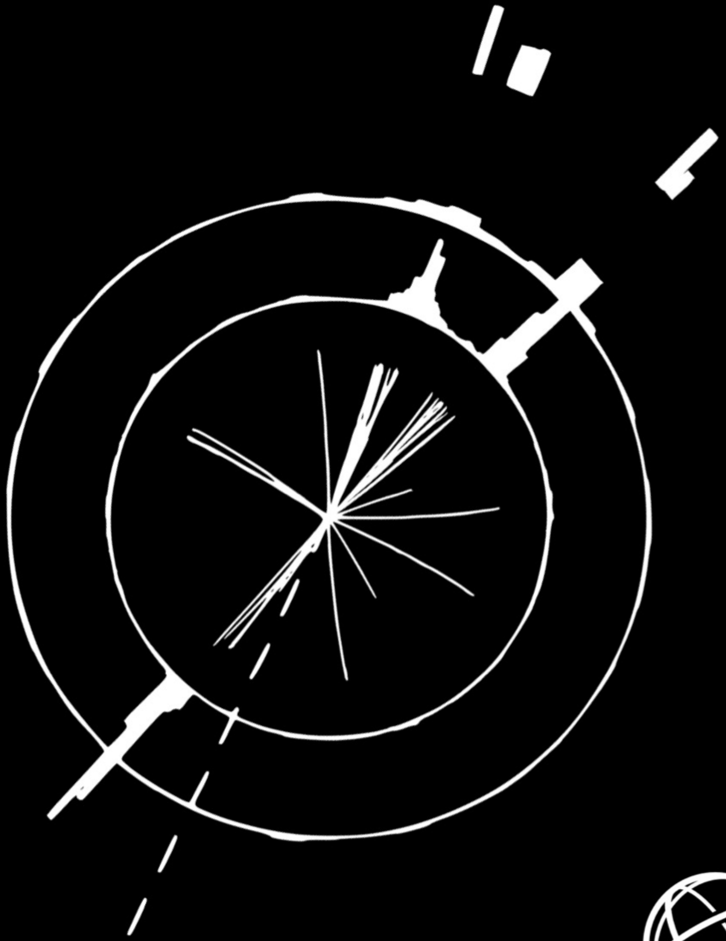


Higgs Physics

Highlights and Prospects

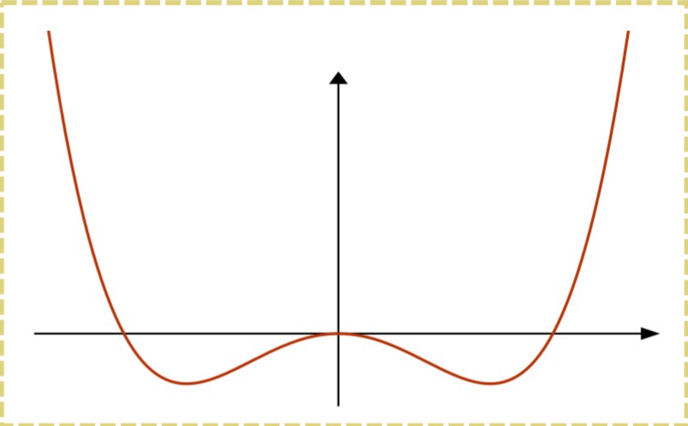
Brian Moser on behalf of the ATLAS Group

Nikhef Jamboree

18/12/2018

The central role of the Higgs boson in the Standard Model

- A rough sketch of the SM Lagrangian density:



$$\begin{aligned}\mathcal{L}_{\mathrm{SM}} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\psi}\not{D}\psi \\ & + |D_\mu\phi|^2 - \mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2 \\ & + y_{ij}\psi_i\phi\psi_j + \mathrm{h.c.}\end{aligned}$$

Higgs interactions

→ Higgs mechanism

→ Yukawa terms

The central role of the Higgs boson in the Standard Model

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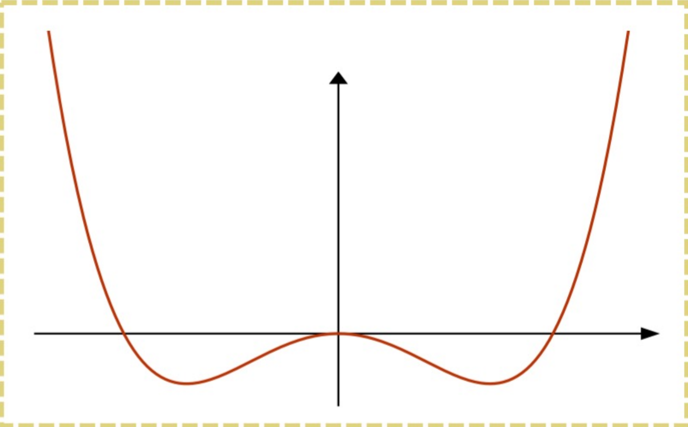

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\begin{aligned}
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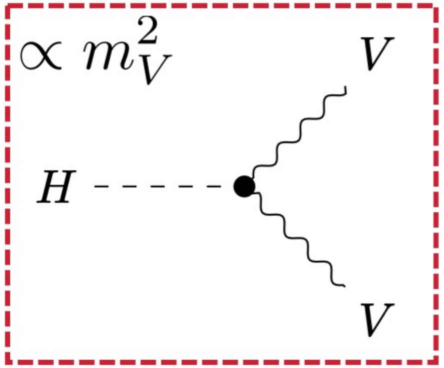
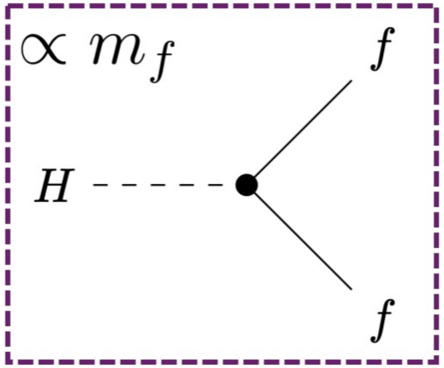
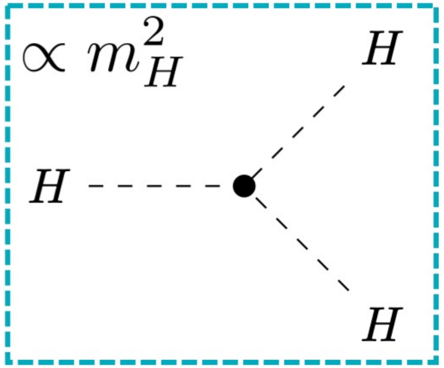
→ Higgs mechanism

→ Yukawa terms







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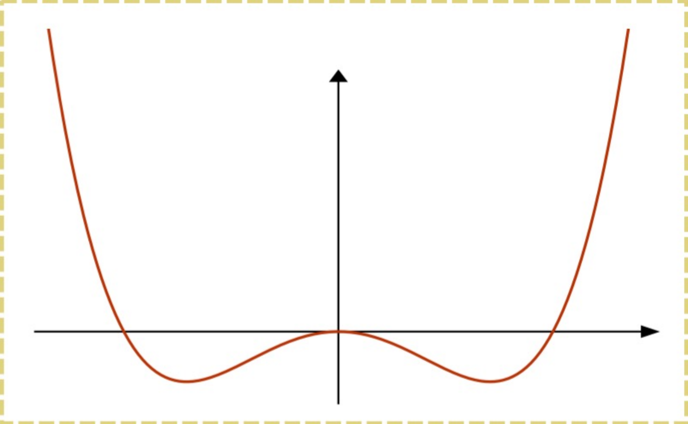
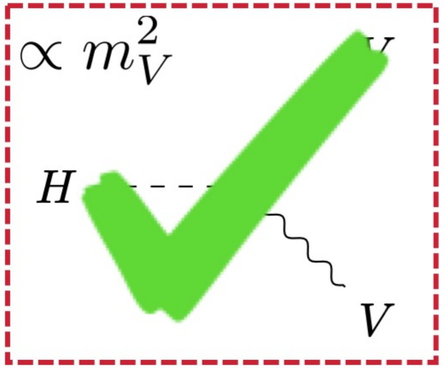


Lucrezia's talk



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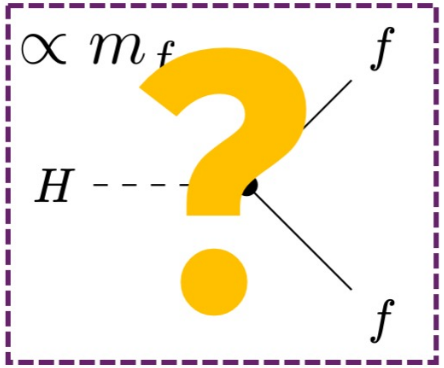

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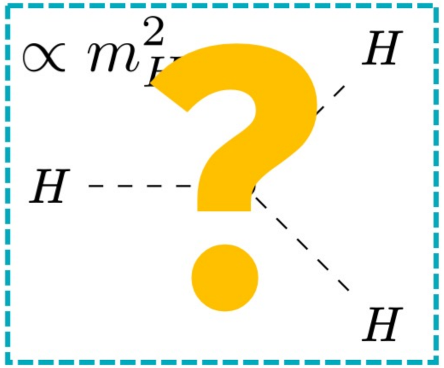
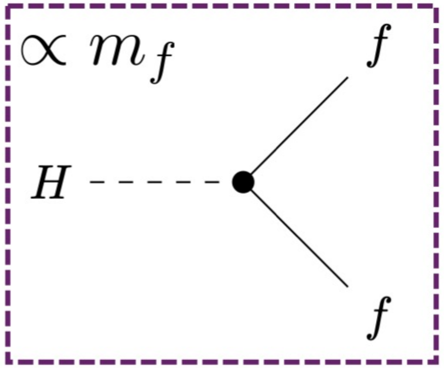
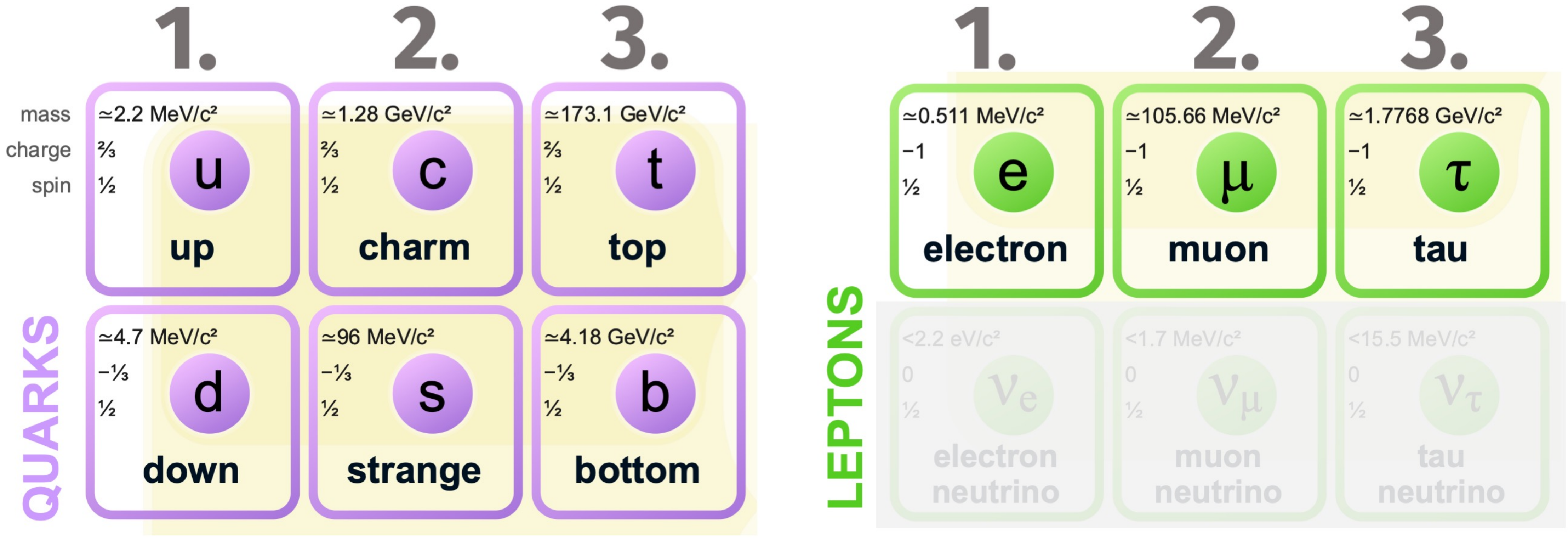


The Higgs-fermion sector after last year‘s Jamboree





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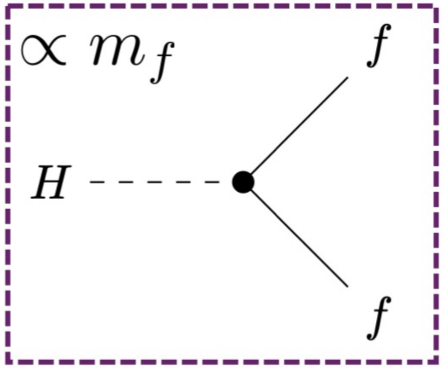
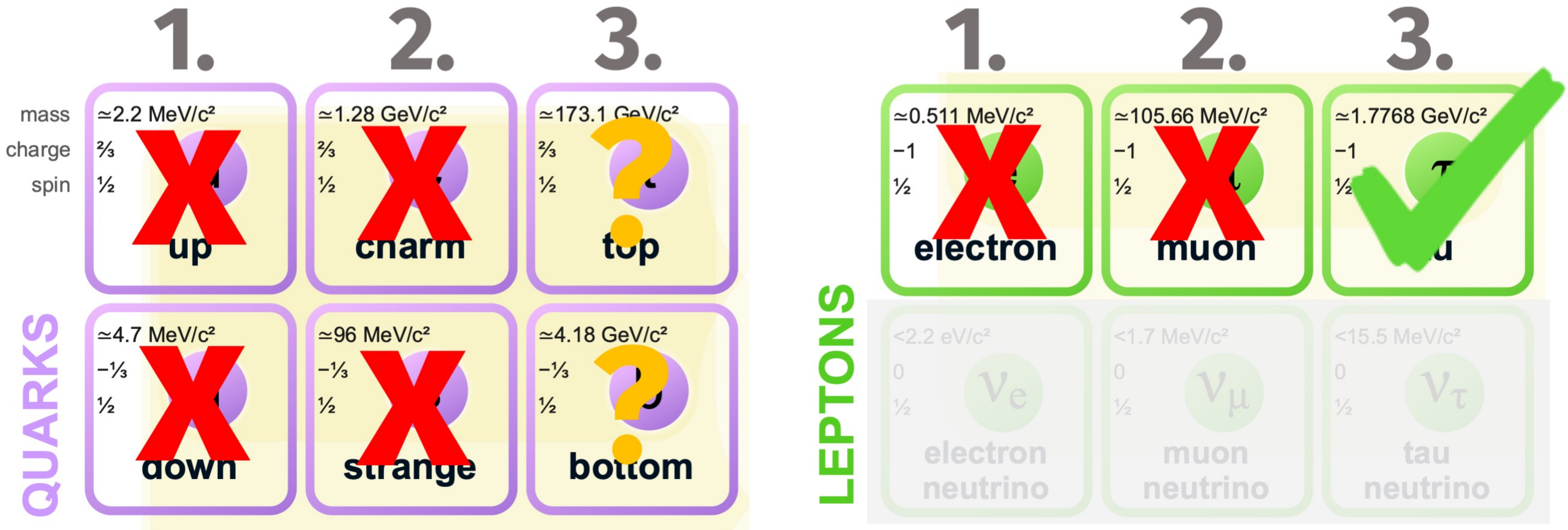
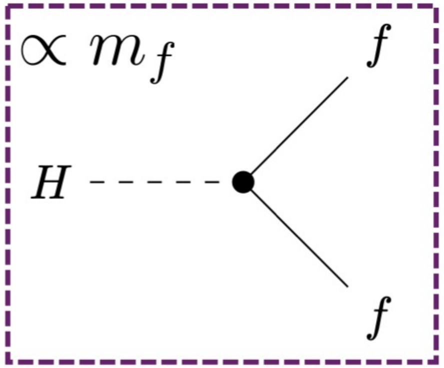




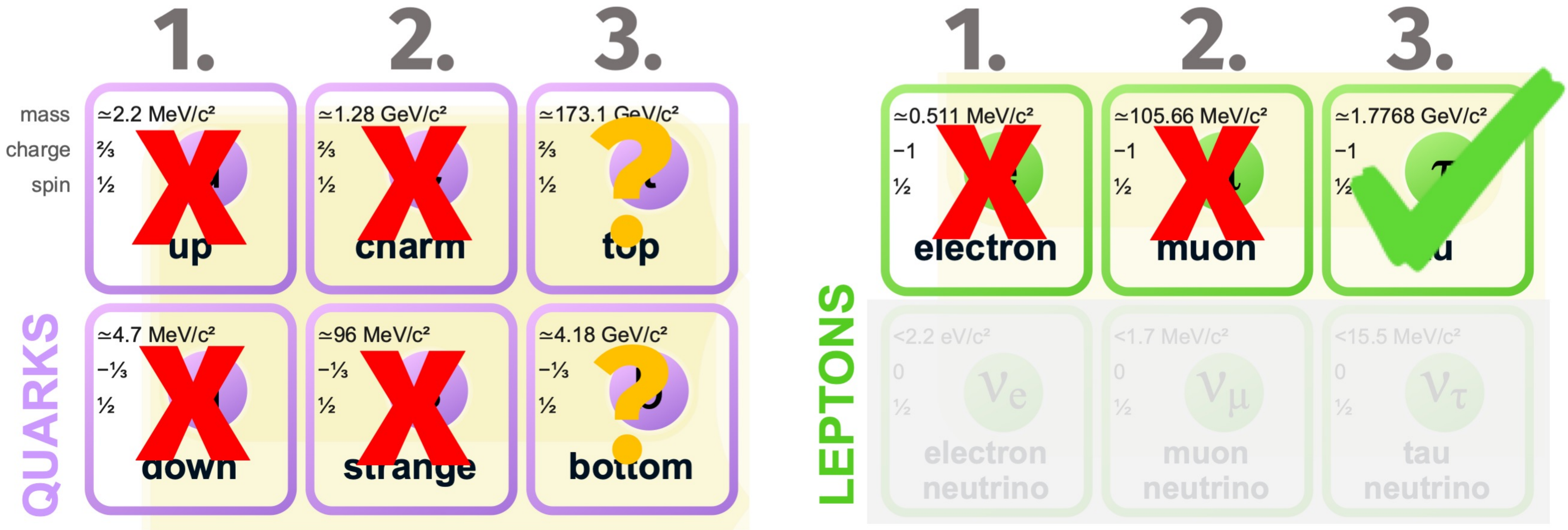
(Not interpreting the effective Higgs-gluon and -photon couplings as quark-loops)

The Higgs-fermion sector after last year's Jamboree

- Coupling to quarks?
- Similar coupling to up- and down-type quarks?



