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博士学位论文

在 ATLAS 实验上寻找超出标准模型希格斯粒子

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摘 要

关键词： ATLAS, 超出标准模型希格斯粒子, ITk

Abstract

Keywords: ATLAS, BSM Higgs, ITk

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符号列表

字符

Symbol	Description	Unit
R	the gas constant	$\text{m}^2 \cdot \text{s}^{-2} \cdot \text{K}^{-1}$
C_v	specific heat capacity at constant volume	$\text{m}^2 \cdot \text{s}^{-2} \cdot \text{K}^{-1}$
C_p	specific heat capacity at constant pressure	$\text{m}^2 \cdot \text{s}^{-2} \cdot \text{K}^{-1}$
E	specific total energy	$\text{m}^2 \cdot \text{s}^{-2}$
e	specific internal energy	$\text{m}^2 \cdot \text{s}^{-2}$
h_T	specific total enthalpy	$\text{m}^2 \cdot \text{s}^{-2}$
h	specific enthalpy	$\text{m}^2 \cdot \text{s}^{-2}$
k	thermal conductivity	$\text{kg} \cdot \text{m} \cdot \text{s}^{-3} \cdot \text{K}^{-1}$
S_{ij}	deviatoric stress tensor	$\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}$
τ_{ij}	viscous stress tensor	$\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}$
δ_{ij}	Kronecker tensor	1
I_{ij}	identity tensor	1

算子

Symbol	Description
Δ	difference
∇	gradient operator
δ^\pm	upwind-biased interpolation scheme

缩写

CFD	Computational Fluid Dynamics
CFL	Courant-Friedrichs-Lewy
EOS	Equation of State
JWL	Jones-Wilkins-Lee
WENO	Weighted Essentially Non-oscillatory
ZND	Zel'dovich-von Neumann-Doering

第一部分

hh/SS 信号寻找

第 1 章 数据和蒙特卡罗样本

1.1 数据样本

本分析利用 2015 年和 2016 年 ATLAS 探测器收集的质心系能量为 13 TeV 的数据，排除掉受损或者探测器未完全运作时的数据，其积分亮度为 36.1 fb^{-1} 。其中，2015 年和 2016 年的数据收集情况如图 1.1 所示。

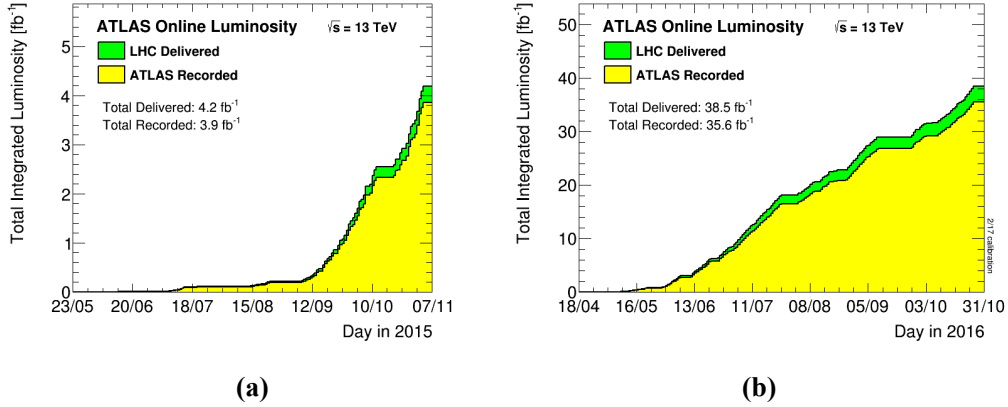


图 1.1 ATLAS 数据收集情况: (a) 2015 年, (b) 2016 年。

1.2 蒙特卡罗样本

1.2.1 信号样本

信号样本包含两种模型，分别为希格斯粒子对 ($gg \rightarrow (X) \rightarrow hh$) 和类希格斯粒子对 ($gg \rightarrow X \rightarrow SS$)。

1.2.1.1 $gg \rightarrow (X) \rightarrow hh$

1. SM 信号（非共振态模式），即 $gg \rightarrow hh$ ，利用包含 NLO 修正的双希格斯粒子模型 [1]，在 MadGraph5_aMC@NLO [2, 3] 中产生。其产生截面为 33.4 fb [4, 5]，考虑了 NNLO QCD 修正和 including resummation of soft-gluon emission at next-to-next-to-leading-logarithmic (NNLL) accuracy for $m_H = 125.09 \text{ GeV}$ 。

2. 共振态模式 ($gg \rightarrow X \rightarrow hh$) 也利用包含 NLO 修正的 2HDMCP_EFT 的信号模型 [6]，在 MadGraph5_aMC@NLO 中产生。其中重标量粒子 X，即共振态粒子，被假设具有远小于实验精度的衰变宽度；在实际模拟中，其宽度设为 10 MeV ，并考虑四个质量点，分别为 260 GeV , 300 GeV , 400 GeV 和 500 GeV 。此过程产生截面假设为 1 pb 。

DSID	lepton charge	m_X [GeV]	Num. Events	Simulation	e/a/s/r/p-tags
344133	++	Non-res	500000	AFII	e5060, a766, a821, r7676, p2949
344134	--	Non-res	500000	AFII	e5060, a766, a821, r7676, p2949
343704	++	260	100000	AFII	e5234, a766, a821, r7676, p2949
343712	--	260	100000	AFII	e5234, a766, a821, r7676, p2949
343706	++	300	100000	AFII	e5234, a766, a821, r7676, p2949
343714	--	300	100000	AFII	e5234, a766, a821, r7676, p2949
343709	++	400	100000	AFII	e5153, a766, a821, r7676, p2949
343717	--	400	100000	AFII	e5153, a766, a821, r7676, p2949
343711	++	500	100000	AFII	e5153, a766, a821, r7676, p2949
343719	--	500	100000	AFII	e5234, a766, a821, r7676, p2949

表 1.1 Summary of the MC hh samples which have been produced for study.

两个希格斯粒子均被要求衰变到 W 玻色子对，随后，其中两个 $W^+(W^-)$ 被要求衰变到轻子（包括 τ ），而另两个 $W^-(W^+)$ 则到强子对。这一系列衰变通过 Herwig++ [7] 实现，也包括随后的 showering 和强子化过程，其衰变分支比为 $BR(hh \rightarrow 4W \rightarrow \ell^+ \nu \ell^+ qqqq) = 4.4 \times 10^{-3}$ 。两种模式的信号样本的产生情况总结如表 1.1 所示。

1.2.1.2 $gg \rightarrow X \rightarrow SS$

$gg \rightarrow X \rightarrow SS$ 利用 Pythia 8 在 LO 阶产生，PDF 为 A14NNPDF2.3LO，模型为 HiggsBSM:gg2A3， X 和 S 均假设具有远小于实验分辨率的宽度，为各自质量的 1%。与 $gg \rightarrow (X) \rightarrow hh$ 类似， S 被要求衰变到两个 W 玻色子，其中两个 $W^+(W^-)$ 被要求衰变到轻子（包括 τ ），而另两个 $W^-(W^+)$ 则到强子对。随后的 showering 和强子化过程也由 Pythia 8 实现。 m_X 和 m_S 选择使得 $4W$ 末态能够最显著。同样的， $gg \rightarrow X \rightarrow SS$ 截面假设为 1 pb，而 $BR(S \rightarrow WW)$ 则依赖于 m_S ，即希格斯粒子在不同质量点的衰变分支比 [8]。表 1.2 总结了此信号样本产生情况。

1.2.2 背景样本

多玻色子 (VV/VVV) 和 $V\gamma$ 样本通过 Sherpa 2.1 [9] 在 NLO 阶产生； $V + jets$ 则通过 Sherpa 2.2 在 NLO 阶产生，此两种过程均采用 CT10 PDF。 VH 利用 Pythia 8 在 LO 阶产生，采用 NNPDF2.3LO PDF。 $t\bar{t}$ 通过 Powheg-Box 2.0 [10] 在 NLO 阶产生，而后传递到 Pythia 8 进行 parton showering 和强子化模拟，采用 PDF 为

Charge	m_X	m_S	BR(two SS leptons)	DSID	N_{events}
++	280 GeV	135 GeV	1.47×10^{-2}	344927	25000
	300 GeV	135 GeV	1.535×10^{-2}	344928	25000
	320 GeV	135 GeV	1.535×10^{-2}	344930	25000
	340 GeV	135 GeV	1.535×10^{-2}	344933	25000
	340 GeV	145 GeV	3.454×10^{-2}	344934	25000
	340 GeV	155 GeV	6.049×10^{-2}	344935	24000
	340 GeV	165 GeV	8.842×10^{-2}	344936	25000
--	280 GeV	135 GeV	1.47×10^{-2}	344937	25000
	300 GeV	135 GeV	1.535×10^{-2}	344938	25000
	320 GeV	135 GeV	1.535×10^{-2}	344940	25000
	340 GeV	135 GeV	1.535×10^{-2}	344943	25000
	340 GeV	145 GeV	3.454×10^{-2}	344944	24000
	340 GeV	155 GeV	6.049×10^{-2}	344945	25000
	340 GeV	165 GeV	8.842×10^{-2}	344946	25000

表 1.2 Summary of the MC $X \rightarrow SS$ signal samples used.

NNPDF2.3LO。单顶夸克过程 ($t + X$) 同样通过 Powheg-Box 2.0 在 NLO 阶产生, 但传递到 Pythia 6.4 [11] 进行后续模拟, 采用 PDF 则为 CT10。 $t\bar{t}V$ 样本则在 NLO 阶通过 MadGraph5_aMC@NLO + Pythia 8 产生, 采用 PDF 为 NNPDF2.3LO。 $t\bar{t}H$ 样本通过 MadGraph5_aMC@NLO + Herwig++ 产生, PDF 为 NNPDF3.0 [12]。更多关于这些背景过程的产生及模拟过程可参考文献 [13–15]。

第 2 章 事例筛选和信号优化

2.1 粒子鉴别及筛选

2.1.1 Object definitions in 4W

粒子鉴别遵循 ATLAS 一般流程，如章节 ?? 所述。对于 4W 分析，进一步的粒子筛选条件总结如表 2.1 所示。

粒子	选择条件	
电子	Baseline	Tight
	$E_T > 10 \text{ GeV}$ $ \eta < 2.47$, 排除 $1.37 < \eta < 1.52$ 区间 LooseLH ID, Loose isolation $ z_0 \sin \theta < 0.5 \text{ mm}$, $d_0/\sigma(d_0) < 5$	TightLH ID FixedCutTight $(E_T^{\text{cone20}}/p_T < 0.06, p_T^{\text{varcone20}}/p_T < 0.06)$
μ	$p_T > 10 \text{ GeV}$ $ \eta < 2.5$ Loose ID, Loose isolation $ z_0 \sin \theta < 0.5 \text{ mm}$, $d_0/\sigma(d_0) < 3$	Tight ID FixedCutTightTrackOnly $(p_T^{\text{varcone20}}/p_T < 0.06)$
Jet	$p_T > 25 \text{ GeV}$, $ \eta < 2.5$ $ \text{JVT} < 0.59$ if $p_T < 60 \text{ GeV}$ and $ \eta < 2.4$	
MET	$E_T^{\text{miss,TRK}}$	

表 2.1 4W 物理分析粒子筛选条件总结

2.1.2 Overlap removal

经过粒子基准（baseline）筛选之后，为了进一步保证没有误重建的重复粒子，专门的 overlap removal 需要完成。该分析中的 overlap removal 总结如表 2.2 所示。

Keep	Remove	Cone size (ΔR)
muon	electron	0.1
electron	electron(lower p_T)	0.1
electron	jet	0.3
jet	muon	$\min(0.4, 0.04+10[\text{GeV}]/p_T(\mu))$

表 2.2 Overlap removal in 4W analysis.

2.2 事例筛选

2.2.1 初步筛选

所选事例应当通过如下初步筛选条件：

- **GRL**

2015 data: data15_13TeV.periodAllYear_DetStatus-v79-repro20-02
_DQDefects-00-02-02_PHYS_StandardGRL_All_Good_25ns.xml

2016 data: data16_13TeV.periodAllYear_DetStatus-v88-pro20-21
_DQDefects-00-02-04_PHYS_StandardGRL_All_Good_25ns.xml

- **Event cleaning criteria:** cleaning for Tile corrupted events, LAr noise bursts and corrupted data

- **Vertex criteria:** events are required to contain at least one primary vertex with ≥ 2 associated tracks. The detailed selection on the vertex can be found in [?]

- **Trigger:**

对于 2015 年数据，满足以下任一 trigger：

- Single lepton triggers:
 - * HLT_mu20_loose_L1MU15
 - * HLT_mu50
 - * HLT_e24_lhmedium_L1EM20VH
 - * HLT_e60_lhmedium
 - * HLT_e120_lhloose
- Dilepton triggers:
 - * HLT_2e12_lhloose_L12EM10VH
 - * HLT_e17_lhloose_mu14
 - * HLT_mu18_mu8noL1

对于 2016 年数据，满足以下任一 trigger：

- Single lepton triggers:

- * HLT_mu24_ivarmedium
- * HLT_mu50
- * HLT_e24_lhtight_nod0_ivarloose
- * HLT_e60_lhmedium_nod0
- * HLT_e140_lhloose_nod0
- Dilepton triggers:
- * HLT_2e17_lhvloose_nod0
- * HLT_e17_lhloose_nod0_mu14
- * HLT_mu22_mu8noL1

与数据一样，模拟样本也应当满足以上 trigger 条件，其相应的 trigger 效率修正已添加到每个样本事例中

- 选择通过章节 2.1.1 所述的粒子。
- 轻子数：
 - 两个相同电荷的轻子。
 - 每个 tight 电子应当满足 $\text{ChargeIDBDTTight} > 0.067$ ，此变量是用来压低“假”电子，如附录 ?? 所述。
 - 至少有一个轻子应当能匹配以上任一或多个 trigger，除此之外，大横动量轻子 p_T 应大于 30 GeV，小横动量轻子大于 20 GeV。
- 排除掉任何含有 b -jet 的事例。
- $E_T^{\text{miss,TRK}} > 10 \text{ GeV}$ 。
- 因为 Drell-Yan 过程目前并不能被 MC 很好模拟，所以为了避免此问题，双轻子不变质量应大于 15 GeV。
- 为了压低来自于 Z +jets 过程的本底（电荷误判）， $|M(\ell\ell) - M(Z)| > 10 \text{ GeV}$ 条件须通过。
- jet 数的要求依赖于质量点的选择，低（高）质量点要求至少 2（3）个 jet。此项会在 ?? 深入讨论。

以上的事例筛选过程总结在表 2.3。最后，通过以上筛选条件的事例根据轻子味道分为三个分析道，为 $ee \mu\mu$ 和 $e\mu$ 。表 2.4 展示了标准模型希格斯对信号经过以上一系列条件时的事例数和效率变化，此处对应亮度为 36.1 fb^{-1} ，截面 ($gg \rightarrow hh$) 为 33.4 fb。图 2.1（图 2.2）展示所有 hh (SS) 信号样本的经过初步筛选之后的效率，可以看到：一是随着 m_X 或者 m_S 的增加，效率相应增加（对于 SS ，在 $m_X = 340 \text{ GeV}$, $m_S = 135 \text{ GeV}$ 质量点的效率下降是因为从此点开始要求至少三个

Pre-selections	GRL
	Event clean criteria
	Pass any trigger applied
	Select objects following object definitions
	Overlap removal
	Two tight same-signed leptons, with at least one trigger matched
	$p_T(\ell_1) > 30 \text{ GeV}, p_T(\ell_2) > 20 \text{ GeV}$
	b veto
	$E_T^{miss} > 10 \text{ GeV}$
	$M(\ell\ell) > 15 \text{ GeV}$
	$ M(\ell\ell) - M(Z) > 10 \text{ GeV}$ in ee channel
	$N_{\text{jet}} \geq 2(3)$

表 2.3 The event cleaning criteria.

jet)；二是 $e\mu$ 道具有最高的效率值， $\mu\mu$ 次之， ee 最低，这是因为理论上 $e\mu$ 的分支比是其他两个道的两倍，以及 μ 比 e 具有更好的鉴别效率。

2.2.2 信号优化

2.2.2.1 hh 信号优化

本分析中的显著信号是两个相同电荷的轻子和 jet 数。两个希格斯粒子倾向于出射到两个相反的半球，随后，两个希格斯粒子均衰变到 W 玻色子，总共四个 W 玻色子中有两个是不在壳的，而不在壳的 W 玻色子会贡献相当部分的低动量的 jet ($p_T < 25 \text{ GeV}$)。在图 2.3a到2.3e中可以看到（此图未通过初步筛选条件），很大一部分的第四条 jet p_T 是低于 25 GeV 的，甚至在高质量信号点。那么加上基本的筛选条件之后，大部分信号事例只有三条 jet，如图 2.3f所示。同时可以发现，对于低质量点，即 $m_X=260 \text{ GeV}$ 和 $m_X=300 \text{ GeV}$ ，其大部分事例最多只有 2 条 jet。所以，对于不同的质量点，应当应用不同的 jet 数条件，对于低质量点，要求 $N_{\text{jet}} \geq 2$ ，而高质量点， $N_{\text{jet}} \geq 3$ 。为了证实该分类能够给出最高的信号显著性，考虑本底后，详细检查可见附录 ?? 最后，为了提高信号显著性，一系列动力学被重建，从而用来优化信号，具体优化方法会在章节 ?? 具体讨论，以下列出一些具有区分度的变量：

- $M(l\bar{l})$, the invariant mass of two same-signed leptons;
- MET , missing transverse energy;
- $M(jj)^W$, the invariant mass of two closest jets among all selected good jets;

Cut flow	Event yield			Efficiency		
Evgen	-			100%		
HIGG8D1	2.76			56.34%		
Event cleaning	2.76			56.34%		
Trigger	2.10			44.84%		
Channel	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$
OB, OLR	0.29	0.28	0.56	5.86%	6.23%	11.96%
Tight leptons, trigger match	0.14	0.20	0.33	2.33%	3.46%	5.68%
$p_T(\ell)$	0.11	0.15	0.24	1.93%	2.70%	4.53%
b veto	0.10	0.14	0.23	1.79%	2.49%	4.18%
MET	0.10	0.14	0.22	1.76%	2.45%	4.10%
Drell-Yan cut	0.10	0.14	0.22	1.76%	2.44%	4.10%
Z veto	0.08	0.14	0.22	1.58%	2.44%	4.10%
$N_{\text{jet}} \geq 3$	0.05 ± 0.002	0.09 ± 0.002	0.14 ± 0.003	1.03%	1.92%	2.99%

表 2.4 The cutflow of pre-selection for non-resonant hh signal. The cross-section of $pp \rightarrow hh$ is 33.41 fb. The event yields are normalized to the luminosity of 36.1 fb^{-1} , corresponding to the final state of two-signed leptons. The statistical uncertainty is added in the last row.

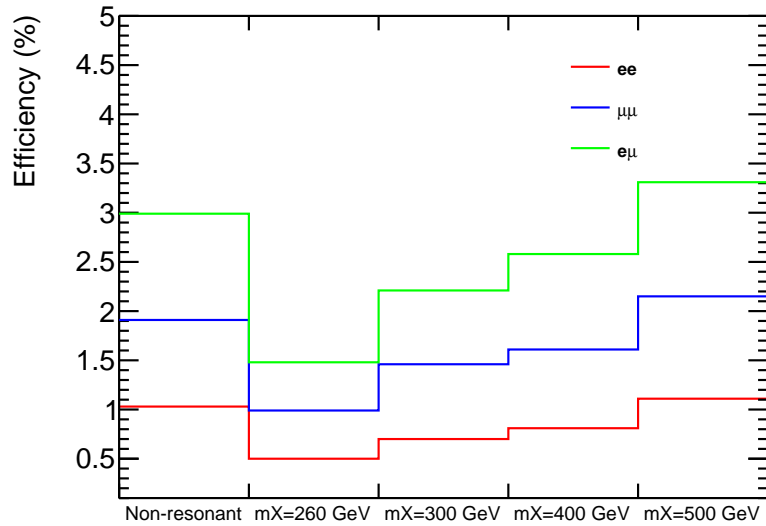


图 2.1 The final efficiency of pre-selections for hh signal samples.

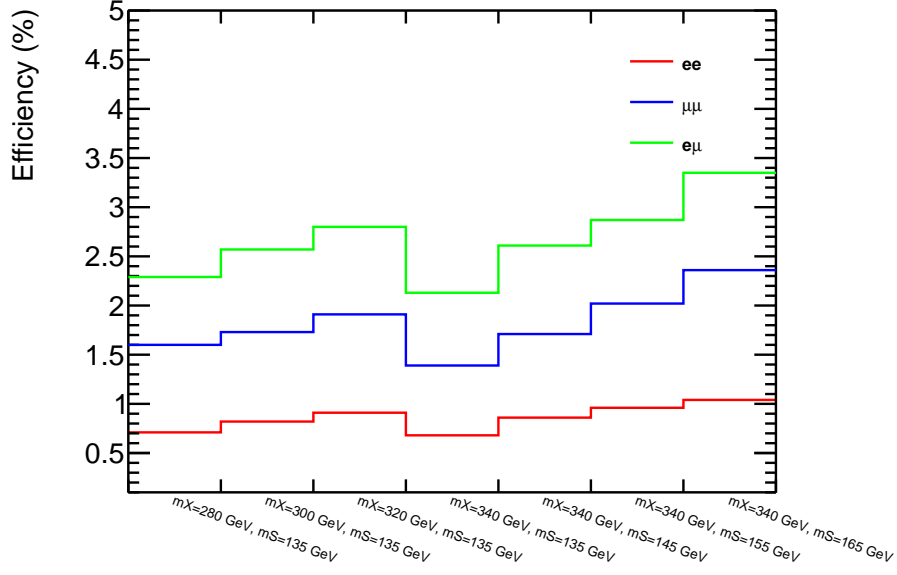


图 2.2 The final efficiency of pre-selections for SS signal samples.

- $M(l_1 jj)$, the invariant mass of leading lepton and two closest jets;
- $M(all)$, the invariant mass of all selected objects;
- M_T , the transverse mass of all selected objects;
- $\Delta R_{min}(\ell_1, j)$, ΔR distance between leading lepton and the closest jet;
- $\Delta R_{min}(\ell_2, j)$, ΔR distance between sub leading lepton and the closest jet;

2.2.2.2 SS 信号优化

S 标量粒子所取质量从 135 GeV 到 165 GeV, X 粒子从 280 GeV 到 340 GeV。 SS 与 hh 具有类似的动力学性质, 为了尽可能增加信号显著性, N_{jet} 分类适用于此, 具体如下:

- 固定 $m_S = 135$ GeV: $m_X = 280$ GeV, $m_X = 300$ GeV and $m_X = 320$ GeV; $N_{jet} \geq 2$ 。
- 固定 $m_X = 340$ GeV: $m_S = 135$ GeV, $m_S = 145$ GeV, $m_S = 155$ GeV and $m_S = 165$ GeV; $N_{jet} \geq 3$ 。

前述章节 2.2.2.1 的动力学变量也可用来进一步优化信号显著性。

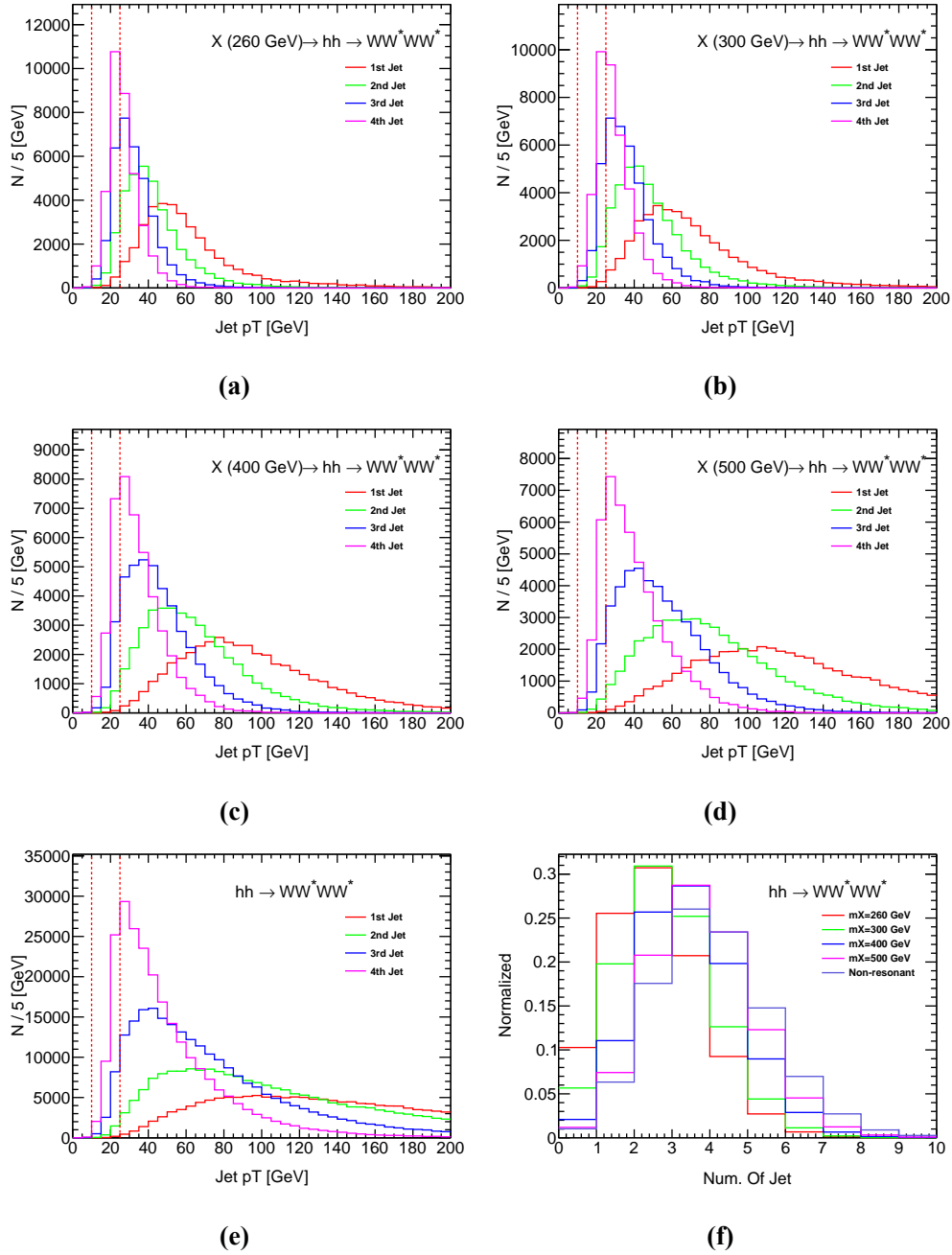


图 2.3 Distributions of p_T and number of jet for signal. Figure 2.3a to Figure 2.3e are distributions of p_T of jet before 25 GeV cuts, corresponding for $m_X=260, 300, 400, 500$ GeV and non-resonant signal. Two dashed vertical lines are $p_T=10$ GeV and $p_T=25$ GeV, respectively. Figure 2.3f is number of jet distribution after 25 GeV cuts.

