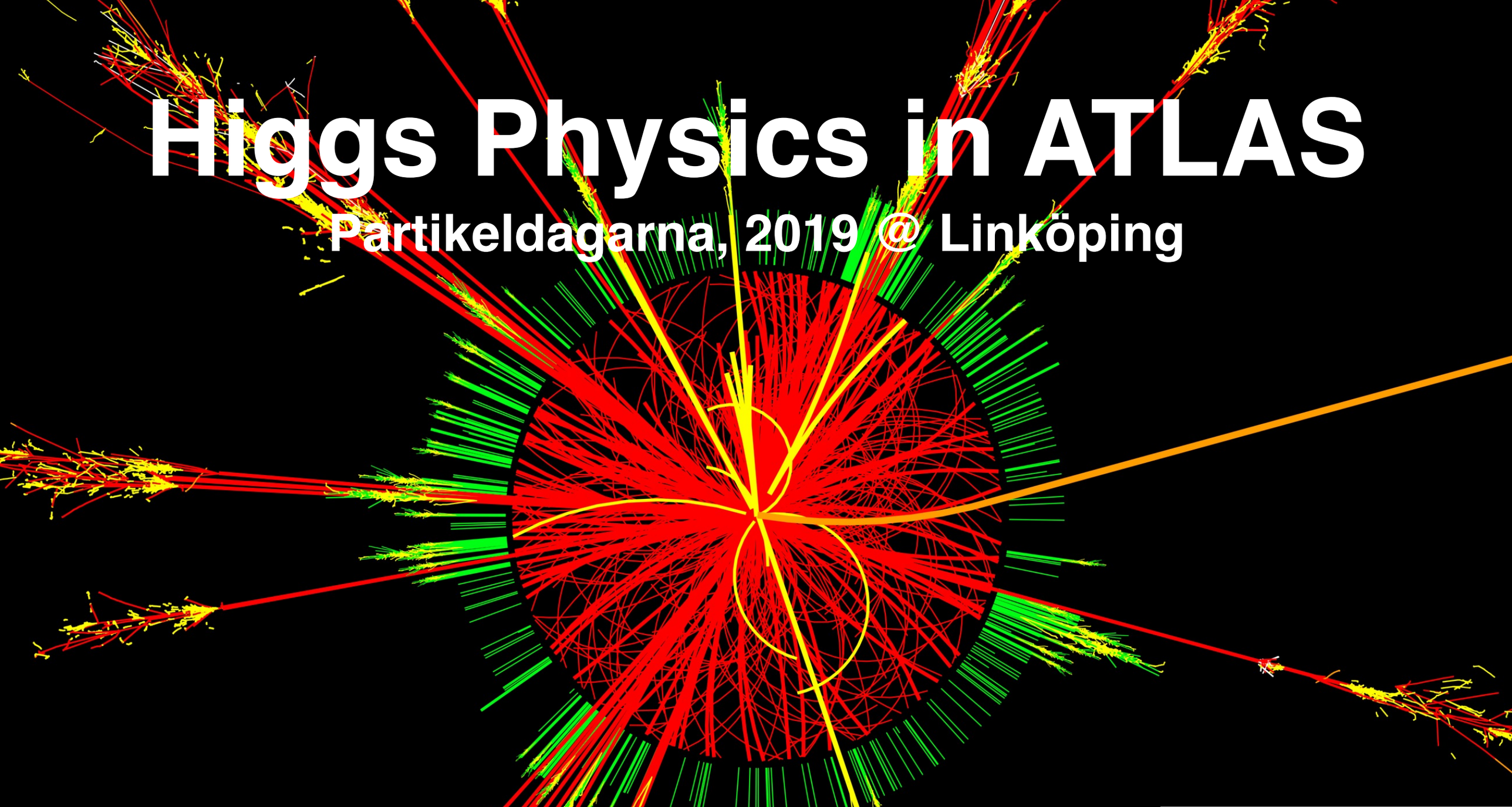
Higgs Physics in ATLAS

Partikeldagarna, 2019 @ Linköping



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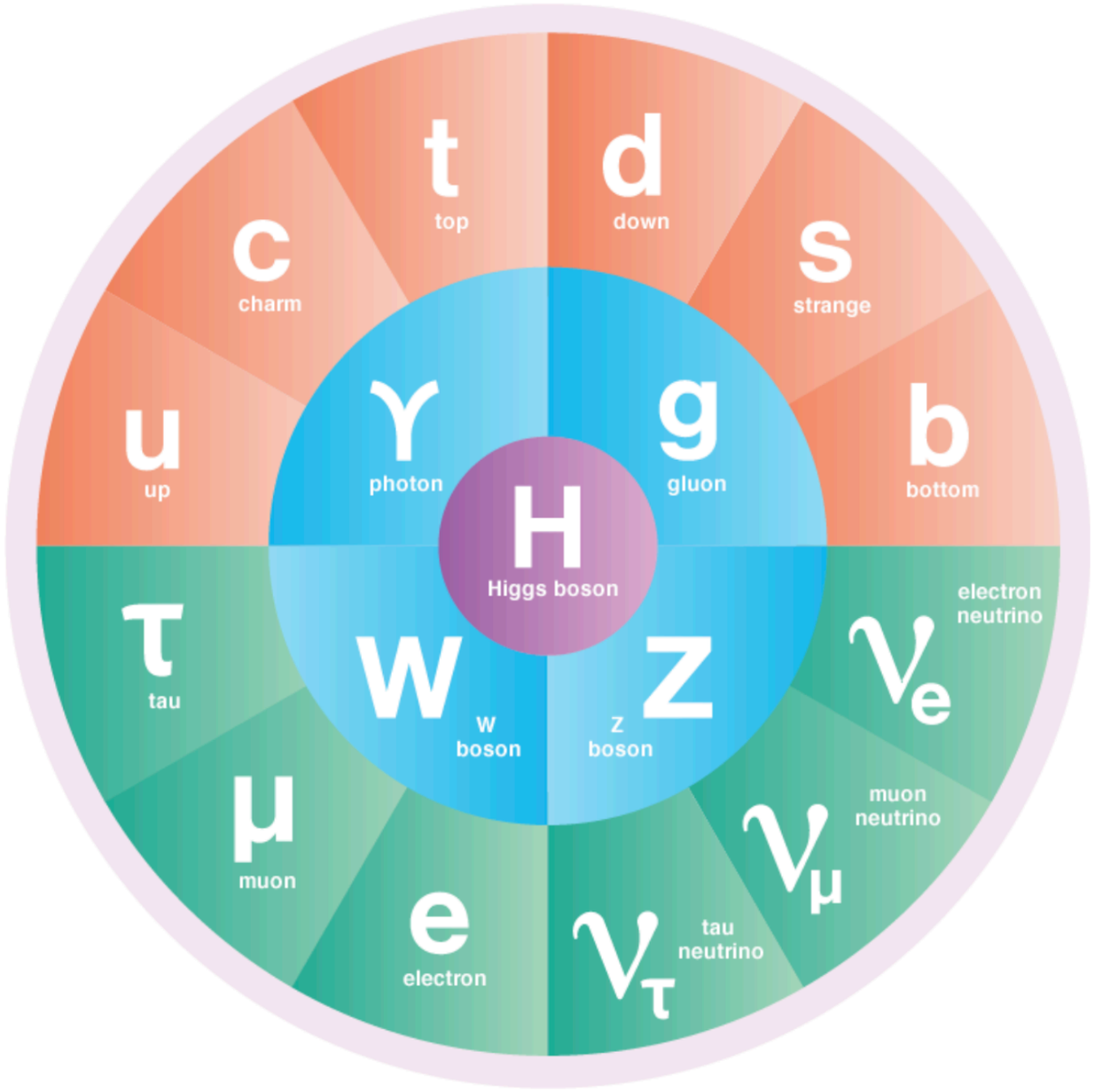
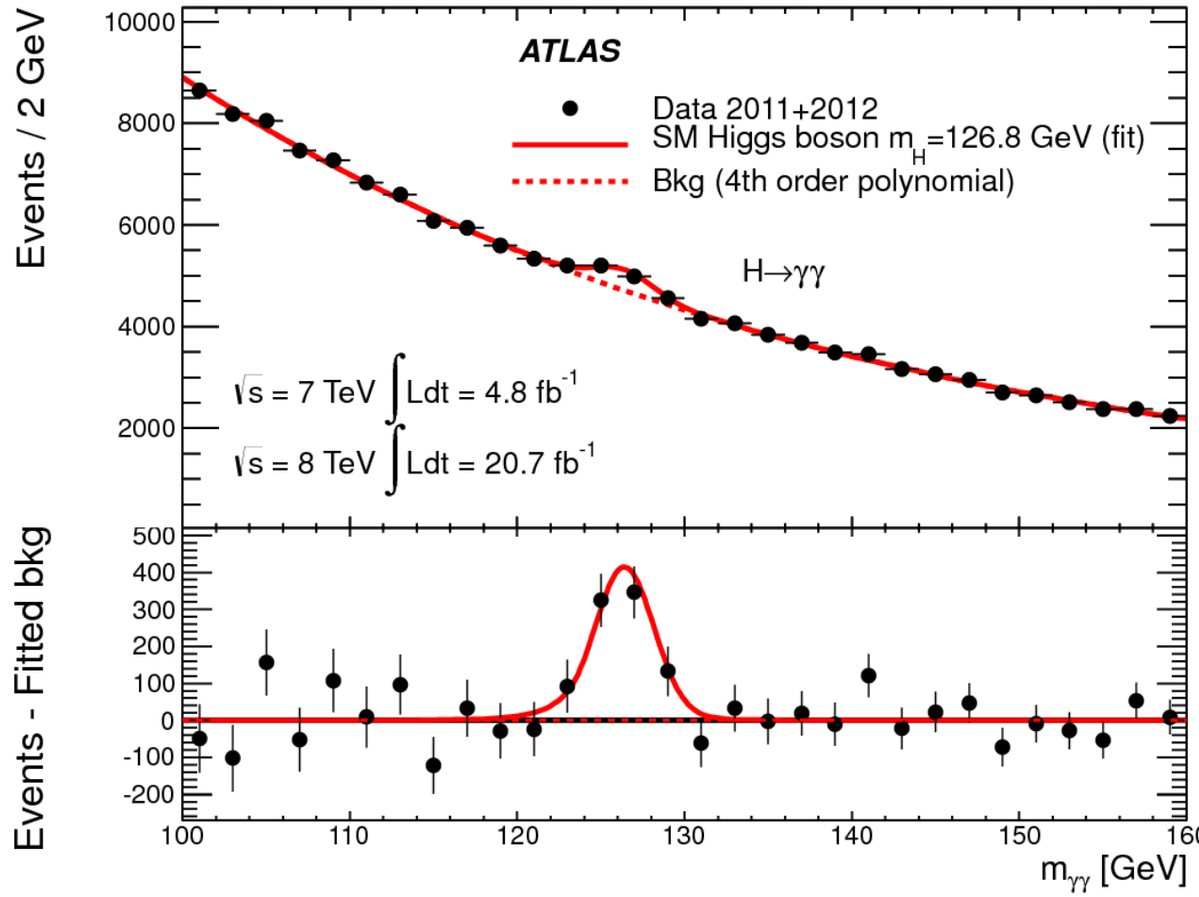
Why do we care ?

- Higgs boson **discovered** during Run 1 of the LHC.
- The only experimentally verified **fundamental scalar** … **SPECIAL !**

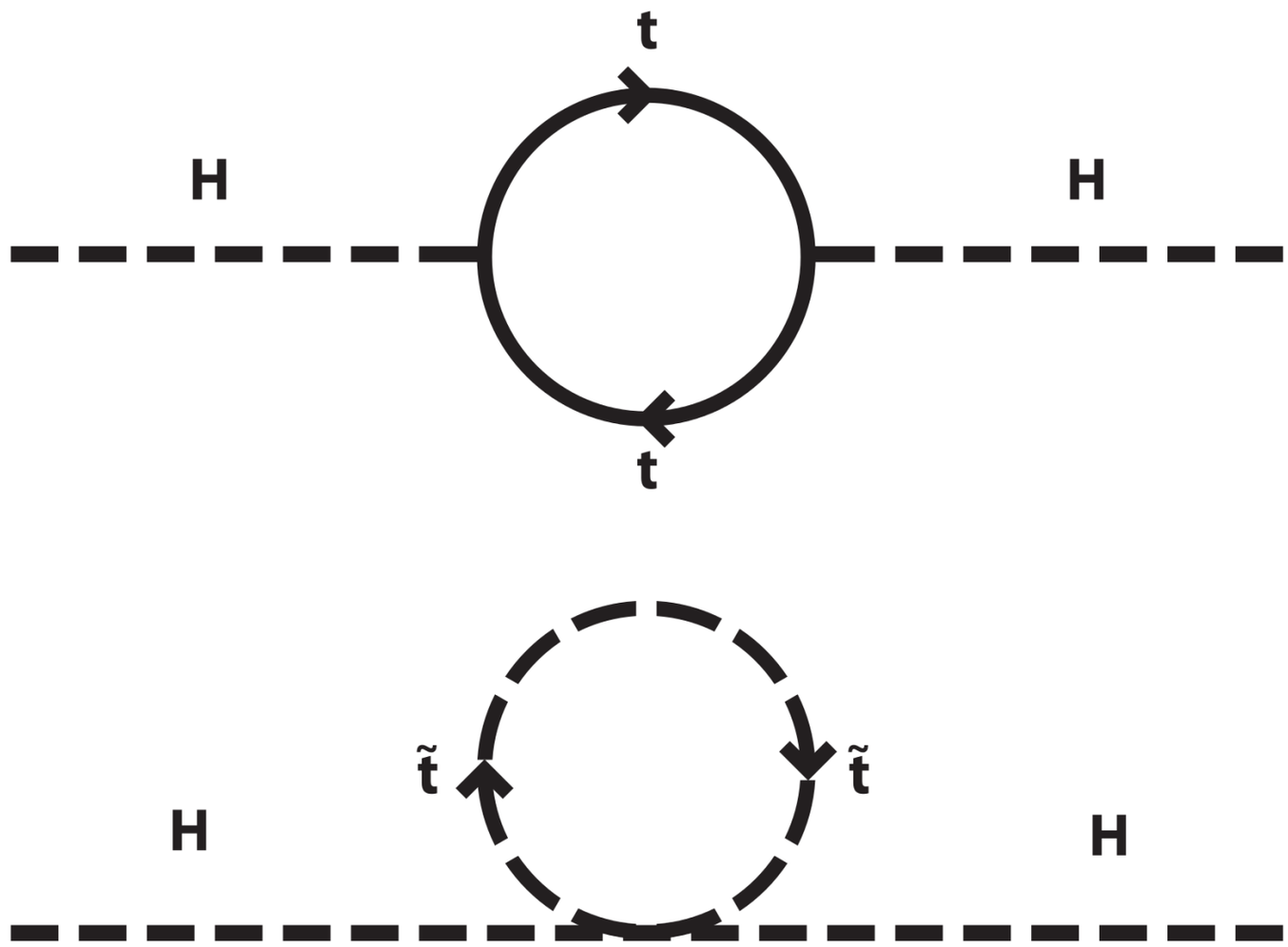




From arXiv:1207.7214

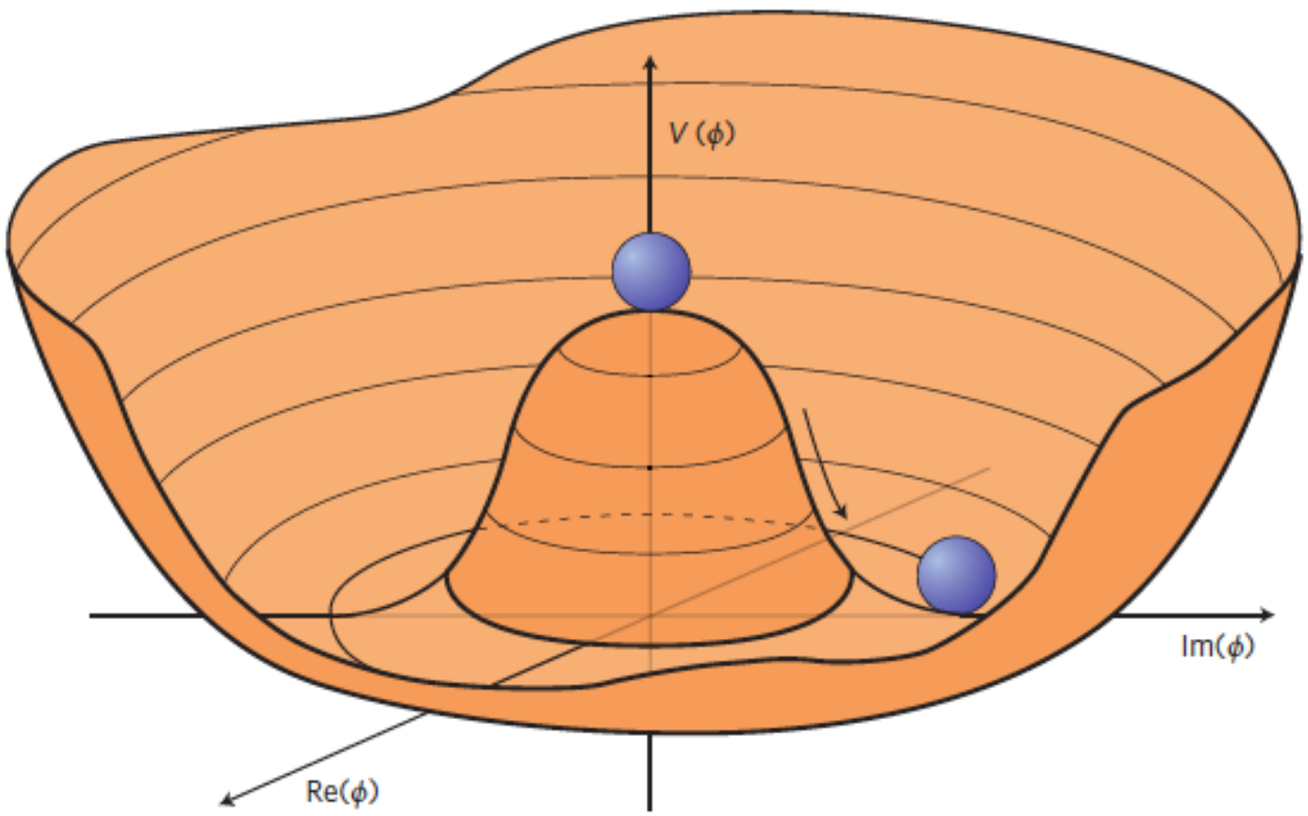
Why do we care ?

