Strong SUSY at ATLAS and CMS

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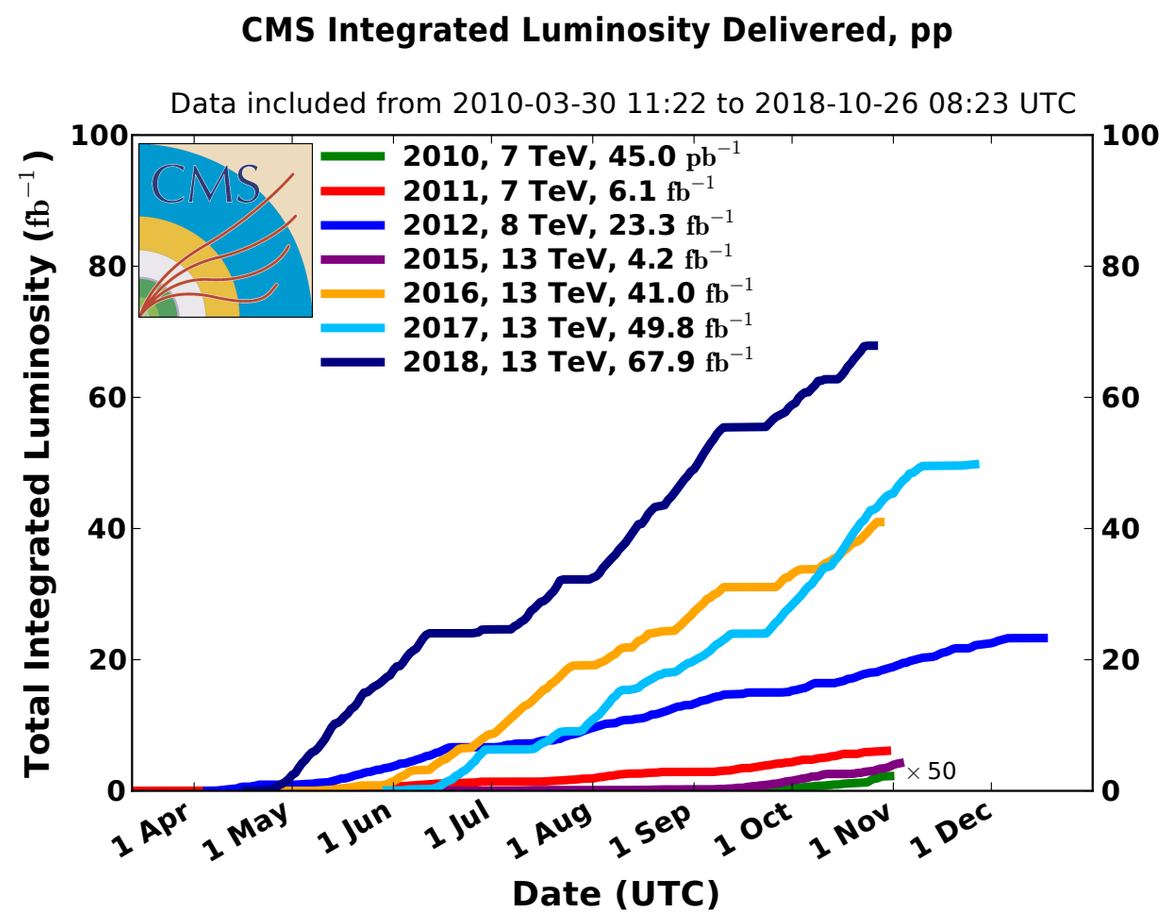
On behalf on the ATLAS and CMS Collaborations

Moriond QCD 2019

Introduction

- **LHC performed very well, delivering > 150 fb^{-1}**
- Huge challenge to quickly process this amount of data
  - Understand detector & object performance
  - p_T^{miss} tails very important for SUSY searches
- Most results on full Run 2 data set will come in Summer



- **SUSY searches are expanding**
  - Big inclusive searches complemented by dedicated searches to close gaps in coverage
  - Machine learning for H, b, c, top,… tagging
  - Improved analysis techniques

Overview of recent Strong SUSY results

- **ATLAS**
  - bjets+H+p_T^{miss} (139 fb^{-1}) — ATLAS-CONF-2019-011
  - Displaced vertex/muon (136 fb^{-1}) — ATLAS-CONF-2019-006 → K. Pedro
  - Stop via $t\bar{t}$ spin correlations (36 fb^{-1}) — arxiv.org:1903.07570 → R. Schoefbeck
  - ≥3b+p_T^{miss} (80 fb^{-1}) — ATLAS-CONF-2018-041
  - Stop with c tagging (36 fb^{-1}) — arxiv:1805.01649
  - τ_h+jets+p_T^{miss} (36 fb^{-1}) — arxiv:1808.06358
- **CMS**
  - Jets + M_{T2} (137 fb^{-1}) — CMS-PAS-SUS-19-005
  - Same-sign 2l + ≥3l (137 fb^{-1}) — CMS-PAS-SUS-19-008
  - GGM combination (36 fb^{-1}) — CMS-PAS-SUS-18-005
  - 2 photons + p_T^{miss} (36 fb^{-1}) — arxiv:1903.07070
  - (b)jets + photon (36 fb^{-1}) — arxiv:1901.06726 → S. Beauceron
  - Stop in top corridor (36 fb^{-1}) — arxiv:1901.01288
- ATLAS public results page: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
- CMS public results page: http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/index.html

137 fb^{-1}

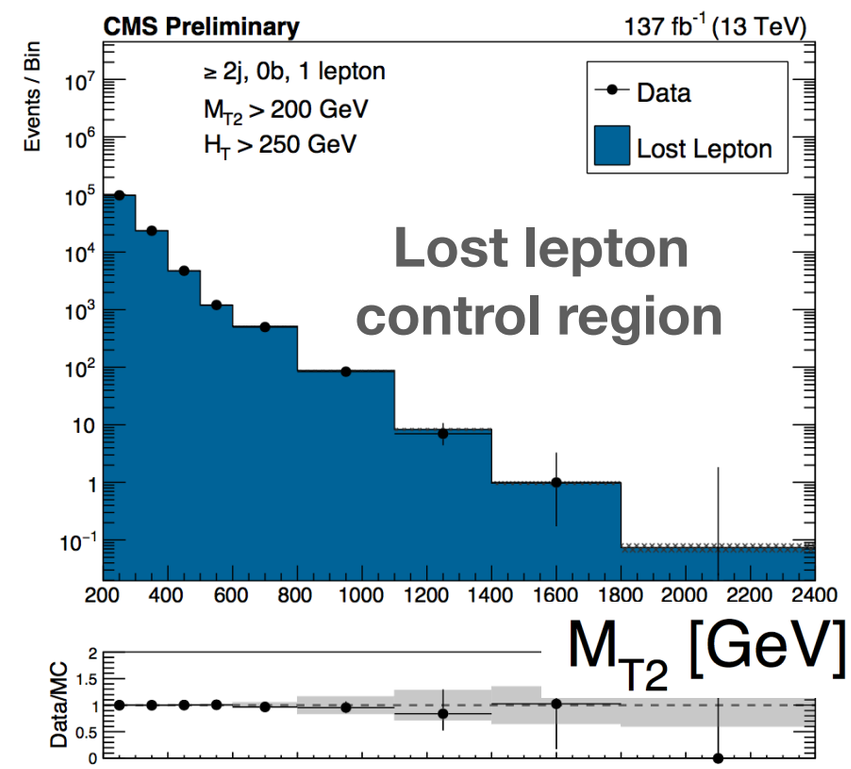
NEW

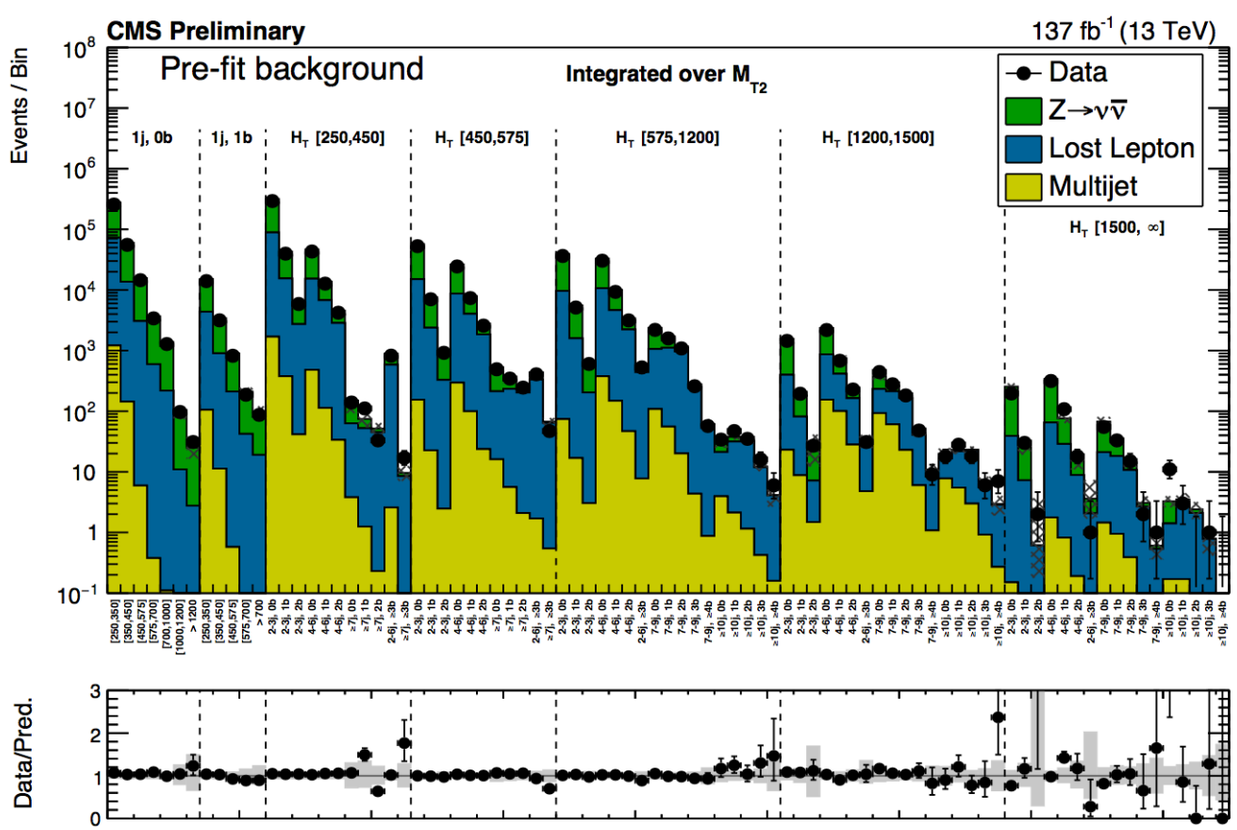
SUS-19-005

Jets + M_{T2}

- **Inclusive search targeting wide range of strong SUSY models**
- 282 signal regions defined using H_T, N_j, N_b, M_{T2}
- Backgrounds estimated using data control regions
  - Lost lepton: p_T^{miss} from $W \rightarrow l\nu$
  - Irreducible, p_T^{miss} from $Z \rightarrow \nu\nu$
  - p_T^{miss} from jet mismeasurements

NEW disappearing track selection covered by K. Pedro





We observe no evidence for an excess above the expected background event yield

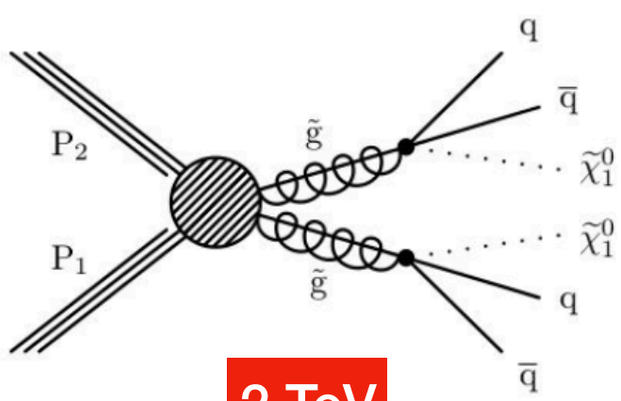
137 fb^{-1}

NEW

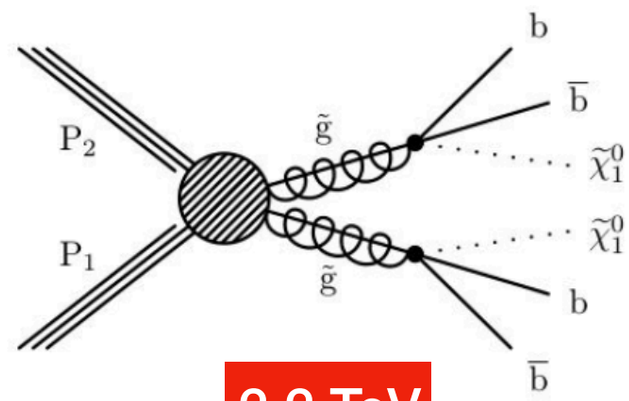
SUS-19-005

Jets + M_{T2}

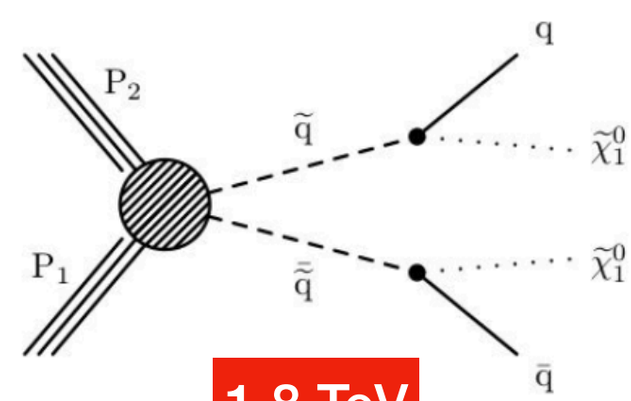
- Interpret using simplified models of squark and gluino production
- Extend reach by 150—350 GeV compared to 36 fb^{-1} results



