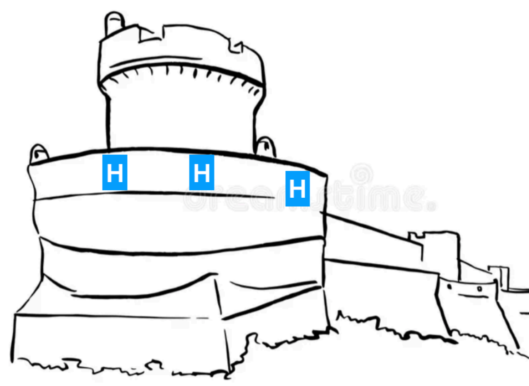
- H(bb) = 58.1%, H(ττ) = 6.26%, H(WW) = 21.5%, H(gg) = 8.18%, H(ZZ) = 2.6%, H(γγ) = 0.23%
- σ_{HHH}(14 TeV, NNLO) = 0.1fb
- Aim at σ^{95} = 100 x σ_{HHH} = 10 fb; Run 2 x σ^{95} ~ 1000 events; Run 2 x σ^{95} x ε ~100 events
- To set a limit, need expected yield of 3 signal events: do not consider Br < 3% for now
- **HHH → 6b: 19.5%**
- **HHH → bbbbττ: 6.3%; bbbb$\tau_h\tau_h$: 2.7%**
- **HHH → bbbbWW → 4b4j: 9.9%**
- **HHH → bbbbgg → 4b2j: 8.3%**
- HHH → bbbbWW → 4b2jℓv: 5.9%
- ~~HHH → bbττWW → 2b2τ4j: 2.1%~~
- ~~HHH → bbbbWW → 4b2ℓ2v: 0.9%~~
- ~~HHH → bbττττ: 0.68%~~
- ~~HHH → bbbbγγ: 0.23%~~

41% - Focus on these topologies: 4b + jets

N.B.1: this is SIMPLER than HH → 4b
All the techniques developed for that analysis can be reused if desired
Backgrounds by construction are order of magnitude or more lower

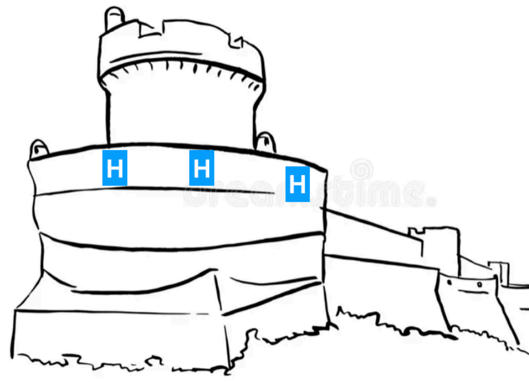
N.B.2: WW → lvjj, while promising, doesn't have a mass peak

“Simpler than HH=>4b”, but still



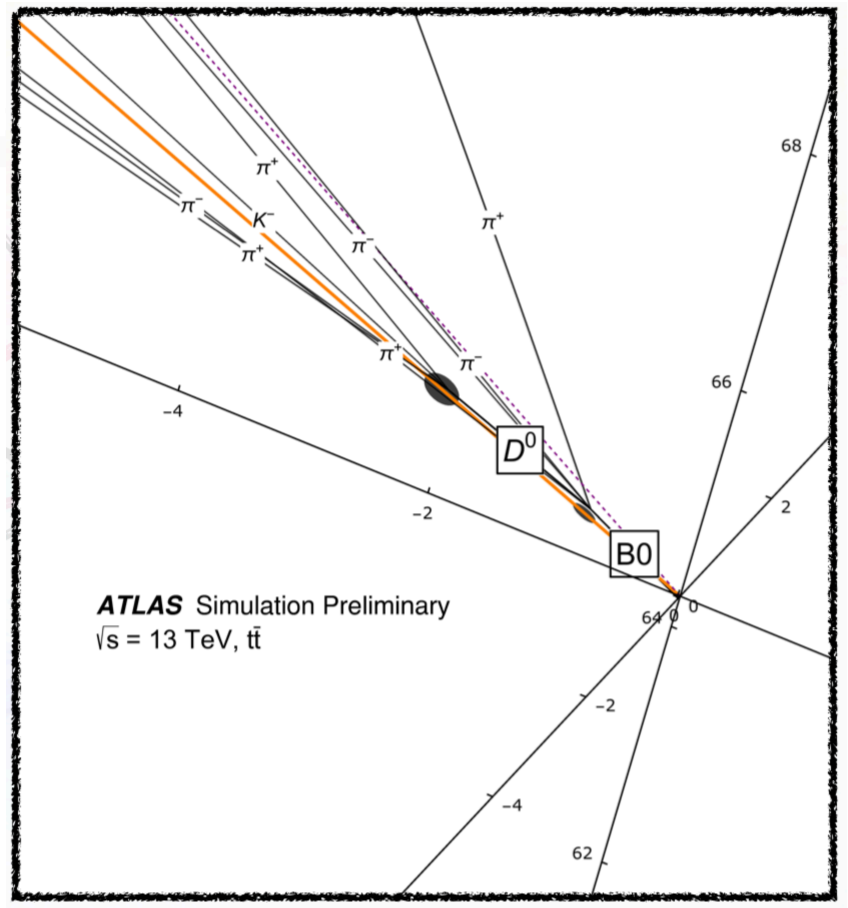
- Small number of events
  - Improve HF-tagging
  - Improve triggers
- Smart event reconstruction and jet pairings
  - Boosted jets numerology
  - Full event reconstruction
  - Extra QCD jets
- Background modeling to improve sensitivity
  - Data driven control and validation regions
- Event generation with multi-b / multi-jet final states
  - For ML algorithms training

