Di-Higgs physics at ATLAS

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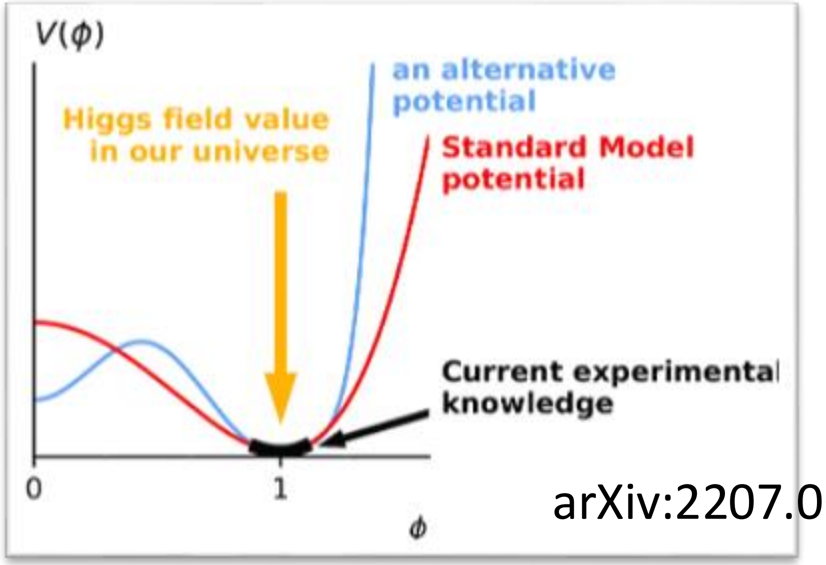
Nature of EWSB

- We have no idea on the thermal history of the EW symmetry breaking



arXiv:2207.00478

- SM assumed simplest form

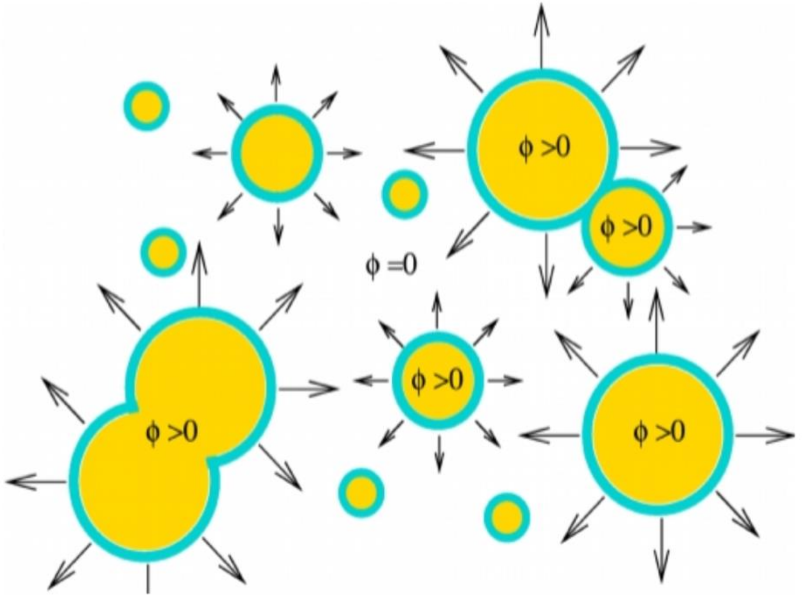
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

- Nature can be more complicated

$$' = V + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

- Sakharov's Conditions for Baryon-gensis
  - B Violation
  - C/CP Violation
  - **Departure from Thermal Equilibrium**

1st order or **2nd order** Phase Transition?

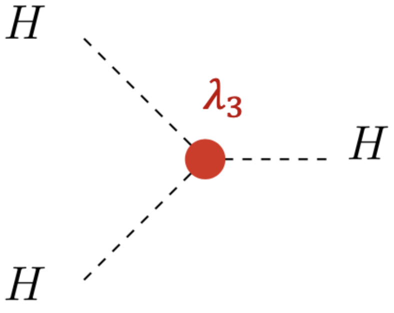


Probe Higgs potential

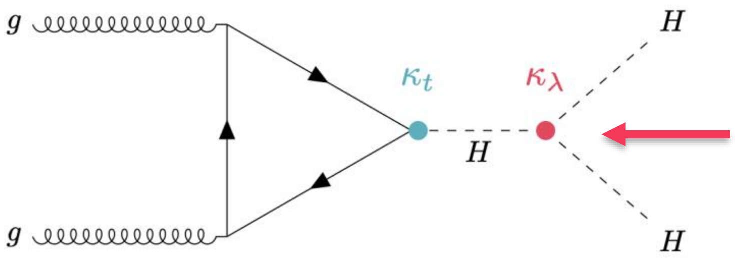
- Expand Higgs potential about the minimum

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4 + O(H^5) \qquad \lambda_3 = \lambda_4 = \lambda_{SM} = \frac{m_H^2}{2v^2} \qquad \lambda_i = 0 \text{ for } i \geq 5$$

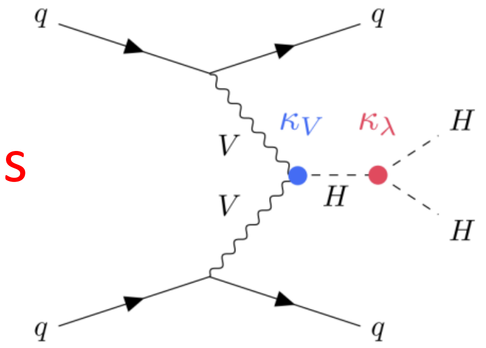
- Multi-Higgs production is a direct probe of Higgs potential!



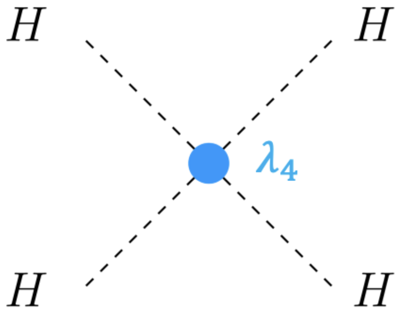
Di-Higgs production



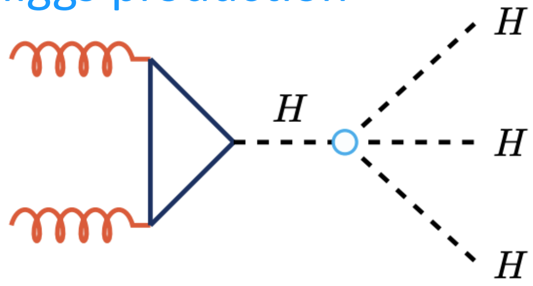
Defined as λ_3/λ_{SM}



$\sigma_{hh} \simeq 31 fb$ at 13TeV



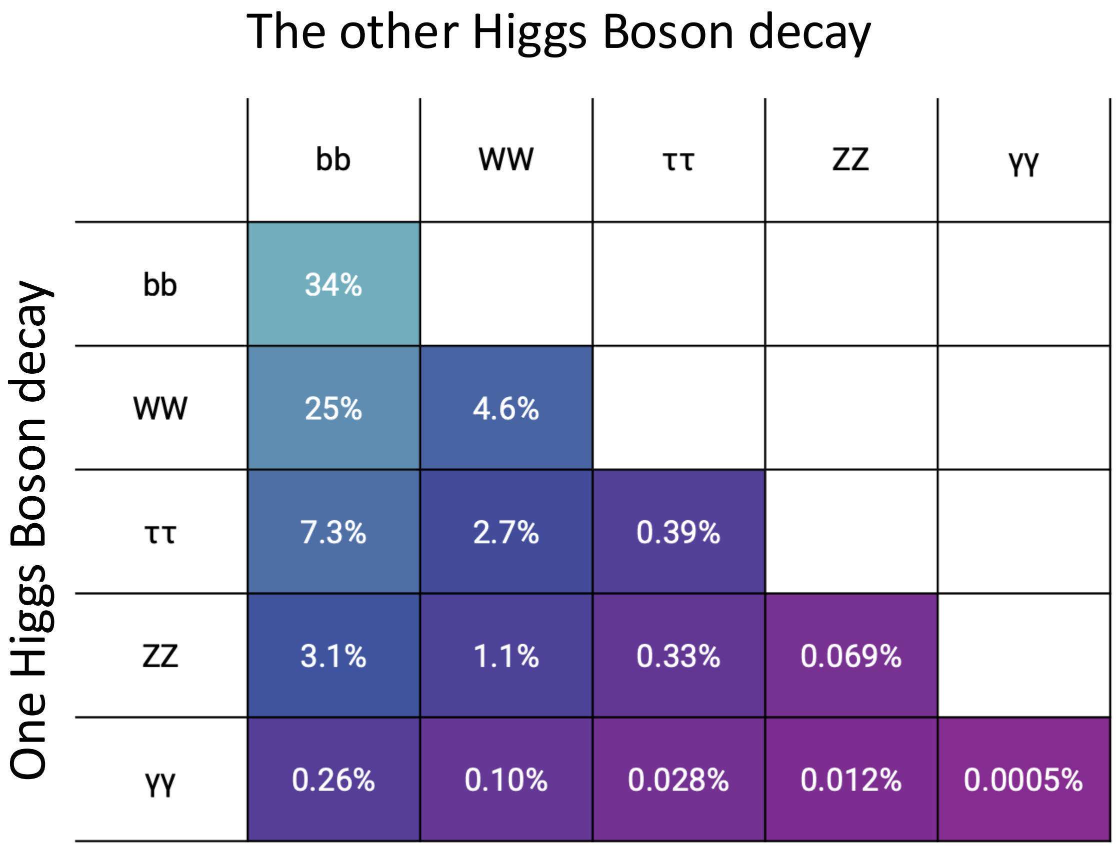
Tri-Higgs production



- HHH is far beyond the reach of LHC

HH Decays

- 5 major analyses channels
  - bbbb (resolved(PRD 108 (2023) 052003), boosted VBF (PLB 858 (2024) 139007))
  - bb$\tau\tau$ (PRD 110 (2024) 032012)
  - bb$\gamma\gamma$ (JHEP 01 (2024) 066)
  - bbll+MET (JHEP 02 (2024) 037)
  - Multi-lepton (JHEP 08 (2024) 164)
- Combination: PRL 133 (2024) 10, 101801, PRL 132 (2024) 231801
- **Covers almost all decay modes!**



The other Higgs Boson decay

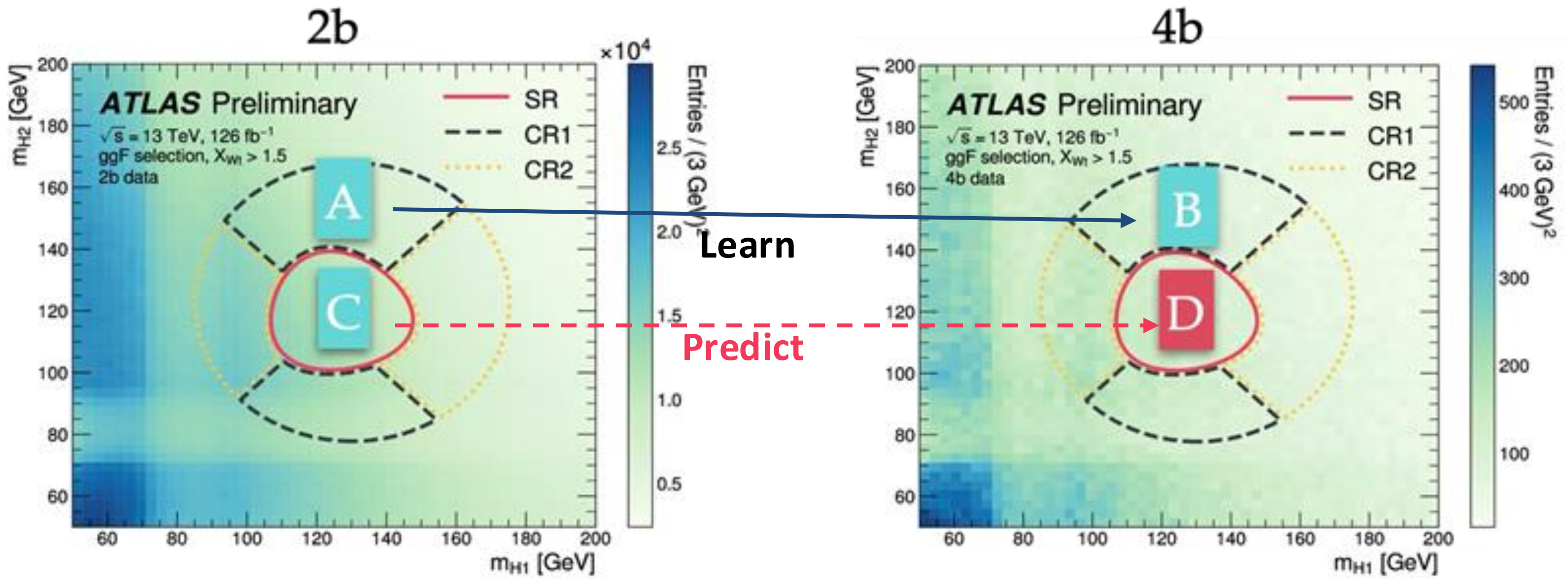
One Higgs Boson decay

	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%

HH→bbbb

- Largest branching ratio: 34%, suffers from huge backgrounds
  - Main backgrounds: QCD multi-jets, top quark pair
- Analysis strategy
  - ≥4 b quark jets, two categories: ggF and VBF (m_{jj} > 1 TeV and $\Delta\eta_{jj}$ > 3)
  - Utilize two Higgs bosons invariant mass
  - Data-driven background modeling with machine learning techinique

$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\,\mathrm{GeV}}{0.1 m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\,\mathrm{GeV}}{0.1 m_{H2}}\right)^2}$$



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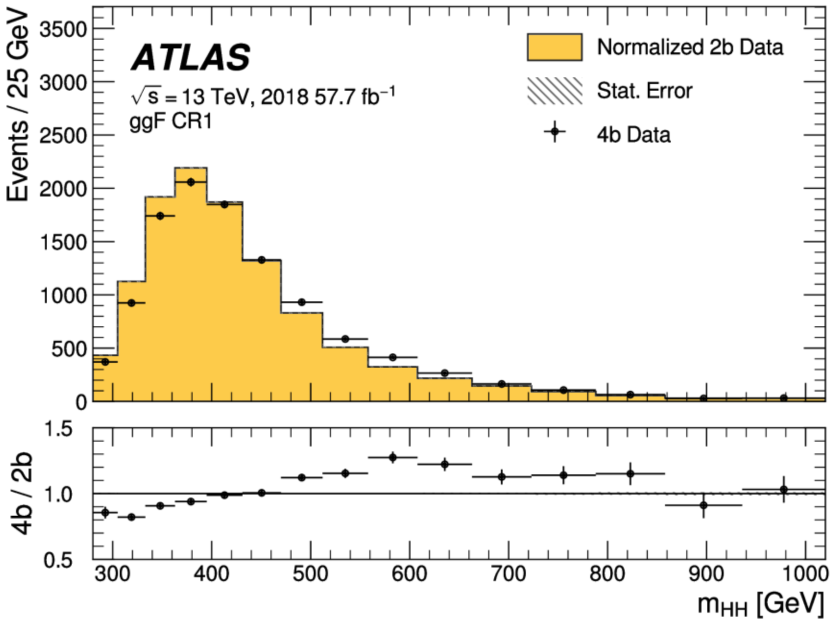
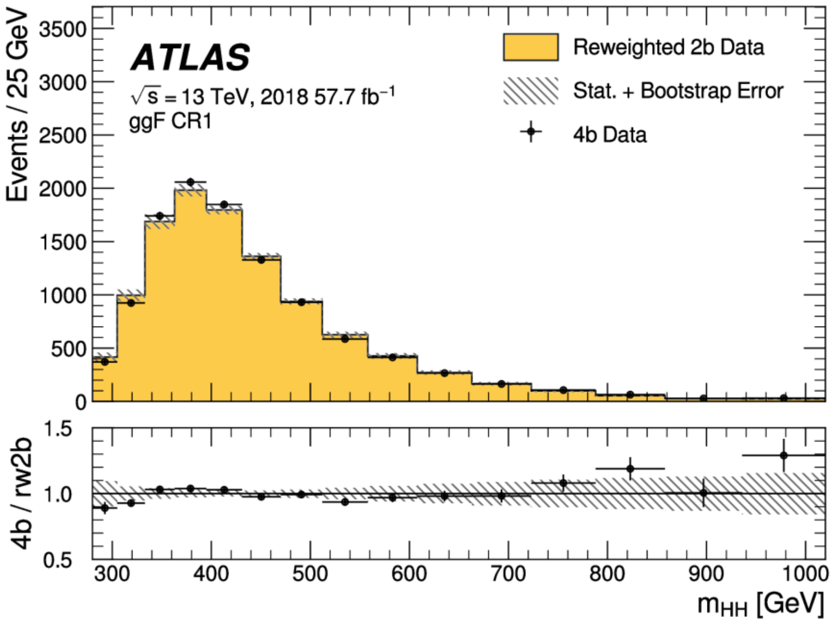
Before Correction



