

国家重点研发计划：基于ATLAS高亮度数据检验标准模型和Higgs机制
与寻找新物理

课题2：Higgs粒子自耦合研究

黄燕萍

中国科学院高能物理研究所

H+HH 课题交流研讨会，2026.8.20

报告内容

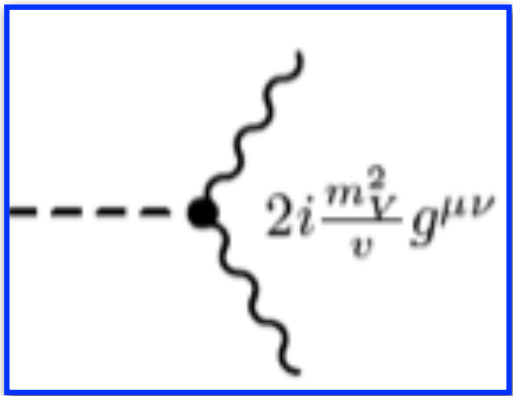
- ❖ 研究目标和研究内容
- ❖ 物理分析进展和考核指标完成情况
- ❖ 研究团队和人才培养
- ❖ 组织管理情况和年度技术报告情况
- ❖ 经费使用情况

希格斯自相互作用

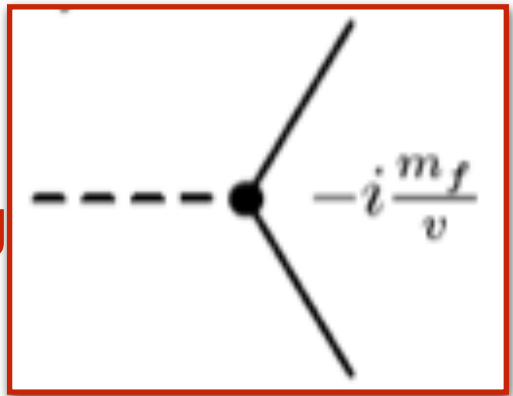
当前LHC实验最重要的物理目标之一：测量希格斯性质，检验标准模型并理解希格斯场的真空自发破缺机制

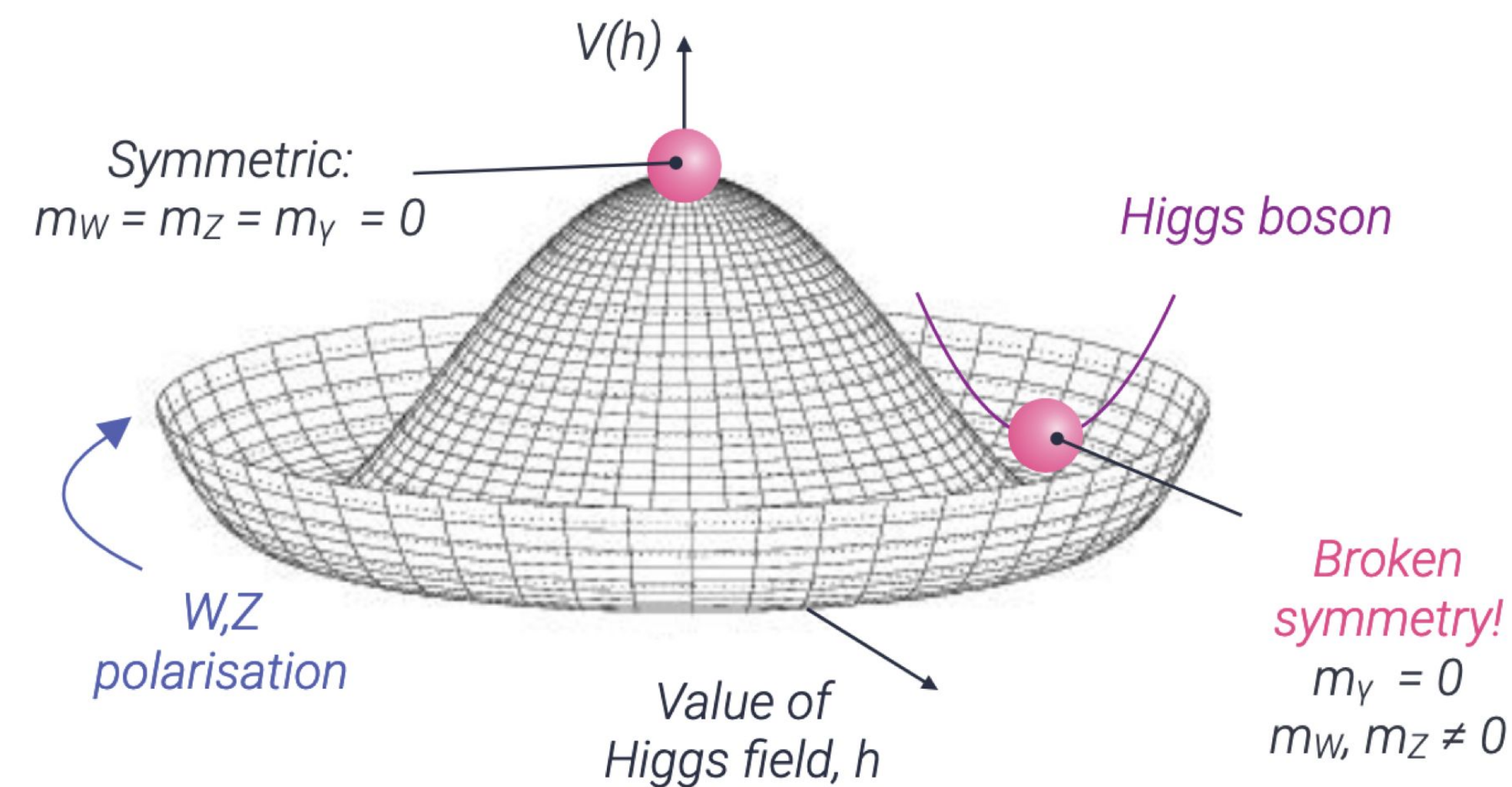
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + \underbrace{D_{\mu}\Phi^{\dagger}D^{\mu}\Phi}_{\text{Self-coupling}} - V(\Phi) + \underbrace{\bar{\Psi}_L\hat{Y}\Phi\Psi_R}_{\text{Yukawa coupling}} + h.c.$$

Gauge coupling



Self-coupling



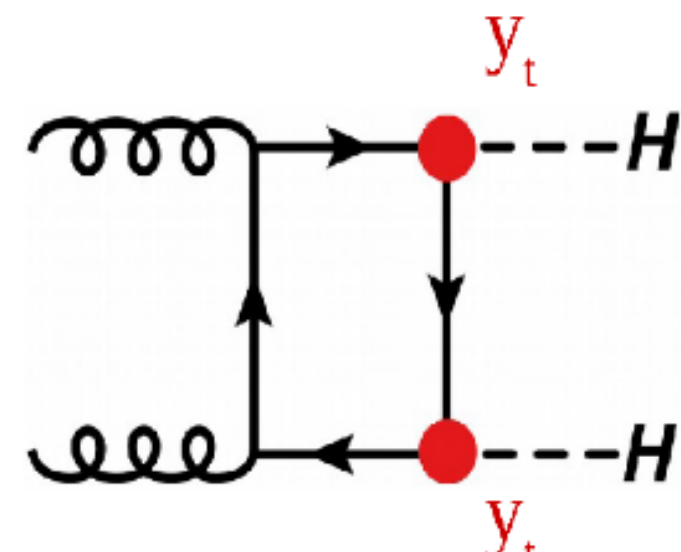
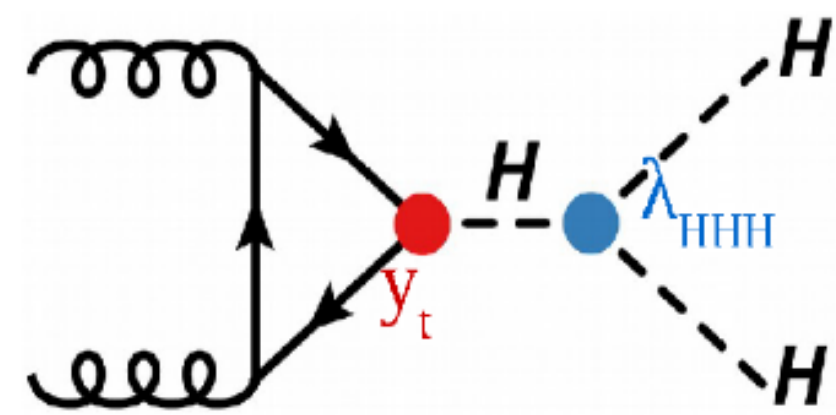


- 希格斯自相互作用是希格斯三类基本相互作用中唯一没有被实验证实的
- 希格斯自相互作用决定了希格斯势能的形状
(宇宙如何自发对称性破缺并赋予粒子质量)

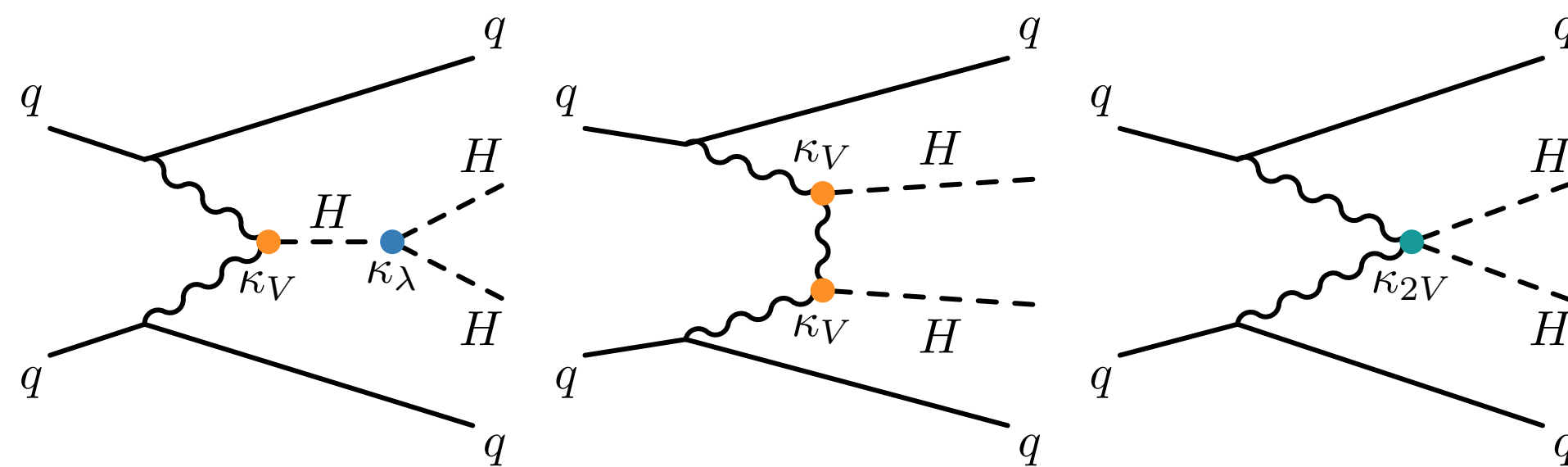
$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 h^3 + \frac{1}{4}\lambda_4 h^4$$

with $\lambda_3^{\text{SM}} = \lambda_4^{\text{SM}} = \frac{m_H^2}{2v^2}$

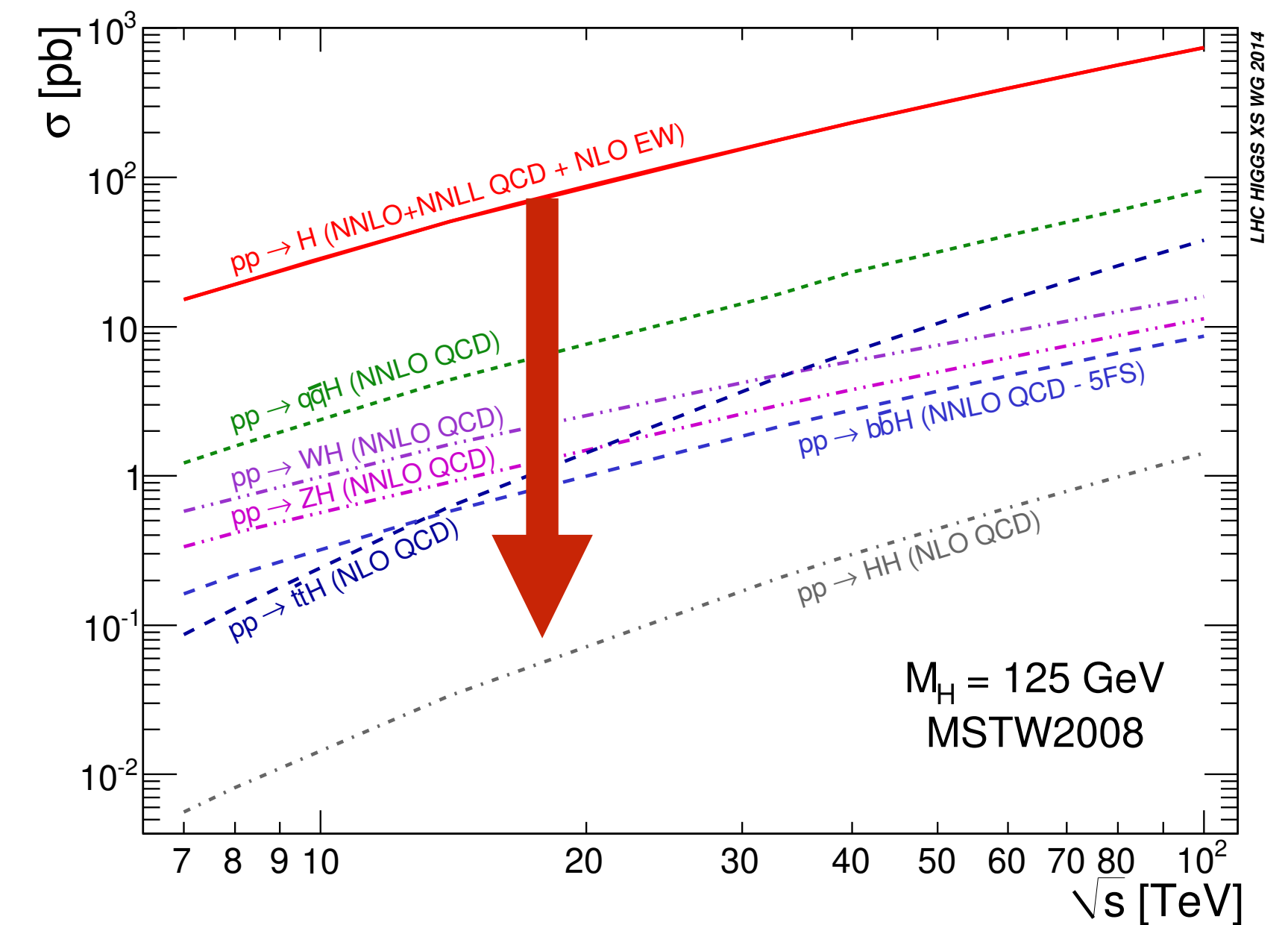
LHC实验上希格斯自相互作用的直接测量



NNLO $\sigma_{HH}(\text{ggF}) = 31.02^{+2.2\%}_{-5.0\%} (\text{Scale}) \pm 3.0\% (\alpha_s + \text{PDF}) \pm 2.6\% (m_{\text{top}}) \text{ fb}$