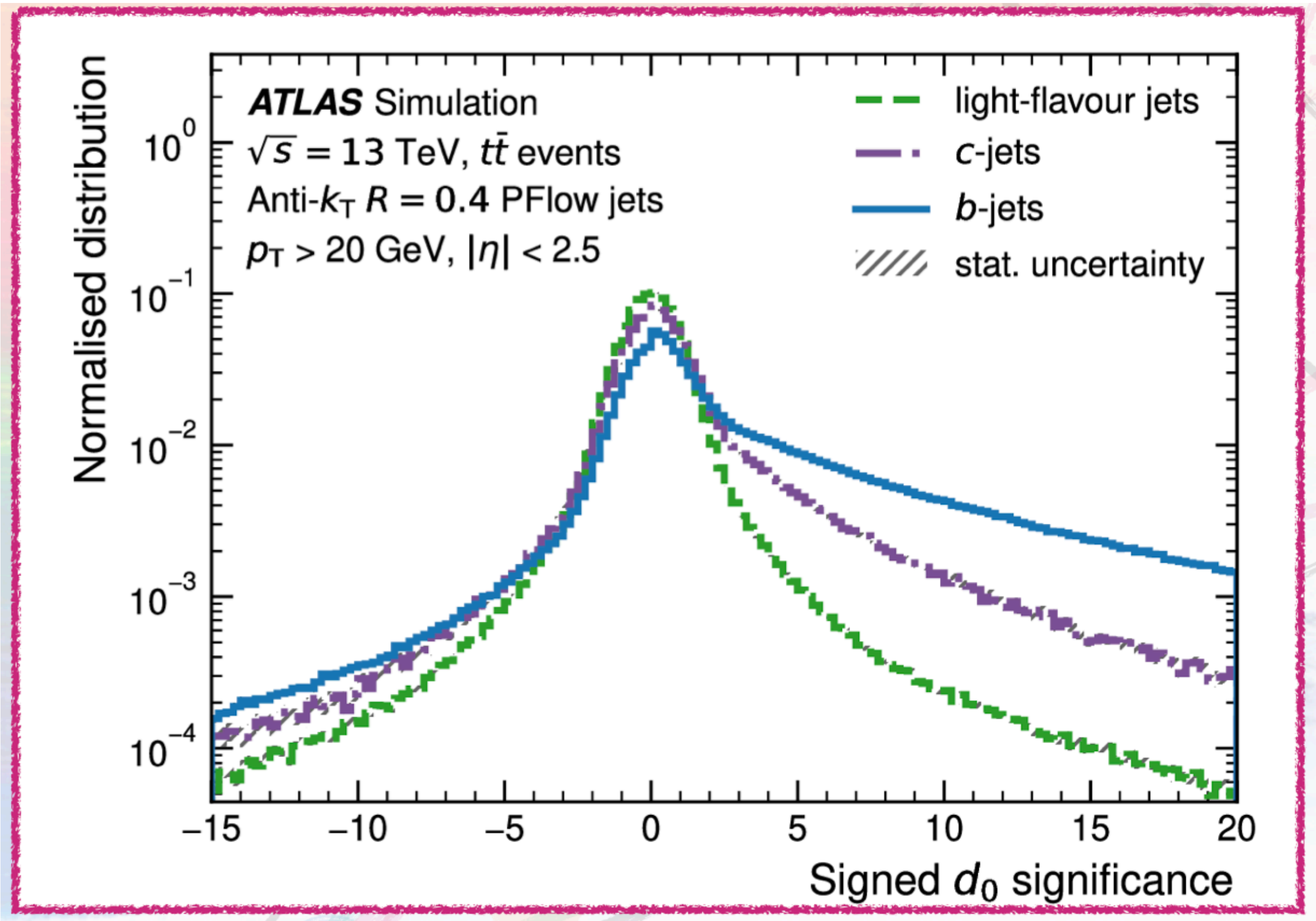
Flavor Tagging generalities

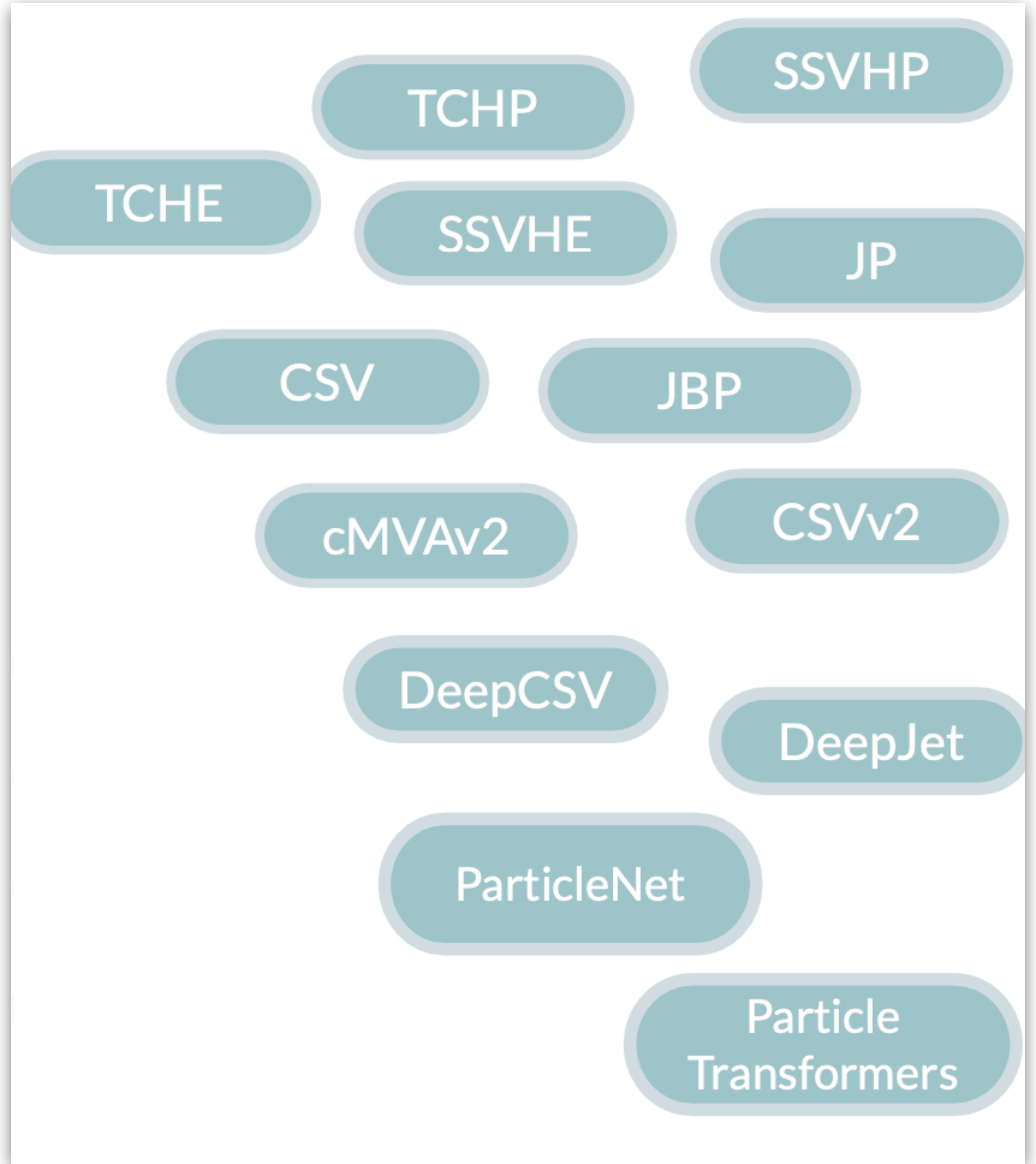


Chen/Liu/Karkout/Kolosova

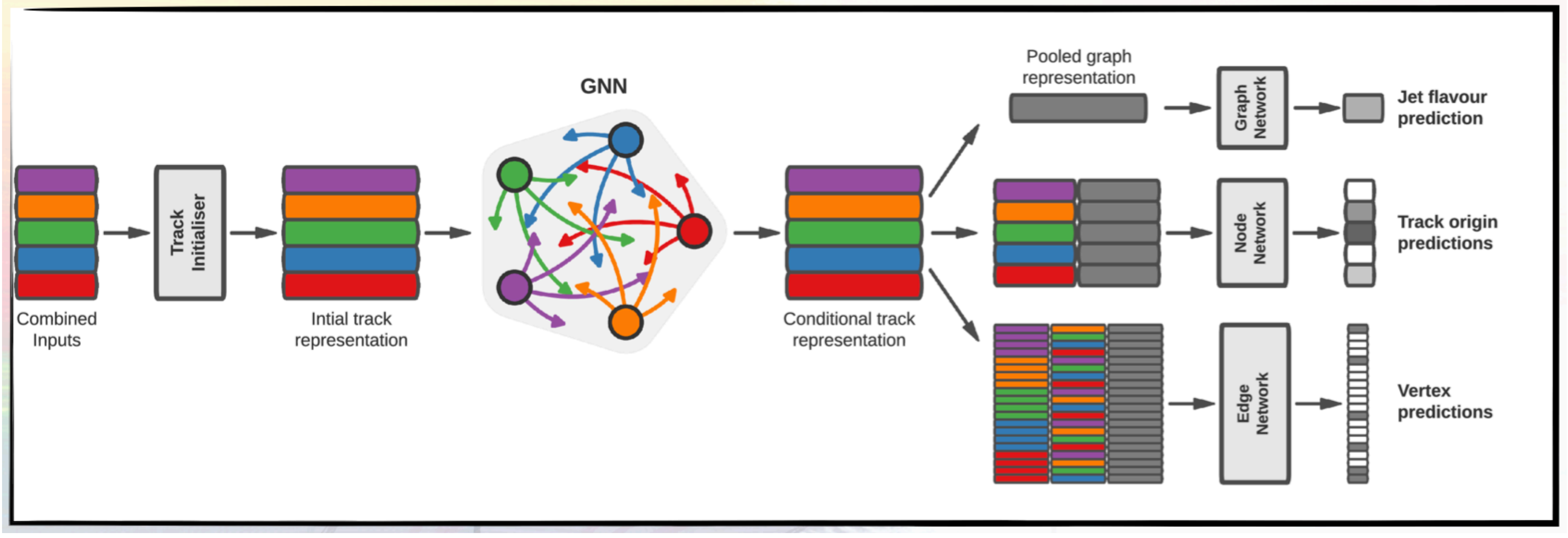
- HF-jets:
  - ~ps lifetime (few mm): secondary vertices, displaced tracks
  - Harder fragmentation, larger mass, charm decays/terciary vertices
  - Leptons 20% (10%) in b (c) hadron decays
- Tagging algorithms
  - Since Tevatron [CDF] times
  - Take advantage of silicon trackers, close to beam pipe
  - “Combine” all these properties… work of last 30 yrs
  - B-jets vs light jets vs charm => keep fakes low
  - Then charm more explicitly
  - More and more (and more) ML
  - Lots of internal [& external] collaboration competition :)
  - Improvements with time + add to the trigger
  - Relatively newer boosted X=>bb/cc taggers
- ATLAS
  - Recurring NNs [RNNIP], Deep IP [DIPS], GNN, + transformer + combine
- CMS
  - Similar evolution, ParticleNet / Particle Transformer are the latest [GNN engines]







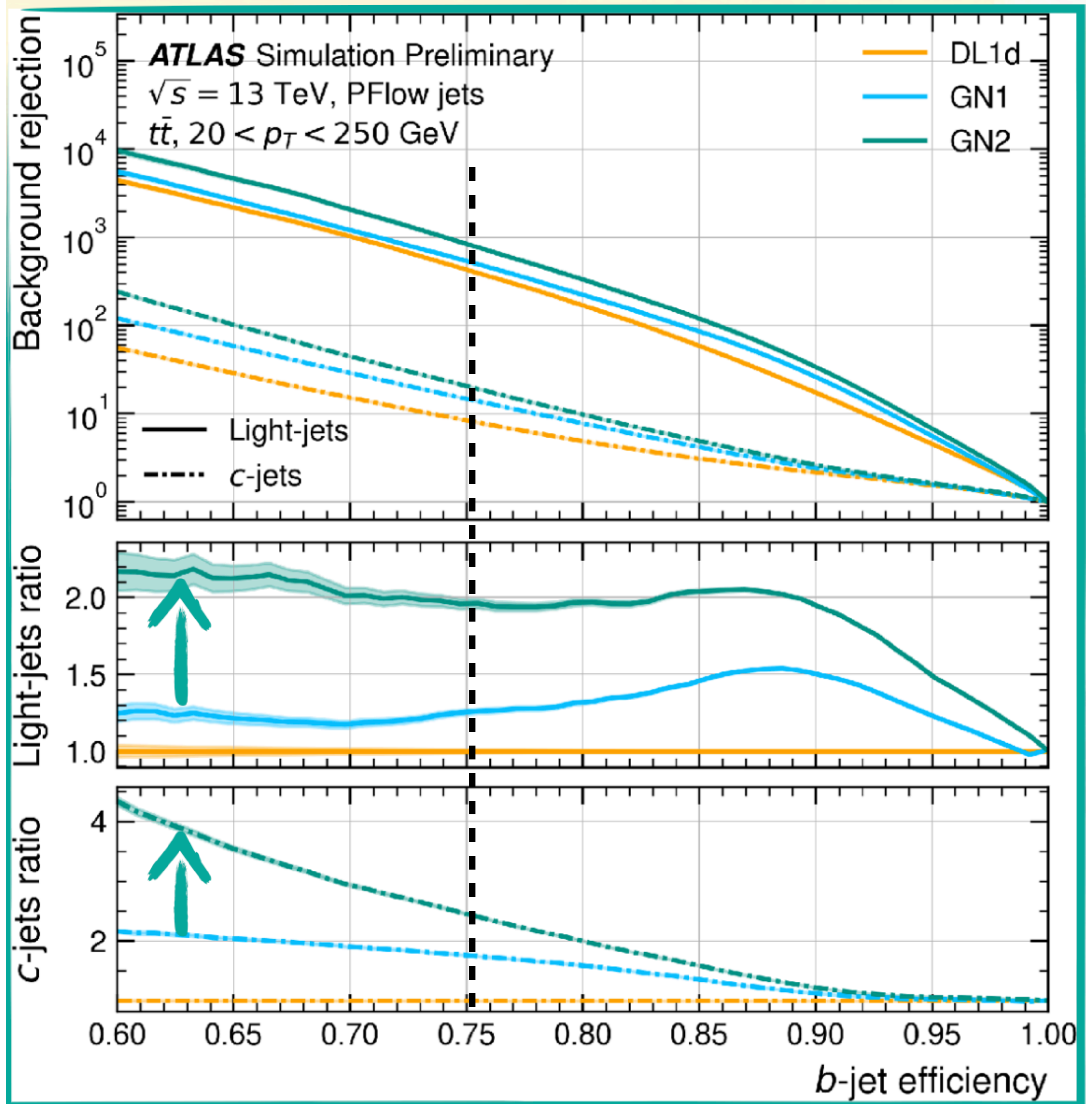
Improved performance !



Flavor tagging performance e.g.

