SUSY searches at $\sqrt{s}$ = 13 TeV with two same-sign leptons or three leptons, jets and E_T^{miss} at the ATLAS detector

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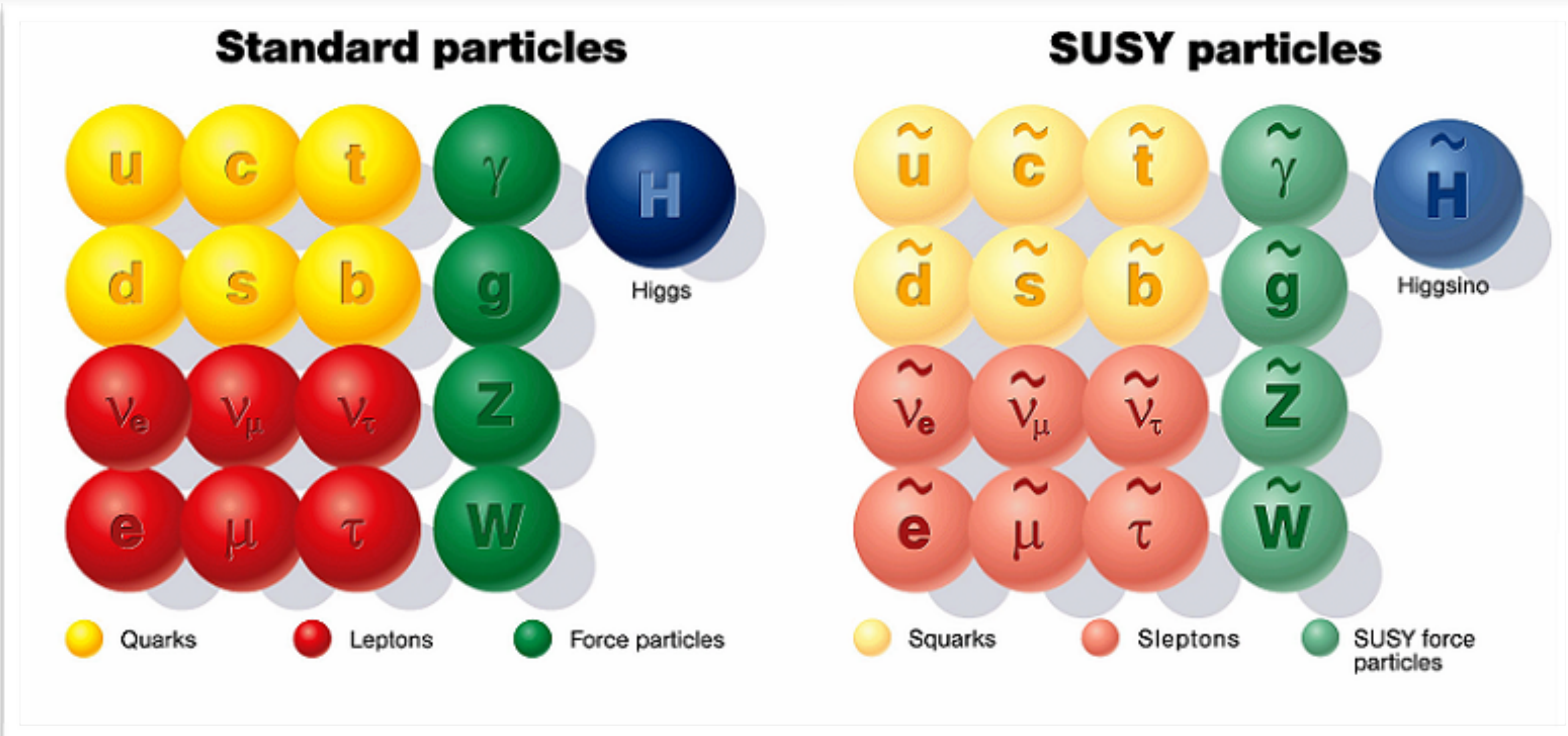
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC

Motivation

- search for strongly produced SUSY particles in **multi-lepton signatures**;
- 2 same-sign(SS) or 3 leptons(3L) production rare in SM, very **low background**;
- powerful in **compressed SUSY scenario and in R-Parity Violated models searches**;

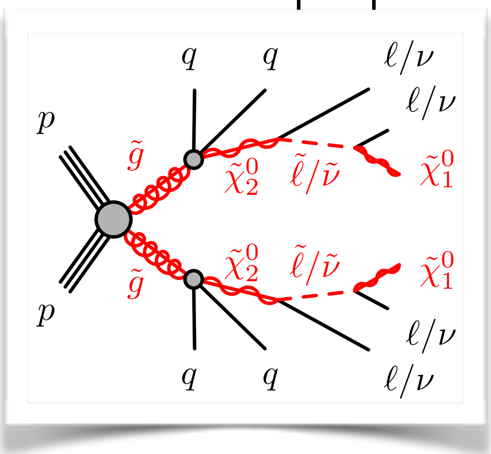


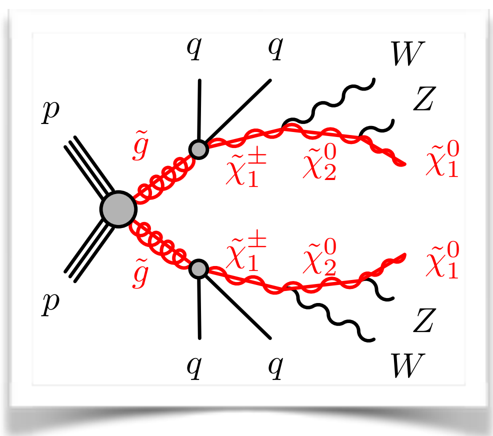
I will report here on results on LHC Run2 data (36.1 fb^{-1}), as documented in JHEP09(2017)084

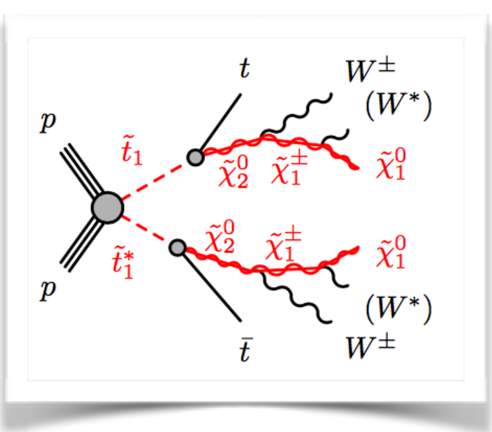
Signatures with strong production

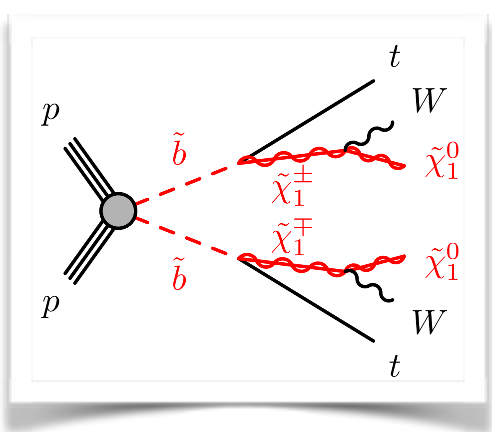
RPC SUSY processes

- Two scenarios focus on gluino pair production with decays into light quarks and multiple leptons;
- Other two target the direct production of sbottom and stop pairs (3LSS) decaying via off-shell top quark;



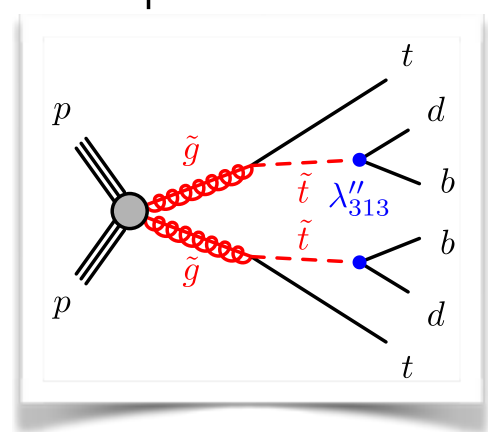


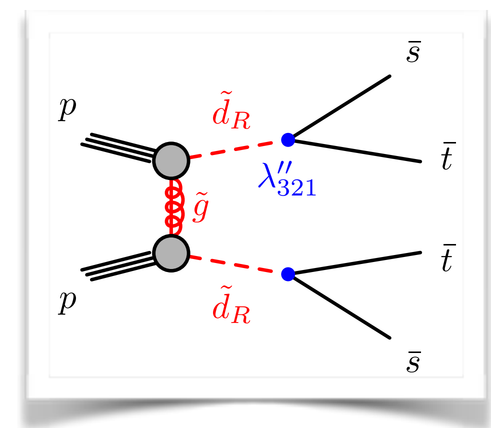


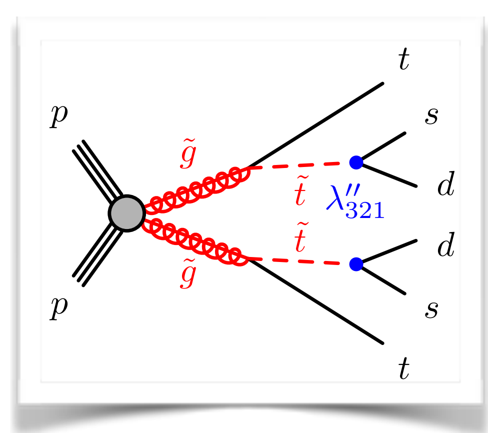


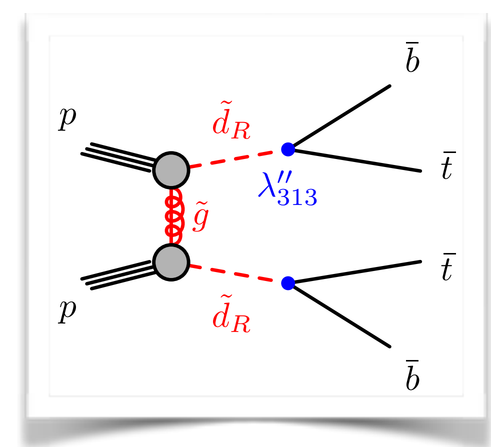
RPV SUSY processes

- Gluino and squarks may decay directly to top quarks, leading to final states with SS leptons and b-jets;
- Scenarios with gluino pair production followed by stop-mediated decay or right-handed sdown production









Signal Region

- Studies to find the best cut for each signal model in several **kinematic variables**
- Definition of 19 overlapping SR which **maximise the significance** of the studied SUSY models:

