Double Higgs production in ATLAS

Seminar at University College London

February 15th 2019

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In this talk…

- Double Higgs production
  - SM
  - BSM
  - At the LHC
- Searches in ATLAS
  - Channels included in the combination
- Combined result $36fb^{-1}$
- Prospects in HL-LHC

- Not in this talk:
  - more production mechanisms (VBF, ttHH etc)
  - Searches in CMS
  - Channels not included in the combination
  - Prospects beyond HL-LHC

If I missed your favourite topic, let's discuss at the end!

Double Higgs production in the Standard Model (SM)

- Higgs potential: $V(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{1}{4}\lambda\varphi^4$
- Expand around the vacuum expectation value: $V(\varphi) \rightarrow V(\upsilon + h)$
- $V(h) = V_0 + \lambda\upsilon^2 h^2 + \lambda\upsilon h^3 + \frac{1}{4}\lambda h^4 + \cdots$
- $V(h) = V_0 + \frac{1}{2}m_h{}^2 h^2 + \frac{m_h{}^2}{2\upsilon^2}\upsilon h^3 + \frac{1}{4}\frac{m_h{}^2}{2\upsilon^2}h^4 + \cdots$

$\upsilon = \frac{\mu}{\sqrt{\lambda}}$ and $\mu = \frac{m_h{}^2}{2}$

Mass term: $\frac{1}{2}m_h{}^2 h^2$

Higgs trilinear self-coupling: $\frac{m_h{}^2}{2\upsilon^2}\upsilon h^3$

Higgs quadratic self-coupling: $\frac{1}{4}\frac{m_h{}^2}{2\upsilon^2}h^4$

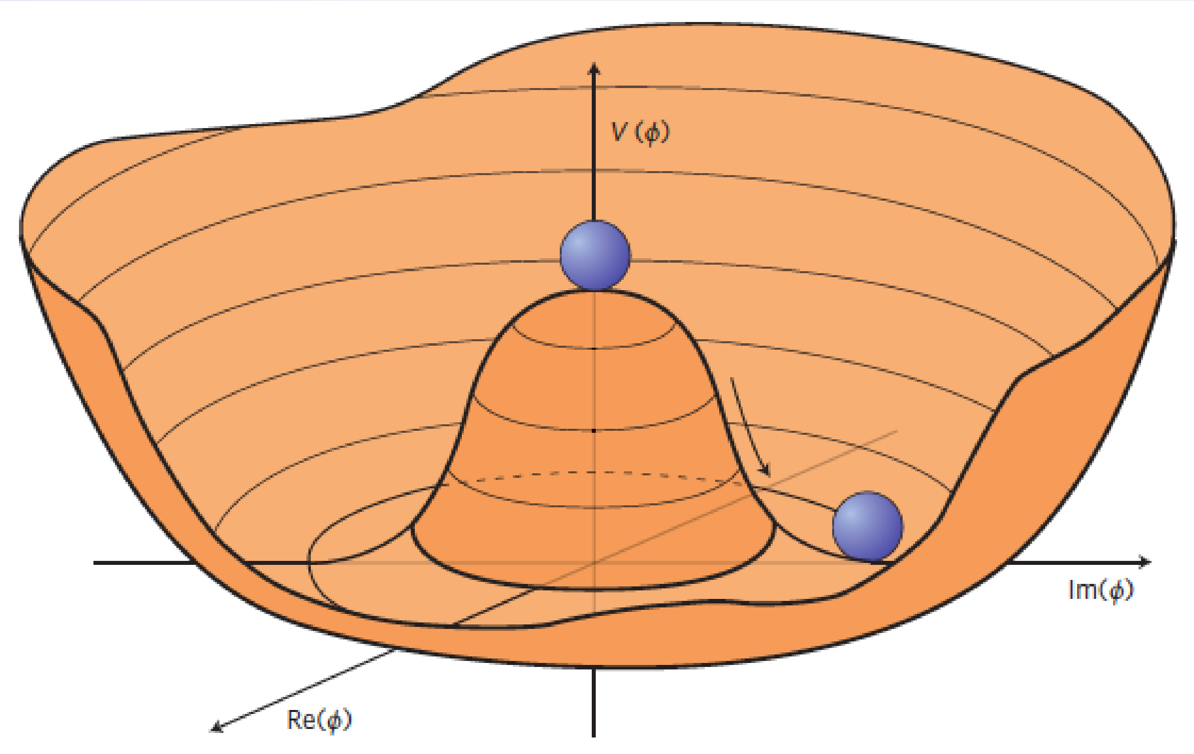
In the SM υ=246 GeV and λ=0.13

Double Higgs production → Higgs trilinear self-coupling

This is what this talk is about (mostly)

Double Higgs production in the Standard Model (SM)

- Higgs potential: $V(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{1}{4}\lambda\varphi^4$
- Expand around the vacuum expectation value: $V(\varphi) \rightarrow V(\upsilon + h)$
- $V(h$
- $V(h$ … $^4) + \cdots$



$\upsilon = \frac{\mu}{\sqrt{\lambda}}$ and $\mu = \frac{{m_h}^2}{2}$

In the SM υ=246 GeV and λ=0.13

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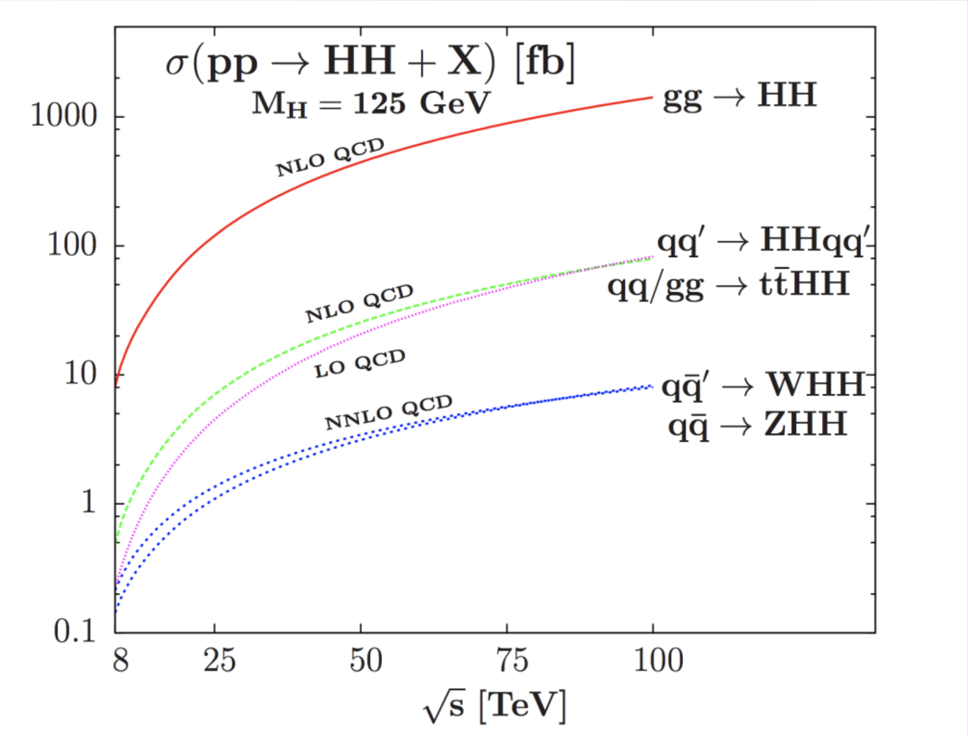
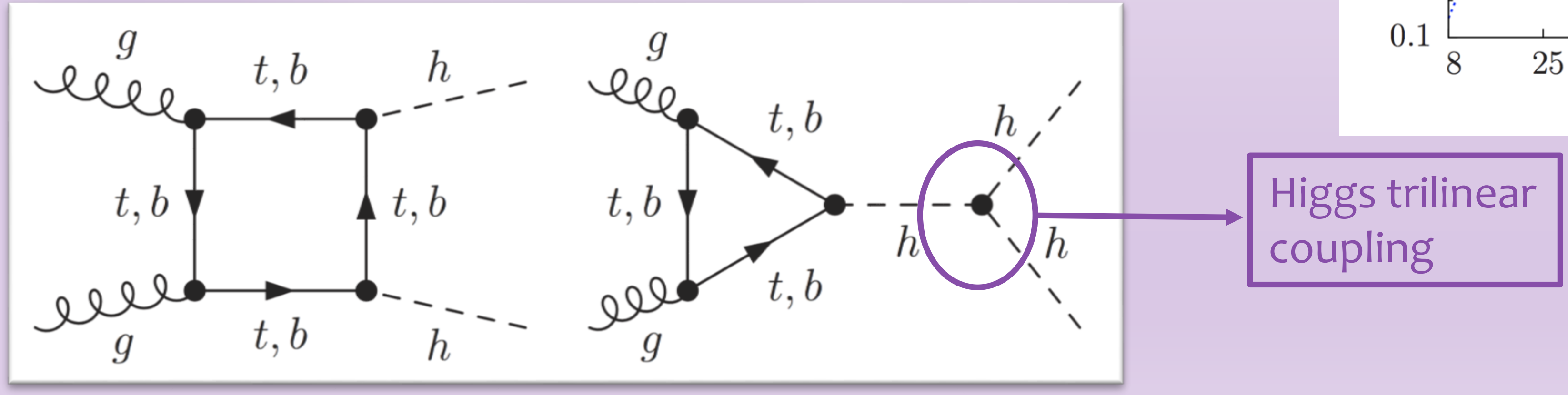
Double Higgs production at the LHC

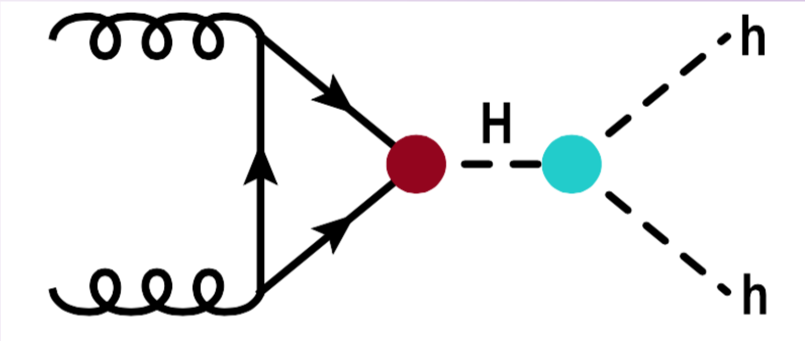


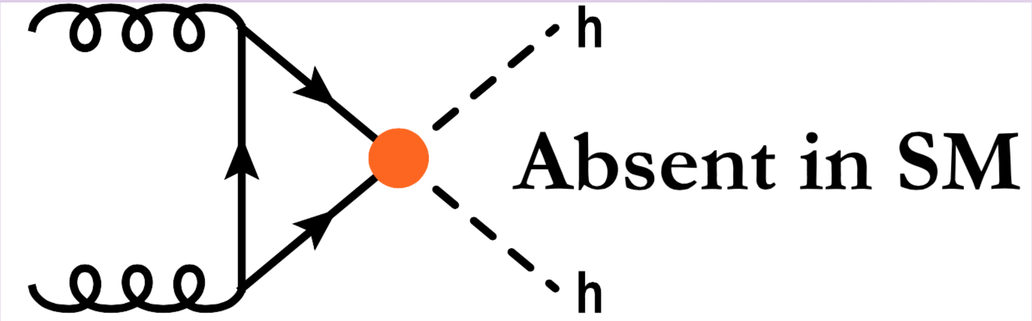
- At the LHC dominant production mechanism for SM double Higgs production is gluon fusion
- The "box" and "triangle" diagrams interact destructively
- SM cross-section very small !! ~40 fb
- (~1000 times smaller than single Higgs production)



Double Higgs production at the LHC (2)

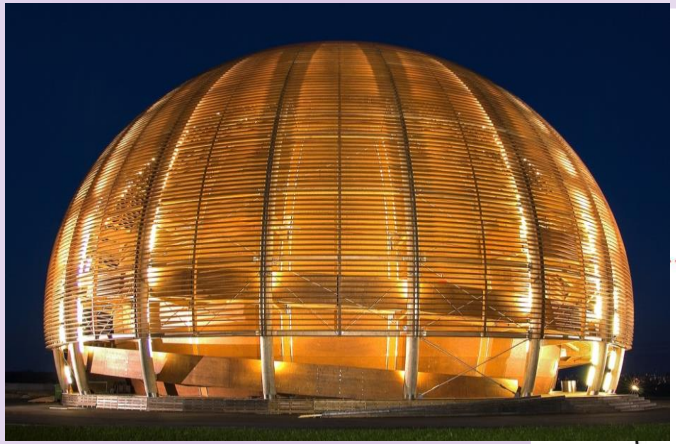
- Beyond the standard model
  - resonant production
  - KK graviton G predicted in the Randal-Sundrum model
  - 2HDM (the heavy neutral scalar H)
- Non resonant BSM enhancements
  - Activating tthh vertex, altering λ_{HHH}

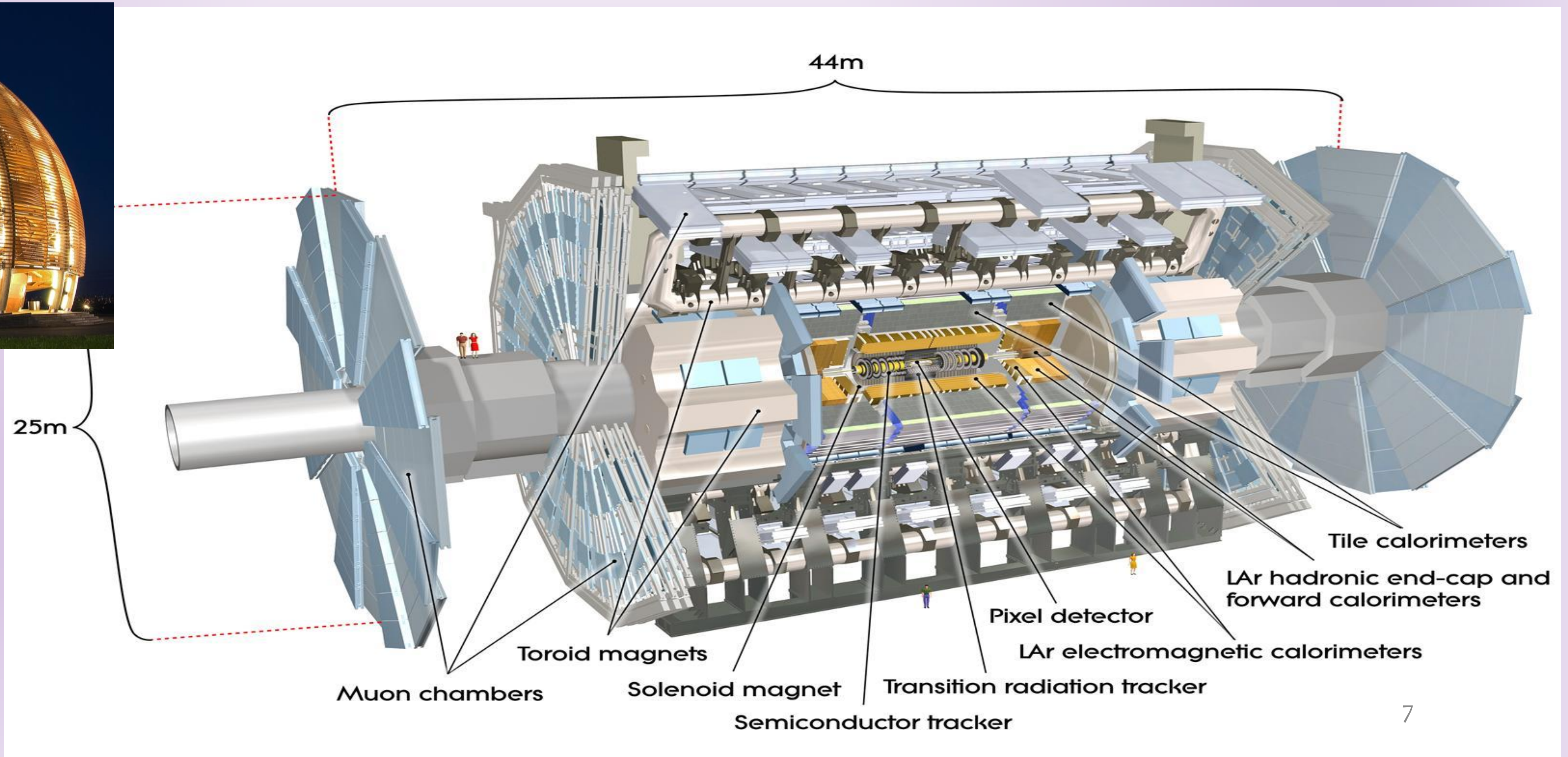




The ATLAS detector

- One of the experiments along the Large Hadron Collider in the Geneva (p-p collisions)





