Search for Higgs boson pair production with ATLAS Run2 and Run3 data

Tong Li for the ATLAS APC-SJTU team

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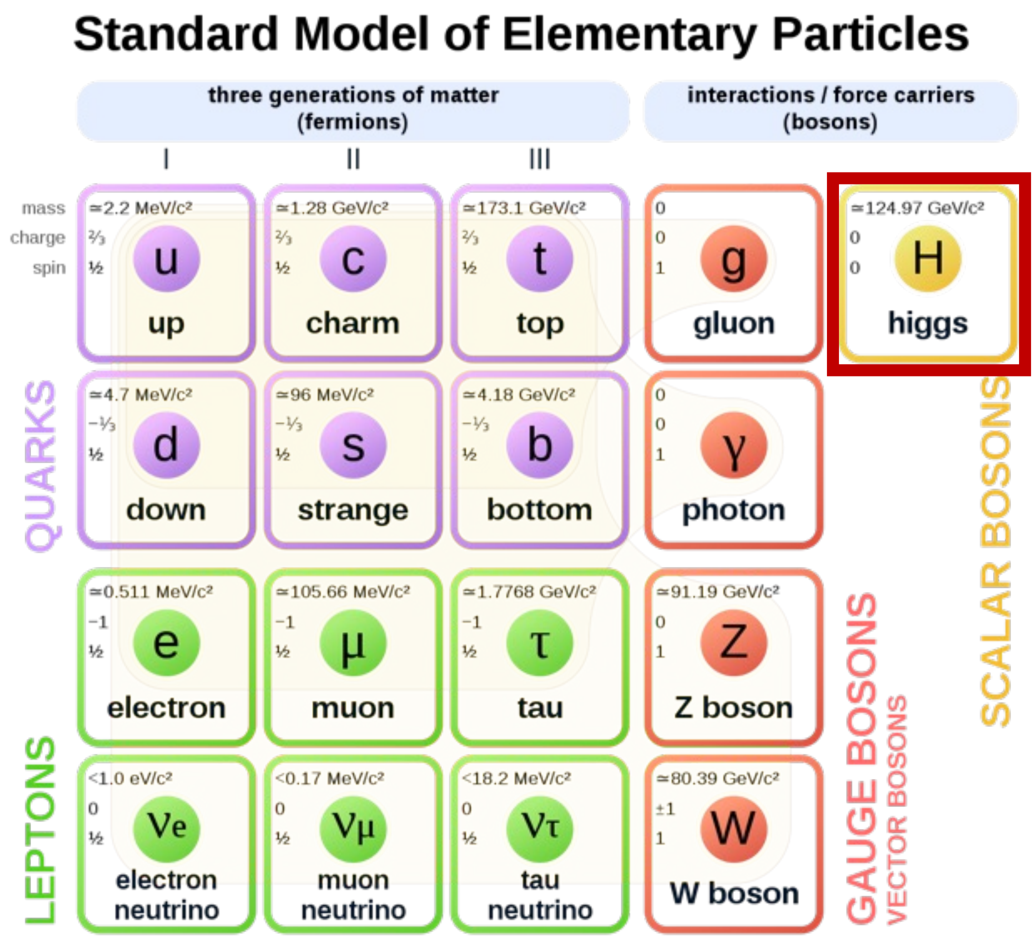
Outline

- Introduction
  - Standard Model and Higgs boson
  - Large Hadron Collider and ATLAS detector
- Search for Higgs pair with $bb\tau\tau$ final state (arXiv:2404.12660)
- Search for Higgs pair with $bb\gamma\gamma$ final state (JHEP 01 (2024) 066)
- Combinations of Higgs pair searches
  - Resonant HH combination (arXiv:2311.15956, accepted by Phys. Rev. Lett.)
  - Non-resonant HH combination (ATLAS-CONF-2024-006)
- Summary

Introduction

- As a thoroughly tested theory, Standard Model has great successes in Particle Physics
- A scalar field, Higgs field present throughout the universe, with a non-zero vacuum expectation value
- Fundamental particles acquire mass through their interaction with the Higgs field

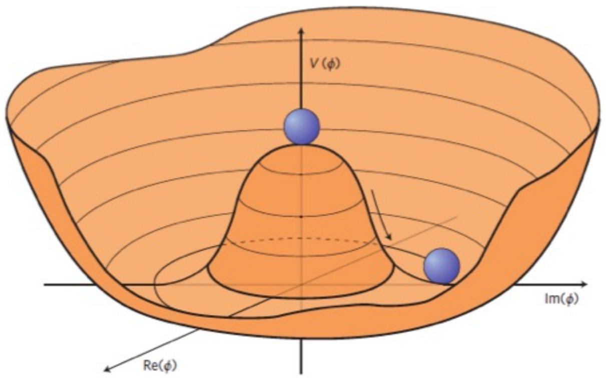


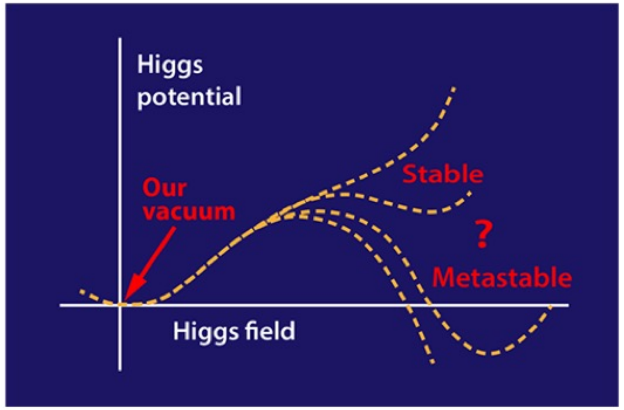
The Higgs potential and Higgs self-coupling

$$|\phi|_{\text{min}} = \sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{\nu}{\sqrt{2}}, \nu = 246 \text{ GeV}$$

When $\mu^2 < 0$ the potential has a minimum at:

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

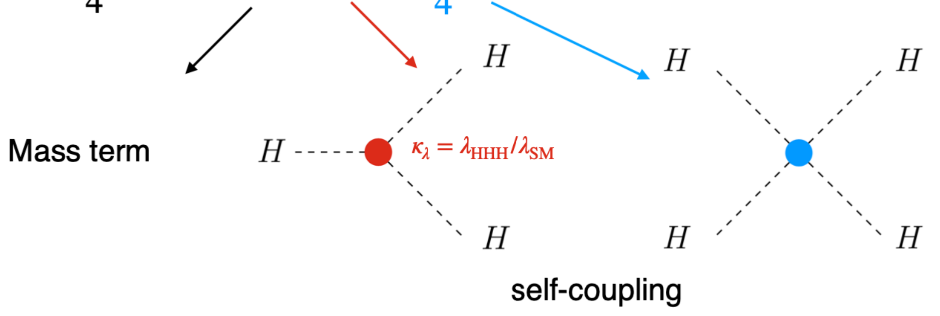




- Measurement of λ is crucial to reconstruction the Higgs potential and therefore test the Higgs mechanism
- Baryogenesis requires a first order electroweak phase transition, which would lead to a modification to the Higgs potential

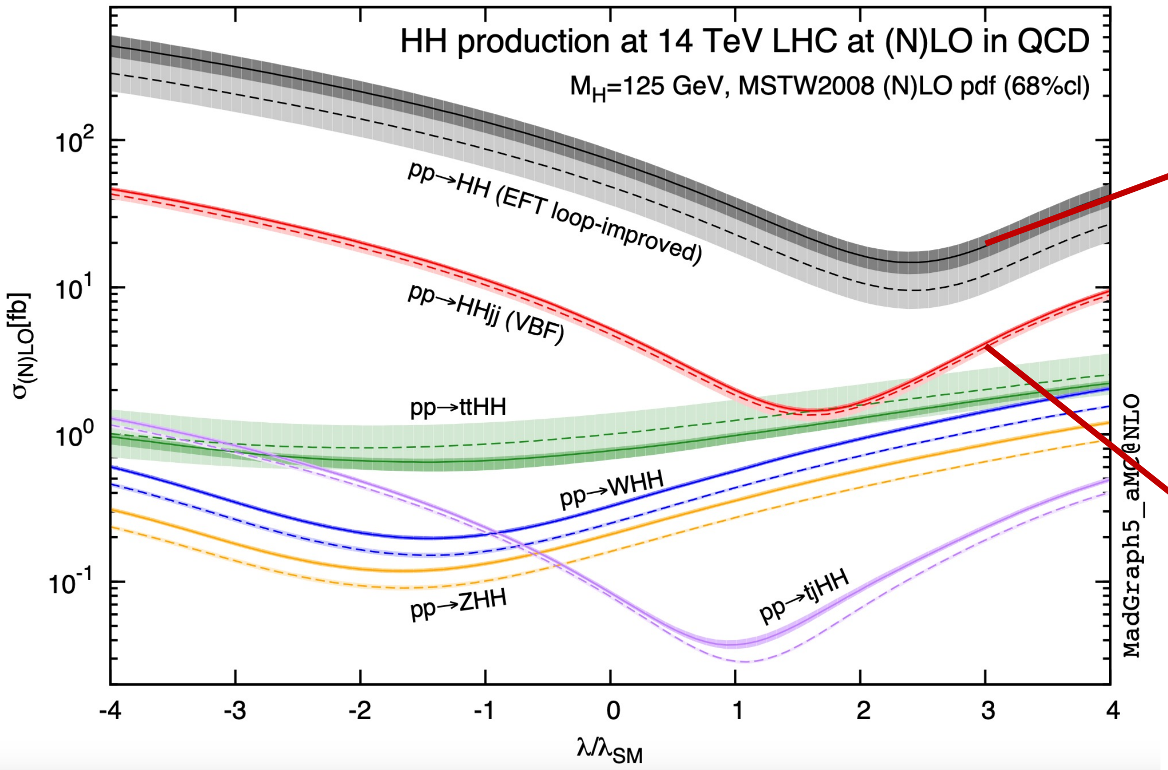
- ➢ Direct exploring the potential at each Higgs field value is not possible
- ➢ Probing the Higgs-self coupling is a key towards pinning down exact shape of the potential
- ➢ Study of Higgs boson pair production (HH) can shed light

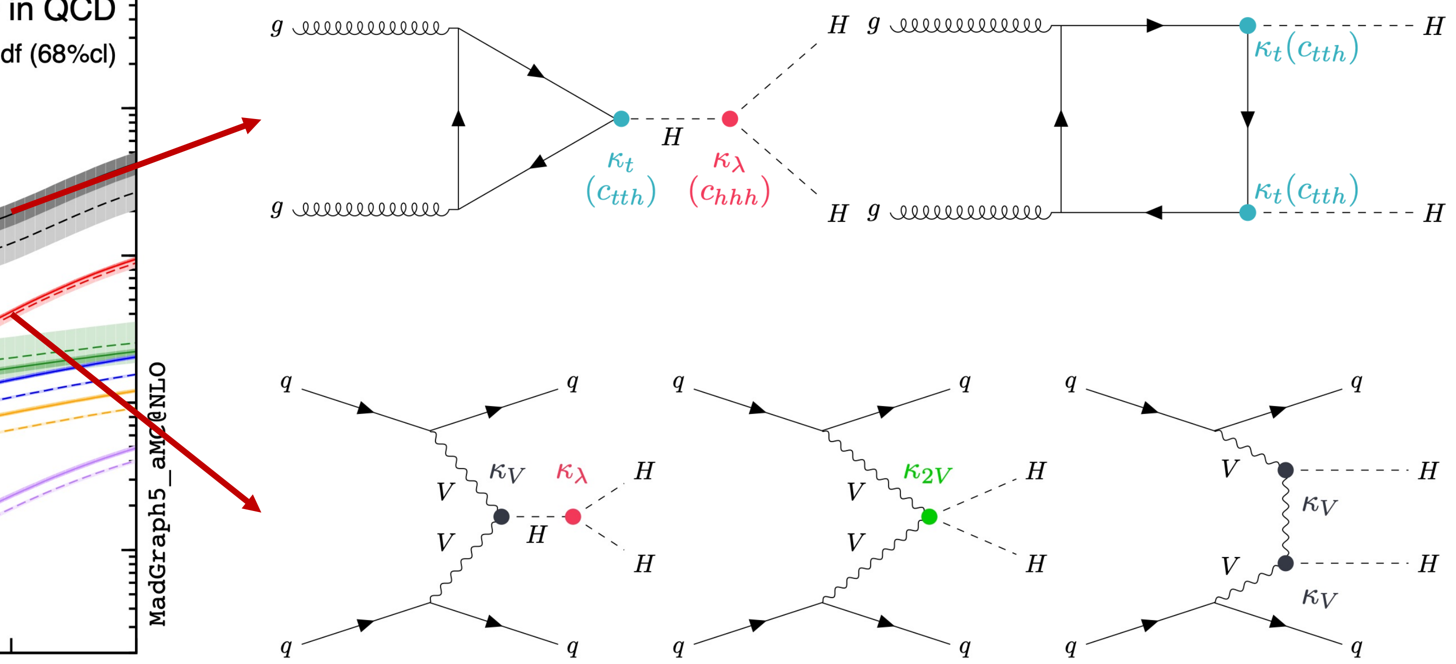
$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \supset \lambda\nu^2h^2 + \lambda\nu h^3 + \frac{\lambda}{4}h^4$$



Higgs pair production at LHC

- Search for Higgs boson pair production is directly connected to probing the Higgs potential
- SM σ_{HH} @ 13 TeV ~ 33 fb





Higgs pair decay channels

- Three most sensitive decay channels for HH search:
- HH→bbbb (BR: 34%):
  - The most abundant final state
  - Challenging multi-jet backgrounds
- HH→bbγγ (BR: 0.26%):
  - Excellent $m_{\gamma\gamma}$ resolution
  - Low decay fraction
- HH→bbττ (BR: 7.3%):
  - Happy medium

