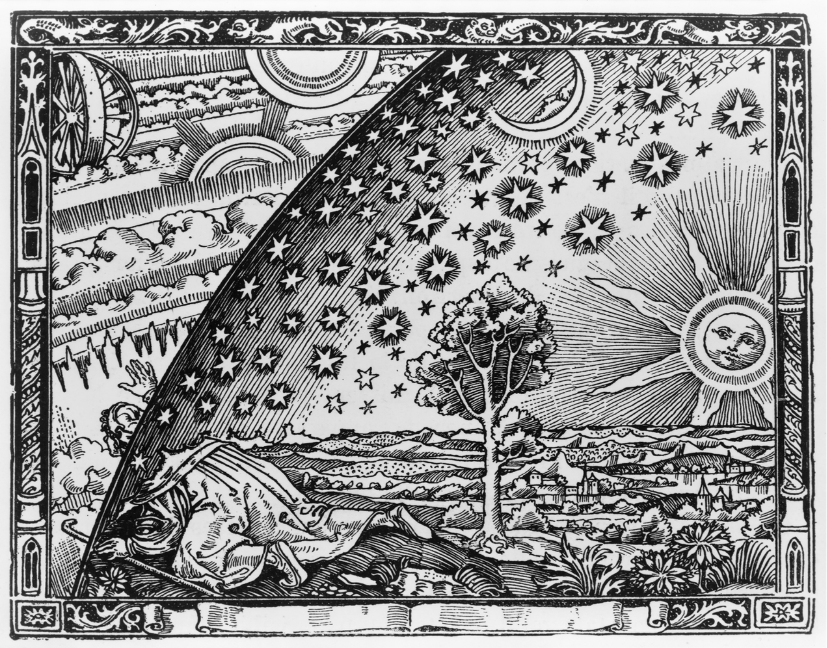
To the Higgs and beyond

Hamburg International Summer School
14 – 25 July 2025

Katharina Behr



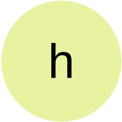
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ATLAS EXPERIMENT

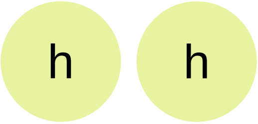
DESY.

Outline

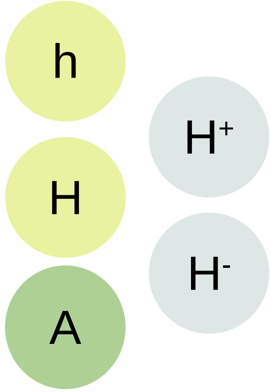
> **Part 1: The vacuum is not empty**
  – The Higgs boson in the Standard Model
  – Characterization of the Higgs boson since its discovery

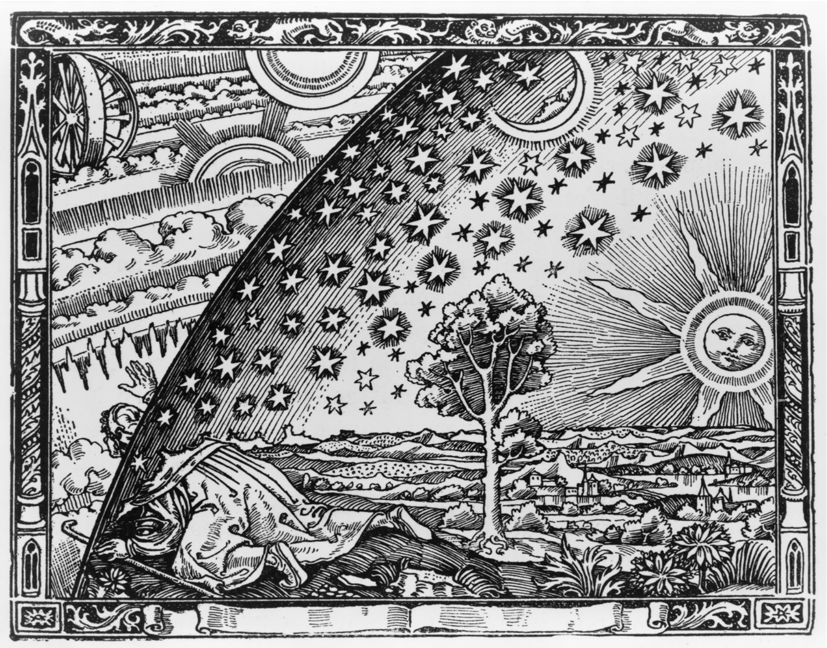


> **Part 2: What is the fingerprint of the vacuum?**
  – Unravelling the Higgs potential
  – Higgs boson pair production
  – Extra: Triple Higgs production



> **Part 3: Is there even more to the vacuum?**
  – Extended Higgs sectors
  – Extra: news from the ttbar threshold
  – Outlook: the future of the LHC and beyond





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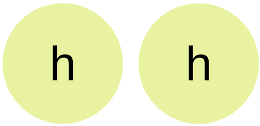
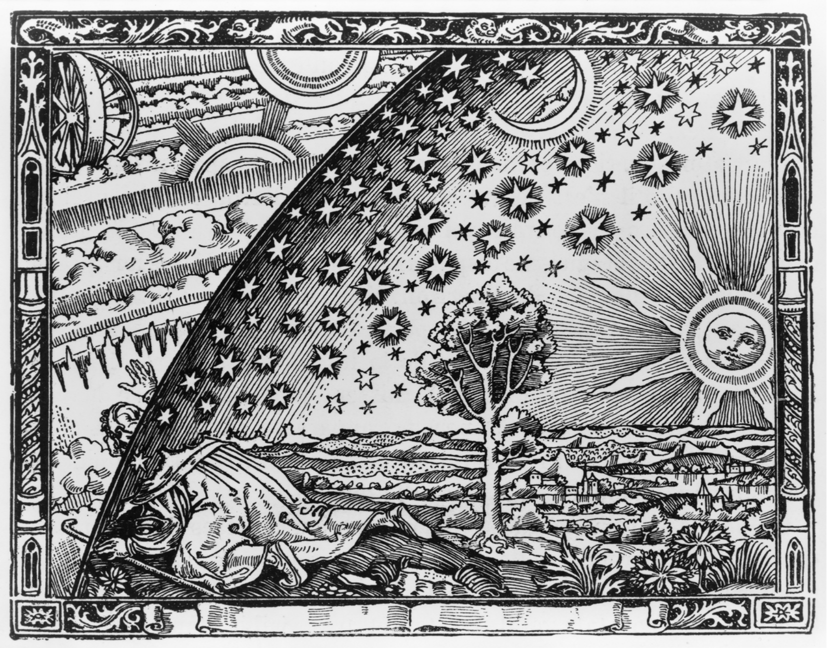
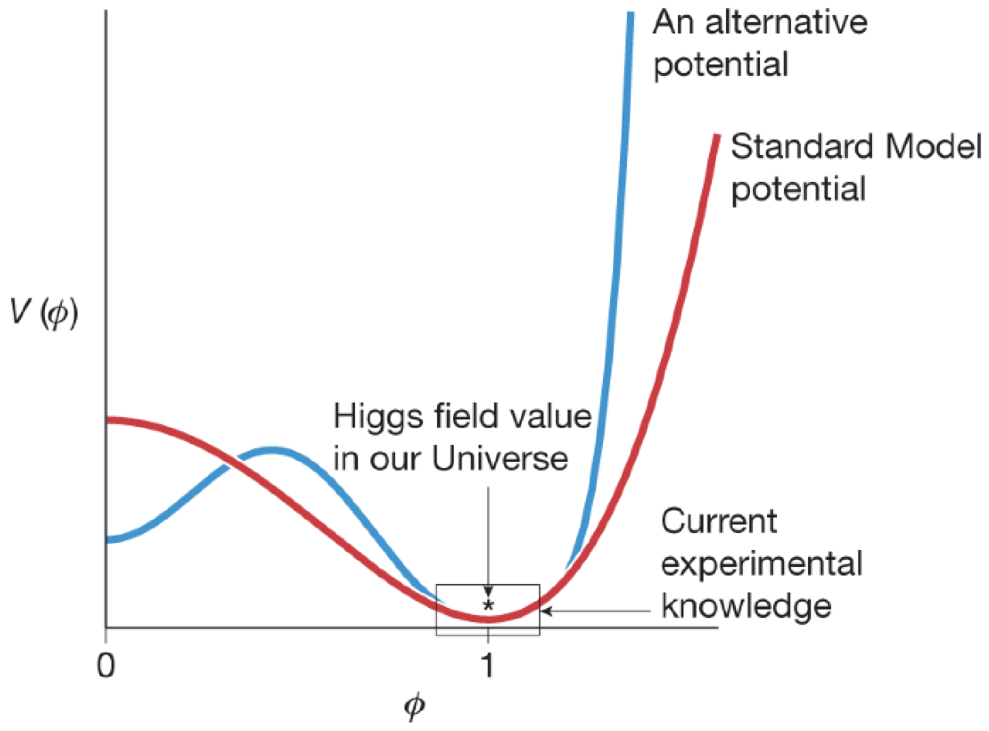




A key piece of missing information

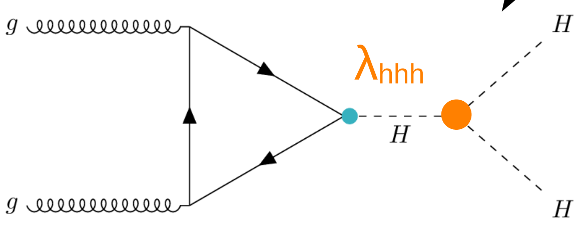
- Full shape of the Higgs potential
- Current measurements in single Higgs bosons only probe potential around minimum

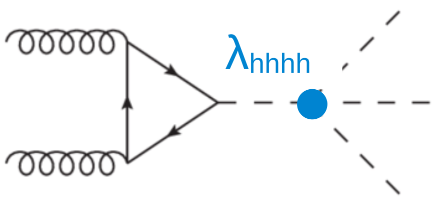


A key piece of missing information

- Full shape of the Higgs potential
- Current measurements in single Higgs bosons only probe potential around minimum
- SM prediction: Mexican hat potential

$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \lambda_3 h^3 + \frac{1}{4!} \lambda_4 h^4.$$

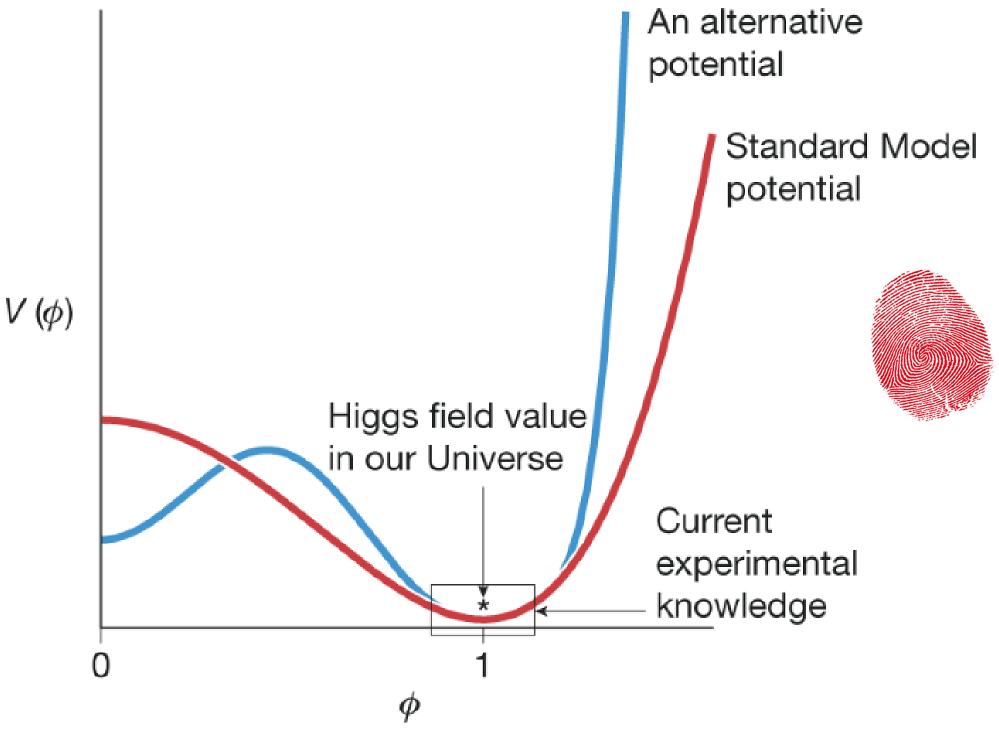




$m_h^2 = 2\lambda v^2$ (Higgs mass term),

$\lambda_3 = 3\lambda v = \frac{3m_h^2}{2v}$ (trilinear Higgs coupling),

$\lambda_4 = \lambda = \frac{m_h^2}{2v^2}$ (quartic Higgs coupling).



A key piece of missing information

- BSM: many different shapes possible
- E.g. extra scalar singlet

$$\boxed{V(h,H) = V_{\mathrm{SM}}(h) + \frac{1}{2}m_H^2 H^2 + \frac{1}{2}\mu_{hH} hH + \frac{\lambda_{hH}}{2}h^2H^2 + \frac{\lambda_{3H}}{3!}H^3 + \frac{\lambda_{4H}}{4!}H^4}$$

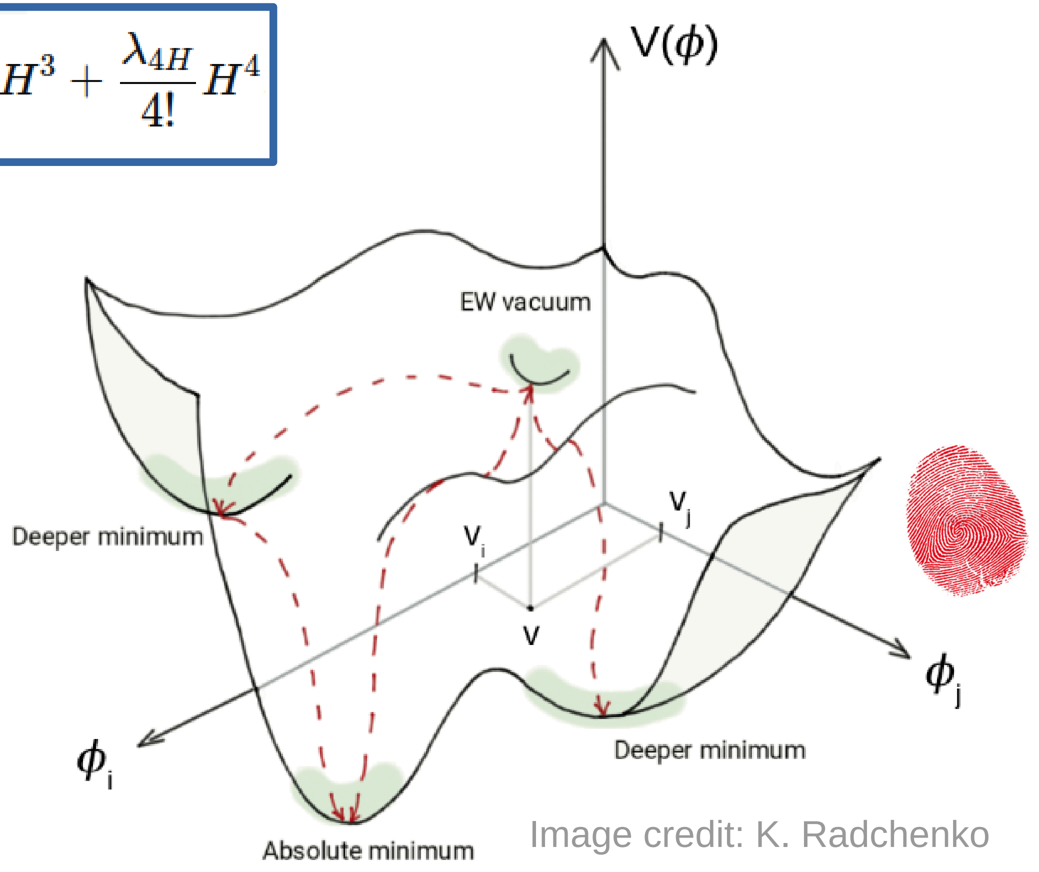


Image credit: K. Radchenko

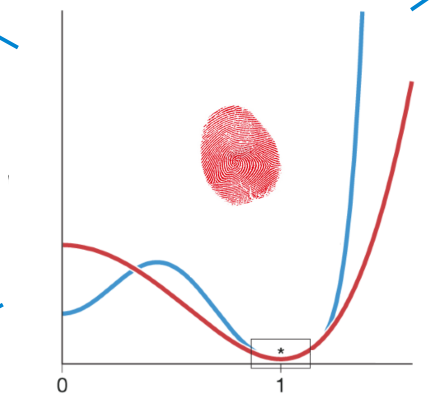
- Smoking-gun hints of extended Higgs sectors:
  - Deviation of self-coupling from SM value
    → This lecture!
  - Presence of extra Higgs bosons
    → Tomorrow's lecture

Why care about the full potential?

> Higgs potential may provide answers to many key open questions in particle physics

Stability of the universe?

Higgs portal(s) to DM?



Fundamental scalar?

Evolution of early universe?

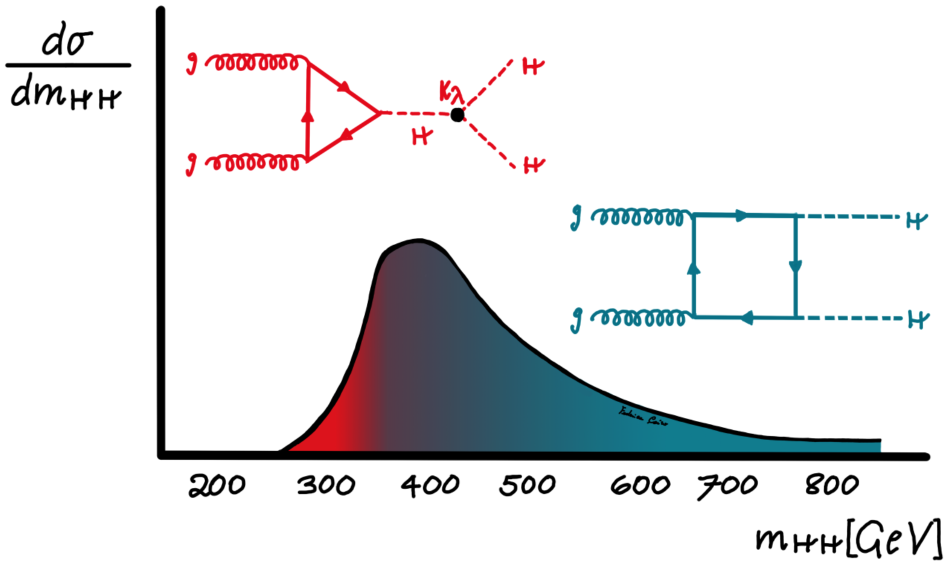
Origin of the baryon asymmetry?

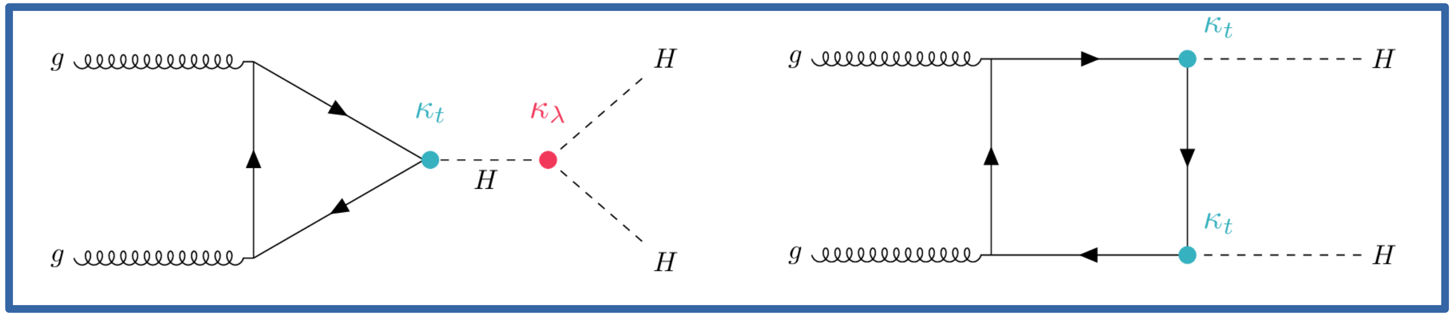
Higgs pair production at the LHC

- Challenge: di-Higgs cross-section around 1800 times smaller than single Higgs cross-section
- ggF production (90.2%): leading sensitivity to trilinear coupling λ_{hhh}

$\kappa_\lambda = \lambda_3 / \lambda^{SM}_{hhh}$

$\kappa_{2V} = \lambda_{hhVV} / \lambda^{SM}_{hhh}$





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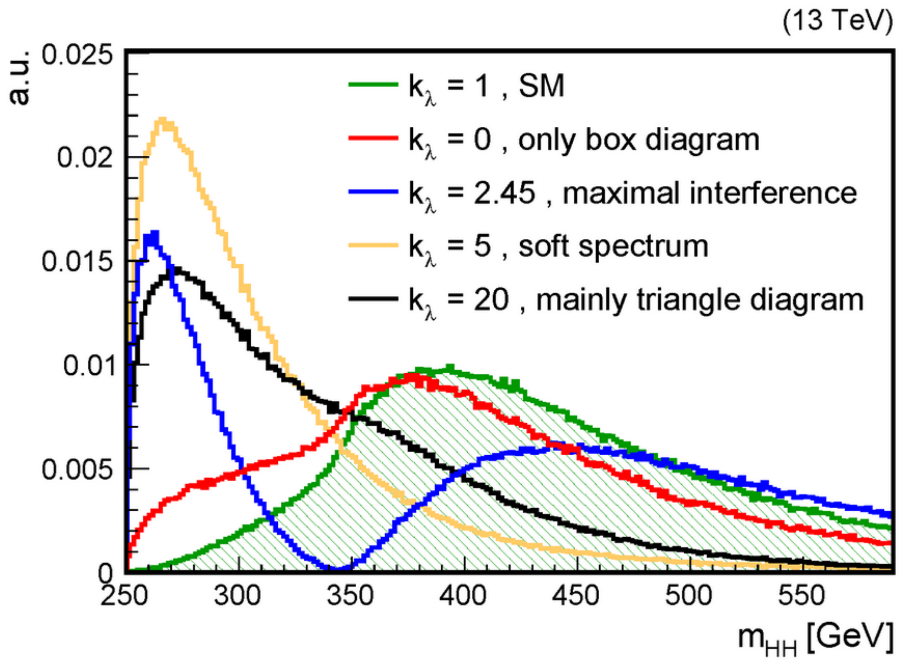
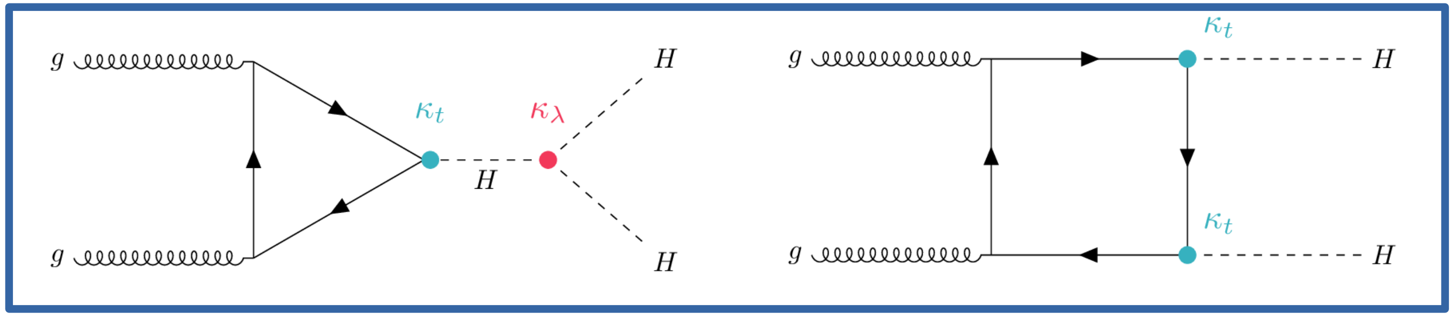
Softer spectrum away from SM value





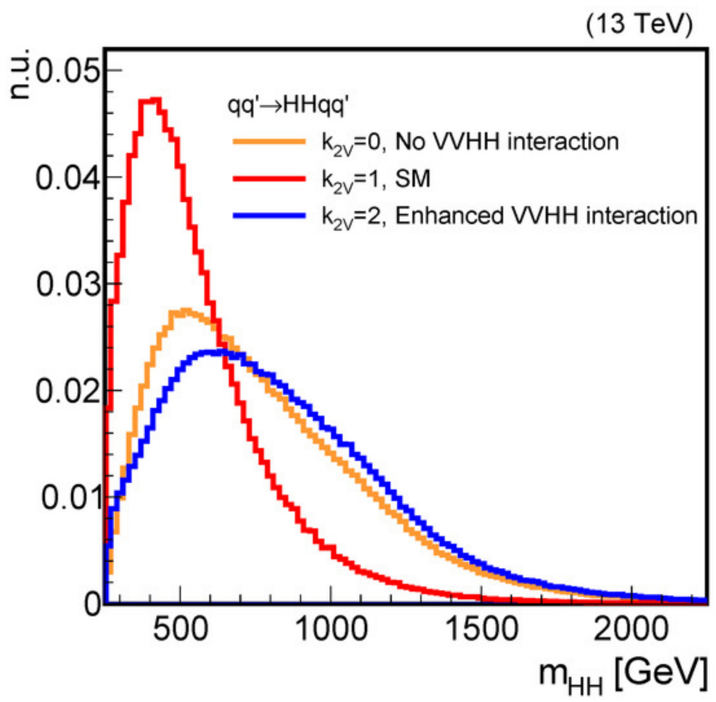
Higgs pair production at the LHC

- Challenge: di-Higgs cross-section around 1800 times smaller than single Higgs cross-section
- ggF production (90.2%): leading sensitivity to trilinear coupling λ_{hhh}
- VBF production (5%): unique access to di-Higgs-di-vector-boson coupling λ_{hhvv}

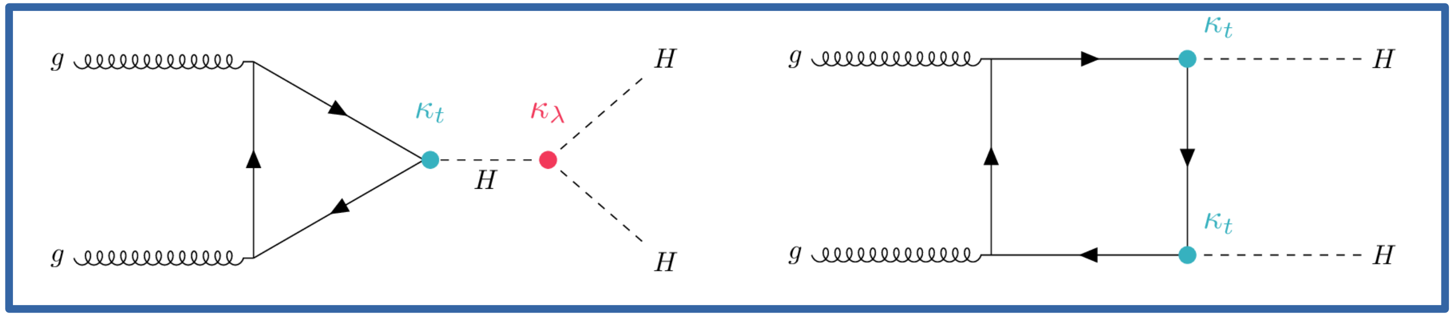
$\kappa_\lambda = \lambda_3 / \lambda^{SM}_{hhh}$

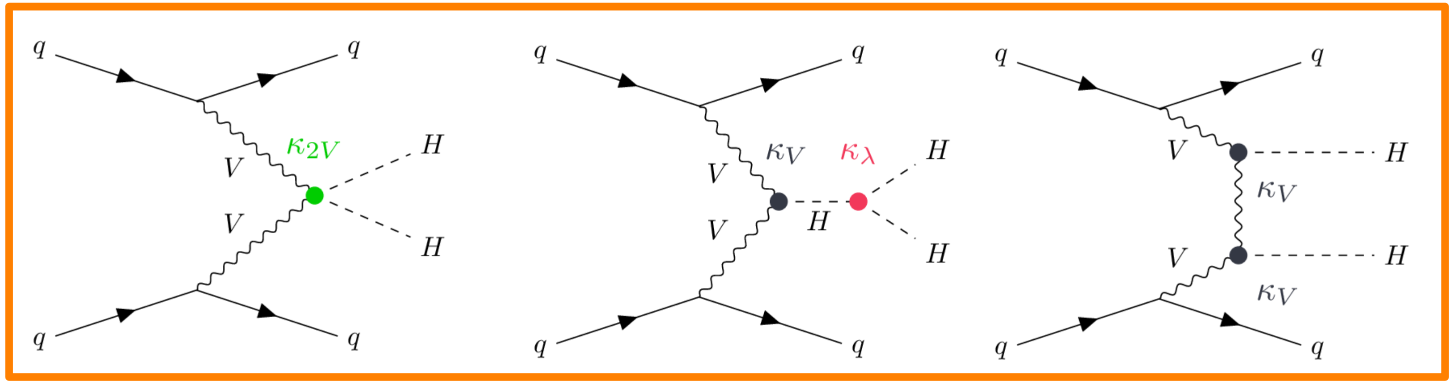
$\kappa_{2V} = \lambda_{hhVV} / \lambda^{SM}_{hhh}$

Harder spectrum away from SM value



31.05 fb

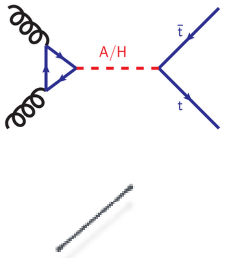




1.72 fb

How to find a needle in a haystack?

> Isolate small signal from huge dataset



Signal

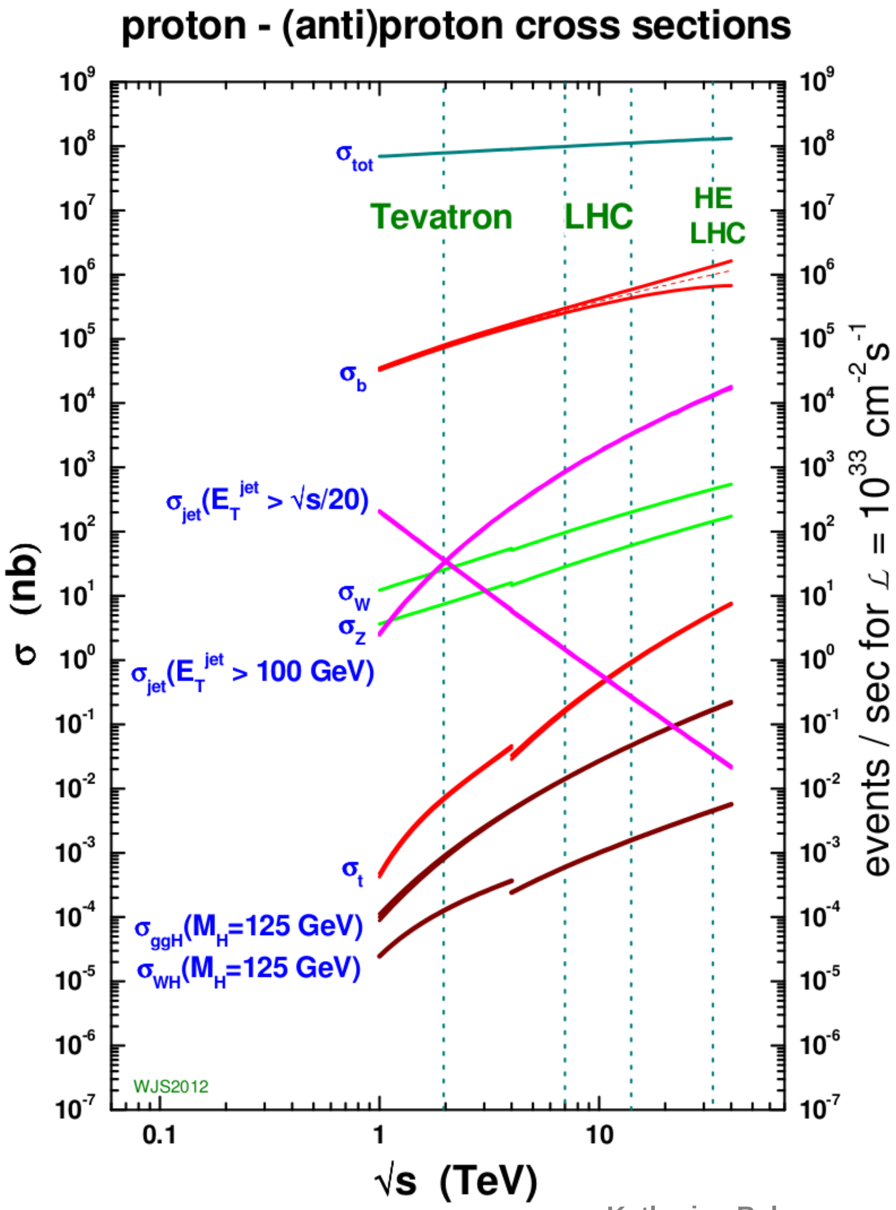
(a.k.a. the needle)

Background

(a.k.a. the haystack)

(...it's meant to be a haystack)

T.G. McCarthy



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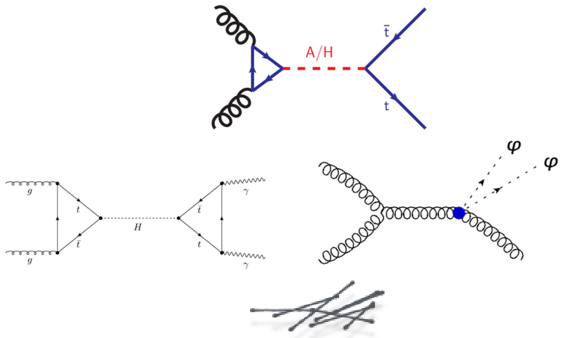
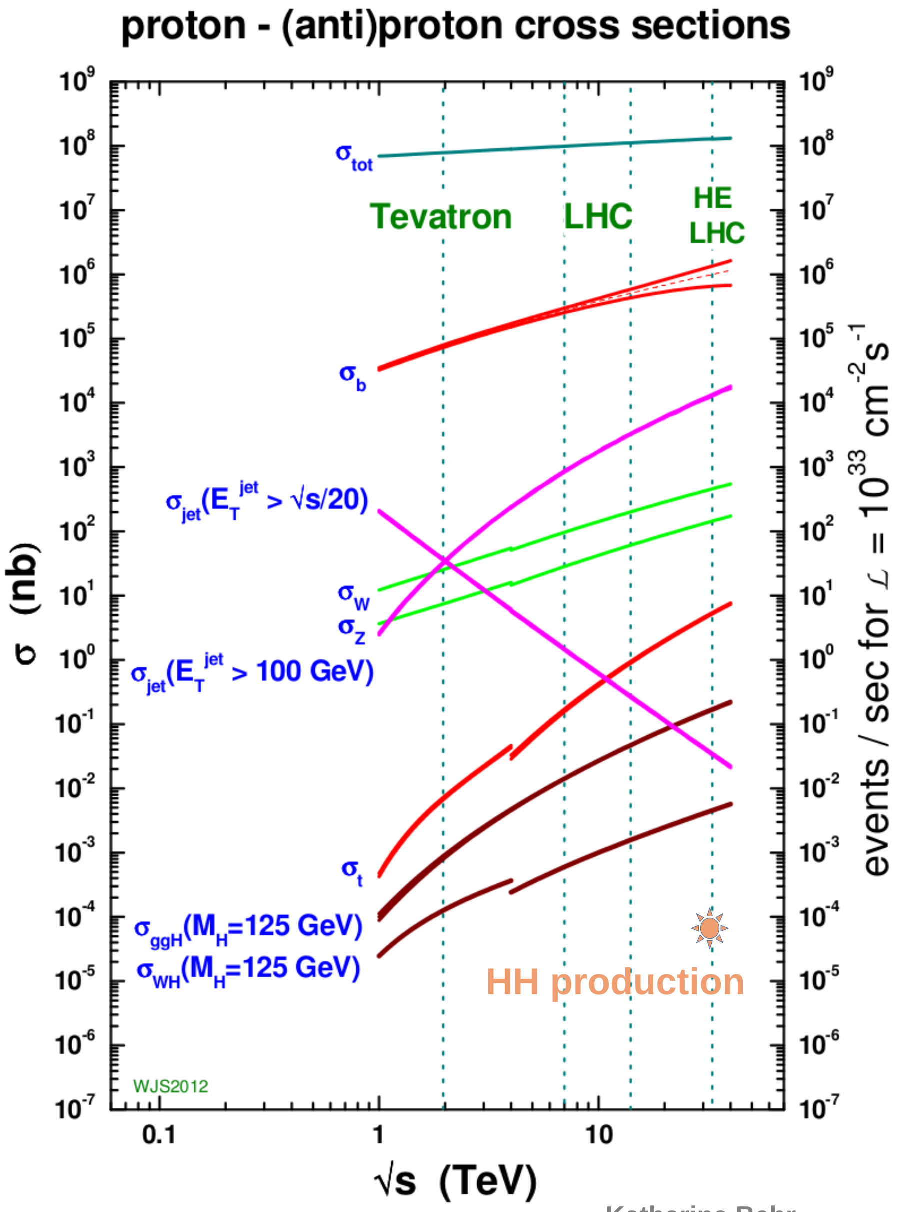


Signal
(several needles)

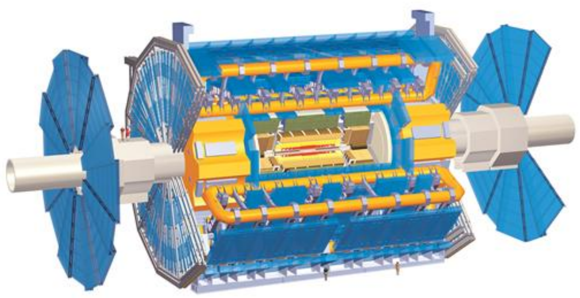
Backgrounds
(several different types of haystacks)
(will all be blended together into a big mess)

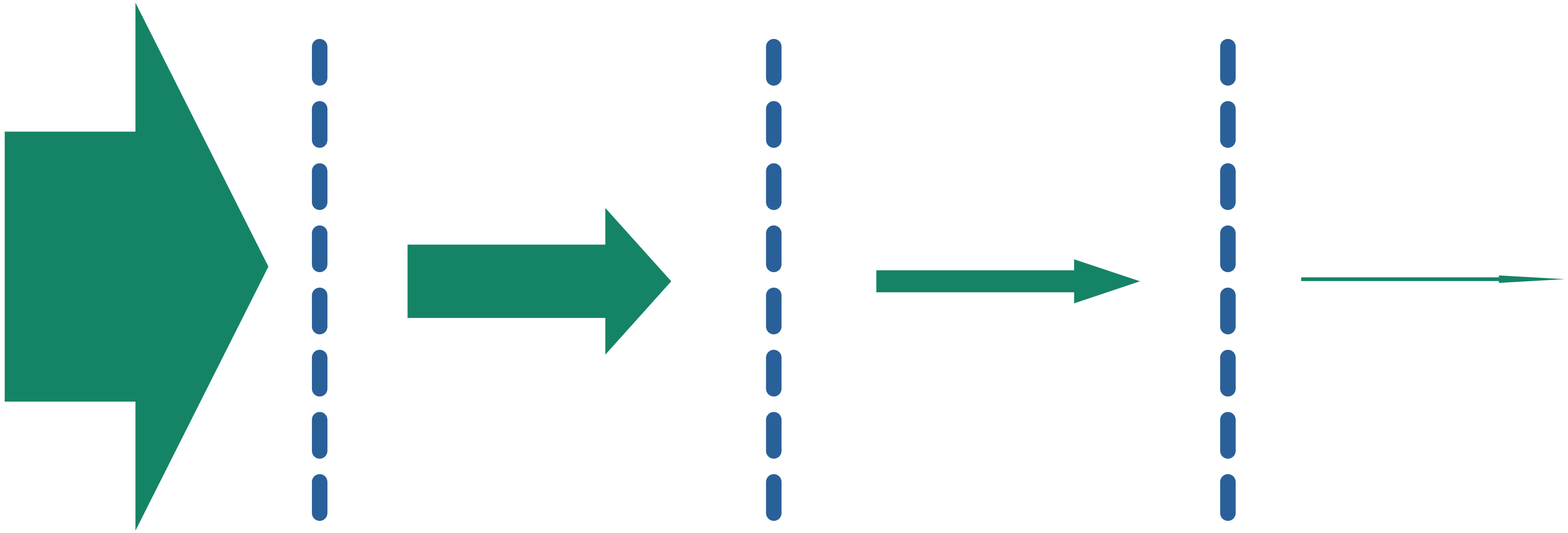
T.G. McCarthy



How to find a needle in a haystack?