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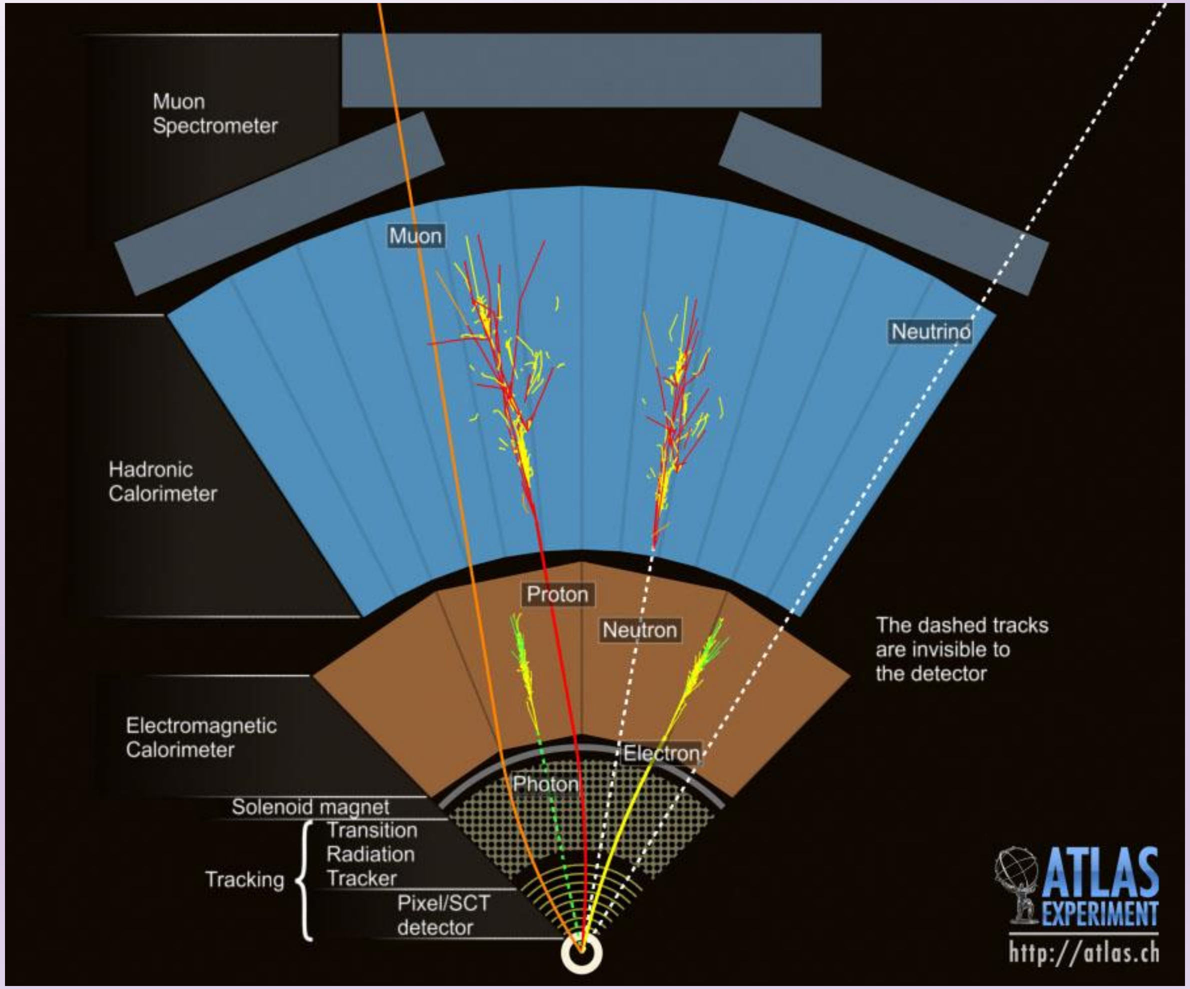
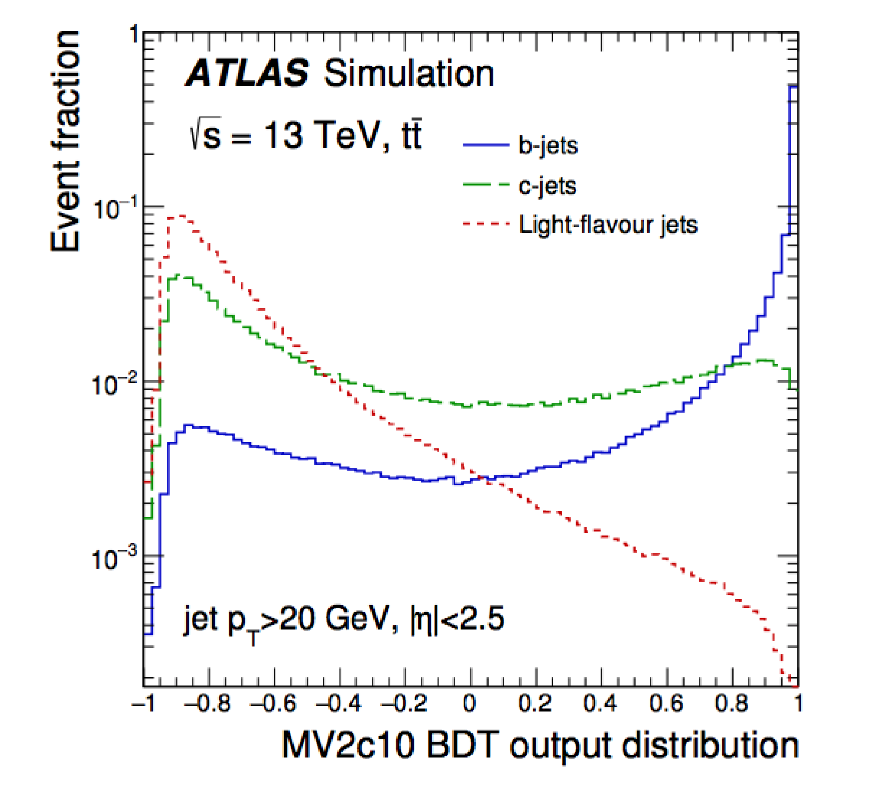


- b-jets are really important for Higgs physics due to the large BR, H->bb BR 0.6
- information from the inner tracker are used to identify b-jets

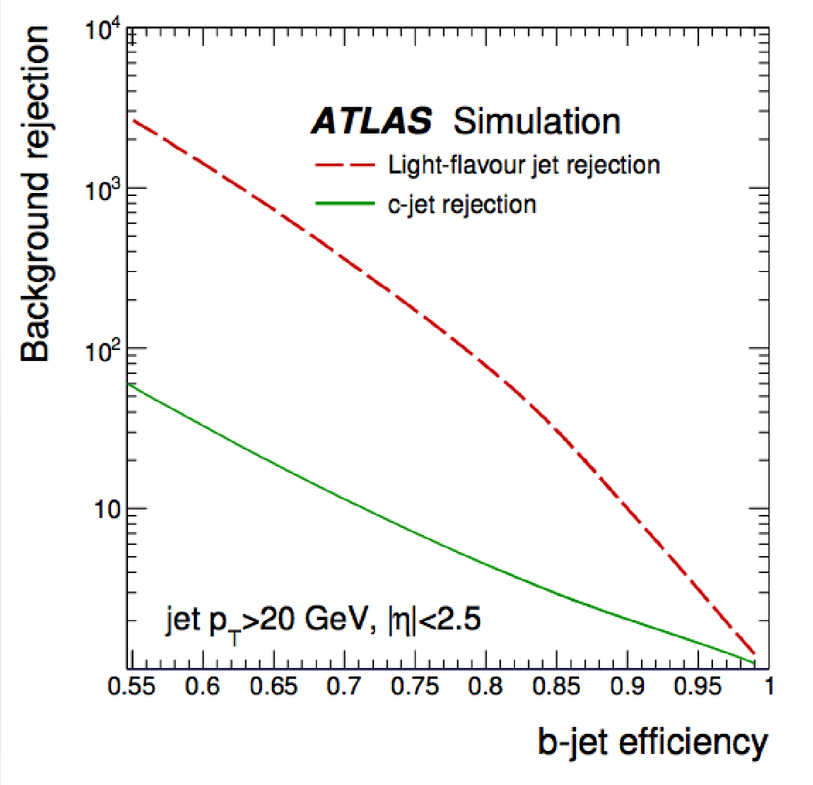
b-tagging in ATLAS

JHEP 08 (2018) 89

ATLAS is using multivariate "b-tagging" algorithms, such as MV2c10



The analyses use 60%-85% efficiency (In HH mostly 70%)



HH decays

bbbb:
the highest branching fraction, large multijet background

bbττ:
relatively large branching fraction, cleaner final state

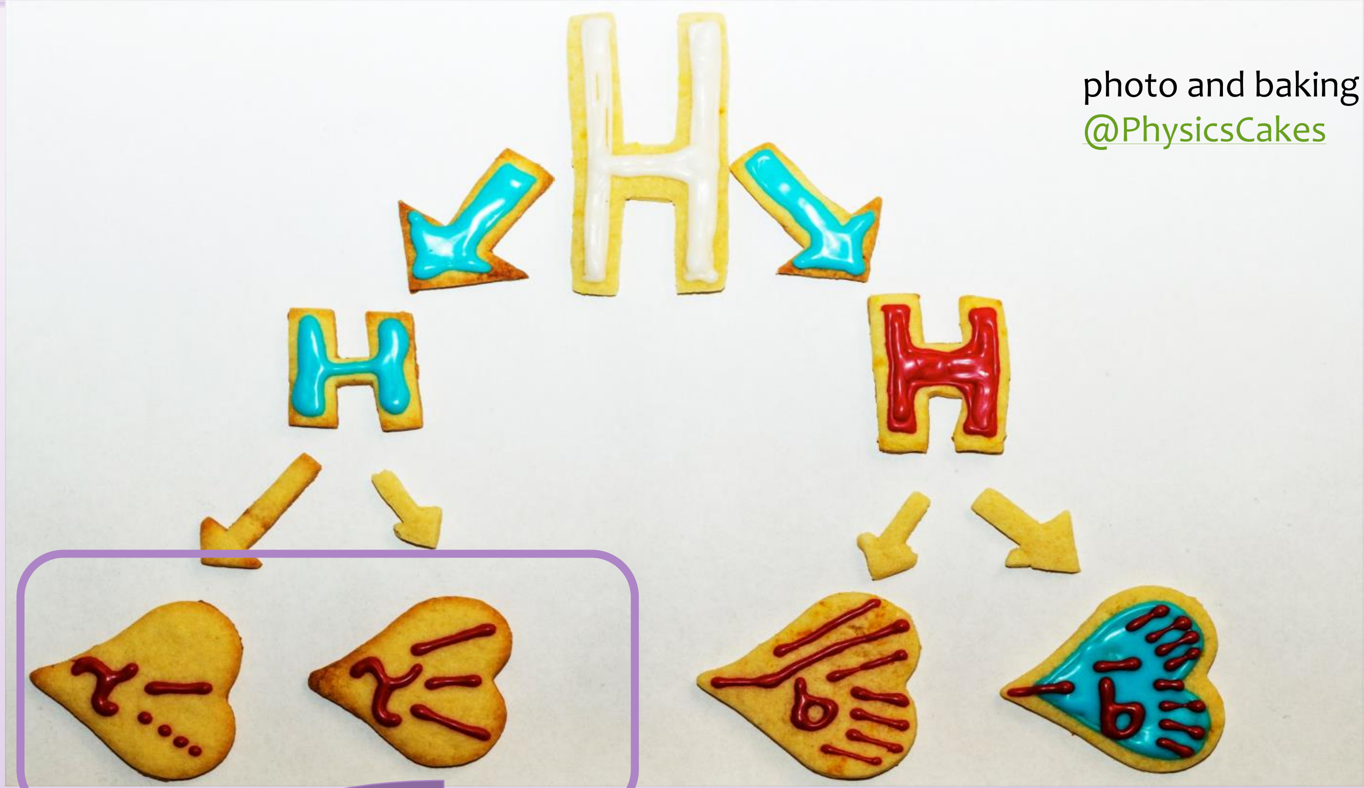
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0053%

WWbb,WWWW and WWγγ also studied!

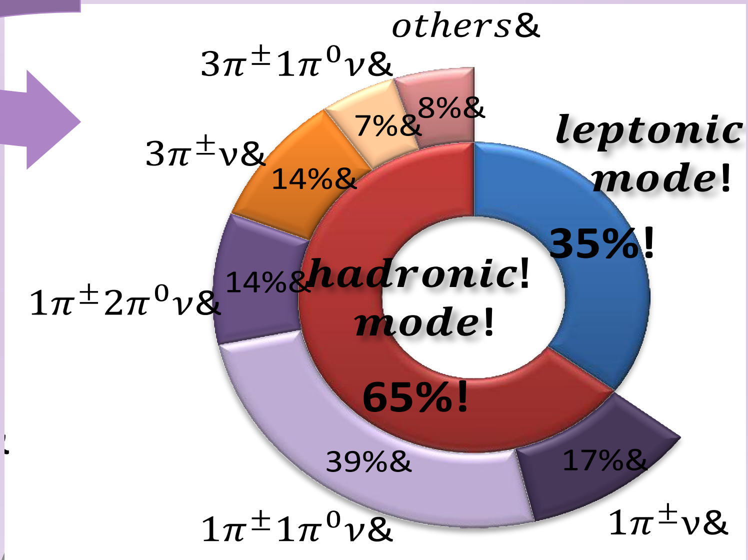
bbγγ:
small branching fraction, clean signal extraction due to the narrow $h \rightarrow \gamma\gamma$ mass peak

bbττ final states

photo and baking credit: @PhysicsCakes



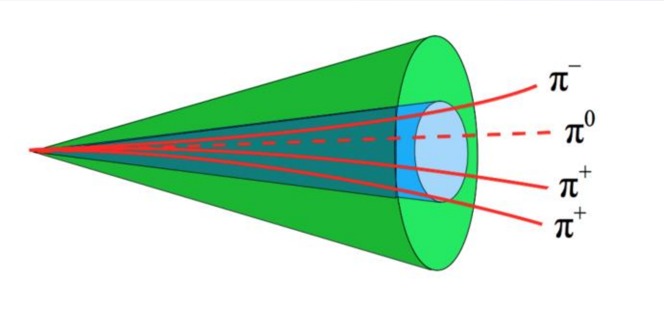
- 2 channels
  - $\tau_h \tau_{e/\mu}$ branching ratio 23%
  - $\tau_h \tau_h$ branching ratio 42%
- Final states with 2 b-tagged jets
- Signal hypotheses
  - Non-resonant production (e.g. SM)
  - Resonant production
    Mass points 260 GeV- 1TeV
    Benchmark scenarios:
    - 2HDM heavy scalar
    - Spin 2 Randall-Sundrum graviton (RSG)

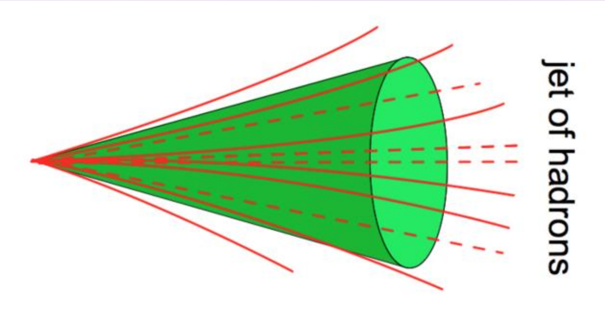


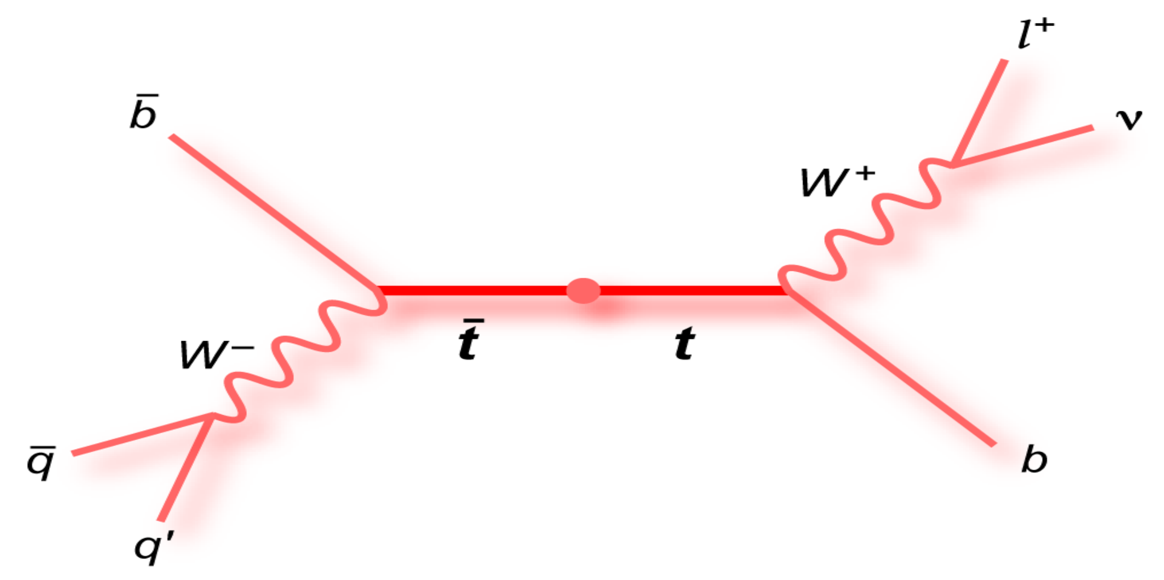
https://arxiv.org/pdf/1808.00336.pdf

bbττ analysis strategy

- Main background processes for $\tau_h\tau_{e/\mu}$ and $\tau_h\tau_h$
  - ttbar
  - QCD
  - Z+bb,cc or bc
  - **jets faking τ_h**
- Use fake factor (FF) method for the fake τ background (jet -> τ)
  - FF is the ratio of the number of fake-τ_h that pass the τ identification to the number that fail
  - contribution from multiple processes $FF_{comb} = FF_{QCD} * R_{QCD} + FF_{ttbar/W+jets} * (1-R_{QCD})$
  - R_{QCD} is the fraction of fake- τ_h that comes from QCD multijets
  - 1 and 3 track decays treated separately
  - The FF are estimated in control regions.
    - Inverse τ_h identification selection in $\tau_h\tau_{e/\mu}$
    - Region where the τ decay products have the same charge and inverse isolation selection in $\tau_h\tau_h$







bbττ Boosted Decision Trees (BDTs)

- Using BDTs, a multivariate method for signal and background discrimination
- Trained especially for different resonant masses.
- The $\tau_h\tau_h$ channel is trained against all major backgrounds.
  The $\tau_h\tau_l$ channel is trained only against ttbar

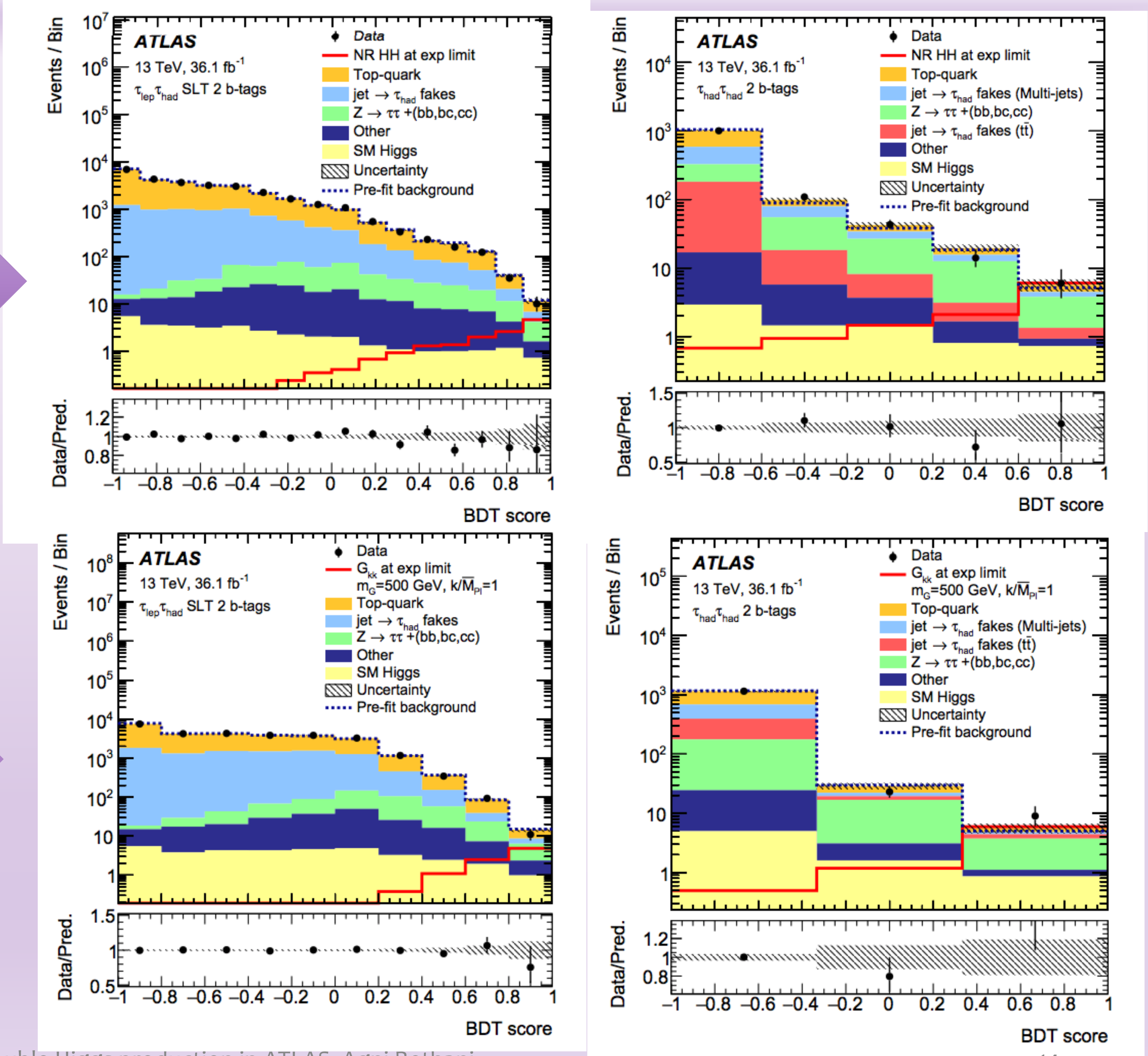
Variable	$\tau_{lep}\tau_{had}$ channel (SLT resonant)	$\tau_{lep}\tau_{had}$ channel (SLT non-resonant & LTT)	$\tau_{had}\tau_{had}$ channel
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	✓
E_T^{miss}	✓		
E_T^{miss} ϕ centrality	✓		✓
m_T^W	✓	✓	
$\Delta\phi(H,H)$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