APC-SJTU team involved

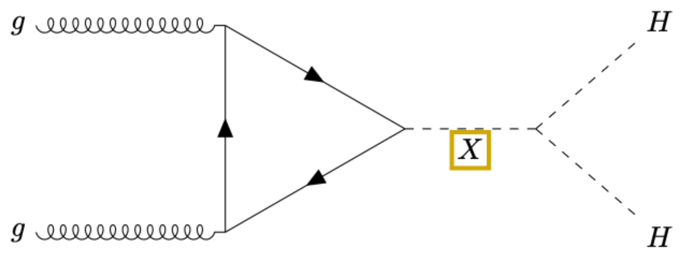
Large decay fraction

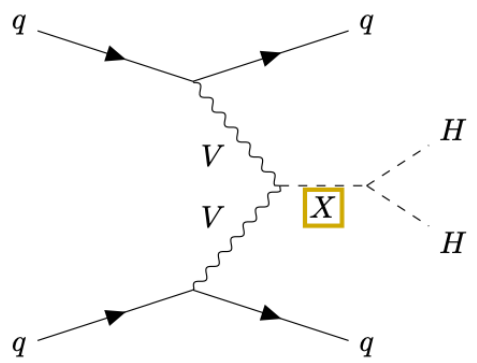
	bb	WW	ττ	ZZ	γγ
bb	**34%**				
WW	25%	4.6%			
ττ	**7.3%**	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	**0.26%**	0.10%	0.028%	0.012%	0.0005%

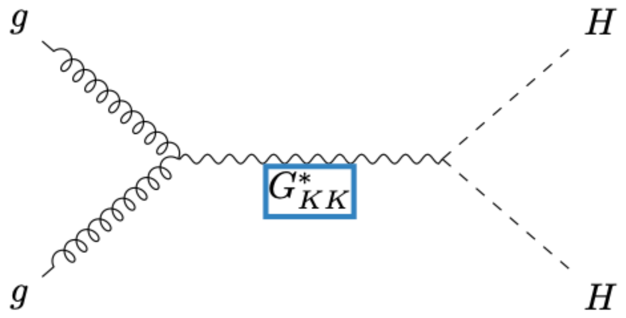
Clean final state

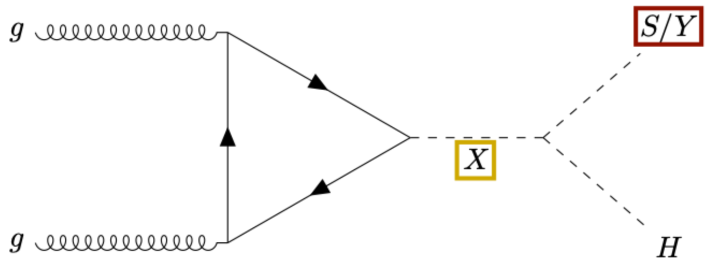
Search for new physics in HH final states

- The HH final state allows also to explore new topologies:
  - Spin-0: for example predicted by Two-Higgs-Doublet-Models completed by an Electroweak Singlet
  - Spin-2: for example predicted by a Kaluza-Klein graviton in the context of the bulk Randall-Sundrum (RS) model of warped extra dimensions





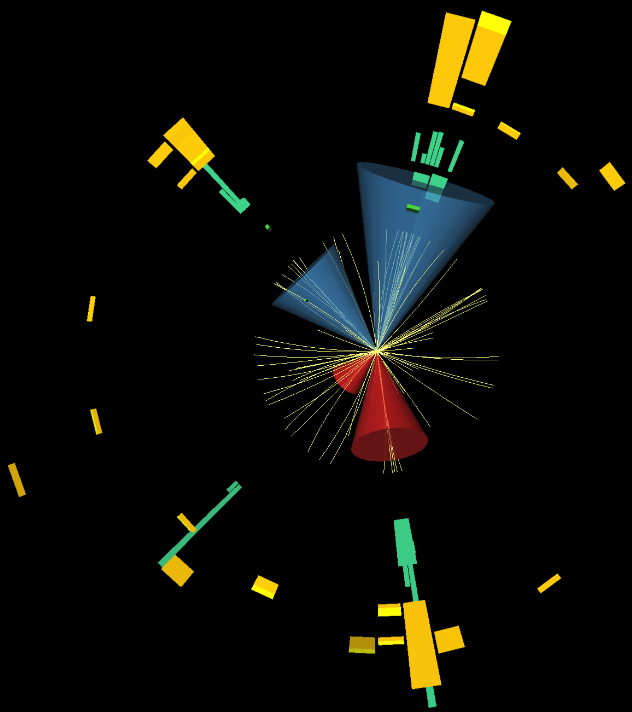


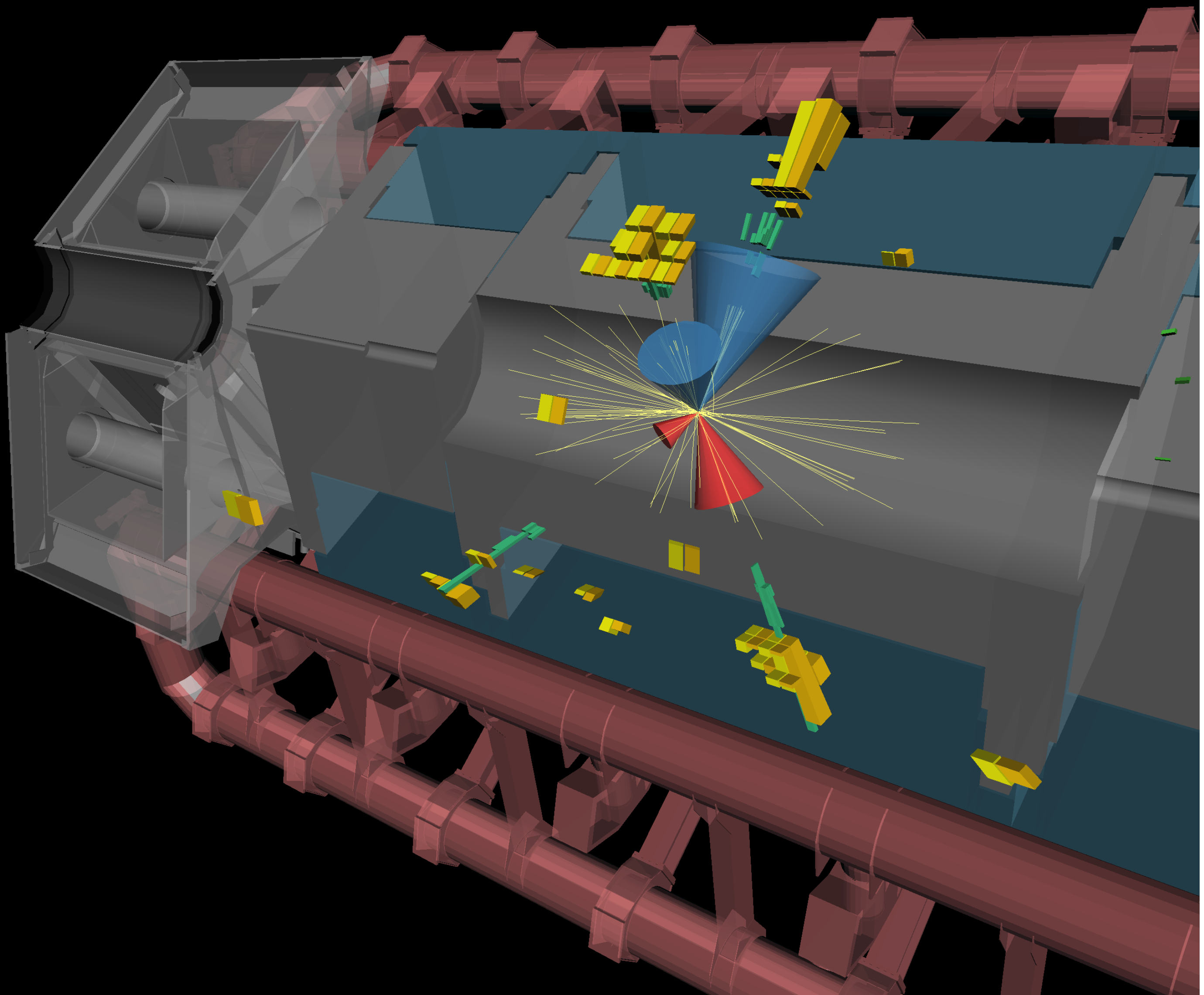


Search for Higgs pair in $bb\tau\tau$

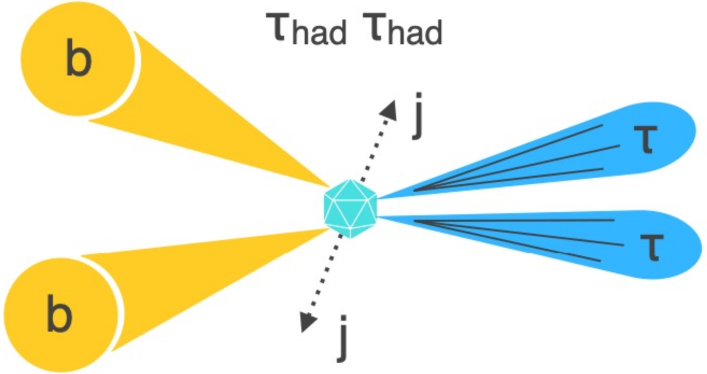
(Ang Li, Yulei Zhang)

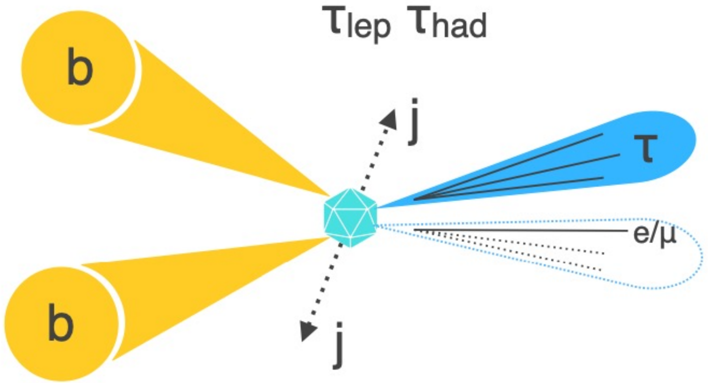
Run: 339535
Event: 996385095
2017-10-31 00:02:20 CEST

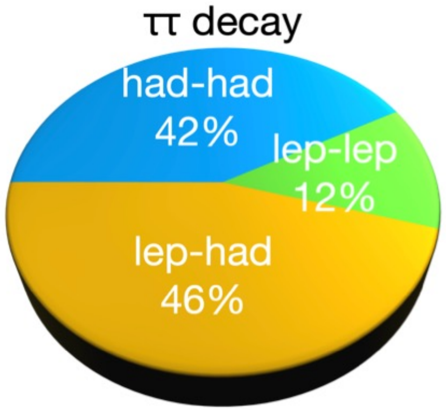




Event selection and categorization





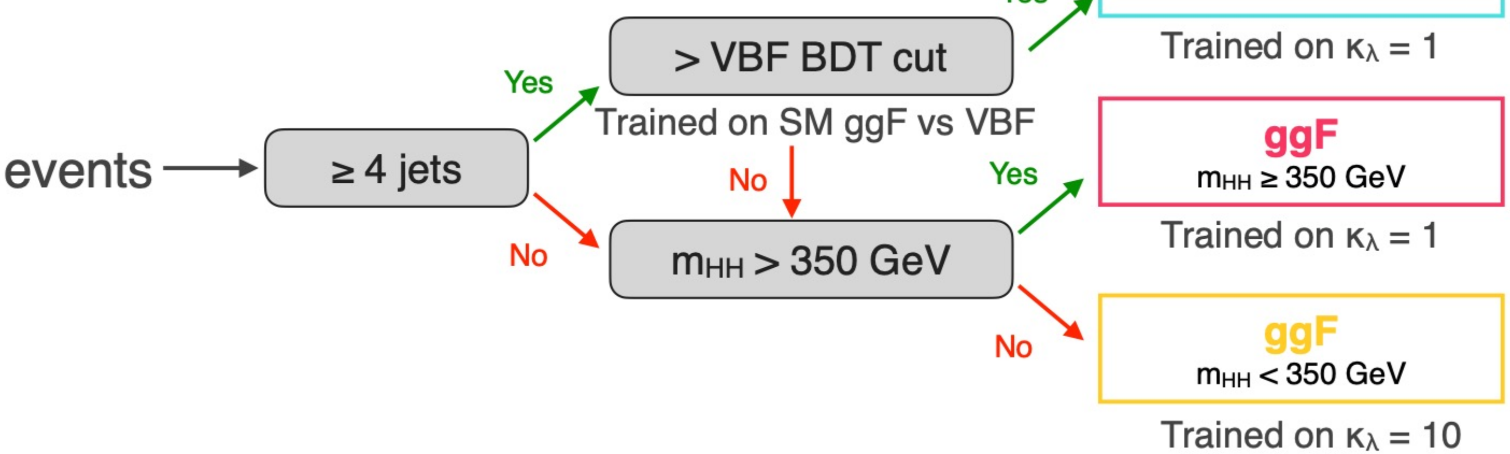


- Single-τ_{had} and di-τ_{had} triggers (high purity)
- 2 τ_{had}, e/μ veto

- Single ℓ trigger (large acceptance)
- 1 τ_{had}, 1 e/μ

- ℓ + τ_{had} trigger (low ℓ p_T)
- 1 τ_{had}, 1 e/μ

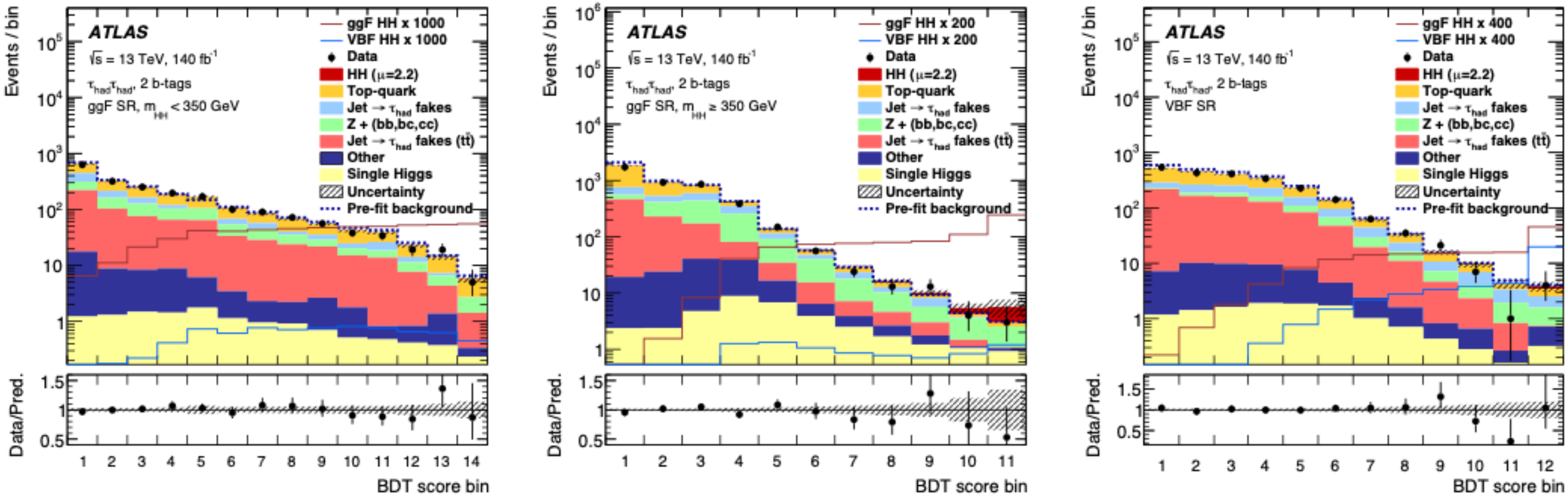
- 2 b-jets, $m_{\tau\tau} > 60$ GeV



× 3 types of triggers = 9 categories

BDT distributions

- Predicted and observed distribution of the BDT score shown in:
  - low-m_{HH} (left), high-m_{HH} (middle), and VBF region (right)
- The signal and background are shown at post-fit level as obtained from the combined likelihood fit to data