After Correction



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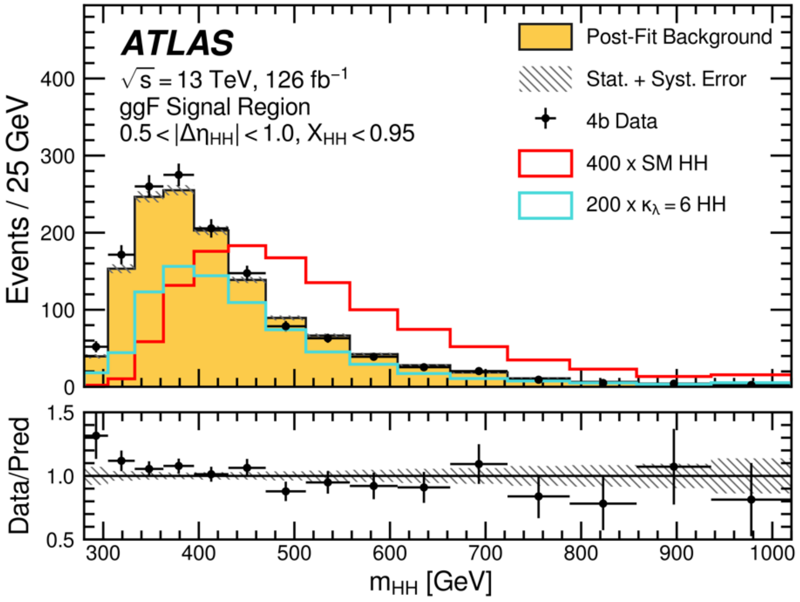
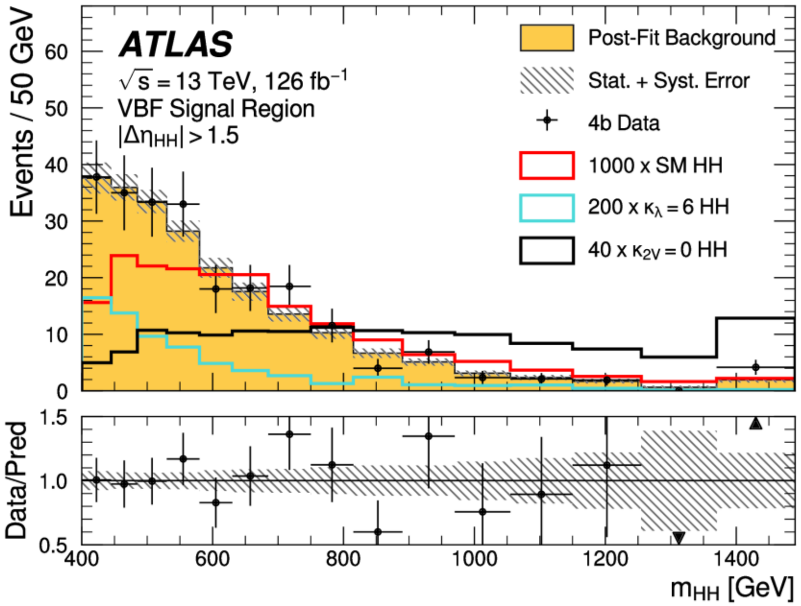
ggF
Signal Region

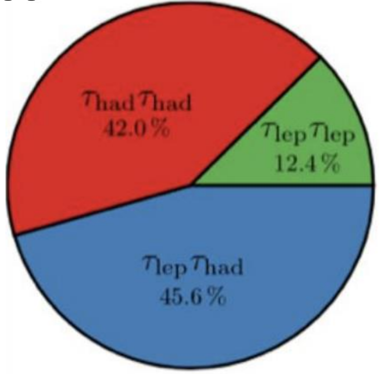


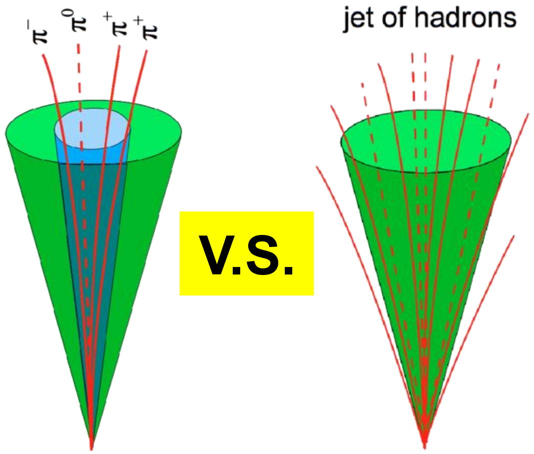
VBF
Signal Region

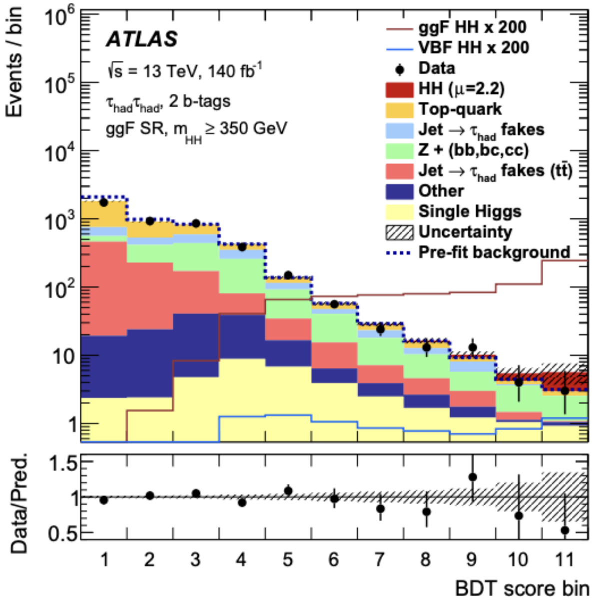


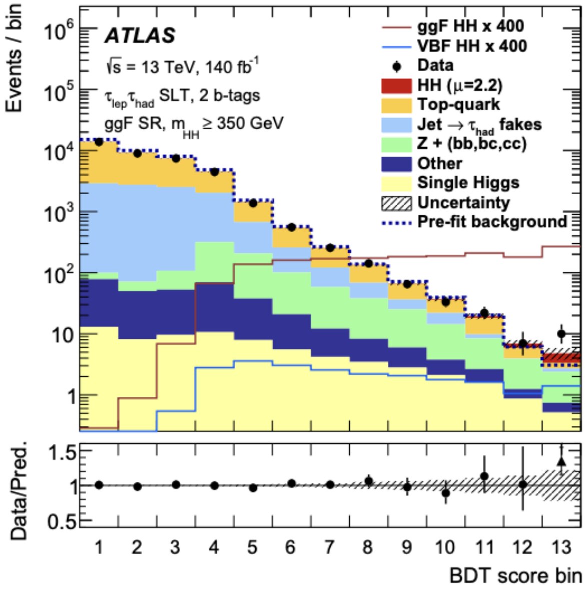
HH→bb$\tau\tau$

- Moderate branching ratio (7.3%), less backgrounds. **Best sensitivity to SM HH**
- Two sub-channels for different $\tau\tau$ decay modes: $\tau_{had}\tau_{had}, \tau_{lep}\tau_{had}$
- Main backgrounds
  - Real tau, e.g. ttbar and Z+HF, modeled by MC, with normalization correction from the control regions
  - Fake τ_{had} background estimated data-drivenly





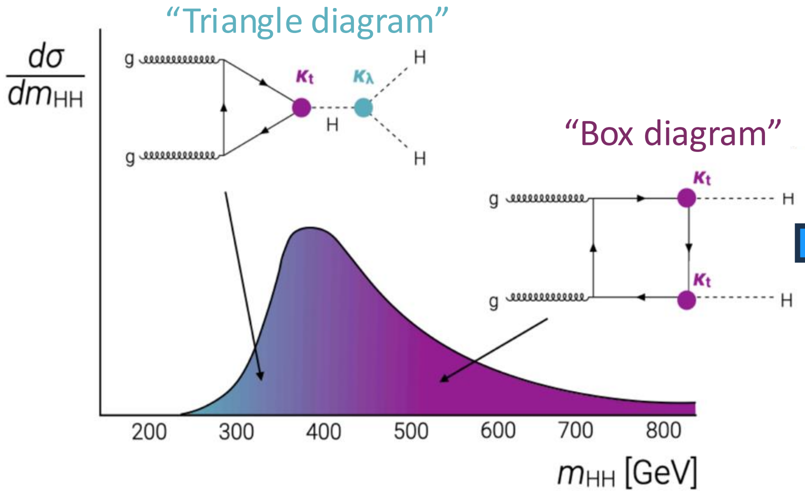


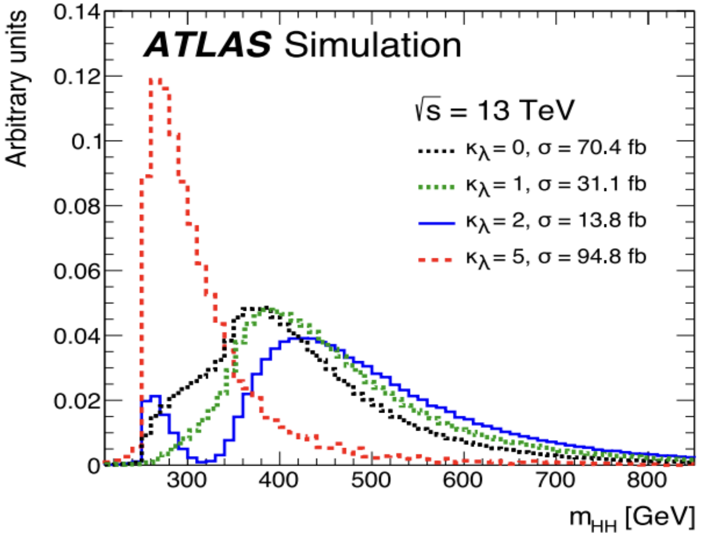


HH → $bb\gamma\gamma$

- Very small branching ratio (0.26%), clean final state
  - Excellent $m_{\gamma\gamma}$ and $m_{bb\gamma\gamma}$ resolution, strongest constraint at high κ_λ
- Two HH Feynman diagrams contribute to different kinematic region

m_{HH} shape change with κ_λ





Need attention to softer kinematic events for better constraints on κ_λ

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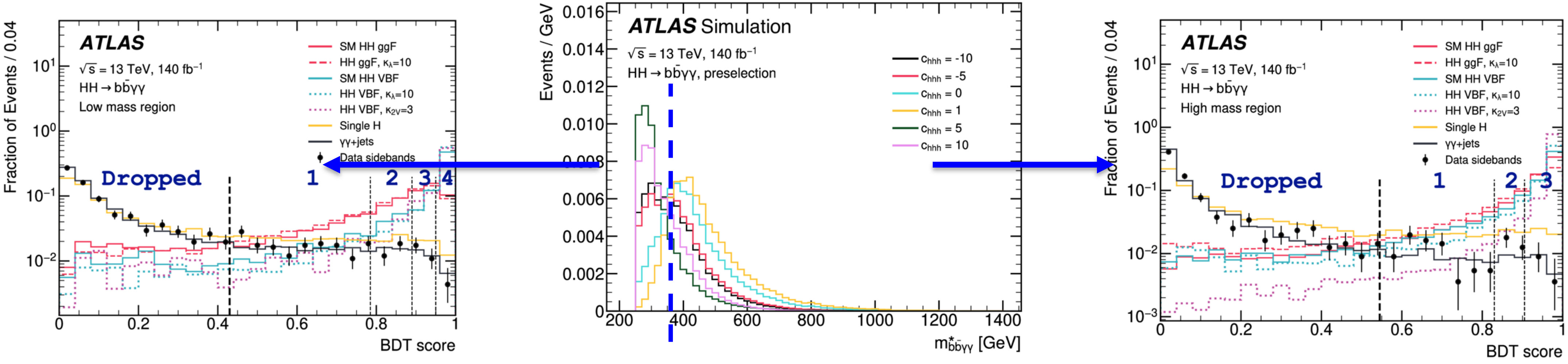
- Two HH Feynman diagrams contribute to different kinematic region
  - **Categorized by $\boldsymbol{m^*_{bb\gamma\gamma}}$ and BDT**

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\ \mathrm{GeV}) - (m_{\gamma\gamma} - 125\ \mathrm{GeV})$$