bbττ BDT score

NR signal

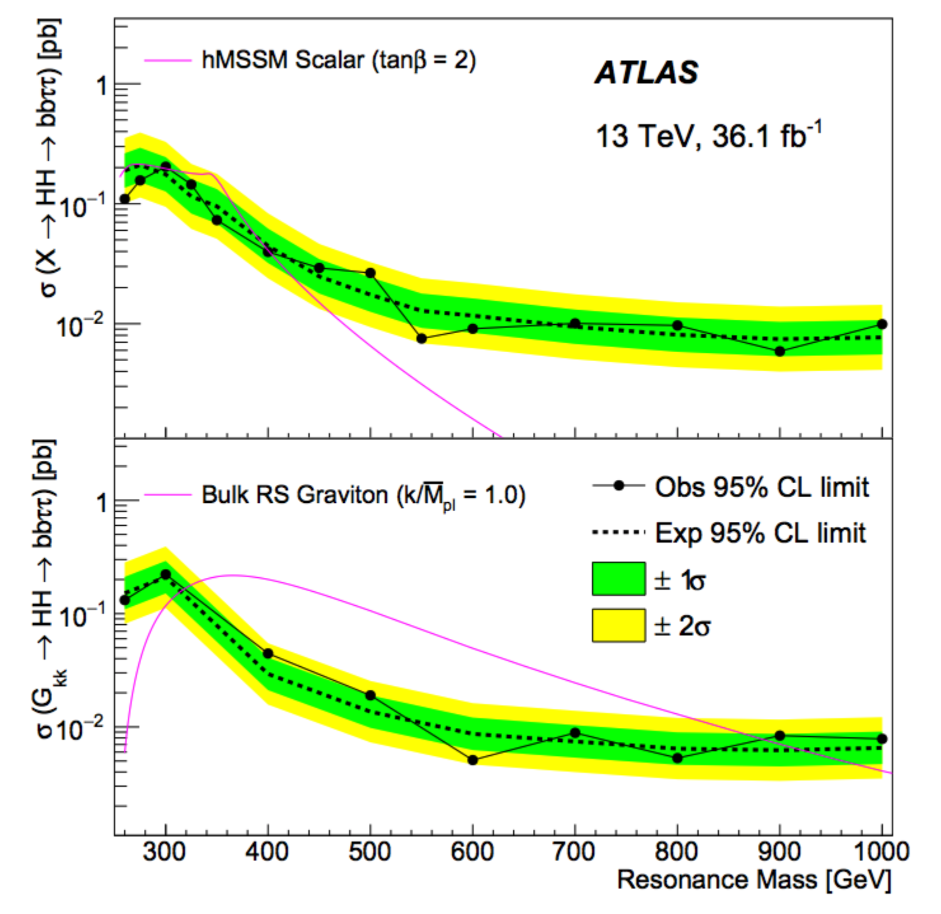
RSG signal

- The BDT scores are used as the final discriminant for every channel and signal.
- NO CUT is applied on the BDT score.



bbττ results

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

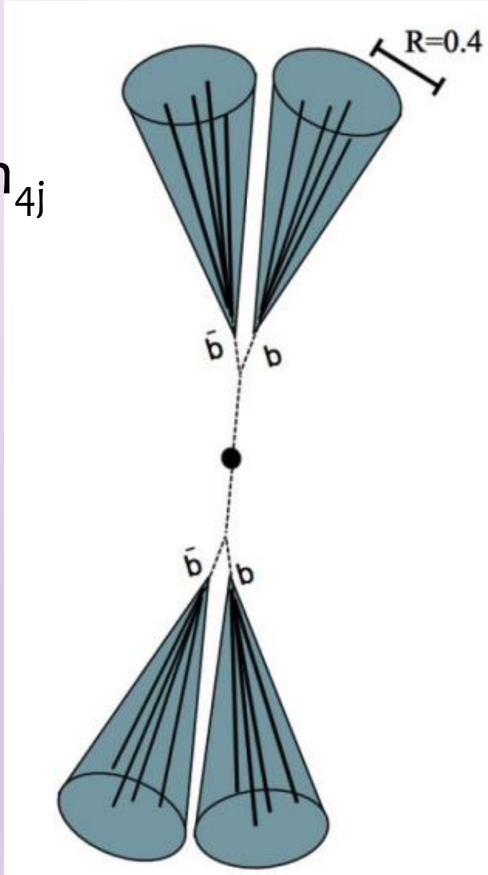


The non-resonant result is:
observed (expected)
12.7 (14.8) xSM prediction
This is the best single channel limit in HH production in the world, ever!
Comparable with the CMS combined result ;)

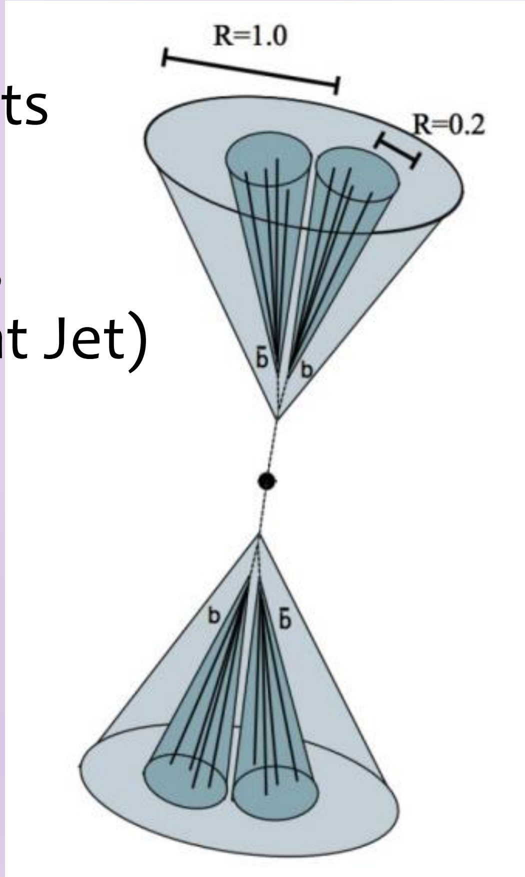
bbbb final states

https://arxiv.org/pdf/1804.06174.pdf

- Resolved
- Reconstruct 4 b-jets
  Final discriminator m_{4j}
- Signal hypotheses
  - non-resonant
  - Resonant signal
    m_X 260-1400 GeV

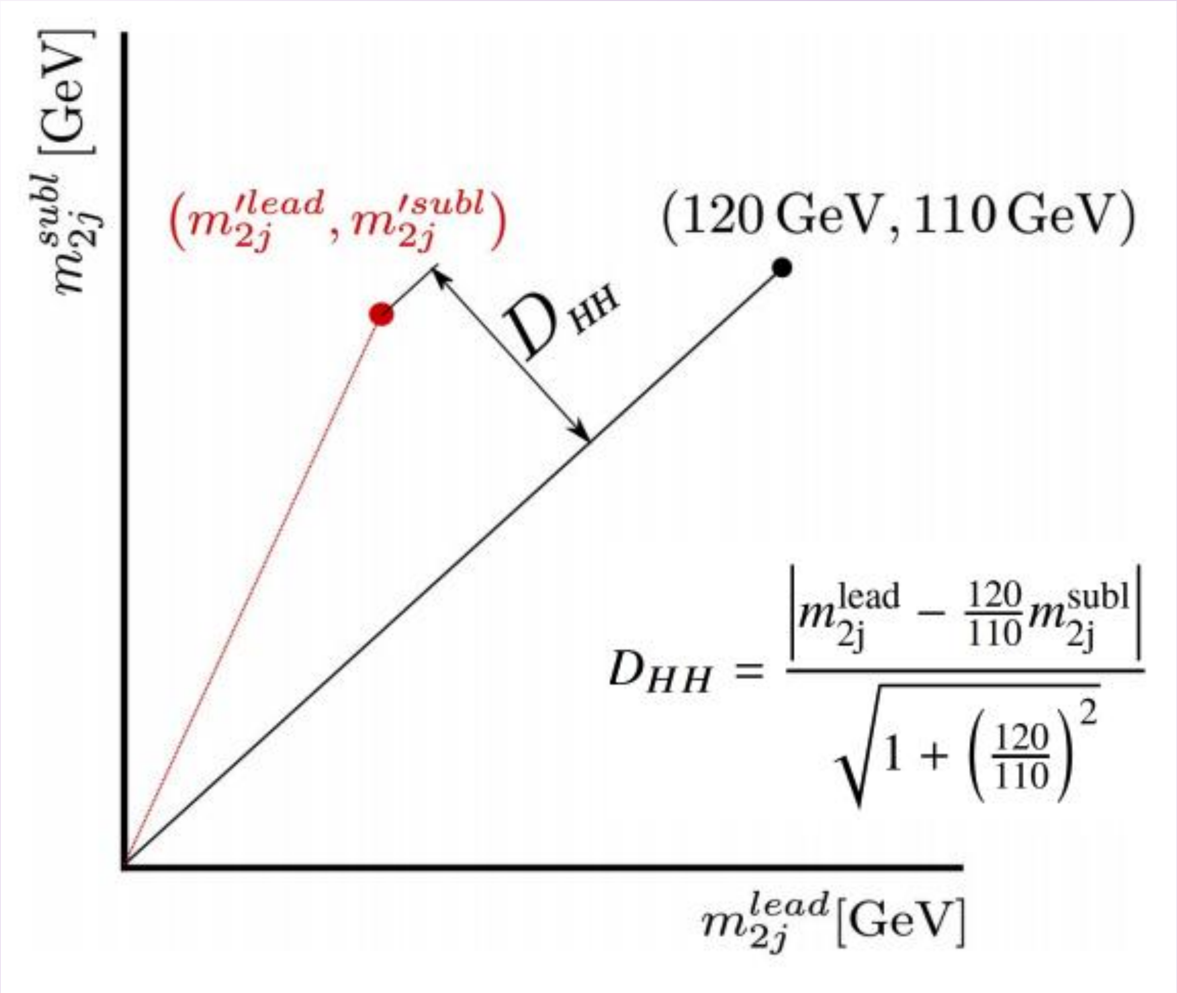


- Boosted
- Cannot resolve the 2 b-jets
  Final discriminator m_{jj}
- Categories : 2, 3, 4 b-tags
  (2-tags: b from a different Jet)
- Signal hypotheses
  - Resonant signal
    m_X 800-3000 GeV



bbbb: Resolved analysis

- 3 possible combinations- combinatoric background
  - Need the combination most consistent with a HH topology
  - Select hh pair that has the minimal distance to the diagonal line.
    i.e. minimise D_{HH}
  - In simulation, this leads to at least 90% correct pairings



bbbb: Resolved analysis

Event selection

$$X_{HH} = \sqrt{\left(\frac{m_{2j}^{lead} - 120\ \text{GeV}}{0.1 m_{2j}^{lead}}\right)^2 + \left(\frac{m_{2j}^{subl} - 110\ \text{GeV}}{0.1 m_{2j}^{subl}}\right)^2} < 1.6$$

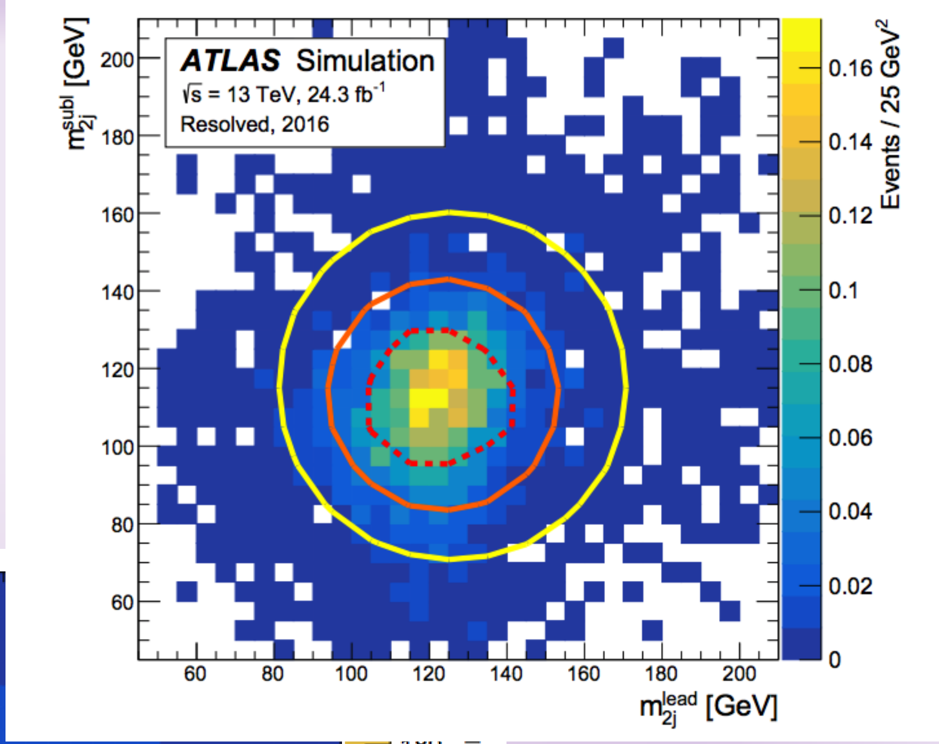
QCD multi-jets

- Use 2-tag sample for shape template
- Weights are applied, estimated in the side band and validated in the control region

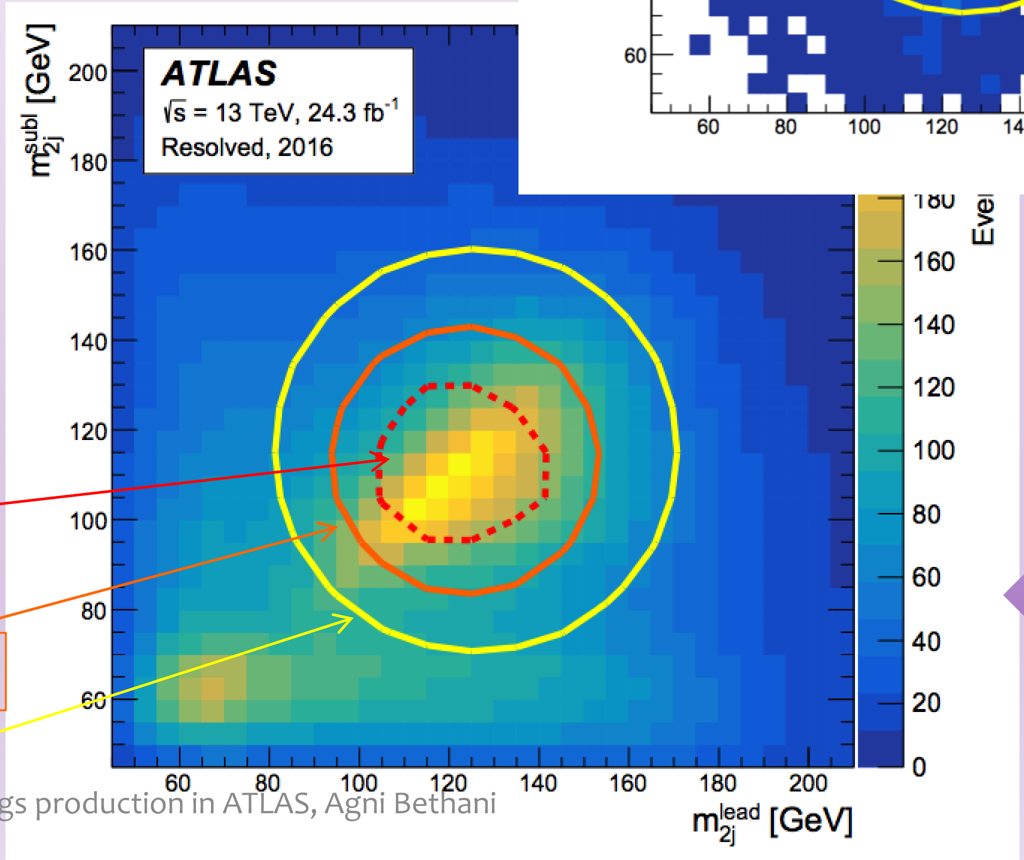
ttbar

- Shape from simulation

Normalisation
from fit in sidebands



Signal



Signal region

control region

side band

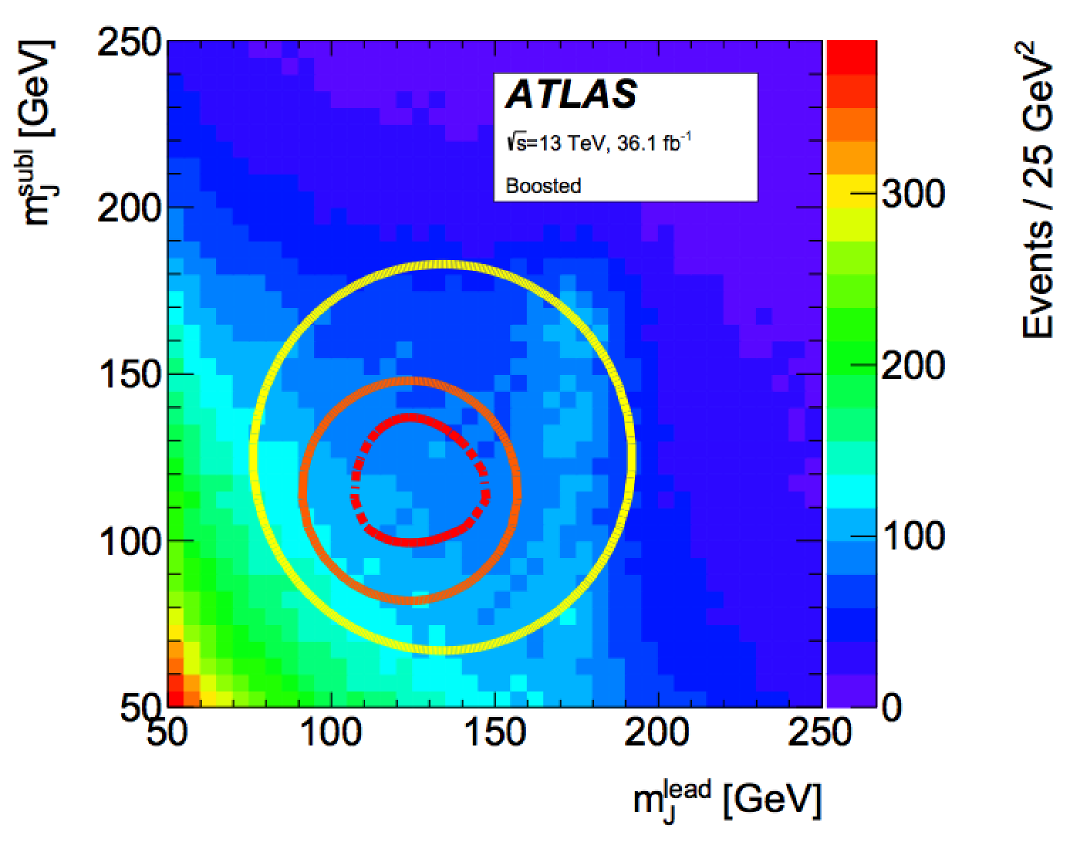
multi-jets

bbbb: boosted analysis

- The cut X_{HH} becomes:

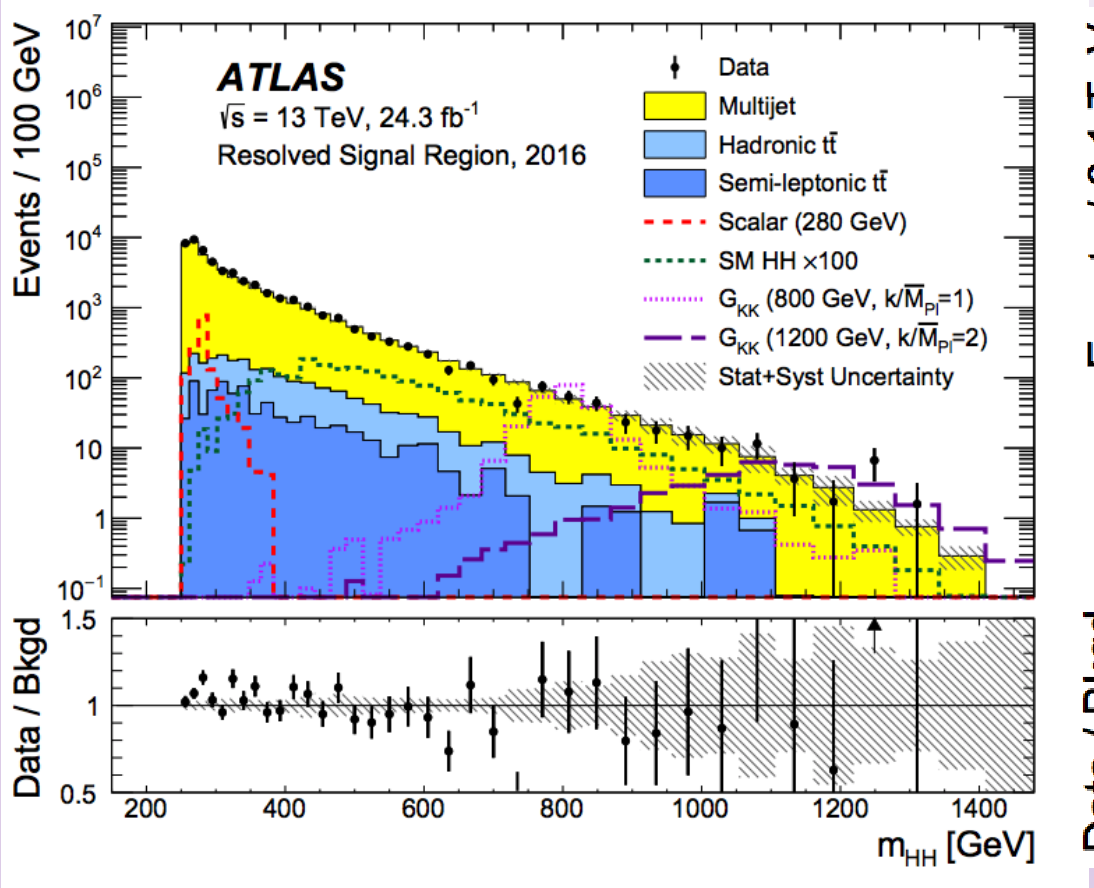
$$X_{HH} = \sqrt{\left(\frac{m_J^{lead} - 124\text{ GeV}}{0.1 m_J^{lead}}\right)^2 + \left(\frac{m_J^{subl} - 115\text{ GeV}}{0.1 m_J^{subl}}\right)^2} < 1.6,$$

- Shape of multijets using events with less b-tags.
  (e.g. 2 b-tag category using 1 b-tag events)
- ttbar from simulation
- Normalisation from side band

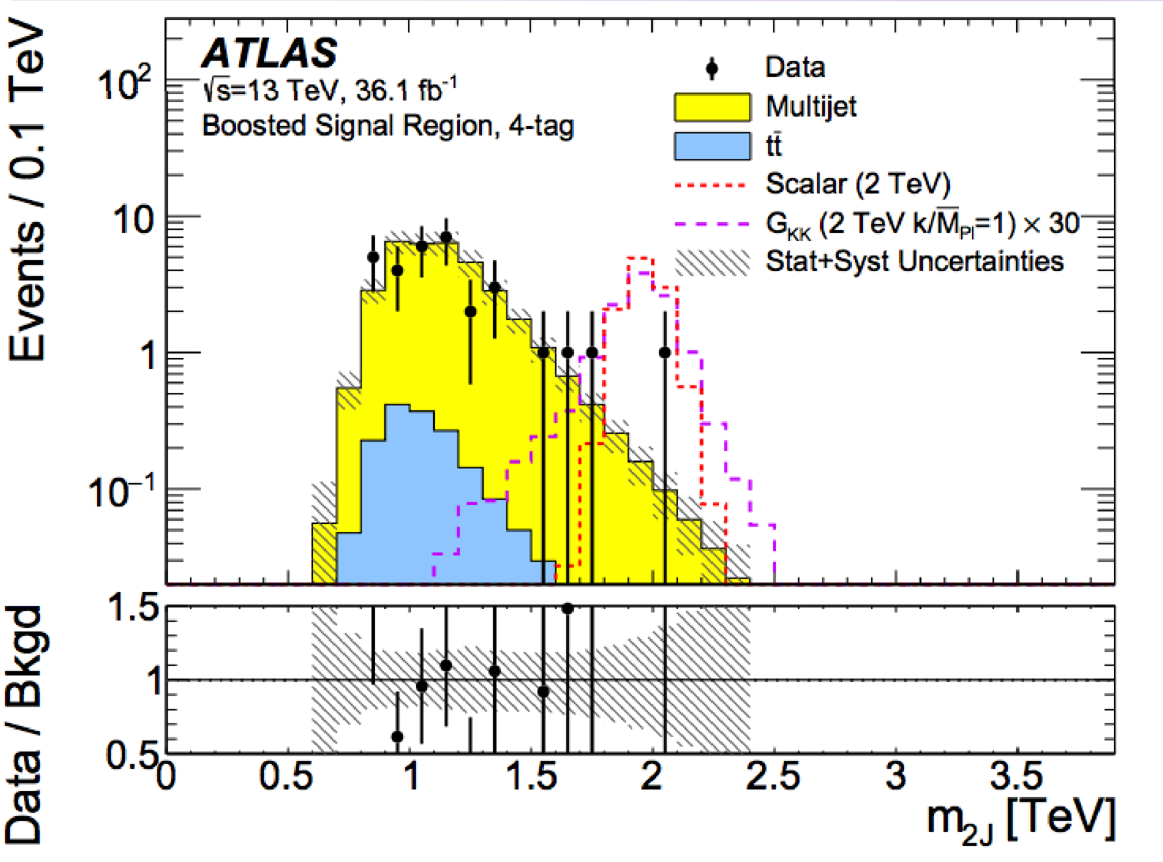


bbbb discriminants

Resolved 2016 dataset



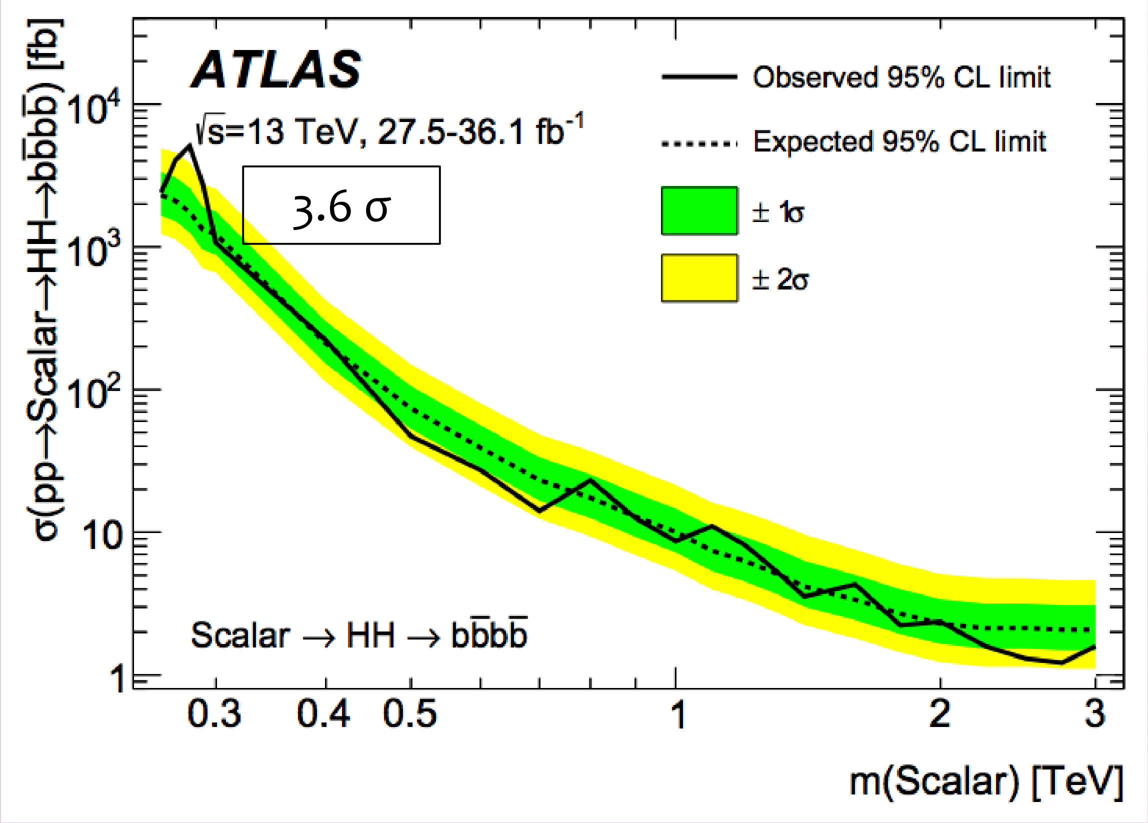
Boosted, 4b-tag category

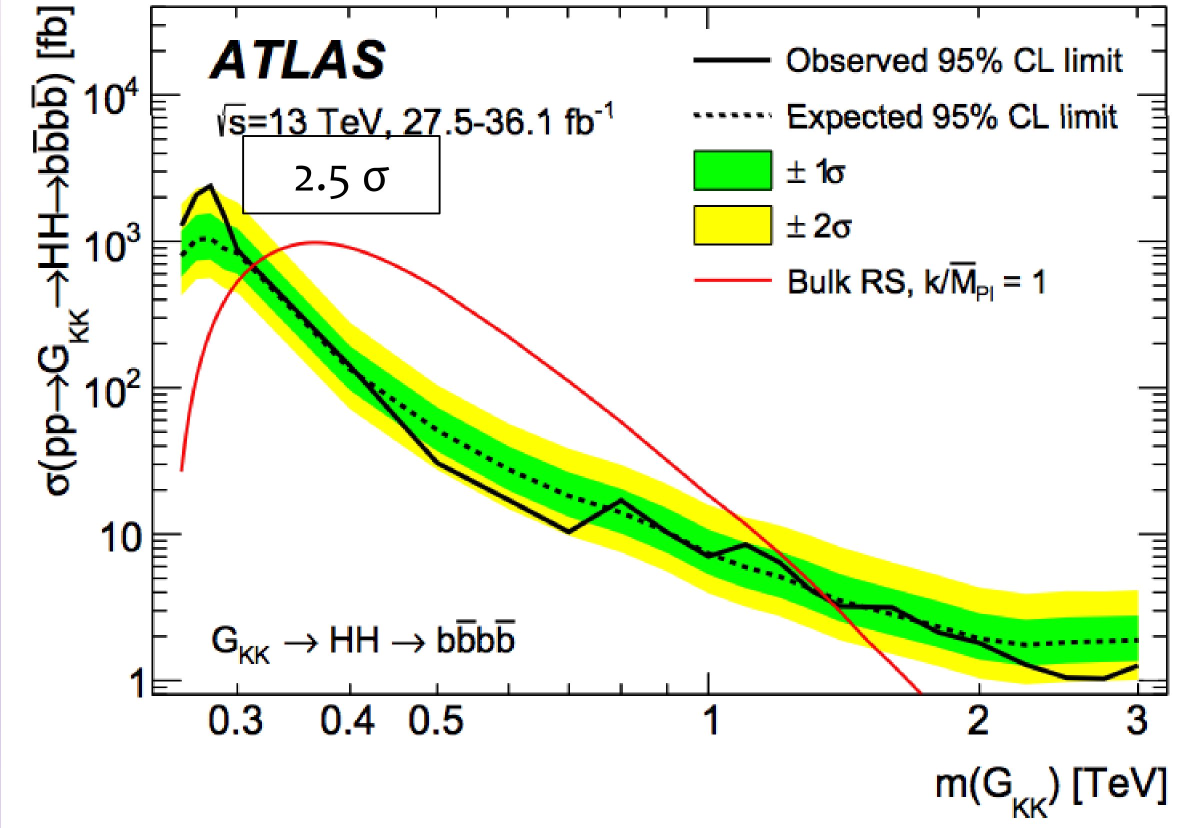


bbbb results

Non-resonant limits on σ/σ_{SM}

Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5

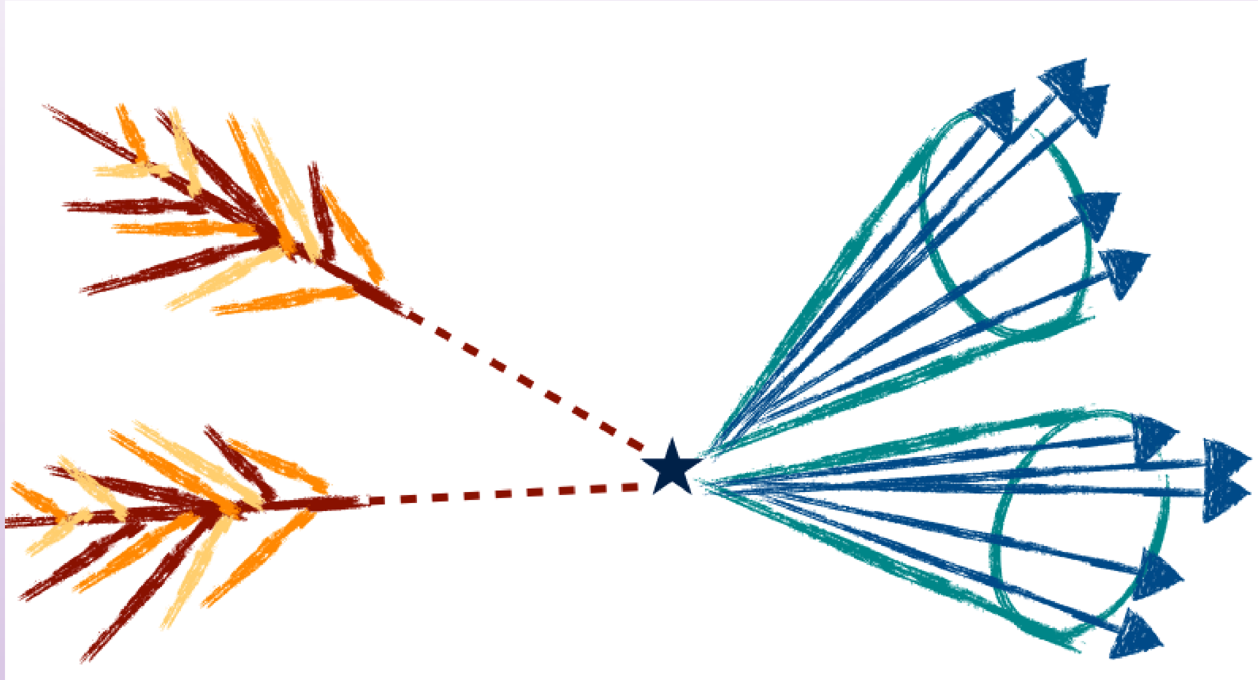




bbγγ final state

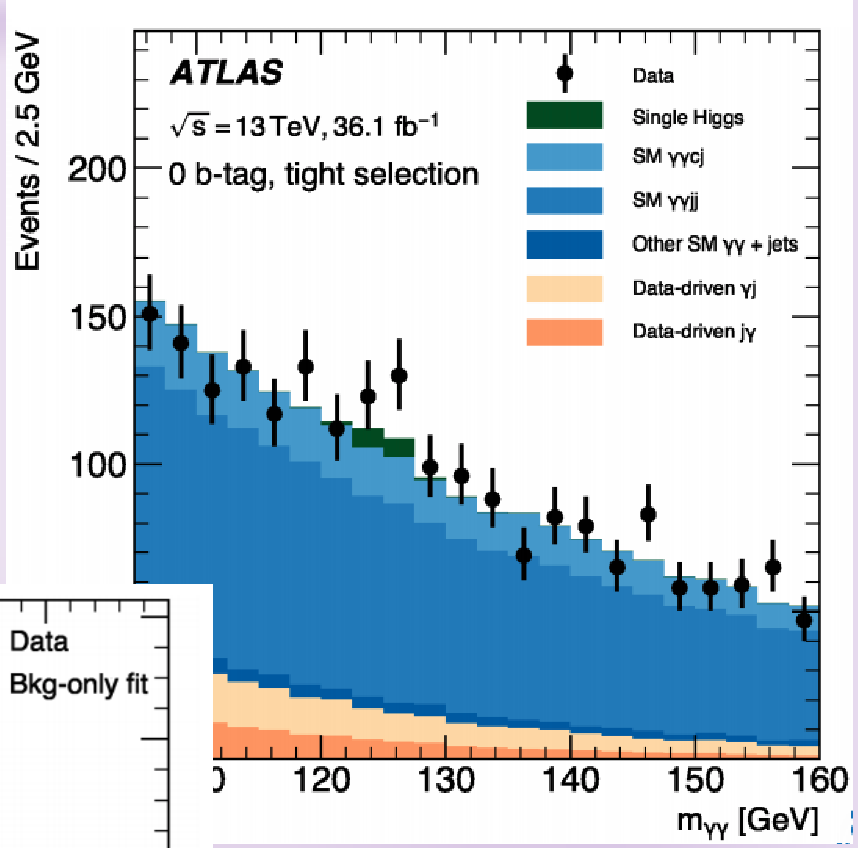
https://arxiv.org/pdf/1807.04873.pdf

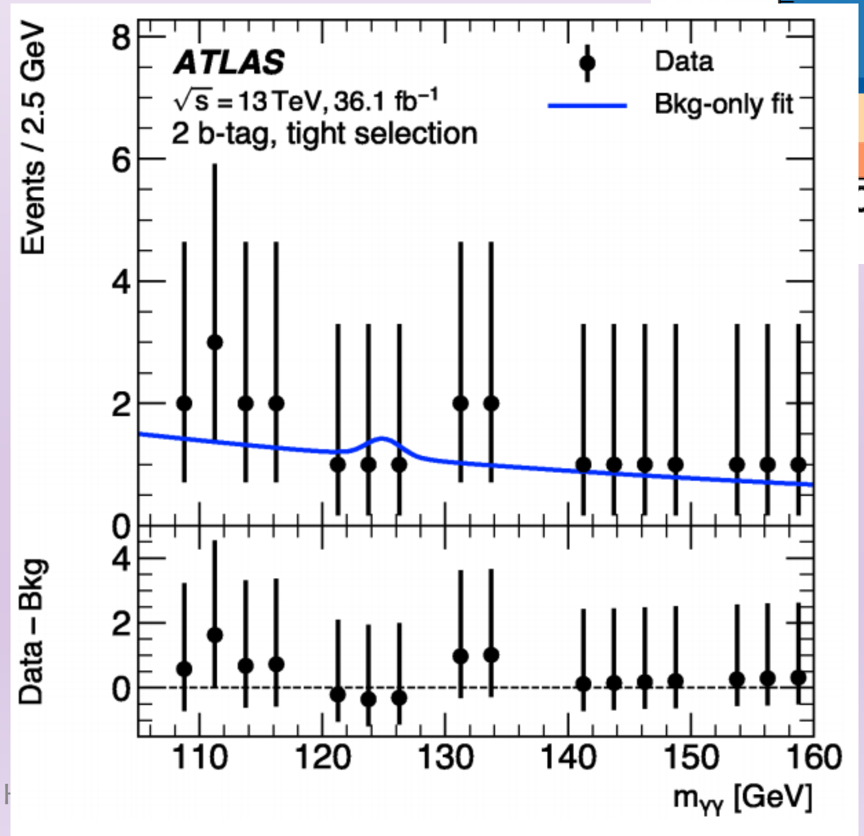
- 2 photons and jets
- Exploiting 2 b-jet and 1 b-jet categories
  - Additional categories (loose and tight) based on jet p_T
- Non-resonant and resonant signal search
- Resonant mass range 260-1000 GeV



bbγγ

- Backgrounds:
  - continuum multi-jet
  - multi-photon (gg, gj, jj, w/ j->g, etc.)
  - Single Higgs: ttH, ZH, ggH
- Reweight MC to data in 0 b-tag region
- Background modeling: exponential + double-sided crystal ball
- Signal modeling: double sided crystal ball





