

在ATLAS实验上利用双光子末态寻找标准模型希格斯粒子的VBF产生机制



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博士论文答辩
2019年11月15日

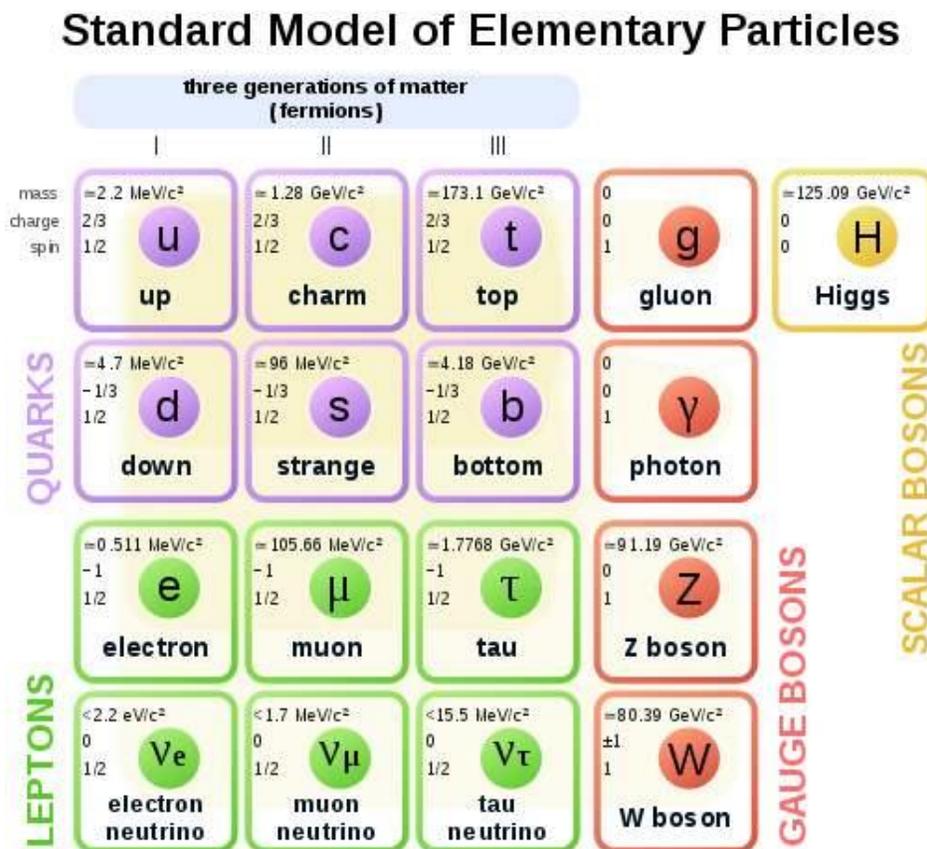


提纲

- 理论背景
- LHC和ATLAS探测器
- 粒子重建、鉴别、刻度
- 事例筛选和子类优化
- 信号建模
- 背景建模
- 系统误差
- 统计解释
- 结果

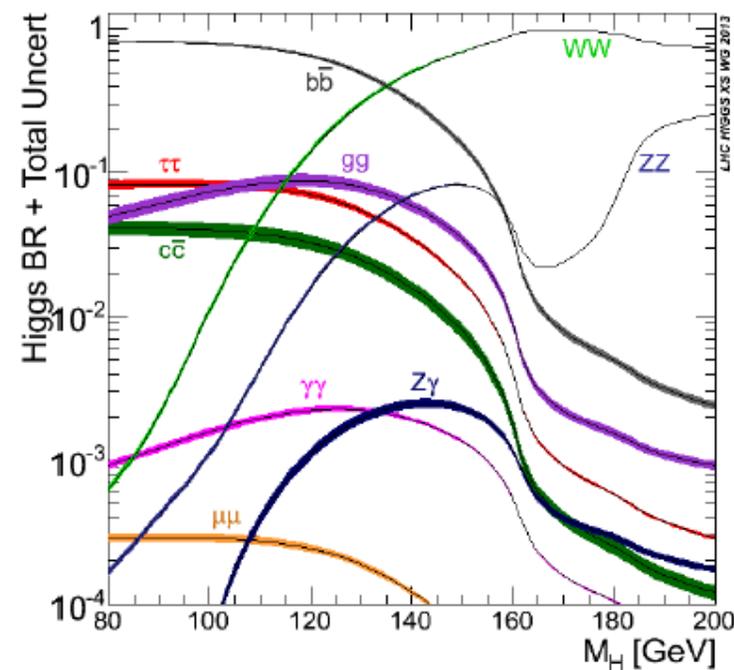
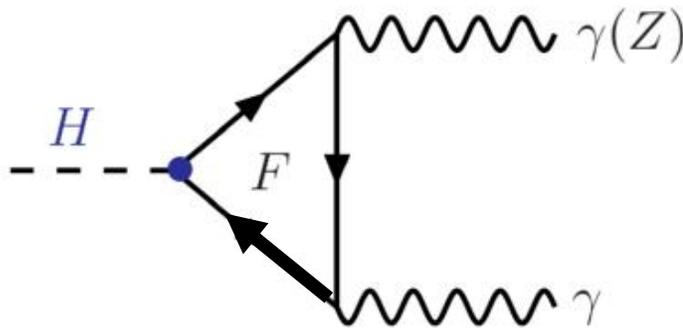
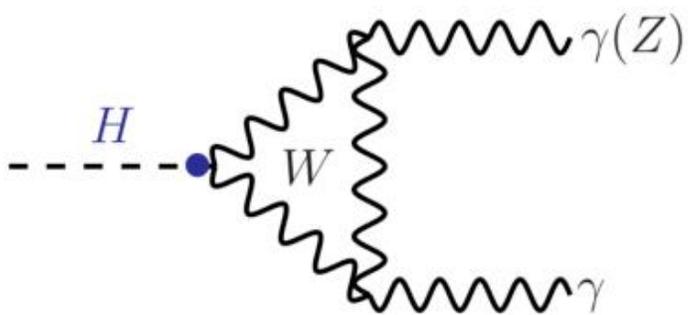
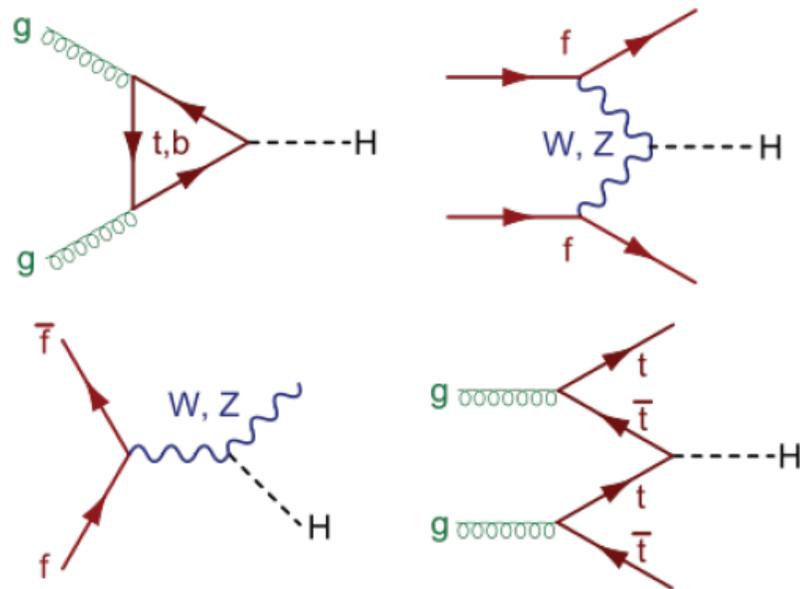
标准模型和希格斯粒子

- 费米子是组成物质结构的基本粒子
- 玻色子传递基本相互作用
- 希格斯机制解释了自发对称性破缺，赋予基本粒子质量
 - 预言了希格斯粒子的存在

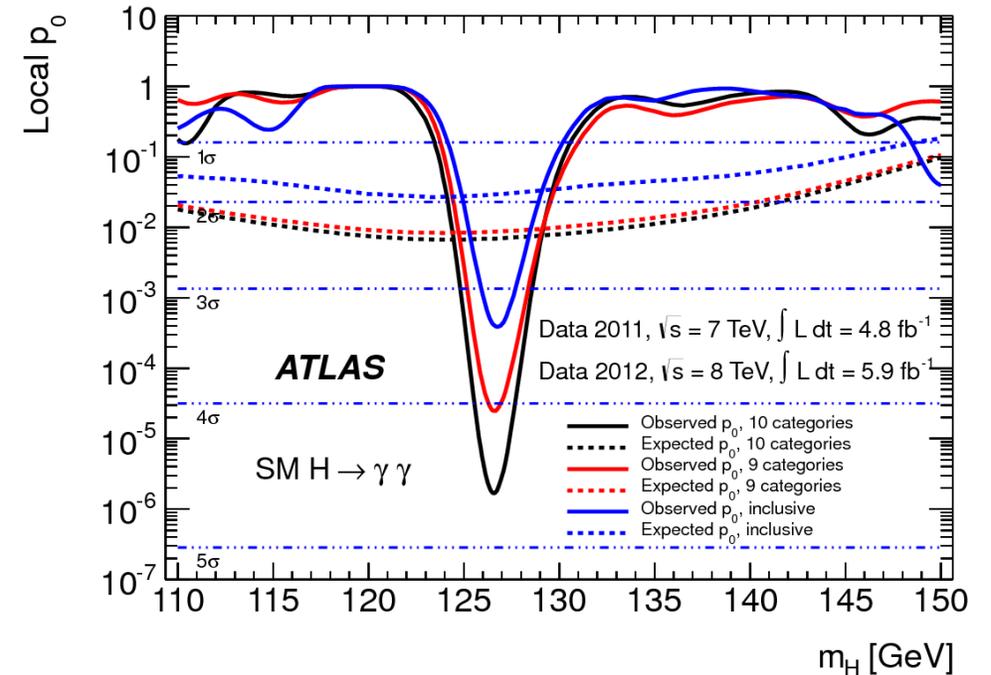
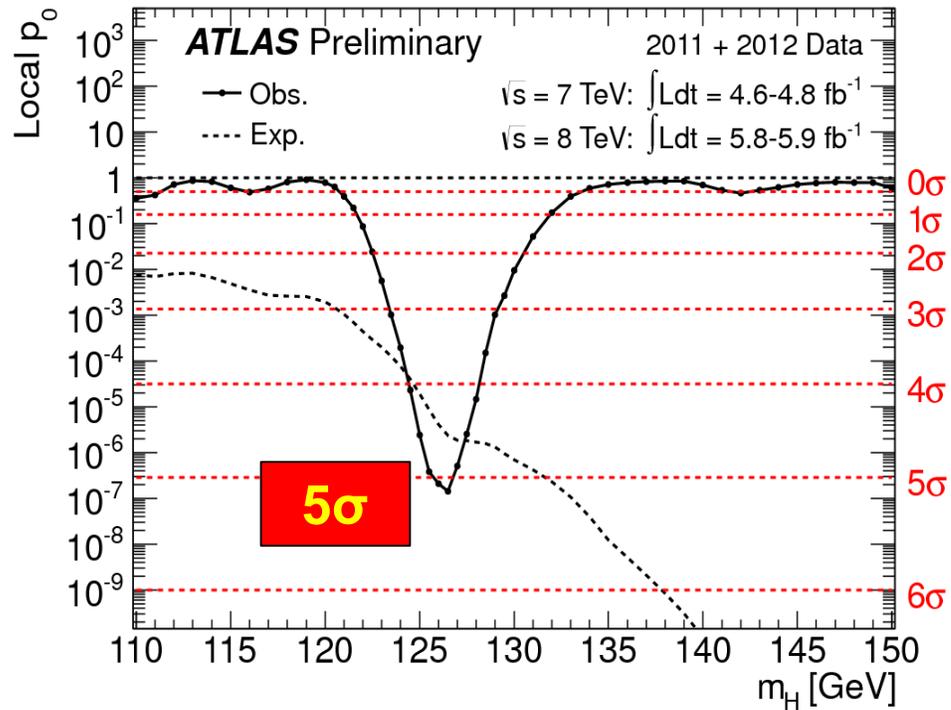


双光子衰变和VBF产生机制

- 产生机制
 - ggF, VBF, VH, ttH
- 衰变模式
 - 双光子: 0.228%



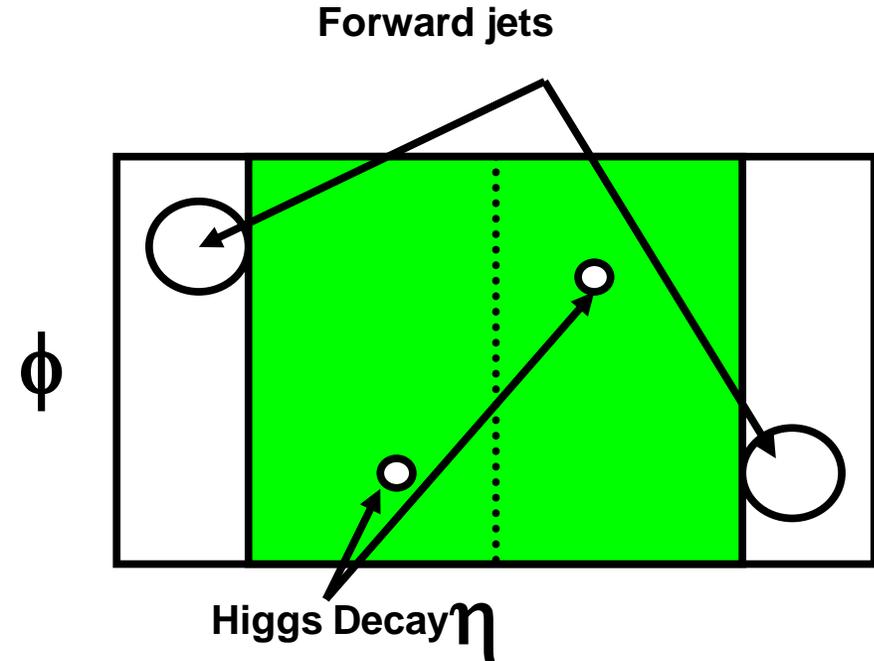
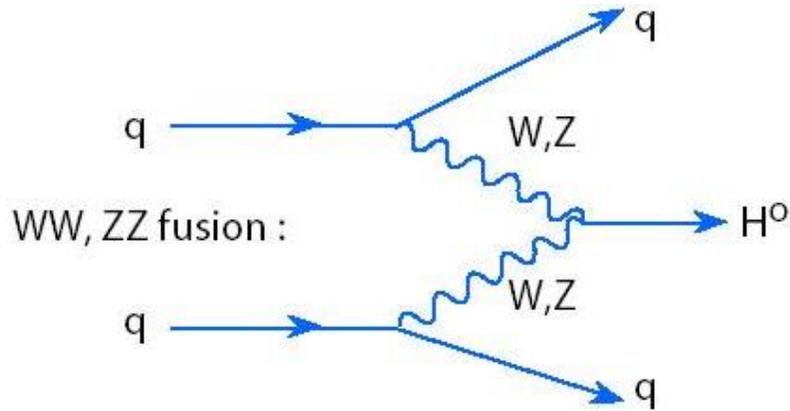
VBF在ATLAS希格斯粒子发现中的贡献



引入VBF $H \rightarrow \gamma\gamma$: 从红的曲线(4 σ) → 黑的曲线(4.4 σ)

- 2012年7月，希格斯粒子在ATLAS和CMS被观测到，其中 $H \rightarrow \gamma\gamma \square ZZ \omega 0$; $\square!$.
- VBF $H \rightarrow \gamma\gamma$ 4 σ 提高到4.4 σ 。