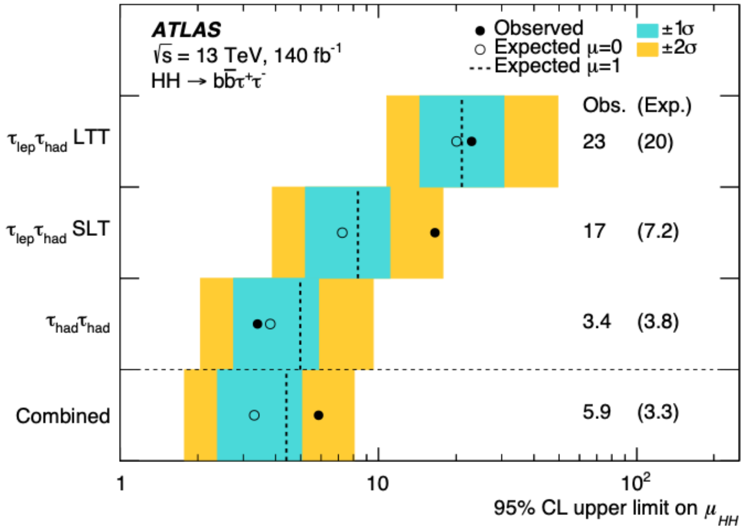


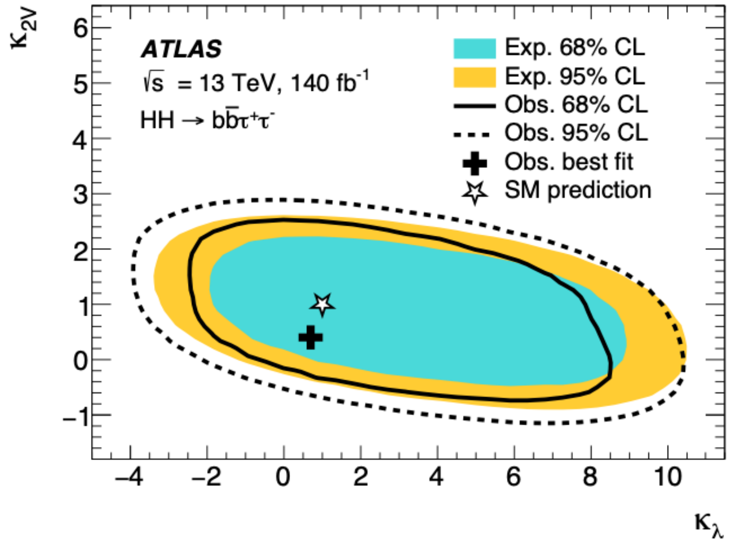
Results

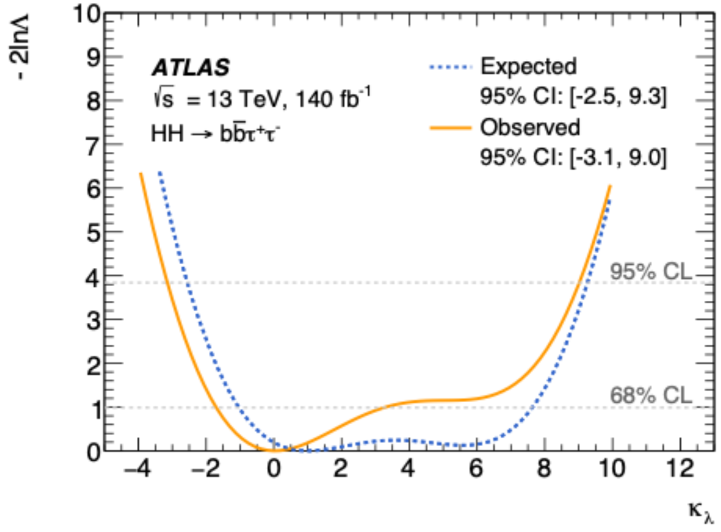
- 95% CL upper limit on HH signal strength (top left)

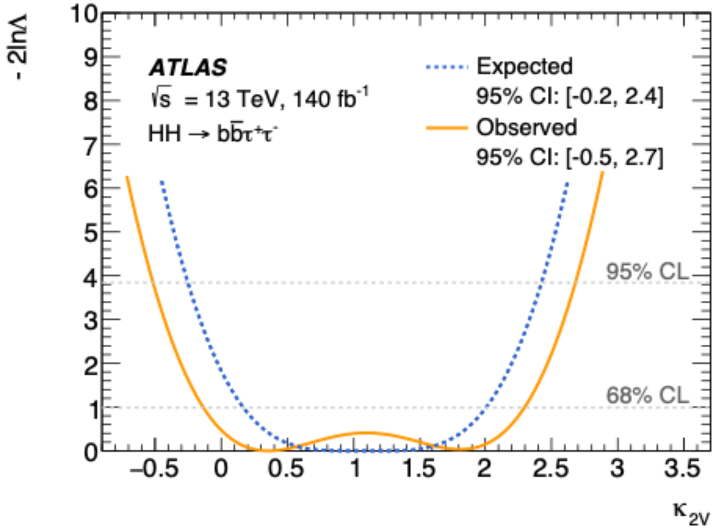
$$\mu_{HH} = (\sigma_{\text{ggF}} + \sigma_{\text{VBF}})/(\sigma^{\text{SM}}_{\text{ggF}} + \sigma^{\text{SM}}_{\text{VBF}})$$

- Likelihood contours in the κ_λ - κ_{2V} parameter space (top right)
- Values of -2lnΛ for different κ_λ and κ_{2V} hypotheses obtained from fits to data and Asimov dataset (bottom)
- Asimov dataset: a representative dataset where the observed data is exactly equal to the expected value of the model

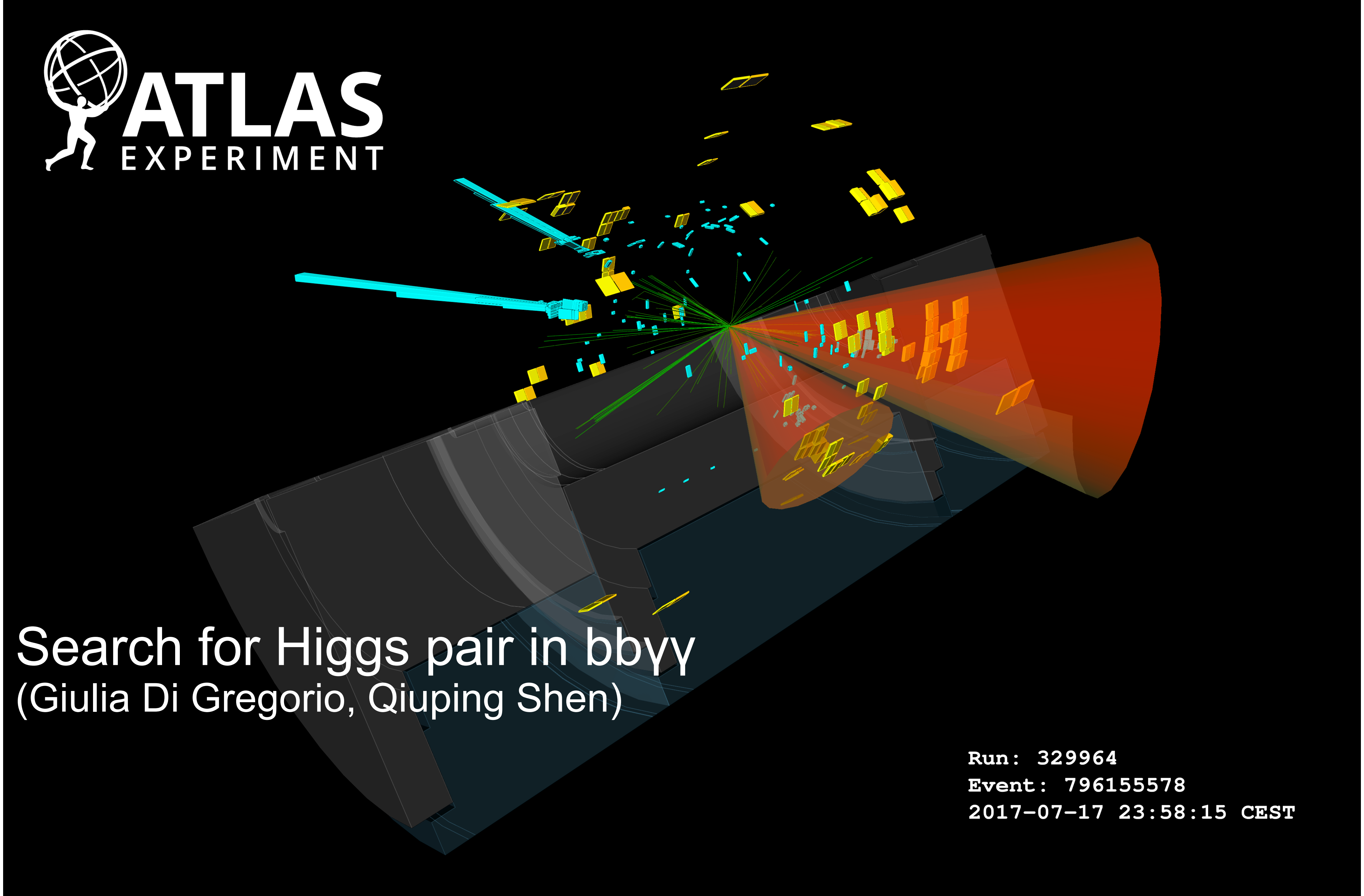








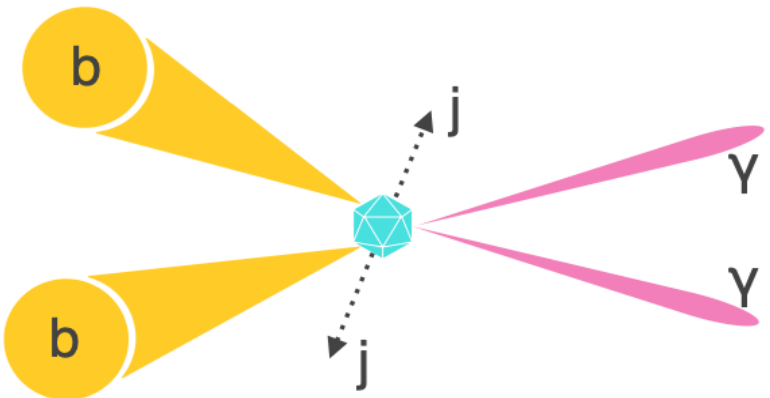
ATLAS
EXPERIMENT



Search for Higgs pair in bbγγ

(Giulia Di Gregorio, Qiuping Shen)

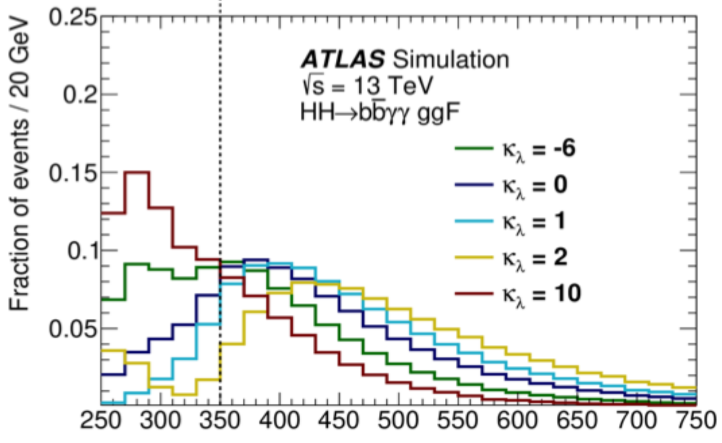
Event selection and categorization



VBF jet pair selected by a dedicated BDT

- Diphoton triggers
- 2 b-jets and 2 photons
  - $105 < m_{\gamma\gamma} < 160$ GeV
- Suppress $t\bar{t}H$ and $t\bar{t}$
  - Lepton (e, μ) veto
  - < 6 central jets