Final discriminant For non-resonant signal

bbγγ results

Non-resonant:

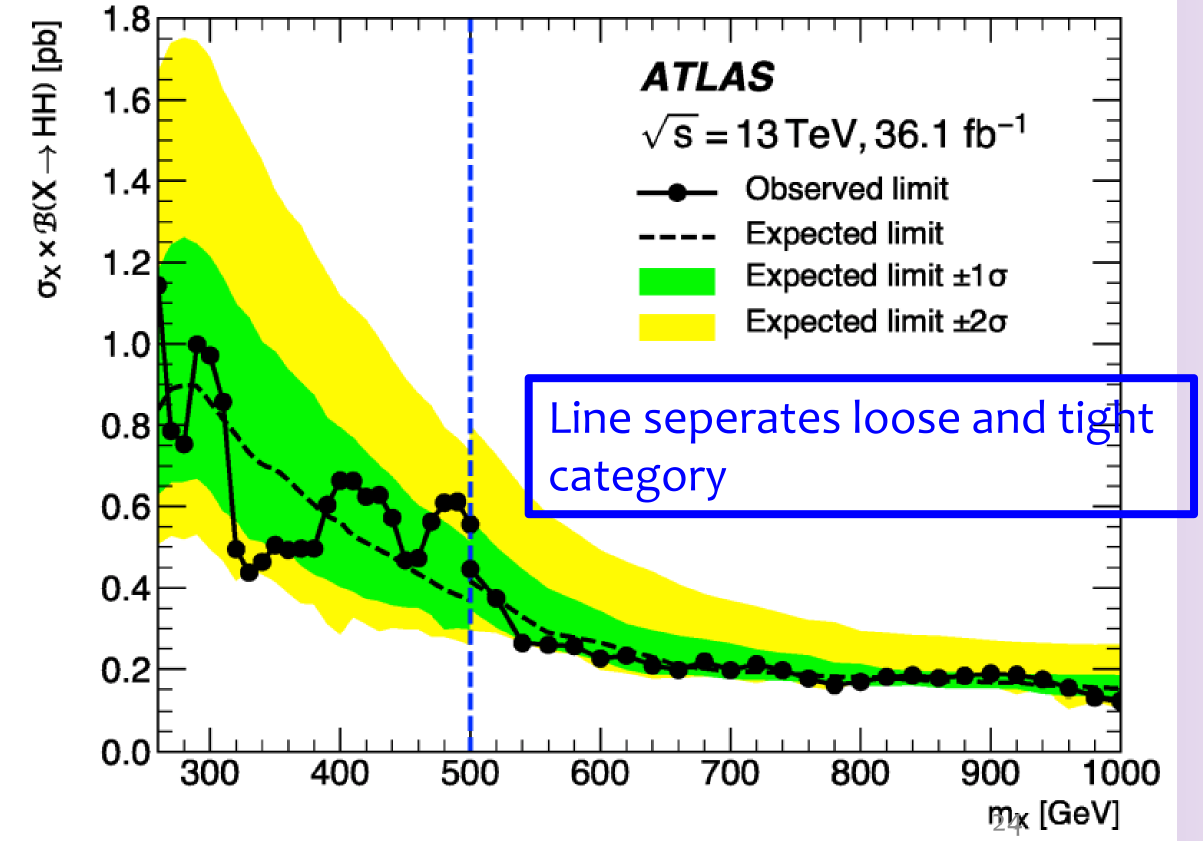
Final discriminant $m_{\gamma\gamma}$ with m_{bb}=125GeV

Non-resonant limits on σ/σ_{SM}

	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

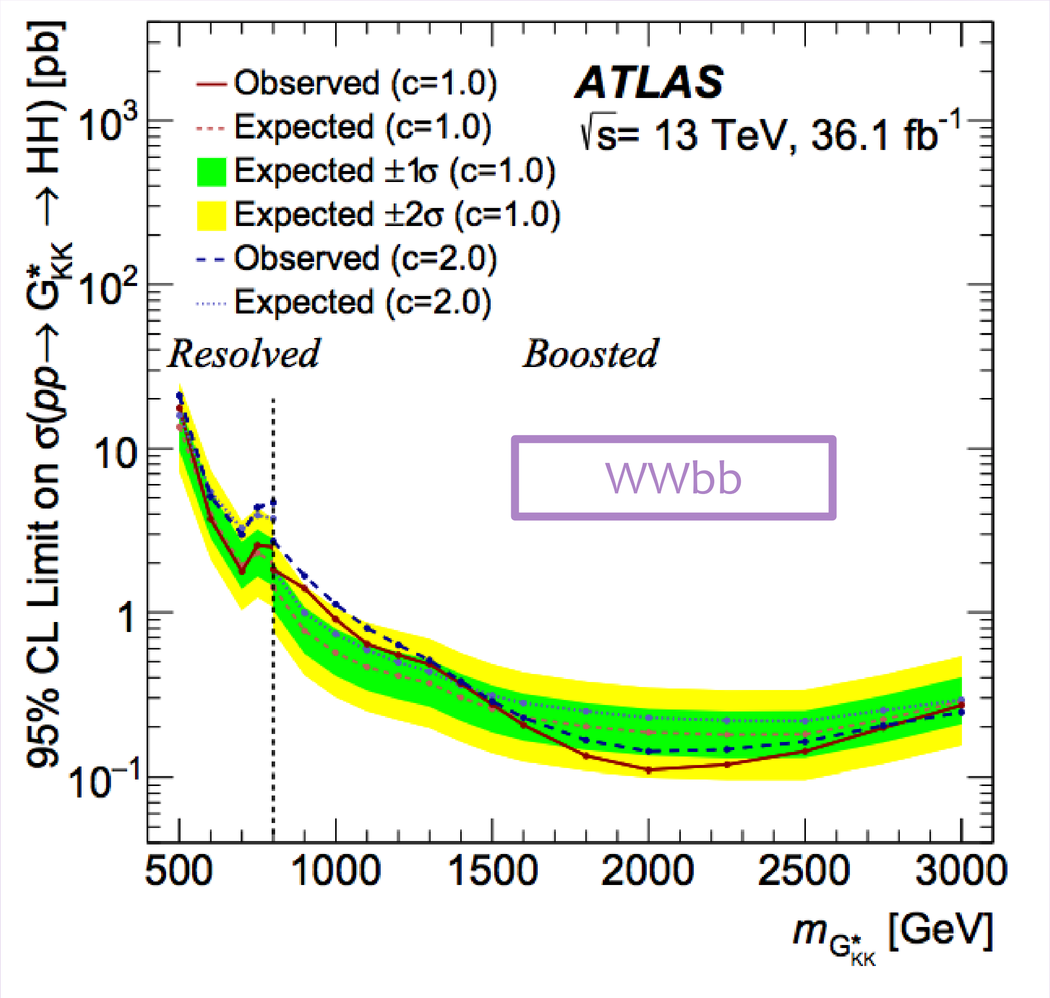
Resonant:

Final discriminant $m_{\gamma\gamma jj}$ with $m_{\gamma\gamma}$=m_{bb} =125GeV



WWbb, WWγγ and WW

- Non included in the combination
- Will become interesting with more data (and energy in the future!)
- Fresh results!
- WWbb https://arxiv.org/abs/1811.04671
  - 300 (exp. 300) x σ_{SM}
- WWγγ https://arxiv.org/abs/1807.08567
  - 230(exp. 160) x σ_{SM}
- WWWW on the way too!



ATLAS combined result

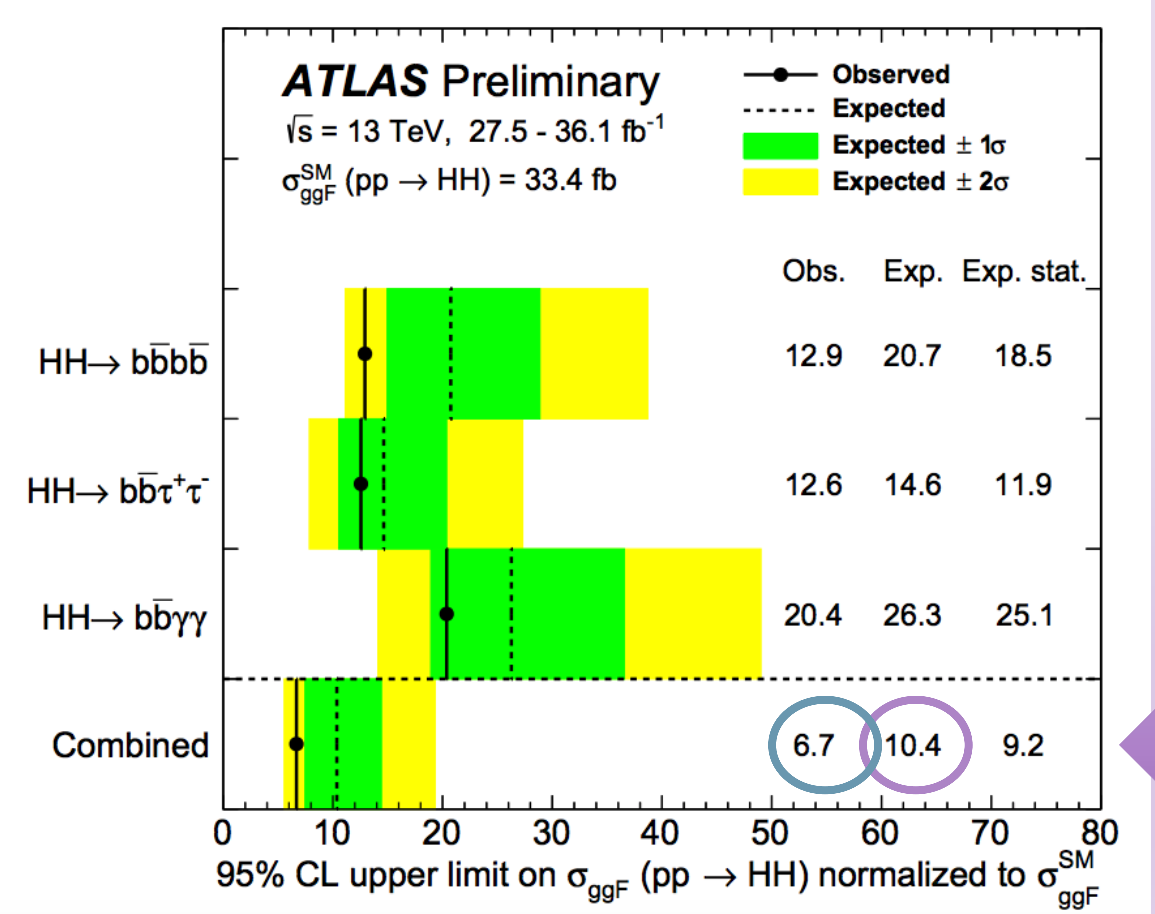
bb$\tau\tau$, bbbb and bb$\gamma\gamma$

ATLAS-CONF-2018-043

HH combination

- bbbb, bbττ, bbγγ are included in the combination.
- integrated luminosity of 36.1 fb^{-1}
- The combination is realised by constructing a combined likelihood function that takes into account data, models and systematic uncertainties
- All the signal regions considered are orthogonal, or have negligible overlap.
- Instrumental and luminosity uncertainties correlated across the channels.
- The acceptance and the background modeling uncertainties are treated as uncorrelated.
- Theoretical uncertainties on the total signal cross-section are not considered.

HH combined result for non-resonant production

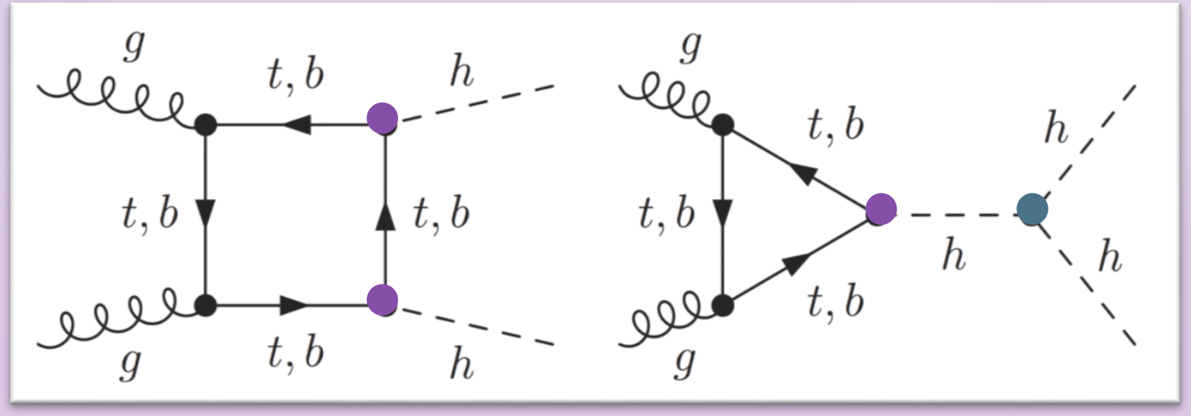


Best limit on HH to date!

Varying the Higgs coupling

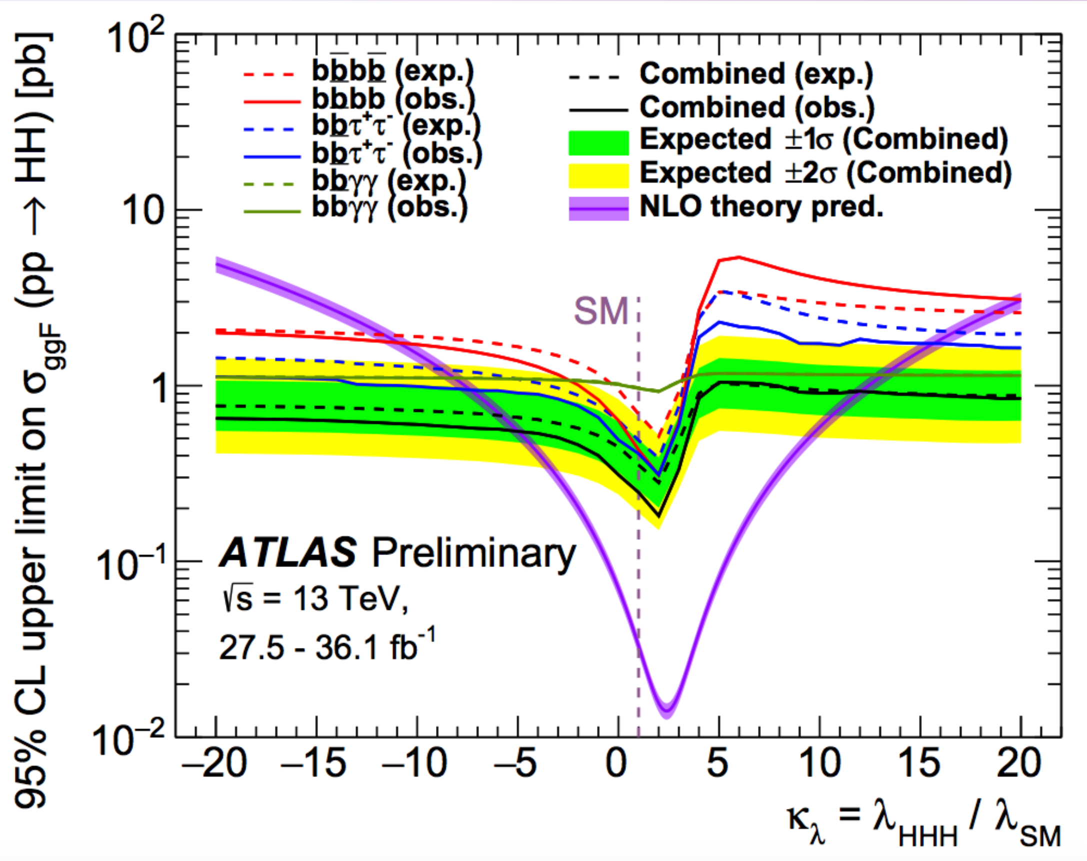
- Using scale factors:
  $\kappa_t = g_{ttH} / g_{ttH}^{SM}$ and $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$
- $A(\kappa_t, \kappa_\lambda) = \kappa^2_t B + \kappa_t \kappa_\lambda T$

We consider k_t=1 (i.e. Higgs-top coupling set to its SM value)



Constraints on κ_λ

- 4b bbττ bbγγ combination
- dashed: expected
  solid: observed
- Observed (expected) constraints on scale factor κ_λ: $-5.0 < \kappa_\lambda < 12.1$ ($-5.8 < \kappa_\lambda < 12.0$)