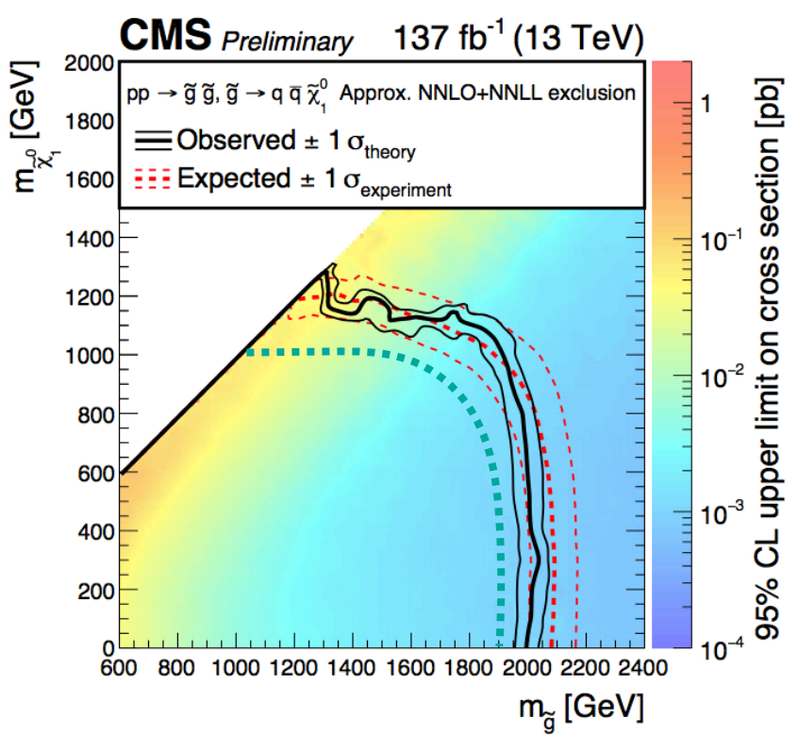
2 TeV

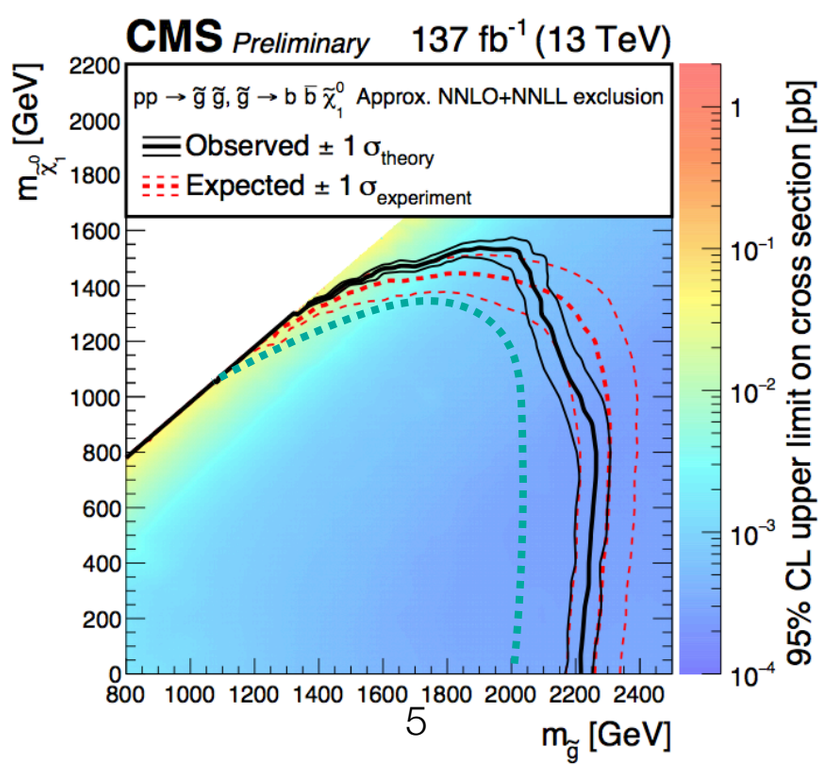


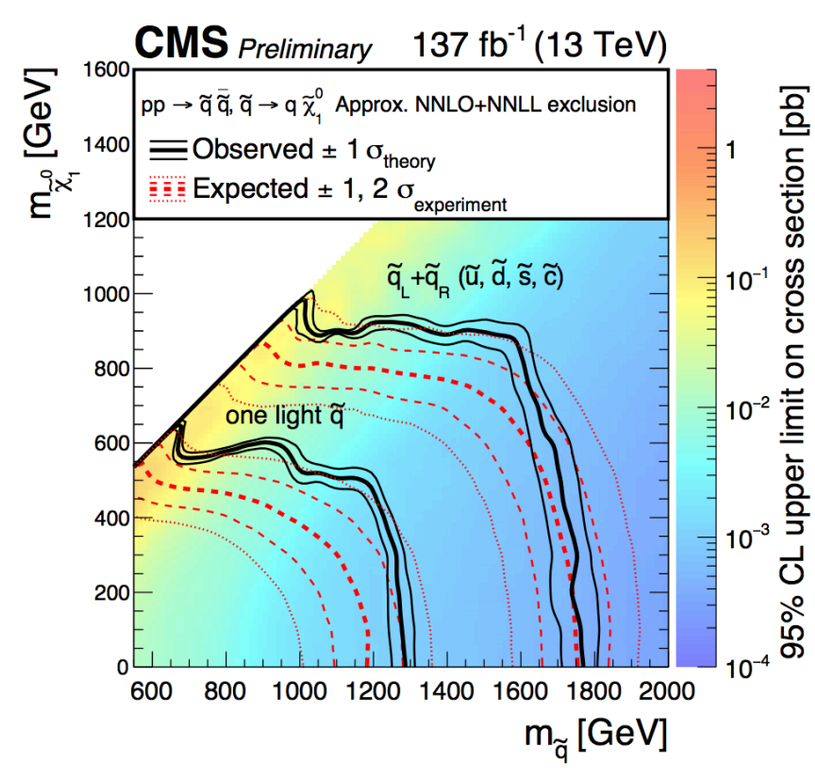
2.2 TeV



1.8 TeV







ATLAS EXPERIMENT

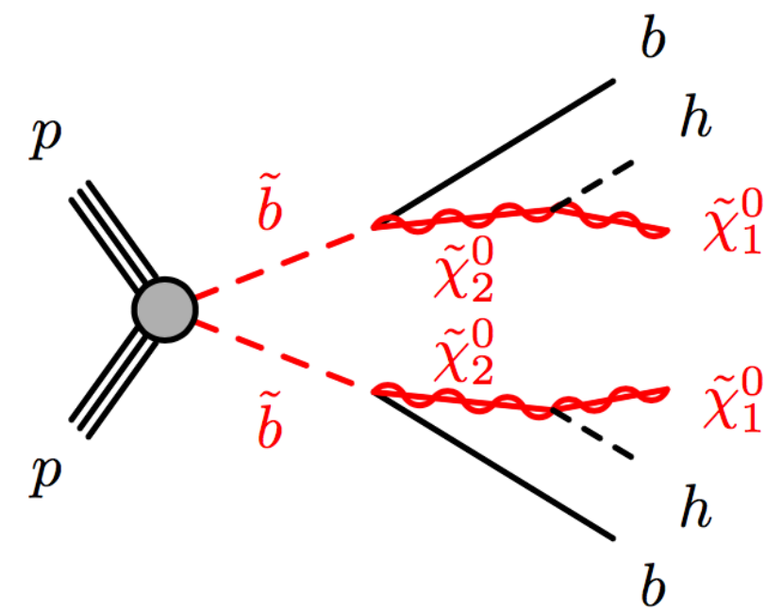
139 fb^{-1}

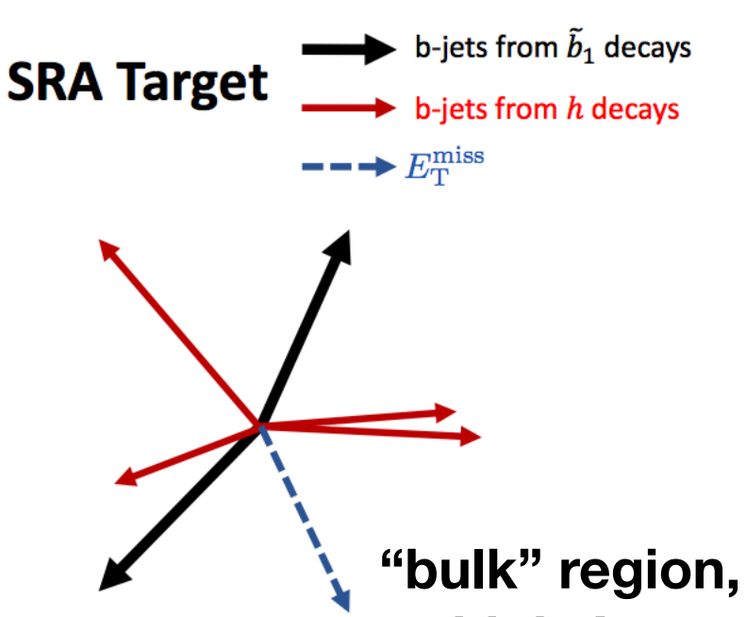
NEW

ATLAS-CONF-2019-011

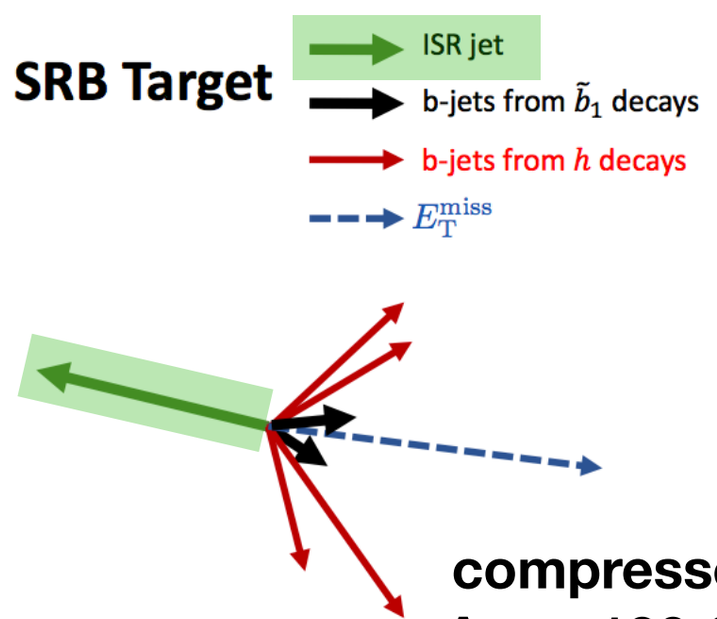
bjets + H + p_T^{miss}

- **Use Higgs boson as probe for new physics**
  - Exploit large branching fraction of $H \to b\bar{b}$
  - Use ΔR and invariant mass of Higgs candidates
- Search regions with **many b-jets and p_T^{miss}**
  - Optimized to target different regions of phase space, e.g. bulk vs compressed
- Main background is $t\bar{t}$ or Z+jets, estimated using 1- and 2-lepton data control regions

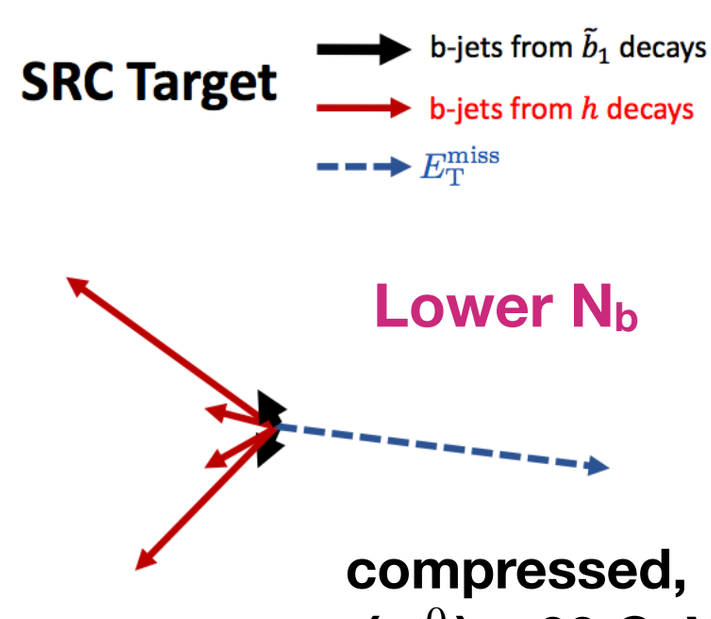




"bulk" region, high Δm



compressed, Δm = 130 GeV



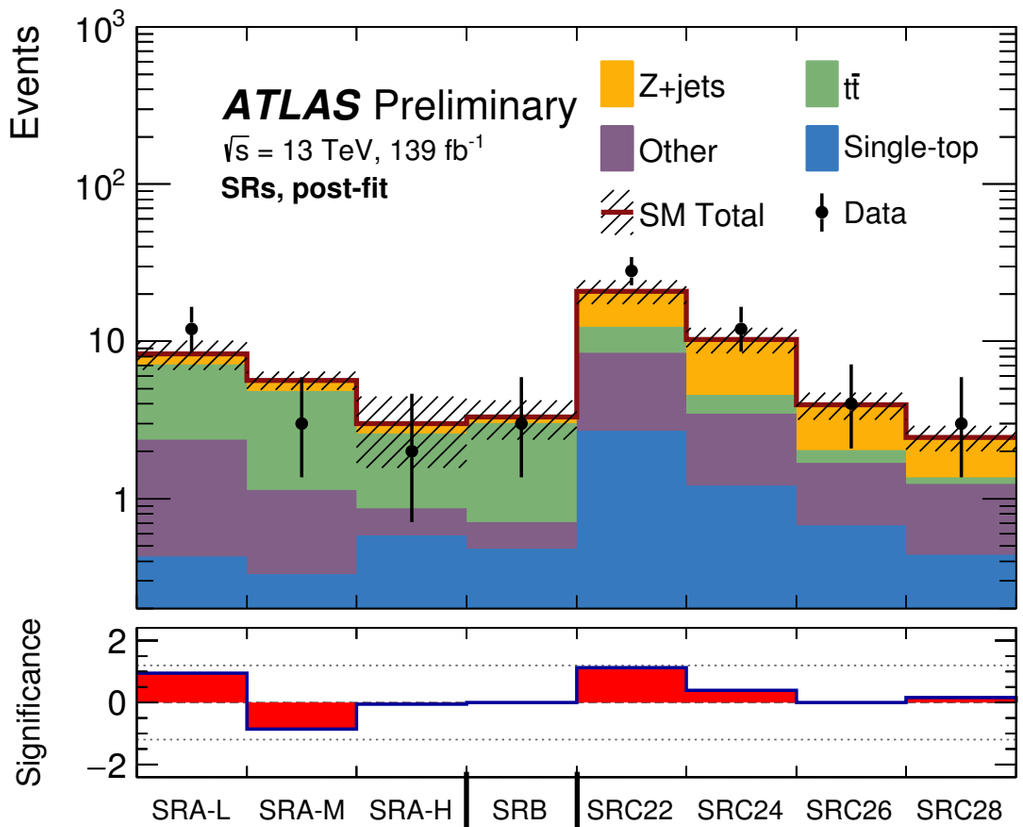
compressed, m($\tilde{\chi}_1^0$) = 60 GeV

NEW

ATLAS-CONF-2019-011

139 fb^{-1}

bjets + H + p_T^{miss}



"bulk" region, high Δm

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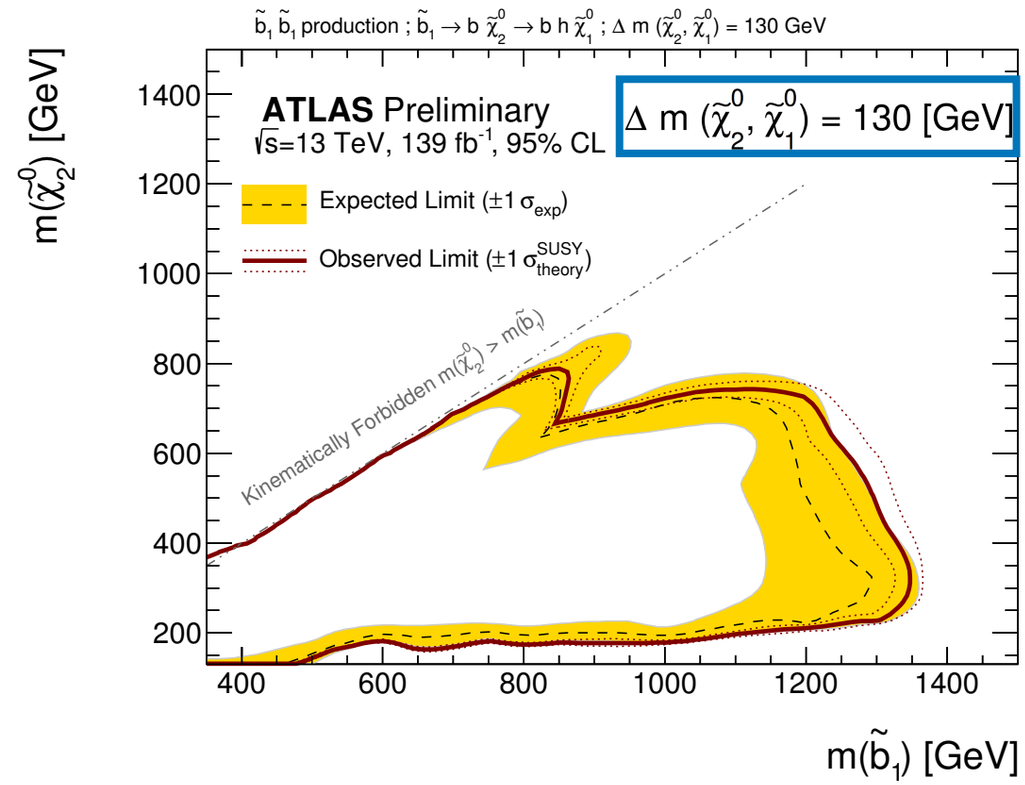
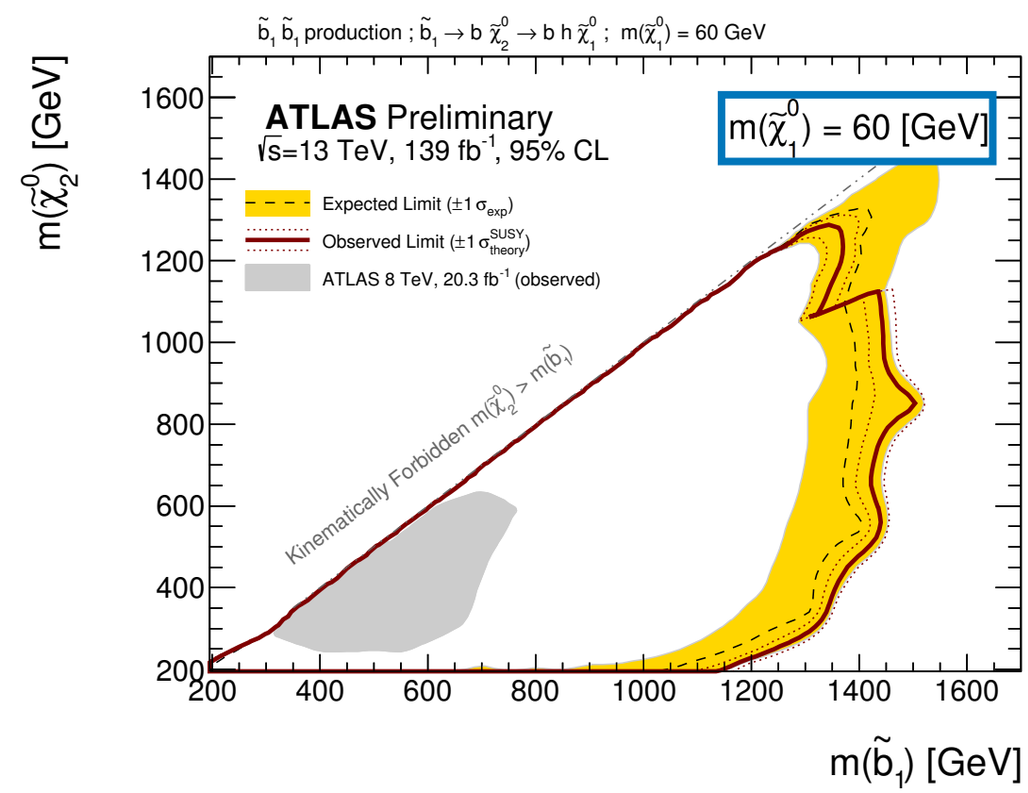




- Sbottom quarks excluded up to 1400 GeV for m($\tilde{\chi}_1^0$)=60GeV
- Sensitivity reduced when Higgs boson is just barely on shell

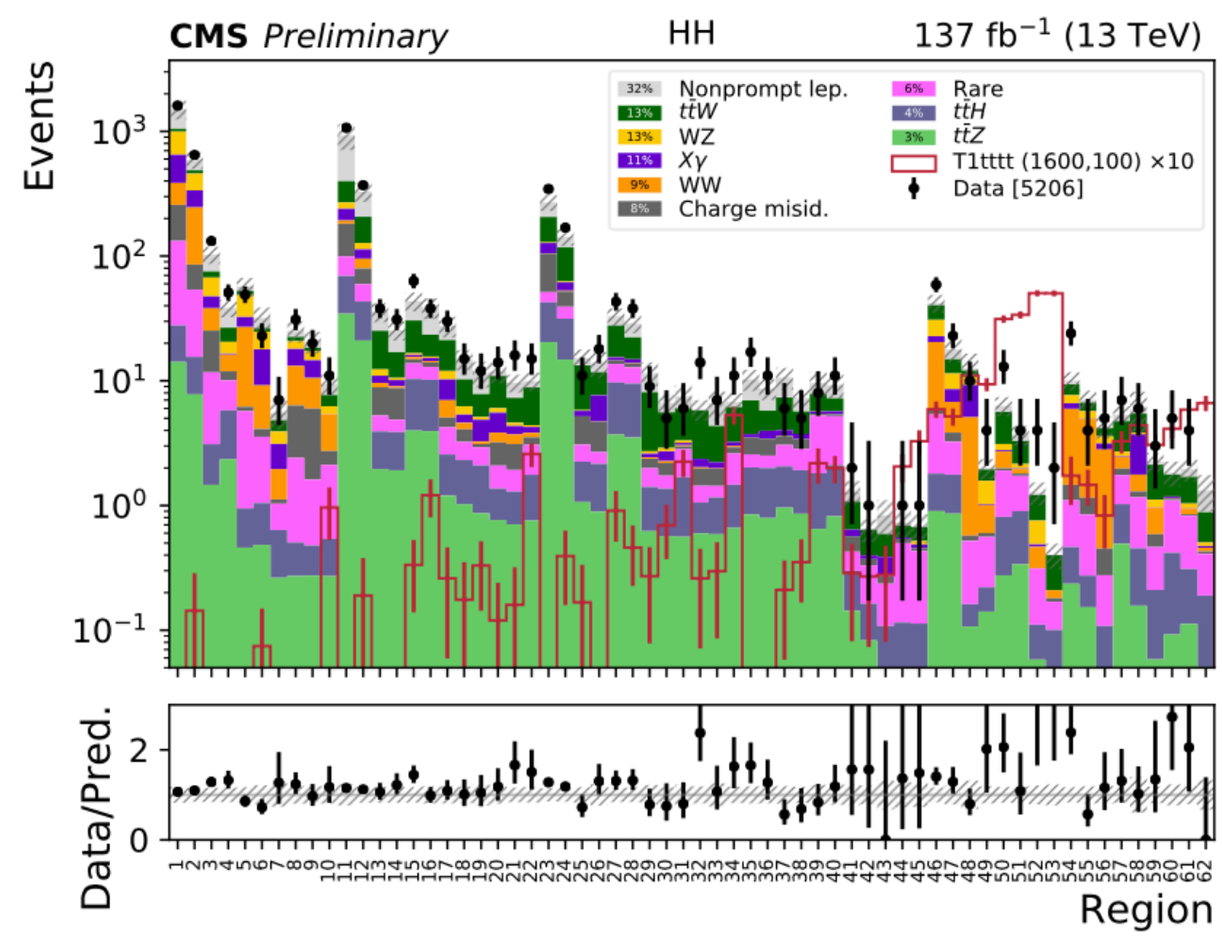
137 fb^{-1}

NEW

SUS-19-008

SS + multilepton

- Processes producing 2 same-sign or ≥3 leptons very rare in SM
  → **Low-background environment for searches**
- Broad search targeting gluinos, top squarks, bottom squarks
- 168 search regions defined using kinematic variables: lepton p_T, N_j, N_b, m_T^{min}, H_T, p_T^{miss}, lepton charge
- **Includes regions at low p_T^{miss} → sensitivity to RPV models**
- Main backgrounds:
  - Rare SM, e.g. WZ, ttW, …
  - Nonprompt leptons
  - Electron charge flip
- Good agreement between data and prediction is observed