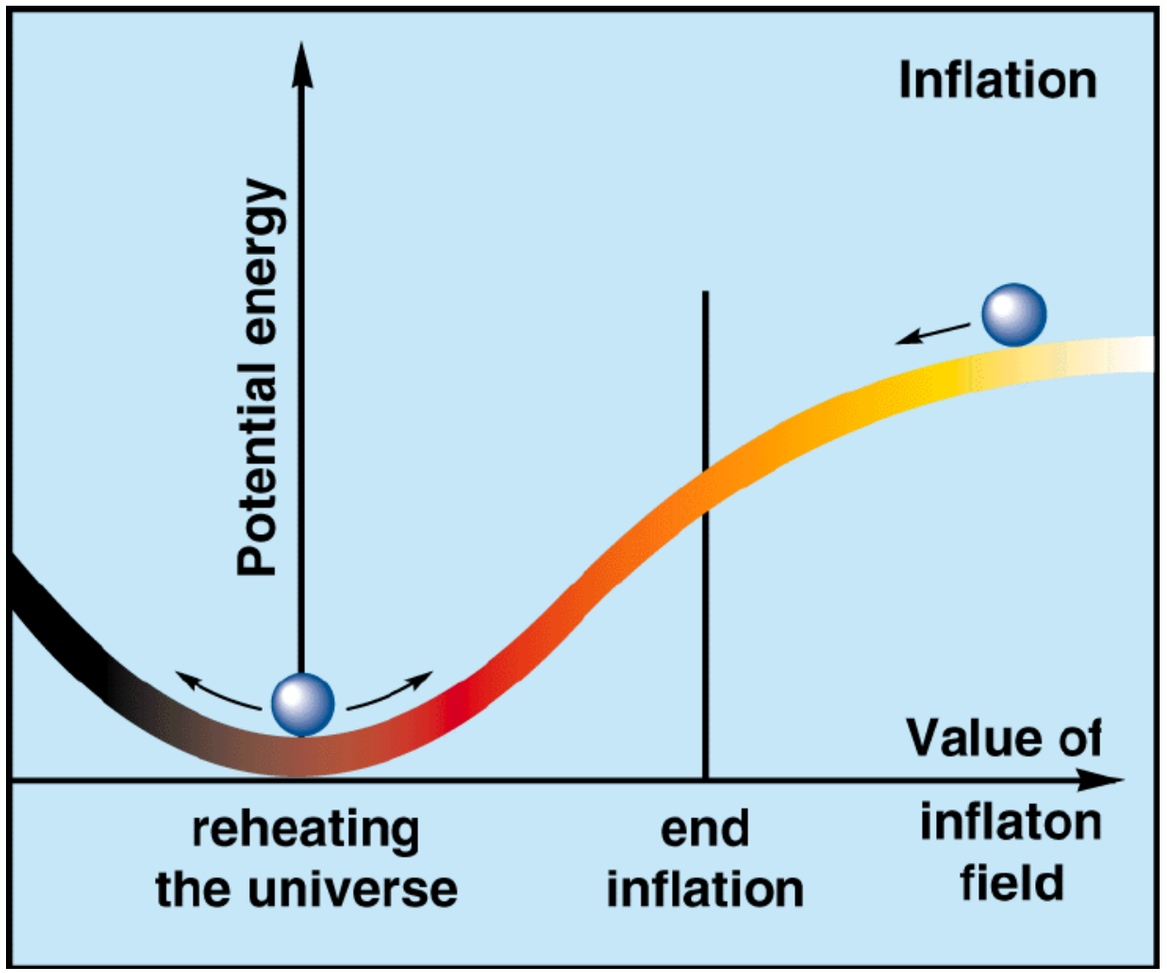
- Higgs mass explained by popular beyond Standard Model (BSM) theories like Supersymmetry … **SPECIAL !**



Why do we care ?

- Higgs potential directly connects **particle physics** and **cosmology** … **SPECIAL !**





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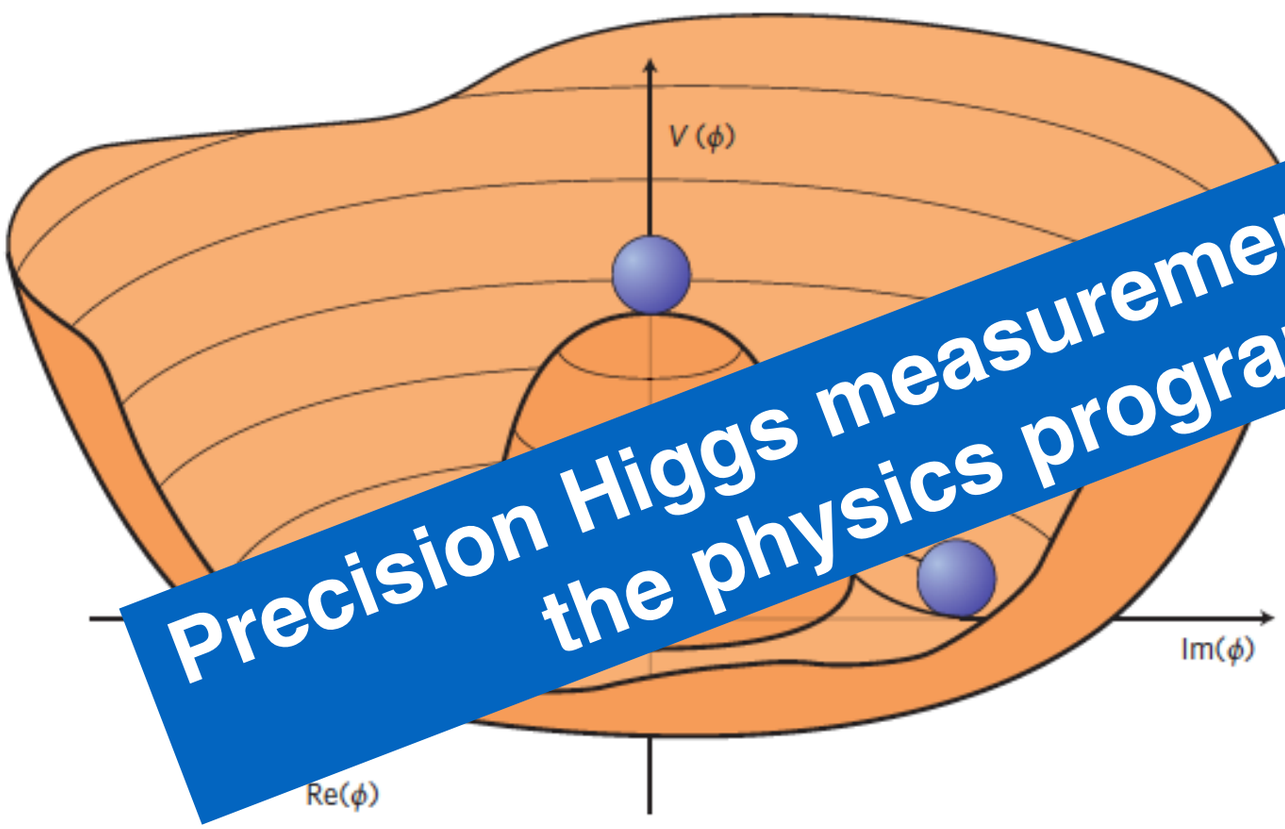
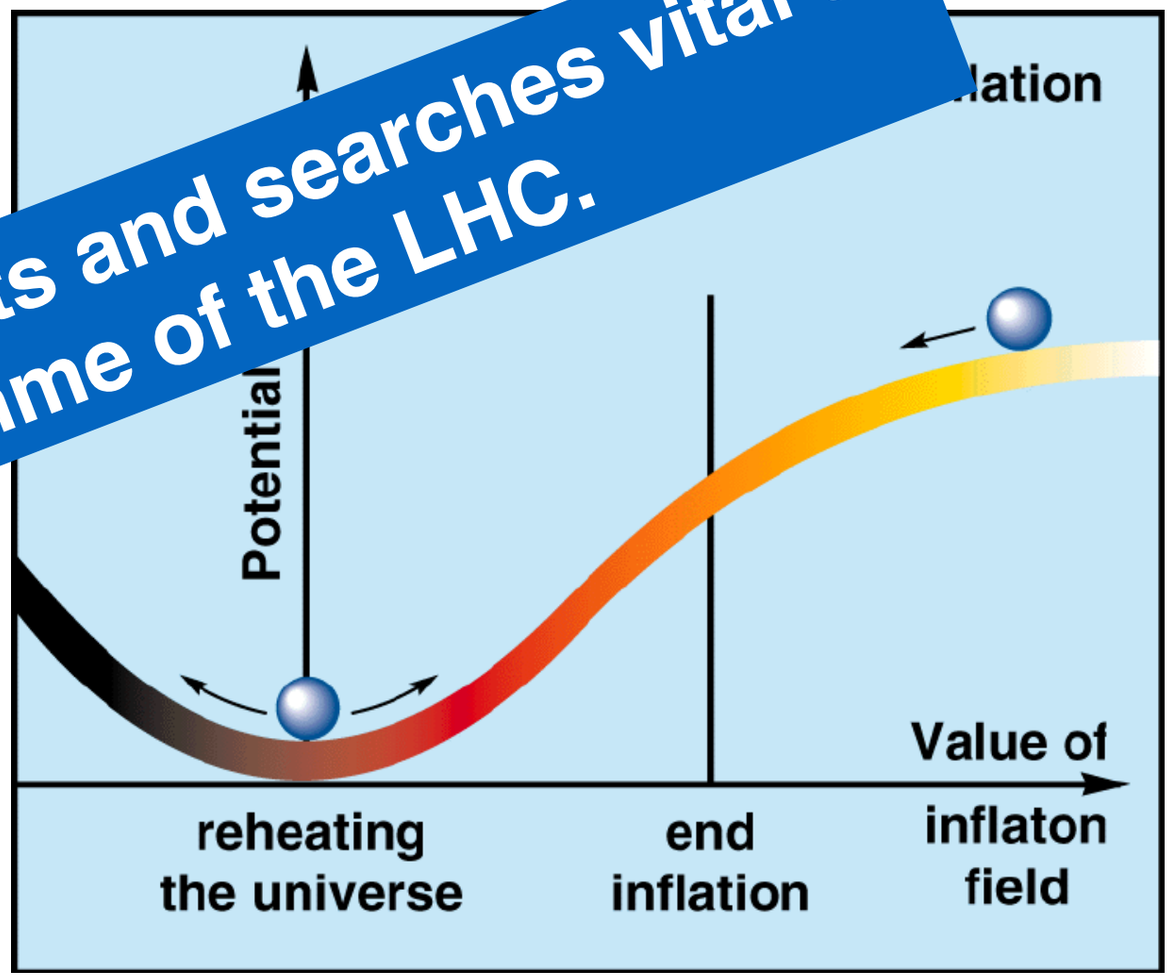
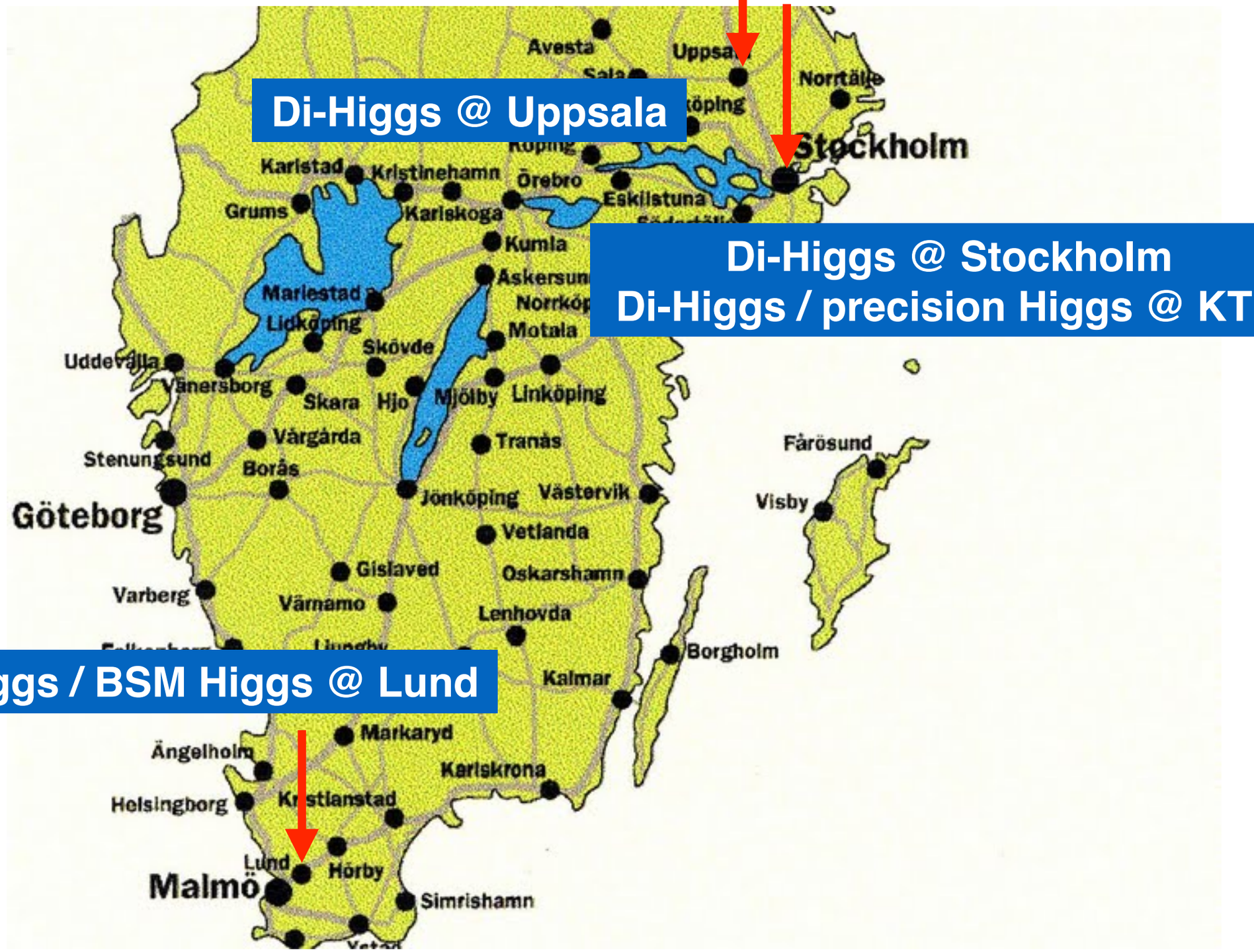




Precision Higgs measurements and searches vital to the physics programme of the LHC.