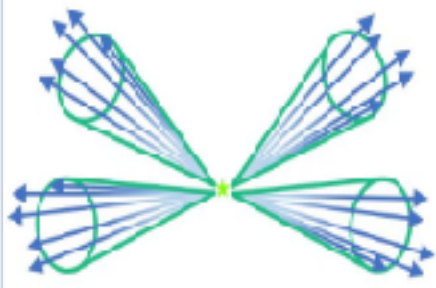
N3LO $\sigma_{HH}(\text{VBF}) = 1.72^{+0.03\%}_{-0.04\%} (\text{Scale}) \pm 2.1\% (\alpha_s + \text{PDF}) \text{ fb}$



- 通过HH产生过程直接测量希格斯三线自相互作用
- **挑战：** 稀有HH产生过程，产率比单希格斯过程低3个数量级 ($\sigma(\text{gg} \rightarrow \text{HH}) \sim 0.1\% \times \sigma(\text{gg} \rightarrow \text{H})$)

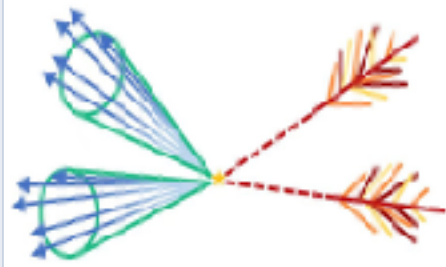
研究内容

$HH \rightarrow 4b$



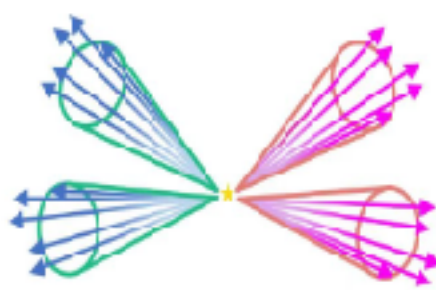
- ✓ 高分支比
- ✓ 但高QCD本底

$HH \rightarrow b\bar{b}\gamma\gamma$



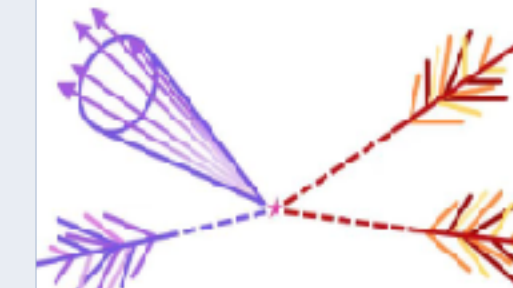
- ✓ 低分支比, 背景干净
- ✓ 可重建 $\gamma\gamma$ 质量峰

$HH \rightarrow b\bar{b}\tau\tau$



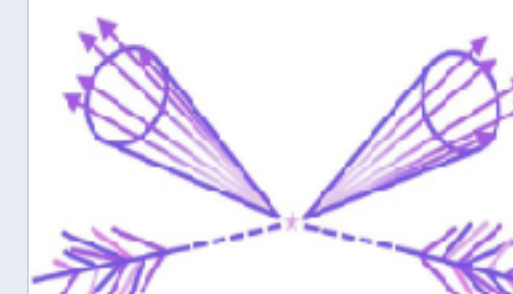
- ✓ 中等分支比
- ✓ 末态干净

$HH \rightarrow WW\gamma\gamma$



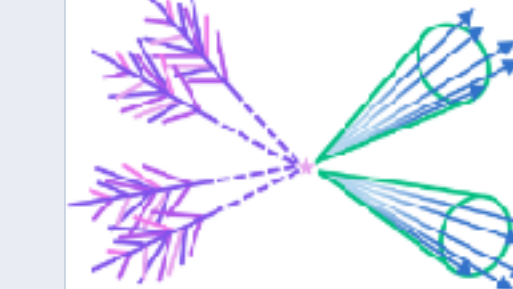
- ✓ 低分支比
- ✓ 低背景
- ✓ $\gamma\gamma$ 质量峰

$HH \rightarrow WWWW$



- ✓ 分为2LSS, 3L, 4L类
- ✓ 不同策略, 压低QCD

$HH \rightarrow ZZbb$



- ✓ ZZ 质量峰;
- ✓ 末态干净

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

基于LHC/ATLAS Run2和部分Run3高统计量的数据, 结合HH不同末态的优势, 开展HH寻找并探究希格斯自相互作用 (三个研究方向):

- ◆ 多底夸克末态HH截面测量: $H \rightarrow b\bar{b}$ 高分支比, $H \rightarrow \gamma\gamma$ 高信号效率和分辨, $H \rightarrow \tau\tau$ 高信噪比
- ◆ 多轻子末态HH截面测量: 提供HH研究的重要补充
- ◆ HH联合测量: 联合不同衰变模式, 以得到最灵敏的HH和希格斯自相互作用测量

课题3主要考核指标

- ❖ 多底夸克末态HH截面测量: HH截面预期上限达到 $2.7 \times \sigma_{\text{SM}}$
 - ⊙ 中期进展进展: $2.6 \times \sigma_{\text{SM}}$ 截面上限 (超出预计科学目标)
- ❖ 多轻子末态HH截面测量: HH截面测量预期上限达到 $12 \times \sigma_{\text{SM}}$
 - ⊙ 中期进展进展: $11 \times \sigma_{\text{SM}}$ 截面上限 (超出预计科学目标)
- ❖ HH 联测测量: HH截面测量预期上限达到 $2.4 \times \sigma_{\text{SM}}$
 - ⊙ 中期进展进展: $1.7 \times \sigma_{\text{SM}}$ 截面上限 (超出预计科学目标)

物理分析进展和考核指标完成情况

研究方向一：多底夸克末态HH截面测量 — $HH \rightarrow b\bar{b}\gamma\gamma$

优越性: 由于光子的高效率和良好分辨，通过双光子谱直接提取 $H \rightarrow \gamma\gamma$ 信号

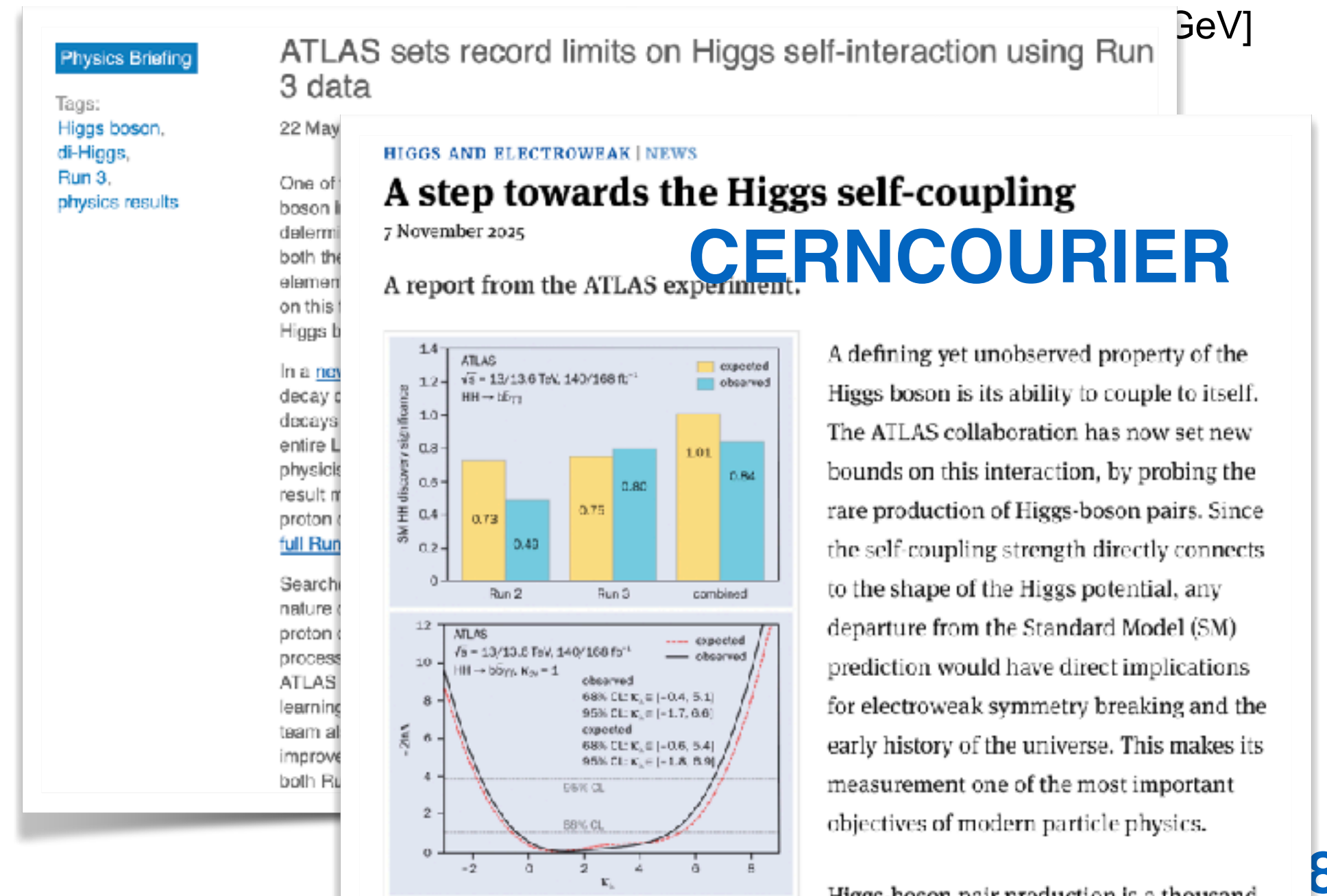
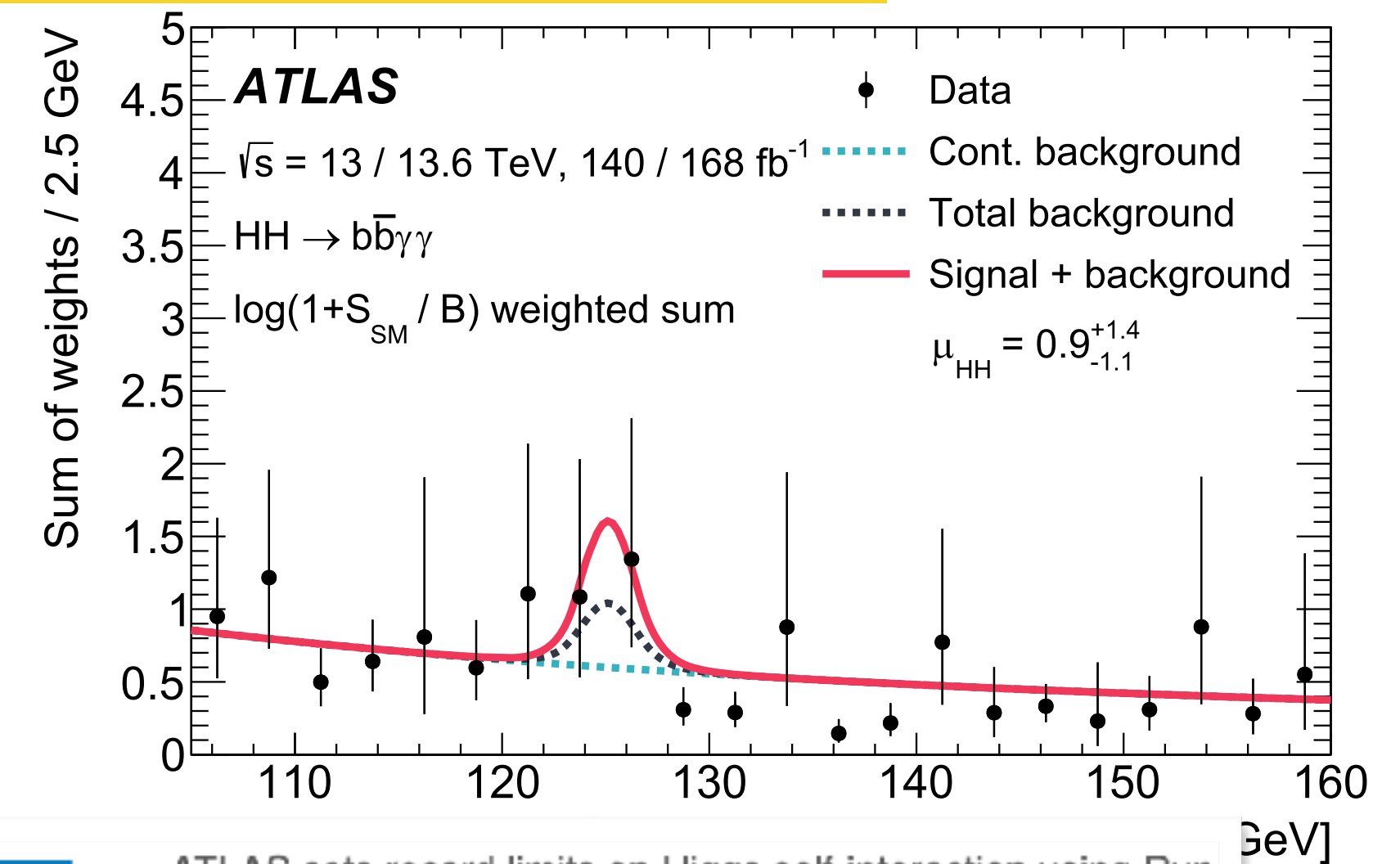
□ 完成Full-Run2 测量和 Run2+partial Run3 联合测量

- 首次HH单道显著性达到 1σ
- 分析方法策略的优化和更高的统计量数据，**显著提高灵敏度~90%**
- 观测(期望)HH截面上限值： **$3.7(2.6) \times SM$**
- 希格斯自耦合强度 κ_λ 束缚区间 $[-1.7, 6.6]$ ，与Run2 HH联合测量结果 $[-1.2, 7.2]$ 相当。