Chen/Liu/Karkout/Kolosova

ATLAS

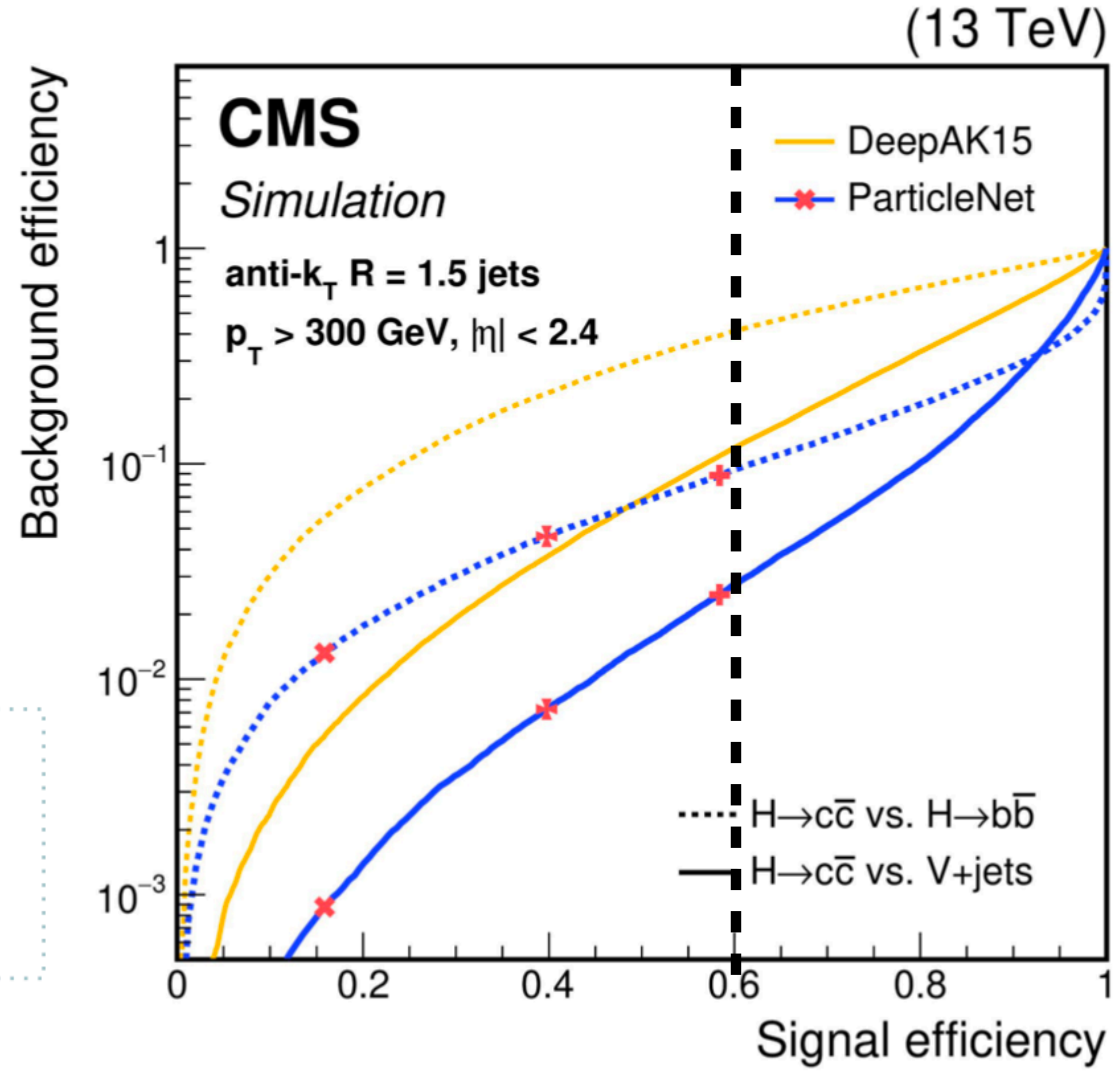


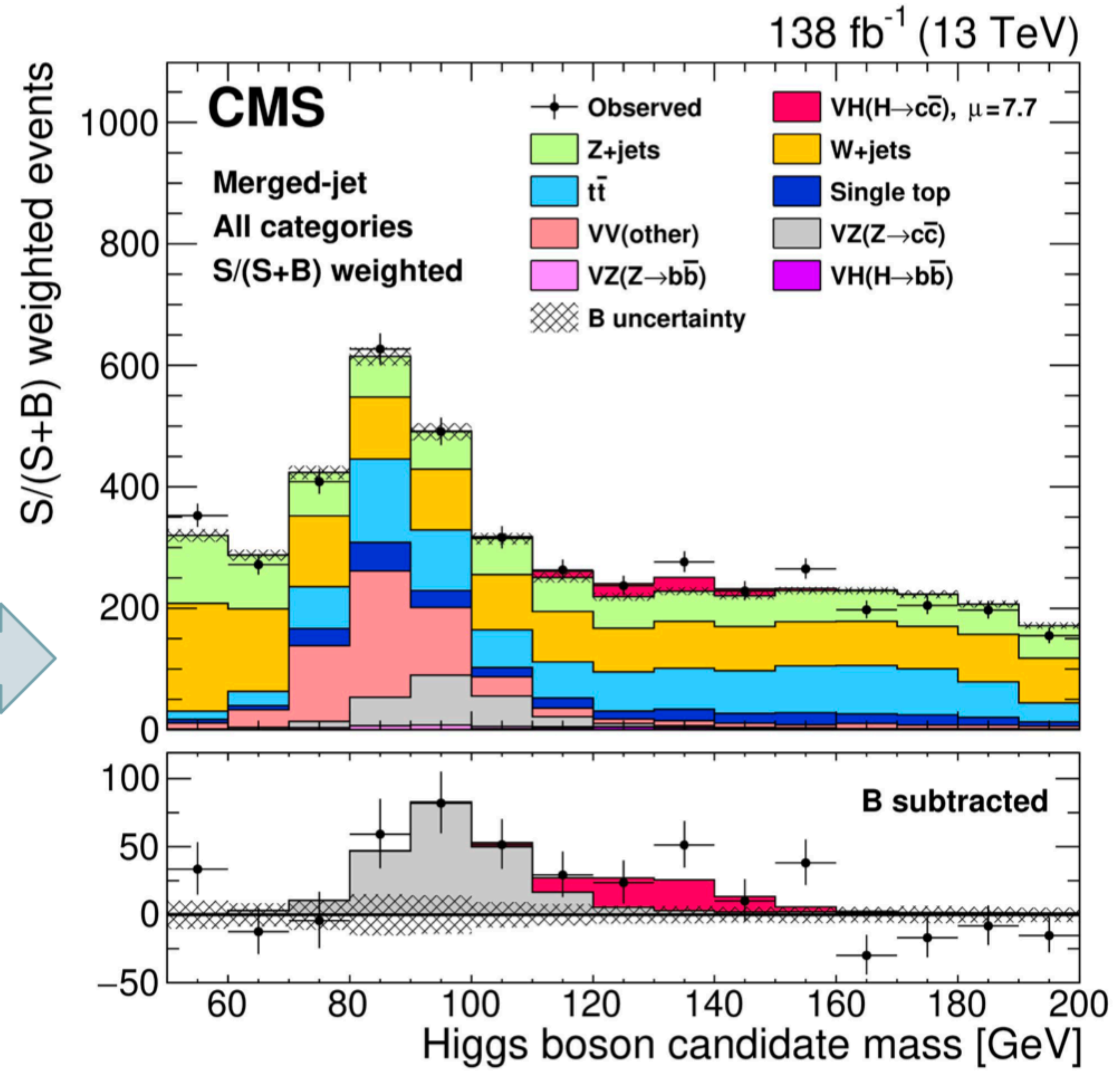
CMS

- Search for **H→cc** in association with a leptonically decaying W/Z boson where H is Lorentz-boosted
- Use of ParticleNet to discriminate **H→cc** from **H→bb** and **V+jets**

First observation of Z→cc at hadron collider (5.7σ)!

Merged-jet H→cc identification
DeepJet Vs. ParticleNet



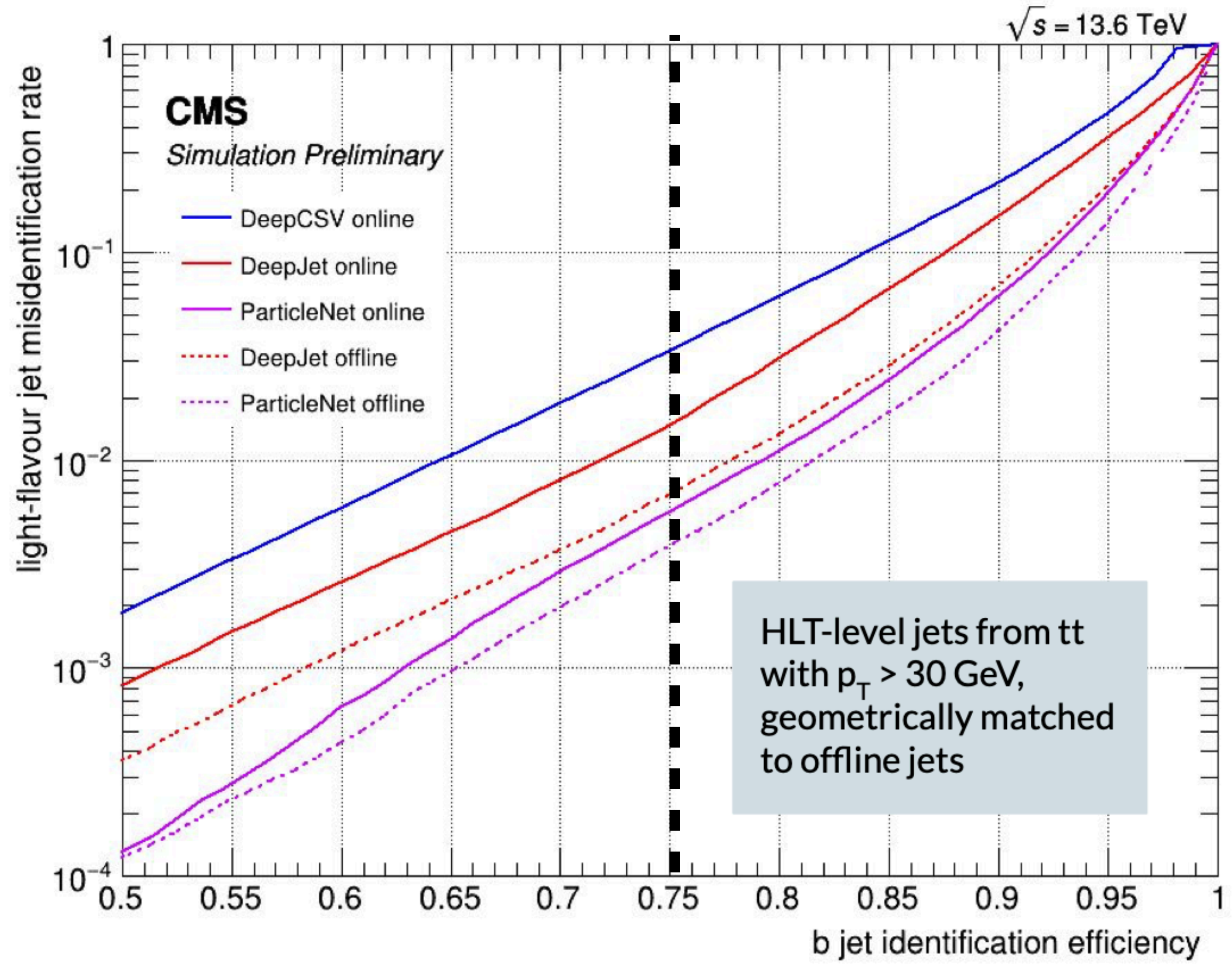


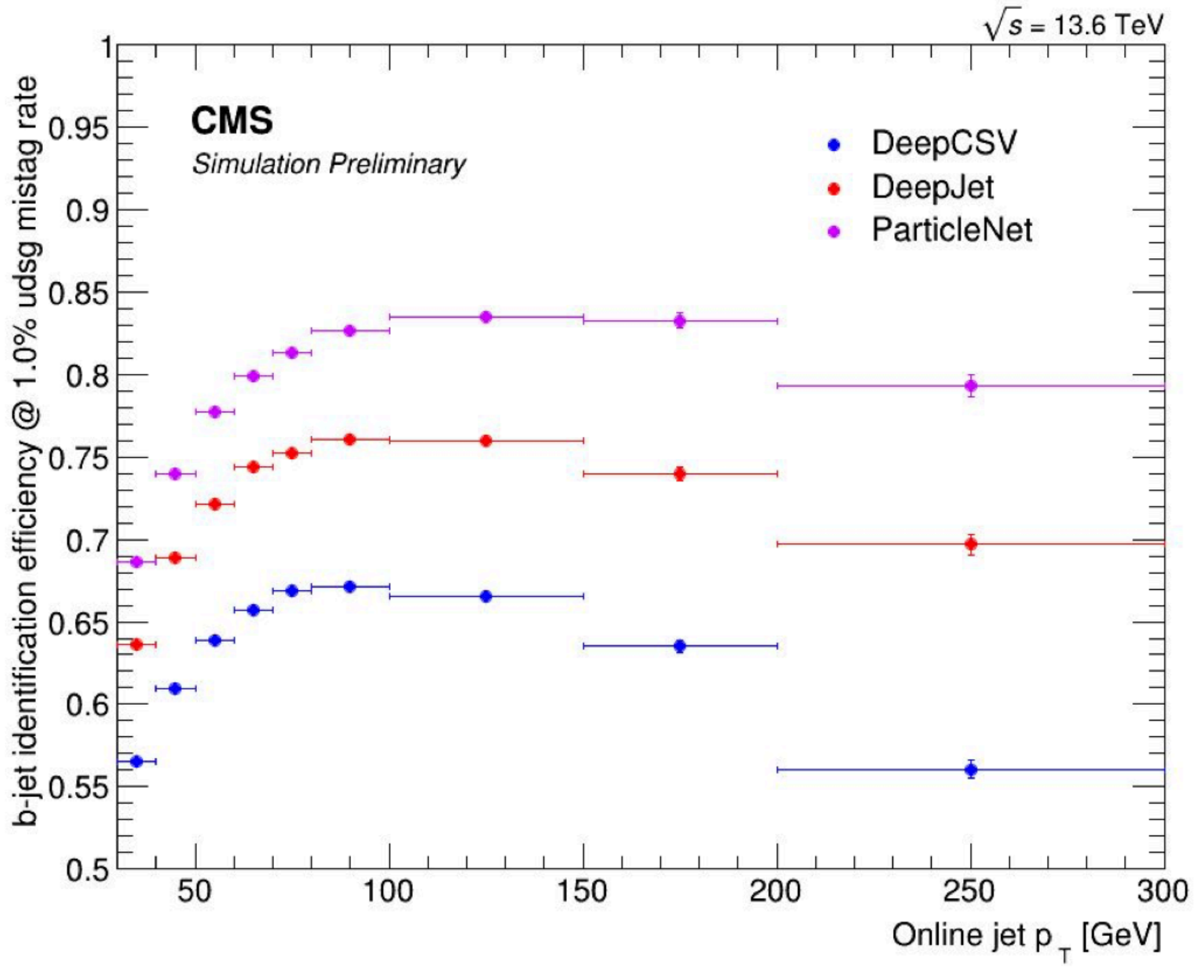
Flavor Tagging @ trigger

Chen/Liu/Karkout/Kolosova

- Important for a myriad of physics searches
  - Trigger rate dominated by QCD multijets
    - Historically managed by increasing pT threshold
    - Asymmetric thresholds for multi-jet signatures help
  - Target HF production @ trigger level
    - Reduce rate and increase phase-space reach in analyses with HF in final states [lower turn on region]
- Moving to ML algorithms @ trigger level
  - Not only to tag directly b/c/light, but also reject g=>bb, without affecting much multi H(bb) ! (ATLAS in progress)
  - Particle Net [lighter] in CMS operational in Run 3 !
  - Deep-tau bbtautau @ CMS also operational
- Q: can we/should we target final state reconstruction/pairing with ML @ trigger level, not just final state objects? [A: yes]