Signal region Name	$N_{\text{leptons}}^{\text{signal}}$	$N_{b-\text{jets}}$	N_{jets}	$p_{\text{T,jet}}$ [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	m_{eff} [GeV]	$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}$	Other
Rpc2L2bS	$\geq$ 2SS	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	–
Rpc2L2bH	$\geq$ 2SS	≥ 2	≥ 6	> 25	–	> 1800	> 0.15	–
Rpc2Lsoft1b	$\geq$ 2SS	≥ 1	≥ 6	> 25	> 100	–	> 0.3	$20,10 < p_{\text{T}}^{\ell_1}, p_{\text{T}}^{\ell_2} < 100$ GeV
Rpc2Lsoft2b	$\geq$ 2SS	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	$20,10 < p_{\text{T}}^{\ell_1}, p_{\text{T}}^{\ell_2} < 100$ GeV
Rpc2L0bS	$\geq$ 2SS	$= 0$	≥ 6	> 25	> 150	–	> 0.25	–
Rpc2L0bH	$\geq$ 2SS	$= 0$	≥ 6	> 40	> 250	> 900	–	–
Rpc3L0bS	≥ 3	$= 0$	≥ 4	> 40	> 600	–	–	–
Rpc3L0bH	≥ 3	$= 0$	≥ 4	> 40	> 200	> 1600	–	–
Rpc3L1bS	≥ 3	≥ 1	≥ 4	> 40	> 200	> 600	–	–
Rpc3L1bH	≥ 3	≥ 1	≥ 4	> 40	> 200	> 1600	–	–
Rpc2L1bS	$\geq$ 2SS	≥ 1	≥ 6	> 25	> 150	> 600	> 0.25	–
Rpc2L1bH	$\geq$ 2SS	≥ 1	≥ 6	> 25	> 250	–	> 0.2	–
Rpc3LSS1b	$\geq \ell^\pm\ell^\pm\ell^\pm$	≥ 1	–	–	–	–	-	veto $81 < m_{e^\pm e^\pm} < 101$ GeV
Rpv2L1bH	$\geq$ 2SS	≥ 1	≥ 6	> 50	–	> 2200	–	–
Rpv2L0b	= 2SS	$= 0$	≥ 6	> 40	–	> 1800	–	veto $81 < m_{e^\pm e^\pm} < 101$ GeV
Rpv2L2bH	$\geq$ 2SS	≥ 2	≥ 6	> 40	–	> 2000	–	veto $81 < m_{e^\pm e^\pm} < 101$ GeV
Rpv2L2bS	$\geq \ell^-\ell^-$	≥ 2	≥ 3	> 50	–	> 1200	–	
Rpv2L1bS	$\geq \ell^-\ell^-$	≥ 1	≥ 4	> 50	–	> 1200	–	–
Rpv2L1bM	$\geq \ell^-\ell^-$	≥ 1	≥ 4	> 50	–	> 1800	–	–

Reminder:

$m_{\text{eff}} = \sum p_{\text{T}}(\text{lep}) + \sum p_{\text{T}}(\text{jets}) + E_{\text{T}}^{\text{miss}}$

Each SR is motivated by different SUSY scenarios;

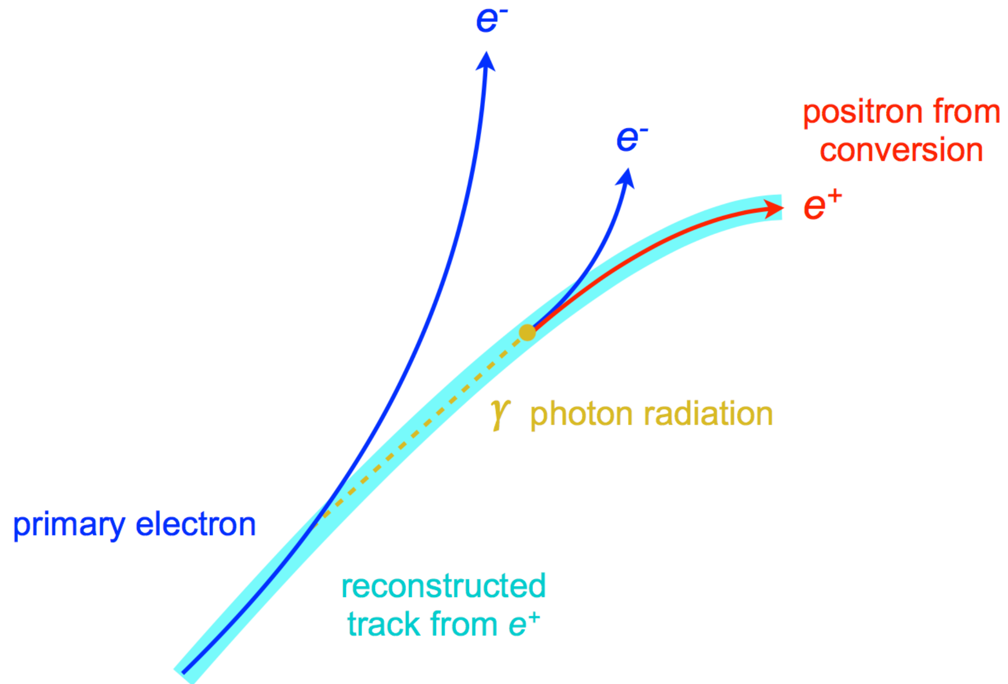
N.B. For the **RPV**, no $E_{\text{T}}^{\text{miss}}$ cut is required as no LSP particle is expected, additional requirement on the charge of the leptons is applied for the direct sdown production;

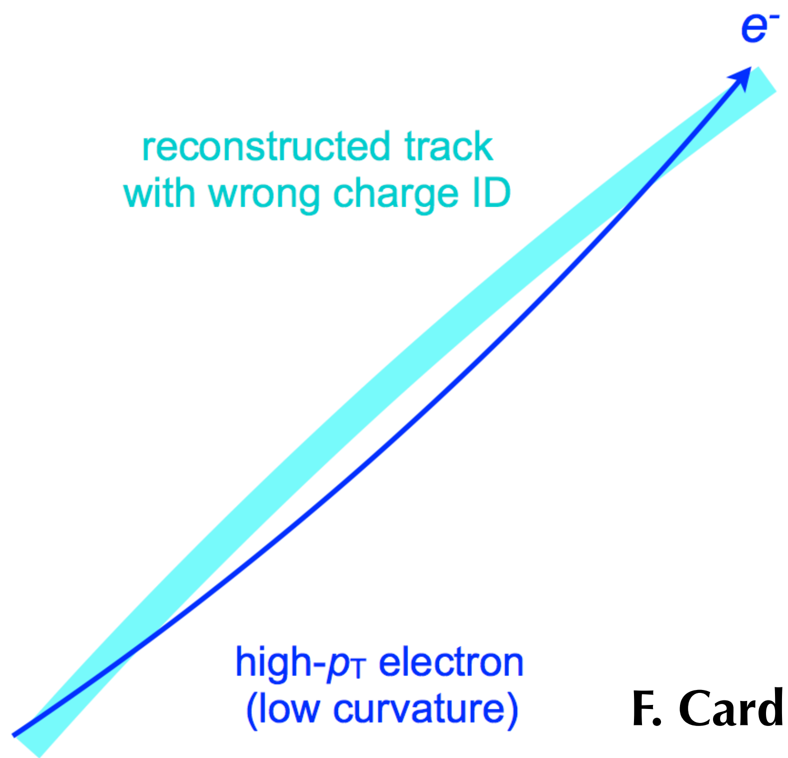
Background

Searches in SS and 3L are characterised by low SM background

There are three different types of backgrounds:

1. **prompt multi-lepton background**: dominated by ttV and VV, estimated from MC samples;
2. **charge flip background**: electrons having emitted a hard bremsstrahlung photon which subsequently converted to an e^+e^- pair, negligible for muons;
3. **“fake" leptons background**: hadrons misidentified as leptons, with leptons originating from heavy-flavour decays and electrons from photon conversion;





F. Cardillo

Prompt lepton background

Source: few SM processes produce events with two same-charge or 3 real leptons

- **Associated production of tops and bosons:** $t\bar{t}V(j)$ is the main background but also contribution from $\bar{t}Z$, ttWW and 4top, characterised by large jet multiplicity and the presence of b-jets (1b and 2b SRs);
- **Multiple bosons production:** WWjj, WZ, ZZ are the dominant processes in addition to WH, ZH and VVV, characterised by low jet multiplicity but larger cross-section -> (0b SRs);

The **total uncertainty** after the SR selection is given by: **cross-section uncertainty, modelling of the kinematic distributions**, **renormalisation and factorisation**;

Source: two opposite-sign leptons for which charge of one lepton is **mis-measured**

The electron charge-flip probability ε is extracted from $Z/\gamma^* \rightarrow e^+e^-$ data sample:

1. selecting SS and OS electron pairs with $m_{ee} \in [75,100]$ GeV;
2. likelihood fit with ε as a free parameter and number of SS/OS pairs as input;
3. ε is extracted as a function of the electron p_T and η;
4. comparison with MC simulation to validate the control region;