第 3 章 背景估计

4W 物理分析背景分为可以贡献两个相同电荷的过程 (promptSS)，电荷误鉴别 (QmisID) 和“假”轻子过程 (fakes)。promptSS 主要来自 $t\bar{t}V$, VV , tV 以及 $t\bar{t}H$ 过程，该背景可用 MC 估计。QmisID 一般来自于 $Z + jets$ 和 $t\bar{t}$ (轻子衰变过程)。fakes 来自于 $W + jets$, $t\bar{t}$ (半轻子衰变) 过程，其中一个 jet 被误判成轻子或者一个轻子来源于 b -jet (non-prompt)。目前 ATLAS MC 不能很好地描述 QmisID 和 fakes，如图 3.1 所示，如果所有背景均用 MC 模拟，可以看到，数据跟预期有非常大的偏差。所以，这表明 data-driven 的方法去估计 QmisID 和 fakes 是有必要的。在以下章节中，将分别讲述 QmisID 和 fakes 的估计方法。

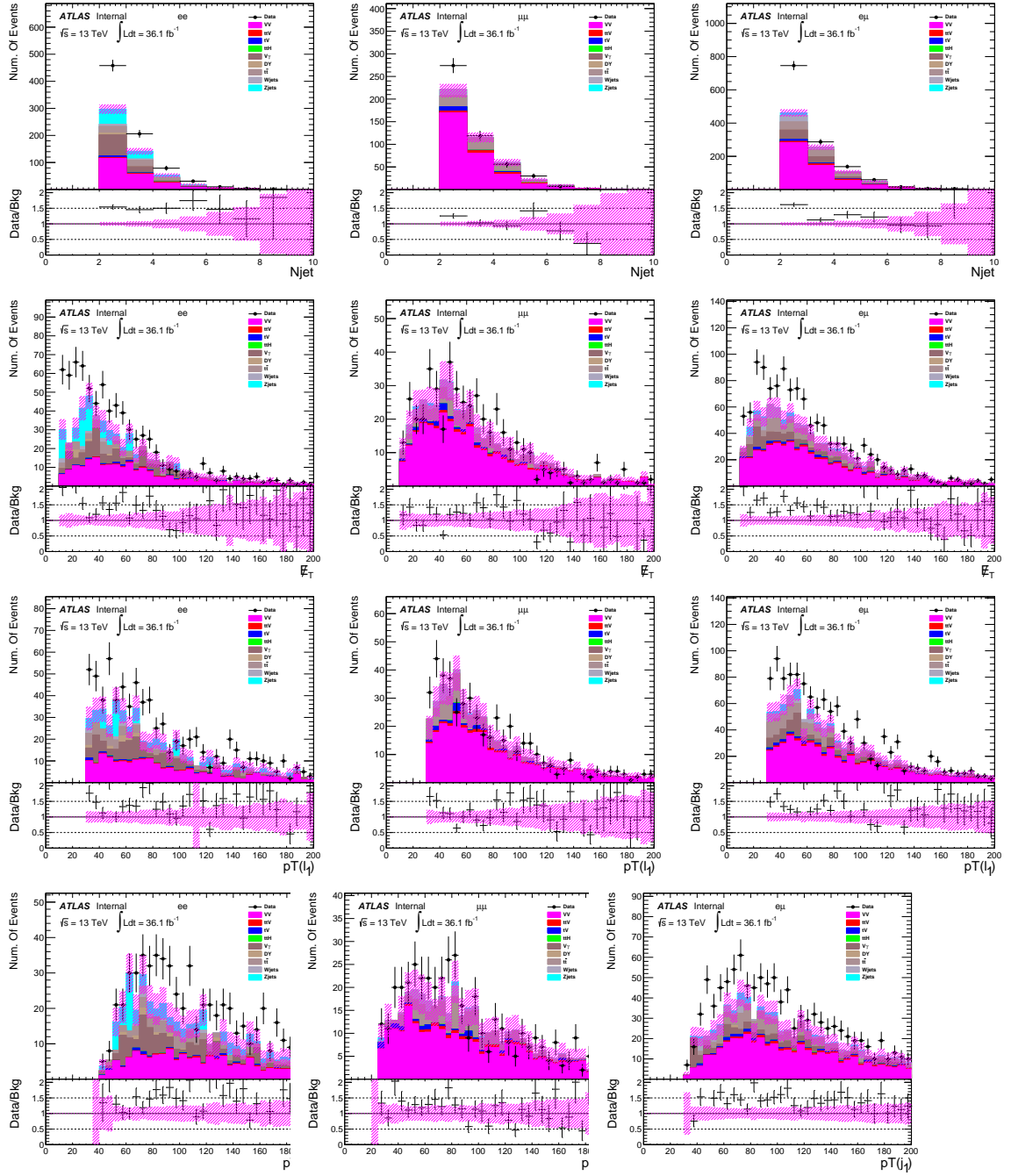


图 3.1 The comparison between data and all MC backgrounds at pre-selection level. Left: ee , middle: $\mu\mu$, right: $e\mu$. The slashed pink bands are corresponding to statistical uncertainties. Each process is normalized to the luminosity of 36.1 fb^{-1} .

3.1 QmisID 估计

双轻子为同电荷和同味道双轻子的 Z veto 的选择条件，会极大地压低 $t\bar{t}$ 和 $Z + jets$ 背景，但如果一个电荷误判，即使很低的误判率，但考虑到这两种过程的极大截面，仍有相当一部分的 QmisID 会贡献到最终背景中。根据 8 TeV 的研究 [16]， μ 电荷误判率非常低（一般低于 10^{-5} ）¹，所以只考虑电子电荷误判背景。

电子电荷误判有两种原因：

- 当电子穿过探测器材料时，出射一个光子（韧致辐射）；而后这个光子转换成一对正负电子，然而在随后的径迹重建中，带相反电荷的电子被利用，从而导致电荷误判。韧致辐射依赖于探测器材料密度，而探测器材料密度随着 $|\eta|$ 变化，所以电子的电荷误判率也依赖于 $|\eta|$ 。
- 第二种贡献相对来讲比较小，主要是因为测量精度不够，当电子径迹的曲率很小或者内部探测器径迹与量能器的簇射匹配错误时，得到完全相反曲率的径迹，从而导致电荷误判。所以，当电子具有高横动量时这个效应比较明显，那么误判率也依赖于 p_T 。

3.1.1 似然函数方法

一般假设电子电荷误判率不依赖于产生模式，因为 Z 玻色子产生截面大，而且其不变质量峰重建比较好，所以 Z 过程可以用来测量电子电荷误判率，采用似然函数技术 [17]，构建的似然函数如下：

$$\ln L(\varepsilon|N_{SS}, N) = \sum_{i,j} \ln[N^{ij}(\varepsilon_i + \varepsilon_j - 2\varepsilon_i\varepsilon_j)]N_{SS}^{ij} - N^{ij}(\varepsilon_i + \varepsilon_j - 2\varepsilon_i\varepsilon_j) \quad (3.1)$$

其中， ε_i 和 ε_j 分别为 $\eta - p_T$ 二维区间中第 i 个和第 j 个电子的误判率， N_{SS} 和 N 是观察到的相同电荷事例数和总事例数。 $\eta - p_T$ 区域总共分为 28 个小区域，其 $|\eta|$ 和 p_T 的分界线分别为 $[0., 0.60, 1.1, 1.37, 1.52, 1.70, 2.00, 2.47]$ 和 $[10, 60, 90, 130, 1000]$ GeV。随后，为了得到电子电荷误判率，需按照以下过程进行：

1. 按照 Z 玻色子过程筛选双轻子数据，其中轻子质量要求应与章节2所述一致。

¹The rate of charge mis-identification for muons is only affected by the track curvature. Because of the long lever arm to the muon system and the fact that the charge is measured in both the inner detector and muon spectrometer the mis-identification rates of the muon charge are very low, making this background negligible compared to the other sources of background

2. 在所选数据中通过高斯函数拟合 Z 不变质量谱，得到 Z 不变质量拟合值 κ 和标准偏差 σ 。而后分为如下三个区间，

A	B	C
$(\kappa - 8\sigma, \kappa - 4\sigma)$	$(\kappa \pm 4\sigma)$	$(\kappa + 4\sigma, \kappa + 8\sigma)$

3. 为了进一步提高 Z 玻色子纯度，剩余本底会被减去，即 $N_Z = n_B - \frac{n_A + n_C}{2}$ 。

4. 所选数据根据电荷分为 SS 和 OS，利用最大似然函数法得到各个 $|\eta| - p_T$ 区间的误判率。

图3.2展示电子电荷误判率随着 $|\eta|$ 增加而增大，因为在高 $|\eta|$ 粒子会穿过更多探测器材料；误判率也随着 p_T 增大而增大，这与前面的讨论一致。最后，利用公式 3.2 计算出 ee 和 $e\mu$ 道经过初步筛选后，在 $N_{\text{jet}} \geq 2$ 时 ($N_{\text{jet}} \geq 3$) 的误判事例数分别为 101.47 ± 0.60 (35.60 ± 0.38) 和 18.21 ± 0.23 (8.38 ± 0.16)。

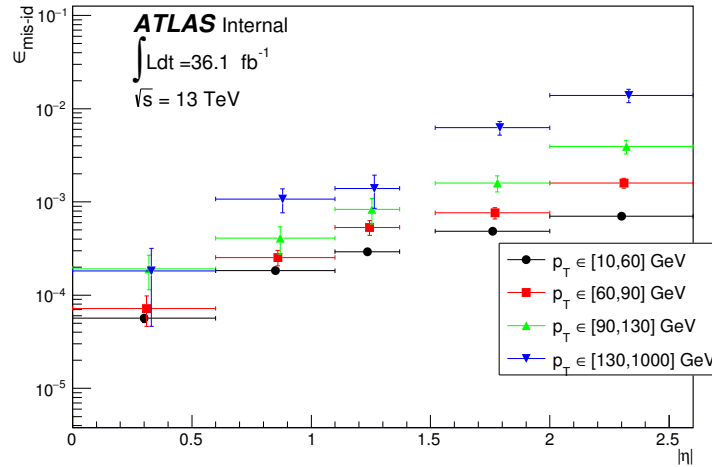


图 3.2 The electron charge mis-identification rates as a function of $(|\eta|, p_T)$ computed in data with the likelihood method.

$$N_{ee}^{\text{QmisID}} = \frac{\varepsilon_i + \varepsilon_j - 2\varepsilon_i\varepsilon_j}{1 - \varepsilon_i - \varepsilon_j + 2\varepsilon_i\varepsilon_j} N^{\text{OS}}, N_{e\mu}^{\text{QmisID}} = \frac{\varepsilon}{1 - \varepsilon} N^{\text{OS}} \quad (3.2)$$

3.1.2 系统误差

在 QmisID 估计中，考虑了三种系统误差：

1. 每个 $|\eta| - p_T$ 小区域中的统计误差；
2. 为了证实似然函数方法的可靠性，可以利用 Z MC 进行以上的误判率估计，因为在 MC 中，电子误判率是已知的，从而比较似然函数估计值与真实值就

可判断该方法的可靠程度（closure test）。图 3.3 比较了真实值与似然函数估计值，总体上是一致的。该项差距将作为 QmisID 的系统误差之一。

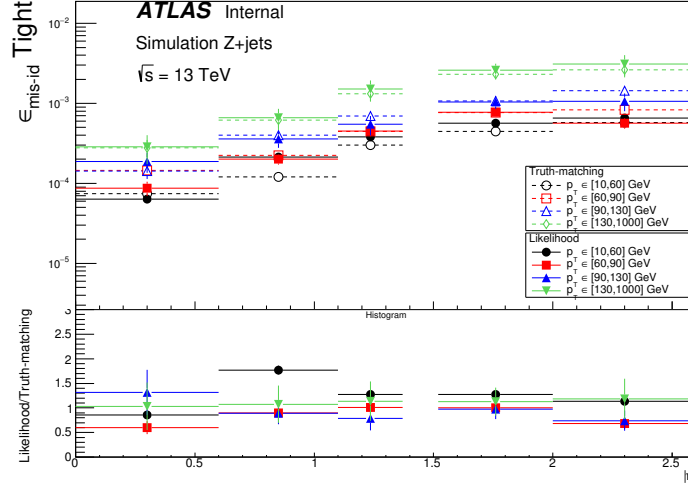


图 3.3 The comparison between the charge mis-identification rates of electrons measured in simulated $Z \rightarrow e^+e^-$ events with the truth-matching method and the 2D likelihood method.

3. Z 峰区间的变动会影响 QmisID 的估计，所以，如果偏移 Z 峰 1σ ，其 QmisID 率的相对变化考虑成系统误差。

图 3.4 总结了几种系统误差在不同 $|\eta| - p_T$ 的相对大小，随着 p_T 的增加统计误差越来越大，因为大部分电子是低动量的，其次是似然函数误差在低动量区更显著。

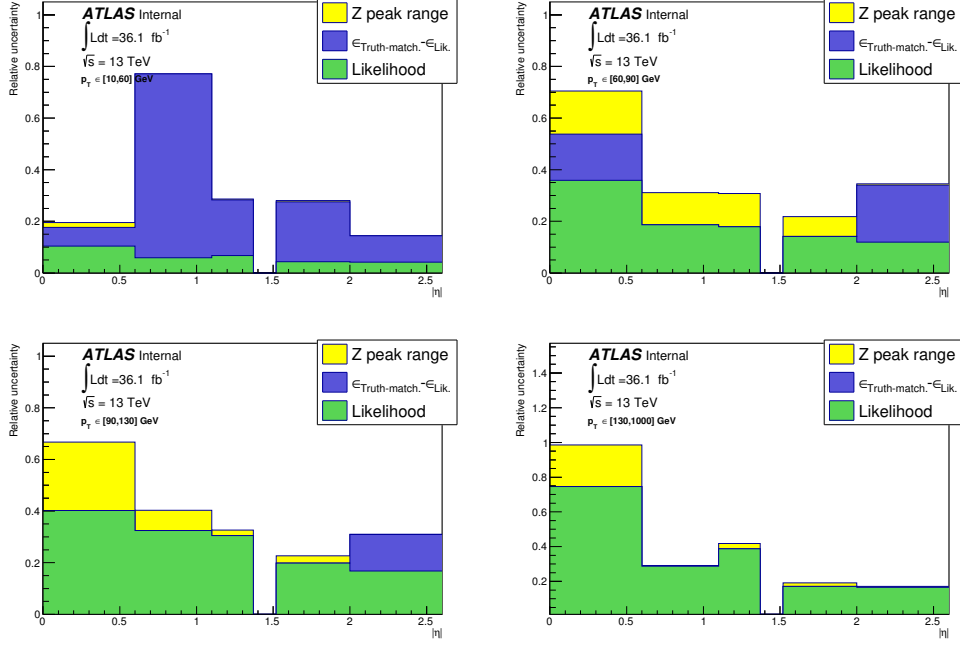


图 3.4 The systematic uncertainty on the charge mis-identification rate, for different bins in p_T and $|\eta|$.

3.2 Fakes 估计

误鉴别粒子是一项非常重要的本底，因为对其形成机制理解不够准确，MC 并不能很好地描述，所以有必要使用 **data-driven** 的方法去估计该项本底。在该分析中，我们使用 **fake factor** 的方法。

3.2.1 Fake factor 方法

在 4W 分析中，Fake factor 方法的假设是 fake factor 不依赖于 jet 数，其定义是具有两个 **tight** SS 轻子的事例数与具有一个 **tight** 和一个 **anti-tight** 的轻子的事例数比例，如等式 3.3 所示。

$$\theta_\ell = \frac{N_{\ell\ell}}{N_{\ell\bar{\ell}}} \quad (3.3)$$

其中， ℓ 为 **tight** 电子或者 μ 子， $\bar{\ell}$ 是 **anti-tight** 的轻子。通常，分母的选择是 **fake factor** 中最困难的部分：分母的选择应当使得真实轻子极大地压低，而尽量增大误鉴别轻子的比例。如果分母选择条件越严格，与外延相关的系统误差越小，但是另一方面，事例越少，相应的统计误差越大。所以，为了优化整体的系统误差，必须考虑到这些相反的影响。一般来讲，利用 **ID** 和 **isolation** 条件可以很好地压低误鉴别的电子，而 **isolation** 和碰撞参数可以用来压低误鉴别 μ 子 [18]。在本分析中， ℓ 和 $\bar{\ell}$ 的定义如表 3.1 和表 3.2 所示。

	tight electron	anti-tight electron
ID	TightLH	fail TightLH
isolation	isolationFixedCutTight	-
QmisID	ChargeIDBDTTight>0.067	ChargeIDBDTTight>0.067

表 3.1 definitions of tight electrons and anti-tight electrons. In addition to the inverted ID requirement, anti-tight electrons are required to pass the loose selection criteria.

	tight muon	anti-tight muon
ID	Tight	-
isolation	isolationFixedCutTightTrackOnly	fail isolationFixedCutTightTrackOnly

表 3.2 definitions of tight muons and anti-tight muons. In addition to the inverted isolation requirement, anti-tight muons are required to pass the loose selection criteria.

值得指出的是，因为在本分析中，有两个 N_{jet} 类别，所以对于低质量点，计算 fake factor 时要求一个 jet；对于高质量点，要求 1 到 2 个 jet。总结如表 3.3 所示。接下来，作为例子，我们将只展示高质量点的 fakes 的计算方式。之前提过，

	Region	Fake factor CR (low jet multiplicity region)	SR (high jet multiplicity region)
Low mass	$hh: m_X=260, 300 \text{ GeV}$ $SS: \text{Fixing } m_S=135 \text{ GeV}, m_X=280, 300, 320 \text{ GeV}$	$N_{\text{jet}}=1$	$N_{\text{jet}} \geq 2$
High mass	$hh: m_X=400, 500 \text{ GeV}, \text{no-resonant}$ $SS: \text{Fixing } m_X=340 \text{ GeV}, m_S=135, 145, 155 \text{ and } 165 \text{ GeV}$	$1 \leq N_{\text{jet}} \leq 2$	$N_{\text{jet}} \geq 3$

表 3.3 Summary of different regions used to estimate fakes for low mass and high mass searches.

本底包括 fakes, QmisID, $V\gamma$ 和 promptSS，为了不重复考虑这些本底，实际计算 fake factor 时应当减去这些本底，如公式 3.5 所示。

$$\theta_e(1 \leq N_{\text{jet}} \leq 2) = \frac{N_{ee}^{\text{data}} - N_{ee}^{\text{promptSS}} - N_{ee}^{V\gamma} - N_{ee}^{\text{QmisID}}}{N_{e\cancel{e}}^{\text{data}} - N_{e\cancel{e}}^{\text{promptSS}} - N_{e\cancel{e}}^{V\gamma} - N_{e\cancel{e}}^{\text{QmisID MC}}}(1 \leq N_{\text{jet}} \leq 2) \quad (3.4)$$

$$\theta_\mu(1 \leq N_{\text{jet}} \leq 2) = \frac{N_{\mu\mu}^{\text{data}} - N_{\mu\mu}^{\text{promptSS}} - N_{\mu\mu}^{V\gamma}}{N_{\mu\cancel{\mu}}^{\text{data}} - N_{\mu\cancel{\mu}}^{\text{promptSS}} - N_{\mu\cancel{\mu}}^{V\gamma}}(1 \leq N_{\text{jet}} \leq 2) \quad (3.5)$$

可以看到，promptSS, QmisID 和 $V\gamma$ 在分子分母中均被减去。promptSS 用 MC 估计，并且要求其中一个轻子能够匹配到真实轻子 (truth-matching)。 $V\gamma$ 也利用

MC 估计, 但是并不要求 truth-matching, 因为其中一个轻子很可能来自于 γ 。对于 QmisID, 分子中的 N_{ee}^{QmisID} 计算如章节 3.1 所述, 而 $N_{e\cancel{e}}^{\text{QmisID MC}}$ 直接利用 MC 估计, 其中要求电子 truth-matching。表 ?? 到表 ?? 总结在不同 N_{jet} 类别下, 用来计算 fake factor 各个成分的值。

Selections		VV	$t\bar{t}V$	tV	$t\bar{t}H$	$V\gamma$	QmisID	Data
$N_{\text{jet}} = 1$	ee	204.64 \pm 19.13	1.09 \pm 0.08	5.08 \pm 0.93	0.03 \pm 0.01	135.94 \pm 12.84	164.46 \pm 0.65	976
	$e\cancel{e}$	44.26 \pm 3.51	0.13 \pm 0.03	8.25 \pm 1.32	0.00 \pm 0.00	67.33 \pm 10.49	135.54 \pm 71.62	1116

表 3.4 Observed number of data and expected events yields in low jet multiplicity region, which is used for fake factor calculation of electron in low mass search. Uncertainties are statistical.

Selections		VV	$t\bar{t}V$	tV	$t\bar{t}H$	$V\gamma$	Data
$N_{\text{jet}} = 1$	$\mu\mu$	296.37 \pm 9.72	1.92 \pm 0.11	5.91 \pm 1.01	0.02 \pm 0.02	0.00 \pm 0.00	455
	$\mu\cancel{\mu}$	56.84 \pm 5.00	0.13 \pm 0.03	20.80 \pm 2.34	0.00 \pm 0.00	0.63 \pm 0.45	378

表 3.5 Observed number of data and expected events yields in low jet multiplicity region, which is used for fake factor calculation of muon in low mass search. Uncertainties are statistical.

Selections		VV	$t\bar{t}V$	tV	$t\bar{t}H$	$V\gamma$	QmisID	Data
$1 \leq N_{\text{jet}} \leq 2$	ee	309.38 \pm 19.75	3.67 \pm 0.16	11.27 \pm 1.47	0.10 \pm 0.02	213.30 \pm 17.29	230.40 \pm 0.81	1434
	$e\cancel{e}$	66.58 \pm 5.19	0.39 \pm 0.06	15.85 \pm 1.89	0.02 \pm 0.01	104.00 \pm 12.71	187.16 \pm 78.65	1591

表 3.6 Observed number of data and expected events yields in low jet multiplicity region, which is used for fake factor calculation of electron in high mass search. Uncertainties are statistical.

Selections		VV	$t\bar{t}V$	tV	$t\bar{t}H$	$V\gamma$	Data
$1 \leq N_{\text{jet}} \leq 2$	$\mu\mu$	463.01 \pm 11.61	6.14 \pm 0.21	15.20 \pm 2.26	0.17 \pm 0.03	0.01 \pm 0.01	729
	$\mu\cancel{\mu}$	74.30 \pm 5.40	0.45 \pm 0.06	43.59 \pm 3.37	0.02 \pm 0.01	1.62 \pm 0.74	658

表 3.7 Observed number of data and expected events yields in low jet multiplicity region, which is used for fake factor calculation of muon in high mass search. Uncertainties are statistical.