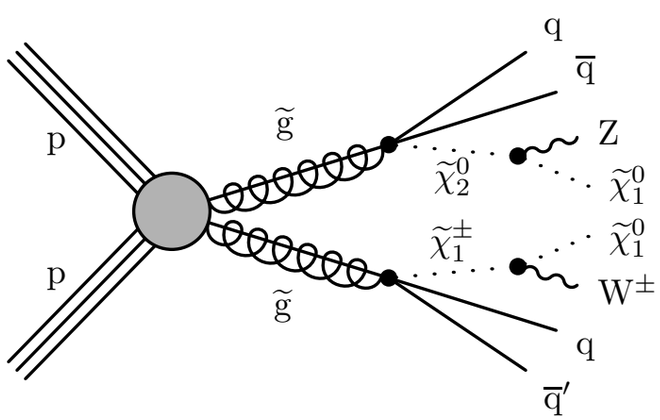
137 fb^{-1}

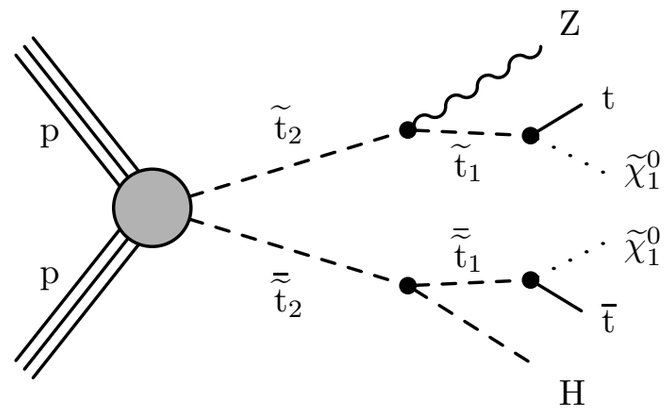
NEW

SUS-19-008

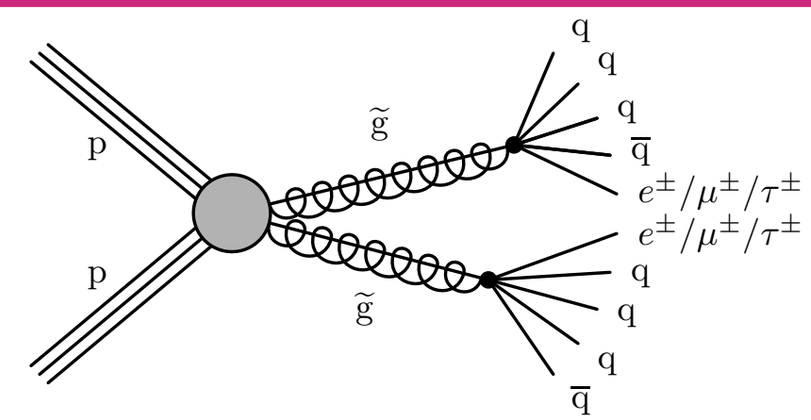
SS + multilepton

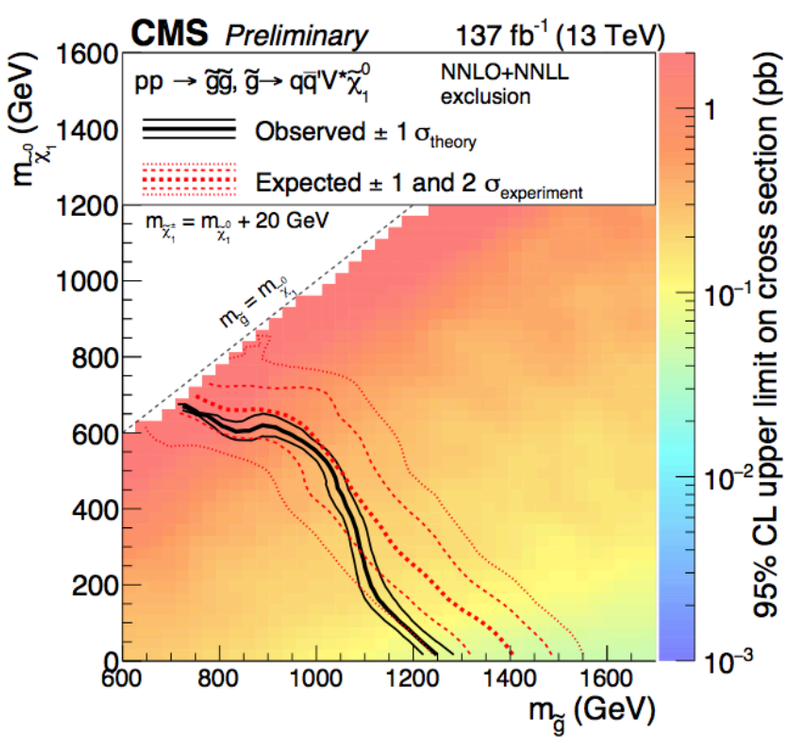
- Reach extended by 150–200 GeV compared to 36 fb^{-1}

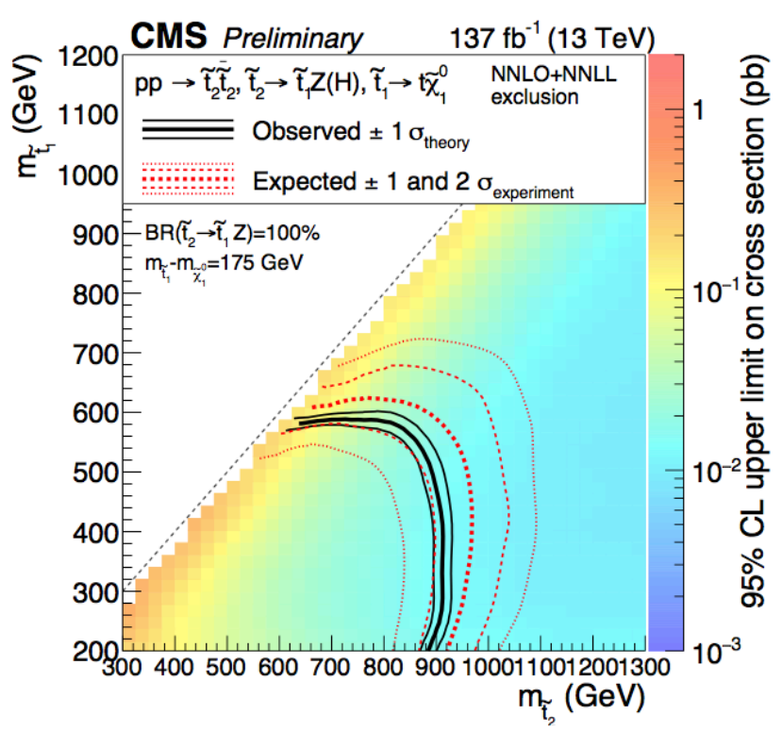


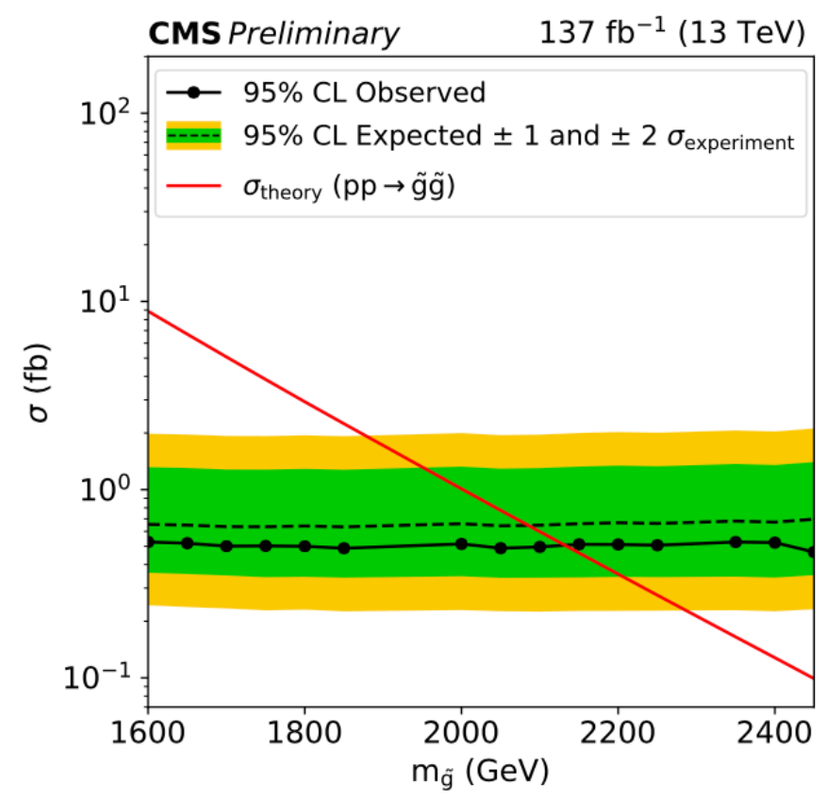


New interpretation!









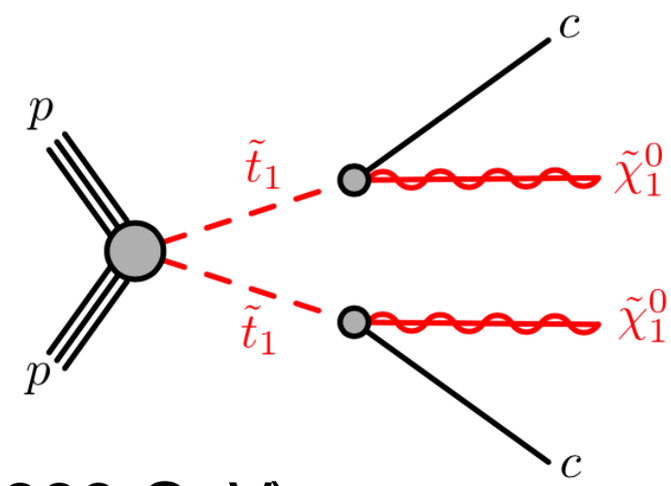
JHEP 09 (2018) 050

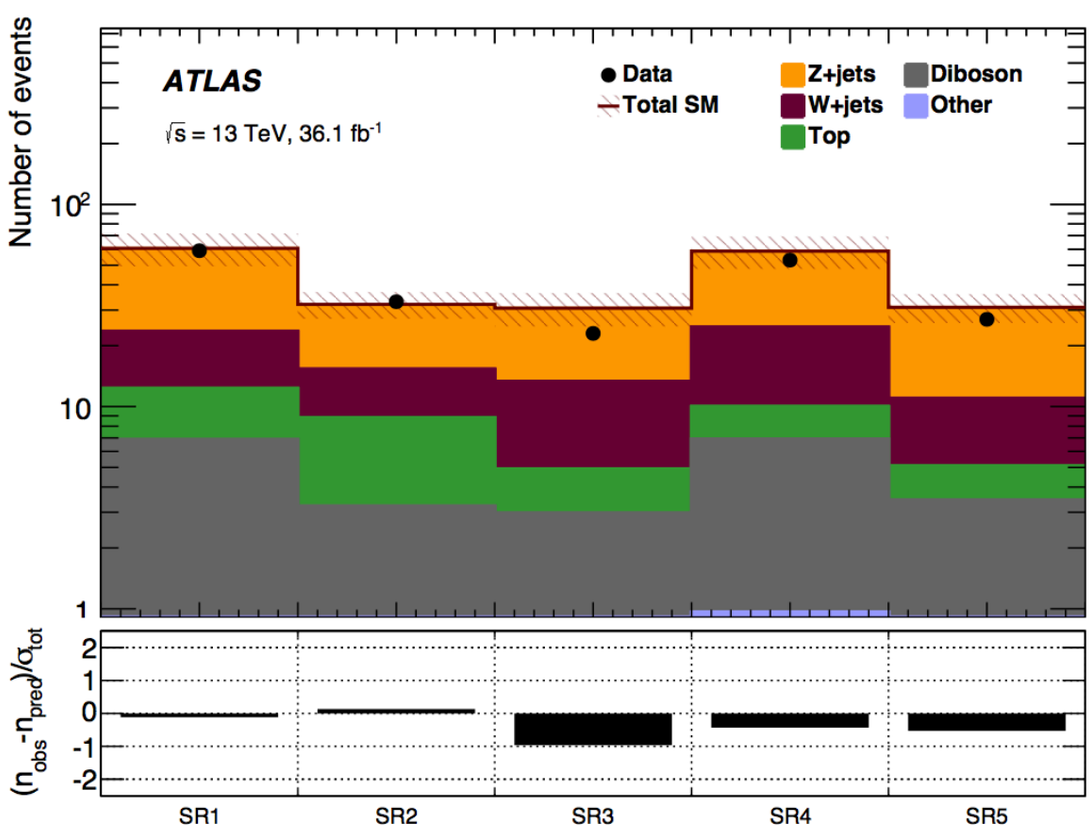
ATLAS EXPERIMENT

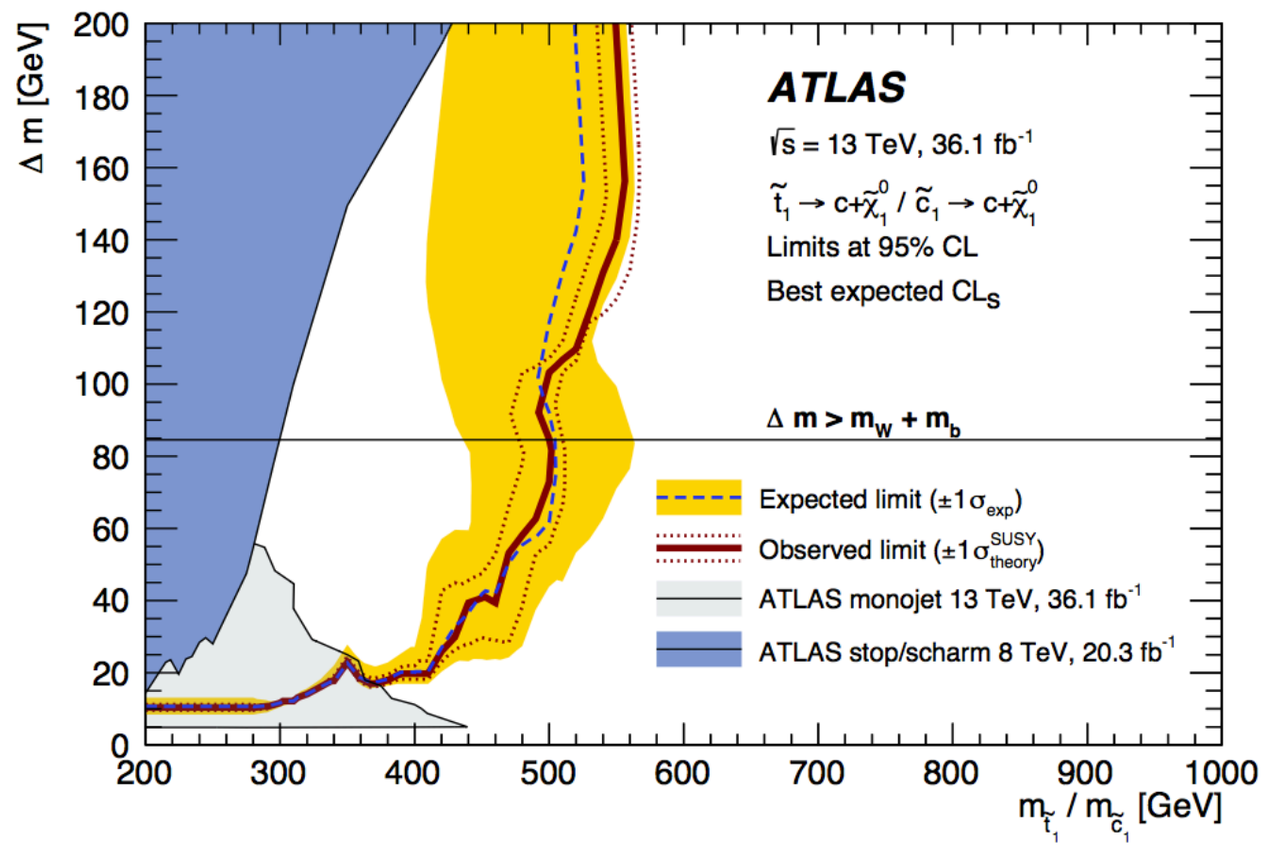
36 fb^{-1}

Top squarks

- Recent results with partial data set focusing on tricky corners of phase space
- **'Compressed spectra' with charm tagging** and high p_T^{miss} (from ISR boost)
- Also sensitive to charm squark production (up to 800 GeV)







Low Δm → **High Δm**

36 fb-1 | 36 fb-1

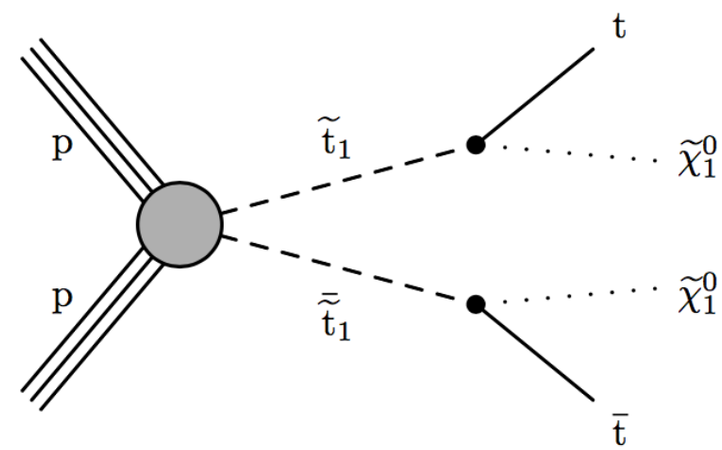
NEW

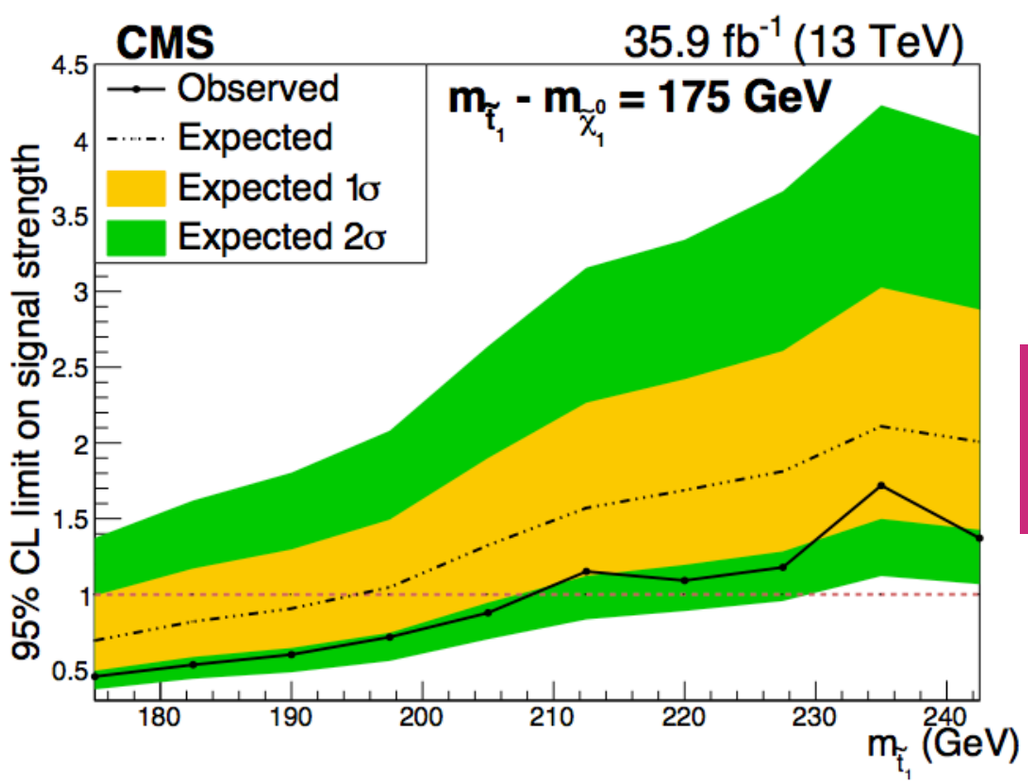
arXiv:1901.01288
arXiv:1903.07570

Top corridor

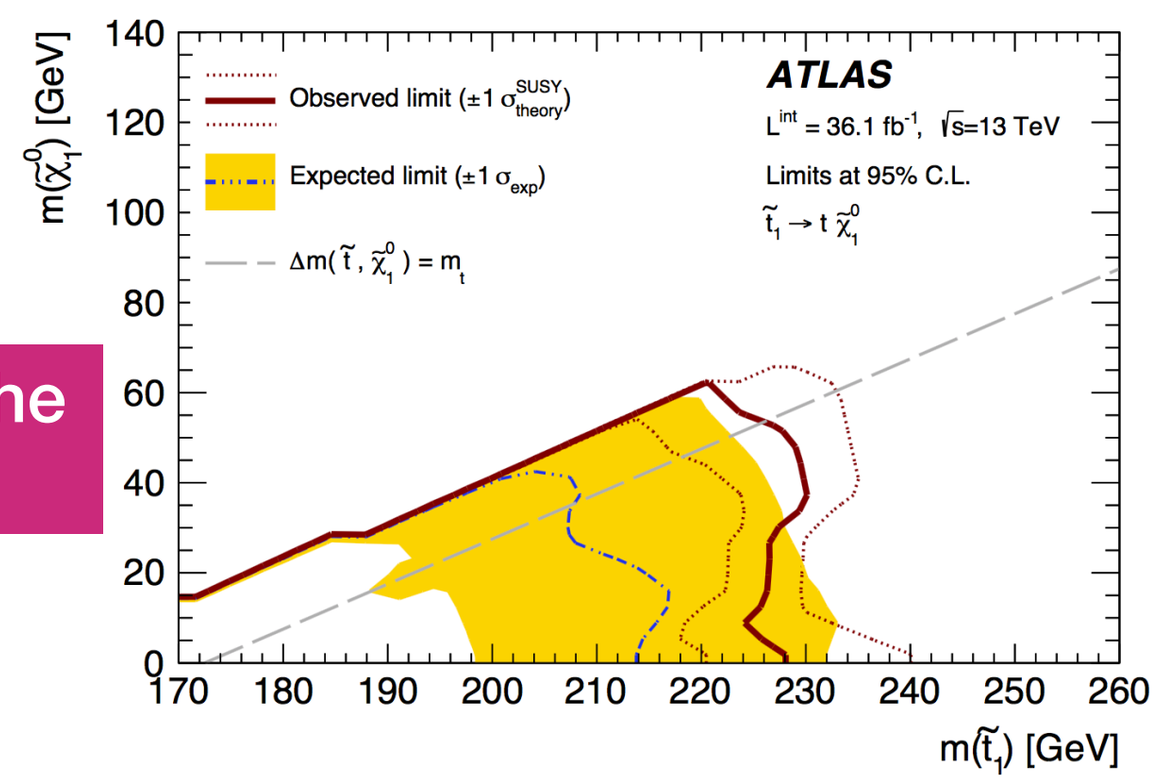
$$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx 175\,\mathrm{GeV}$$

- Top quarks from squark decay produced ~at rest, looks very much like SM ttbar
- Needs precision approach — use eμ final state:
  - **Precise estimate of ttbar** and extra discrimination using M_{T2} variable
  - Exploit ttbar **spin correlations:** double-differential distributions of lepton Δϕ (uncorrelated tt from stops) and Δη (scalar more central)





Closing the gaps!