Targets BSM κ_λ | High mass sensitive for SM and BSM κ_{2V}

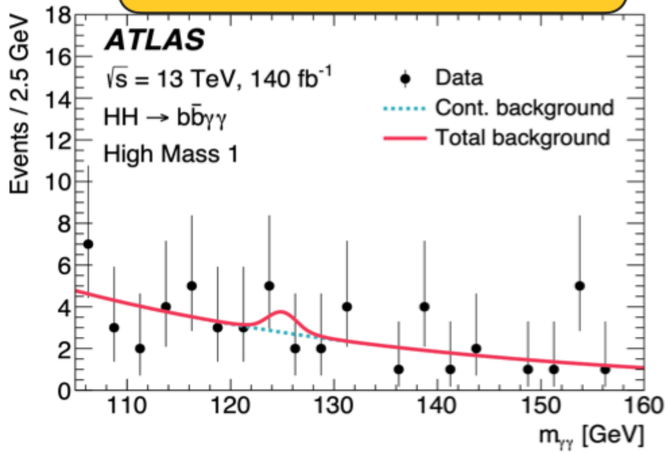


$m_{b\bar{b}\gamma\gamma} + (125 - m_{b\bar{b}}) + (125 - m_{\gamma\gamma})$ GeV

High mass BDT
3 categories defined by BDT score

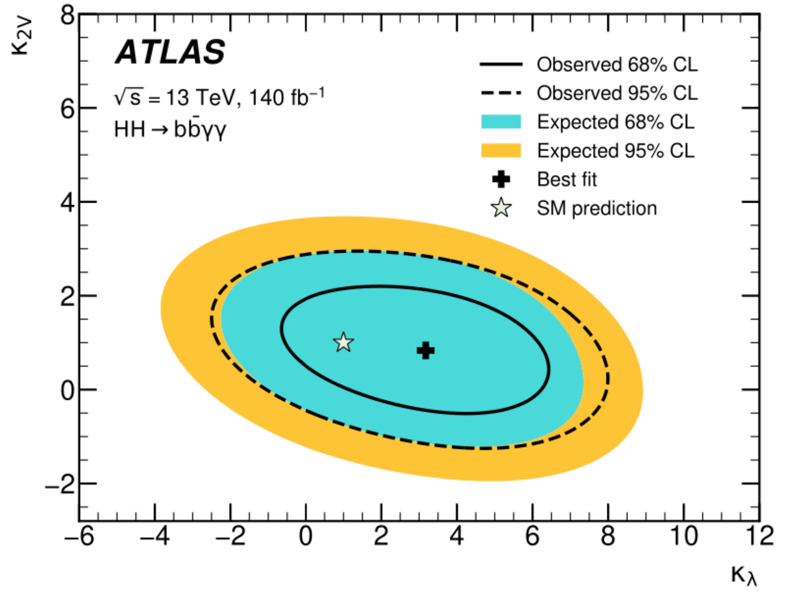
Low mass BDT
4 categories defined by BDT score

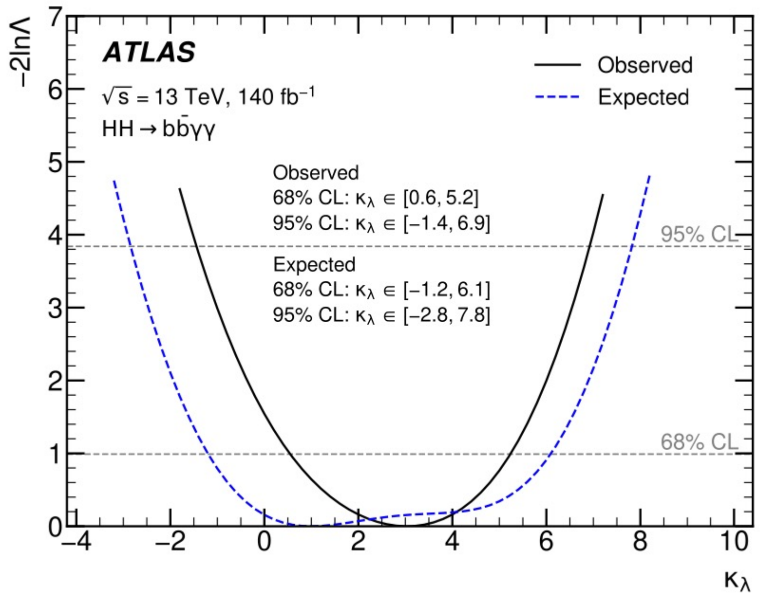
Fit 7 $m_{\gamma\gamma}$ spectra

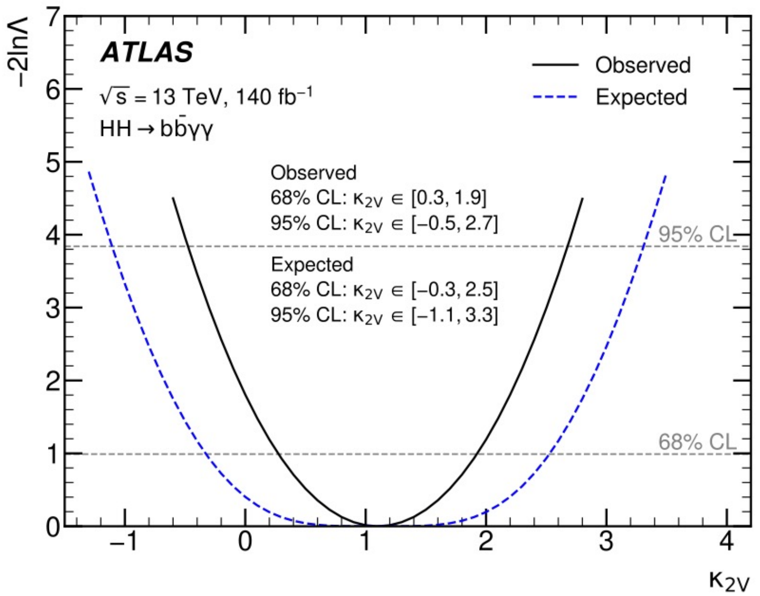


Results

- 68% and 95% CL likelihood contours in the κ_λ - κ_{2V} parameter space (top)
- Values of -2lnΛ for different κ_λ and κ_{2V} hypotheses obtained from fits to data and Asimov dataset (bottom)

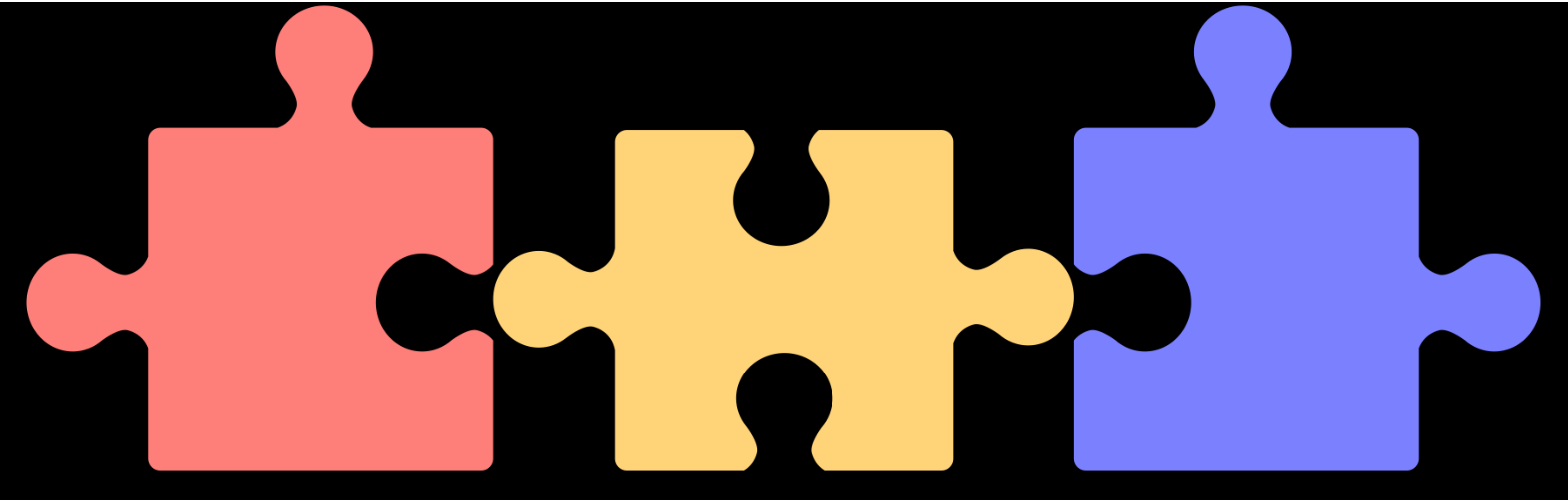






Combination of Higgs pair searches: Non-resonant

(Tong Li)



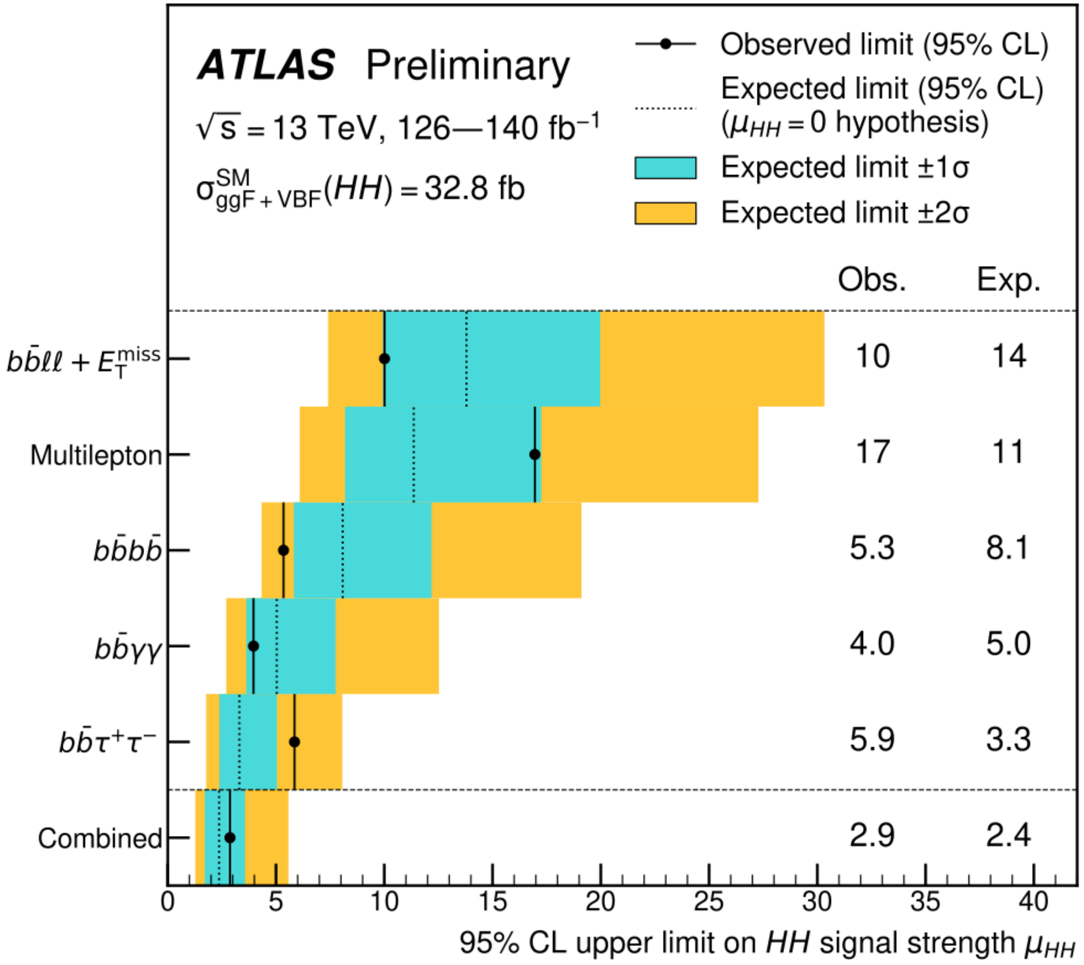
Combination results

➢ 95% CL limits on HH signal strength:

- μ_{HH} < 2.9 (2.4 exp)
  - μ_{ggF} < 2.9 (2.4 exp)
  - μ_{VBF} < 44.3 (47.5 exp)
- σ_{HH} < 85.8 (71.1 exp) fb