最终, 根据公式 3.5, 得到各种类别的 fake factor, 总结在表 3.8。接下来, 就

Selections	Fake factor	Value
$N_{\text{jet}} == 1$	θ_e	0.5401 ± 0.0311
	θ_μ	0.5033 ± 0.0503
$1 \leq N_{\text{jet}} \leq 2$	θ_e	0.5472 ± 0.0264
	θ_μ	0.4544 ± 0.0350

表 3.8 Summary of fake factors of electron and muon with different N_{jet} requirements. Uncertainties are statistical.

可以计算在信号区，即高 N_{textjet} 区，的 fakes 估计值。计算方法如下：

$$N_{ee}^{\text{fakes}}(N_{\text{jet}} \geq 3) = (N_{e\cancel{e}}^{\text{data}} - N_{e\cancel{e}}^{\text{promptSS}} - N_{e\cancel{e}}^{V\gamma} - N_{e\cancel{e}}^{\text{QmisID MC}})(N_{\text{jet}} \geq 3) \times \theta_e \quad (3.6)$$

$$N_{\mu\mu}^{\text{fakes}}(N_{\text{jet}} \geq 3) = (N_{\mu\cancel{\mu}}^{\text{data}} - N_{\mu\cancel{\mu}}^{\text{promptSS}} - N_{\mu\cancel{\mu}}^{V\gamma})(N_{\text{jet}} \geq 3) \times \theta_\mu \quad (3.7)$$

$$N_{e\mu}^{\text{fakes}}(N_{\text{jet}} \geq 3) = (N_{e\cancel{\mu}} - N_{e\cancel{\mu}}^{\text{promptSS}} - N_{e\cancel{\mu}}^{V\gamma} - N_{e\cancel{\mu}}^{\text{QmisID}})(N_{\text{jet}} \geq 3) \times \theta_\mu \quad (3.8)$$

$$+ (N_{\cancel{e}\mu} - N_{\cancel{e}\mu}^{\text{promptSS}} - N_{\cancel{e}\mu}^{V\gamma} - N_{\cancel{e}\mu}^{\text{QmisID MC}})(N_{\text{jet}} \geq 3) \times \theta_e$$

各个成分的选择同样遵循计算 fake factor 时要求，表 3.9（表 3.10）总结各种成分在 $N_{\text{textjet}} \geq 2$ ($N_{\text{textjet}} \geq 3$) 时的数值。最后，计算得到信号区的 fakes 结果

Selections		VV	$t\bar{t}V$	tV	$t\bar{t}H$	$V\gamma$	QmisID	Data
$N_{\text{jet}} \geq 2$	$e\cancel{e}$	37.39 ± 4.24	1.67 ± 0.12	11.55 ± 1.62	0.19 ± 0.04	51.74 ± 8.67	137.17 ± 33.00	829
	$\mu\cancel{\mu}$	32.41 ± 2.83	1.44 ± 0.15	38.97 ± 3.15	0.12 ± 0.03	1.01 ± 0.59	-	583
	$\cancel{e}\mu$	39.71 ± 3.06	2.02 ± 0.17	15.46 ± 2.13	0.19 ± 0.04	53.50 ± 9.21	195.94 ± 19.80	708
	$e\cancel{\mu}$	17.89 ± 2.50	0.42 ± 0.10	17.00 ± 1.99	0.03 ± 0.02	0.75 ± 0.39	0.43 ± 0.03	267

表 3.9 Observed number of data and expected events yields in high jet multiplicity region, which is used to predict fakes in low mass search. Uncertainties are statistical.

如表 3.11 所示。其中，只考虑了统计误差，其计算方式为 $\theta_\ell \times \sqrt{N_{\ell\cancel{\ell}}^{\geq 2\text{jet}(3\text{jet})}}$ [18]。

3.2.2 系统误差

计算 fake factor 时有如下系统误差：

1. **统计误差**，低 N_{jet} 区的统计误差会传递到 fake factor；
2. **QmisID**，QmisID 的贡献在 ee 道是比较大的，其系统误差也会传递到 θ_ℓ 的计算。

Selections		VV	$t\bar{t}V$	tV	$t\bar{t}H$	$V\gamma$	QmisID	Data
$N_{\text{jet}} \geq 3$	$e\ell$	15.07 \pm 1.83	1.41 \pm 0.11	3.96 \pm 0.90	0.17 \pm 0.03	15.07 \pm 4.85	85.54 \pm 6.45	354
	$\mu\mu$	14.95 \pm 1.94	1.12 \pm 0.13	16.18 \pm 2.01	0.10 \pm 0.03	0.03 \pm 0.03	-	303
	$\ell\mu$	17.84 \pm 2.04	1.60 \pm 0.16	6.71 \pm 1.62	0.18 \pm 0.04	17.98 \pm 5.18	102.56 \pm 5.64	287
	$e\mu$	4.78 \pm 1.06	0.36 \pm 0.09	7.68 \pm 1.24	0.02 \pm 0.02	0.44 \pm 0.27	0.21 \pm 0.03	149

表 3.10 Observed number of data and expected events yields in high jet multiplicity region, which is used to predict fakes in high mass search. Uncertainties are statistical.

Selections	$N_{\text{jet}} \geq 2$			$N_{\text{jet}} \geq 3$		
	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$
Event yield	318.27 \pm 9.64	256.20 \pm 8.06	332.69 \pm 9.62	127.38 \pm 6.10	122.97 \pm 5.58	138.25 \pm 6.16

表 3.11 Estimated jet fakes in three channels with different selections. Uncertainties are statistical.

3. **Closure test**, 此分析中 fake factor 的假设是其值不依赖于 jet 数, 但此假设本身是有误差的, 所以为了考虑此项误差, 可以利用 MC (semi-leptonic $t\bar{t}$) 重复一遍 fake factor 方法, 将真实的 fakes 与预测值作为系统误差。具体流程如下:

- 要求 $1 \leq N_{\text{jet}} \leq 2$, 其中为了增大统计量, 去除 b -veto, Z veto 和轻子 p_T 选择条件。

- 选择 ee ($e\ell$) 和 $\mu\mu$ ($\mu\mu$) 事例, 计算 fake factor ($\frac{N_{\ell\ell}}{N_{\ell\ell}}$):
 $\theta_e = 0.32 \pm 0.12$, $\theta_\mu = 0.12 \pm 0.04$;

- 预测高 N_{extjet} 区的 fakes 数 ($\theta \times N_{\ell\ell}$)。

表 3.12 的总结了在 $t\bar{t}$ MC 中真实 fakes, 预测值以及它们之间的相对差别, 其中 $e\mu$ 道最大的相对差别会作为 fake factor closure 系统误差。

	Predicted	Real	Relative difference
ee	24.69 \pm 9.47	26.92 \pm 2.06	9.03%
$\mu\mu$	30.44 \pm 10.00	34.88 \pm 2.35	14.59%
$e\mu$	40.80 \pm 11.31	56.63 \pm 3.01	38.80%

表 3.12 Non-closure uncertainty on θ_e and θ_μ . To reduce the statistical error, SS, $p_T(\ell)$ and $M(\ell\ell) > 15$ GeV requirements are dropped in pre-selections.

4. **样本成分**, 低 N_{jet} 与高 N_{jet} 区的一个显著区别是背景成分, 以表 3.13 为例证, 可以看到, 随着 jet 数的增加, $t\bar{t}$ 的比例相应增大。不同味道的 jet 具有不同的误鉴别率, 从而不同本底会有不同的 fake factor。在此估计中, fake factor 是在低 N_{jet} 区估计的, 而后应用在高 N_{jet} , 那么从表 3.13 推论出, $t\bar{t}$ 本底被低估了。为了补偿此项偏差, 可以重复以上 fake factor 方法, 加上至少一个 b -jet 的条件。最后, 把他们之间的差别作为系统误差, 结果如表 3.14 所示。

Pre-selections	$N_{\text{jet}}=1$			$N_{\text{jet}}=2$			$N_{\text{jet}} \geq 3$		
	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$
Sherpa W+jets	38.84	30.74	152.01	4.49	13.98	49.85	5.20	3.96	19.88
Sherpa $t\bar{t}$	7.20	-0.34	10.32	9.62	37.35	62.95	15.66	28.04	59.79
$N_{t\bar{t}}/N_{\text{W+jets}}$	0.19	-0.011	0.068	2.14	2.67	1.26	3.01	7.08	3.00

表 3.13 The contribution from $t\bar{t}$ becomes bigger as more jets are required. W+jets and $t\bar{t}$ (semi-leptonic) MC samples are produced with the same generator (Sherpa).

$N_{\text{jet}}=1$	with b veto	with b -jet	uncer.
θ_e	0.5401 ± 0.0311	0.7228 ± 0.1919	33.83%
θ_μ	0.5033 ± 0.0503	0.3438 ± 0.0856	31.69%
$1 \leq N_{\text{jet}} \leq 2$	with b veto	with b -jet	uncer.
θ_e	0.5472 ± 0.0264	0.8000 ± 0.1171	46.20%
θ_μ	0.4544 ± 0.0350	0.3060 ± 0.0413	48.50%

表 3.14 The fake factors with and without b -jet.

5. **prompt SS 产生截面**, 在 fake factor 计算中, prompt SS 作为减去项, 那么它们的截面理论值也会影响 fake factor 的结果, 它们的理论误差会传递到 fake factor 的误差中, 其中低于 1% 影响的过程被忽略。

Fake factor 的所有系统误差总结在表 3.15 和表 Table 3.16 中。可以发现, 最显著的误差是 Non-closure 和样本成分; 对于 μ 而言, WZ 的产生截面也有 30% 到 40% 的影响, 而对于 electron fake factor, QmisID 误差大小约为 30%; 其次是统计误差最小, 只有不到 10% 的影响, 说明轻子选择条件是比较合理的, 没有引入较大统计误差; 虽然在各个 N_{jet} 类别, 电子 fake factor 误差略高于 μ 子的, 但它们

总误差都在 60% 到 72% 之间。

	$N_{\text{jet}} == 1$	$1 \leq N_{\text{jet}} \leq 2$
Statistics	5.76	4.82
QmisID	33.0	30.0
θ_e syst.	38.80	38.80
Sample dependence	33.83	46.20
$W^\pm W^\pm$	1.22	2.08
WZ	8.93	7.94
$V\gamma$	11.15	12.28
QmisID MC	1.50	2.00
Total	63.09	69.18

表 3.15 Summary of systematic uncertainty on θ_e with different N_{jet} selections(in %).

	$N_{\text{jet}} == 1$	$1 \leq N_{\text{jet}} \leq 2$
Statistics	9.99	7.70
θ_μ syst.	38.80	38.80
Sample dependence	31.69	48.50
$W^\pm W^\pm$	6.06	10.39
WZ	39.0	33.6
Total	64.55	71.79

表 3.16 Summary of systematic uncertainty on θ_μ with different N_{jet} selections(in %).

3.2.3 总预期本底估计

表 3.17和表 3.18分别总结在 $N_{\text{jet}} \geq 2$ 和 $N_{\text{jet}} \geq 3$ 时, 经过初步筛选之后, 的各项本底的估计值与观测数据数; 表内的误差考虑了 fakes 的统计误差和 fake factor 的系统误差, 假设它们相互独立, 总的误差为 $\sqrt{(\theta_\ell^{\text{sys.}} \times N_{\text{jet fakes}}^{\text{median}})^2 + \theta_\ell \times N_{\text{jet fakes}}^{\text{median}}}$, 其中 $\theta_\ell^{\text{sys.}}$ 是 fake factor 系统误差值, $N_{\text{jet fakes}}^{\text{median}}$ 是 fakes 预期值。在三个轻子道中, fakes 都占有比较大的比例, 都高于 30%, 尤其在 ee 中, fakes 作为最大的本底成分, 高达 44%。图 3.5和图 3.6是 N_{jet} 的分布, 分别对应 $N_{\text{jet}} \geq 2$ 和 $N_{\text{jet}} \geq 3$ 。

相比图 3.1，数据与预期本底吻合度得到极大地提升，其偏差基本控制在 2 个标准偏差之内。

	ee	$\mu\mu$	$e\mu$
Jet fakes	318.27±201.23	256.20±165.77	332.69±156.43
PromptSS	208.92±6.64	334.71±8.74	560.18±10.63
$V + \gamma$	105.39±12.43	0.01±0.01	107.99±15.17
QmisID	101.47±0.60	0.00±0.00	18.21±0.23
Total backgrounds	734.07±201.72	590.93±166.00	1019.06±157.52
Observed	790	487	1257

表 3.17 Event yields at pre-selection level, corresponding to $N_{\text{jet}} \geq 2$. The total uncertainties include all systematics on fakes and statistical uncertainties on the others. PromptSS and $V + \gamma$ are normalized to the luminosity of 36.1 fb^{-1} .

	ee	$\mu\mu$	$e\mu$
Jet fakes	127.38±88.52	122.97±88.60	138.25±69.55
PromptSS	95.34±4.30	154.40±5.64	262.03±7.04
$V + \gamma$	28.03±4.52	0.01±0.01	51.62±13.75
QmisID	35.60±0.38	0.00±0.00	8.38±0.16
Total backgrounds	286.35±88.74	277.38±88.78	460.27±71.25
Observed	332	213	511

表 3.18 Event yields at pre-selection level, corresponding to $N_{\text{jet}} \geq 3$. The total uncertainties include all systematics on fakes and statistical uncertainties on the others. PromptSS and $V + \gamma$ are normalized to the luminosity of 36.1 fb^{-1} .

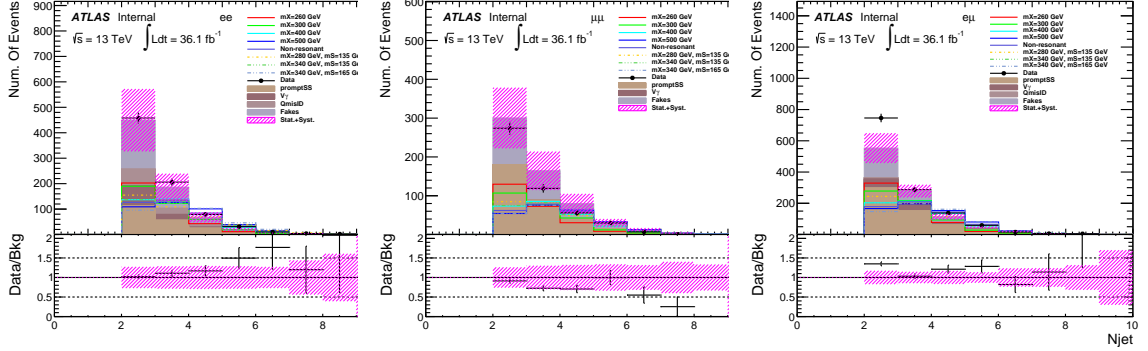


图 3.5 The comparisons between data and backgrounds at pre-selection level, corresponding to $N_{\text{jet}} \geq 2$. Left: ee , middle: $\mu\mu$, right: $e\mu$. The uncertainties, represented by slashed bands, include all systematics on fakes and statistical uncertainties on the other background components. PromptSS and $V + \gamma$ are normalized to the luminosity of 36.1 fb^{-1} .

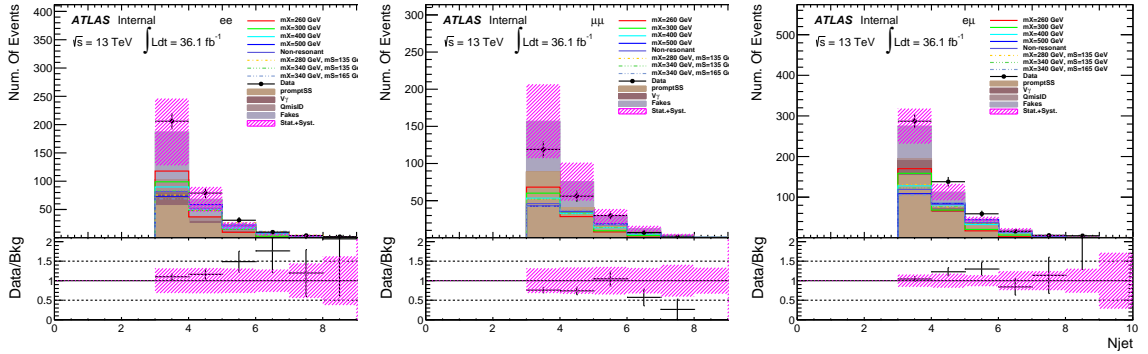


图 3.6 The comparisons between data and backgrounds at pre-selection level, corresponding to $N_{\text{jet}} \geq 3$. Left: ee , middle: $\mu\mu$, right: $e\mu$. The uncertainties, represented by slashed bands, include all systematics on fakes and statistical uncertainties on the other background components. PromptSS and $V + \gamma$ are normalized to the luminosity of 36.1 fb^{-1} .

第4章 信号优化

在初步筛选之后，为了进一步加强信号显著性，利用动力学性质进行信号优化是有必要的。因为每个信号质量点的动力学性质差别较大，所以，每个质量点都会进行信号优化过程，而后通过各自动力学选择条件之后的区域才作为每个质量点的最终信号区。

4.1 优化策略

MVA 方法用于确定不同运动学变量的分离能力，并考虑所有变量之间的相关性。最终，前五个运动学变量用于形成优化选择，分别是 $M(\ell\ell)$, $\Delta R_{min}(\ell_2, j)$, $\Delta R_{min}(\ell_1, j)$, $M_{\ell_1 jj}$ 和 $M(all)$ ，它们具有很强的分离能力，而且相互之间的相关性很低(图 4.1)。通常， $M(\ell\ell)$ 和 $M_{\ell_1 jj}$ 对低质量点敏感，而其余对高质量和非共振信号敏感。基于这些知识， $\Delta R_{min}(\ell_1, j)$, $M(\ell\ell)$, $M_{\ell_1 jj}$ 和 $M(all)$ 用于在低质量搜索中形成优化削减，而 $\Delta R_{min}(\ell_2, j)$, $\Delta R_{min}(\ell_1, j)$, $M(\ell\ell)$ 和 $M_{\ell_1 jj}$ 用于高质量搜索中。它们的相应分布分别见图 4.2和图 4.3。

TMVA 包 (CutsSA 选项) [19] 用于实现最佳筛选。所有背景: promptSS , $V\gamma$, QmisID 和 fakes 都包含在训练中。为了减少对变量筛选顺序的依赖，每次仅训练 2 个变量。在每个信号效率工作点 (WP)，在测试样本中对每个事例应用对应的选择条件，并计算显著性 (S/\sqrt{B})。随后，选择具有最高信号显著性的 WP，对应该 WP 的 2 个变量筛选值即为最佳选择，最后再对剩下两个变量重复以上步骤。图 4.4展示 SM 希格斯粒子对搜寻中 $\mu\mu$ 分析道的效率，各个运动学变量的选择上下限以及显著性随信号效率 WP 的分布。对剩余的分析道或者其他质量点重复此操作，即可得到所有质量点的分析道的最佳优化选择条件。值得指出的是，对于 SS 信号优化，因为各个质量点之间的运动学性质比较接近，所以只针对 $m_S = 135 \text{ GeV}$, $m_X = 300 \text{ GeV}$ ($m_X = 340 \text{ GeV}$, $m_S = 145 \text{ GeV}$) 进行优化，而后应用在所有的低 (高) 质量点。

最终考虑从低到高 (和非共振) 质量点筛选值的单调性，一定的选择调整被执行。最终的选择总结在表 4.1，表 4.2和表 4.3中，分别对应于 hh 低质量， hh 高质量和 SS 信号寻找。

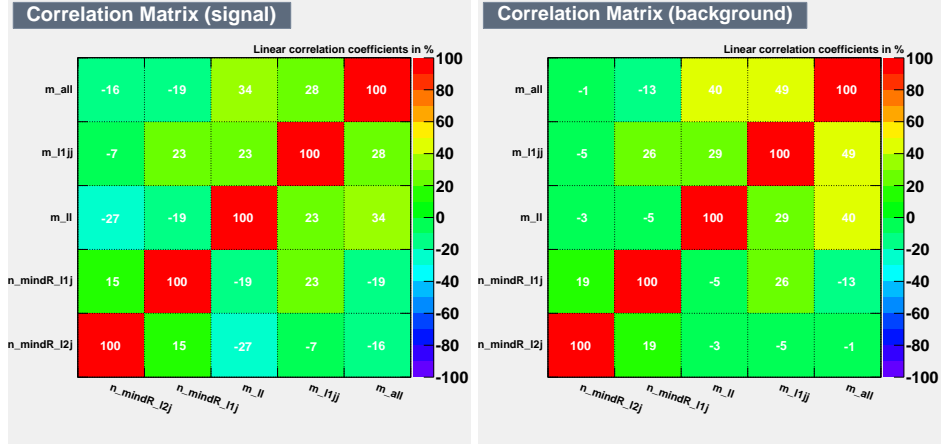


图 4.1 Correlation check of input training variables.

	Channel	$\Delta R_{min}(\ell_1, j)$	$M(l\bar{l})$	$M_{\ell_1 jj}$	$M(all)$
$m_X=260$ GeV	ee	0.35, 1.85	<100	<145	<1100
	$\mu\mu$	0.25, 2.10	<80	<115	<700
	$e\mu$	0.25, 1.80	<85	<135	<650
$m_X=300$ GeV	ee	0.35, 1.75	<120	<160	<1400
	$\mu\mu$	0.20, 1.75	<115	<185	<1000
	$e\mu$	0.20, 1.80	<135	<160	<800

 表 4.1 Summary of optimization selections for the search of $X \rightarrow hh$ ($m_X=260, 300$ GeV). All mass cuts are in GeV.

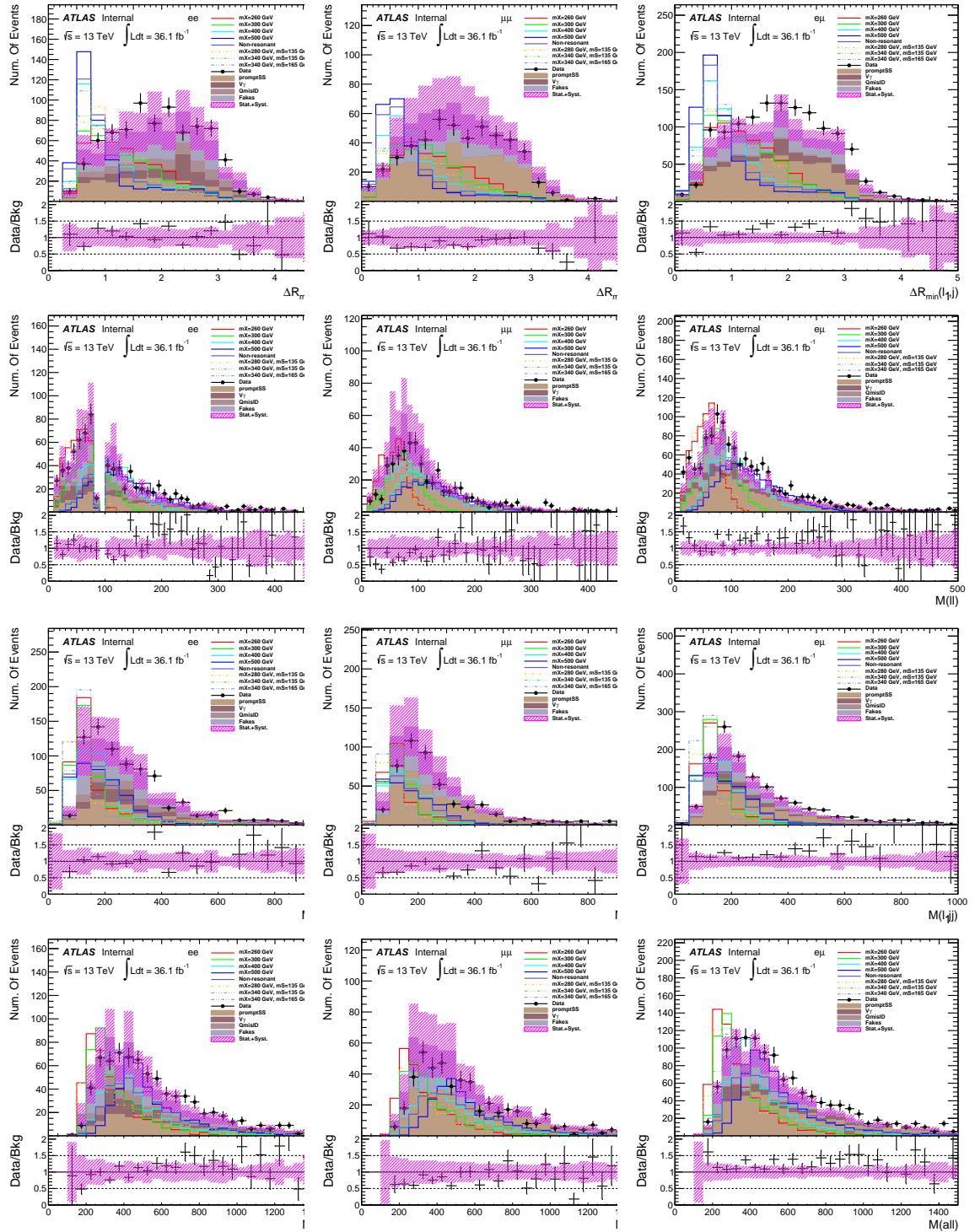


图 4.2 The distributions of kinematic variables that are used to form optimization selections at pre-selection level, corresponding to $N_{\text{jet}} \geq 2$. Left: ee , middle: $\mu\mu$, right: $e\mu$. PromptSS and $V + \gamma$ are normalized to the luminosity of 36.1 fb^{-1} .