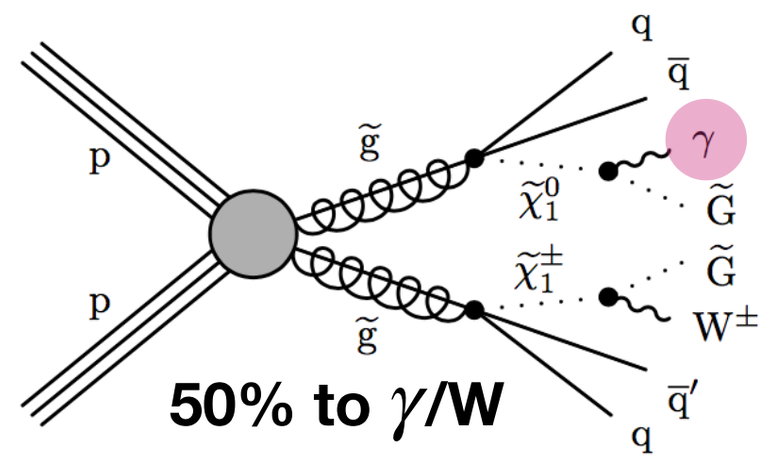
36 fb^{-1}

SUSY with photons

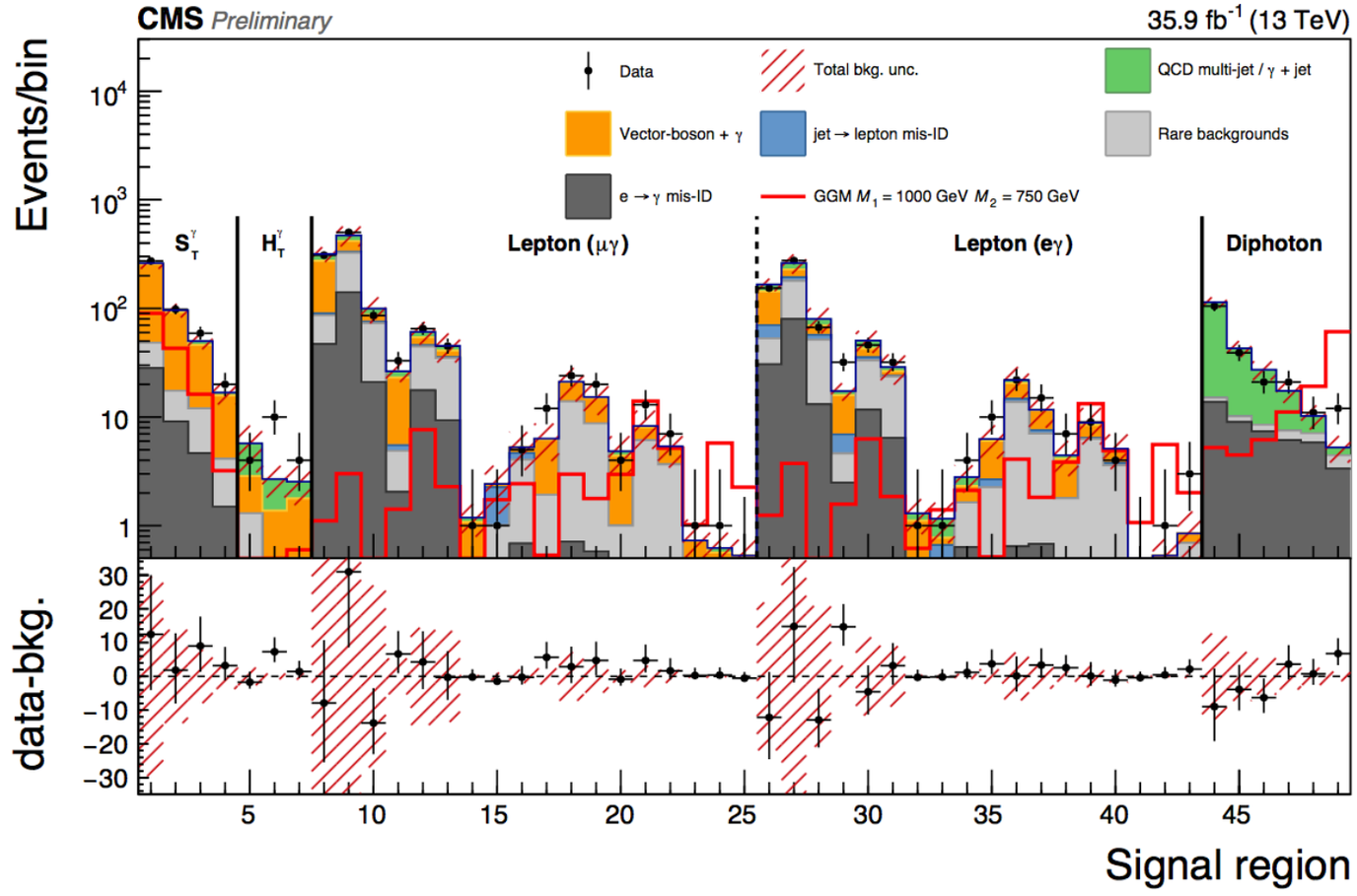
NEW

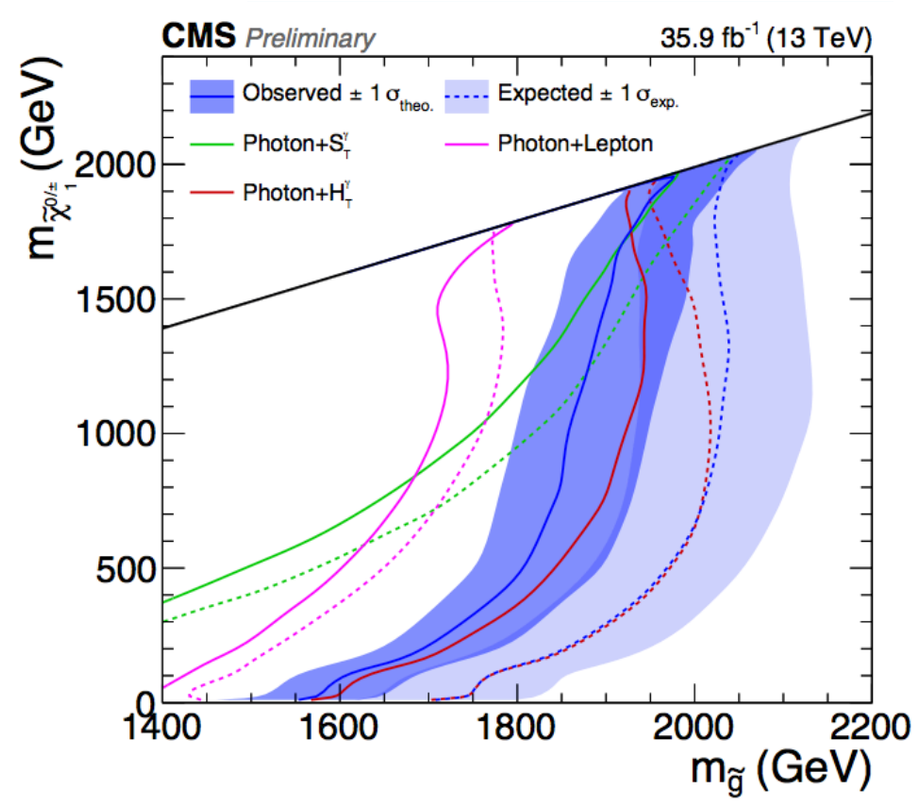
SUS-18-005
arxiv:1903.07070

- Motivated by **gauge-mediated SUSY breaking**
- **Combination** of 4 analyses, overlaps removed:
  - Photon + lepton + p_T^{miss}
  - Photon + S_T + p_T^{miss}
  - Photon + H_T + p_T^{miss}
  - Diphoton + p_T^{miss} (not included for $\tilde{g}\tilde{g}$ interpretation)



Sensitivity extended in compressed region

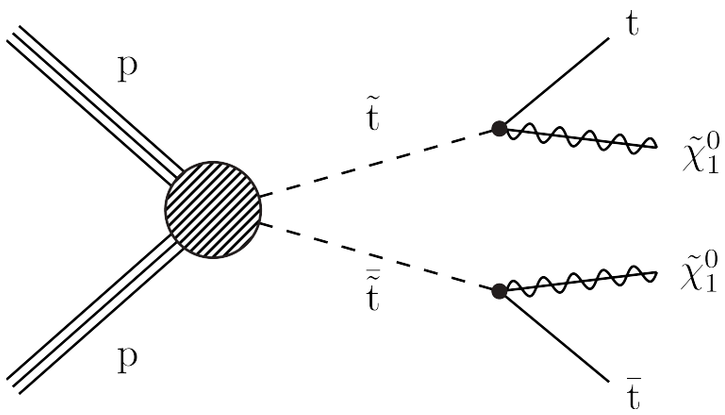




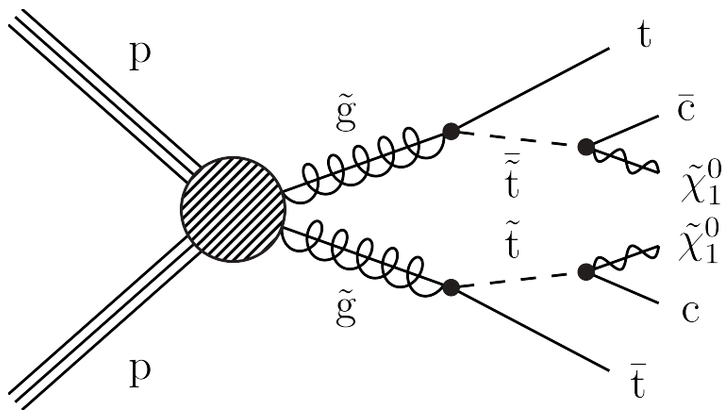
Not shown here: electroweak signatures

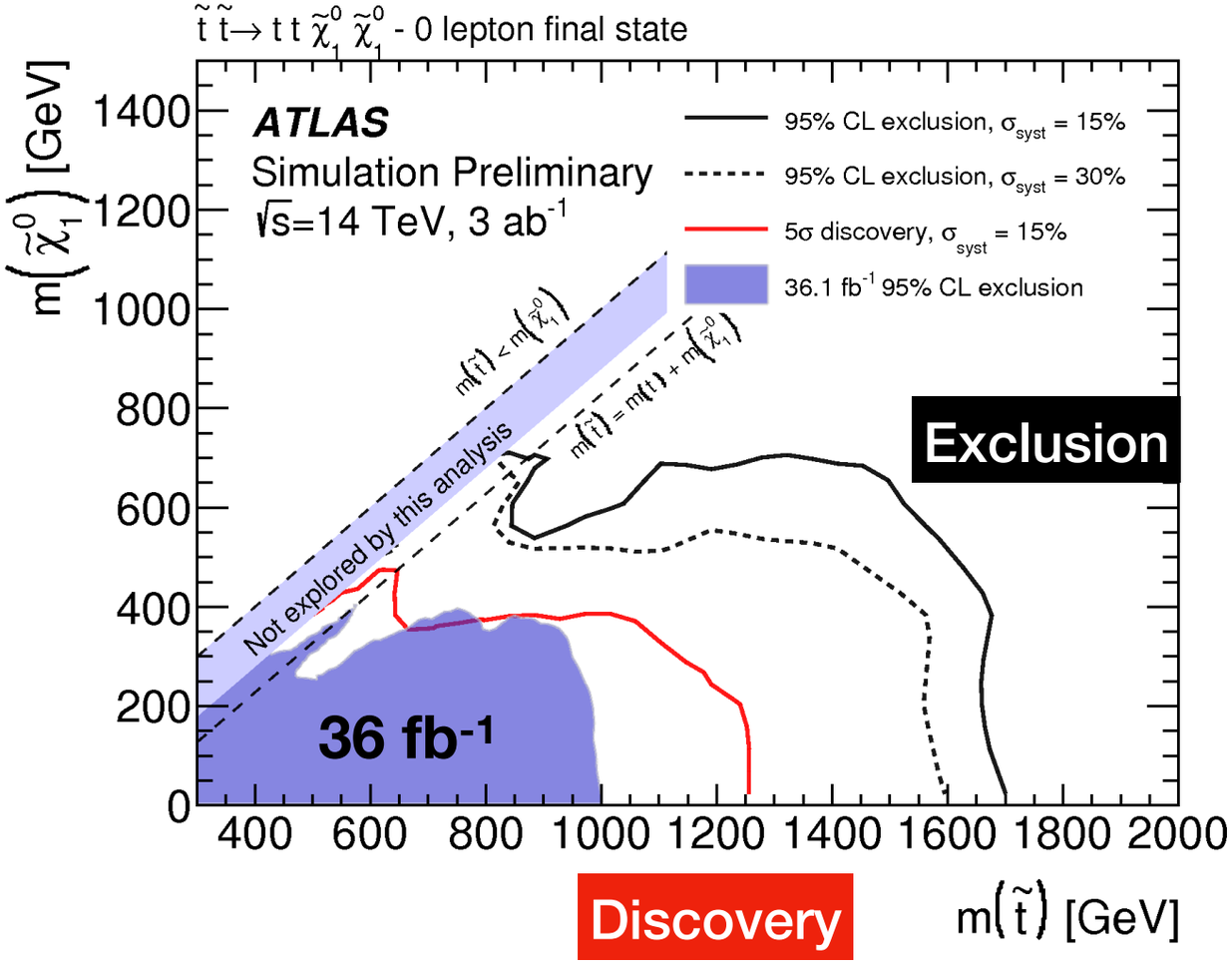
arXiv:1812.07831
arXiv:1902.10229

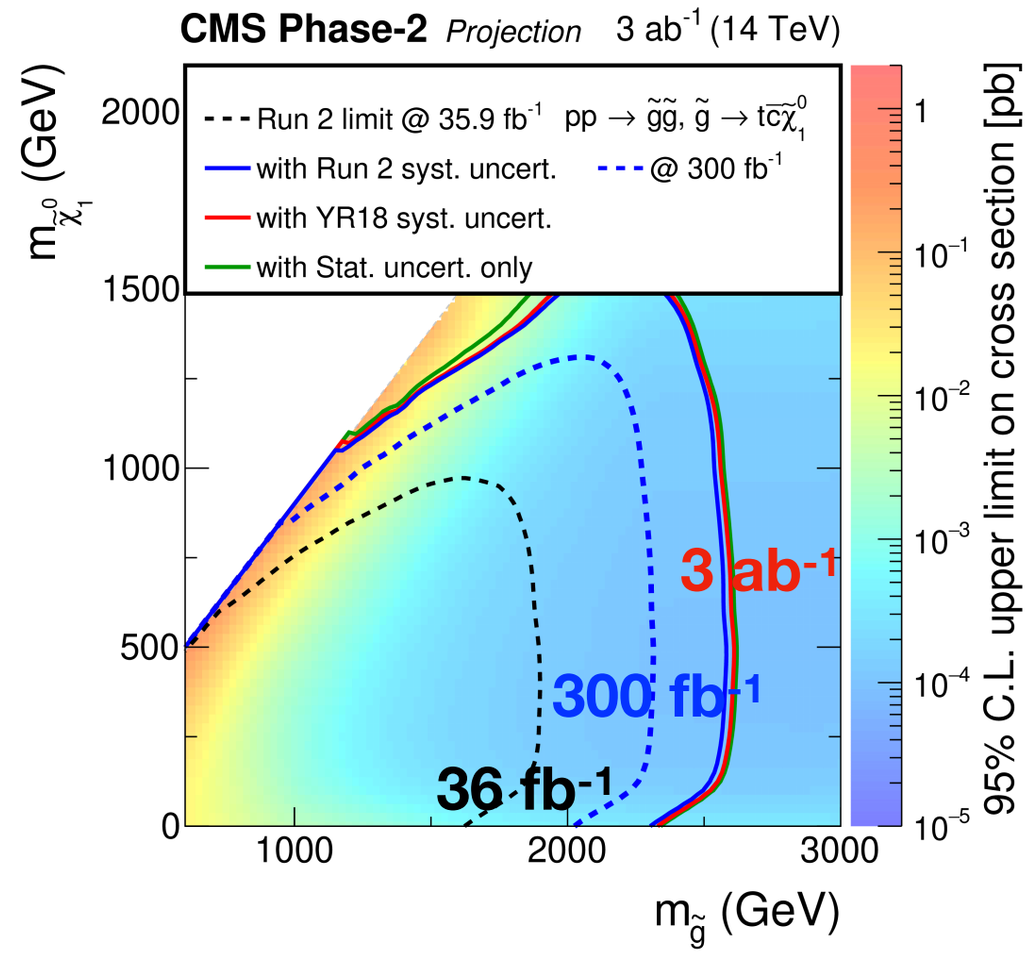
Future projections



Future projections for SUSY sensitivity released as part of CERN Yellow Report







ATL-PHYS-PUB-2018-021

CMS-PAS-FTR-18-037

Summary & outlook

- Successful Run 2 of the LHC finished at the end of 2018
- Now in LS2, preparing for Run 3
- **First full Run 2 results on strong SUSY presented**
  - Exclude gluinos up to 2.2 TeV and sbottoms up to 1.4 TeV in simplified models
  - Many more results to come in next months
- **Dedicated analyses with slightly longer time scales**
  - Results with 2016+2017 data still appearing
  - Going after difficult corners of phase space and closing gaps
- **Not done yet! HL-LHC data set allows for increase in sensitivity of 0.5—1 TeV**