- Define criteria that characterise chosen signal in detector
- Apply selection criteria to reduce background
- Signal-enriched region (signal region)



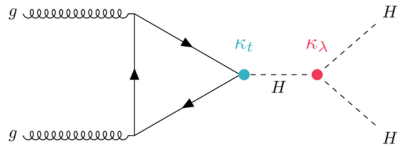


Trigger selection (online)

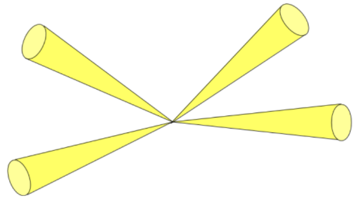
Coarse pre-selection (offline)

Tight signal region selection (offline)

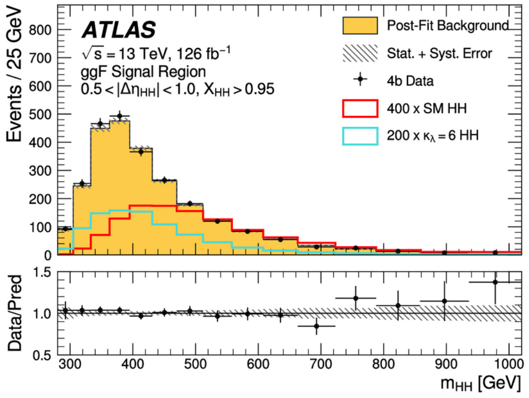
Data analysis 101



> Pick and study a signal of interest (MC simulation)



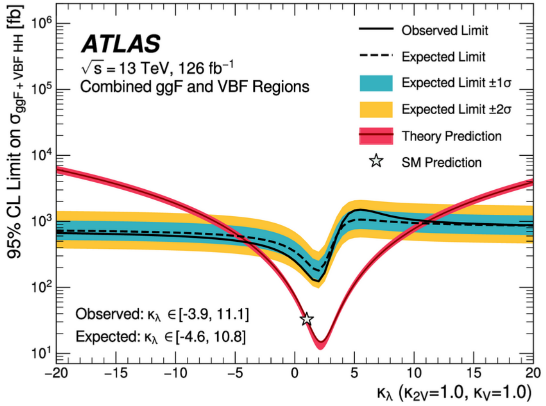
> Select subset of events enriched in signal (signal region)



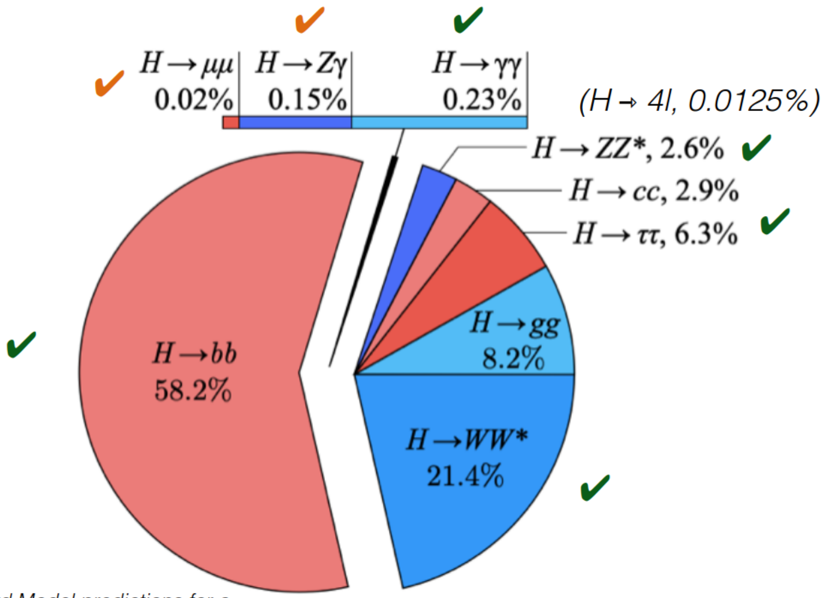
> Estimate backgrounds and systematic uncertainties

- Often via control regions enriched in background

> Test agreement between SM prediction and data (likelihood fits)



Signatures of di-Higgs production



(Standard Model predictions for a Higgs boson with mass 125 GeV)

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

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> Three most sensitive channels:
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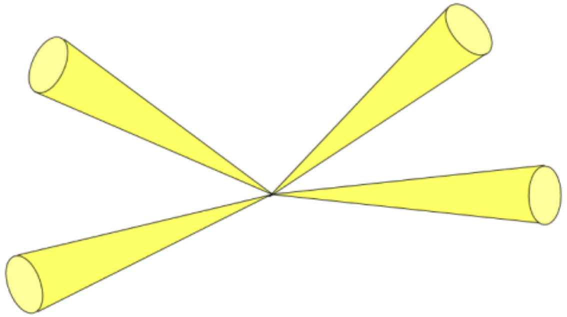
Event topologies in the *bbbb* channel

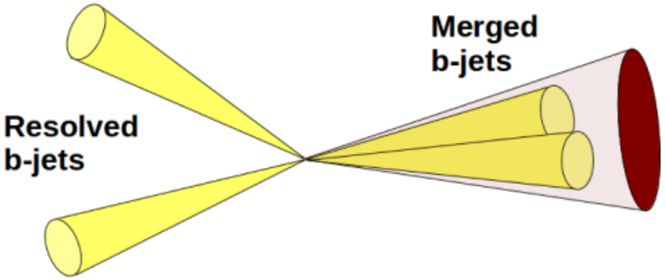
- Three possible topologies depending on Lorentz boost of the two Higgs bosons
- Identification of heavy flavour crucial:
  - *b*-tagging for resolved decays
  - $h \rightarrow bb$ tagging for merged decays

Resolved

$\varepsilon_{\mathrm{sig}} \sim \varepsilon_{b}^{4}$

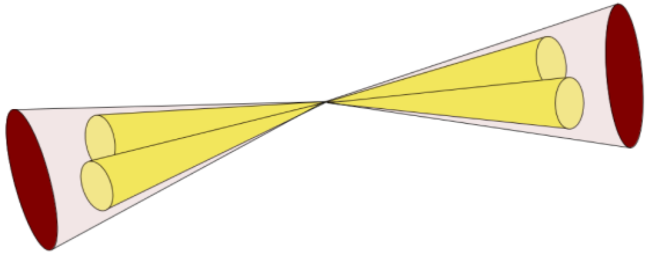


[Intermediate]



Merged

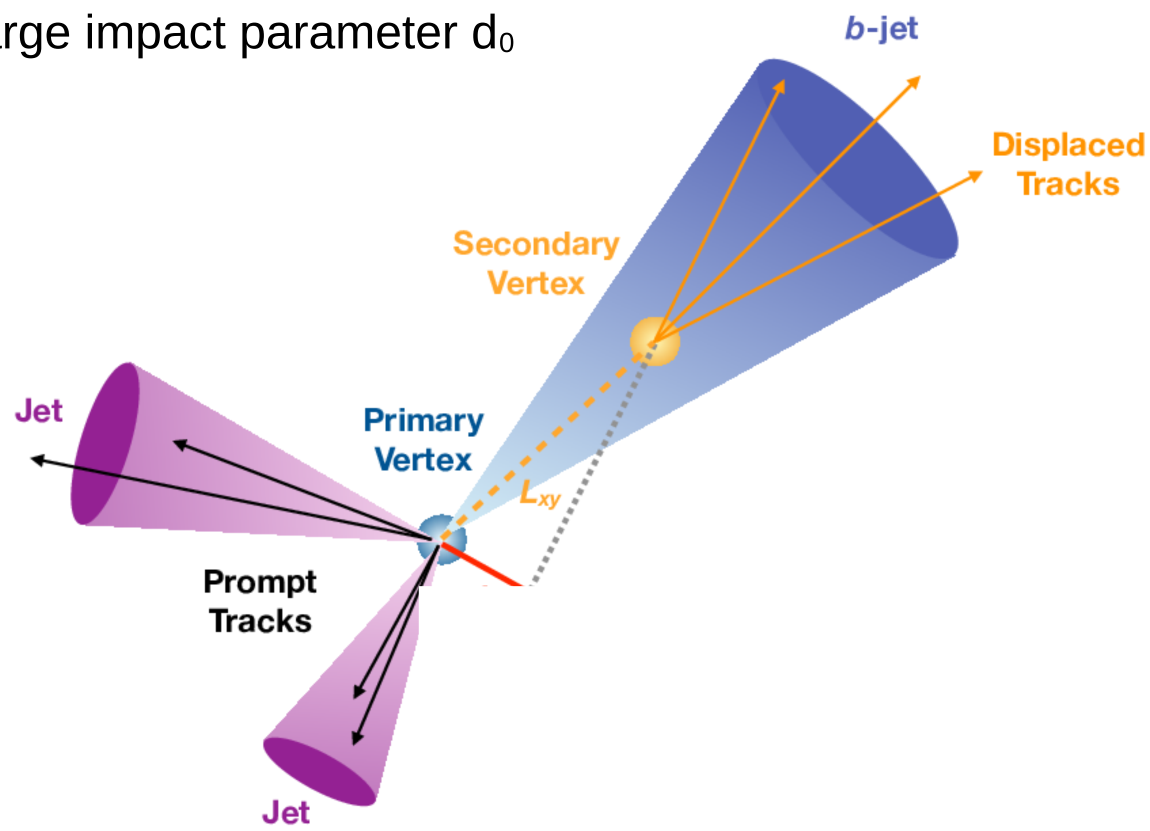
$\varepsilon_{\mathrm{sig}} \sim \varepsilon_{Xbb}^{2}$



b-tagging

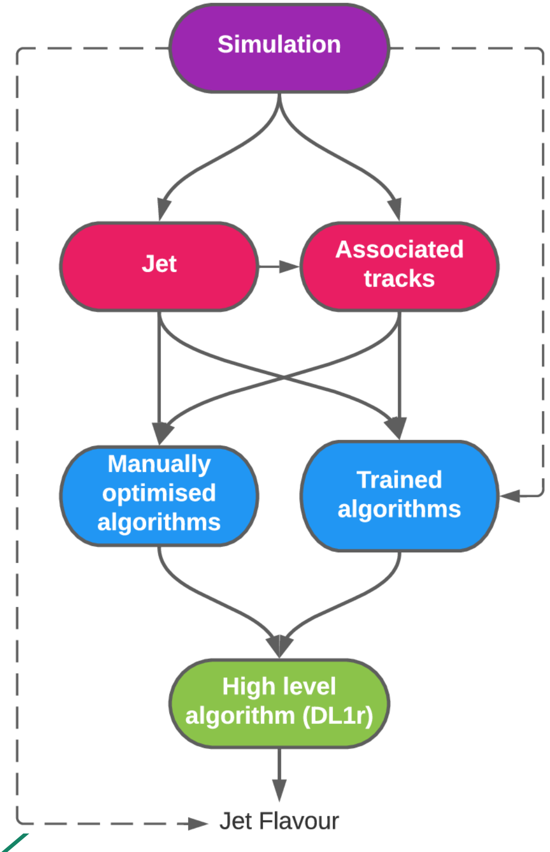
> Identification of jets initiated by *b*-quarks based on properties of resulting *B*-hadron

- Secondary decay vertex
- Significant decay length of O(mm – cm)
- Tracks not pointing back to primary vertex → large impact parameter d_0

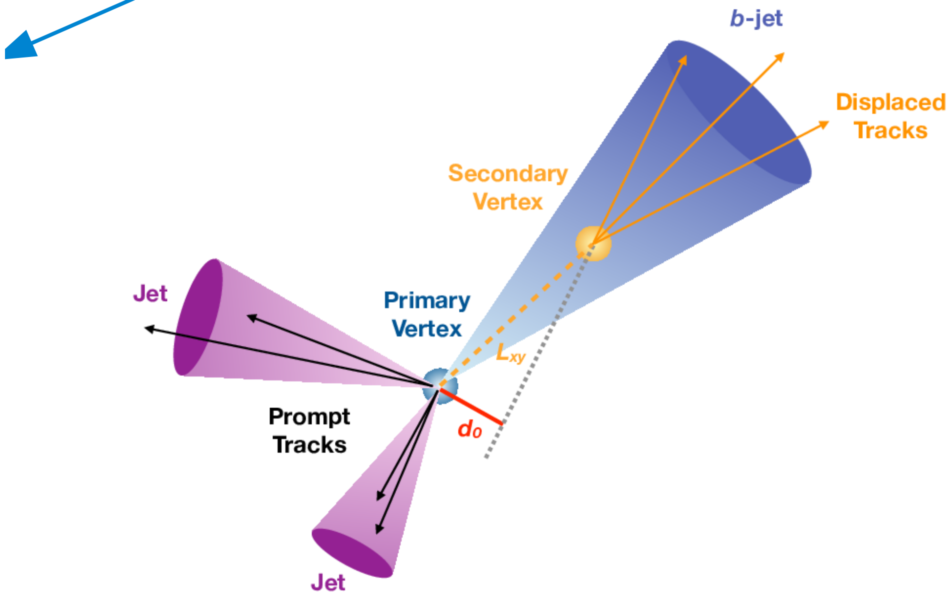


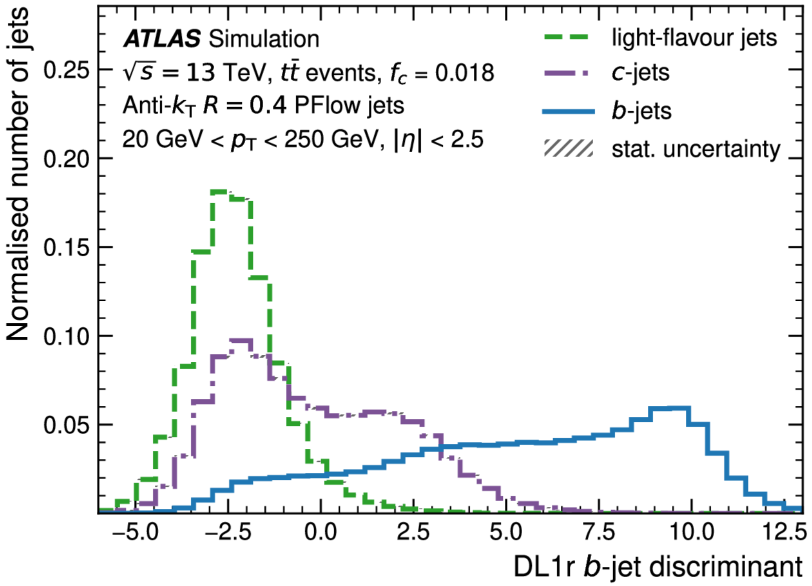
b-tagging (Run 2)

> Combine all information in high-level deep neural net discriminator



Secondary vertex based
Track IP (d_0) based





Higgs tagging (Run 2)

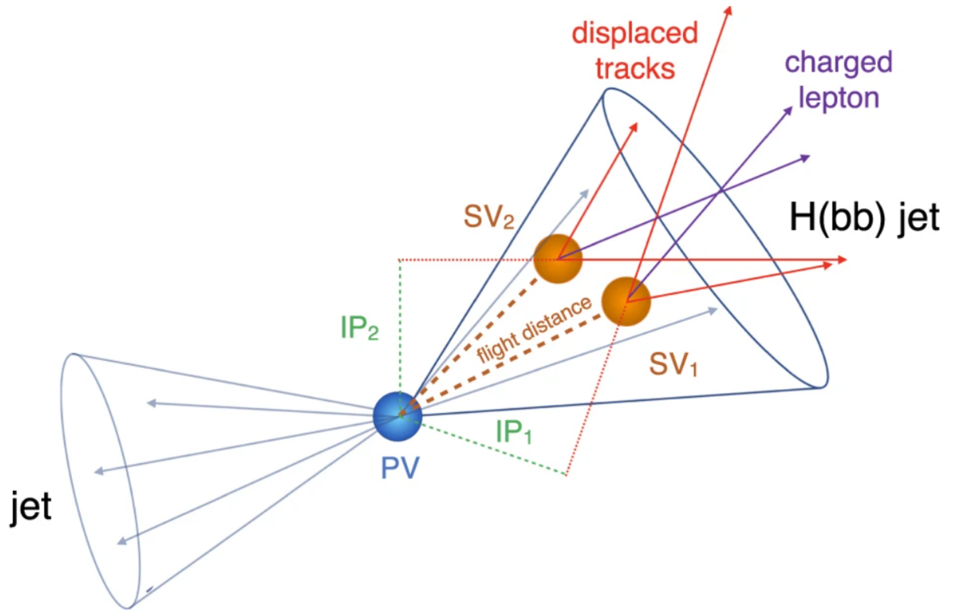
ATL-PHYS-PUB-2020-019

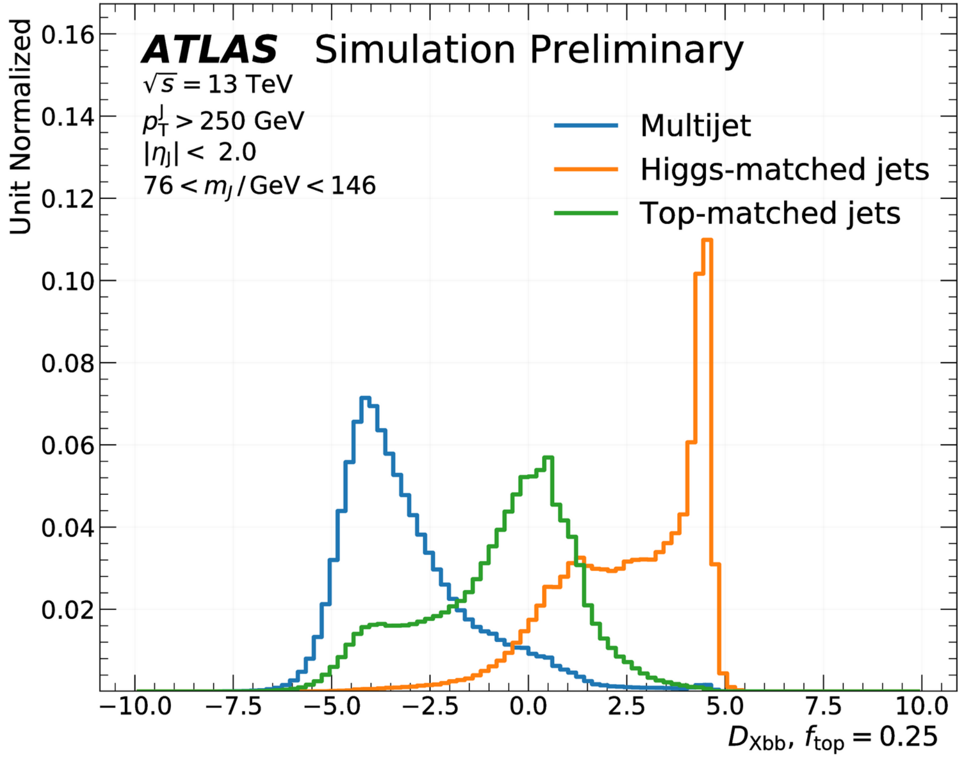
> Large calorimeter jet with fixed radius parameter R=1.0

> Identify small-radius subjets and check if they are *b*-tagged using standard *b*-tagging algorithm

> DNN classifier combining the following inputs:

- DL1r scores of 2-3 sub-jets
- Large-*R* jet kinematics





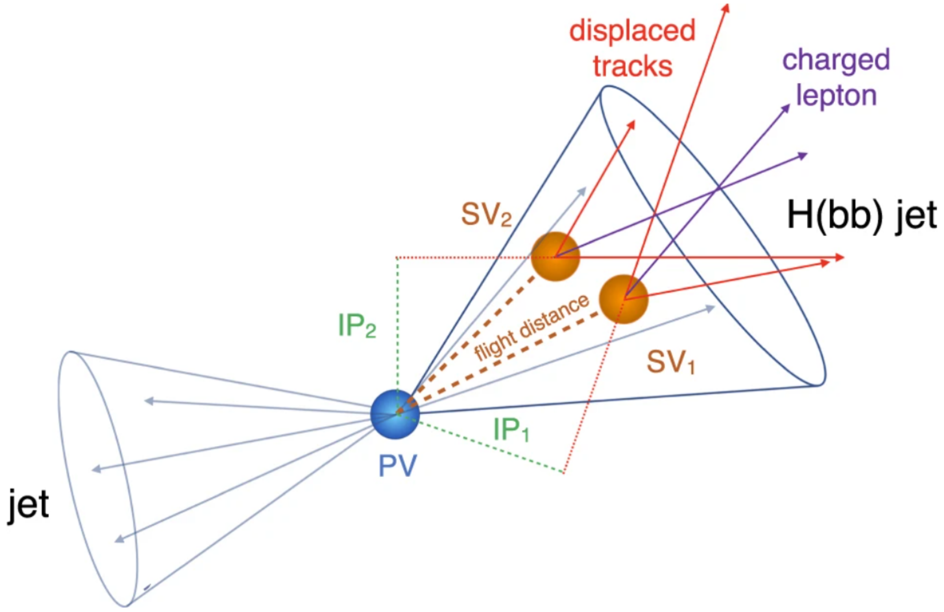
Next-generation taggers (Run 3) – transformers!

> Inputs: low-level objects (tracks, particle-flow objects)

> Significant performance improvements for analyses using *b*- and *h*→ *bb* jets

- x 2 better top and multijet rejection for 70% signal efficiency

> Need accurate tracks reconstruction!



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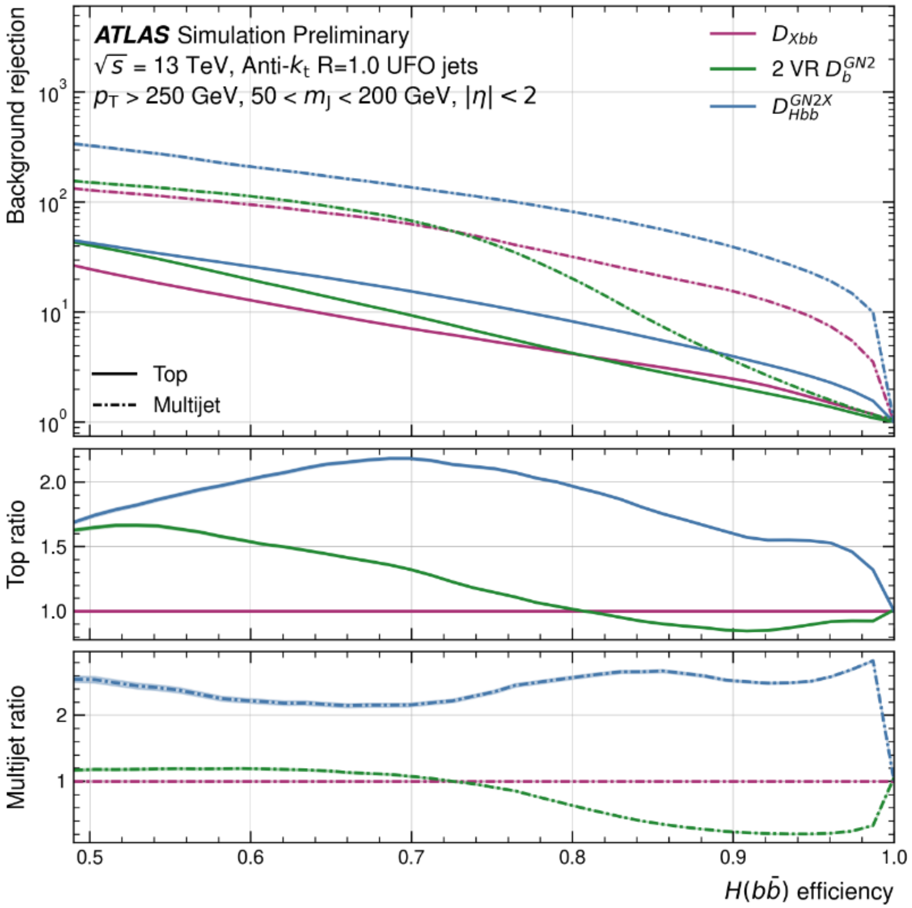
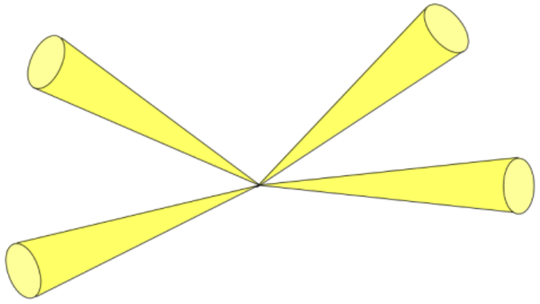


Analysis strategy for the *bbbb* channel

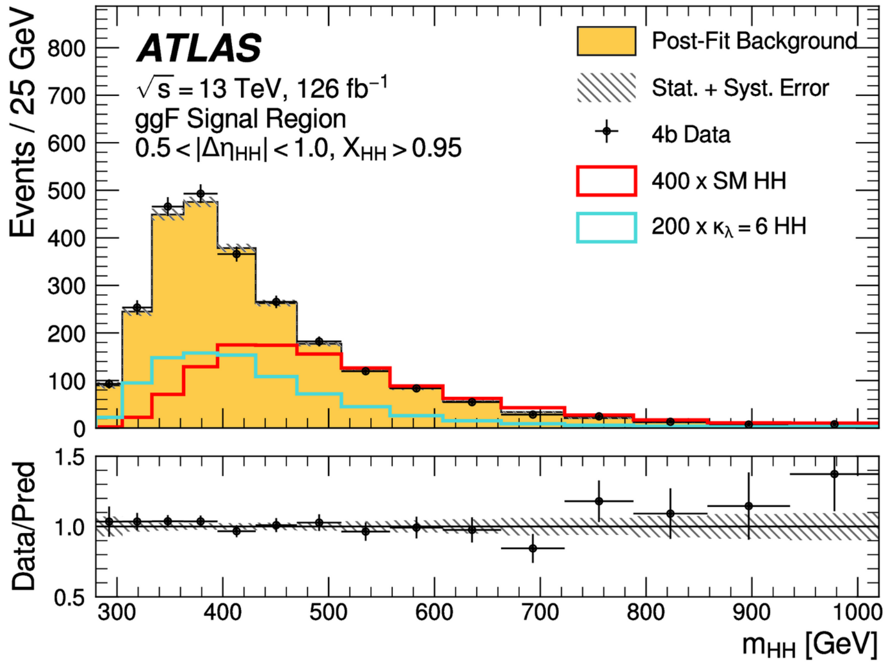
> Focus on resolved topologies here: ≥ 4 *b*-jets (signal region)

> Combinatorial problem: assign *b*-jets to the two Higgs decays

- Different possible approaches, based on m_{bb} or $\Delta R(b,b)$
- Focus on four leading *b*-jets → three possible combinations
- Choose configuration where Higgs candidate with the higher p_T has smallest $\Delta R(b,b)$



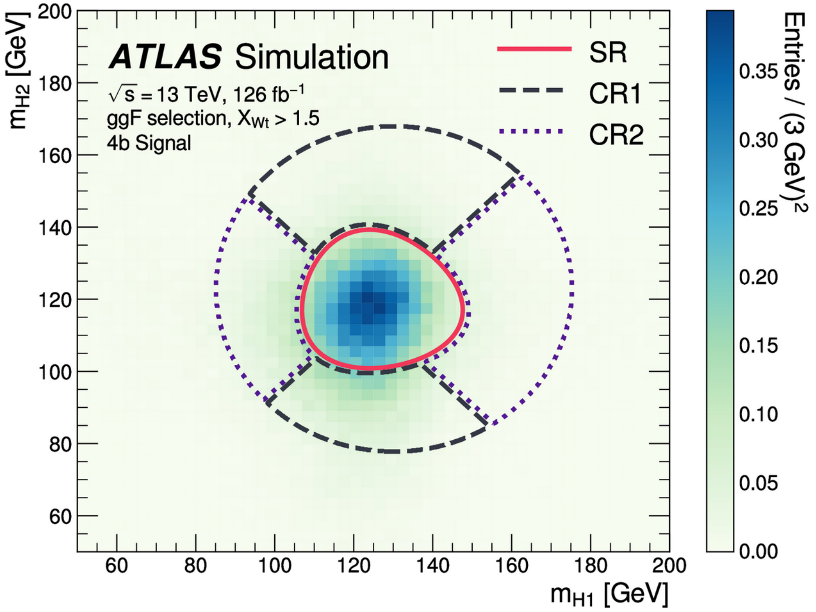
> Reconstruct m_{hh}

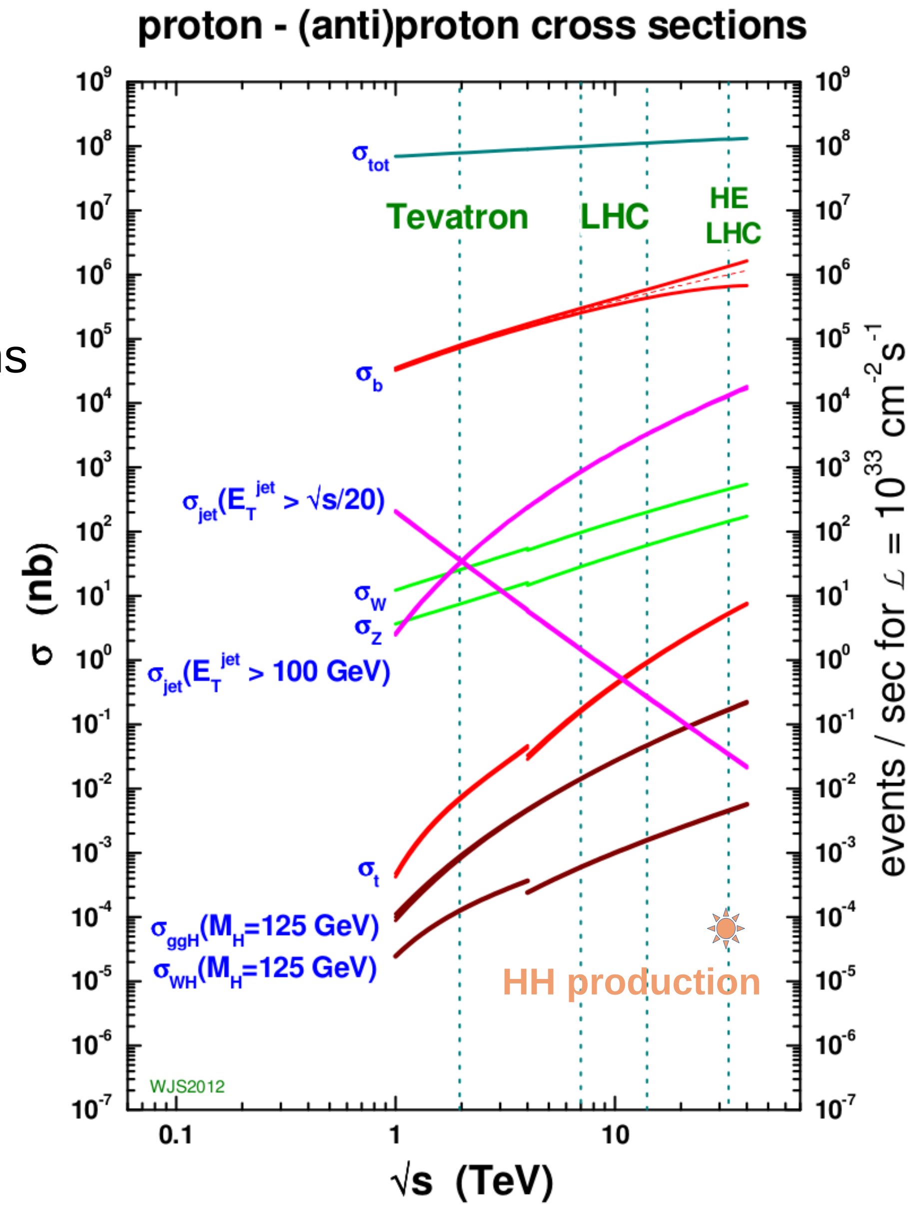


Background processes

> Background dominated by real *b*-jets and jets mis-identified as *b*-jets

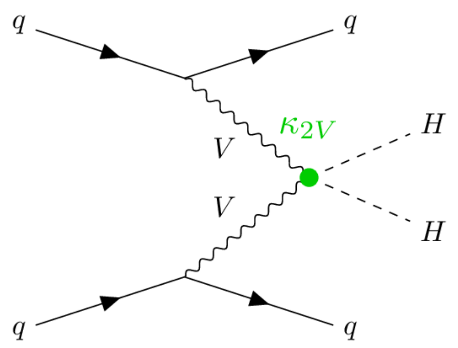
- Difficult to model in simulation due to relevance of detector effects
- Estimated using data in signal-depleted control regions