- First and second generation?

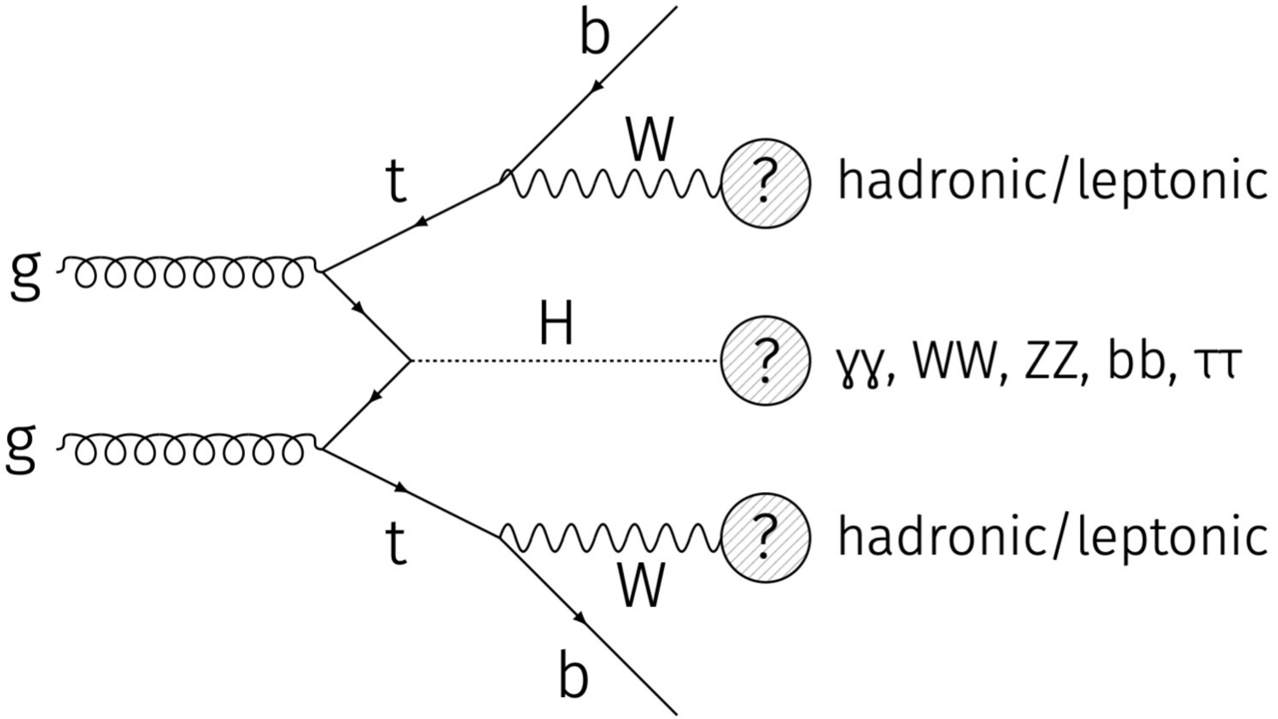


(Not interpreting the effective Higgs-gluon and -photon couplings as quark-loops)

Third Generation

The hunt for ttH production

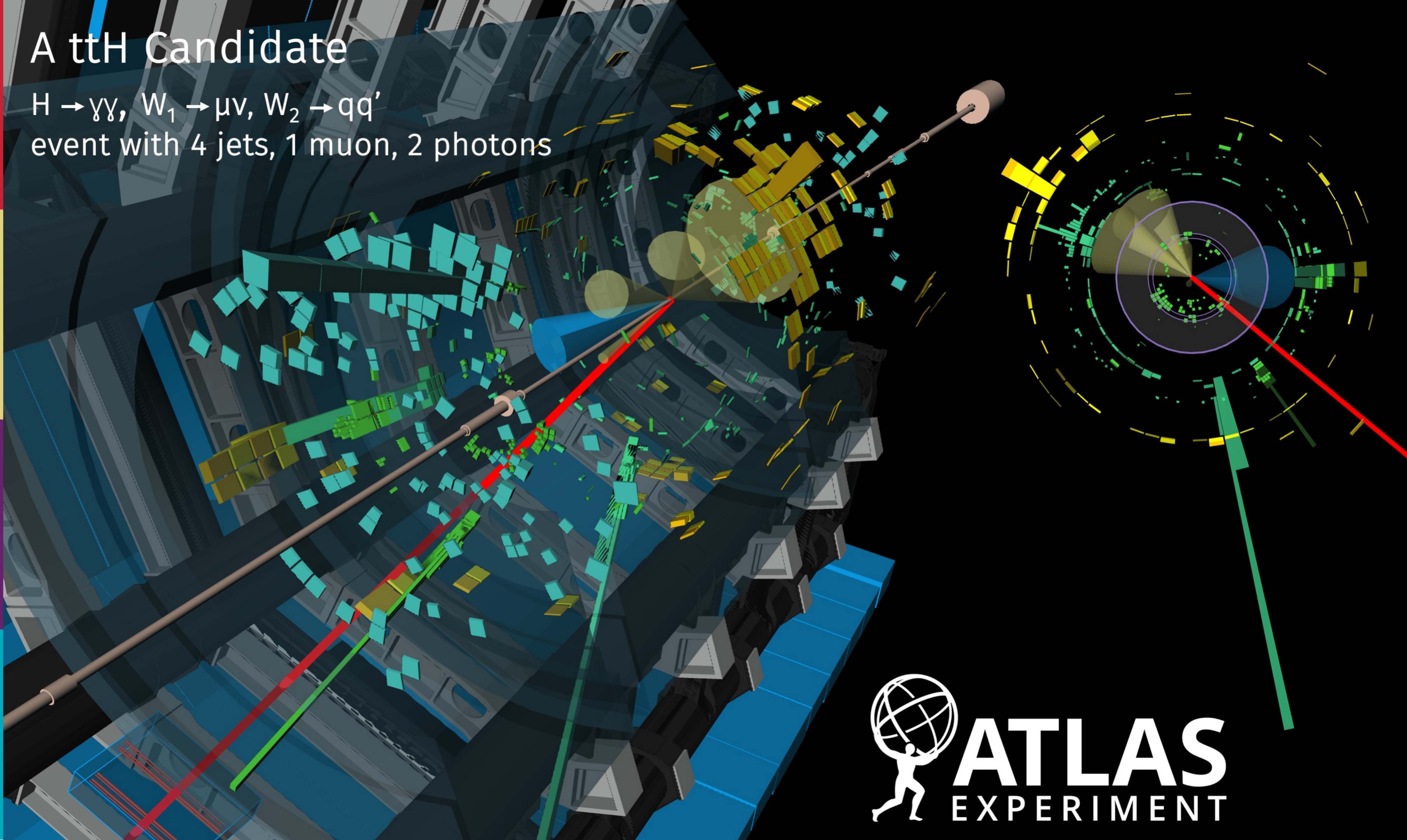
- Top: heaviest particle in the Standard Model – Yukawa coupling y_{top} ~ 1
- y_{top} influences $V(\phi)$ at high ϕ ⟶ EW vacuum stability



- Large Nikhef involvement (mostly ttH(bb)): Tim Wolf, Snezana Nektarijevic, Luca Colasurdo, Frank Filthaut, Nicolo de Groot, Pamela Ferrari

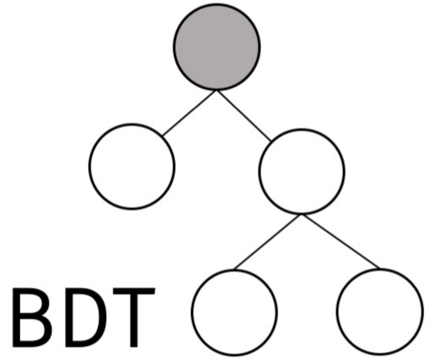
A ttH Candidate

$H \to \gamma\gamma$, $W_1 \to \mu\nu$, $W_2 \to qq'$
event with 4 jets, 1 muon, 2 photons

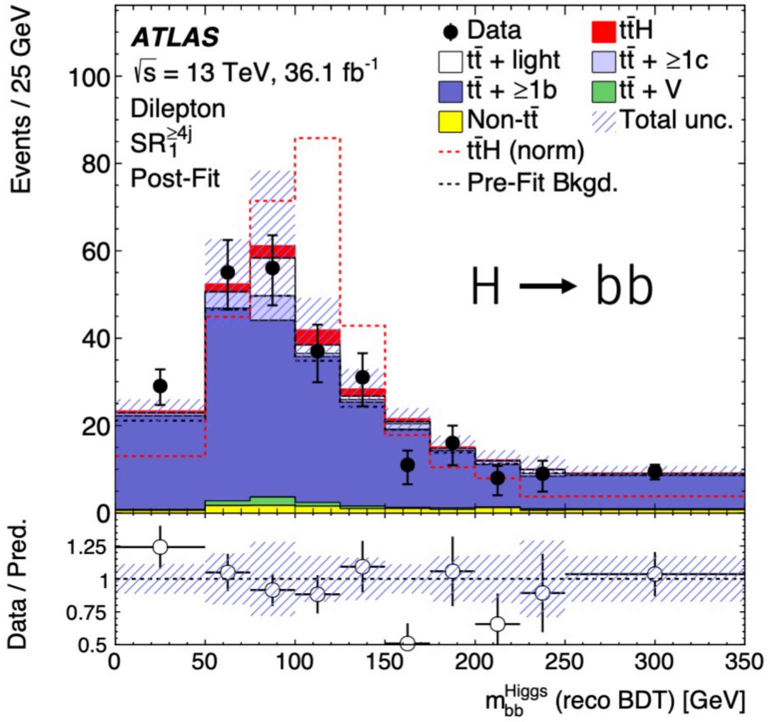


The hunt for ttH production: Observation 🎉

Separate the phase space in regions of diff. purity

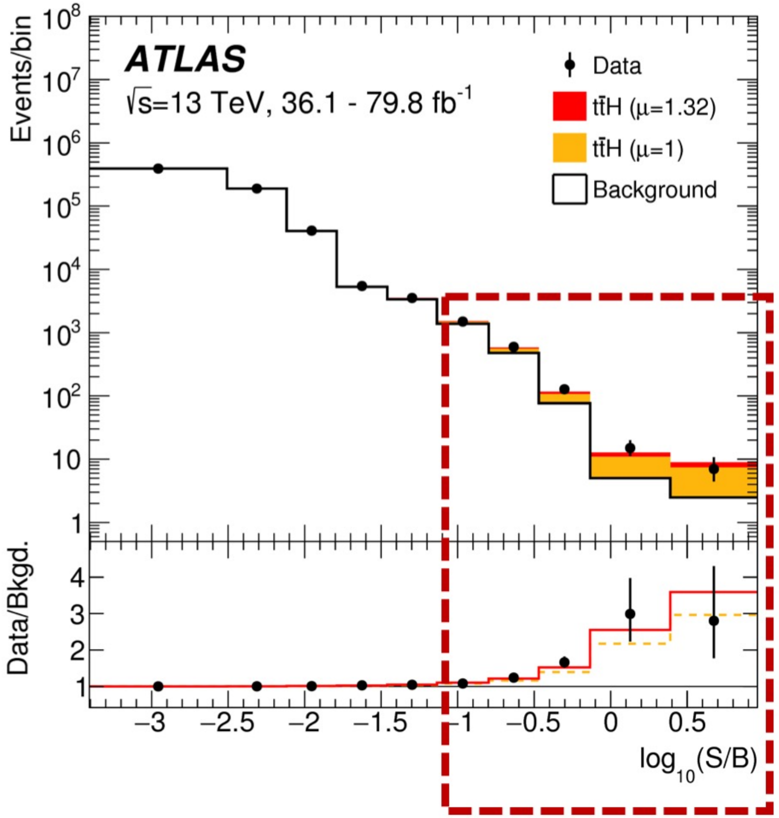


Combining all categories per channel



+ H → {γγ, WW, ZZ, ττ}

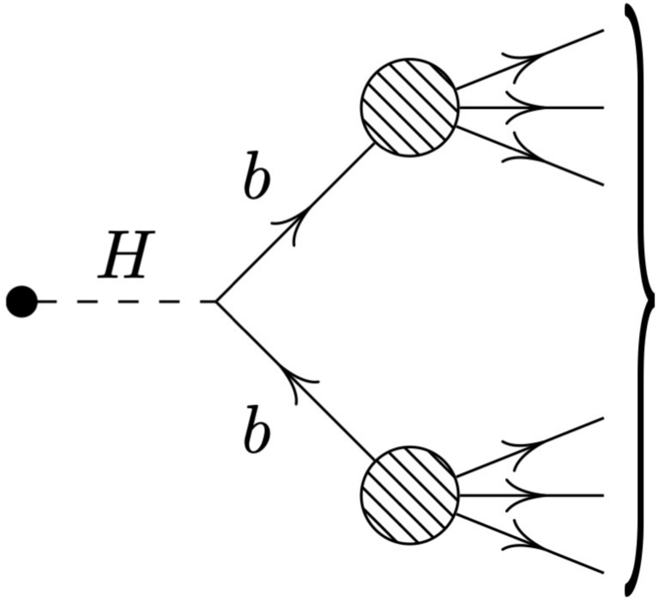
Combining all channels



→ Z_{obs} (ttH) = 5.8 σ

The hunt for H → bb

- Branching ratio H → bb ~ 58%



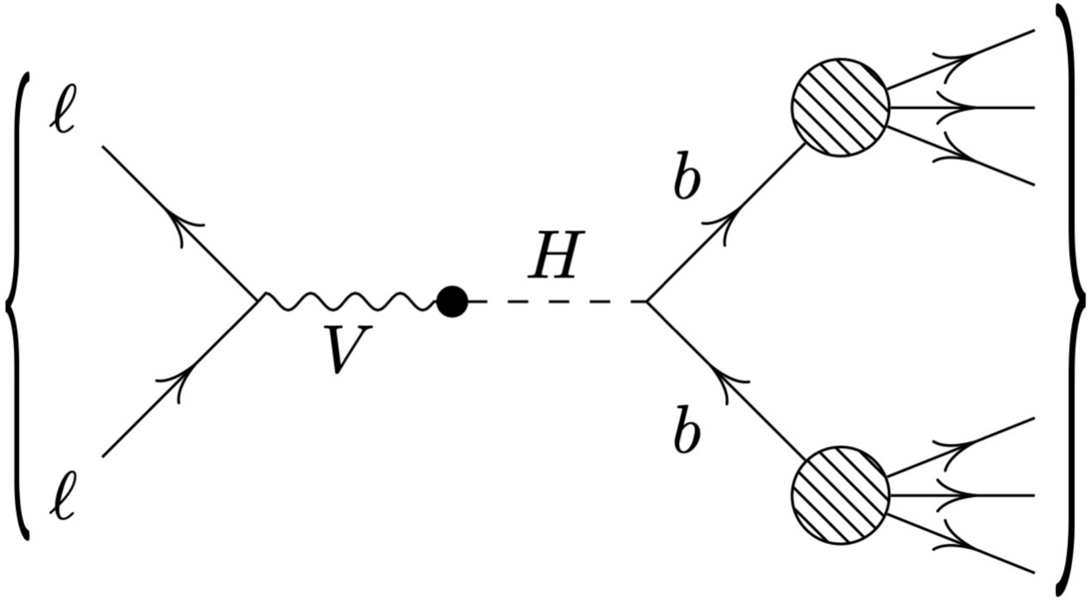
Hadronic signature at a hadron collider

$$\frac{\sigma(bb)}{\sigma(H)} \sim 10^7$$

The hunt for H → bb

- Branching ratio H → bb ~ 58%

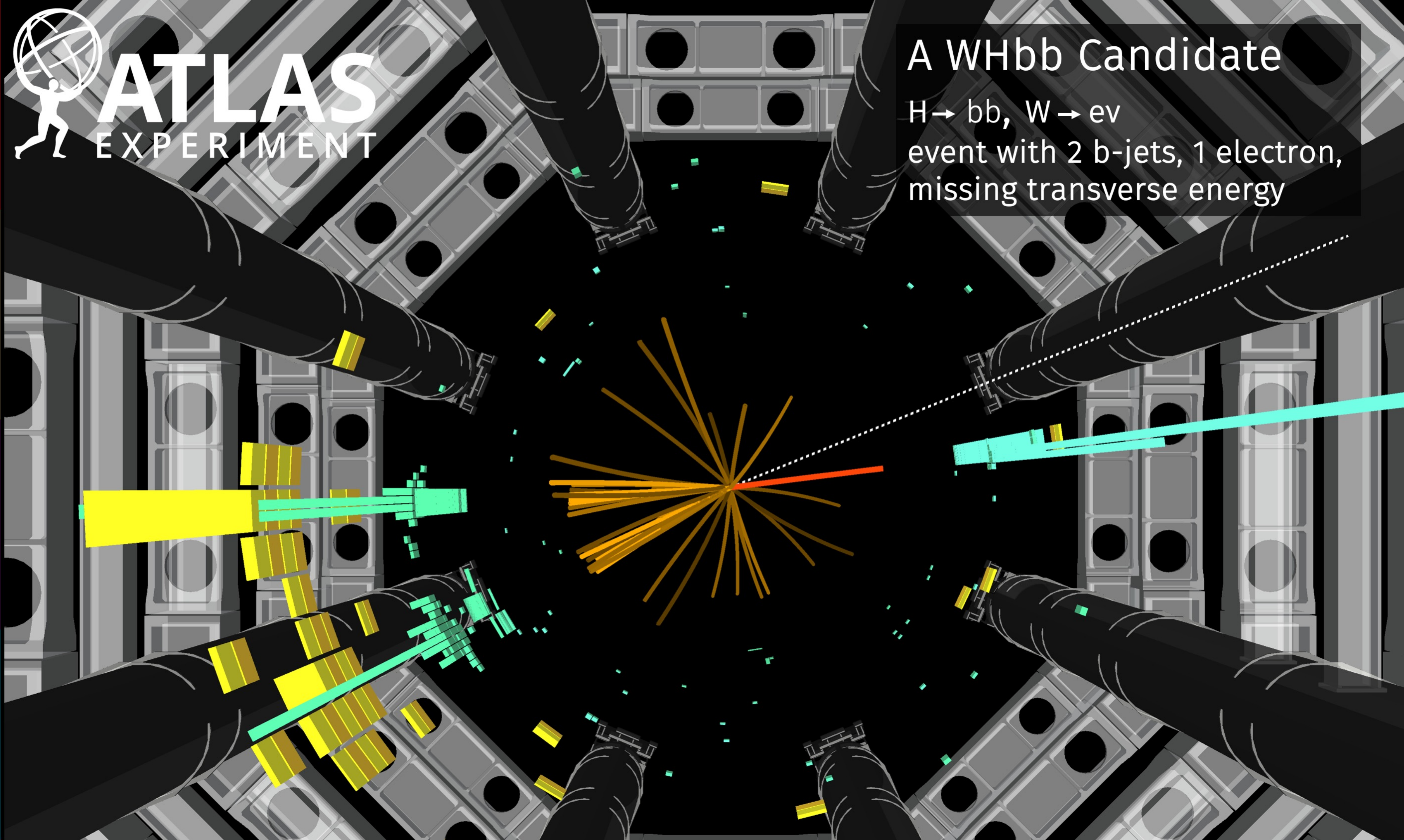
Higgsstrahlung
to gain leptons
→ clean + “rarer” signatures