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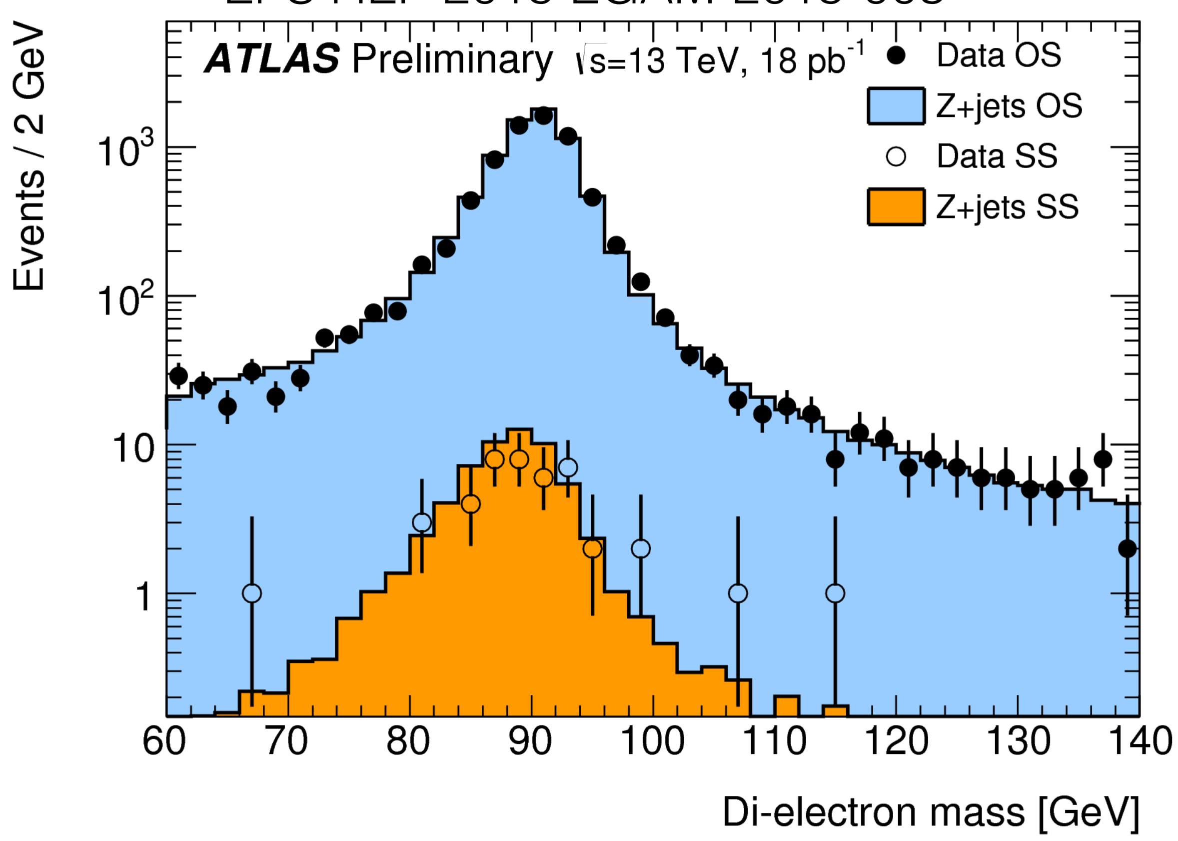
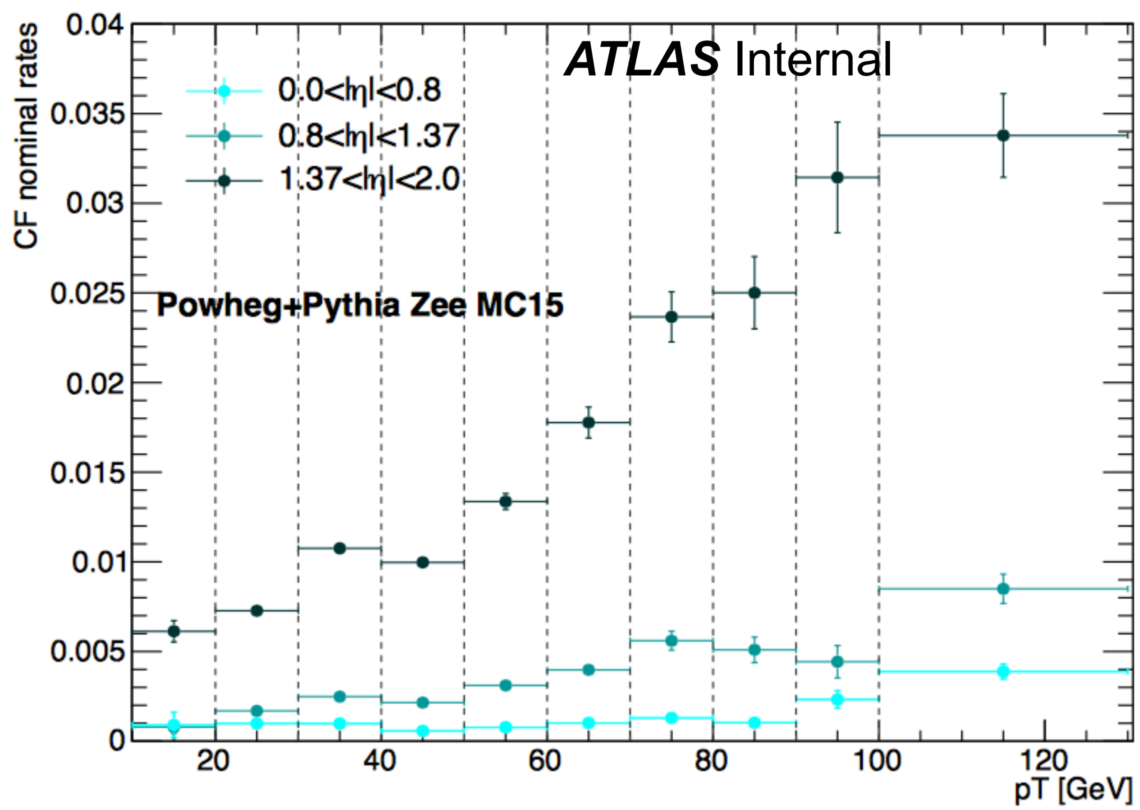




5. the event yield in Signal and Validation Regions is obtained by applying the measured ε with the same kinematic requirements (p_T ,η) of the SR and VR.

Fake lepton background

Source: events with fake lepton originating from heavy-flavor meson decay

The estimation is done with a dynamic matrix method, which is based on the relation between:

Measurable quantities
- N_T: # of tight leptons (signal);
- N_L: # of loose not tight leptons (pre-selected);

Physical quantities
- N_R: # of real leptons;
- N_F: # of fake leptons;

Efficiencies
- ε: real lepton efficiency;
- ζ: fake lepton efficiency;

$$r = \begin{pmatrix} n_R \\ n_F \end{pmatrix} \quad t = \begin{pmatrix} n_T \\ n_L \end{pmatrix} \quad \phi_j = \begin{pmatrix} \varepsilon_j & \zeta_j \\ 1-\varepsilon_j & 1-\zeta_j \end{pmatrix} \quad \Rightarrow \quad t_\beta = \phi_{j\beta}^{\ \alpha} r_\alpha,$$

For each event with N leptons and a measured tight/loose combination a weight is applied to the output combination, for example:

Given an event with 3 leptons ($e^+e^-\mu^+$) in the configuration TTL (Tight-Tight-Loose), the matrix method will produce:

$$\textbf{Input} \qquad\qquad \textbf{Output}$$

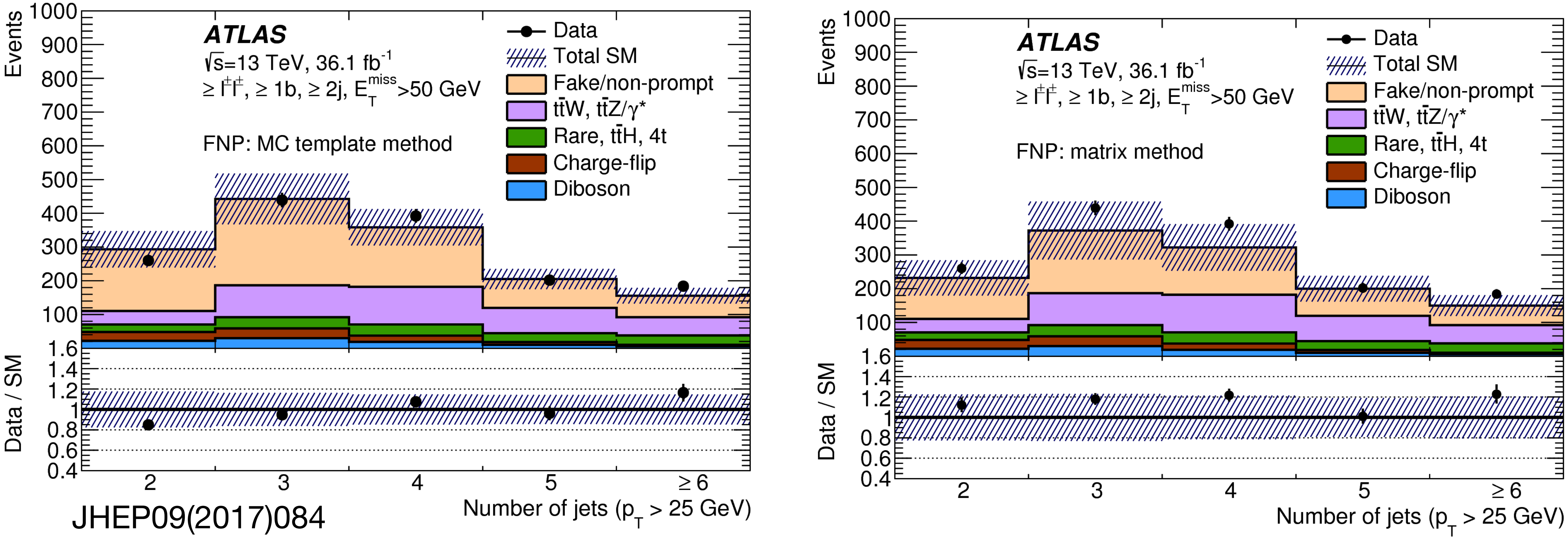
$$e^+e^-\mu^+, TLL \longrightarrow \begin{cases} LLL & w_{LLL} & e_L^+e_L^-\mu_L^+ & \text{Fails cuts} \\ \cdots & \cdots & & \\ TTL & w_{TTL} & e_T^+e_T^-\mu_L^+ & \text{Fails cuts} \\ TLT & w_{TLT} & e_T^+e_L^-\mu_T^+ & \text{2 lepton SS} \\ LTT & w_{LTT} & e_L^+e_T^-\mu_T^+ & \text{Fails cuts} \\ TTT & w_{TTT} & e_T^+e_T^-\mu_T^+ & > \text{2 lepton} \end{cases}$$

Only two pass the selection cuts

Final fakes yields

Predictions from the MC template and matrix methods in the SR and VR are consistent with each other -> a weighted average of the two results is used.

MC Template Method: CR (low ETmiss, meff and jet multiplicity) are used to rescale MC samples with "fake" leptons in order to match with data and then extrapolate the background in the SR.



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Combined estimate is always dominated by systematic uncertainties (not always the case when using only MM due to low stats in the control regions)