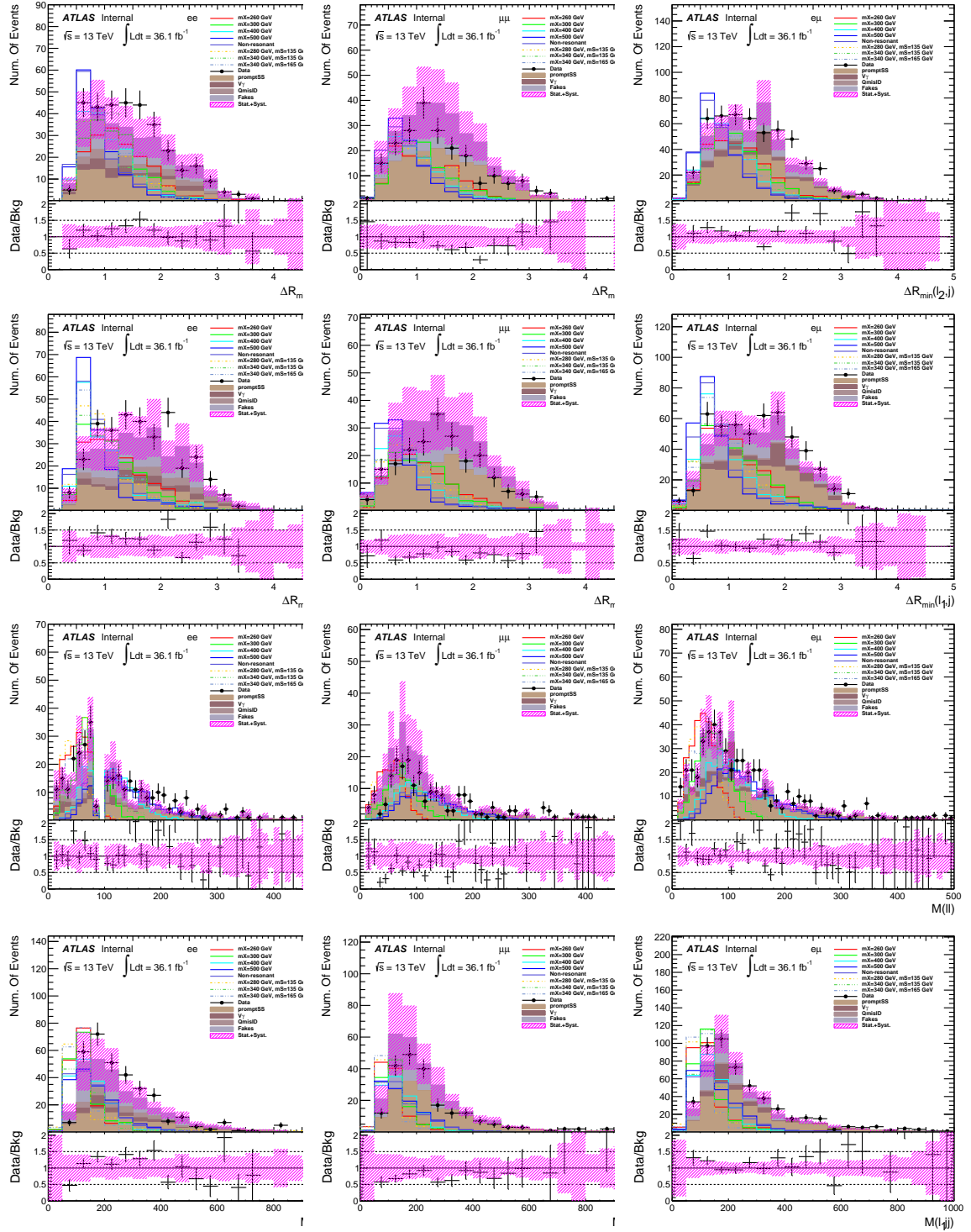
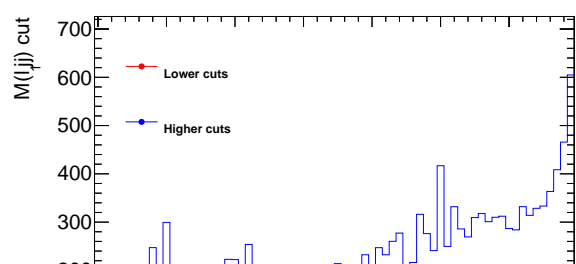
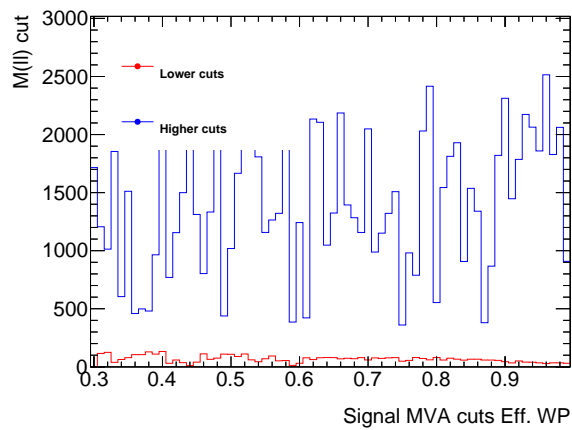
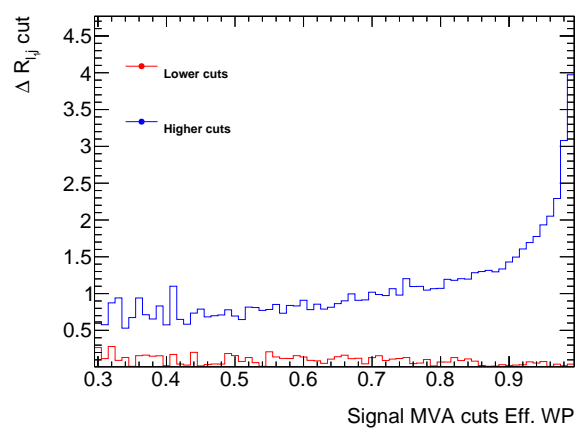
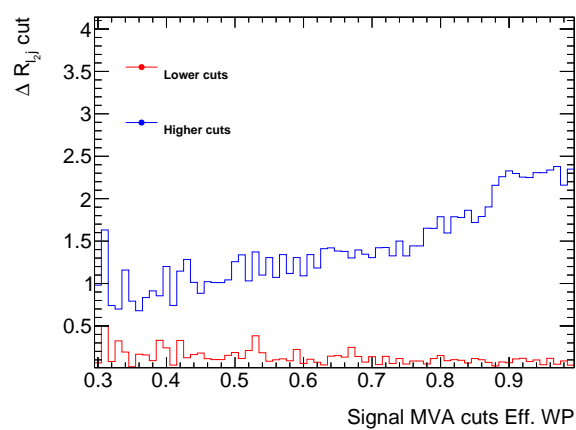
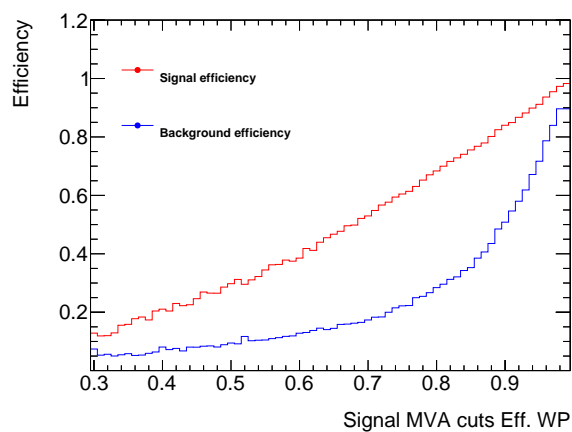


图 4.3 The distributions of kinematic variables that are used to form optimization selections at pre-selection level, corresponding to $N_{\text{jet}} \geq 3$. Left: ee , middle: $\mu\mu$, right: $e\mu$. PromptSS and $V + \gamma$ are normalized to the luminosity of 36.1 fb^{-1} .



	Channel	$\Delta R_{min}(\ell_2, j)$	$\Delta R_{min}(\ell_1, j)$	$M(ll)$	$M_{\ell_{1jj}}$
$m_X=400$ GeV	ee	0.35, 1.50	0.30, 1.25	45, 235	40, 285
	$\mu\mu$	0.20, 1.20	0.20, 1.20	40, 215	30, 260
	$e\mu$	0.20, 1.50	0.20, 1.05	35, 195	30, 235
$m_X=500$ GeV	ee	0.20, 1.15	0.20, 1.15	100, 270	40, 285
	$\mu\mu$	0.20, 1.05	0.20, 0.75	60, 250	30, 310
	$e\mu$	0.20, 1.00	0.20, 0.80	75, 250	35, 350
Non- resonant	ee	0.20, 1.40	0.20, 1.15	55, 270	40, 285
	$\mu\mu$	0.20, 1.05	0.20, 0.75	60, 250	30, 310
	$e\mu$	0.20, 1.15	0.20, 0.80	75, 250	35, 350

表 4.2 Summary of optimization selections for the search of $X \rightarrow hh(m_X=400, 500$ GeV and non-resonant). All mass cuts are in GeV.

	Channel	$\Delta R_{min}(\ell_2, j)$	$\Delta R_{min}(\ell_1, j)$	$M(ll)$	$M_{\ell_{1jj}}$
$m_X=300$ GeV, $m_S=135$ GeV	ee	0.35, 2.5	0.4, 1.65	<80	50, 150
	$\mu\mu$	0.25, 2.05	0.2, 1.85	< 95	50, 150
	$e\mu$	0.25, 1.7	0.25, 1.65	< 95	50, 150
$m_X=340$ GeV, $m_S=145$ GeV	ee	0.35, 1.85	0.2, 1.65	< 130	50, 190
	$\mu\mu$	0.2, 2.0	0.2, 1.65	< 115	50, 185
	$e\mu$	0.25, 1.6	0.25, 1.6	< 150	50, 150

表 4.3 Summary of optimization selections for the search of $X \rightarrow SS$. All mass cuts are in GeV.

4.2 优化效率检查

为了防止过度优化或者欠优化的情况，可以检查每个信号 MC 经过以上选择条件之后的效率。图 4.5和图 4.6分别表示 hh 和 SS 信号相对于经过初步筛选条件之后的选择效率。总体上大多数质量点的选择效率相当接近，但是由于优化时每两个变量一组，它们之间的相关性在三个分析道中略有不同，并且各个分析道具有不同的背景组成，导致不同质量点不同分析道具有不同效率的趋势。

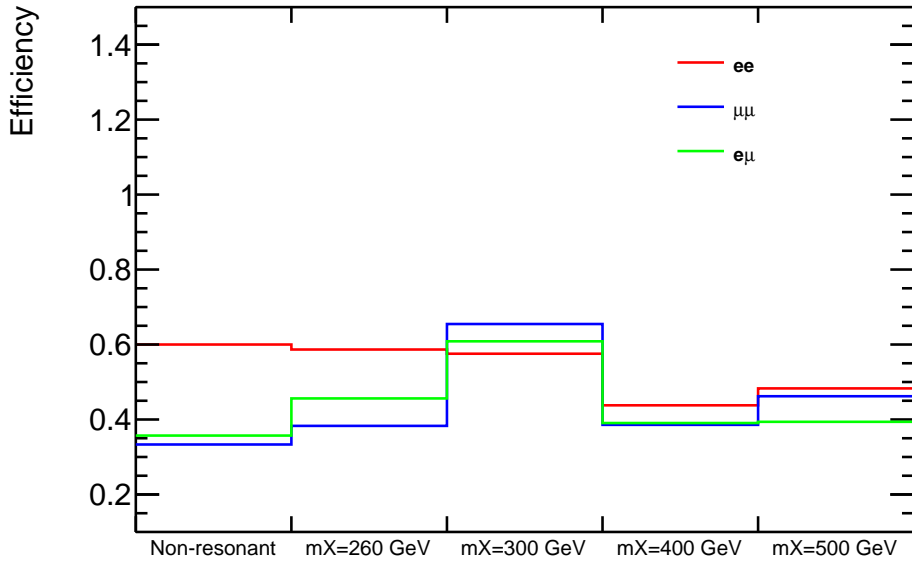


图 4.5 Signal efficiency with respect to pre-selections in ee , $\mu\mu$ and $e\mu$ channel after applying all of the optimisation selections for the non-resonant and resonant hh signal.

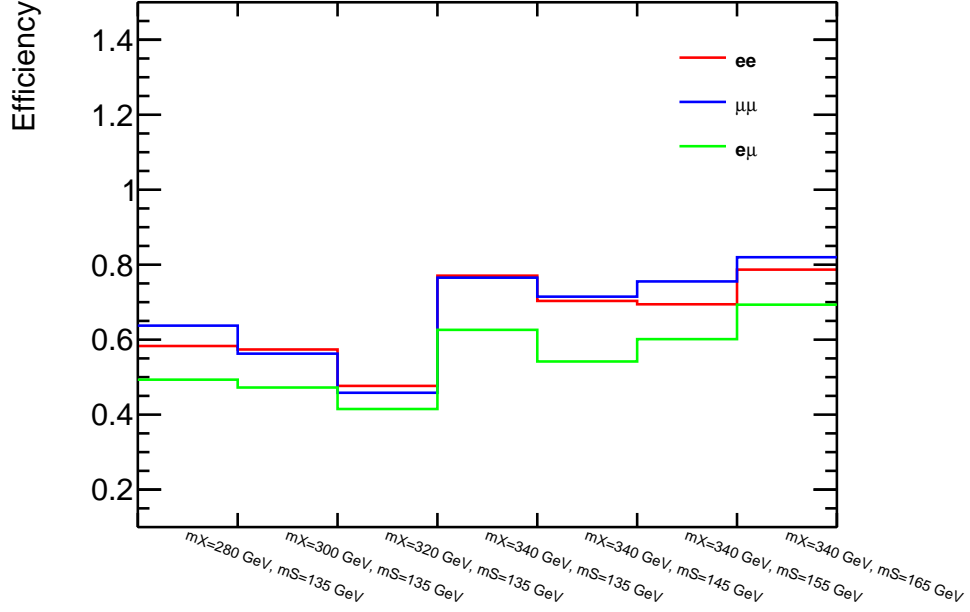


图 4.6 Signal efficiency with respect to pre-selections in ee , $\mu\mu$ and $e\mu$ channel after applying all of the optimisation selections for the resonant SS signal.

4.3 信号及背景筛选结果

经过所有筛选条件之后，表 4.4到表 4.24展示各个质量点不同分析道中的各种背景，预期信号以及观测事例数的结果。总预期本底的误差包括了所有的系统误差，并考虑了非 fakes 本底的系统误差 (syst1) 与 fakes 本底的系统误差 (syst2) 的反相关性质。对于每个质量点的每个分析道，一个运动学变量的分布也被展示，从图 4.7到图 4.13。

4.3.1 hh 搜寻筛选结果

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, f)$	$46.87 \pm 2.91(\text{stat.}) \pm 14.06(\text{syst.})$	$16.25 \pm 3.99(\text{stat.}) \pm 8.12(\text{syst.})$	$15.60 \pm 0.24(\text{stat.}) \pm 5.15(\text{syst.})$	$64.87 \pm 5.96(\text{stat.}) \pm 44.88(\text{syst.})$	$143.59 \pm 7.74(\text{stat.}) \pm 17.04(\text{syst1.}) \pm 44.88(\text{syst2.})$	158	0.04 ± 0.00
$\Delta R_{min}(l_1, j)$	$16.38 \pm 1.80(\text{stat.}) \pm 4.91(\text{syst.})$	$2.89 \pm 1.04(\text{stat.}) \pm 1.45(\text{syst.})$	$5.23 \pm 0.13(\text{stat.}) \pm 1.72(\text{syst.})$	$26.32 \pm 3.79(\text{stat.}) \pm 18.21(\text{syst.})$	$50.81 \pm 4.33(\text{stat.}) \pm 5.40(\text{syst1.}) \pm 18.21(\text{syst2.})$	62	0.03 ± 0.00
$M(\ell\ell)$	$11.70 \pm 1.65(\text{stat.}) \pm 3.51(\text{syst.})$	$0.95 \pm 0.34(\text{stat.}) \pm 0.48(\text{syst.})$	$3.38 \pm 0.10(\text{stat.}) \pm 1.12(\text{syst.})$	$21.24 \pm 3.41(\text{stat.}) \pm 14.70(\text{syst.})$	$37.28 \pm 3.80(\text{stat.}) \pm 3.72(\text{syst1.}) \pm 14.70(\text{syst2.})$	46	0.03 ± 0.00
$M(l_1 jj)$	$8.37 \pm 1.04(\text{stat.}) \pm 2.51(\text{syst.})$	$0.54 \pm 0.24(\text{stat.}) \pm 0.27(\text{syst.})$	$2.61 \pm 0.09(\text{stat.}) \pm 0.86(\text{syst.})$	$17.46 \pm 3.09(\text{stat.}) \pm 12.08(\text{syst.})$	$28.98 \pm 3.27(\text{stat.}) \pm 2.67(\text{syst1.}) \pm 12.08(\text{syst2.})$	35	0.03 ± 0.00

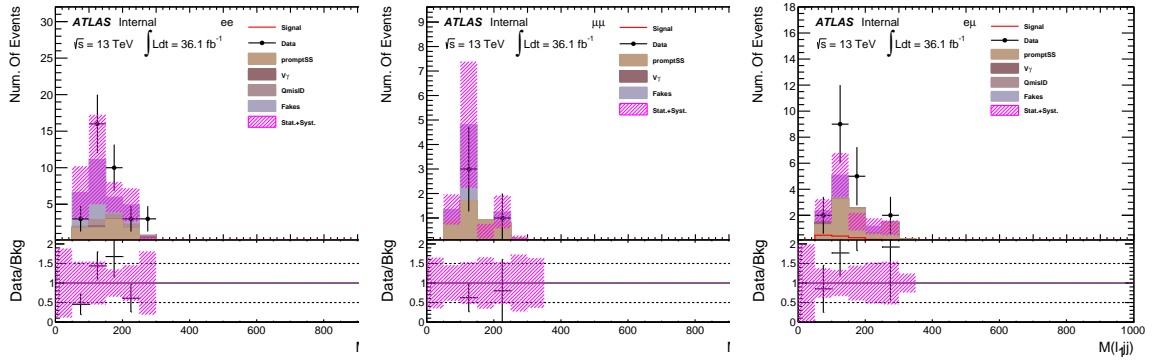
表 4.4 The unblinded results of non-resonant search in ee channel.

4.3.2 SS 搜寻筛选结果

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$47.41 \pm 2.70(\text{stat.}) \pm 14.22(\text{syst.})$	$0.01 \pm 0.01(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$37.76 \pm 4.14(\text{stat.}) \pm 27.11(\text{syst.})$	$85.17 \pm 4.94(\text{stat.}) \pm 14.22(\text{syst1.}) \pm 27.11(\text{syst2.})$	72	0.07 ± 0.00
$\Delta R_{min}(l_1, j)$	$9.52 \pm 1.17(\text{stat.}) \pm 2.86(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$5.59 \pm 1.59(\text{stat.}) \pm 4.01(\text{syst.})$	$15.11 \pm 1.98(\text{stat.}) \pm 2.86(\text{syst1.}) \pm 4.01(\text{syst2.})$	10	0.04 ± 0.00
$M(\ell\ell)$	$6.21 \pm 0.97(\text{stat.}) \pm 1.86(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$4.01 \pm 1.35(\text{stat.}) \pm 2.88(\text{syst.})$	$10.22 \pm 1.66(\text{stat.}) \pm 1.86(\text{syst1.}) \pm 2.88(\text{syst2.})$	4	0.04 ± 0.00
$M(l_1 jj)$	$4.50 \pm 0.74(\text{stat.}) \pm 1.35(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$3.56 \pm 1.27(\text{stat.}) \pm 2.55(\text{syst.})$	$8.05 \pm 1.47(\text{stat.}) \pm 1.35(\text{syst1.}) \pm 2.55(\text{syst2.})$	4	0.03 ± 0.00

 表 4.5 The unblinded results of non-resonant search in $\mu\mu$ channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$94.91 \pm 3.97(\text{stat.}) \pm 28.47(\text{syst.})$	$15.89 \pm 4.14(\text{stat.}) \pm 7.95(\text{syst.})$	$3.46 \pm 0.11(\text{stat.}) \pm 1.14(\text{syst.})$	$48.27 \pm 4.96(\text{stat.}) \pm 24.35(\text{syst.})$	$162.53 \pm 7.59(\text{stat.}) \pm 29.58(\text{syst1.}) \pm 24.35(\text{syst2.})$	194	0.11 ± 0.00
$\Delta R_{min}(l_1, j)$	$19.61 \pm 1.80(\text{stat.}) \pm 5.88(\text{syst.})$	$1.88 \pm 0.94(\text{stat.}) \pm 0.94(\text{syst.})$	$0.68 \pm 0.05(\text{stat.}) \pm 0.22(\text{syst.})$	$9.16 \pm 2.20(\text{stat.}) \pm 5.30(\text{syst.})$	$31.33 \pm 2.99(\text{stat.}) \pm 5.96(\text{syst1.}) \pm 5.30(\text{syst2.})$	44	0.06 ± 0.00
$M(\ell\ell)$	$11.34 \pm 1.29(\text{stat.}) \pm 3.40(\text{syst.})$	$0.24 \pm 0.21(\text{stat.}) \pm 0.12(\text{syst.})$	$0.34 \pm 0.03(\text{stat.}) \pm 0.11(\text{syst.})$	$1.73 \pm 0.94(\text{stat.}) \pm 0.89(\text{syst.})$	$13.65 \pm 1.61(\text{stat.}) \pm 3.41(\text{syst1.}) \pm 0.89(\text{syst2.})$	21	0.05 ± 0.00
$M(l_1 jj)$	$9.28 \pm 1.15(\text{stat.}) \pm 2.79(\text{syst.})$	$0.24 \pm 0.21(\text{stat.}) \pm 0.12(\text{syst.})$	$0.27 \pm 0.03(\text{stat.}) \pm 0.09(\text{syst.})$	$1.33 \pm 0.82(\text{stat.}) \pm 0.66(\text{syst.})$	$11.13 \pm 1.43(\text{stat.}) \pm 2.79(\text{syst1.}) \pm 0.66(\text{syst2.})$	18	0.05 ± 0.00

 表 4.6 The unblinded results of non-resonant search in $e\mu$ channel.

 图 4.7 The unblinded $M(l_1 jj)$ distribution after all optimization selections, corresponding to non-resonance search.