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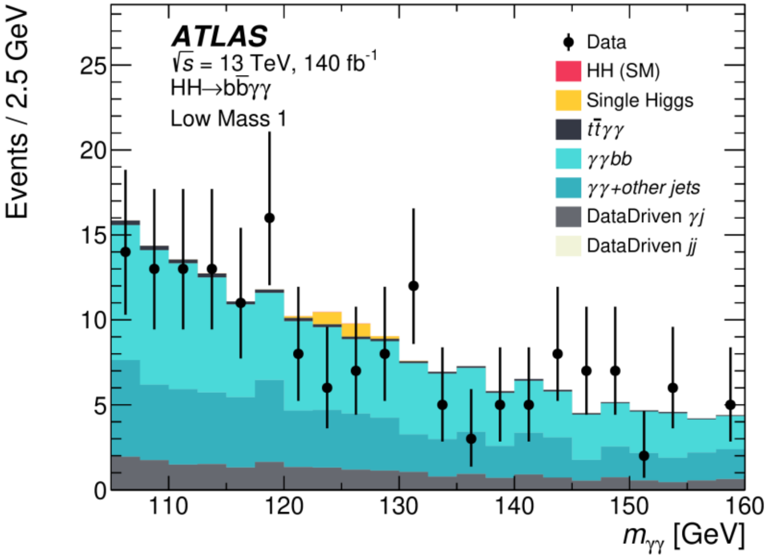
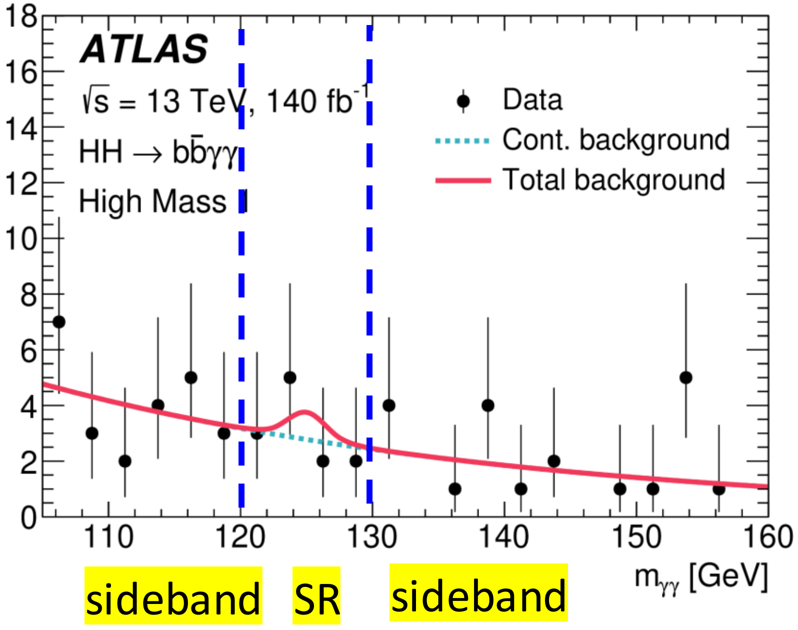
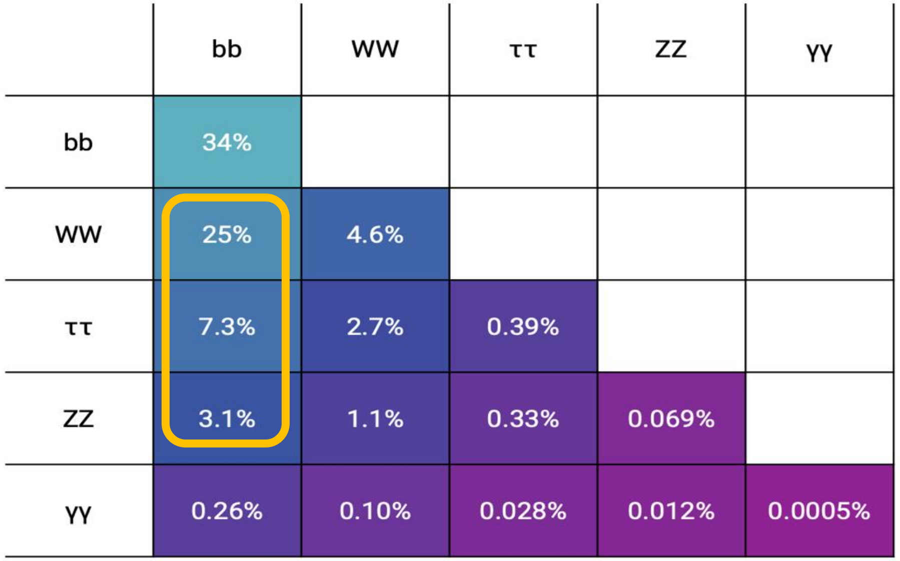




- Final discriminant $m_{\gamma\gamma}$, background modelled using exponential function in data sideband

HH → bbll+MET

- Leptonic decay of $WW, \tau\tau, ZZ$ (Branching ratio ~ 2.9%)



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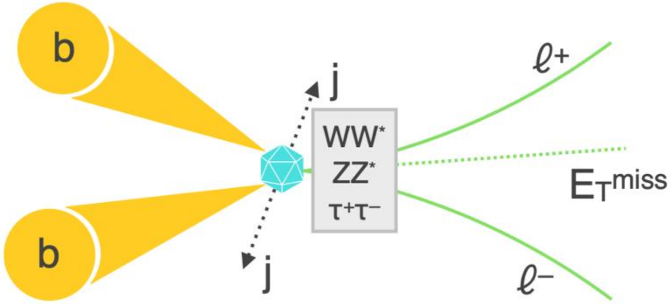
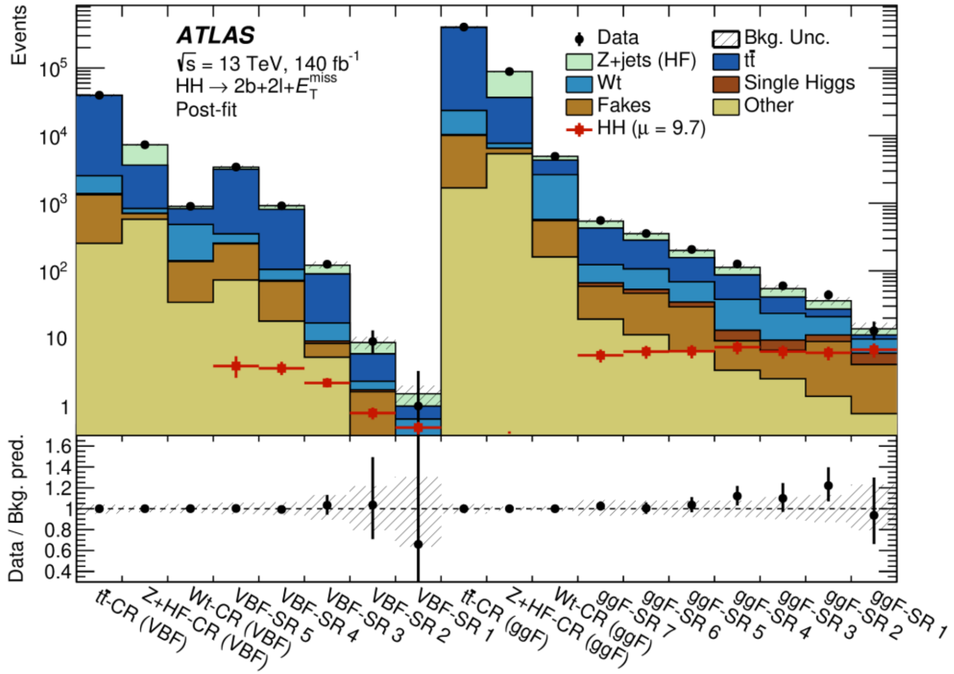
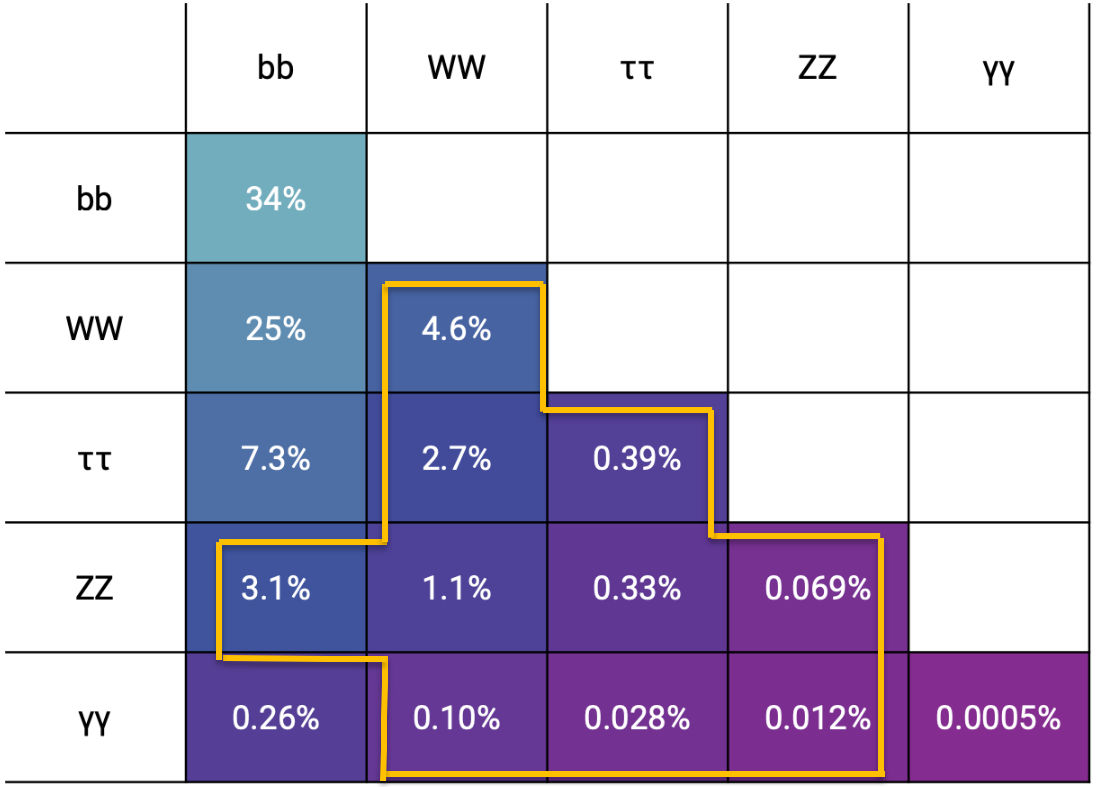




- Define SR by m_{ll}, similar background as $bb\tau\tau$
  - Data-driven fake lepton background
- Discriminant: ggF: DNN score, VBF: BDT score

HH → multilepton

- Target on non-res. HH, decaying to: bbZZ, 4V (V= W or Z), VVττ, 4τ, γγVV and γγττ
  - Branching ratio ~ 6.5%
  - Events categorized based on the multiplicity of e or μ, hadronic τ, and γ



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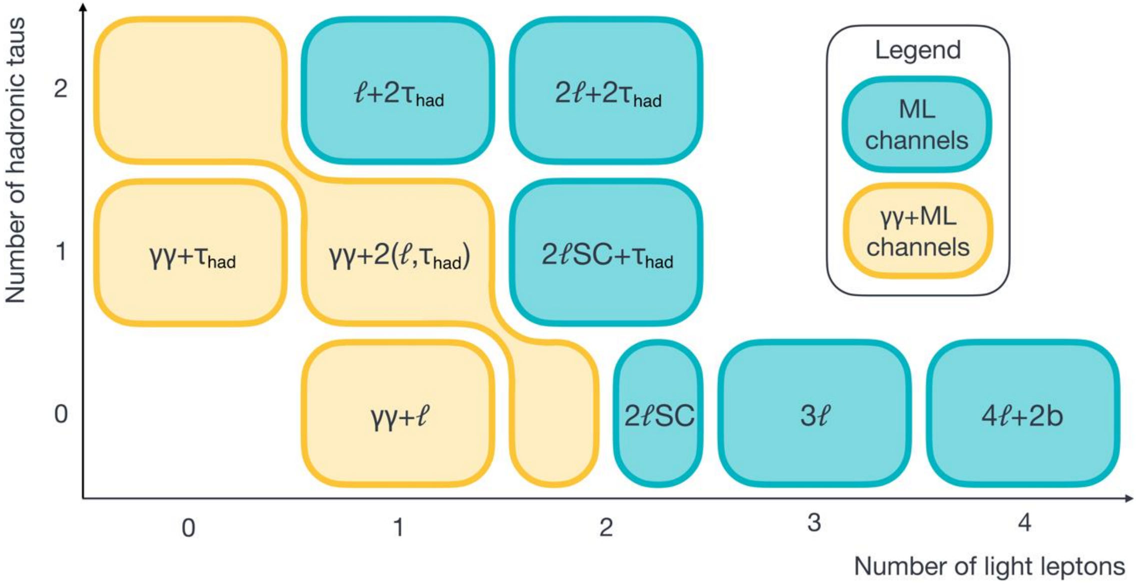
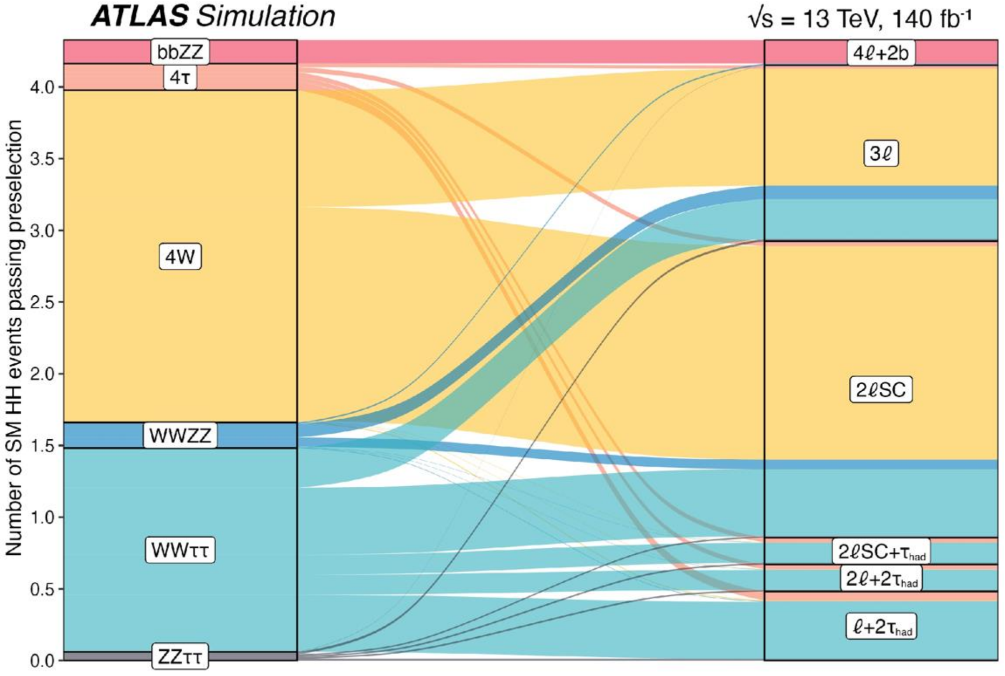
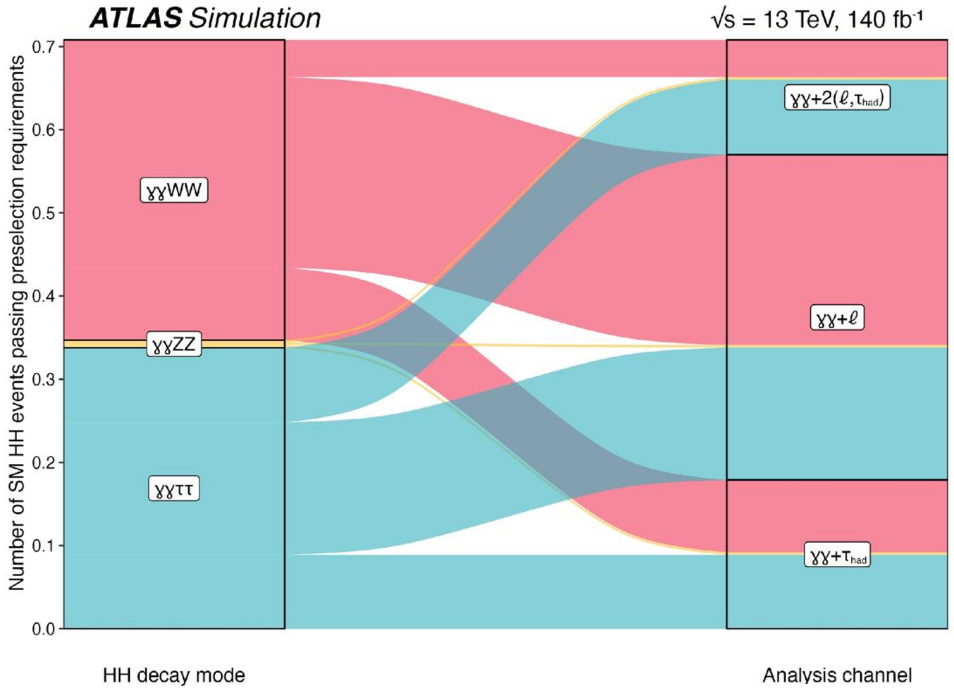
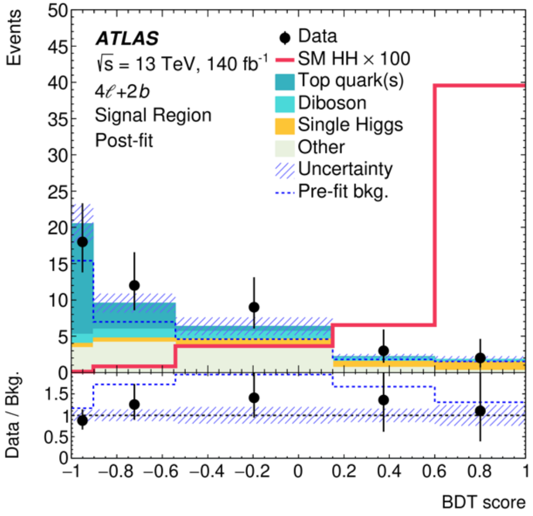
- 9 categories based on N. of τ_{had}, e/μ, $\gamma\gamma$