VBF事例的特征



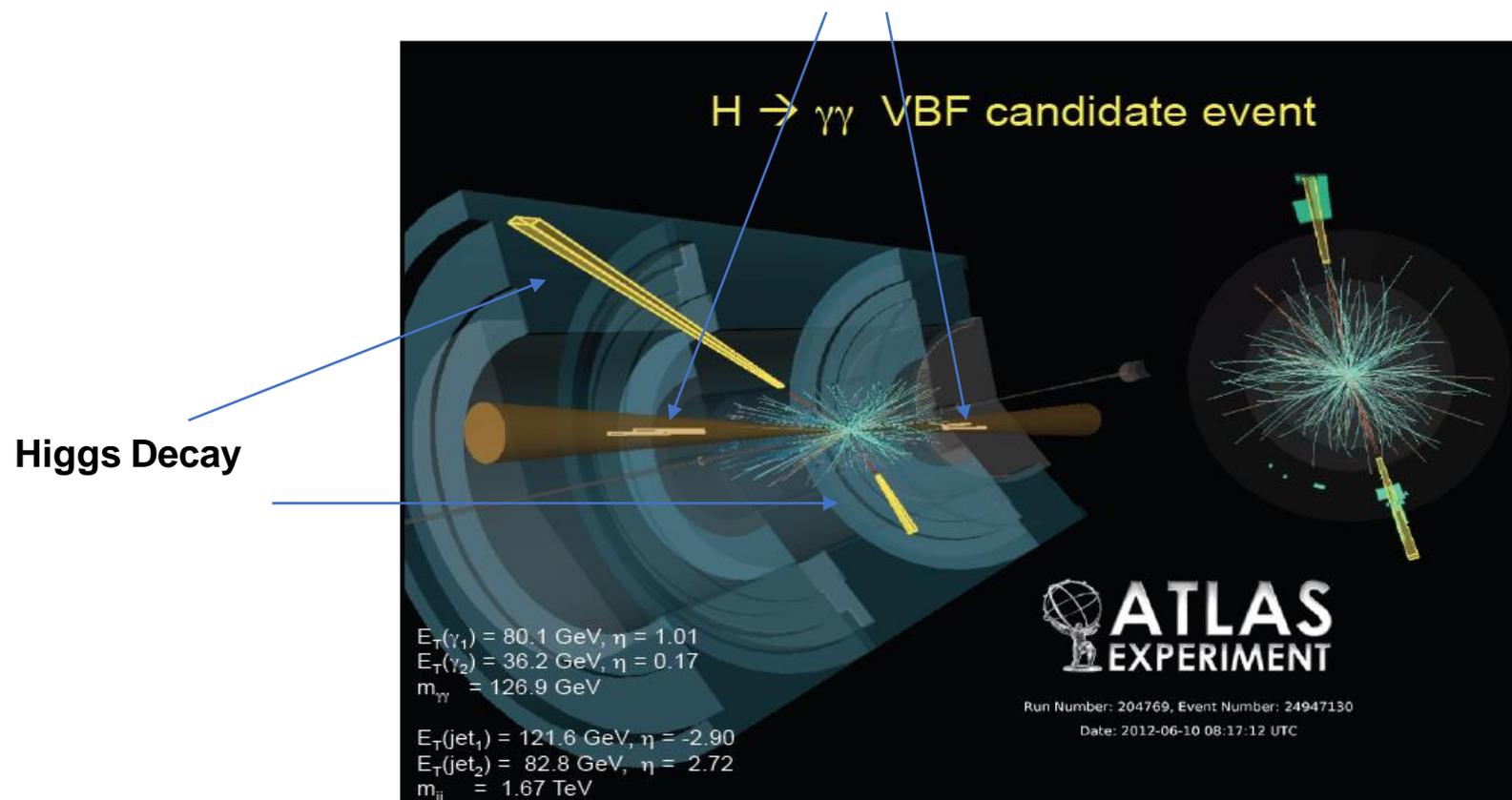
- 两个高boosted前向性喷注。
- 在探测器central 区域没有喷注行为。
 - Central jet veto首次发表于PRD 42 3052 (1990)

Wisconsin Pheno. Group:

T. Han, D.L. Rainwater, D. Zeppenfeld et al.

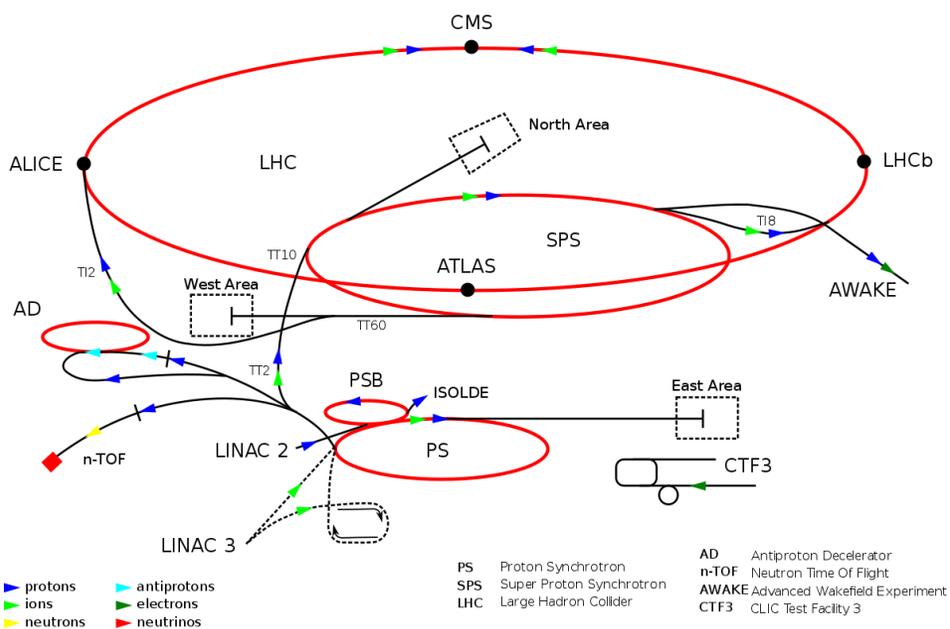
典型的ATLAS VBF希格斯粒子衰变到双光子事例

VBF tagged jets

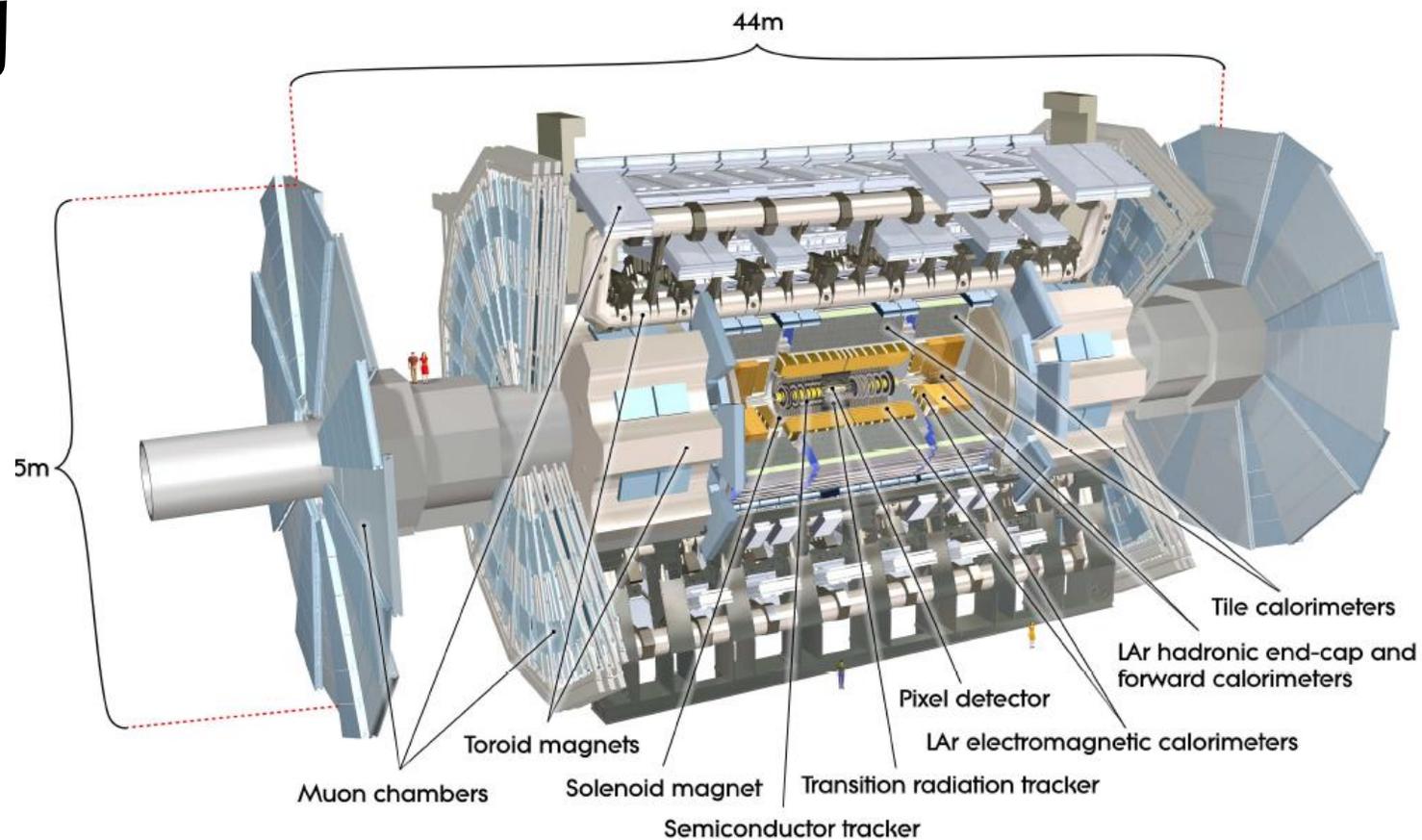


LHC和ATLAS探测器

• LHC加速器结构

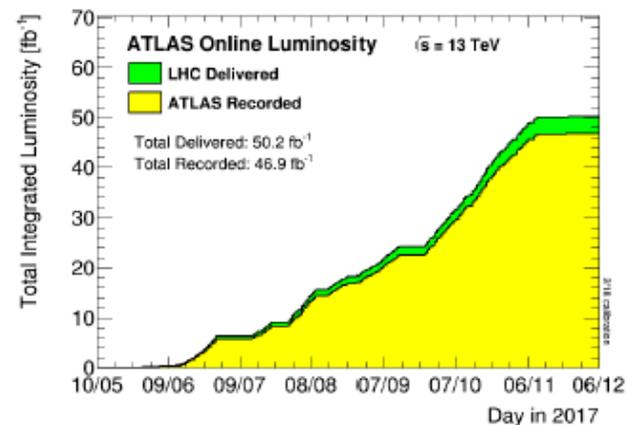
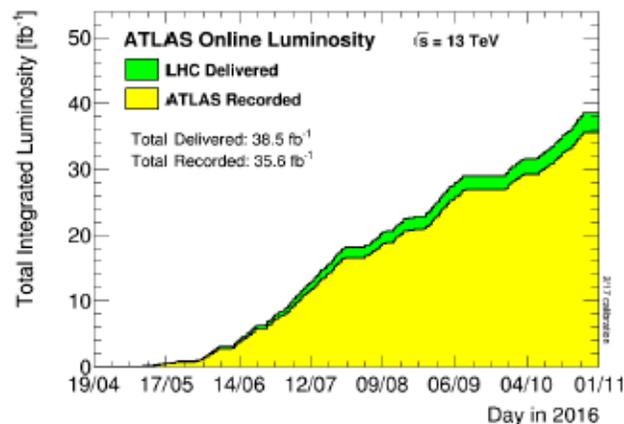
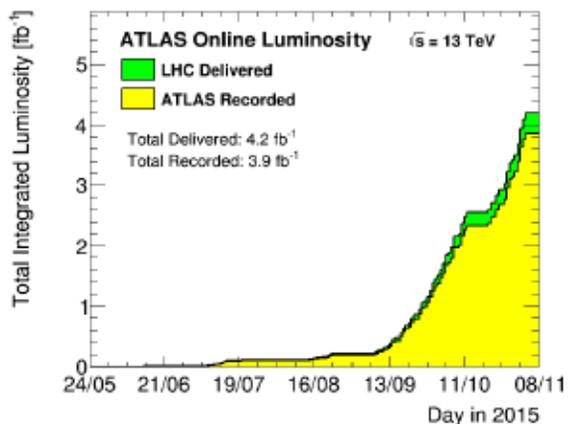


• ATLAS探测器



数据和模拟样本

- 2015-2017 80fb⁻¹

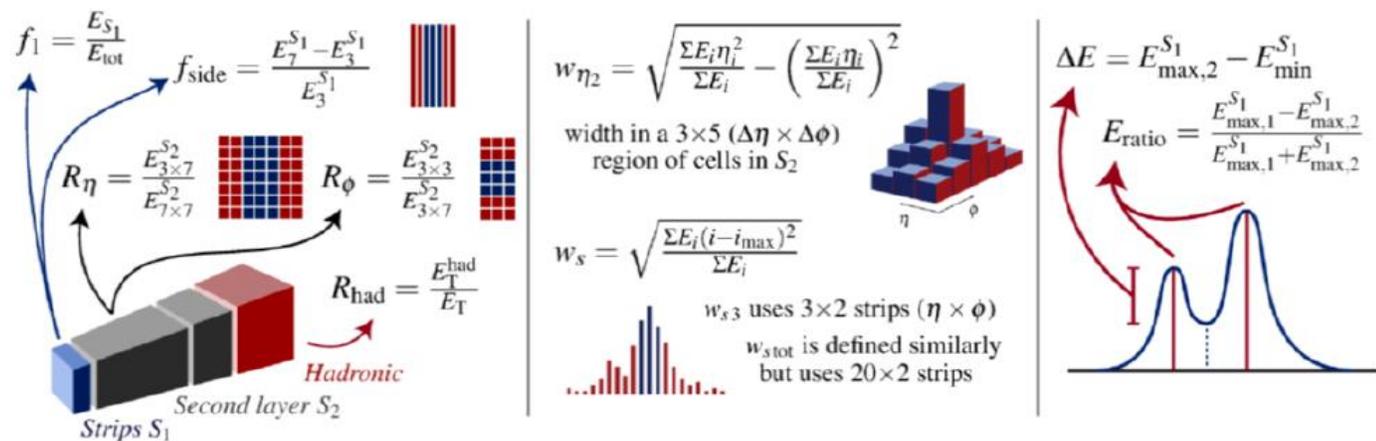
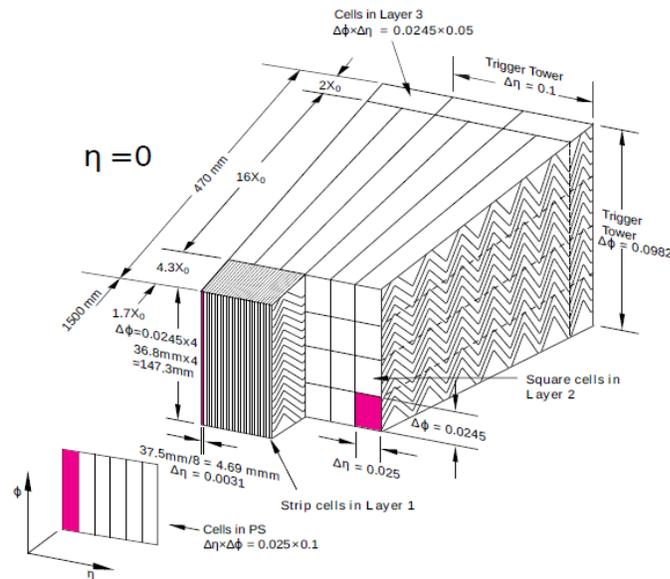


- 模拟样本

Process	Generator	Showering	PDF set	$\frac{\sigma[\text{pb}]}{\sqrt{s}=13 \text{ TeV}}$	Order of calculation
ggH	POWHEG NNLOPS	PYTHIA8	PDF4LHC15	48.52	N3LO(QCD)+NLO(EW)
VBF	POWHEG BOX	PYTHIA8	PDF4LHC15	3.78	NNLO(QCD)+NLO(EW)
WH	POWHEG BOX	PYTHIA8	PDF4LHC15	1.37	NNLO(QCD)+NLO(EW)
$q\bar{q} \rightarrow ZH$	POWHEG BOX	PYTHIA8	PDF4LHC15	0.76	NNLO(QCD)+NLO(EW)
$gg \rightarrow ZH$	POWHEG BOX	PYTHIA8	PDF4LHC15	0.12	NLO+NLL(QCD)
$t\bar{t}H$	MG_aMC@NLO	PYTHIA8	NNPDF3.0	0.51	NLO(QCD)+NLO(EW)
$b\bar{b}H$	MG_aMC@NLO	PYTHIA8	CT10	0.49	5FS(NNLO)+4FS(NLO)
tH	MG_aMC@NLO	PYTHIA8	CT10	0.07	4FS(LO)
tWH	MG_aMC@NLO	HERWIG++	CT10	0.02	5FS(NLO)
$\gamma\gamma$	SHERPA	SHERPA	CT10		
$V\gamma\gamma$	SHERPA	SHERPA	CT10		