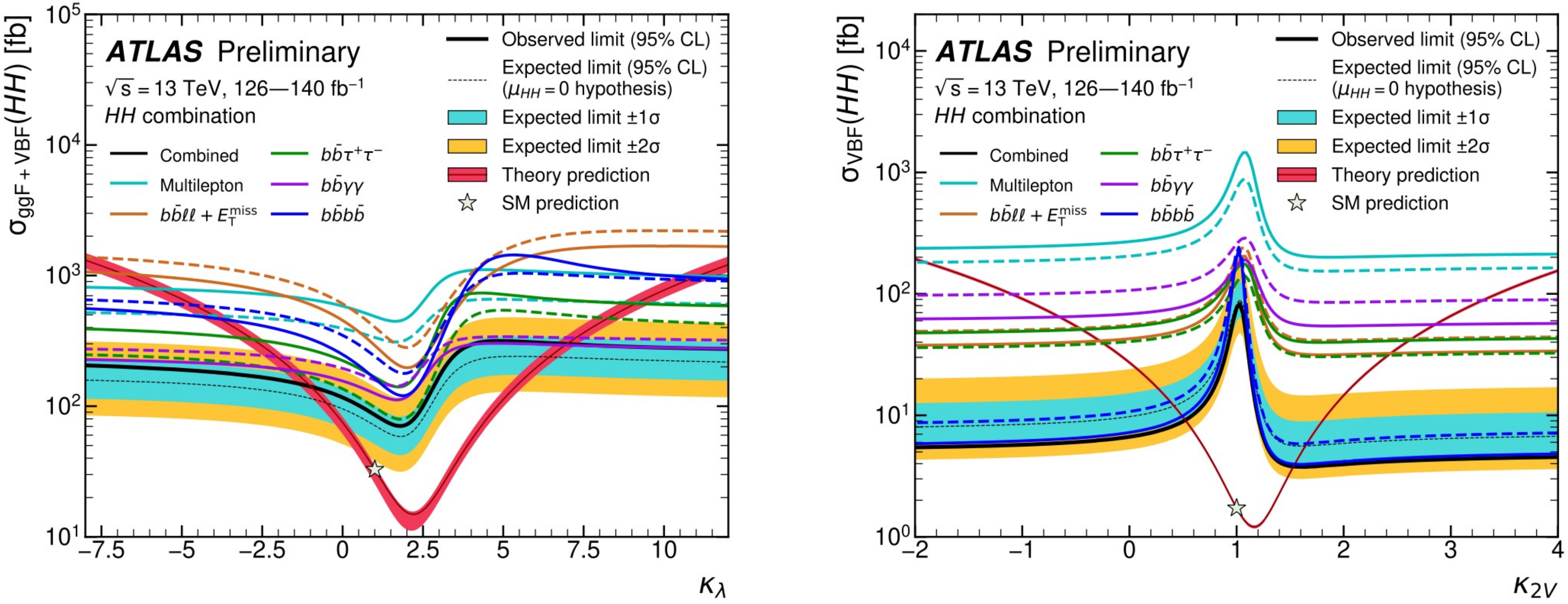
➢ Dominant uncertainties

- HH theory cross section uncertainty

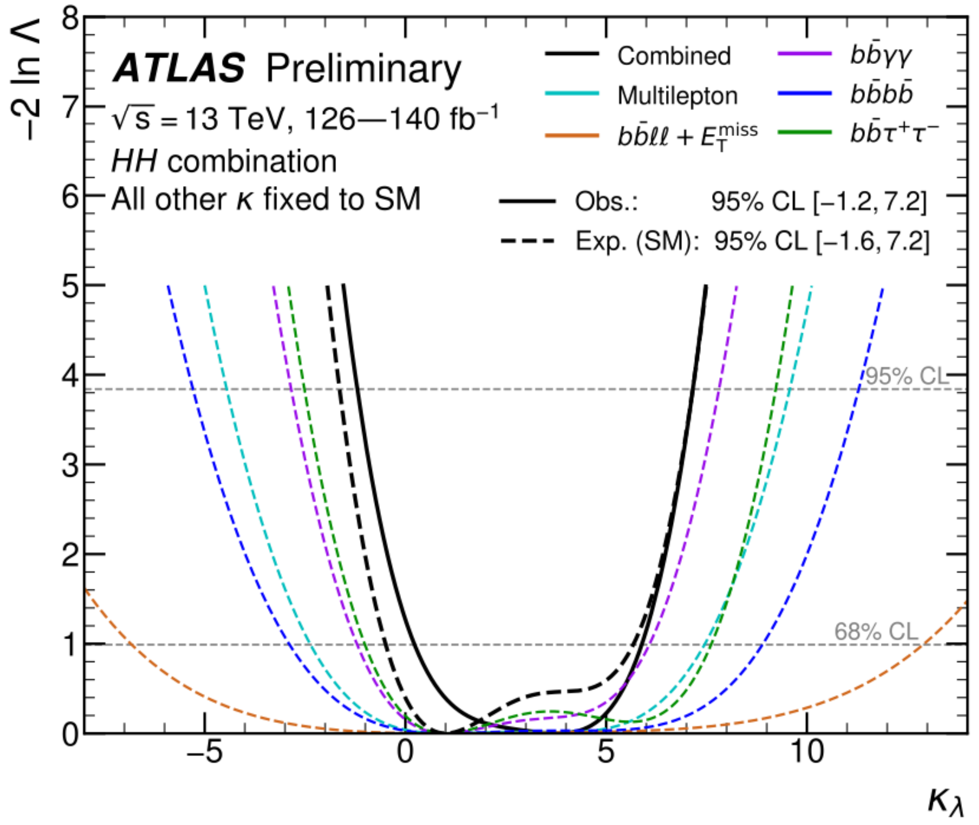


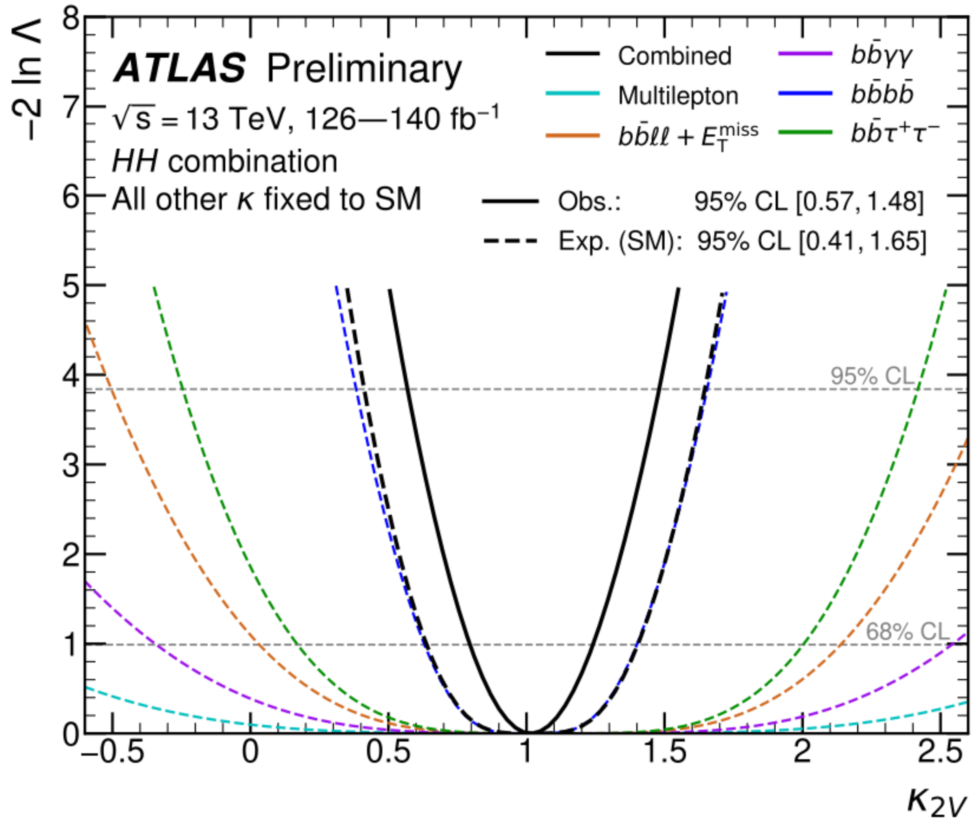
Combination results

- When κ_λ (κ_{2V}) moves away from SM, kinematics gets softer (harder)
  - Left: bbττ excellent performance at SM, degrading quickly in positive κ_λ
  - Right: bbγγ is not super sensitive in high kinematics regime



Combination results

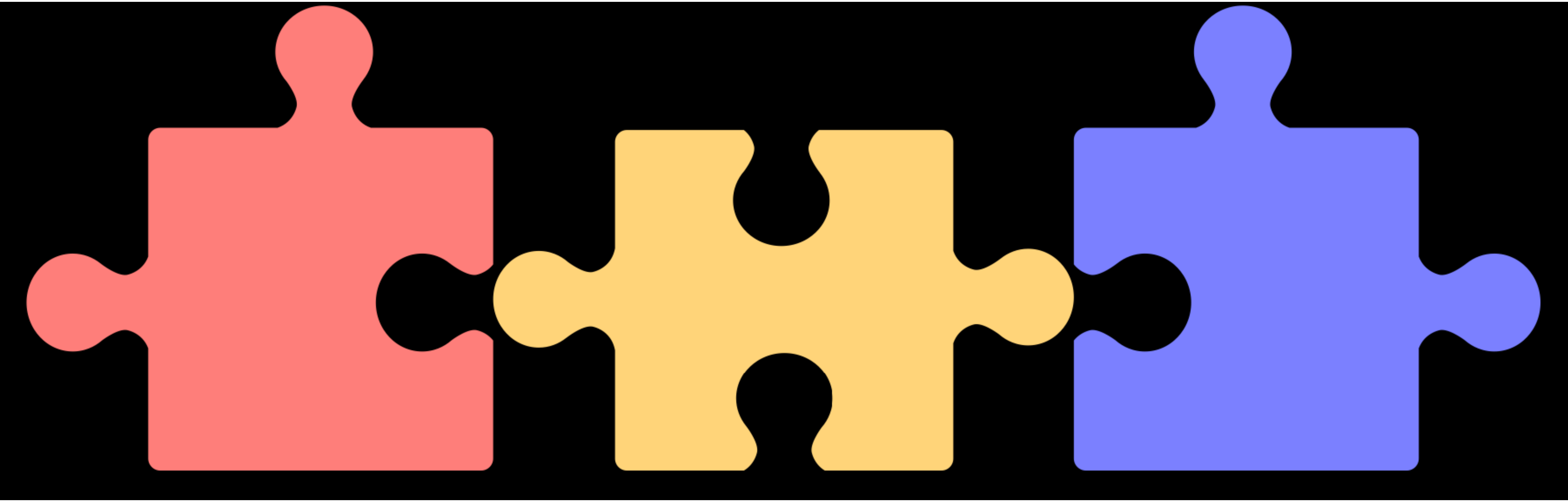




	Best fit	Obs 95% CL	Exp 95% CL	Leading channel
κ_λ	3.8	[−1.2, 7.2]	[−1.6, 7.2]	bbγγ, bbττ
κ_{2V}	1.0	[0.6, 1.5]	[0.4, 1.6]	bbbb (boosted)

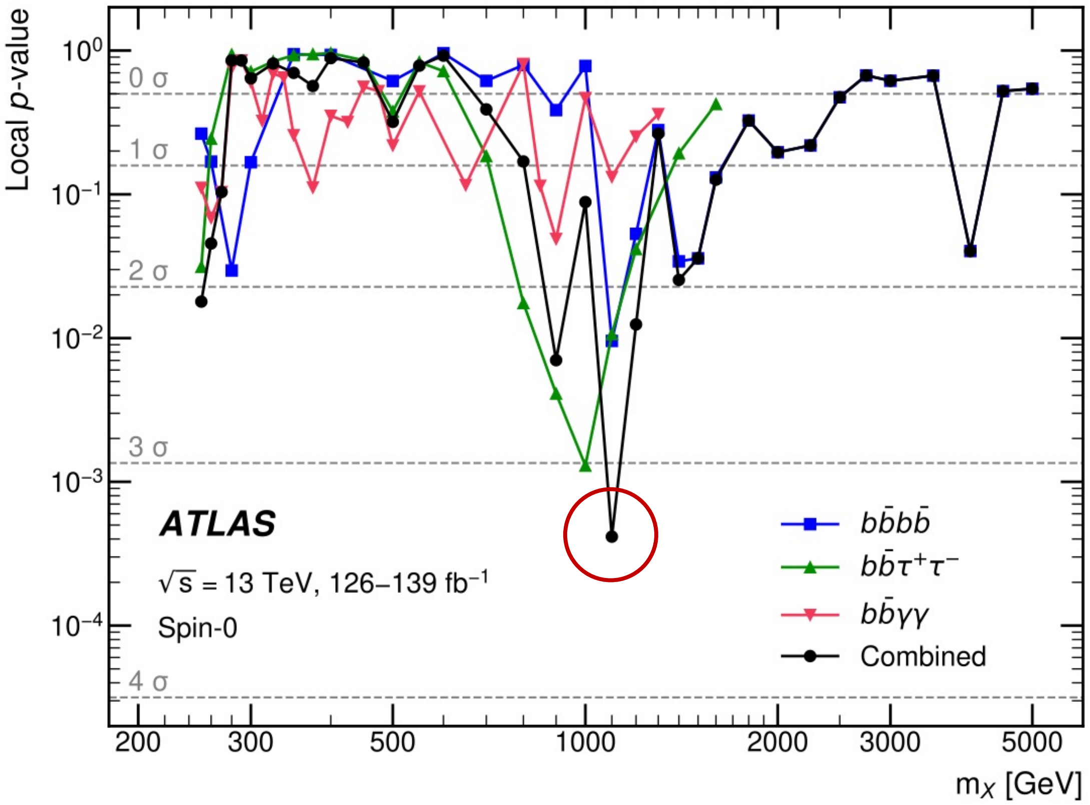
Combination of Higgs pair searches: Resonant

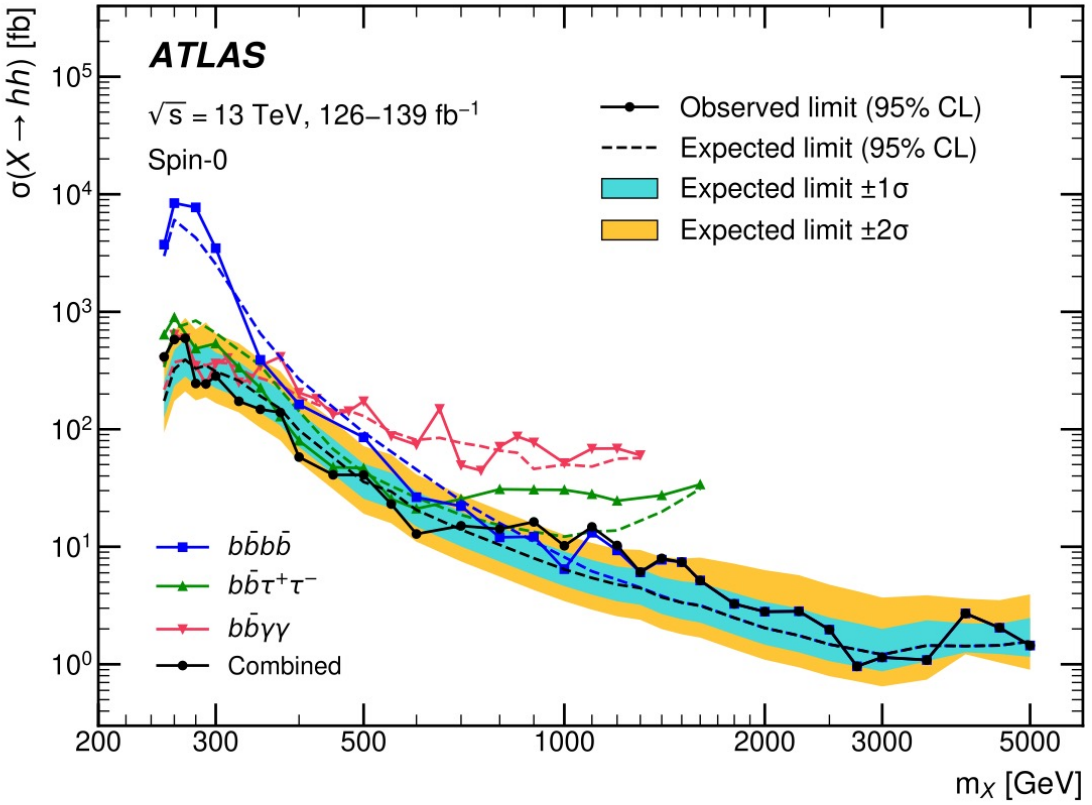
(Tong Li)



Combination results

- Found a small excess with combined local (global) significance of 3.2 σ (2.1 σ) at 1.1 TeV