Hadronic signature at a hadron collider

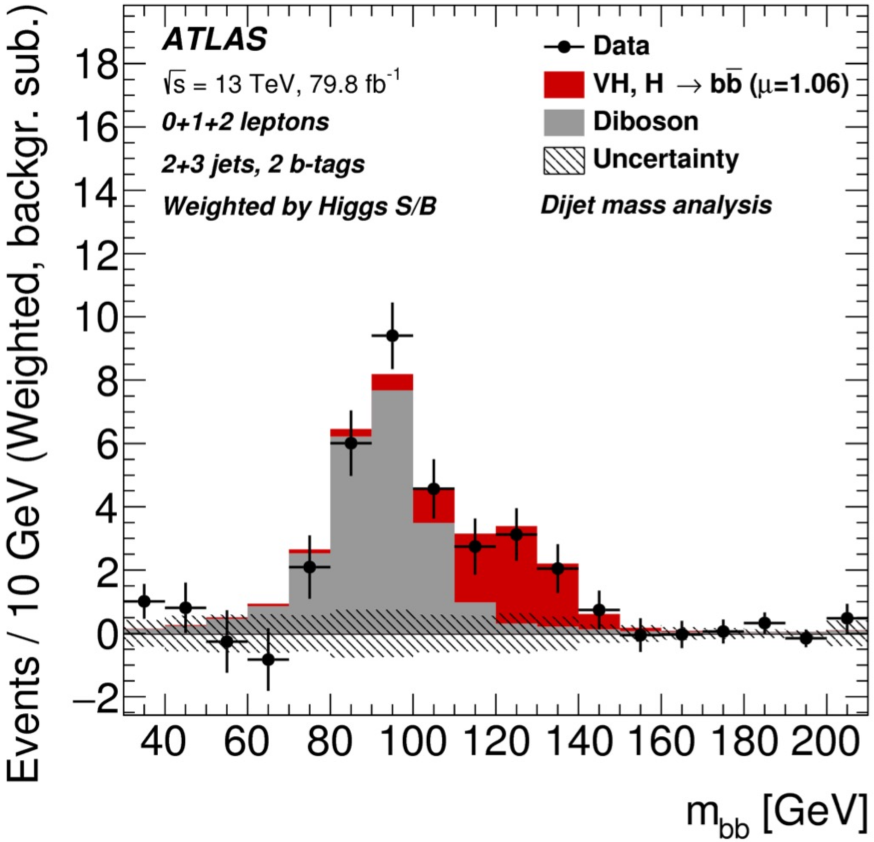
A WHbb Candidate

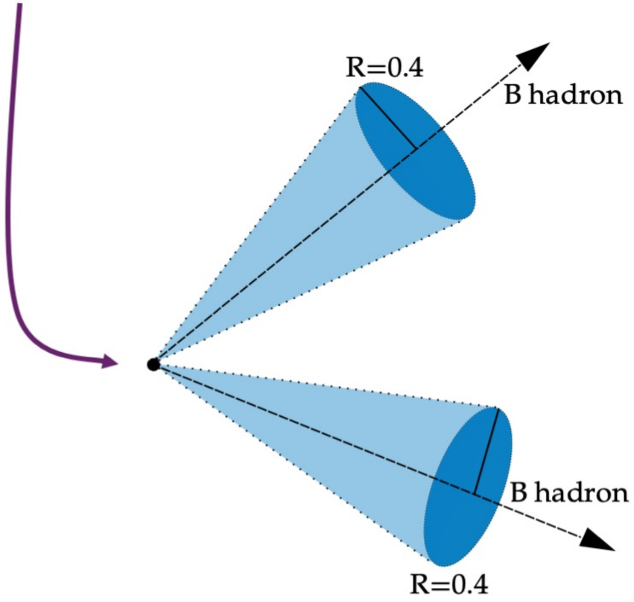
$H \rightarrow bb$, $W \rightarrow e\nu$
event with 2 b-jets, 1 electron, missing transverse energy



The hunt for H → bb: Observation 🎉

- Most sensible variable: Invariant di-jet mass (= m_{Higgs})



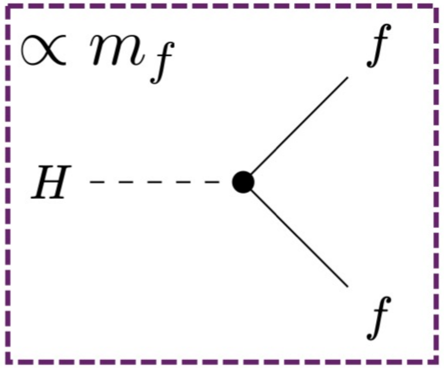


- Nikhef involvement: Hannah Arnold, Frank Filthaut

- Actual analysis uses a BDT that separates signal and background to fit
- Observation in combination with other analyses (e.g. ttHbb): **Z_{obs} (Hbb) = 5.3 σ**

The Higgs-fermion sector at this year‘s Jamboree

- Coupling to quarks?
- Similar coupling to up- and down-type quarks?



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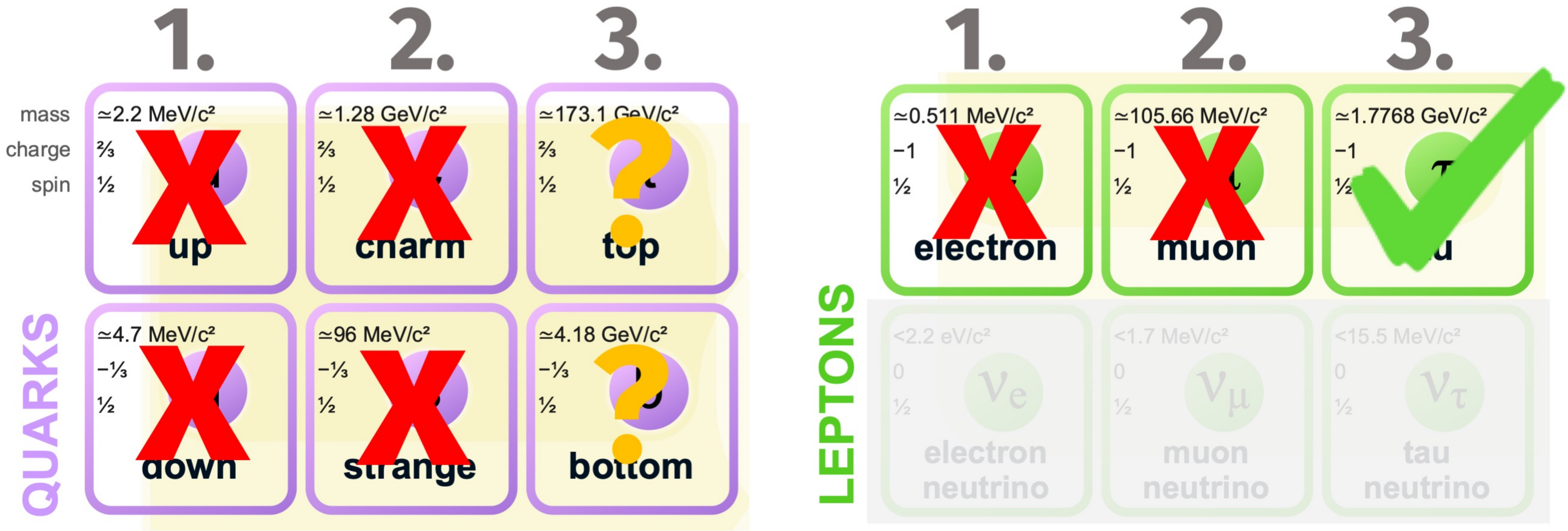

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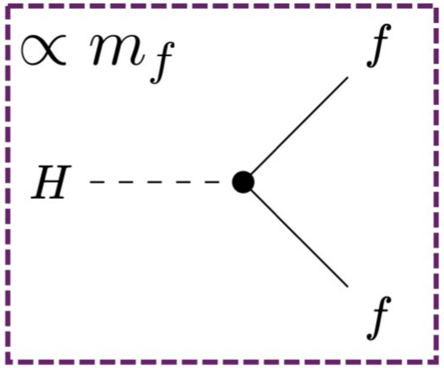

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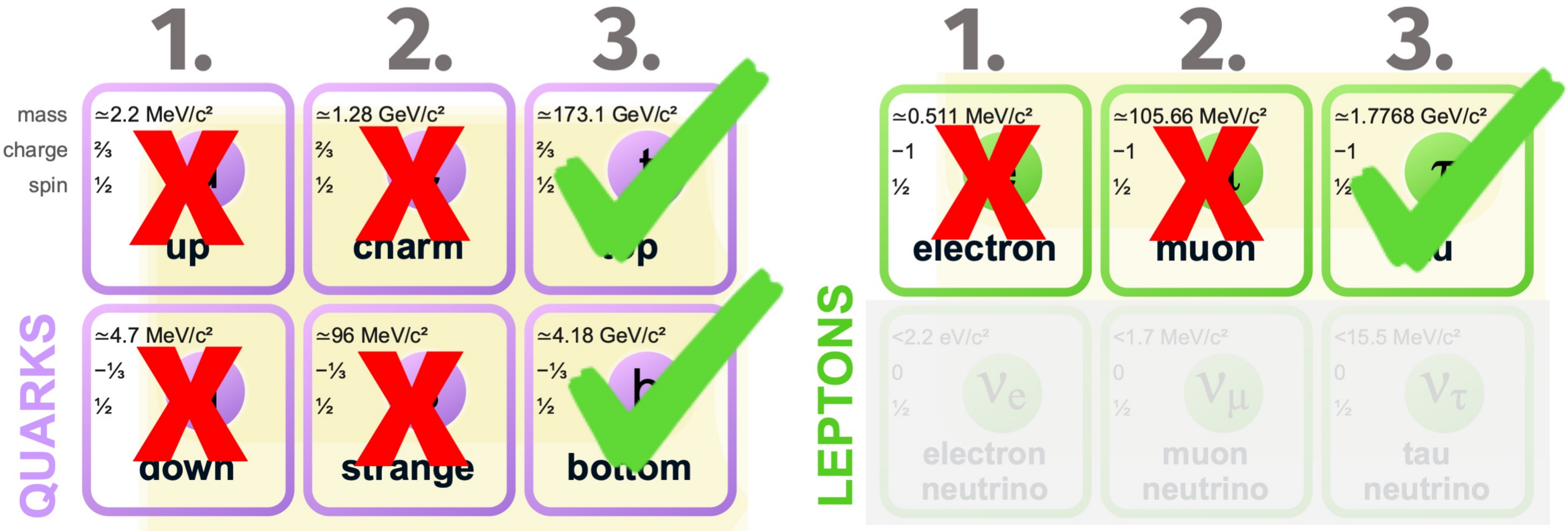

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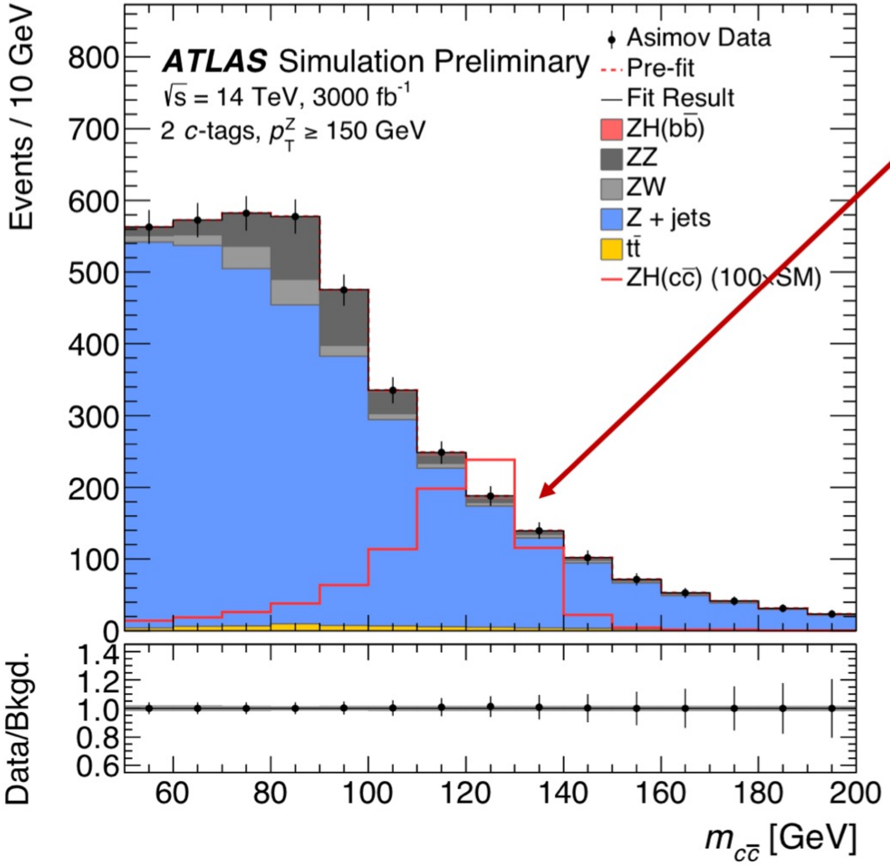
Second Generation

H → cc

- "Conceptually" similar to (VH) H → bb (exchange b for c)
  but c-tagging extremely difficult
- Analysis using 2015 and 2016 dataset, 2-lepton channel only:

$$\mu(ZH \to \ell\ell cc) < 107\,@\,95\%\text{CL}$$



Current limit would look like this @ HL-LHC

Room for improvement!

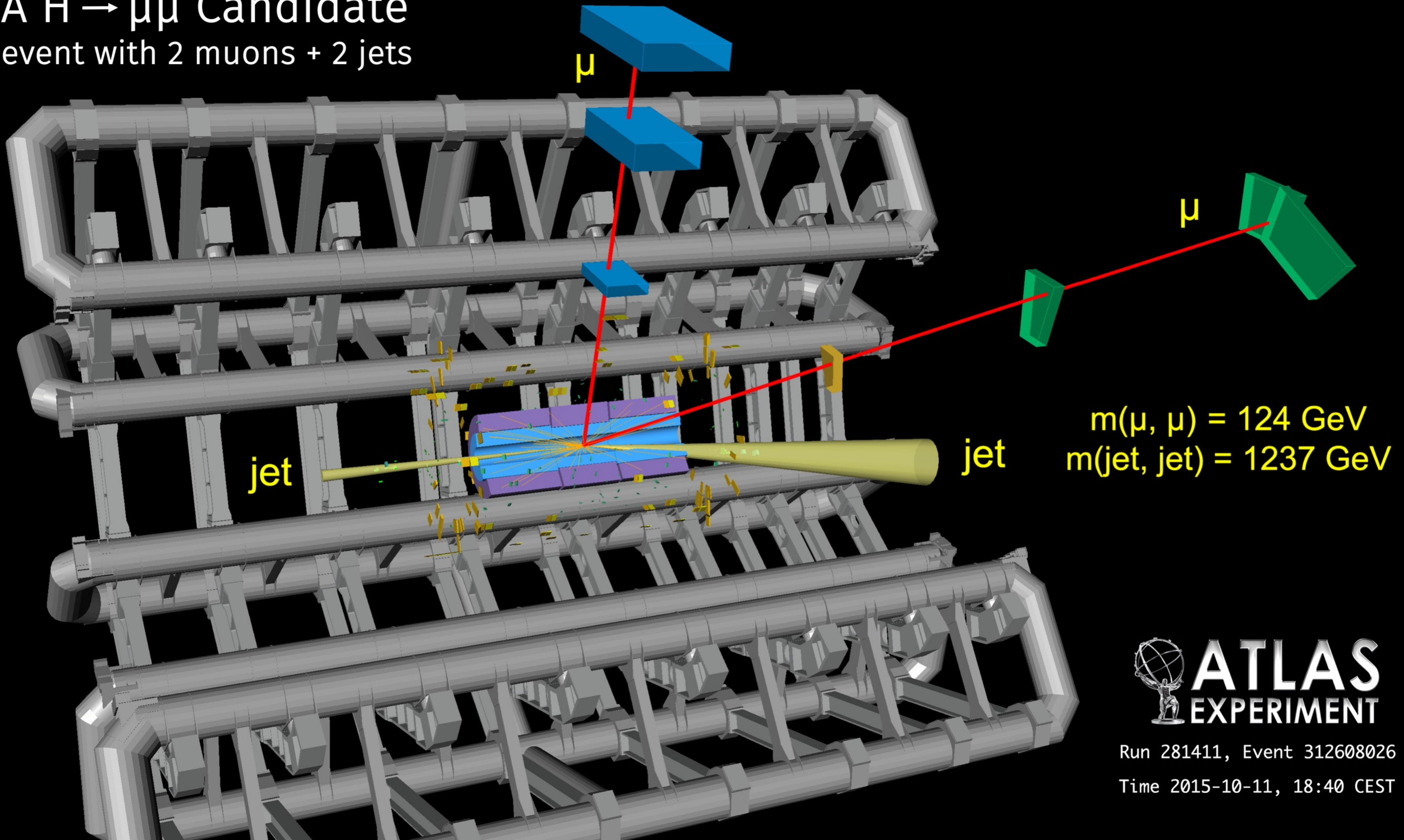
- Tagging
- Add channels
- Calibration
- Categorization

Observation at HL-LHC?