Backup

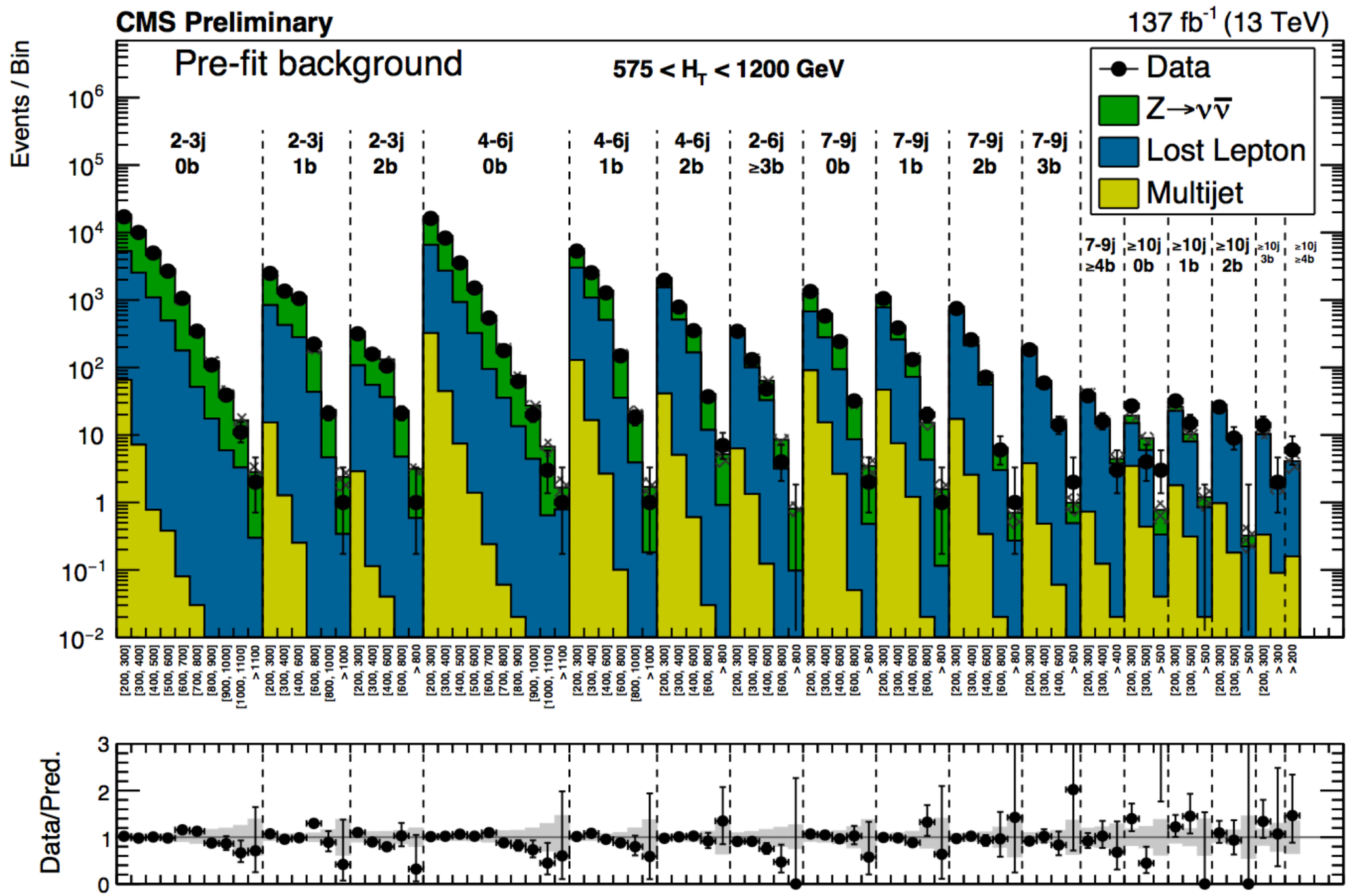
To be filled out

Jets + M_{T2}

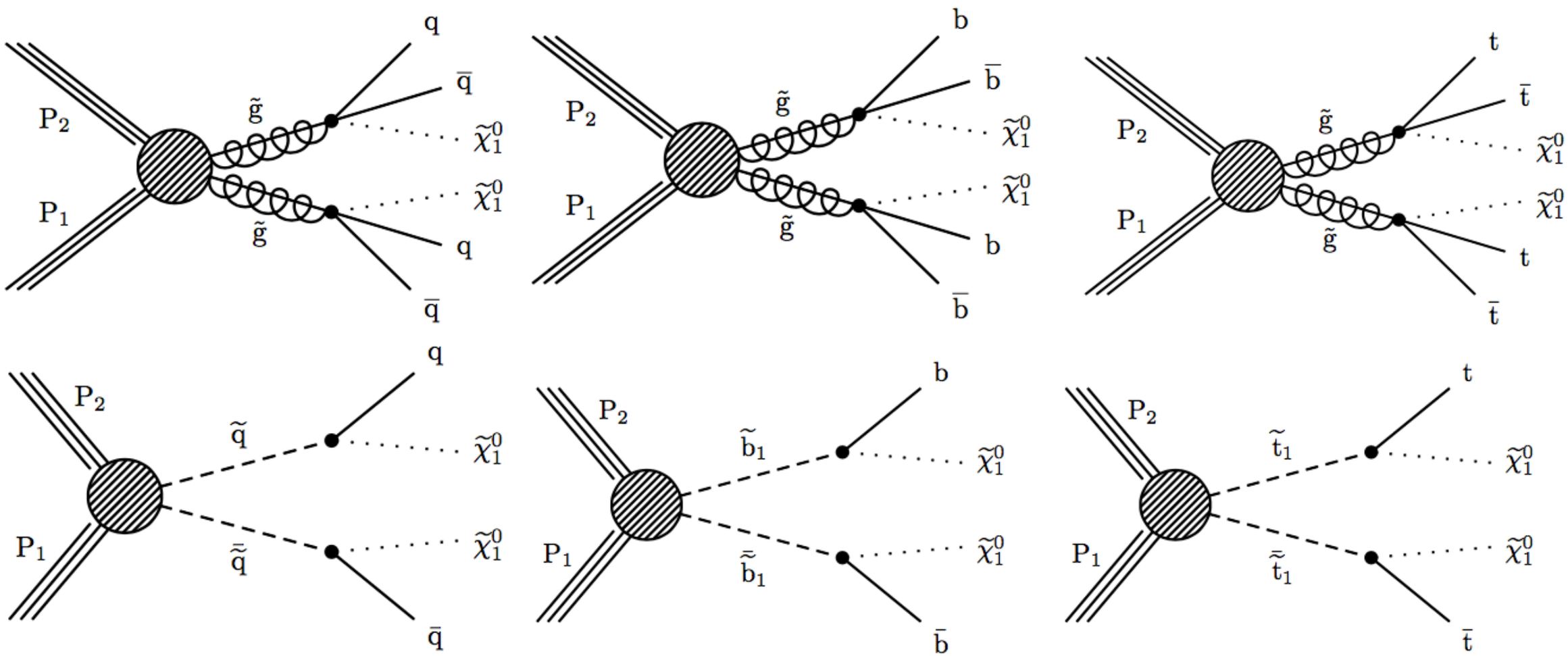
$$M_{T2} = \min_{\vec{p}_T^{\,\mathrm{miss}\,X(1)} + \vec{p}_T^{\,\mathrm{miss}\,X(2)} = \vec{p}_T^{\,\mathrm{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

Jet selection	$R = 0.4$, $p_T > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$
b tag selection	$p_T > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$
p_T^{miss}	$p_T^{\mathrm{miss}} > 250\,\mathrm{GeV}$ for $H_T < 1200\,\mathrm{GeV}$, else $p_T^{\mathrm{miss}} > 30\,\mathrm{GeV}$ $\Delta\phi_{\mathrm{min}} = \Delta\phi\left(p_T^{\mathrm{miss}}, j_{1,2,3,4}\right) > 0.3$ $\lvert\vec{p}_T^{\,\mathrm{miss}} - \vec{H}_T^{\mathrm{miss}}\rvert / p_T^{\mathrm{miss}} < 0.5$
M_{T2}	Inclusive M_{T2} search (if $N_j \geq 2$): $M_{T2} > 200\,\mathrm{GeV}$ for $H_T < 1500\,\mathrm{GeV}$, else $M_{T2} > 400\,\mathrm{GeV}$ Search for disappearing tracks (if $N_j \geq 2$): $M_{T2} > 200\,\mathrm{GeV}$
Veto muon	$p_T > 10\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$, $p_T^{\mathrm{sum}} < 0.2\,p_T^{\mathrm{lep}}$
Veto muon track	$p_T > 5\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$, $M_T < 100\,\mathrm{GeV}$, $p_T^{\mathrm{sum}} < 0.2\,p_T^{\mathrm{lep}}$
Veto electron	$p_T > 10\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$, $p_T^{\mathrm{sum}} < 0.1\,p_T^{\mathrm{lep}}$
Veto electron track	$p_T > 5\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$, $M_T < 100\,\mathrm{GeV}$, $p_T^{\mathrm{sum}} < 0.2\,p_T^{\mathrm{lep}}$
Veto track	$p_T > 10\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$, $M_T < 100\,\mathrm{GeV}$, $p_T^{\mathrm{sum}} < 0.1\,p_T^{\mathrm{track}}$
p_T^{sum} cone (isolation)	Veto e or μ: $\Delta R = \min(0.2, \max(10\,\mathrm{GeV}/p_T^{\mathrm{lep}}, 0.05))$ Veto track: $\Delta R = 0.3$

Jets + M_{T2}


CMS Preliminary
137 fb^{-1} (13 TeV)
Pre-fit background
575 < H_T < 1200 GeV
Data
$Z \to \nu\bar{\nu}$
Lost Lepton
Multijet
Events / Bin
Data/Pred.
2-3j 0b
2-3j 1b
2-3j 2b
4-6j 0b
4-6j 1b
4-6j 2b
2-6j ≥3b
7-9j 0b
7-9j 1b
7-9j 2b
7-9j 3b
7-9j ≥4b
≥10j 0b
≥10j 1b
≥10j 2b
≥10j 3b
≥10j ≥4b

Jets + M_{T2}

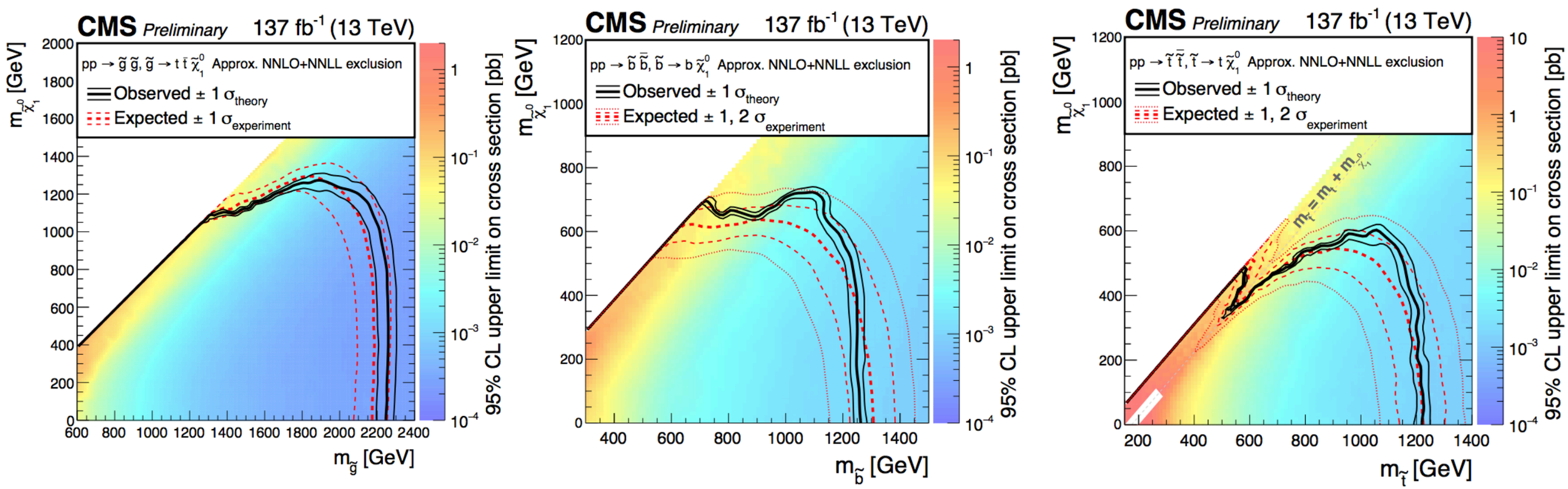


Jets + M_{T2}

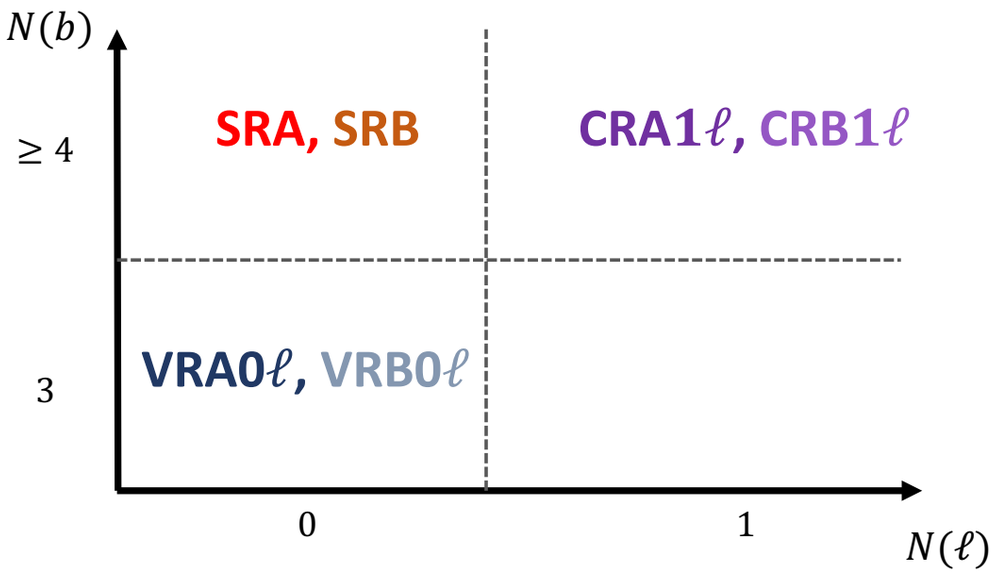
Table 2: Typical values of the systematic uncertainties as evaluated for the simplified models of SUSY used in the context of this search. The high statistical uncertainty in the simulated signal sample corresponds to a small number of signal bins with low acceptance, which are typically not among the most sensitive signal bins to that model point.

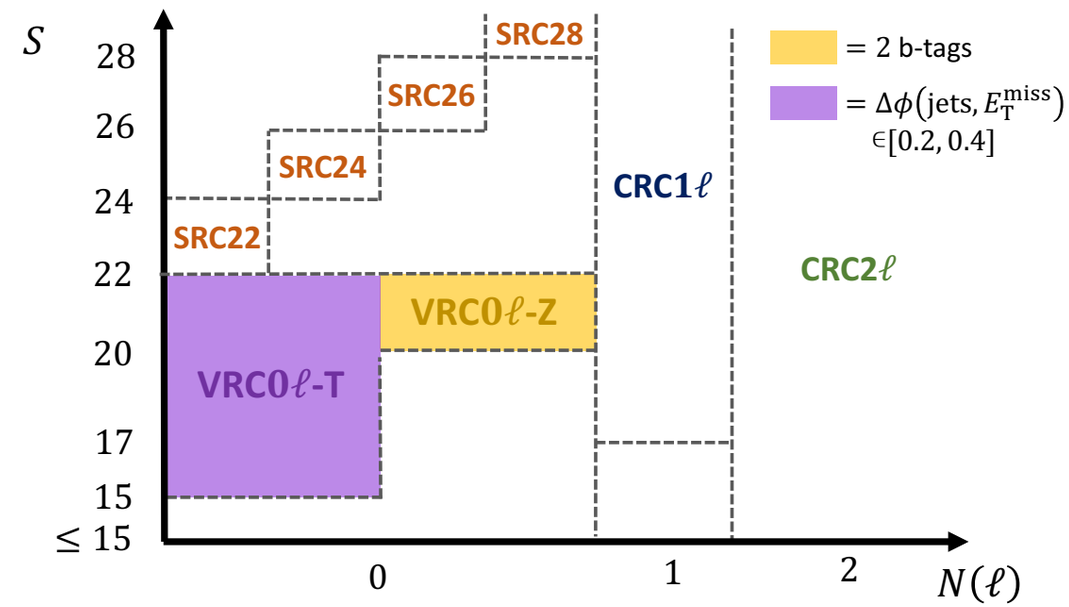
Source	Range [%]
Integrated luminosity	2.3–2.5
Limited size of MC samples	1–100
Renormalization and factorization scales	5
ISR modeling	0–30
b tagging efficiency, heavy flavors	0–40
b tagging efficiency, light flavors	0–20
Lepton efficiency	0–20
Jet energy scale	5
Fast simulation p_T^{miss} modeling	0–5