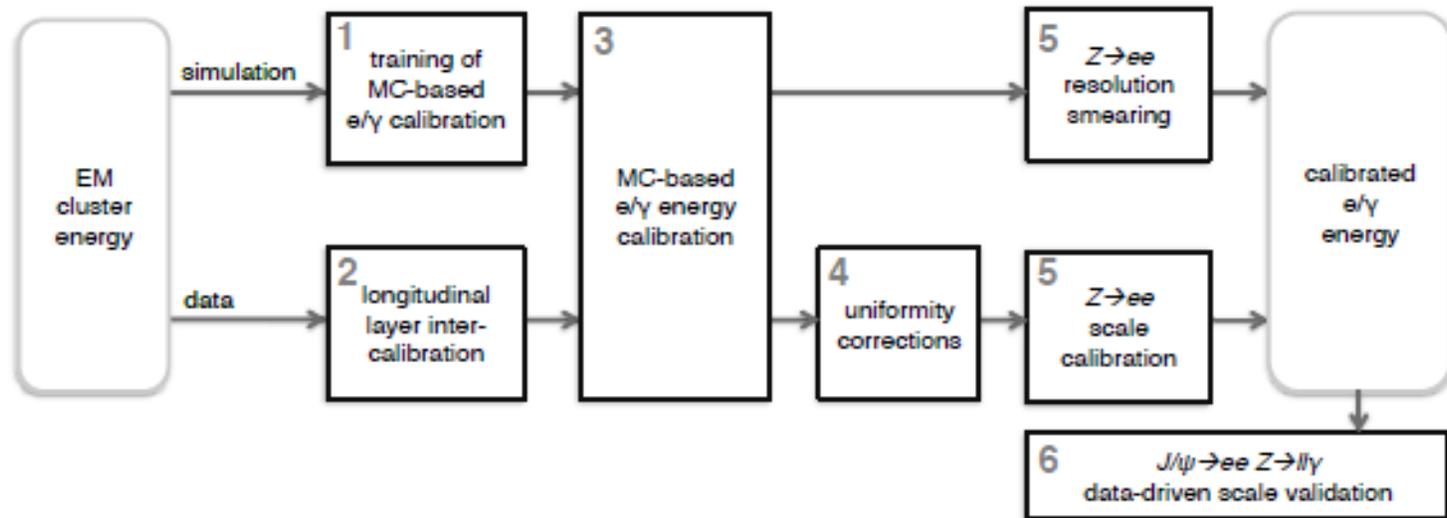
粒子重建、鉴别、刻度 (1)

- 光子重建
 - 簇射团重建
 - 径迹匹配
 - 转换顶点重建
- 光子鉴别
 - 排除来自喷注的假光子
 - 基于簇射团形状和能量分布
 - 假光子的簇射团更宽
 - 矩形筛选条件



粒子重建、鉴别和刻度 (2)

- 光子刻度



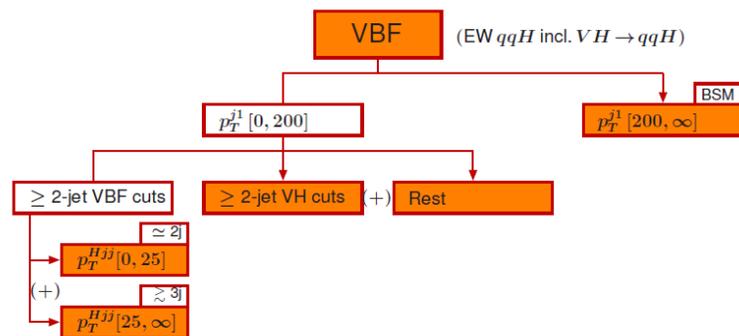
- 光子孤立化

- 排除误判的假光子

criteria	calo ISO	track ISO
loose	$E_T^{ISO} _{\Delta R < 0.2} < 0.065 E_T$	$p_T^{ISO} _{\Delta R < 0.2} < 0.05 p_T$
tight	$E_T^{ISO} _{\Delta R < 0.4} < 0.022 E_T + 2.45 \text{ GeV}$	$p_T^{ISO} _{\Delta R < 0.2} < 0.05 p_T$
calo-only	$E_T^{ISO} _{\Delta R < 0.4} < 0.022 E_T + 2.45 \text{ GeV}$	

事例筛选和子类优化

- 单举 (inclusive) 筛选条件
 - GRL, 触发, 两光子顶点
 - 两个“宽松的”光子
 - 两个“严格的”“孤立的”光子
 - 相对横动量 $p_{T\gamma 1(2)} / m_{\gamma\gamma} > 0.35(0.25), 105 < m_{\gamma\gamma} < 160 \text{ GeV}$
- 子类
 - 为了提高不同产生模式的信号显著度, 根据运动学特征对筛选条件进行优化
 - Simplified Template Cross Section
 - $p_{THjj} < 25 \text{ GeV}$
 - $p_{THjj} > 25 \text{ GeV}$



所有的子类的总结

- 根据不同产生模式的运动学特征和 STXS 的划分，将所有实例分为 29 个子类
- 10 个 ggF 子类
- 7 个 H+2jets 子类
- 5 个 VH leptonic 子类
- 7 个 ttH 子类

Category label	Selection
ttH lep BDT1	$N_{lep} \geq 1, N_{b-jet} \geq 1, BDT_{ttHlep} > 0.987$
ttH lep BDT2	$N_{lep} \geq 1, N_{b-jet} \geq 1, 0.942 < BDT_{ttHlep} < 0.987$
ttH lep BDT3	$N_{lep} \geq 1, N_{b-jet} \geq 1, 0.705 < BDT_{ttHlep} < 0.942$
ttH had BDT1	$N_{lep} = 0, N_{jets} \geq 3, N_{b-jet} \geq 1, BDT_{ttHhad} > 0.996$
ttH had BDT2	$N_{lep} = 0, N_{jets} \geq 3, N_{b-jet} \geq 1, 0.991 < BDT_{ttHhad} < 0.996$
ttH had BDT3	$N_{lep} = 0, N_{jets} \geq 3, N_{b-jet} \geq 1, 0.971 < BDT_{ttHhad} < 0.991$
ttH had BDT4	$N_{lep} = 0, N_{jets} \geq 3, N_{b-jet} \geq 1, 0.911 < BDT_{ttHhad} < 0.971$
VH dilep	$N_{lep} \geq 2, 70 \text{ GeV} \leq m_{\ell\ell} \leq 110 \text{ GeV}$
VH lep High	$N_{lep} = 1, m_{e\gamma} - 89 \text{ GeV} > 5 \text{ GeV}, p_T^{\ell+E_T^{miss}} > 150 \text{ GeV}$
VH lep Low	$N_{lep} = 1, m_{e\gamma} - 89 \text{ GeV} > 5 \text{ GeV}, p_T^{\ell+E_T^{miss}} < 150 \text{ GeV}, E_T^{miss} \text{ significance} > 1$
VH MET High	$150 \text{ GeV} < E_T^{miss} < 250 \text{ GeV}, E_T^{miss} \text{ significance} > 9 \text{ or } E_T^{miss} > 250 \text{ GeV}$
VH MET Low	$80 \text{ GeV} < E_T^{miss} < 150 \text{ GeV}, E_T^{miss} \text{ significance} > 8$
qqH BSM	$N_{jets} \geq 2, p_{T,j1} > 200 \text{ GeV}$
VH had BDT tight	$60 \text{ GeV} < m_{jj} < 120 \text{ GeV}, BDT_{VH} > 0.78$
VH had BDT loose	$60 \text{ GeV} < m_{jj} < 120 \text{ GeV}, 0.35 < BDT_{VH} < 0.78$
VBF high- p_T^{Hjj} BDT tight	$ \Delta\eta_{jj} > 2, \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2}) < 5, p_T^{Hjj} > 25 \text{ GeV}, BDT_{VBF}^{high} > 0.47$
VBF high- p_T^{Hjj} BDT loose	$ \Delta\eta_{jj} > 2, \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2}) < 5, p_T^{Hjj} > 25 \text{ GeV}, -0.32 < BDT_{VBF}^{high} < 0.47$
VBF low- p_T^{Hjj} BDT tight	$ \Delta\eta_{jj} > 2, \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2}) < 5, p_T^{Hjj} < 25 \text{ GeV}, BDT_{VBF}^{low} > 0.87$
VBF low- p_T^{Hjj} BDT loose	$ \Delta\eta_{jj} > 2, \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2}) < 5, p_T^{Hjj} < 25 \text{ GeV}, 0.26 < BDT_{VBF}^{low} < 0.87$
ggF 2J BSM	$N_{jets} \geq 2, p_T^{\gamma\gamma} \geq 200 \text{ GeV}$
ggF 2J High	$N_{jets} \geq 2, p_T^{\gamma\gamma} \in [120, 200] \text{ GeV}$
ggF 2J Med	$N_{jets} \geq 2, p_T^{\gamma\gamma} \in [60, 120] \text{ GeV}$
ggF 2J Low	$N_{jets} \geq 2, p_T^{\gamma\gamma} \in [0, 60] \text{ GeV}$
ggF 1J BSM	$N_{jets} = 1, p_T^{\gamma\gamma} \geq 200 \text{ GeV}$
ggF 1J High	$N_{jets} = 1, p_T^{\gamma\gamma} \in [120, 200] \text{ GeV}$
ggF 1J Med	$N_{jets} = 1, p_T^{\gamma\gamma} \in [60, 120] \text{ GeV}$
ggF 1J Low	$N_{jets} = 1, p_T^{\gamma\gamma} \in [0, 60] \text{ GeV}$
ggF 0J Fwd	$N_{jets} = 0, \text{ one photon with } \eta > 0.95$
ggF 0J Cen	$N_{jets} = 0, \text{ two photons with } \eta \leq 0.95$

VBF产生机制的运动学特征

- 两个前向的高动量喷注

- 两个前向喷注
- 高动量喷注
- 两光子在中心区域，喷注在前向区域
- 两光子和高动量喷注的横动量和为零
- 否决含有三喷注的事例

$$\langle S^2 \rangle = \frac{1}{2} \int \frac{(\hat{y}_s(y) - \hat{y}_b(y))^2}{\hat{y}_s(y) + \hat{y}_b(y)} dy$$

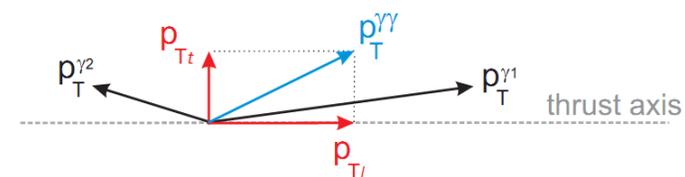
→ 大 $\Delta\eta_{jj}$

→ 大 m_{jj}

→ 大 $\Delta R_{\gamma,j}$

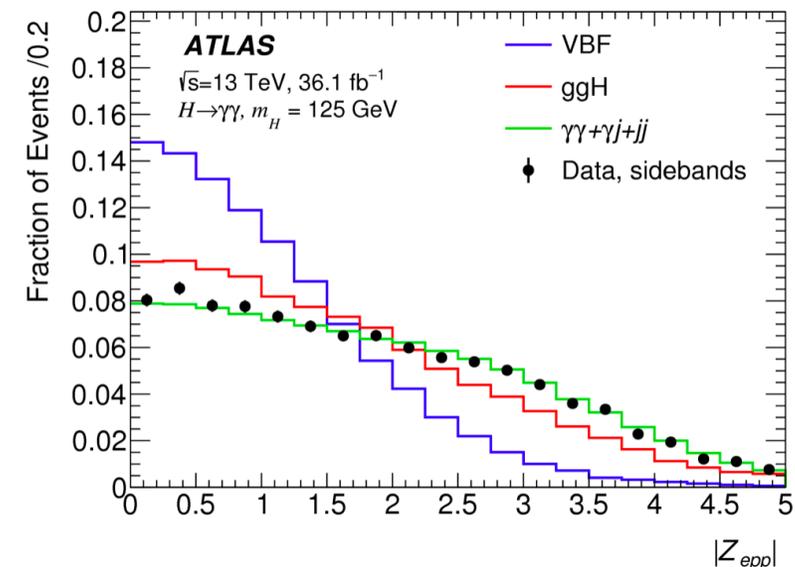
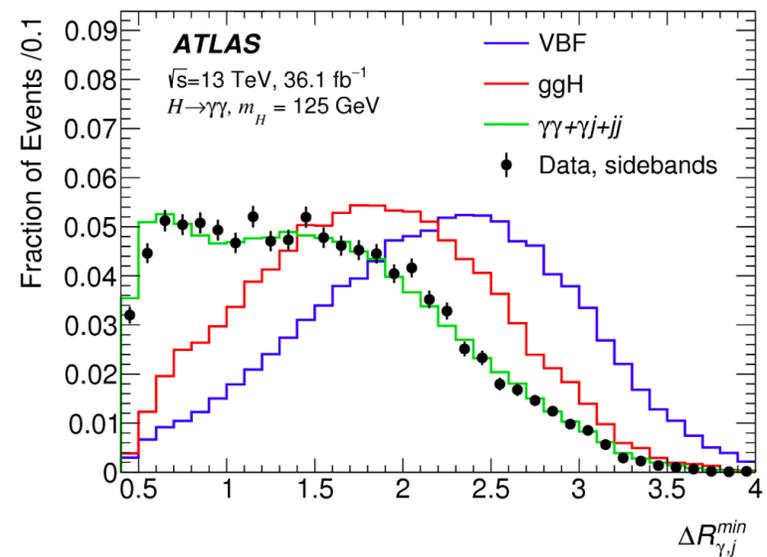
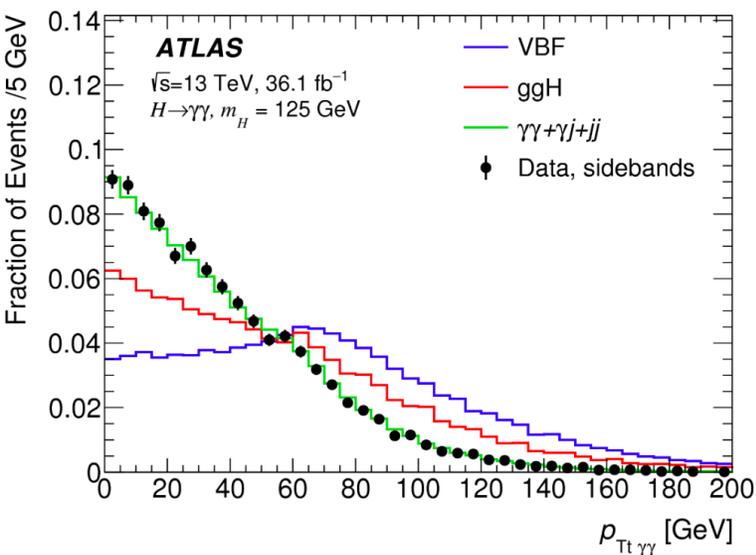
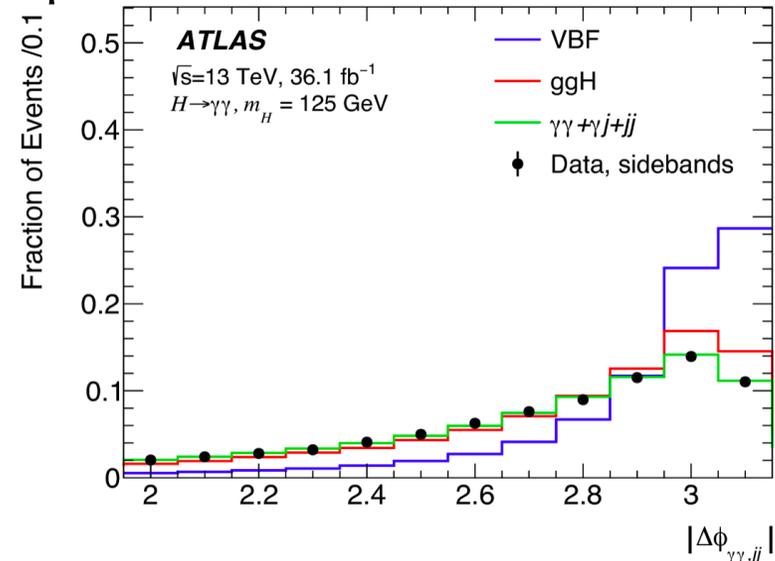
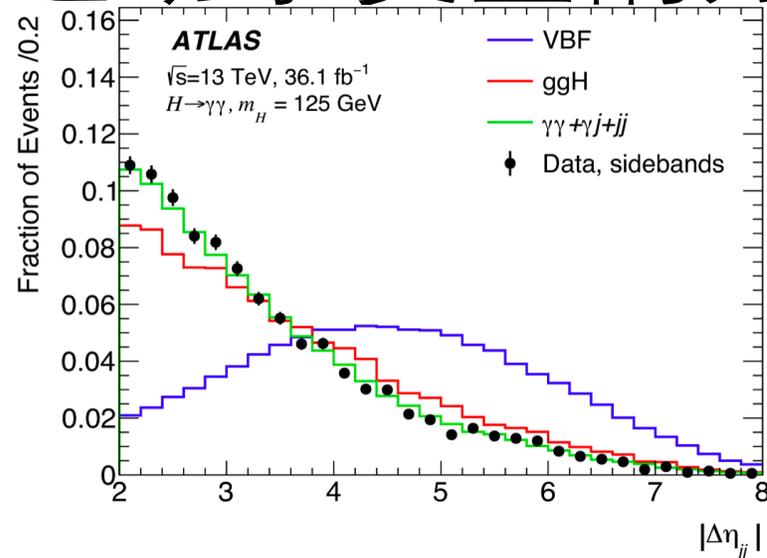
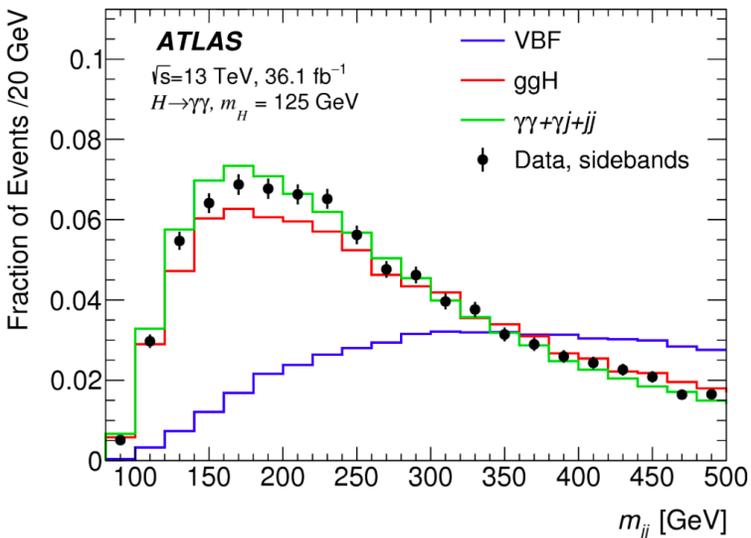
→ 大 p_{Tt}