- Nikhef: Marko Stamenkovic, Hannah Arnold, Tristan du Pree

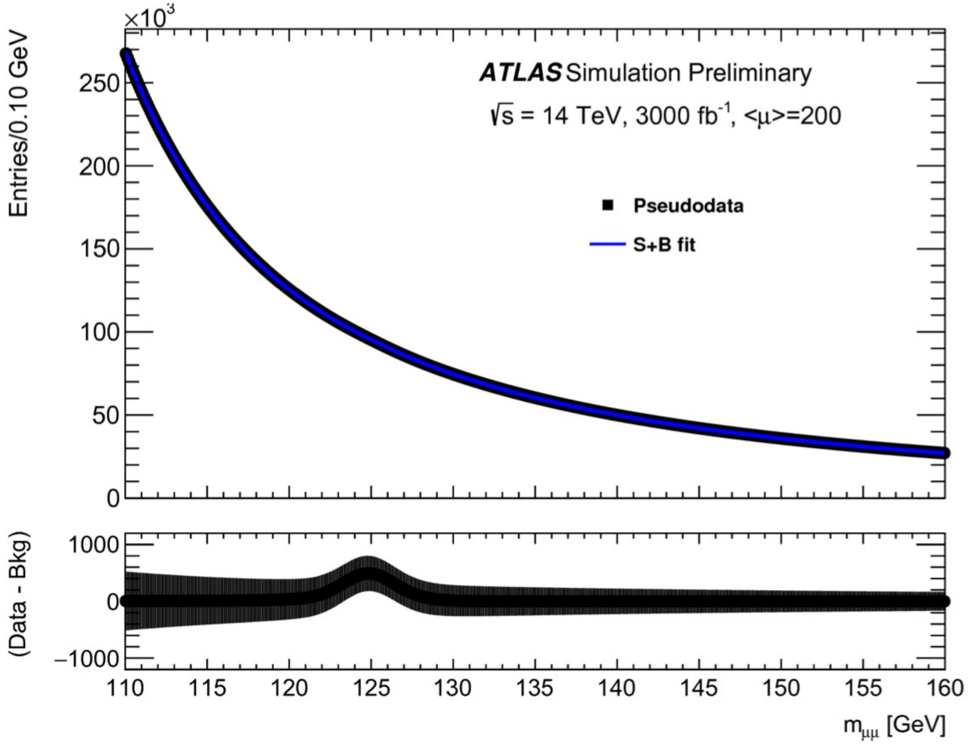
A $H \to \mu\mu$ Candidate

event with 2 muons + 2 jets



H → μμ

- Tiny branching ratio (0.02%) but very distinct signatures
- Searched for in gluon-fusion (ggF) and vector-boson fusion (VBF) as considered production mechanisms
- Current limits (using 80 fb^{-1}): $\mu < 2.1 \,@\, 95\%\mathrm{CL}$



Current improvements:

- Thorough test of background modelling functions
- Resolution improvement by smart event categorization

How close can we get?

- Full Run 2 dataset: $\mathbf{Z_{exp} \sim 2\,\sigma}$
- HL-LHC dataset: $\mathbf{Z_{exp} > 9\,\sigma}$

- Nikhef involvement: Alice Alfonsi, Wouter Verkerke

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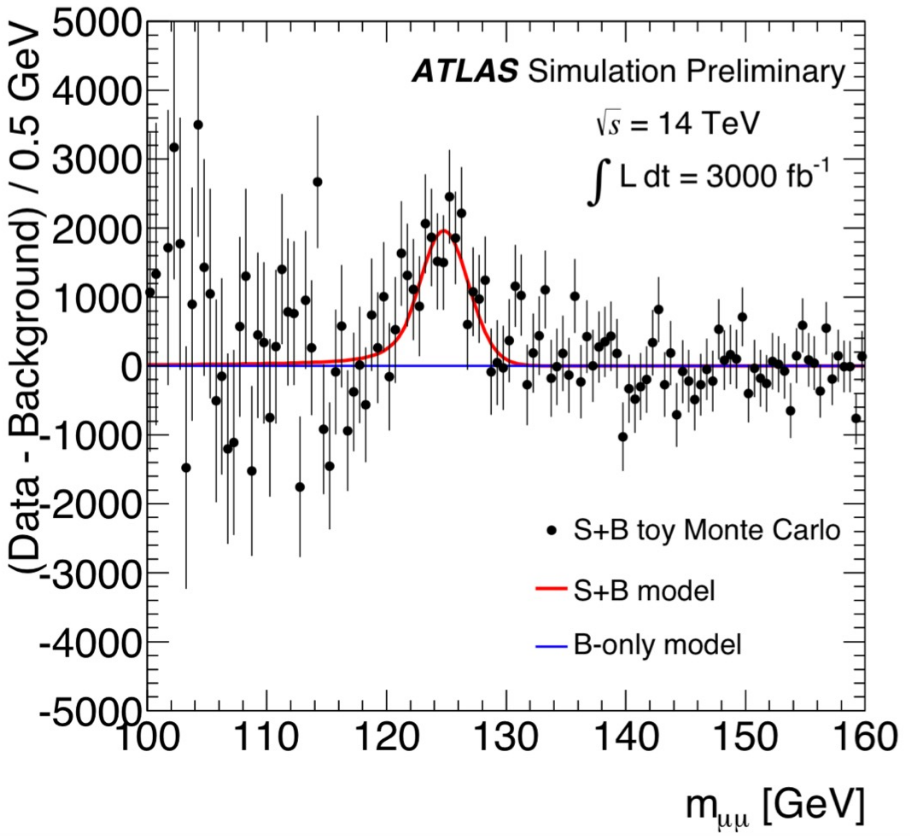

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The Higgs-fermion sector in the future

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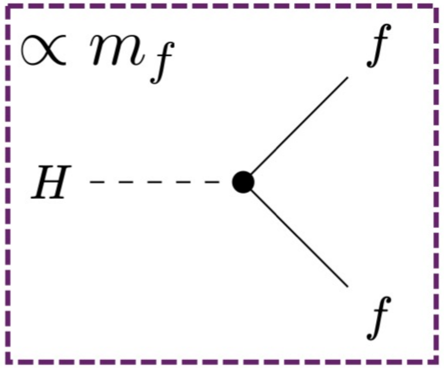
- ~~Similar coupling to up- and down-type quarks?~~



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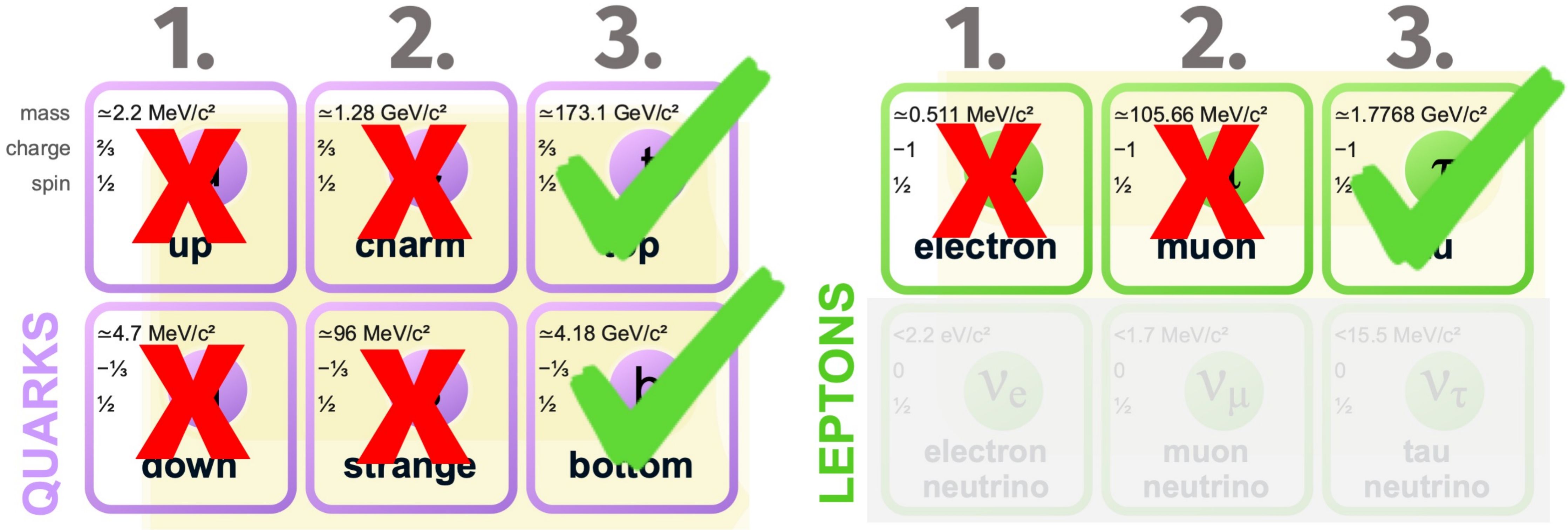

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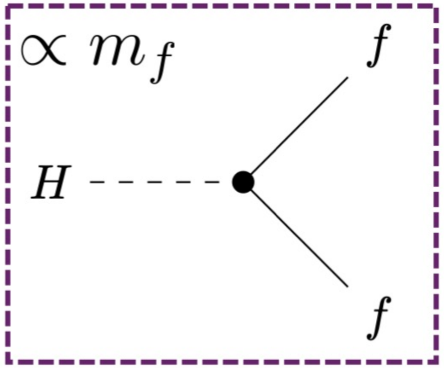
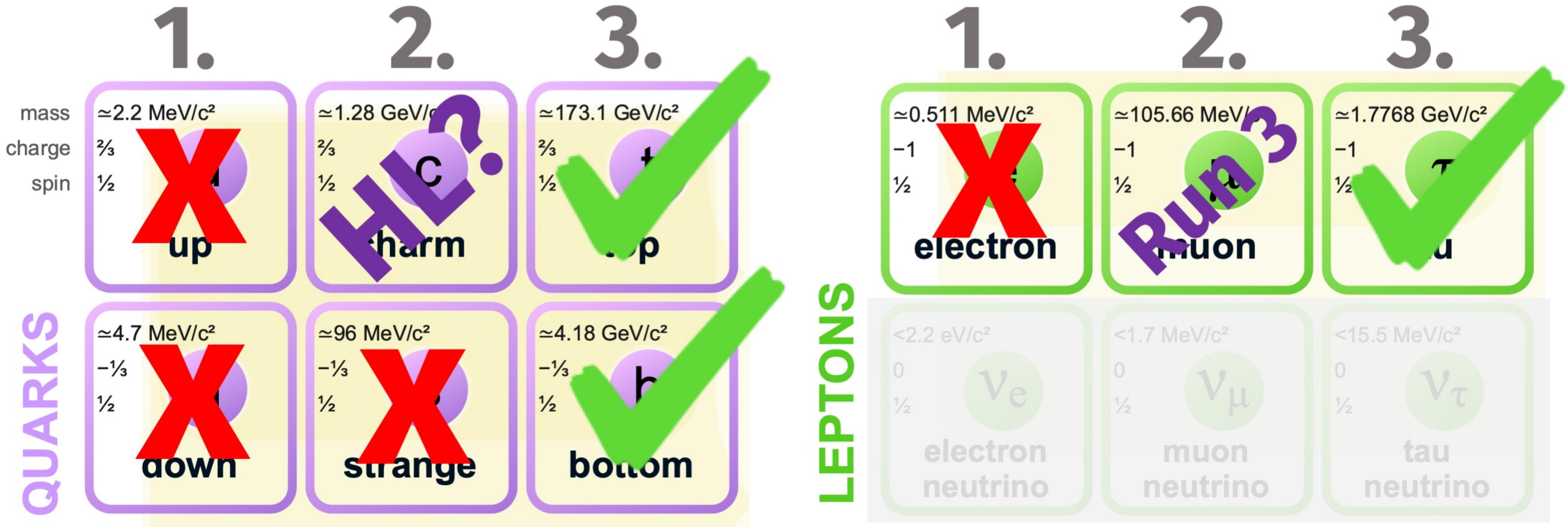


- Fir… …eneration?

2. gen. in reach



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Is this the end of the story?

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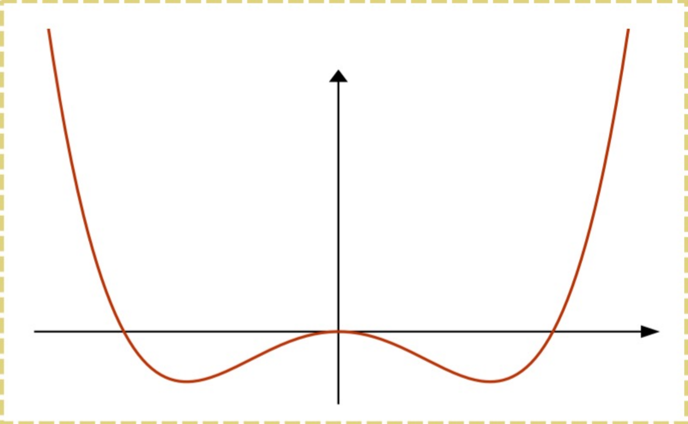

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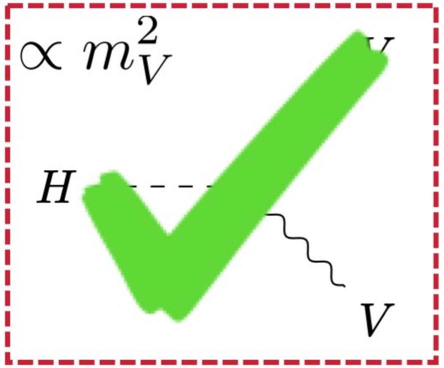
$|D_\mu \phi|^2$, $\lambda(\phi^\dagger\phi)^2$ → Higgs mechanism

$y_{ij}\psi_i\phi\psi_j + \text{h.c.}$ → Yukawa terms

Lucrezia's talk



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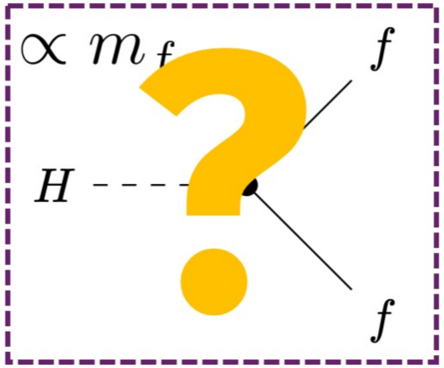

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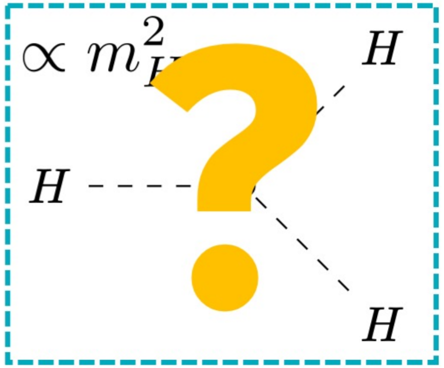

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→ Higgs mechanism

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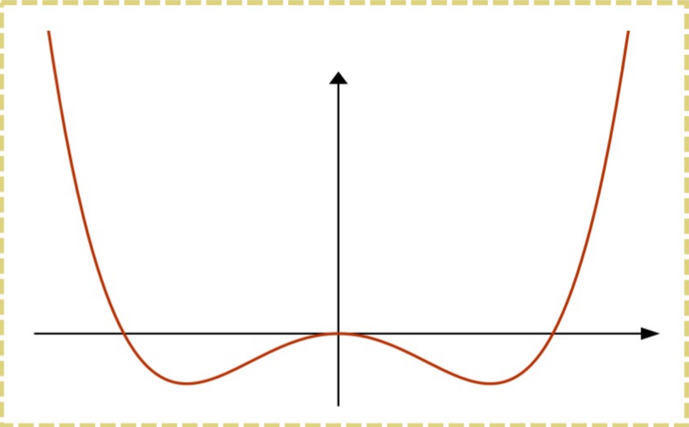

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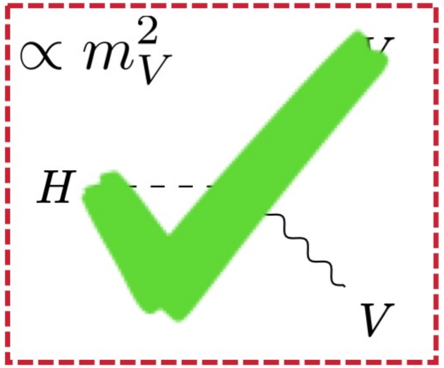