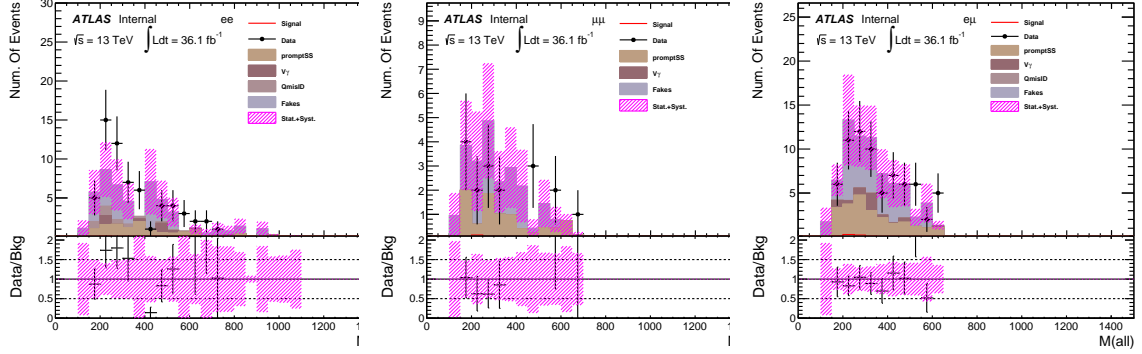
	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$110.96 \pm 4.65(\text{stat.}) \pm 33.29(\text{syst.})$	$37.23 \pm 6.02(\text{stat.}) \pm 18.61(\text{syst.})$	$39.43 \pm 0.35(\text{stat.}) \pm 13.01(\text{syst.})$	$145.41 \pm 8.86(\text{stat.}) \pm 91.74(\text{syst.})$	$333.03 \pm 11.69(\text{stat.}) \pm 40.30(\text{syst1.}) \pm 91.74(\text{syst2.})$	371	0.59 ± 0.00
$\Delta R_{min}(l_1, j)$	$39.91 \pm 2.89(\text{stat.}) \pm 11.97(\text{syst.})$	$21.34 \pm 4.74(\text{stat.}) \pm 10.67(\text{syst.})$	$17.43 \pm 0.18(\text{stat.}) \pm 5.75(\text{syst.})$	$86.67 \pm 6.84(\text{stat.}) \pm 54.68(\text{syst.})$	$165.35 \pm 8.81(\text{stat.}) \pm 17.04(\text{syst1.}) \pm 54.68(\text{syst2.})$	173	0.58 ± 0.00
$M(\ell\ell)$	$12.41 \pm 1.74(\text{stat.}) \pm 3.72(\text{syst.})$	$3.34 \pm 1.26(\text{stat.}) \pm 1.67(\text{syst.})$	$4.78 \pm 0.06(\text{stat.}) \pm 1.58(\text{syst.})$	$28.20 \pm 3.90(\text{stat.}) \pm 17.79(\text{syst.})$	$48.72 \pm 4.45(\text{stat.}) \pm 4.37(\text{syst1.}) \pm 17.79(\text{syst2.})$	63	0.44 ± 0.00
$M(l_1 jj)$	$11.71 \pm 1.71(\text{stat.}) \pm 3.51(\text{syst.})$	$3.34 \pm 1.26(\text{stat.}) \pm 1.67(\text{syst.})$	$4.68 \pm 0.06(\text{stat.}) \pm 1.55(\text{syst.})$	$27.96 \pm 3.89(\text{stat.}) \pm 17.64(\text{syst.})$	$47.70 \pm 4.43(\text{stat.}) \pm 4.19(\text{syst1.}) \pm 17.64(\text{syst2.})$	62	0.44 ± 0.00

 表 4.7 The unblinded results of $m_X=260$ GeV search in ee channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$207.37 \pm 6.74(\text{stat.}) \pm 62.21(\text{syst.})$	$0.01 \pm 0.01(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$181.81 \pm 9.57(\text{stat.}) \pm 117.36(\text{syst.})$	$389.18 \pm 11.70(\text{stat.}) \pm 62.21(\text{syst1.}) \pm 117.36(\text{syst2.})$	309	1.21 ± 0.04
$\Delta R_{min}(l_1, j)$	$73.92 \pm 4.34(\text{stat.}) \pm 22.18(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$91.31 \pm 6.78(\text{stat.}) \pm 58.94(\text{syst.})$	$165.23 \pm 8.05(\text{stat.}) \pm 22.18(\text{syst1.}) \pm 58.94(\text{syst2.})$	102	1.07 ± 0.04
$M(\ell\ell)$	$10.34 \pm 1.52(\text{stat.}) \pm 3.10(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$17.80 \pm 2.99(\text{stat.}) \pm 11.49(\text{syst.})$	$28.13 \pm 3.36(\text{stat.}) \pm 3.10(\text{syst1.}) \pm 11.49(\text{syst2.})$	20	0.56 ± 0.03
$M(l_1 jj)$	$8.79 \pm 1.47(\text{stat.}) \pm 2.64(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$14.91 \pm 2.74(\text{stat.}) \pm 9.63(\text{syst.})$	$23.70 \pm 3.11(\text{stat.}) \pm 2.64(\text{syst1.}) \pm 9.63(\text{syst2.})$	17	0.54 ± 0.03

 表 4.8 The unblinded results of $m_X=260$ GeV search in $\mu\mu$ channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$282.43 \pm 7.10(\text{stat.}) \pm 84.73(\text{syst.})$	$36.01 \pm 5.38(\text{stat.}) \pm 18.00(\text{syst.})$	$9.42 \pm 0.16(\text{stat.}) \pm 3.11(\text{syst.})$	$169.37 \pm 9.45(\text{stat.}) \pm 78.88(\text{syst.})$	$497.22 \pm 12.99(\text{stat.}) \pm 86.67(\text{syst1.}) \pm 78.88(\text{syst2.})$	589	1.69 ± 0.05
$\Delta R_{min}(l_1, j)$	$105.47 \pm 4.54(\text{stat.}) \pm 31.64(\text{syst.})$	$18.73 \pm 4.47(\text{stat.}) \pm 9.37(\text{syst.})$	$2.02 \pm 0.04(\text{stat.}) \pm 0.67(\text{syst.})$	$103.33 \pm 7.37(\text{stat.}) \pm 47.60(\text{syst.})$	$229.55 \pm 9.74(\text{stat.}) \pm 33.00(\text{syst1.}) \pm 47.60(\text{syst2.})$	244	1.53 ± 0.05
$M(\ell\ell)$	$29.17 \pm 2.42(\text{stat.}) \pm 8.75(\text{syst.})$	$5.89 \pm 1.87(\text{stat.}) \pm 2.95(\text{syst.})$	$0.54 \pm 0.02(\text{stat.}) \pm 0.18(\text{syst.})$	$45.62 \pm 4.90(\text{stat.}) \pm 20.94(\text{syst.})$	$81.23 \pm 5.77(\text{stat.}) \pm 9.23(\text{syst1.}) \pm 20.94(\text{syst2.})$	80	1.04 ± 0.04
$M(l_1 jj)$	$23.61 \pm 2.14(\text{stat.}) \pm 7.08(\text{syst.})$	$4.87 \pm 1.67(\text{stat.}) \pm 2.44(\text{syst.})$	$0.46 \pm 0.01(\text{stat.}) \pm 0.15(\text{syst.})$	$41.89 \pm 4.69(\text{stat.}) \pm 19.28(\text{syst.})$	$70.84 \pm 5.42(\text{stat.}) \pm 7.49(\text{syst1.}) \pm 19.28(\text{syst2.})$	70	0.99 ± 0.04

 表 4.9 The unblinded results of $m_X=260$ GeV search in $e\mu$ channel.

 图 4.8 The unblinded $M(all)$ distribution after all optimization selections, corresponding to resonance ($m_X=260$ GeV) search.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$102.50 \pm 4.47(\text{stat.}) \pm 30.75(\text{syst.})$	$33.03 \pm 5.51(\text{stat.}) \pm 16.52(\text{syst.})$	$35.61 \pm 0.33(\text{stat.}) \pm 11.75(\text{syst.})$	$128.89 \pm 8.34(\text{stat.}) \pm 81.32(\text{syst.})$	$300.04 \pm 10.96(\text{stat.}) \pm 36.83(\text{syst1.}) \pm 81.32(\text{syst2.})$	343	0.80 ± 0.06
$\Delta R_{min}(l_1, j)$	$49.48 \pm 3.15(\text{stat.}) \pm 14.84(\text{syst.})$	$22.72 \pm 5.05(\text{stat.}) \pm 11.36(\text{syst.})$	$22.09 \pm 0.21(\text{stat.}) \pm 7.29(\text{syst.})$	$92.54 \pm 7.07(\text{stat.}) \pm 58.38(\text{syst.})$	$186.83 \pm 9.25(\text{stat.}) \pm 20.06(\text{syst1.}) \pm 58.38(\text{syst2.})$	194	0.74 ± 0.06
$M(\ell\ell)$	$18.49 \pm 1.92(\text{stat.}) \pm 5.55(\text{syst.})$	$5.31 \pm 2.21(\text{stat.}) \pm 2.65(\text{syst.})$	$7.27 \pm 0.08(\text{stat.}) \pm 2.40(\text{syst.})$	$36.86 \pm 4.46(\text{stat.}) \pm 23.25(\text{syst.})$	$67.93 \pm 5.34(\text{stat.}) \pm 6.60(\text{syst1.}) \pm 23.25(\text{syst2.})$	90	0.61 ± 0.06
$M(l_1 jj)$	$18.15 \pm 1.91(\text{stat.}) \pm 5.44(\text{syst.})$	$5.31 \pm 2.21(\text{stat.}) \pm 2.65(\text{syst.})$	$7.22 \pm 0.08(\text{stat.}) \pm 2.38(\text{syst.})$	$36.34 \pm 4.43(\text{stat.}) \pm 22.93(\text{syst.})$	$67.02 \pm 5.31(\text{stat.}) \pm 6.51(\text{syst1.}) \pm 22.93(\text{syst2.})$	89	0.61 ± 0.06

 表 4.10 The unblinded results of $m_X=300$ GeV search in ee channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$169.68 \pm 6.15(\text{stat.}) \pm 50.90(\text{syst.})$	$0.01 \pm 0.01(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$142.15 \pm 8.46(\text{stat.}) \pm 91.75(\text{syst.})$	$311.83 \pm 10.46(\text{stat.}) \pm 50.90(\text{syst1.}) \pm 91.75(\text{syst2.})$	245	1.80 ± 0.06
$\Delta R_{min}(l_1, j)$	$97.25 \pm 4.96(\text{stat.}) \pm 29.17(\text{syst.})$	$0.01 \pm 0.01(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$120.11 \pm 7.77(\text{stat.}) \pm 77.53(\text{syst.})$	$217.36 \pm 9.22(\text{stat.}) \pm 29.17(\text{syst1.}) \pm 77.53(\text{syst2.})$	141	1.66 ± 0.06
$M(\ell\ell)$	$50.83 \pm 3.33(\text{stat.}) \pm 15.25(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$78.24 \pm 6.28(\text{stat.}) \pm 50.51(\text{syst.})$	$129.07 \pm 7.11(\text{stat.}) \pm 15.25(\text{syst1.}) \pm 50.51(\text{syst2.})$	79	1.47 ± 0.05
$M(l_1 jj)$	$47.98 \pm 3.29(\text{stat.}) \pm 14.39(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$77.49 \pm 6.25(\text{stat.}) \pm 50.02(\text{syst.})$	$125.47 \pm 7.06(\text{stat.}) \pm 14.39(\text{syst1.}) \pm 50.02(\text{syst2.})$	74	1.46 ± 0.05

 表 4.11 The unblinded results of $m_X=300$ GeV search in $\mu\mu$ channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$285.01 \pm 7.13(\text{stat.}) \pm 85.50(\text{syst.})$	$36.28 \pm 5.39(\text{stat.}) \pm 18.14(\text{syst.})$	$9.46 \pm 0.16(\text{stat.}) \pm 3.12(\text{syst.})$	$170.21 \pm 9.47(\text{stat.}) \pm 79.34(\text{syst.})$	$500.96 \pm 13.02(\text{stat.}) \pm 87.46(\text{syst1.}) \pm 79.34(\text{syst2.})$	596	2.64 ± 0.07
$\Delta R_{min}(l_1, j)$	$182.33 \pm 5.88(\text{stat.}) \pm 54.70(\text{syst.})$	$26.12 \pm 4.79(\text{stat.}) \pm 13.06(\text{syst.})$	$3.99 \pm 0.07(\text{stat.}) \pm 1.32(\text{syst.})$	$139.61 \pm 8.57(\text{stat.}) \pm 64.37(\text{syst.})$	$352.05 \pm 11.44(\text{stat.}) \pm 56.25(\text{syst1.}) \pm 64.37(\text{syst2.})$	397	2.57 ± 0.07
$M(\ell\ell)$	$68.67 \pm 3.59(\text{stat.}) \pm 20.60(\text{syst.})$	$10.73 \pm 2.76(\text{stat.}) \pm 5.36(\text{syst.})$	$1.41 \pm 0.03(\text{stat.}) \pm 0.47(\text{syst.})$	$66.72 \pm 5.92(\text{stat.}) \pm 30.48(\text{syst.})$	$147.52 \pm 7.45(\text{stat.}) \pm 21.29(\text{syst1.}) \pm 30.48(\text{syst2.})$	163	2.05 ± 0.06
$M(l_1 jj)$	$59.41 \pm 3.38(\text{stat.}) \pm 17.82(\text{syst.})$	$8.94 \pm 2.50(\text{stat.}) \pm 4.47(\text{syst.})$	$1.24 \pm 0.03(\text{stat.}) \pm 0.41(\text{syst.})$	$62.74 \pm 5.74(\text{stat.}) \pm 28.94(\text{syst.})$	$132.33 \pm 7.12(\text{stat.}) \pm 18.38(\text{syst1.}) \pm 28.94(\text{syst2.})$	144	1.99 ± 0.06

 表 4.12 The unblinded results of $m_X=300$ GeV search in $e\mu$ channel.

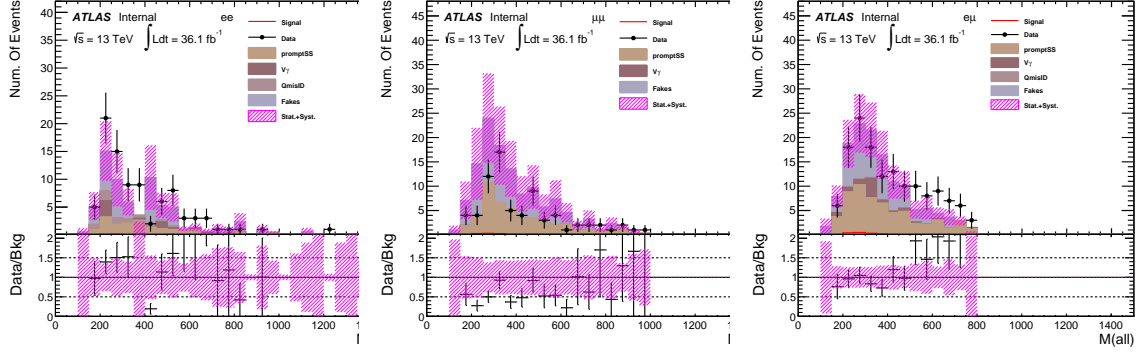


图 4.9 The unblinded $M(all)$ distribution after all optimization selections, corresponding to resonance ($m_X=300$ GeV) search.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$52.12 \pm 3.04(\text{stat.}) \pm 15.64(\text{syst.})$	$17.85 \pm 4.08(\text{stat.}) \pm 8.93(\text{syst.})$	$17.54 \pm 0.26(\text{stat.}) \pm 5.79(\text{syst.})$	$69.22 \pm 6.15(\text{stat.}) \pm 47.89(\text{syst.})$	$156.73 \pm 7.99(\text{stat.}) \pm 18.91(\text{syst1.}) \pm 47.89(\text{syst2.})$	182	3.33 ± 0.08
$\Delta R_{min}(l_1, j)$	$20.98 \pm 1.96(\text{stat.}) \pm 6.29(\text{syst.})$	$3.51 \pm 1.10(\text{stat.}) \pm 1.76(\text{syst.})$	$6.68 \pm 0.15(\text{stat.}) \pm 2.20(\text{syst.})$	$27.96 \pm 3.91(\text{stat.}) \pm 19.35(\text{syst.})$	$59.14 \pm 4.52(\text{stat.}) \pm 6.90(\text{syst1.}) \pm 19.35(\text{syst2.})$	75	2.34 ± 0.07
$M(\ell\ell)$	$16.15 \pm 1.83(\text{stat.}) \pm 4.85(\text{syst.})$	$1.25 \pm 0.42(\text{stat.}) \pm 0.63(\text{syst.})$	$4.50 \pm 0.12(\text{stat.}) \pm 1.49(\text{syst.})$	$21.82 \pm 3.46(\text{stat.}) \pm 15.09(\text{syst.})$	$43.73 \pm 3.93(\text{stat.}) \pm 5.11(\text{syst1.}) \pm 15.09(\text{syst2.})$	59	2.27 ± 0.07
$M(l_1 jj)$	$11.56 \pm 1.25(\text{stat.}) \pm 3.47(\text{syst.})$	$0.83 \pm 0.34(\text{stat.}) \pm 0.41(\text{syst.})$	$3.46 \pm 0.10(\text{stat.}) \pm 1.14(\text{syst.})$	$19.09 \pm 3.23(\text{stat.}) \pm 13.21(\text{syst.})$	$34.94 \pm 3.48(\text{stat.}) \pm 3.67(\text{syst1.}) \pm 13.21(\text{syst2.})$	46	2.16 ± 0.07

表 4.13 The unblinded results of $m_X=400$ GeV search in ee channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$59.36 \pm 3.01(\text{stat.}) \pm 17.81(\text{syst.})$	$0.01 \pm 0.01(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$51.25 \pm 4.83(\text{stat.}) \pm 36.79(\text{syst.})$	$110.61 \pm 5.69(\text{stat.}) \pm 17.81(\text{syst1.}) \pm 36.79(\text{syst2.})$	99	1.72 ± 0.06
$\Delta R_{min}(l_1, j)$	$25.36 \pm 1.92(\text{stat.}) \pm 7.61(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$18.80 \pm 2.92(\text{stat.}) \pm 13.50(\text{syst.})$	$44.17 \pm 3.50(\text{stat.}) \pm 7.61(\text{syst1.}) \pm 13.50(\text{syst2.})$	37	1.38 ± 0.05
$M(\ell\ell)$	$18.50 \pm 1.72(\text{stat.}) \pm 5.55(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$17.02 \pm 2.78(\text{stat.}) \pm 12.22(\text{syst.})$	$35.51 \pm 3.27(\text{stat.}) \pm 5.55(\text{syst1.}) \pm 12.22(\text{syst2.})$	26	1.34 ± 0.05
$M(l_1 jj)$	$13.82 \pm 1.38(\text{stat.}) \pm 4.15(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$14.09 \pm 2.53(\text{stat.}) \pm 10.11(\text{syst.})$	$27.91 \pm 2.88(\text{stat.}) \pm 4.15(\text{syst1.}) \pm 10.11(\text{syst2.})$	19	1.30 ± 0.05

表 4.14 The unblinded results of $m_X=400$ GeV search in $\mu\mu$ channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, j)$	$145.72 \pm 5.10(\text{stat.}) \pm 43.72(\text{syst.})$	$23.17 \pm 4.97(\text{stat.}) \pm 11.59(\text{syst.})$	$5.06 \pm 0.13(\text{stat.}) \pm 1.67(\text{syst.})$	$72.77 \pm 6.07(\text{stat.}) \pm 36.36(\text{syst.})$	$246.72 \pm 9.35(\text{stat.}) \pm 45.26(\text{syst1.}) \pm 36.36(\text{syst2.})$	283	3.33 ± 0.08
$\Delta R_{min}(l_1, j)$	$46.01 \pm 2.73(\text{stat.}) \pm 13.80(\text{syst.})$	$7.96 \pm 3.23(\text{stat.}) \pm 3.98(\text{syst.})$	$1.69 \pm 0.07(\text{stat.}) \pm 0.56(\text{syst.})$	$27.03 \pm 3.75(\text{stat.}) \pm 14.31(\text{syst.})$	$82.70 \pm 5.65(\text{stat.}) \pm 14.38(\text{syst1.}) \pm 14.31(\text{syst2.})$	93	2.34 ± 0.07
$M(\ell\ell)$	$33.90 \pm 2.37(\text{stat.}) \pm 10.17(\text{syst.})$	$6.54 \pm 3.20(\text{stat.}) \pm 3.27(\text{syst.})$	$0.86 \pm 0.04(\text{stat.}) \pm 0.28(\text{syst.})$	$20.86 \pm 3.29(\text{stat.}) \pm 11.11(\text{syst.})$	$62.16 \pm 5.17(\text{stat.}) \pm 10.69(\text{syst1.}) \pm 11.11(\text{syst2.})$	69	2.27 ± 0.07
$M(l_1 jj)$	$24.13 \pm 1.97(\text{stat.}) \pm 7.24(\text{syst.})$	$2.47 \pm 1.25(\text{stat.}) \pm 1.23(\text{syst.})$	$0.60 \pm 0.03(\text{stat.}) \pm 0.20(\text{syst.})$	$17.82 \pm 3.06(\text{stat.}) \pm 9.80(\text{syst.})$	$45.02 \pm 3.84(\text{stat.}) \pm 7.35(\text{syst1.}) \pm 9.80(\text{syst2.})$	57	2.16 ± 0.07

表 4.15 The unblinded results of $m_X=400$ GeV search in $e\mu$ channel.

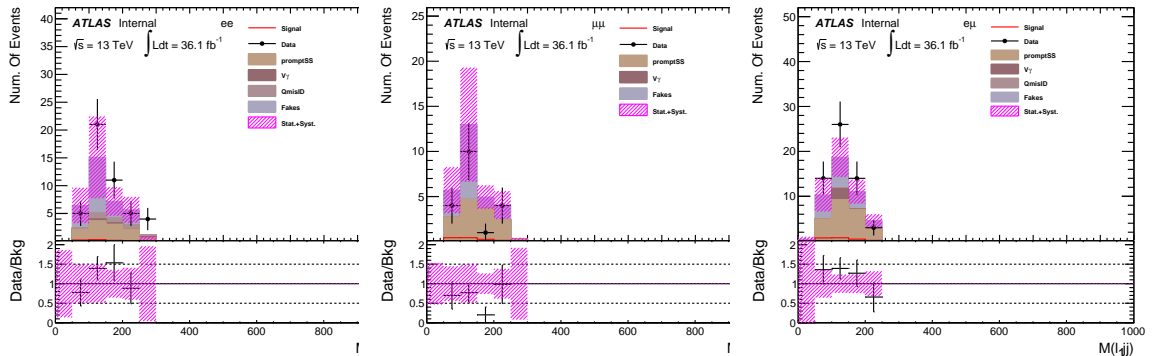


图 4.10 The unblinded $M(l_1 jj)$ distribution after all optimization selections, corresponding to resonance ($m_X=400$ GeV) search.

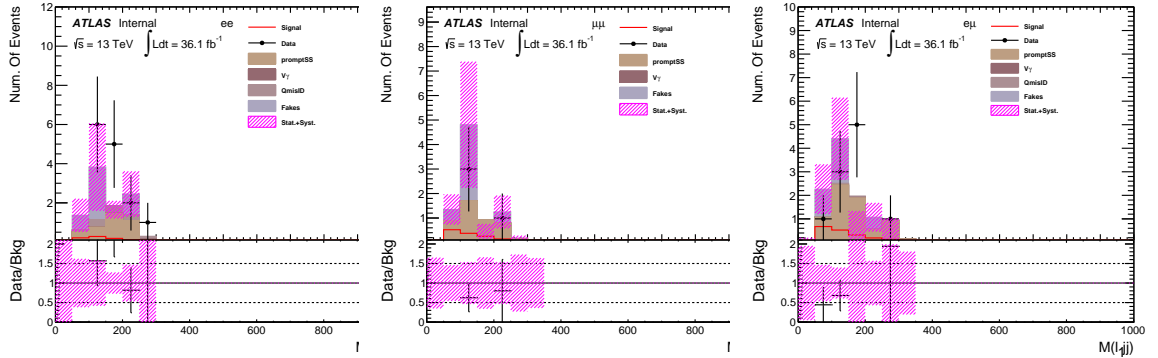
	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, f)$	$36.10 \pm 2.66(\text{stat.}) \pm 10.83(\text{syst.})$	$12.21 \pm 3.77(\text{stat.}) \pm 6.10(\text{syst.})$	$11.32 \pm 0.21(\text{stat.}) \pm 3.73(\text{syst.})$	$49.72 \pm 5.22(\text{stat.}) \pm 34.39(\text{syst.})$	$109.34 \pm 6.96(\text{stat.}) \pm 12.98(\text{syst1.}) \pm 34.39(\text{syst2.})$	117	1.40 ± 0.05
$\Delta R_{min}(l_1, f)$	$13.11 \pm 1.68(\text{stat.}) \pm 3.93(\text{syst.})$	$1.89 \pm 0.95(\text{stat.}) \pm 0.94(\text{syst.})$	$4.00 \pm 0.12(\text{stat.}) \pm 1.32(\text{syst.})$	$17.81 \pm 3.12(\text{stat.}) \pm 12.32(\text{syst.})$	$36.81 \pm 3.67(\text{stat.}) \pm 4.26(\text{syst1.}) \pm 12.32(\text{syst2.})$	47	1.13 ± 0.04
$M(\ell\ell)$	$5.40 \pm 0.79(\text{stat.}) \pm 1.62(\text{syst.})$	$0.36 \pm 0.19(\text{stat.}) \pm 0.18(\text{syst.})$	$1.59 \pm 0.08(\text{stat.}) \pm 0.53(\text{syst.})$	$6.65 \pm 1.91(\text{stat.}) \pm 4.60(\text{syst.})$	$14.01 \pm 2.08(\text{stat.}) \pm 1.71(\text{syst1.}) \pm 4.60(\text{syst2.})$	21	0.90 ± 0.04
$M(l_1 jj)$	$3.92 \pm 0.70(\text{stat.}) \pm 1.17(\text{syst.})$	$0.12 \pm 0.05(\text{stat.}) \pm 0.06(\text{syst.})$	$1.24 \pm 0.07(\text{stat.}) \pm 0.41(\text{syst.})$	$4.03 \pm 1.48(\text{stat.}) \pm 2.79(\text{syst.})$	$9.31 \pm 1.64(\text{stat.}) \pm 1.25(\text{syst1.}) \pm 2.79(\text{syst2.})$	14	0.85 ± 0.04