→ 大 $\Delta\Phi_{\gamma\gamma,jj}$

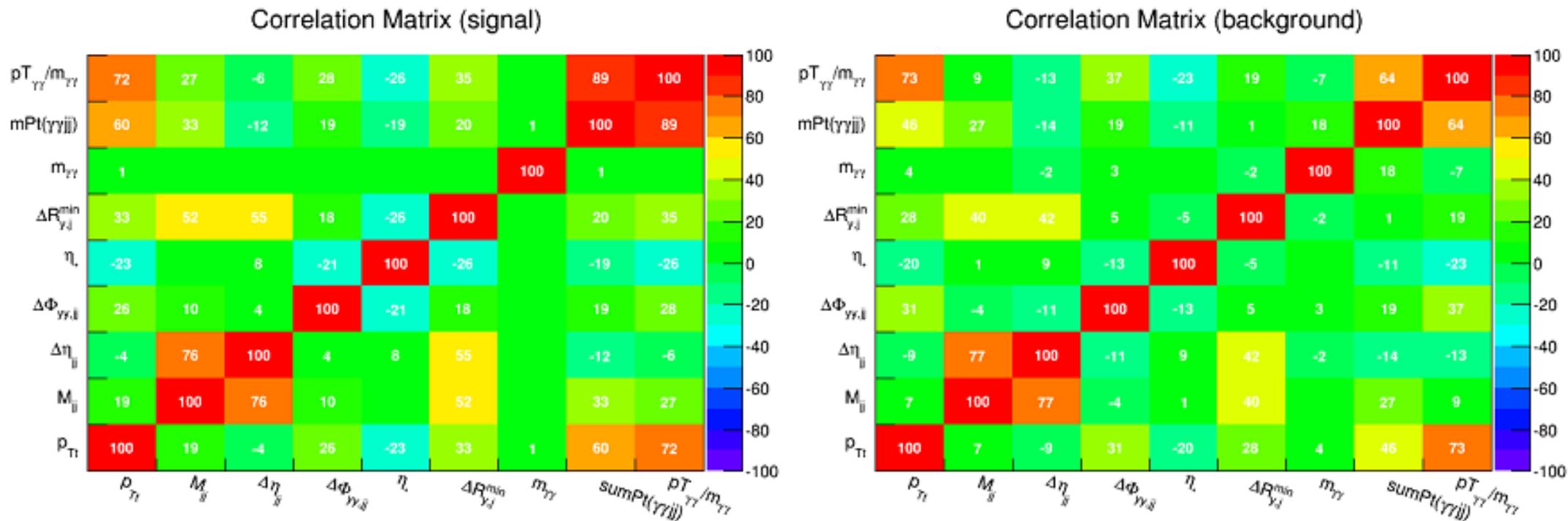


Variables	Definition	Separation power
m_{jj}	Invariant mass of dijet	0.256
$\Delta\eta_{jj}$	Pseudo-rapidity separation of dijet	0.130
$\Delta\Phi_{\gamma\gamma,jj}$	Azimuthal angle between diphoton and dijet system	0.199
p_{Tt}	Diphoton p_T projected perpendicular to the diphoton thrust axis	0.235
$\Delta R_{\gamma,j}^{min}$	Minimum ΔR between one of the two leading photons and the corresponding leading jets	0.185
$\eta^{Zeppenfeld}$	$ \eta_{\gamma\gamma} - 0.5 * (\eta_{j1} + \eta_{j2}) $	0.126

运动学变量的分布



变量之间的相关性



选择的变量与双光子质量有较低的相关性

优化筛选条件的策略

- 信号样本：模拟样本，归一到预期亮度和产生截面
- 背景样本：
 - 两光子模拟样本描述连续的两光子背景
 - 数据中没有通过“严格的”鉴别条件或者孤立化条件描述 γ -jet和jet-jet事例
 - 不同背景成分的比例用data-driven方法估计
 - 将不同背景按照比例混合，归一到data sideband
- 筛选条件扫描
 - 矩形筛选条件（cut-based）：扫描每个变量的截断值
 - 增长决策树（BDT, boosted decision tree）：扫描BDT的截断值
- 信号显著度

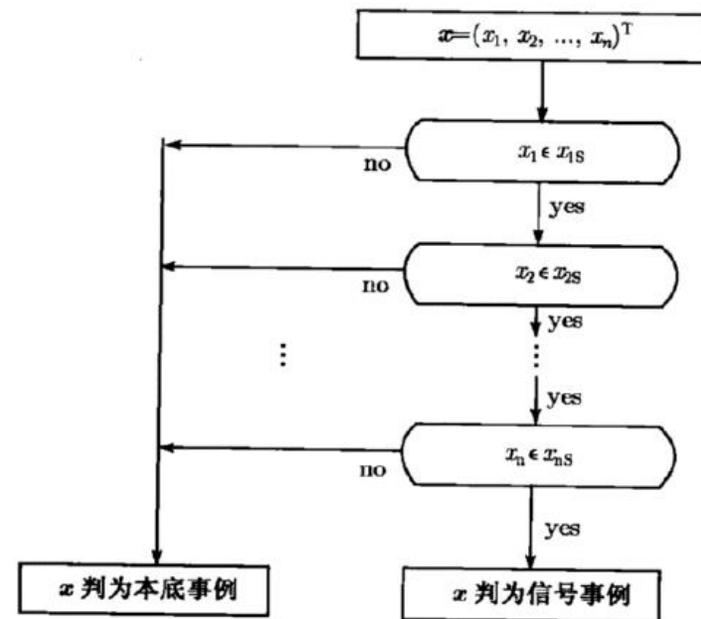
$$\sigma_{VBF} = \sqrt{2 \times ((N_{VBF} + N_{ggH} + N_{bkg}) \times \ln(1 + \frac{N_{VBF}}{N_{ggH} + N_{bkg}}) - N_{VBF})}$$

矩形筛选条件的优化

- 优化每一个筛选变量的阈值以得到最大的信号显著度
- 定义两个子类，它们是不互相包含的
- 表为 4fb^{-1} 时的预期信号显著度

	m_{jj}	$\Delta\eta_{jj}$	$\Delta\Phi_{\gamma\gamma,jj}$	$\Delta R_{\gamma,j}^{\min}$	$\eta^{\text{Zeppenfeld}}$	significance
tight	$> 500 \text{ GeV}$	> 3.9	> 3	> 1.4	> 2.4	0.72
loose	$> 350 \text{ GeV}$	> 2.5	> 2.7	-	-	0.29

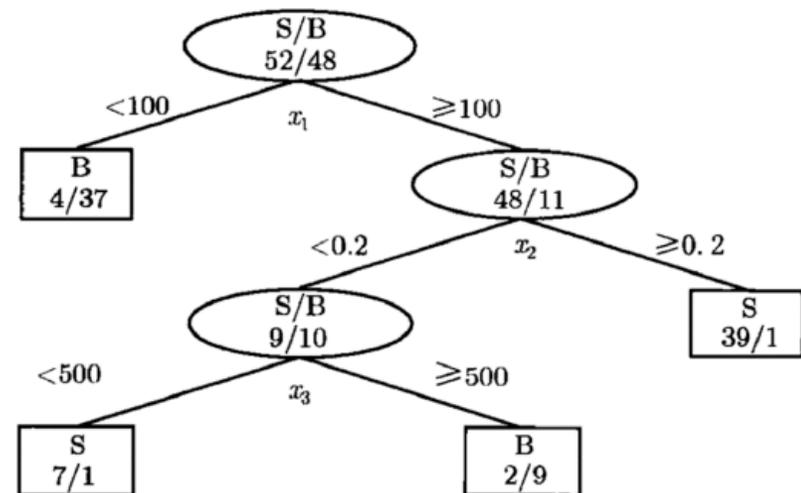
- 优点：操作简单
- 缺点：信号效率低，无法处理变量之间的关联



增长决策树 (BDT) 优化

- 决策树发展而来的多变量分析算法
- 第N棵树构建完成之后，提高误判事例的权重，重新构建第N+1棵树
- 所有决策树输出结果的加权平均值作为最终结果
- 优点：
 - 处理变量之间的关联
 - 提高信号效率

相比于cut-based方法，信号显著度提高28个百分点。BDT方法作为最终的子类定义的方法。

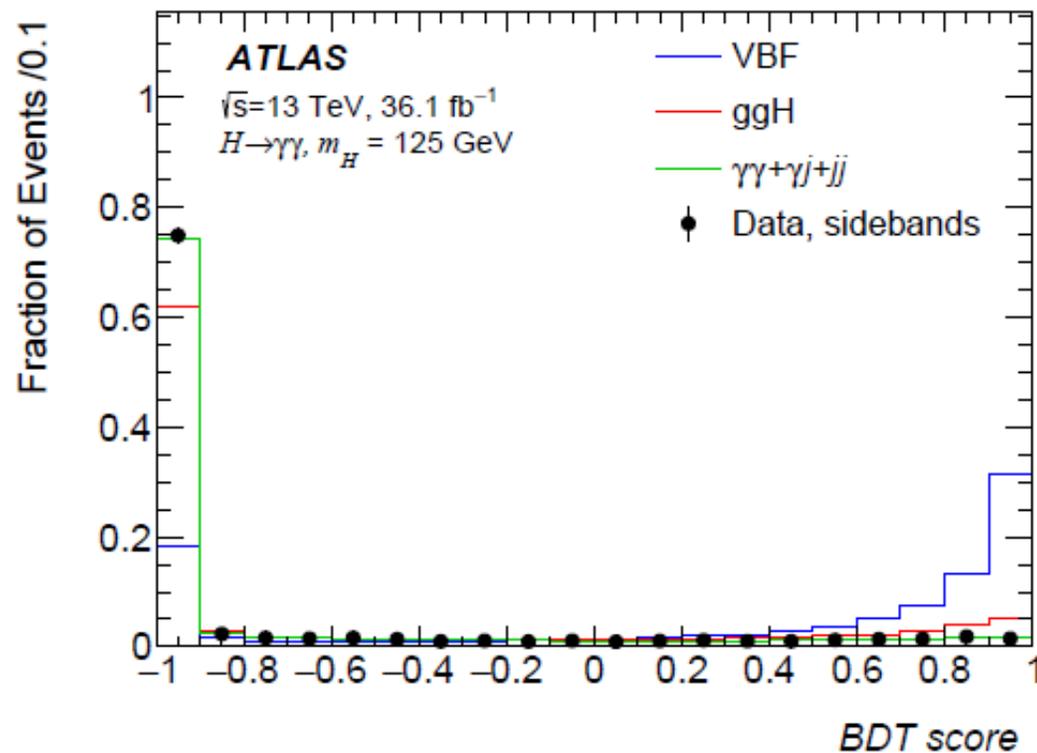
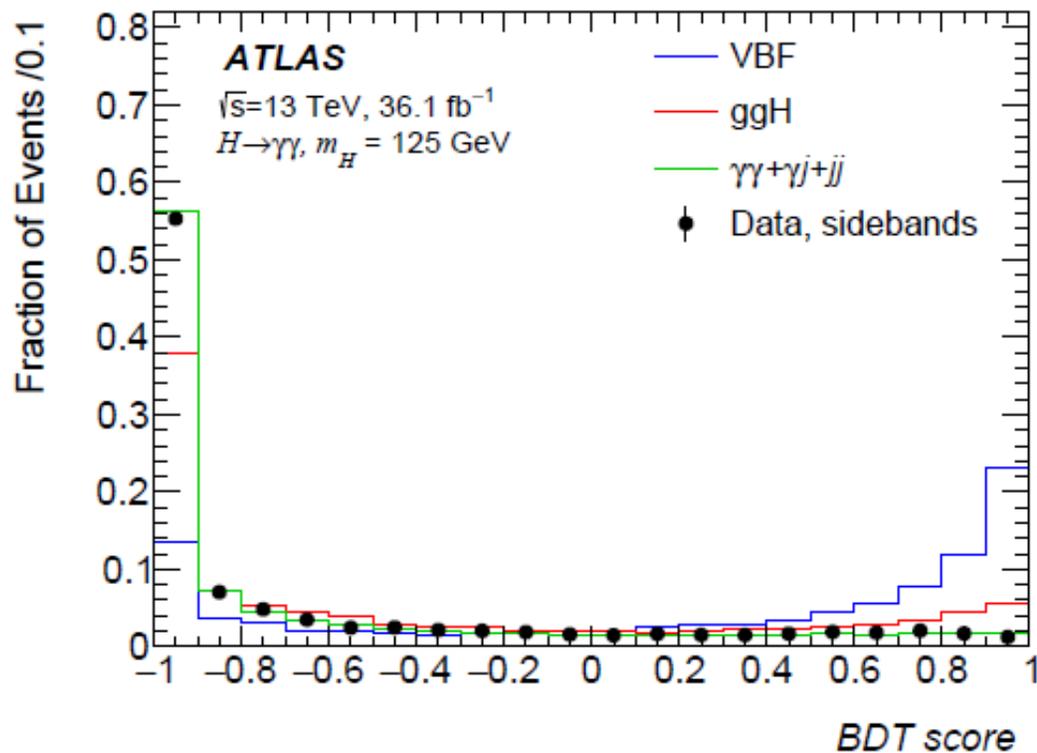


	cut-based tight	cut-based loose	MVA tight	MVA loose
VBF	2.22	2.57	1.64	2.17
ggF	0.83	3.51	0.51	1.90
background	8.06	74.74	2.42	17.71
VBF purity	0.73	0.42	0.76	0.53
significance	0.72	0.29	0.88	0.47
combined significance	0.78		1.00	

Normalized to 4fb^{-1}

BDT的分布

- 为了测量STXS, 在 $p_{\text{TH}jj} < 25 \text{ GeV}$ 和 $p_{\text{TH}jj} > 25 \text{ GeV}$ 区间内各自训练一个BDT。