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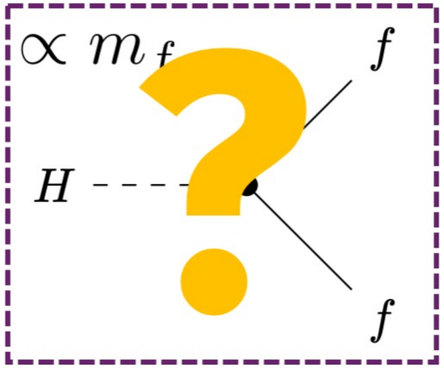
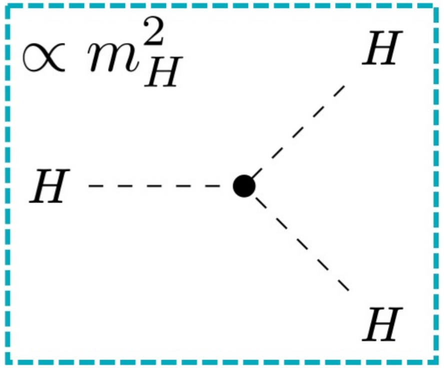
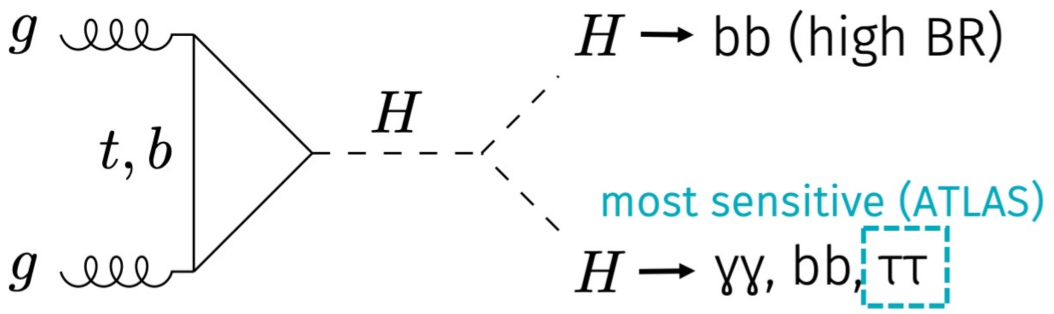


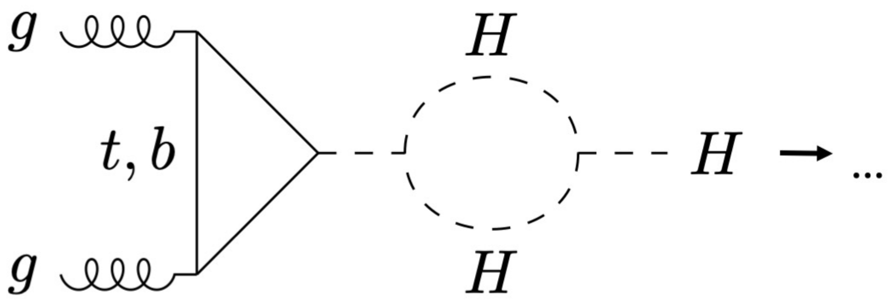


The Higgs boson self-coupling



direct search

vs.



loop contribution

Current results from direct search: $\kappa_\lambda = \lambda_{\mathrm{meas}}/\lambda_{\mathrm{SM}} \in [-5.0, 12.1]\,@\,95\%\,\mathrm{CL}$

- Models for EW baryogenesis usually require $\kappa_\lambda > 2$

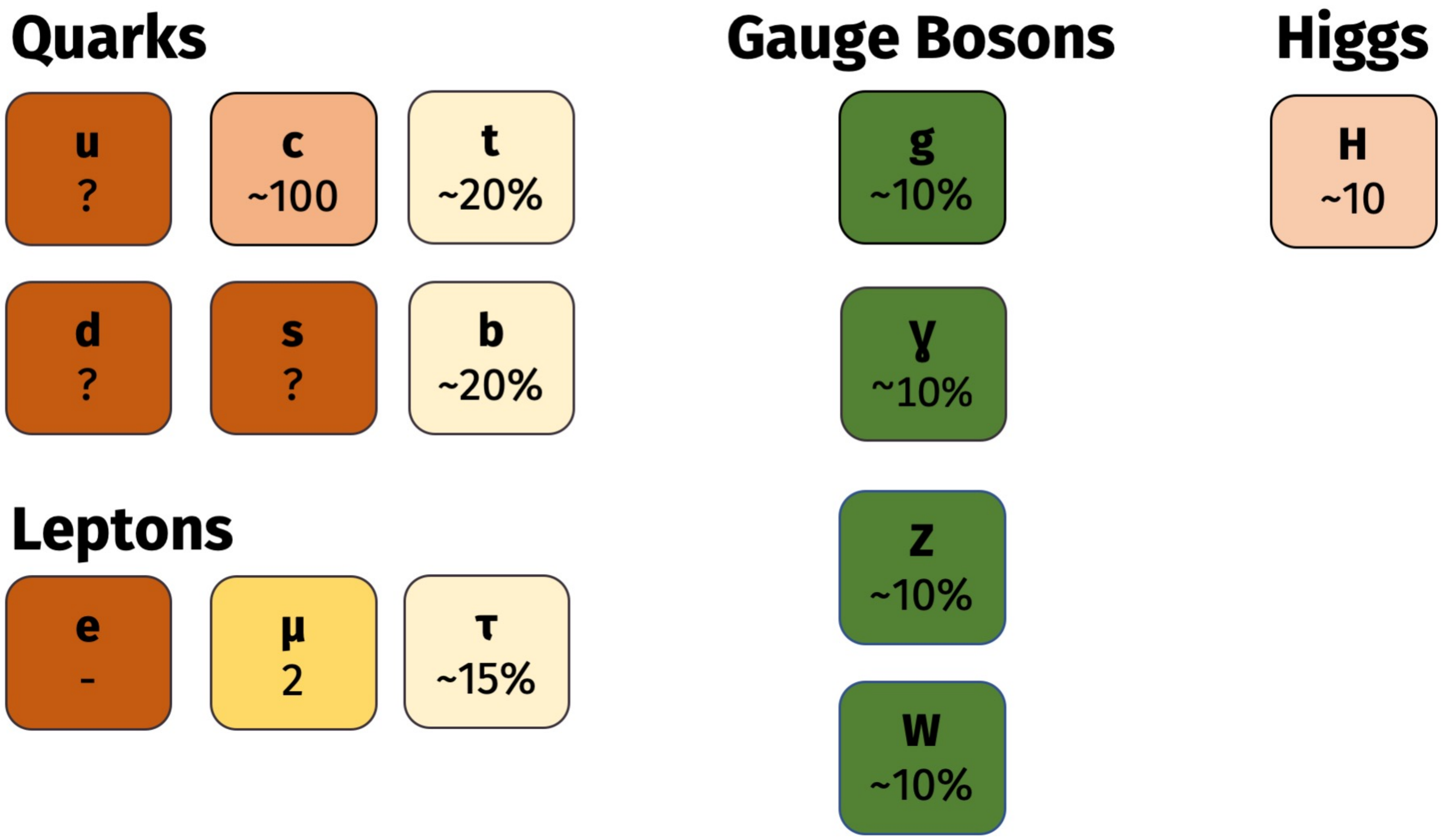
How far can we go?

- ATLAS direct search (end of HL-LHC): $\mathbf{Z_{exp} \sim 3\,\sigma}$
- CMS combination: $\mathbf{Z_{exp} \sim 4\,\sigma}$ ⟶ 50% unc. on κ_λ [0.5, 1.5]
- Observation by combining with indirect search?
- Nikhef: Pamela Ferrari, Bob van Eijk, Stefano Manzoni, Alessio Pizini

Precision as the ultimate probe for the Higgs sector

The LHC Higgs legacy

- Higgs couplings currently known (if already observed) with ~ 10% (~ bosons) to 20% (~ fermions) precision



Uncertainties on leading-order coupling modifiers κ

The LHC Higgs legacy

- Higgs couplings currently known (if already observed) with ~ 10% (~ bosons) to 20% (~ fermions) precision ⟶ where can we go with the HL-LHC?

Quarks

u ?	**c** O(1)	**t** 4%
d ?	**s** ?	**b** 4%

Leptons

e -	**μ** 7%	**τ** 3%

Gauge Bosons

g 3%
γ 3%
Z 2%
W 2%

Higgs

H 50%

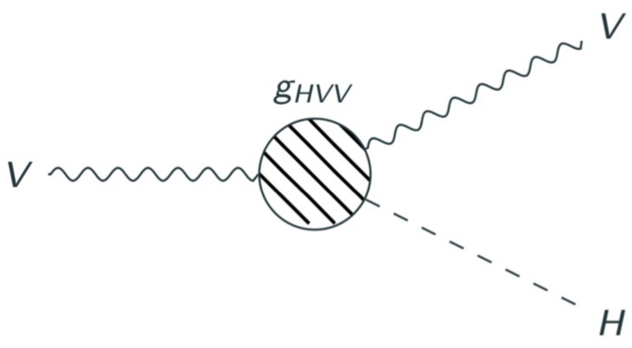
Uncertainties on leading-order coupling modifiers κ

Using the Higgs sector as a BSM portal?

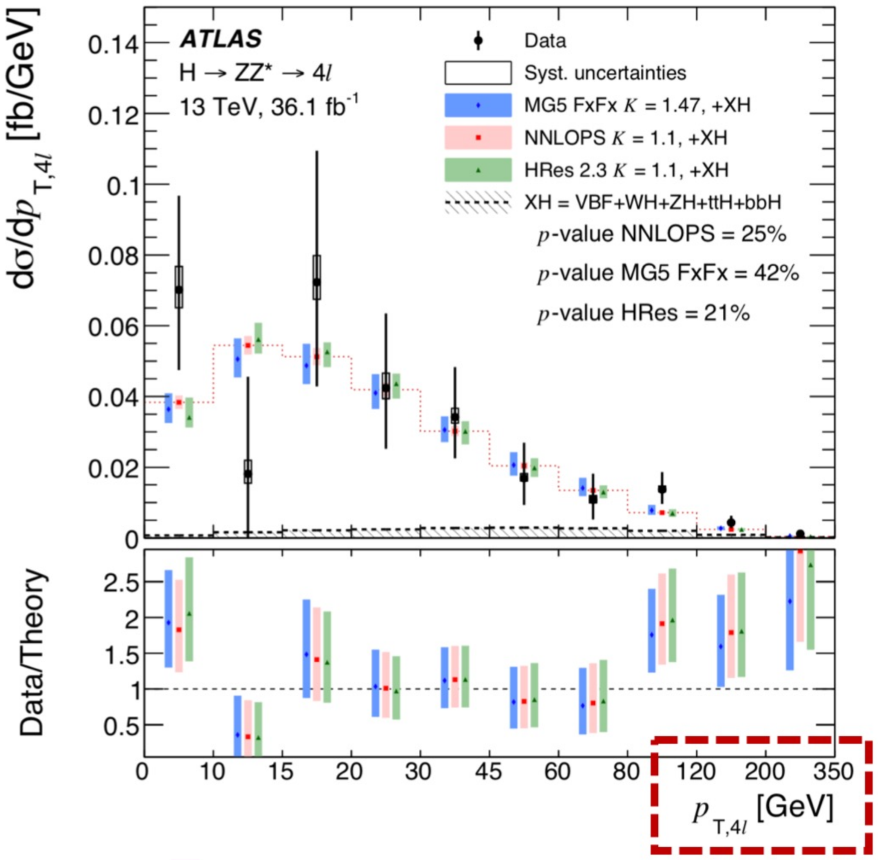
$H \rightarrow bb$: Targeting boosted regimes

- Probing the corners of the phase space: ultra high p_T Higgs bosons

- EFT approach to search for new physics

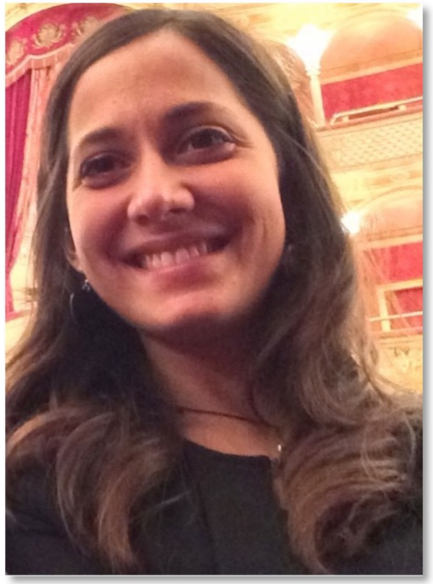


$$\propto \mathrm{SM} + c \times \left(\frac{p_T}{\Lambda}\right)^2$$



Use H → bb

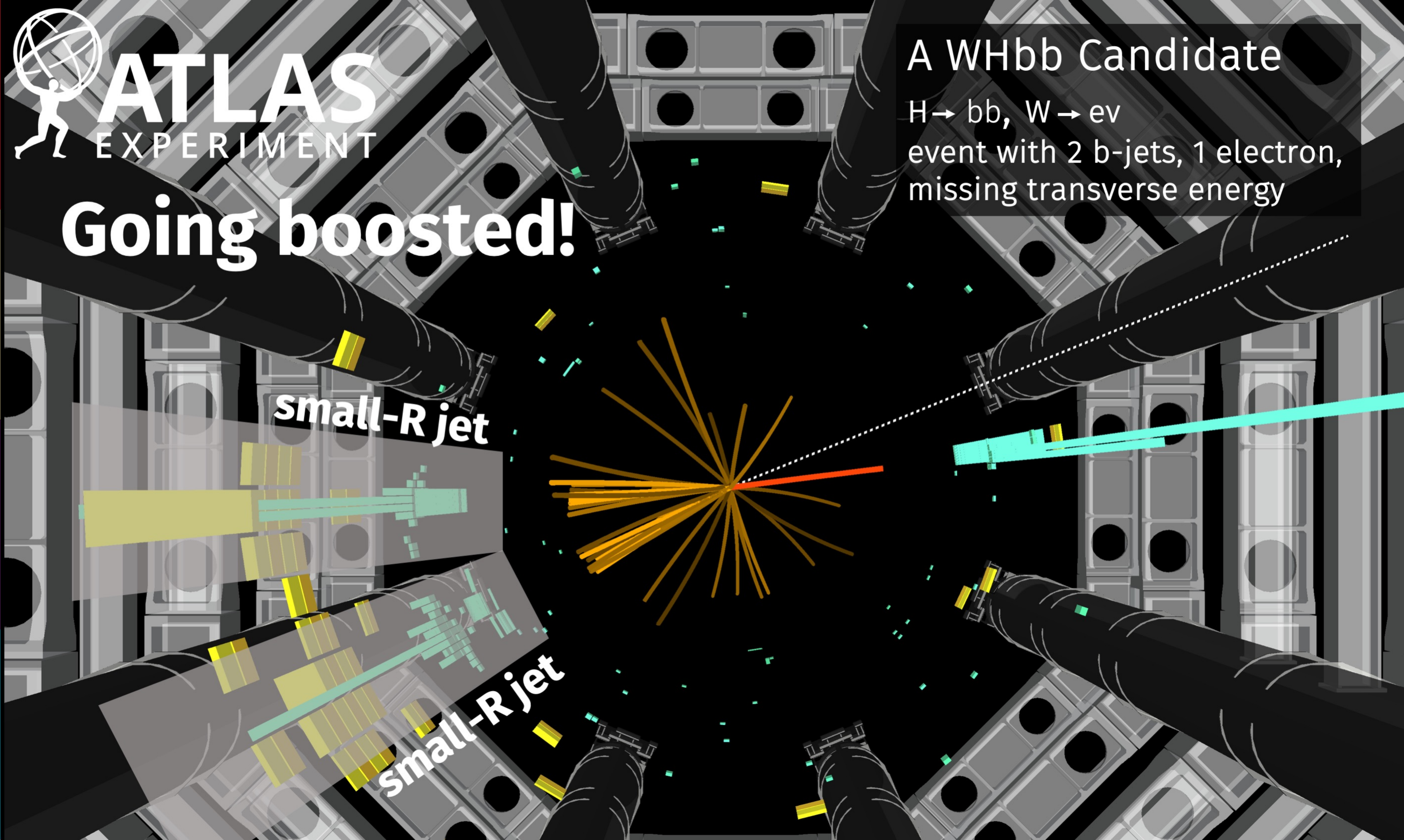
- Nikhef involvement: Tristan du Pree, Hannah Arnold, Frank Filthaut, Nicolo de Groot, Veronica Fabiani, BM

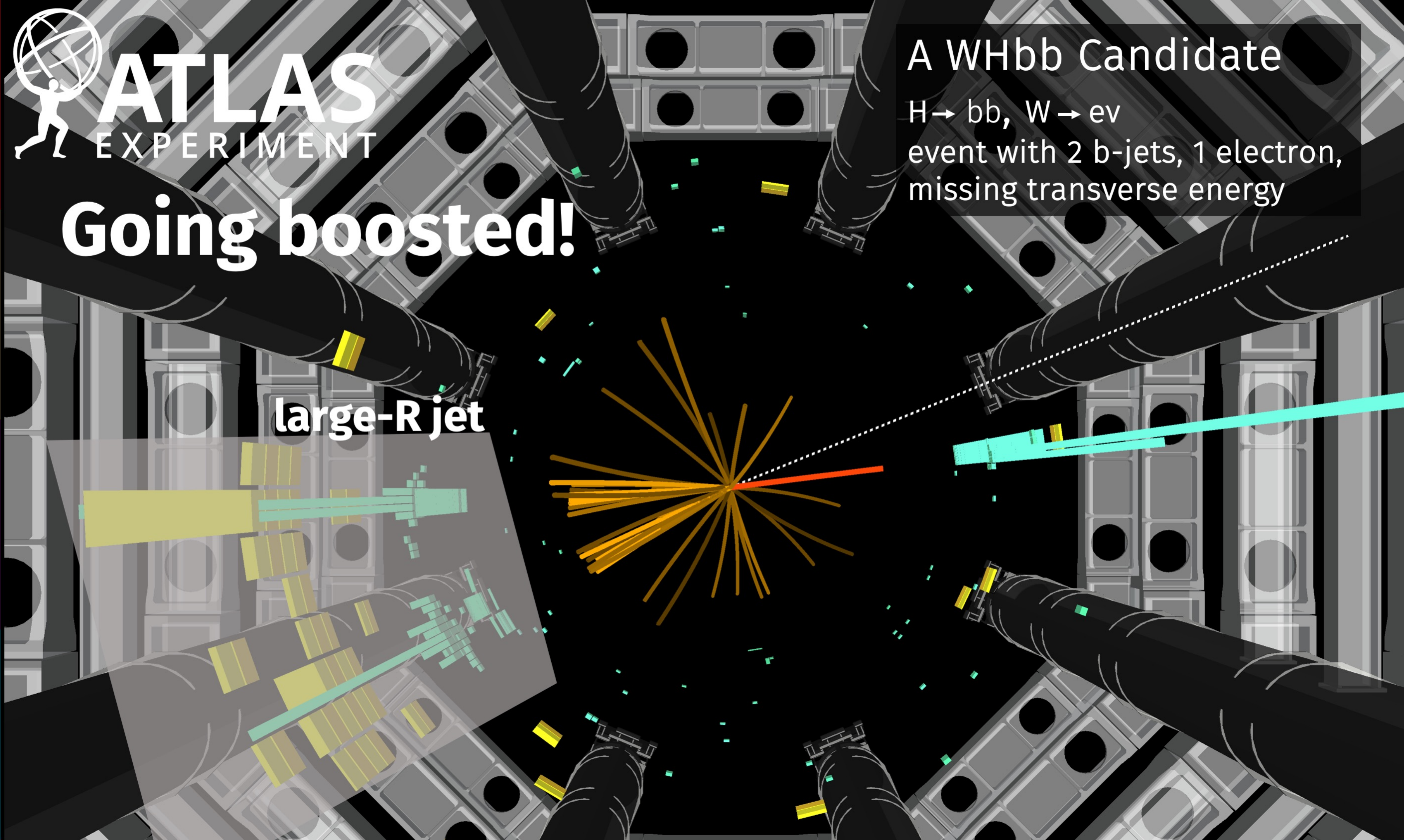


Going boosted!