Background validation

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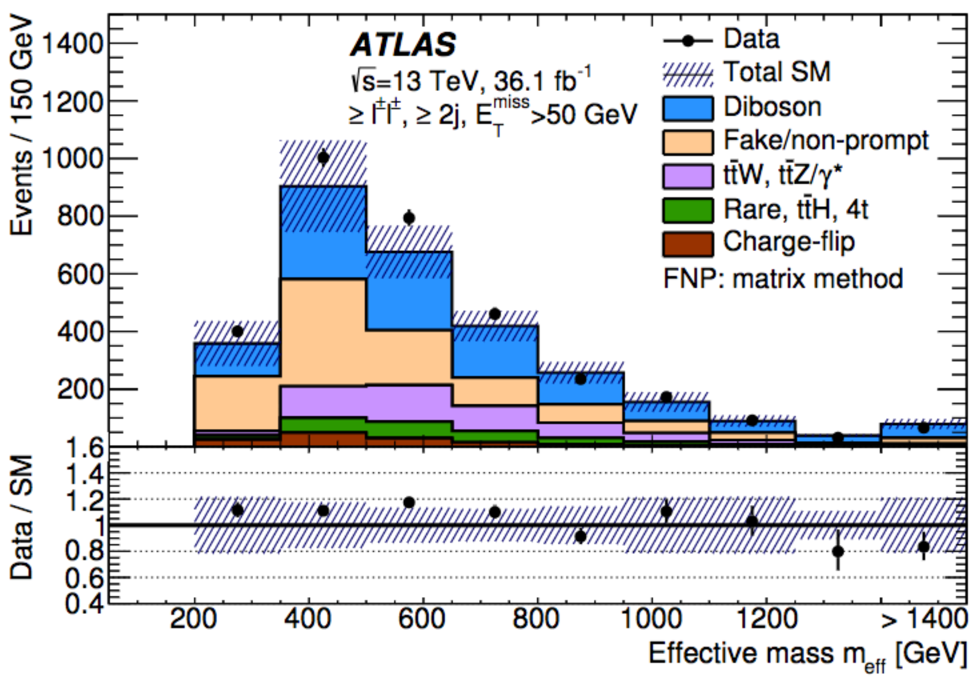
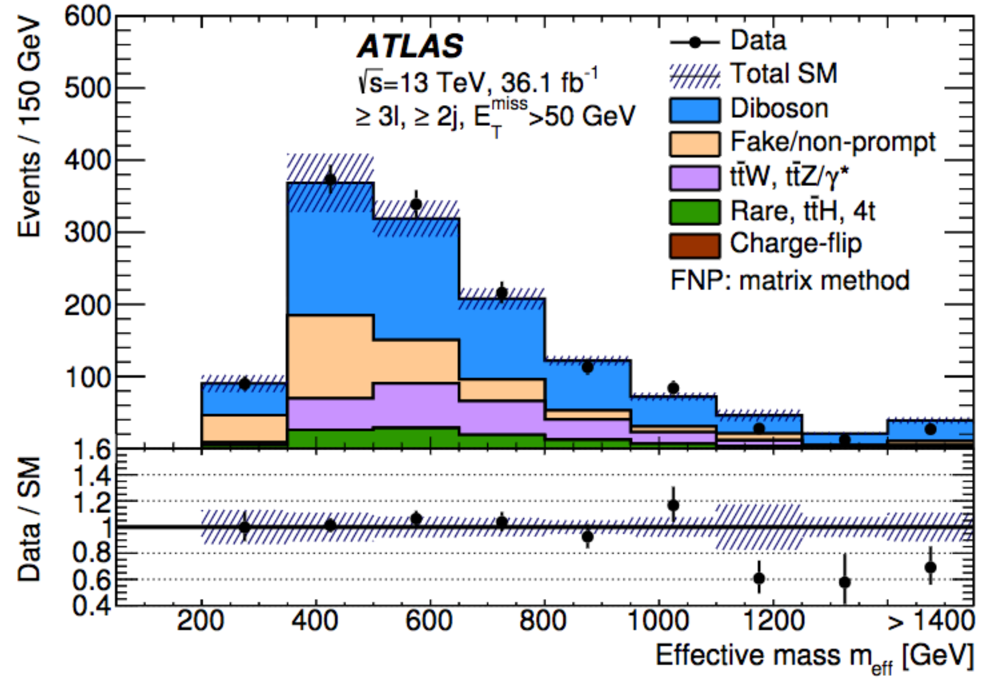




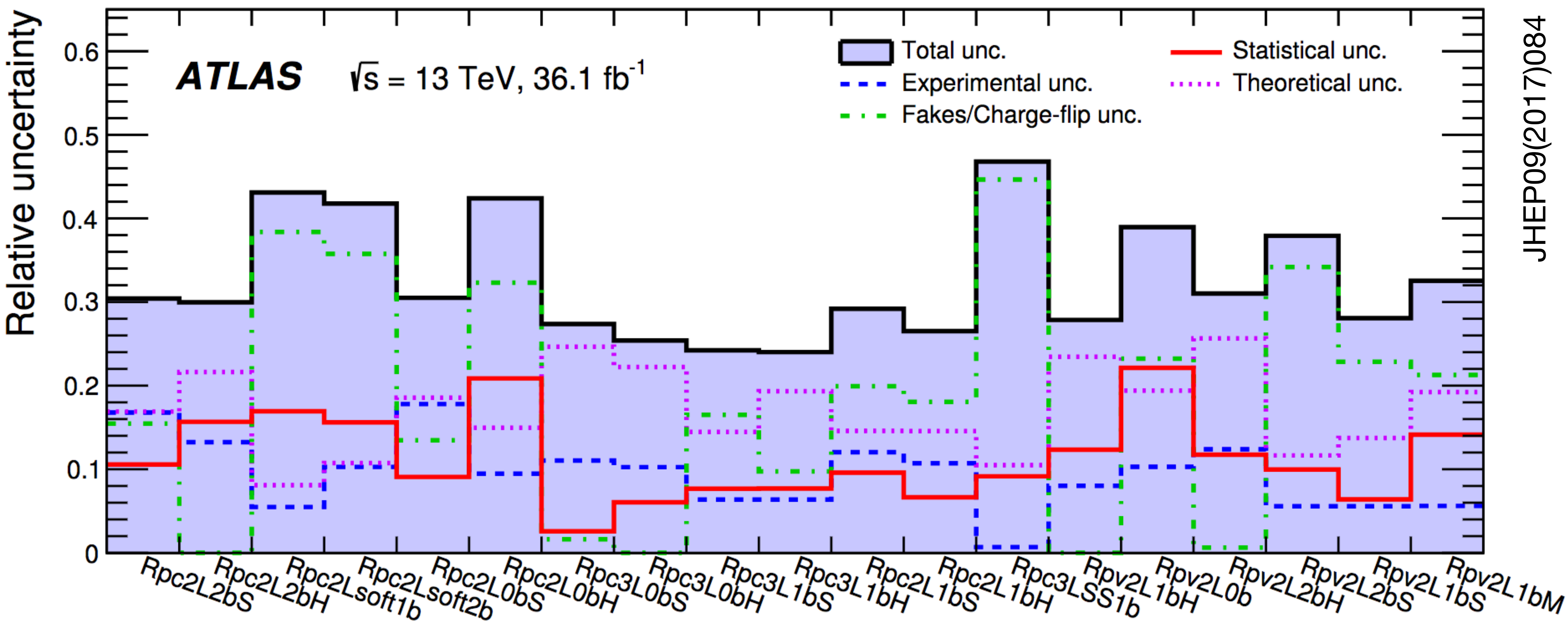
Checking the Data/MC agreement at pre-selection level to validate the total background estimation

Dedicated validation regions are defined to verify the estimate of the ttV,WZ and WW background in the signal regions.

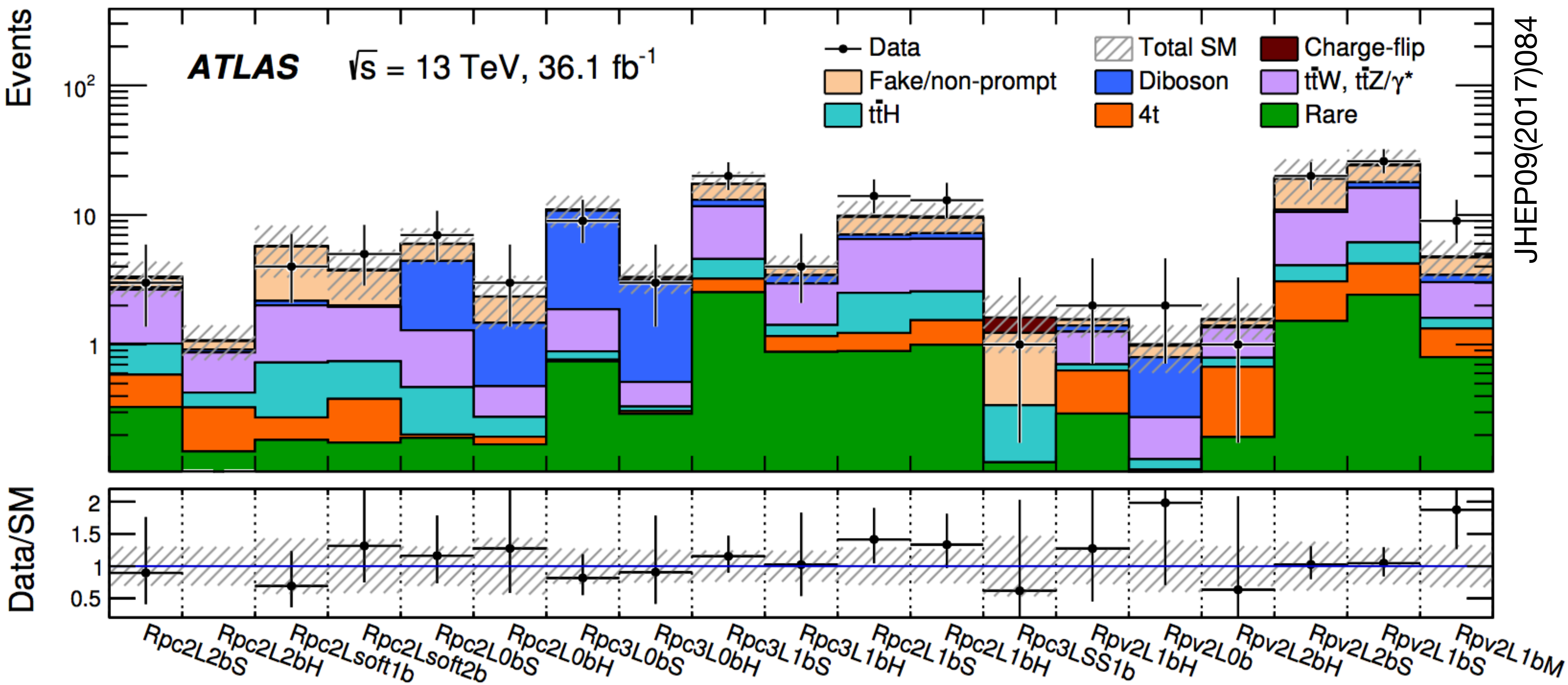
Validation Region	$t\bar{t}W$	$t\bar{t}Z$	WZ4j	WZ5j	$W^\pm W^\pm jj$
$t\bar{t}Z/\gamma^*$	6.2 ± 0.9	123 ± 17	17.8 ± 3.5	10.1 ± 2.3	1.06 ± 0.22
$t\bar{t}W$	19.0 ± 2.9	1.71 ± 0.27	1.30 ± 0.32	0.45 ± 0.14	4.1 ± 0.8
$t\bar{t}H$	5.8 ± 1.2	3.6 ± 1.8	1.8 ± 0.6	0.96 ± 0.34	0.69 ± 0.14
$4t$	1.02 ± 0.22	0.27 ± 0.14	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02
$W^\pm W^\pm$	0.5 ± 0.4	—	—	—	26 ± 14
WZ	1.4 ± 0.8	29 ± 17	200 ± 110	70 ± 40	27 ± 14
ZZ	0.04 ± 0.03	5.5 ± 3.1	22 ± 12	9 ± 5	0.53 ± 0.30
Rare	2.2 ± 0.5	26 ± 13	7.3 ± 2.1	3.0 ± 1.0	1.8 ± 0.5
Fake/non-prompt leptons	18 ± 16	22 ± 14	49 ± 31	17 ± 12	13 ± 10
Charge-flip electrons	3.4 ± 0.5	—	—	—	1.74 ± 0.22
Total SM background	57 ± 16	212 ± 35	300 ± 130	110 ± 50	77 ± 31
Observed	71	209	257	106	99

Systematic sources

Total uncertainty ~30% in the SRs, dominated by fake-lepton uncertainties in low m_{eff} regions and theory uncertainties in the high m_{eff} SRs:

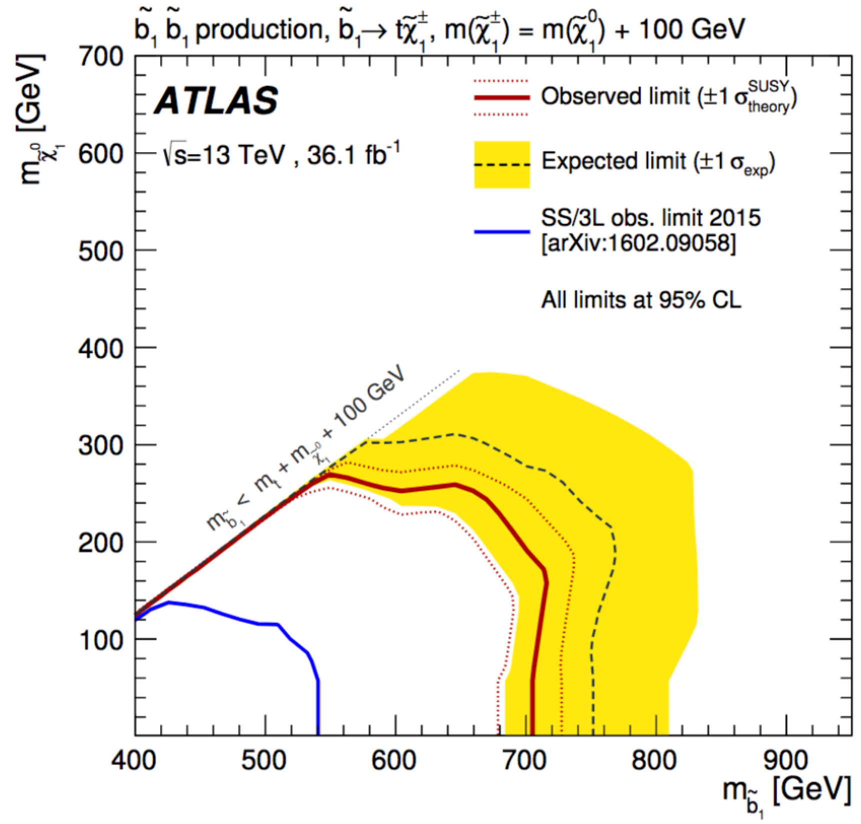


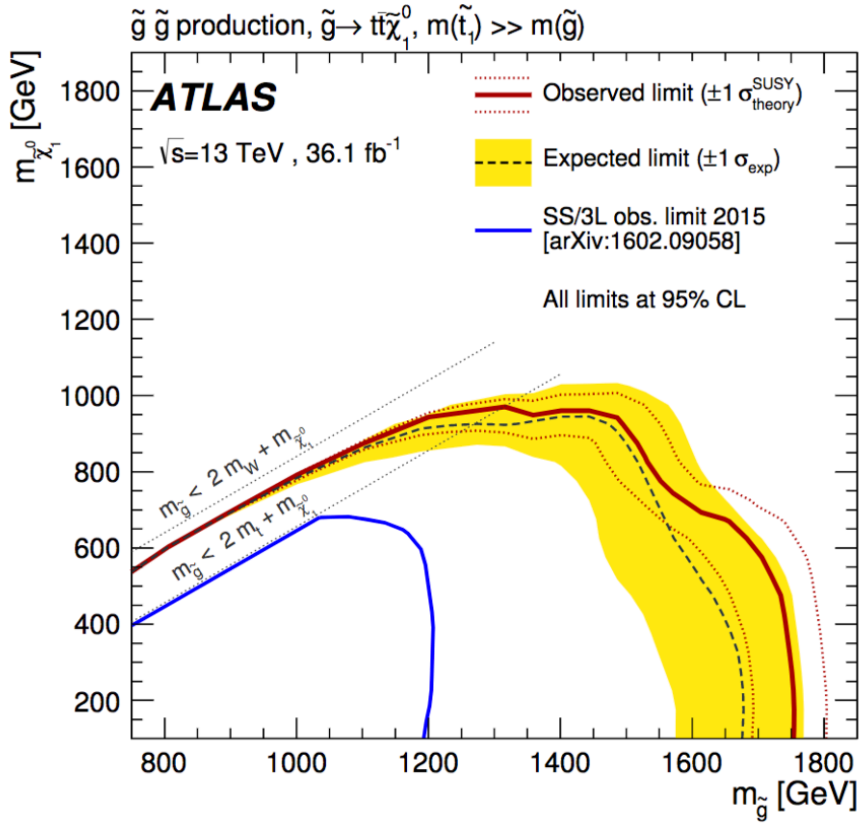
Data in Signal Regions



No significant excess observed in data

Exclusion plots





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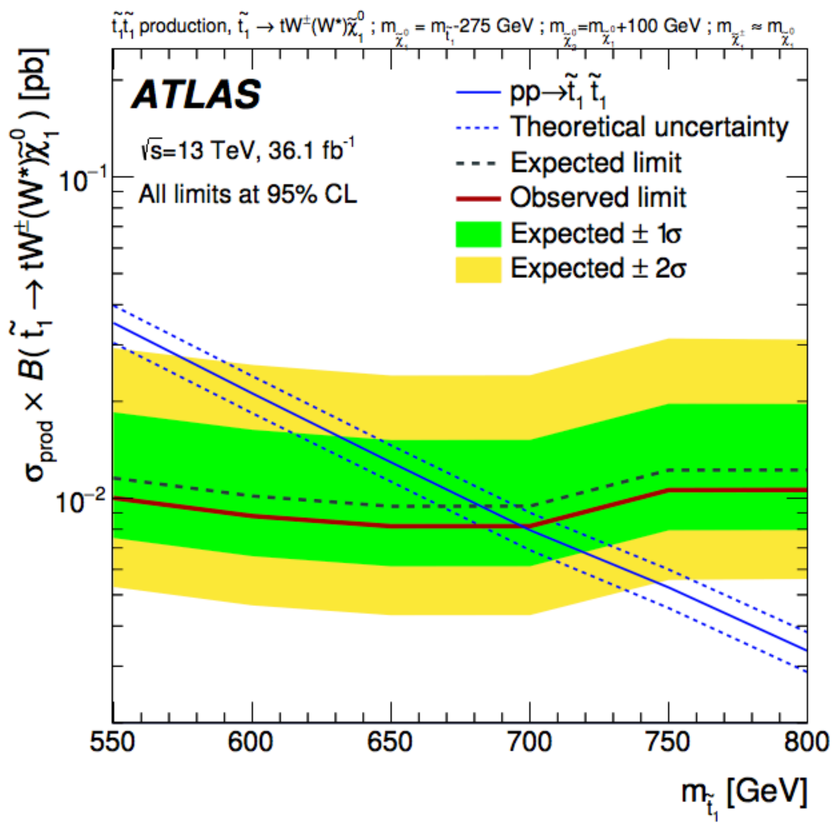

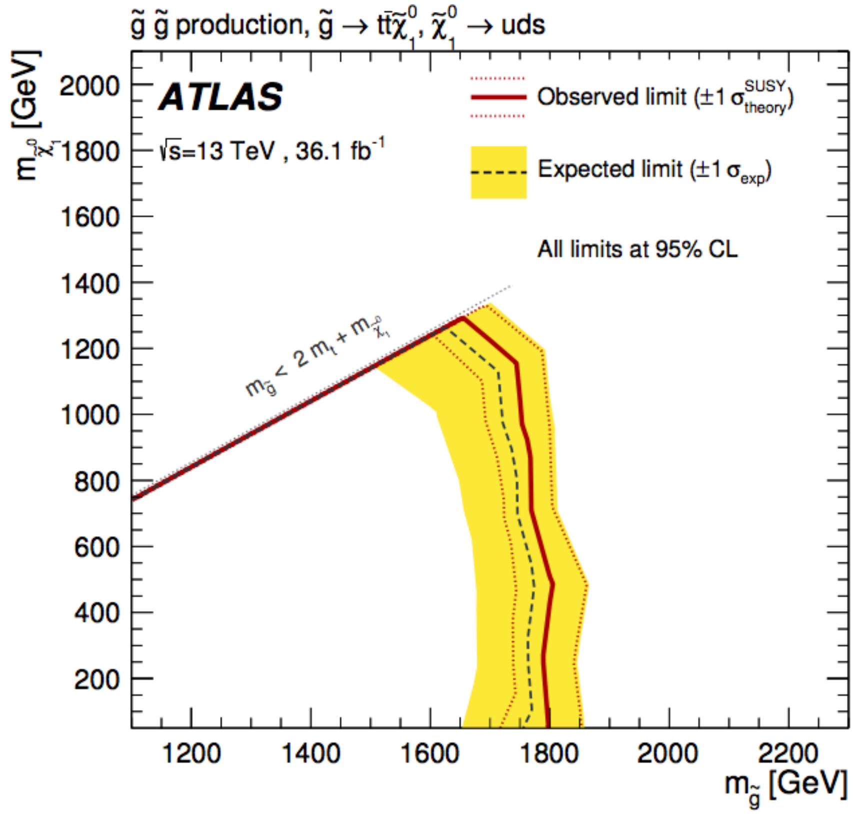

Conclusions

- **Search** for SUSY in final states with same-sign leptons, L = 36 fb^{-1} at 13TeV
  → interesting signature with low SM background, great sensitivity to new physics!
- **No evidence** of BSM processes;
- **Exclusion limits** set on various natural SUSY scenarios:
  - gluino production in RPC models are excluded up to 1.87 TeV for a light LSP mass;
  - sbottom production excluded up to 700 GeV in models with $\tilde{b}_1 \to tW^- \tilde{\chi}_1^0$
  - in RPV scenarios, down squark-right probed up to 500 GeV;
  - All RPV models with gluing below 1.3 TeV are excluded;

- **New analysis starting: the goal is a paper for Moriond 2019 with full Run-2 luminosity!**

BACKUP

Validation Regions

Validation Region	$N_{\text{leptons}}^{\text{signal}}$	$N_{b\text{-jets}}$	N_{jets}	$p_{\text{T}}^{\text{jet}}$ [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	m_{eff} [GeV]	Other
$t\bar{t}W$	$= 2SS$	≥ 1	≥ 4 $(e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm})$ ≥ 3 $(\mu^{\pm}\mu^{\pm})$	> 40 > 25	> 45	> 550	$p_{\text{T}}^{\ell_2} > 40\,\text{GeV}$ $\sum p_{\text{T}}^{b\text{-jet}} / \sum p_{\text{T}}^{\text{jet}} > 0.25$
$t\bar{t}Z$	≥ 3 ≥ 1 SFOS pair	≥ 1	≥ 3	> 35	—	> 450	$81 < m_{\text{SFOS}} < 101\,\text{GeV}$
$WZ4$j	$= 3$	$= 0$	≥ 4	> 25	—	> 450	$E_{\text{T}}^{\text{miss}} / \sum p_{\text{T}}^{\ell} < 0.7$
$WZ5$j	$= 3$	$= 0$	≥ 5	> 25	—	> 450	$E_{\text{T}}^{\text{miss}} / \sum p_{\text{T}}^{\ell} < 0.7$
$W^{\pm}W^{\pm}jj$	$= 2SS$	$= 0$	≥ 2	> 50	> 55	> 650	veto $81 < m_{e^{\pm}e^{\pm}} < 101\,\text{GeV}$ $p_{\text{T}}^{\ell_2} > 30\,\text{GeV}$ $\Delta R_{\eta}(\ell_{1,2}, j) > 0.7$ $\Delta R_{\eta}(\ell_1, \ell_2) > 1.3$
All VRs	Veto events belonging to any SR						

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MC Template Method

Control regions (low ETmiss, meff and jet multiplicity) are used to rescale MC samples with "fake" leptons in order to match with data and then extrapolate the background in the SR.