 表 4.16 The unblinded results of $m_X=500$ GeV search in ee channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, f)$	$47.41 \pm 2.70(\text{stat.}) \pm 14.22(\text{syst.})$	$0.01 \pm 0.01(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$37.76 \pm 4.14(\text{stat.}) \pm 27.11(\text{syst.})$	$85.17 \pm 4.94(\text{stat.}) \pm 14.22(\text{syst1.}) \pm 27.11(\text{syst2.})$	72	2.29 ± 0.06
$\Delta R_{min}(l_1, f)$	$9.52 \pm 1.17(\text{stat.}) \pm 2.86(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$5.59 \pm 1.59(\text{stat.}) \pm 4.01(\text{syst.})$	$15.11 \pm 1.98(\text{stat.}) \pm 2.86(\text{syst1.}) \pm 4.01(\text{syst2.})$	10	1.50 ± 0.04
$M(\ell\ell)$	$6.21 \pm 0.97(\text{stat.}) \pm 1.86(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$4.01 \pm 1.35(\text{stat.}) \pm 2.88(\text{syst.})$	$10.22 \pm 1.66(\text{stat.}) \pm 1.86(\text{syst1.}) \pm 2.88(\text{syst2.})$	4	1.43 ± 0.04
$M(l_1 jj)$	$4.50 \pm 0.74(\text{stat.}) \pm 1.35(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$3.56 \pm 1.27(\text{stat.}) \pm 2.55(\text{syst.})$	$8.05 \pm 1.47(\text{stat.}) \pm 1.35(\text{syst1.}) \pm 2.55(\text{syst2.})$	4	1.40 ± 0.04

 表 4.17 The unblinded results of $m_X=500$ GeV search in $\mu\mu$ channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg	Observed	signal
$\Delta R_{min}(l_2, f)$	$71.26 \pm 3.23(\text{stat.}) \pm 21.38(\text{syst.})$	$12.92 \pm 3.94(\text{stat.}) \pm 6.46(\text{syst.})$	$2.74 \pm 0.10(\text{stat.}) \pm 0.90(\text{syst.})$	$40.57 \pm 4.57(\text{stat.}) \pm 20.90(\text{syst.})$	$127.48 \pm 6.85(\text{stat.}) \pm 22.35(\text{syst1.}) \pm 20.90(\text{syst2.})$	152	3.41 ± 0.07
$\Delta R_{min}(l_1, f)$	$15.07 \pm 1.61(\text{stat.}) \pm 4.52(\text{syst.})$	$0.63 \pm 0.23(\text{stat.}) \pm 0.31(\text{syst.})$	$0.53 \pm 0.05(\text{stat.}) \pm 0.18(\text{syst.})$	$6.42 \pm 1.86(\text{stat.}) \pm 4.17(\text{syst.})$	$22.64 \pm 2.47(\text{stat.}) \pm 4.53(\text{syst1.}) \pm 4.17(\text{syst2.})$	30	2.19 ± 0.06
$M(\ell\ell)$	$8.61 \pm 1.15(\text{stat.}) \pm 2.58(\text{syst.})$	$0.03 \pm 0.03(\text{stat.}) \pm 0.02(\text{syst.})$	$0.27 \pm 0.03(\text{stat.}) \pm 0.09(\text{syst.})$	$2.10 \pm 1.04(\text{stat.}) \pm 1.10(\text{syst.})$	$11.01 \pm 1.55(\text{stat.}) \pm 2.59(\text{syst1.}) \pm 1.10(\text{syst2.})$	13	1.94 ± 0.05
$M(l_1 jj)$	$7.07 \pm 1.04(\text{stat.}) \pm 2.12(\text{syst.})$	$0.03 \pm 0.03(\text{stat.}) \pm 0.01(\text{syst.})$	$0.21 \pm 0.02(\text{stat.}) \pm 0.07(\text{syst.})$	$1.70 \pm 0.93(\text{stat.}) \pm 0.86(\text{syst.})$	$9.01 \pm 1.40(\text{stat.}) \pm 2.12(\text{syst1.}) \pm 0.86(\text{syst2.})$	10	1.91 ± 0.05

 表 4.18 The unblinded results of $m_X=500$ GeV search in $e\mu$ channel.

 图 4.11 The unblinded $M(\ell_1 jj)$ distribution after all optimization selections, corresponding to resonance ($m_X=500$ GeV) search.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg
$\Delta R_{min}(l_2, f)$	$177.91 \pm 6.06(\text{stat.}) \pm 53.37(\text{syst.})$	$84.84 \pm 11.72(\text{stat.}) \pm 42.42(\text{syst.})$	$81.84 \pm 0.54(\text{stat.}) \pm 27.01(\text{syst.})$	$257.46 \pm 11.79(\text{stat.}) \pm 162.43(\text{syst.})$	$602.05 \pm 17.70(\text{stat.}) \pm 73.33(\text{syst1.}) \pm 162.43(\text{syst2.})$
$\Delta R_{min}(l_1, f)$	$84.62 \pm 3.98(\text{stat.}) \pm 25.39(\text{syst.})$	$29.21 \pm 5.40(\text{stat.}) \pm 14.60(\text{syst.})$	$29.29 \pm 0.30(\text{stat.}) \pm 9.67(\text{syst.})$	$102.28 \pm 7.43(\text{stat.}) \pm 64.53(\text{syst.})$	$245.41 \pm 10.02(\text{stat.}) \pm 30.84(\text{syst1.}) \pm 64.53(\text{syst2.})$
$M(\ell\ell)$	$29.09 \pm 2.45(\text{stat.}) \pm 8.73(\text{syst.})$	$18.51 \pm 4.62(\text{stat.}) \pm 9.25(\text{syst.})$	$12.04 \pm 0.15(\text{stat.}) \pm 3.97(\text{syst.})$	$58.21 \pm 5.61(\text{stat.}) \pm 36.73(\text{syst.})$	$117.84 \pm 7.67(\text{stat.}) \pm 13.32(\text{syst1.}) \pm 36.73(\text{syst2.})$
$M(l_1 jj)$	$10.16 \pm 1.50(\text{stat.}) \pm 3.05(\text{syst.})$	$3.34 \pm 1.26(\text{stat.}) \pm 1.67(\text{syst.})$	$3.77 \pm 0.06(\text{stat.}) \pm 1.24(\text{syst.})$	$20.43 \pm 3.32(\text{stat.}) \pm 12.89(\text{syst.})$	$37.69 \pm 3.86(\text{stat.}) \pm 3.69(\text{syst1.}) \pm 12.89(\text{syst2.})$
	X280, S135	X300, S135	X320, S135	Observed	
$\Delta R_{min}(l_2, f)$	3.04 ± 0.21	3.54 ± 0.19	4.09 ± 0.22	647	
$\Delta R_{min}(l_1, f)$	2.48 ± 0.19	2.92 ± 0.18	3.40 ± 0.20	284	
$M(\ell\ell)$	2.38 ± 0.18	2.61 ± 0.17	2.70 ± 0.18	128	
$M(l_1 jj)$	1.86 ± 0.16	2.10 ± 0.15	2.04 ± 0.16	50	

 表 4.19 The unblinded results of the searches for $m_X=280$ GeV, $m_X=300$ GeV and $m_X=320$ GeV(fixing $m_S=135$ GeV) in ee channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg
$\Delta R_{min}(l_2, j)$	229.53 \pm 6.81(stat.) \pm 68.86(syst.)	0.01 \pm 0.01(stat.) \pm 0.00(syst.)	0.00 \pm 0.00(stat.) \pm 0.00(syst.)	188.45 \pm 9.74(stat.) \pm 121.65(syst.)	417.99 \pm 11.88(stat.) \pm 68.86(syst1.) \pm 121.65(syst2.)
$\Delta R_{min}(l_1, j)$	137.67 \pm 5.13(stat.) \pm 41.30(syst.)	0.01 \pm 0.01(stat.) \pm 0.00(syst.)	0.00 \pm 0.00(stat.) \pm 0.00(syst.)	121.81 \pm 7.83(stat.) \pm 78.63(syst.)	259.49 \pm 9.36(stat.) \pm 41.30(syst1.) \pm 78.63(syst2.)
$M(\ell\ell)$	65.75 \pm 3.73(stat.) \pm 19.73(syst.)	0.00 \pm 0.00(stat.) \pm 0.00(syst.)	0.00 \pm 0.00(stat.) \pm 0.00(syst.)	87.44 \pm 6.63(stat.) \pm 56.44(syst.)	153.19 \pm 7.61(stat.) \pm 19.73(syst1.) \pm 56.44(syst2.)
$M(l_1 jj)$	21.62 \pm 2.05(stat.) \pm 6.49(syst.)	0.00 \pm 0.00(stat.) \pm 0.00(syst.)	0.00 \pm 0.00(stat.) \pm 0.00(syst.)	43.90 \pm 4.70(stat.) \pm 28.34(syst.)	65.52 \pm 5.13(stat.) \pm 6.49(syst1.) \pm 28.34(syst2.)
	X280, S135	X300, S135	X320, S135	Observed	
$\Delta R_{min}(l_2, j)$	6.37 \pm 0.27	7.13 \pm 0.29	7.74 \pm 0.31	355	
$\Delta R_{min}(l_1, j)$	5.71 \pm 0.26	6.23 \pm 0.28	6.82 \pm 0.29	210	
$M(\ell\ell)$	5.51 \pm 0.26	5.51 \pm 0.26	5.43 \pm 0.26	104	
$M(l_1 jj)$	4.43 \pm 0.24	4.31 \pm 0.22	3.96 \pm 0.23	46	

表 4.20 The unblinded results of the searches for $m_X=280$ GeV, $m_X=300$ GeV and $m_X=320$ GeV(fixing $m_S=135$ GeV) in $\mu\mu$ channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg
$\Delta R_{min}(l_2, j)$	305.75 \pm 7.53(stat.) \pm 91.72(syst.)	47.54 \pm 6.37(stat.) \pm 23.77(syst.)	10.98 \pm 0.19(stat.) \pm 3.62(syst.)	174.03 \pm 9.56(stat.) \pm 79.98(syst.)	538.30 \pm 13.74(stat.) \pm 94.82(syst1.) \pm 79.98(syst2.)
$\Delta R_{min}(l_1, j)$	155.59 \pm 5.15(stat.) \pm 46.68(syst.)	19.51 \pm 4.02(stat.) \pm 9.76(syst.)	5.65 \pm 0.13(stat.) \pm 1.87(syst.)	92.23 \pm 6.96(stat.) \pm 42.10(syst.)	272.99 \pm 9.54(stat.) \pm 47.72(syst1.) \pm 42.10(syst2.)
$M(\ell\ell)$	69.36 \pm 3.51(stat.) \pm 20.81(syst.)	12.81 \pm 3.74(stat.) \pm 6.41(syst.)	1.40 \pm 0.04(stat.) \pm 0.46(syst.)	66.56 \pm 5.91(stat.) \pm 30.43(syst.)	150.14 \pm 7.83(stat.) \pm 21.78(syst1.) \pm 30.43(syst2.)
$M(l_1 jj)$	25.91 \pm 2.24(stat.) \pm 7.77(syst.)	4.70 \pm 1.66(stat.) \pm 2.35(syst.)	0.49 \pm 0.02(stat.) \pm 0.16(syst.)	39.17 \pm 4.54(stat.) \pm 18.25(syst.)	70.27 \pm 5.33(stat.) \pm 8.12(syst1.) \pm 18.25(syst2.)
	X280, S135	X300, S135	X320, S135	Observed	
$\Delta R_{min}(l_2, j)$	8.34 \pm 0.33	9.25 \pm 0.33	10.86 \pm 0.40	649	
$\Delta R_{min}(l_1, j)$	6.87 \pm 0.29	7.74 \pm 0.31	8.98 \pm 0.37	302	
$M(\ell\ell)$	6.52 \pm 0.28	6.87 \pm 0.29	7.18 \pm 0.32	155	
$M(l_1 jj)$	5.15 \pm 0.23	5.46 \pm 0.26	5.37 \pm 0.28	62	

表 4.21 The unblinded results of the searches for $m_X=280$ GeV, $m_X=300$ GeV and $m_X=320$ GeV(fixing $m_S=135$ GeV) in $e\mu$ channel.

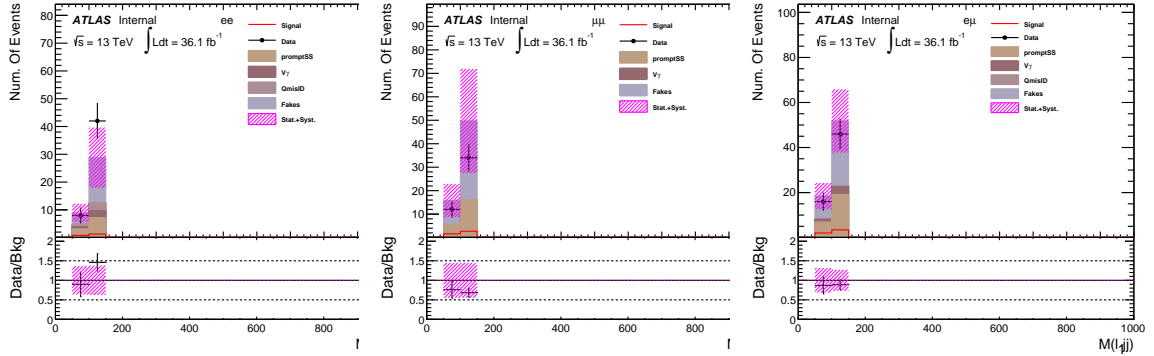


图 4.12 The unblinded $M(\ell_1 jj)$ distribution after all optimization selections, corresponding to SS low mass search. The signal shown here is $m_X=300$ GeV, $m_S=135$ GeV.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg
$\Delta R_{min}(l_2, j)$	67.65 \pm 3.53(stat.) \pm 20.30(syst.)	20.22 \pm 4.14(stat.) \pm 10.11(syst.)	23.49 \pm 0.31(stat.) \pm 7.75(syst.)	84.19 \pm 6.79(stat.) \pm 58.24(syst.)	195.54 \pm 8.70(stat.) \pm 23.96(syst1.) \pm 58.24(syst2.)
$\Delta R_{min}(l_1, j)$	39.86 \pm 2.57(stat.) \pm 11.96(syst.)	10.52 \pm 2.58(stat.) \pm 5.26(syst.)	13.01 \pm 0.21(stat.) \pm 4.29(syst.)	43.87 \pm 4.90(stat.) \pm 30.35(syst.)	107.26 \pm 6.11(stat.) \pm 13.75(syst1.) \pm 30.35(syst2.)
$M(\ell\ell)$	22.40 \pm 2.12(stat.) \pm 6.72(syst.)	7.57 \pm 2.41(stat.) \pm 3.79(syst.)	8.57 \pm 0.15(stat.) \pm 2.83(syst.)	35.70 \pm 4.42(stat.) \pm 24.70(syst.)	74.24 \pm 5.47(stat.) \pm 8.21(syst1.) \pm 24.70(syst2.)
$M(l_1 jj)$	11.57 \pm 1.34(stat.) \pm 3.47(syst.)	3.51 \pm 1.21(stat.) \pm 1.75(syst.)	4.22 \pm 0.08(stat.) \pm 1.39(syst.)	24.59 \pm 3.67(stat.) \pm 17.01(syst.)	43.89 \pm 4.09(stat.) \pm 4.13(syst1.) \pm 17.01(syst2.)
	X340, S135	X340, S145	X340, S155	X340, S165	Observed
$\Delta R_{min}(l_2, j)$	2.95 \pm 0.20	9.19 \pm 0.52	17.48 \pm 0.94	29.64 \pm 1.58	
$\Delta R_{min}(l_1, j)$	2.56 \pm 0.19	8.26 \pm 0.50	15.41 \pm 0.86	27.84 \pm 1.51	
$M(\ell\ell)$	2.38 \pm 0.19	7.83 \pm 0.49	15.31 \pm 0.85	27.84 \pm 1.51	
$M(l_1 jj)$	2.22 \pm 0.18	7.15 \pm 0.47	13.95 \pm 0.82	25.66 \pm 1.44	

表 4.22 The unblinded results of the searches for $m_S=135$ GeV, $m_S=145$ GeV, $m_S=155$ GeV and $m_S=165$ GeV(fixing $m_X=340$ GeV) in ee channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg
$\Delta R_{min}(l_{2,j})$	$116.18 \pm 4.57(\text{stat.}) \pm 34.85(\text{syst.})$	$0.01 \pm 0.01(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$102.27 \pm 6.82(\text{stat.}) \pm 73.42(\text{syst.})$	$218.45 \pm 8.21(\text{stat.}) \pm 34.85(\text{syst1.}) \pm 73.42(\text{syst2.})$
$\Delta R_{min}(l_{1,j})$	$72.61 \pm 3.46(\text{stat.}) \pm 21.78(\text{syst.})$	$0.01 \pm 0.01(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$64.78 \pm 5.43(\text{stat.}) \pm 46.50(\text{syst.})$	$137.39 \pm 6.44(\text{stat.}) \pm 21.78(\text{syst1.}) \pm 46.50(\text{syst2.})$
$M(\ell\ell)$	$39.34 \pm 2.56(\text{stat.}) \pm 11.80(\text{syst.})$	$0.01 \pm 0.01(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$55.61 \pm 5.03(\text{stat.}) \pm 39.92(\text{syst.})$	$94.96 \pm 5.64(\text{stat.}) \pm 11.80(\text{syst1.}) \pm 39.92(\text{syst2.})$
$M(l_1 jj)$	$22.92 \pm 1.79(\text{stat.}) \pm 6.88(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$0.00 \pm 0.00(\text{stat.}) \pm 0.00(\text{syst.})$	$39.33 \pm 4.23(\text{stat.}) \pm 28.24(\text{syst.})$	$62.25 \pm 4.59(\text{stat.}) \pm 6.88(\text{syst1.}) \pm 28.24(\text{syst2.})$
	X340, S135	X340, S145	X340, S155	X340, S165	Observed
$\Delta R_{min}(l_{2,j})$	5.92 ± 0.26	19.02 ± 0.83	38.96 ± 1.50	64.54 ± 2.19	172
$\Delta R_{min}(l_{1,j})$	5.39 ± 0.25	17.52 ± 0.81	36.36 ± 1.47	61.47 ± 2.14	113
$M(\ell\ell)$	4.89 ± 0.24	16.51 ± 0.79	35.05 ± 1.44	61.31 ± 2.14	66
$M(l_1 jj)$	4.34 ± 0.23	14.90 ± 0.75	32.26 ± 1.39	56.55 ± 2.06	38

表 4.23 The unblinded results of the searches for $m_S=135$ GeV, $m_S=145$ GeV, $m_S=155$ GeV and $m_S=165$ GeV(fixing $m_X=340$ GeV) in $\mu\mu$ channel.

	promptSS	$V + \gamma$	QmisID	Fakes	Total bkg
$\Delta R_{min}(l_{2,j})$	$158.05 \pm 5.26(\text{stat.}) \pm 47.42(\text{syst.})$	$24.53 \pm 4.99(\text{stat.}) \pm 12.26(\text{syst.})$	$5.42 \pm 0.13(\text{stat.}) \pm 1.79(\text{syst.})$	$79.82 \pm 6.36(\text{stat.}) \pm 39.91(\text{syst.})$	$267.81 \pm 9.65(\text{stat.}) \pm 49.01(\text{syst1.}) \pm 39.91(\text{syst2.})$
$\Delta R_{min}(l_{1,j})$	$93.10 \pm 4.03(\text{stat.}) \pm 27.93(\text{syst.})$	$13.51 \pm 3.65(\text{stat.}) \pm 6.76(\text{syst.})$	$3.28 \pm 0.10(\text{stat.}) \pm 1.08(\text{syst.})$	$49.78 \pm 5.03(\text{stat.}) \pm 25.05(\text{syst.})$	$159.67 \pm 7.41(\text{stat.}) \pm 28.76(\text{syst1.}) \pm 25.05(\text{syst2.})$
$M(\ell\ell)$	$65.27 \pm 3.46(\text{stat.}) \pm 19.58(\text{syst.})$	$10.94 \pm 3.53(\text{stat.}) \pm 5.47(\text{syst.})$	$1.47 \pm 0.04(\text{stat.}) \pm 0.49(\text{syst.})$	$42.40 \pm 4.64(\text{stat.}) \pm 21.29(\text{syst.})$	$120.08 \pm 6.78(\text{stat.}) \pm 20.34(\text{syst1.}) \pm 21.29(\text{syst2.})$
$M(l_1 jj)$	$23.53 \pm 2.01(\text{stat.}) \pm 7.06(\text{syst.})$	$3.53 \pm 1.29(\text{stat.}) \pm 1.76(\text{syst.})$	$0.52 \pm 0.02(\text{stat.}) \pm 0.17(\text{syst.})$	$25.49 \pm 3.64(\text{stat.}) \pm 13.58(\text{syst.})$	$53.07 \pm 4.36(\text{stat.}) \pm 7.28(\text{syst1.}) \pm 13.58(\text{syst2.})$
	X340, S135	X340, S145	X340, S155	X340, S165	Observed
$\Delta R_{min}(l_{2,j})$	8.50 ± 0.34	24.75 ± 0.83	49.33 ± 1.64	85.30 ± 2.45	308
$\Delta R_{min}(l_{1,j})$	7.51 ± 0.31	21.64 ± 0.78	43.74 ± 1.54	79.38 ± 2.37	179
$M(\ell\ell)$	7.41 ± 0.31	21.53 ± 0.78	43.57 ± 1.54	79.38 ± 2.37	131
$M(l_1 jj)$	5.58 ± 0.27	16.64 ± 0.68	35.70 ± 1.41	69.41 ± 2.23	64

表 4.24 The unblinded results of the searches for $m_S=135$ GeV, $m_S=145$ GeV, $m_S=155$ GeV and $m_S=165$ GeV(fixing $m_X=340$ GeV) in $e\mu$ channel.

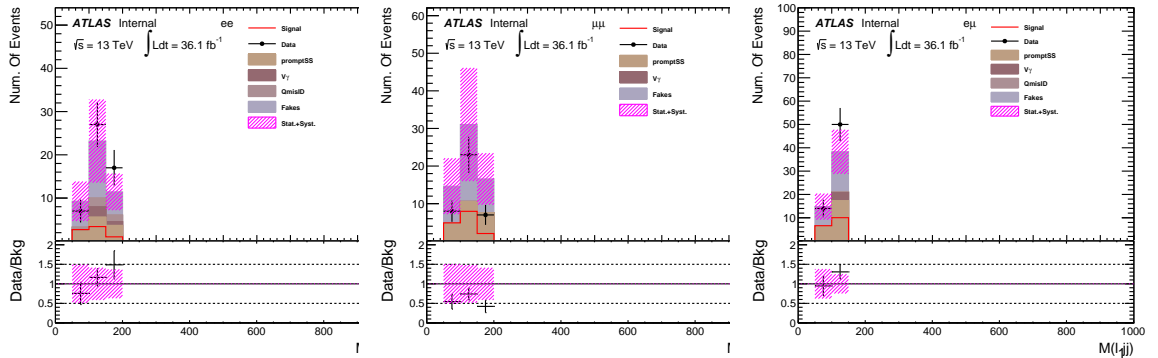


图 4.13 The unblinded $M(\ell_1 jj)$ distribution after all optimization selections, corresponding to SS high mass search. The signal shown here is $m_X=340$ GeV, $m_S=145$ GeV.