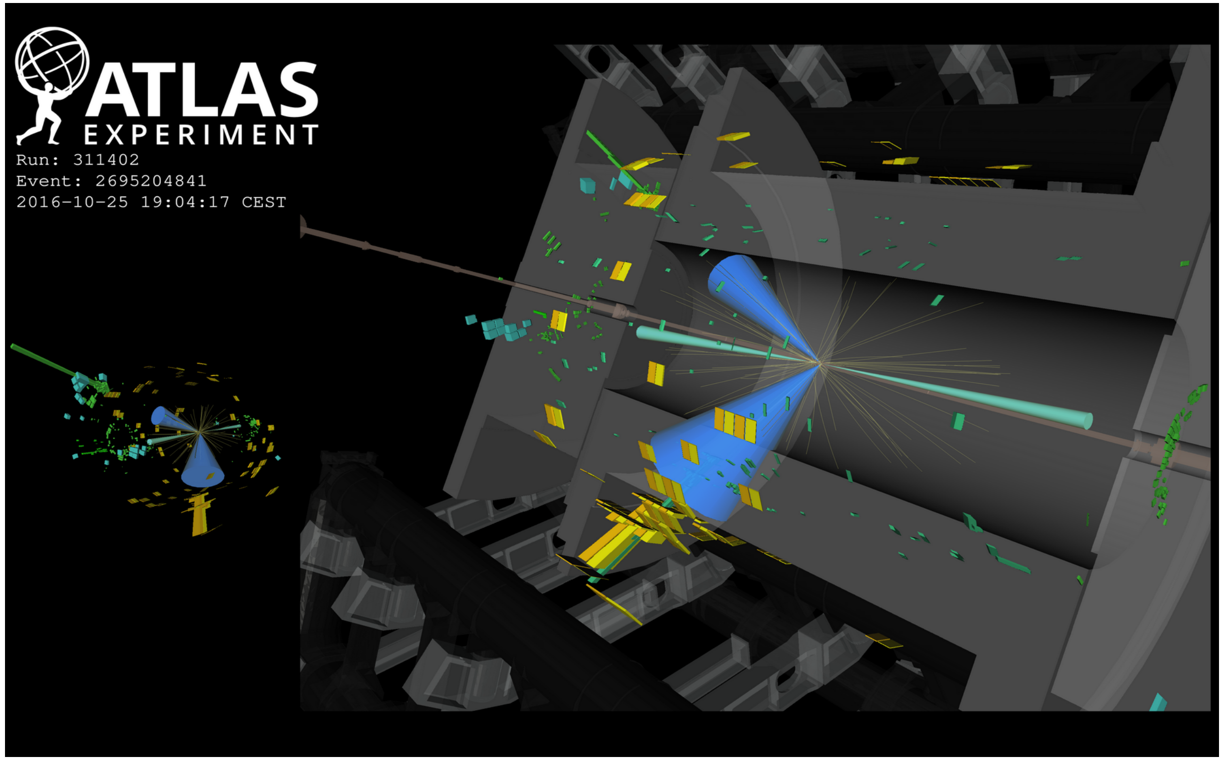


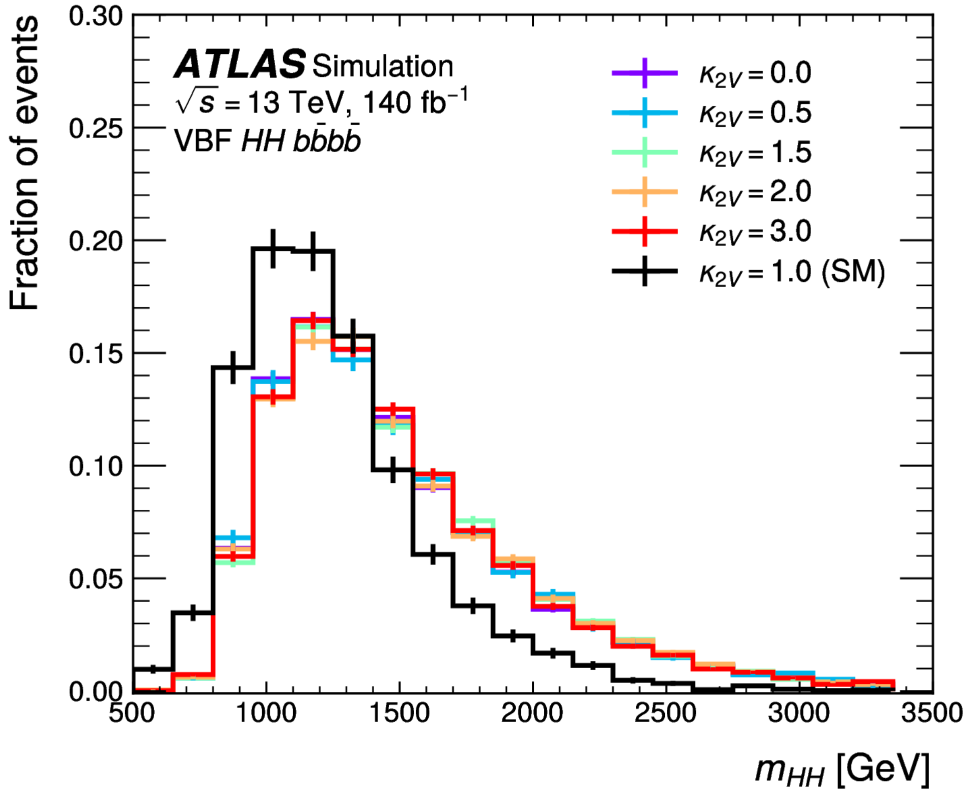


Extra: the hhVV coupling

- Focus on production via vector-boson fusion
- Select events with two forward jets and two merged Higgs boson decays
- Topologies with boosted Higgs boson particularly sensitive to non-SM values of k_{2V}







Signatures of di-Higgs production

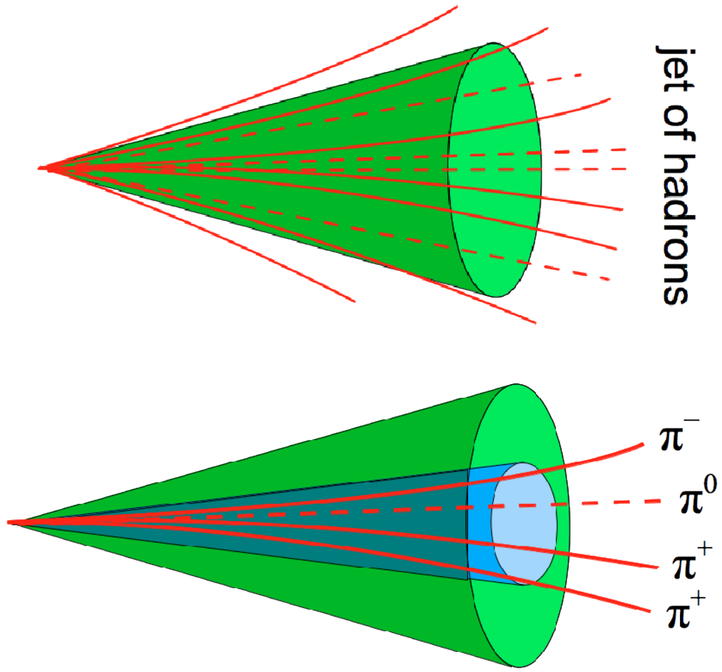
> Three most sensitive channels:

- *bbbb*: largest BR (34%), large multi-*b*-jet background
- *bbττ*: medium BR (7.3%), good signal purity

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Signature of the bbττ channel

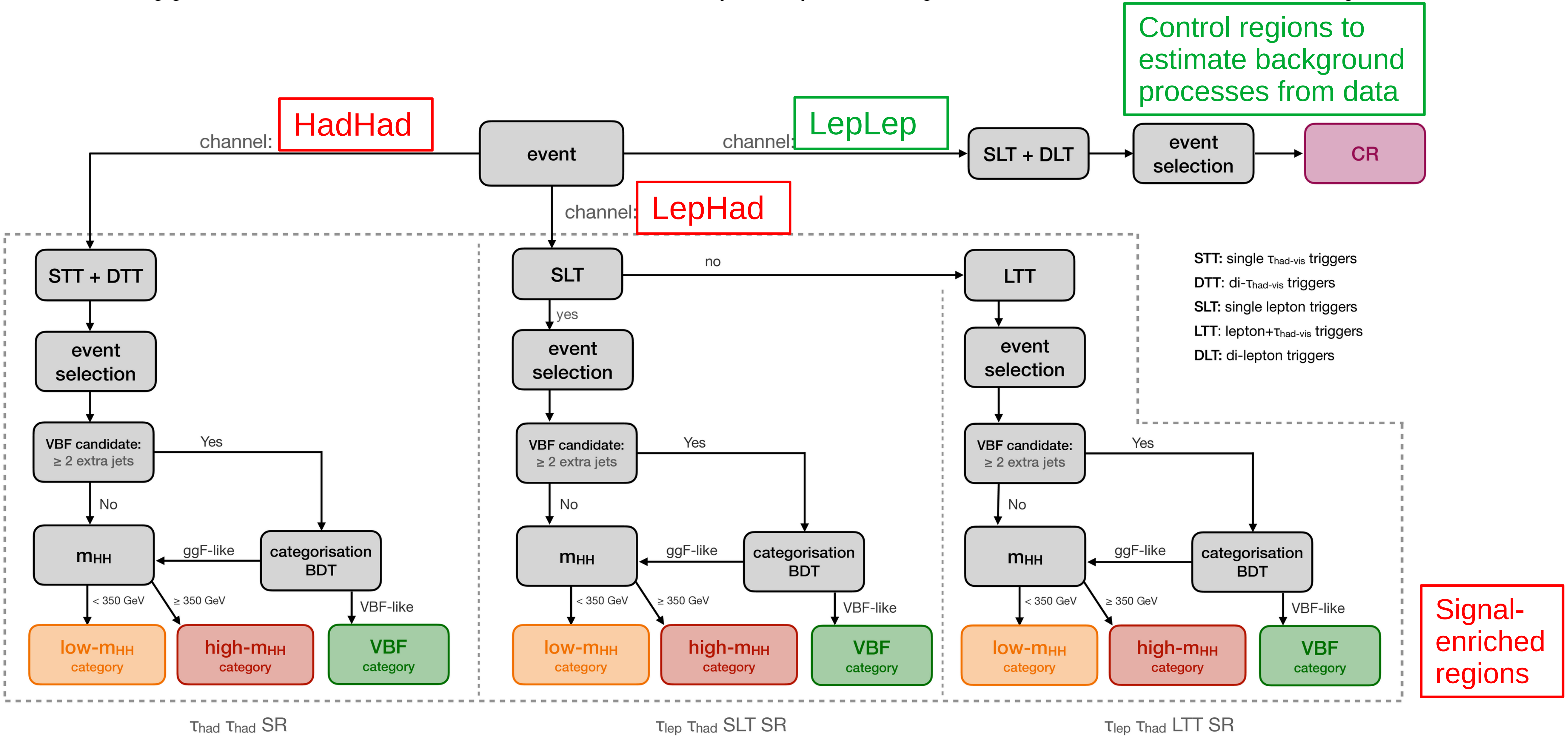
- τ-leptons decay before interacting with the detector
- Leptonic decay: $\tau_{lep} \rightarrow e/\mu + 2\nu$
- Hadronic decays:
  - $\tau_{had} \rightarrow 3\pi^{\pm} + X + \nu$ (3-prong)
  - $\tau_{had} \rightarrow \pi^{\pm} + X + \nu$ (1-prong)
- τ-taggers to identify hadronic τ decays
  - Run-2: BDTs
  - Run-3: transformers (similar to *b*-taggers)
- Two orthogonal channels:
  - LepHad: $\tau_{lep}\, \tau_{had}$
  - HadHad: $\tau_{had}\, \tau_{had}$



3-
prong

Complex analysis strategy for the *bbττ* channel

> Different triggers, various Boosted Decision Trees (BDTs) to categories events and enhance signal



Signatures of di-Higgs production

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  - *bbbb*: largest BR (34%), large multi-*b*-jet background
  - *bbττ*: medium BR (7.3%), good signal purity
  - *bbγγ*: clean channel, but low BR (0.26%)

	bb	WW	ττ	ZZ	γγ
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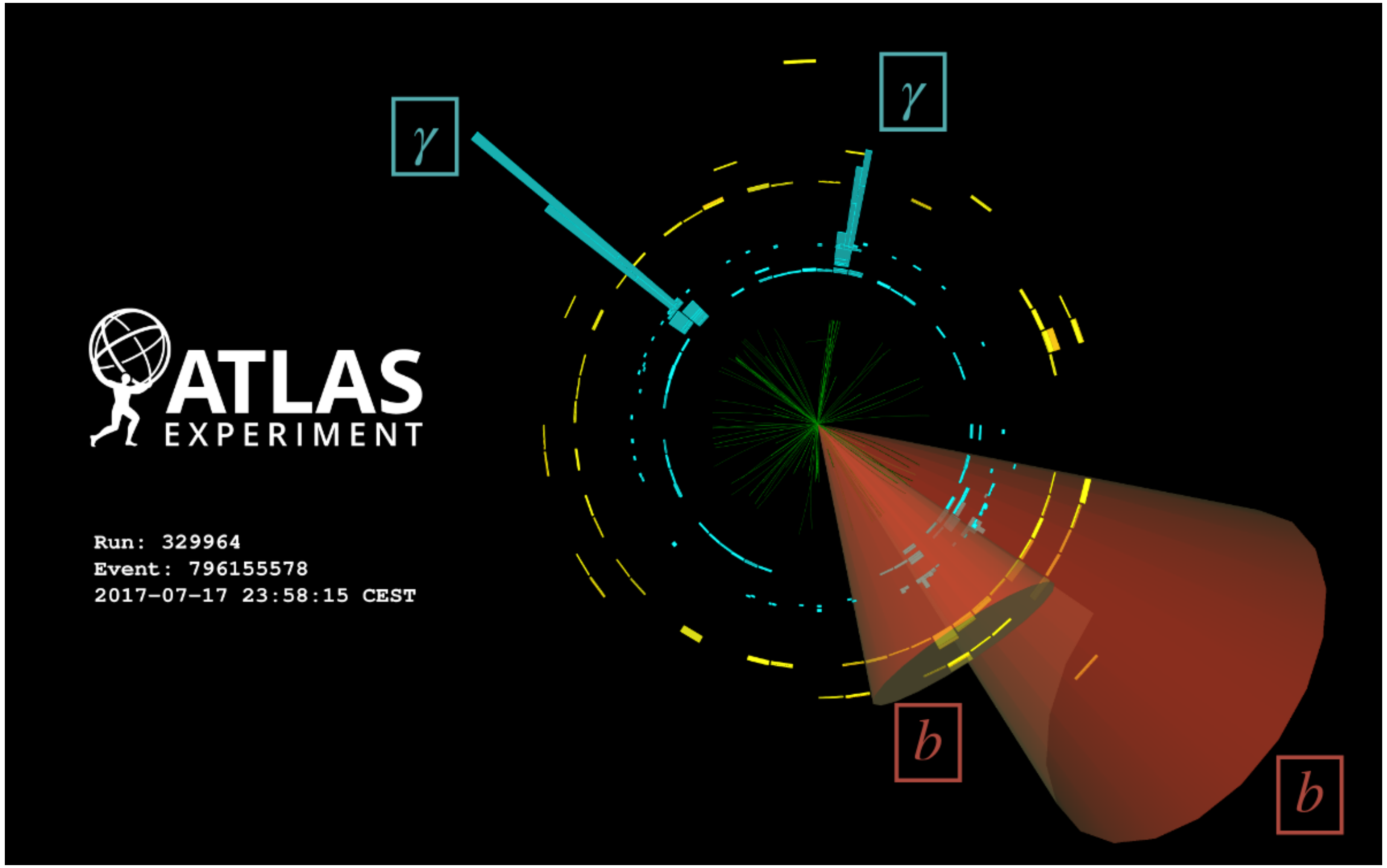
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Signature of the *bbyy* channel

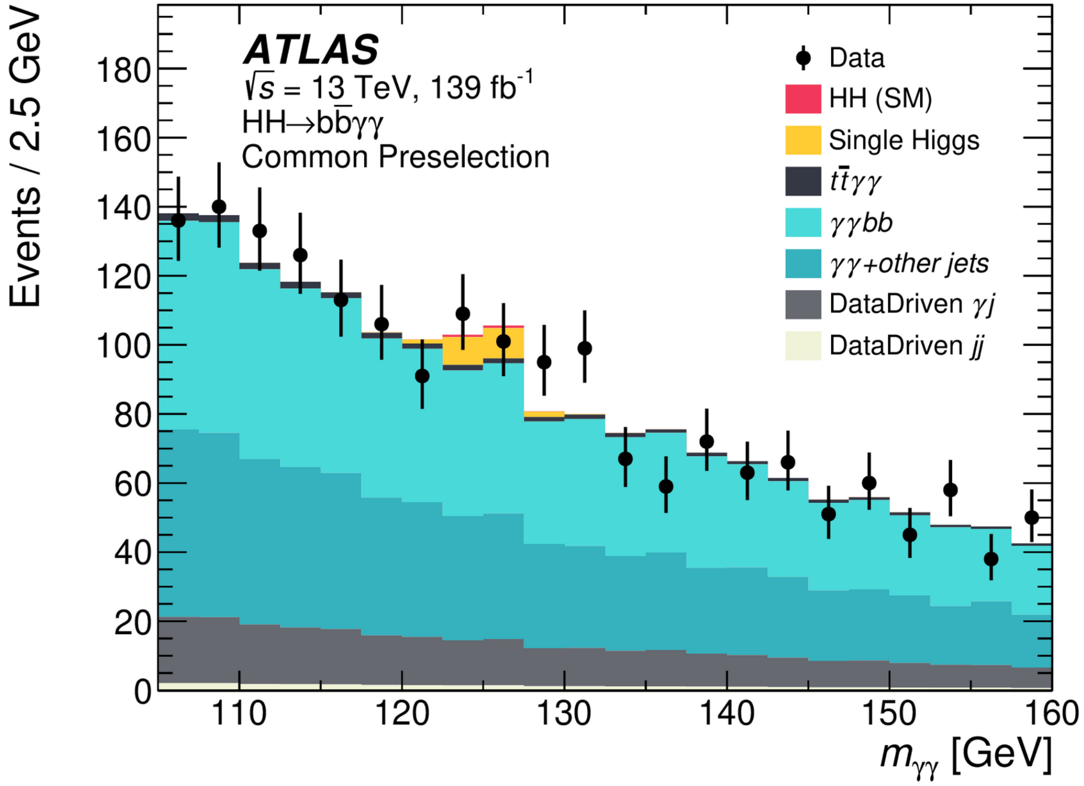
- Photons can be efficiently and precisely with the electromagnetic calorimeters
- Require events with two photons and at least two b-tagged jets
- Straightforward reconstruction of two Higgs candidates

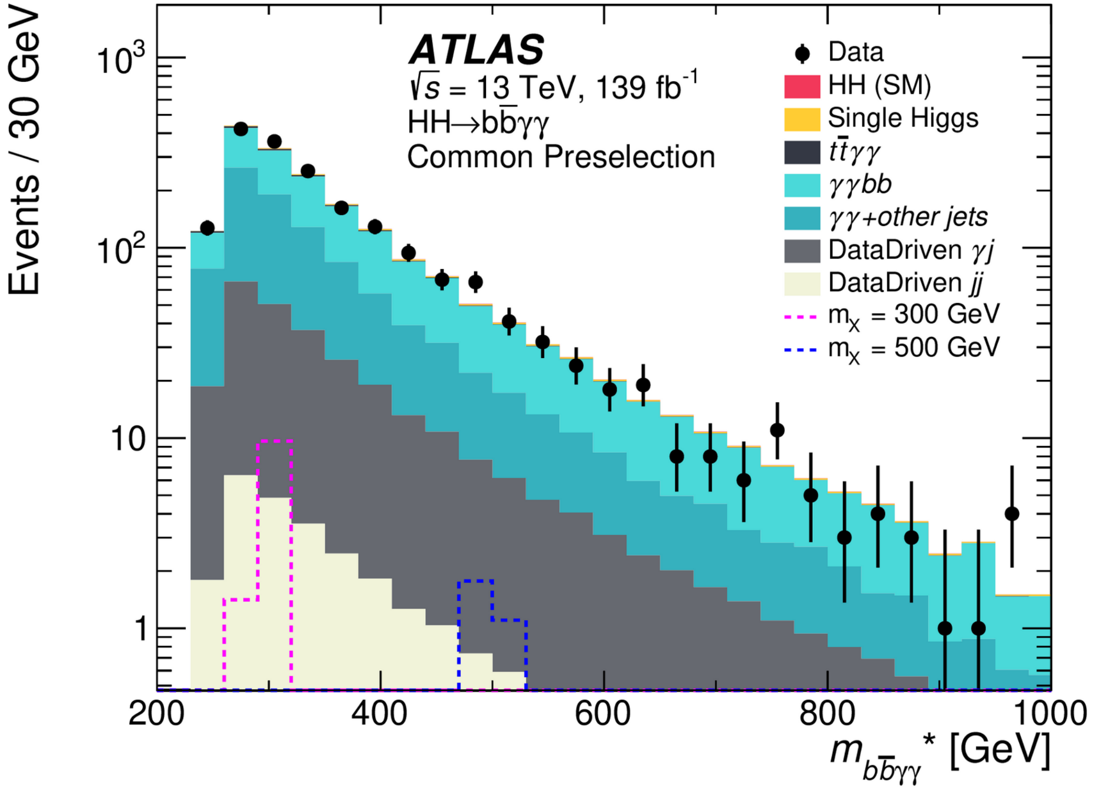


Analysis strategy of the *bbγγ* channel

>

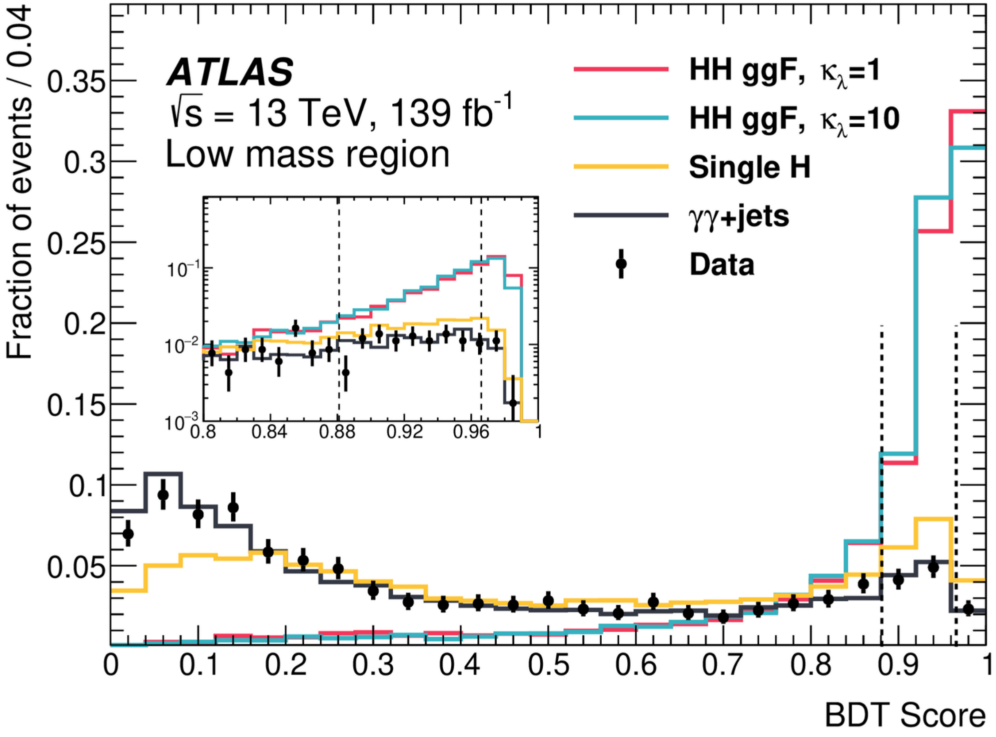
> Main backgrounds from real photons produced in association with jets → taken from simulation

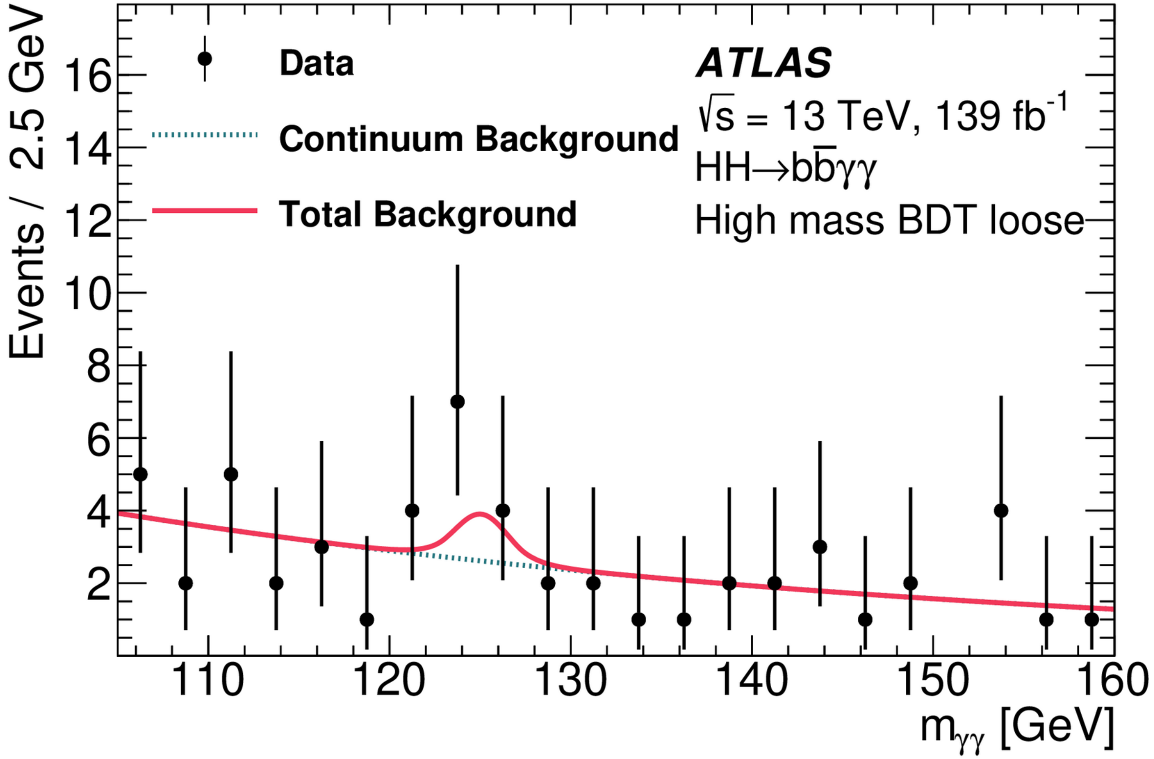




Analysis strategy of the *bbyy* channel

- Multivariate methods to improve suppress background processes
- Focus on on Higgs decay to photons – much better mass resolution compared to decay to *bb*
- Check if there is an excess compared to the background - which now includes single-Higgs production!

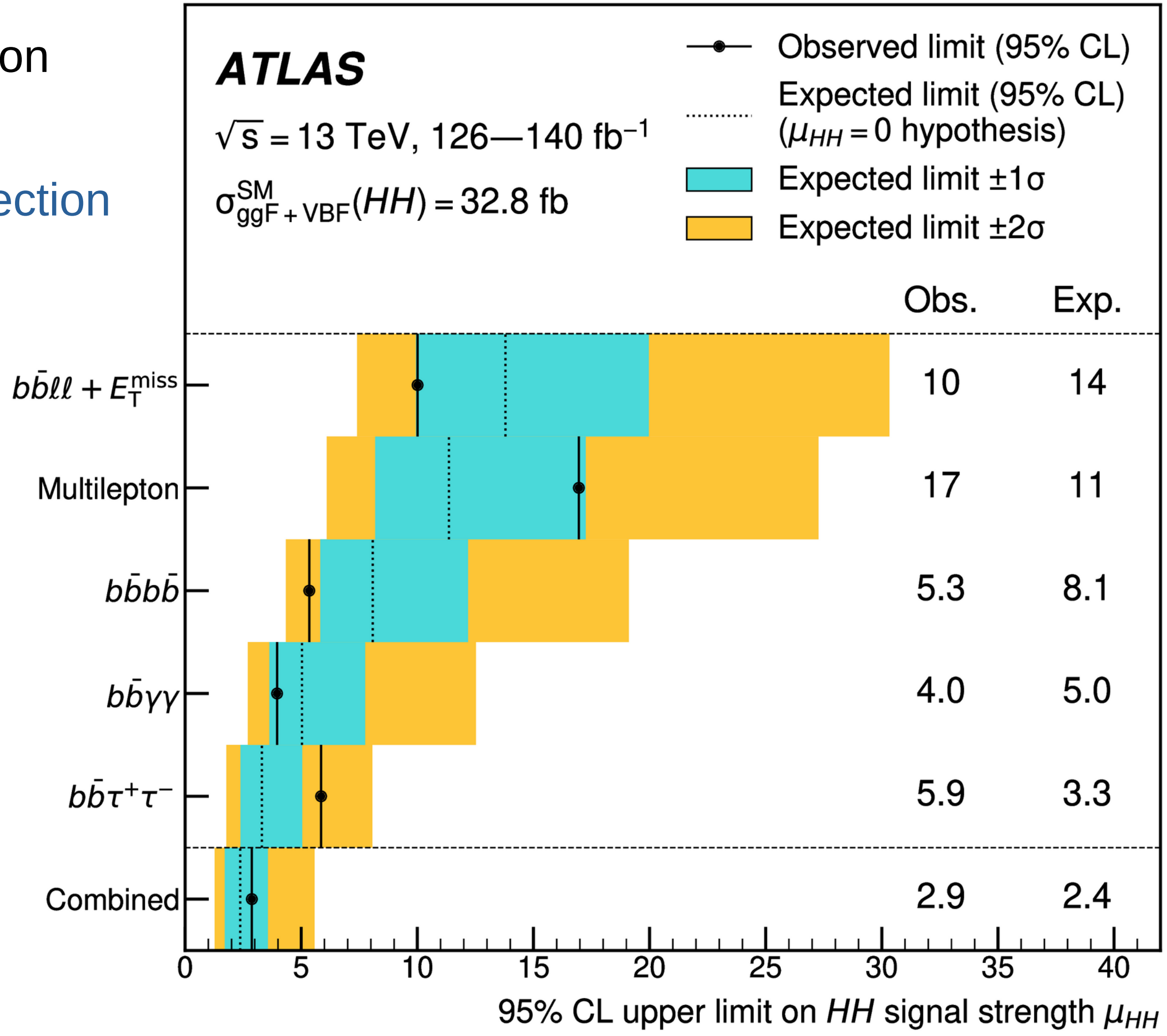




Putting all results together

Phys. Rev. Lett. 133 (2024) 101801

- No di-Higgs signal observed yet
- Instead set upper limits on production cross-section
- Or more precisely, on the signal strength:
  μ_{HH} = measured cross-section / expected cross-section
- How "far away" are we from probing the SM?



- Statistical combination of three leading channels + sub-dominant channels
- Current best constraints on Higgs pair production

$\boxed{\mu_{hh} < 2.9 \text{ (2.4 exp.)}}$

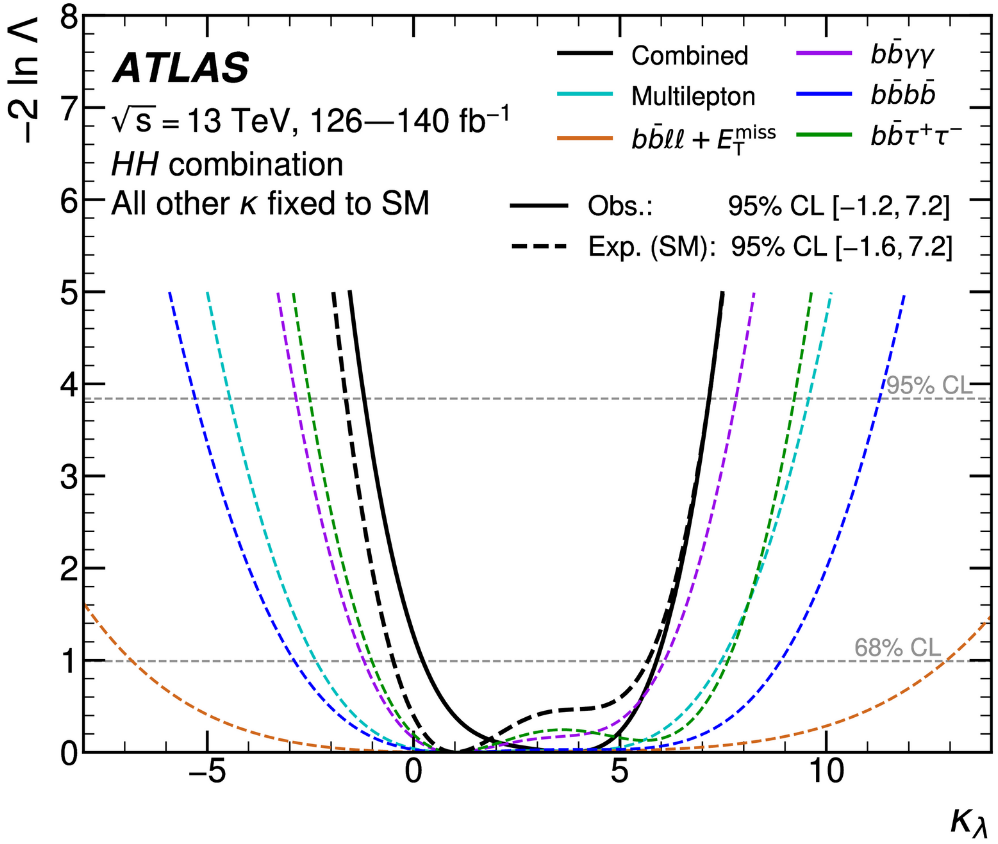
Putting all results together

Phys. Rev. Lett. 133 (2024) 101801

> Significant improvement in expected sensitivity on κ_λ

Observed: $\kappa_\lambda \in [-1.2, 7.2]$
Expected: $\kappa_\lambda \in [-1.6, 7.2]$

Dominated by *bbττ* and *bbγγ*
(photon and lepton triggers powerful at low m_{hh})