其他的可能的提高

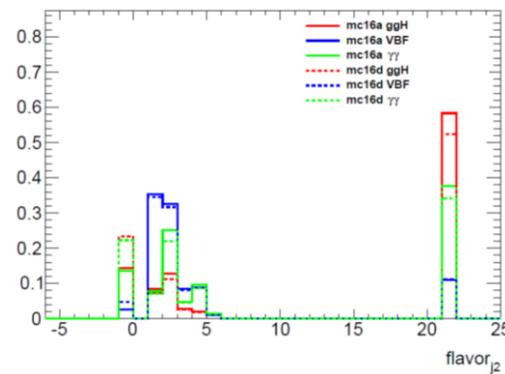
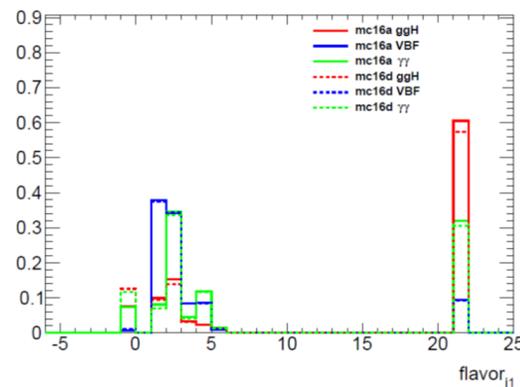
- Quark/gluon喷注鉴别

- 物理上，ggF过程中的喷注主要为胶子喷注，VBF过程中为夸克喷注
- 相比于夸克喷注，胶子喷注径迹数更多
- 径迹级别的变量可以用来区分二者

- 五个径迹相关的变量

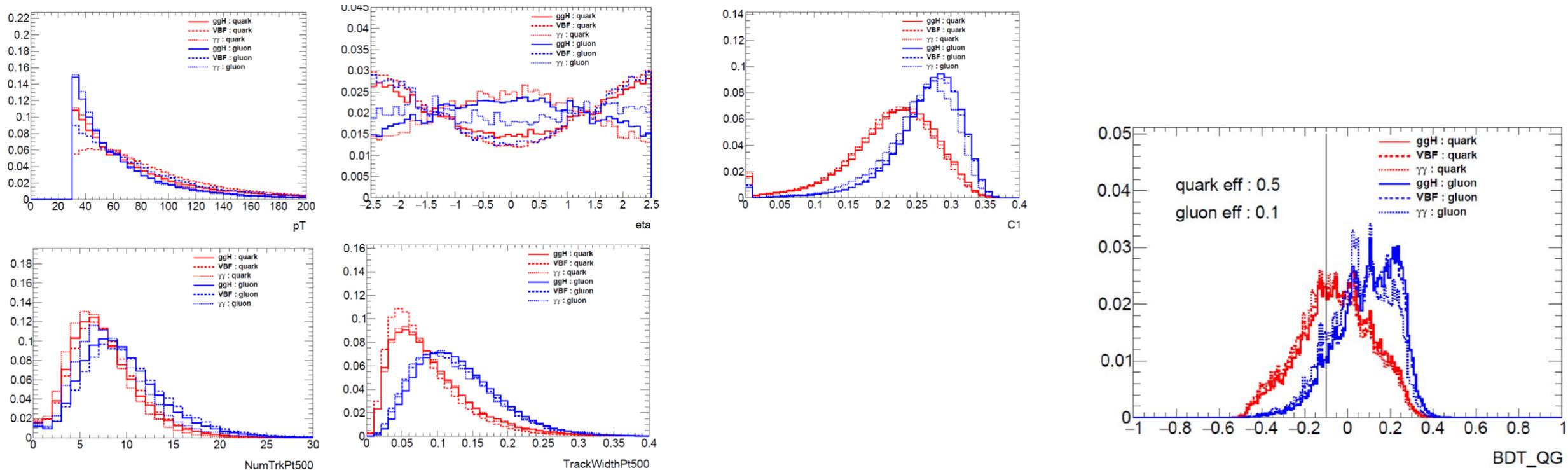
- 横动量, \mathbf{p}_T
- 赝快度, η
- 径迹数, N_{track}
- 横动量加权的喷注宽度, $w_{\text{trk}} = \frac{\sum_i p_{T,\text{trk}} \Delta R_{\text{trk},\text{jet}}}{\sum_i p_{T,\text{trk}}}$
- 两点能量关联函数, $c_\beta = \frac{\sum_{i,j} E_{T,i} E_{T,j} (\Delta R_{i,j})^\beta}{(\sum_i E_{T,i})^2}$

Truth level 喷注的味道



基于径迹的分类器

- 5个变量的分布和BDT



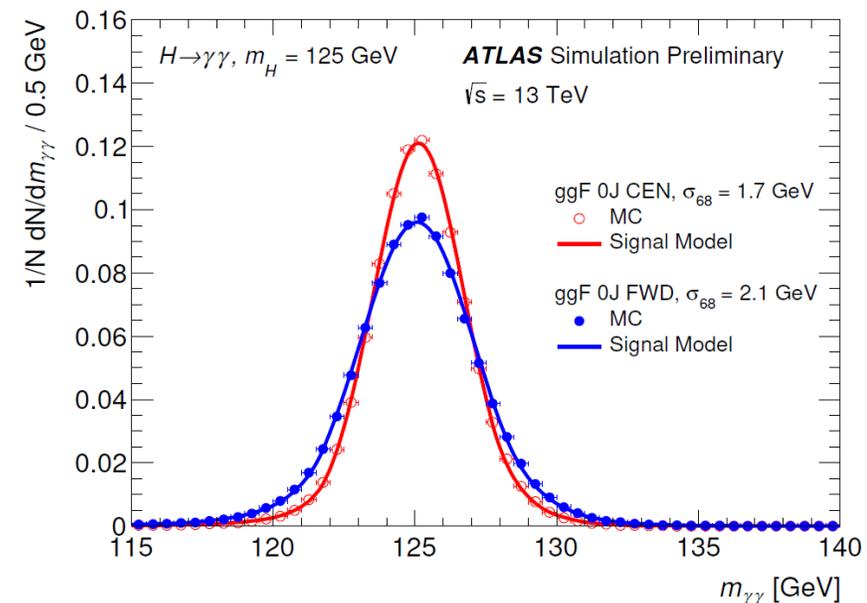
- 将喷注鉴别的BDT加入到事例筛选中，信号显著度的提高小于5%

信号建模

- 双边水晶球分布 (Double-Sided Crystal Ball, DSCB)
 - 中心区域是高斯分布, 两边尾巴是幂函数

$$f_{DSCB}(m_{\gamma\gamma}) = N \times \begin{cases} e^{-t^2} & \text{if } -\alpha_{low} < t < \alpha_{high} \\ \frac{e^{-\frac{1}{2}\alpha_{low}^2}}{[\frac{1}{R_{low}}(R_{low}-\alpha_{low}-t)]^{n_{low}}} & \text{if } t < -\alpha_{low} \\ \frac{e^{-\frac{1}{2}\alpha_{high}^2}}{[\frac{1}{R_{high}}(R_{high}-\alpha_{high}+t)]^{n_{high}}} & \text{if } t > \alpha_{high} \end{cases}$$

- 分别拟合每个子类中信号样本的不变质量谱



背景建模

- 背景分解——data driven method
- 根据光子的鉴别和孤立能量信息，分成15个CR和1个SR
- 在每一个区域内，预期的事例数用筛选效率，误判率和总背景数描述，其中，效率有模拟样本得到，误判率和总背景数从数据中拟合得到

$$\begin{aligned}
 N_{AA} = & \epsilon_{ID}^1 \epsilon_{ISO}^1 \epsilon_{ID}^2 \epsilon_{ISO}^2 \times N_{\gamma\gamma} \\
 & + \epsilon_{ID}^1 \epsilon_{ISO}^1 f_{ID}^2 f_{ISO}^2 \times N_{\gamma j} \\
 & + f_{ID}^1 f_{ISO}^1 \epsilon_{ID}^2 \epsilon_{ISO}^2 \times N_{j\gamma} \\
 & + f_{ID}^{1'} f_{ISO}^{1'} f_{ID}^{2'} f_{ISO}^{2'} \epsilon_{ISO}^{jj} \times N_{jj}
 \end{aligned}$$

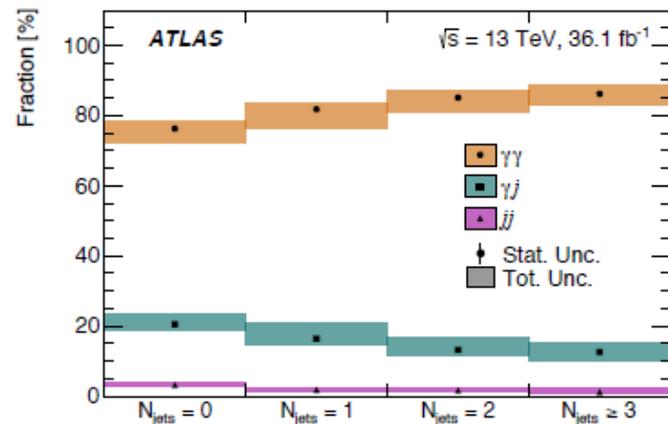
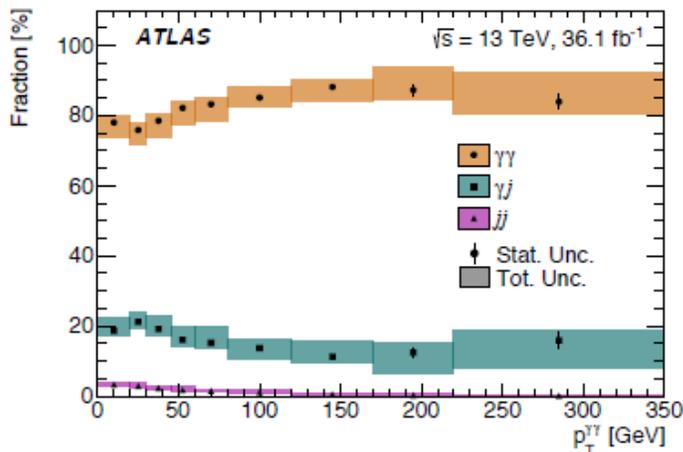
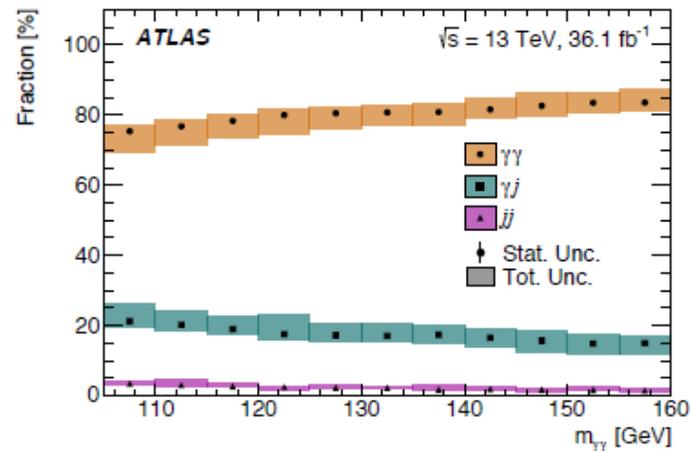
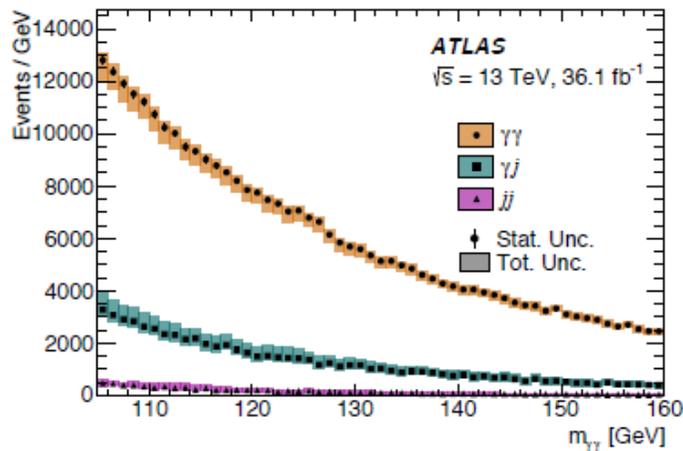
2 nd γ	Tight isolated			SR
	Non-tight isolated			
	Tight Non-isolated			
	Non-tight Non-isolated	tight Non-isolated	Non-tight isolated	Tight isolated

- 用最小二乘法拟合得到信号区域内的各背景成分的比例

1st γ

背景建模

- $m_{\gamma\gamma}$, $p_{T\gamma\gamma}$, N_{jet} 区间中的各背景的比例
- $N_{\text{jet}} \geq 2$ 时的背景比例作为产生背景模板的输入值
- 背景中两光子事例的比例 $\sim 80\%$

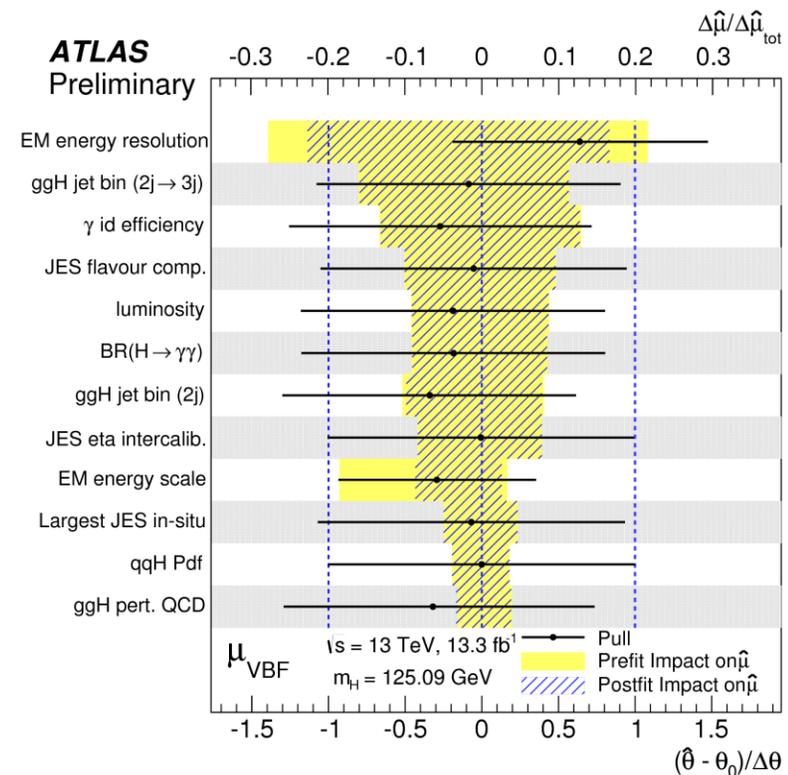


背景建模

- 背景形状——产信号的方法
 - 产生大统计量的背景模拟样本，减少统计涨落
 - 用S+B的函数拟合背景模板
 - 拟合得到的信号事例数叫做 N_{SS}
 - 要求 $N_{SS}/S_{ref} < 0.1, N_{SS}/\Delta N_{ss} < 0.2$
 - 如果有多个函数满足要求，选择自由度最小的函数作为拟合函数

系统误差

- 理论误差
 - QCD scale, PDF, Parton Shower, BR
- 实验误差
 - 亮度, 触发, 光子, 喷注, pile-up, 轻子, MET等
- 信号和背景形状误差
 - 光子能标和能量分辨, 赝信号



统计模型

- 预期事例产额:
$$N_i = N_i^S + N_i^B + N_i^{spur} \theta_{spur}$$
- 两光子不变质量谱:
$$f_i(m_{\gamma\gamma}, \theta) = ((N_i^{sig} + N_i^{spur} \theta_{spur}) f_i^{sig}(m_{\gamma\gamma}, \theta) + N_i^{bkg} f_i^{bkg}(m_{\gamma\gamma}, \theta)) / N_i$$
- 似然函数:
$$L_i = Poisson(n_i | N_i(\theta)) \prod_{j=1}^{n_i} f_i(m_{\gamma\gamma}^j, \theta) G(\theta)$$
- 检验统计量:
$$\lambda(\mu) = -2 \ln \frac{\mathcal{L}(\mu, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$$

结果——36.1fb⁻¹

- 观测的两光子不变质量谱
- 测量得到的信号强度

$$\mu = 0.99^{+0.15}_{-0.14} = 0.99 \pm 0.12(stat)^{+0.06}_{-0.05}(exp)^{+0.07}_{-0.05}(theo)$$

$$\mu_{ggH} = 0.81^{+0.19}_{-0.18} = 0.81 \pm 0.16(stat)^{+0.07}_{-0.06}(exp)^{+0.07}_{-0.05}(theo)$$