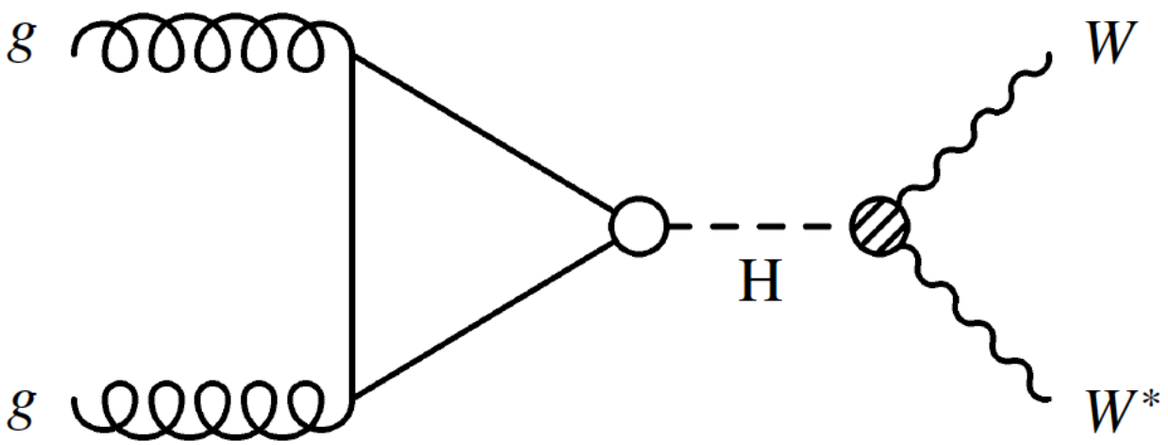
And *who* cares ? …



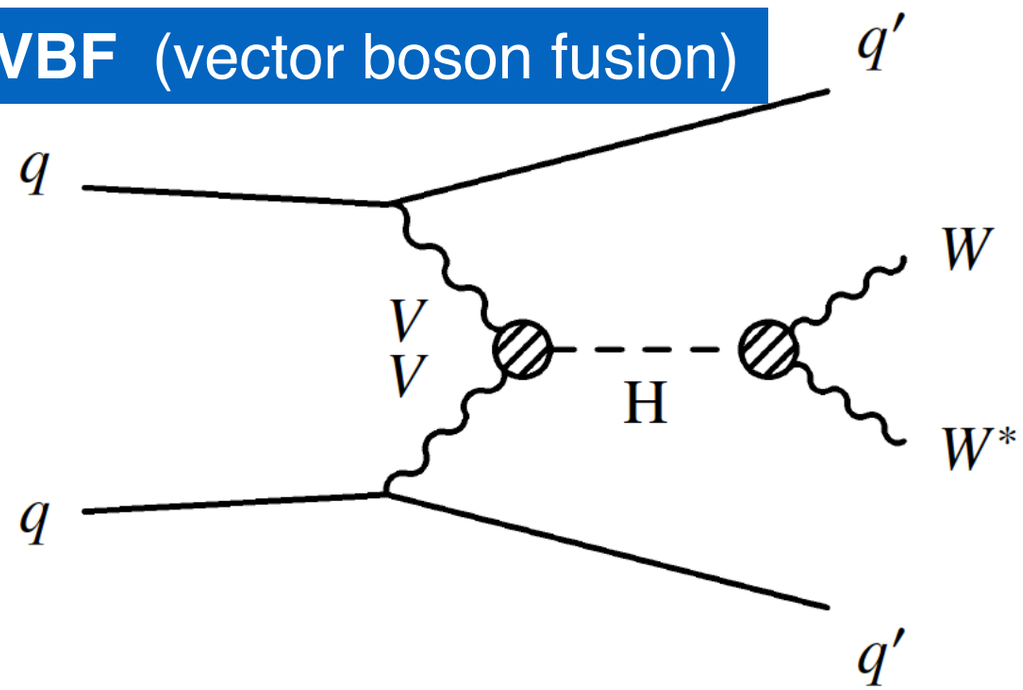
Precision Measurements

$H \rightarrow WW^*$ Measurements

ggF (gluon-gluon fusion)

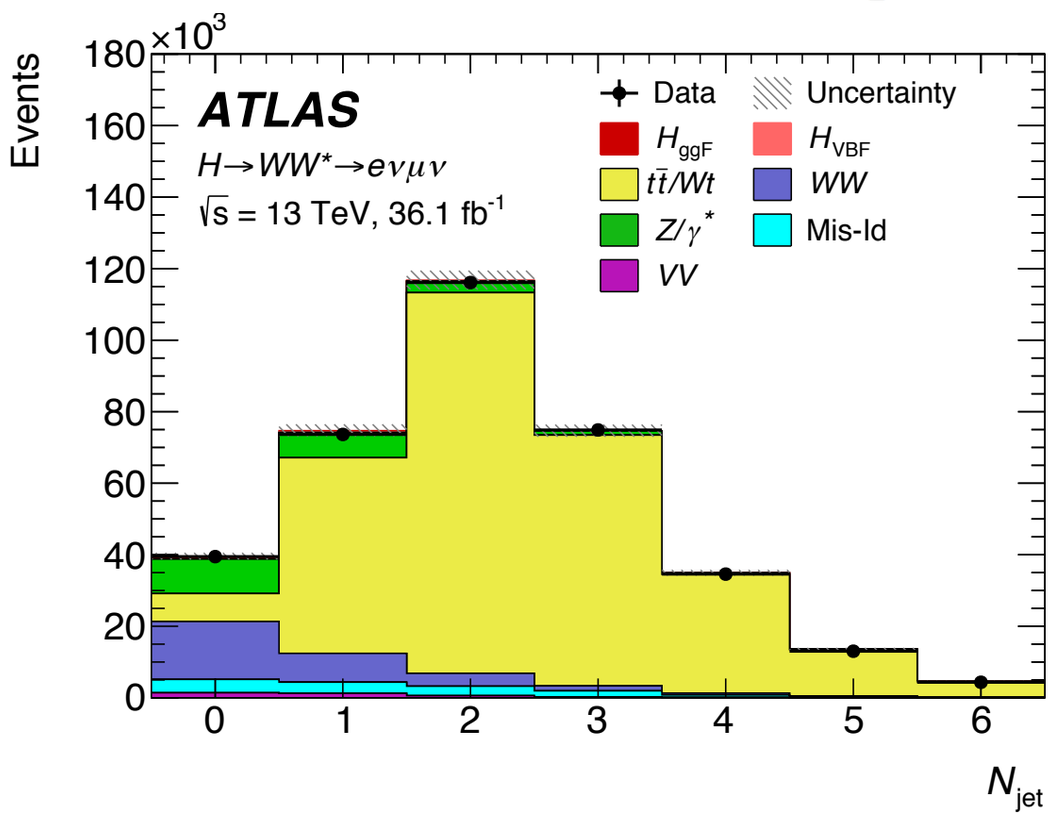


VBF (vector boson fusion)



- WW^* **second-largest branching fraction (BF) + clean final states** => precise and rigorous test of the SM prediction.
- $W \rightarrow l\nu$ => single leptons triggers and a dilepton e-μ trigger.
- **Categorisation based on N_{jet}**:
  N_{jet} = 0,1 => ggF; N_{jet} = 2+ => VBF

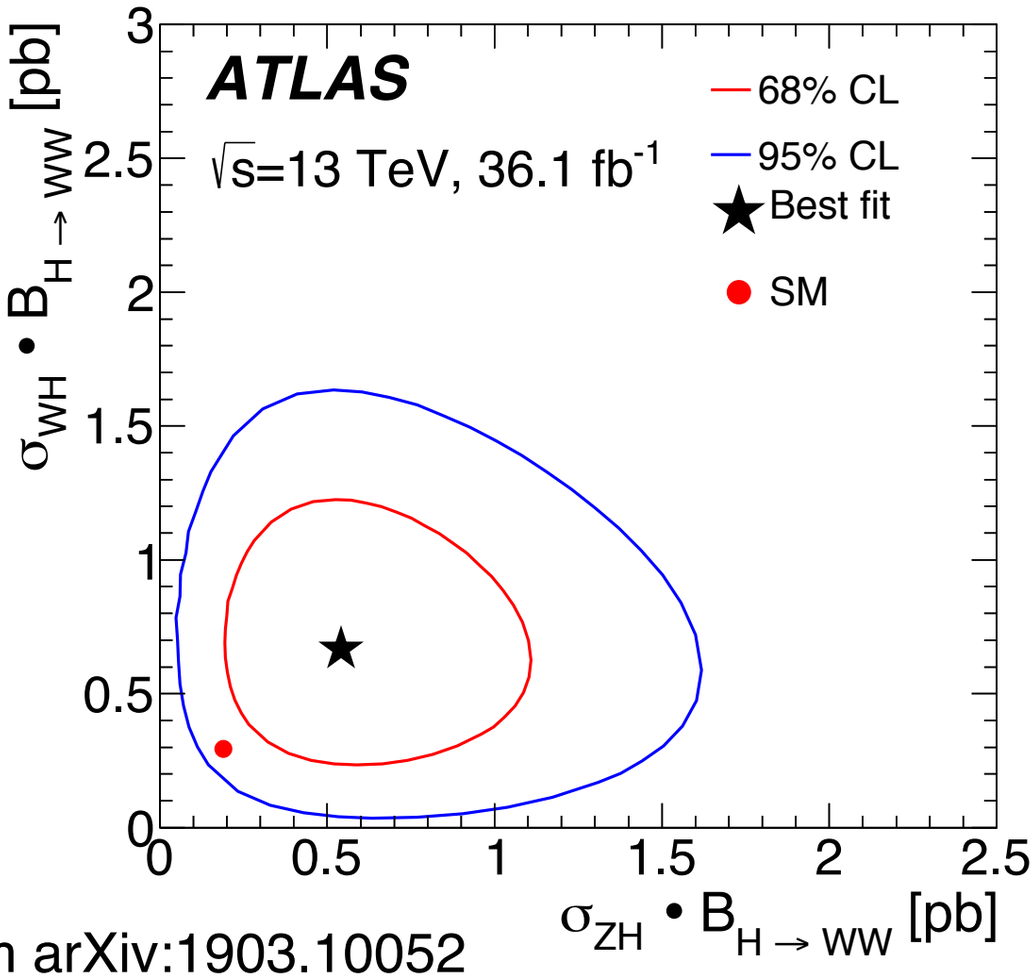
From arXiv:1808.09054



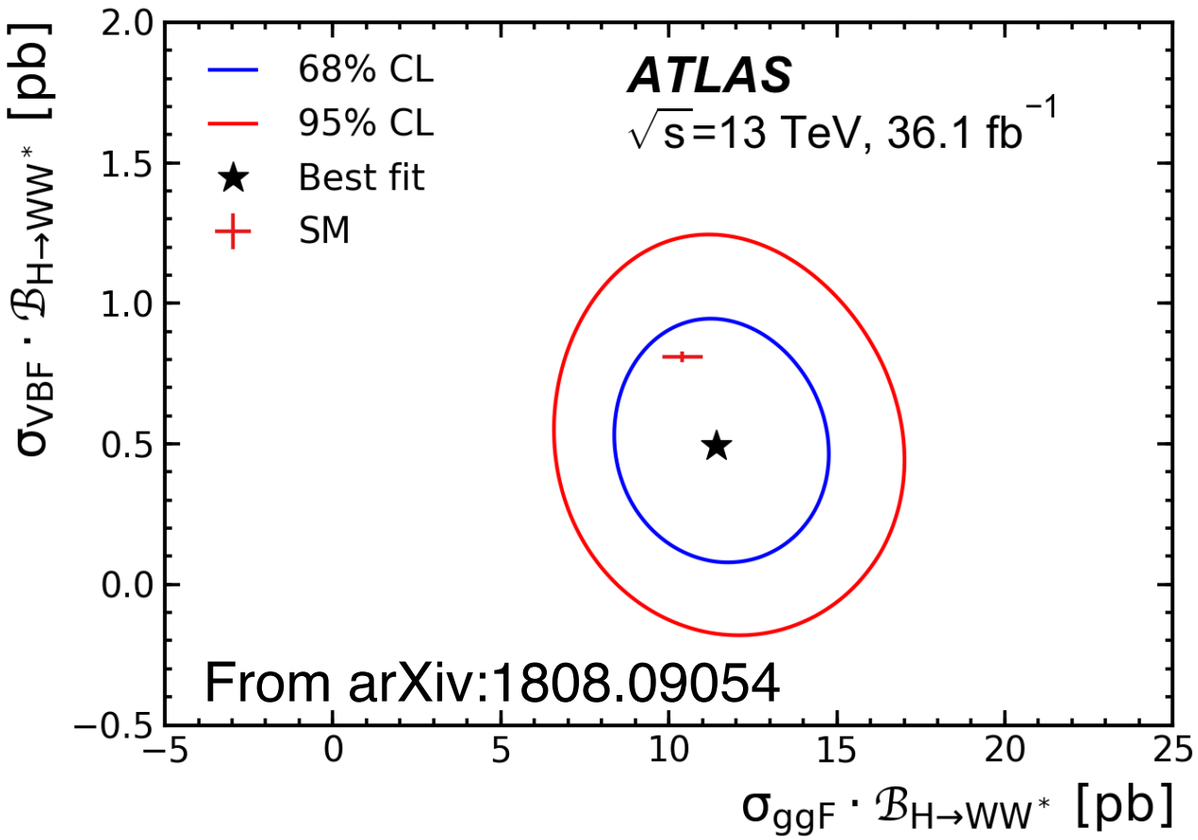
$H \rightarrow WW^*$ Measurements

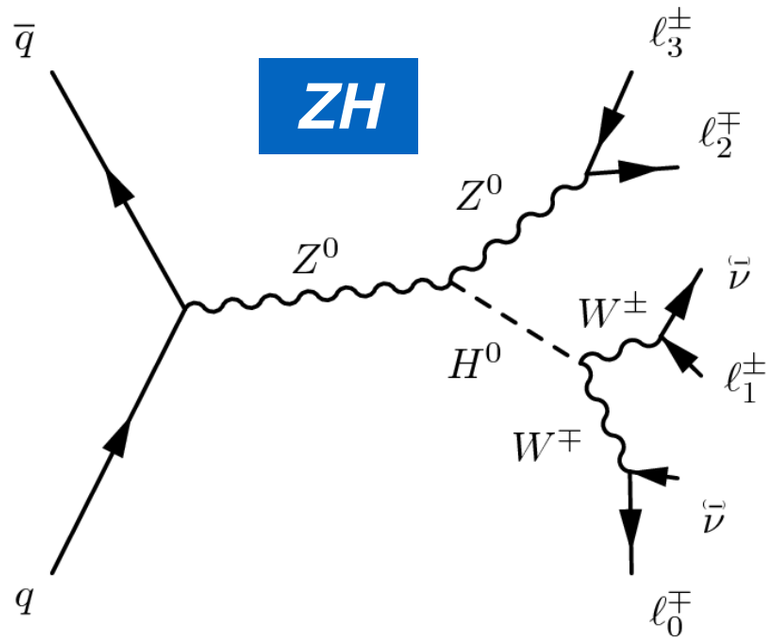
- **Measured cross-sections consistent with SM**, with *gg*F measured at 6.0 (5.3) σ and VBF to 1.8 (2.6) σ.

- Second analysis also measured the very small ***V(=Z/W)H* production** cross-section.