A WHbb Candidate

$H \rightarrow bb$, $W \rightarrow e\nu$
event with 2 b-jets, 1 electron, missing transverse energy

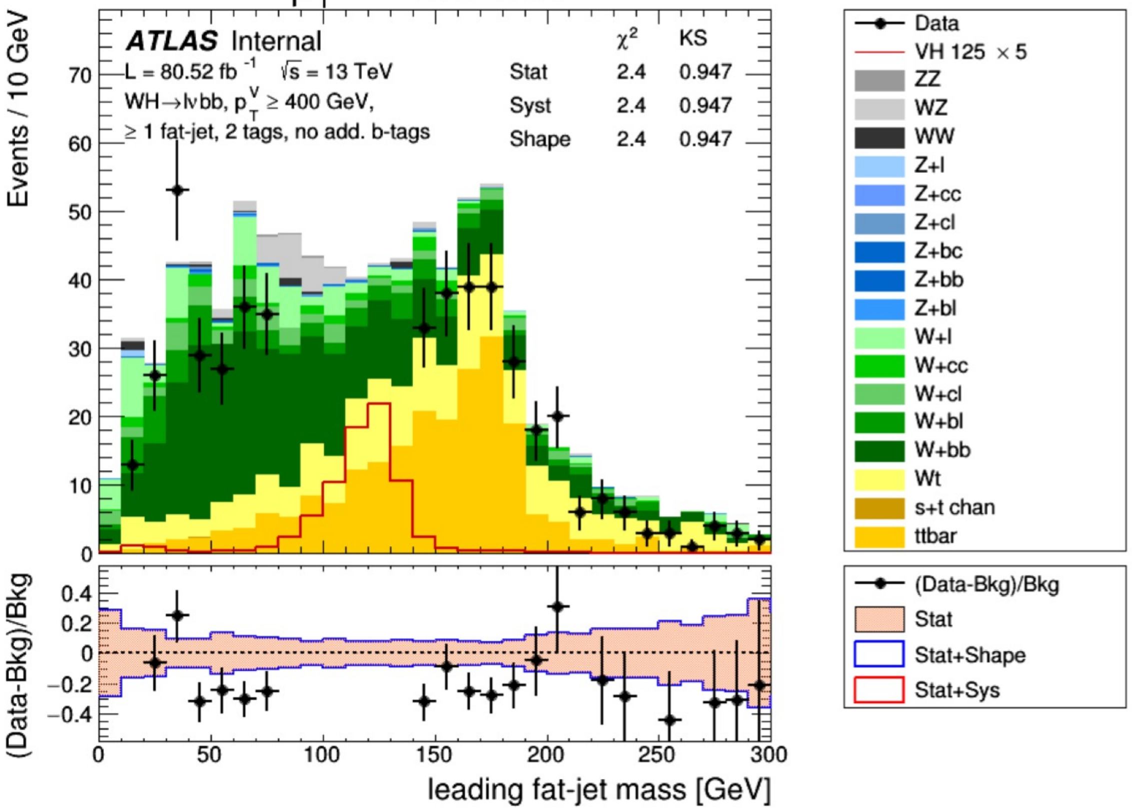


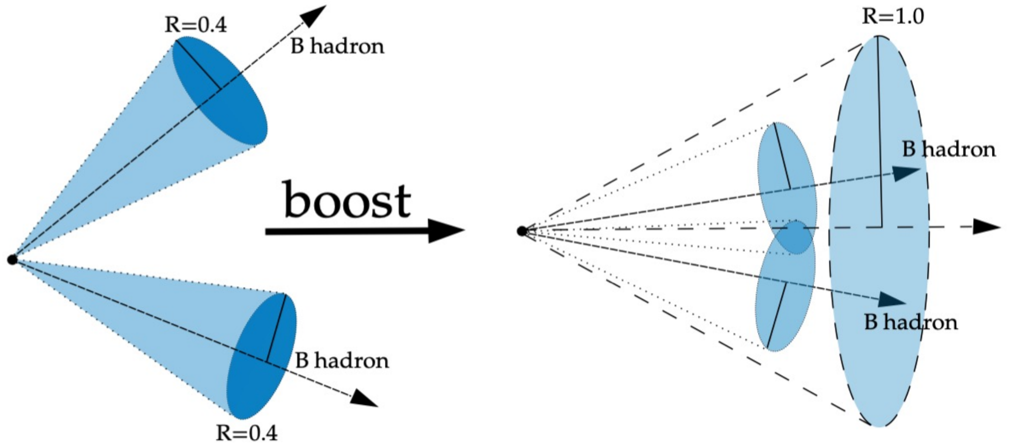

ATLAS
EXPERIMENT
Going boosted!
A WHbb Candidate
H→ bb, W → eν
event with 2 b-jets, 1 electron,
missing transverse energy
large-R jet

Boosted H→bb: A first look

- Special reconstruction techniques as the two b-jets from the Higgs decay start to merge at p_T^{Higgs} ~ 625 GeV ⟶ reconstruct both in one large-R jet

p_T^V > 400 GeV





- Full Run-2: **~ 2.5 σ for p_T^V > 400 GeV**

A brief closing remark

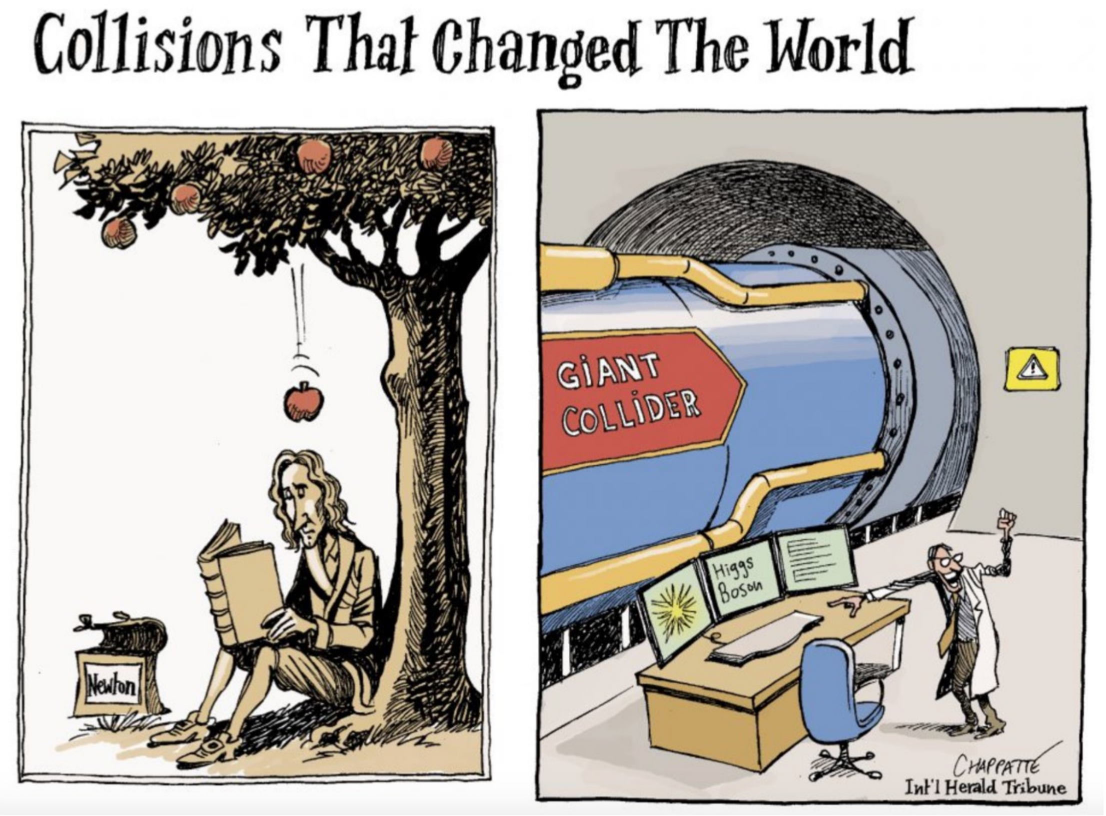
- 2018: Year of the Higgs couplings:
  - Couples directly to quarks
  - Couples similarly to up- and down-type quarks (prop. to their mass)

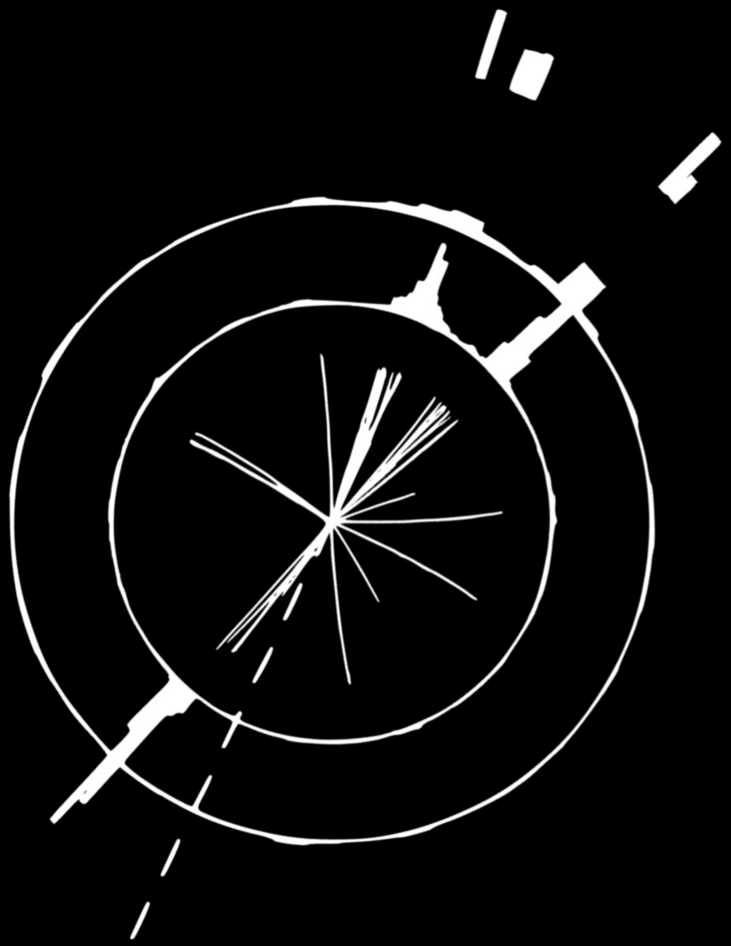
- Nikhef played/plays (and has to play) a vital role in Higgs physics

- Getting in reach of second generation couplings (what about the first?)

- Precision in the Higgs sector can and must be used as a portal for BSM physics

Exciting times ahead – stay tuned!





Backup

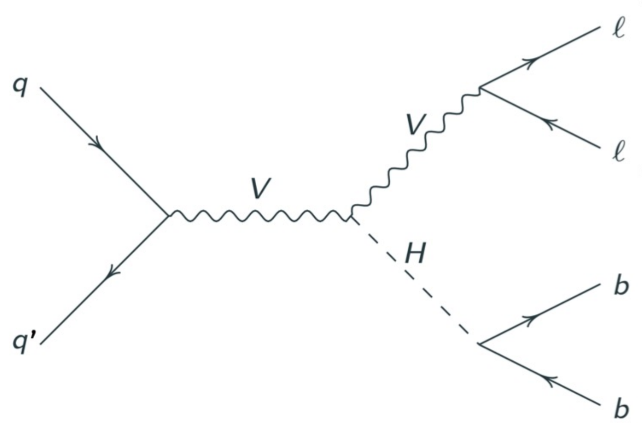
Why to care about the bottom Yukawa?

- Heaviest particle, the Higgs boson can decay to at rest ⟶ it will do so in **~ 58%** of all times
- Largest contribution to the total Higgs width (affects all branching ratios)
- Best chance to observe the Higgs coupling to a down-type quark

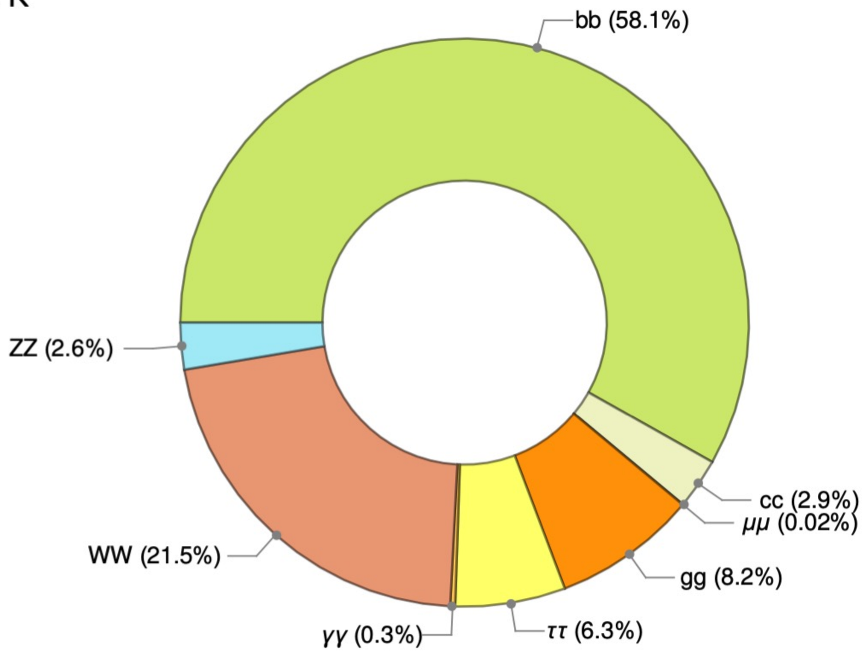
The difficulty:

- Looking for a hadronic signature at a hadron collider ☹
- Pairs of b-quarks are produced O(10^7) times more often than Higgs bosons ☹

⟶ Consider production in **association with a leptonically decaying vector boson** to get inimitable and clean detector signatures ☺



Split final states according to **charged lepton multiplicity** (0, 1 or 2)



Higgs boson branching ratios

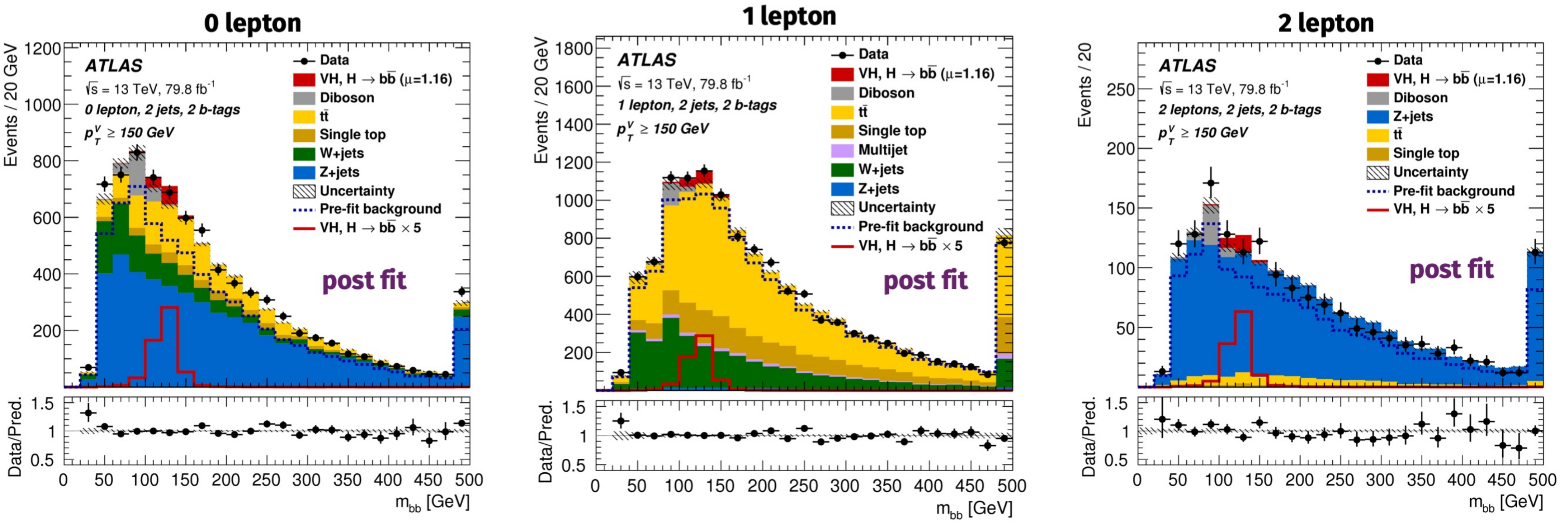
The search for (VH)H→bb

- Most discriminant variable: Invariant di-jet mass $\mathbf{m_{bb}}$ (peaks at the nominal Higgs mass)
- First **observation** (combining with other production channels) in September, analyzing all data collected up to 2017, with a signal strength of

$$\mu = \frac{[\sigma(VH) \times \mathrm{BR}(H \to bb)]_{\mathrm{meas}}}{[\sigma(VH) \times \mathrm{BR}(H \to bb)]_{\mathrm{SM}}} = 1.16 \pm 0.16(\mathrm{stat.})^{+0.21}_{-0.19}(\mathrm{syst.})$$