1. Six non overlapping CR are defined:

- **CR0b**: events without b-jets where leptons are ee,eμ,$\mu\mu$;
- **CR1b**: events with at least one b-jet where the leptons are ee,eμ,$\mu\mu$;

2. Events (2SS leptons or more with ETmiss>25GeV) are categorised depending on the source:

- **prompt isolated leptons**;
- **charge flip electrons**;
- **"fake" leptons**; →
  - **EL HF**: electron fake coming from b-hadron decays;
  - **MU HF**: muon fake coming from b-hadron decays;
  - **EL LF**: electron fake coming from light-hadron decays;
  - **MU LF**: muon fake coming from light-hadron decays;

3. Fit with a likelihood function defined as a Poissonian distribution times the 5 correction factors (free parameters), these are the applied to the MC predictions in the SR.

Yields in SR

Signal Region	Rpc2L2bS	Rpc2L2bH	Rpc2Lsoft1b	Rpc2Lsoft2b	Rpc2L0bS	Rpc2L0bH
$t\bar{t}W$, $t\bar{t}Z\gamma^*$	1.6 ± 0.4	0.44 ± 0.14	1.3 ± 0.4	1.21 ± 0.33	0.82 ± 0.31	0.20 ± 0.10
$t\bar{t}H$	0.43 ± 0.25	0.10 ± 0.06	0.45 ± 0.24	0.36 ± 0.21	0.27 ± 0.15	0.08 ± 0.07
$4t$	0.26 ± 0.13	0.18 ± 0.09	0.09 ± 0.05	0.21 ± 0.11	0.01 ± 0.01	0.02 ± 0.02
Diboson	0.10 ± 0.10	0.04 ± 0.02	0.17 ± 0.09	0.05 ± 0.03	3.1 ± 1.4	1.0 ± 0.5
Rare	0.33 ± 0.18	0.15 ± 0.09	0.18 ± 0.10	0.17 ± 0.10	0.19 ± 0.11	0.17 ± 0.10
Fake/non-prompt leptons	0.5 ± 0.6	0.15 ± 0.15	3.5 ± 2.4	1.7 ± 1.5	1.6 ± 1.0	0.9 ± 0.9
Charge-flip electrons	0.10 ± 0.01	0.02 ± 0.01	0.08 ± 0.02	0.08 ± 0.02	0.05 ± 0.01	0.01 ± 0.01
Total Background	3.3 ± 1.0	1.08 ± 0.32	5.8 ± 2.5	3.8 ± 1.6	6.0 ± 1.8	2.4 ± 1.0
Observed	3	0	4	5	7	3
S^{95}_{obs}	5.5	3.6	6.3	7.7	8.3	6.1
S^{95}_{exp}	$5.6^{+2.2}_{-1.5}$	$3.9^{+1.4}_{-0.4}$	$7.1^{+2.5}_{-1.5}$	$6.2^{+2.6}_{-1.5}$	$7.5^{+2.6}_{-1.8}$	$5.3^{+2.1}_{-1.3}$
σ_{vis} [fb]	0.15	0.10	0.17	0.21	0.23	0.17
p_0 (Z)	0.71 (–)	0.91 (–)	0.69 (–)	0.30 (0.5σ)	0.36 (0.4σ)	0.35 (0.4σ)

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Yields in SR

Signal Region	**Rpc3L0bS**	**Rpc3L0bH**	**Rpc3L1bS**	**Rpc3L1bH**	**Rpc2L1bS**	**Rpc2L1bH**	**Rpc3LSS1b**
$t\bar{t}W$, $t\bar{t}Z\gamma^*$	0.98 ± 0.25	0.18 ± 0.08	7.1 ± 1.1	1.54 ± 0.28	4.0 ± 1.0	4.0 ± 0.9	—
$t\bar{t}H$	0.12 ± 0.08	0.03 ± 0.02	1.4 ± 0.7	0.25 ± 0.14	1.3 ± 0.7	1.0 ± 0.6	0.22 ± 0.12
$4t$	0.02 ± 0.01	0.01 ± 0.01	0.7 ± 0.4	0.28 ± 0.15	0.34 ± 0.17	0.54 ± 0.28	—
Diboson	8.9 ± 2.9	2.6 ± 0.8	1.4 ± 0.5	0.48 ± 0.17	0.5 ± 0.3	0.7 ± 0.3	—
Rare	0.7 ± 0.4	0.29 ± 0.16	2.5 ± 1.3	0.9 ± 0.5	0.9 ± 0.5	1.0 ± 0.6	0.12 ± 0.07
Fake/non-prompt leptons	0.23 ± 0.23	0.15 ± 0.15	4.2 ± 3.1	0.5 ± 0.5	2.5 ± 2.2	2.3 ± 1.9	0.9 ± 0.7
Charge-flip electrons	—	—	—	—	0.25 ± 0.04	0.25 ± 0.05	0.39 ± 0.08
Total Background	11.0 ± 3.0	3.3 ± 0.8	17 ± 4	3.9 ± 0.9	9.8 ± 2.9	9.8 ± 2.6	1.6 ± 0.8
Observed	9	3	20	4	14	13	1
S^{95}_{obs}	8.3	5.4	14.7	6.1	13.7	12.4	3.9
S^{95}_{exp}	$9.3^{+3.1}_{-2.3}$	$5.5^{+2.2}_{-1.5}$	$12.6^{+5.1}_{-3.4}$	$5.9^{+2.2}_{-1.8}$	$10.0^{+3.7}_{-2.6}$	$9.7^{+3.4}_{-2.6}$	$4.0^{+1.8}_{-0.3}$
σ_{vis} [fb]	0.23	0.15	0.41	0.17	0.38	0.34	0.11
p_0 (Z)	0.72 (–)	0.85 (–)	0.32 (0.5σ)	0.46 (0.1σ)	0.17 (1.0σ)	0.21 (0.8σ)	0.56 (–)

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Yields in SR

Signal Region	Rpv2L1bH	Rpv2L0b	Rpv2L2bH	Rpv2L2bS	Rpv2L1bS	Rpv2L1bM
$t\bar{t}W$, $t\bar{t}Z\gamma^*$	0.56 ± 0.14	0.14 ± 0.08	0.56 ± 0.15	6.5 ± 1.3	10.1 ± 1.7	1.4 ± 0.5
$t\bar{t}H$	0.07 ± 0.05	0.02 ± 0.02	0.12 ± 0.07	1.0 ± 0.5	1.9 ± 1.0	0.28 ± 0.15
$4t$	0.34 ± 0.17	0.01 ± 0.01	0.48 ± 0.24	1.6 ± 0.8	1.8 ± 0.9	0.53 ± 0.27
Diboson	0.14 ± 0.06	0.52 ± 0.21	0.04 ± 0.02	0.42 ± 0.16	1.7 ± 0.6	0.42 ± 0.15
Rare	0.29 ± 0.17	0.10 ± 0.06	0.19 ± 0.13	1.5 ± 0.8	2.4 ± 1.2	0.8 ± 0.4
Fake/non-prompt leptons	0.15 ± 0.15	0.18 ± 0.31	0.15 ± 0.15	8 ± 7	6 ± 6	1.3 ± 1.2
Charge-flip electrons	0.02 ± 0.01	0.03 ± 0.02	0.03 ± 0.01	0.46 ± 0.08	0.74 ± 0.12	0.10 ± 0.02
Total Background	1.6 ± 0.4	1.0 ± 0.4	1.6 ± 0.5	19 ± 7	25 ± 7	4.8 ± 1.6
Observed	2	2	1	20	26	9
S^{95}_{obs}	4.8	5.2	3.9	17.5	18.1	11.4
S^{95}_{exp}	$4.1^{+1.9}_{-0.4}$	$4.0^{+1.7}_{-0.3}$	$4.1^{+1.8}_{-0.4}$	$16.8^{+5.2}_{-4.2}$	$17.2^{+5.9}_{-4.2}$	$7.3^{+2.5}_{-1.8}$
σ_{vis} [fb]	0.13	0.14	0.11	0.48	0.50	0.31
p_0 (Z)	0.33 (0.4σ)	0.19 (0.9σ)	0.55 (–)	0.48 (0.1σ)	0.44 (0.2σ)	0.07 (1.5σ)