From arXiv:1903.10052



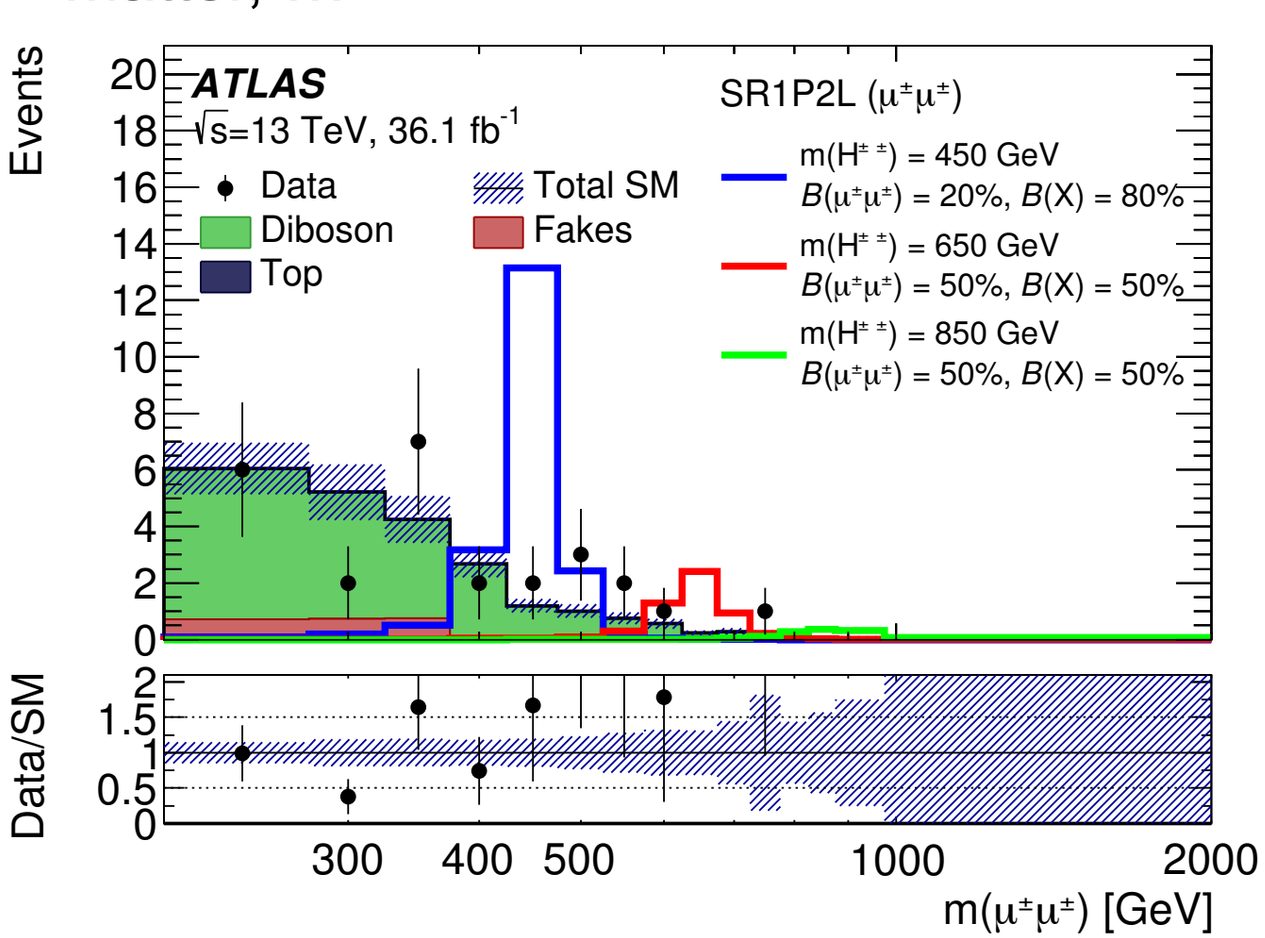


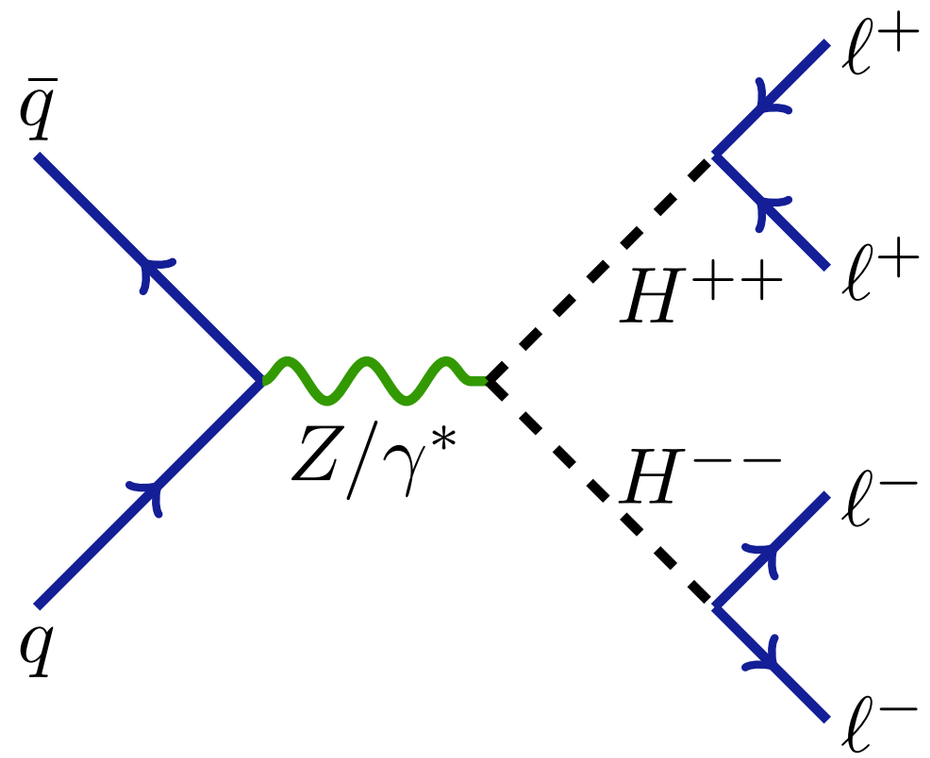
Direct BSM Searches

Searches for Charged Higgses

- $H^{++(--)} \longrightarrow e^{+(-)}e^{+(-)}/\mu^{+(-)}\mu^{+(-)}/e^{+(-)}\mu^{+(-)}$ search with 2015+2016 data.

- $H^{++(--)}$ occur in a **variety of BSM theories**: left-right symmetric models, little Higgs theories, type-II seesaw, scalar singlet dark matter, …





- Dilepton invariant masses **above 200 GeV define search regions.**

- **Vetos events with at least one *b*-tagged jet**, to reduce background. Have 3- and 4-lepton search regions.

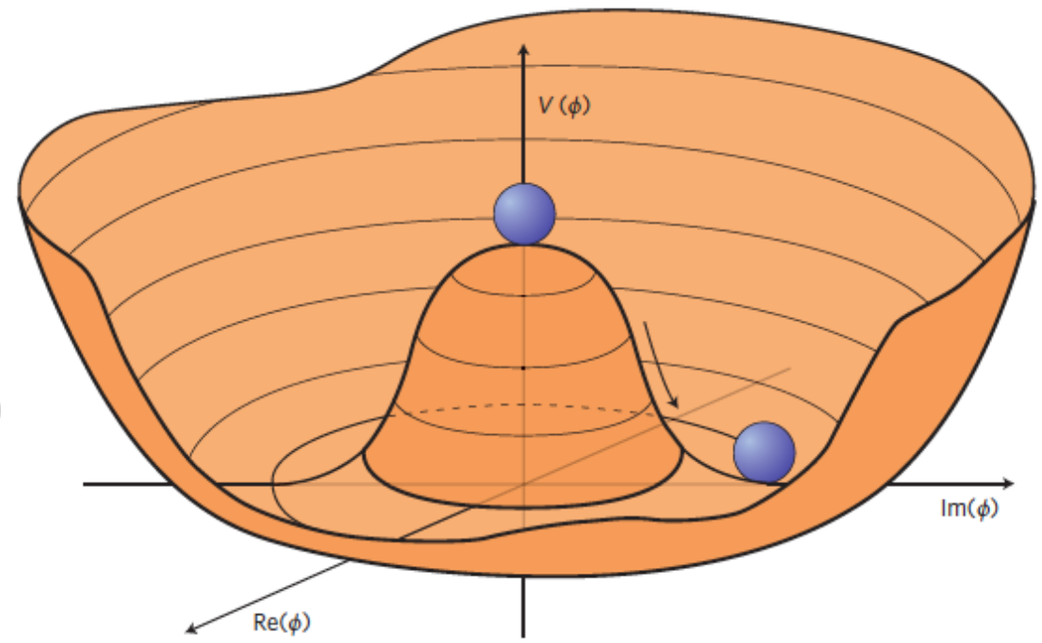
From arXiv:1710.09748

HH: BSM meets Precision

The Global Higgs Potential

- *HH* production probes the **global** shape of the **Higgs potential**.

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

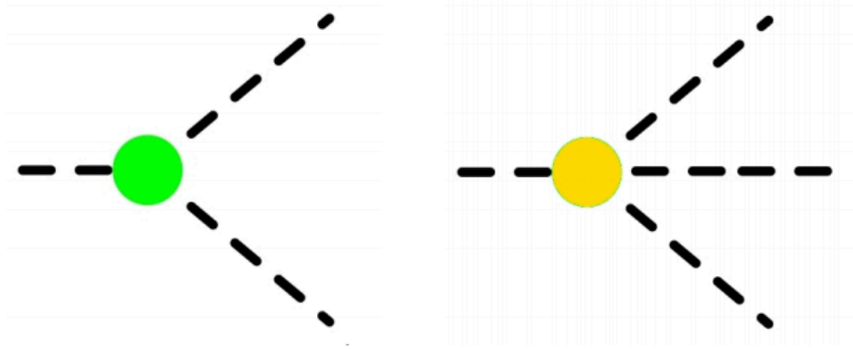


Perturb minimum, *v*, by amount *h* $V(\phi) \to V(v+h)$

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

$$= V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4 + \ldots$$

Higgs mass *HH* production *HHH* production



Test the SM predictions:

$$v = \frac{\mu}{\sqrt{\lambda}} = 246\,\mathrm{GeV}$$

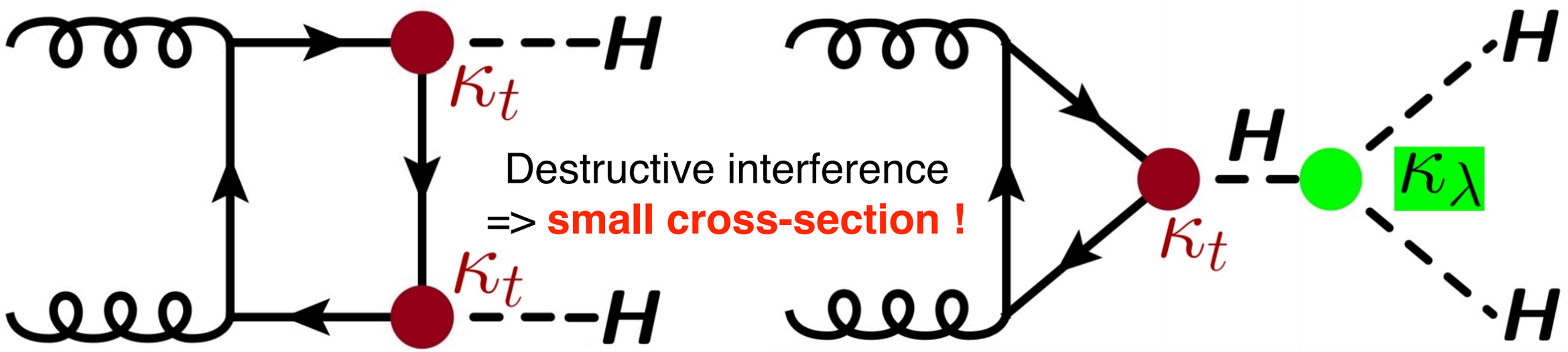
$$\lambda = \frac{m_h^2}{2v^2} \approx 0.13$$

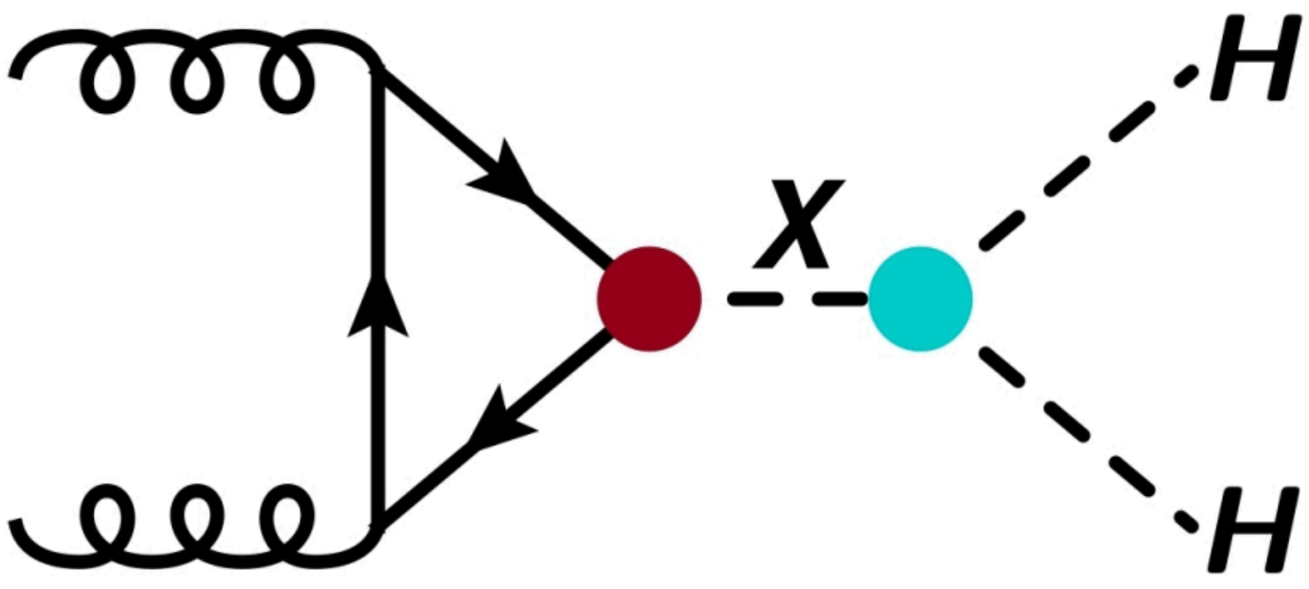
Cosmological implications !