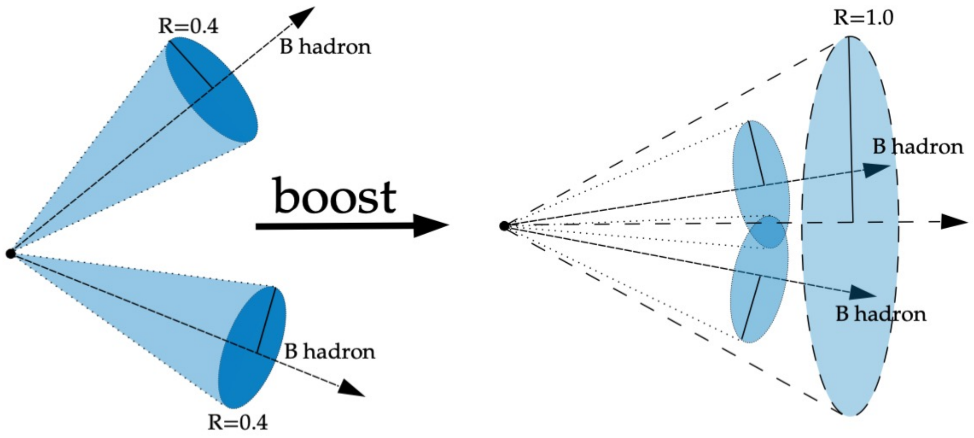
Limiting factors:

- Theor. signal uncertainties (50%), background modelling (50%), b-tagging uncertainties (35%)

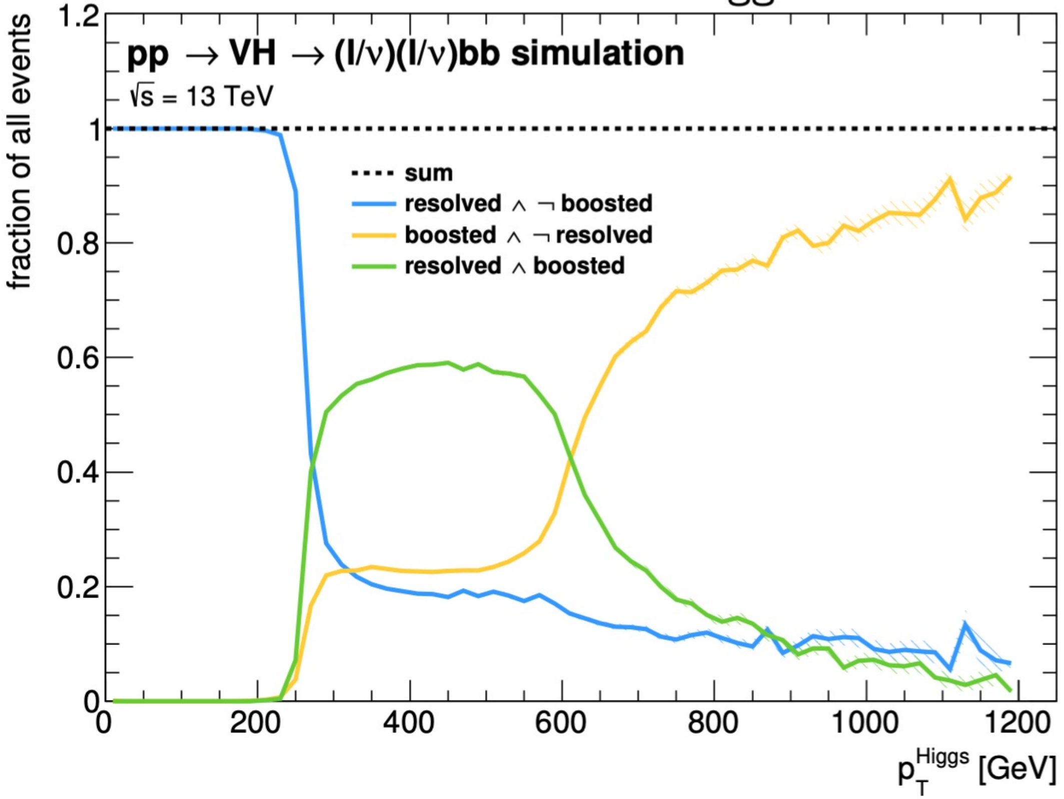


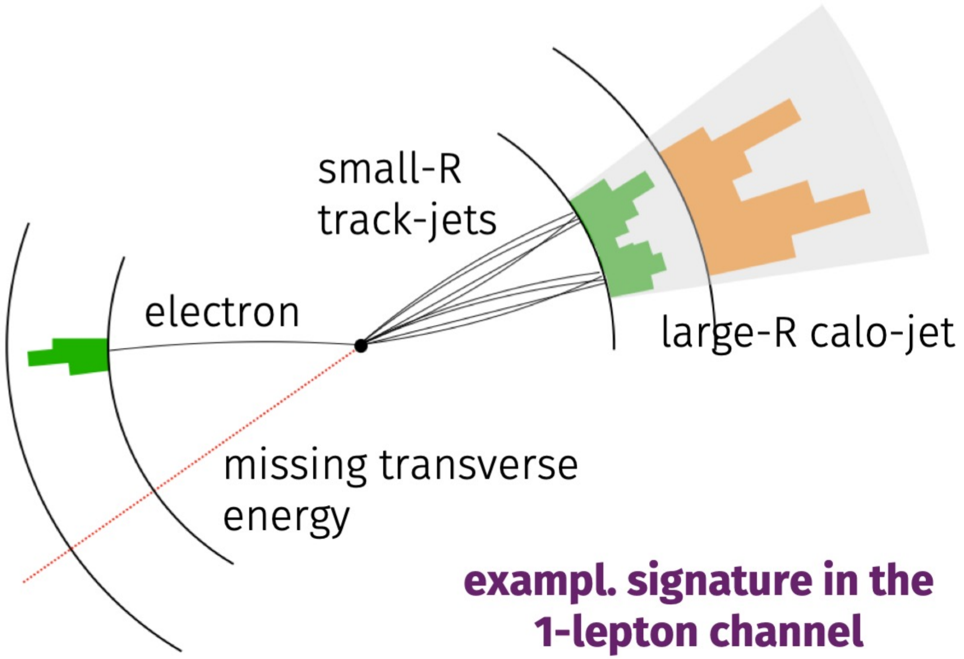
H→bb: Targeting boosted regimes

- Large dataset allows to look at phase spaces of very large momentum transfer (high Higgs p_T)
- These require special reconstruction techniques as the two b-jets from the Higgs decay start to merge at p_T^{Higgs} ~ 625 GeV ⟶ reconstruct both in one large-R jet



How to reconstruct the Higgs boson?





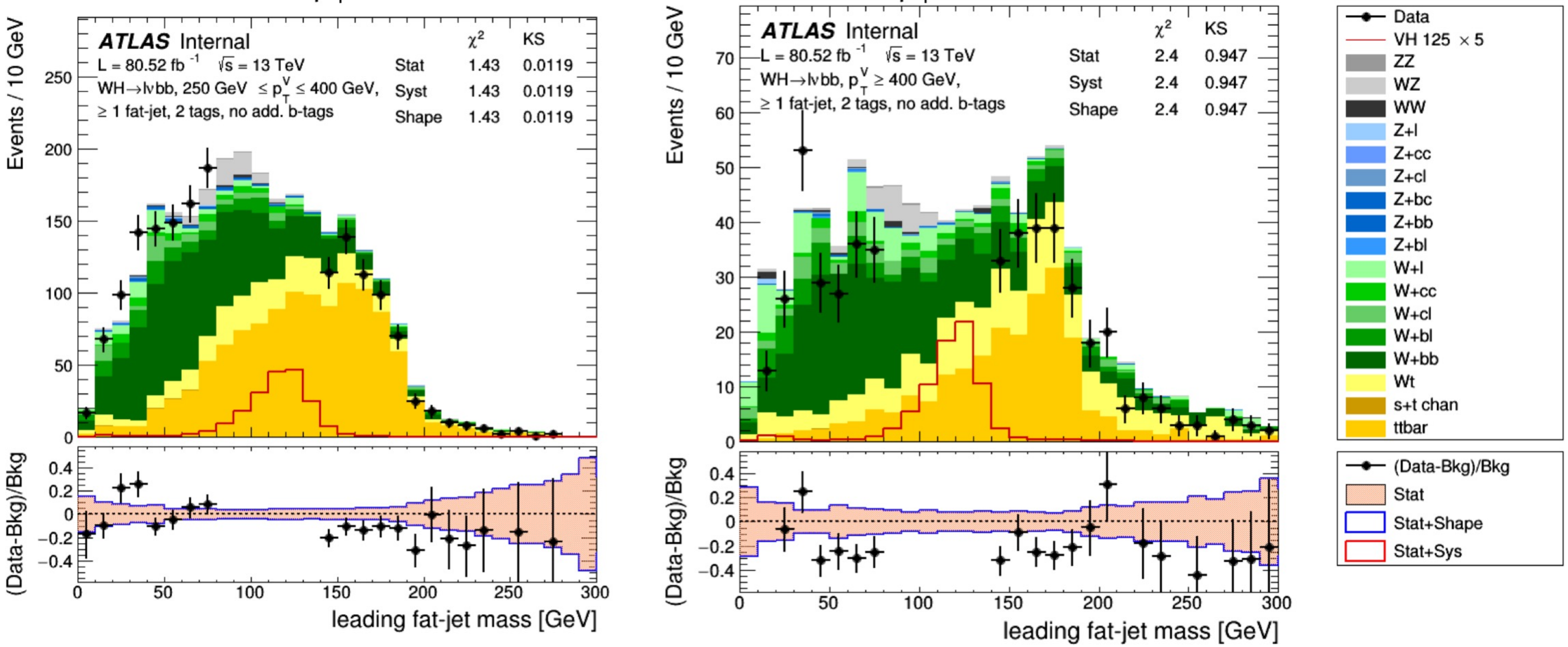
exampl. signature in the 1-lepton channel

Boosted H→bb: An exemplary look at the 1-lepton channel

- Shown: Higgs candidate mass for different W boson p_T ranges; signal scaled by a factor of 5

250 GeV < p_T^V < 400 GeV

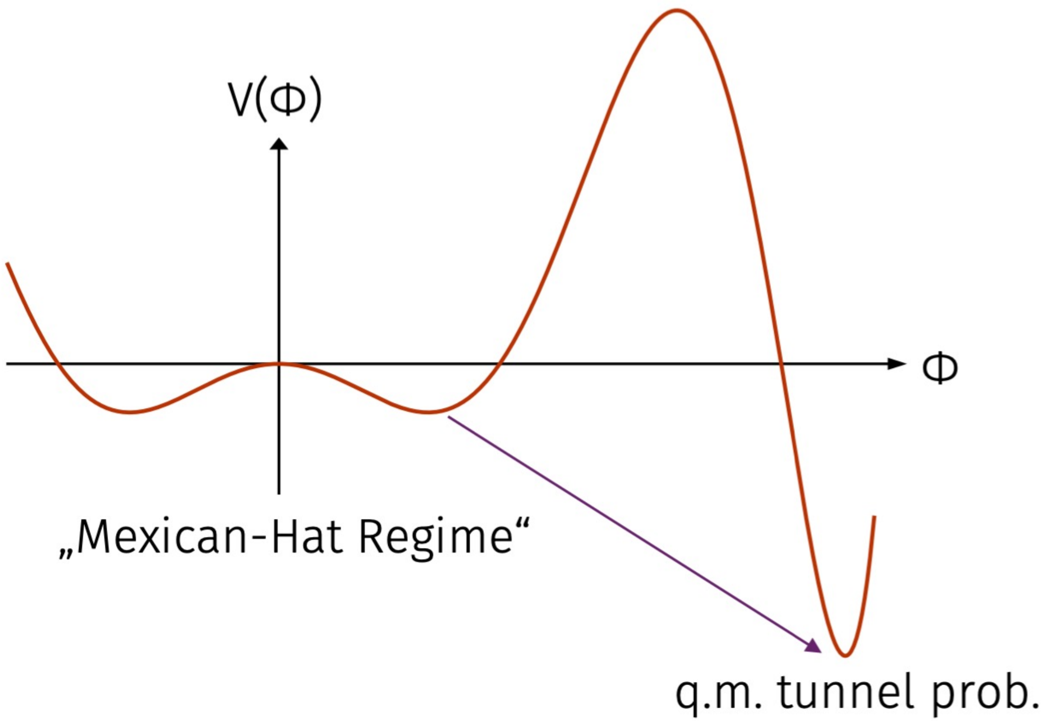
p_T^V > 400 GeV

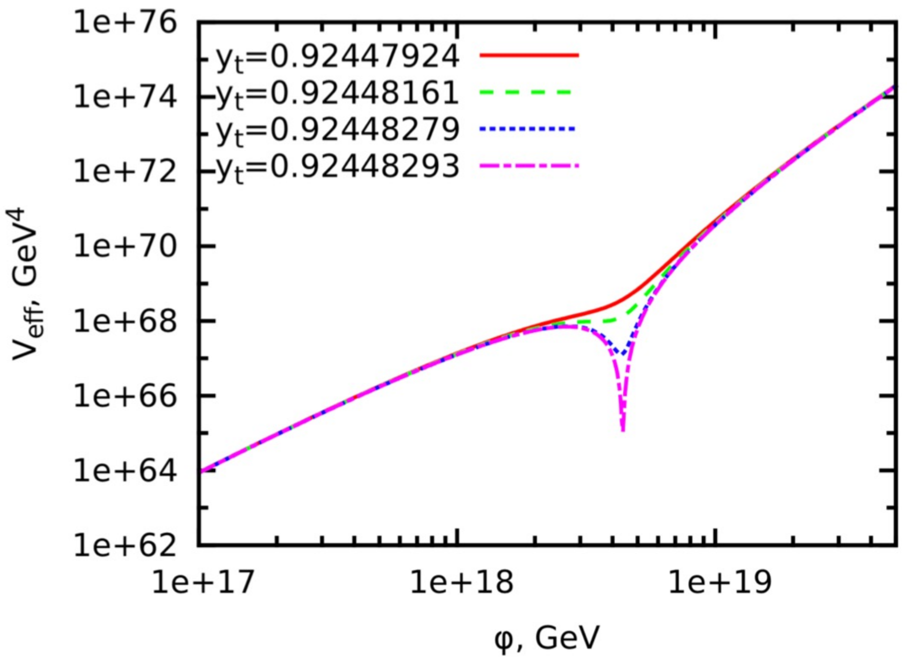


- Main backgrounds: W+jets and ttbar (no substructure information used; improvement in c-rejection?)
- Diboson peak nicely visible ⟶ boosted VV?
- Looks very promising

Why to care about the top Yukawa?

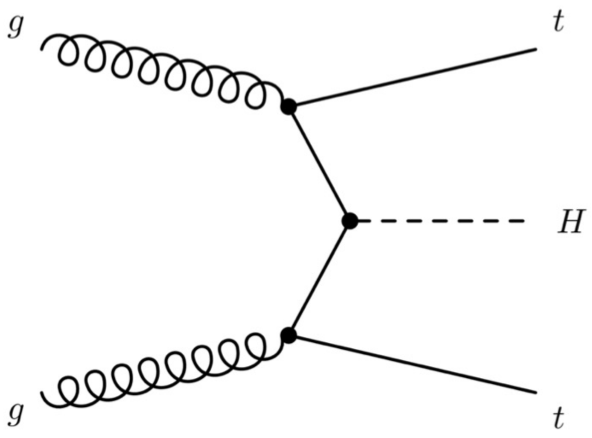
- Despite not being a TOE, the SM itself is a self-consistent QFT up to the QED Landau pole at $O(10^{286}\ \mathrm{eV})$
- Currently, no clear sign where the scale of new physics should be
- Define an energy scale where the SM becomes theoretically inconsistent or contradicts observations?
- EW vacuum stability dominated by the interplay of the Higgs- and the top-mass (RGE for λ)
- With the given configurations, we live in a meta stable universe, but a tiny change in y_t has drastic effects on the lifetime ⟶ measure it!