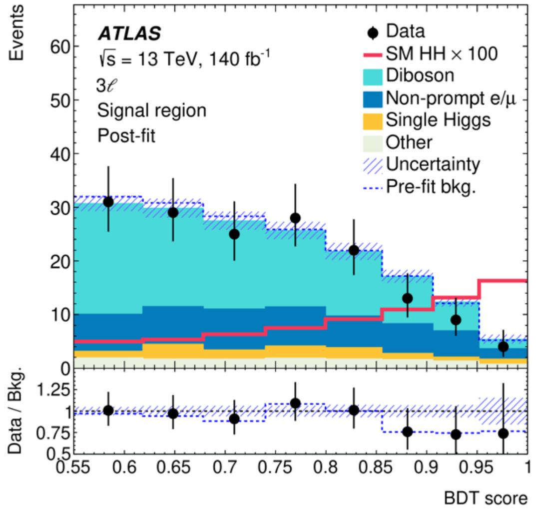


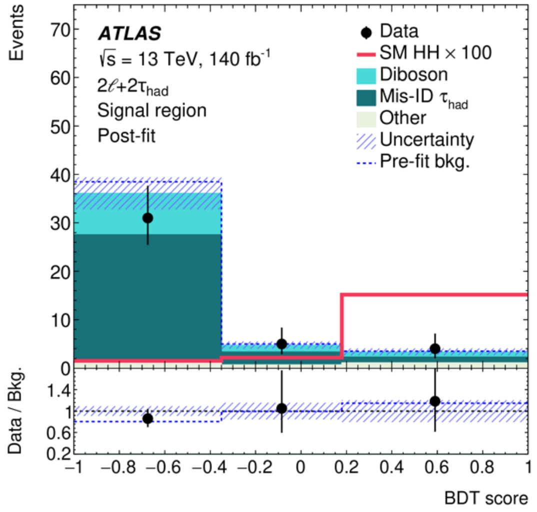
HH → multilepton

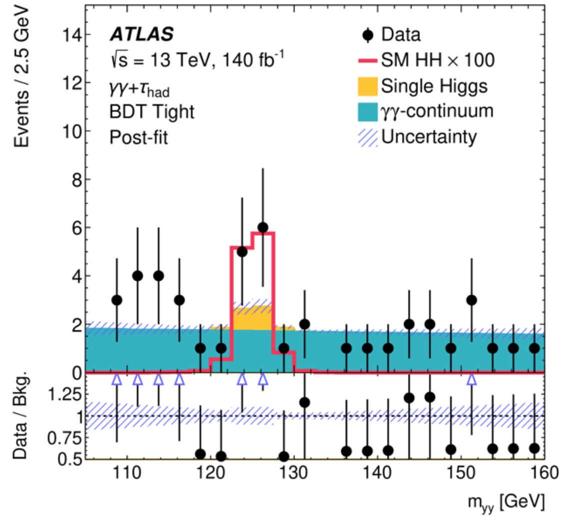






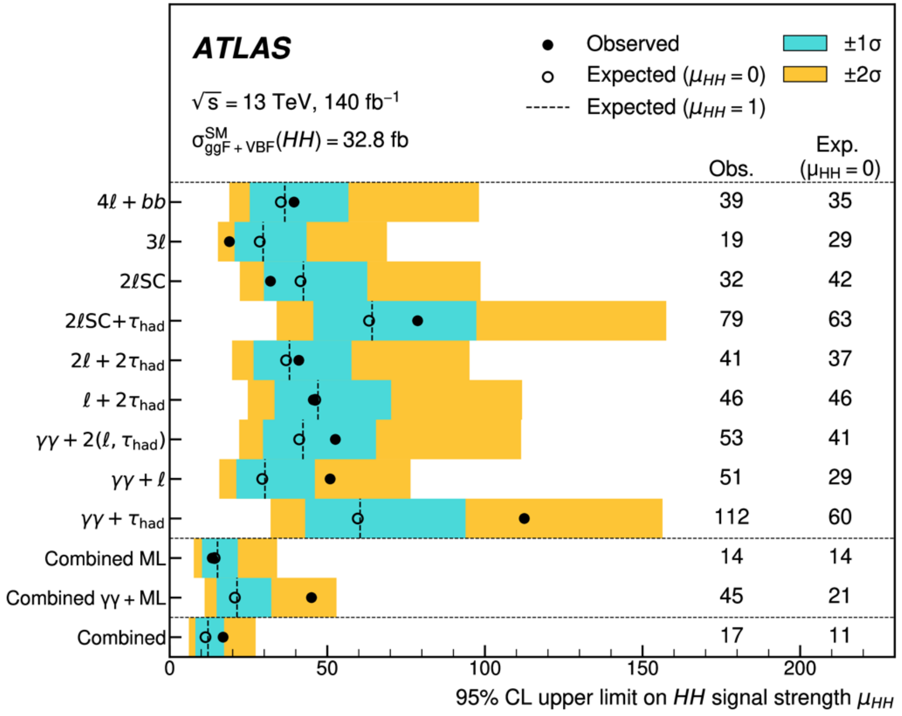


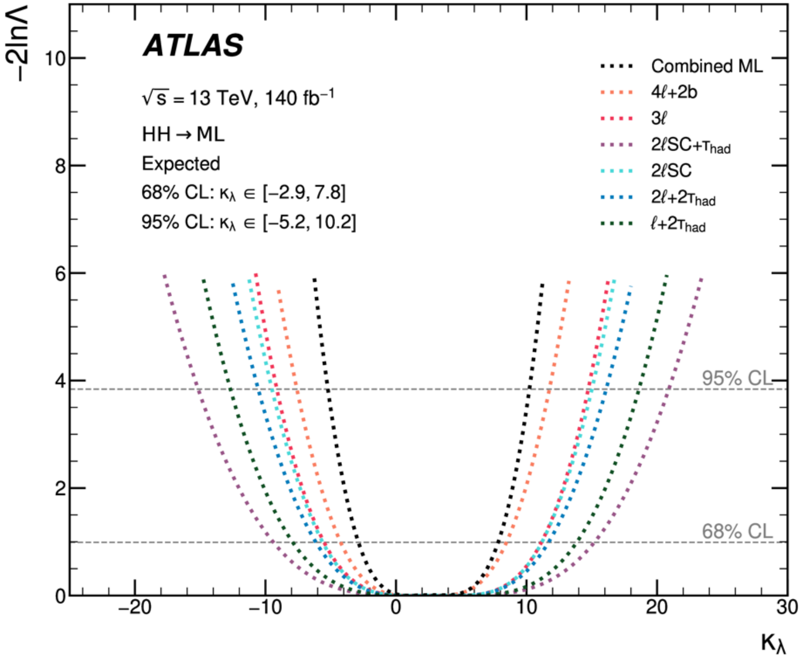


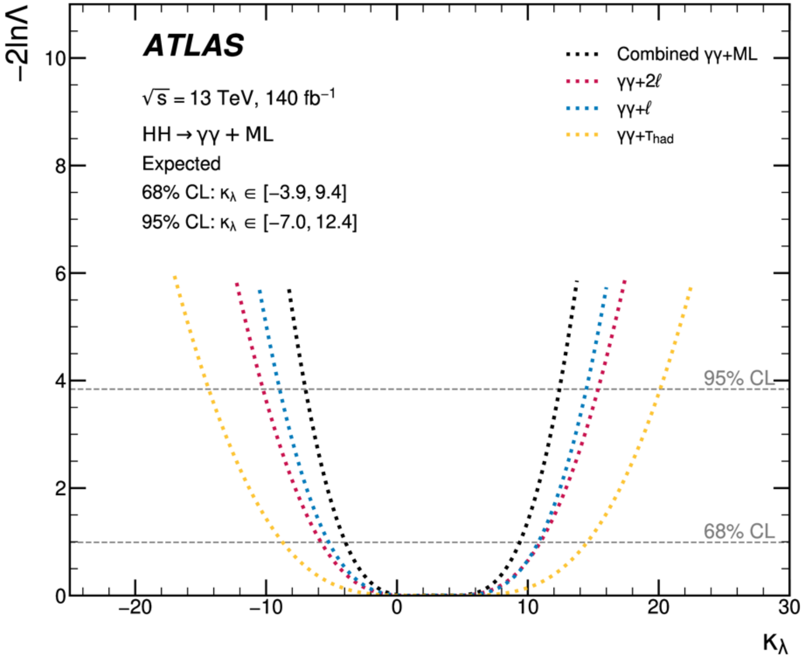


HH → multilepton

- First time at ATLAS, one of the leading channels
  - Upper limit: 10 (14 exp)







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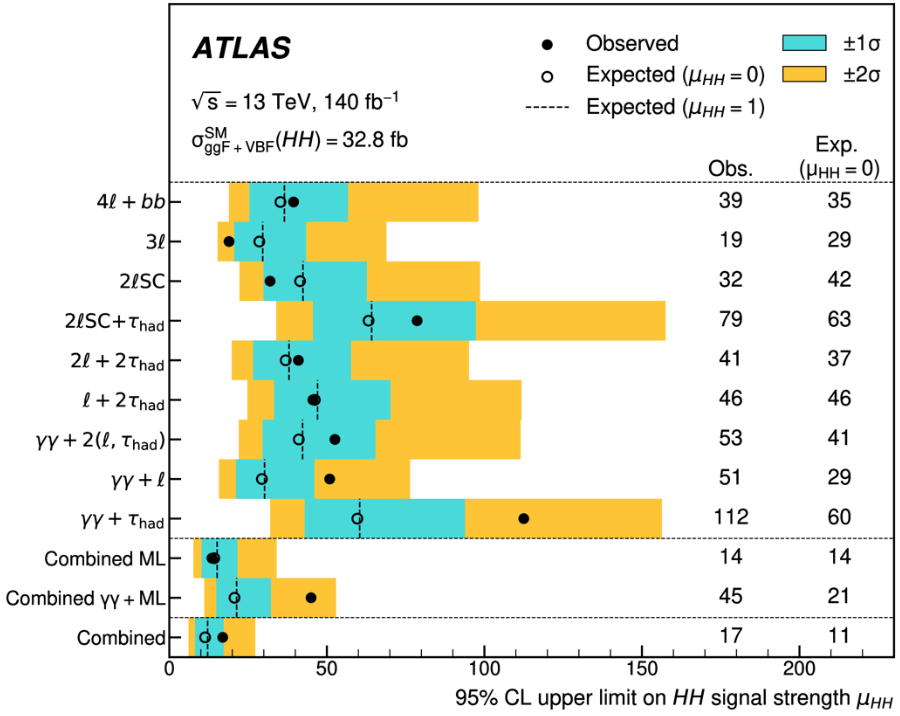


方亚泉 高能所研究员，1974-2025

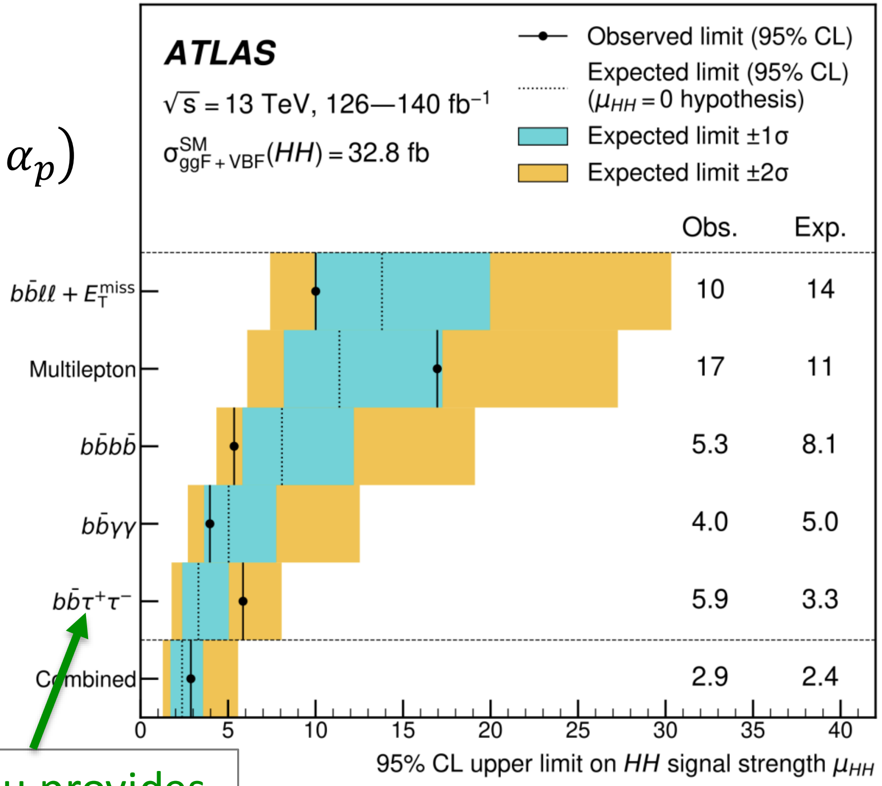
HH Combination

- Combine all available channels to make the most of our data
  - Built combined likelihood from products of likelihoods in each channel
  - Overlaps/correlations/compatibility carefully studied

$$\mathcal{L}(\mathcal{D},\mathcal{G}|\mu,\alpha) = \prod_{c}\left(\prod_{r} Prob\left(x_r|\sum_{i} S^{i}(\mu,\alpha) + \sum_{j} B^{j}(\alpha)\right)\right) \times \prod_{p} f_p(a_p|\alpha_p)$$

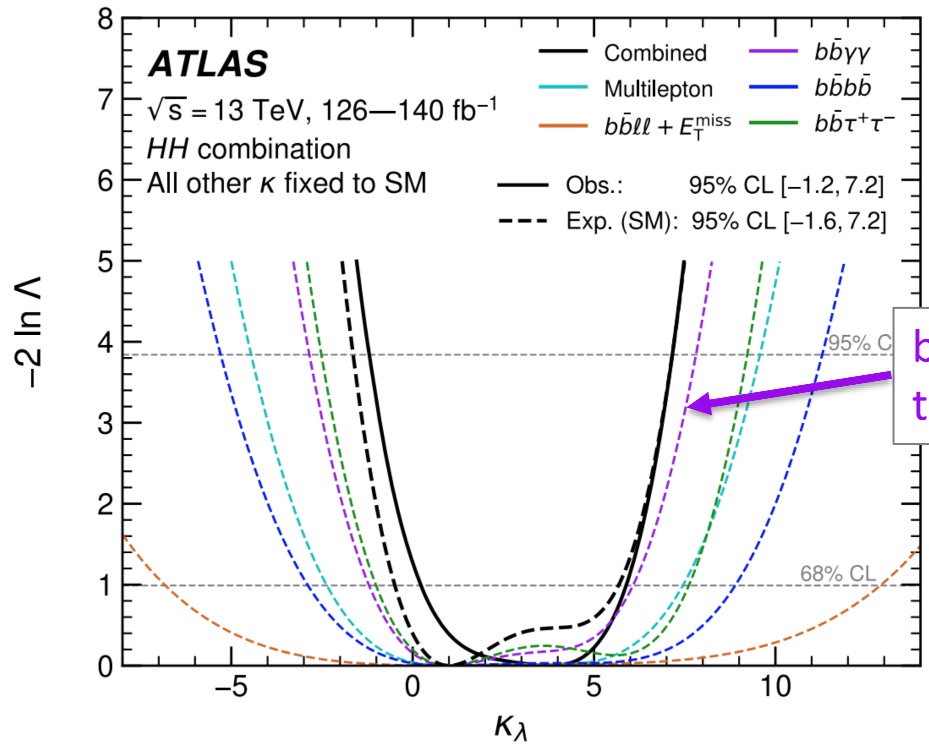
- Full Run-2 data
  - 95% CL upper limit: $\mu_{HH} < 2.9\ (2.4\ exp.)$
  - Signal strength measured at $0.5^{+1.2(+0.9+0.7)}_{-1.0(-0.8-0.6)}$ Systematical