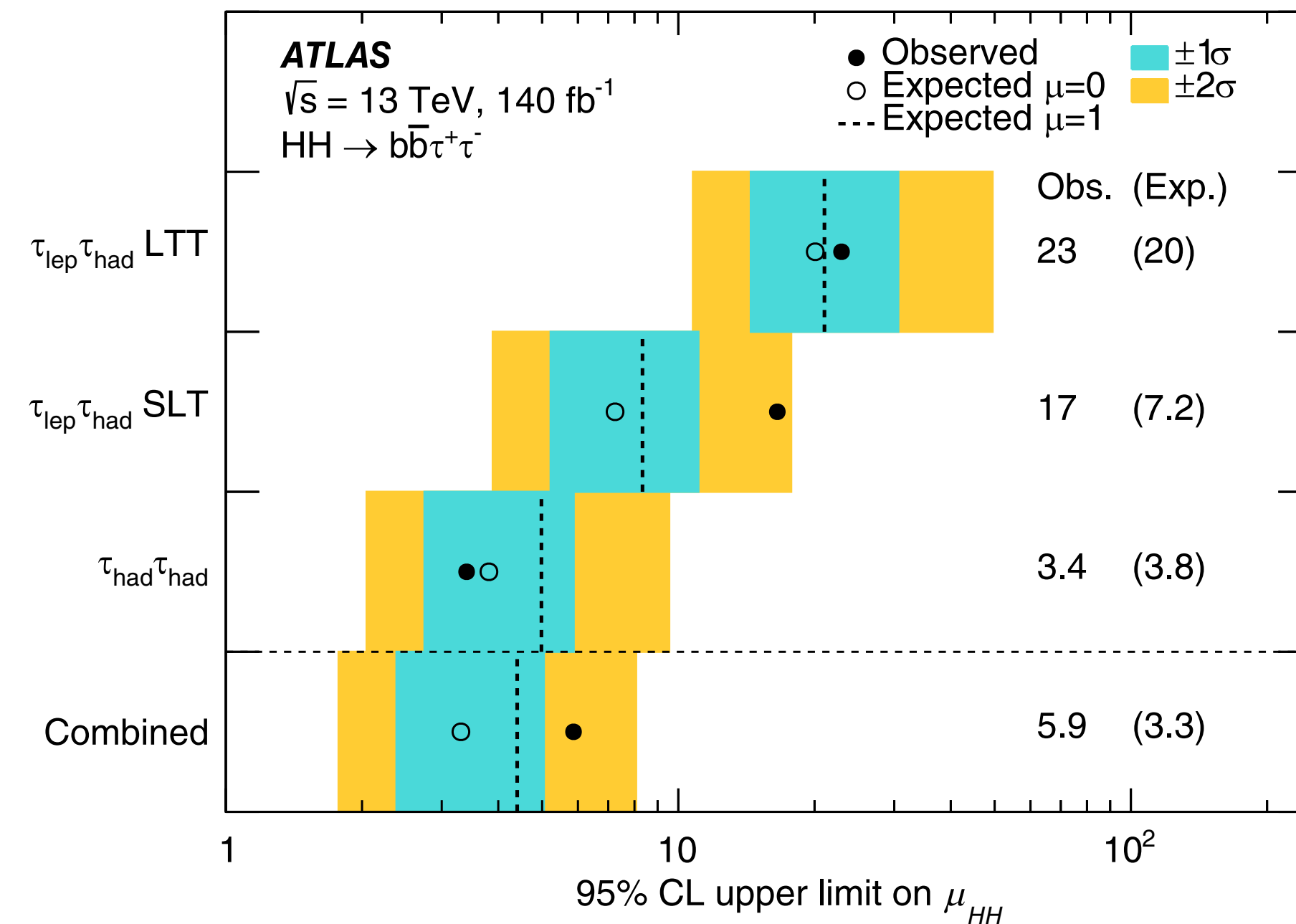
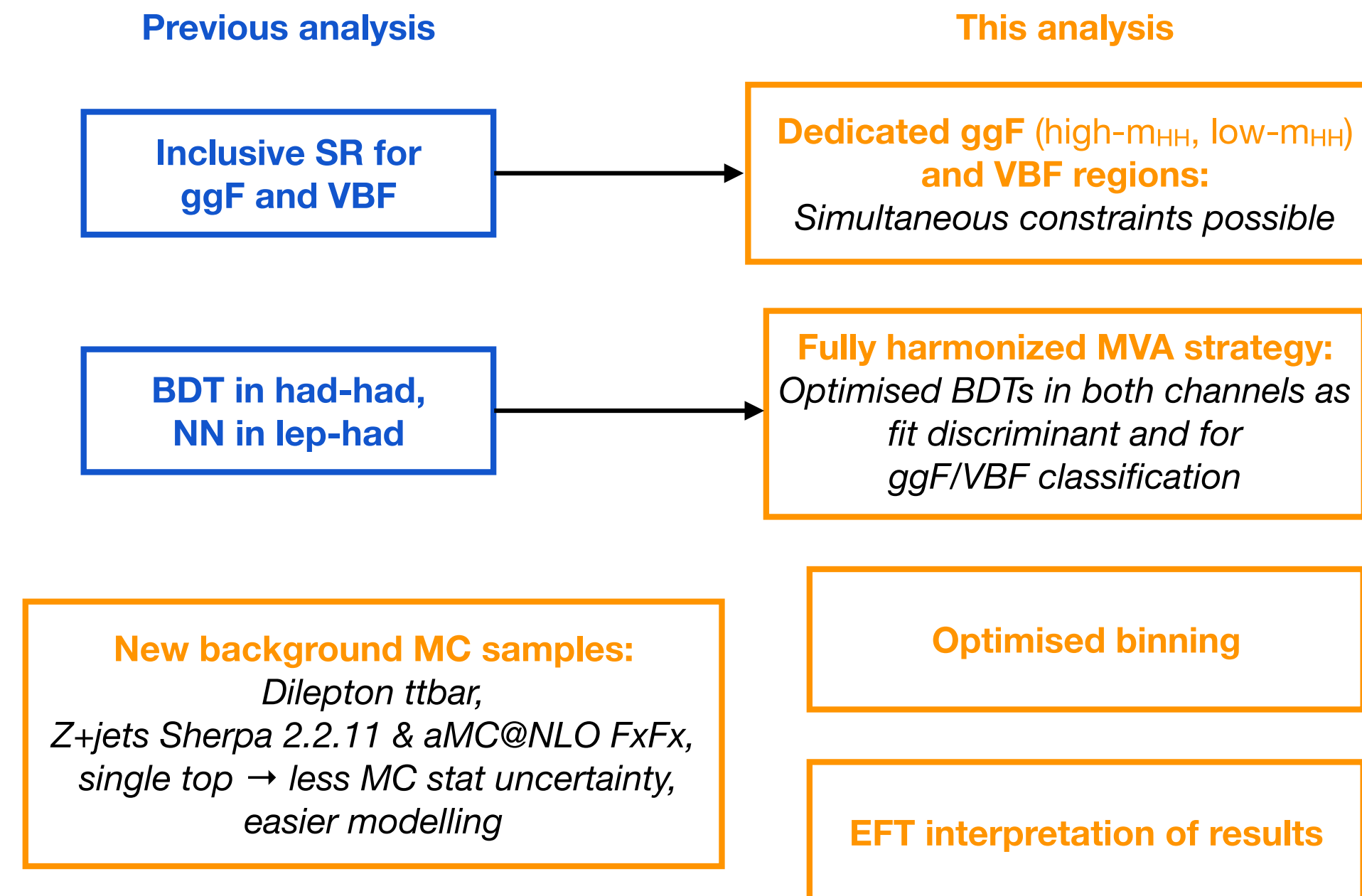
□ 发表两篇文章[JHEP 01 (2024) 066, PLB 876 (2026) 140280]，项目成员担任分析的负责人/内部编辑/ approval talk, **主导贡献**

□ 被ATLAS物理简报和CERNCourier报道

已提前达到预设考核指标(期望值上限 $2.7 \times SM$)



研究方向一：多底夸克末态HH截面测量 — $HH \rightarrow b\bar{b}\tau\tau$



□ 完成Full-Run2测量，发表一篇文章[PRD 110 (2024) 032012]

- **单道HH和 κ_λ 最灵敏测量：**截面观测(期望)上限值为 $5.9 (3.3) \times \sigma_{\text{SM}}$ ，自耦合强度 κ_λ 观测（期望）束缚区间为 $[-2.5, 9.3] ([-0.5, 2.7])$
- **由于分析的优化策略，HH截面测量和 κ_λ 的灵敏度分别提高为 15% 和11%**

研究方向一：多底夸克末态HH截面测量 — $HH \rightarrow b\bar{b}\tau\tau$

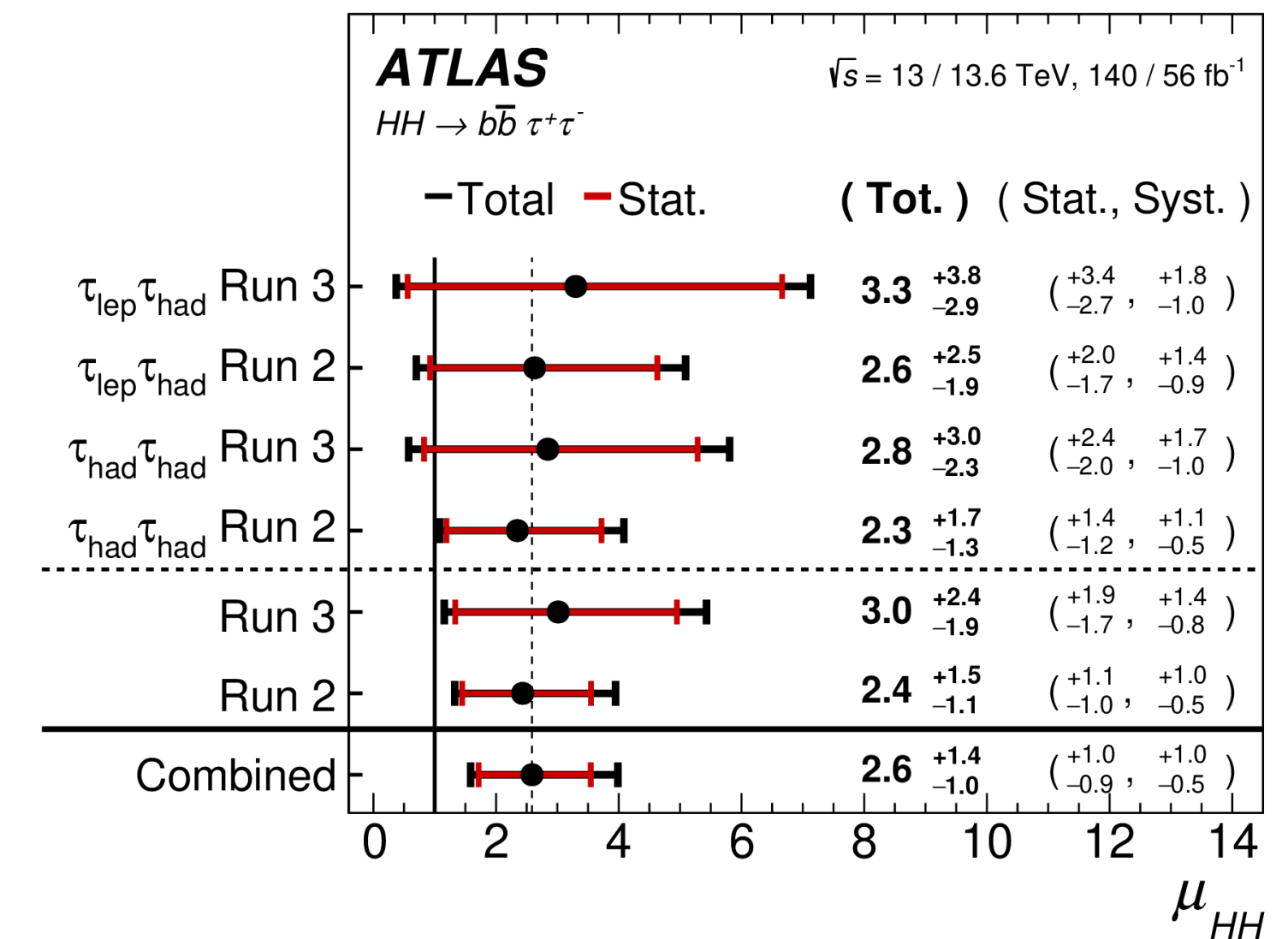
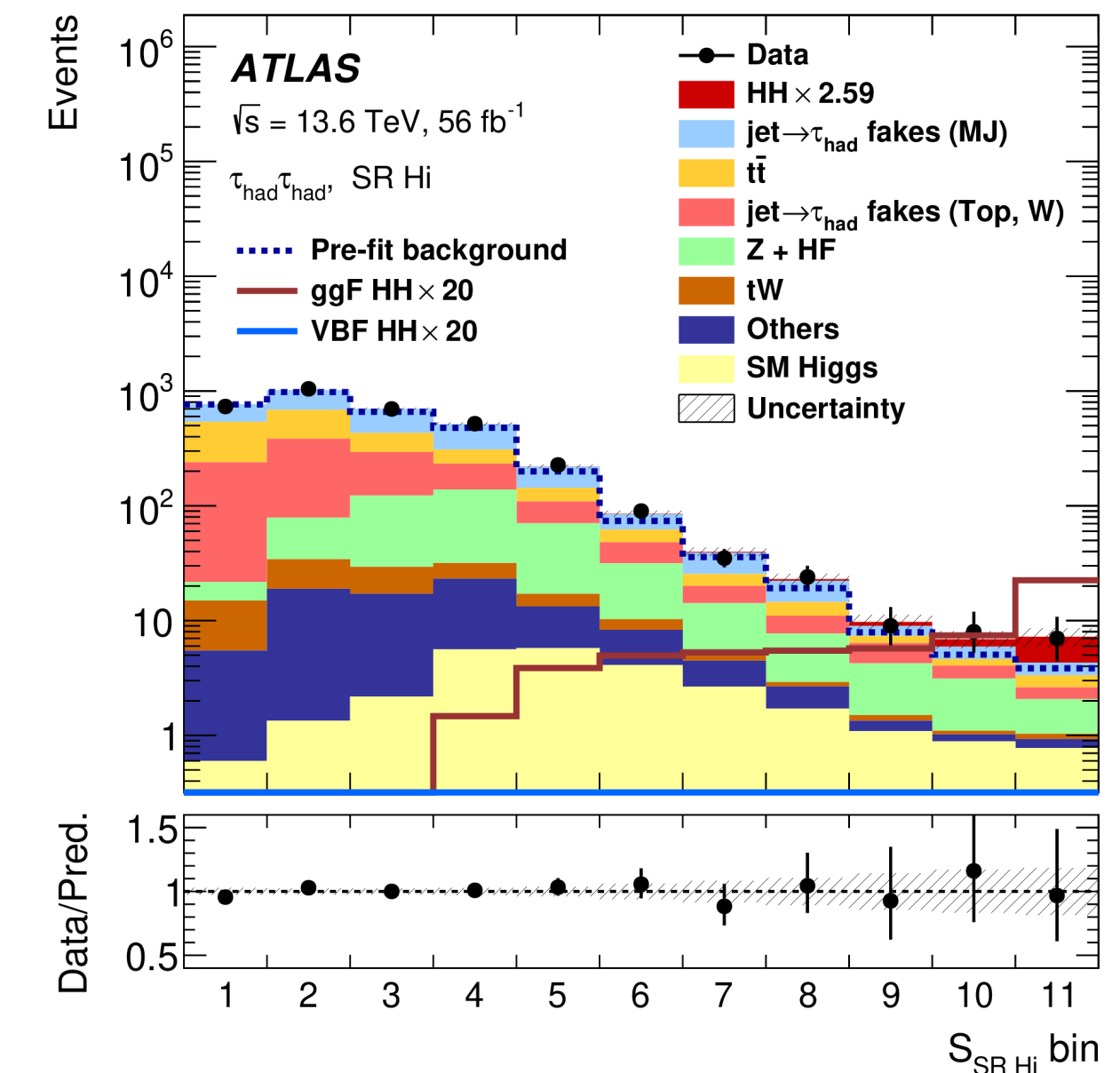
完成Full-Run2 测量和 Run2+partial Run3 联合测量

- 首次HH单道显著性达到**2.6(1.2) σ** (Run2 ATLAS-CMS combination: **1.3 σ** (exp))
- 观测(期望)HH截面上限值：**5.3(2.4) $\times$ SM**
- 希格斯自耦合强度 κ_λ 束缚区间 **$[-3.4, 1.6] \cup [5.5, 10.1]$ ($[-1.7, 8.5]$)**。
- Validation with **ZZ** ($0.64^{+0.39}_{-0.36}$) and **ZH** ($1.52^{+0.52}_{-0.48}$)?