Resonant and Non-Resonant Searches

Stockholm University

Precision measurement $\kappa_t = g_{t\bar{t}H}/g_{t\bar{t}H}^{SM}$ and $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$





Direct BSM search

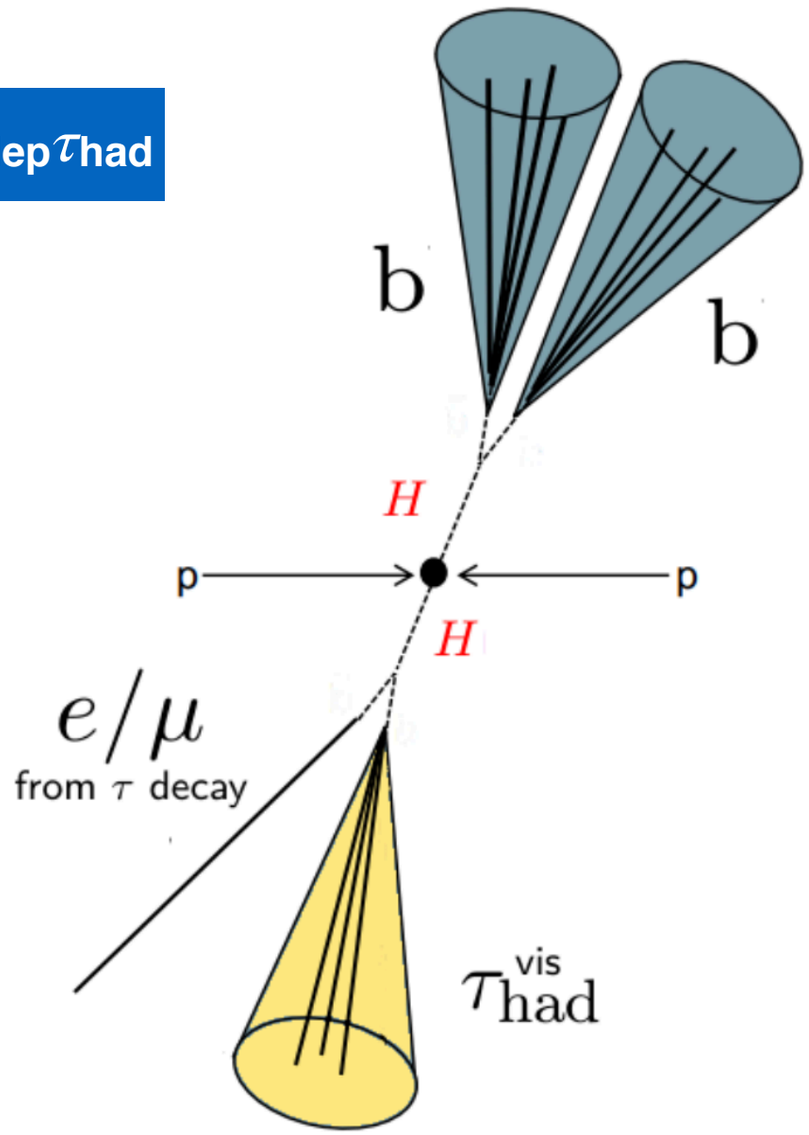
***X* = New Matter**

e.g. Spin-0: *X* = *S*, a new scalar

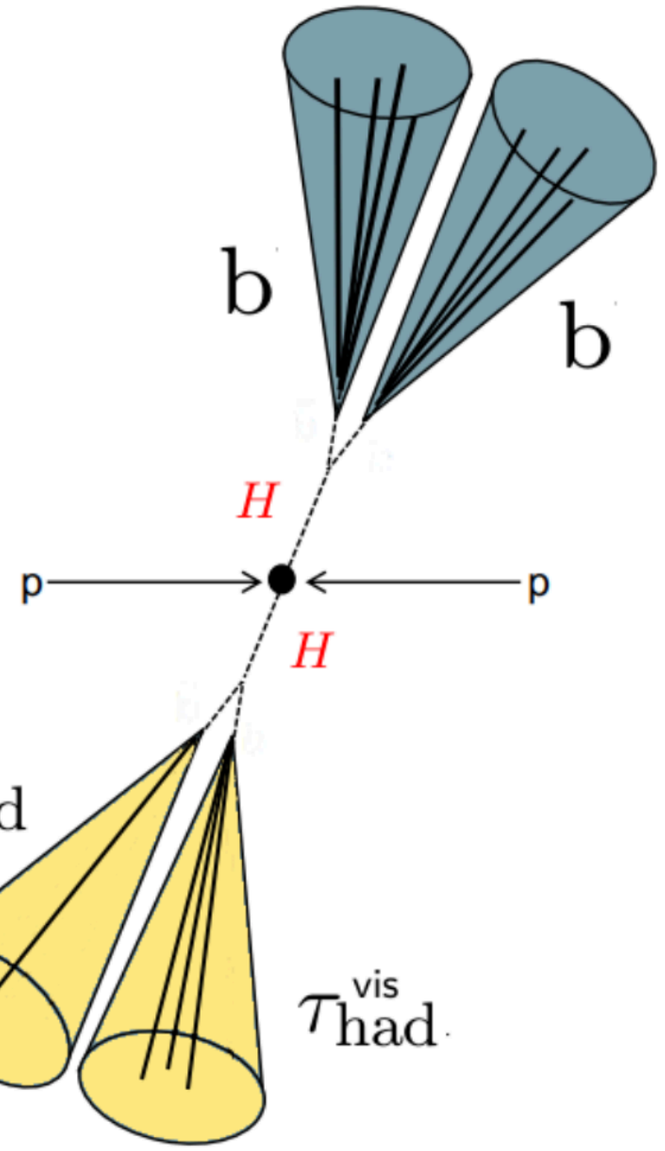
e.g Spin-2 *X* = *G*, Randall-Sundrum graviton

$HH \to bb\tau\tau$

$bb\tau_{lep}\tau_{had}$



$bb\tau_{had}\tau_{had}$

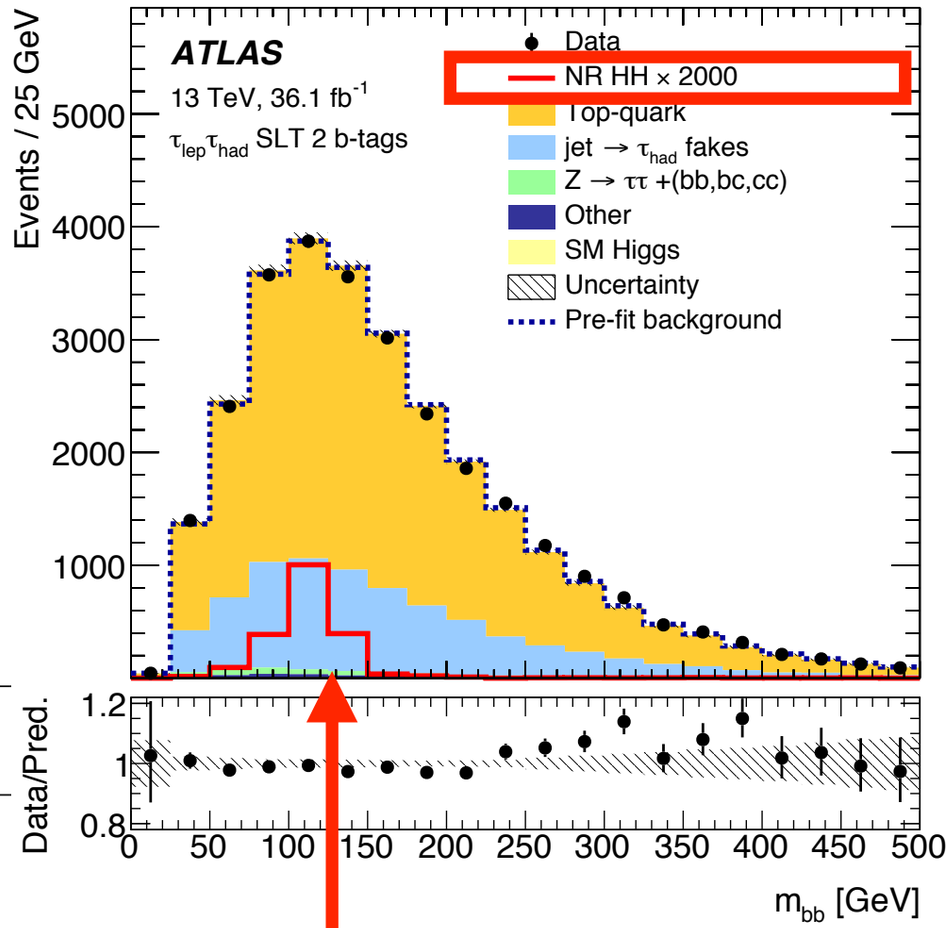


- Single lepton triggering on events, with exactly two *b*-tagged jets and a "missing mass" > 60 GeV.

From arXiv:1808.00336

$HH \to bb\tau\tau$

- Major analysis tool is the **Boosted Decision Tree** algorithm.
- Takes **different combinations of 11 kinematic variables** in the difference lep-had and had-had channels.



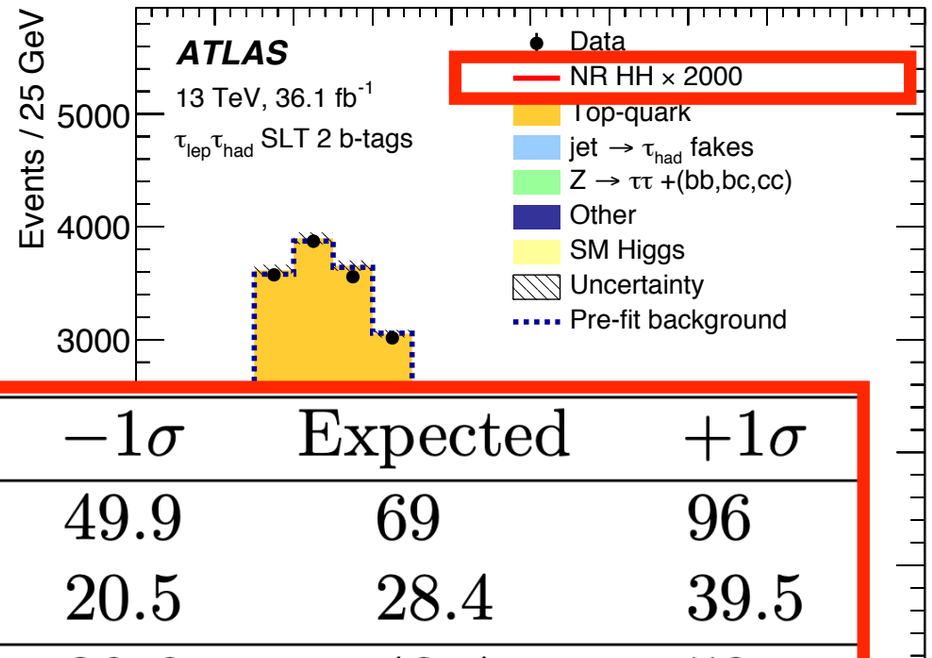
Variable	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT resonant)	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT non-resonant & LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	✓
$E_{\text{T}}^{\text{miss}}$	✓		
$E_{\text{T}}^{\text{miss}}$ ϕ centrality	✓		✓
m_{T}^{W}	✓	✓	
$\Delta\phi(H,H)$	✓		
$\Delta p_{\text{T}}(\text{lep},\tau_{\text{had-vis}})$	✓		
Sub-leading b-jet p_{T}	✓		

- Scale of the signal !
- BDT inputs

From arXiv:1808.00336

$HH \to bb\tau\tau$

- Major analysis tool is the **Boosted Decision Tree** algorithm.
- Takes **different combinations of 11**



		Observed	-1σ	Expected	$+1\sigma$
$\tau_{\text{lep}}\tau_{\text{had}}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57	49.9	69	96
	$\sigma/\sigma_{\text{SM}}$	23.5	20.5	28.4	39.5
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	$\sigma/\sigma_{\text{SM}}$	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	$\sigma/\sigma_{\text{SM}}$	12.7	10.7	14.8	20.6

Var			
m_H			
$m_{\tau\tau}^{\text{M}}$			
m_{bb}			
ΔR			
$\Delta R(b,b)$	✓	✓	✓
$E_{\text{T}}^{\text{miss}}$	✓		
$E_{\text{T}}^{\text{miss}}$ ϕ centrality	✓		✓
m_{T}^{W}	✓	✓	
$\Delta\phi(H,H)$	✓		
$\Delta p_{\text{T}}(\text{lep}, \tau_{\text{had-vis}})$	✓		
Sub-leading b-jet p_{T}	✓		

- Scale of the signal !
- BDT inputs

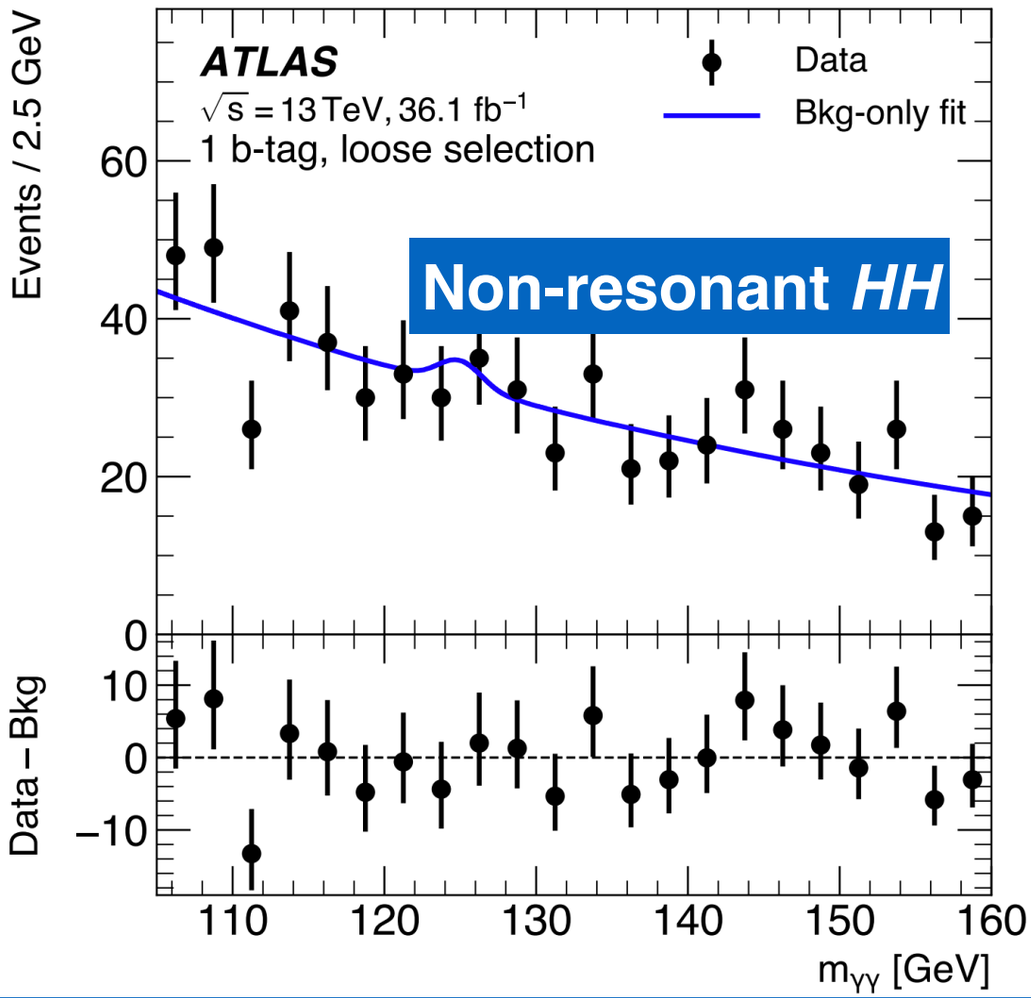
From arXiv:1808.00336

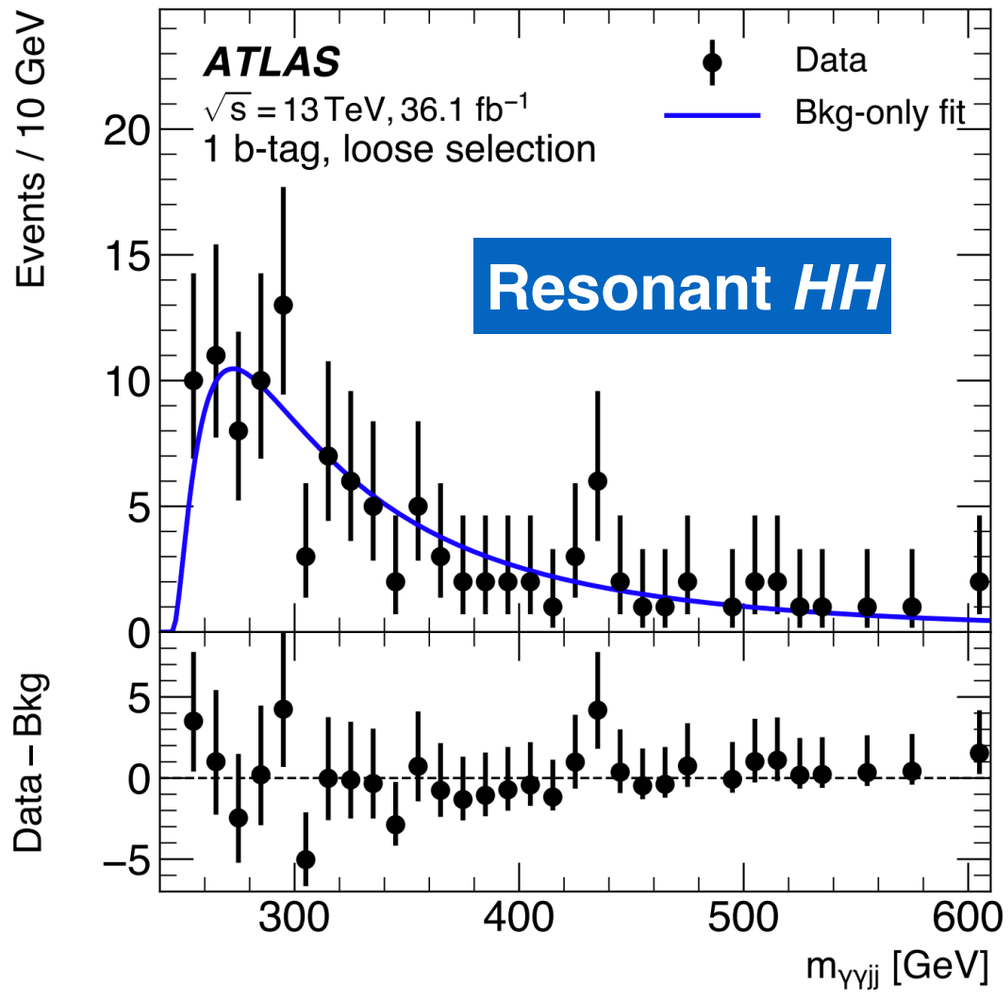
$HH \rightarrow bb\gamma\gamma$

- Trigger on diphoton events, and have deduced **2-, 1-, and 0-*b*-jet regions**: two search regions, and the 0-tag for **data-driven γ+jet** background estimation.