Lighter version of ParticleNet deployed online since the beginning of Run 3





✓ Large improvements with respect to previous b taggers
✓ Closer online-offline performance

✓ 5-10% higher efficiency throughout the jet p_T range wrt. DeepJet

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Run 3 2022 HH trigger (60 Hz):
- L1 H_T > 360 GeV
- ≥ 4 jets with p_T > 70, 50, 40, 35 GeV
- 2 leading-in-**ParticleNet** jets have average b-disc > 0.65

Run 3 2023 HH trigger (180 Hz): Data Parking
- L1 H_T > 280 GeV
- ≥ 4 jets with p_T > 30 GeV
- 2 leading-in-**ParticleNet** jets have average b-disc > 0.55

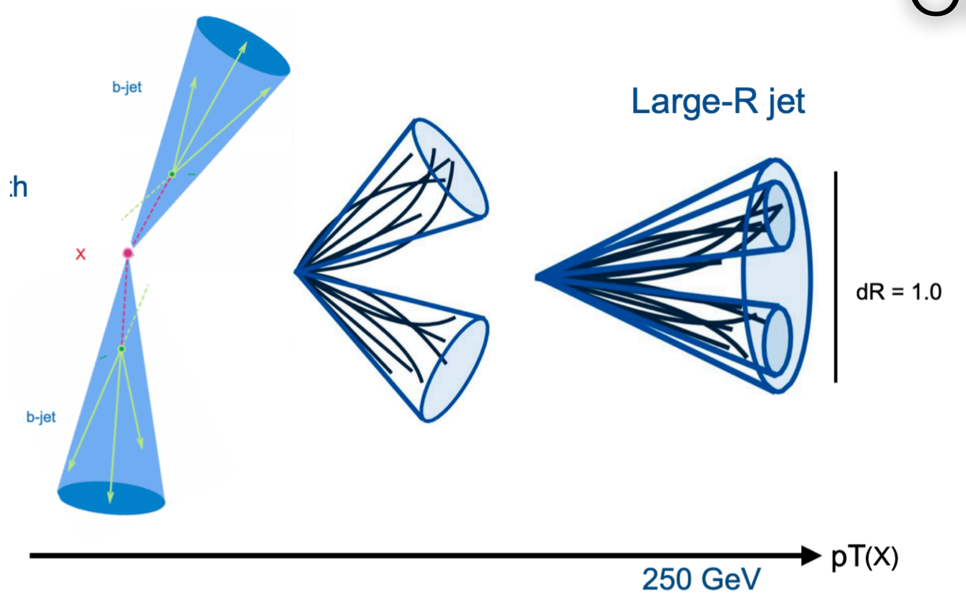
✓ **Run 3 2023 HH trigger** achieves an 82% efficiency, 57% (20%) increase with respect to Run 2 (Run 3 2022) trigger!

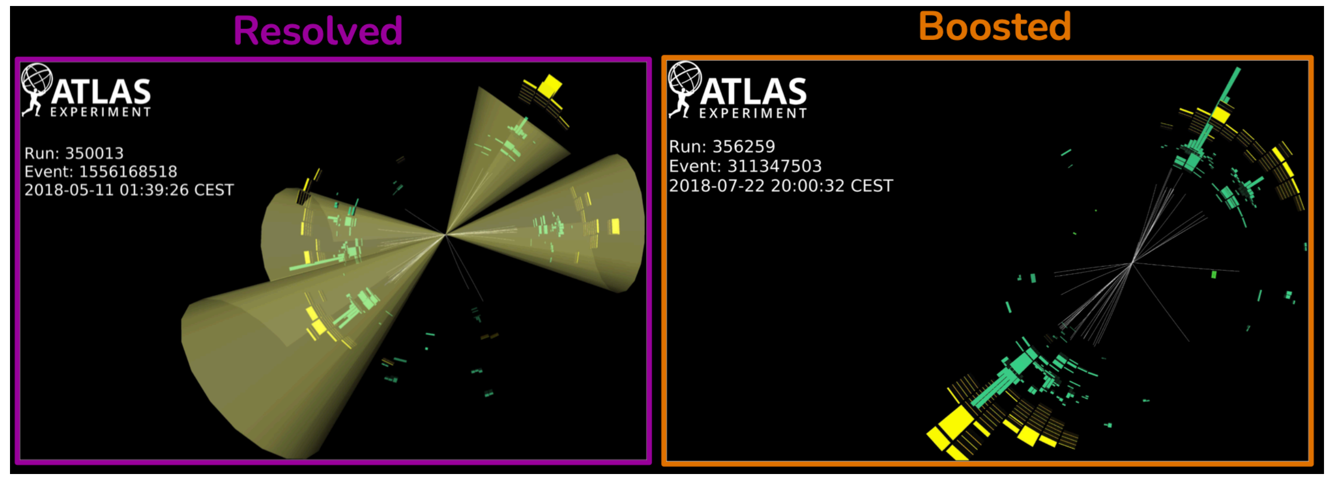
- New trigger targeting HH→4b signals now operates at 180 Hz
  - Large efficiency gain observed in HH→4b, HHH→6b, HH→2b2τ_{had}, HHH→4b2τ_{had} final states!

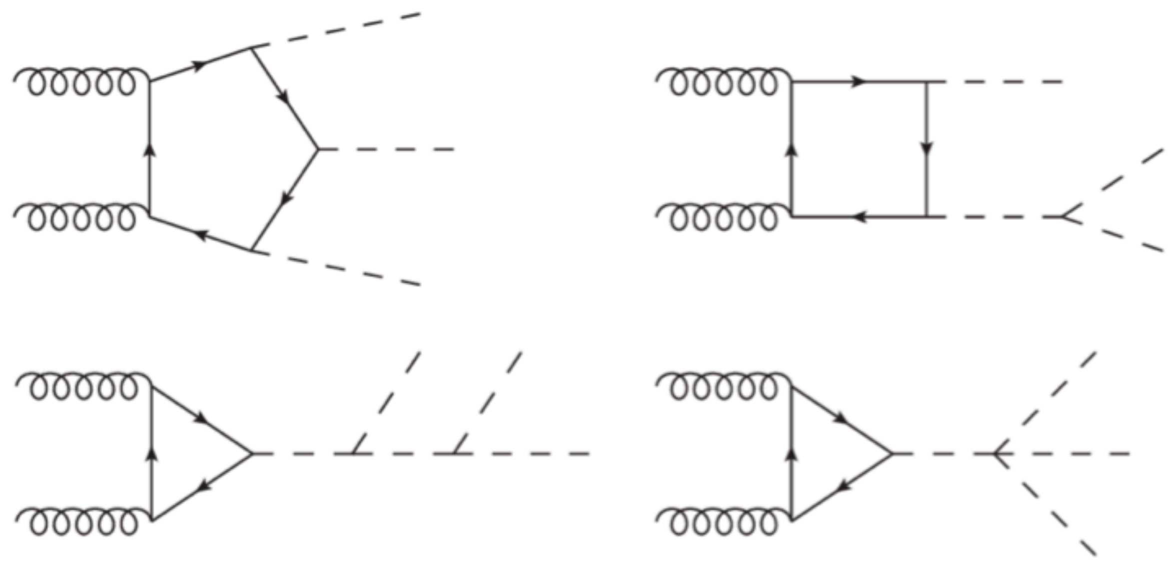
Boosted HF tagging

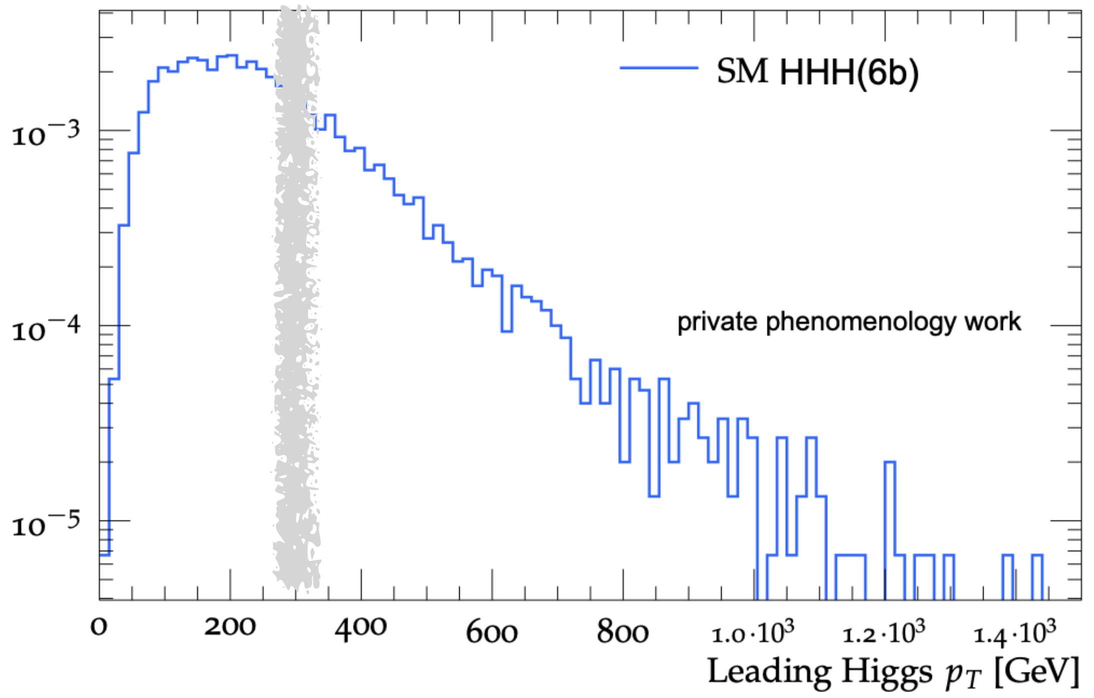
Chen/Liu/Karkout/Kolosova

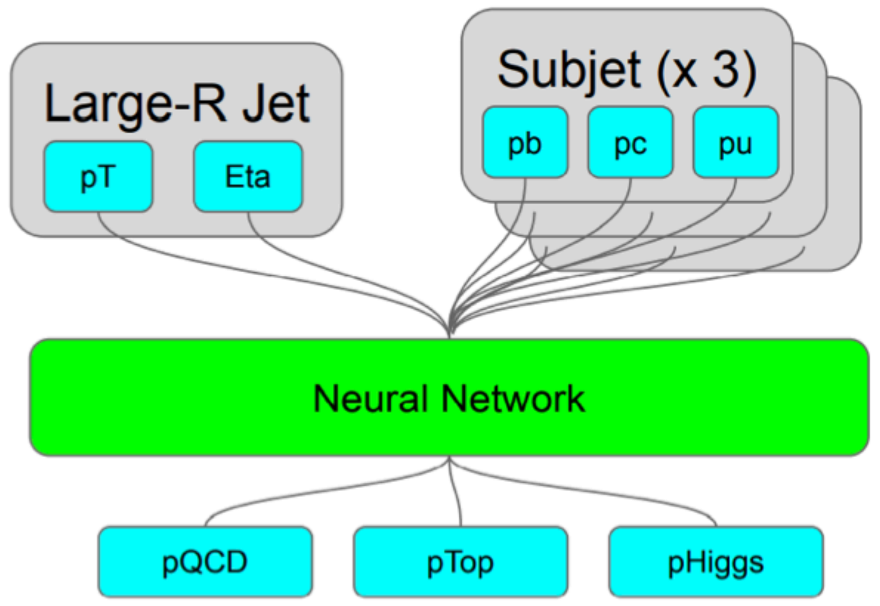
- Boosted vs non-boosted
  - A question of how merged the jets are
  - Can use [too large] large cones in which the jets are anyhow resolved
    - Can combine both e.g. ATLAS Xbb tagger
  - Need to understand not only efficiencies but also how backgrounds behave
  - And systematics…
- Sensitivity should be the final word
  - And will be event/physics dependent
    - Different fractions of merged jets
      - For multijet final states like hhh=>6b for ex.
      - Or for different BSM resonance mass points as TRSM