Putting all results together

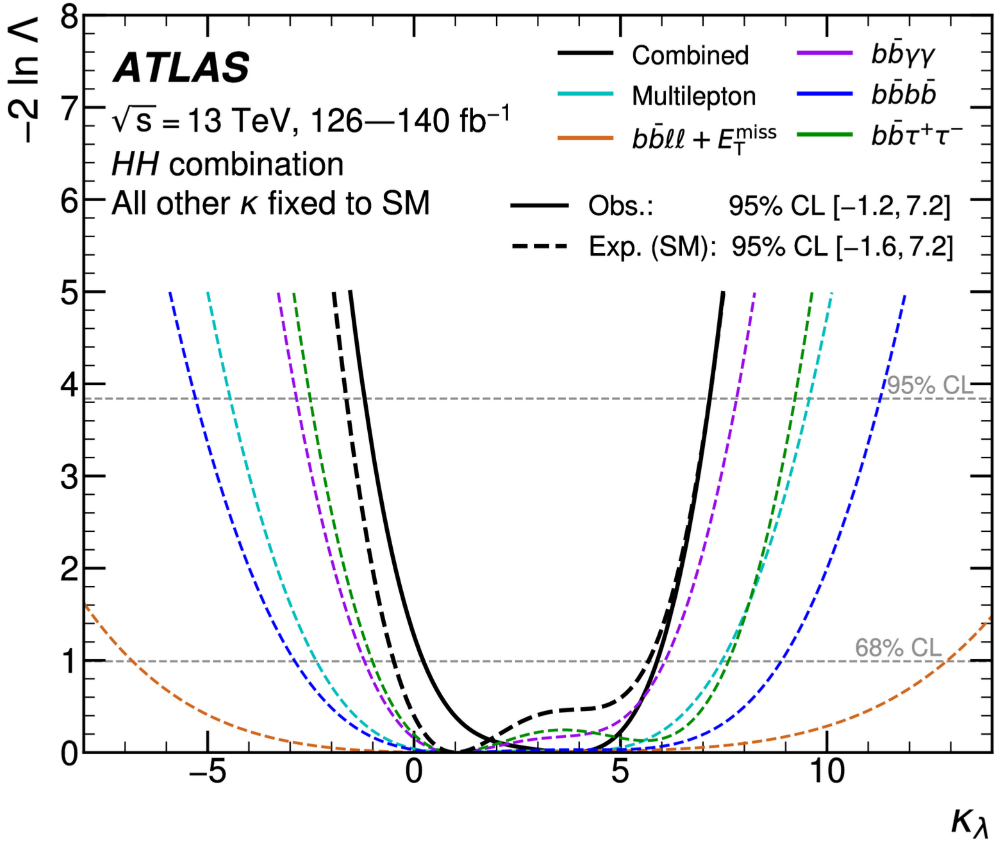
Phys. Rev. Lett. 133 (2024) 101801

> Significant improvement in expected sensitivity on κ_λ

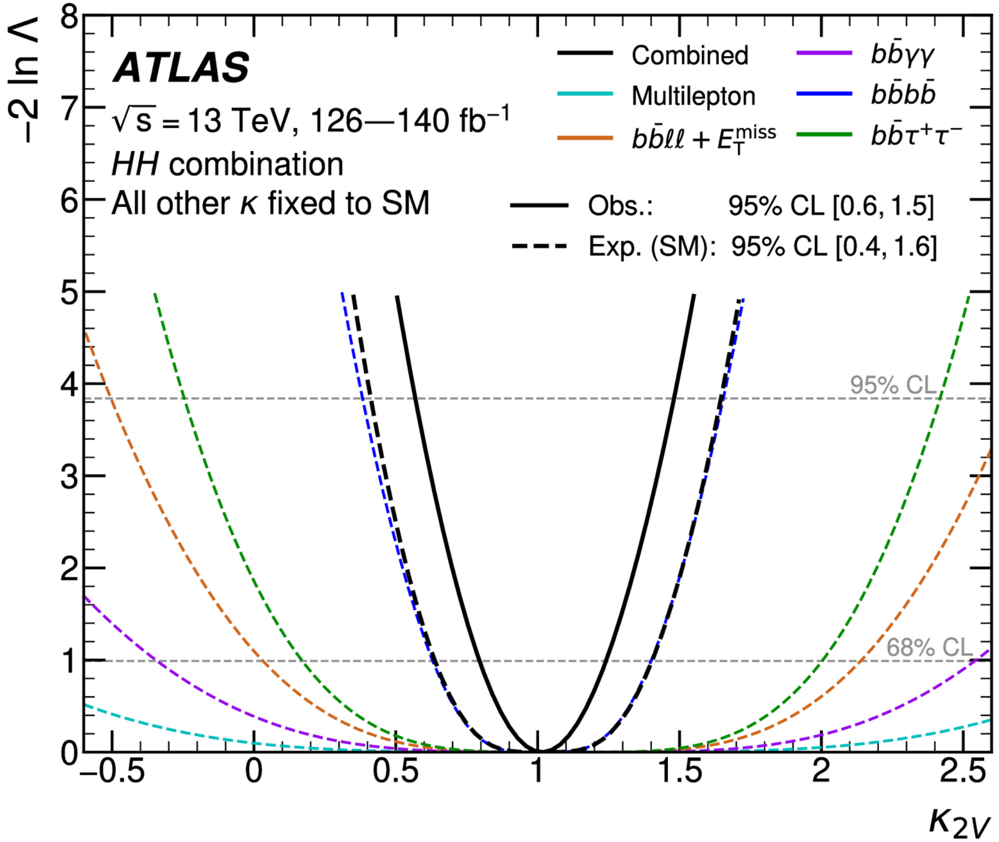
Observed: $\kappa_\lambda \in [-1.2, 7.2]$
Expected: $\kappa_\lambda \in [-1.6, 7.2]$

Observed: $\kappa_{2V} \in [-0.6, 1.5]$
Expected: $\kappa_{2V} \in [-0.4, 1.6]$

Dominated by *bbττ* and *bbγγ*
(photon and lepton triggers powerful at low m_{hh})



Dominated by boosted VBF *bbbb*
(boosted *bbbb* signatures powerful at high m_{hh})



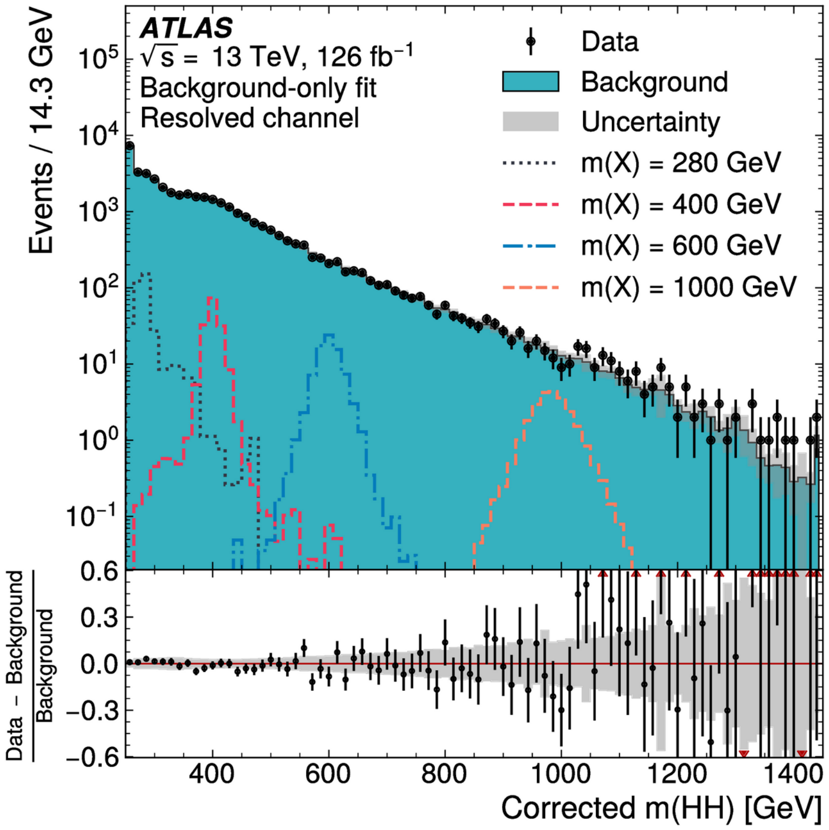
Resonant Higgs pair production

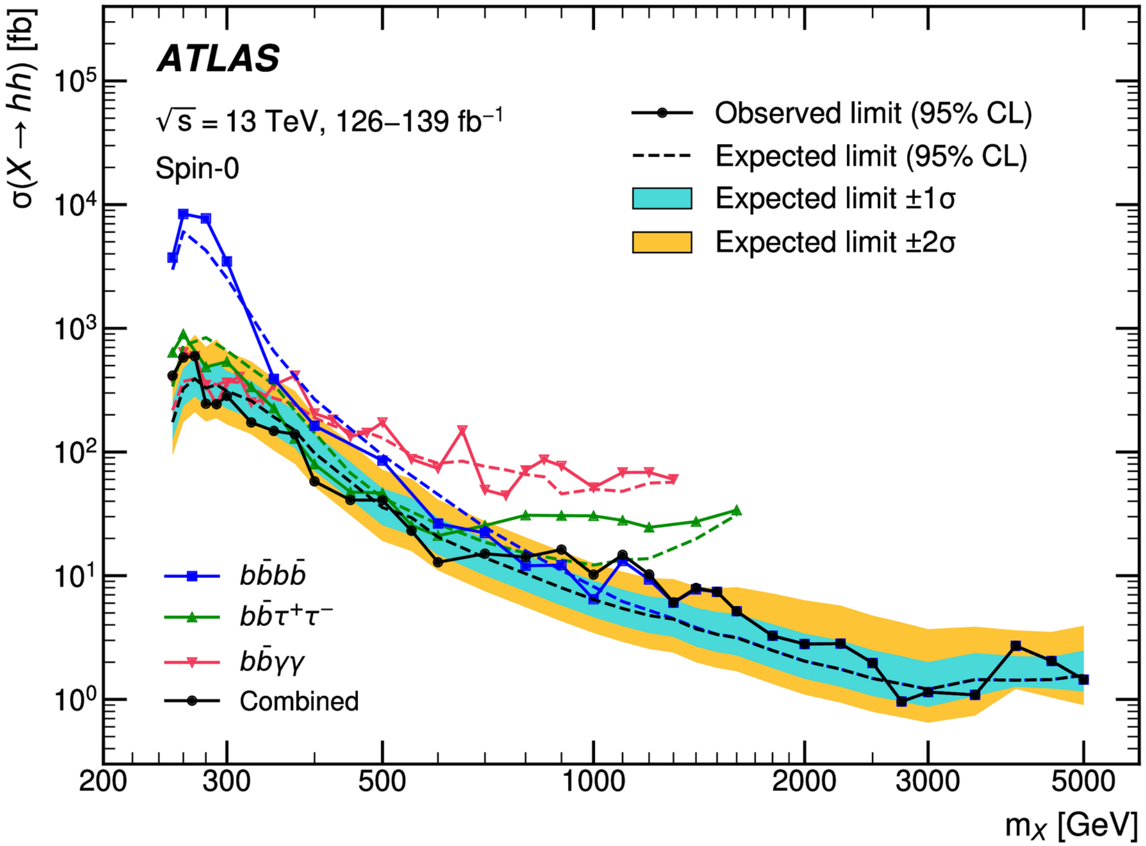
> BSM theories predict extra heavy states that can decay into a pair of Higgs bosons: $pp \rightarrow X \rightarrow hh$

- More details tomorrow

> Search for local "bump" in hh invariant mass spectrum (similar to 2012 Higgs discovery)

Example: *bbbb* channel





Resonant Higgs pair production

> BSM theories predict extra heavy states that can decay into a pair of Higgs bosons: $pp \rightarrow X \rightarrow hh$

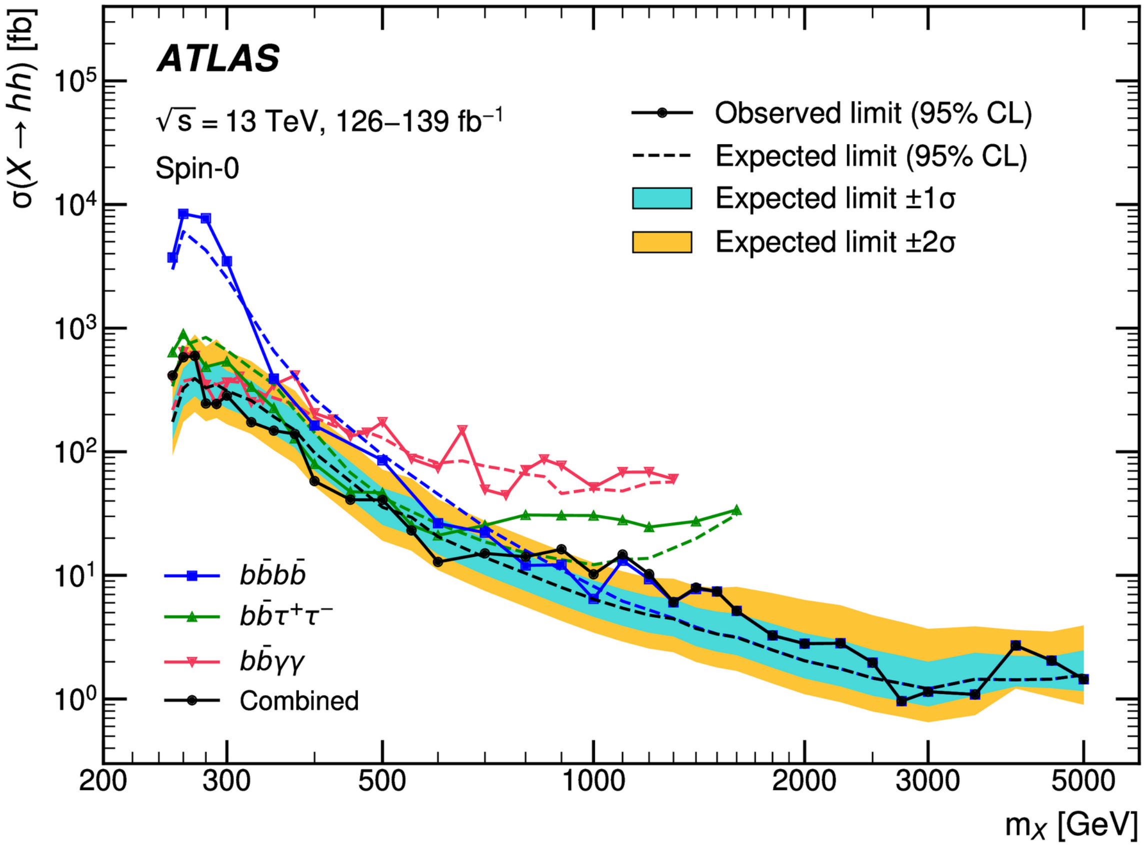
- More details tomorrow

> Search for local “bump” in hh invariant mass spectrum (similar to 2012 Higgs discovery)

> *bbyy*: clean channel, most competitive in low m_X region where hadronic backgrounds are large

> *bbbb:* dominates in high-mass region where sensitivity is limited by signal statistics

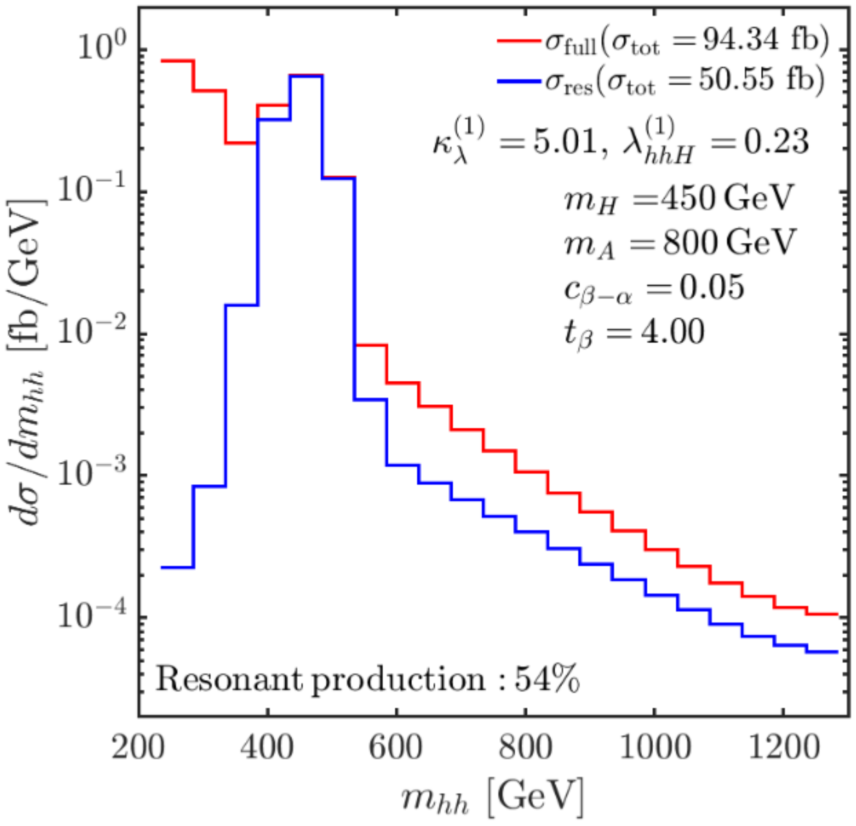
> *bbττ*: dominant in medium region

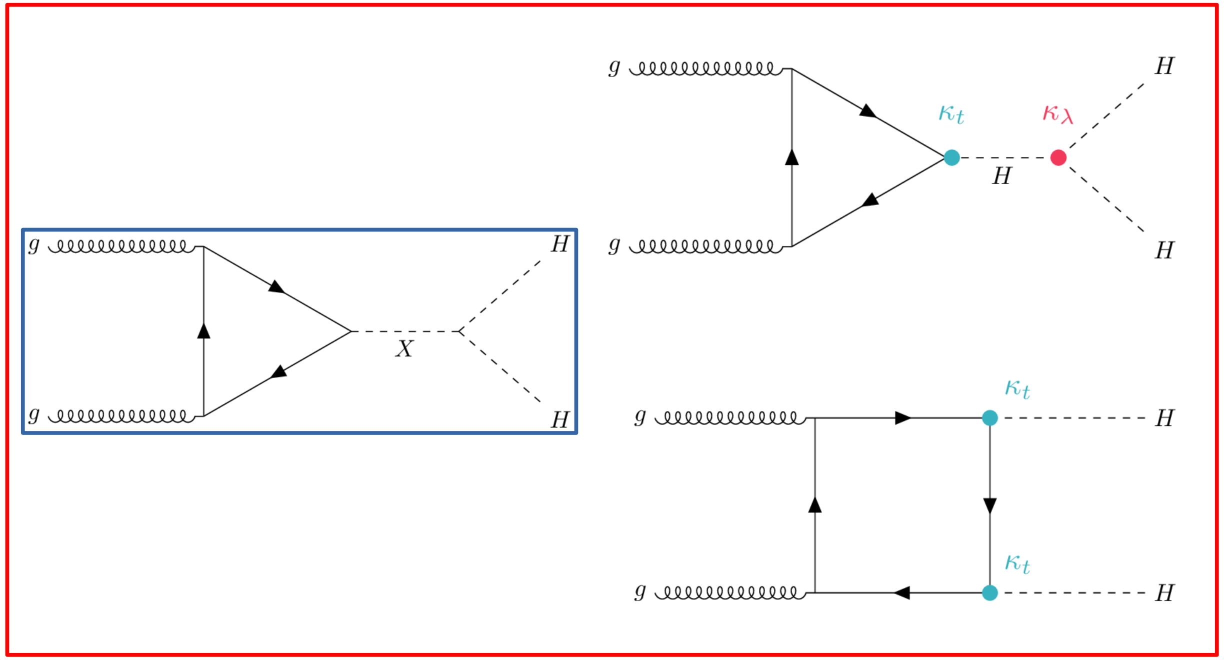


Aside: Interference

- Current resonant $X \to hh$ searches do not consider interference with non-resonant production (or higher-order effects)
- Reduced sensitivity for some benchmarks that may be falsely excluded by resonant searches

K. Rachenko, G. Weiglein et al. arXiv:2403.14776





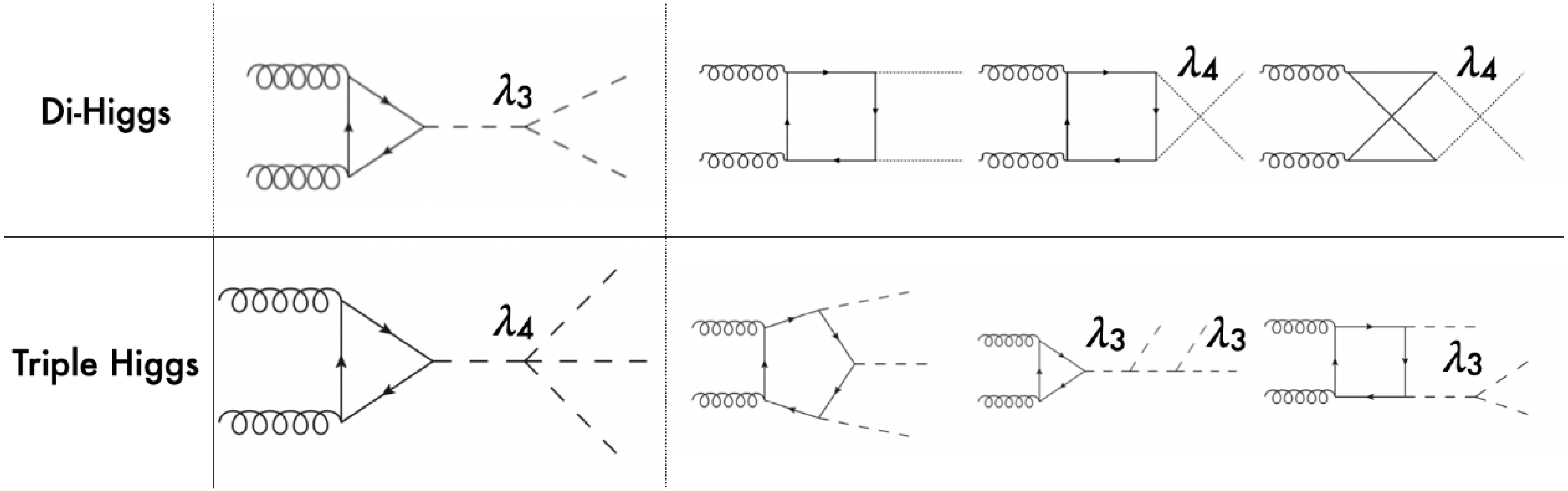
Not twins … but triplets!

> Recent effort to search for triple Higgs production at the LHC

> Most direct access to quartic Higgs coupling with modifier κ_4

> Process ~400 times rare than Higgs pair production!

- Expect around 10 events for *hhh* production in full LHC Run-2 dataset (across all decay modes)

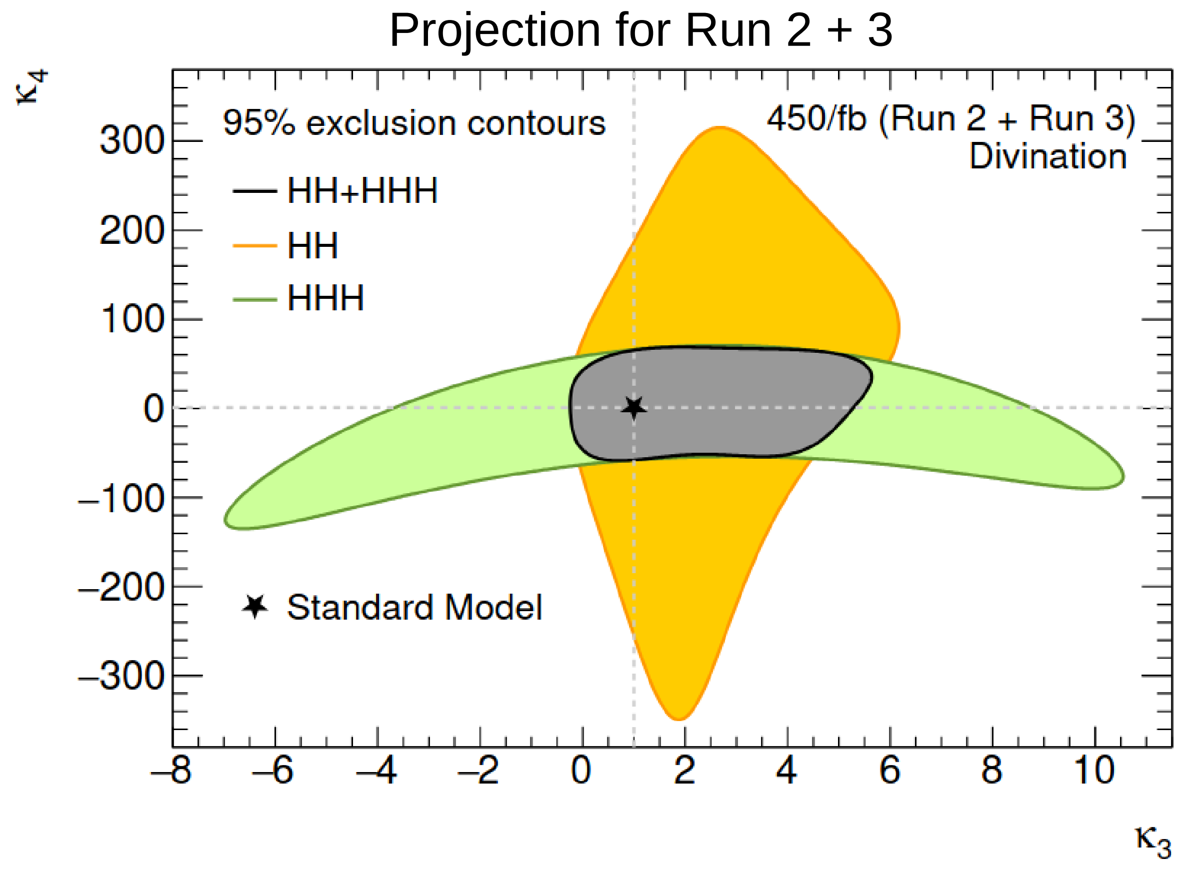


31 fb

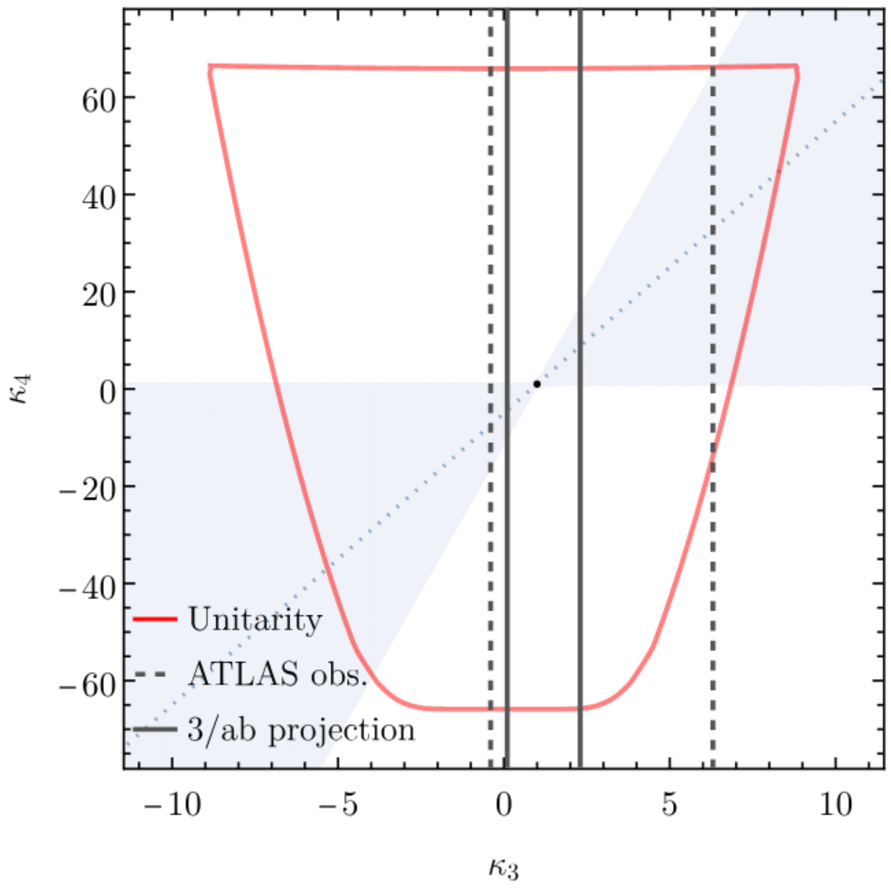
0.08 fb

Complementarity between *hh* and *hhh* searches

- Searches for Higgs triplets expected to provide better constraints on κ_4
- Current best constraints from theoretical considerations (unitarity)



P. Stylianou, G. Weiglein
[Eur.Phys.J.C 84 (2024) 4, 366]

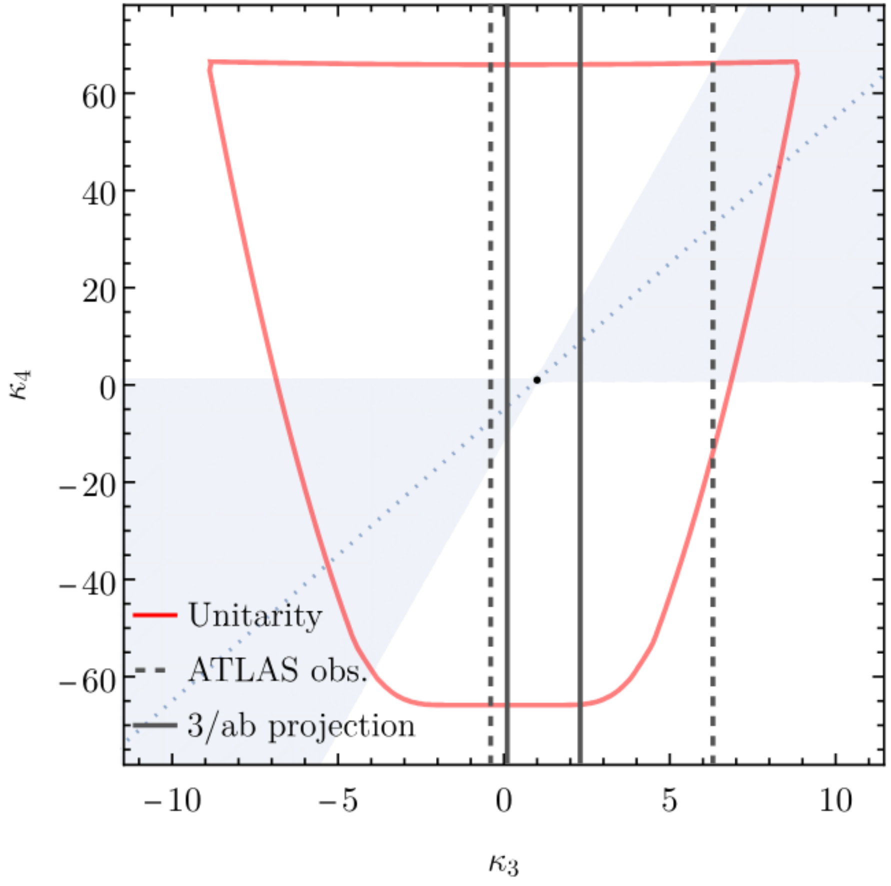


Why do we care?

- Constraints on κ_4 seem loose by comparison
- Little explored probe of BSM physics
  - BSM effects could affect κ_4 much more than κ_3
  - Resonant enhancement in extended Higgs sectors

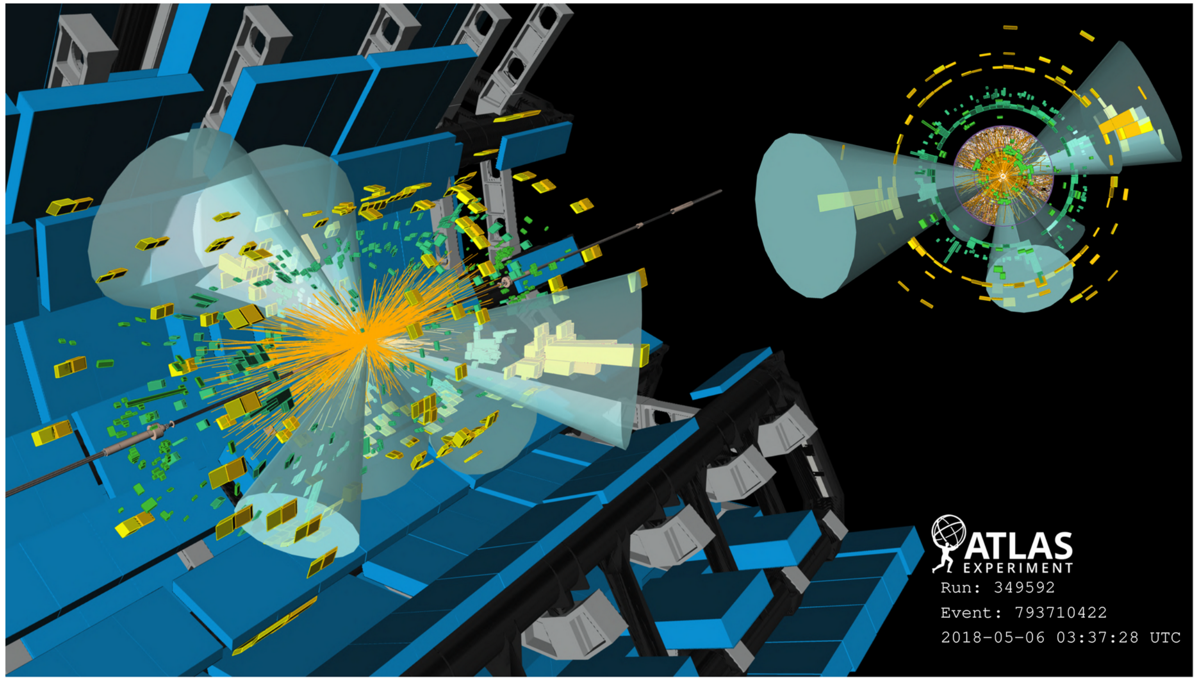
$$(\kappa_3 - 1) = \boxed{\frac{C_6 v^2}{\lambda \Lambda^2}},$$
$$(\kappa_4 - 1) = \boxed{\frac{6 C_6 v^2}{\lambda \Lambda^2}} + \frac{4 C_8 v^4}{\lambda \Lambda^4}$$
$$\simeq 6(\kappa_3 - 1) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

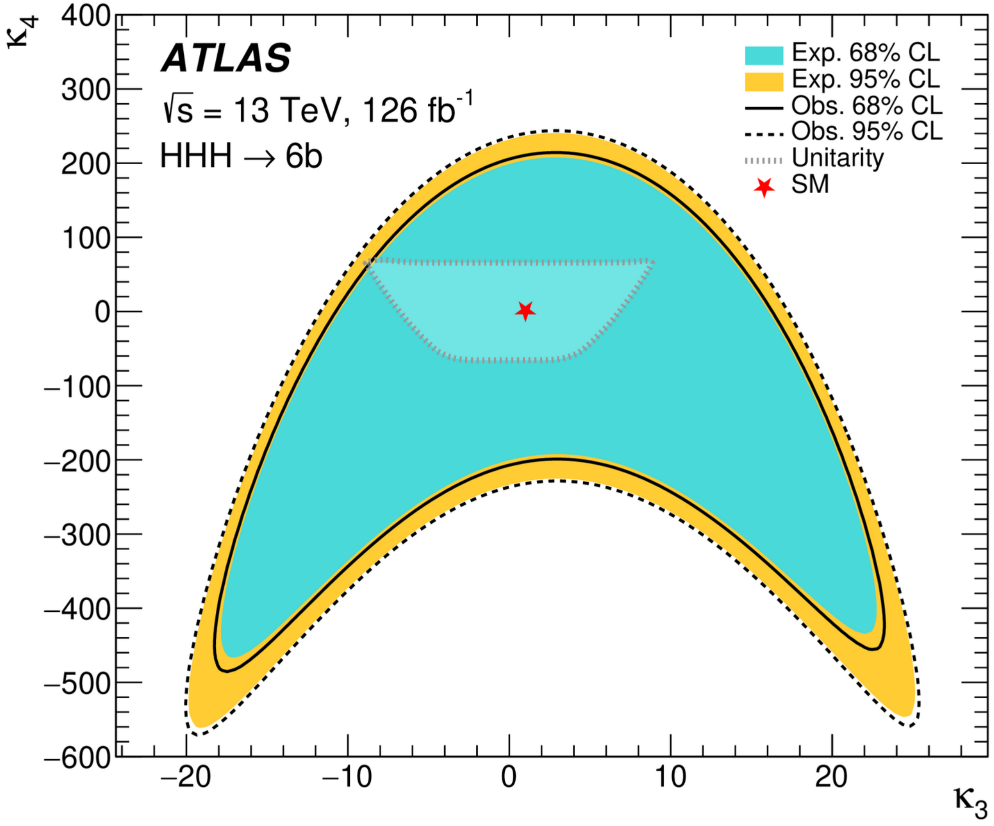
P. Stylianou, G. Weiglein
[Eur.Phys.J.C 84 (2024) 4, 366]



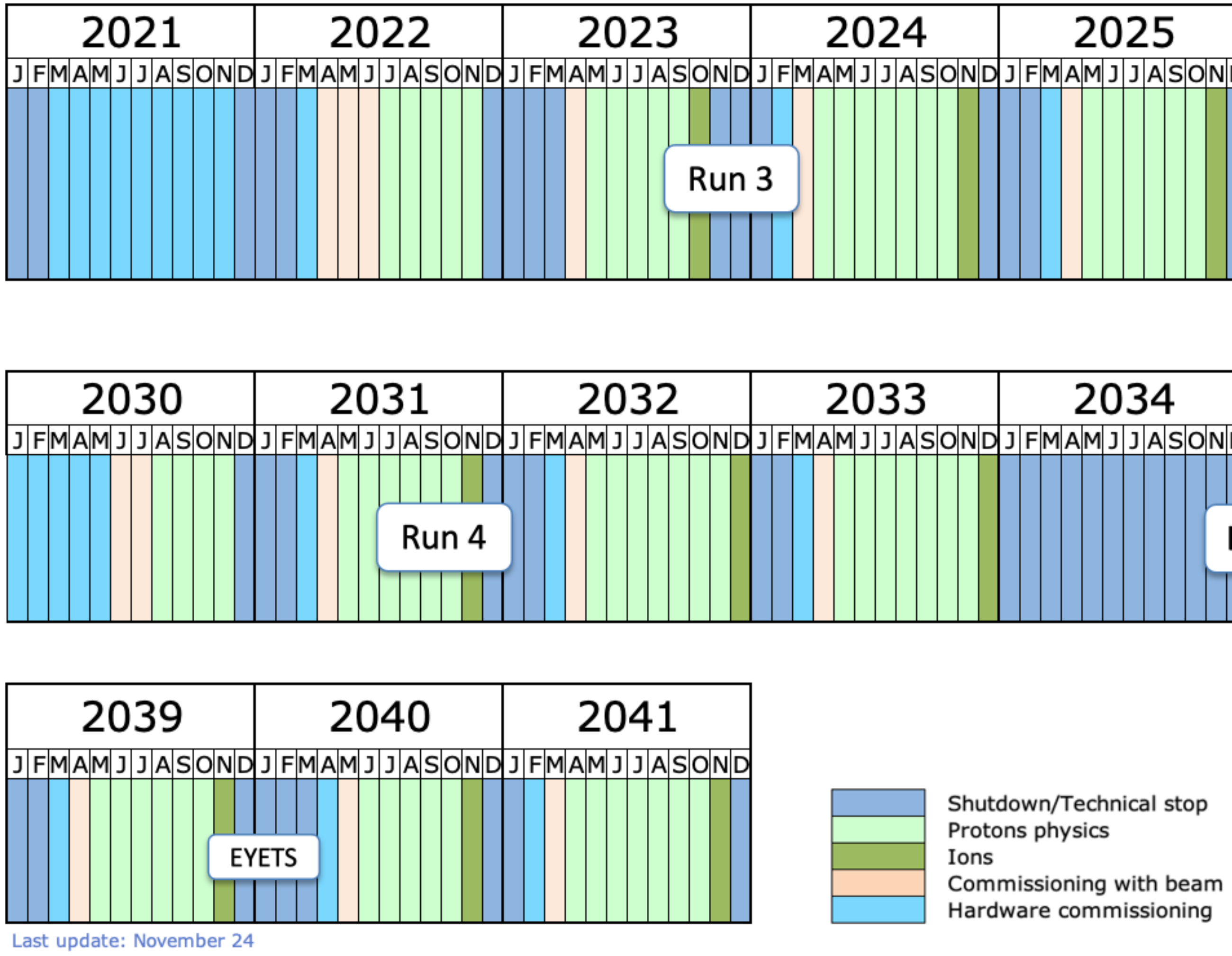
First search for triple Higgs production