- Fit **$m_{\gamma\gamma}$ in the non-resonant channel, and $m_{\gamma\gamma jj}$ in the resonant channel**, which is sensitive to different *X*-particle resonances.

From arXiv:1807.04873





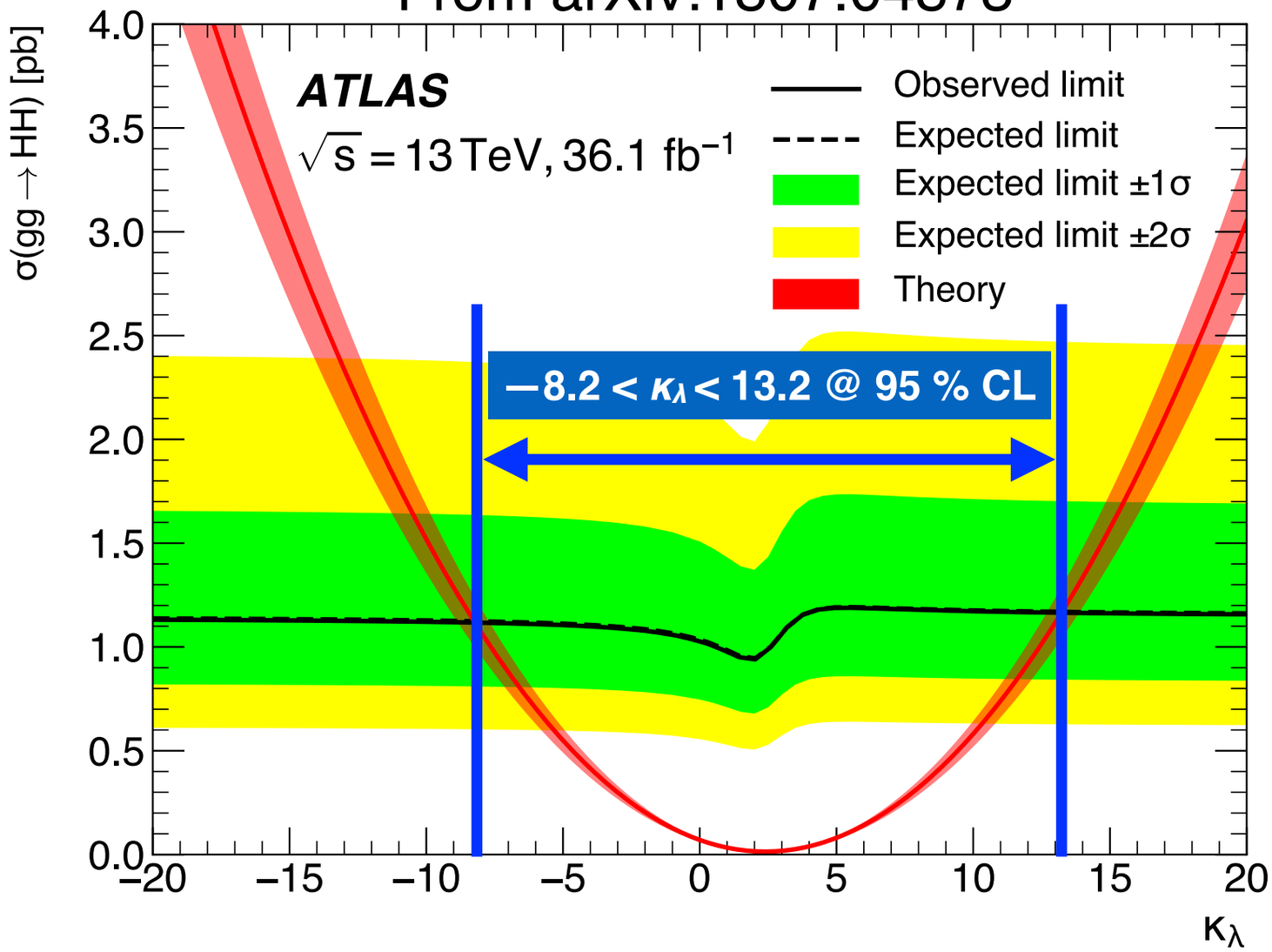
$HH \rightarrow bb\gamma\gamma$

- **Set limits on both the Higgs self-coupling and the production cross-section for non-resonant *HH*.**

- *bbγγ* sets stringent constraints on κ_λ.

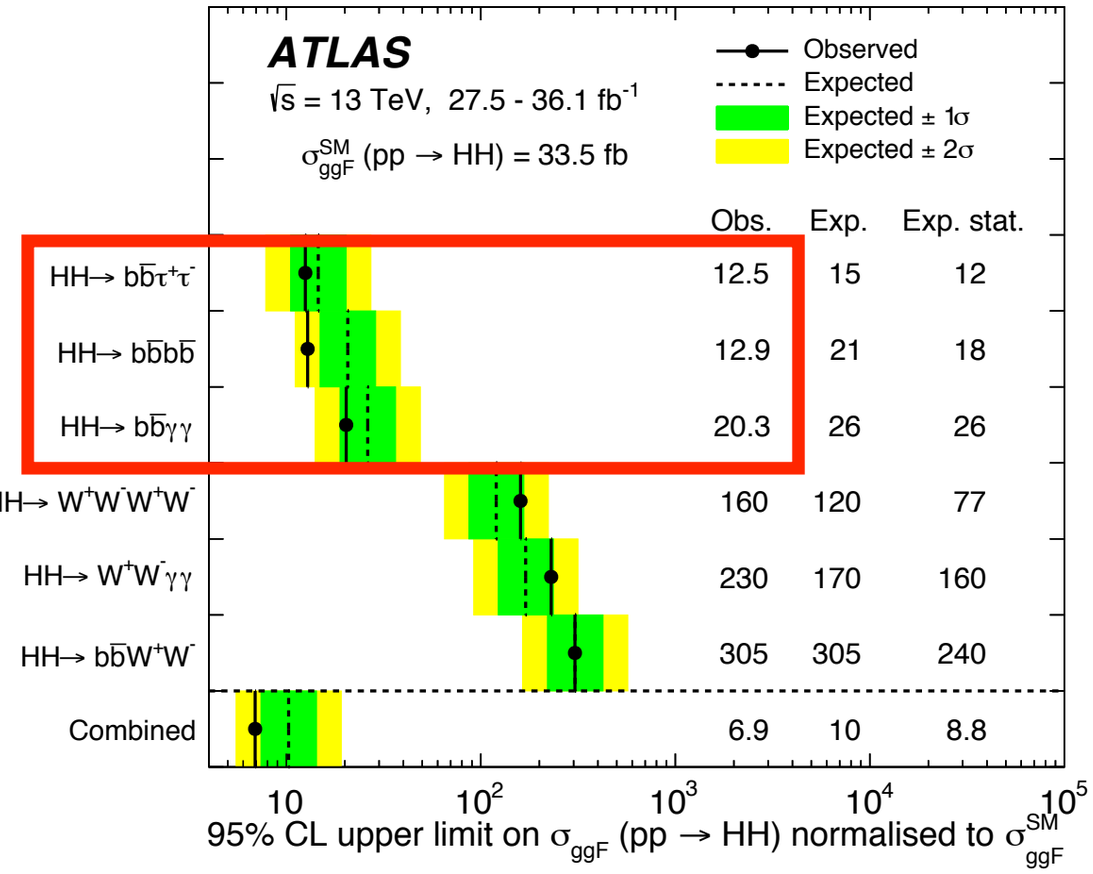
- Upper limits on the mass of *X(HH)* → *bbγγ* set using the resonant channel.

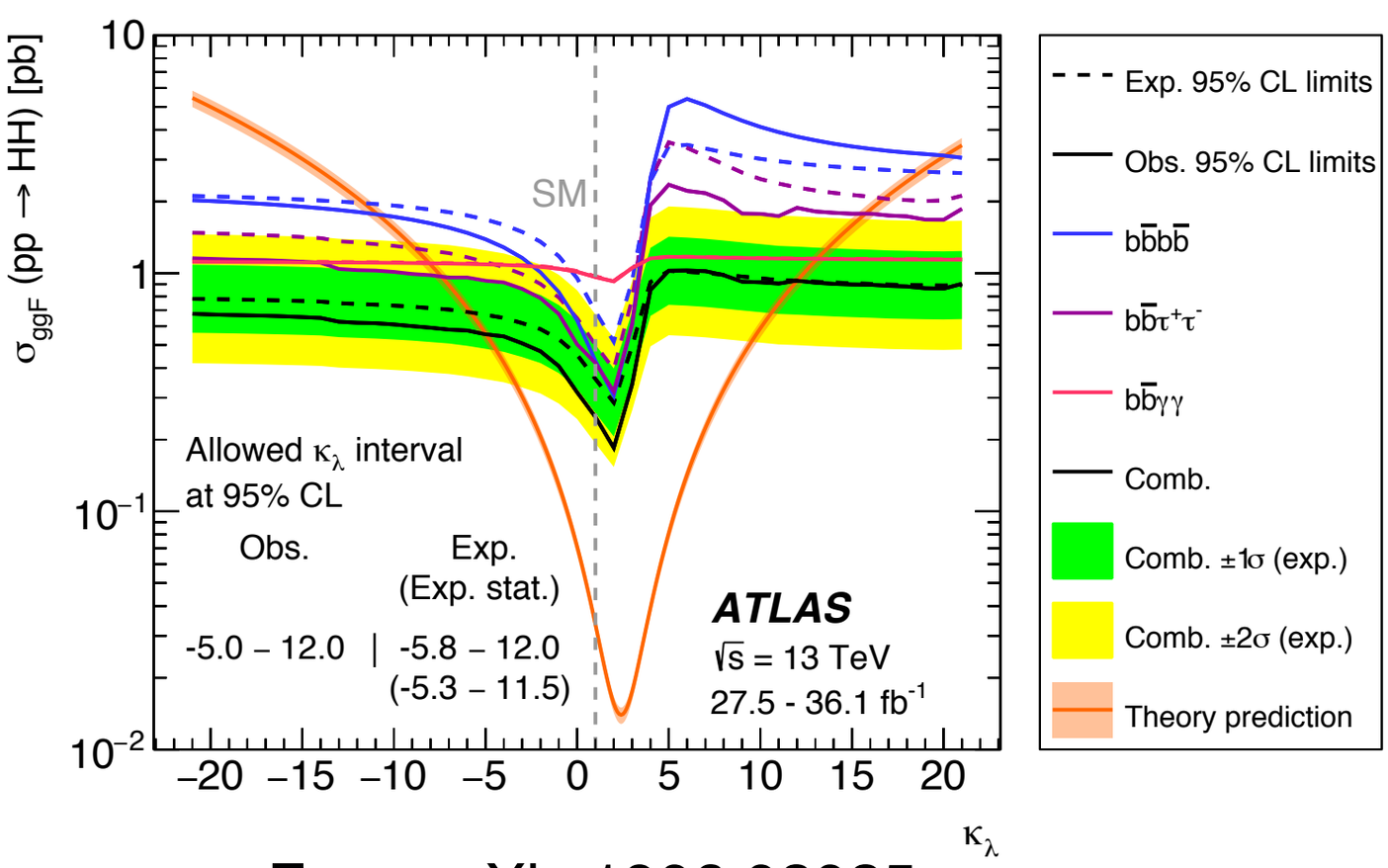
From arXiv:1807.04873



	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg\to HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of σ_{SM}	22	28	20	40

HH Combinations





From arXiv:1906.02025

- *bbττ, bbγγ, bbbb* provide the most sensitive limits on the cross-section of non-resonant *HH* production.
- **Combine *bbττ, bbγγ, bbbb*** in a 2015+2016 limit of —5.0 < κ_λ < 12.0.

Summary

- The Higgs boson is special and probing its properties at the **precision, %-level** is a major undertaking and goal for the LHC over the next 10 years.

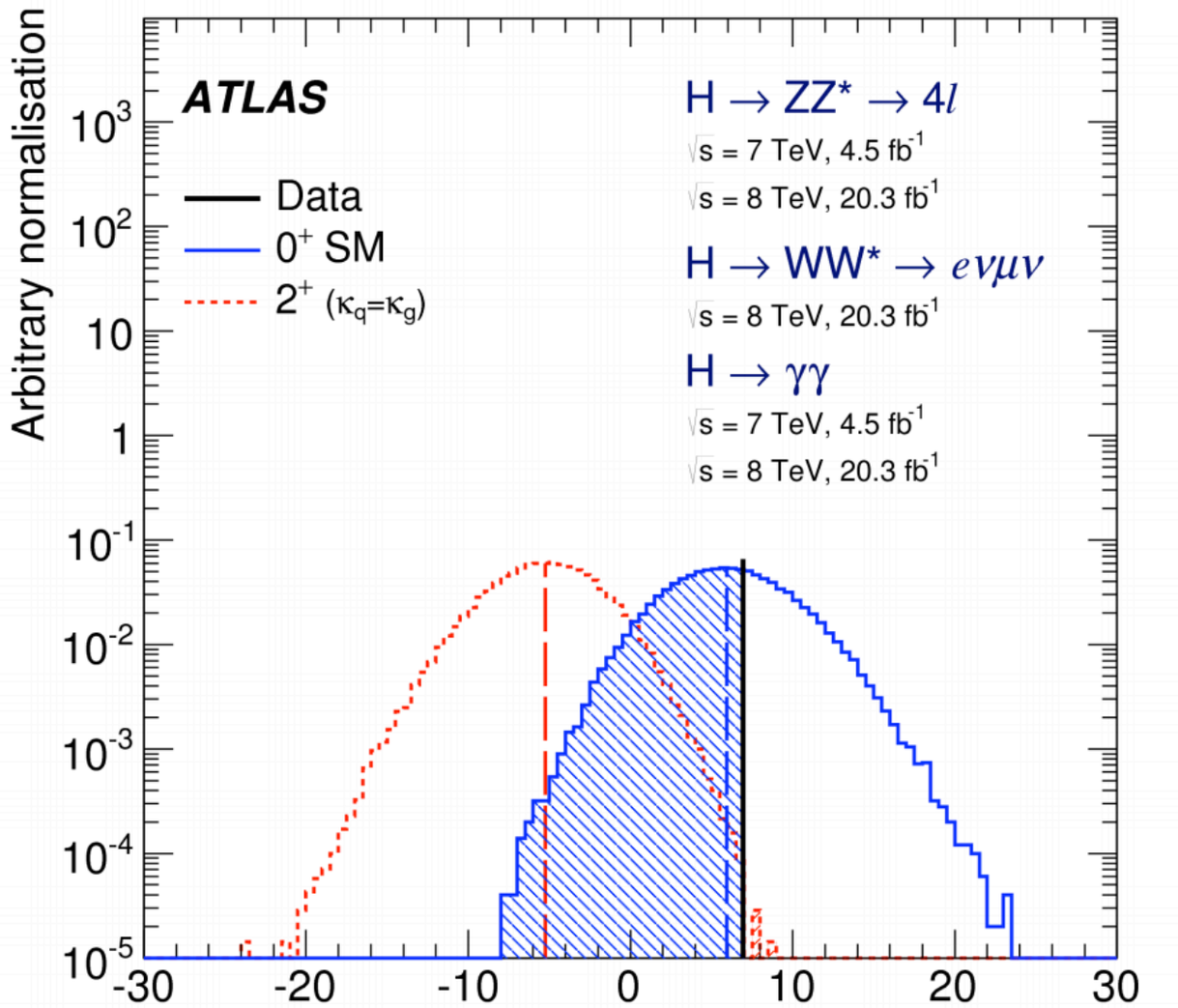
- **Sweden's ATLAS groups are playing a leading role** in precision Higgs measurements ($H \rightarrow WW^*$), direct searches for BSM Higgs production, and di-Higgs final states.