发表文章[arxiv:2607.26879], , 贡献

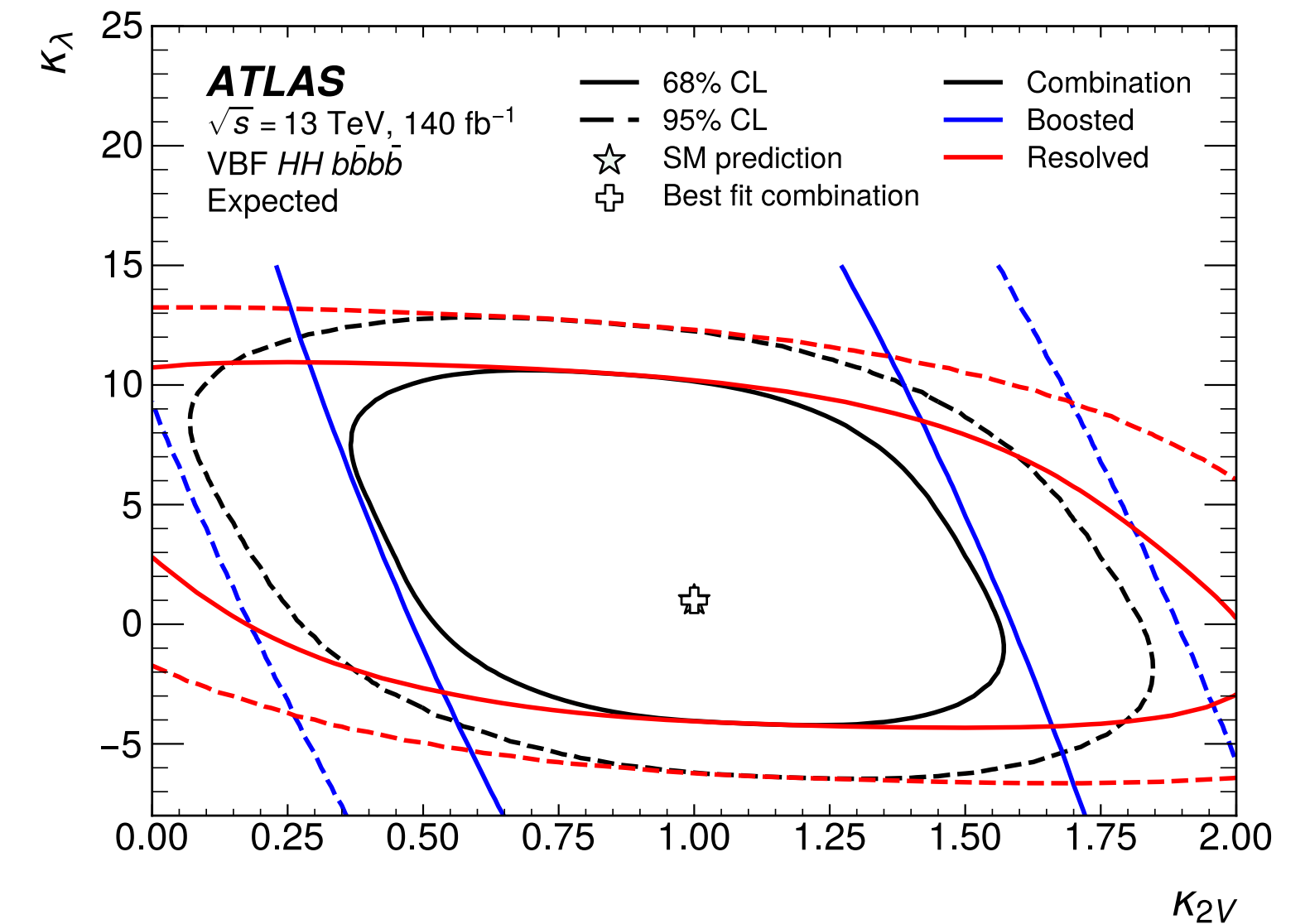
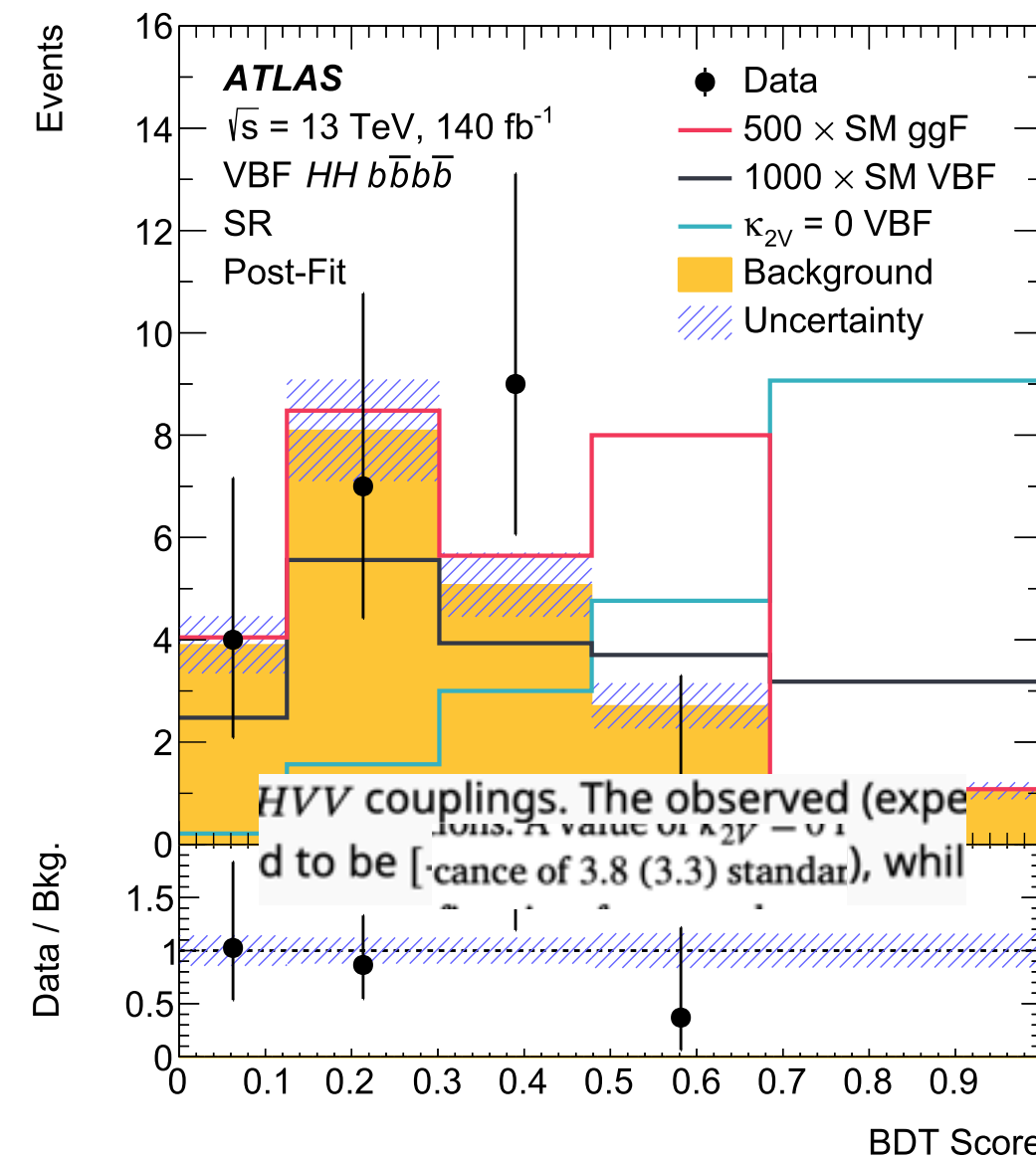
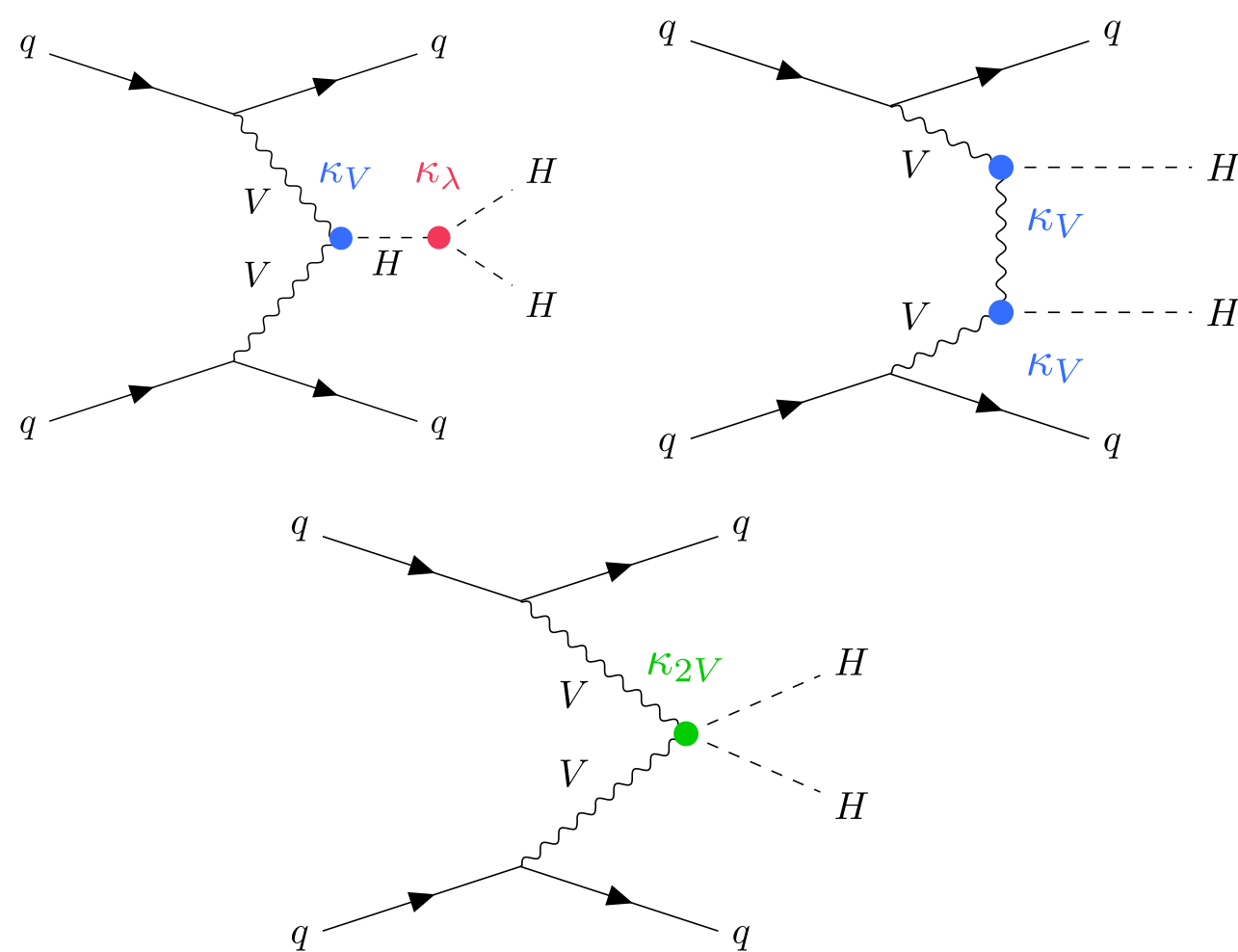
分析方法策略的优化和更高的统计量数据, 显著提高灵敏度

- Addition of Run3 data (15%)
- Improved flavor tagging (10%)
- Improved classification strategy (15-20%)



研究方向一：多底夸克末态HH截面测量 — $HH \rightarrow bbbb$

HH的最大衰变模式 $HH \rightarrow bbbb$ (58.2%)