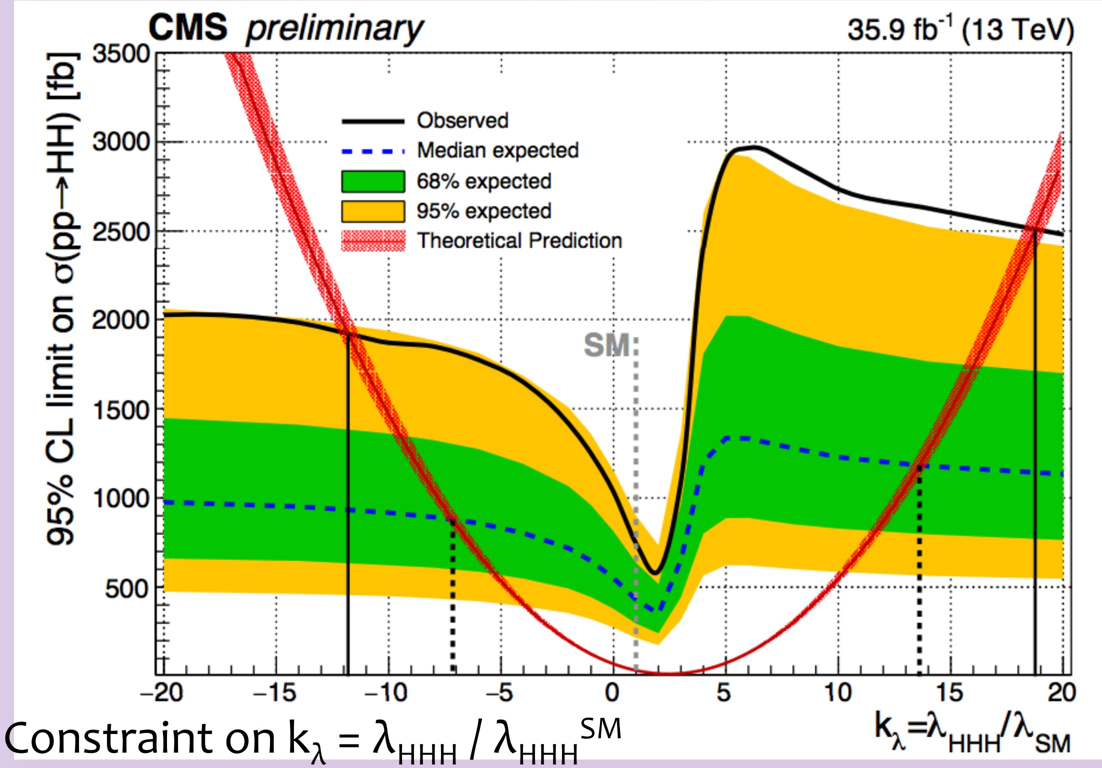


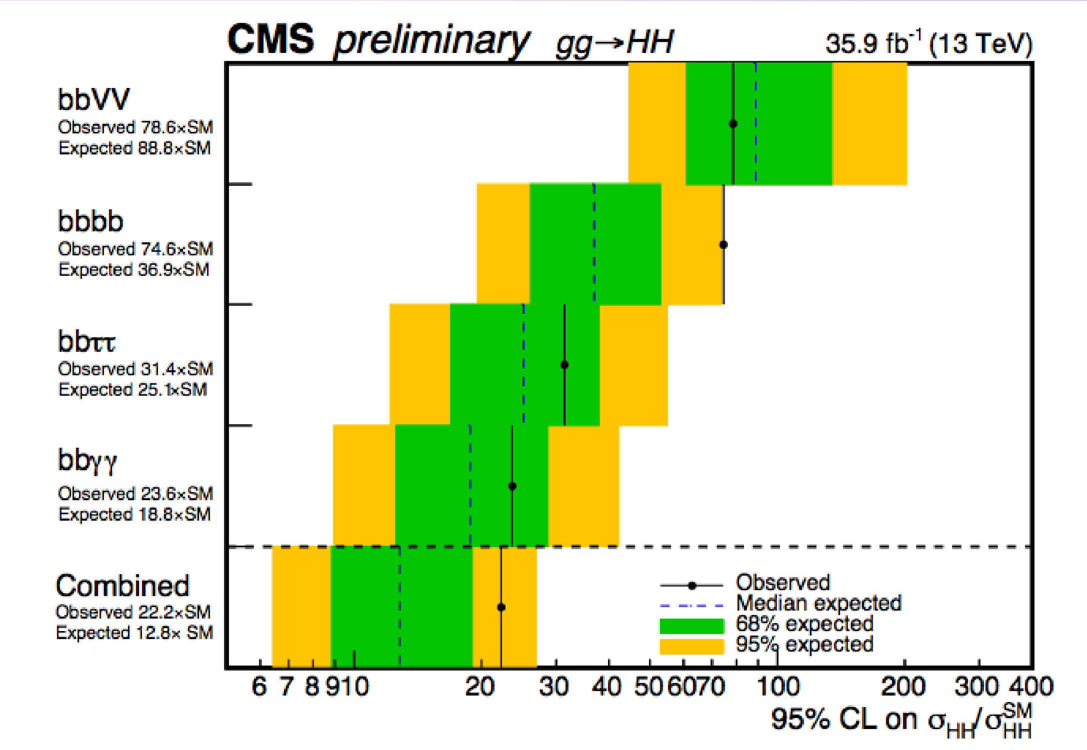
Combined CMS result

CMS-PAS-HIG-17-030

Combined limit on σ / σ^{SM}

Observed : 22.2 Expected : 12.8



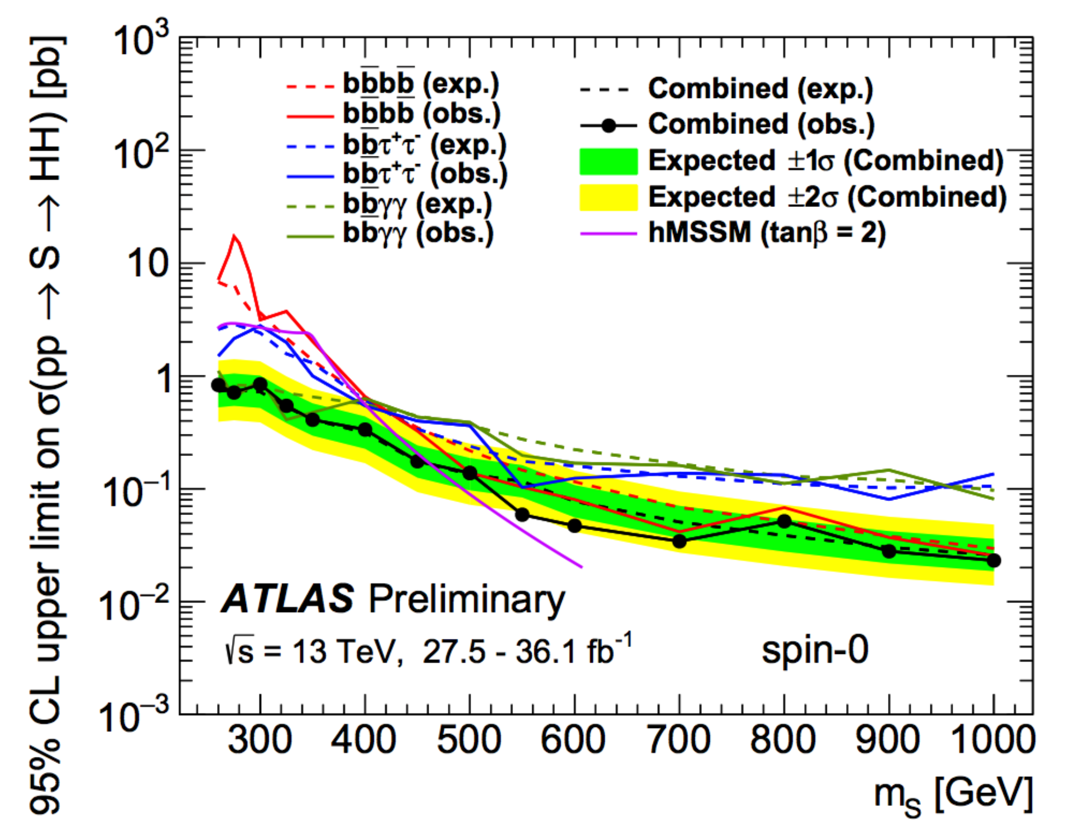


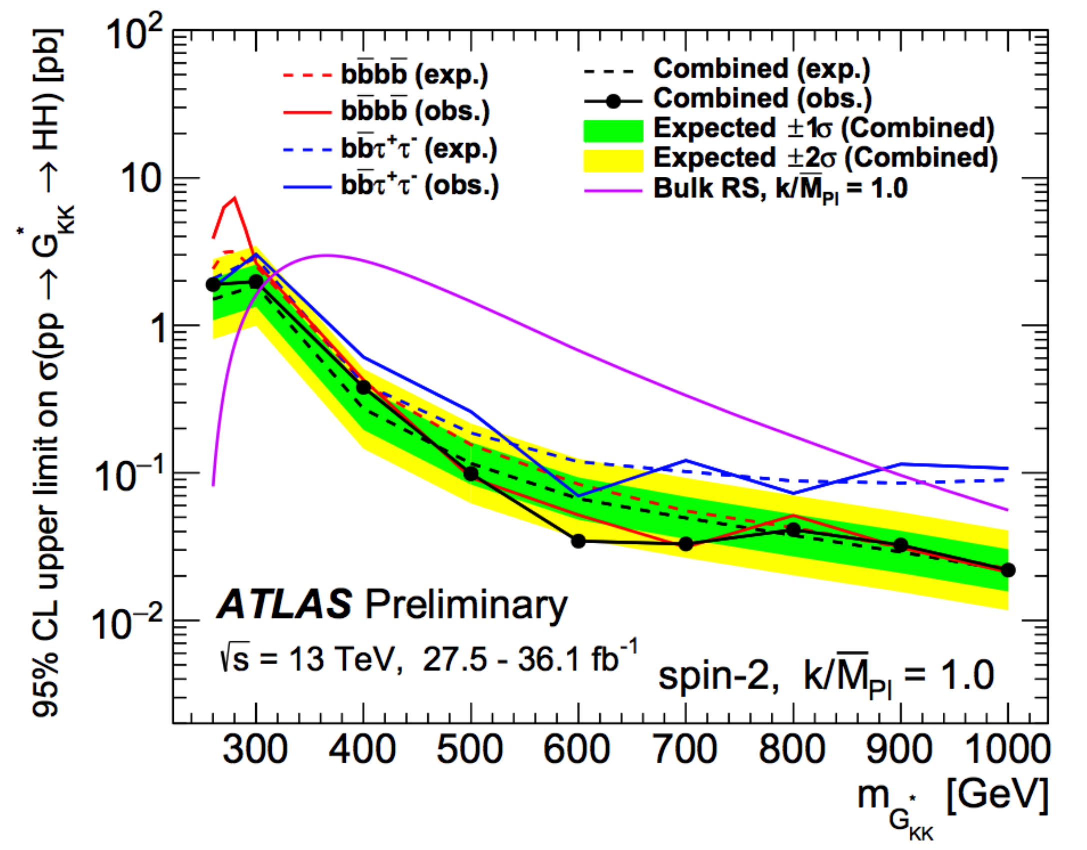
Constraint on $k_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$

Observed : $-11.8 < k_\lambda < 18.8$

Expected : $-7.1 < k_\lambda < 13.6$

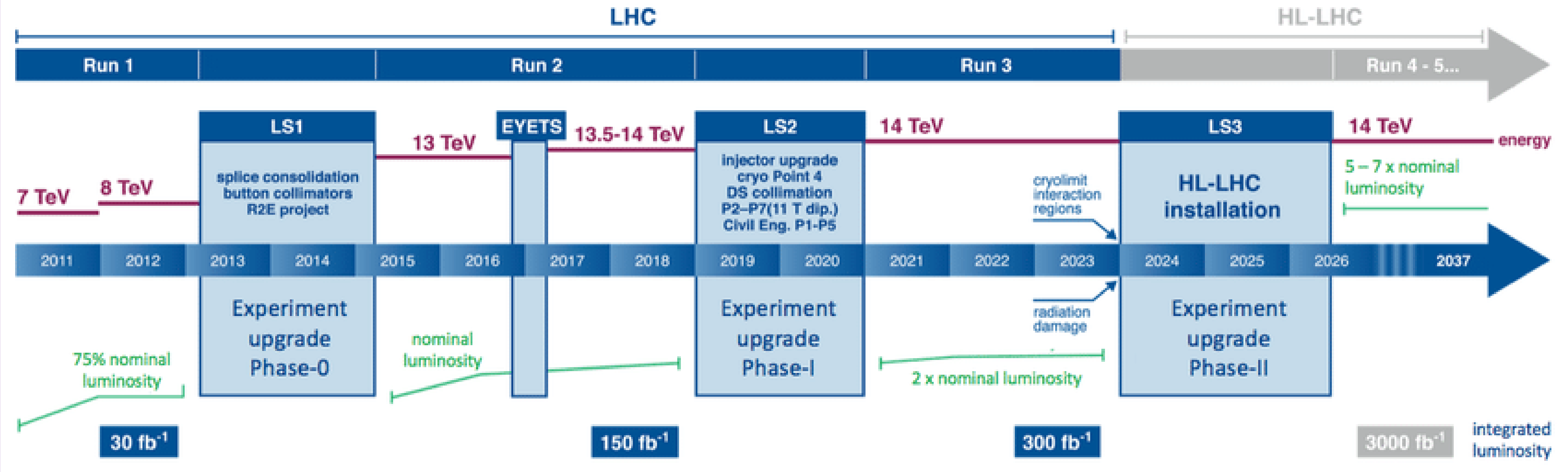
HH combined result for resonant production





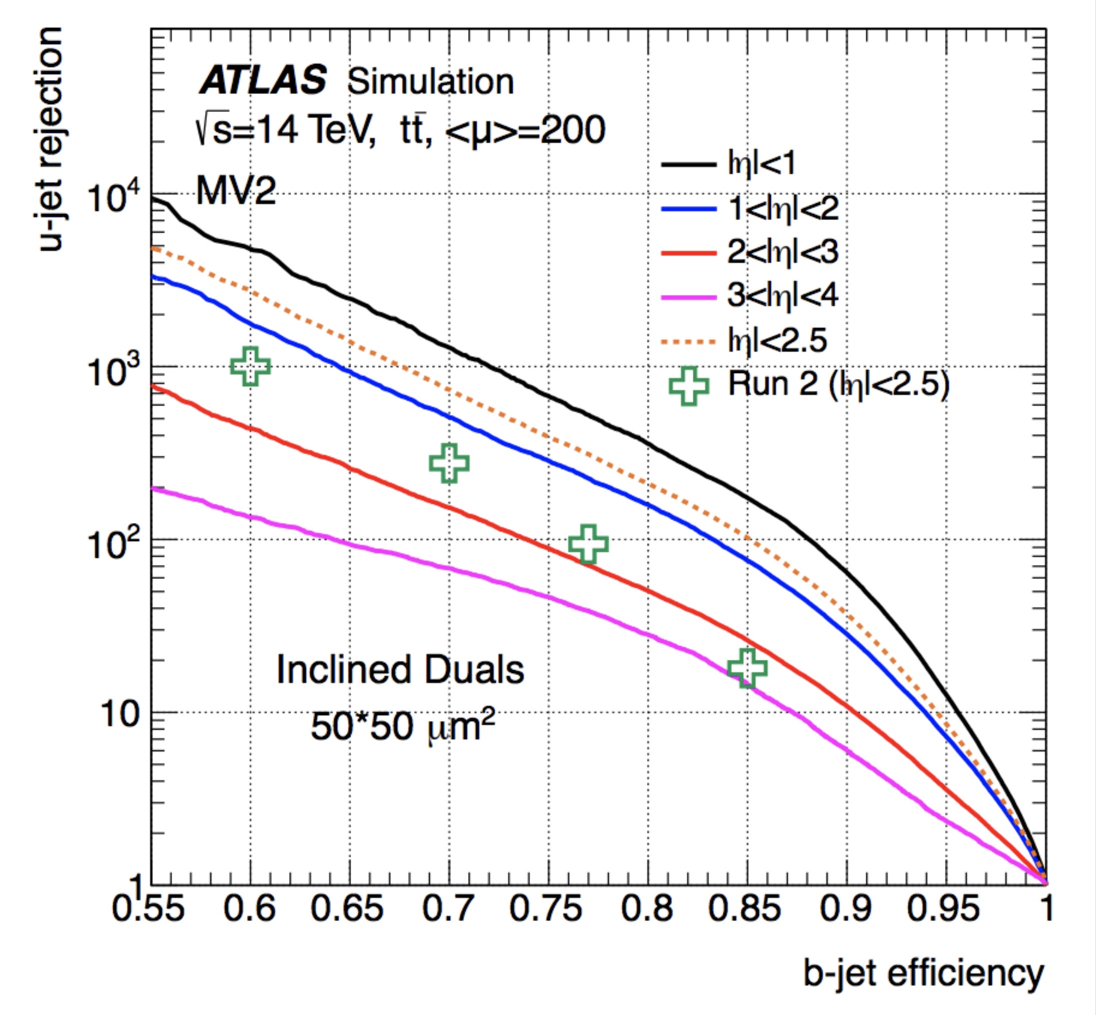
HL-LHC prospects

- bbbb and bbγγ published in ATLAS PIXEL TDR (CERN-LHCC-2017-021)
- New note became public on Christmas eve! (ATL-PHYS-PUB-2018-053) Included bbbb, bbττ, bbγγ and their combination.