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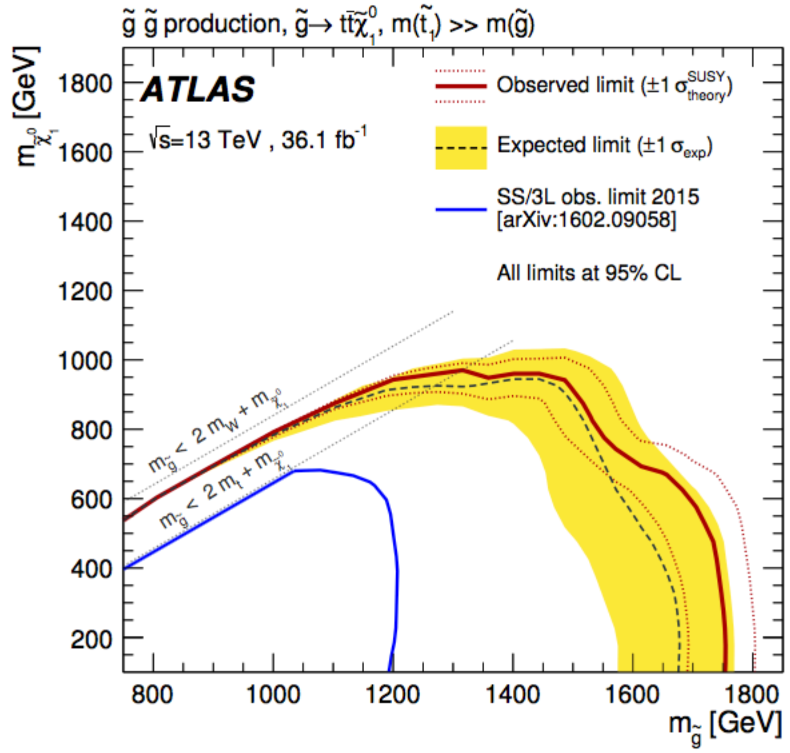
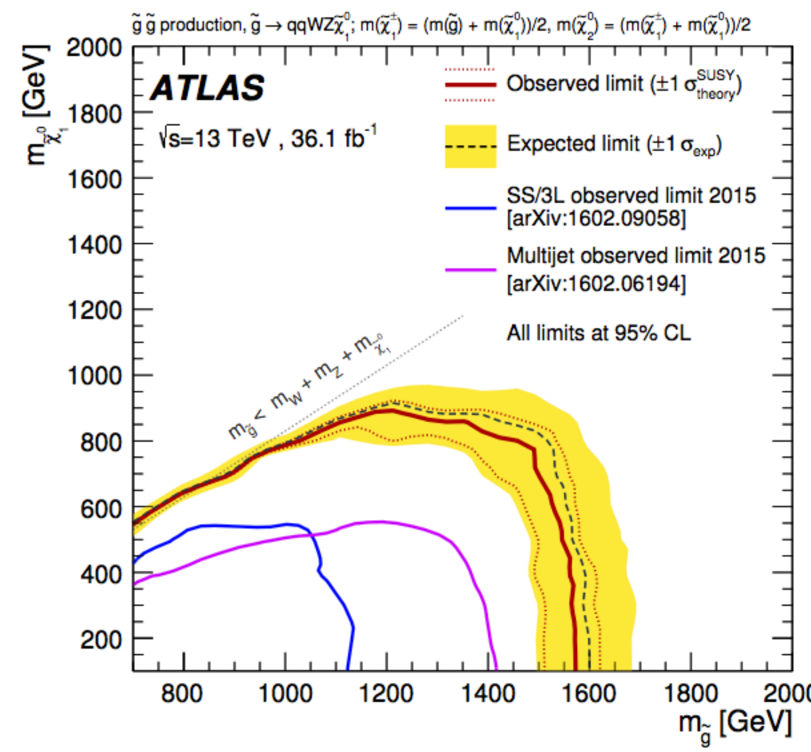
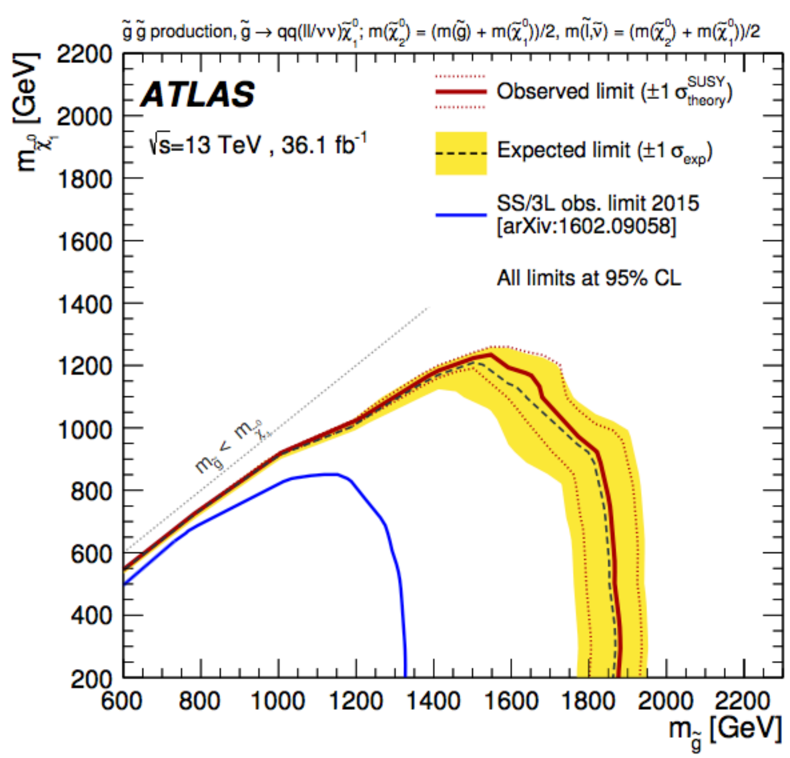


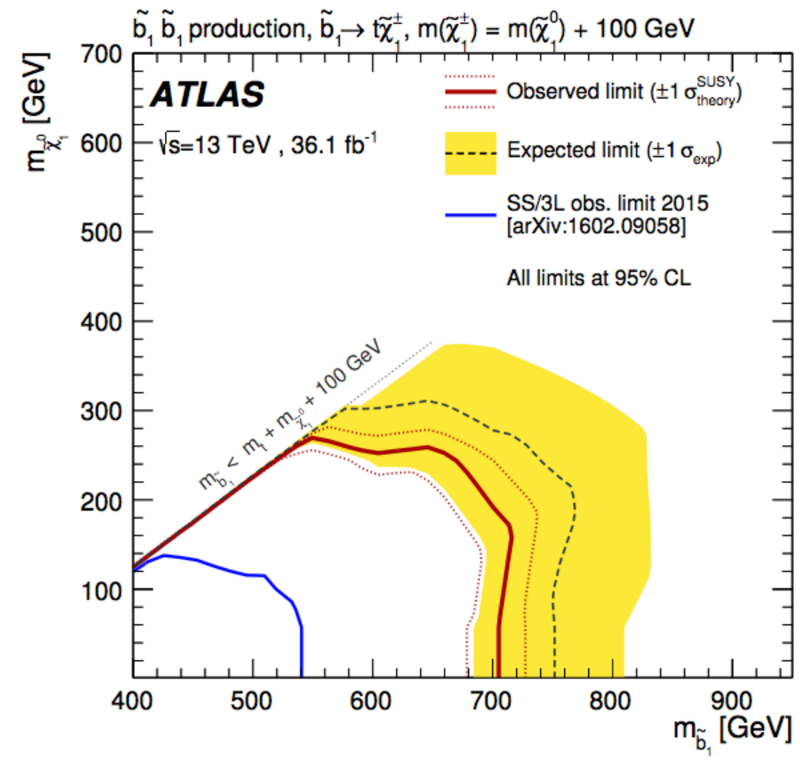
(a) Rpc2L2bS/H, Rpc2Lsoft1b/2b



(b) Rpc2L0bS, Rpc2L0bH



(c) Rpc3L0bS, Rpc3L0bH



(d) Rpc2L1bS, Rpc2L1bH

Exclusion plots

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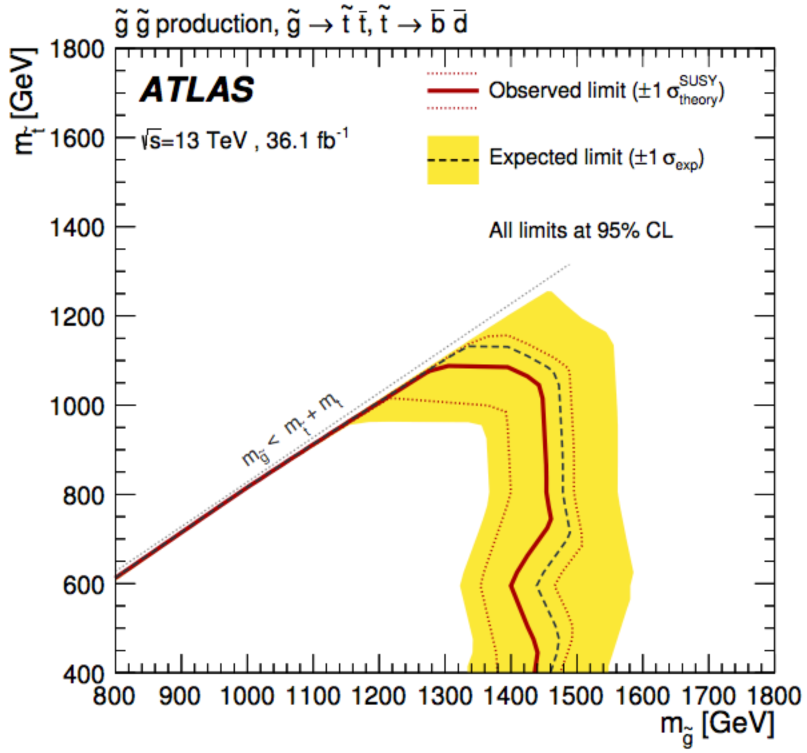
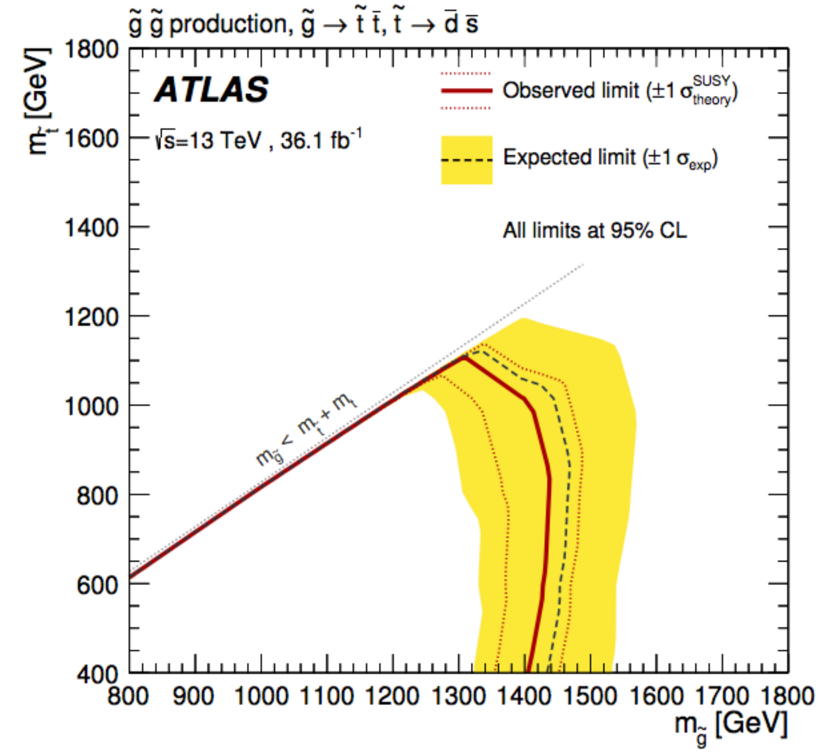
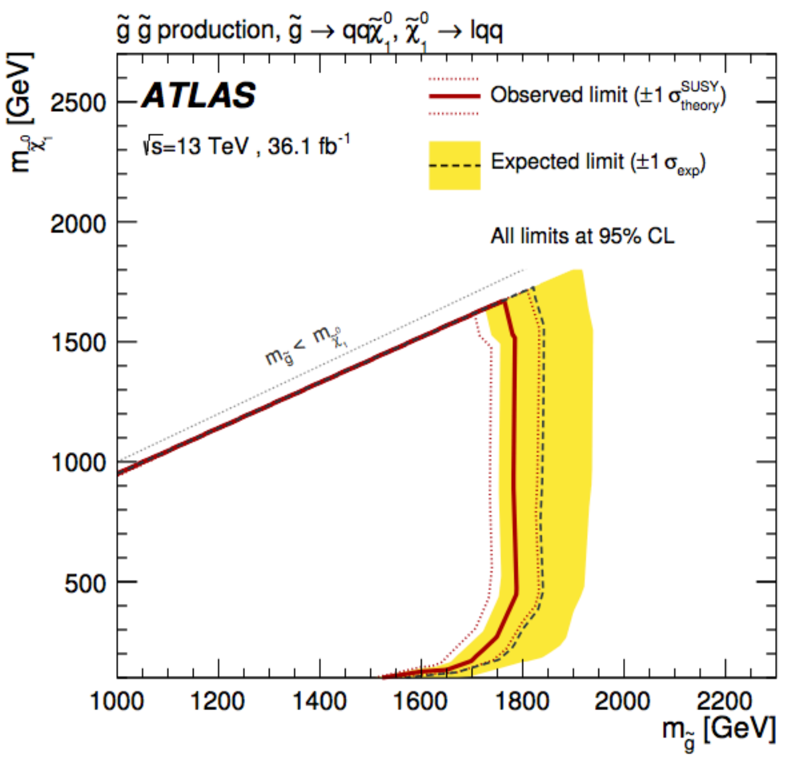