- > First experimental constraints on κ_4, first constraints beyond unitarity constraints!
- > Final states with six b-quarks (largest branching ratio)
- > Machine-learning techniques crucial to suppress large hadronic background
- > Sensitivity limited by available data statistics





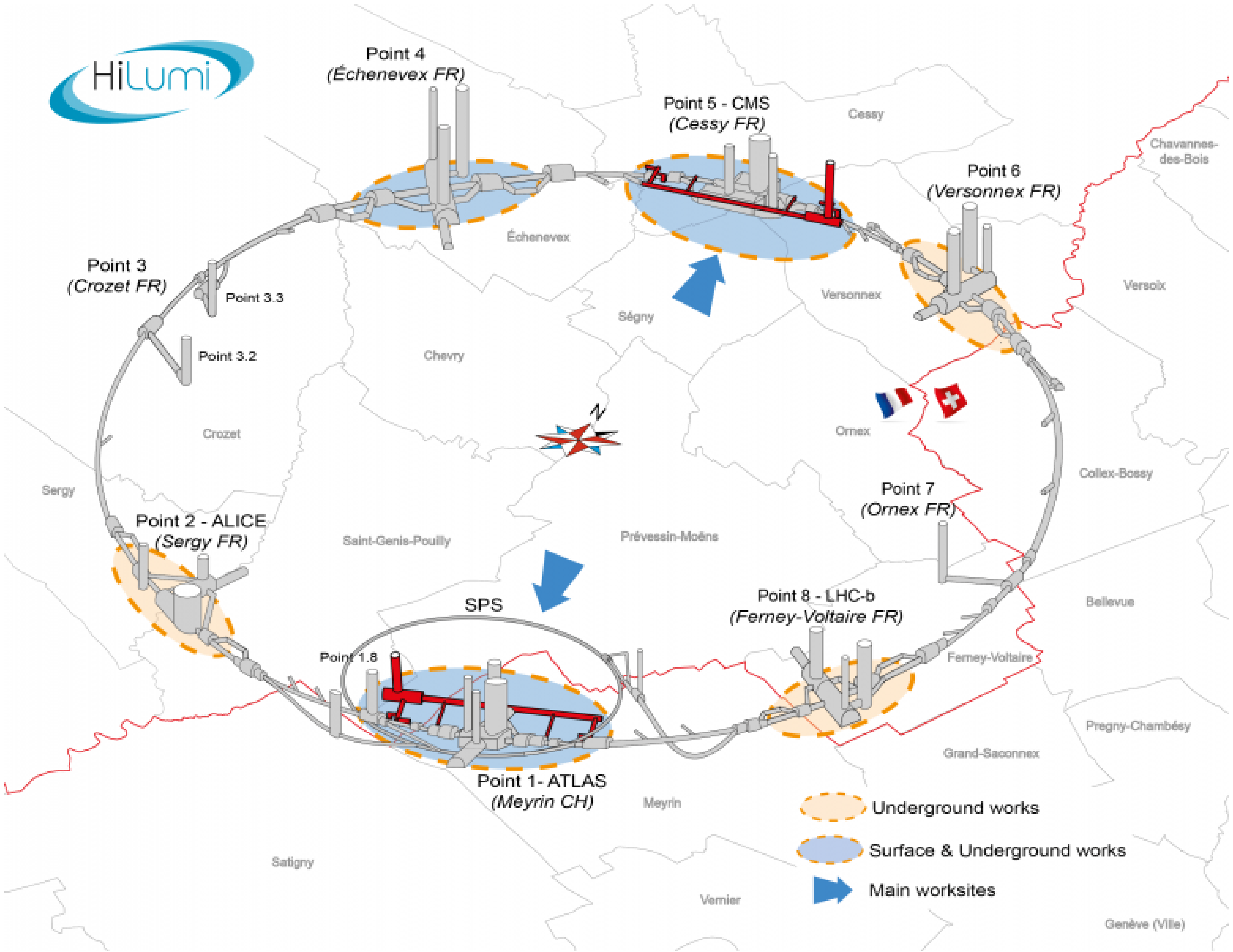
Where do we go from here?



High-Luminosity LHC (2030 - 2041)

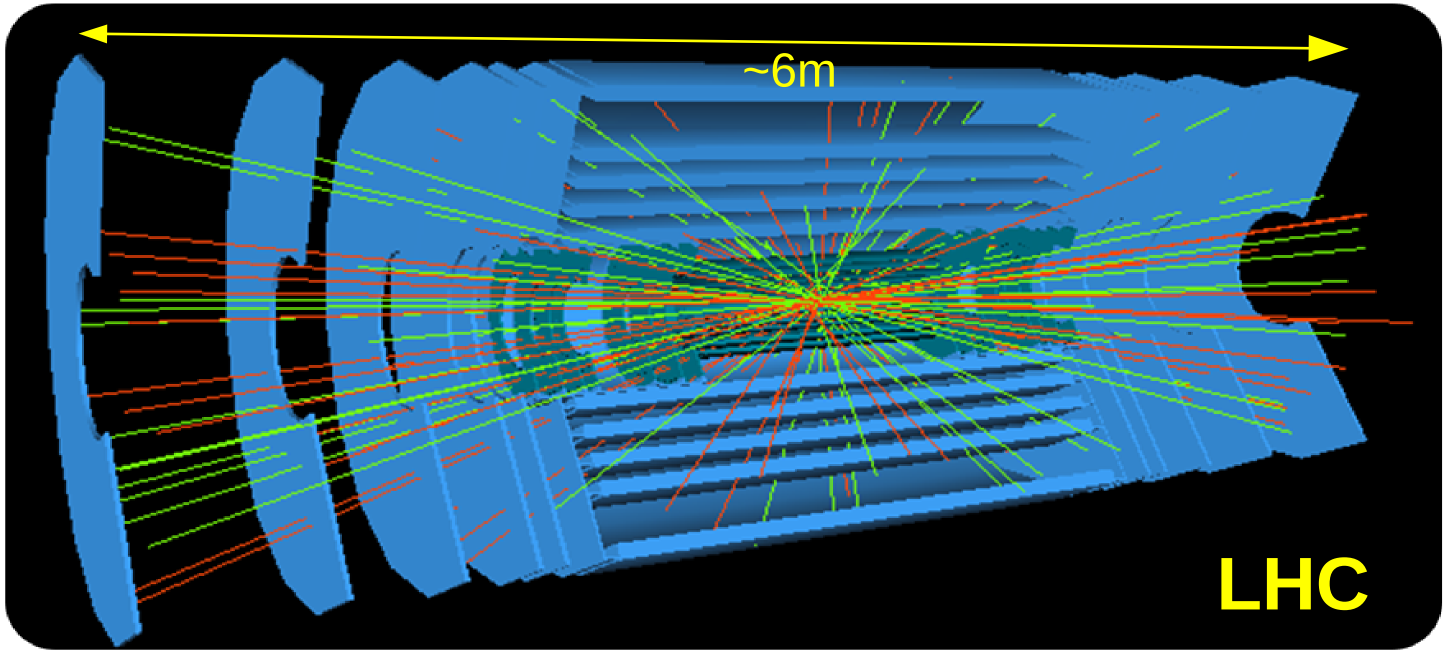
> Final dataset goal: 3000 fb^{-1}

> Compared to >300 fb^{-1} for Run 2+3



Challenges

> Significant increase in number of interactions per bunch crossing and particle flux

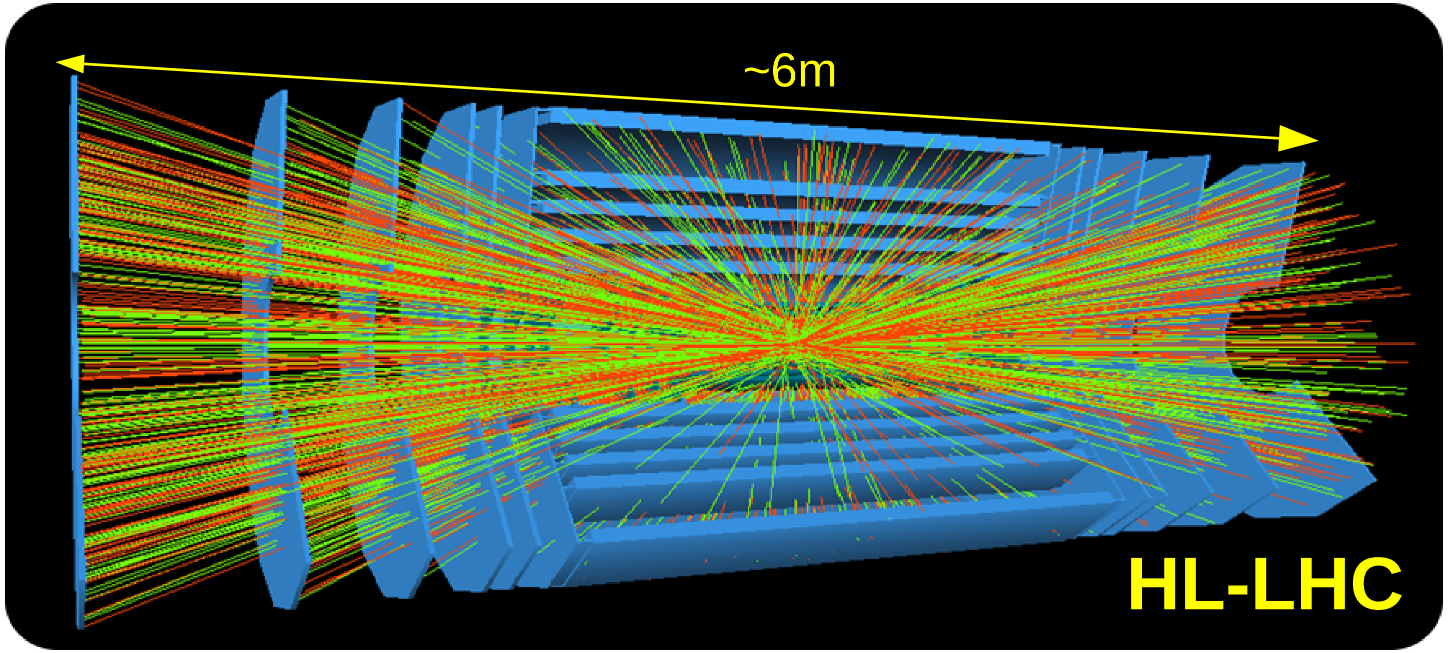


New ATLAS Inner Tracker

25 interactions (Run 1)

Challenges

> Significant increase in number of interactions per bunch crossing and particle flux

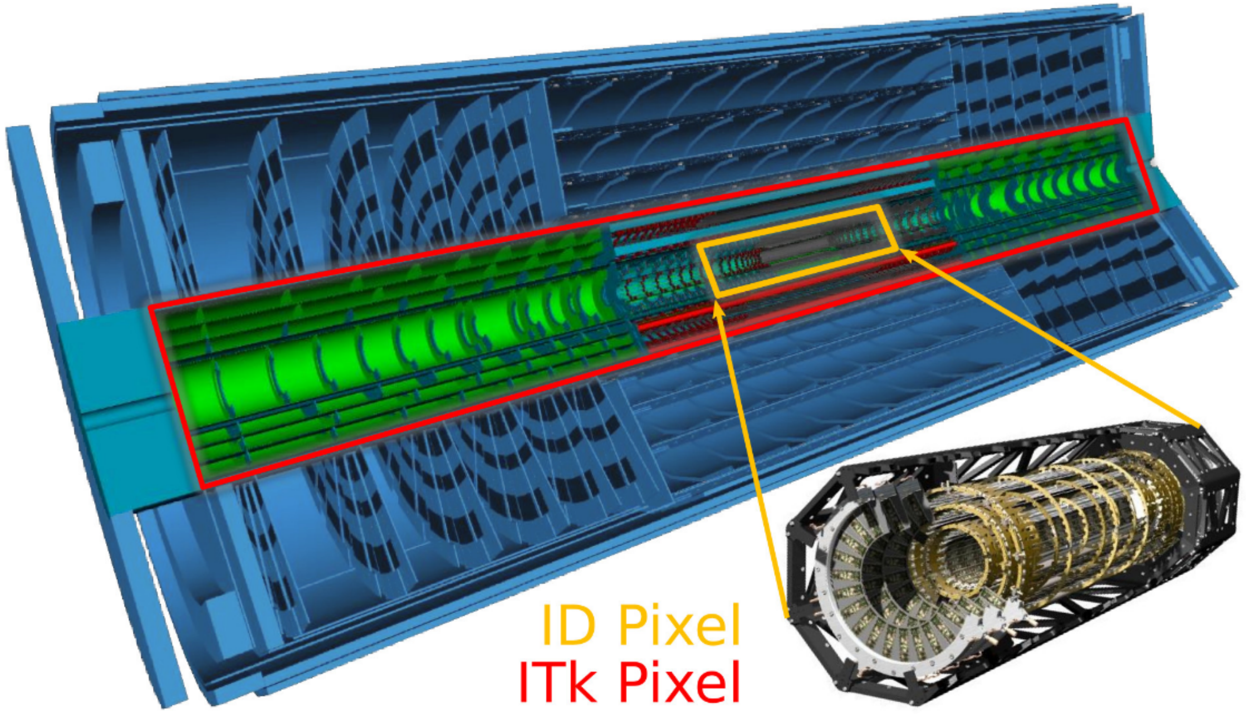


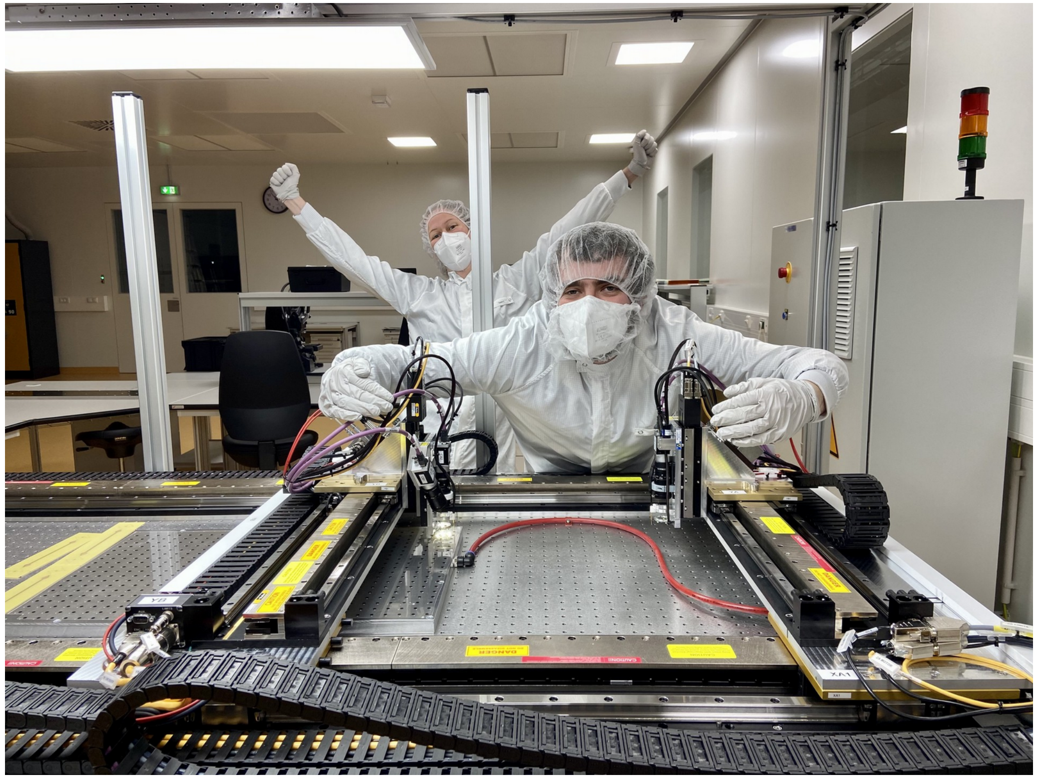
200 interactions

New ATLAS Inner Tracker

Major LHC detector upgrades

- For example brand-new all-silicon tracking detector for ATLAS (Inner Tracker, ITk)
- Up to 4 times higher granularity in innermost pixel layers



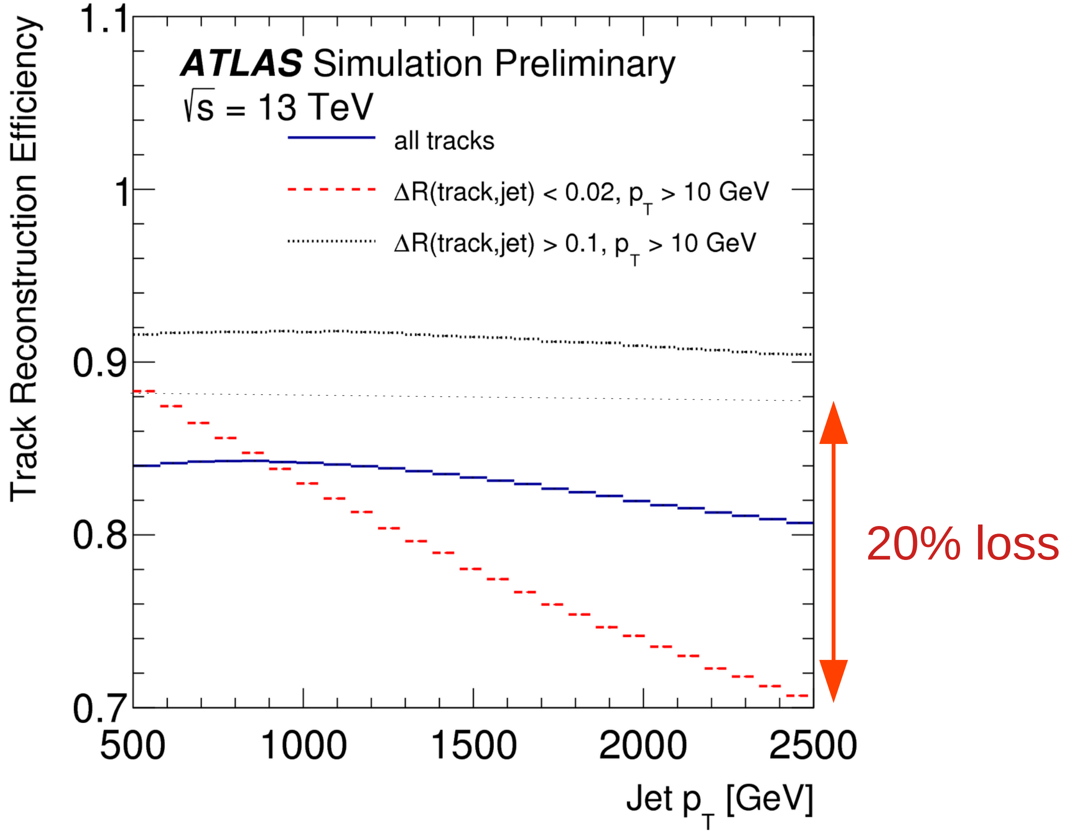


Partially constructed at DESY!

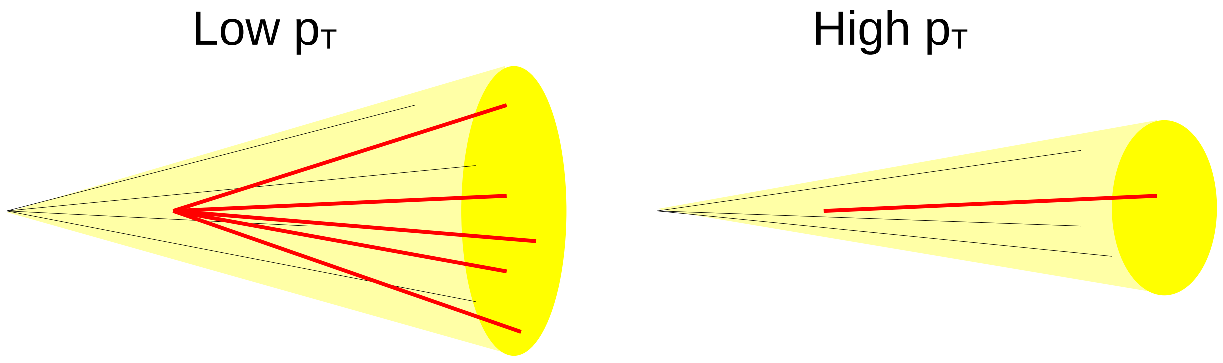
Major improvements in track reconstruction

> Example: reconstructing tracks in cores of high-p_T jets (dense environments)

Current detector



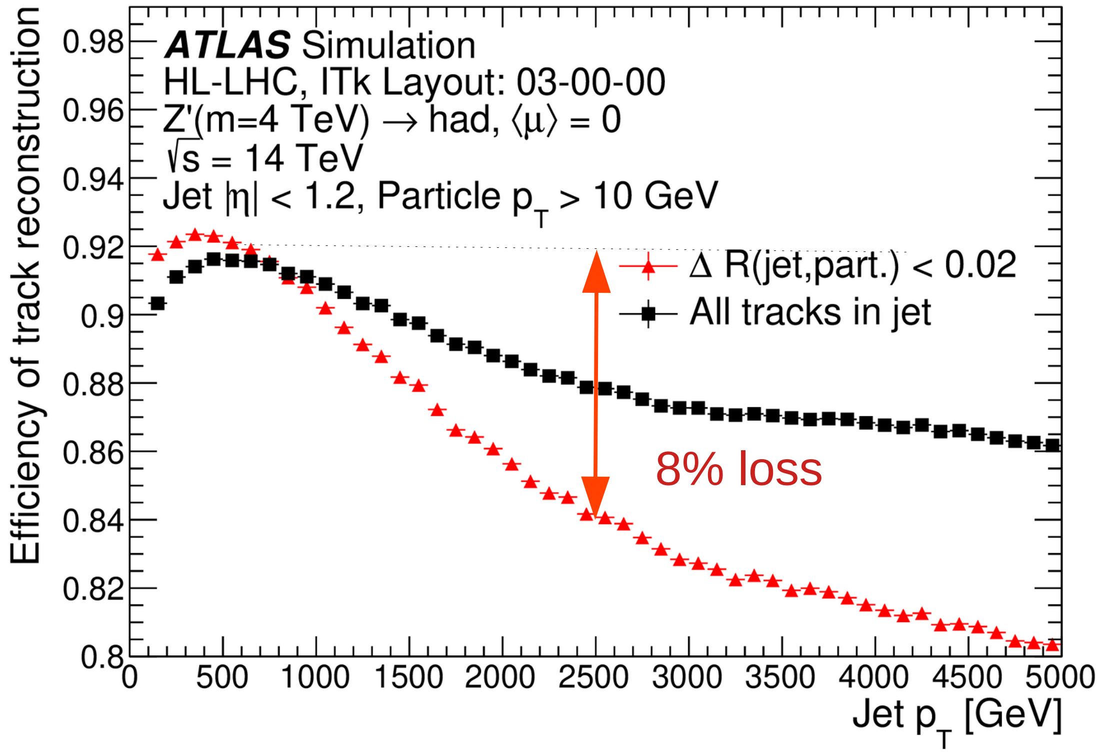
b-jets with p_T = 1 TeV:
30% contain ≤ 1 track from *b*-hadron decay
(4-5 expected)

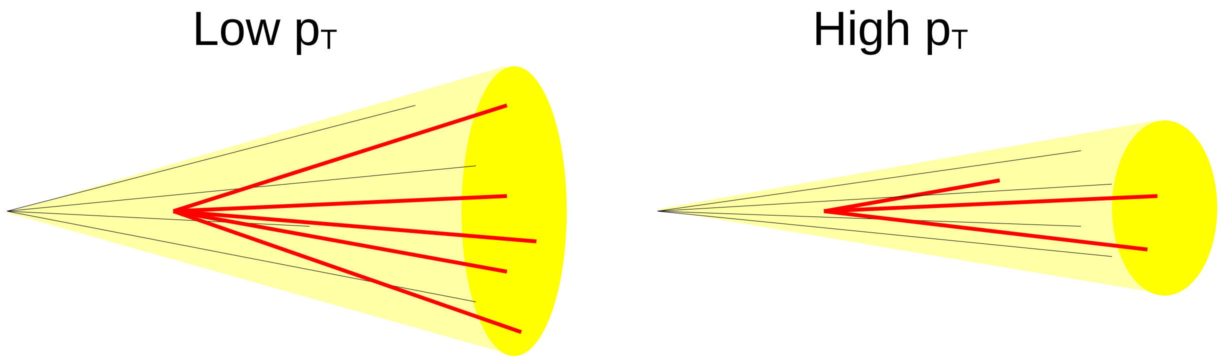


Major improvements in track reconstruction

- Example: reconstructing tracks in cores of high-p_T jets (dense environments)
- Tracking efficiency significantly improved in jet cores → better inputs for *b*-tagging

ITk

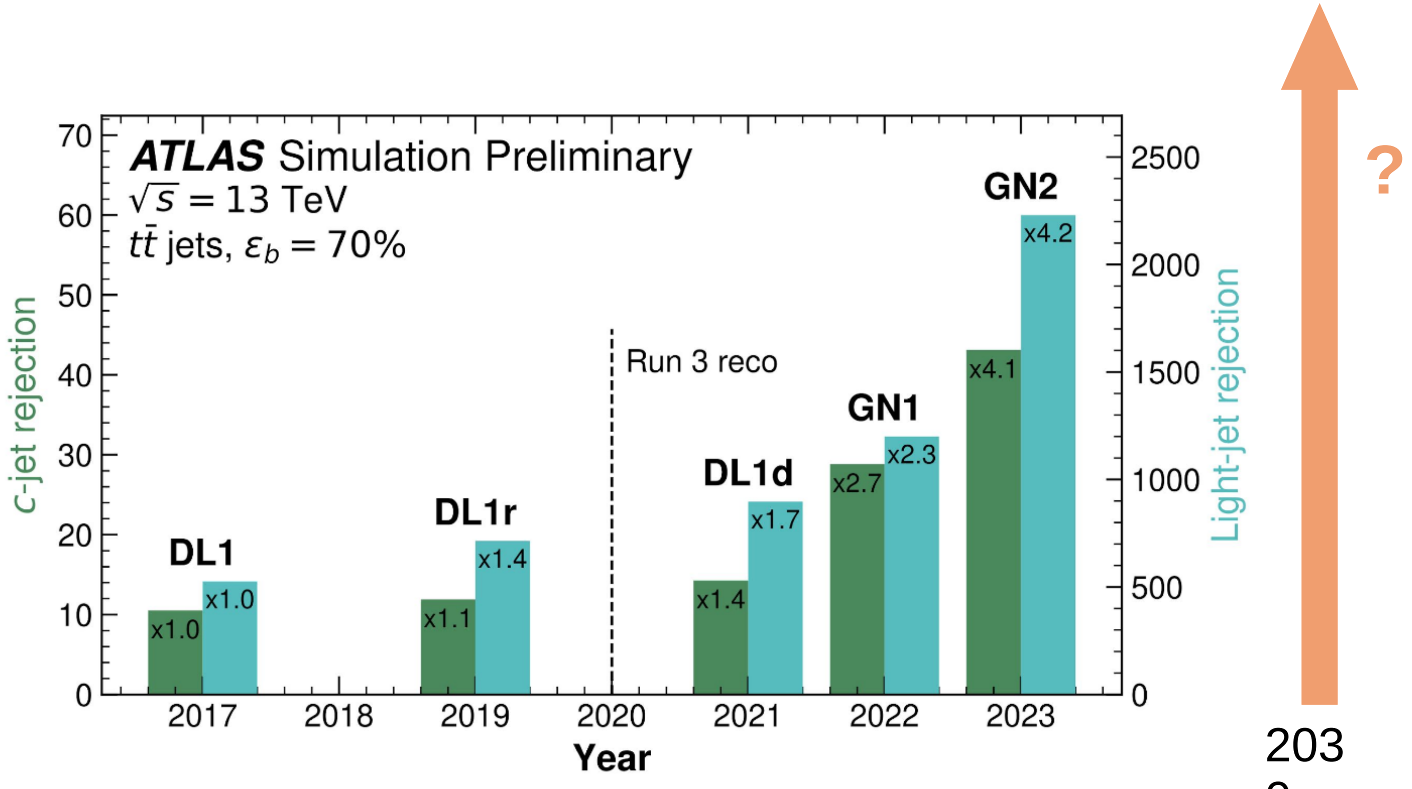




Algorithmic improvements for the HL-LHC

> Improvements in *b*-tagging crucial for (di-)Higgs analyses

- Better inputs due to more efficient and accurate tracking and vertexing
- More performant algorithms (e.g. transformers)

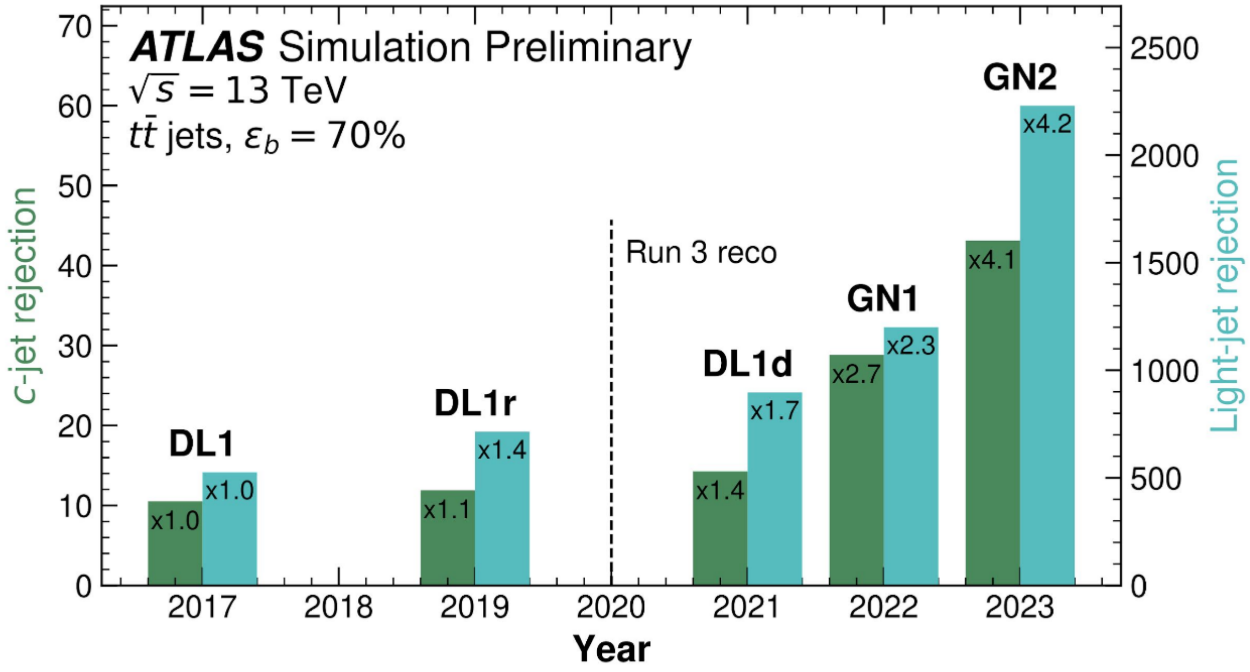


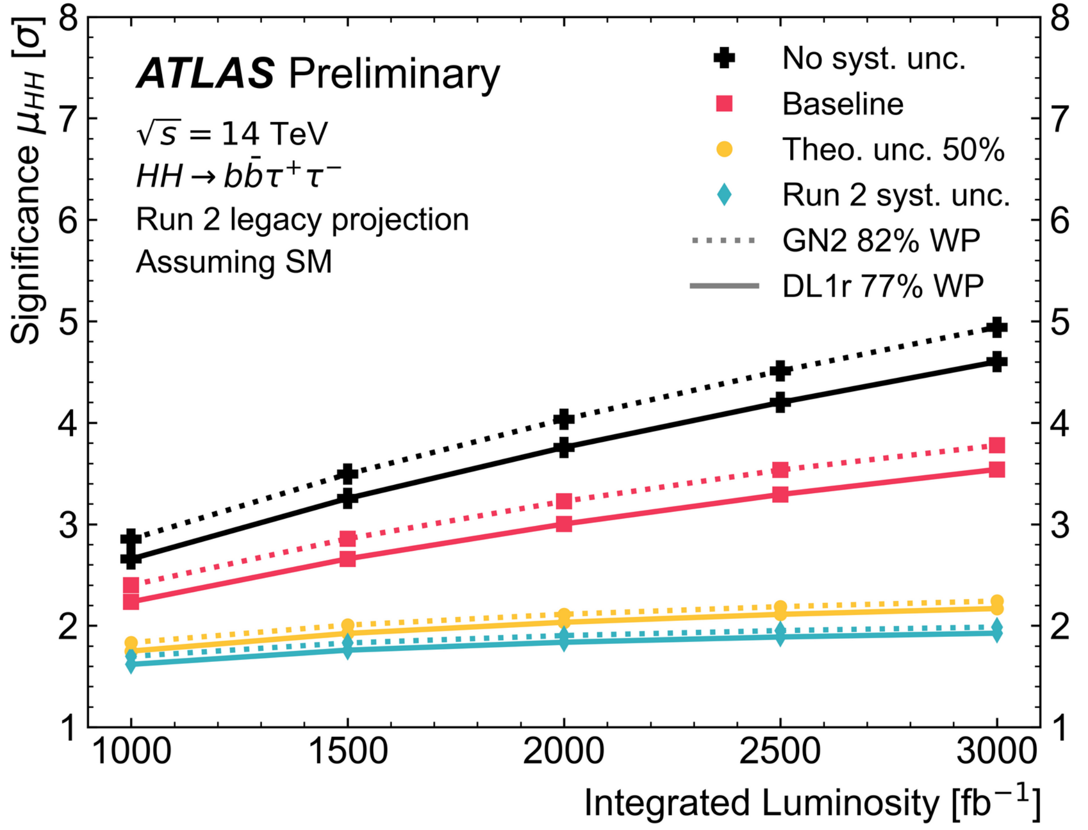
2030

Discovery potential for Higgs pair production at HL-LHC

- Example: projection in *bbττ* channel
- Largest leverage: experimental improvements
  - Especially *b*-tagging performance
  - Reduction of systematic uncertainties

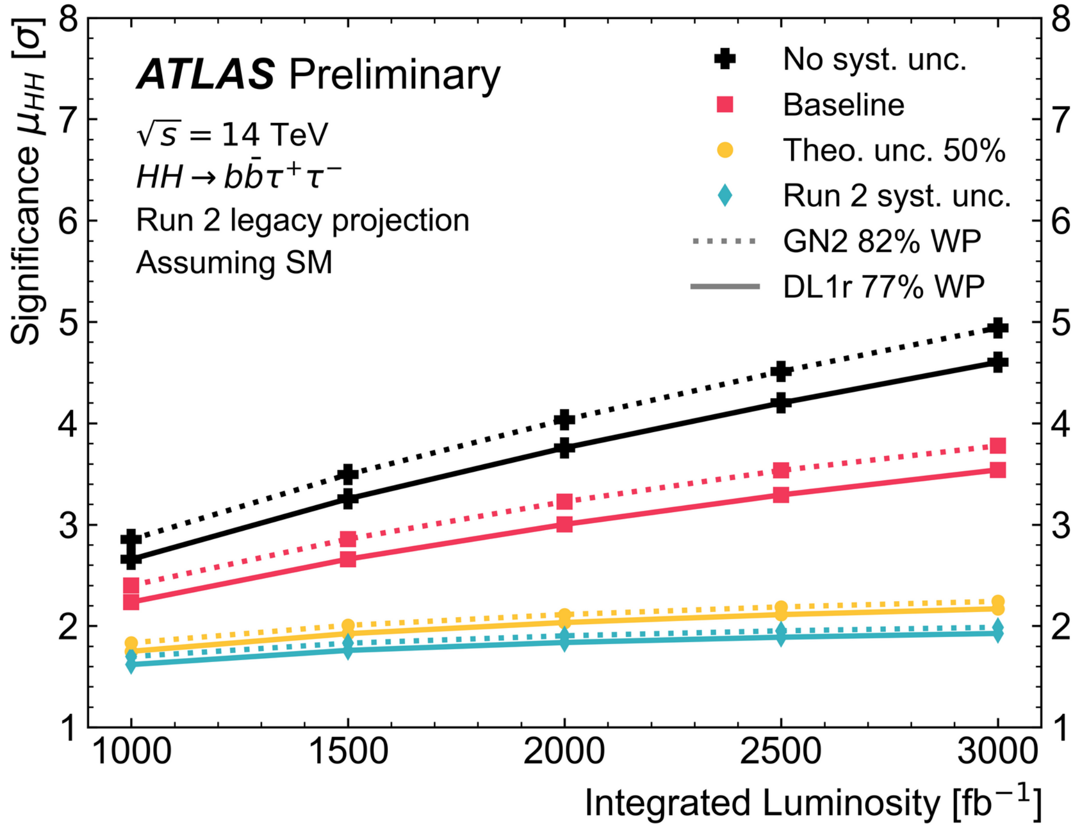
Baseline: halve theory uncertainties, reduce selected experimental uncertainties with lumi





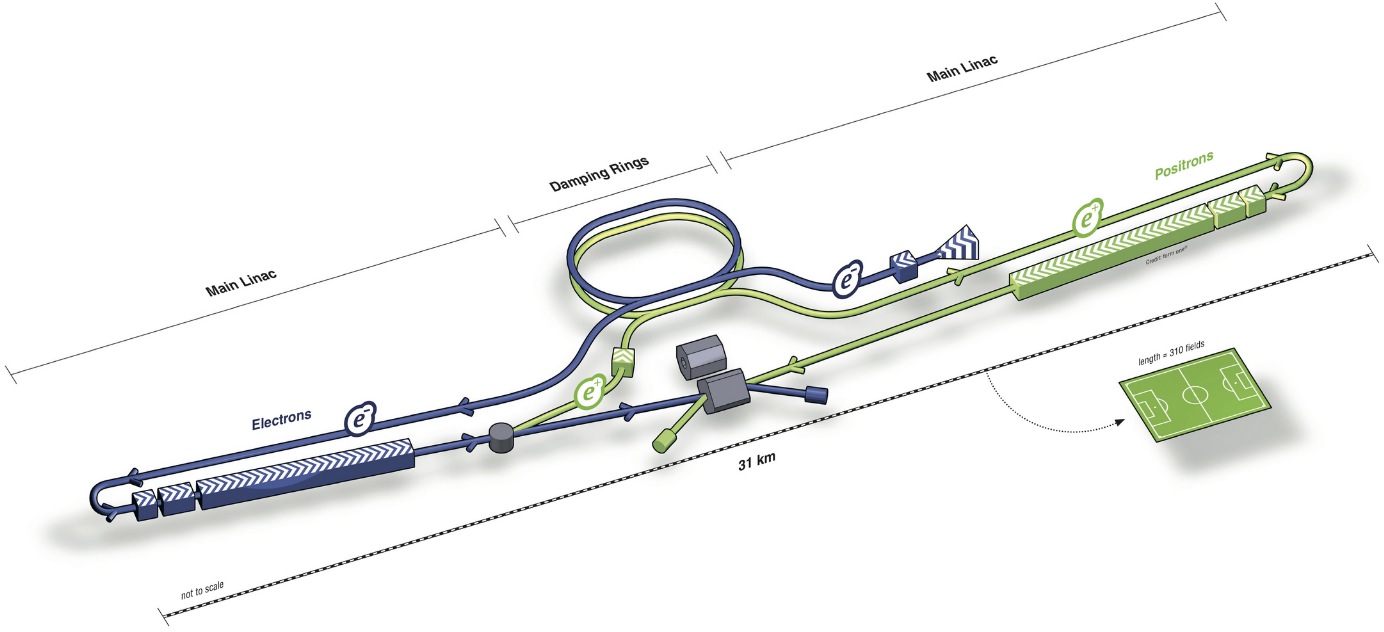
Discovery potential for Higgs pair production at HL-LHC

- Expect to see evidence (≥ 3σ) in *bbττ* alone before end of HL-LHC
- Similar projections currently under way for European Strategy for Particle Physics Update
- Good prospects for discovery by combining several ch
- Further experimental improvements can further boost sensitivity!