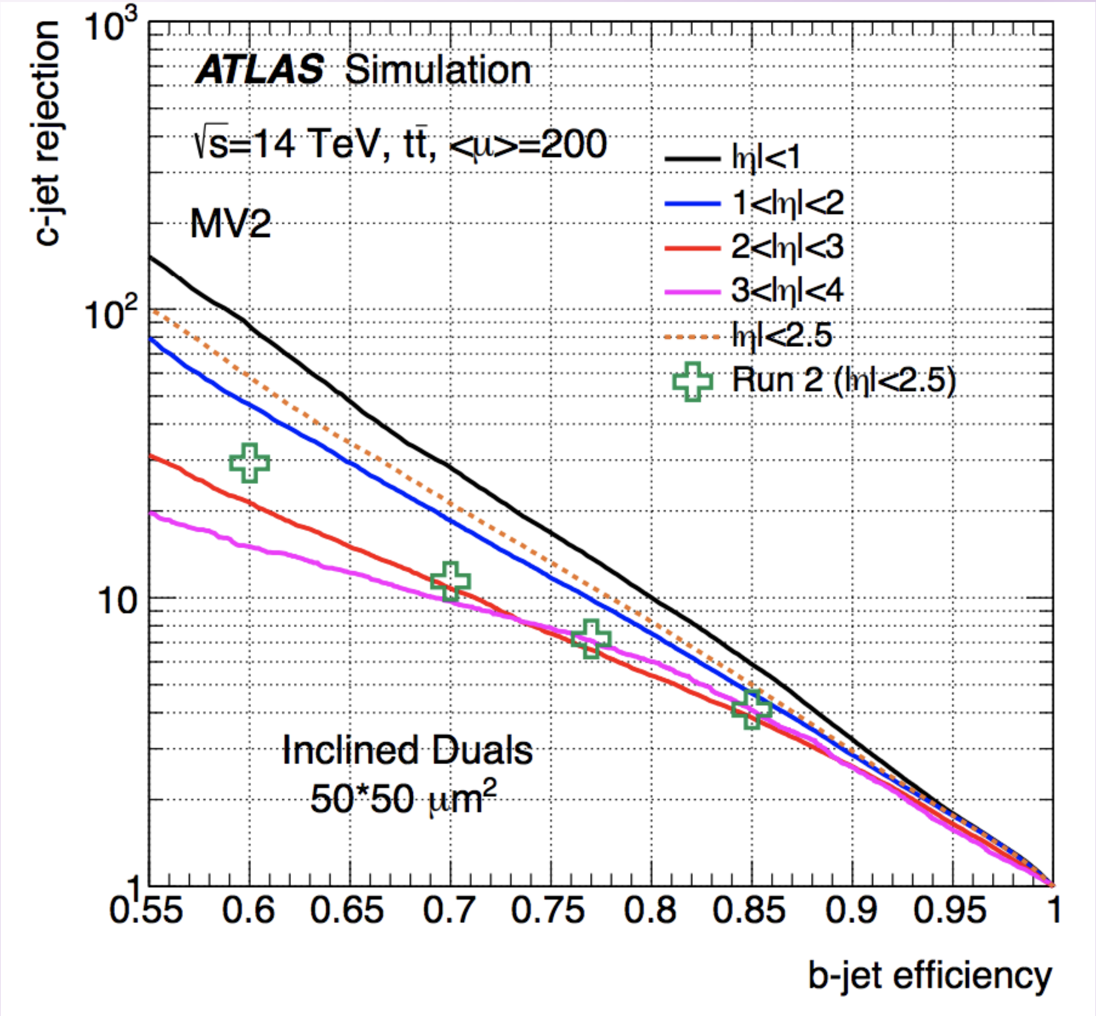
bbbb and bbττ extrapolation LHC⟶ HL-LHC

- extrapolation of the Run-2 result: L = 36.2 → L = 3000 fb−1
- Signal and background distributions scaled by $f = L_{|target}/L_{|current}$
- Background distributions scaled by 1.18 to account for an increase in cross-section
- Normalizations fixed to the best Run-2 fit values
- Pixel TDR detector layout → improved b-tagging performance (8% per b-jet)



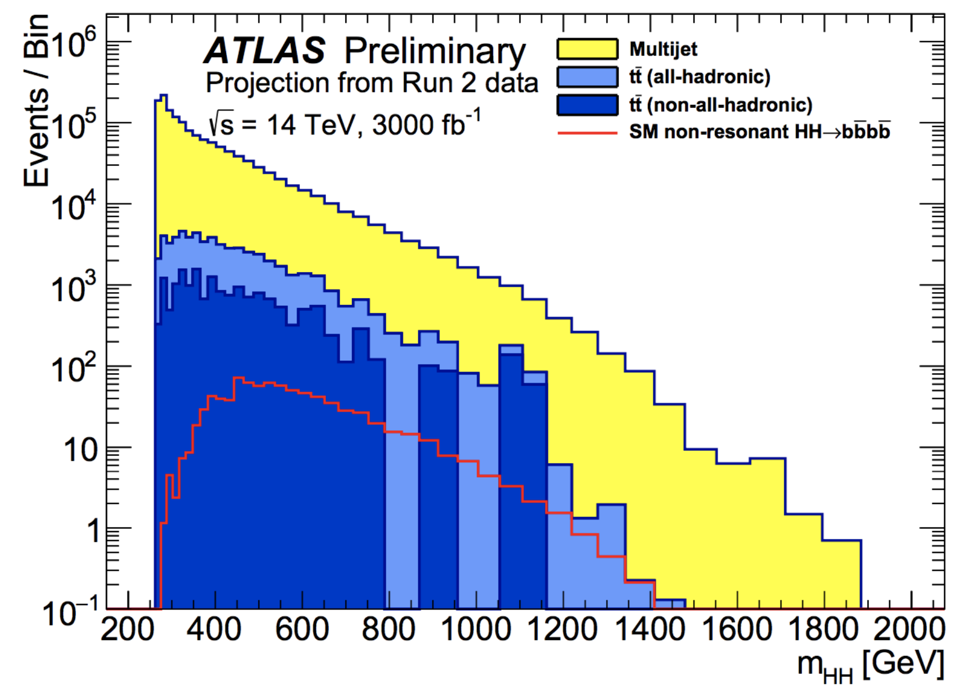
bbbb and bbττ extrapolation LHC→ HL-LHC

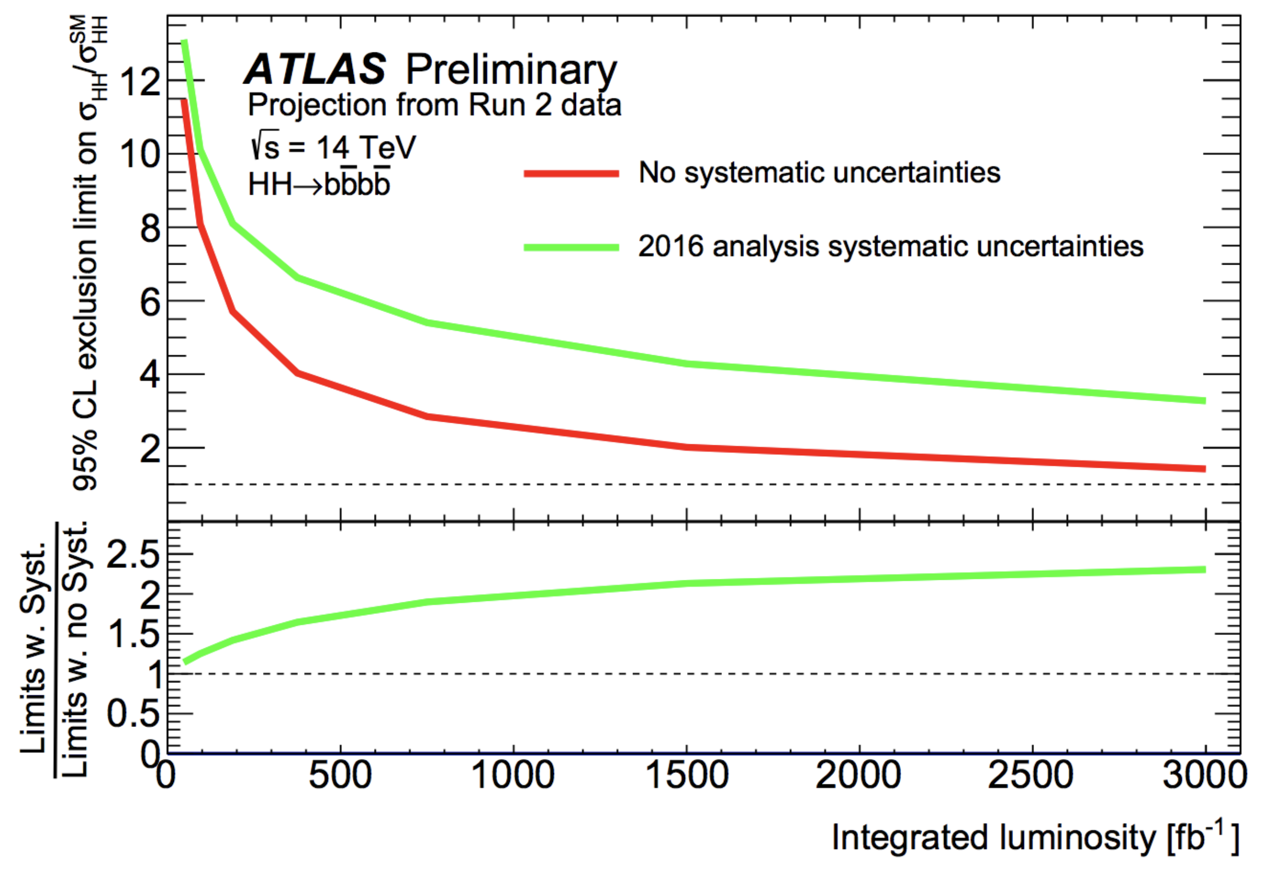
- extrapolation of the Run-2 result: L = 24.3 → L = 3000 fb−1
- Signal and background distributions scaled by $f = L_{|target}/L_{|current}$
- Background distributions scaled by 1.18 to account for an increase in cross-section
- Normalizations fixed to the best Run-2 fit values
- Pixel TDR detector layout → improved b-tagging performance (8% per b-jet)



bbbb analysis

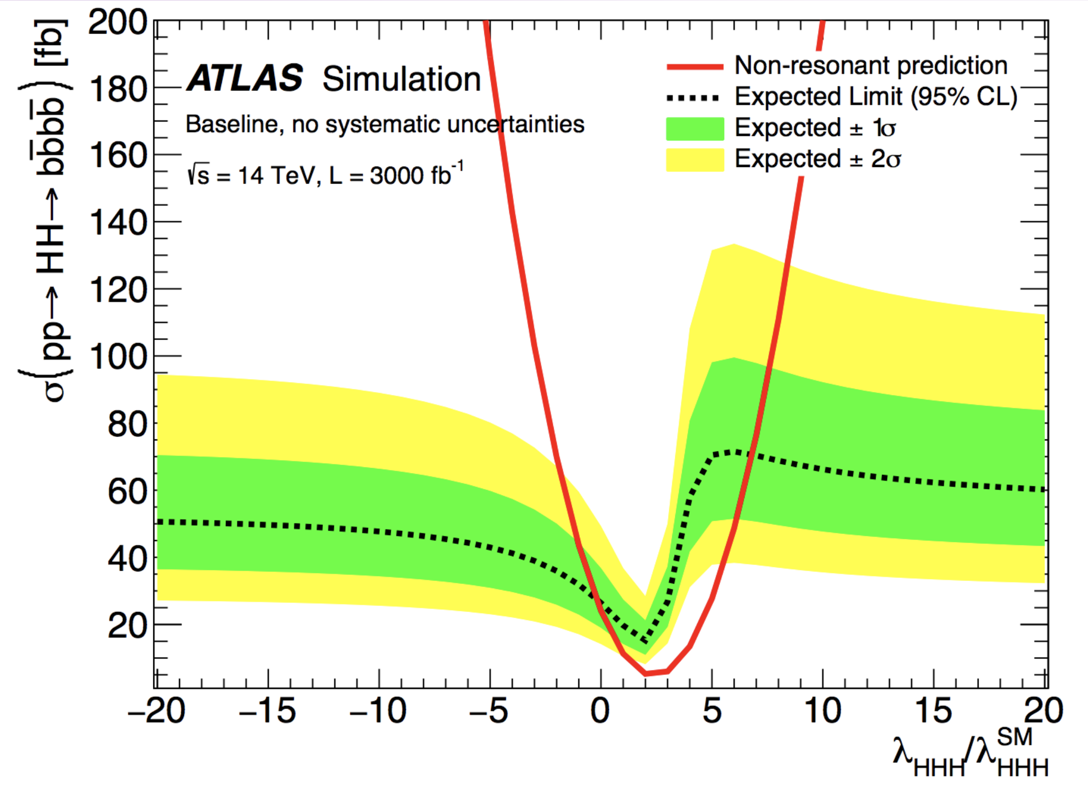
- "Resolved" analysis method used (not boosted reconstruction of four jets)
- Background: ~ 95% multijet and ~ 5% ttbar
- Extrapolation of the 95% C.L. exclusion limit:
  without systematics: $\boldsymbol{\sigma/\sigma_{SM}=1.5}$
  with current level of systematics: $\boldsymbol{\sigma/\sigma_{SM}=5.2}$



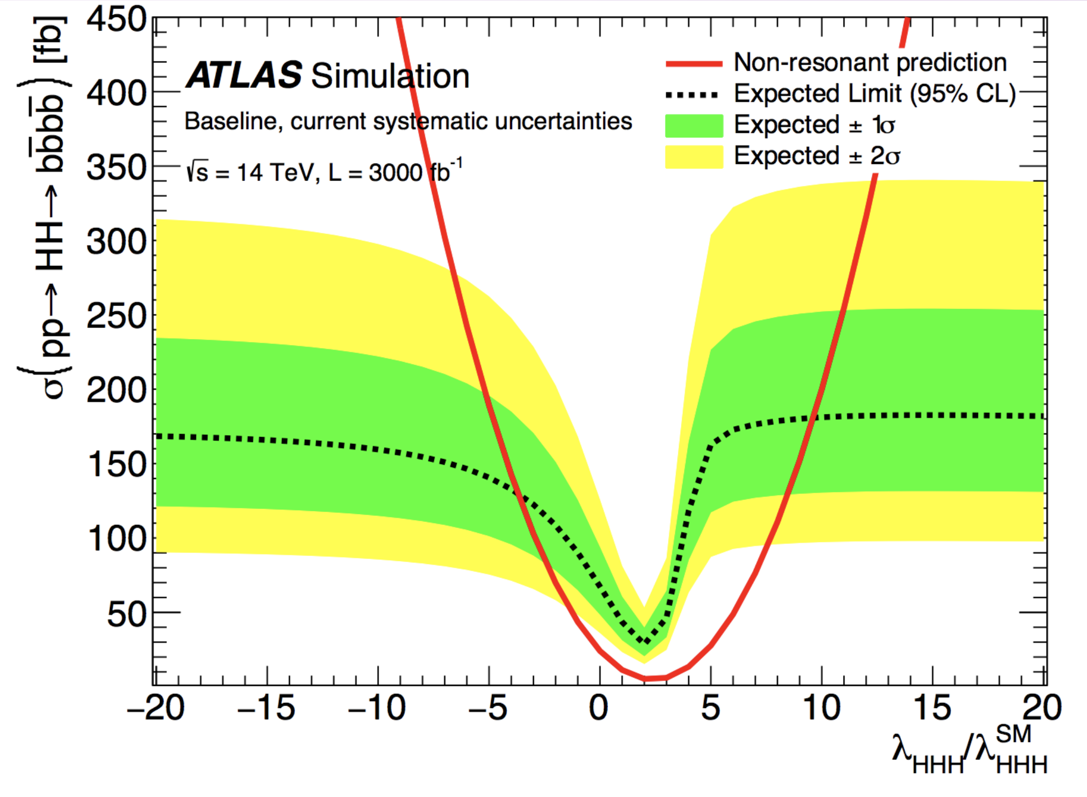


bbbb results

No systematics



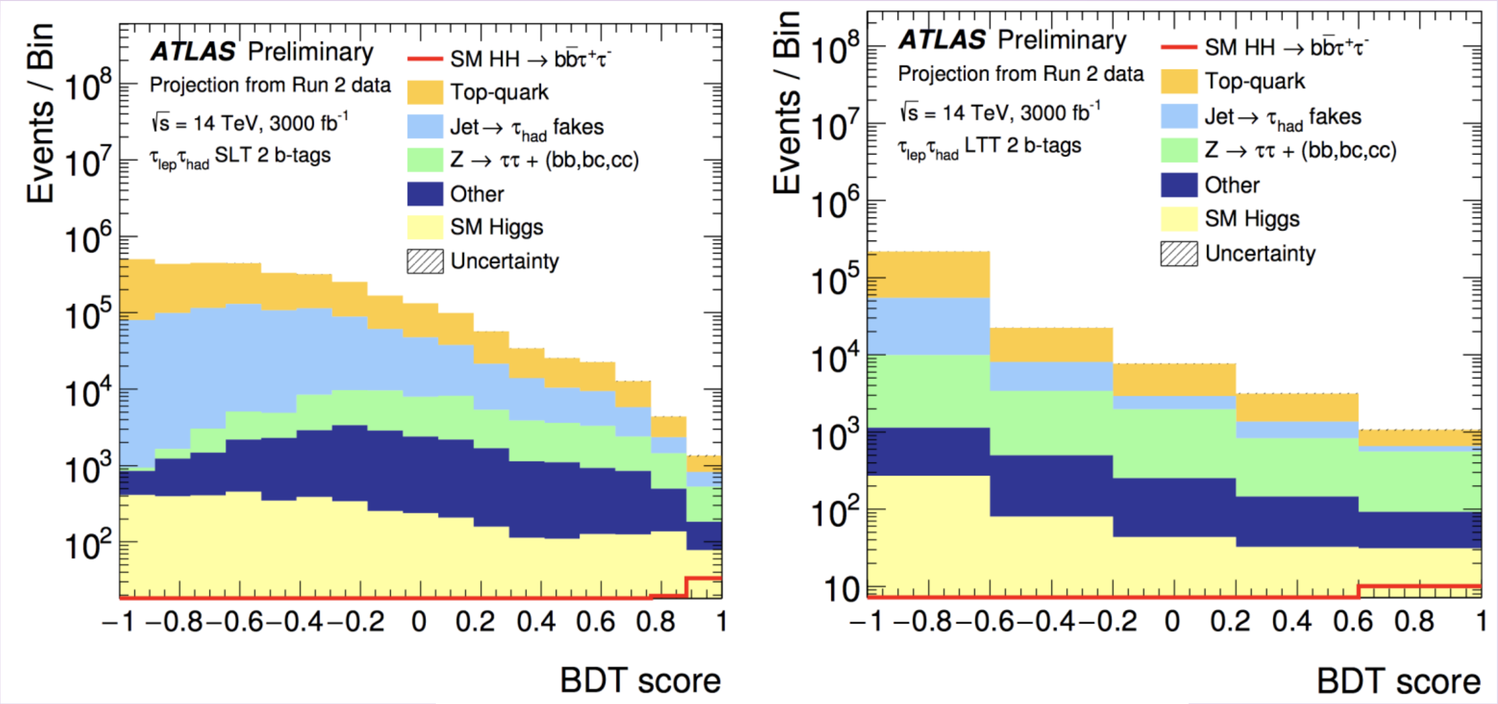
Current systematics

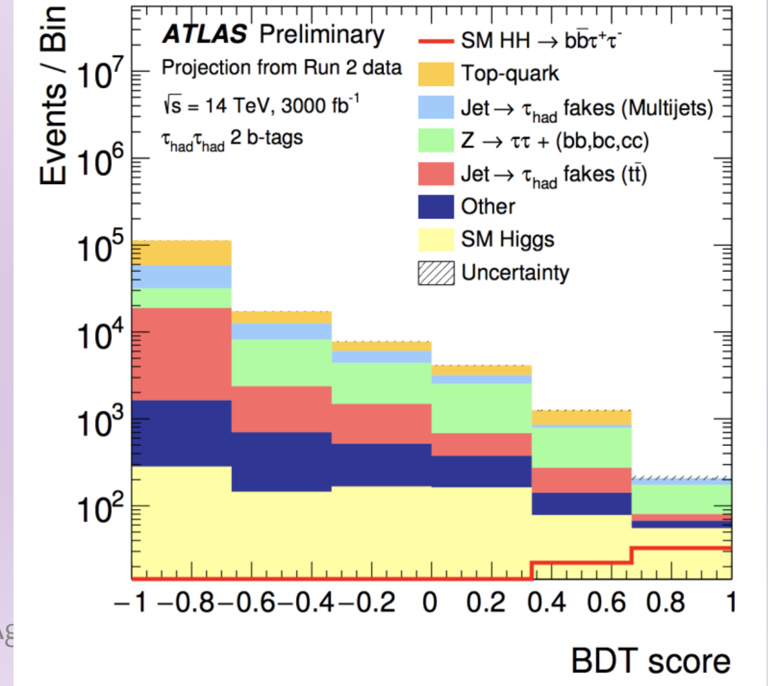


without systematics: $0.2 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 7.0$
with systematics: $-3.5 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 11$