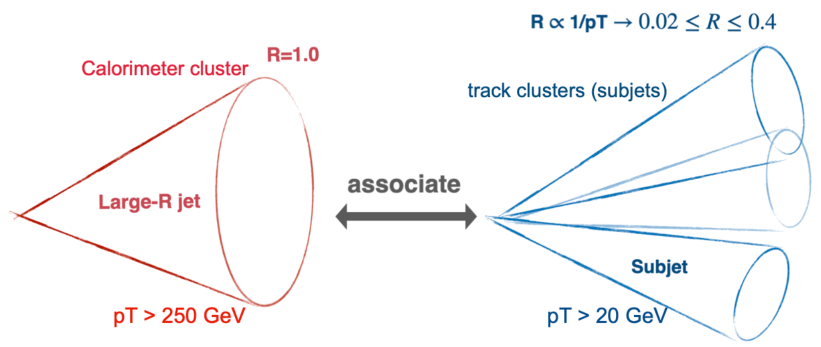


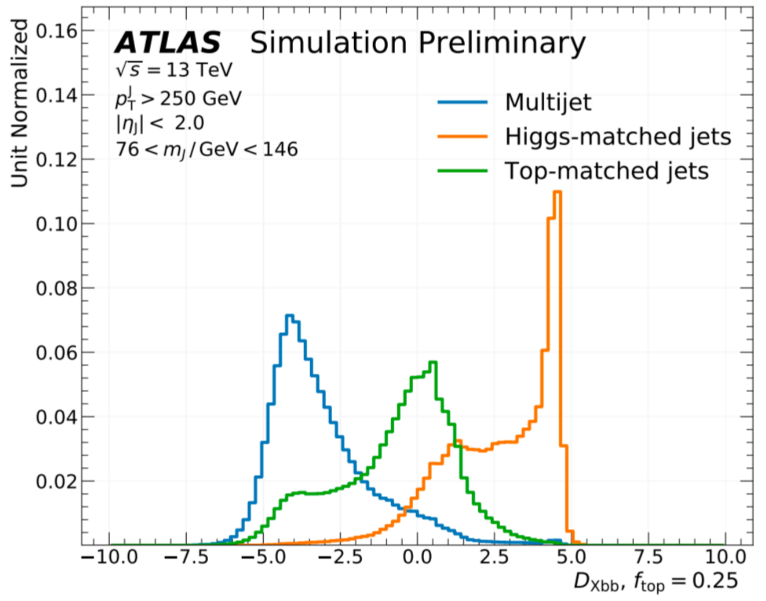


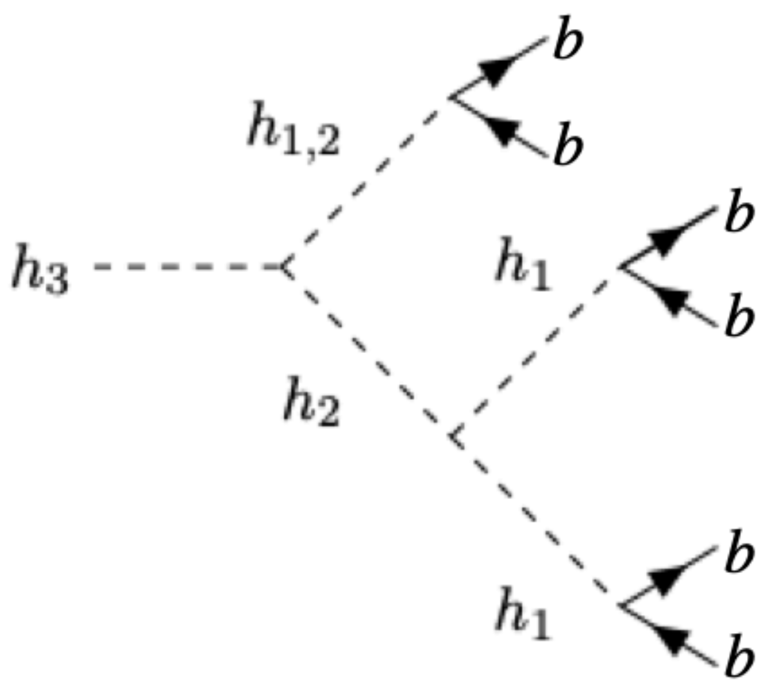


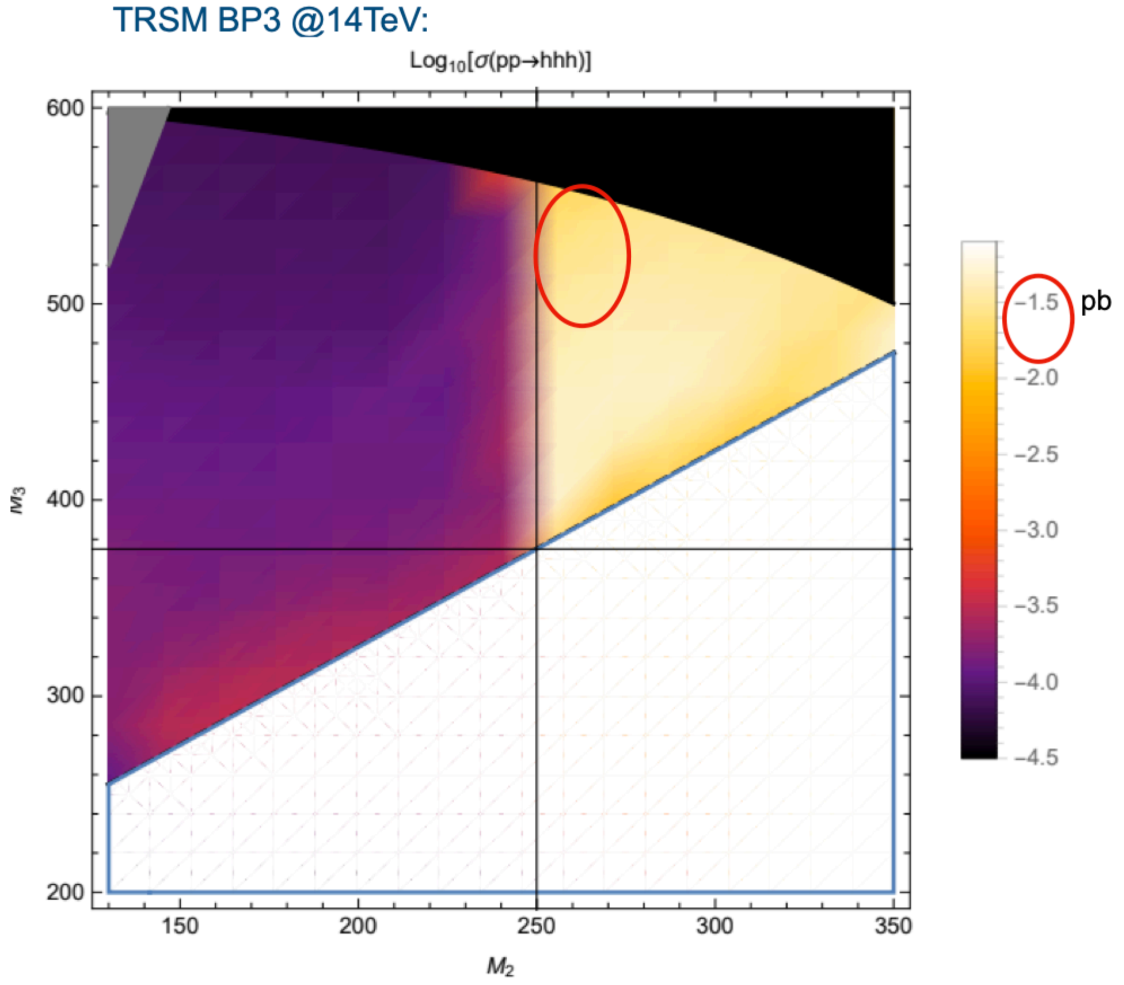


ATLAS Xbb tagger



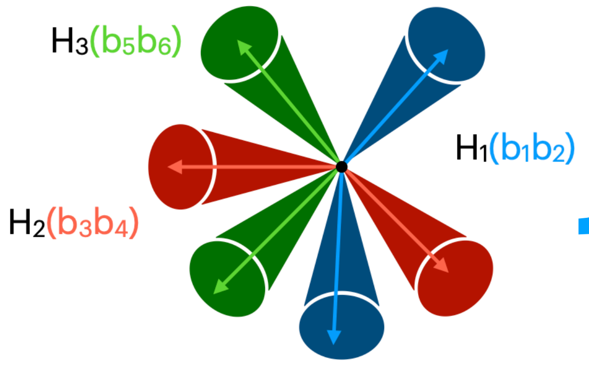






HHH pairing/reconstruction strategies

Balunas/Landsberg/Li/Stamenkovic/Ganguly

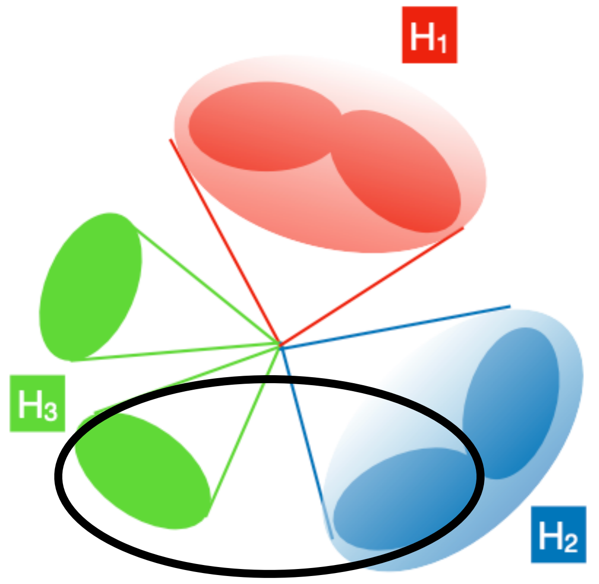


- Useful to reconstruct correctly the H's in the event
  - Can help much with differentiation from background!
  - Different strategies for different mix of boosted [merged]/ resolved
  - ISR and FSR complicate matters further !
- ML techniques being implemented: ___Net
  - e.g. SPA-Net [symmetry preserving attention network]
    - Rank the pairings
      - Assignment probability + detection probability