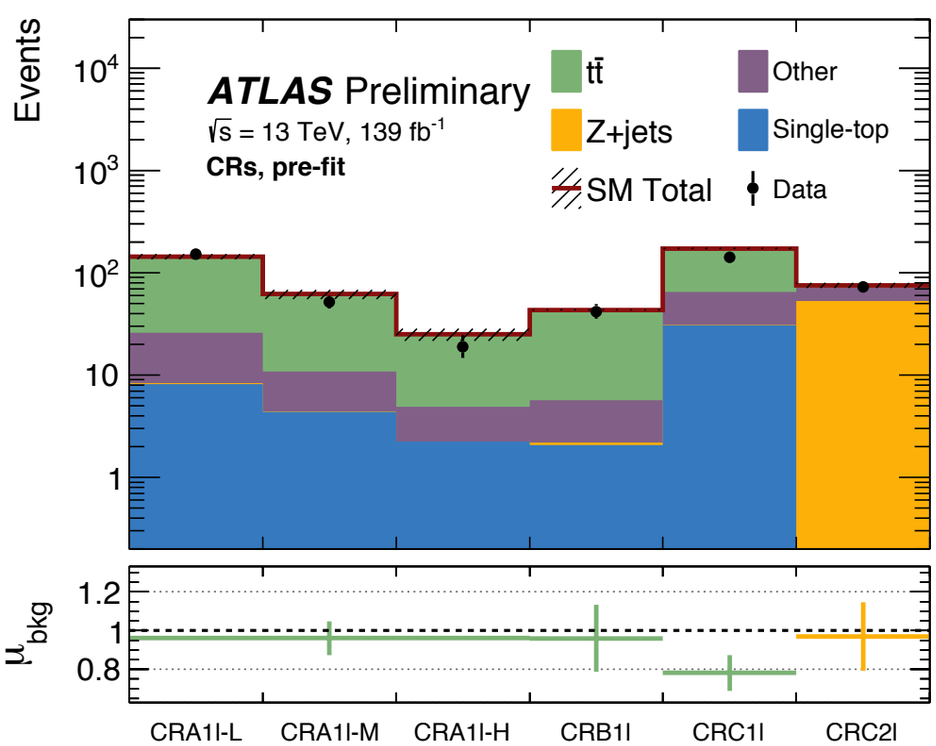
Jets + M_{T2}

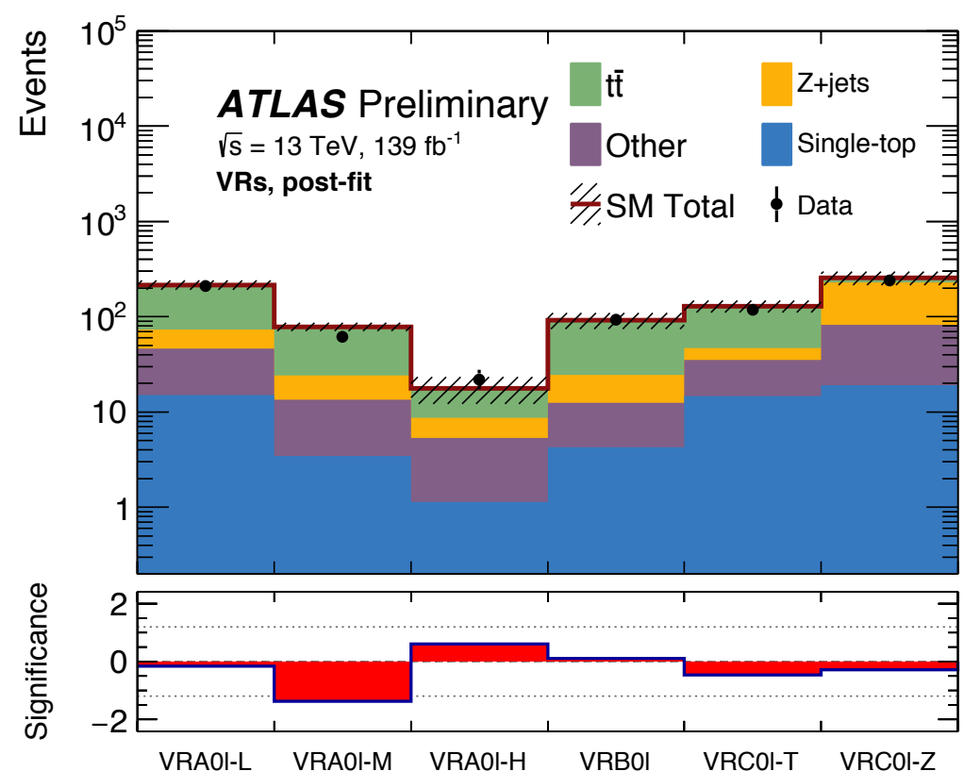

CMS Preliminary 137 fb-1 (13 TeV)
pp → g̃ g̃, g̃ → t t̄ χ̃01 Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1 σexperiment
mχ̃01 [GeV]
mg̃ [GeV]
95% CL upper limit on cross section [pb]
CMS Preliminary 137 fb-1 (13 TeV)
pp → b̃ b̃̄, b̃ → b χ̃01 Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1, 2 σexperiment
mχ̃01 [GeV]
mb̃ [GeV]
95% CL upper limit on cross section [pb]
CMS Preliminary 137 fb-1 (13 TeV)
pp → t̃ t̃̄, t̃ → t χ̃01 Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1, 2 σexperiment
mt̃ = mt + mχ̃01
mχ̃01 [GeV]
mt̃ [GeV]
95% CL upper limit on cross section [pb]

bjets+H+ p_T^{miss}









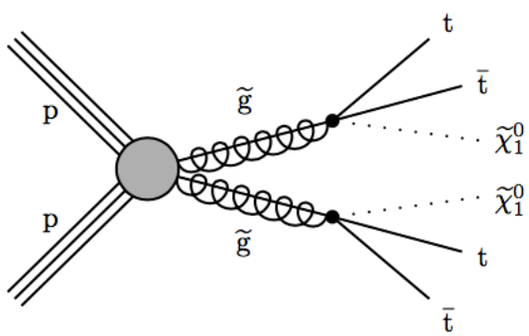
bjets+H+ p_T^{miss}

Variable	SRA	SRA-L	SRA-M	SRA-H
N_{leptons} (baseline)	$= 0$		$= 0$	
N_{jets}	≥ 6		≥ 6	
$N_{\text{b-jets}}$	≥ 4		≥ 4	
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 350		> 350	
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_{\text{T}}^{\text{miss}})$ [rad]	> 0.4		> 0.4	
τ veto	Yes		Yes	
$p_{\text{T}}(b_1)$ [GeV]	> 200		> 200	
$\Delta R_{\text{max}}(b, b)$	¿ 2.5		¿ 2.5	
$\Delta R_{\text{max-min}}(b, b)$	¡ 2.5		¡ 2.5	
$m(h_{\text{cand}})$ [GeV]	> 80		> 80	
m_{eff} [TeV]	> 1.0	$\in [1.0, 1.5]$	$\in [1.5, 2.0]$	> 2.0

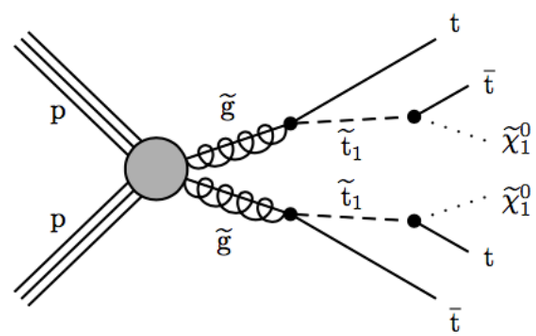
Variable	SRB
N_{leptons} (baseline)	$= 0$
N_{jets}	≥ 5
$N_{\text{b-jets}}$	≥ 4
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 350
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_{\text{T}}^{\text{miss}})$ [rad]	> 0.4
τ veto	Yes
$m(h_{\text{cand1}}, h_{\text{cand2}})_{\text{avg}}$ [GeV]	$\in [75, 175]$
leading jet not b-tagged	Yes
$p_{\text{T}}(j_1)$ [GeV]	> 350
$\lvert\Delta\phi(j_1, E_{\text{T}}^{\text{miss}})\rvert$ [rad]	> 2.8
m_{eff} [TeV]	> 1

Variable	SRC	SRC22	SRC24	SRC26	SRC28
N_{leptons} (baseline)	$= 0$		$= 0$		
N_{jets}	≥ 4		≥ 4		
$N_{\text{b-jets}}$	≥ 3		≥ 3		
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 250		> 250		
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_{\text{T}}^{\text{miss}})$ [rad]	> 0.4		> 0.4		
$\mathcal{S}$	> 22	$\in [22, 24]$	$\in [24, 26]$	$\in [26, 28]$	> 28

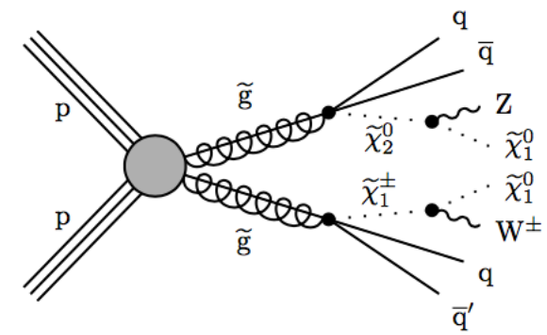
SS + multilepton



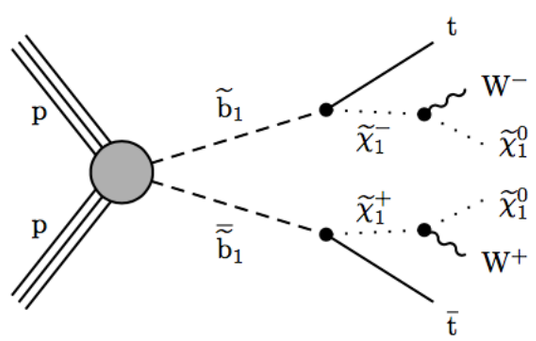
(a) T1tttt



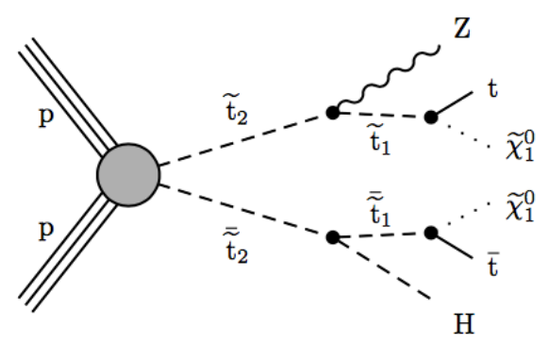
(b) T5tttt



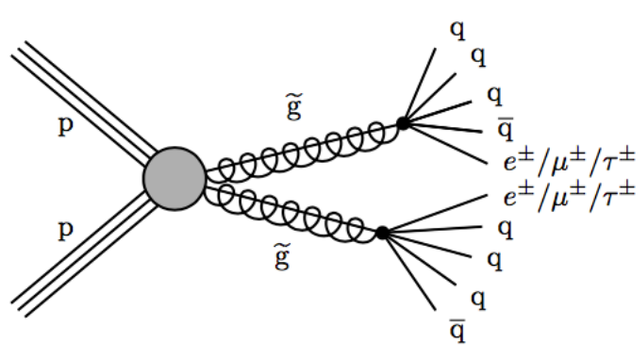
(c) T5qqqqWZ

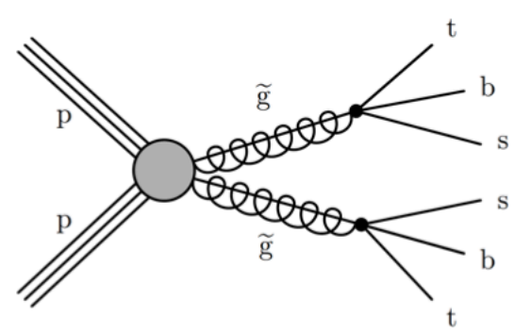


(d) T6ttWW



(e) T6ttHZ

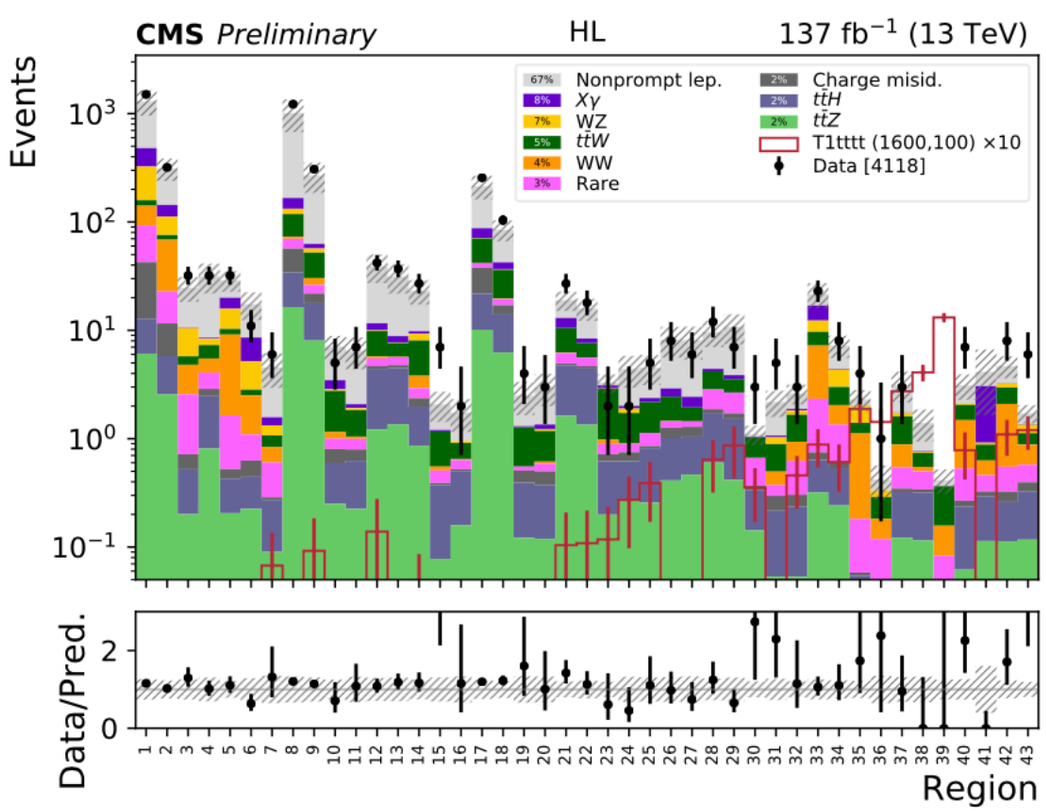


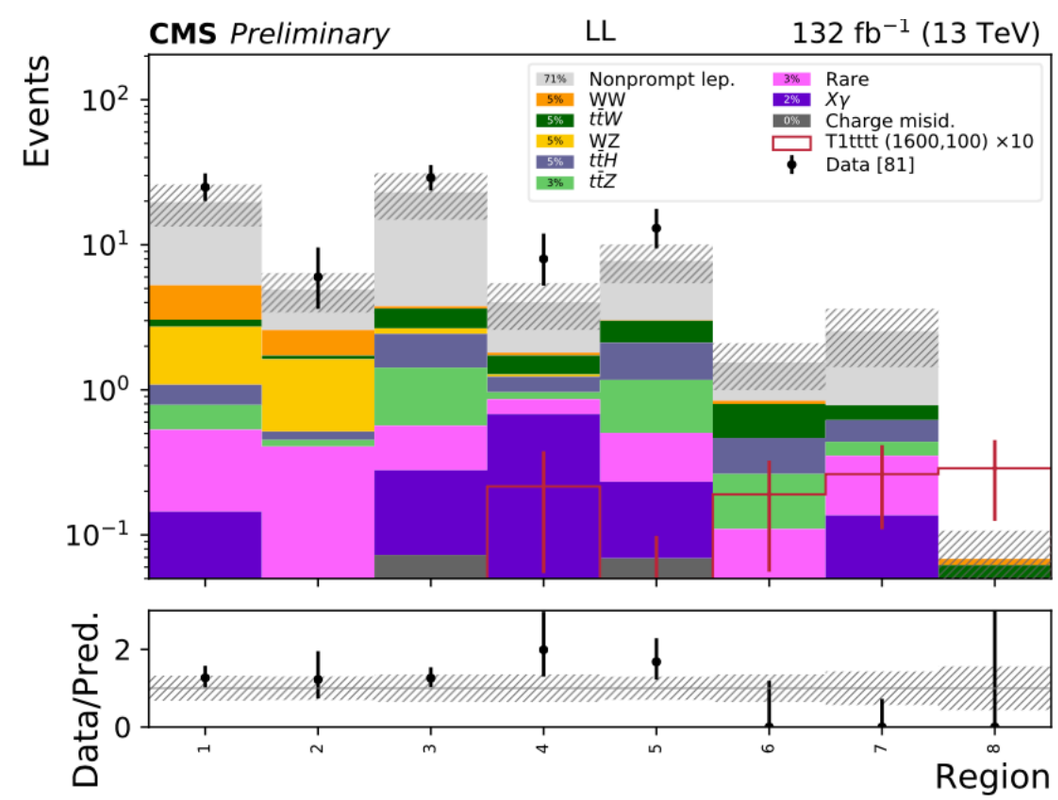


SS + multilepton

Six exclusive categories are then built:

- SSHH: exactly 2 leptons, both with $p_T > 25\,\text{GeV}$, and $p_T^{\text{miss}} > 50\,\text{GeV}$.
- SSHL: exactly 2 leptons, one with $p_T > 25\,\text{GeV}$, one with $p_T < 25\,\text{GeV}$ and $p_T^{\text{miss}} > 50\,\text{GeV}$.
- SSLL: exactly 2 leptons, both with $p_T < 25\,\text{GeV}$ and $p_T^{\text{miss}} > 50\,\text{GeV}$.
- LM (low p_T^{miss}): exactly 2 leptons, both with $p_T > 25\,\text{GeV}$, and $p_T^{\text{miss}} < 50\,\text{GeV}$.
- ML (multilepton): ≥ 3 leptons, at least one with $p_T > 25\,\text{GeV}$, $p_T^{\text{miss}} > 50\,\text{GeV}$.