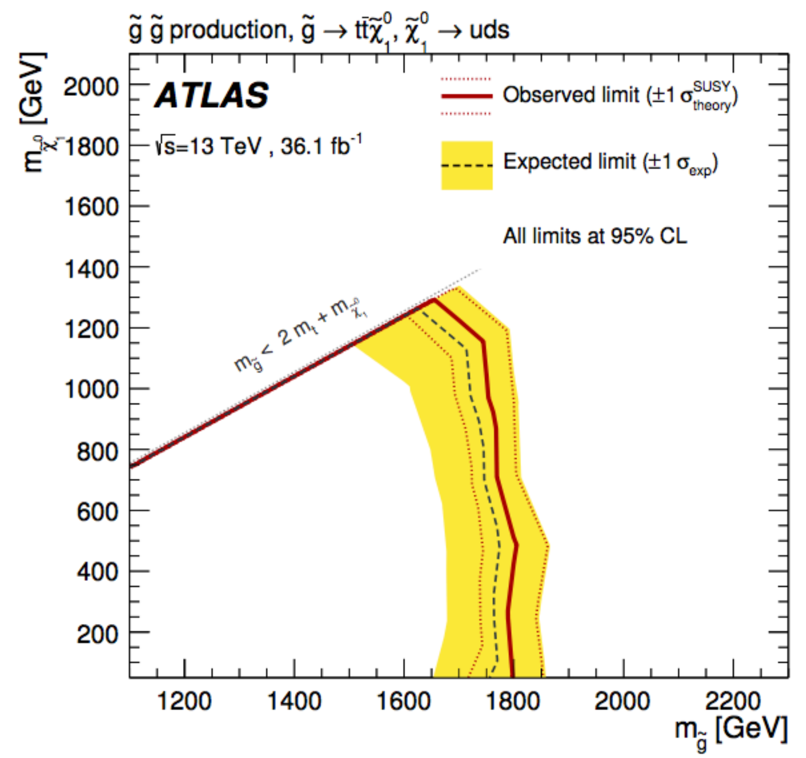
(a) Rpv2L1bH



(b) Rpv2L1bH



(c) Rpv2L0b



(d) Rpv2L2bH

Exclusion plots

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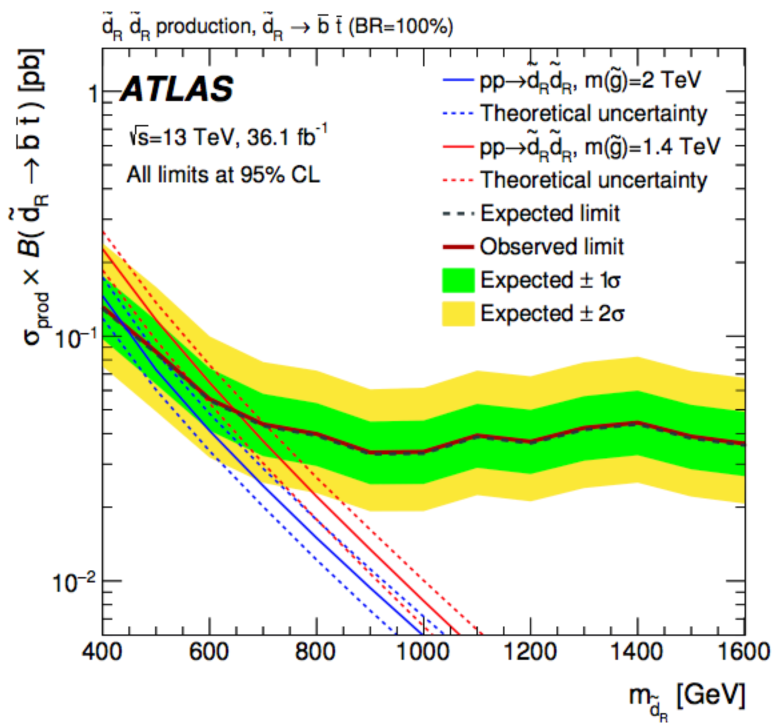
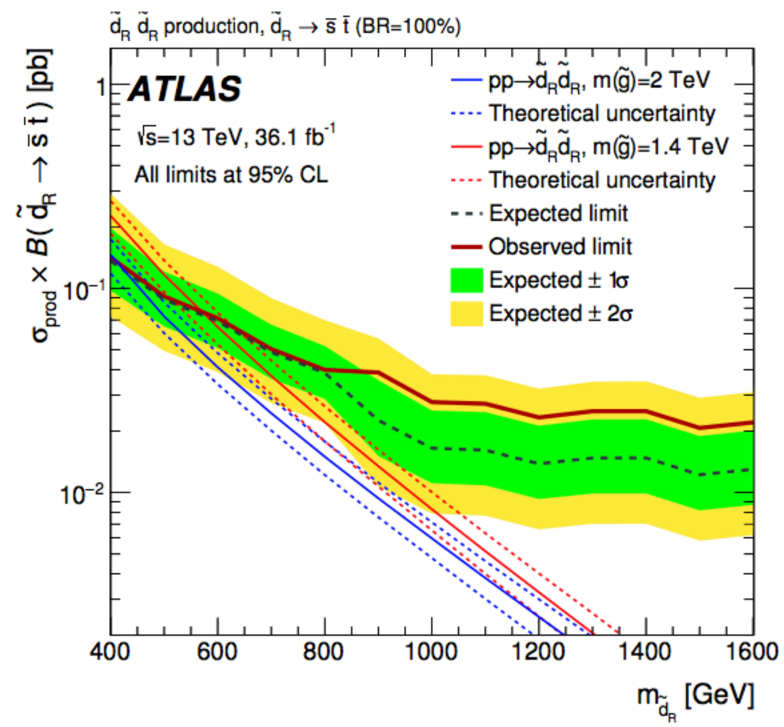
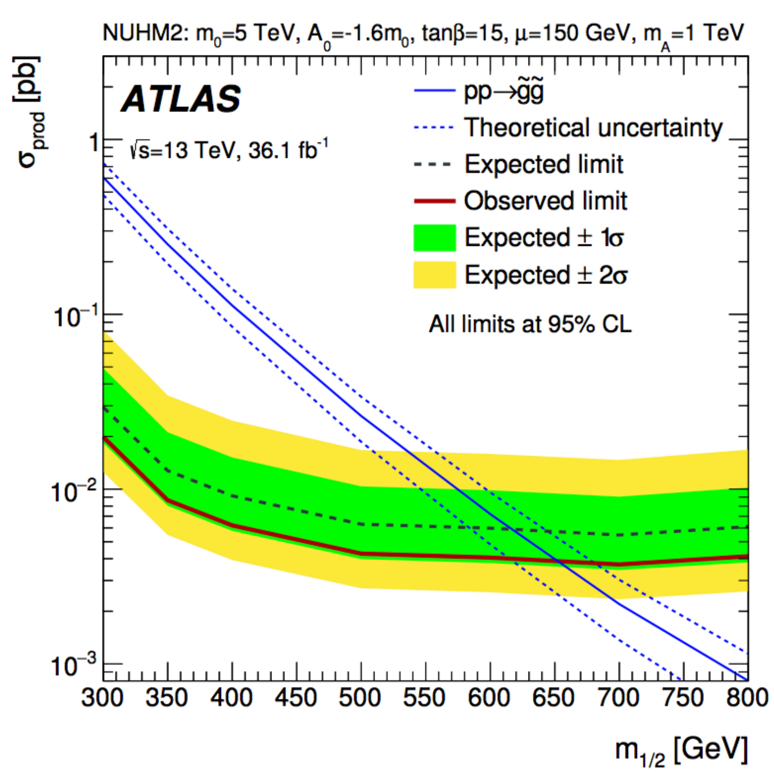
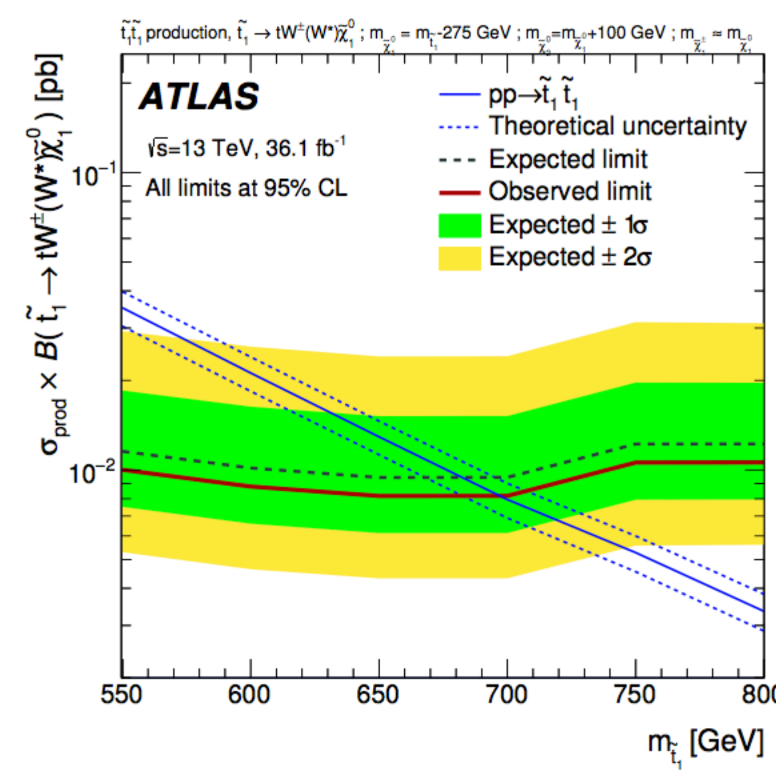


(e) Rpv2L2bS



(f) Rpv2L1bS, Rpv2L1bM





(e) Rpc3LSS1b