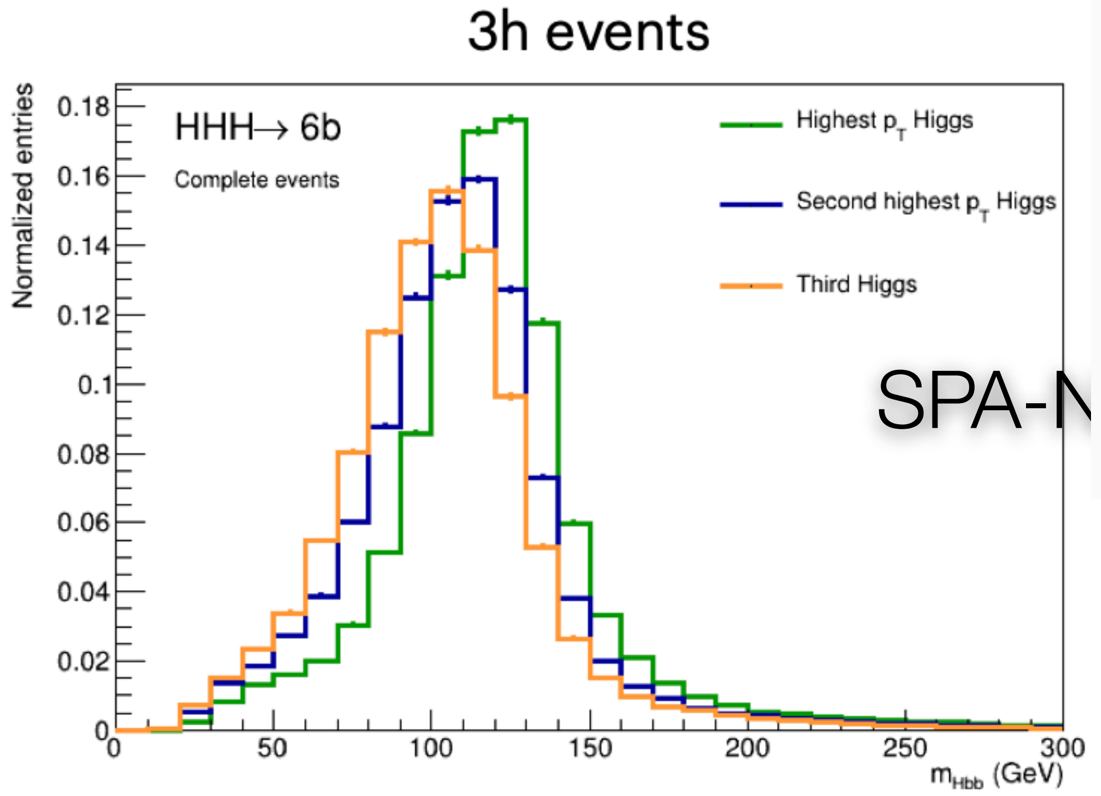
      Input jet features:

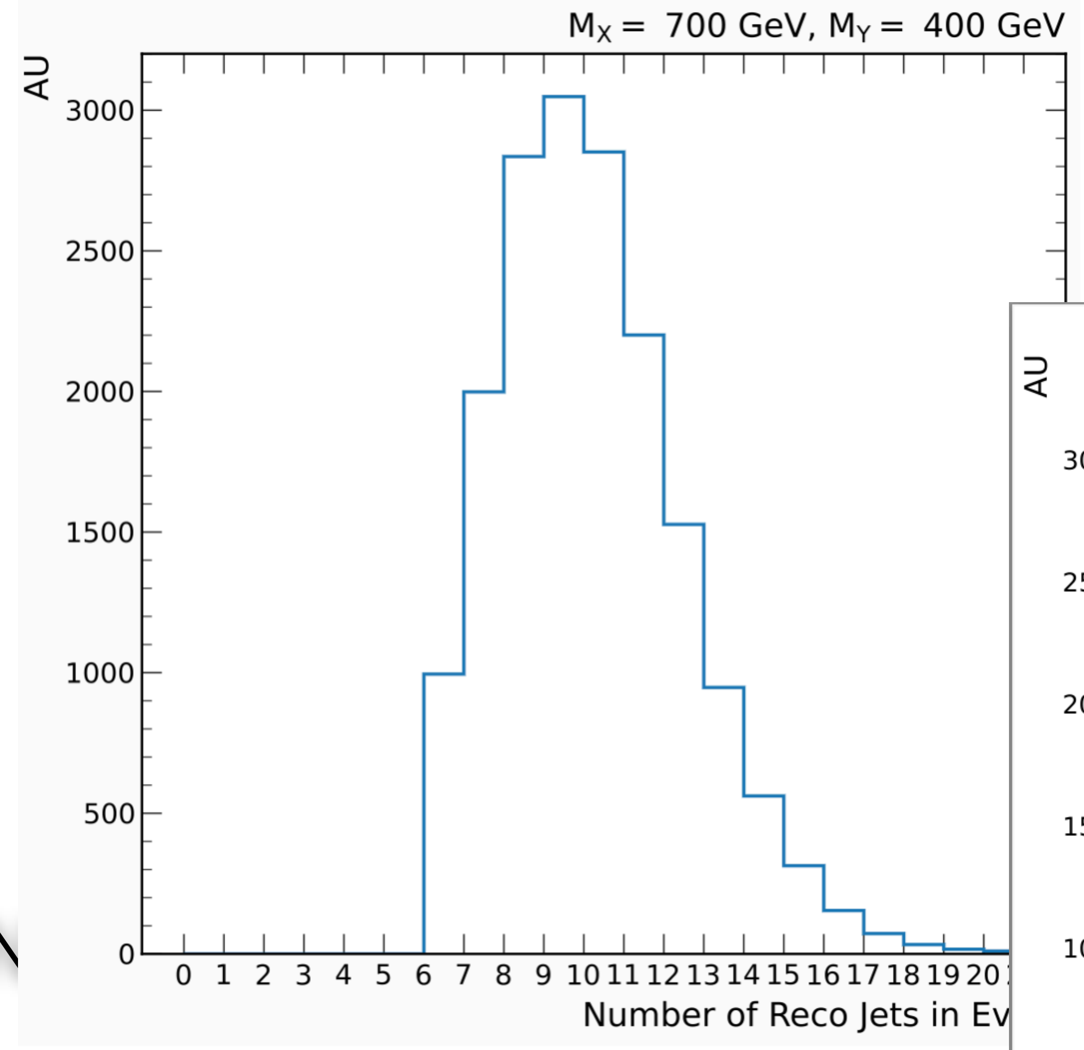
      - p_T (log-normalized), η (normalized), $\sin\phi$, $\cos\phi$, and boolean b-tag score
    - Reconstruct events in which not all Higgses are present fiducially
    - Compares ML vs baseline (mass minimization)
      - Wins on purity
      - Background sculpting?
      - Working on boosted…
  - e.g. LorenzNet
    - GNN for full event reconstruction

- **Merged jets help tremendously against combinatorics:**
  - HHH → 6b: $C^2_6 \times C^2_4 \times C^2_2$ / 3! = 15 x 6 x 1 / 6 = 15 combinations
  - HHH → 4b+J: $C^2_4 \times C^2_2$ / 2! = 6 x 1 / 2 = 3 combinations!
  - HHH → 2b+2J and HHH → 3J = 1 combination each!!

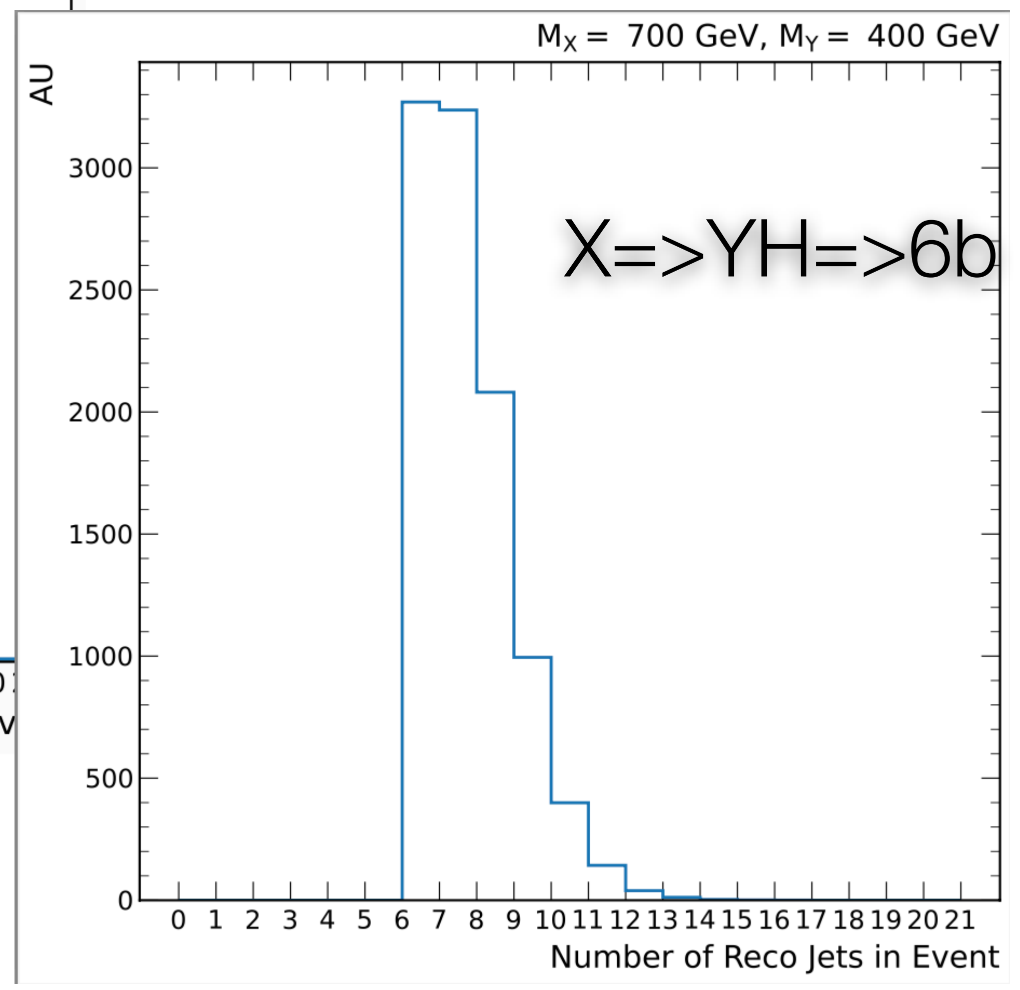


Handle with care





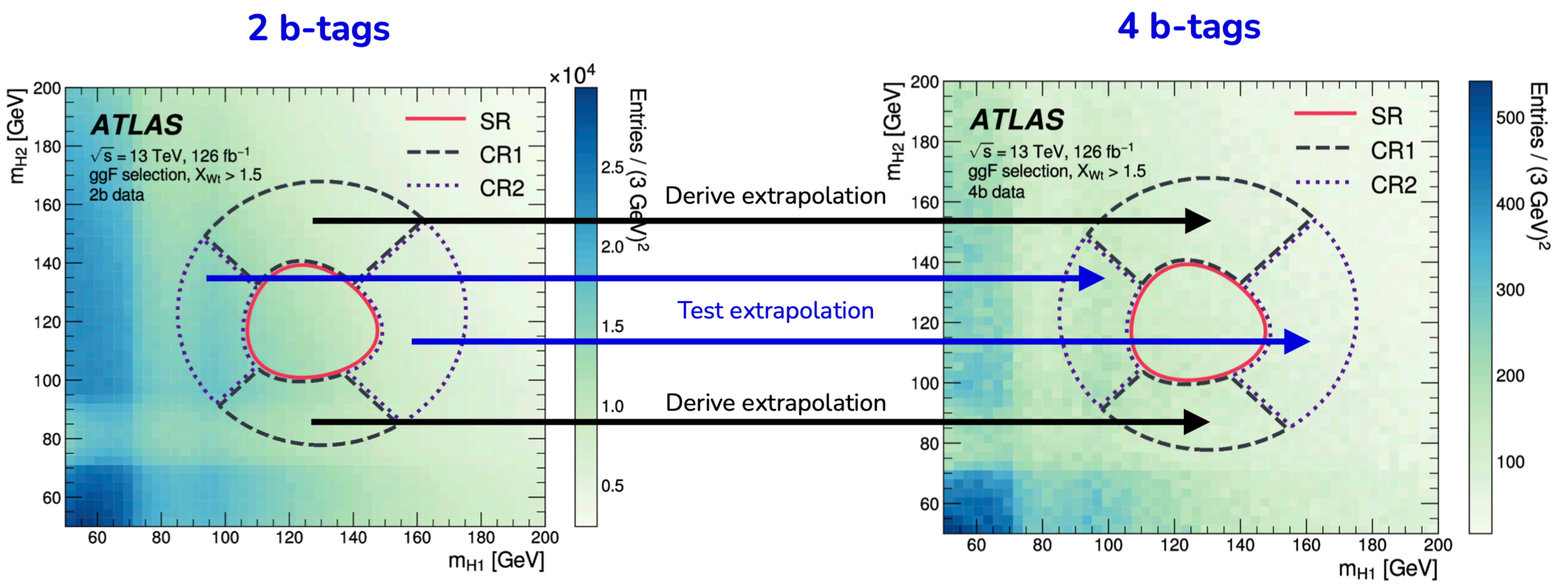
Not 6 !