SS + multilepton

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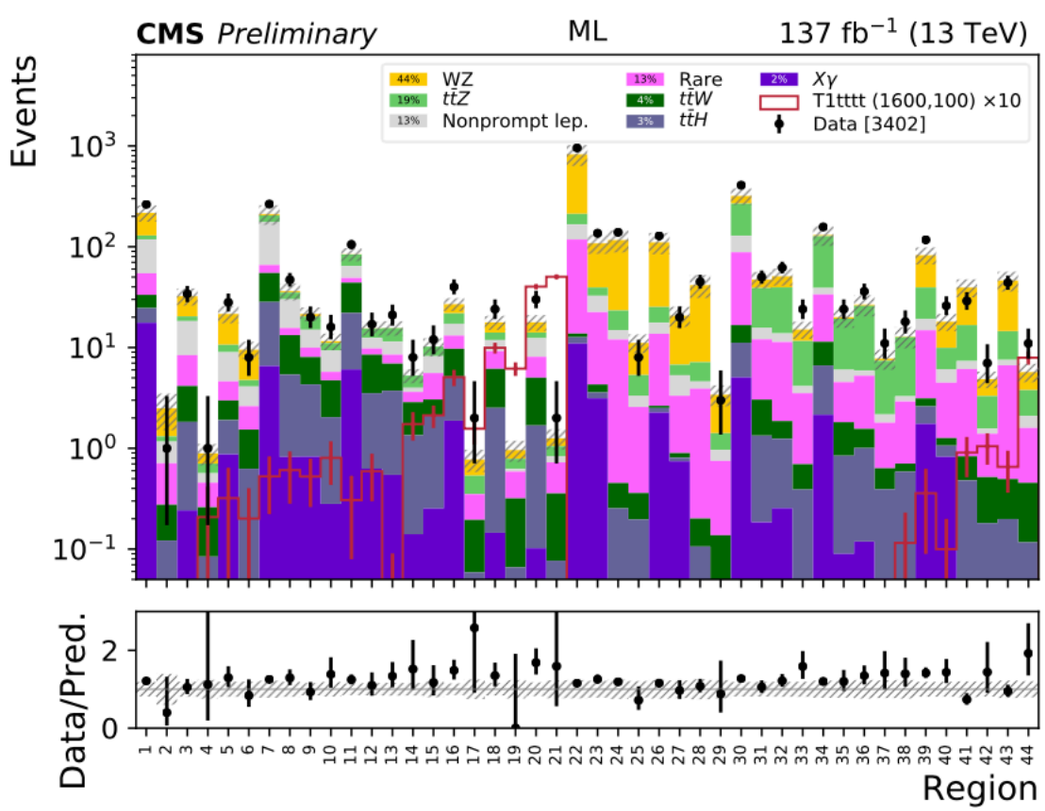
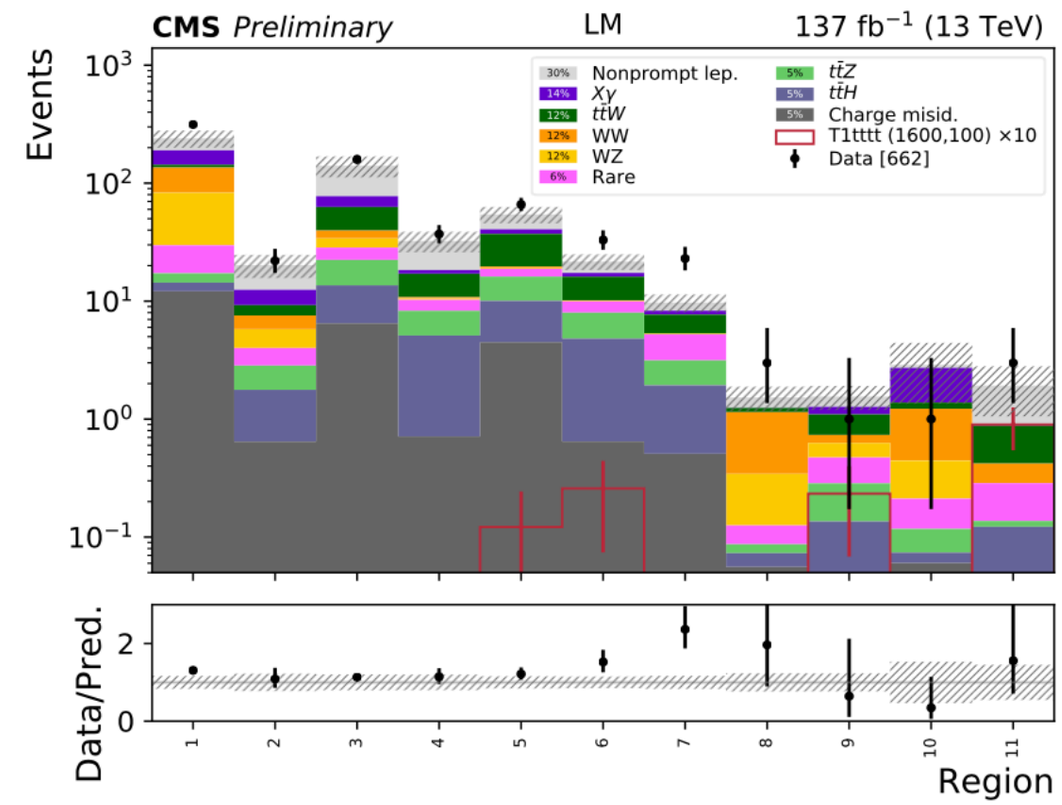
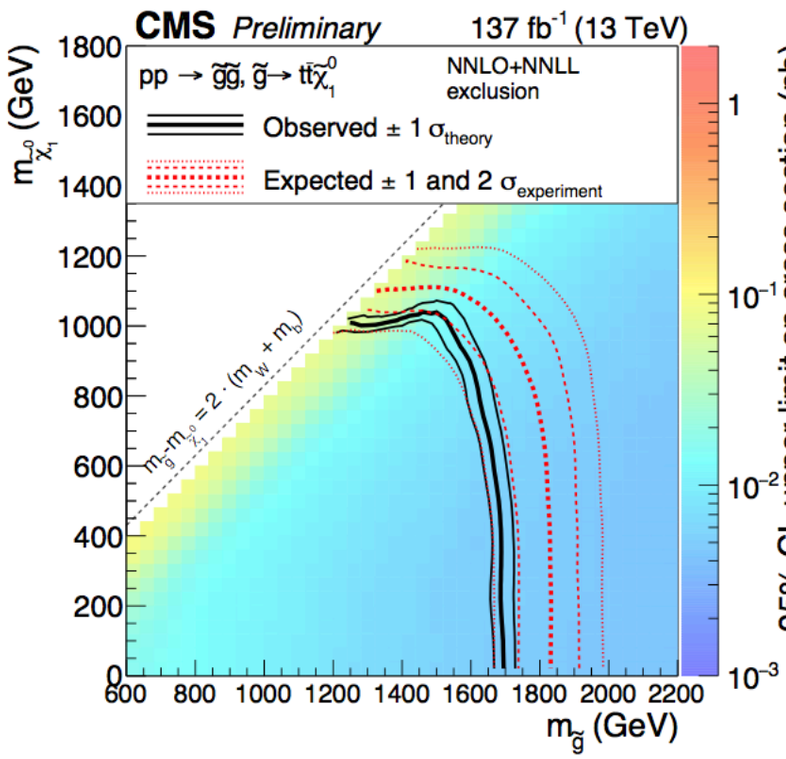
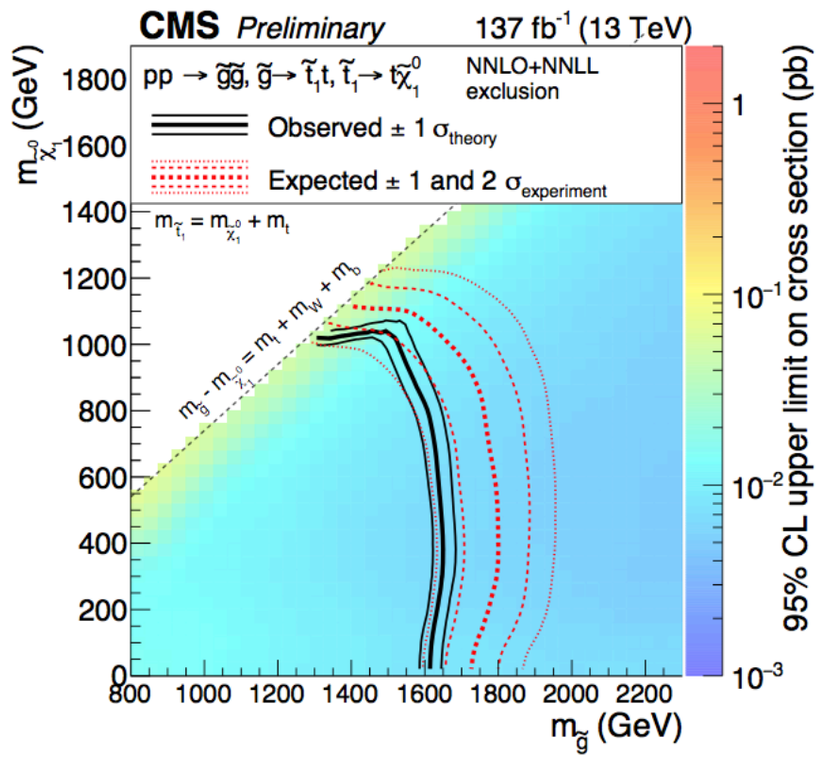
- SSHH: exactly 2 leptons, both with $p_T > 25\,\text{GeV}$, and $p_T^{\text{miss}} > 50\,\text{GeV}$.
- SSHL: exactly 2 leptons, one with $p_T > 25\,\text{GeV}$, one with $p_T < 25\,\text{GeV}$ and $p_T^{\text{miss}} > 50\,\text{GeV}$.
- SSLL: exactly 2 leptons, both with $p_T < 25\,\text{GeV}$ and $p_T^{\text{miss}} > 50\,\text{GeV}$.
- LM (low p_T^{miss}): exactly 2 leptons, both with $p_T > 25\,\text{GeV}$, and $p_T^{\text{miss}} < 50\,\text{GeV}$.
- ML (multilepton): ≥ 3 leptons, at least one with $p_T > 25\,\text{GeV}$, $p_T^{\text{miss}} > 50\,\text{GeV}$.

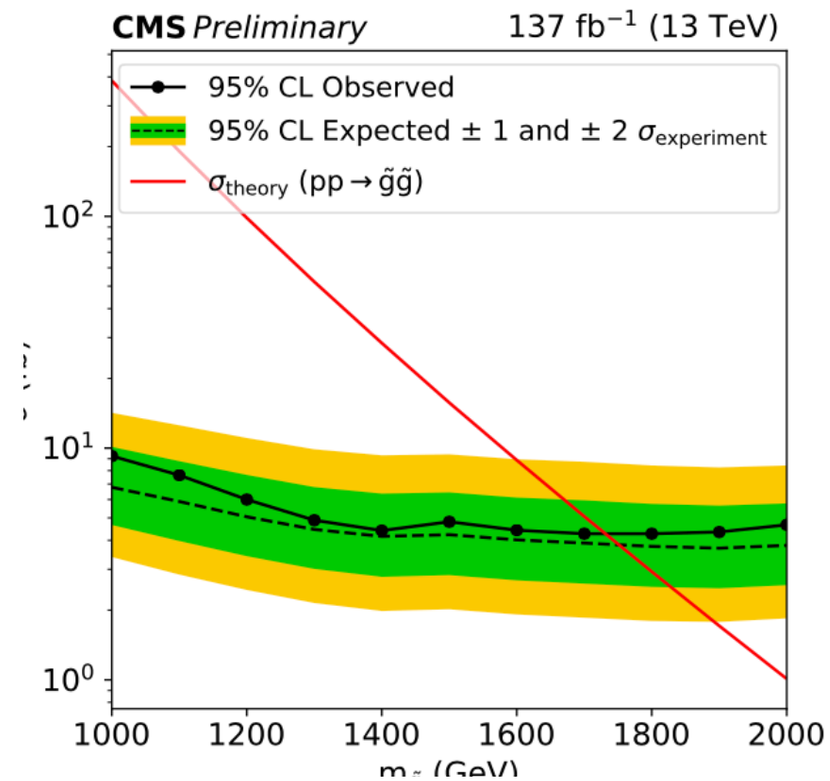


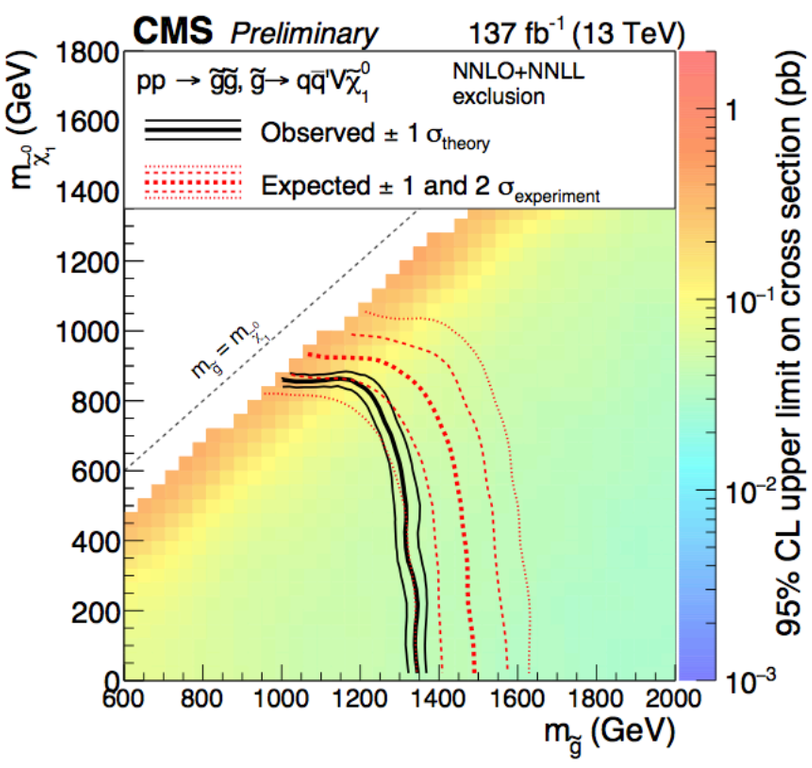


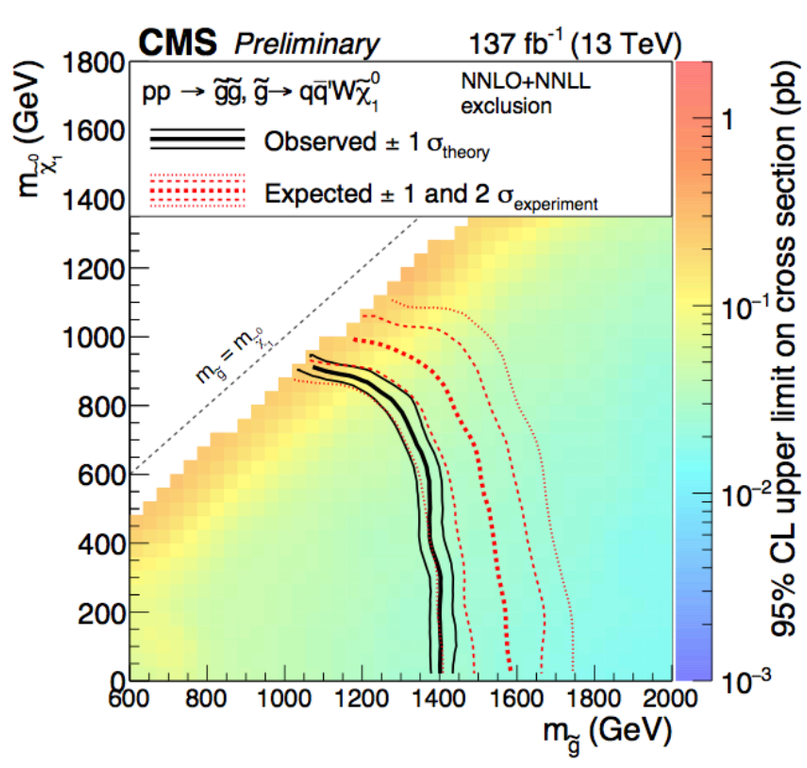
SS + multilepton

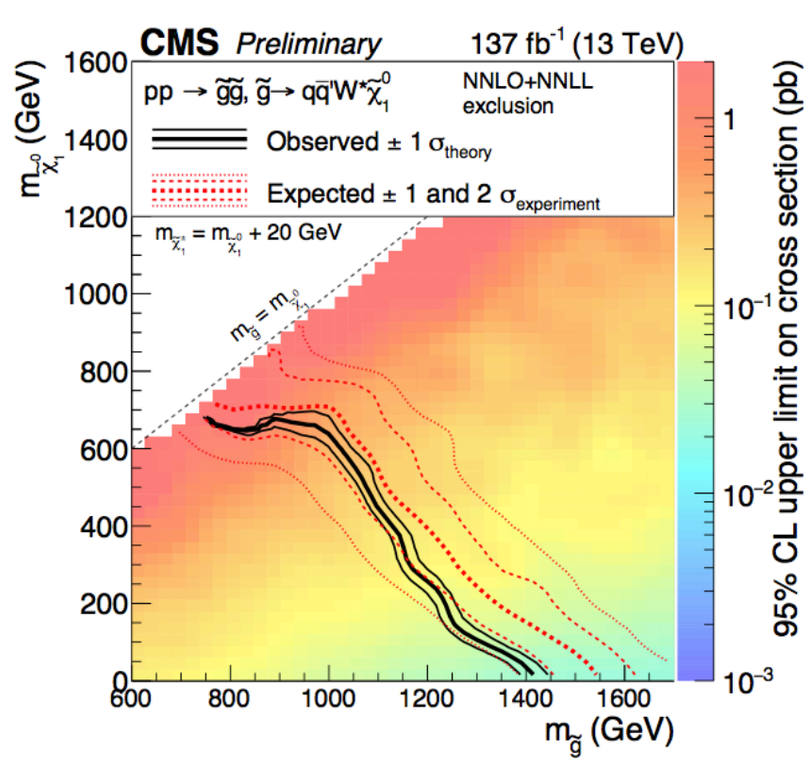




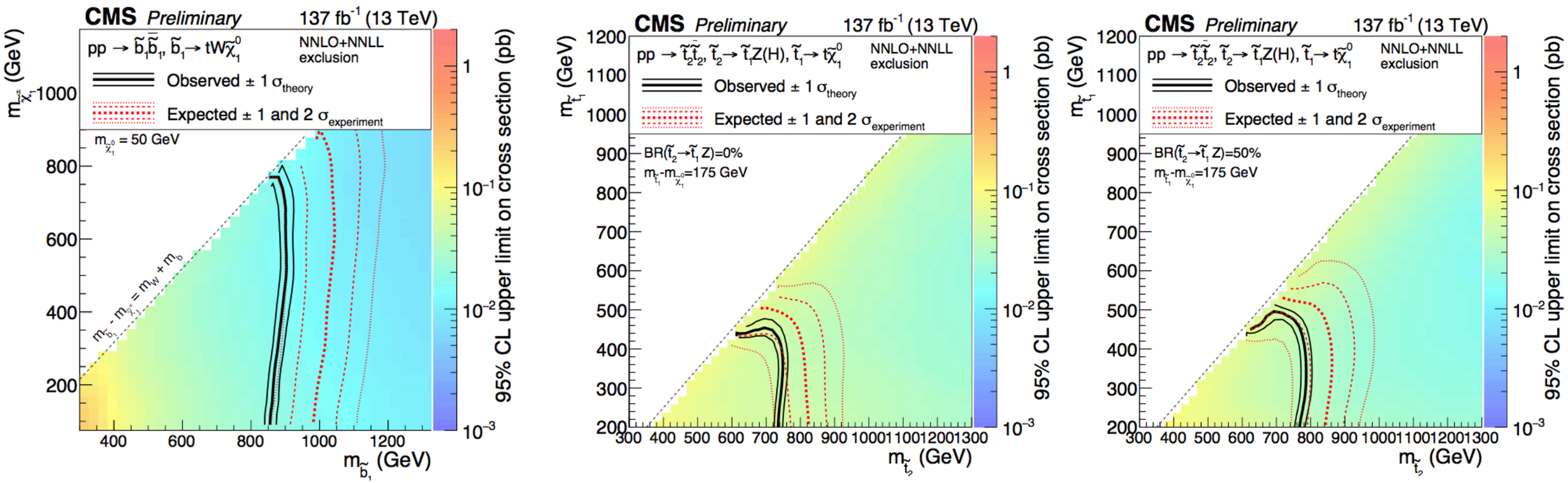








SS + multilepton



SS + multilepton

Table 7: Summary of the sources of uncertainty and their effect on the yields of different processes in the SRs. The first two groups list experimental and theoretical uncertainties assigned to processes estimated using simulation, while the last group lists uncertainties assigned to processes whose yield is estimated from data. The uncertainties in the first group also apply to signal samples. Reported values are representative for the most relevant signal regions.