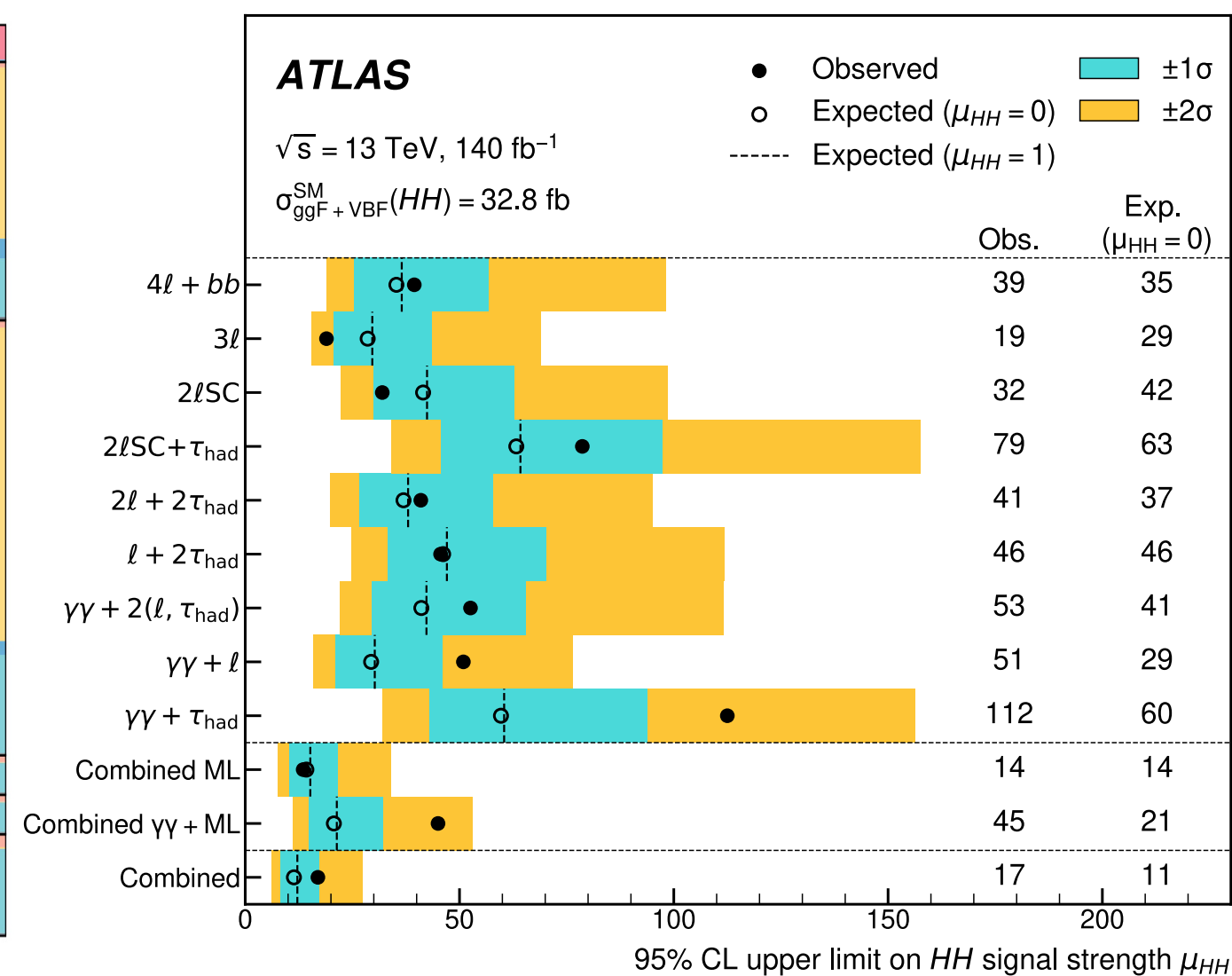
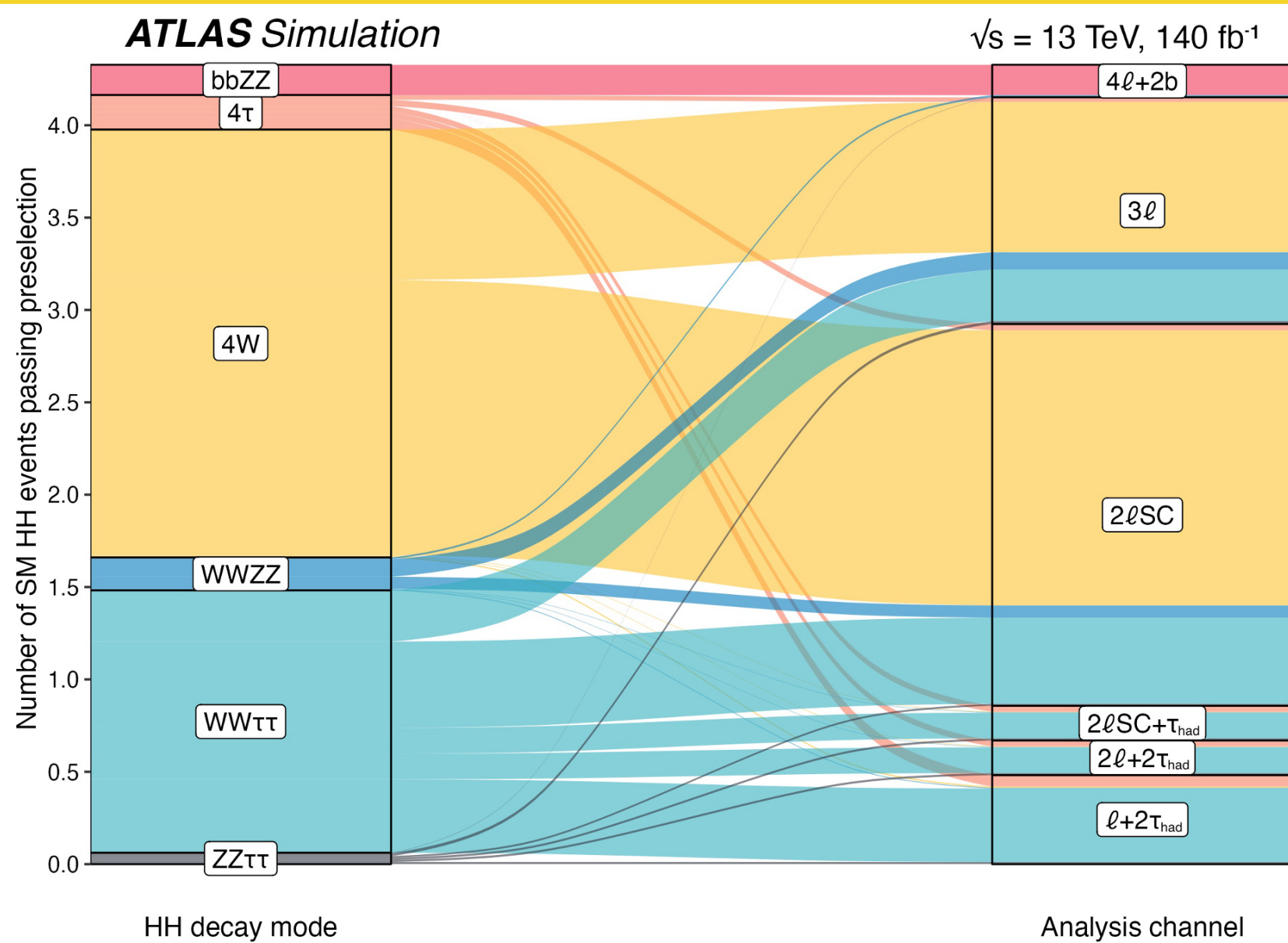
PLB 858 (2024) 139007

□ 完成Full-Run2 Boosted $HH \rightarrow bbbb$ 测量，发表一篇文章[PLB 858 (2024) 139007]

- 通过VBF HH产生模式直接探索HHVV耦合强度，通过resolved和boosted联合研究很好地约束 k_λ - k_{2V} 平面
- 希格斯自耦合强度 k_λ 保持resolved测量精度 (观测(期望)限制区间 $[-3.5, 11.3]$ ($[-5.4, 11.4]$))
- 观测到排除 $k_{2V}=0$ 的迹象,观测(期望)显著性为 $3.8(3.3)\sigma$ 。

研究方向二：多轻子末态HH截面测量— $HH \rightarrow \text{Multi-lepton}$

提供重要补充($HH \rightarrow bbZZ/4V/VV\tau\tau/4\tau/\gamma\gamma VV/\gamma\gamma\tau\tau$, 6.5% BR), 提高希格斯自耦合作用测量敏感度



JHEP 08 (2024) 164

Physics Briefing

Tags:
Higgs boson,
physics results,
di-Higgs

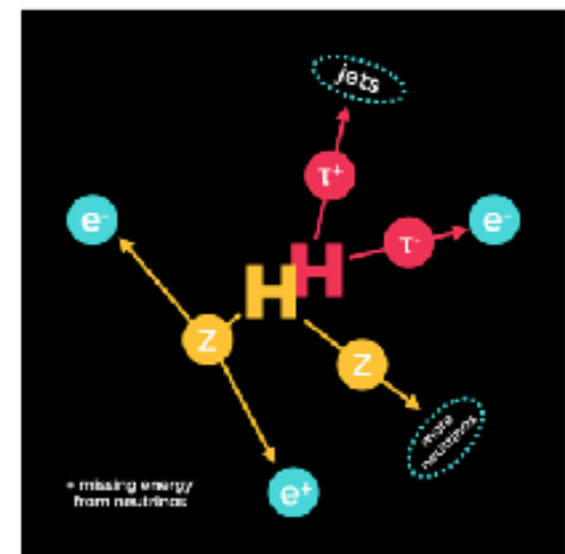
Menu of the day: Di-Higgs soup!

19 April 2024 | By ATLAS Collaboration

If spotting one Higgs boson is interesting, what happens when you spot two at the same time? Well, imagine the Higgs boson as a special magnet. With just one magnet, you can learn how it interacts with different materials like wood or iron. But with two magnets, you can investigate how they interact with each other. Similarly, by investigating how pairs of Higgs bosons are created and how they behave, physicists can uncover secrets about the Higgs boson itself and learn about its role in the Universe.

When a Higgs boson is produced, it decays almost immediately to other particles. In previous ATLAS analyses, researchers searched for di-Higgs production by looking for specific Higgs-boson decays. For instance, they focused on one Higgs boson decaying to a pair of bottom (b) quarks, while the other decayed to a pair of photons (γ). This method can work well when both Higgs bosons can be easily reconstructed.

Yet the many possible decay processes of the Higgs boson present a challenge to this approach. Higgs bosons can also decay into two W bosons, two Z bosons, or two tau leptons (τ). These particles in turn decay into electrons, muons, quarks (which

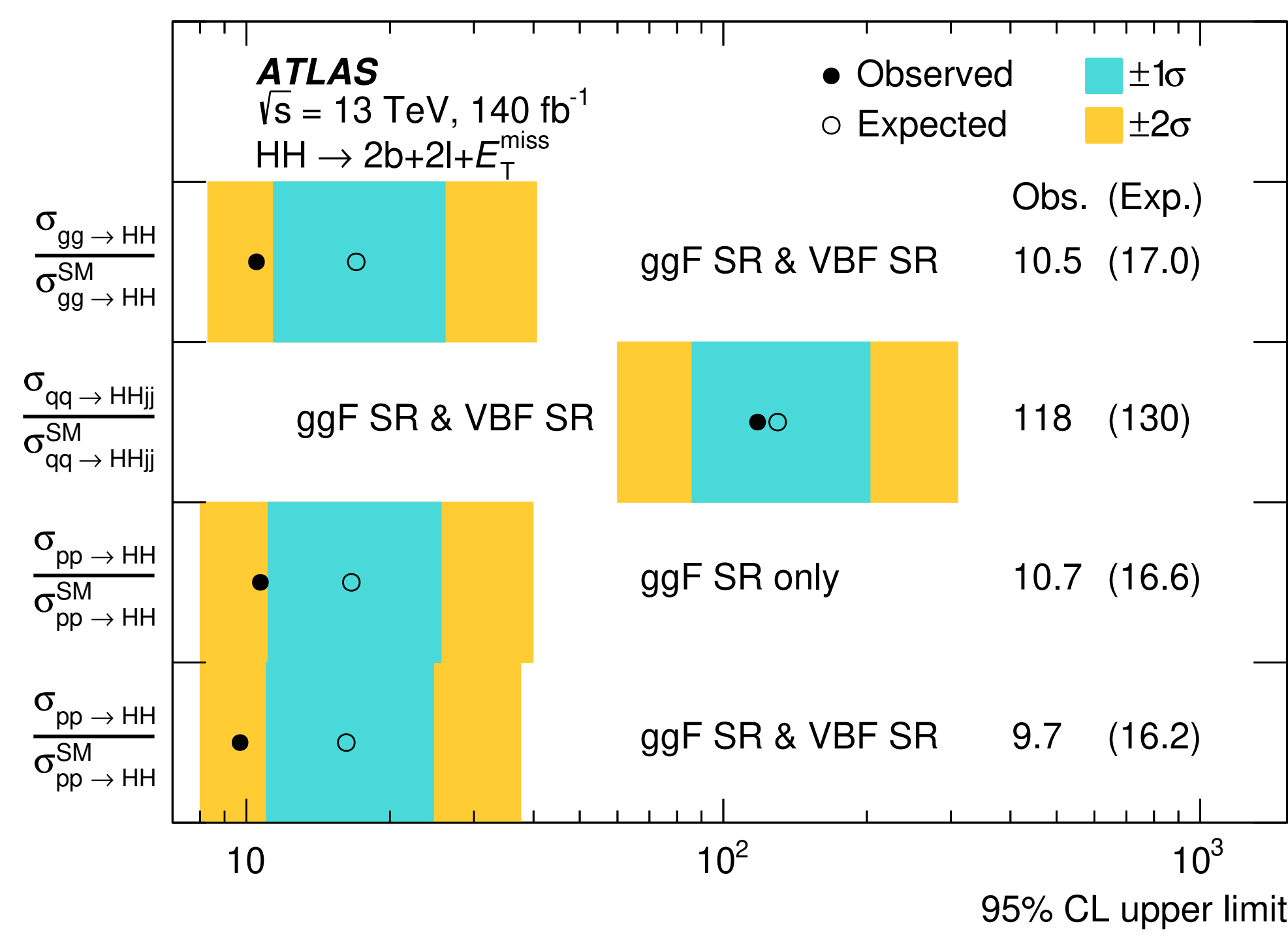
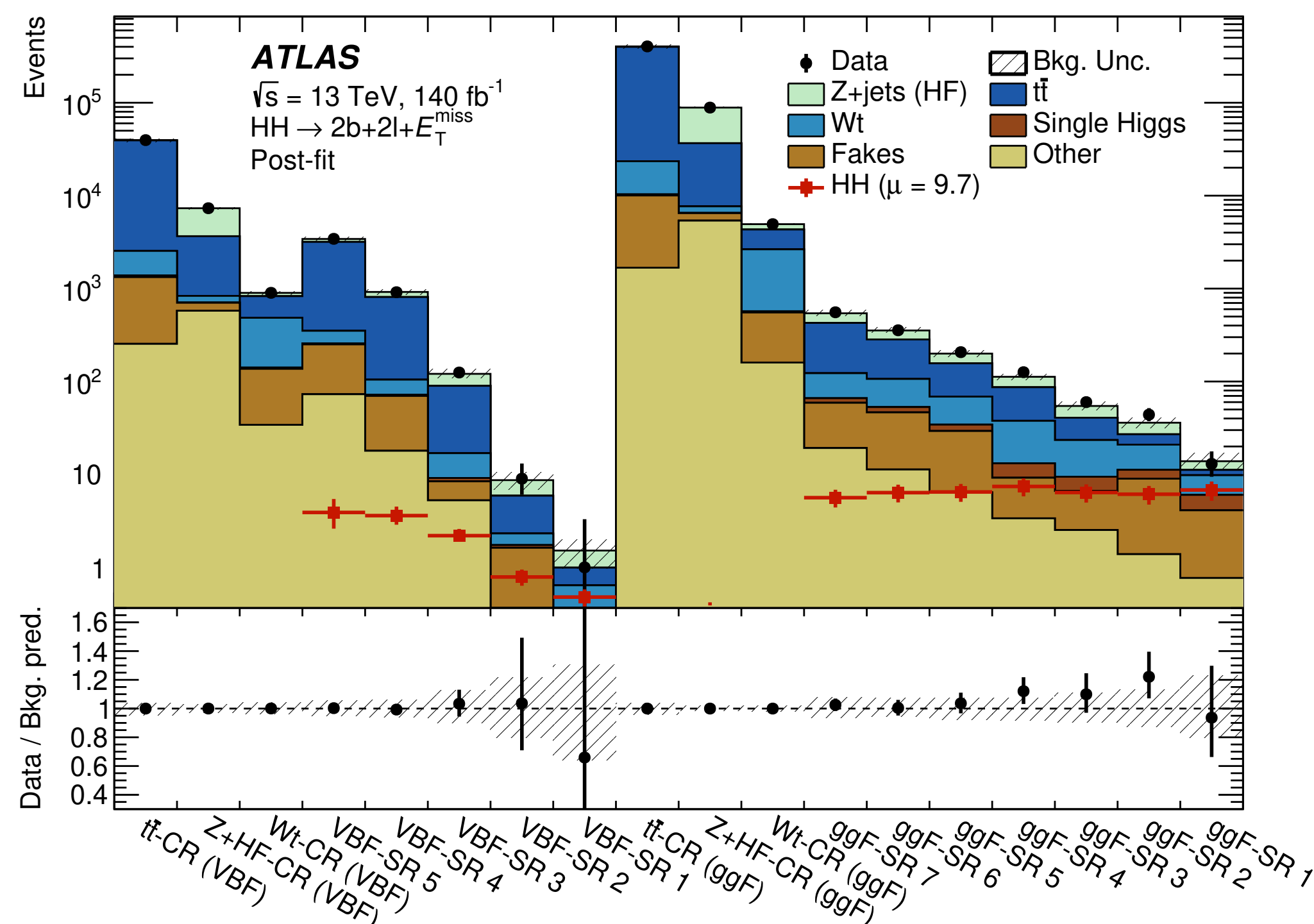