Background modeling

Balunas/others

- For multi-jet/b final states
  - MC is useful for analysis guidance
  - For ML training we need large b-enriched datasets
- Care to not shape background as signal (e.g. mass)
- For accurate background shape determination data in control regions is used
  - Need to extrapolate to signal regions
  - Use validation regions to check extrapolation
  - Mindful of statistics and systematics
  - Critical, non-trivial, part of the analyses !!



ATLAS Run 2 HH4b analysis

Note: CMS uses 3=>4 and BDT reweighing

$$d\sigma_{\mathrm{PP}\to\mathrm{final}} = \sum_{\mathrm{i,j,final}} \int dx_1 dx_2 d\Phi_{\mathrm{final}} f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2) \frac{d\hat{\sigma}_{\mathrm{ij}\to\mathrm{final}}}{d\Phi_{\mathrm{final}}} \Theta_{\mathrm{cuts}}$$

Parton Distributions Functions	**Partonic Cross Sections**
Extracted from data at various experiments/energies. PDFs are universal and their evolution is perturbative (LO, NLO, NNLO…)	Expansion in the coupling constants (LO, NLO, NNLO…), also including enhanced all-order terms (LL, NLL, NNLL…)

Precision theory is a multilateral challenge

- push frontier of the perturbative QCD expansion (NLO, NNLO, N³LO)
- heavy-top and bottom/charm mass effects
- mixed QCD-electroweak corrections
- resummation of large logarithmically enhanced terms to all orders
- fully exclusive description of the final state through parton showers
  - improving the accuracy of parton showers
  - matching fixed-order calculations and parton showers
- modelling of non-perturbative effects (or ways to reduce them)
- issues with jet-flavour
- uncertainties due to input parameters: strong coupling, PDFs, masses… ⇒ ways to reduce these uncertainties
- …

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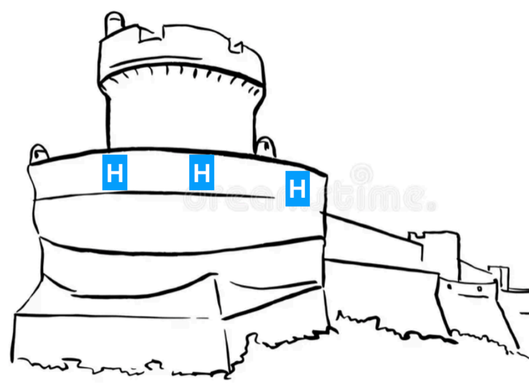
QCD precision

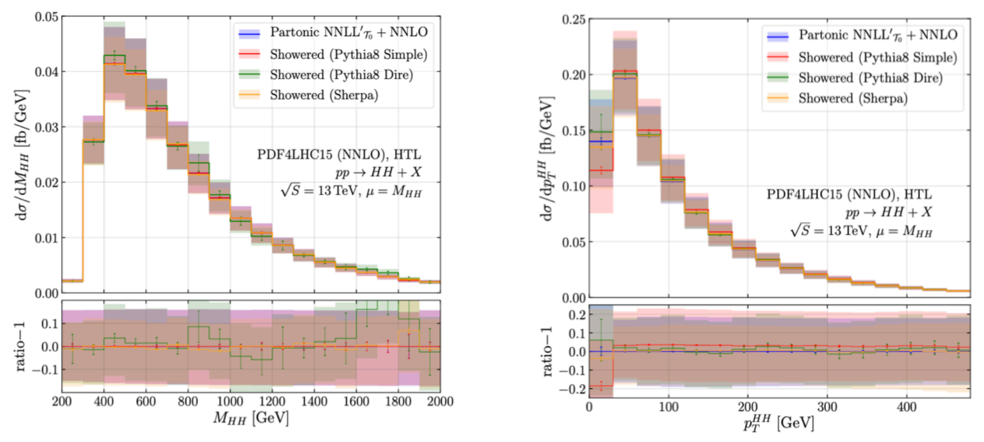


Zanderighi

- **More precision more sensitivity**
  - NLO HH QCD is a solved problem
- Not just rates but kinematics distortion
- NNLO 2=>2 SM model processes done
  - 2=>3 next frontier
  - 2=>4 not being addressed yet
- NNLO + PS
  - 2-2 w/ bosons and w/HQ ok
  - Nothing beyond yet

NNLO+PS: gg → HH

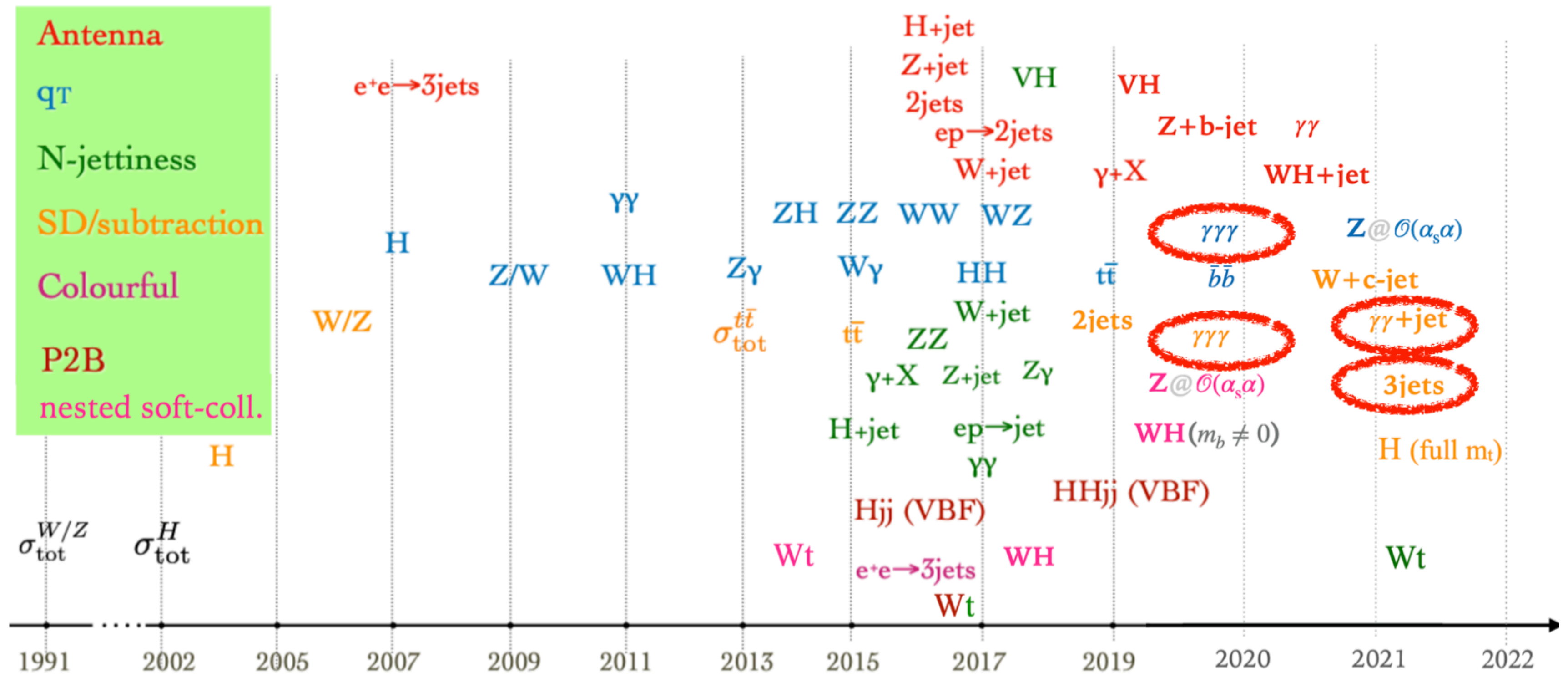
Alioli et al 2212.10489



Good agreement with analytic results for inclusive quantities. Exclusive simulations allow to implement fiducial cuts and exclusive distributions accurately

NNLO: status

adapted from A. Huss/G. Salam



Different colour: different way to handle intermediate divergences

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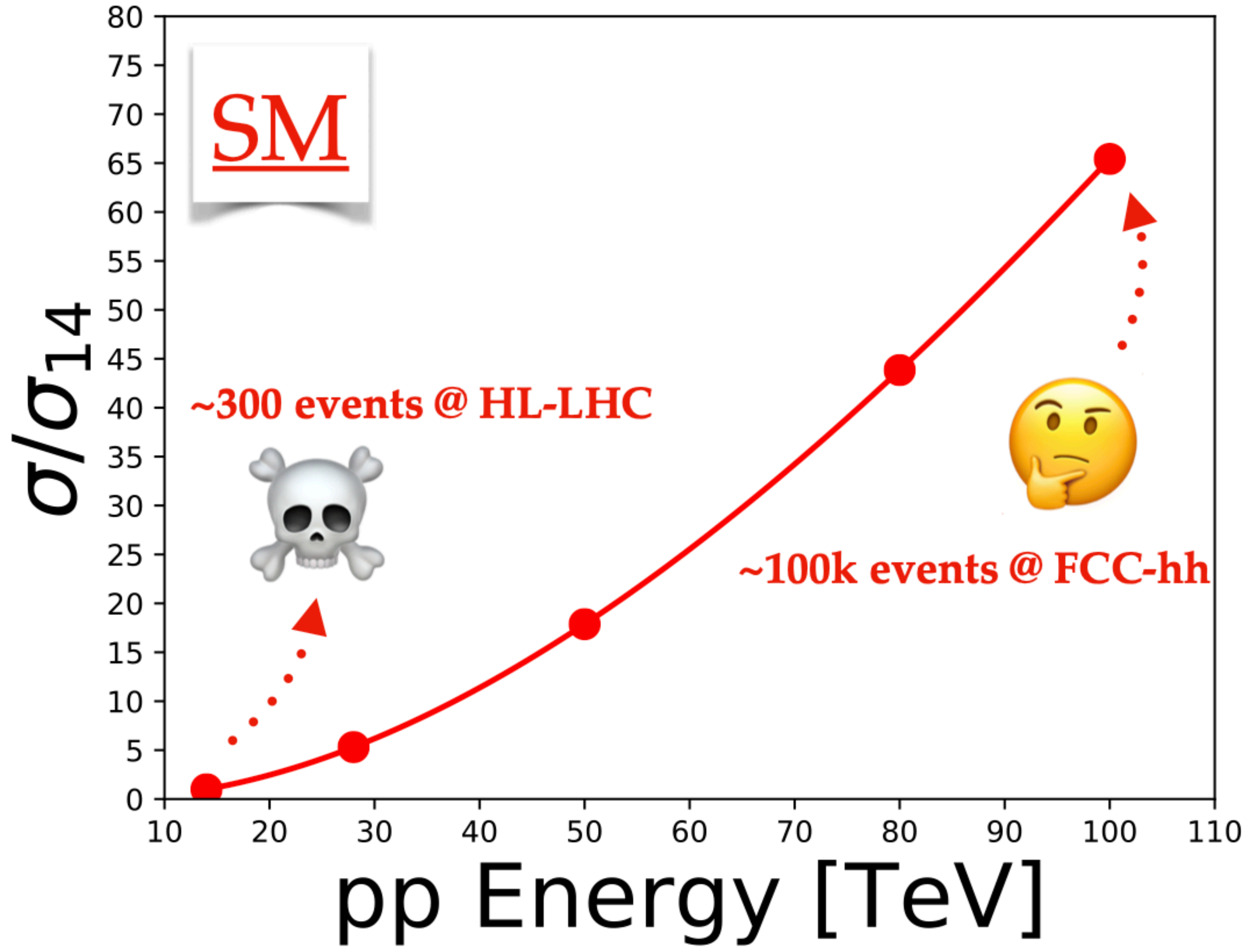
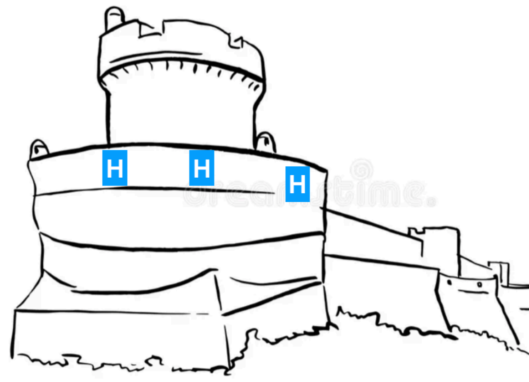
HHH constraints @ 100 TeV

Papaefstathiou/Fuks/Sakurai

- Cranking up the pp energy could help!