Summary

- Searches for Higgs pair production are performed in various channels using ATLAS full Run2 dataset
- Compared with last round of results:
  - Up to 20% sensitivity improvement in $bb\tau\tau$ channel (previous results)
  - Up to 17% sensitivity improvement in $bb\gamma\gamma$ channel (previous results)

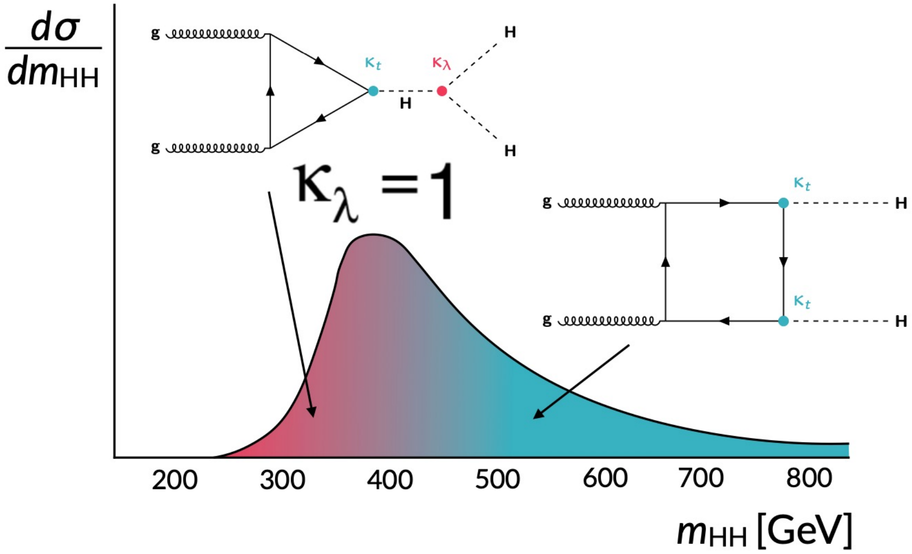
- By combining results from various decay channels, we continue to tighten the constraints on Higgs pair production
  - providing valuable insights into Higgs self-interaction, and potential new physics beyond the Standard Model

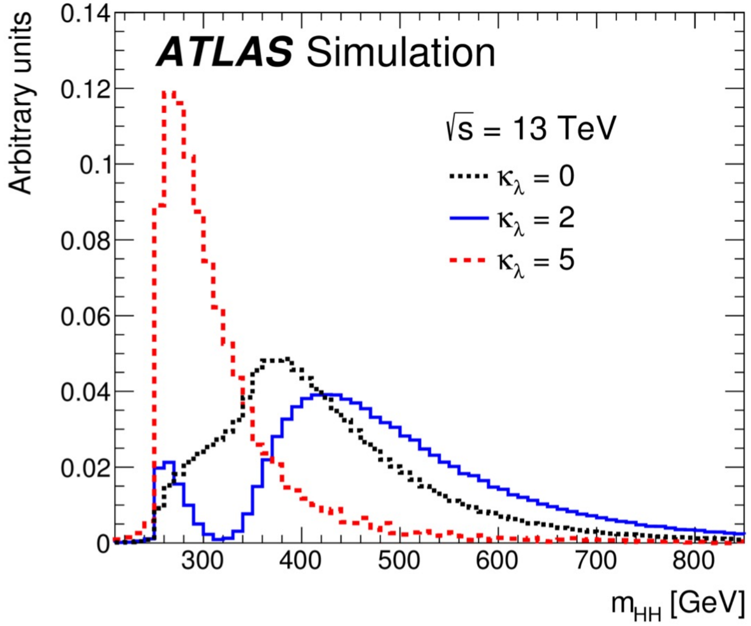
➢ The APC-SJTU team plays an important role in Higgs pair searches using Run2 dataset
  ➢ Will continue being active in Run3 analyses → Now working/starting to work using Run3 dataset (Cen Mo, Alexis Maloizel, Tong Li)

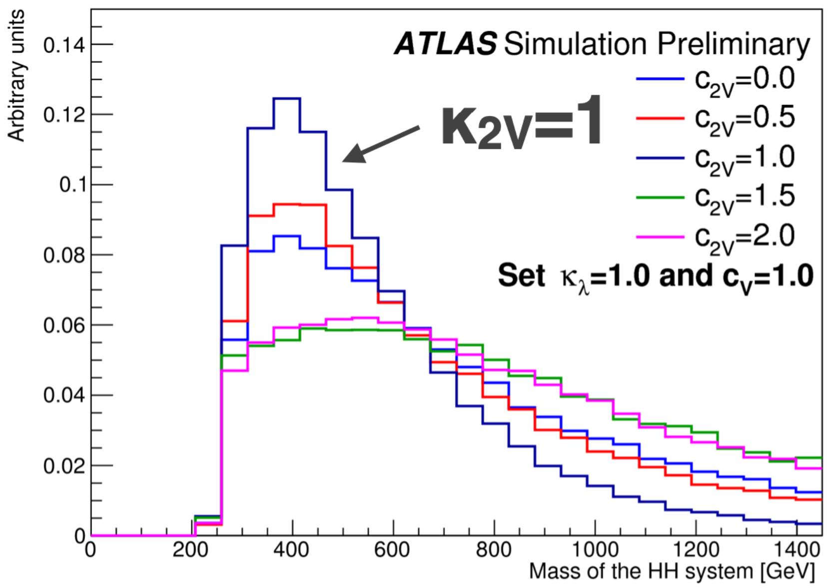
Back Up

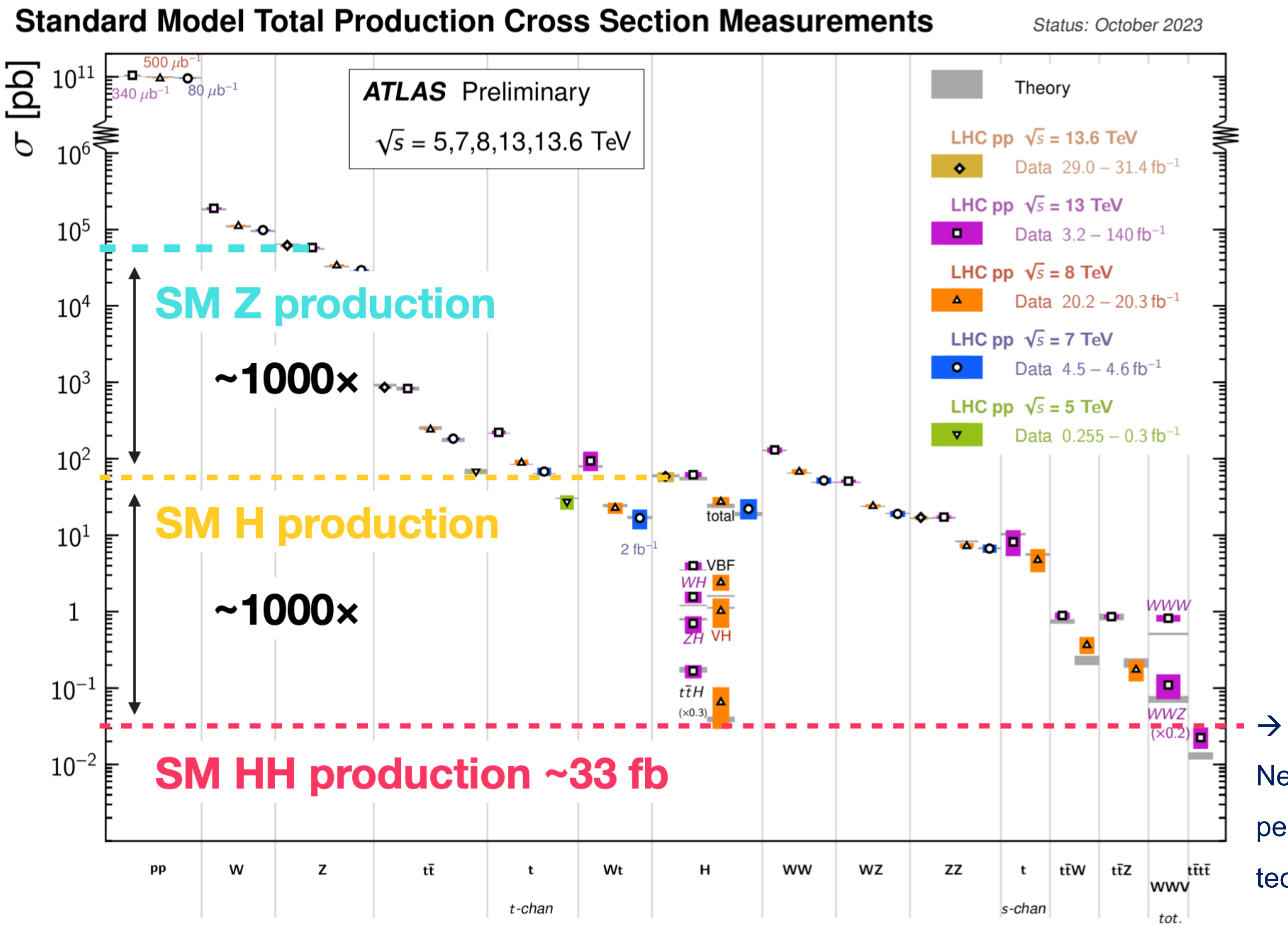
Challenges in Higgs pair search

- Destructive interference between triangle and box amplitudes
  - m_{HH} shape strongly depends on κ
- κ_λ ~ 2.4 max. destruction at m_{HH} ~ 350 GeV
- Soft kinematic distributions for large $|\kappa_\lambda|$
  - Decay production difficult to detect
- Hard kinematic distributions for large $|\kappa_{2V}|$
- ➢ Need excellent experimental performance and analysis techniques