Statistical (dominant)



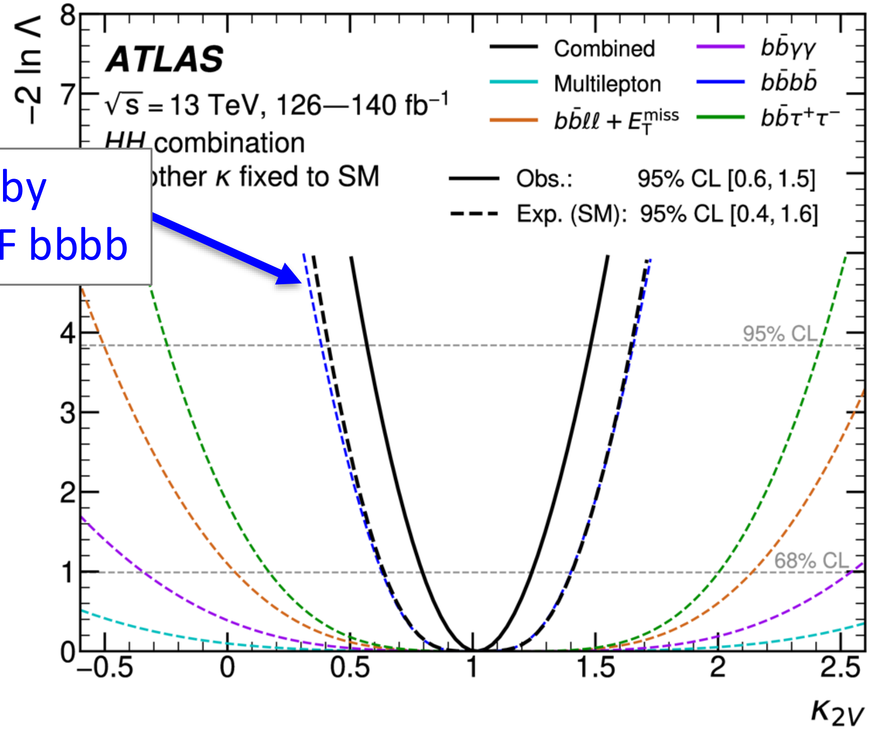
bbtautau provides the best sensitivity

Combined Results: Coupling



bbyy most sensitive to the upper bound

Dominated by boosted VBF bbbb



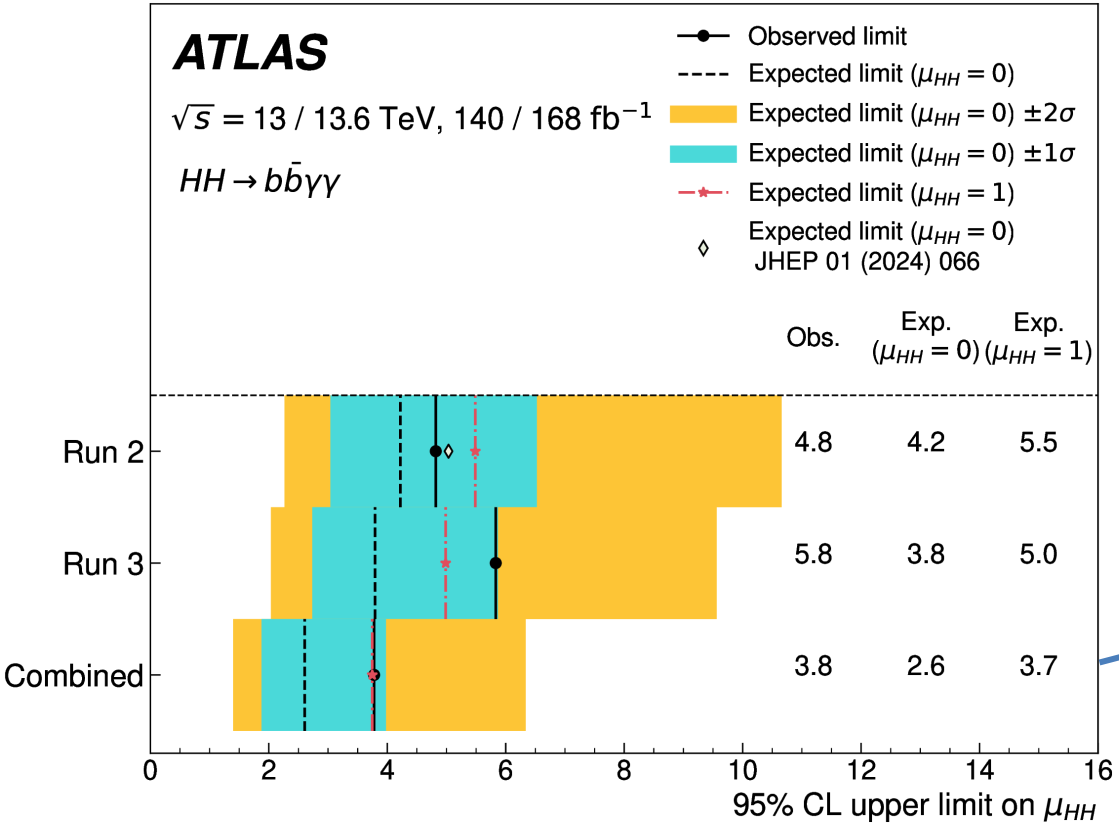
	Best-fit	68% CI	95% CI
Expected	1.0	[-0.5, 5.7]	[-1.6, 7.2]
Observed	3.8	[0.2, 5.9]	[-1.2, 7.2]

	Best-fit	68% CI	95% CI
Expected	1.00	[0.64, 1.40]	[0.41, 1.65]
Observed	1.02	[0.79, 1.24]	[0.57, 1.48]

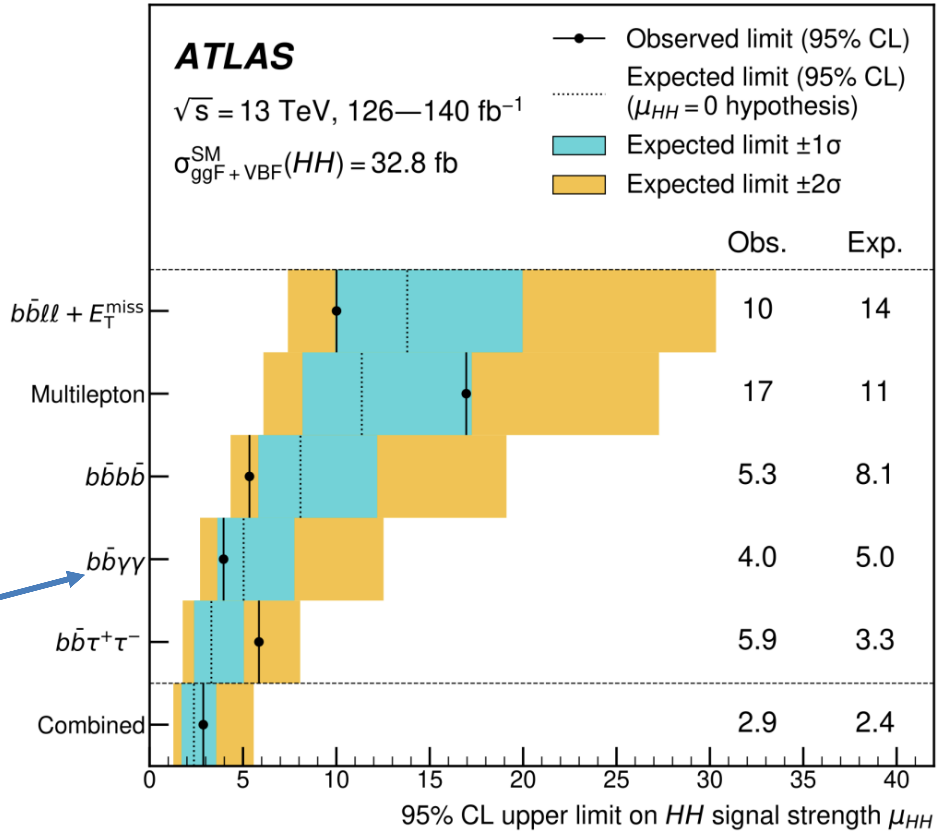
- Further constraint from single Higgs measurement, using higher order correction

New results bb$\gamma\gamma$

- Run-2 + partial Run-3 (2022-2024): significant improvement (arXiv:2507.03495)



	Obs.	Exp. ($\mu_{HH} = 0$)	Exp. ($\mu_{HH} = 1$)
Run 2	4.8	4.2	5.5
Run 3	5.8	3.8	5.0
Combined	3.8	2.6	3.7



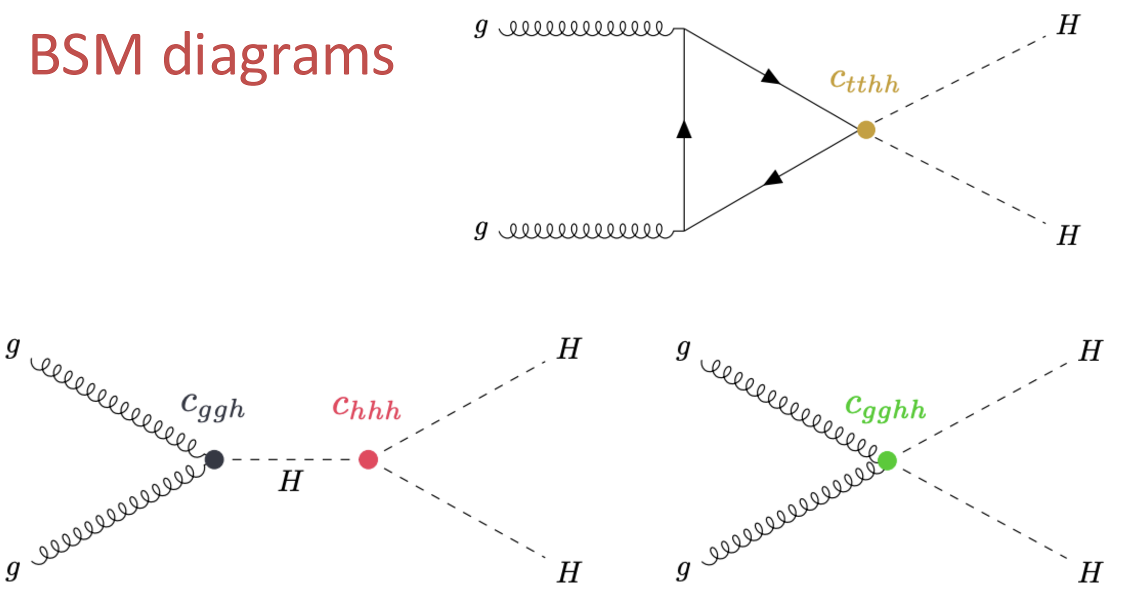
	Obs.	Exp.
$b\bar{b}\ell\ell + E_T^{miss}$	10	14
Multilepton	17	11
$b\bar{b}b\bar{b}$	5.3	8.1
$b\bar{b}\gamma\gamma$	4.0	5.0
$b\bar{b}\tau^+\tau^-$	5.9	3.3
Combined	2.9	2.4

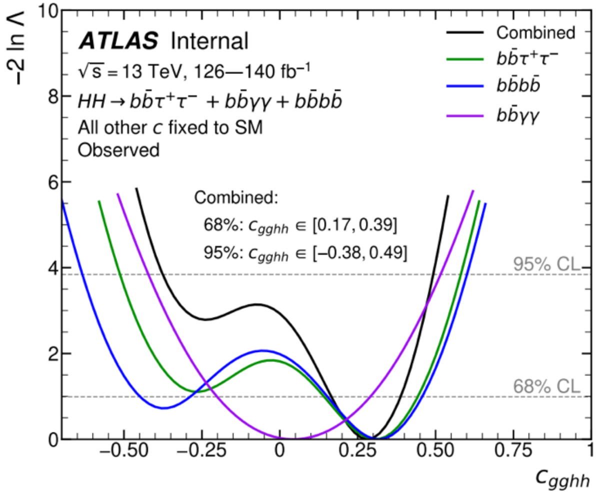
With simple calculation on top of our head,
the new combined expected upper limit at 1.9x SM

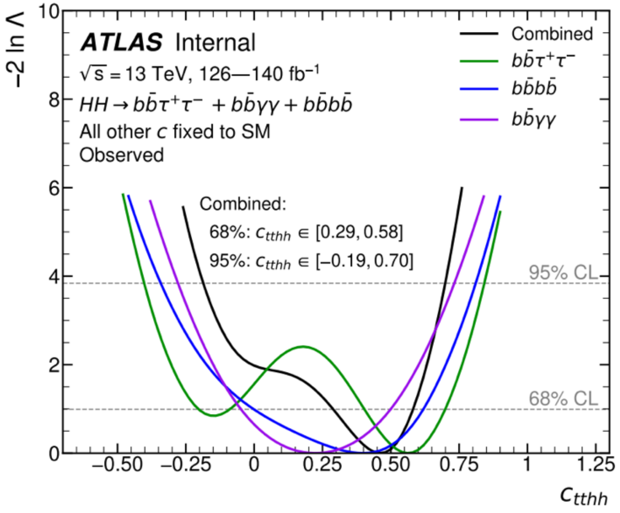
EFT Interpretation

- Model-independent interpretation using HEFT
  - Define single- and di- Higgs anomalous couplings separately
  - HH production is especially sensitive to Wilson Coefficients: $c_{hhh}(=\kappa_\lambda), c_{gghh}, c_{tthh}$
  - Take the 3 leading channels, ggF-only: bbbb, bbττ, bbγγ