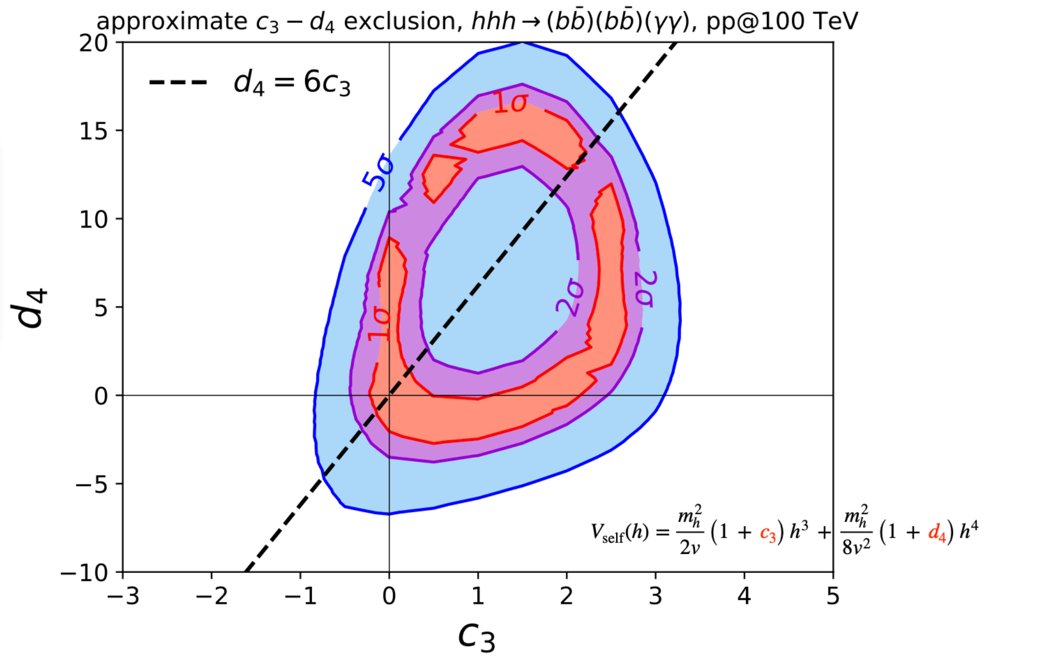


~ ×60 increase in cross section 14 TeV → 100 TeV.



c_3, d_4 constraints

$$V_{\rm self}(h) = \frac{m_h^2}{2v}\left(1 + c_3\right) h^3 + \frac{m_h^2}{8v^2}\left(1 + d_4\right) h^4$$



$\mathcal{O}(1)$ constraints on c_3, d_4, c_6 can be obtained at a 100TeV collider with $30\ \text{ab}^{-1}$

The golden (clean) $4b2\gamma$ mode

- Extremely efficient *b*-tagging desirable
- Good photon resolution
- ★ 2σ reachable in the SM
- Excellent probe of BSM

[Papaefstathiou & Sakurai (JHEP`16)]
[BF, Kim & Lee (PRD`16)]
[Chen, Yan, Zhao, Zhao & Zhong (PRD`16)]

The $4b2\tau$ mode

- Exploiting boosted Higgses and high-level variables
- Good double-tau tagging crucial
- ★ 2σ reachable in the SM

[BF, Kim & Lee (PLB`17)]

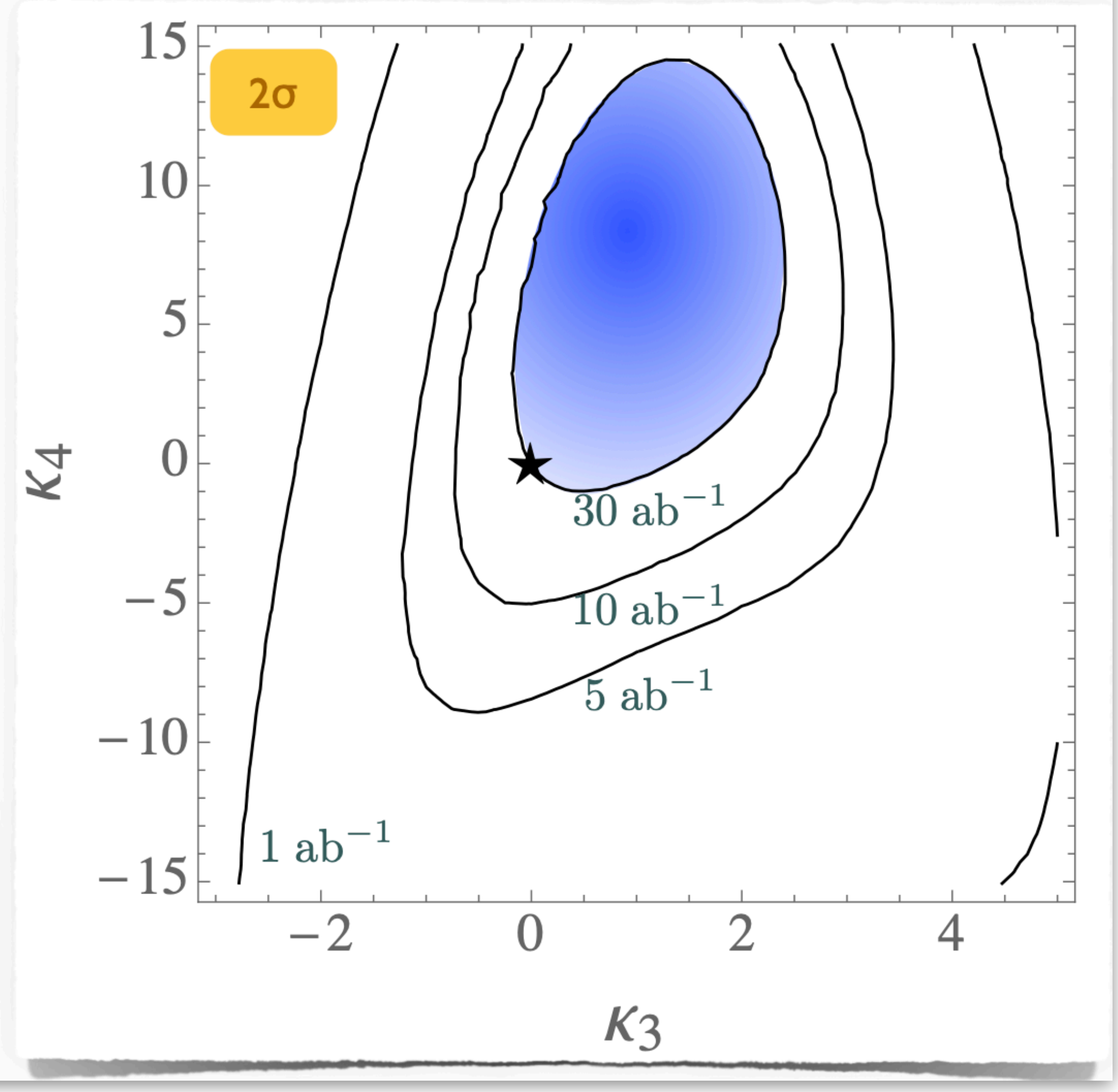
2σ on the SM with 30 ab^{-1}

The $4b2\tau$ mode as a probe of new physics

- Complicated analysis required
- Negative κ_3 severely constrained (larger rates)
- If κ_3 constrained otherwise, then potential κ_4 constraints
- An important fraction of the parameter space not probed
  → Destructive interferences

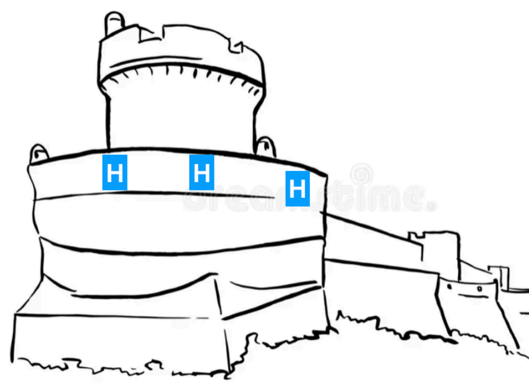
Potential for combination with the $4b2\gamma$ and $6b$ modes

- Also with more modern techniques (boosted Higgs)
- Also with better *b*-tagging performance



2-sigma now
=> discovery later

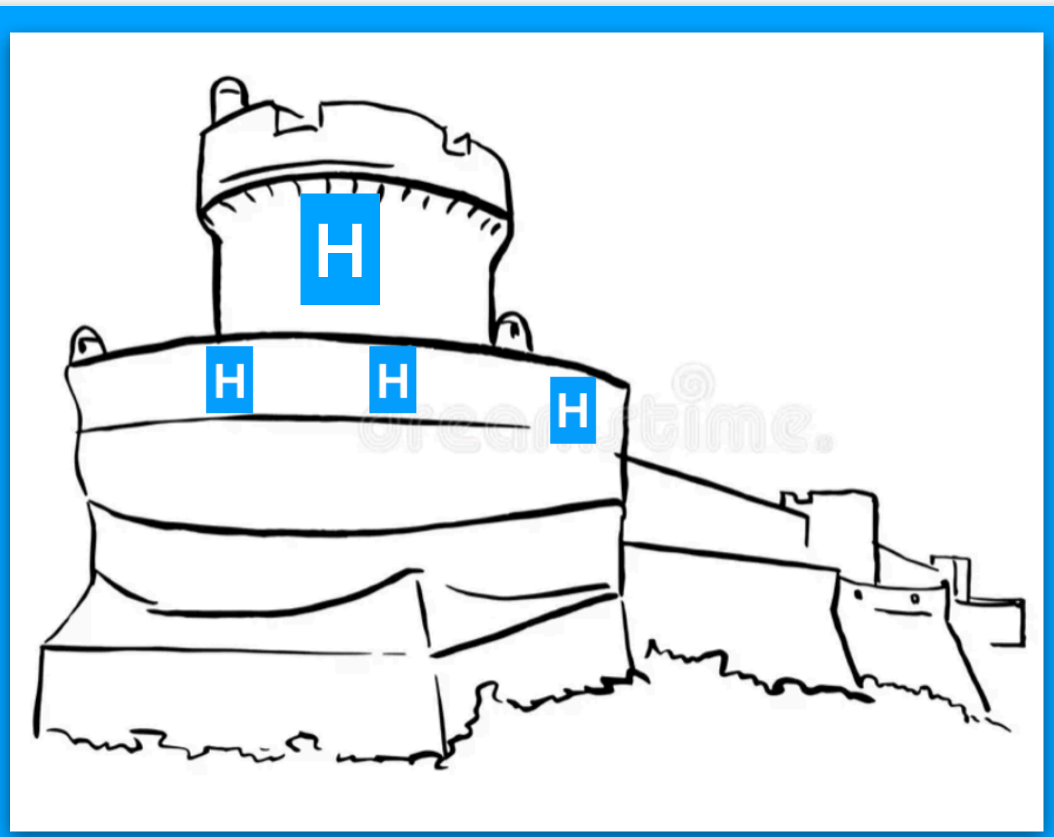
Final remarks



- HHH SM prospects @ LHC
  - Bleak, dim, hopeless?
  - But H=>bb was thought of the same… done and done
  - So was HH… and we'll get to it - promise!
- We are doing the right thing here in figuring out how
  - Our knowledge & tools evolve continuously
  - Workshops catalyze the process
- There is anyway [earlier/good] hope for BSM HHH
  - Many opportunities for discovery
- Also, experimentally, we should just search. period.

What's next ?

Higgs Pairs Workshop 2022



2024 ?