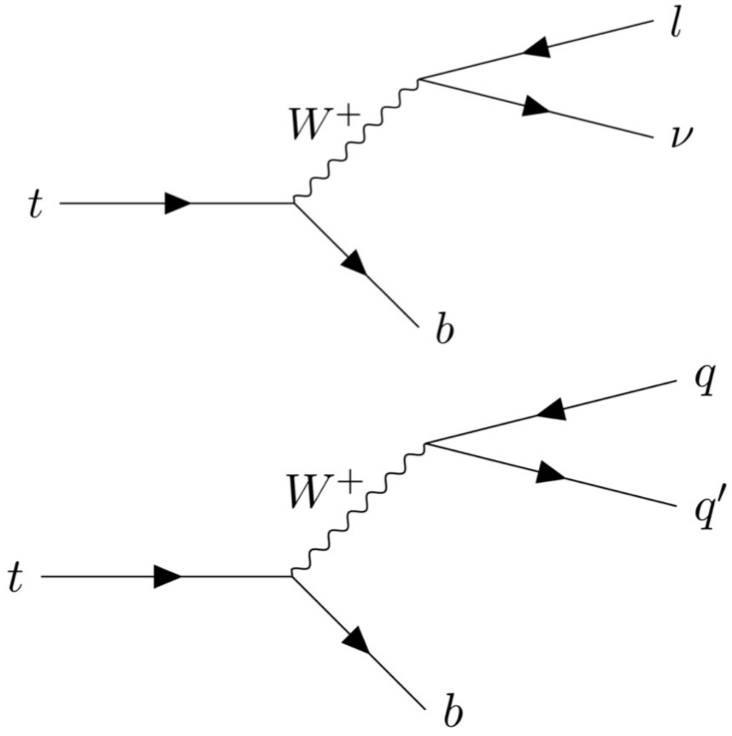


The search for ttH

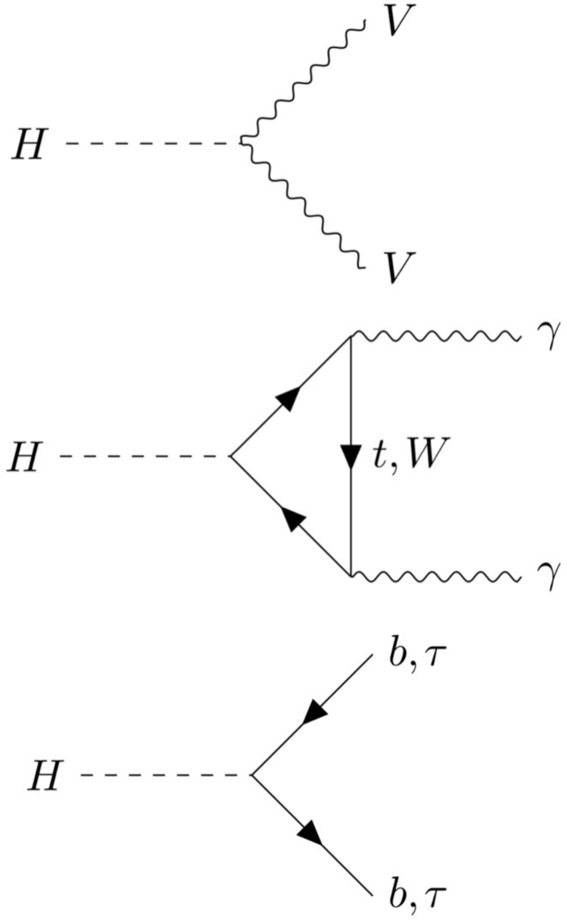
- Lot’s of combinatorics to exploit: Multiple possible top- and Higgs-decay channels to look at
- Each channel has its pros and cons ⟶ combine them in a simultaneous likelihood fit



ttH production



top-decays



Higgs-decays

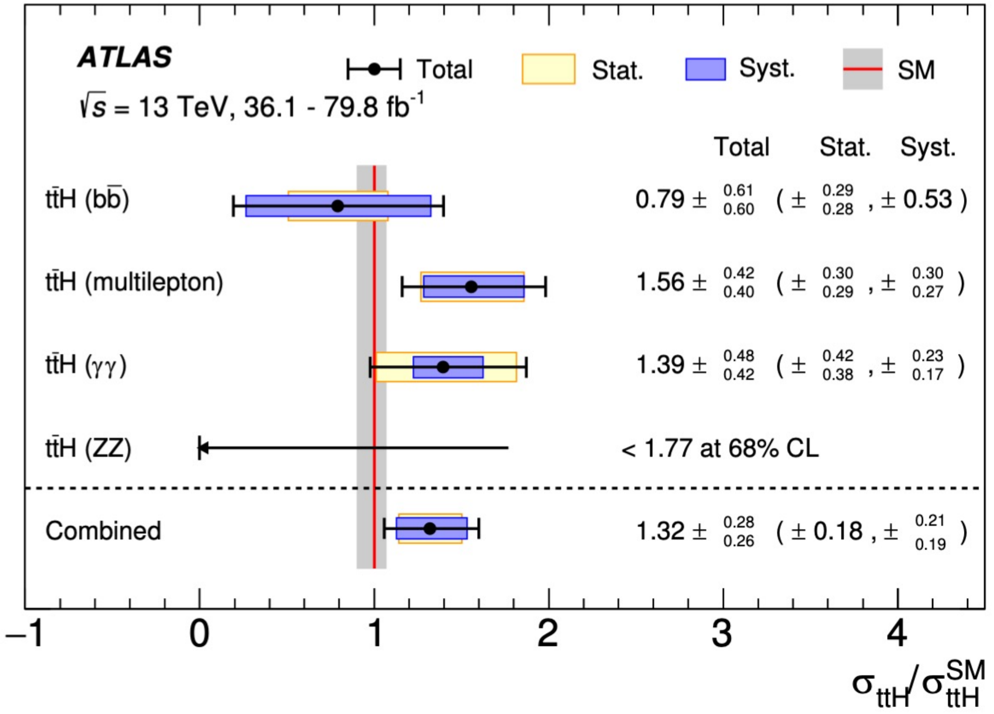
The search for ttH

- Lot's of combinatorics to exploit: Multiple possible top- and Higgs-decay channels to look at
- Each channel has its pros and cons ⟶ combine them in a simultaneous likelihood fit

Analysis	Integrated luminosity [fb^{-1}]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	4.1 σ	3.7 σ
$H \to$ multilepton	36.1	4.1 σ	2.8 σ
$H \to b\bar{b}$	36.1	1.4 σ	1.6 σ
$H \to ZZ^* \to 4\ell$	79.8	0 σ	1.2 σ
Combined (13 TeV)	36.1–79.8	→ 5.8 σ	4.9 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	6.3 σ	5.1 σ

$$\sigma_{\text{meas.}} = 670 \pm 90(\text{stat.})^{+110}_{-100}(\text{syst.})\ \text{fb}$$

$$\sigma_{\text{pred.}} = 507^{+35}_{-50}\ \text{fb}$$ @NLO QCD + EW



Limiting factors:

- Theor. uncertainties on ttH production (40%) and tt+heavy flavor backgrounds (65%)
- Estimation of the fake-lepton contribution (35%)
- Jet/E_T^{miss} uncertainties (35%)

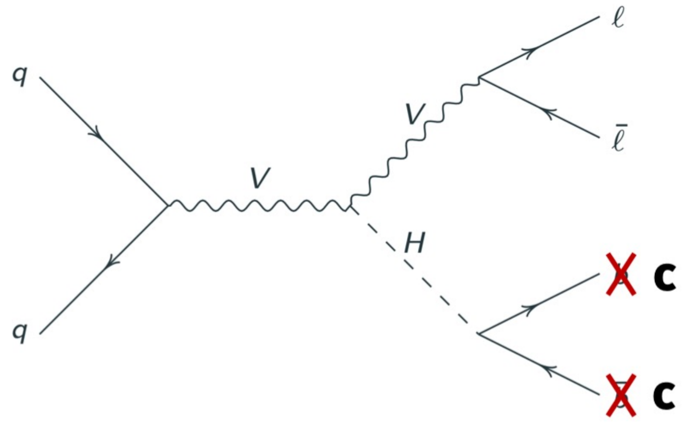
Second-generation quark-coupling: H→cc

- Direct search similar to the (VH) H ⟶ bb (exchange b for c)
- Analysis using 2015 and 2016 dataset, 2-lepton channel only:

$$\mu(ZH \to \ell\ell cc) < 107\,@\,95\%\mathrm{CL}$$

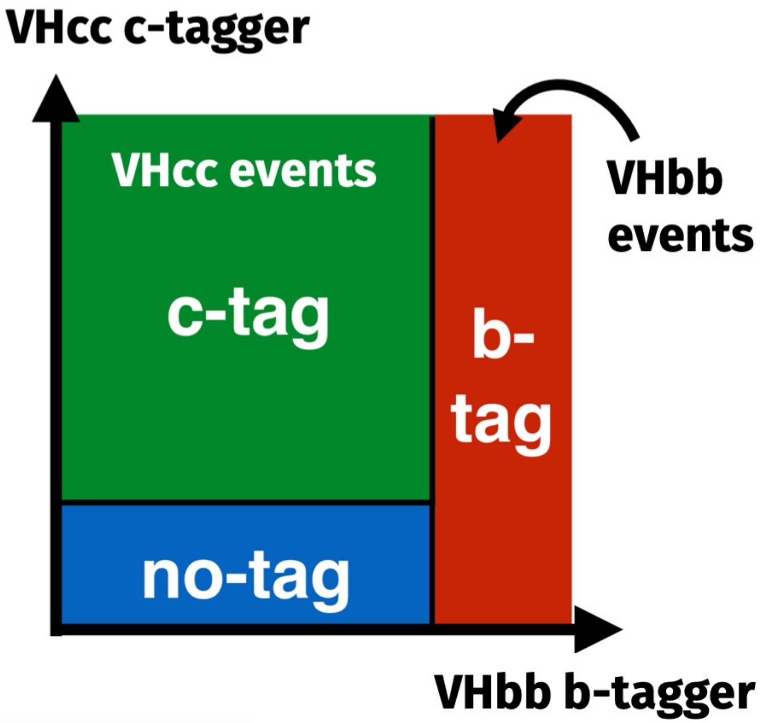
- Similarity to VHbb calls for a orthogonal treatment and a possible combination
  ⟶ change of tagging paradigm needed (2D flavor tagger)

- charm tagging still in its baby shoes
  ⟶ active field of research and room for improvement



Limiting factors:

- Flavor tagging (75%), statistics (50%) and background modelling (50%)



Higgs-charm coupling at HL-LHC:

- Expected (conservative) limit: μ < 6.3 @ 95% CL (compared to μ < 15 from J/Υ+ɣ decays)

Higgs coupling to muons

- Tiny branching ratio (0.02%) but very distinct signatures
- Searched for in gluon-fusion (ggF) and vector-boson fusion (VBF) as considered production mechanisms
- Signal and background modelled using analytical functions (crystal-ball for bkg. and gaussian for signal)
- Current limits (using 80 fb^{-1})

$$\mu < 2.1 \,@\, 95\%\mathrm{CL}$$

Limiting factors:

- Data statistical uncertainties (by far)

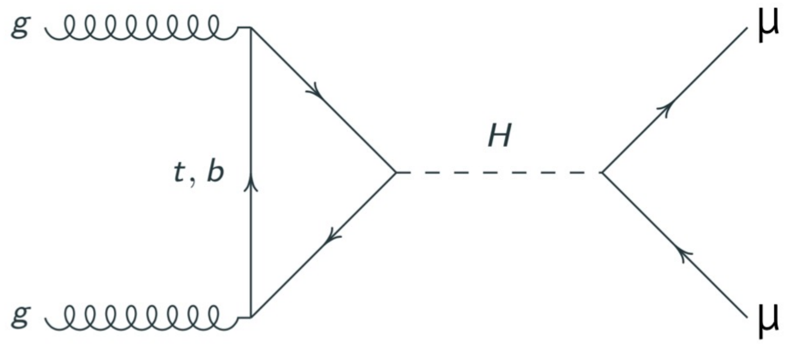
Current improvements:

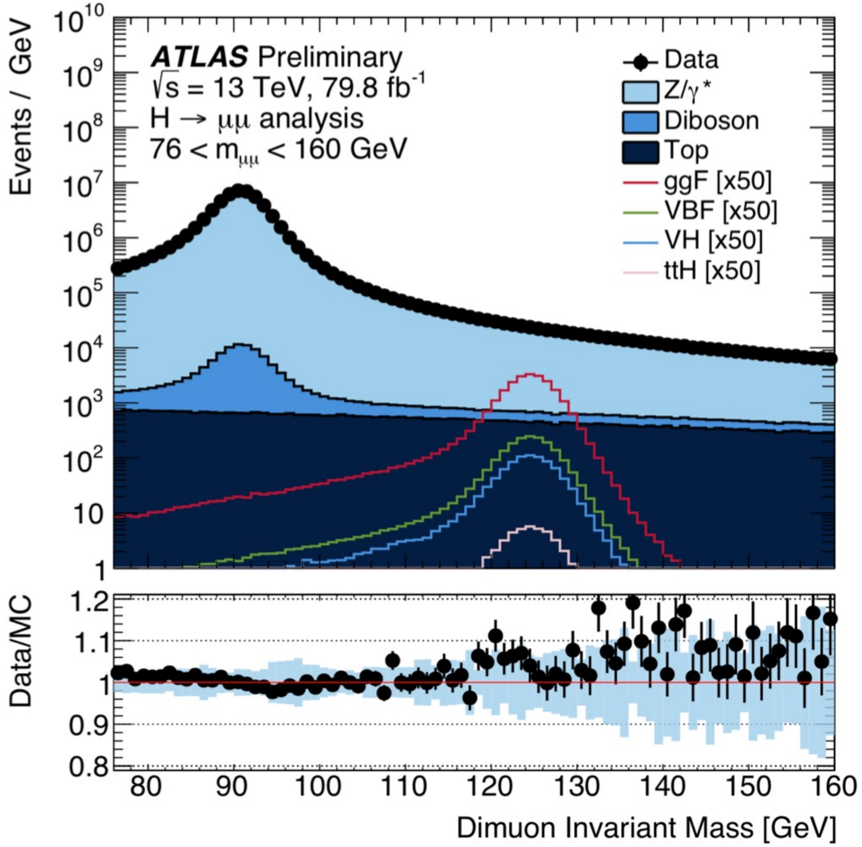
- Thorough test of background modelling functions
- Resolution improvement by smart event categorization

Higgs-muon coupling at HL-LHC

- Huge improvements as currently stat. limited analysis
- Observation with stat. significance > 9 σ expected

exampl. diagram for ggF production



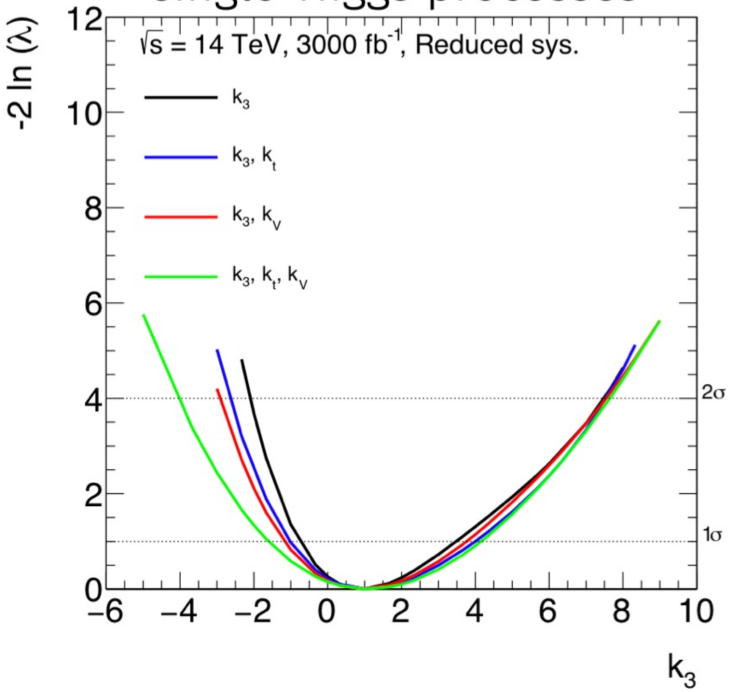


Higgs boson self-coupling

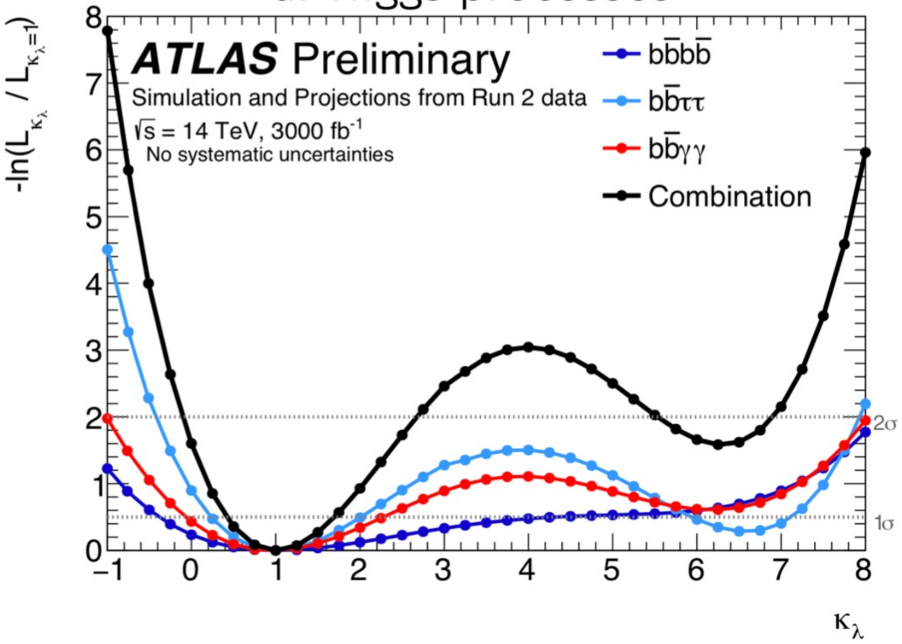
- Only way to access the **Higgs potential term** of the Lagrangian (bosons from covariant derivative, fermions from Yukawa)
- Two possible approaches: Di-Higgs production or via corrections to single-Higgs processes

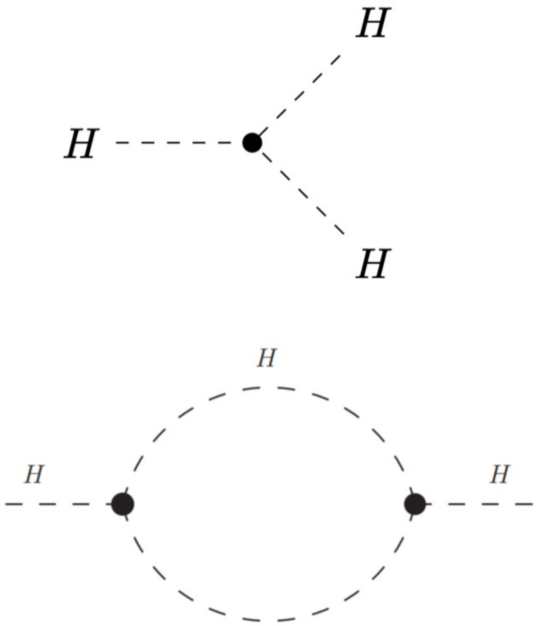
$$V(\phi) = \mu^2(\phi\phi^\dagger) + \lambda(\phi\phi^\dagger)^2$$
$$\subset \lambda v^2 h^2 + \boxed{\lambda v h^3} + \boxed{\frac{\lambda}{4} h^4}$$

single-Higgs processes



di-Higgs processes





- Possible combination interesting. Can we exclude λ > 2 at HL-LHC (needed for EW baryogenesis) ?

Here I wanted to still ask Pamela and Stefano; input stolen from his indico contributions

Quo vadis? Higgs couplings at HL-LHC

- Higgs couplings currently known (if already observed) with ~ 10% to 20% precision
- Dataset analyzed so far (mostly ~ 100 fb^{-1}) is only about 4% of the planned one (3000 fb^{-1})
  → Where can we go in terms of precision?

$$\sigma_i \times \mathrm{B}(H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}(H \to f)$$

The κ-framework:

- Results interpreted as limits on leading-order coupling modifiers κ
- Total uncertainties of a few percent achievable
  → precision area lying ahead!
- Extrapolations are getting much better (i.e. we are improving quicker than expected)
- But, underlying assumptions to be noted