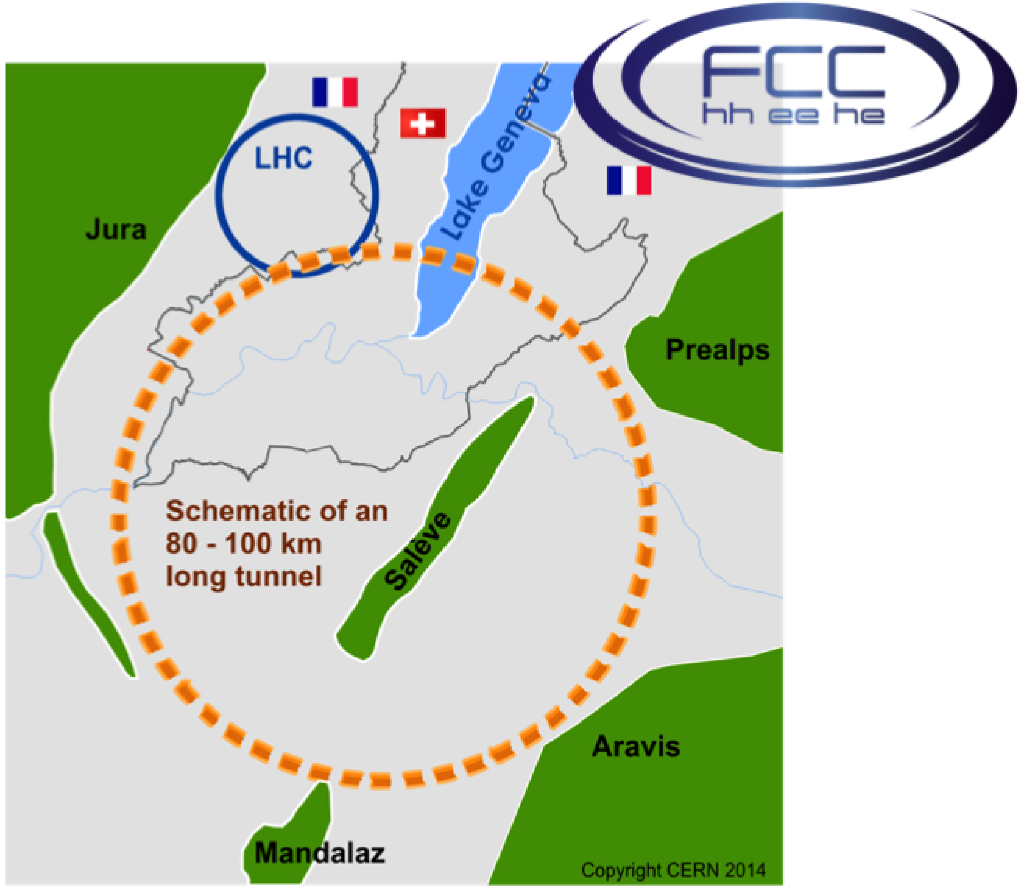


Future Collider Plans

- Higgs factories for precision measurements
- BSM searches also possible



International Linear Collider

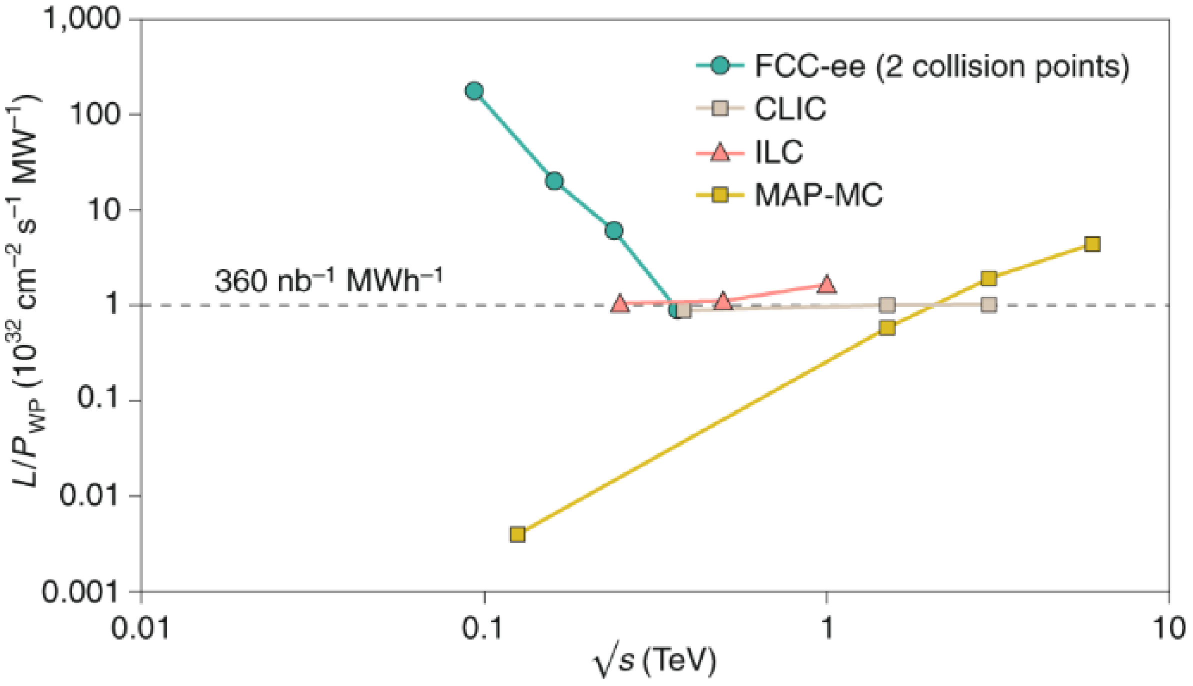


Future Circular Collider

Linear vs circular – it depends on the energy!

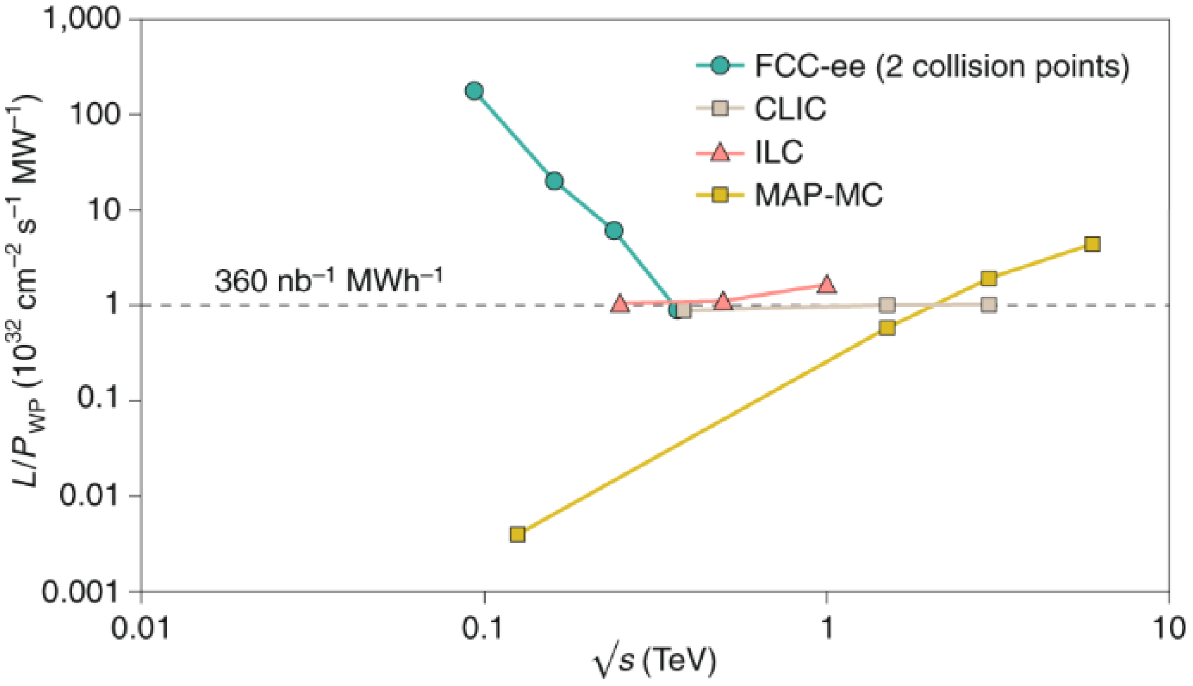
> Circular colliders more competitive at lower collision energies (higher instantaneous luminosity)

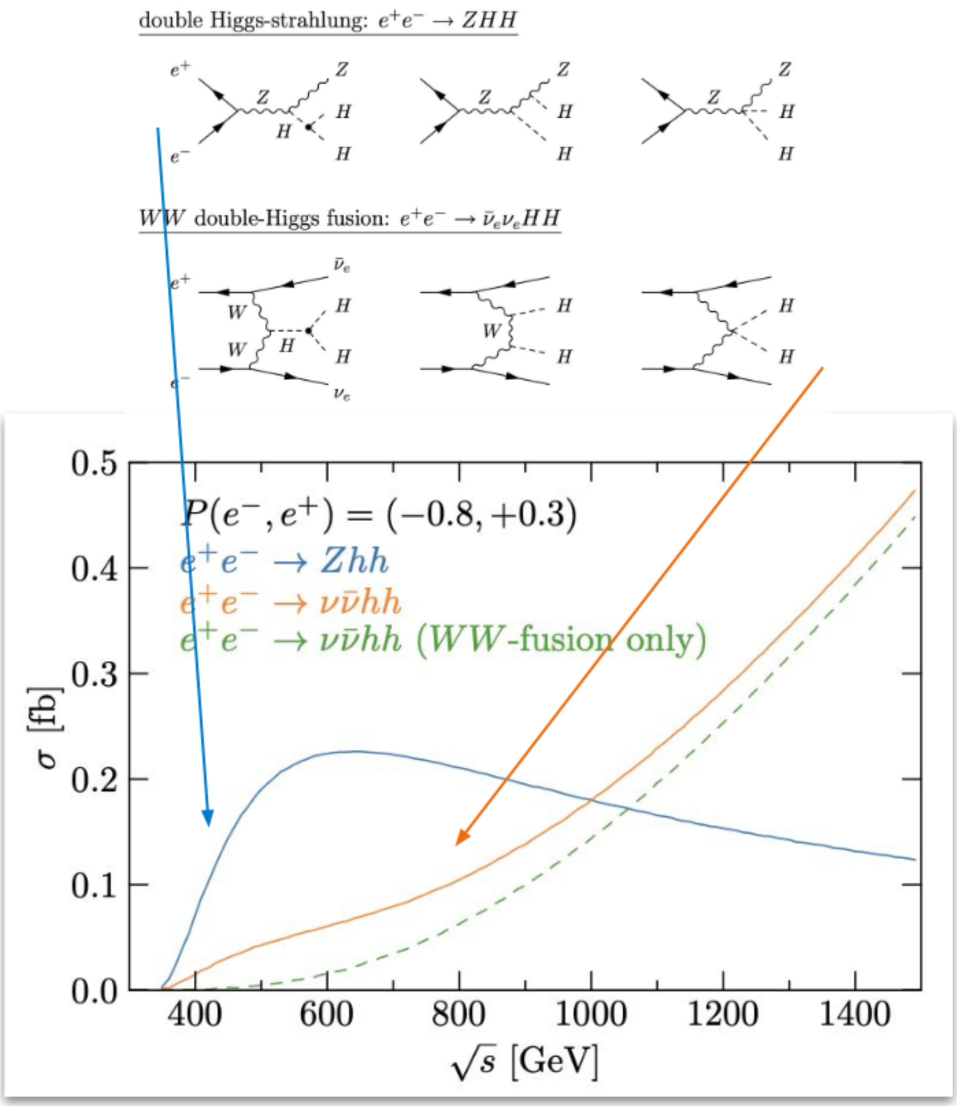
> Linear colliders more competitive at higher collision energies (no losses from synchrotron radiation)



Linear vs circular – it depends on the energy!

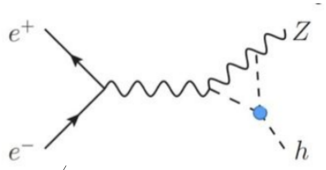
> Direct access to trilinear coupling only for √s > 400 GeV
→ linear collider!

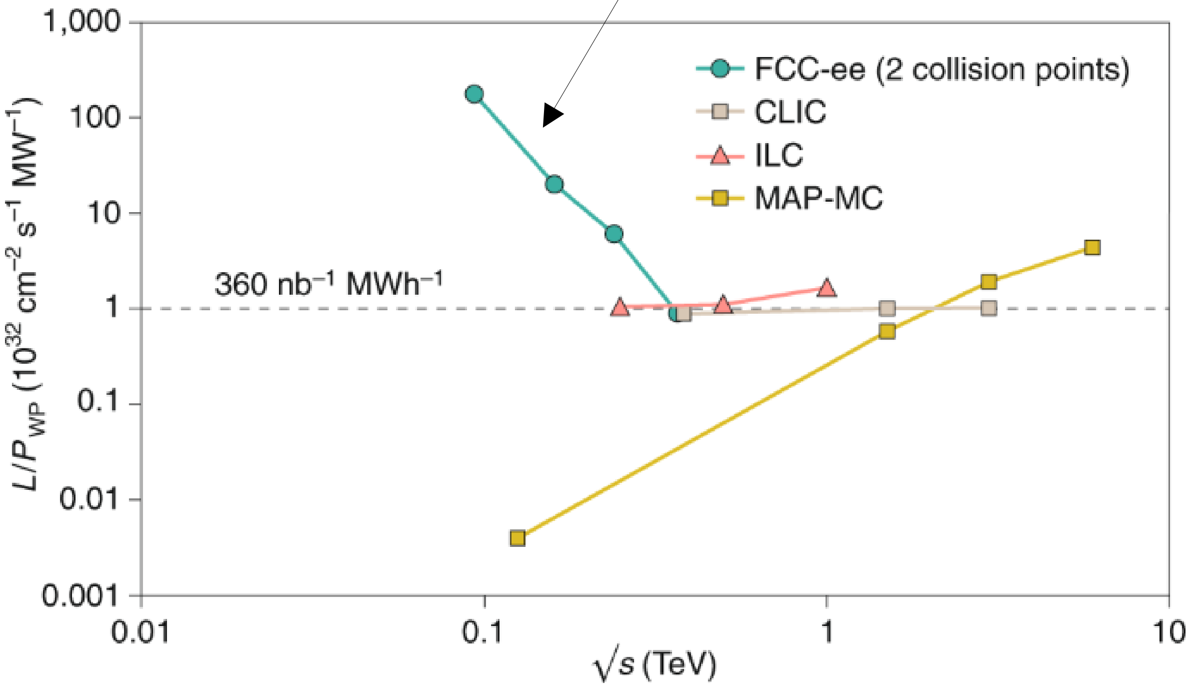


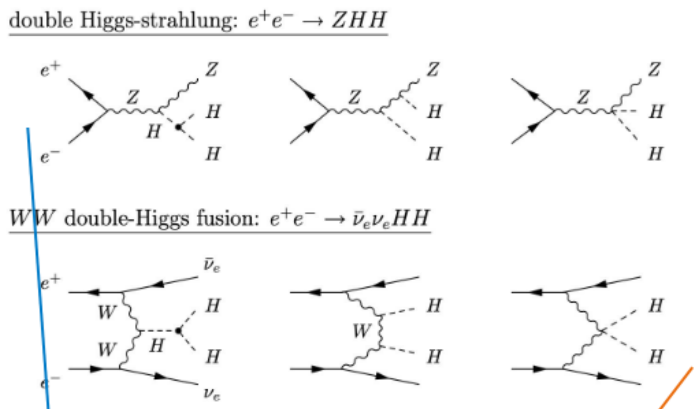


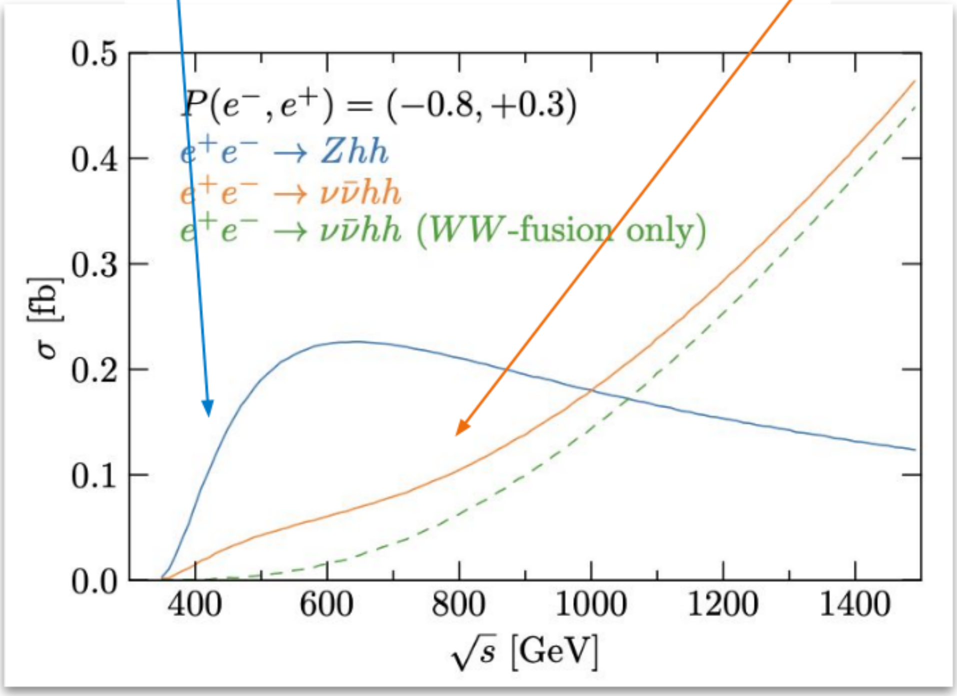
Linear vs circular – it depends on the energy!

- > Direct access to trilinear coupling only for √s > 400 GeV
  → linear collider!
- > Indirect access via single-Higgs production at lower energie
  (model dependence!)

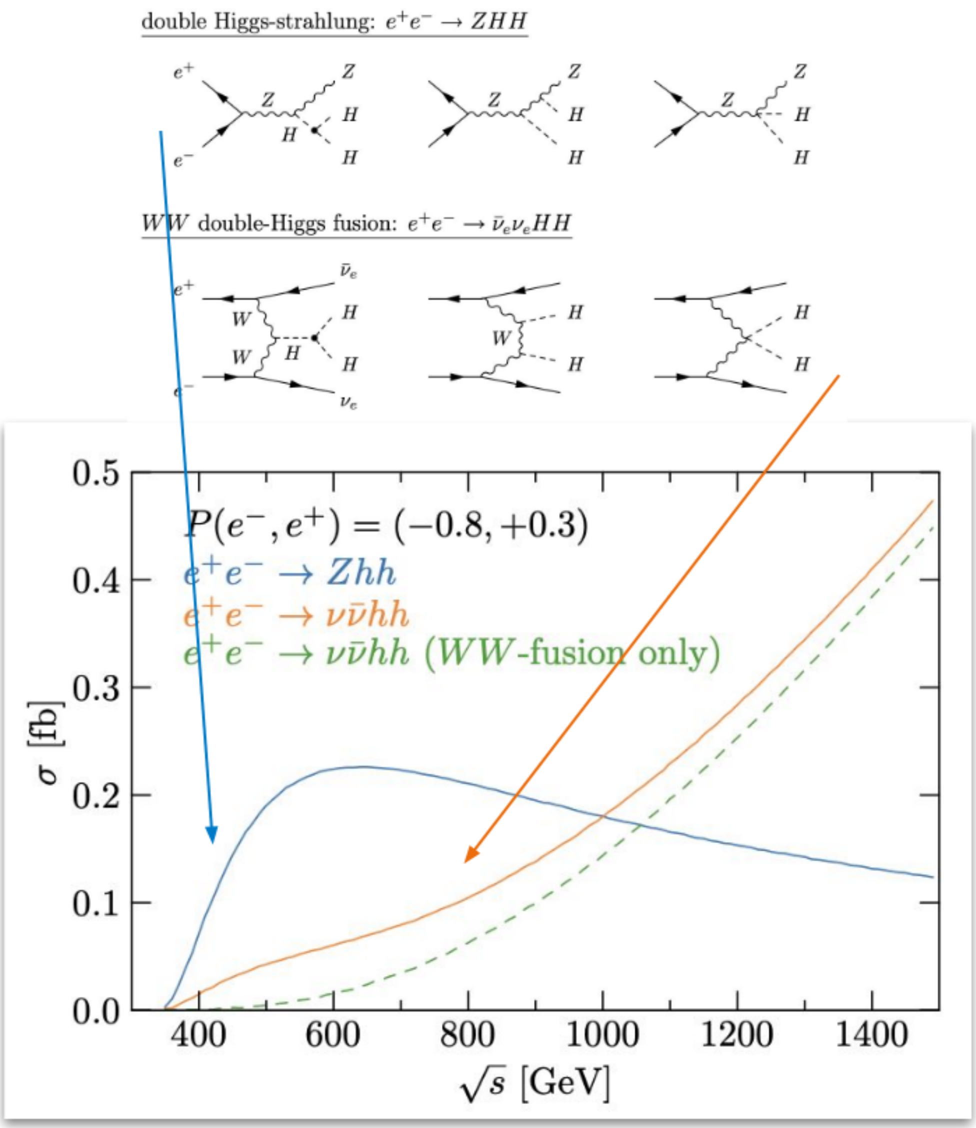




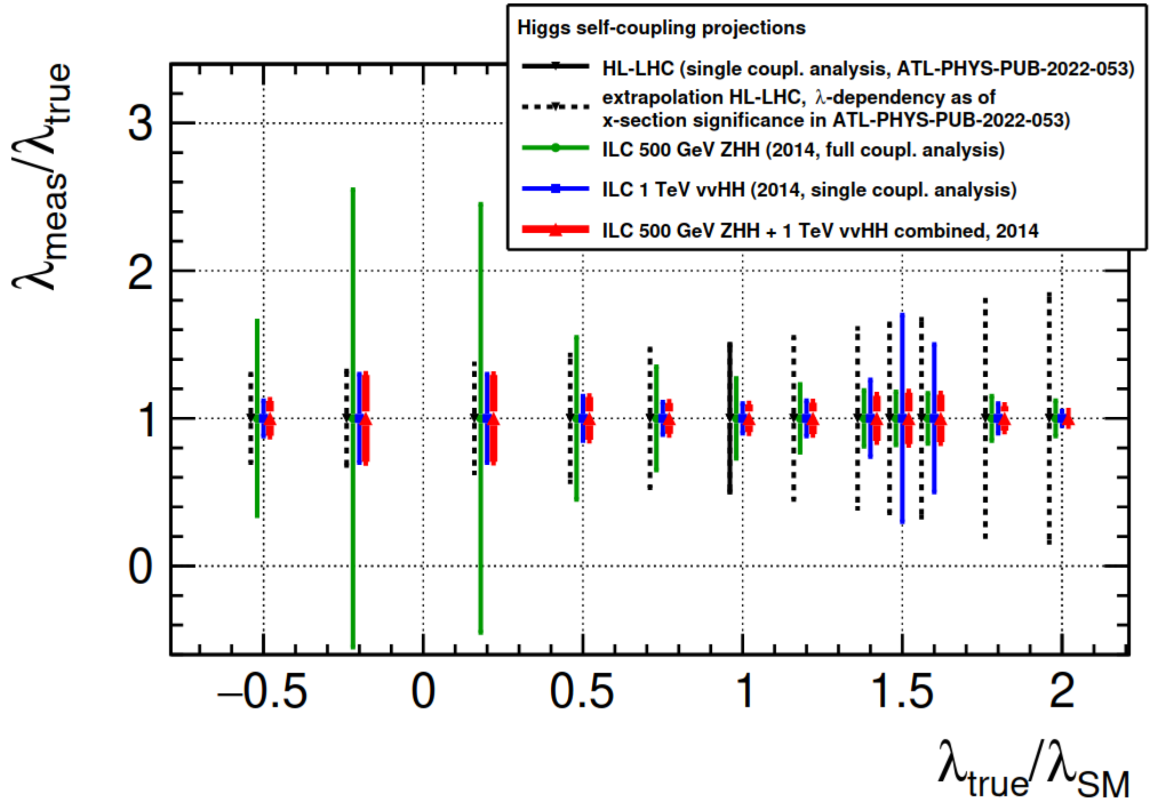




Trilinear coupling at the ILC

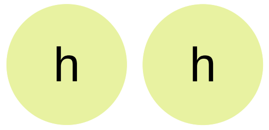


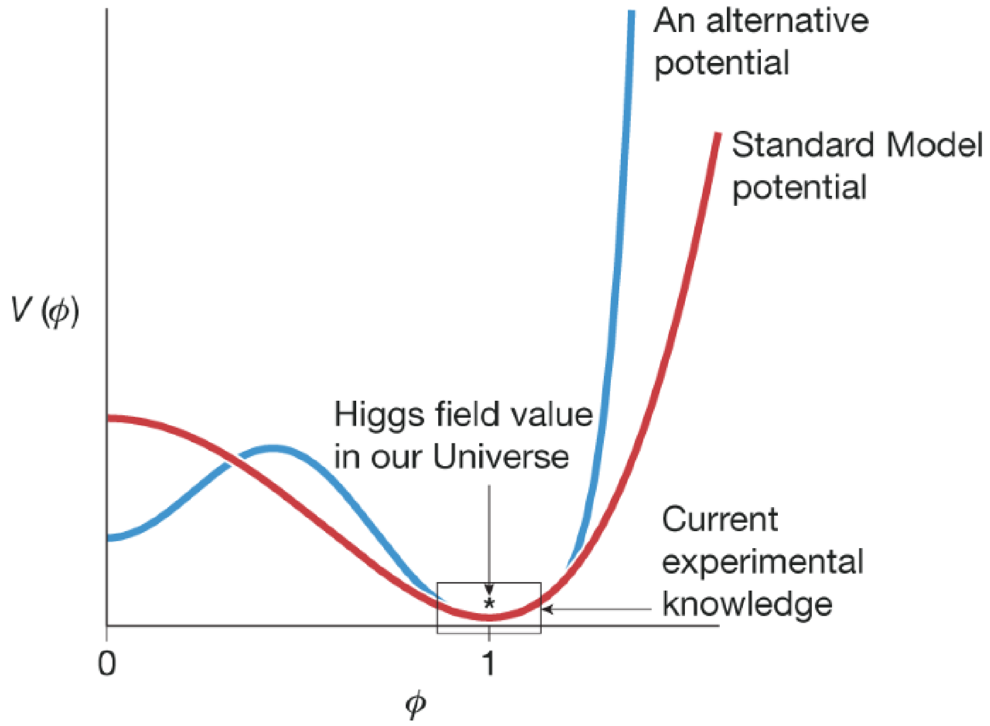
- > ILC (0.5 TeV): ~20% precision achievable on λ_3
- > ILC (1 TeV): ~10% precision (adding WW production)
- > CLIC (3 TeV): ~ 8% precision



Summary: Part 2

- Full shape of the Higgs potential could provide hints at BSM physics.
- Best access via Higgs boson pair production at the LHC.
  - About 1800 times less abundant than single-Higgs production.
- Stringent constraints derived by searches on the LHC Run-2 dataset.
  - Main decay channels: *bbbb*, *bbττ*, *bbγγ*
- Observation expected to be possible at HL-LHC
- Precision measurements possible at future Higgs factories
  - Require collision energies > 500 GeV for model-independent measurements

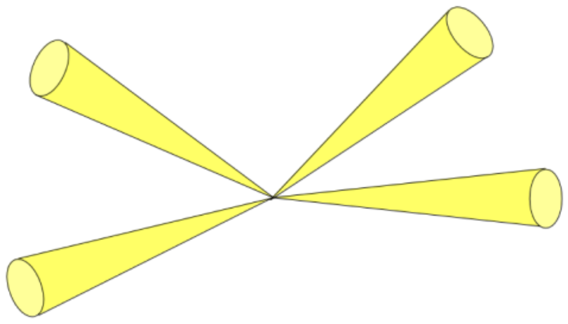


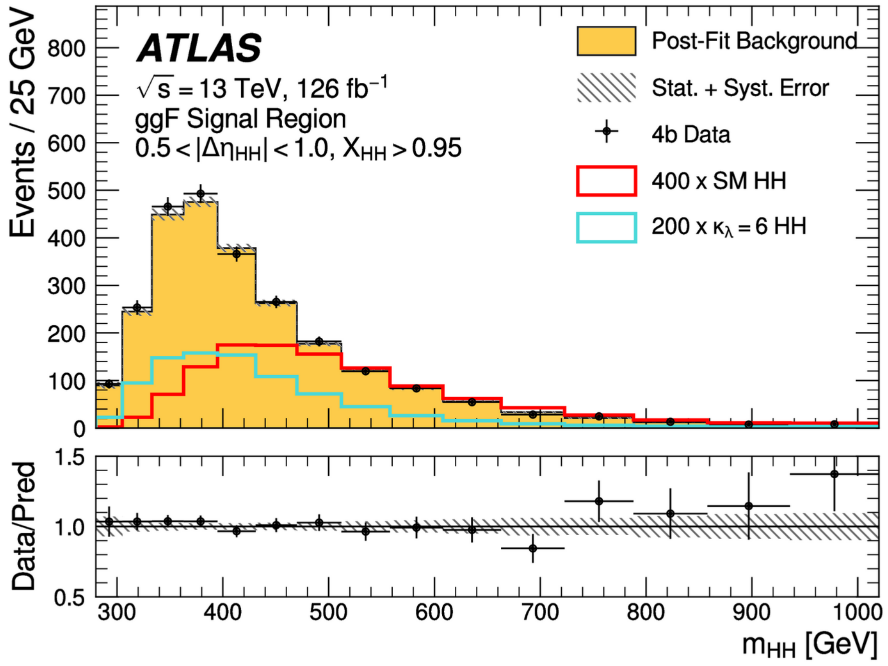


BONUS SLIDES

Analysis strategy for the *bbbb* channel

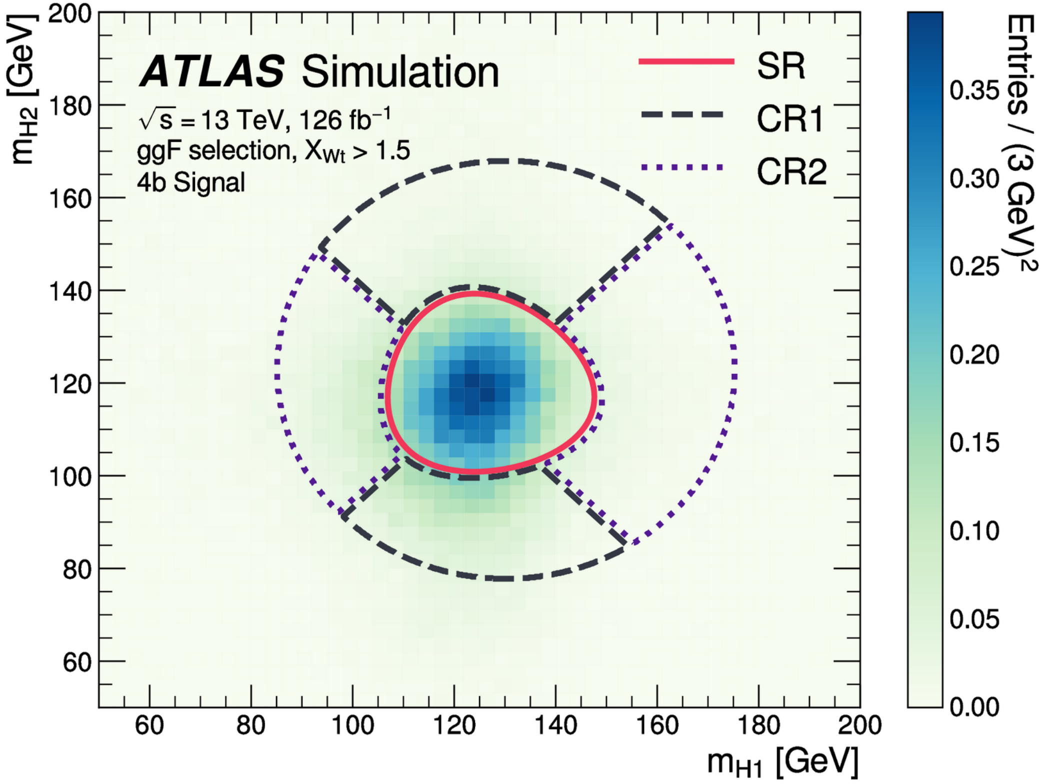
- Focus on resolved topologies here: ≥ 4 jets, ≥ 4 *b*-jets (signal region)
- Combinatorial problem: assign *b*-jets to the two Higgs decays
  - Focus on four leading *b*-jets → three possible combinations
  - Choose configuration where Higgs candidate with the higher p_T has smallest $\Delta R(b,b)$
- Reconstruct m_{hh}
- Likelihood fit of predicted m_{hh} distribution to that in data
  - Prediction allowed to float within uncertainties