BSM diagrams



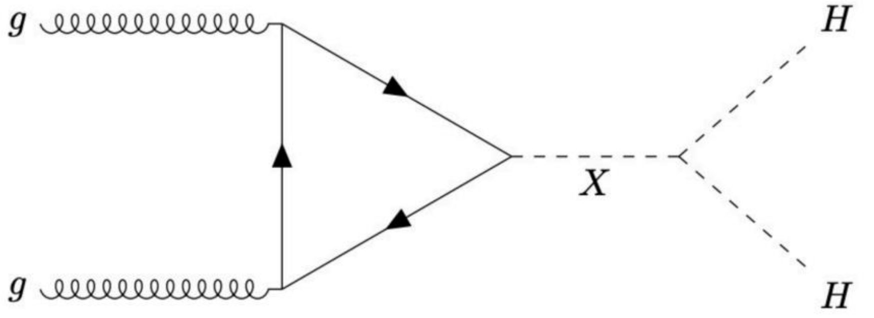




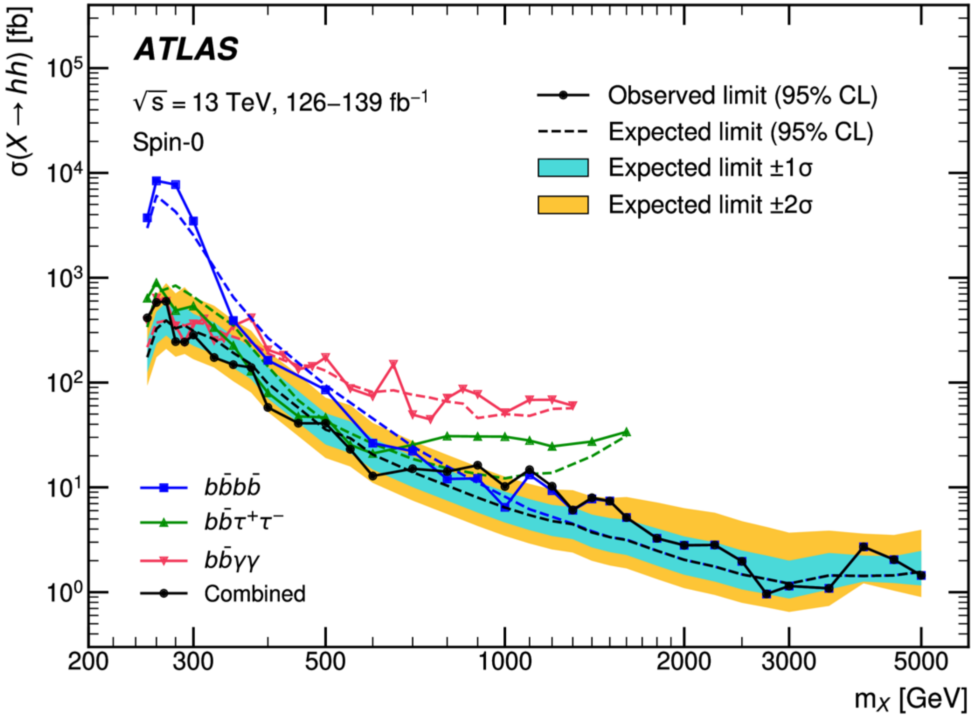
- bbbb and bbττ show mild deviations from SM
- Further studies required

Combined Results: Resonance

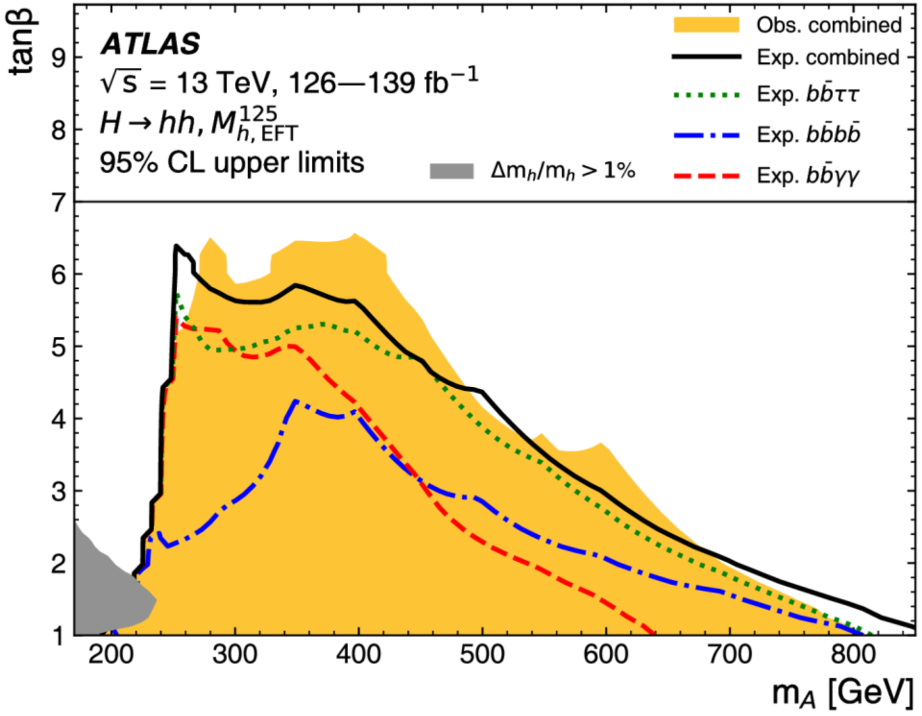
- Search for a narrow-width spin-0 heavy scalar
  - Combine channels: bbbb + bbττ + bbγγ
  - Largest deviation at 1.1TeV ($Z_{local} = 3.3\sigma, Z_{global} = 2.1\sigma$)



Model independent

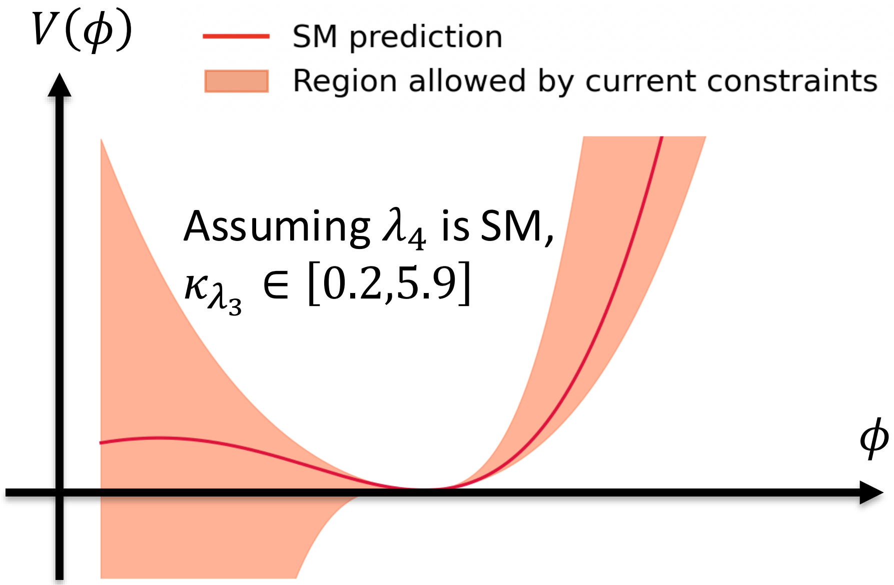


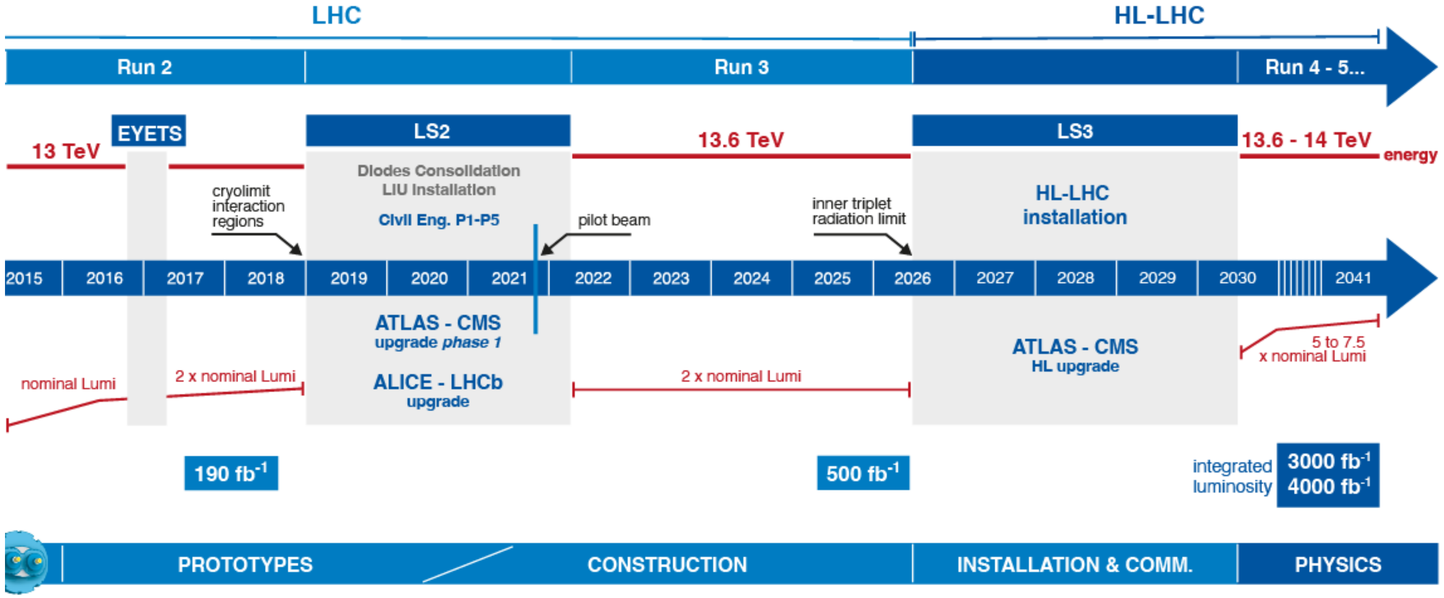
2HDM/hMSSM



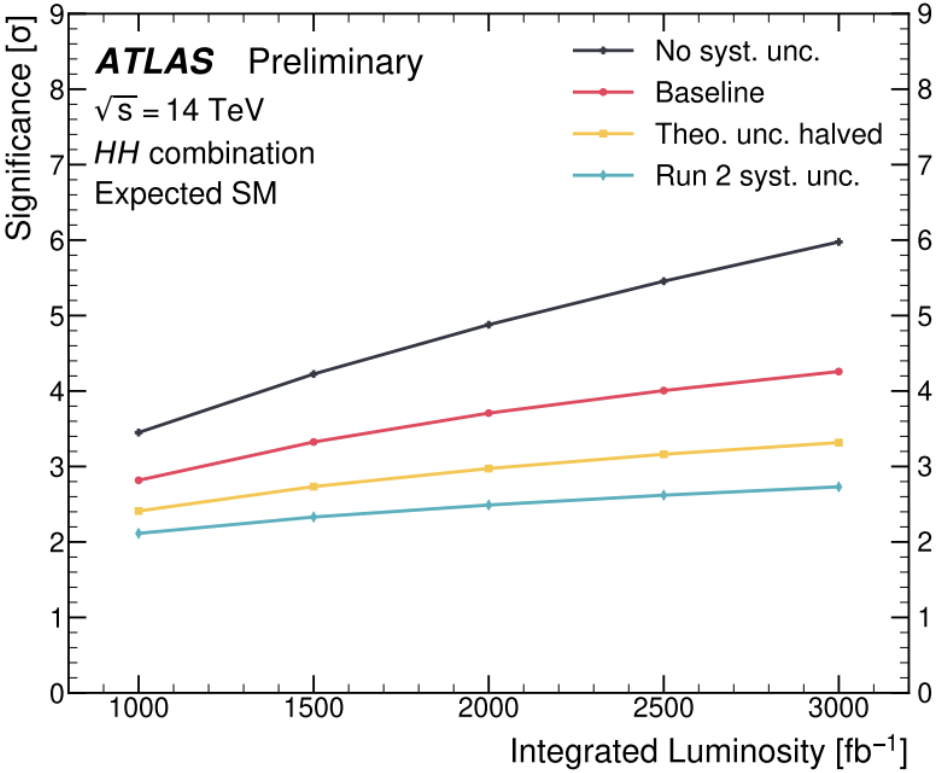
Towards HL-LHC

- Current constraint on κ_λ not sufficient to answer the question of stability of universe
- How precision we can achieve with more date in HL-LHC
  - Use some baseline expectations to account in [ATL-PHYS-PUB-2025-006]

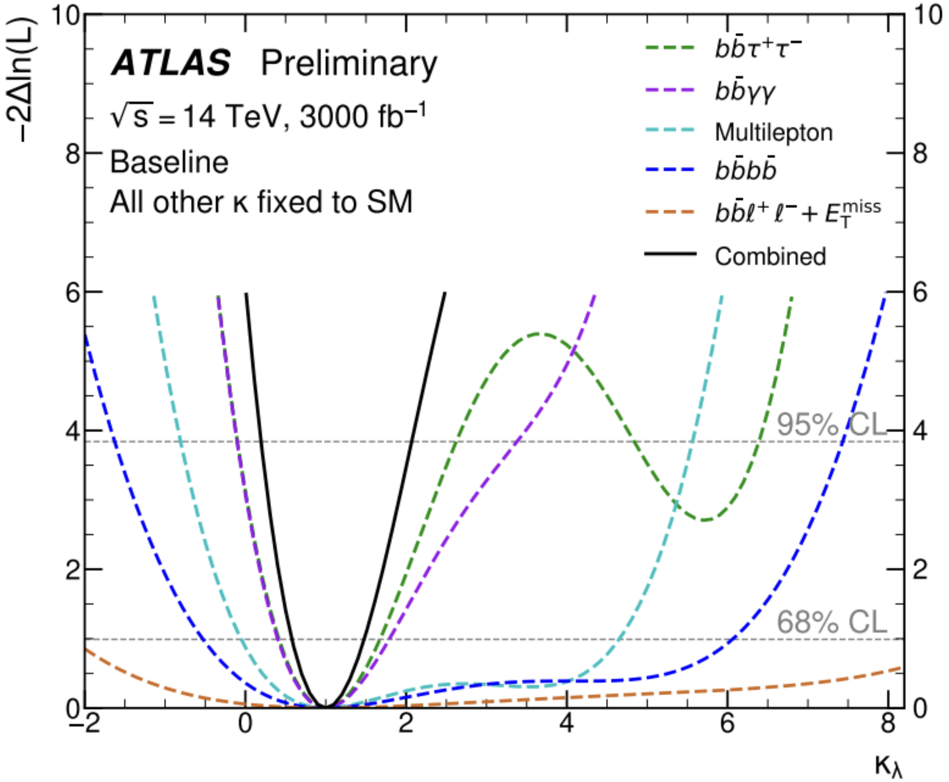




HL-LHC Projection: ATLAS



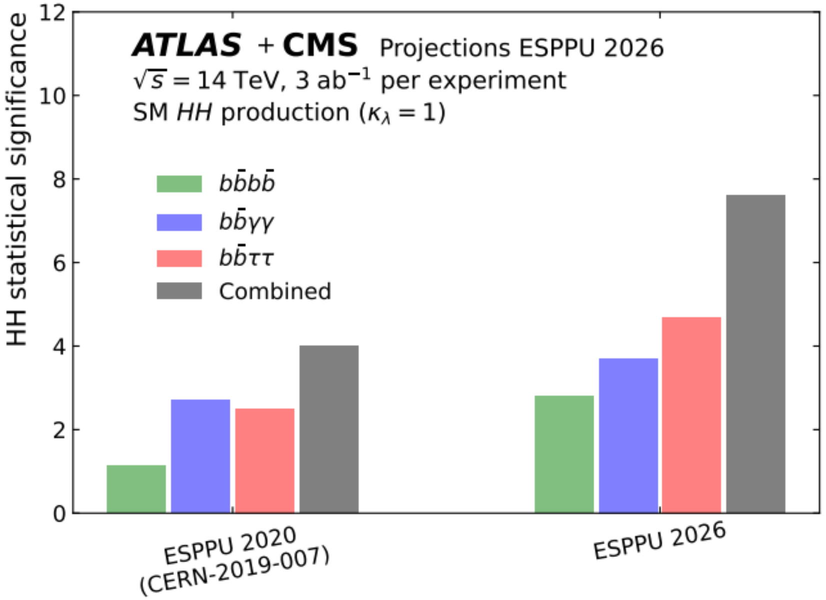
Discovery significance can achieve 4.3σ with 3000/fb