□ 完成Full-Run2, 发表一篇文章[JHEP 08 (2024) 164], 项目成员担任分析的负责人/编辑/approval talk, 主导贡献

- 首次探索多轻子末态: 探索希格斯更多的衰变模式 (ML+ $\gamma\gamma$ +ML), 采用“混合”测量方案
- 测量HH截面, 观测(期望)上限值为 **17 (11) $\times \sigma_{\text{SM}}$**
- 希格斯自耦合强度 k_λ 观测(期望)限制区间[-6.2, 11.6]([-4.5, 9.6])。
- 被ATLAS物理简报报道

已提前达到预设考核指标(期望值上限12 $\times$ SM)

研究方向二：多轻子末态HH截面测量— $HH \rightarrow bbl + E_{T,miss}$

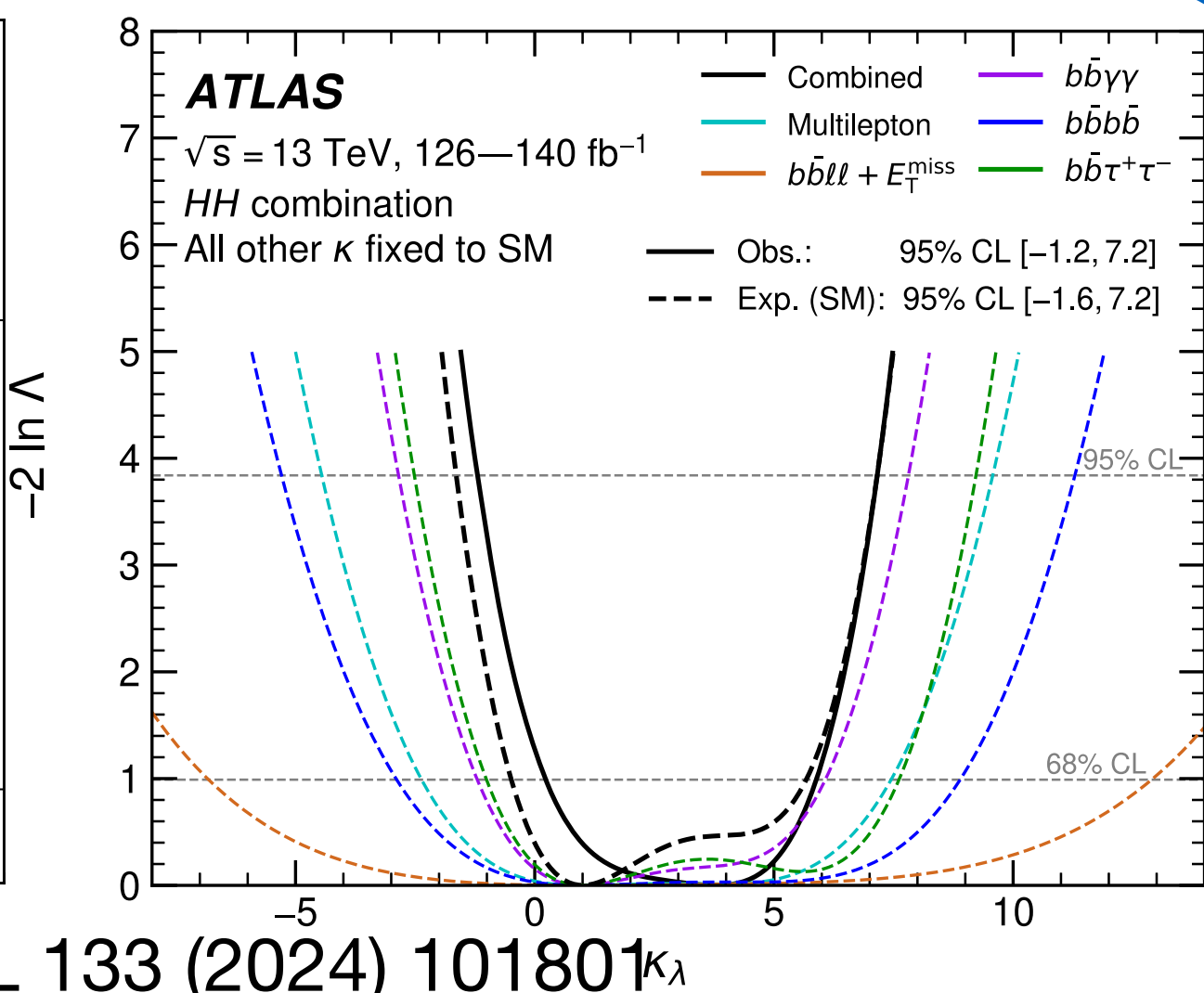
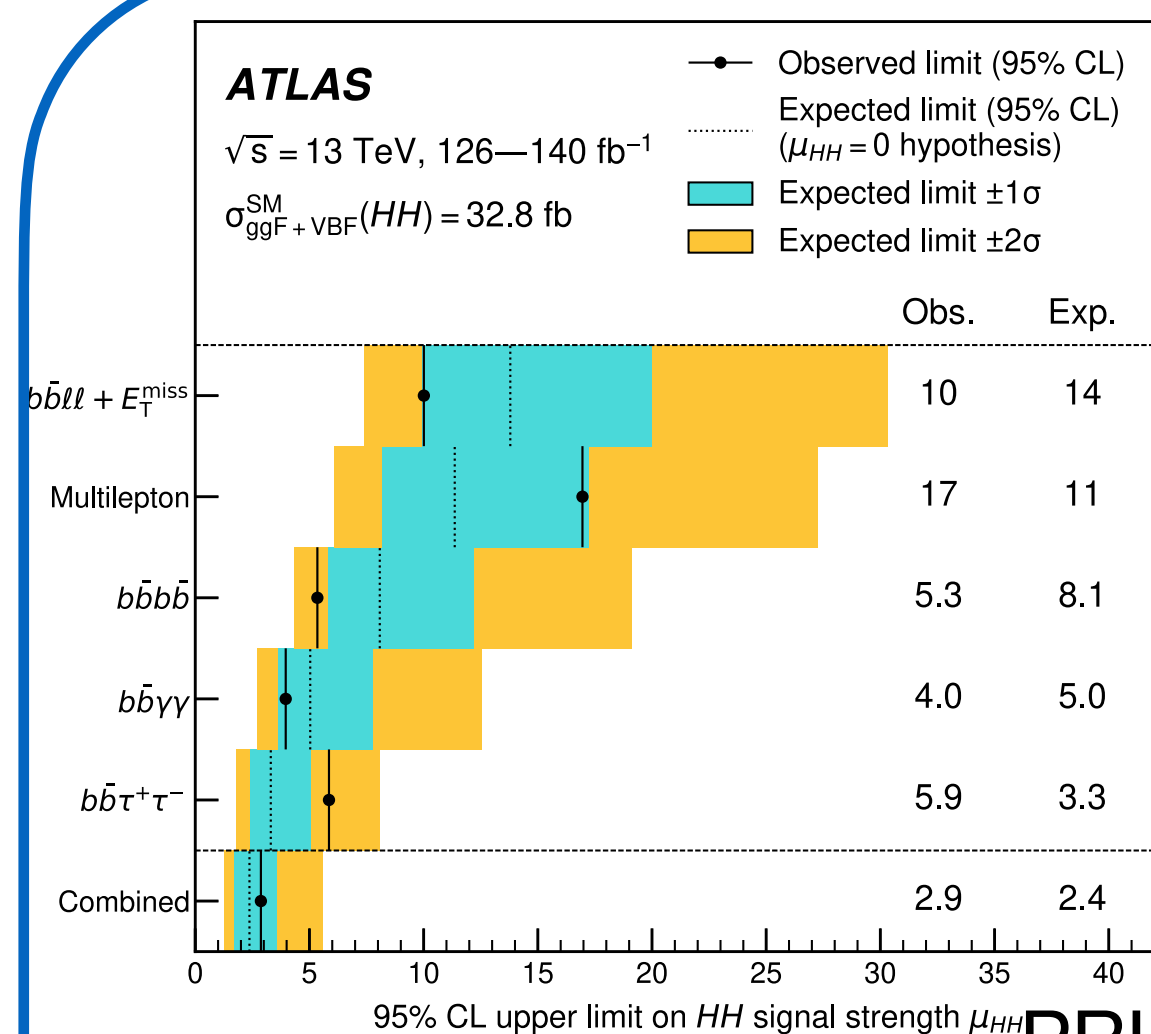


- 完成Run2 $HH \rightarrow bbl + E_{T,miss}$ ($HH \rightarrow bb + WW^*/ZZ^*/\tau^+\tau^- \rightarrow bbl + n\nu$)
- DNN优化提高信号显著性一倍，并首次引入VBF产生模式
 - 观测(期望)HH截面上限值：**9.7(16.2) × SM**
 - 希格斯自耦合强度 k_λ 观测(期望)束缚区间[-6.2, 13.3]([-8.1, 15.5])
 - 发表一篇文章 [JHEP 02 (2024) 037]，项目成员担任分析的负责人/编辑/approval talk，主导贡献

已提前达到预设考核指标(期望值上限12× SM)