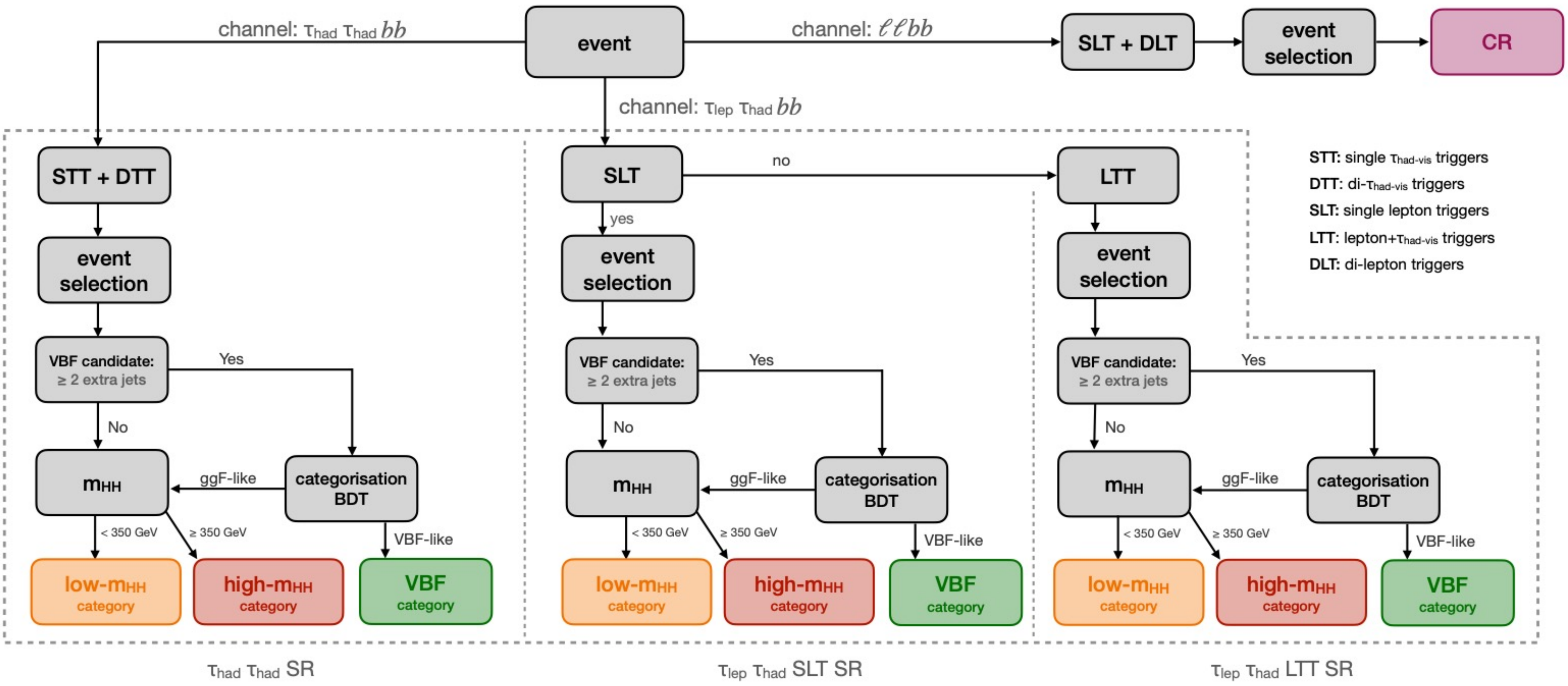




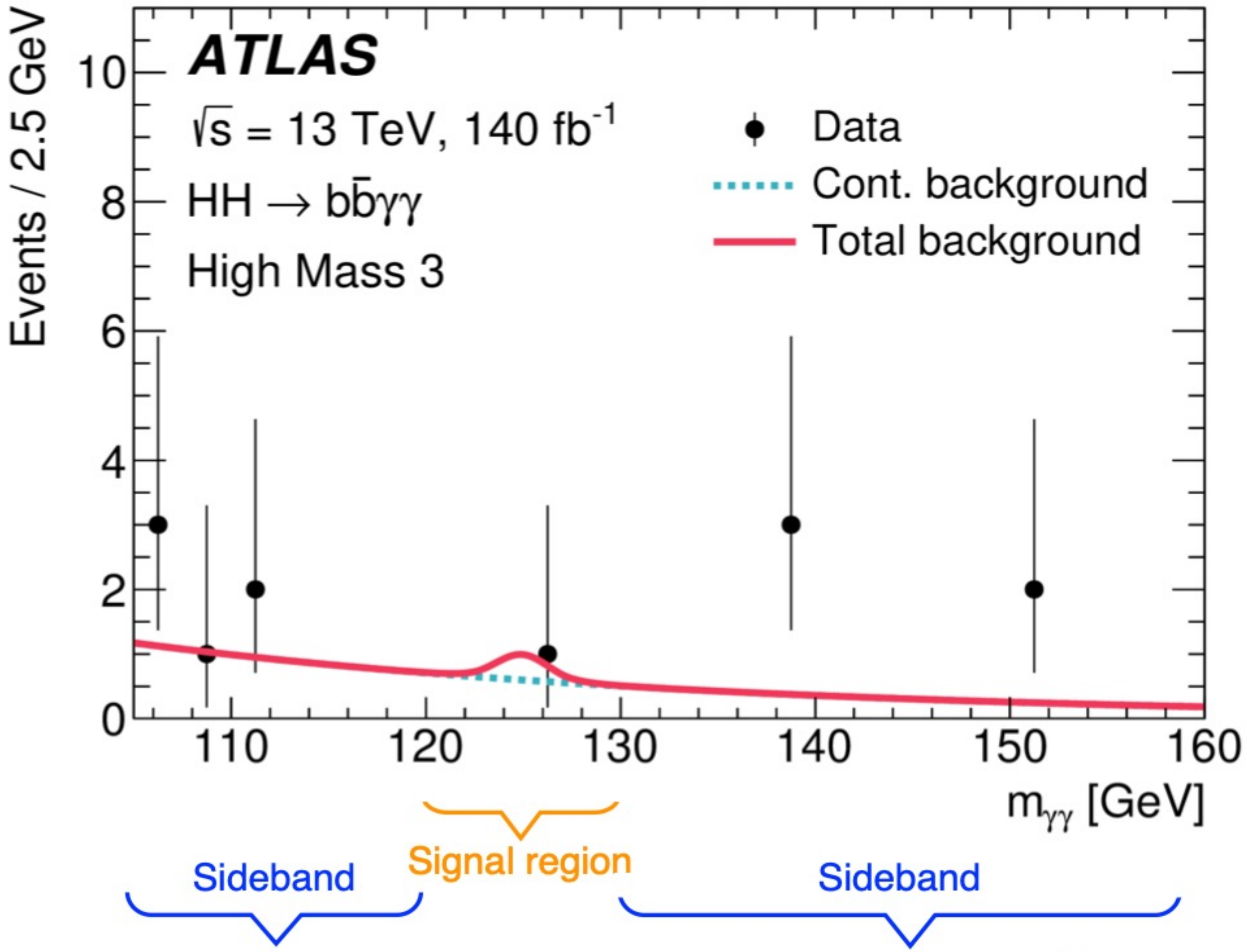
Need excellent experimental performance and analysis techniques

Event selection and categorization

- Targeting semi-leptonic ($\tau_{lep}\tau_{had}$) and fully hadronic ($\tau_{had}\tau_{had}$) di-tau final states



Signal and background modelling



HH and Single H

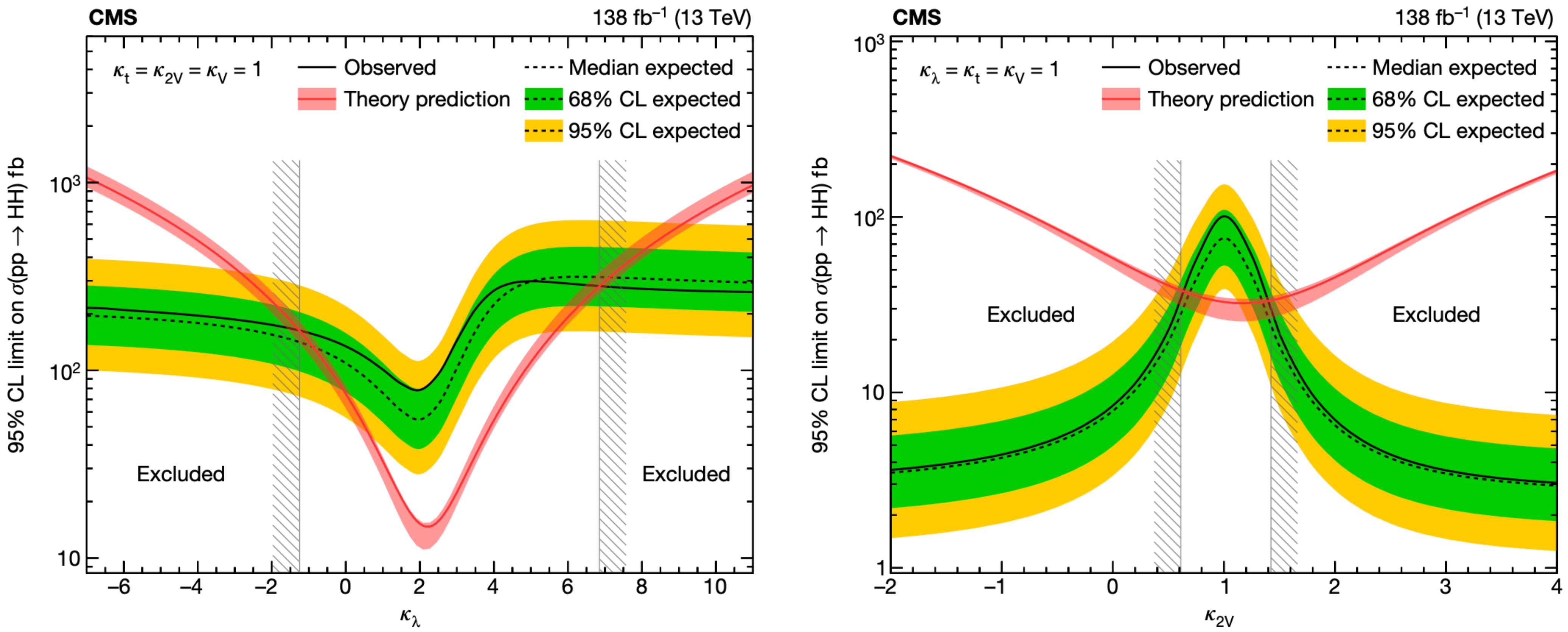
Modelled by double-sided Crystal Ball function. Parameters estimated from MC

γγ + something

Modelled using exponential function. Parameters derived from data sideband

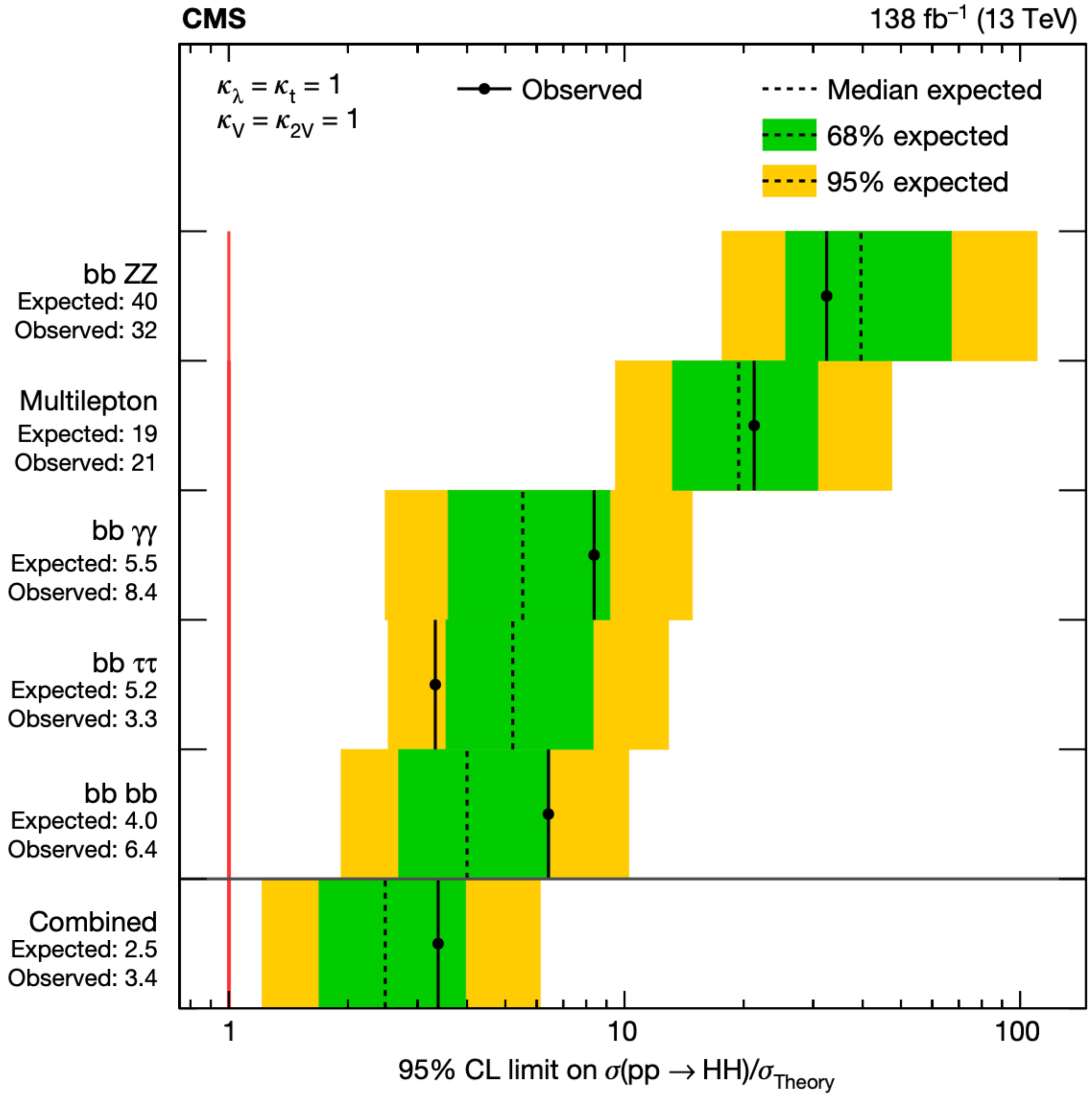
HH @ CMS

- [-1.24, 6.49]
- [0.67, 1.38]



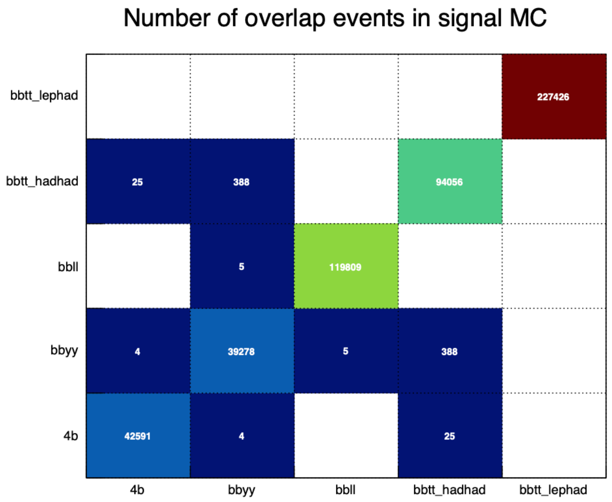
HH @ CMS

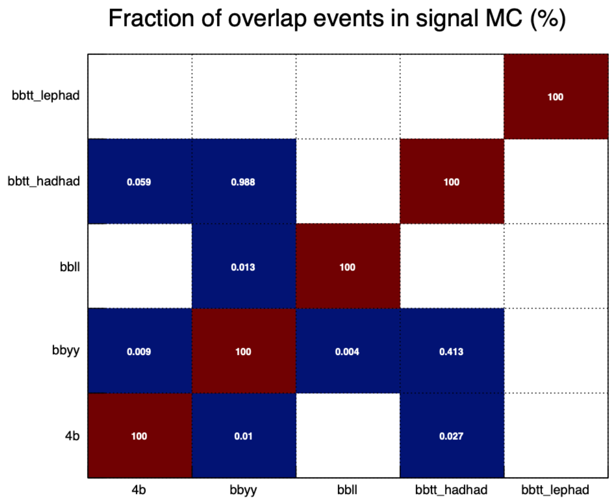
- Obs: 3.4
- Exp: 2.5



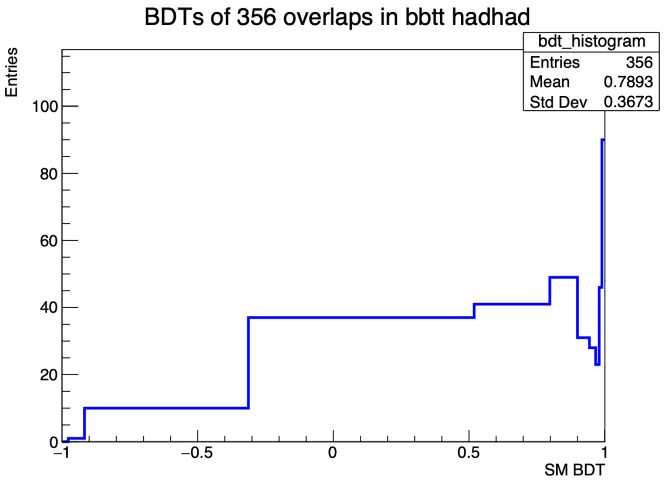
Overlap checks across channels

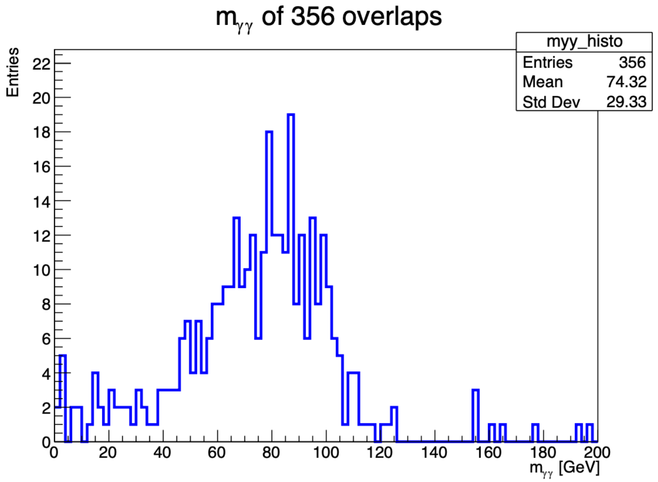
- ✓ HH → bbbb (resolved)
- ✓ HH → bbbb (boosted)
- ✓ HH → bbγγ
- ✓ HH → bbττ
- ✓ HH → bbll+MET
- ✓ HH → multi-lepton