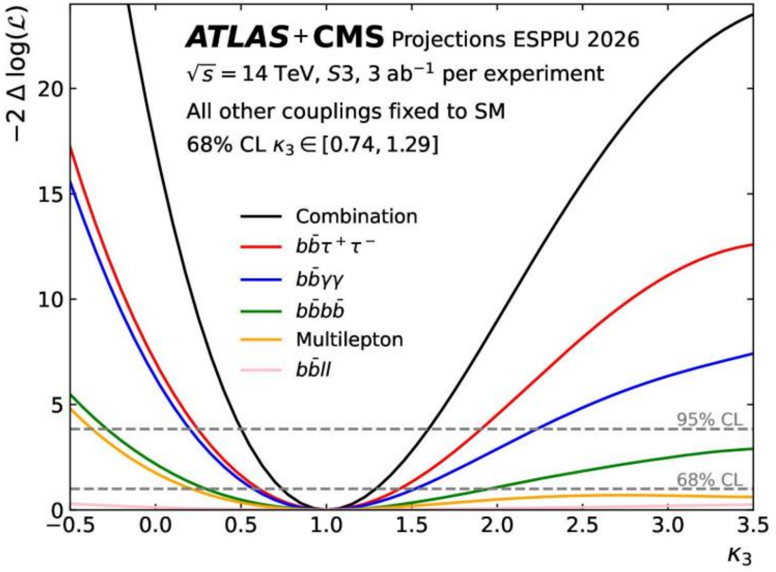


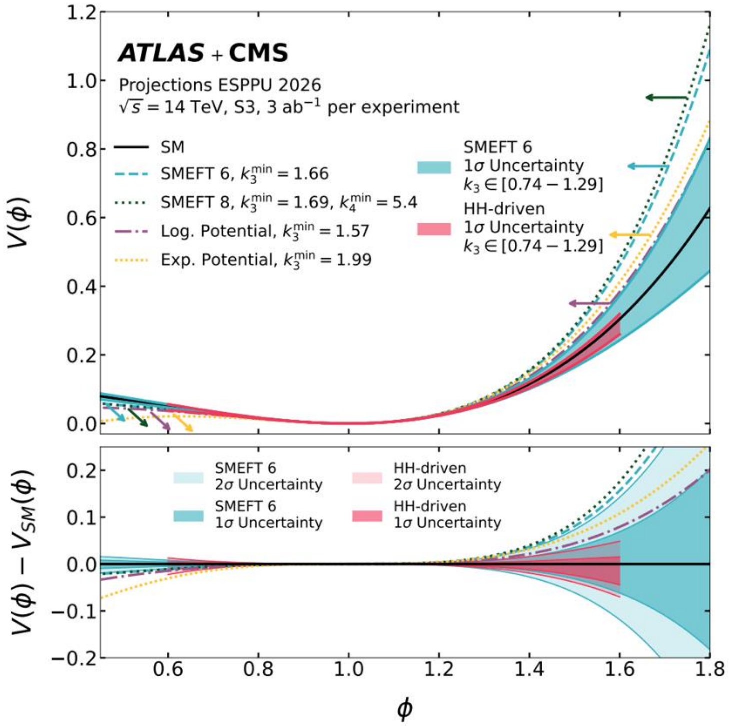
κ_λ expected to be measured at $1.00^{+0.48}_{-0.42}$

HL-LHC Projection: ATLAS+CMS

arXiv:2504.00672







7.2σ significance Expected

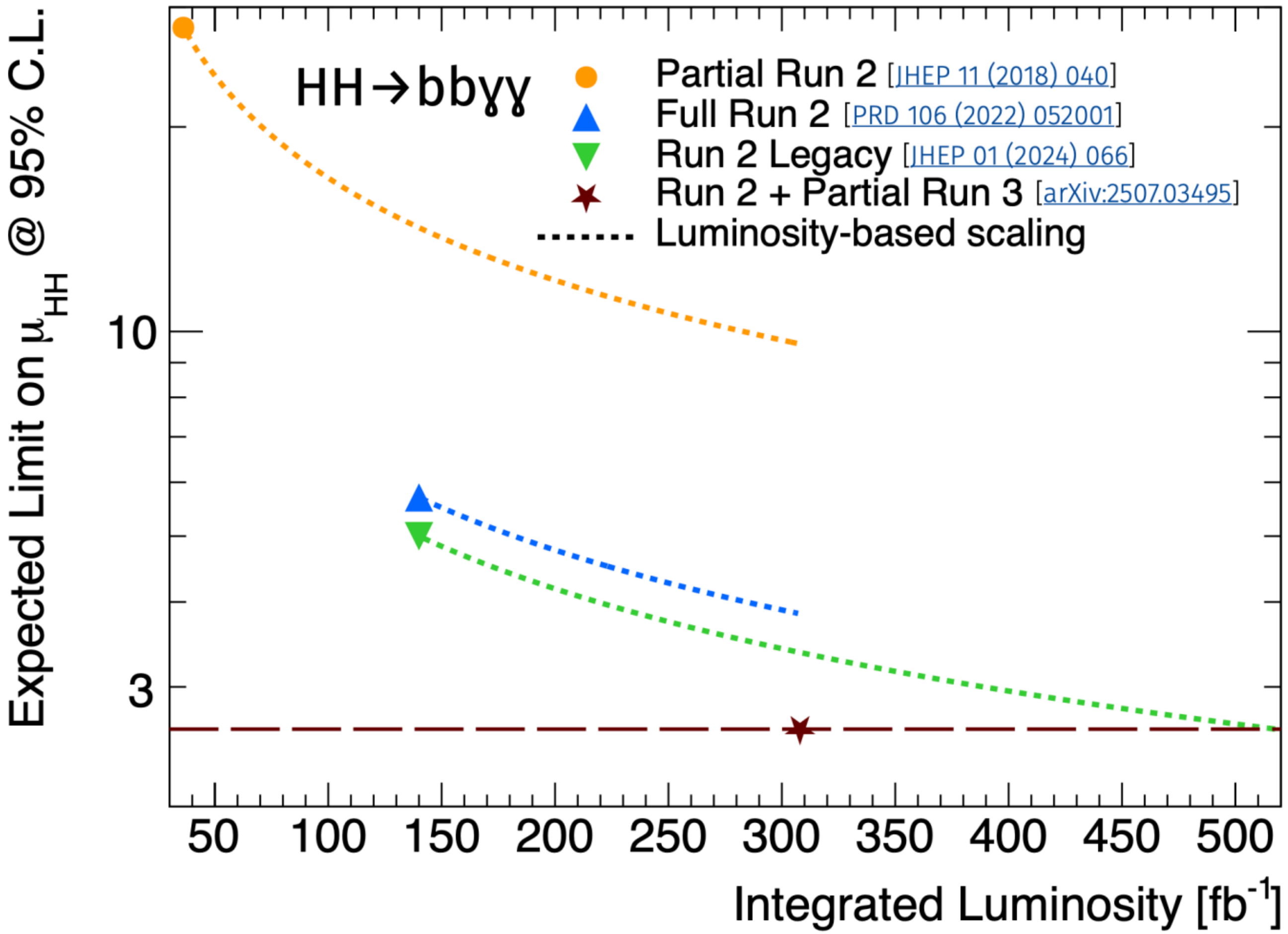
6.0σ with conservative 2 ab^{-1}

Expected to **Discovery** the HH!

<30% κ_λ precision expected

Can exclude physical hypotheses for the shape of the Higgs potential, rather than just eliminating parts of parameter space.

HL-LHC Projection: More optimistic

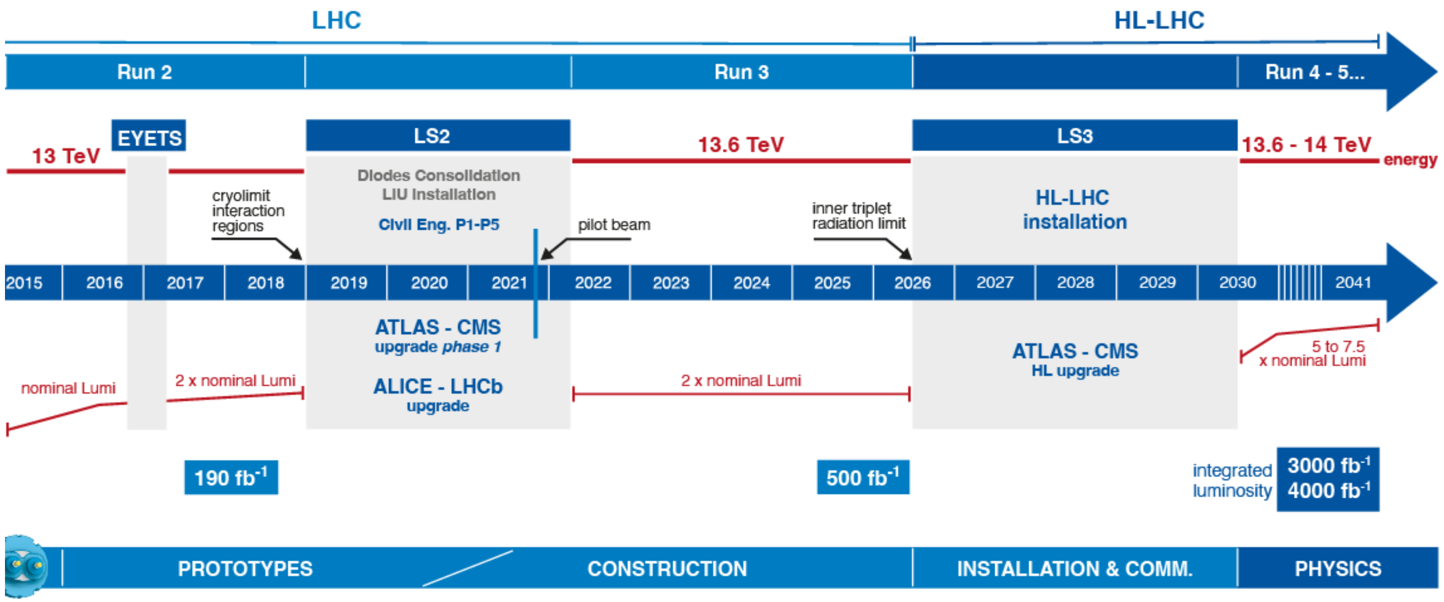


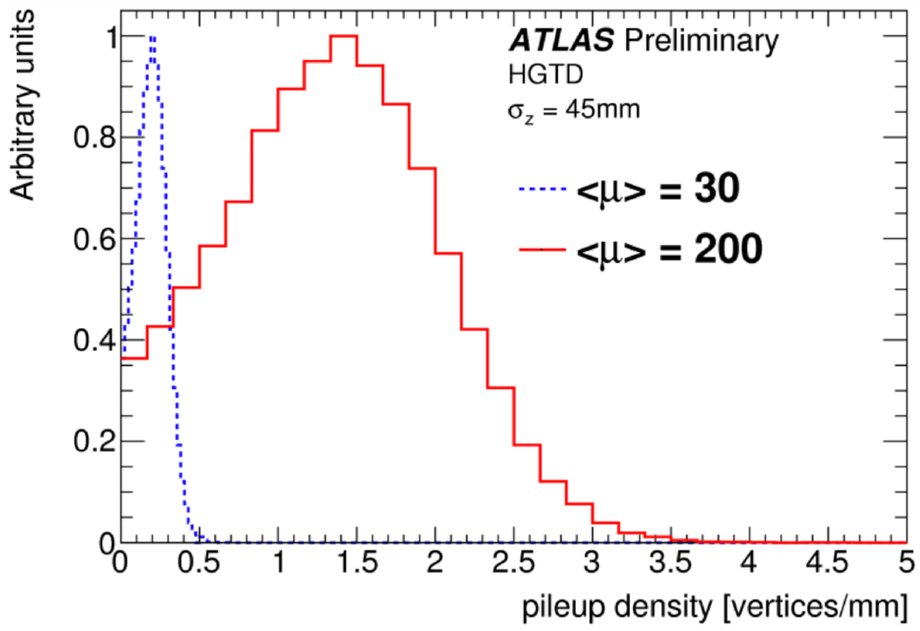
- Keep improving our analyses
  - Otherwise, early Run 2 analysis would need ~ 4200/fb to reach current sensitivity

Tools for future HEP

High-Luminosity (HL-) LHC

- High Luminosity LHC: 2030 -- ~2041
  - 7.5x nominal lumi., integrated lumi. up to 4000 fb^{-1}
  - Up to 200 p-p interactions (“pile-up”) per bunch crossing
  - Requiring higher radiation hardness of the detector

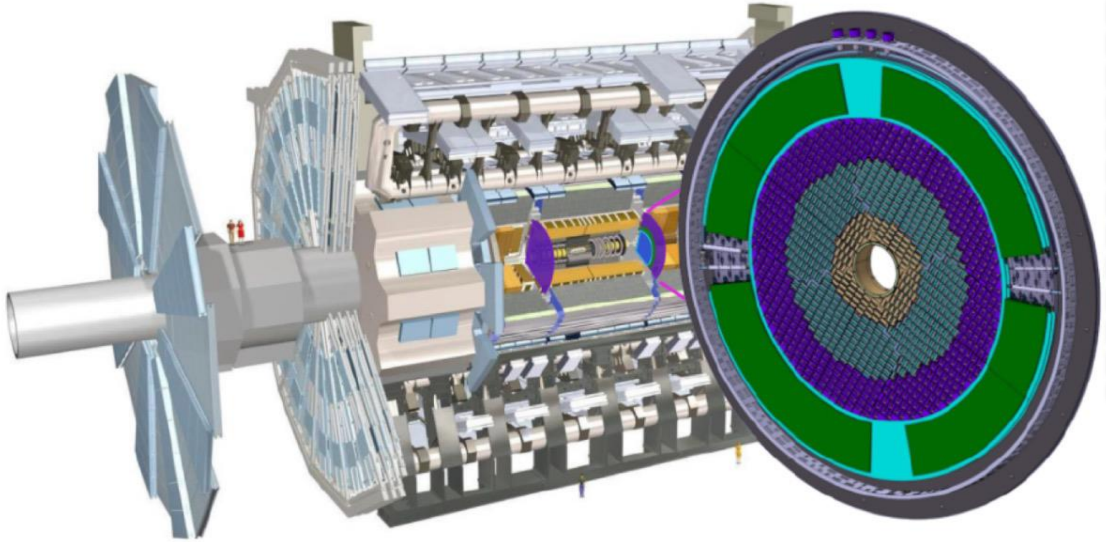


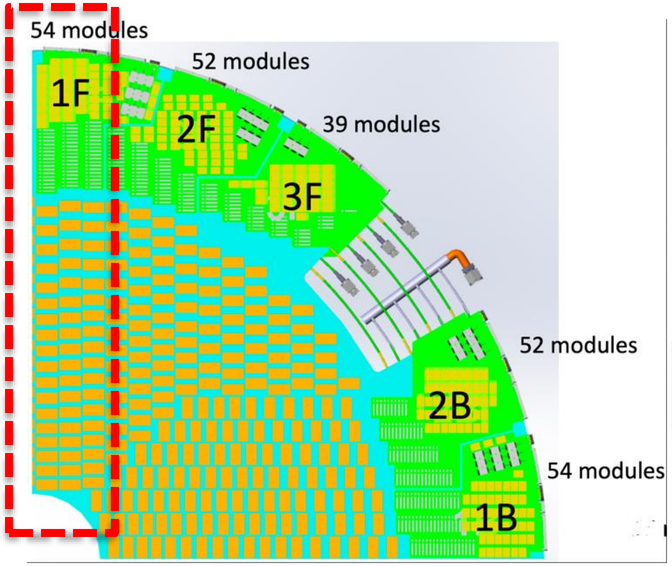


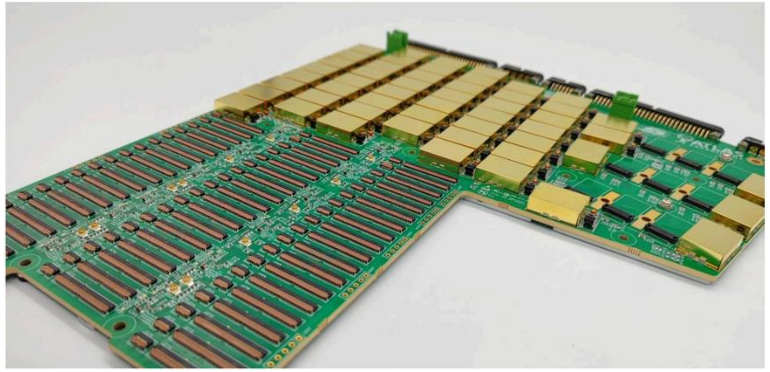
HGTD TDR: CERN-LHCC-2020-007

ATLAS detector upgrade: HGTD

- Installed at ATLAS forward region
  - Per track timing resolution of 30-50 ps to improves vertex reconstruction and pile-up rejection
  - Coverage: 2.4 < |η| < 4.0, measure bunch-by-bunch luminosity