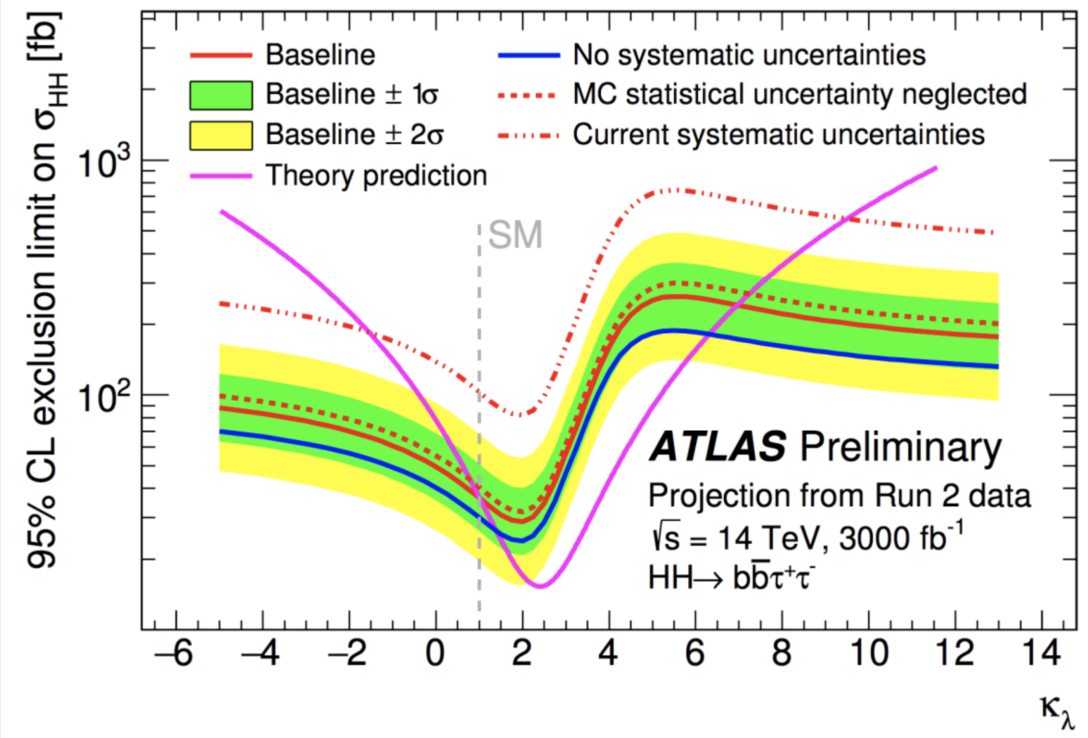
bbττ analysis

- 2 channels,3 signal regions: $\tau_h\tau_{e/\mu}$ SLT and LTT, $\tau_h\tau_h$
- SM Higgs background (ZH, ttbar)
  current measured ATLAS uncertainty (28% and 30%)
- measurements will improved assumes 5% and 10% according to theory





bbττ result



- No systematic: $\boldsymbol{\sigma/\sigma_{SM}}$ =0.80 (2.7 σ)
- Baseline : $\boldsymbol{\sigma/\sigma_{SM}}$ = 0.99 (2.1 σ)
- without systematics:
  $1.4 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 6.3$
  with baseline systematics:
  $1.0 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 7.0$

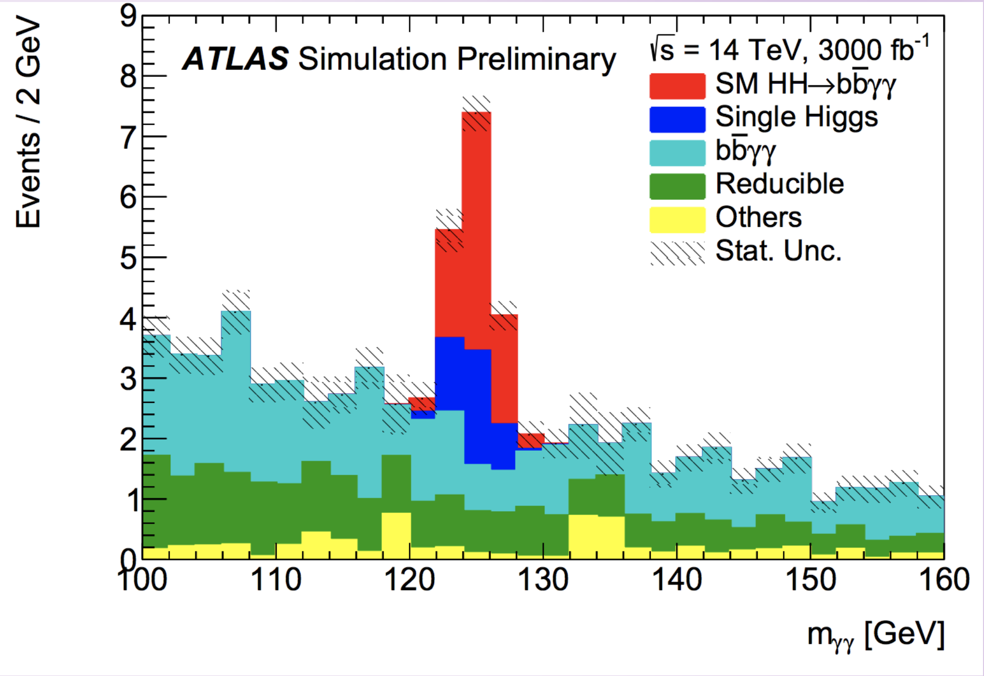
bbγγ at HL-LHC

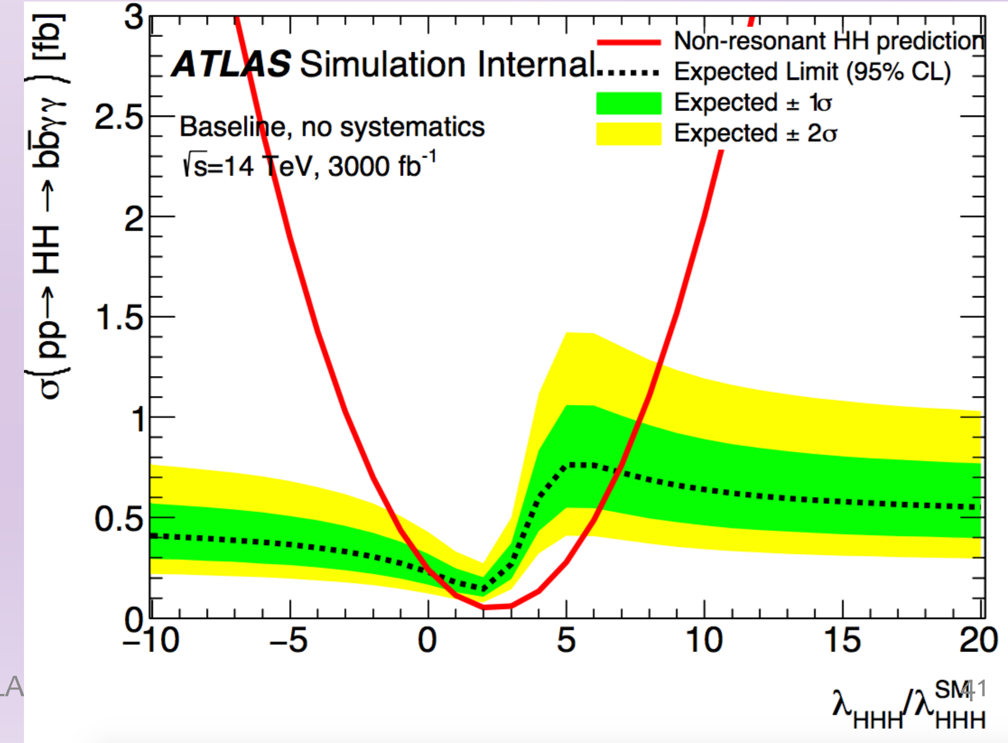
- Study based on $\sqrt{\sigma}$ = 14 TeV Monte Carlo simulations
- The final state particles at truth level are smeared according to the expected detector resolutions assuming a pile-up scenario with 200 overlapping events
(< μ >= 200).
- The expected efficiencies and fake rates for identifying b-jets and photons are used.
- Upgrade performance functions provide parameterized estimates of ATLAS performance for HL-LHC (resolution, efficiencies, fake rates)

bbγγ results

- processes with multiple jets and photons
- Continuum background (exponential) subtracted
- Fit performed on $m_{\gamma\gamma}$ distribution
- Signal and single Higgs background modeled as Gaussians

Expected sensitivity is
no systematics **1.5σ**
Higgs boson self-coupling constrained:
no systematics: **$-0.2<\lambda_{HHH}/\lambda_{HHH}^{SM}<6.9$**

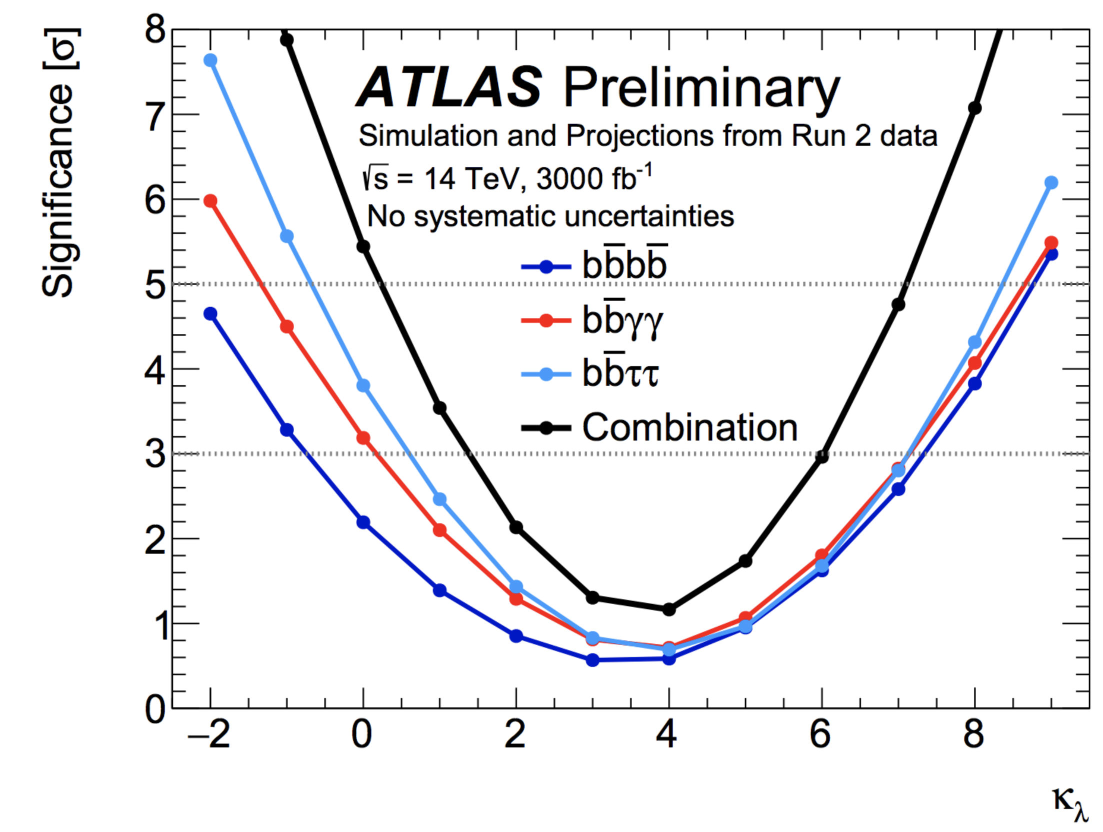


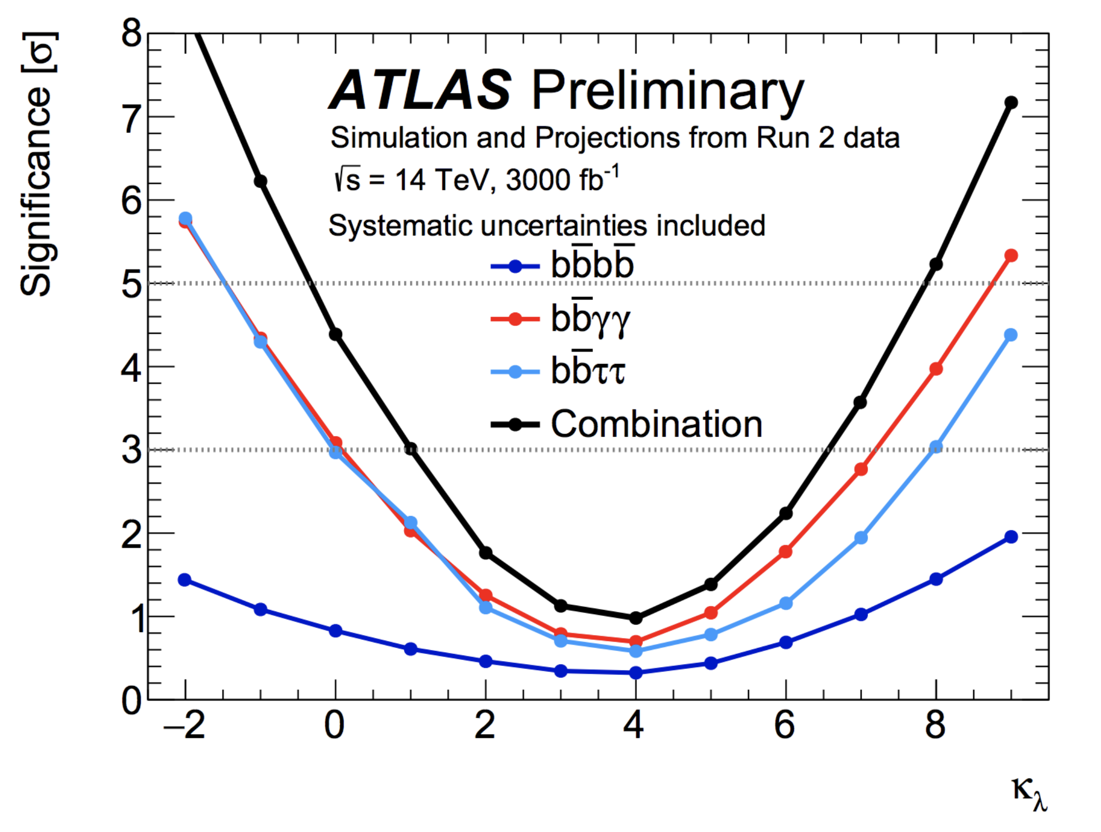


HL-LHC combination significance

Significance of observing HH production

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5 σ	3.0 σ

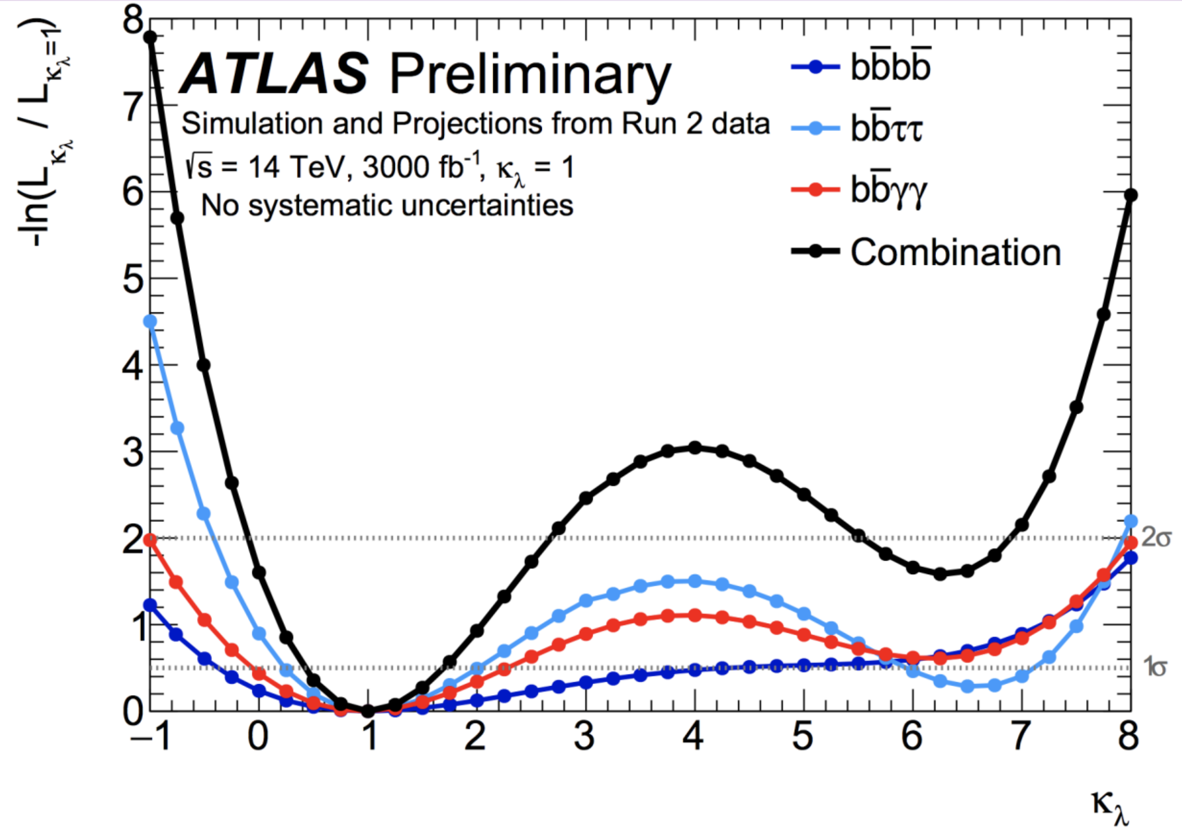




HL-LHC Combination constraints on $\lambda_{HHH}/\lambda_{HHH}^{SM}$

Scenario	1σ CI	2σ CI
Statistical uncertainties only	$0.4 \le \kappa_\lambda \le 1.7$	$-0.10 \le \kappa_\lambda \le 2.7 \cup 5.5 \le \kappa_\lambda \le 6.9$
Systematic uncertainties	$0.25 \le \kappa_\lambda \le 1.9$	$-0.4 \le \kappa_\lambda \le 7.3$

- Sensitivity to κ_λ
- Asimov dataset with backgrounds plus SM HH signal
- The negative natural logarithm of the **ratio of the maximum likelihood fit** for κ_λ to that for the fit with $\kappa_\lambda = 1$



Summary and outlook

- ATLAS provides the best limit on HH production cross-section!

  $\sigma/\sigma^{SM}<6.7$ (expected 10.4)
- bbττ, bbbb and bbγγ contribute to the combination
- bbττ is the most sensitive channel providing alone:
  $\sigma/\sigma^{SM}<12.7$ (expected 14.8)
- The CMS combined result is $\sigma/\sigma^{SM}<22.5$ (expected 12.8)
- New results on more channels WWbb, WWγγ and soon WWWW
- HL-prospects studies performed on bbbb, bbγγ and bbττ and combined!
- More channels and production mechanisms to be included for the end of Run2 analyses (~ about a year's time)
- Future colliders will come into play later, with a rich Higgs physics program too!

Thank you for your attention

Backup material

Missing Mass Calculator (MMC)

- Algorithm developed for τ decays that involve neutrinos
- The algorithm assumes that the missing energy is entirely due to neutrinos and performs a scan on the angles between the neutrino and the visible tau decay products.
- Each solution is weighted according to probability density functions that are derived from simulated τ decays.