- In a certain channel/analysis, the regions (signal, control) are orthogonal





- However, very few events might be selected by 2 or more channels simultaneously
  - Need to check and quantify the impact of potential overlap

Statistical analysis model

- The combination of various channels is performed by constructing a combined likelihood function that considers data, models and systematic uncertainties from all channels:

$$\mathcal{L}(\mathcal{D},\mathcal{G}|\mu,\alpha) = \prod_{c\in\mathbb{C}} \text{Pois}(n_c|\nu_c(\mu,\alpha)) \prod_{e=1}^{n_c} f_c(x_{ce}|\mu,\alpha) \times \prod_{p\in\mathbb{S}} f_p(a_p|\alpha_p)$$

- The profile likelihood ratio is constructed as:

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(0,\hat{\theta}(0))} & \hat{\mu} < 0, \\ \frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu},\hat{\theta})} & \hat{\mu} \geq 0. \end{cases}$$

- The test statistic for limits setting is:

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} = \begin{cases} -2\ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(0,\hat{\theta}(0))} & \hat{\mu} < 0, \\ -2\ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu},\hat{\theta})} & 0 \leq \hat{\mu} \leq \mu, \\ 0 & \hat{\mu} > \mu. \end{cases}$$

Systematic uncertainties and correlation

- Common sources are correlated except if:
  - Different object calibrations used
  - Different post fit profilings from different phase space

Final object reconstructions	bbbb	bbττ	bbγγ	$bb\ell\ell+E_T^{miss}$	multilepton
Luminosity/pileup	✔	✔	✔	✔	✔
Jets	✔	✔	✔	✔	✔
b-tagging	✔	✔	✔	✔	✔
Boosted jet/b-tag	✔				
Electrons		✔		✔	✔
Muons		✔		✔	✔
Taus		✔			✔
Photons			✔		✔
E_T^{miss}		✔	✔	✔	✔

Systematic uncertainties and correlation

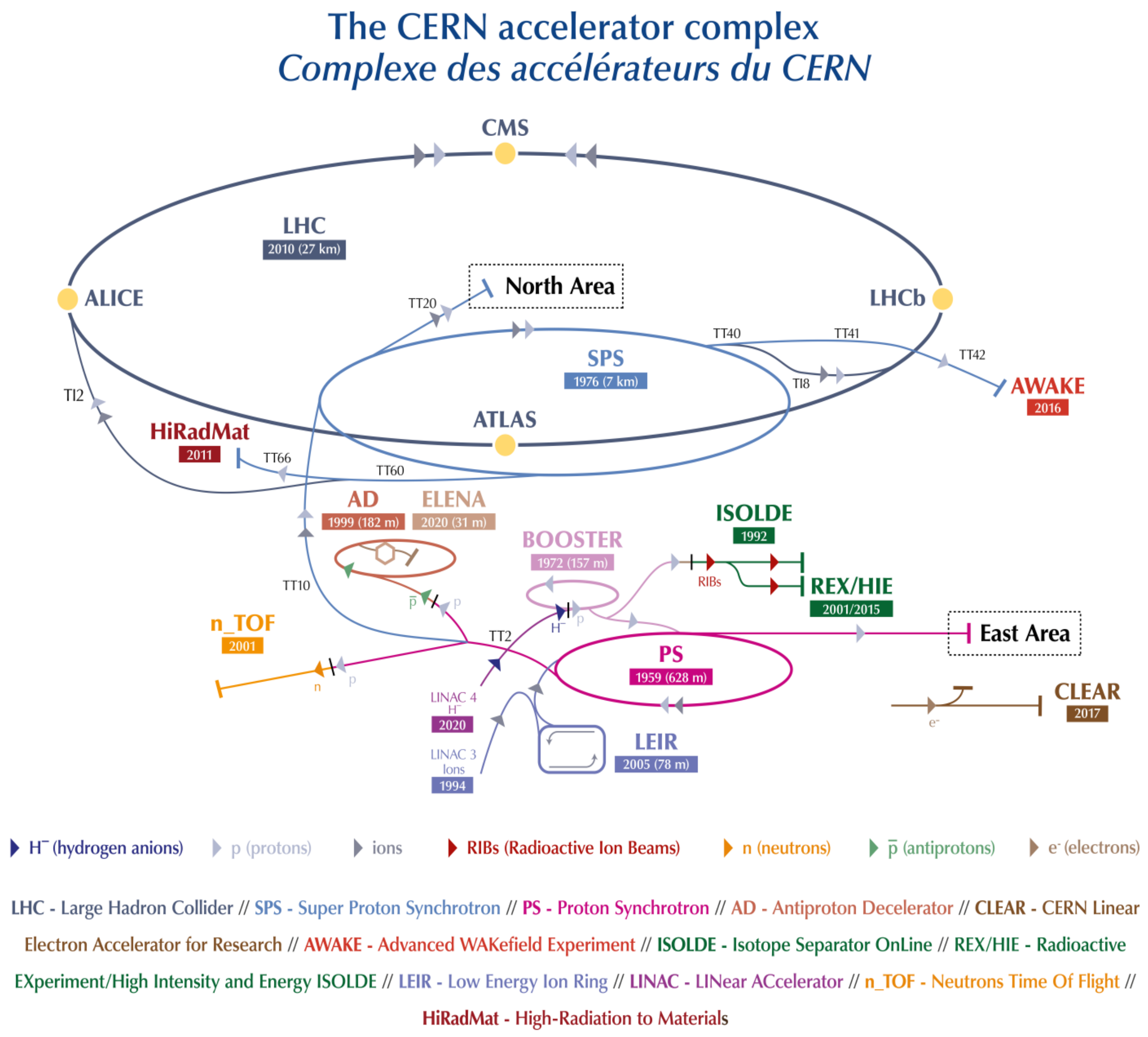
HH signal modelling	bbbb	bbττ	bbγγ	$bb\ell\ell+E_T^{miss}$	multilepton
QCD scale + m_{top}	✔	✔	✔	✔	✔
PDF + α_S	✔	✔	✔	✔	✔
H branching ratio	✔	✔	✔	✔	✔
Parton shower	✔	✔	✔	✔	✔
κ interpolation	✔	✔	✔	✔	
Bkg. modelling	**bbbb**	**bbττ**	**bbγγ**	**$bb\ell\ell+E_T^{miss}$**	**multilepton**
Single Higgs		✔	✔		✔
Top quark		✔		✔	
Z + jets		✔		✔	✔
Diboson		✔			✔
Specific per chan.	✔	✔	✔	✔	✔

empty: unavailable or negligible

- Dominant uncertainties
  - HH cross section theory calculation QCD scale + m_{top} (prefit $^{+6\%}_{-23\%}$ on ggF HH)
  - Normalisation of single H plus heavy-flavour jets on ggF (prefit 100% on ggF H yields)
  - These two contribute most to the correlation

Large Hadron Collider (LHC)

- Located at CERN near Geneva, LHC is the world's largest and most powerful particle accelerator
- Consists of a 27 km ring of superconducting magnets with multiple accelerating structures
- Aims to explore the fundamental forces and particles that make up the universe
- Designed to collide protons at energies of up to 14 TeV
  - 7 (8) TeV in Run1, 13 TeV in Run2
  - 13.6 TeV now in Run3
- 4 major experiments: ATLAS, CMS, ALICE, and LHCb



ATLAS detector

- A Toroidal LHC ApparatuS (ATLAS)
- General-purpose detector designed mainly to search for the Higgs boson and new physics
- With diameter of 25 meters and length of 44 meters

Inner detector

- Tracks and momentum of charged particles

Electromagnetic Calorimeter

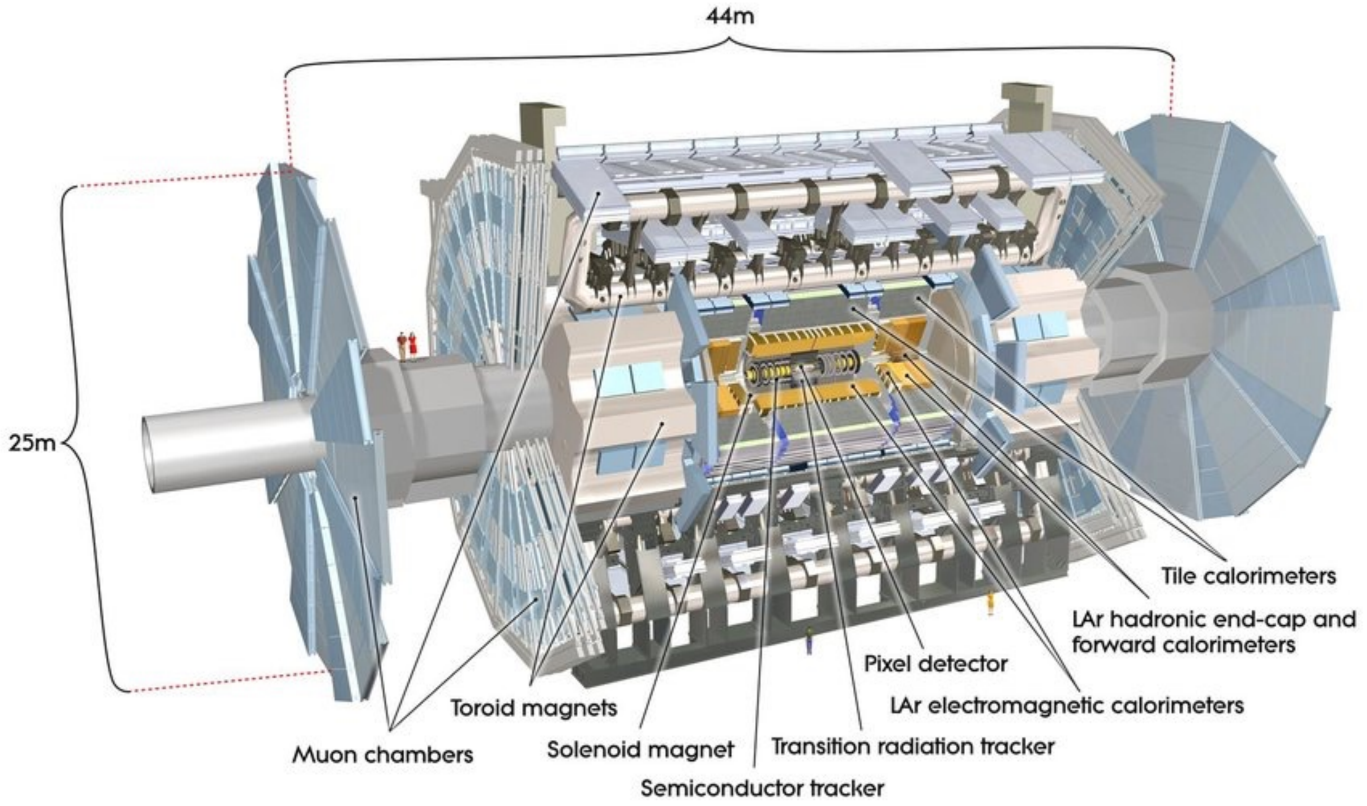
- Energy of electrons and photons

Hadronic Calorimeter

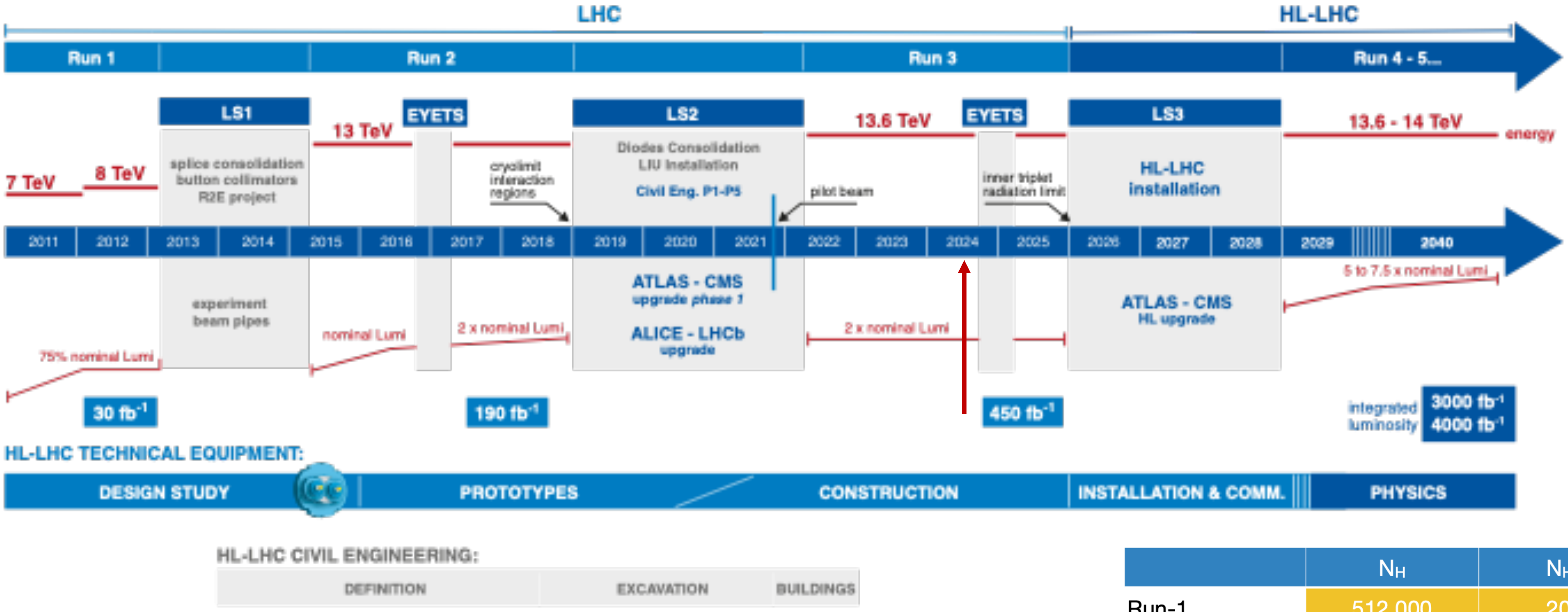
- Energy of hadrons

Muon spectrometer

- Momentum of muons



LHC / HL-LHC Plan



	N_H	N_{HH}
Run-1	512,000	200
Run-2	6,800,000	4,300
Run-3*	7,700,000	5,000
HL-LHC*	165,000,000	110,000

**estimated*