研究方向三：HH联合测量

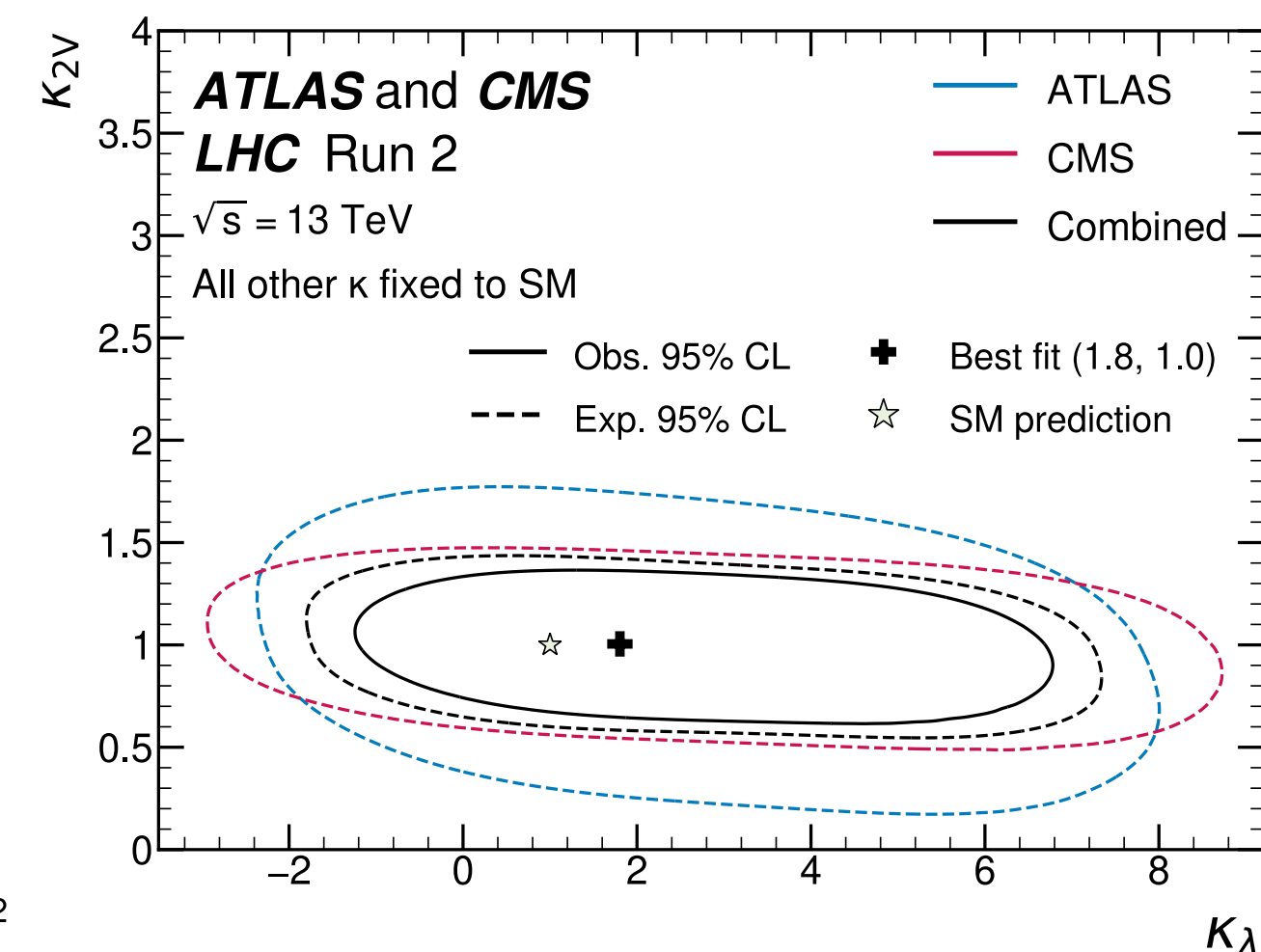
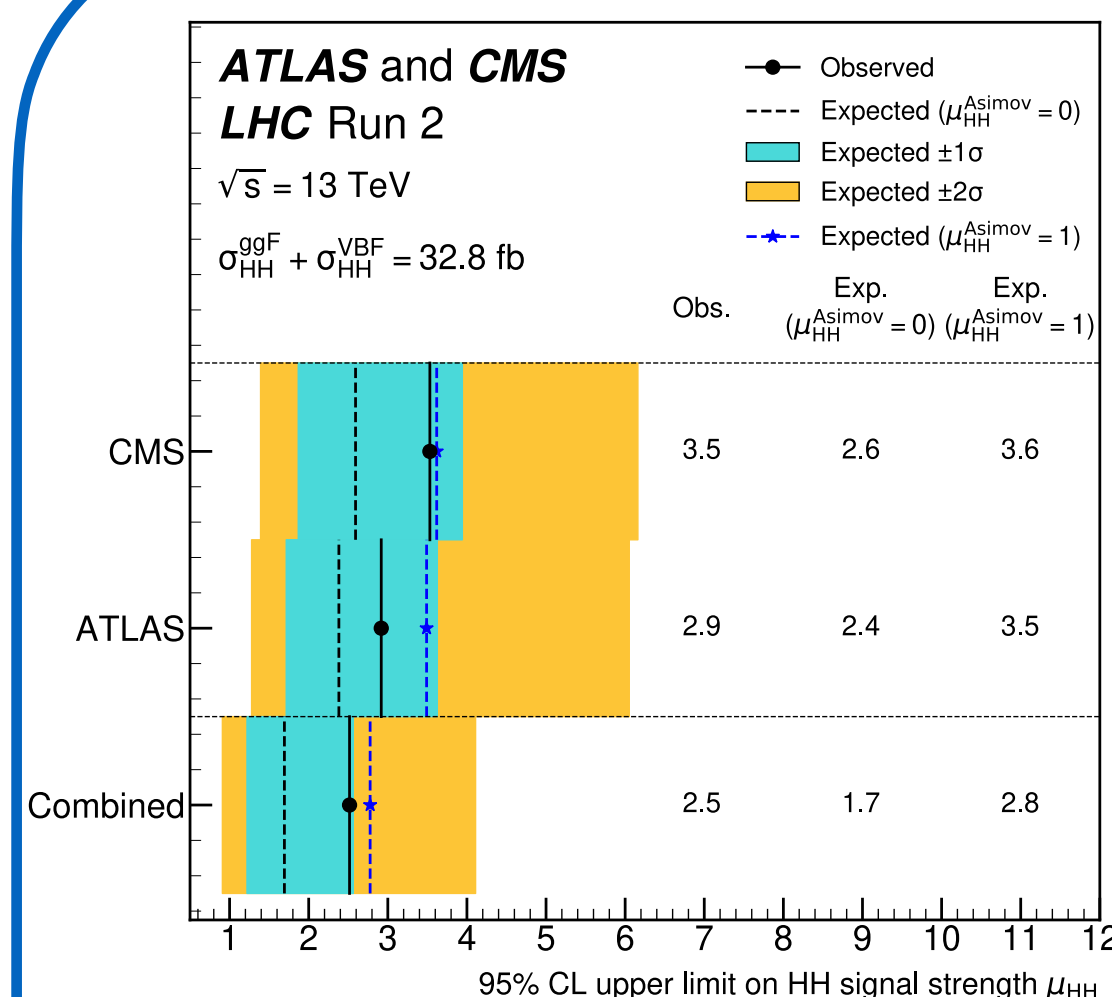
通过多衰变模式的联合研究，给出最灵敏的HH测量



PRL 133 (2024) 101801

完成首个ATLAS HH更多衰变联合测量：

- 全面细致考虑不同衰变模式的重叠效应和系统关联
- 观测(期望)HH截面上限值: **2.9(2.4) × SM**
- 希格斯自耦合强度 κ_λ 观测(期望)束缚区间[-1.2, 7.2]([-1.6, 7.2])
- 发表文章[PRL 133 (2024) 101801], 项目成员担任分析的负责人/内部编辑/approval talk, 主导贡献
- 被ATLAS物理简报和CERN Courier报道



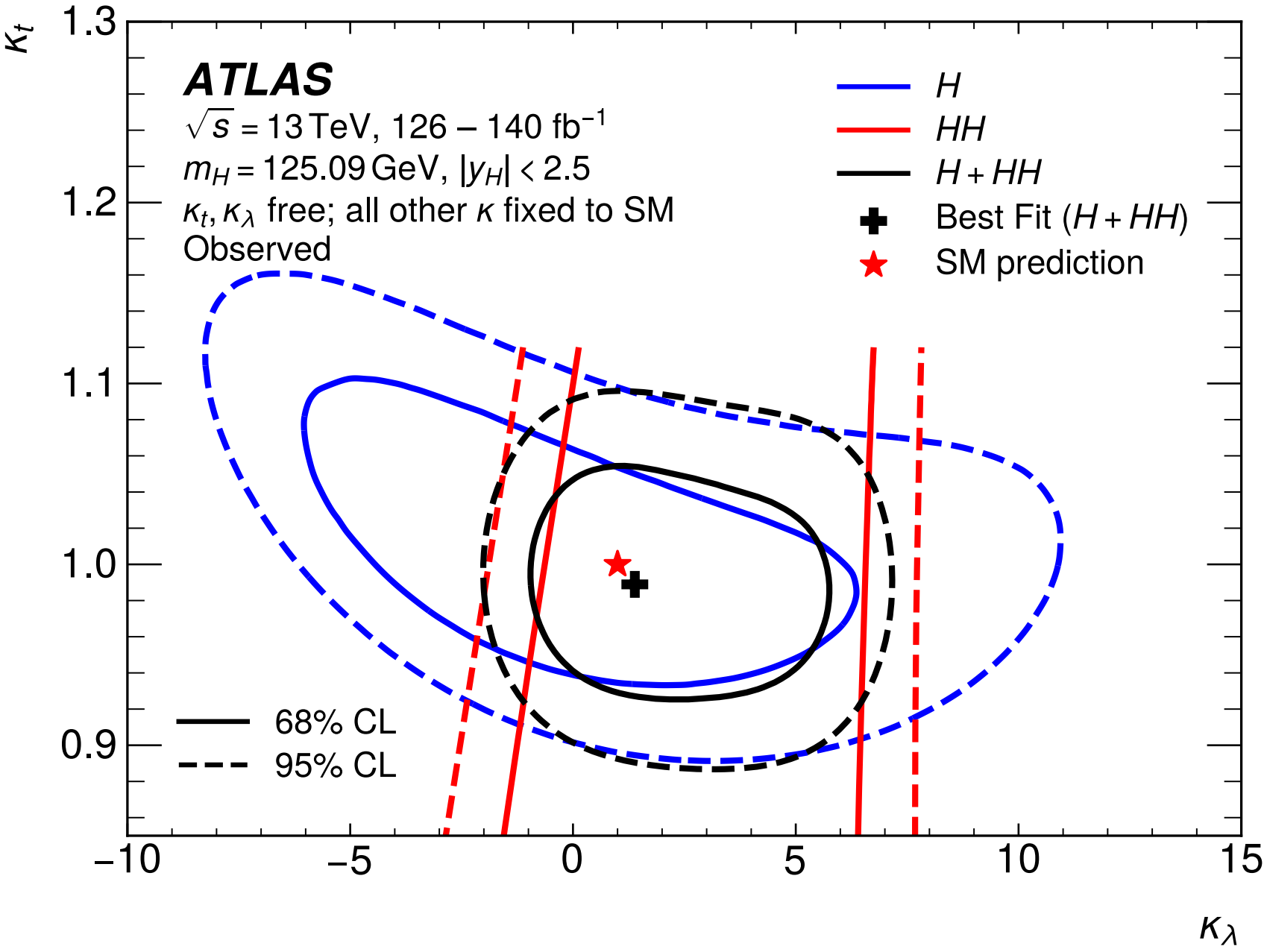
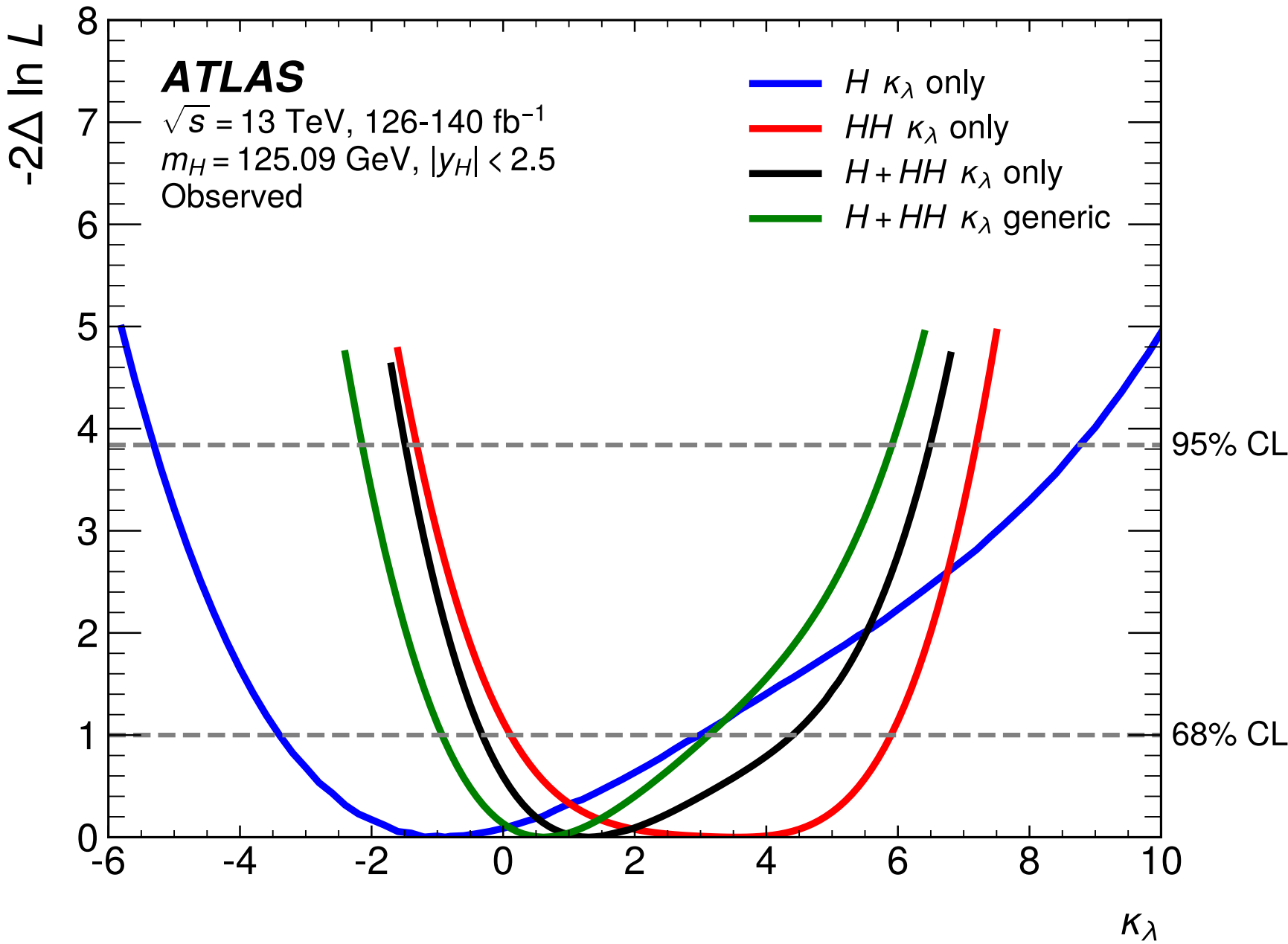
arXiv:2602.23991

完成首个ATLAS-CMS HH联合测量：

- 解决ATLAS-CMS联合框架兼容关键技术
- 观测(期望)HH截面上限值和显著性: **2.5(1.7) × SM, 1.1(1.3)σ**
- 希格斯自耦合强度 κ_λ 观测(期望)束缚区间[-1.2, 7.2]([-1.6, 7.2])
- 文章已被PRL接收, 项目成员担任convener/分析负责人/内部编辑/approval talk, 主导贡献

已提前达到预设考核指标(期望值上限2.4 × SM)