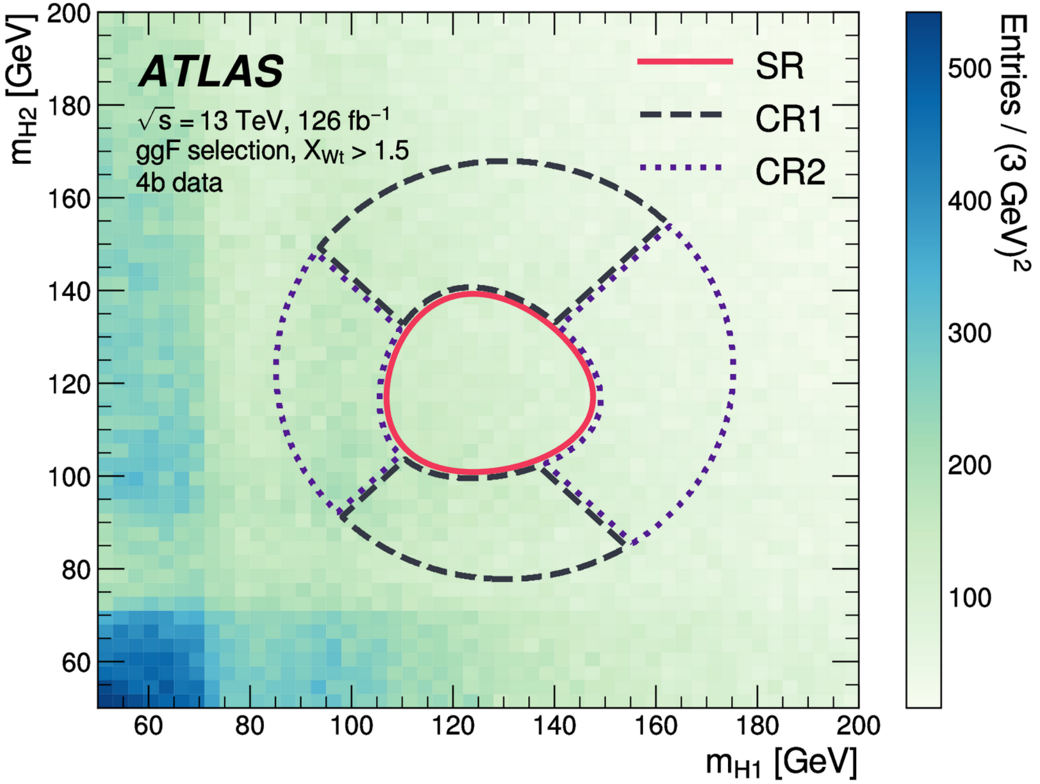




Analysis strategy for the *bbbb* channel

- Signal region: both Higgs candidates' masses close to 125 GeV
- Control regions used to estimate background from multi-jet production from data





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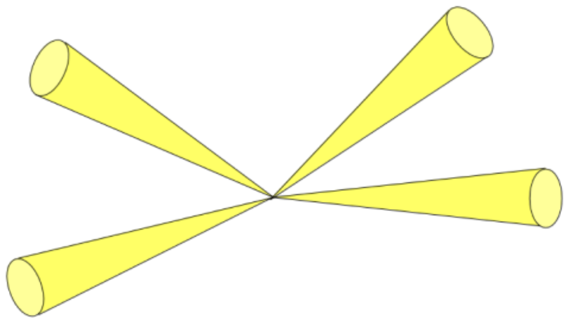

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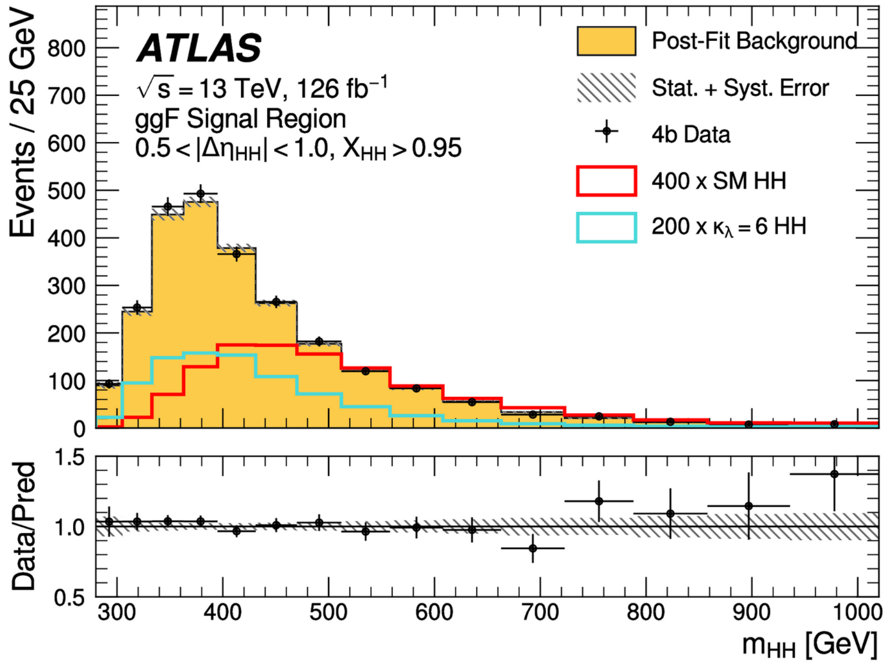
    - Prediction allowed to float within uncertainties



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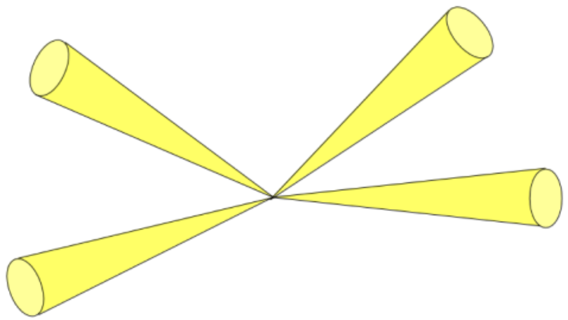
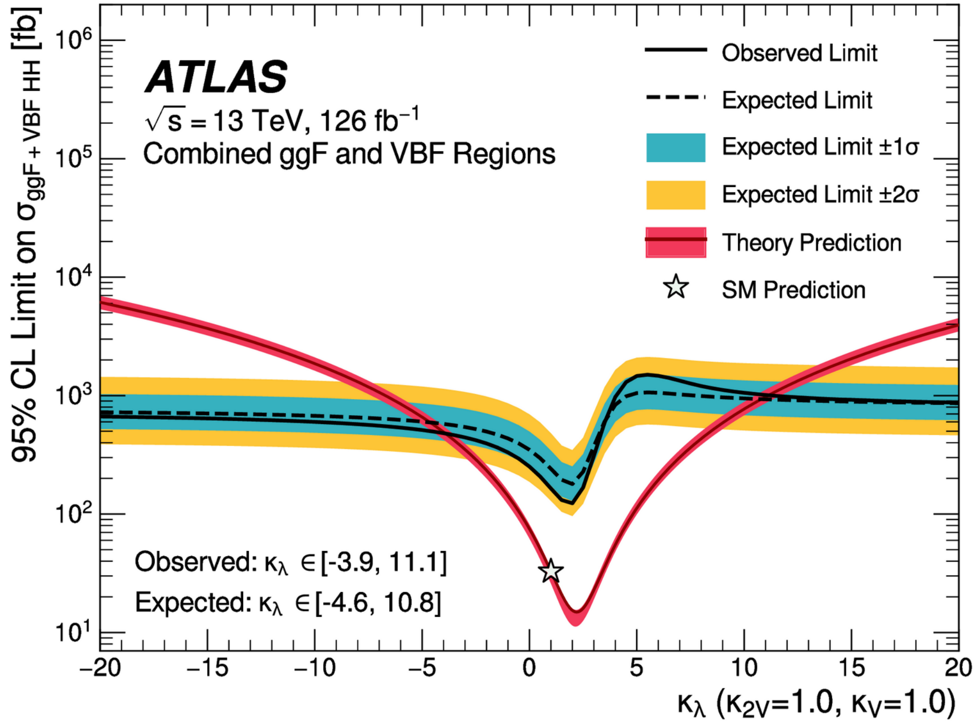
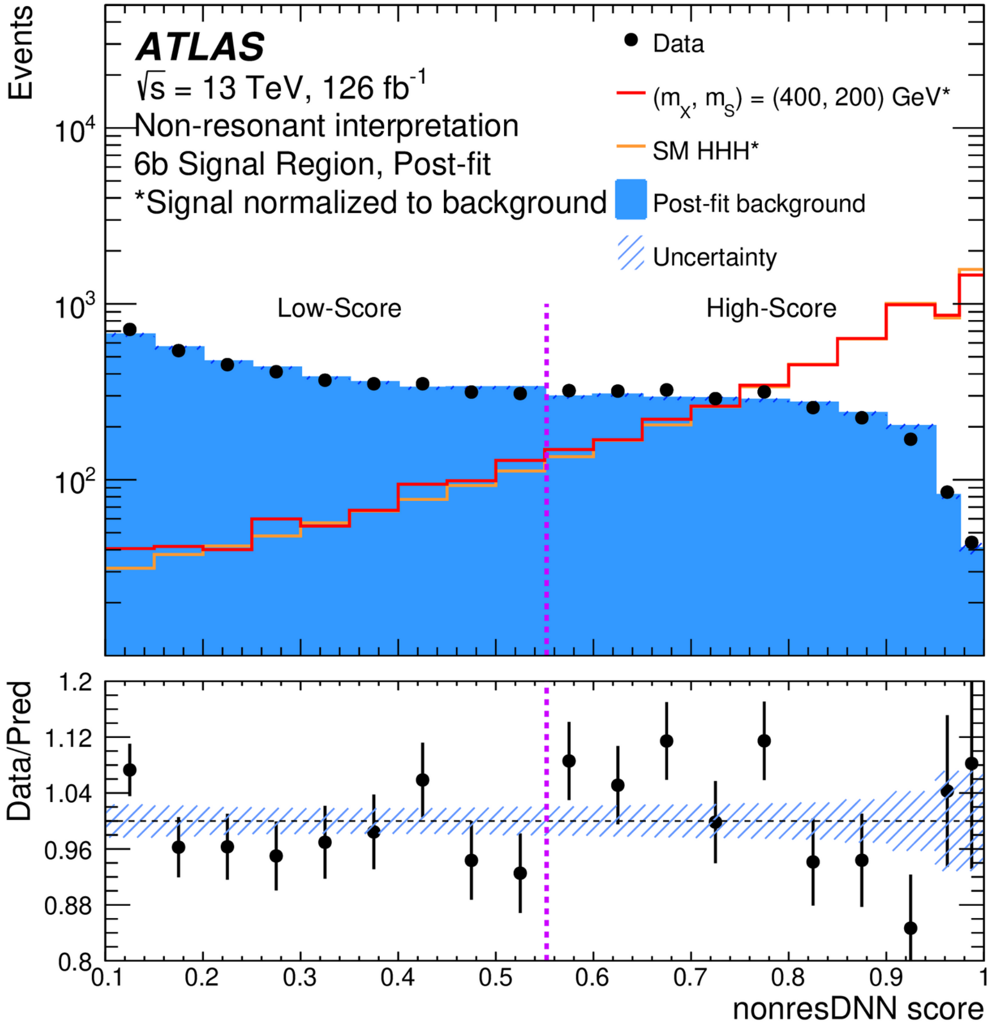
  - Choose configuration where Higgs candidate with the higher p_T has smallest $\Delta R(b,b)$
- Reconstruct m_{hh}
- Likelihood fit of predicted m_{hh} distribution to that in data
  - Prediction allowed to float within uncertainties





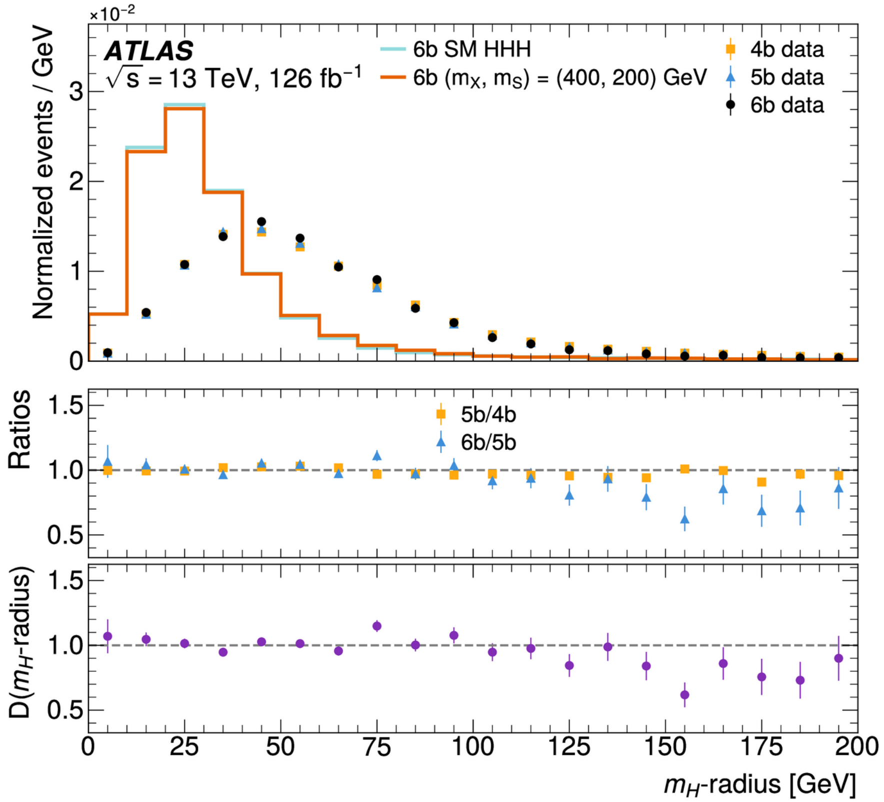
Triple Higgs 6b search

- Use DNNs to discriminate between signal and background
- Distribution of DNN score as discriminating variable
- High-score region:
  - Signal enriched
  - Used to define signal region
- Low-score region:
  - Signal depleted
  - Used to improve background estimate in signal region



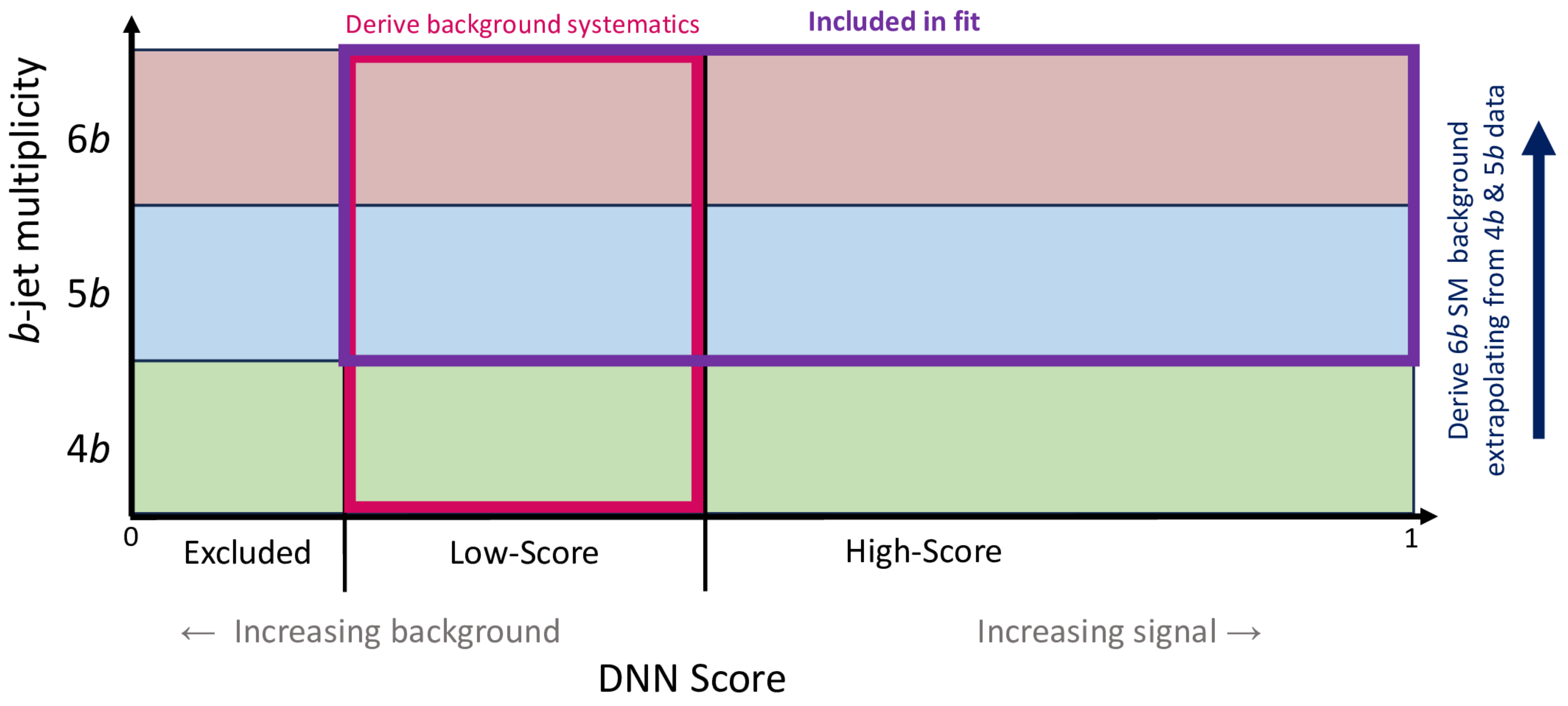
Triple Higgs 6b search

- Use DNNs to discriminate between signal and background
- Separate DNNs for non-resonant (varying κ_3 and κ_4) and resonant (BSM) production
- Trained on high-level variables describing the triple Higgs system



Data-driven background estimate

- Key assumption 1: background kinematics do not change significantly with *b*-jet multiplicity
  - → Background **shape** in signal region taken from 5*b* region
- Key assumption 2: yield ratio N_{5b} / N_{4b} = yield ratio N_{6b} / N_{5b}
  - → Background **normalisation** by extrapolating yields from 4*b* and 5*b* regions
- Validate assumptions in low-score regions and derive systematic uncertainties

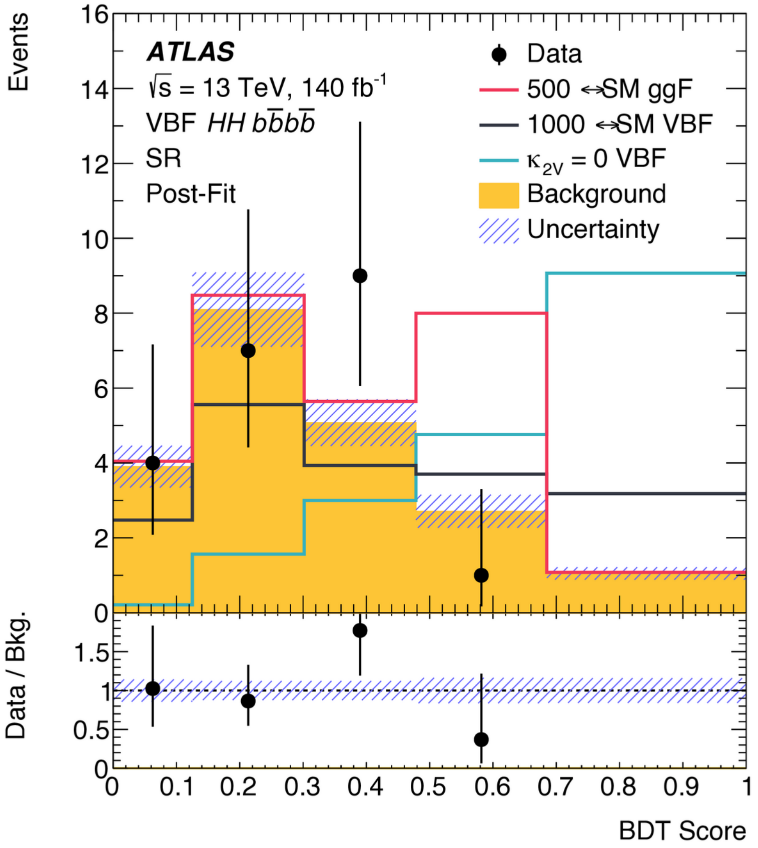


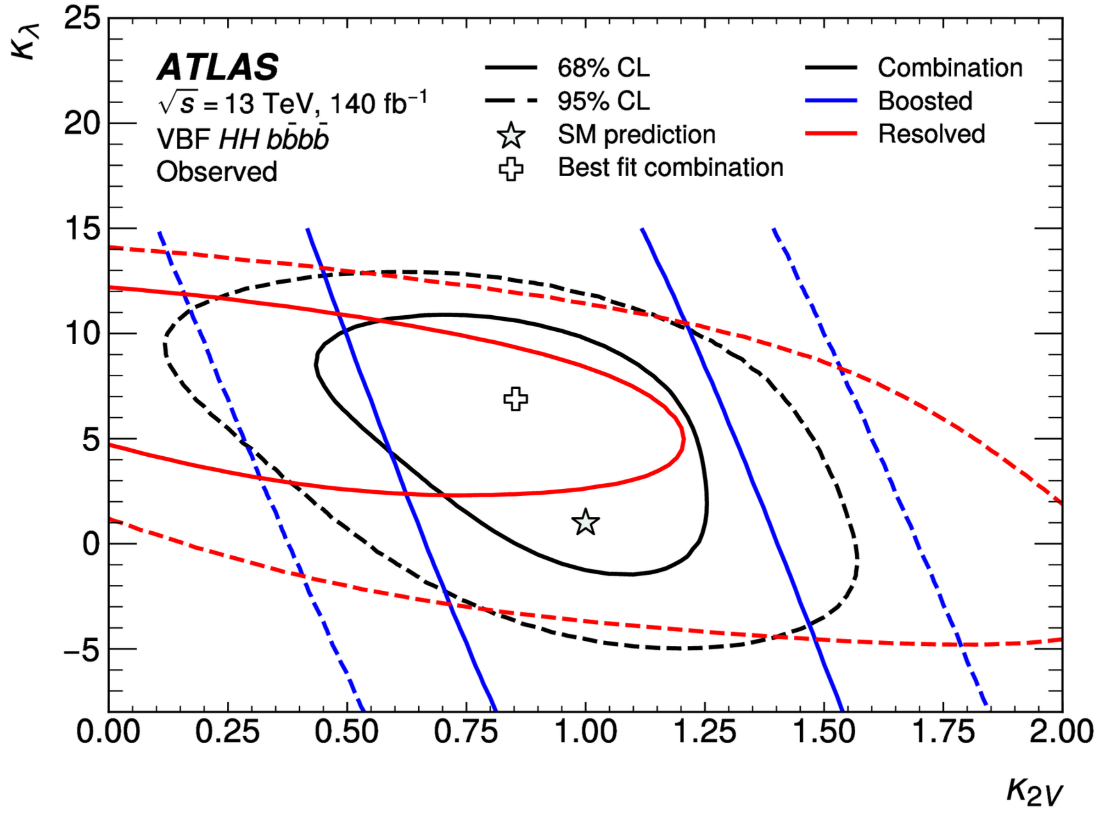
Constraining VVhh in vector-boson fusion

> Search primarily statistics-limited but Xbb tagging uncertainties also have a notable impact

> Interplay between boosted and resolved channels:

- Resolved more sensitive to κ_λ, boosted more sensitive to κ_{2V}

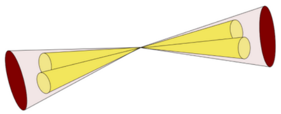




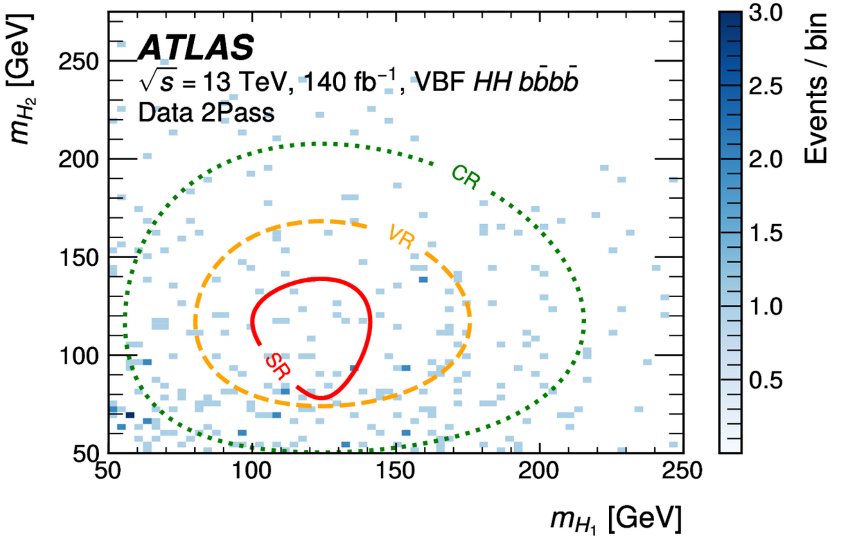
Search for VBF production in boosted *bbbb* events

Phys. Lett. B 858 (2024) 139007

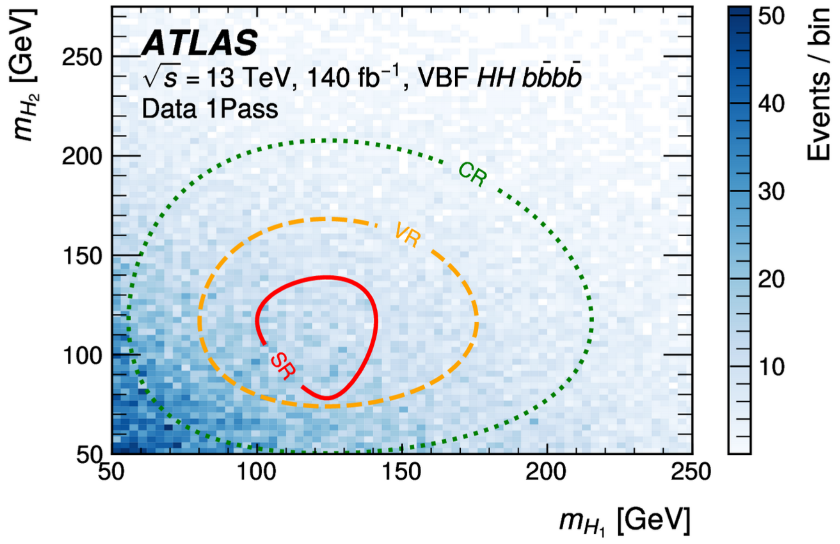
- Main background from QCD multi-jet production estimated from data
  - Both multi-*b*-final states and events with mis-identified *b*-jets (10% ttbar events in total)
- Normalisation factor calculated as event ratio between 2Pass and 1Pass CR
  - $w = 0.0081 \pm 0.0010$
  - Signal contamination in 1Pass CR is <8% in highest BDT bin (below stats uncertainty)

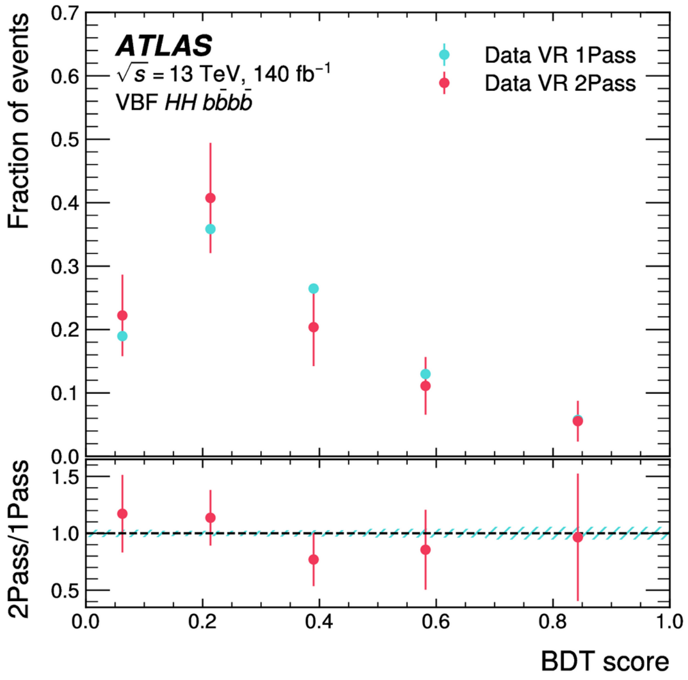


2Pass



1Pass





Search for VBF production in boosted *bbbb* events

Phys. Lett. B 858 (2024) 139007

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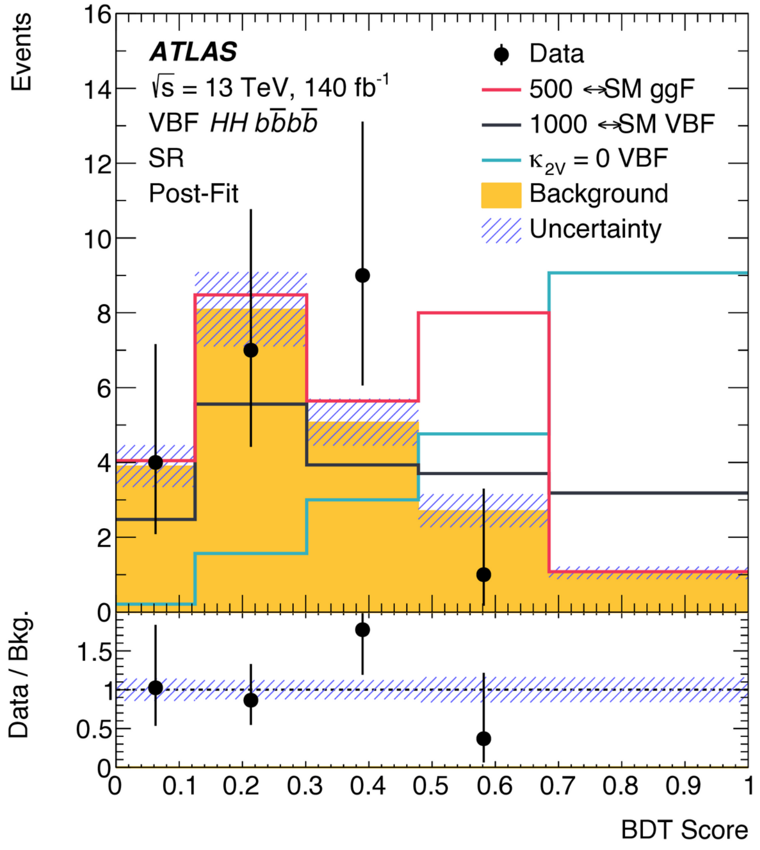
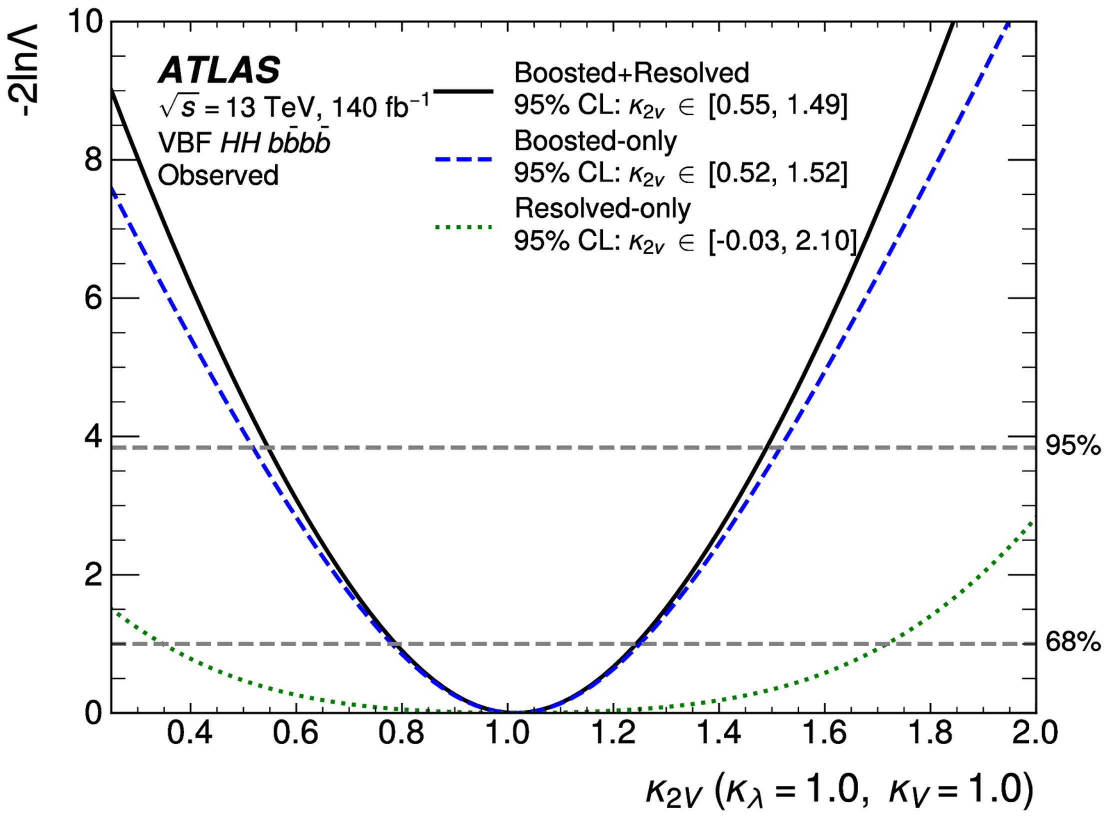
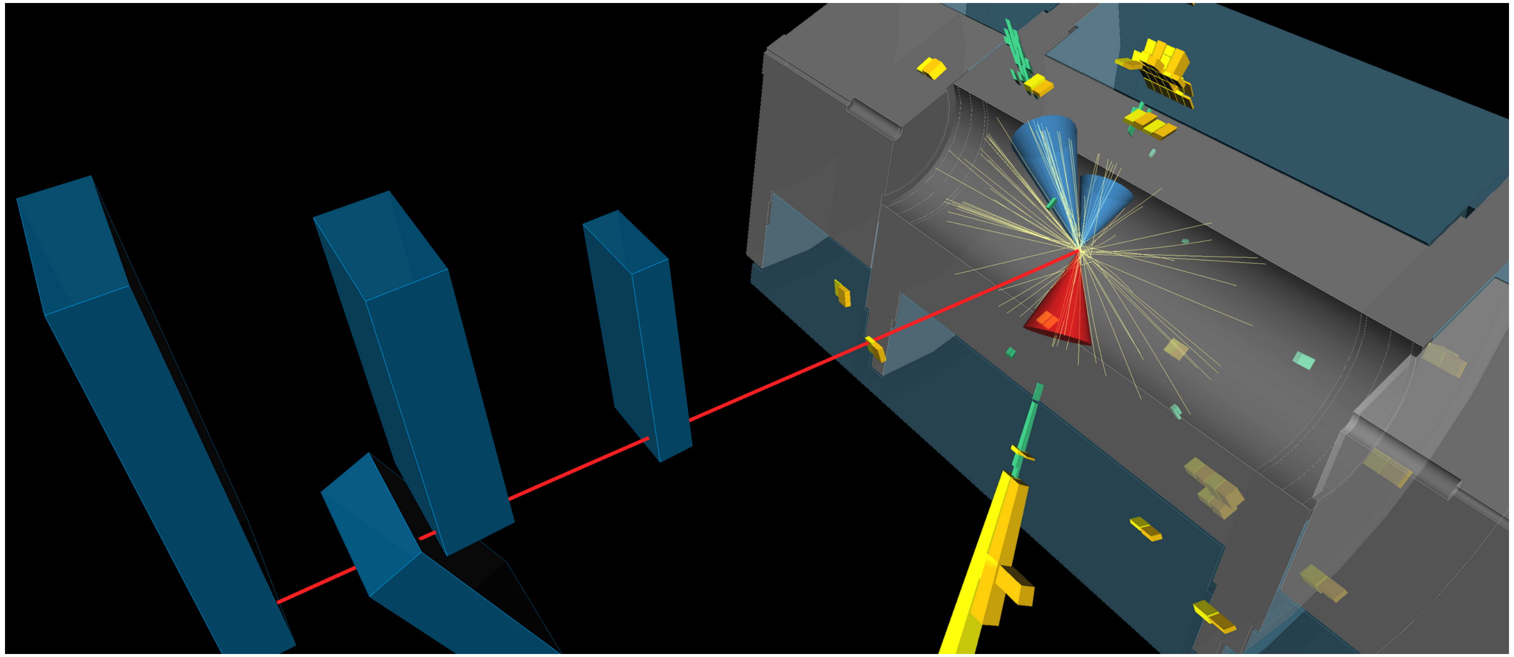




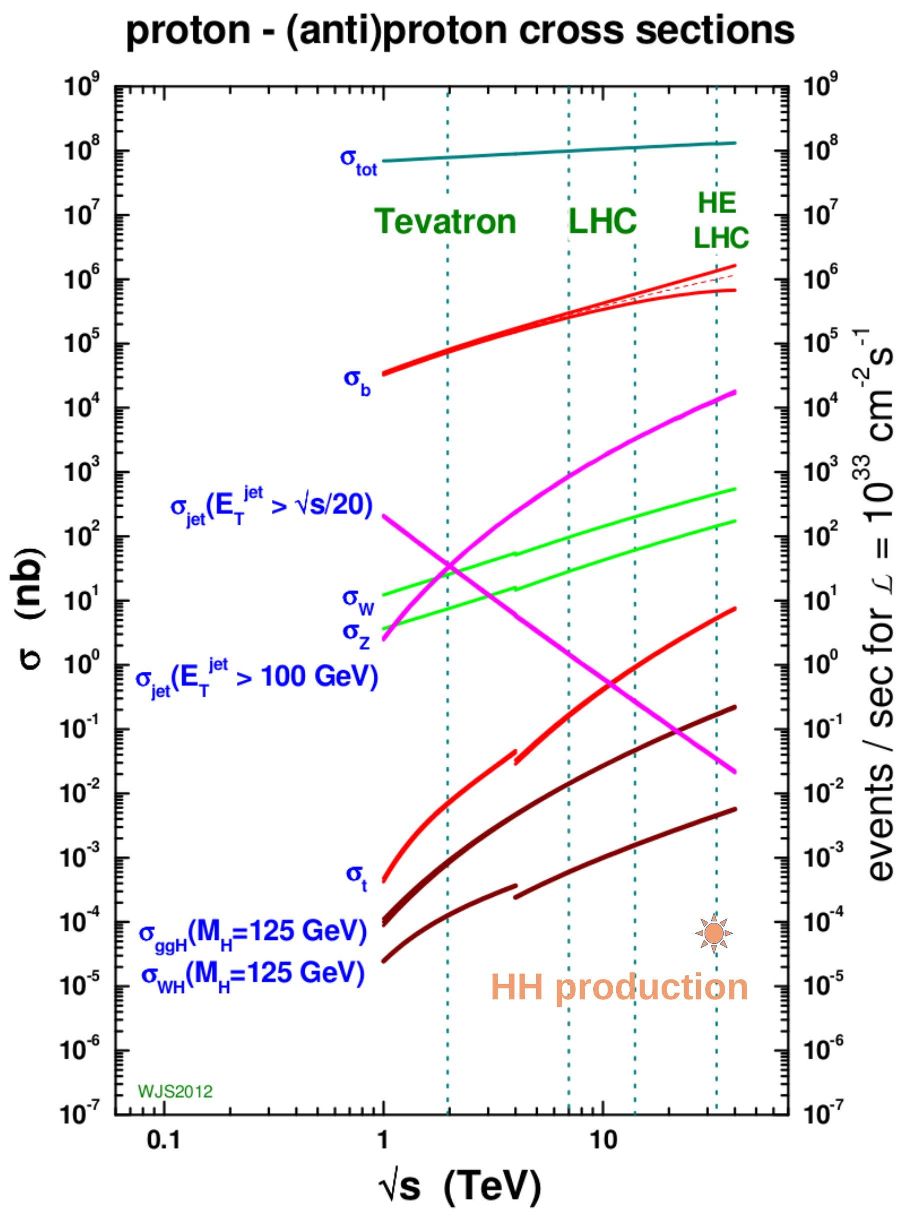
Background processes

- Z+bb
  - With $Z \rightarrow \tau\tau$
  - Also: $Z \rightarrow ee, \mu\mu$ with additional missing energy from mis-measurements
- $tt \rightarrow (Wb)(Wb)$
  - With $(Wb)(Wb) \rightarrow (\tau\nu)b(\tau\nu)b$
  - Also $(Wb)(Wb) \rightarrow (e\nu b)(\mu\nu b)$ ...