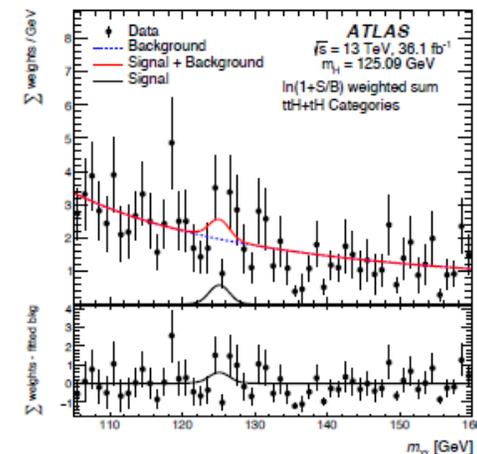
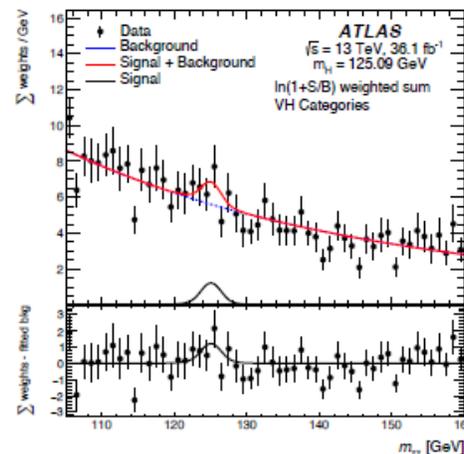
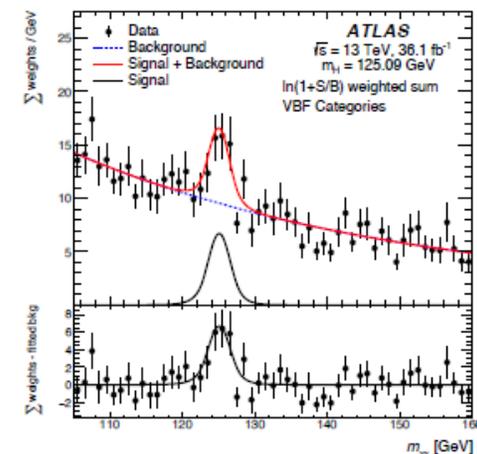
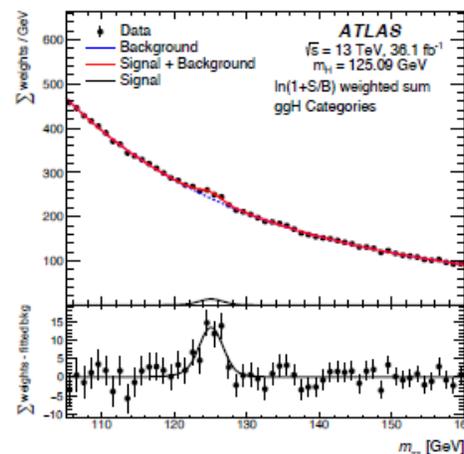
$$\mu_{VBF} = 2.0^{+0.6}_{-0.5} = 2.0 \pm 0.5(stat)^{+0.3}_{-0.2}(exp)^{+0.3}_{-0.2}(theo)$$

$$\mu_{VH} = 0.7^{+0.9}_{-0.8} = 0.7 \pm 0.8(stat)^{+0.2}_{-0.2}(exp)^{+0.2}_{-0.1}(theo)$$

$$\mu_{top} = 0.5^{+0.6}_{-0.6} = 0.5^{+0.6}_{-0.5}(stat)^{+0.1}_{-0.1}(exp)^{+0.1}_{-0.0}(theo)$$

- 这是首次在单一衰变道观测 $\sim 5\sigma$ 的VBF的信号显著度

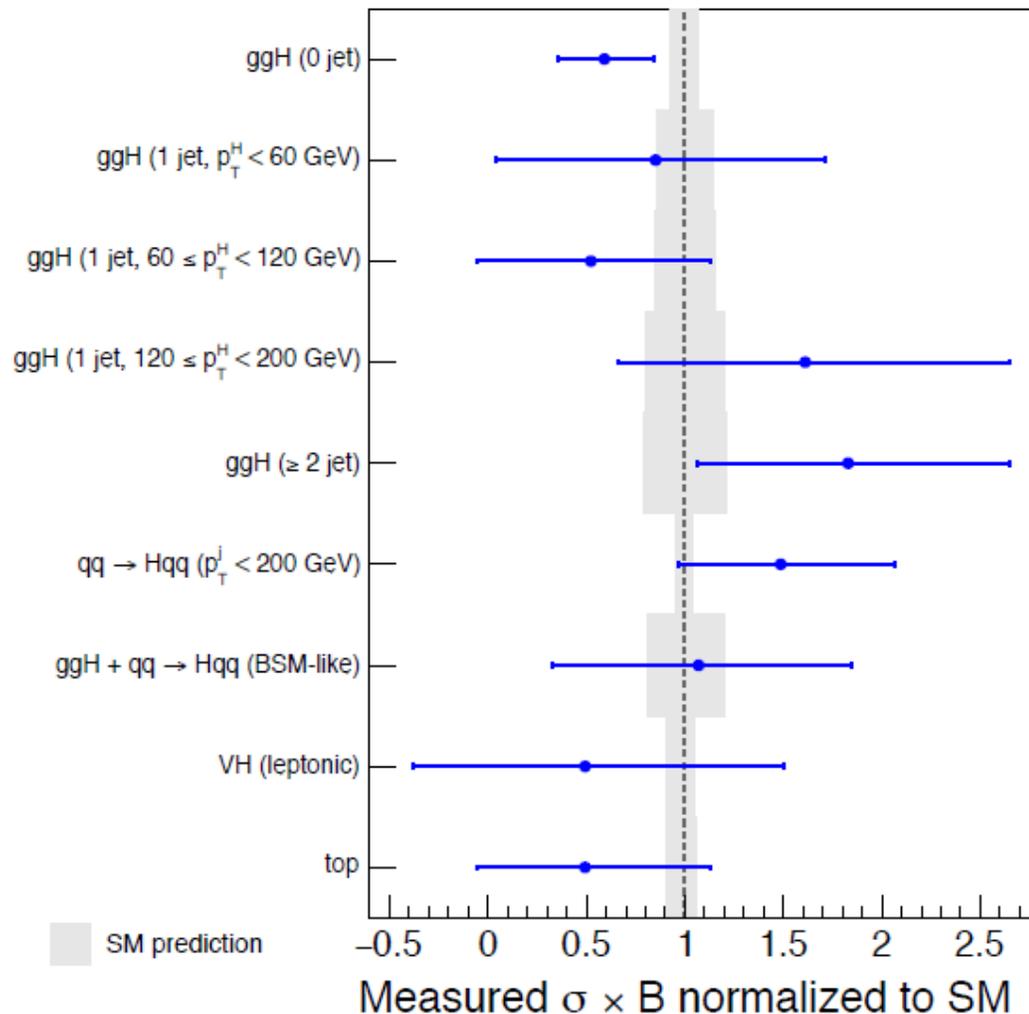
Measurement	Exp. Z_0	Obs. Z_0
μ_{VBF}	2.6σ	4.9σ
μ_{VH}	1.4σ	0.8σ
μ_{top}	1.8σ	1.0σ



结果——36.1fb⁻¹

- STXS
 - 测量结果与标准模型在误差范围内保持一致

Measurement region ($ y_H < 2.5$)	Result		Uncertainty		SM prediction		
	Total	Stat.	Syst.				
ggH, 0 jet	37 ⁺¹⁶ ₋₁₅	(±14	+6	-5)	fb	63 ± 5 fb	
ggH, 1 jet, $p_T^H < 60$ GeV	13 ⁺¹³ ₋₁₂	(±12	+5	-4)	fb	15 ± 2 fb	
ggH, 1 jet, $60 \leq p_T^H < 120$ GeV	5 ± 6	(±6	+2	-1)	fb	10 ± 2 fb	
ggH, 1 jet, $120 \leq p_T^H < 200$ GeV	2.8 ^{+1.7} _{-1.6}	(+1.6	+0.7	-1.5	-0.5)	fb	1.7 ± 0.3 fb
ggH, ≥ 2 jet	20 ⁺⁹ ₋₈	(±8	+4	-3)	fb	11 ± 2 fb	
$qq \rightarrow Hqq, p_T^j < 200$ GeV	15 ⁺⁶ ₋₅	(±5	+3	-2)	fb	10 ± 0.5 fb	
ggH + qq → Hqq, BSM-like	2.0 ± 1.4	(±1.3	±0.6		fb	1.8 ± 0.4 fb	
VH, leptonic	0.7 ^{+1.4} _{-1.3}	(+1.4	+0.4	-1.2	-0.3)	fb	1.4 ± 0.1 fb
Top	0.7 ^{+0.8} _{-0.7}	(+0.8	+0.2	-0.7	-0.1)	fb	1.3 ± 0.1 fb



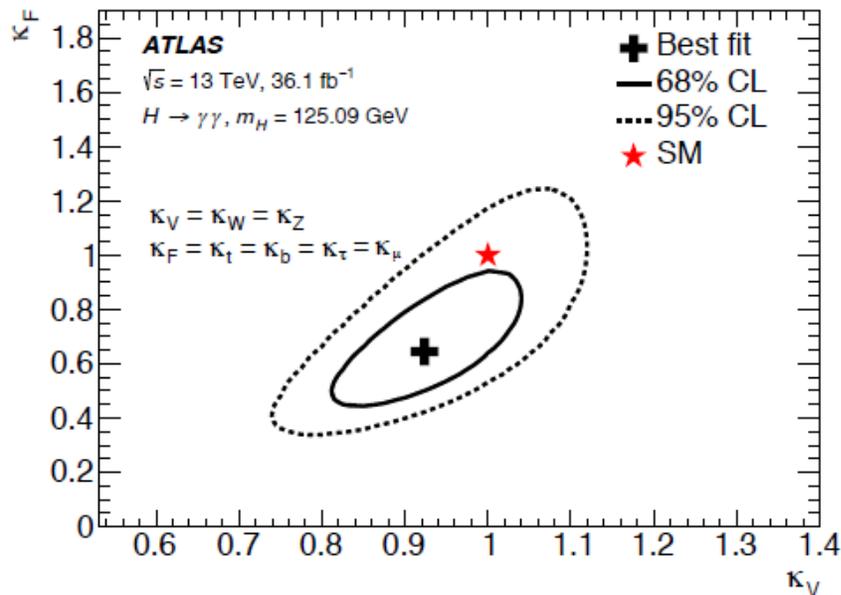
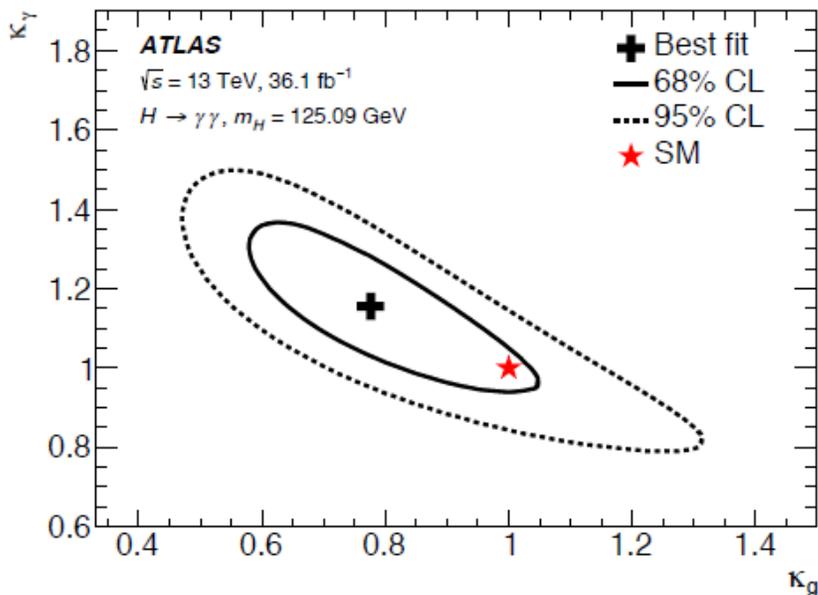
结果——36.1fb-1

• 耦合强度 (kappa-framework)

$$(\sigma \times BR)(H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H)BR_{SM}(H \rightarrow \gamma\gamma) \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

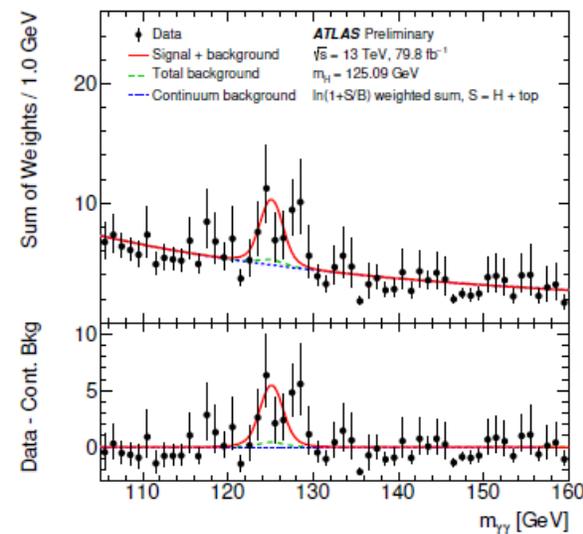
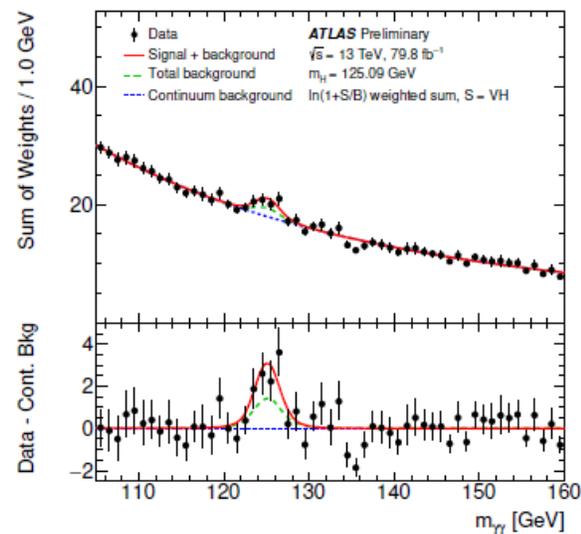
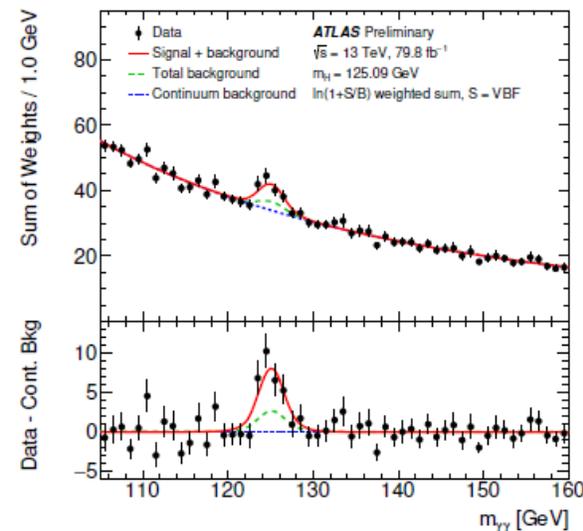
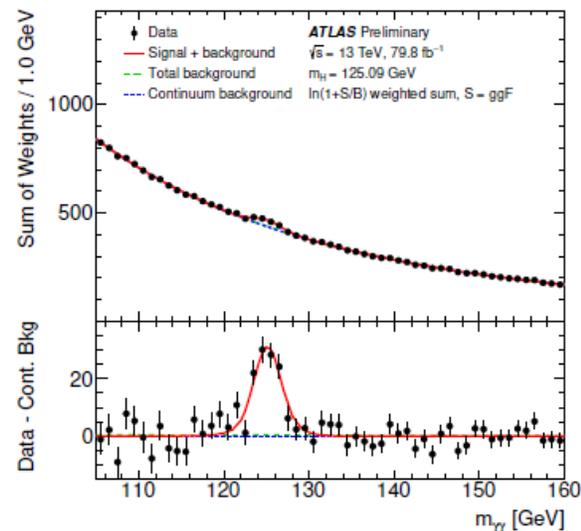
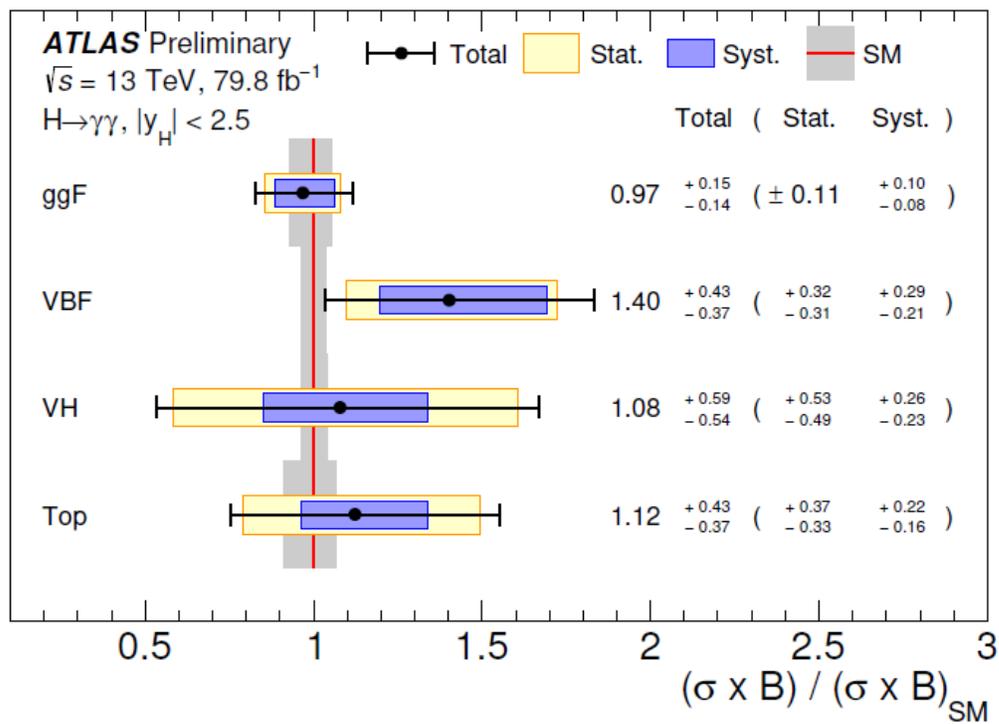
$$\kappa_g = \frac{\kappa_t^2 \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