第 5 章 系统误差

5.1 对撞亮度

2015 年和 2016 年的联合亮度的不确定性为 2.1%，将应用到信号样本和 promptSS 本底上。亮度误差估计利用与文献 [20] 类似的方法得出，来自于 2015 年 8 月和 2016 年 5 月进行的 xy 束流分离扫描对亮度的初步校准结果。

5.2 信号样本理论误差

- 标准模型希格斯对的信号样本的理论误差依据推荐 [21] 是 $^{+4.3}_{-6.0}(\text{scale})^{+5.0}_{-5.0}(\text{Th.})^{+2.1}_{-2.1}(\text{PDF})^{+2.3}_{-2.3}(\alpha_S)\%$ 。
- 共振态希格斯对信号样本利用 CT10 PDF（具有 26 个相互独立参数）产生，其来源于 PDF 的误差通过 LHAPDF6 [22] 估计，每个产生的事例会根据 PDF 参数变动被重新赋予权重：

$$w_i = \frac{x_1 f_{1i}(x_1; Q) x_2 f_{2i}(x_2; Q)}{x_1 f_{10}(x_1; Q) x_2 f_{20}(x_2; Q)} (i = 1, 2, \dots, 52), \quad (5.1)$$

其中“1”和“2”表示硬散射过程中的两个入射部分子，“0”是 PDF 的最佳拟合值，即基准值，而 i 对应 PDF 参数的一次向上或向下变动。每项 PDF 参数变动之后的事例数与使用基准值的事例数差别作为单项误差，而总的 PDF 误差取它们的平方和。对于 SS 样本，PDF 误差则是 NNPDF23 中的 100 项参数变动带来的误差的平方和，结果大约为 6%。

- QCD 重整化和因子化参数同时或者单独加倍（或者减半），然后计算相应变动之后的事例数，最终把与基准值差别最大的一次作为系统误差，对于 hh (SS) 可达到 10% (4%)。

- 部分子簇射产生子的选择可影响信号的接收效率。对于 hh 信号，使用 Pythia 8 作为部分子簇射产生子的信号样本被产生，而后比较其与使用 Herwig++ 的基准信号接收效率的差别，此差别将作为部分子簇射产生模型的系统误差，随着 m_X 的增大，其值从 40% 到 10%；而对于 SS，Pythia 8 内部的所有部分子簇射模型参数变动带来的差别的平方和将作为此项误差，其值大概为 10%。

所有的信号样本的理论误差总结在表 5.1 和表 5.2 中。

hh	SM Higgs pair			$m_X=260$ GeV			$m_X=300$ GeV			$m_X=400$ GeV			$m_X=500$ GeV		
	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$
PDF	4.01	4.07	4.09	3.88	3.80	3.92	3.87	3.78	3.86	3.85	3.75	3.83	3.98	3.94	3.95
PS	13.24	18.18	10.00	26.58	42.65	19.28	30.72	31.65	18.96	22.02	24.48	33.14	1.64	16.59	12.76
Scale	1.39	1.15	6.96	5.78	3.97	0.06	0.13	4.85	0.02	9.86	0.09	3.07	3.91	0.98	1.05

表 5.1 The theoretical uncertainties on $X \rightarrow hh$ production.

hh	$m_X=280$ GeV, $m_S=135$ GeV			$m_X=300$ GeV, $m_S=135$ GeV			$m_X=320$ GeV, $m_S=135$ GeV			$m_X=340$ GeV, $m_S=135$ GeV			$m_X=340$ GeV, $m_S=145$ GeV			$m_X=340$ GeV, $m_S=155$ GeV			$m_X=340$ GeV, $m_S=165$ GeV		
	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$
PDF	5.75	5.79	5.80	5.86	5.87	5.86	5.98	6.06	6.06	6.07	6.37	6.22	6.06	6.14	6.10	6.05	6.22	6.25	6.10	6.18	
PS	4.97	6.50	6.95	5.97	8.12	2.86	3.90	10.69	7.44	8.65	6.16	5.83	10.15	6.24	6.51	7.41	7.32	9.18	9.29	8.74	
Scale	0.55	2.22	3.90	0.55	2.22	3.90	0.55	2.22	3.90	0.36	3.32	1.16	0.36	3.32	1.16	0.36	3.32	1.16	0.36	3.32	

表 5.2 The theoretical uncertainties on $X \rightarrow SS$ production.

5.3 data-driven 本底估计系统误差

QmisID 和 fakes 本底的误差如章节 3 所示，值得指出的是，QmisID 的系统误差对其本身和 fakes 上具有相反的影响。

5.4 本底预期截面误差

promptSS 和 $V\gamma$ 本底利用 MC 估计，其中主要部分是 WZ (70%)，根据三轻子分析道的估计， WZ 的截面误差为 25%。 W^+W^- 本底在 promptSS 占据大约 10%，其误差假设为 50%。剩下的 $V\gamma$, tV , $t\bar{t}V$ 和 $t\bar{t}H$ 的预期截面误差均假设为 50%，为了支持 50% 是一个足够保守的估计，可参见标准模型截面测量实验， tZ 和 ttW (ttZ) 的截面测量误差分别为 15% [23] 和 53.3% (33%) [24]。

5.5 探测器误差

探测器误差主要来源于粒子重建及鉴别，校准等。

- 影响信号运动学分布的系统误差
 - 电子沉积能量测量和分辨率
 - 受低动量径迹影响的 E_T^{miss} 重建误差
 - Jet 能量测量及分辨误差
- 末态重建及选择带来的效率修正误差
 - 轻子重建，鉴别以及孤立效率
 - Pile-up reweighting
 - JVT event weight
 - b -tagging 效率

信号，promptSS 和 $V\gamma$ 同时考虑了这些误差，但在实际操作中，每个分析道每个信号区各自舍弃掉整体影响低于 0.5% 的系统误差。表 5.3 总结了在 hh 搜寻中 $e\mu$ 分析道的系统误差大小。

Uncertainty source	Non-resonant hh	PromptSS	$V\gamma$	Fakes	QmisID
Luminosity	± 2.1	± 2.1	± 2.1	∓ 2.1	
PDF	± 2.1				
Scale	+4.3/-6.0				
Top mass	± 5.0				
α_S	± 2.3				
WZ cross-section		± 12.5		∓ 19.8	
$ssWW$ cross-section		± 8.3		∓ 6.1	
ttV cross-section		± 8.1			
tV cross-section		± 1.2			
ttH cross-section		± 1.9			
$V\gamma$ cross-section			± 50		
Pile-up reweighting	± 3.63	± 2.24	± 20.48		
b-tagging	± 2.63	± 2.8			
JVT	± 0.78	± 0.61	± 0.6		
lepton ID	± 1.1	± 1.2	± 1.0		
JES/JER	± 4.0	± 14.7	± 98		
MET	± 0.8	± 1.24			
QmisID				∓ 16.1	± 30

表 5.3 The summary of systematic uncertainty for the search of non-resonant hh in $e\mu$ channel. All numbers are in %. It should be noted that the non-closure, sample composition and stat. uncertainties are not shown for fakes.

第 6 章 统计结果

在此搜寻中，并没有发现明显信号，所以构建以下似然函数比作为假设检验量。

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

其中 $\hat{\theta}$ 表示无条件拟合， $\hat{\theta}$ 表示有条件拟合（即 μ 为固定值）。利用此假设检验量，在渐近近似分布 [25] 下基于 CL_s 方法 [26] 即可得到产生截面上限。

- 在 95% CL_s 置信度下，标准模型希格斯对 ($pp \rightarrow hh$) 观测（期望）产生截面上限为 5.6 pb (4.8 pb)，即 168 倍（145 倍）标准模型预测值。

- 在 95% CL_s 置信度下，共振态希格斯对 ($pp \rightarrow X \rightarrow hh$) 的产生截面上限如表 6.1 所示，对应图 6.1。

- 在 95% CL_s 置信度下， SS ($pp \rightarrow X \rightarrow SS$) 随 m_S 或 m_X 变化的产生截面上限如表 6.2 和图 6.2 所示。

	SM Higgs pair	260 GeV	300 GeV	400 GeV	500 GeV
Median	144.96	36.96	30.06	12.09	3.37
Observed	168.01	31.53	26.85	11.72	3.04
+2 σ	292.48	87.71	66.75	29.44	7.18
+1 σ	206.69	56.13	44.18	18.33	4.89
-1 σ	104.45	26.63	21.66	8.71	2.43
-2 σ	77.80	19.84	16.14	6.49	1.81

表 6.1 The combined exclusion limits at the 95% CL for the production cross section of a gluon fusion produced X boson times its branching ratio to hh.

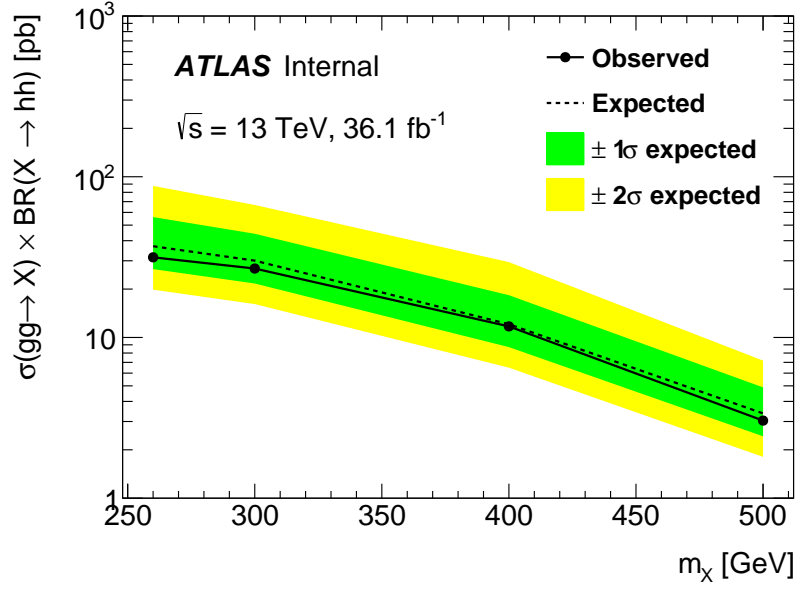


图 6.1 The expected limits for $pp \rightarrow X \rightarrow hh$, as a function of m_X .

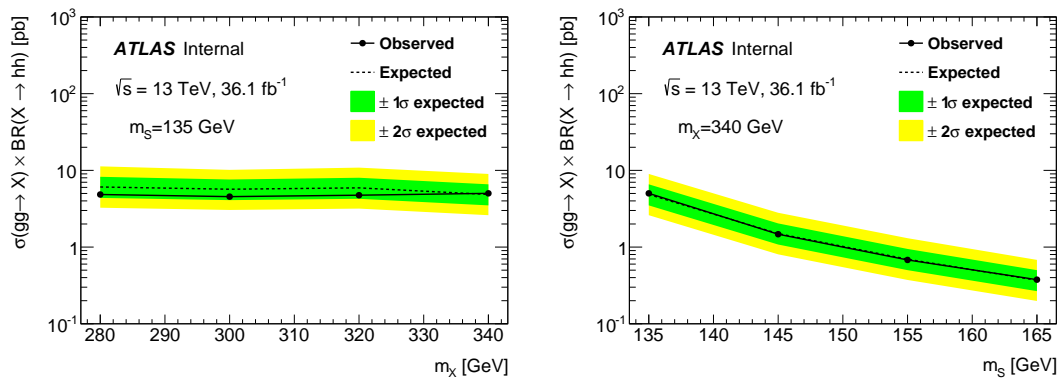


图 6.2 The expected limits for $pp \rightarrow X \rightarrow SS$ production. Left: fixing $m_S=135 \text{ GeV}$; right: fixing $m_X=340 \text{ GeV}$.

	X280, S135	X300, S135	X320, S135	X340, S135	X340, S145	X340, S155	X340, S165
Median	6.07	5.68	5.91	4.85	1.50	0.69	0.37
Observed	4.85	4.55	4.75	5.02	1.47	0.68	0.38
$+2\sigma$	11.28	10.15	10.86	8.98	2.80	1.31	0.68
$+1\sigma$	8.24	7.60	8.01	6.58	2.03	0.95	0.50
-1σ	4.38	4.09	4.26	3.50	1.08	0.50	0.27
-2σ	3.26	3.05	3.17	2.60	0.80	0.37	0.20

表 6.2 The combined exclusion limits at the 95% CL for the production cross section of a gluon fusion produced X boson times its branching ratio to SS.

第 7 章 4W 联合统计结果

为了最大化 4W 分析道的灵敏度，对 3 个现有衰变分析道进行统计组合，包括 2LSS, 3Lep 和 4Lep。统计处理与参考文献 [27, 28] 中描述的相同。每个 bin 的事例数采用泊松假设，联合乘积即可构建似然函数；其中系统误差，即冗余参数，利用高斯函数模拟。值得注意的是，影响多个分析道的系统误差应当使用相同的冗余参数，这样子系统误差对整个实验的影响才能有效一致的传递。检验统计量使用参考文献 [25] 中定义的 profile 似然比 $\Lambda(\mu)$ 。最终应用渐近逼近式修改的频率方法 CL_s [29] 在 95% 置信度下提取上限。

7.1 系统误差相关性

影响多个衰变分析道的系统误差关联考虑，具体关联情况见表 ??。亮度， μ 子，轻子，光子，味道鉴别，pile-up 和 MET 相关的系统误差是相互关联的，而 fakes 相关的误差没有关联，fakes 是在不同的区域估计的。JES uncertainty is not correlated because the knowledge of the source is removed when the simplification of nuisance parameter scheme is done? The uncertainty on the electron efficiency is only correlated between 2L and 3L channels, since 4L uses a different correlation scheme.?

Sys source	number of NP	correlation strategy
Lumi	1NP	correlated
Jet systematic	JES 21NP ¹ , JER 1NP	21NP JES is not correlated, JER is correlated
EGam systematic	EG Scale 1NP, EG resolution 1NP	correlated
Electron systematic	4(ID,RECO,TRIG,ISO) for SS2L/3L, 33(15 uncorr+15corr+3 ISO, reco, TRIG) for 4L	only correlate SS2L and 3L
Muon systematic	Trigger(2NP),ID(4),TTVA(2NP),ISO(2NP),Momentum(3NP)	correlated
Flavor tagging	6(B)+4(C)+15(Light)+2(Extrap)	correlated
MET	3NP	correlated
Pileup	1NP	correlated
MC Stat		not correlated
Fake factor uncertainty	6(2L)+2(3L)+1(4L)	not correlated

7.2 统计模型检查

本章检查在建立的统计模型中的系统误差的拟合结果 (pull)，相关性以及影响排序。为了使得图像更清晰，所有的 pull 图分为两张，其中红点是 4Lep 中的 ZZ 归一因子，因为它并不是高斯函数所模拟，所以其中心值为 1，在联合拟合中的误差大约为 5%。

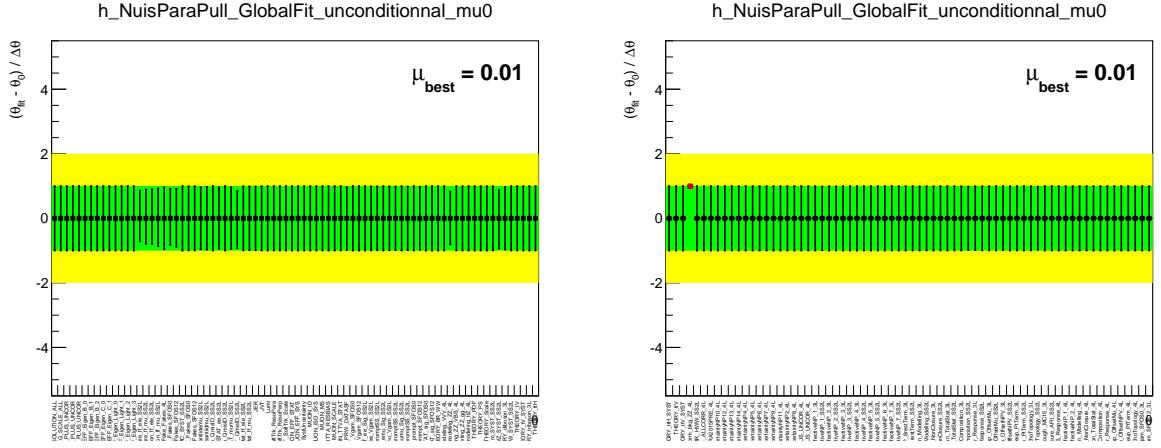
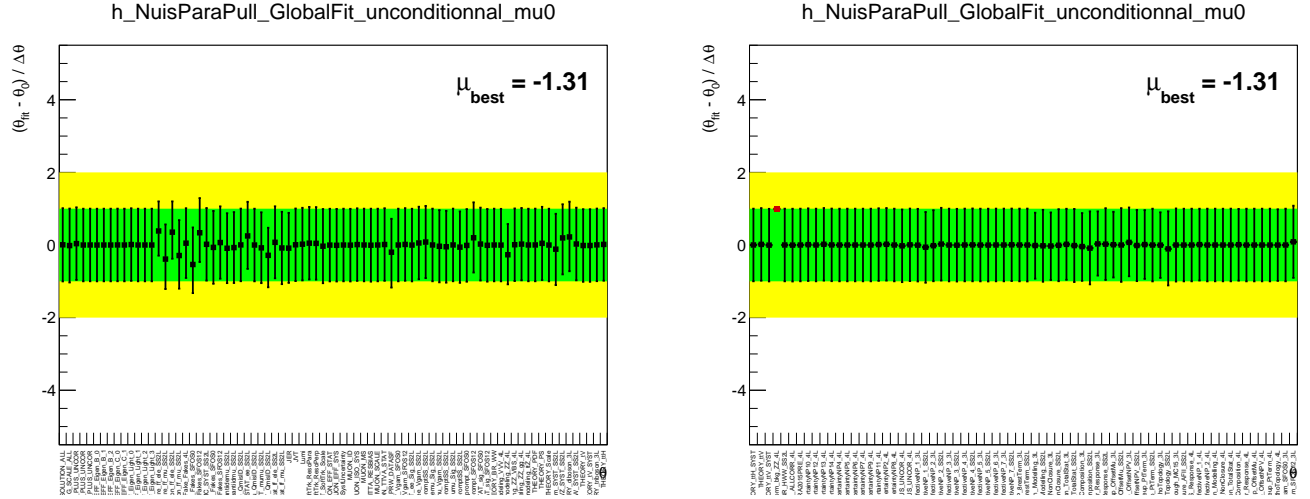
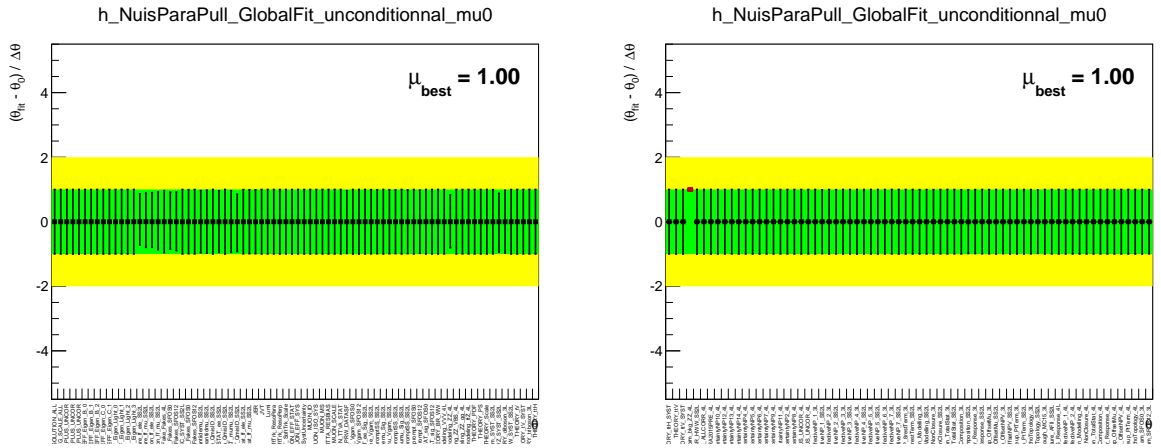
图 7.1到图 7.6展示在 $m_X=260$ GeV 和 $m_X=500$ GeV 两个质量点搜寻中系统误差在不同假设下的拟合结果。在无信号假设和信号 + 预期背景的假设下，pull 的表现是非常合理的。而在实际观测数据的拟合中，因为数据的涨落，2L 的 fakes 误差偏移较大。在图 7.7和图 7.8还可以看到，系统误差之间没有较大相关性。图 7.9和图 7.10是系统误差影响的排序，虚线阴影区表示截面上限随冗余参数向上或向下变化一个标准偏差时的变化，并分别展示在拟合前和拟合后的变化情况。fake factor 的系统误差对最终结果影响最大。在 $m_X=500$ GeV 的 S+B asimov 拟合和观测值拟合中，JET Pileup OffsetMu 对 3L 只有单边的影响，这是源于其对信号和本底的影响是单边的，见表 7.1。

Another check is to fix specific uncertainty to nominal value and quantify the variation of upper limit compared with full systematics uncertainties. Table 7.5, 7.6 and 7.7 summarize the variation of upper limit after switching off certain uncertainty. The upper limit is sensitive to fake uncertainty.

另一个重要检查是在拟合中固定住单个或者多个系统误差，观察结果变化。表 7.5，表 7.6和表 7.7总结在固定住某些系统误差后，拟合截面上限的变化，得出结论拟合结果对 fakes 的误差最敏感，与前述的影响排序是一致的。

alpha_ATLAS_JET_21NP_JET_Pileup_OffsetMu	background		signal		observed
ThreeLep_SFOS0_m500	0.000(+1 σ)/-0.004(-1 σ)(in percentage)	0.00/-0.00(yield)	-0.490(+1 σ)/-0.001(-1 σ)	-0.18/-0.00(yield)	2
ThreeLep_SFOS12_m500	0.000(+1 σ)/0.000(-1 σ)(in percentage)	0.00/0.00(yield)	-0.485(+1 σ)/0.006(-1 σ)	-0.43/0.01(yield)	1

表 7.1 Systematic variation on signal and total background yield. The variation is asymmetric on signal yield.