Background processes

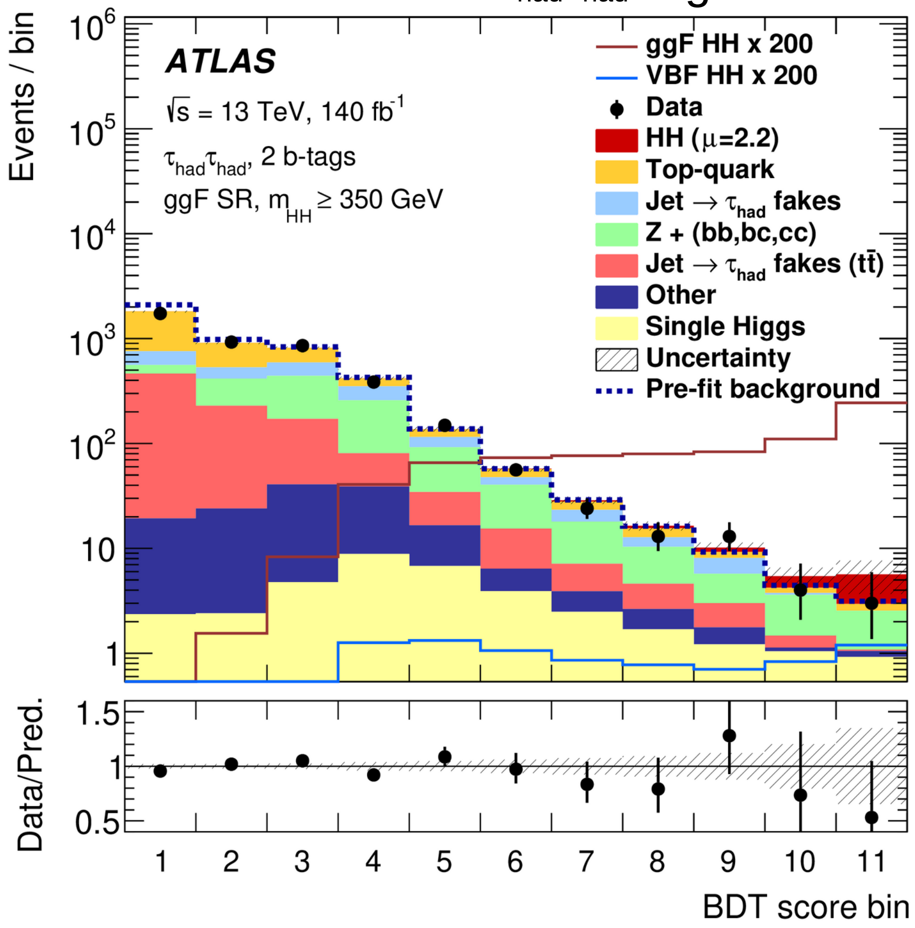
Quiz question:
What SM processes can result in a *bbττ* final state?



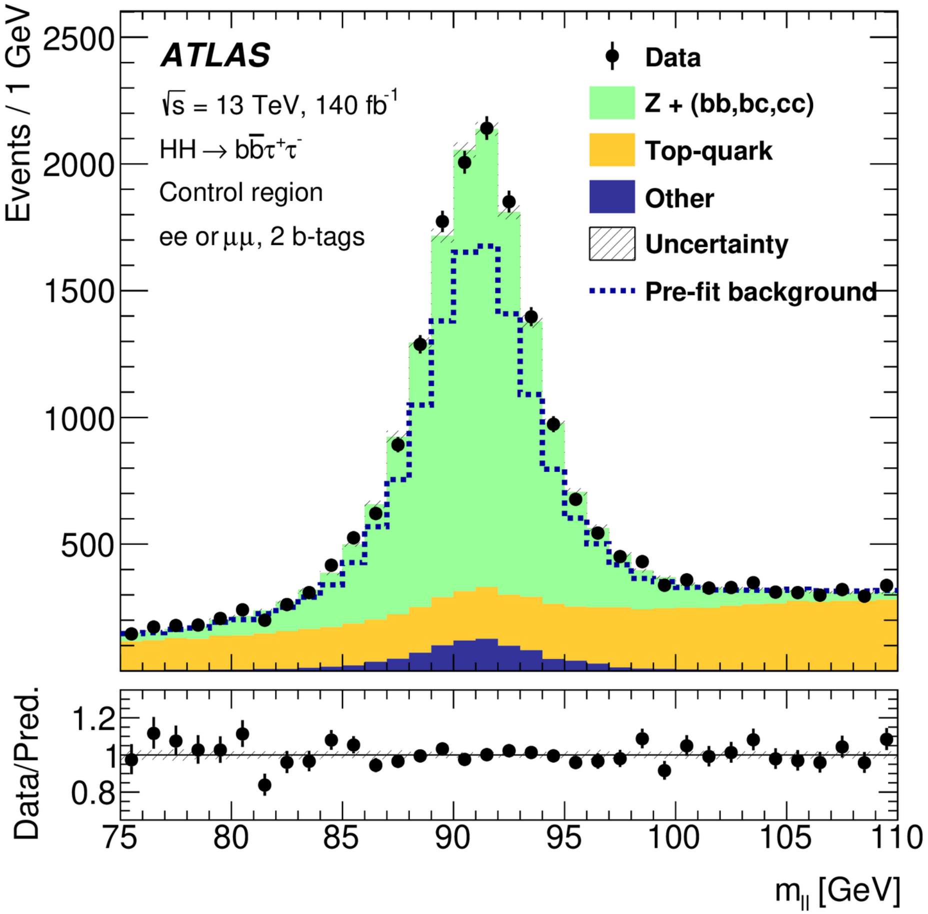
Complex analysis strategy for the *bbττ* channel

- Backgrounds estimated from simulation and corrected using data in control regions
- Simultaneous fit of predictions to data: BDT scores in each signal region + distributions in control regions

BDT score in $\tau_{had}\tau_{had}$ region



Z+jets control region



Complex analysis strategy for the *bbττ* channel

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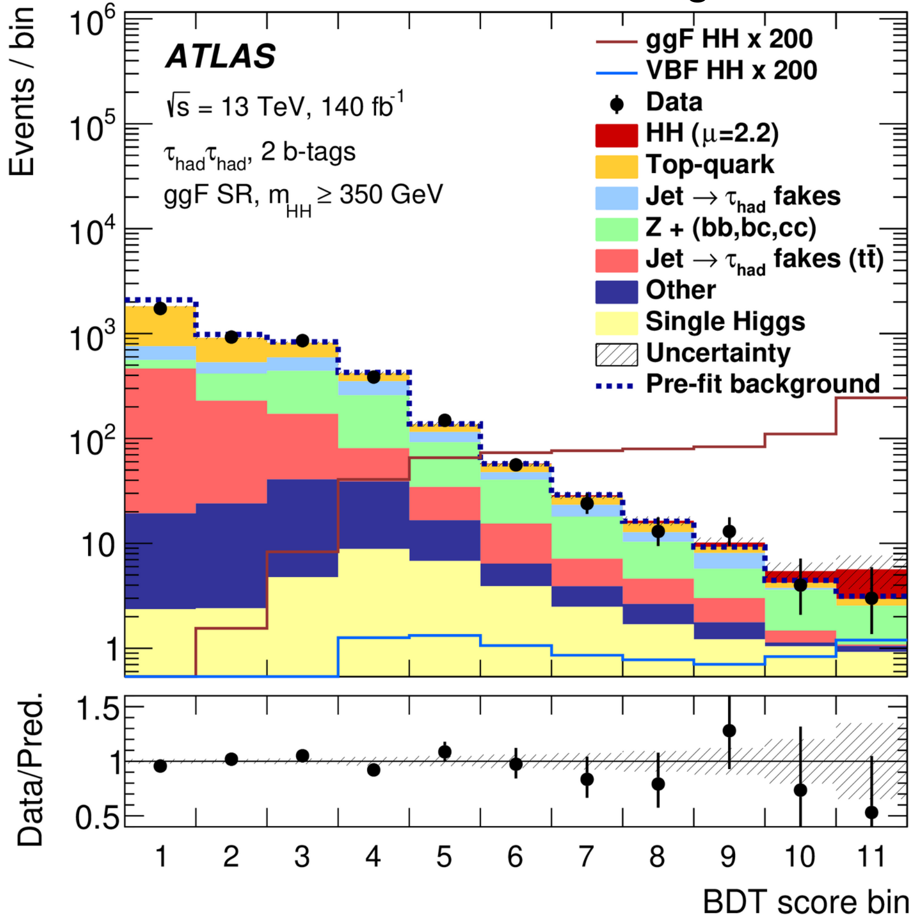
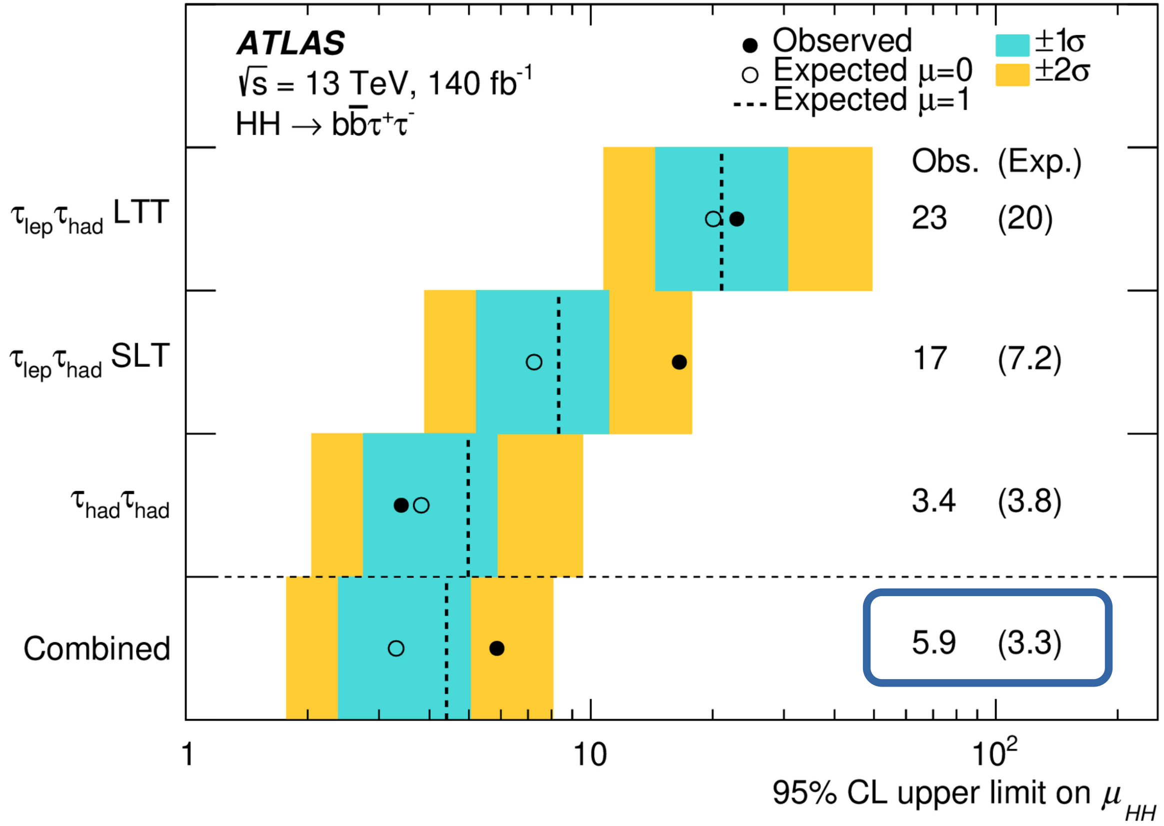


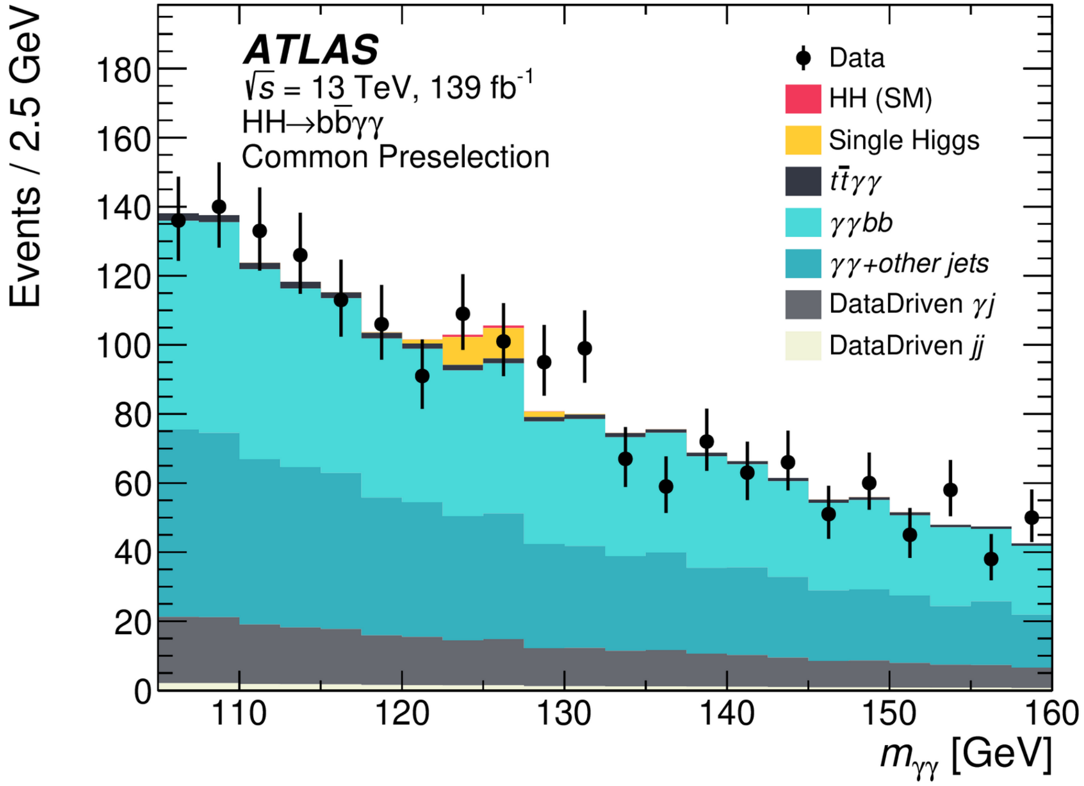
μ_{hh} = measured xsec / SM xsec

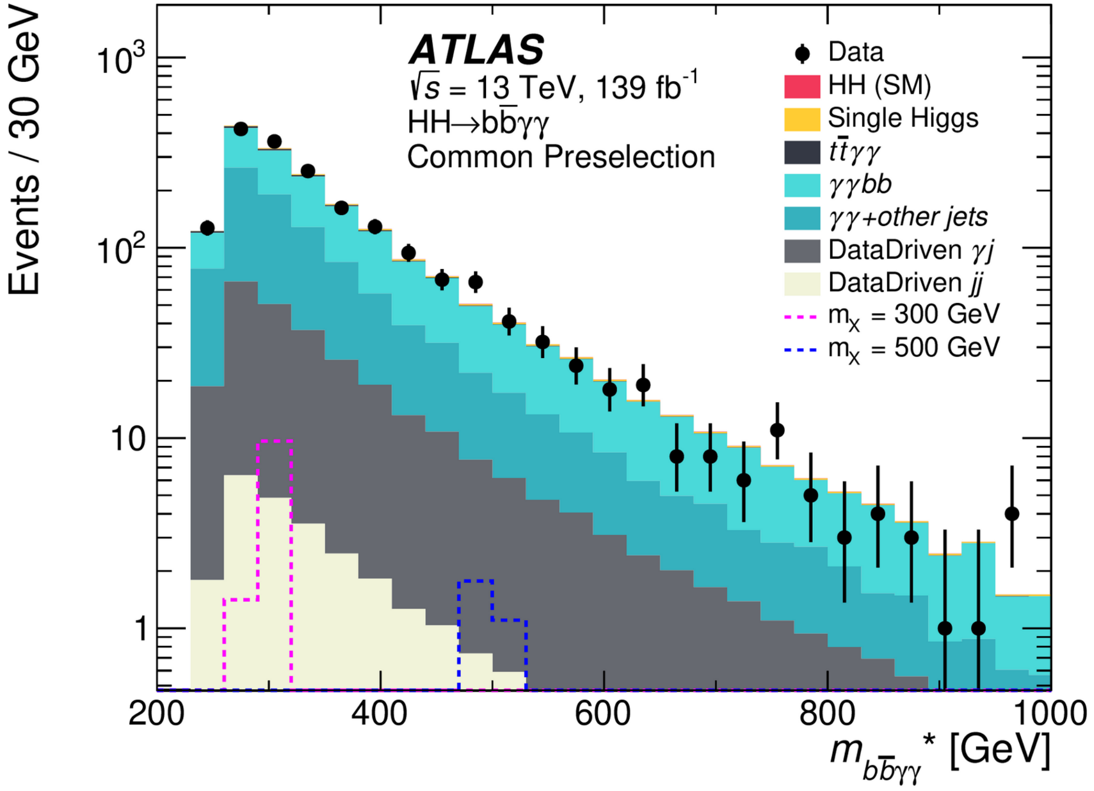


Analysis strategy of the *bbyy* channel

> Mass resolution of Higgs candidate from *yy* much better than *bb*
  - Use m_{yy} as discriminating variable instead of m_{yybb}

> Main backgrounds from real photons produced in association with jets → taken from simulation

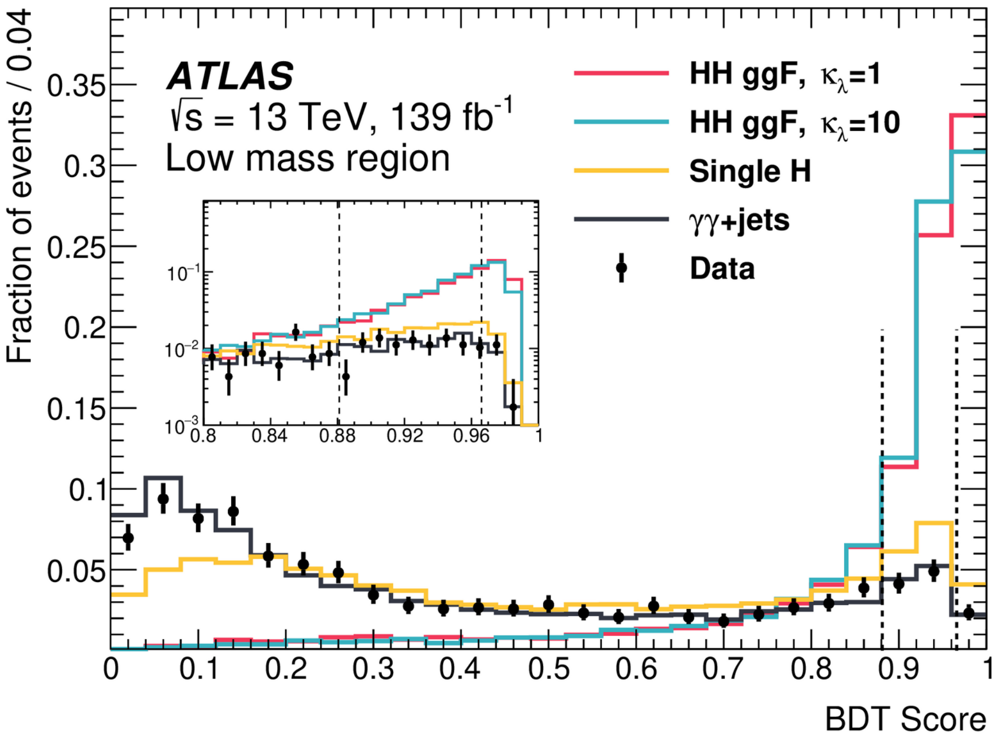


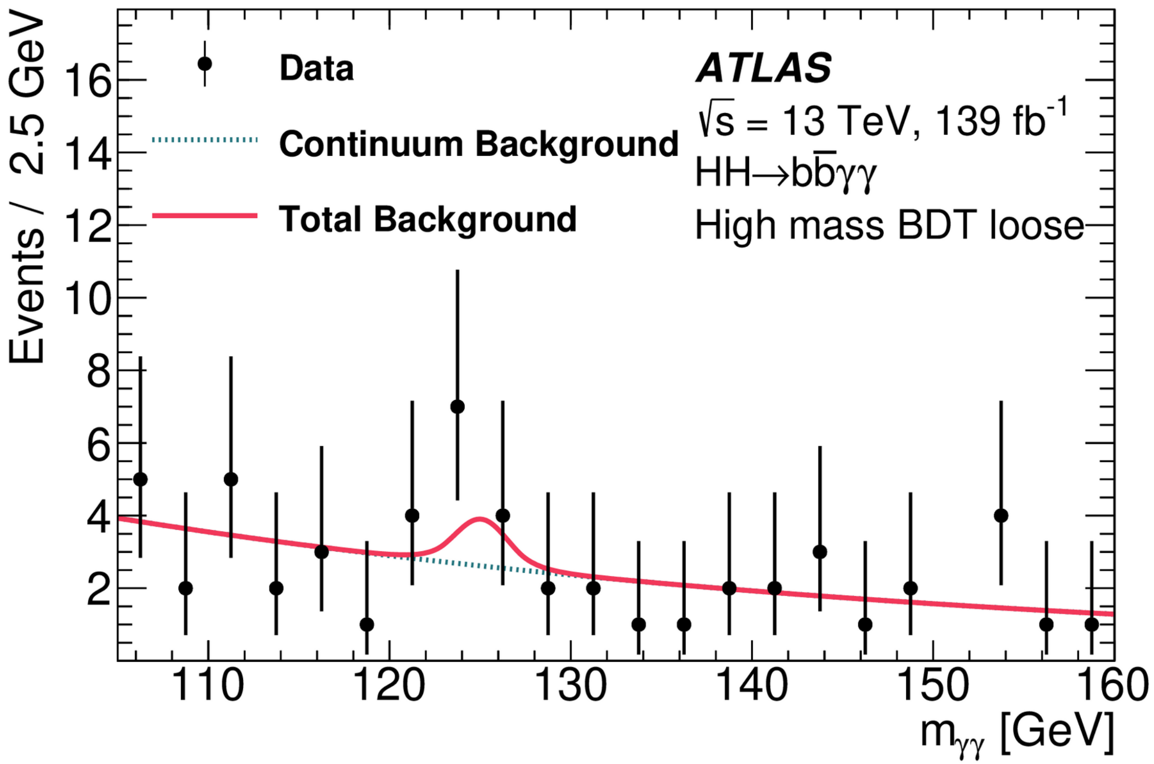


Analysis strategy of the *bbyy* channel

> Multivariate methods to improve signal-background discrimination
  - Trained separately in different m_{bbyy} regions for better sensitivity

> Fit analytic function for signal+background hypothesis to data in each signal region
  - Similar to Higgs-boson discovery and measurements in *yy* decay channel

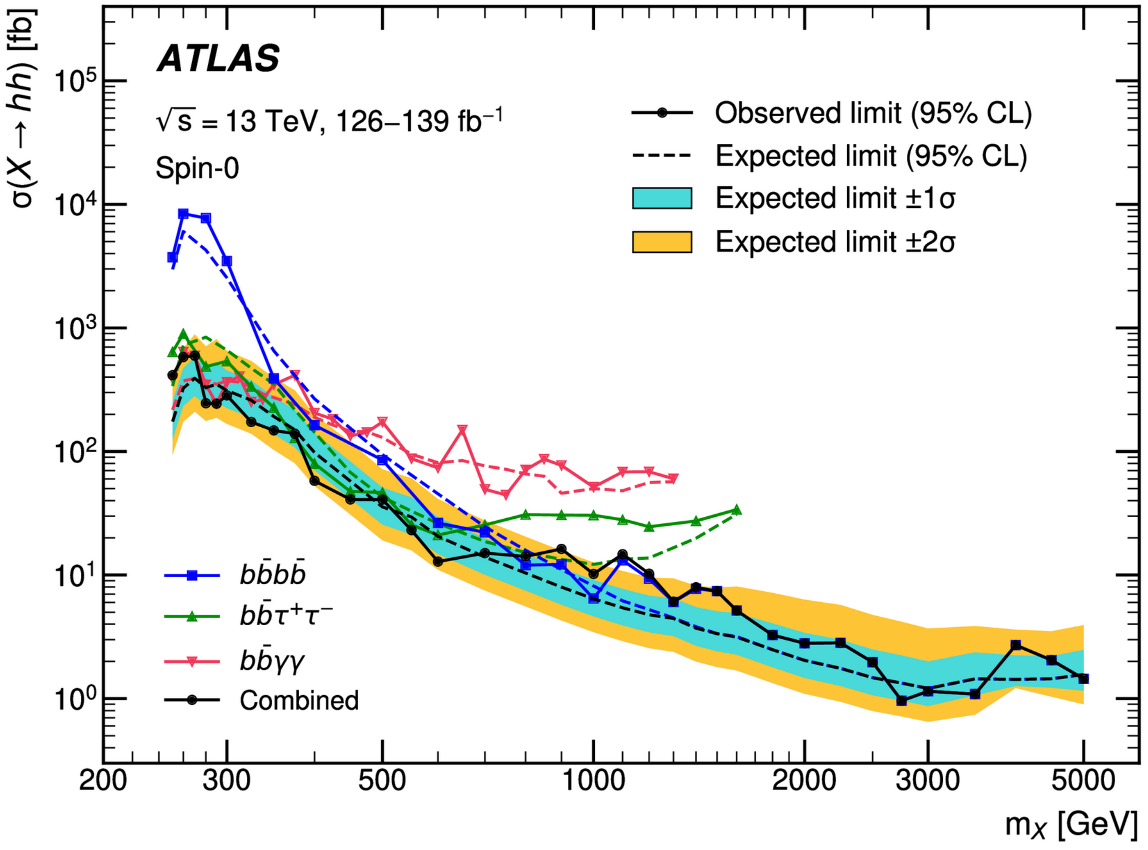




Resonant Higgs pair production

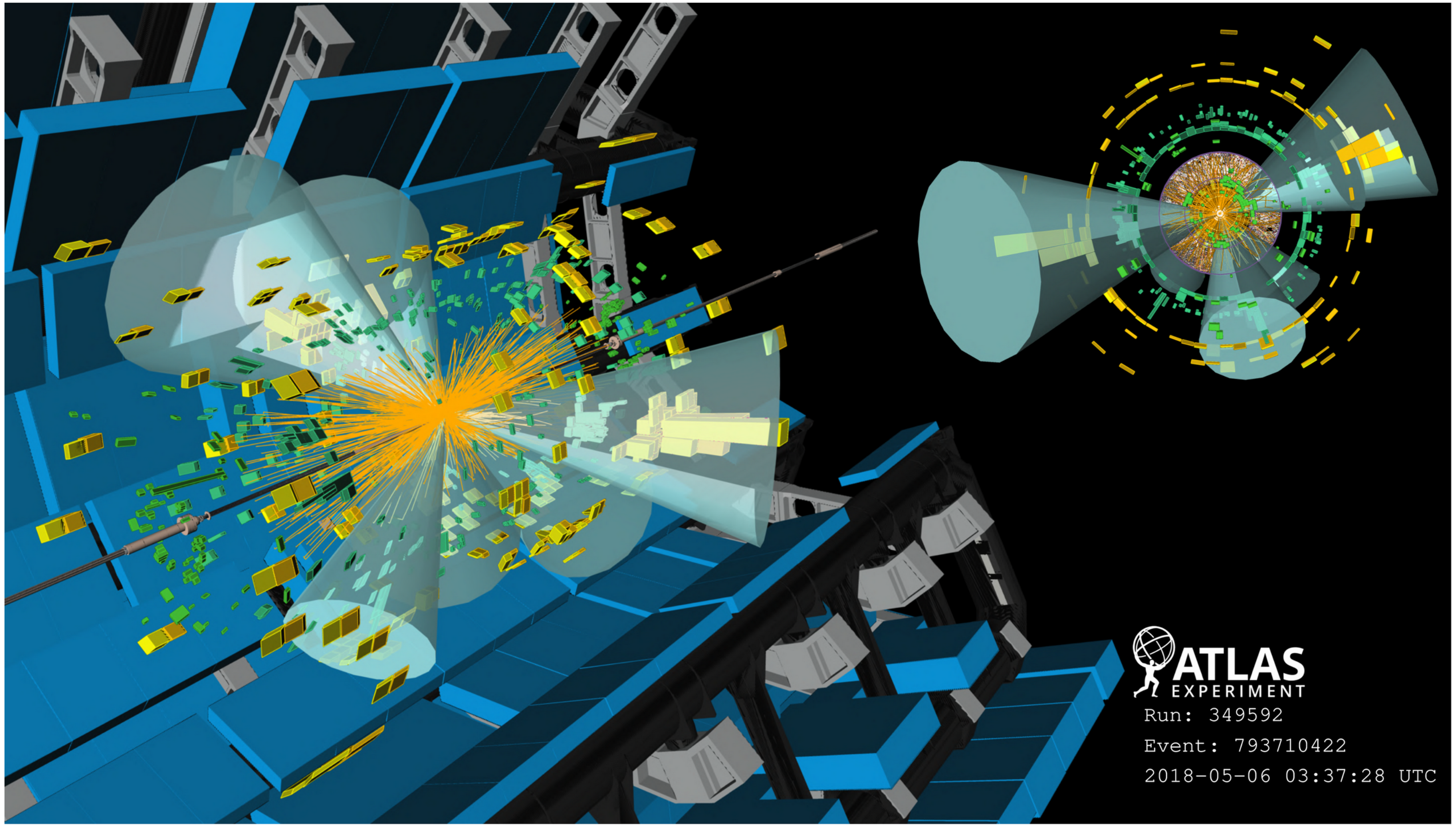
- BSM theories predict extra heavy states that can decay into a pair of Higgs bosons: $pp \rightarrow X \rightarrow hh$
  - More details tomorrow
- Search for local "bump" in hh invariant mass spectrum (similar to 2012 Higgs discovery)

Quiz question:
Why does the bbyy channel dominate at low m_X and the bbbb channel at high m_X?



First search for triple Higgs production

> Final states with six b-quarks: largest branching ratio, large background from multijet production

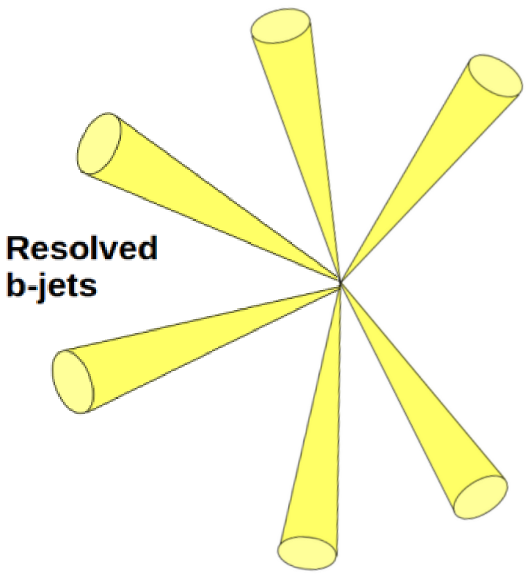


First search for triple Higgs production

- Signal regions: events with at least 6 *b*-tagged jets
- Control & validation regions: events with ==5 and ==4 *b*-tagged jets
- Higgs reconstruction: three *b*-jet pairs that minimises

  $$|m_{h1} - 120\ \text{GeV}| + |m_{h2} - 115\ \text{GeV}| + |m_{h3} - 110\ \text{GeV}|$$

  where $p_{T,h1} > p_{T,h2} > p_{T,h3}$
- DNNs to discriminate between signal and background



Results

- First experimental constraints on κ_4, first constraints beyond unitarity constraints!
- Limited by available data statistics and achievable signal-background ratio
- Significant improvement expected at HL-LHC (studies on-going)

- Searches in cleaner channels have started:
  - Most promising: 4b2τ