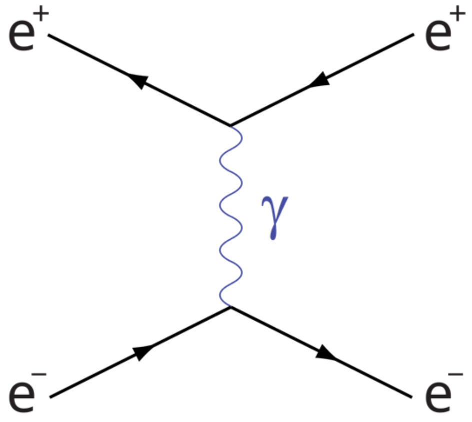


CEPC: LumiCal

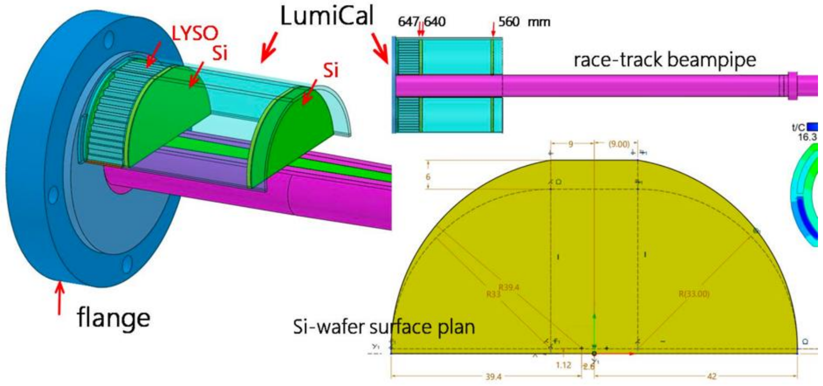
- Small Angle Bhabha Scattering: $e^+e^- \rightarrow e^+e^-$

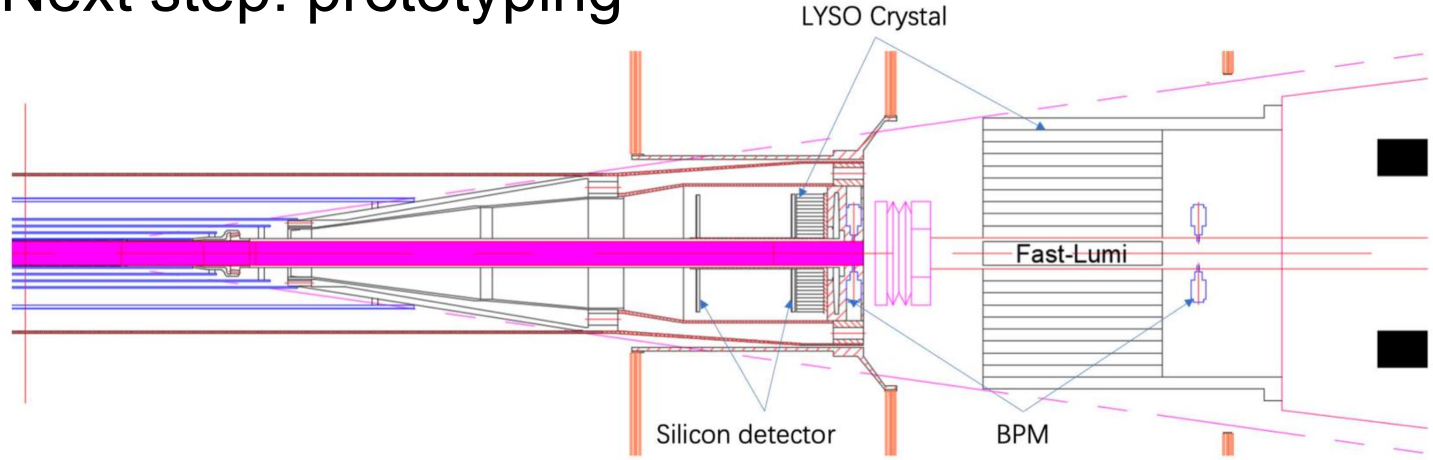
$$\sigma = \frac{1040\ \mathrm{nb\ GeV}^2}{s}\left(\frac{1}{\theta_{min}^2} - \frac{1}{\theta_{max}^2}\right)$$

- Peaked in forward region, at <100 mRad



- Dedicated detector needed
  - Two LYSO+SiPM based detectors on each side of Interaction Point
- TDR published: arXiv:2510.05260. Next step: prototyping

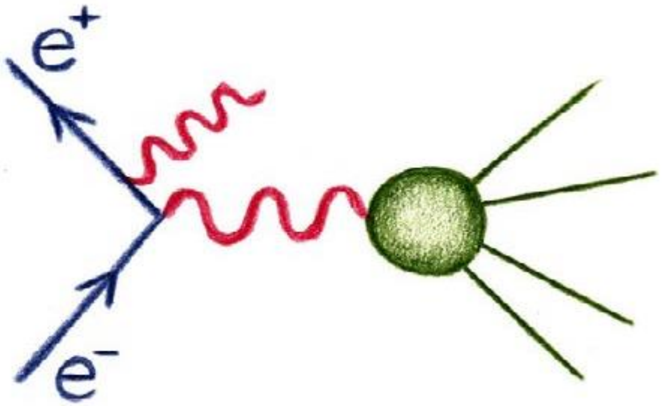


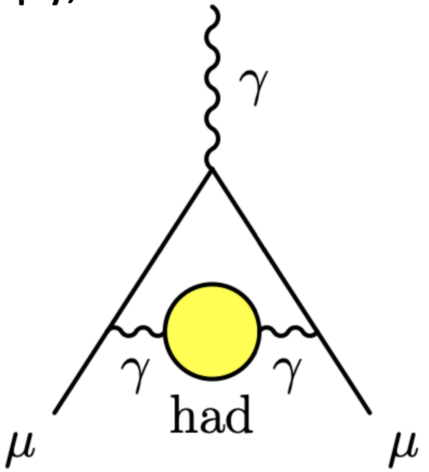


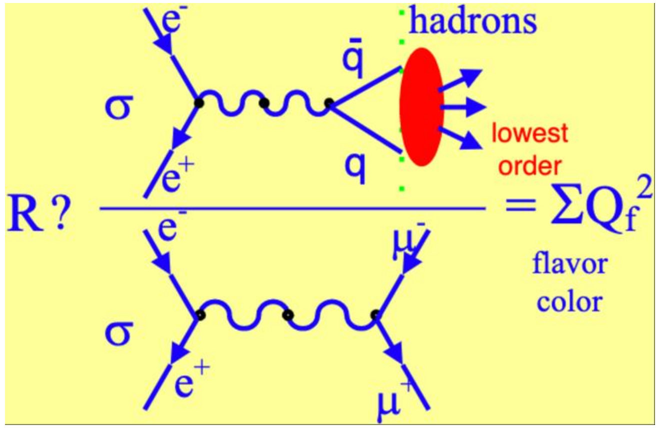
BESIII forward region: ideal place for prototyping

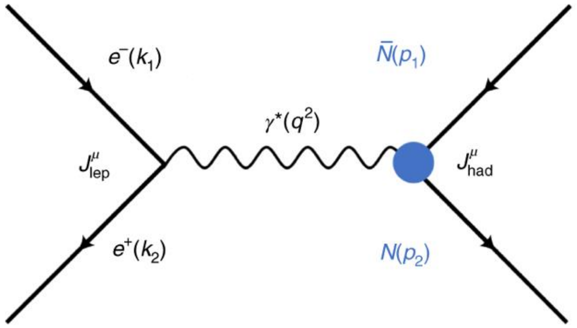
- BEPCII-BESIII: e+e- collider, COM energy: ~2-5 GeV, Luminosity: ~10^{33}cm^{-2}/s
  - Zero-Degree-Calorimeter(ZDC): fast luminosity monitor and ISR photon tagging
  - ISR physics: R-value, Muon g-2: HVP, Nucleon Form Factor, Hadron spectroscopy, etc.

ZDC at forward region,
θ=0 in CMS frame





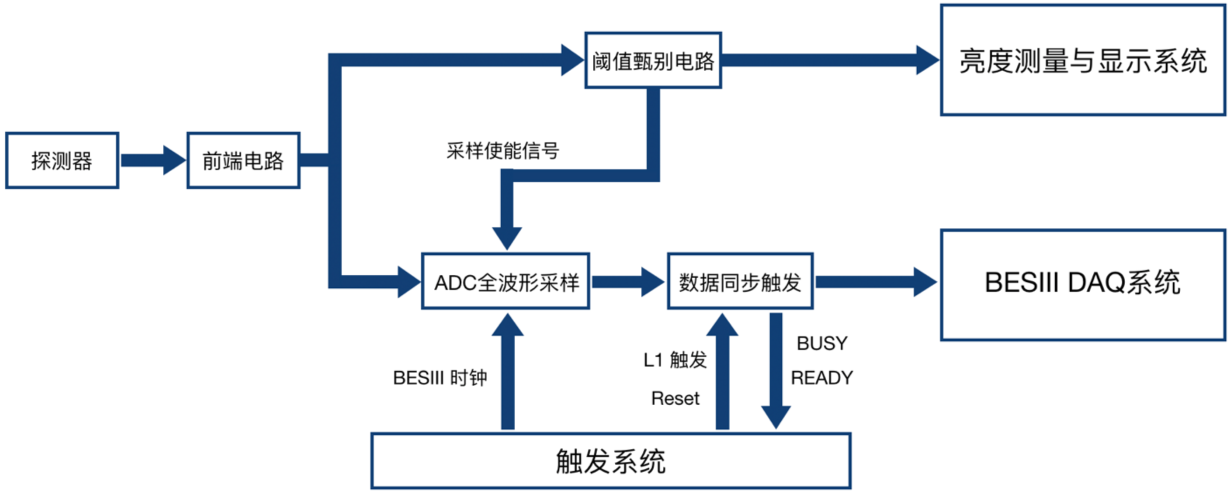




BESIII forward region: ideal place for prototyping

- ZDC: LYSO+SiPM array
  - Same as CEPC LumiCal

- Data-flow chart of ZDC



探测器

前端电路

阈值甄别电路

亮度测量与显示系统

采样使能信号

ADC全波形采样

数据同步触发

BESIII DAQ系统

BESIII 时钟

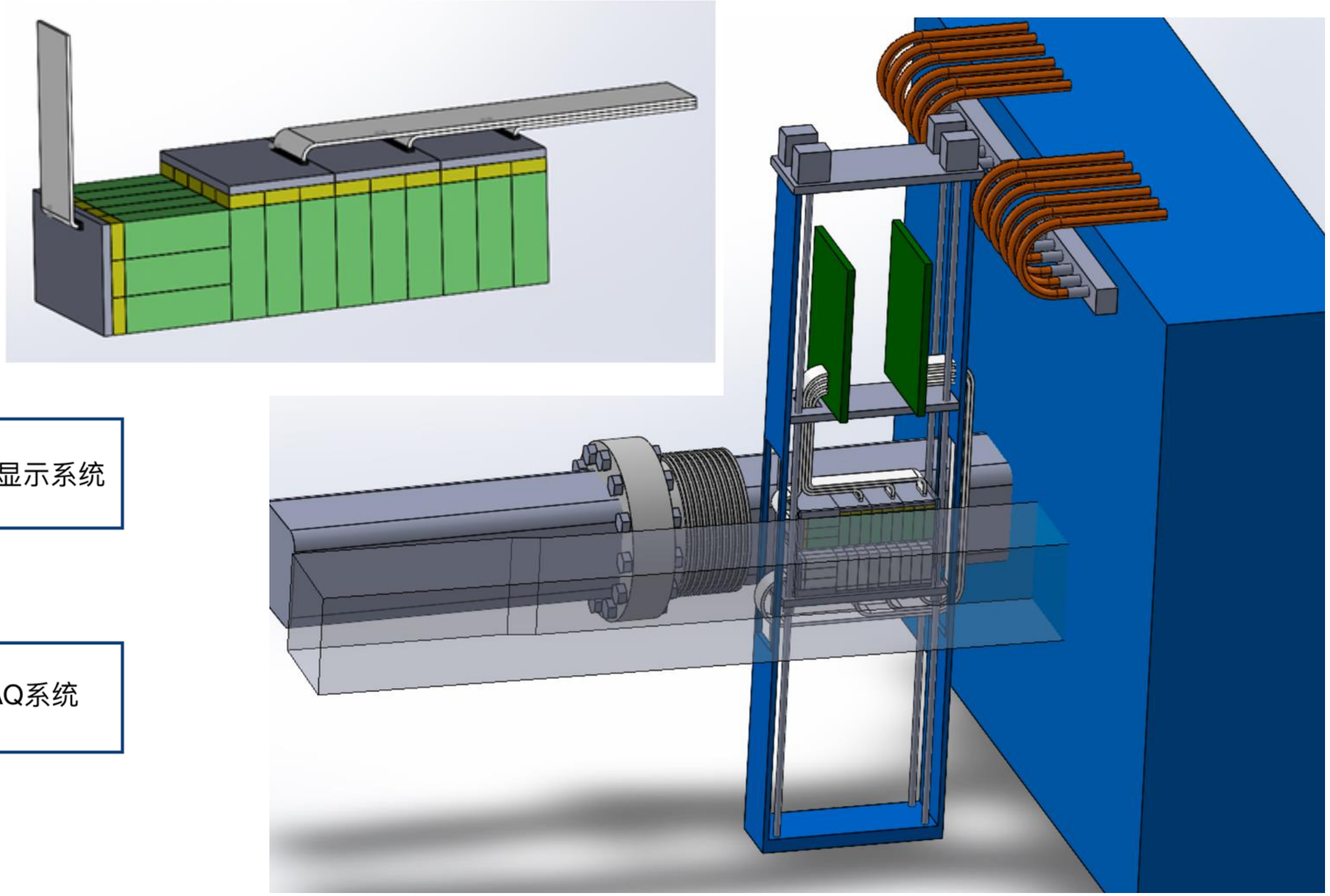
L1 触发

Reset

BUSY

READY

触发系统



Summary

- Final ATLAS HH results with Run-2 data presented
    - 95% CL U.L. : $\mu_{HH} < 2.9\ (2.4\ exp.)$
    - 95% CI on κ_λ: $[-1.2, 7.2]\ ([-1.6, 7.2]\ exp.)$ and κ_{2V}: $[0.57, 1.48]\ ([0.41, 1.65]\ exp.)$
- Looking forward
    - Early Run 3 results coming, e.g. new bbyy results, more to come
    - Further combine with CMS will provide more promising results
    - Future projects, e.g. HL-LHC, CEPC, will give more definite answers
- Detector R&D crucial for the promising results in future
    - E.g. HGTD for ATLAS at HL-LHC, CEPC LumiCal, as well as ZDC at BESIII

backup