 图 7.1 pull check on B-only asimovData of $m_H = 260 GeV$

 图 7.2 pull check on obsData of $m_H = 260 GeV$

 图 7.3 pull check on S+B asimovData of $m_H = 260 GeV$

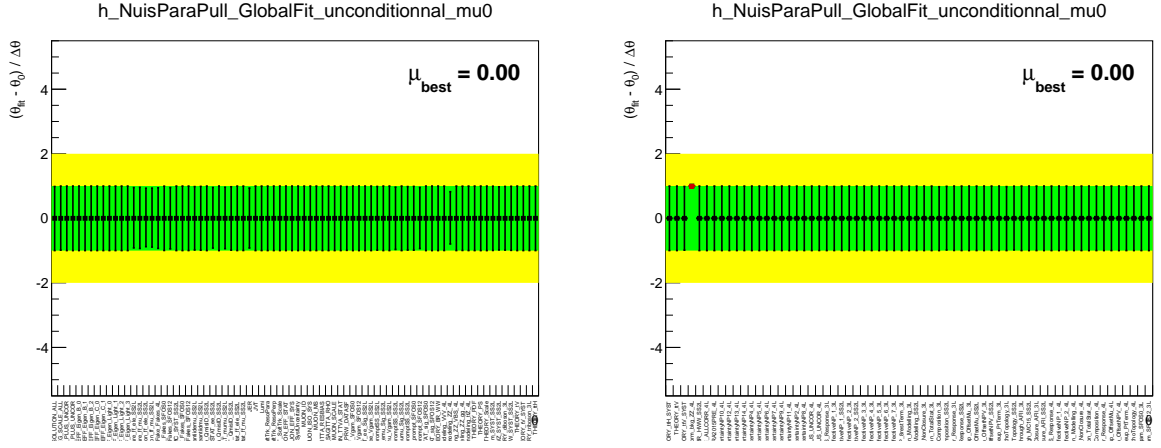


图 7.4 pull check on B-only asimovData of $m_H = 500\text{GeV}$

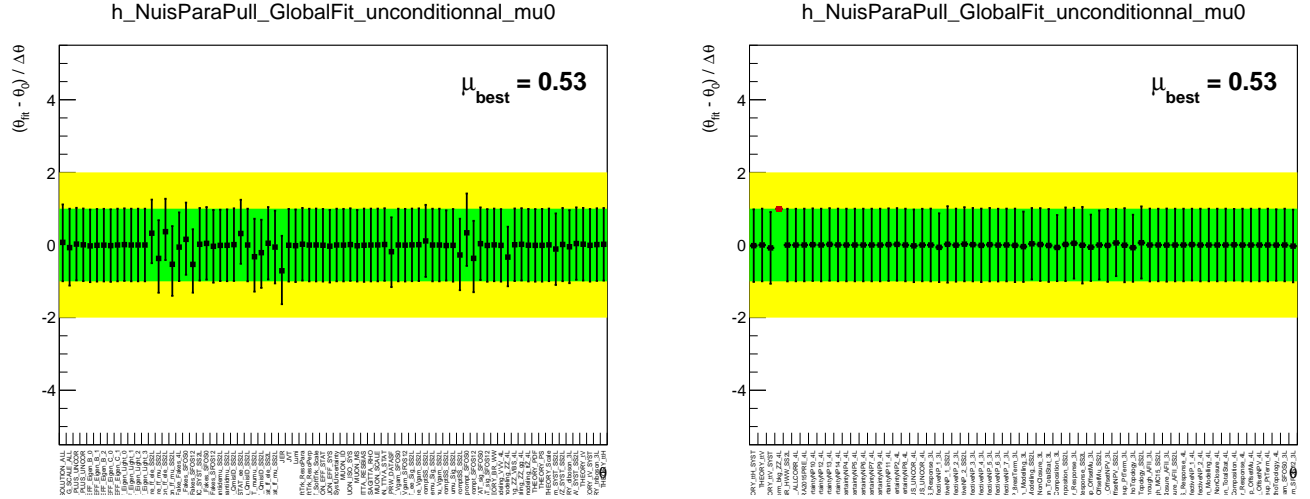


图 7.5 pull check on obsData of $m_H = 500\text{GeV}$

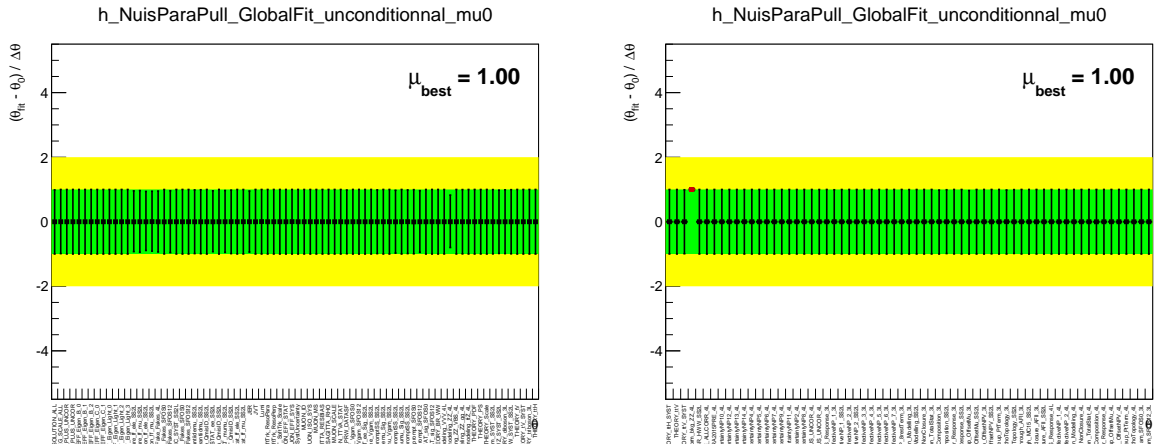


图 7.6 pull check on S+B asimovData of $m_H = 500\text{GeV}$

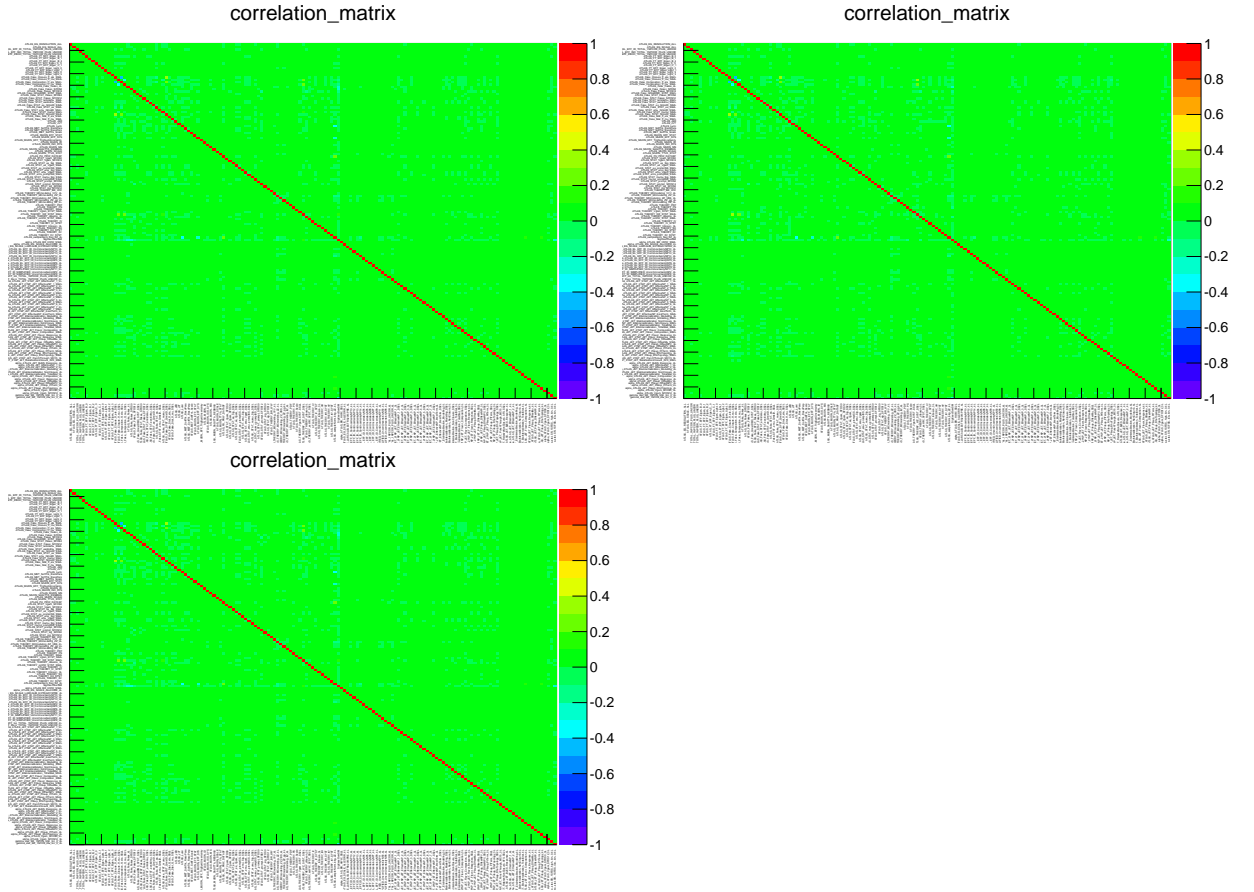


图 7.7 correlation check on B-only asimovData, obsData and S+B asimovData of $m_H = 260\text{GeV}$

$\Delta\text{limit}/\text{limit}$	nonres	$m_H = 260\text{GeV}$	$m_H = 300\text{GeV}$	$m_H = 400\text{GeV}$	$m_H = 500\text{GeV}$
Lumi	0.00	0.01	0.02	0.03	0.00
JET	0.10	0.02	0.05	0.11	0.07
FT	0.01	0.01	0.02	0.03	0.00
EG	0.00	0.01	0.02	0.03	0.00
EL	0.00	0.01	0.02	0.03	0.00
MUON	0.00	0.01	0.02	0.03	0.00
MET	0.00	0.01	0.02	0.03	0.00
MC STAT	0.02	0.01	0.03	0.04	0.03
Fake	0.08	0.10	0.12	0.21	0.11
THEORY	0.05	0.05	0.06	0.10	0.04

表 7.2 $\Delta\text{limit}/\text{limit}$ is shown after switching off specific uncertainty in hh model

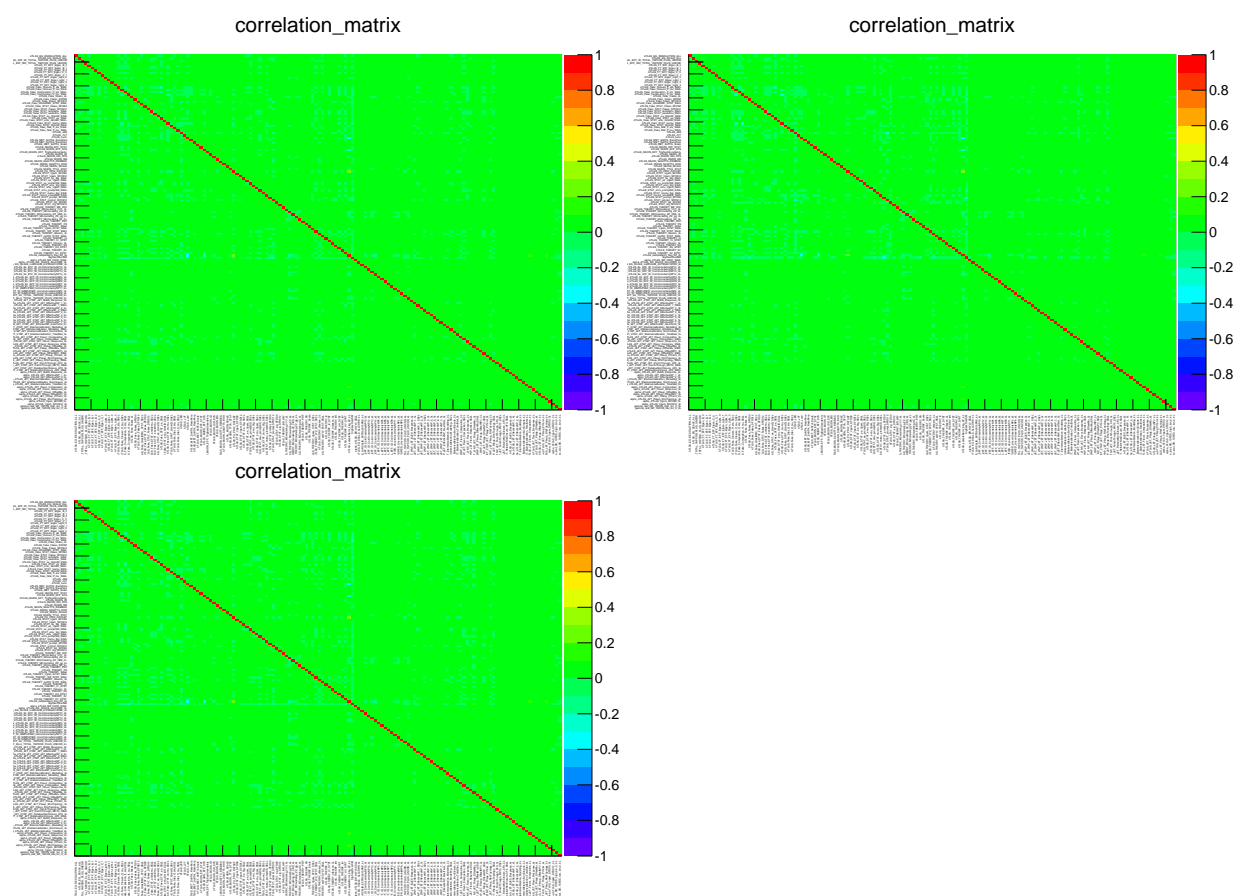


图 7.8 correlation check on B-only asimovData, obsData and S+B asimovData of $m_H = 500 GeV$

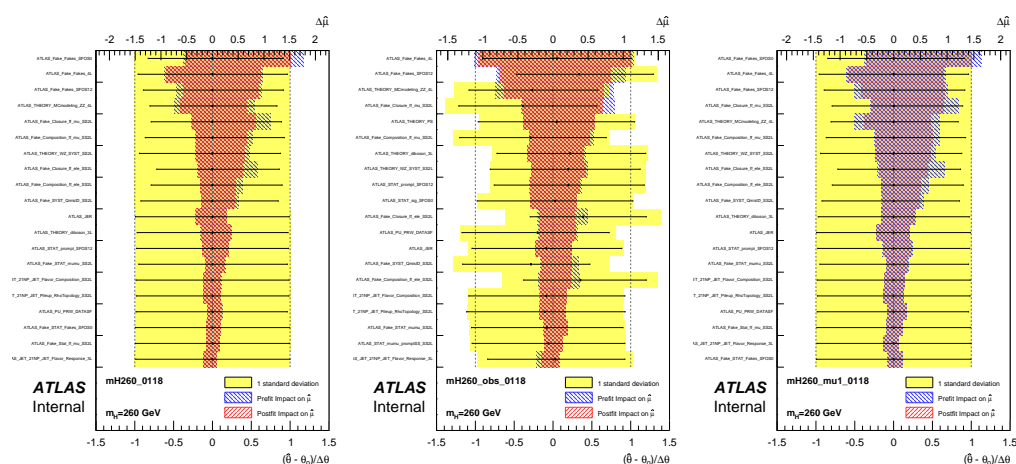


图 7.9 NP ranking check on B-only asimovData, obsData and S+B asimovData of $m_H = 260 GeV$

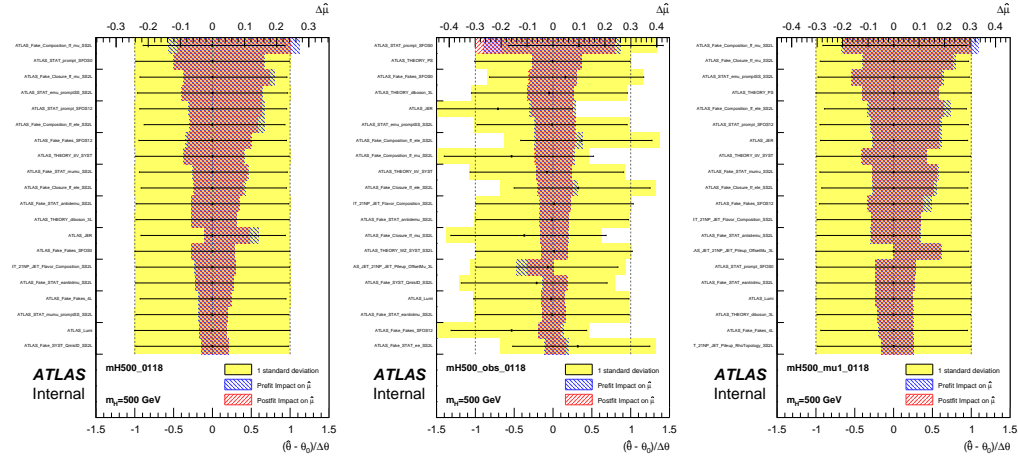


图 7.10 NP ranking check on B-only asimovData, obsData and S+B asimovData of $m_H = 500\text{GeV}$

$\Delta limit/limit$	H280S135	H300S145	H320S155	H340S135
Lumi	0.004	0.001	0.006	0.044
JET	0.011	0.031	0.040	0.086
FT	0.003	0.001	0.004	0.042
EG	0.003	0.001	0.004	0.041
EL	0.003	0.001	0.004	0.042
MUON	0.003	0.001	0.004	0.042
MET	0.003	0.000	0.004	0.042
MC STAT	0.008	0.007	0.012	0.051
Fake	0.131	0.154	0.174	0.190
THEORY	0.030	0.034	0.045	0.071

表 7.3 $\Delta limit/limit$ is shown after switching off specific uncertainty in SS model

$\Delta limit/limit$	H340S135	H340S145	H340S155	H340S165
Lumi	0.044	0.036	0.029	0.023
JET	0.086	0.075	0.026	0.006
FT	0.042	0.037	0.031	0.012
EG	0.041	0.037	0.034	0.000
EL	0.042	0.037	0.034	0.006
MUON	0.042	0.037	0.034	0.006
MET	0.042	0.037	0.034	0.000
MC STAT	0.051	0.037	0.037	0.006
Fake	0.190	0.275	0.289	0.234
THEORY	0.071	0.067	0.055	0.023

表 7.4 $\Delta limit/limit$ is shown after switching off specific uncertainty in SS model

$\Delta limit/limit$	nonres	$m_H = 260 GeV$	$m_H = 300 GeV$	$m_H = 400 GeV$	$m_H = 500 GeV$
Lumi	0.00	0.01	0.02	0.03	0.00
JET	0.10	0.02	0.05	0.11	0.07
FT	0.01	0.01	0.02	0.03	0.00
EG	0.00	0.01	0.02	0.03	0.00
EL	0.00	0.01	0.02	0.03	0.00
MUON	0.00	0.01	0.02	0.03	0.00
MET	0.00	0.01	0.02	0.03	0.00
MC STAT	0.02	0.01	0.03	0.04	0.03
Fake	0.08	0.10	0.12	0.21	0.11
THEORY	0.05	0.05	0.06	0.10	0.04

表 7.5 $\Delta limit/limit$ is shown after switching off specific uncertainty in hh model

$\Delta limit/limit$	H280S135	H300S145	H320S155	H340S135
Lumi	0.004	0.001	0.006	0.044
JET	0.011	0.031	0.040	0.086
FT	0.003	0.001	0.004	0.042
EG	0.003	0.001	0.004	0.041
EL	0.003	0.001	0.004	0.042
MUON	0.003	0.001	0.004	0.042
MET	0.003	0.000	0.004	0.042
MC STAT	0.008	0.007	0.012	0.051
Fake	0.131	0.154	0.174	0.190
THEORY	0.030	0.034	0.045	0.071

表 7.6 $\Delta limit/limit$ is shown after switching off specific uncertainty in SS model

$\Delta limit/limit$	H340S135	H340S145	H340S155	H340S165
Lumi	0.044	0.036	0.029	0.023
JET	0.086	0.075	0.026	0.006
FT	0.042	0.037	0.031	0.012
EG	0.041	0.037	0.034	0.000
EL	0.042	0.037	0.034	0.006
MUON	0.042	0.037	0.034	0.006
MET	0.042	0.037	0.034	0.000
MC STAT	0.051	0.037	0.037	0.006
Fake	0.190	0.275	0.289	0.234
THEORY	0.071	0.067	0.055	0.023

表 7.7 $\Delta limit/limit$ is shown after switching off specific uncertainty in SS model

7.3 联合统计结果

最终提取出的 $hh95\% \text{ CL}_s$ 的截面上限如表 7.8 和图 7.11 所示。标准模型希格斯对的观测（期望）截面上限值 ($pp \rightarrow hh$) 为 159 倍（111 倍）标准模型预测值，观测值在期望值的两个标准偏差以内；对共振态搜寻 ($pp \rightarrow X \rightarrow hh$) 而言，观测值均在一个标准偏差以内，观测（期望）截面上限值随着 m_X 增加从 9.1 pb（9.7 pb）到 2.6 pb（2.4 pb），在低质量区，4L 具有最高的期望显著性，3L 次之，2L 最低，而在高质量区，其顺序刚好相反。在 SS 信号 ($pp \rightarrow SS$) 搜寻中，所有质量点的观测值均在期望值的一个标准偏差以内，观测（期望）截面上限值随 m_X 或 m_S 增大从 1.7 pb（2.2 pb）到 0.17 pb（0.19 pb），其中在低质量区 4L 同样地具有最高的显著性，而在高质量区三个分析道显著性非常接近。

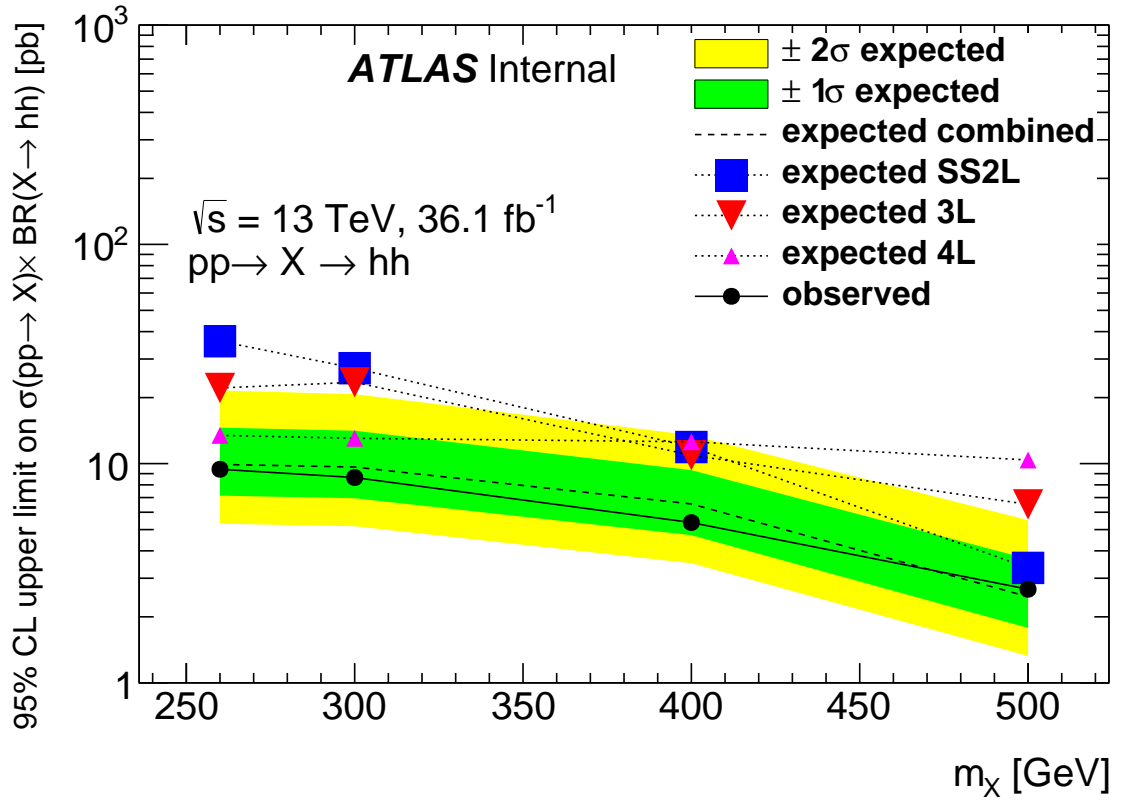


图 7.11 The 95% CL upper limits in WWW channels with all systematic.

Upper Limit(pb)	non-resonant	$m_X = 260$ GeV	$m_X = 300$ GeV	$m_X = 400$ GeV	$m_X = 500$ GeV
expected SS 2L	144.57	27.60	23.88	9.77	3.21
expected 3L	211.94	20.38	20.61	10.26	6.17
expected 4L	387.41	13.44	13.03	12.56	10.37
combined	111.42	9.66	9.41	6.14	2.41
observed	159.29	9.09	8.23	5.19	2.56
+2 σ	215.30	19.84	19.11	11.34	5.08
+1 σ	156.16	13.90	13.48	8.40	3.51
-1 σ	80.28	6.96	6.78	4.43	1.74
-2 σ	59.80	5.18	5.05	3.30	1.30

表 7.8 This table summarizes the expected in each channel and combined channel and the combined observed limit. For non-resonant, the limit is on the ratio over SM Higgs pair prediction.

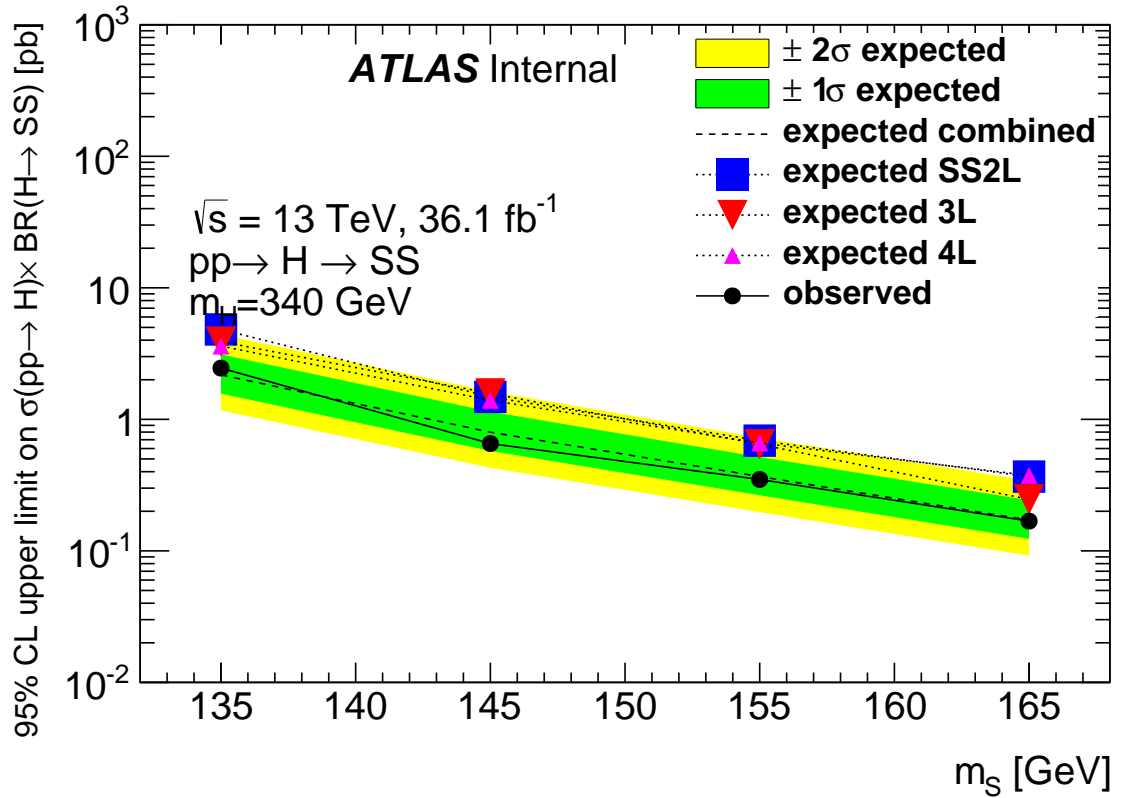


图 7.12 The expected and observed limit with all systematic uncertainty is shown as the function of m_S

	H280_S135	H300_S135	H320_S135	H340_S135	H340_S145	H340_S155	H340_S165
expected SS 2L	5.69	5.41	5.69	4.83	1.48	0.69	0.37
expected 3L	4.05	4.67	5.20	3.90	1.57	0.65	0.25
expected 4L	3.16	3.25	3.57	3.61	1.40	0.66	0.37
combined	2.20	2.43	2.53	2.17	0.92	0.39	0.19
observed	1.74	2.15	2.34	2.45	0.65	0.35	0.17
$+2\sigma$	4.46	4.79	5.13	4.42	1.63	0.72	0.34
$+1\sigma$	3.07	3.33	3.58	3.12	1.14	0.52	0.24
-1σ	1.52	1.66	1.80	1.57	0.58	0.26	0.12
-2σ	1.13	1.24	1.34	1.17	0.43	0.20	0.09

表 7.9 This table shows the expected limit in each channel and the observed limit in $pp \rightarrow SS$ model.

第二部分

通过多轻子道寻找 $t\bar{t}H$ 产生模式

第 1 章 $t\bar{t}H$

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[1] ucasthesis: A LaTeX Thesis Template for the University of Chinese Academy of Sciences, 2014.

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