$$\kappa_\gamma = \frac{\kappa_t^2 \Gamma_{\gamma\gamma}^{tt}(m_H) + \kappa_b^2 \Gamma_{\gamma\gamma}^{bb}(m_H) + \kappa_t \kappa_b \Gamma_{\gamma\gamma}^{tb}(m_H)}{\Gamma_{\gamma\gamma}^{tt}(m_H) + \Gamma_{\gamma\gamma}^{bb}(m_H) + \Gamma_{\gamma\gamma}^{tb}(m_H)}$$



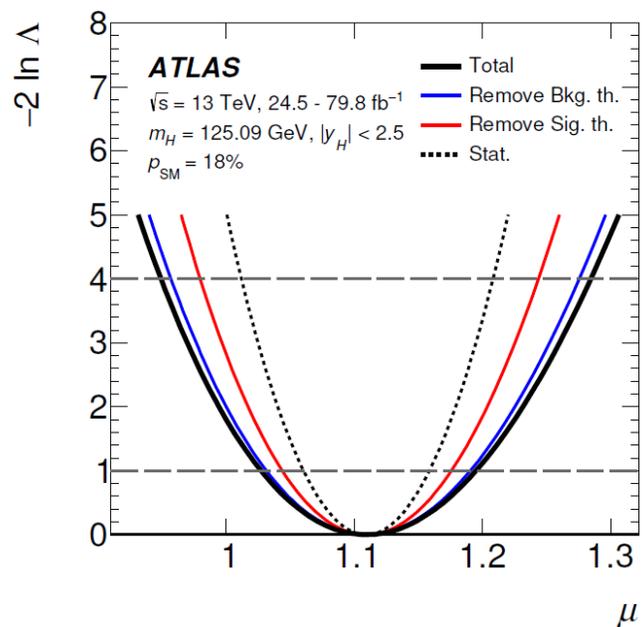
结果——80fb-1

- 观测的事例
- 产生截面



结果-combination

- 所用到的子道和相应数据的积分亮度
- 信号强度

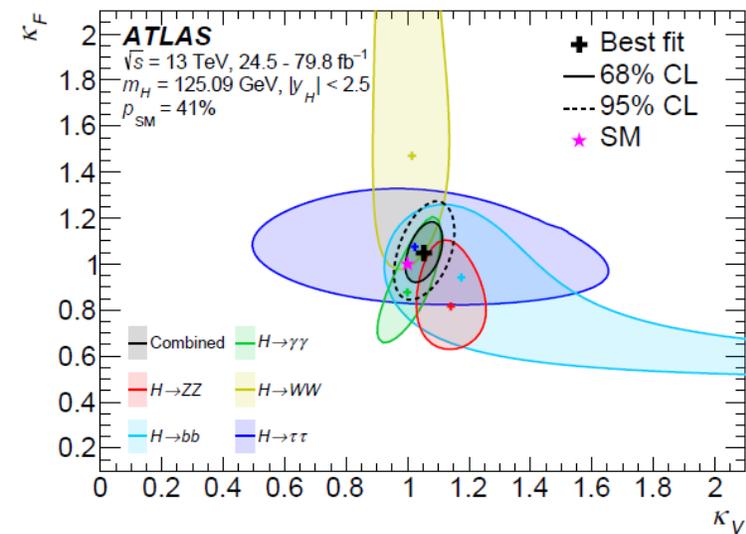


Analysis	Dataset	Integrated luminosity [fb ⁻¹]
$H \rightarrow \gamma\gamma$ (including $t\bar{t}H$, $H \rightarrow \gamma\gamma$)		79.8
$H \rightarrow ZZ^* \rightarrow 4\ell$ (including $t\bar{t}H$, $H \rightarrow ZZ^* \rightarrow 4\ell$)	2015–2017	79.8
VH , $H \rightarrow b\bar{b}$		79.8
$H \rightarrow \mu\mu$		79.8
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$		36.1
$H \rightarrow \tau\tau$		36.1
VBF, $H \rightarrow b\bar{b}$	2015–2016	24.5 – 30.6
$t\bar{t}H$, $H \rightarrow b\bar{b}$ and $t\bar{t}H$ multilepton		36.1
$H \rightarrow \text{invisible}$		36.1
Off-shell $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow ZZ^* \rightarrow 2\ell 2\nu$		36.1

$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05(stat) {}^{+0.05}_{-0.04}(exp) {}^{+0.05}_{-0.04}(sig.th) \pm 0.03(bkg.th)$$

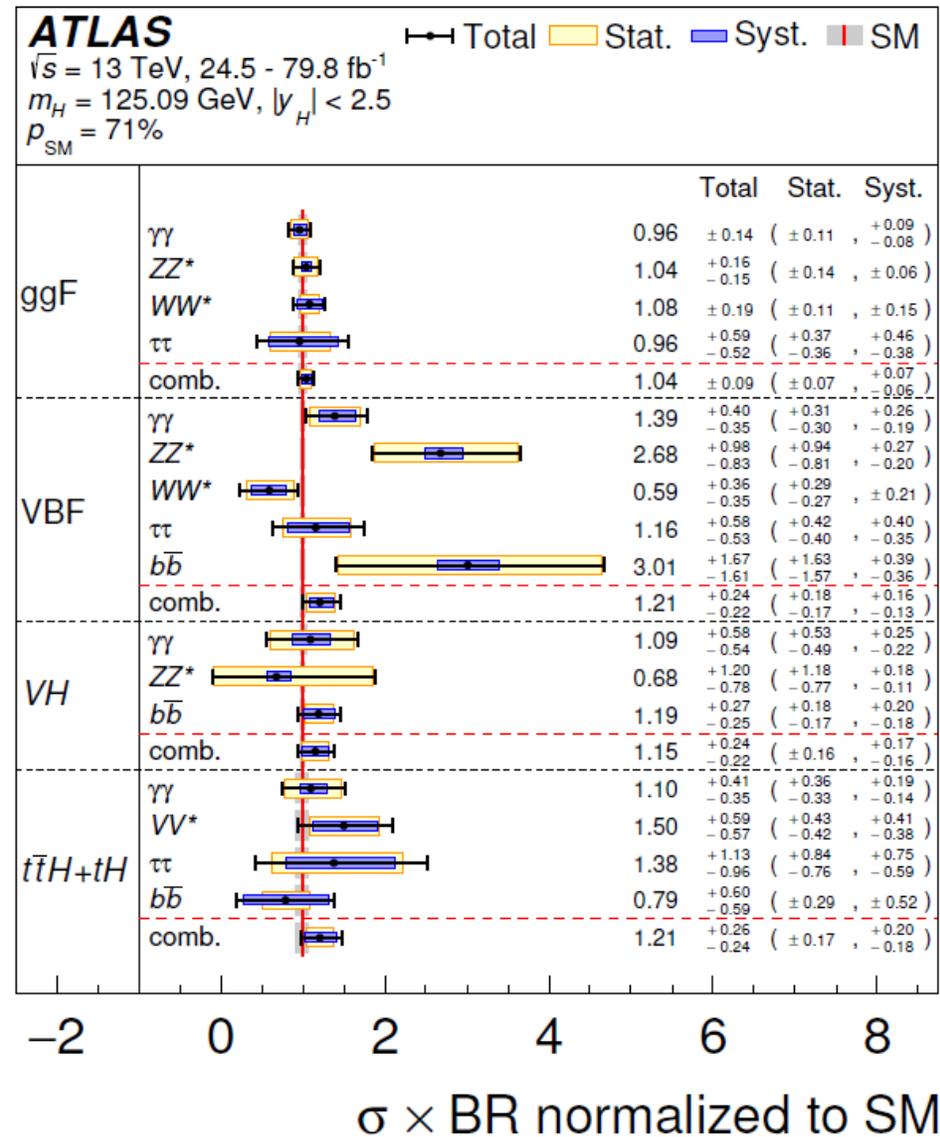
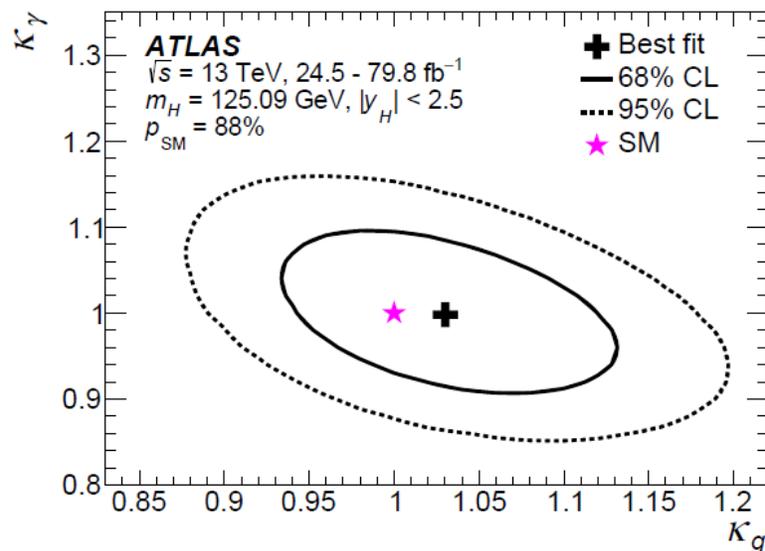
结果——combination

• 各产生模式截面和耦合强度



$$\kappa_\gamma = 1.00 \pm 0.06, \kappa_g = 1.03^{+0.07}_{-0.06}$$

$$\kappa_V = 1.05 \pm 0.04, \kappa_f = 1.05 \pm 0.09$$



总结

- 取得的成果
 - 利用BDT对筛选条件进行优化, 并且发表了 36.1fb^{-1} 和 80fb^{-1} 的结果
 - 首次在单个探测器上观测到VBF希格斯粒子的信号
- 将来的研究方向
 - 更高效率的喷注味道的鉴别方法
 - 更高效的pile-up喷注的压低方法, 新的探测器HGTD (high granularity timing detector) 有助于减少pile-up喷注
 - 先进的机器学习方法
 - 希格斯粒子的CP测量

Backup——发表文章和贡献

- VBF $H \rightarrow \gamma\gamma$

- ICHEP2016: Measurement of fiducial, differential and production cross sections in the $H \rightarrow \gamma\gamma$ decay channel with 13.3 fb^{-1} of 13 TeV proton-proton collision data with the ATLAS detector
- EPS2017: Measurements of Higgs boson properties in the diphoton decay channel with 36.1 fb^{-1} pp collision data at the center-of-mass energy of 13 TeV with the ATLAS detector
- Paper: Measurements of Higgs boson properties in the diphoton decay channel with 36 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector

- Contribution

- Optimization of VBF category
- Internal note editor

Backup——发表文章和贡献(2)

- $HH \rightarrow \gamma\gamma WW^*$
 - Paper: Search for Higgs boson pair production in the $\gamma\gamma WW^*$ channel using pp collision data recorded at $\sqrt{s}=13$ TeV with the ATLAS detector
- Contribution
 - Estimation of theoretical uncertainty, including QCD scale, PDF and parton shower.
 - Spurious signal

Backup——发表文章和贡献 (3)

- $HH \rightarrow WW^* WW^*$
 - Paper: Search for Higgs boson pair production in the $WW^* WW^*$ decay channel using ATLAS data recorded at $\sqrt{s}=13$ TeV
- Contribution
 - Statistic interpretation : combination of three sub-channels, check of statistic model, upper-limit setting

评阅意见

- 1) 作者对整个分析过程各个方面都进行了描述，但对作者本人在分析中的贡献没有进行重点说明；
- 2) 对分析结果缺乏细致的讨论；
- 3) 论文撰写比较随意，文字表述不够严谨，由于粗心造成的笔误较多，需在论文提交前进行修改。

评阅意见

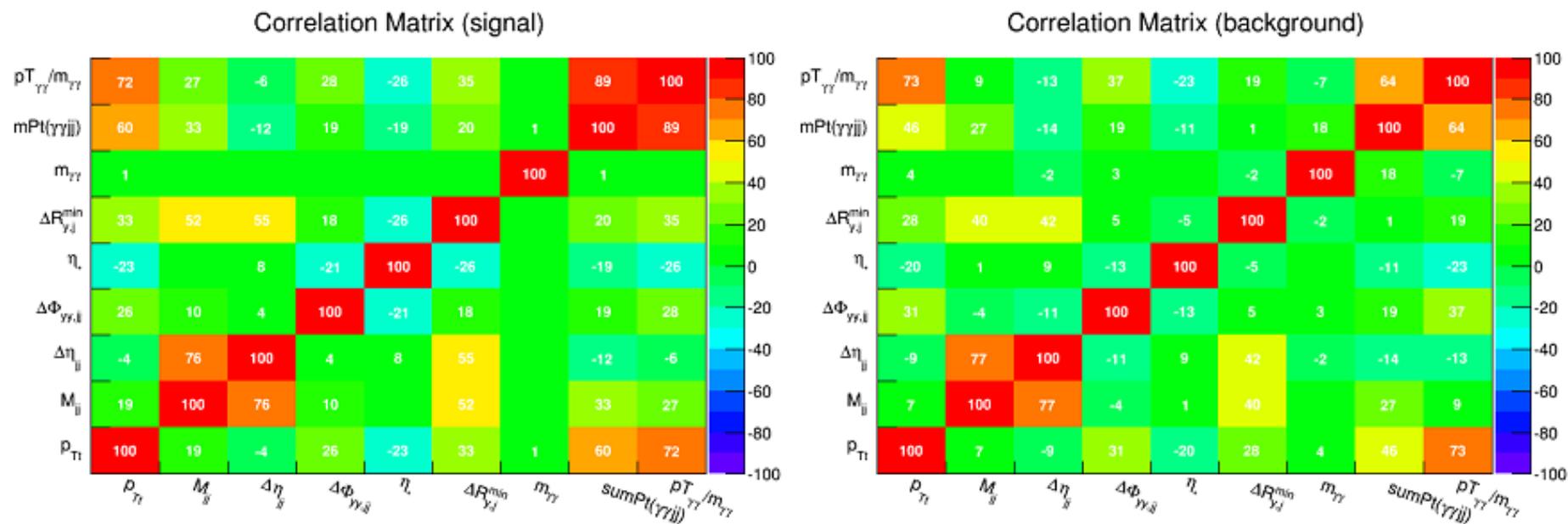
- 希望作者如果可能加强对前人对VBF希格斯粒子研究的叙述，比如在ATLAS希格斯粒子发现中VBF起到作用

评阅意见

- 论文介绍了标准模型和希格斯物理，大型强子对撞机和ATLAS实验，文献综述比较全面深入。论文体现了作者具有扎实的基础和系统深入的专门知识，具有独立科研能力。论文内容完整，结构清晰，写作规范，逻辑清楚，行文流畅。论文达到了博士学位论文的水平，同意答辩。

correlation to m_H

- the used variables should not be correlated to $m_{\gamma\gamma}$



CMS VBF H- $\rightarrow\gamma\gamma$ strategy

Events produced via the VBF mechanism features two jets in the final state separated by a large rapidity gap. A multivariate discriminant is trained to tag the VBF jets kinematics, considering as background the production process of $ggH + \text{jets}$, and is given as input to an additional "combined" multivariate classifier along with the score of the photon identification MVA, the diphoton BDT score, and the ratio $p_{T\gamma\gamma}/m_{\gamma\gamma}$. Figure 7 (left) shows the transformed score of the combined multivariate classifier for data in the mass side-band region 105-115 GeV and 135-145 GeV, along with the predicted VBF and ggH distributions. The classifier score has been transformed such that the signal events from the VBF production mode has a uniform, flat, distribution. A validation of the score of the combined multivariate classifier obtained in $Z \rightarrow e^+e^- + \text{jets}$ events, where the electrons are reconstructed as photons and at least two jets satisfy the requirements listed below to enter the VBF category, is shown in Fig. 7 (right) for data and simulation.