- Di-Higgs production a high profile analysis at the LHC, and Sweden has established itself as one of the key players. E.g. newly-founded **Swedish di-Higgs Working Group** for communication between experimentalists and theorists.

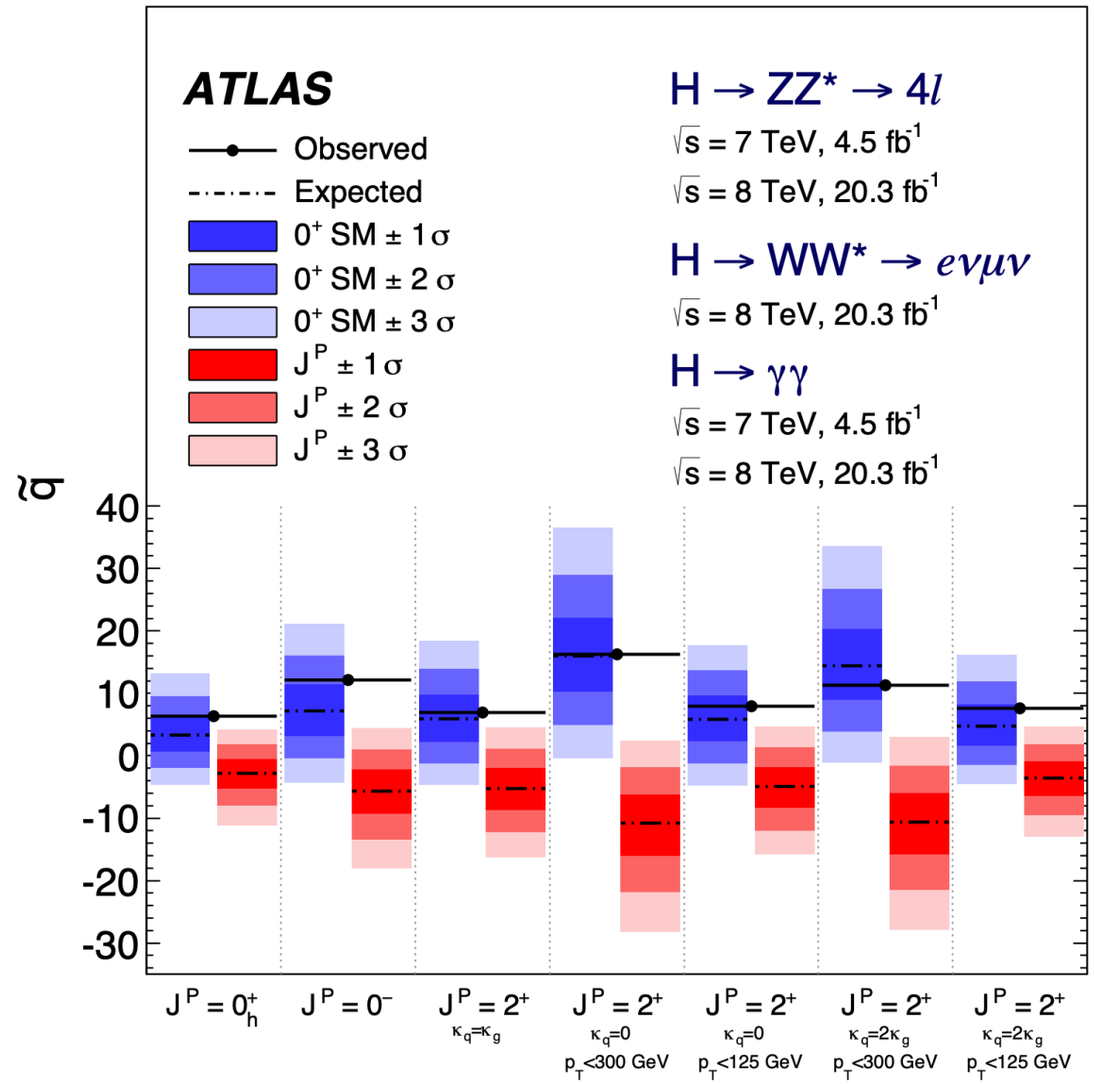
Backup

Why do we care ?

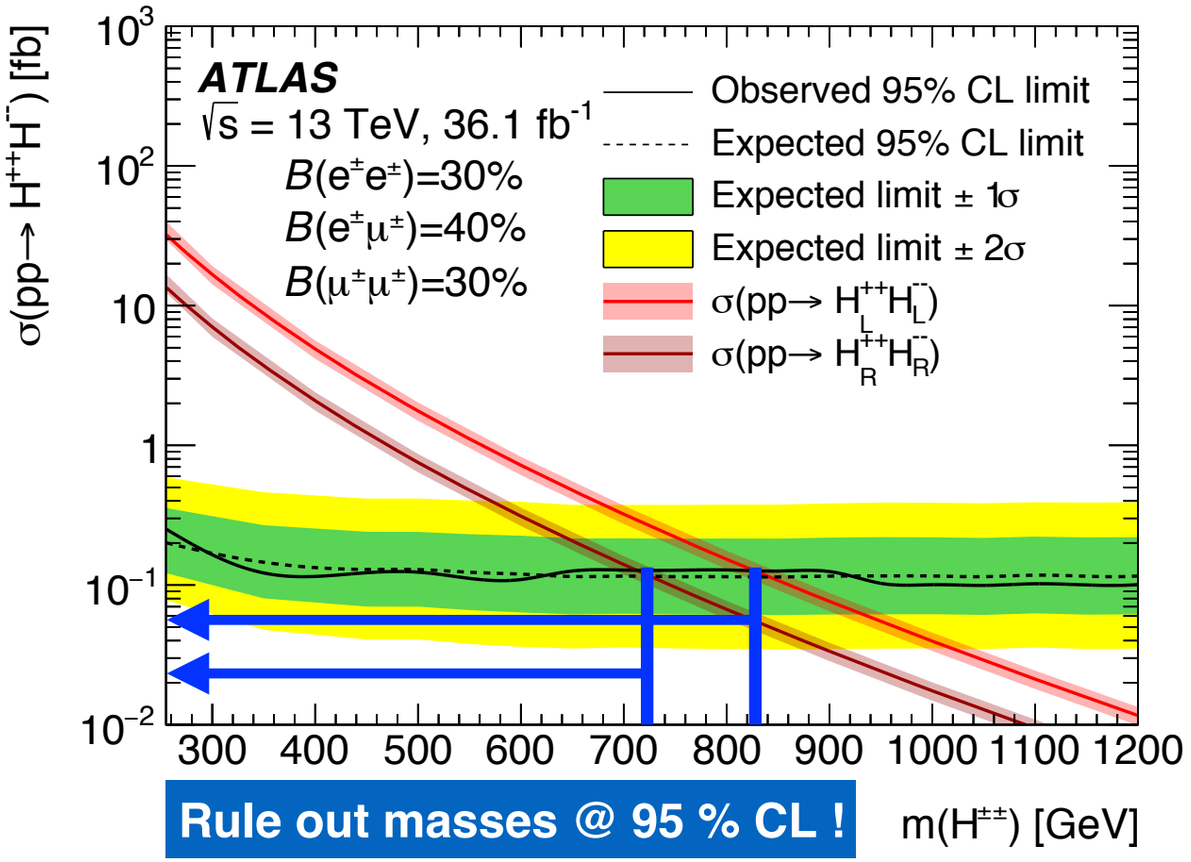
- The only experimentally verified **fundamental scalar** … **SPECIAL !**

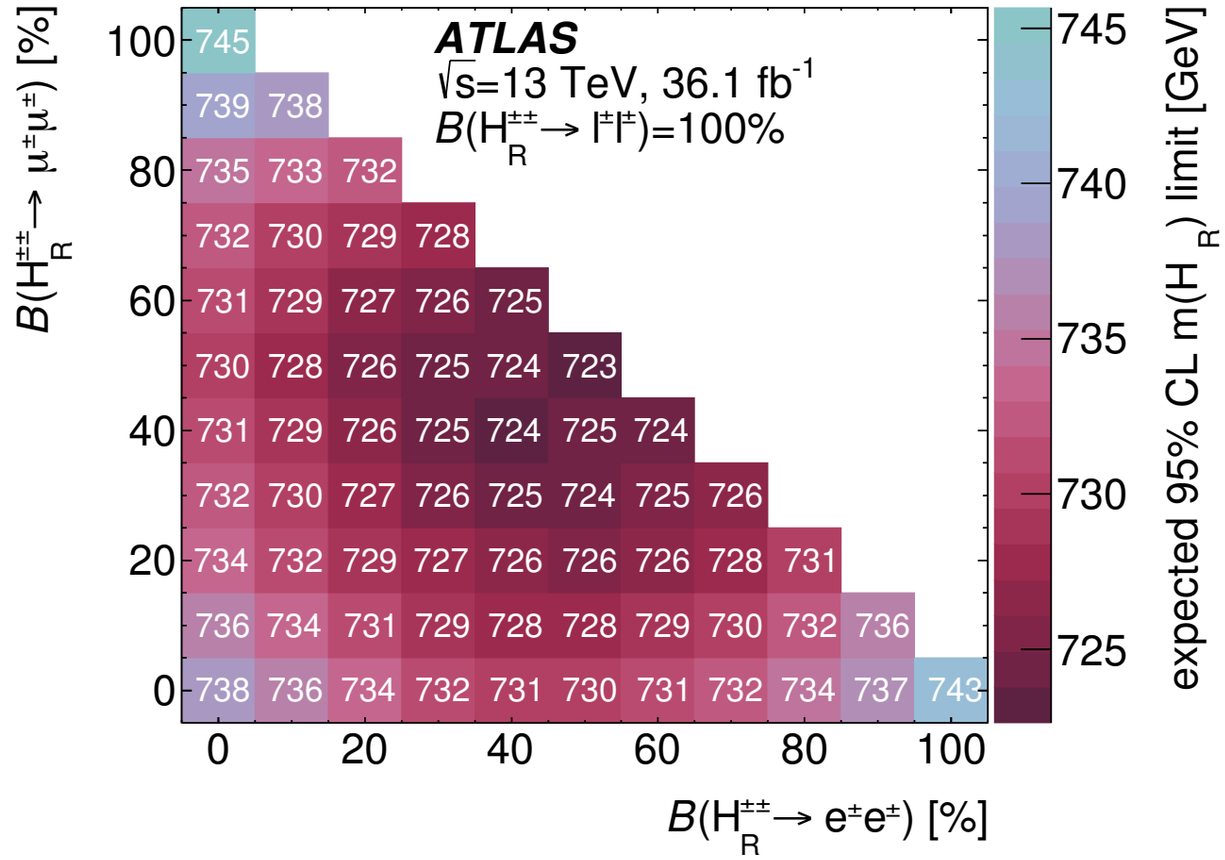


$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{\mathrm{SM}}, \hat{\hat{\mu}}_{J^P_{\mathrm{SM}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{SM}}})}{\mathcal{L}(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}})}$$



Searches for Charged Higgses





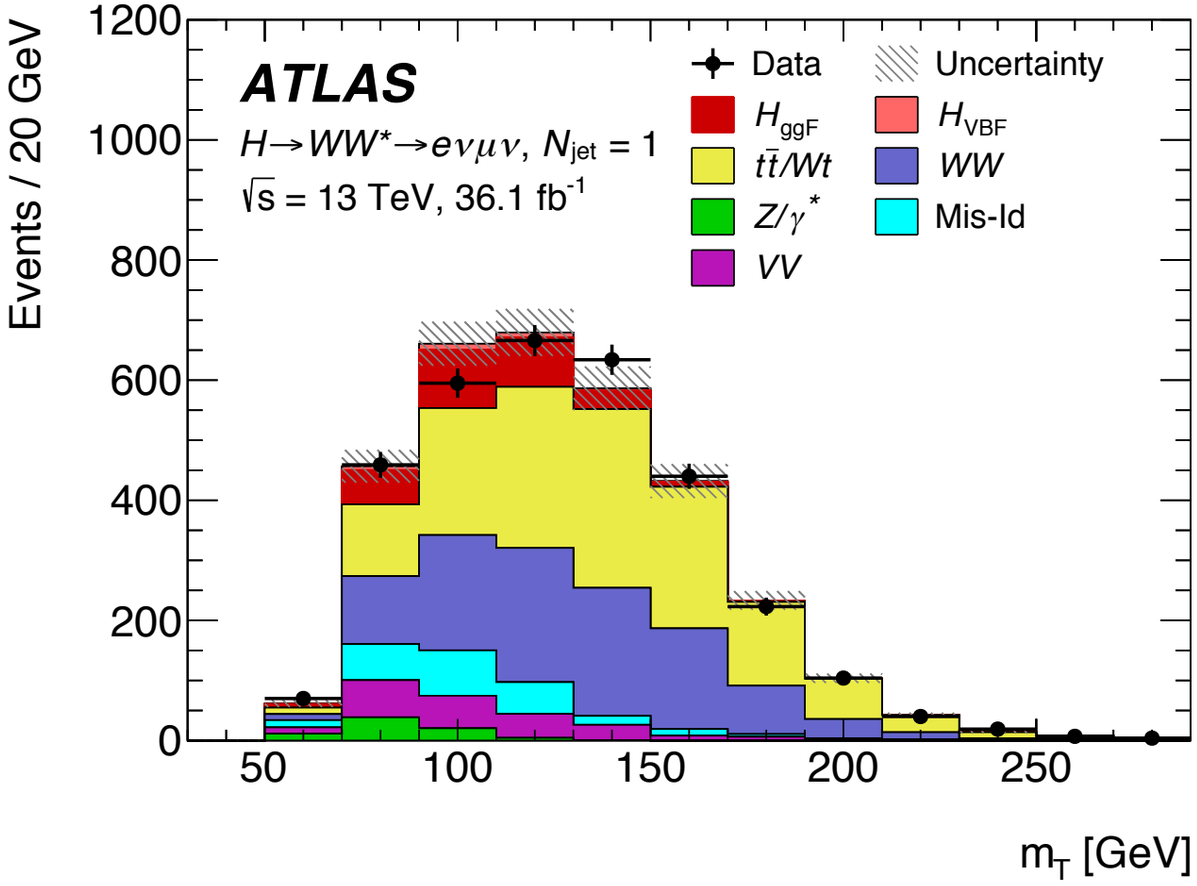
- No statistically significant excesses or bumps in the signal region.
- Set a **combination of limits on the charged Higgs mass**, for BF = 100 % and BF < 100 % (latter particularly favoured by type-II seesaw models).