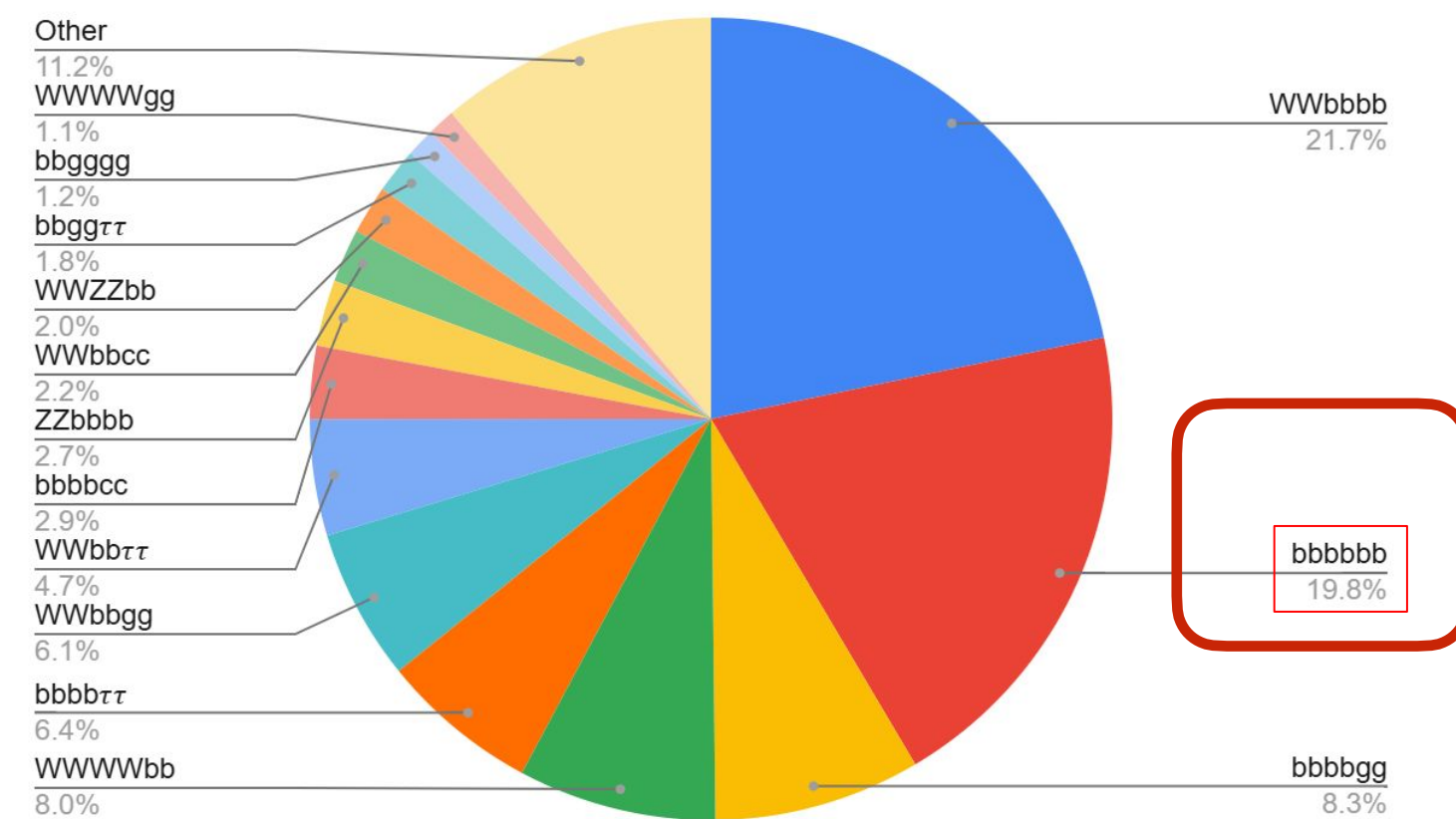
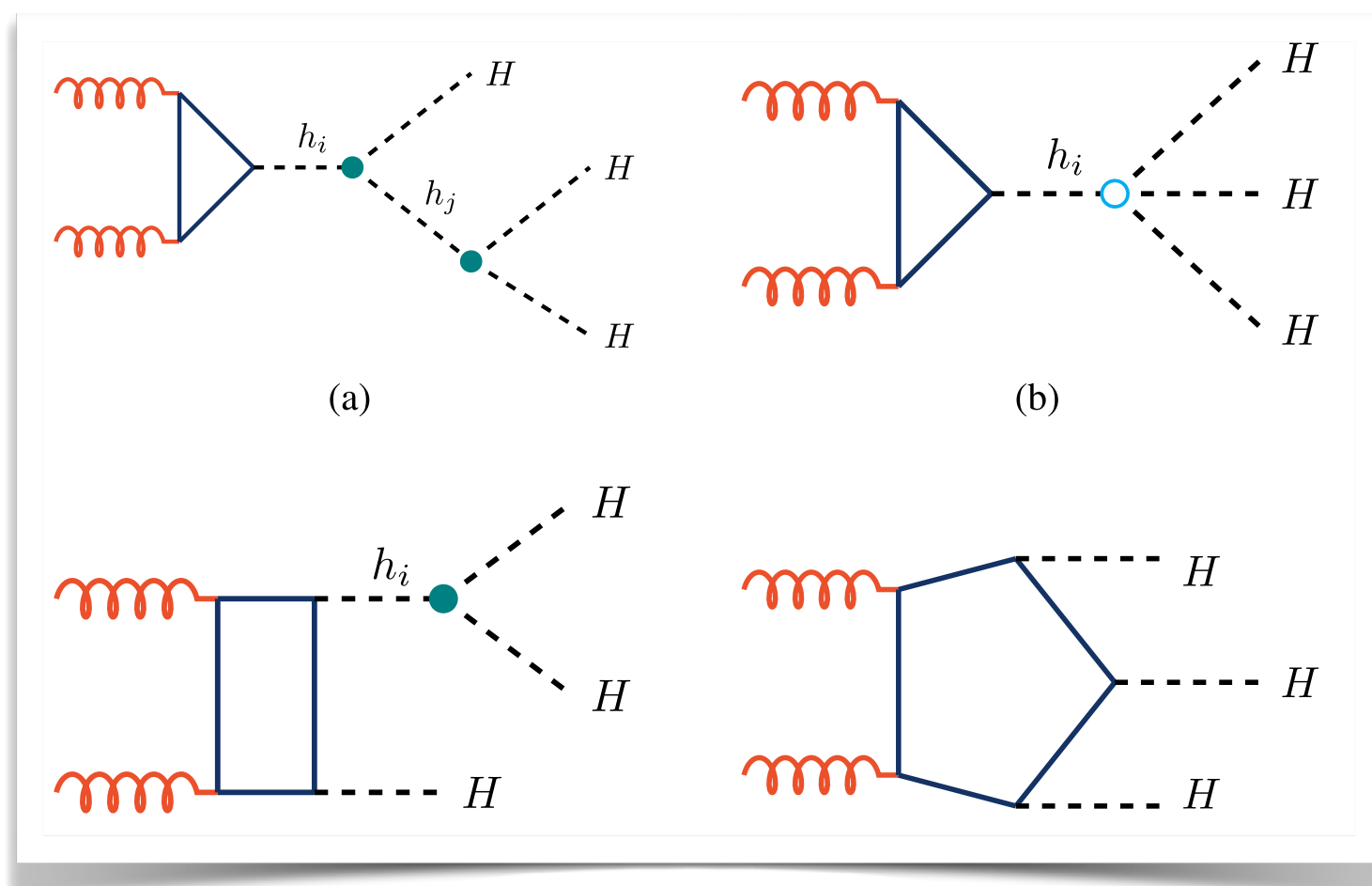
研究方向三：H-HH联合测量



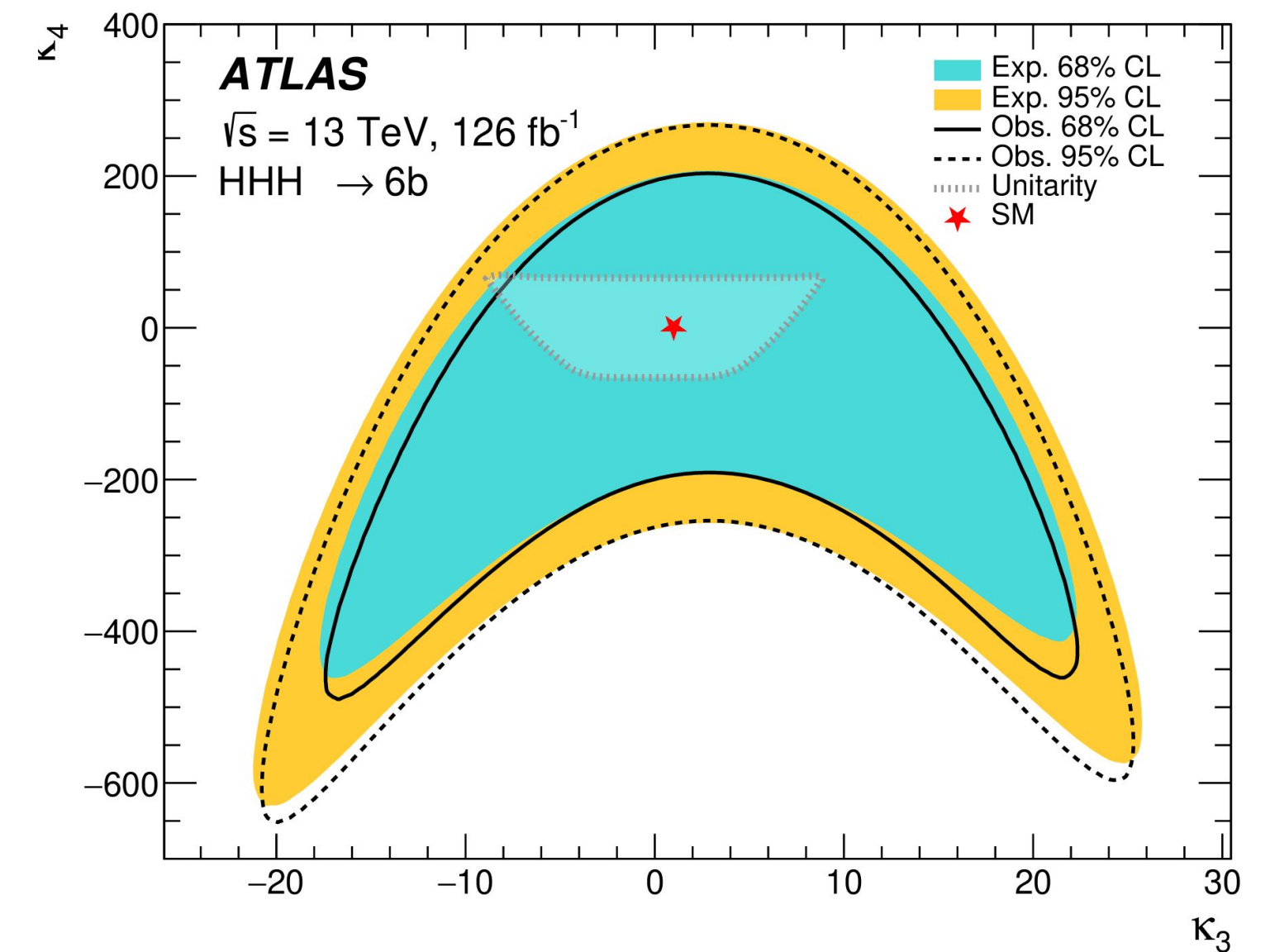
Fit	Best fit	68% CL interval	95% CL interval
Single-Higgs	$-0.9^{+3.9}_{-2.5}$	$[-3.4, 3.0]$	$[-5.3, 8.8]$
Di-Higgs	$3.5^{+2.4}_{-3.4}$	$[0.1, 5.9]$	$[-1.3, 7.2]$
H+HH (others fixed)	$1.3^{+3.1}_{-1.6}$	$[-0.3, 4.4]$	$[-1.5, 6.5]$
H+HH (generic)	$0.6^{+2.5}_{-1.5}$	$[-0.9, 3.1]$	$[-2.1, 5.9]$

10% contribution from H combination
arxiv: 2608.07332

任务书以外的相关研究内容



PRD 111 (2025) 032006



□ 通过 $HHH \rightarrow 6b$ 过程 (19.8%)，首次测量四线Higgs自耦合强度：

- 观测(期望)HHH截面上限值：760 (750) $\times$ SM
- 希格斯自耦合强度 k_λ 观测(期望)束缚区间[-11, 17]([-11, 17])
- 希格斯自耦合强度 k_4 观测(期望)束缚区间[-230, 240]([-230, 240])
- 发表一篇文章 [PRD 111 (2025) 032006]，项目成员担任分析的负责人，主导贡献

文章发表情况

1. Studies of new Higgs boson interactions through nonresonant HH production in the bbgg final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, JHEP 01 (2024)066
2. Search for the nonresonant production of Higgs boson pairs via gluon fusion and vector-boson fusion in the bb tautau final state in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D 110 (2024) 032012
3. Search for pair production of boosted Higgs bosons via vector-boson fusion in the bb^-bb^- final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B 858 (2024) 139007
4. Search for non-resonant Higgs boson pair production in the 2b+2l+ETmiss final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, JHEP 02 (2024) 037
5. Search for non-resonant Higgs boson pair production in final states with leptons, taus, and photons in pp collisions at $s = 13$ TeV with the ATLAS detector, JHEP 08 (2024) 164
6. Combination of Searches for Higgs Boson Pair Production in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector, PRL133(2024) 101801
7. Search for triple Higgs boson production in the 6b final state using pp collisions $\sqrt{s} = 13$ TeV with the ATLAS detector, PRD 111(2025) 032006
8. Study of Higgs boson pair production in the $HH \rightarrow bby\gamma$ final state with 308 fb⁻¹ of data collected at $\sqrt{s} = 13$ TeV and 13.6 TeV by the ATLAS experiment, PLB 876 (2026) 140280
9. Combination of ATLAS and CMS searches for Higgs boson pair production at $\sqrt{s} = 13$ TeV, arXiv:2602.23991 (PRL)

已发表9+2篇期刊文章

下一步工作安排

□ 已完成课题2终期考核指标，**将进一步提高HH和希格斯自耦合强度测量精度**

□ 围绕课题目标，结合分析的复杂度，基于Partial Run3的高统计量数据完善课题研究内容：

- **多底夸克末态HH截面测量：** $HH \rightarrow b\bar{b}\tau\tau$ (Partial Run3), $HH \rightarrow b\bar{b}b\bar{b}$ (Partial Run3)
- **多轻子末态HH截面测量：** $HH \rightarrow b\bar{b}l\bar{l} + E_{T,\text{miss}}$ (Partial Run3) , $HH \rightarrow \text{Multi-lepton}$ (Partial Run3)
- **HH联合测量：** $HH+H$ (Run2), 每个子衰变模式的Run2+Partial Run3联合研究

组织管理和经费使用情况

□ 按项目计划，组织和参加课题相关学术交流讨论

□ 经费完成度为106%

- 中期计划执行数：210万

- 已执行数：223.2万

□ 劳务费严重超额

- 劳务费已全部用完

科目名称	执行数(万)
业务费	109.7
劳务费	70.3
间接费	43.2
总费用	223.2

总结

□ 围绕课题2的研究目标和内容，按计划组织研究任务：

- ◎ 研究方向一（多底夸克末态）：基于Partial Run3数据和 $bb\gamma\gamma$ 末态，完成首个Run3 HH测量
- ◎ 研究方向二（多轻子末态）：完成首次多轻子末态混合测量
- ◎ 研究方向三（HH联合测量）：完成首个ATLAS-only HH联合测量，首次实现ATLAS-CMS HH联合测量
- ◎ 发表11篇期刊文章（2篇PRL，最近投送2篇）
- ◎ 圆满提前达到课题预设考核指标

□ 课题组织/管理、人才培养等各方面情况良好

□ 经费使用情况良好，执行率为106%