Source	Typical uncertainty (%)	Correlation across years
Integrated luminosity	2.3-2.5	Uncorrelated
Lepton selection	$2-10$	Uncorrelated
Trigger efficiency	$2-7$	Uncorrelated
Pileup	$0-6$	Uncorrelated
Jet energy scale	$1-15$	Uncorrelated
b tagging	$1-10$	Uncorrelated
Simulated sample size	$1-20$	Uncorrelated
Scale and PDF variations	$10-20$	Correlated
Theoretical background cross sections	$30-50$	Correlated
Nonprompt leptons	30	Correlated
Charge misidentification	20	Uncorrelated

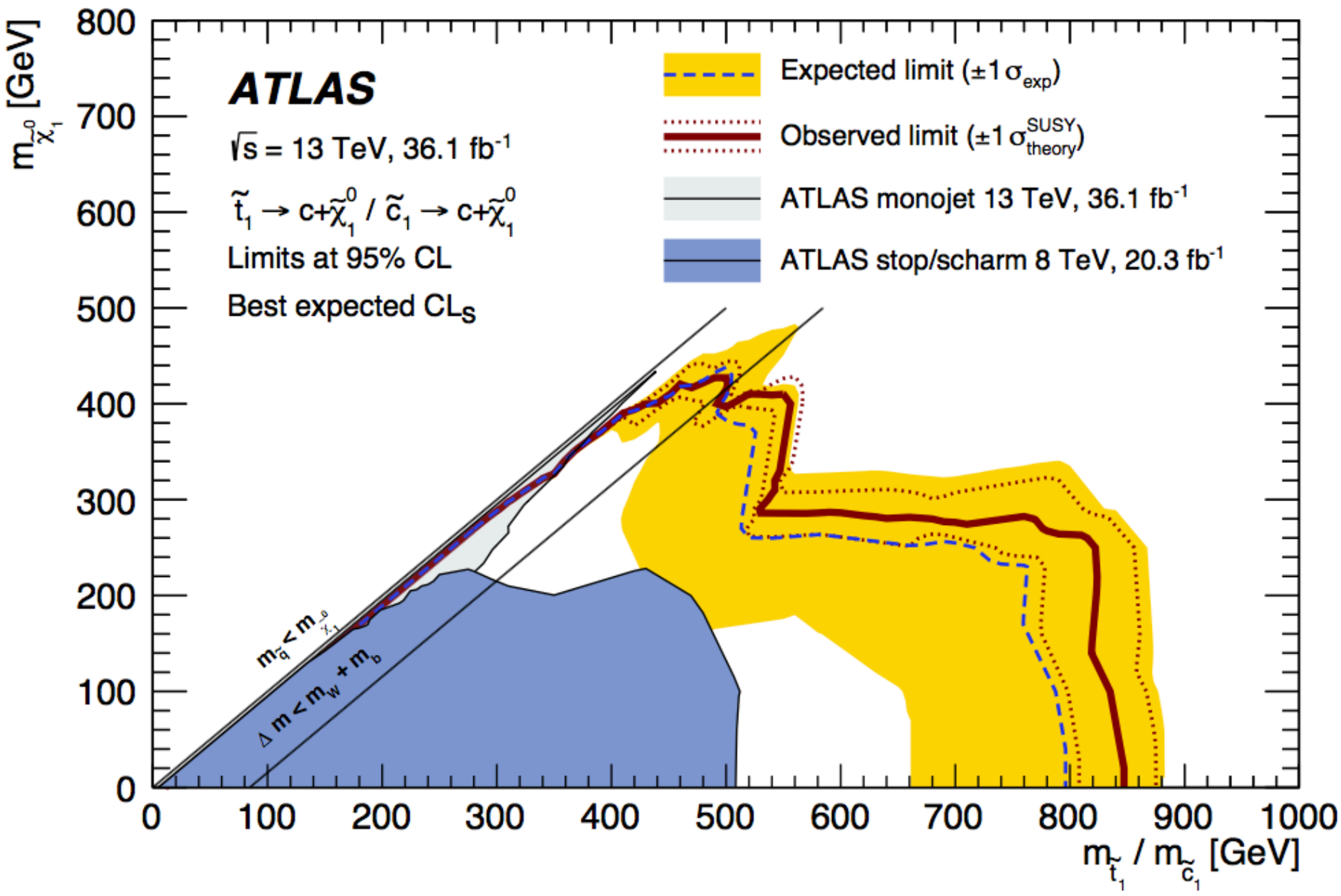
Stop with charm tagging

- A “tight” working point was adopted in the analysis, resulting in a charm-tagging efficiency of about 18%, a b-jet rejection factor of 20, a light-flavour jet rejection factor of 200, and a hadronic τ jet rejection factor of 6,

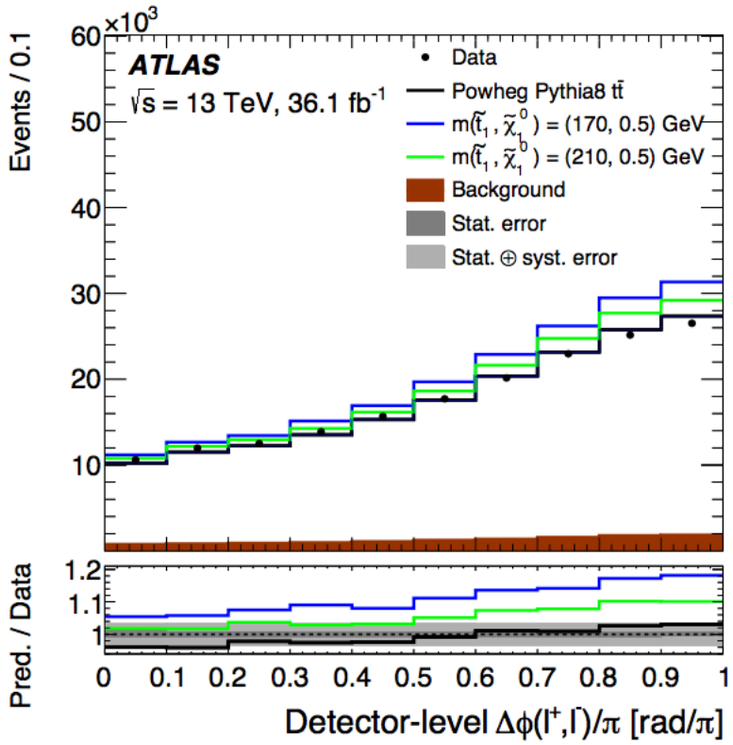
$$m_{\mathrm{T}}^{c} = \min_{c\text{-jets}} \sqrt{2 \cdot E_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{c} \cdot (1 - \cos \Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{c}))},$$

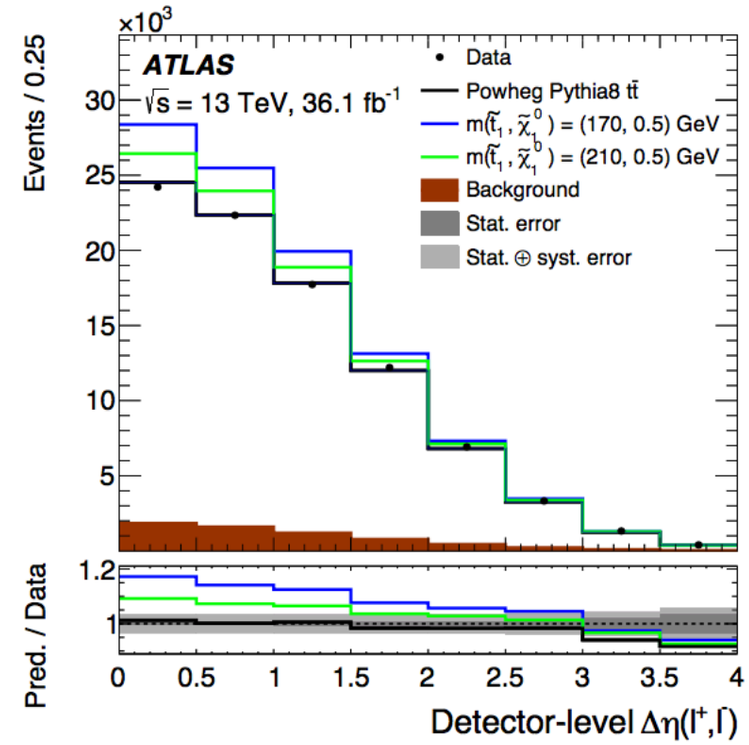
	SR1	SR2	SR3	SR4	SR5
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ triggers				
Leptons	0 e AND 0 μ				
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 500				
$\Delta\phi_{\mathrm{min}}(\mathrm{jet}, \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})$ [rad]	> 0.4				
$N_{c-\mathrm{jets}}$	≥ 1				
N_{jets}	≥ 2	≥ 3	≥ 3	≥ 3	≥ 3
Leading jet c-tag veto	yes	yes	yes	yes	no
$p_{\mathrm{T}}^{j_1}$ [GeV]	> 250	> 250	> 250	> 250	> 300
$p_{\mathrm{T}}^{j_2}$ [GeV]	–	–	> 100	> 140	> 200
$p_{\mathrm{T}}^{j_3}$ [GeV]	–	–	> 80	> 120	> 150
$p_{\mathrm{T}}^{c_1}$ [GeV]	< 100	> 60	> 80	> 100	> 150
m_{T}^{c} [GeV]	∈ (120, 250)	∈ (120, 250)	∈ (175, 400)	> 200	> 400

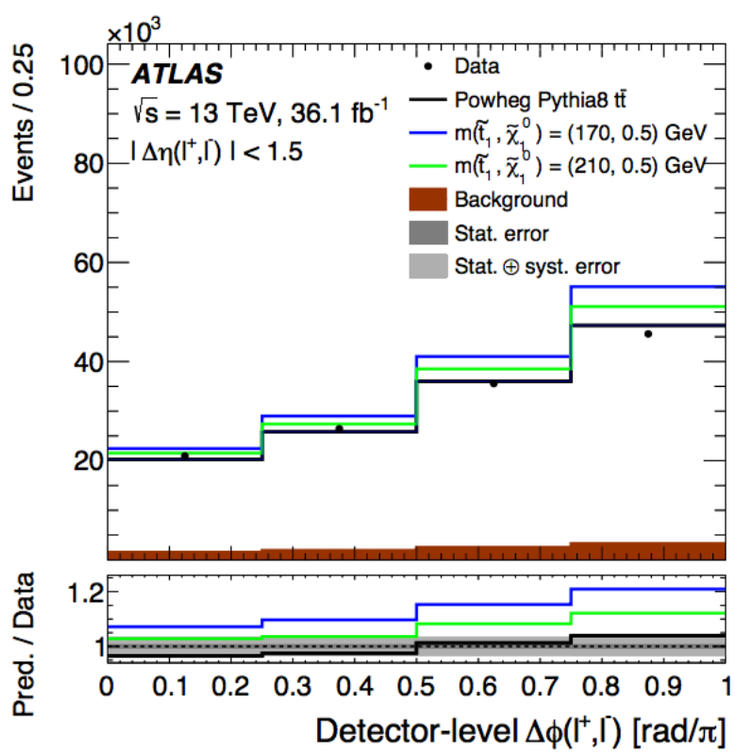
Stop with charm tagging

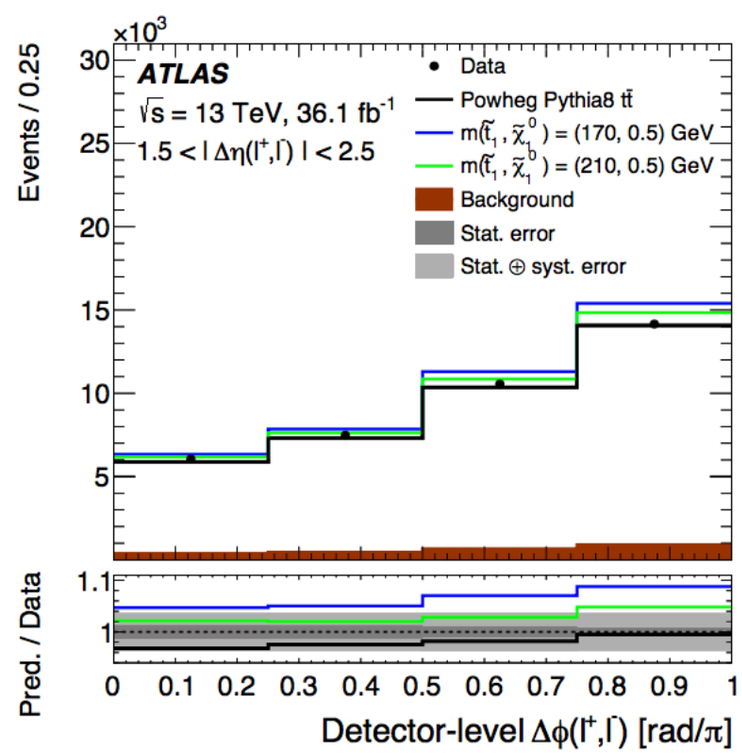


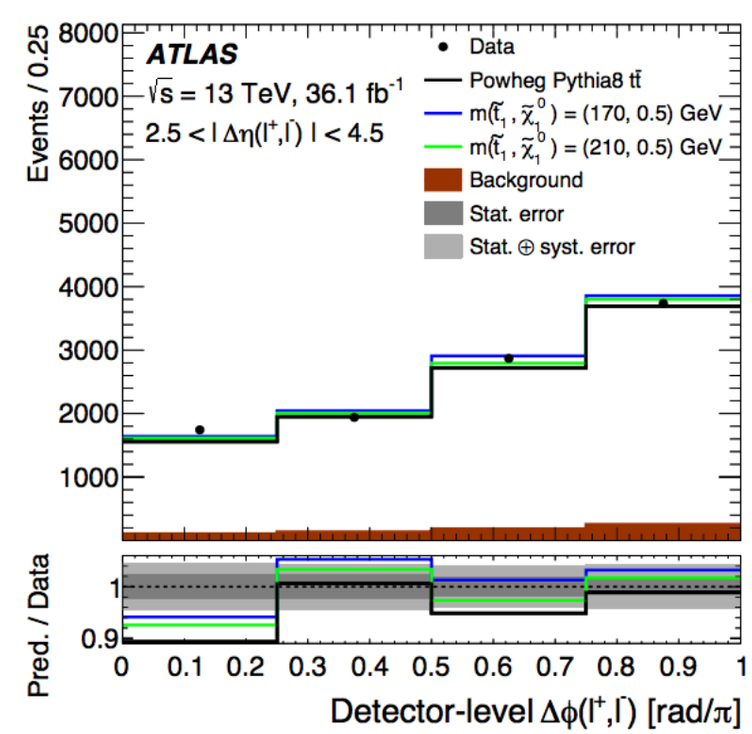
Spin correlations







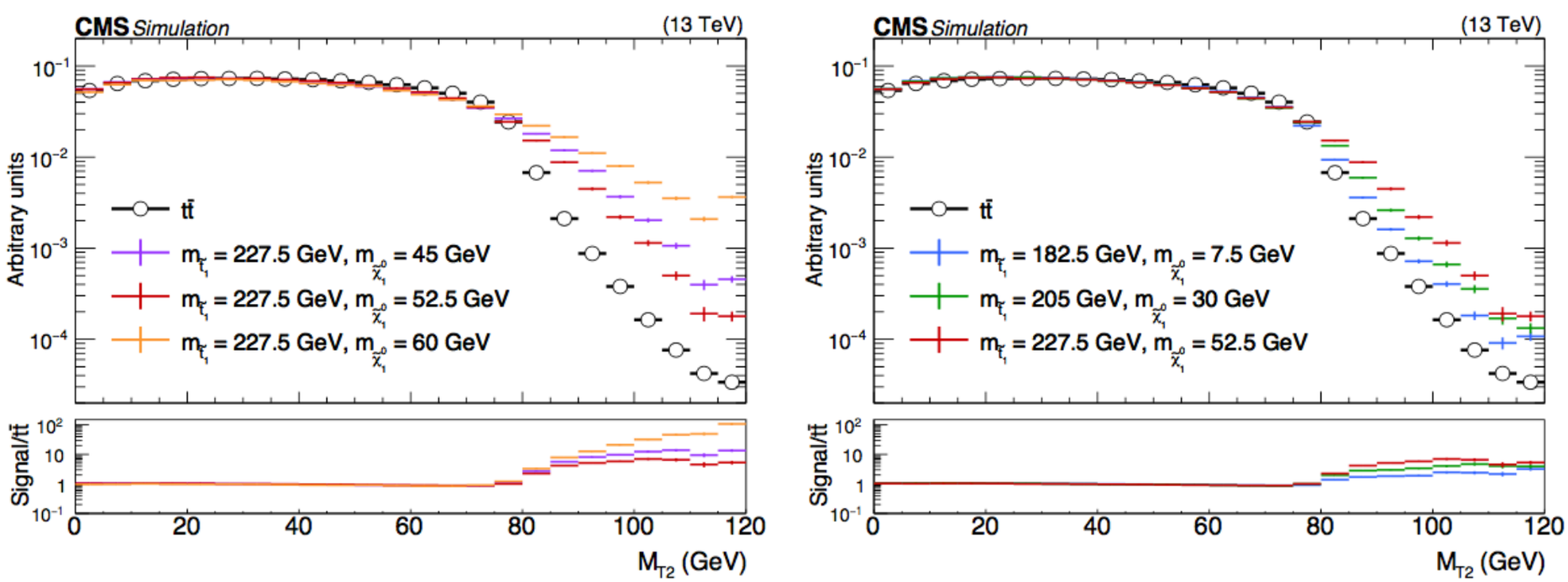




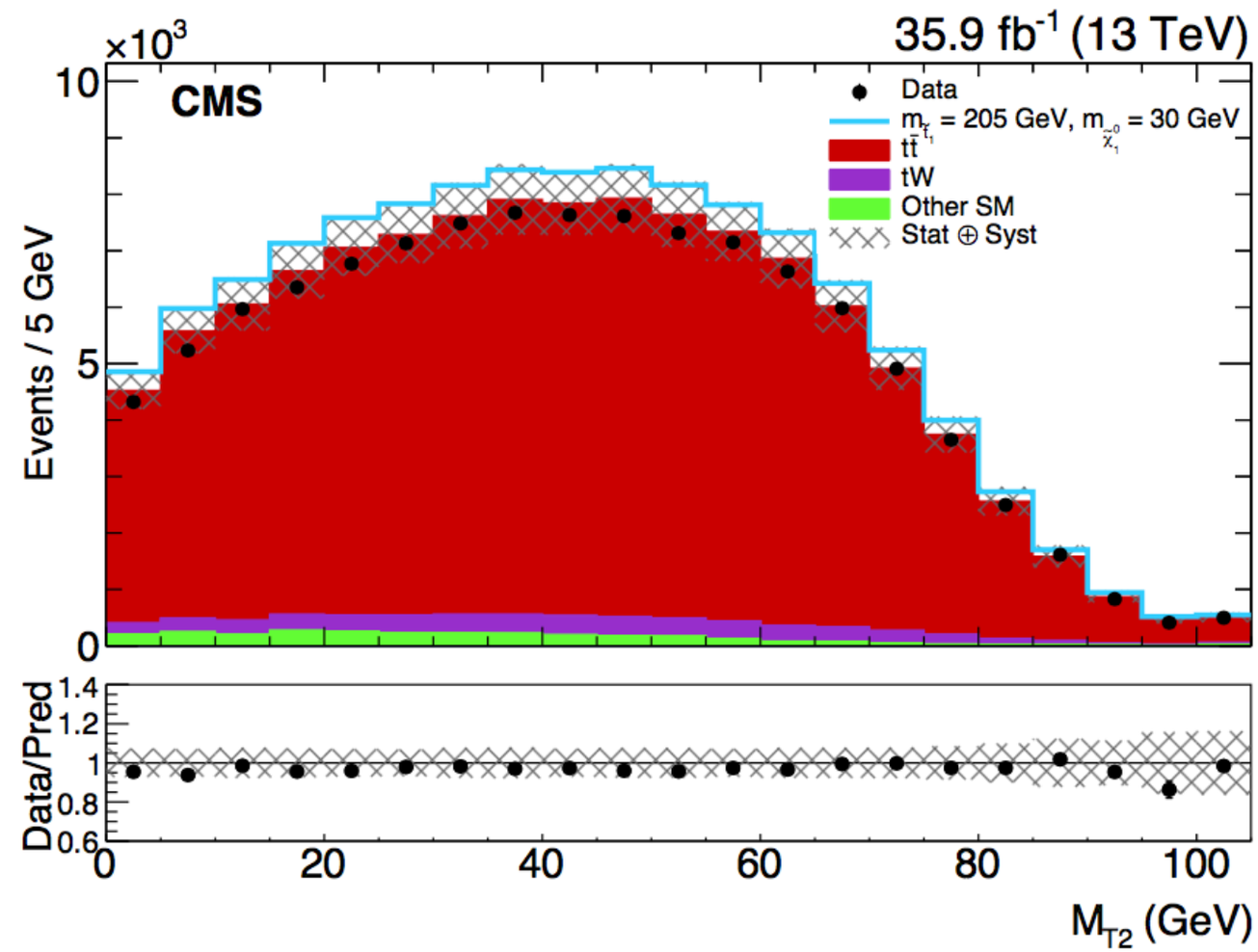
Top corridor — M_{T2}

- The sensitivity of the analysis comes from a precise estimate of the tt background, using MC simulation and exploiting the **6% [54] theoretical uncertainties** on the predicted cross section and the even smaller [31, 69] experimental uncertainties on the measurement. Additional sensitivity comes from the small kinematic differences between the target signal and the tt background, which become more important with increasing top squark mass and increasing mass difference between the top squark and neutralino.

$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T,1}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T,2}}^{\mathrm{miss}} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left(\max \left[m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\ell 1}, \vec{p}_{\mathrm{T,1}}^{\mathrm{miss}}), m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\ell 2}, \vec{p}_{\mathrm{T,2}}^{\mathrm{miss}}) \right] \right)$$

- 

Top corridor — M_{T2}

Source	Range (%)
μ_F and μ_R scales	0.3–1.0
PDF	≈0.6
Initial-state radiation	0.5–1.0
Final-state radiation	0.6–1.2
ME/PS matching (h_{damp})	0.3–2.0
Underlying event	≈0.8
Colour reconnection	≈1.5
Top quark p_T reweighting	0.1–0.5
Top quark mass (acceptance)	≈1.0

Source	Range for $t\bar{t}$ and signal (%)
Muon efficiencies	≈1.4
Electron efficiencies	≈1.5
Trigger efficiency	≈0.6
Lepton energy scale	0.5–2.0
Jet energy scale	1.5–3.0
Jet energy resolution	0.3–3.5
btagging efficiency	1.2–2.0
Mistag efficiency	0.2–0.6
Unclustered energy	0.5–1.5
Pileup	0.5–3.5