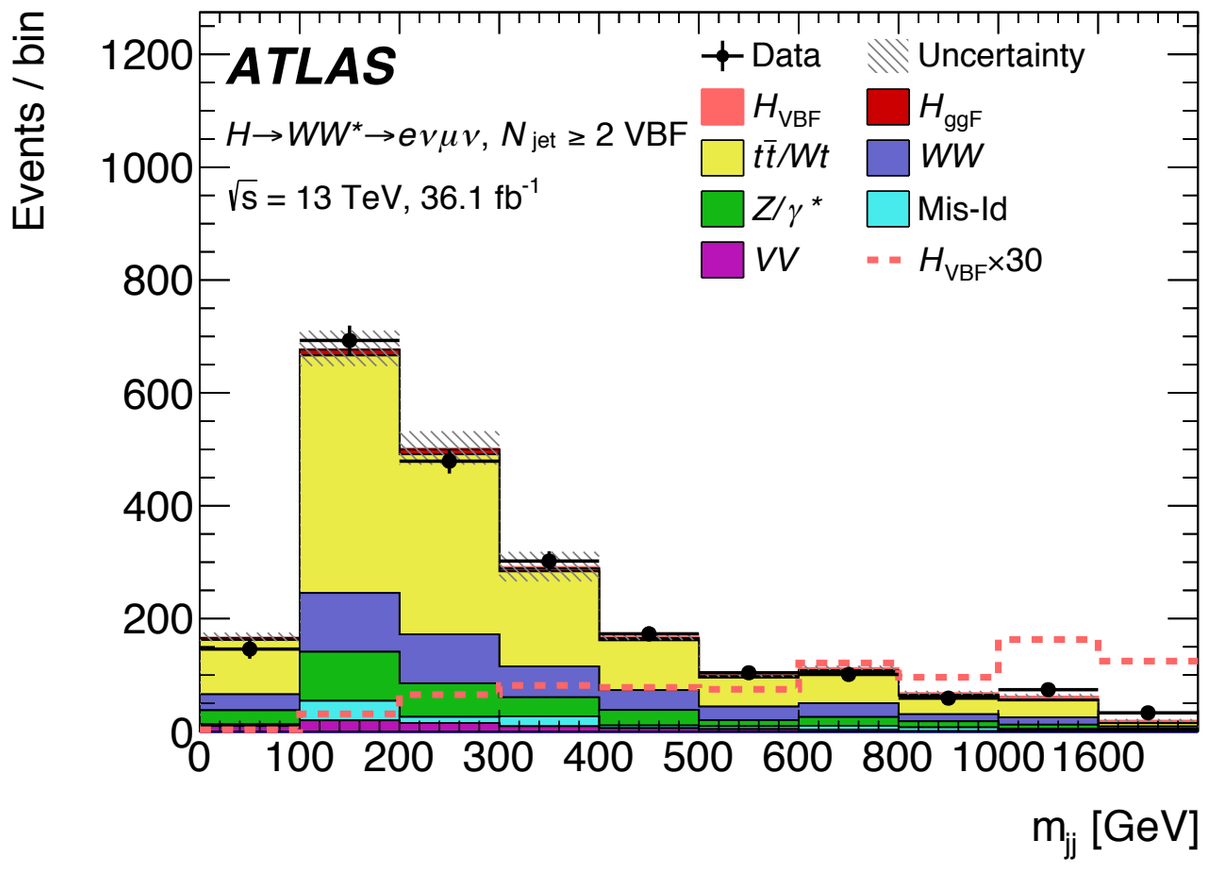
From arXiv:1710.09748

$H \rightarrow WW^*$ Measurements

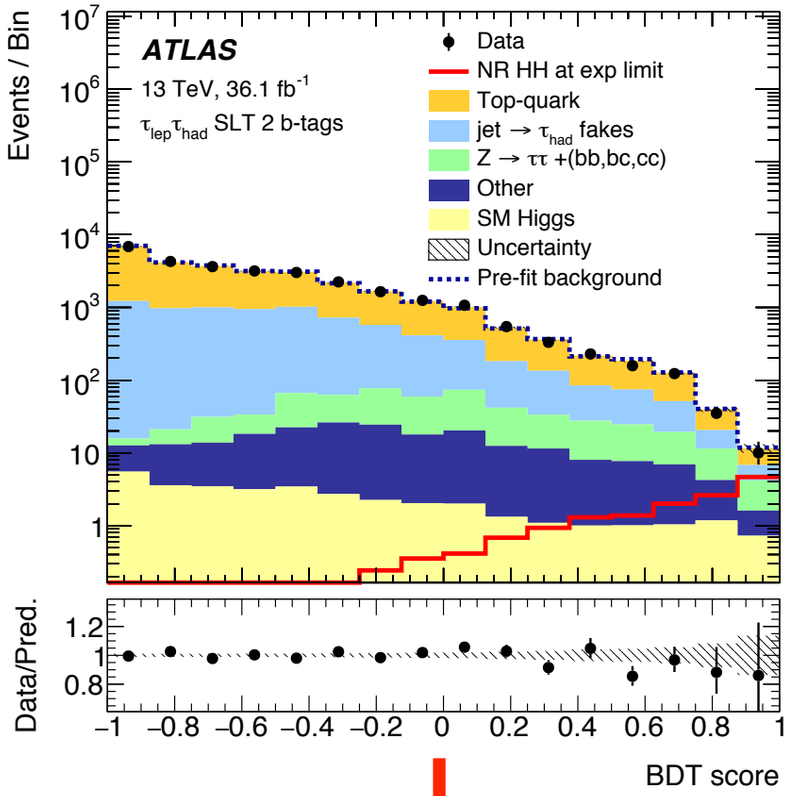
- *b*-tagging, p_T > 20 GeV and m_T cuts used to reduce the **large top production background**.

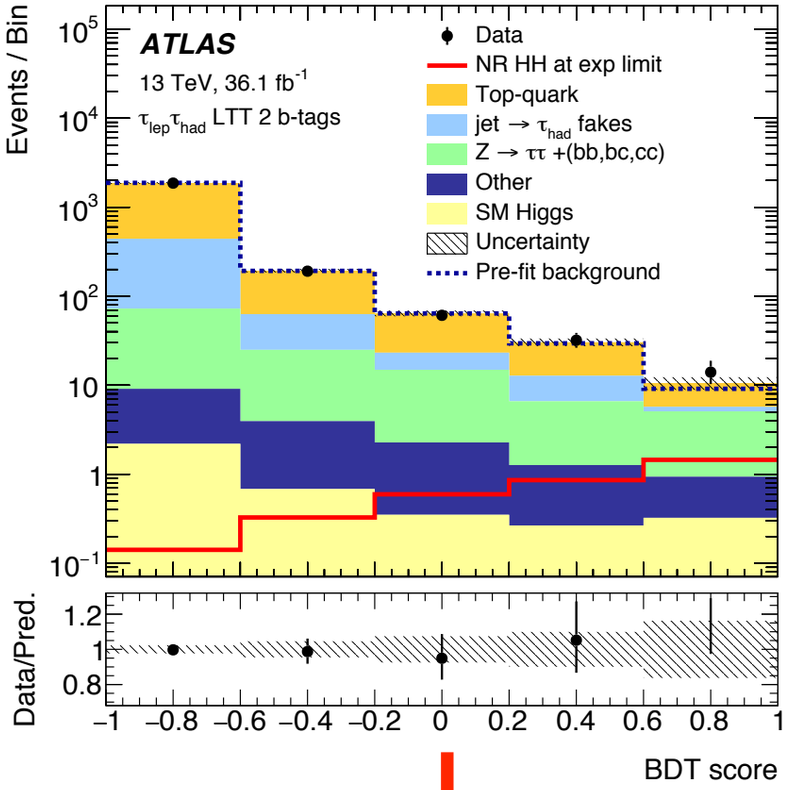
- Additional requirements on dilepton invariant masses and angle between the dilepton system for *gg*F, as well as m_T as the final discriminant; central jet and outside lepton veto used for VBF, followed by a Boosted Decision Tree (BDT) discriminant.

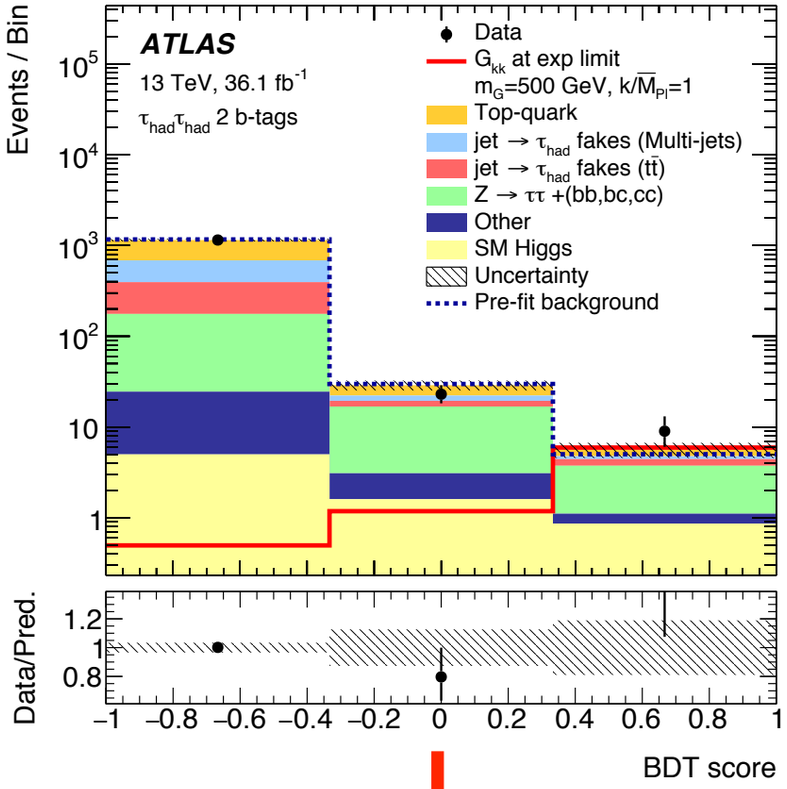




$HH \to bb\tau\tau$







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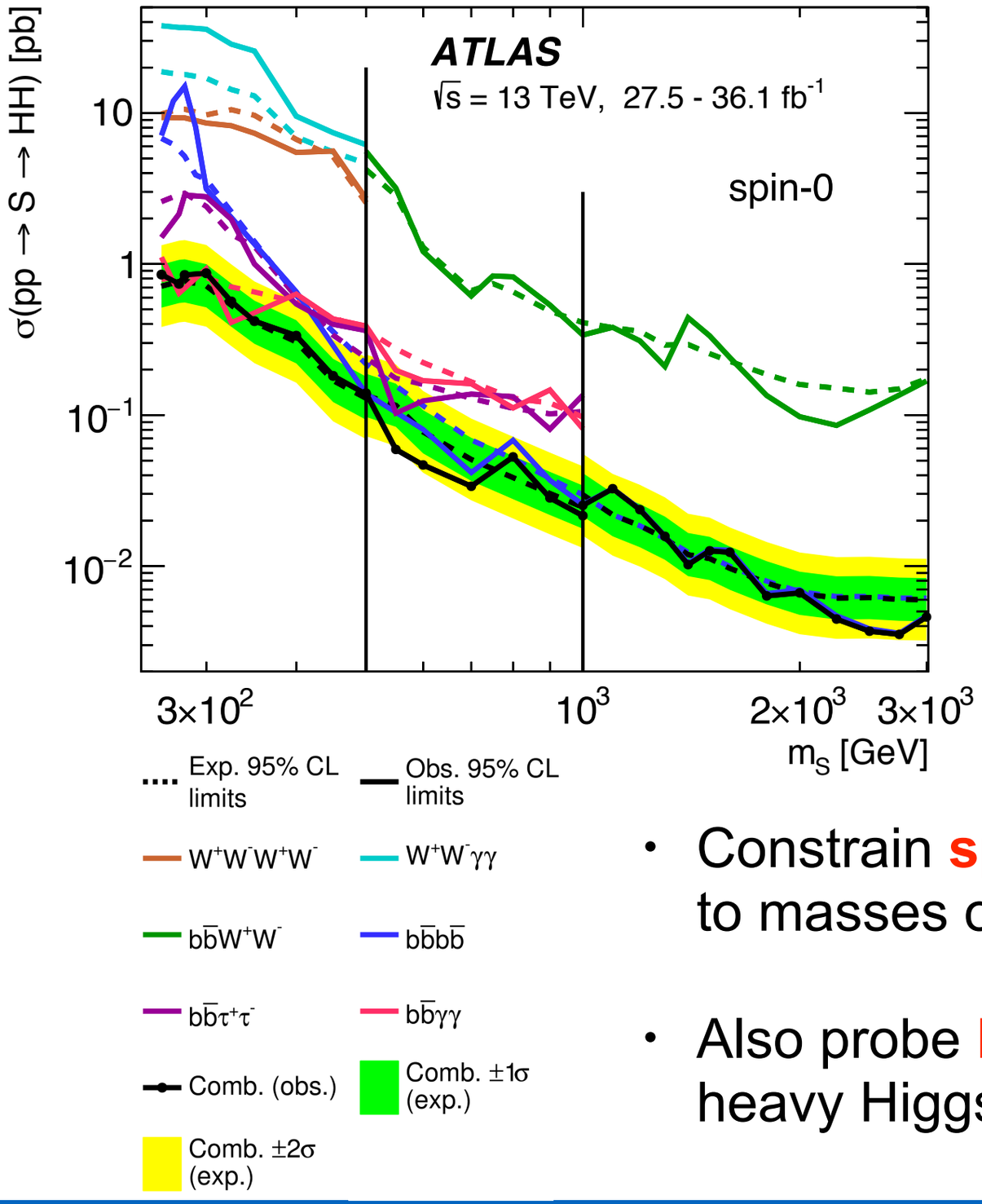
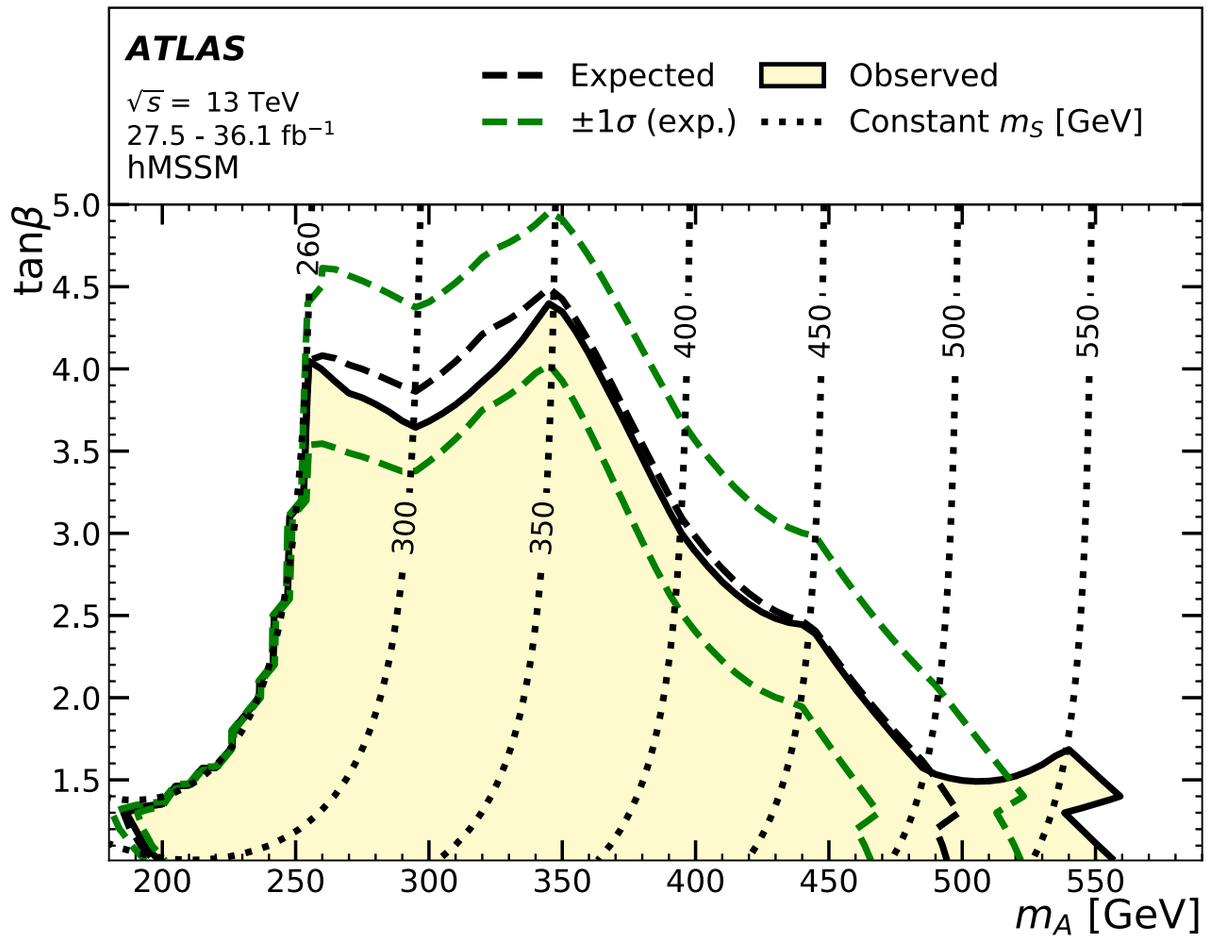
HH Combinations





- Constrain **spin-0 and spin-2 resonance models** up to masses of ~ TeV.
- Also probe **hMSSM parameter space**, constraining heavy Higgs mass up to ~ 500 GeV.

So … where are we headed ?

HL-LHC Prospects

- Extrapolated limits with the HL-LHC could lead to the **5σ discovery of *HH* production**, and a definitive test of the self-coupling in the SM. Further prospects in **ATL-PHYS-PUB-2018-053**.

- Success of discovery dependent on **innovation** and **systematics**.