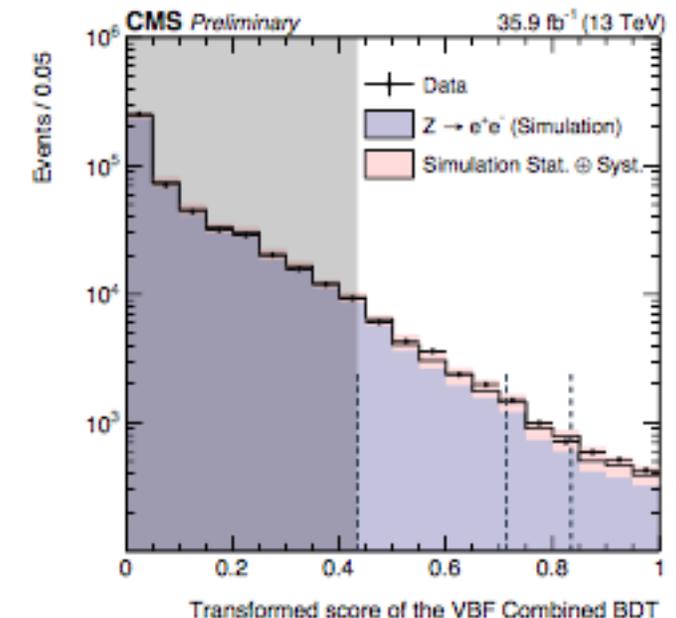
Selections:

- one jet with $p_T > 40$ GeV and one with $p_T > 30$ GeV, both with $|\eta| < 4.7$ and width a tight requirement on the pileup jet identification;
- the invariant mass of the two jets $m_{jj} > 250$ GeV;
- the combined multivariate discriminant greater than 0.43.
- leading photon $p_T > m_{\gamma\gamma}/3$, sub-leading photon $p_T > m_{\gamma\gamma}/4$;
- photon ID BDT score greater than -0.2, in order to provide additional rejection against background events whose kinematics yield a high diphoton BDT score despite one reconstructed photon with a relatively low ID score;

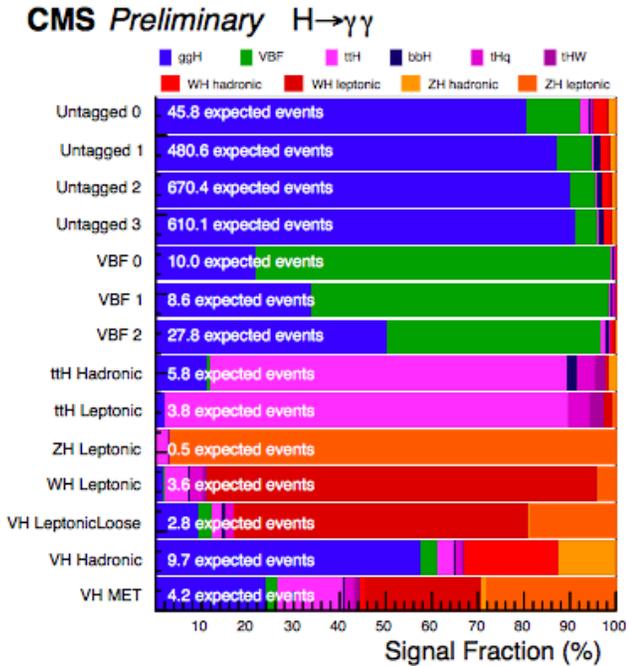
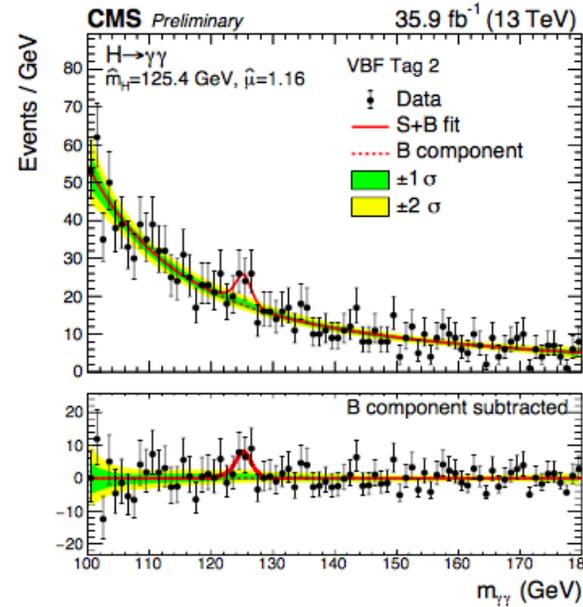
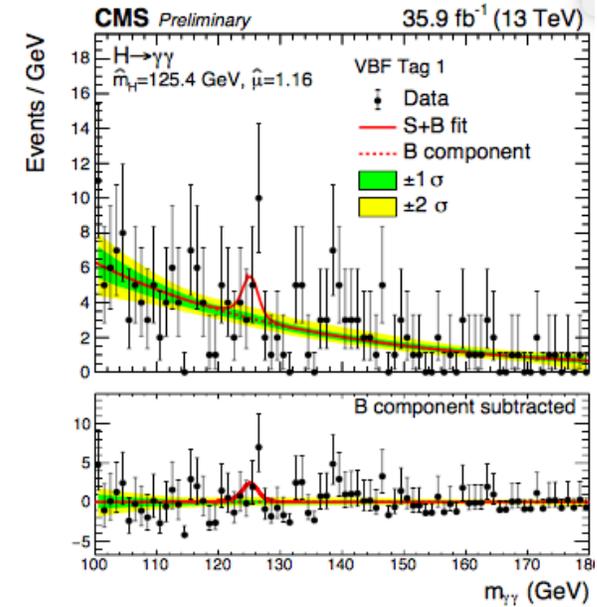
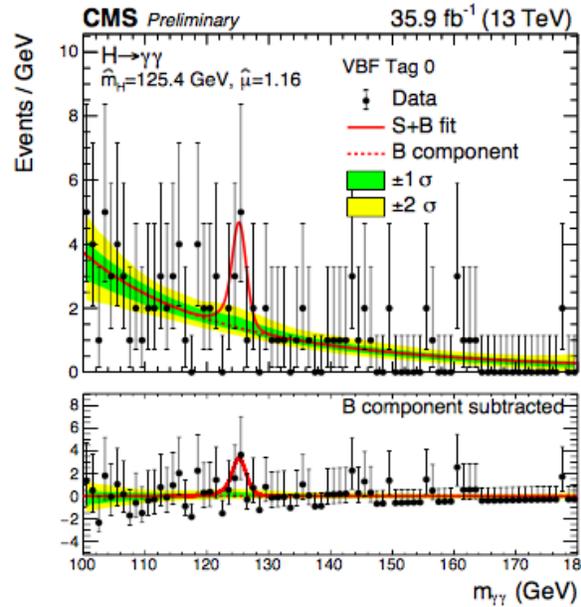
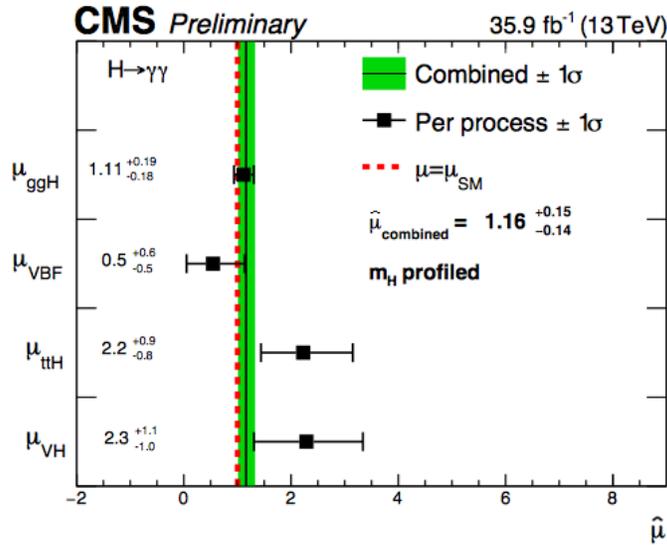
➤ BDT training :

- VBF Higgs vs $ggH + \text{jets}$
- Divided into 3 cats.

➤ Validated with $Z \rightarrow ee$ events

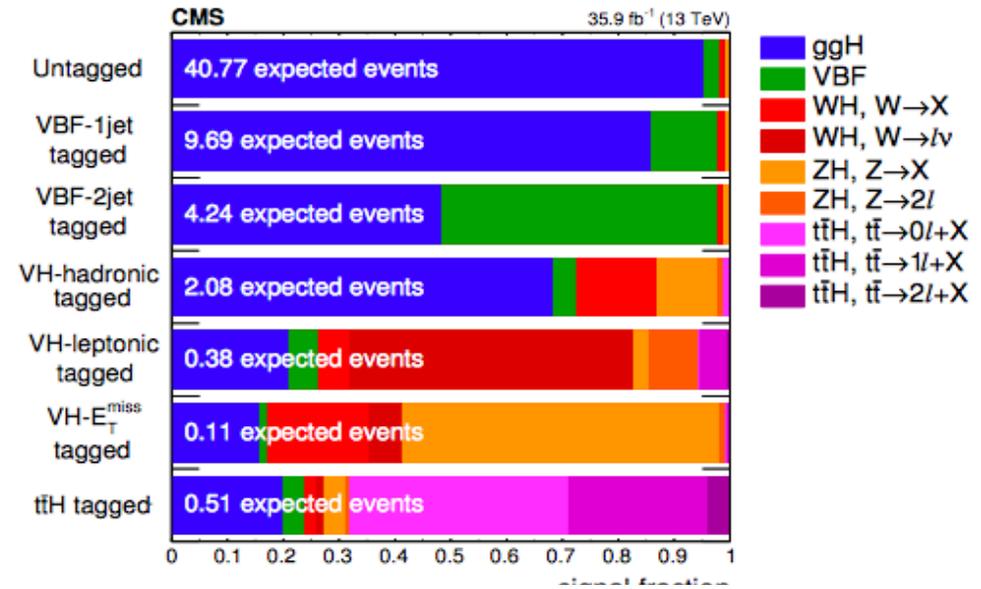
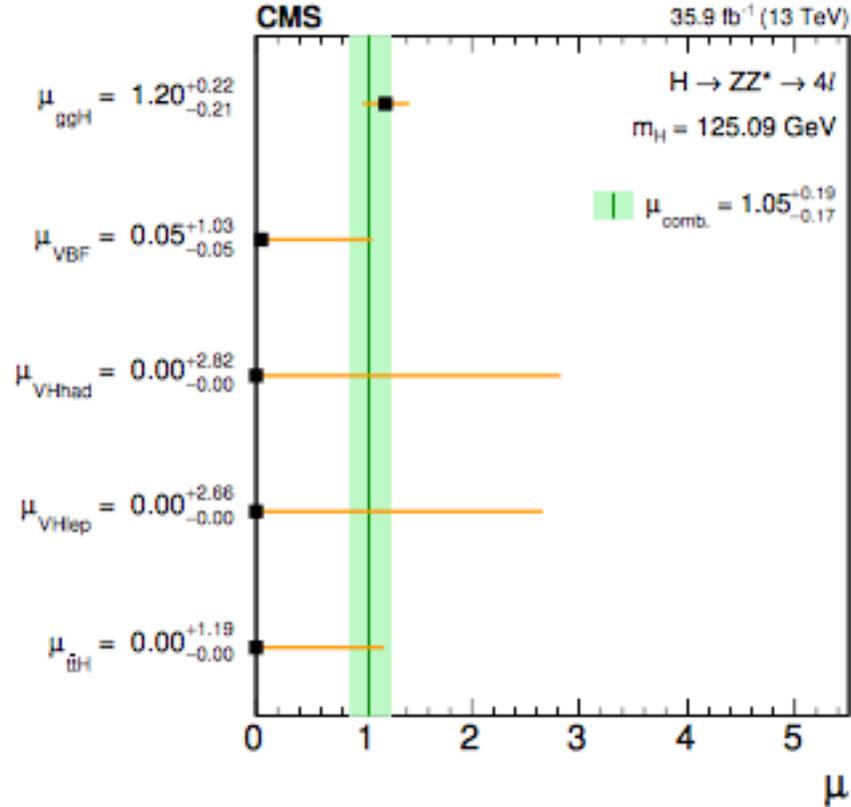


CMS VBF $H \rightarrow \gamma\gamma$



Observed (expected) Significance = 1.1 σ /1.9 σ

CMS VBF H \rightarrow ZZ



	Event category							Inclusive
	Untagged	VBF-1j	VBF-2j	VH-hadr.	VH-lept.	VH- E_T^{miss}	$t\bar{t}H$	
$q\bar{q} \rightarrow ZZ$	19.18	2.00	0.25	0.30	0.27	0.01	0.01	22.01
$gg \rightarrow ZZ$	1.67	0.31	0.05	0.02	0.04	0.01	<0.0	2.09
Z+X	10.79	0.88	0.78	0.31	0.17	0.30	0.27	13.52
Sum of backgrounds	31.64	3.18	1.08	0.63	0.49	0.32	0.28	37.62
uncertainties	+4.30 -3.42	+0.37 -0.32	+0.29 -0.21	+0.13 -0.09	+0.07 -0.07	+0.14 -0.11	+0.09 -0.07	+5.19 -4.18
$gg \rightarrow H$	38.78	8.31	2.04	1.41	0.08	0.02	0.10	50.74
VBF	1.08	1.14	2.09	0.09	0.02	<0.01	0.02	4.44
WH	0.43	0.14	0.05	0.30	0.21	0.03	0.02	1.18
ZH	0.41	0.11	0.04	0.24	0.04	0.07	0.02	0.93
$t\bar{t}H$	0.08	<0.01	0.02	0.03	0.02	<0.01	0.35	0.50
Signal	40.77	9.69	4.24	2.08	0.38	0.11	0.51	57.79
uncertainties	+3.69 -3.62	+1.13 -1.17	+0.55 -0.55	+0.23 -0.23	+0.03 -0.03	+0.01 -0.02	+0.06 -0.06	+4.89 -4.80
Total expected	72.41	12.88	5.32	2.71	0.86	0.43	0.79	95.41
uncertainties	+7.35 -6.27	+1.25 -1.21	+0.78 -0.65	+0.34 -0.28	+0.10 -0.09	+0.15 -0.12	+0.14 -0.12	+9.86 -8.32
Observed	73	13	4	2	1	1	0	94

Table 2. The numbers of expected background and signal events and the number of observed candidate events after the full selection, for each event category, for the mass range $118 < m_{4\ell} < 130$ GeV. The yields are given for the different production modes. The signal and ZZ backgrounds yields are estimated from simulation, while the Z+X yield is estimated from data.