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in Hurghada,
Egypt
CMS
Compact Muon Solenoid
ATLAS
EXPERIMENT
Searches for squarks and gluinos in
R-parity conserving models at the LHC
Christina Agapopoulou, on behalf of the ATLAS and CMS collaborations

Supersymmetry in the standard model of particle physics

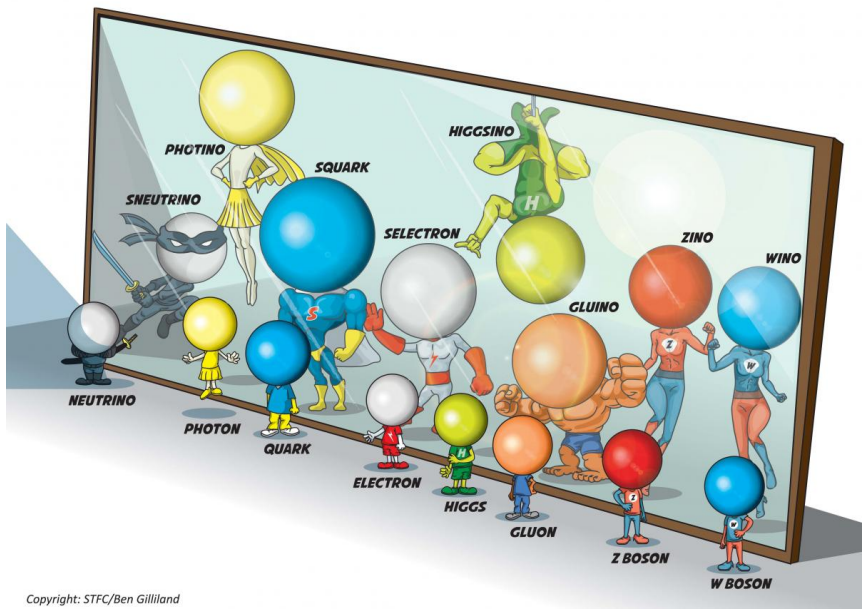
⋆ Supersymmetry, or SUSY, is an extension of the Standard model predicting a partner to each SM fundamental particle with spin differing by 1/2

⋆ a very thorough overview of SUSY and it's motivations given yesterday by Dr. Cem Salih Un

particles in the Minimum Supersymmetric Standard Model

leptons		sleptons ($\tilde{l}$)
quarks		squarks ($\tilde{q}$)
gluons	$\rightarrow$	gluinos ($\tilde{g}$)
W/Z		gauginos
Higgs		higgsinos

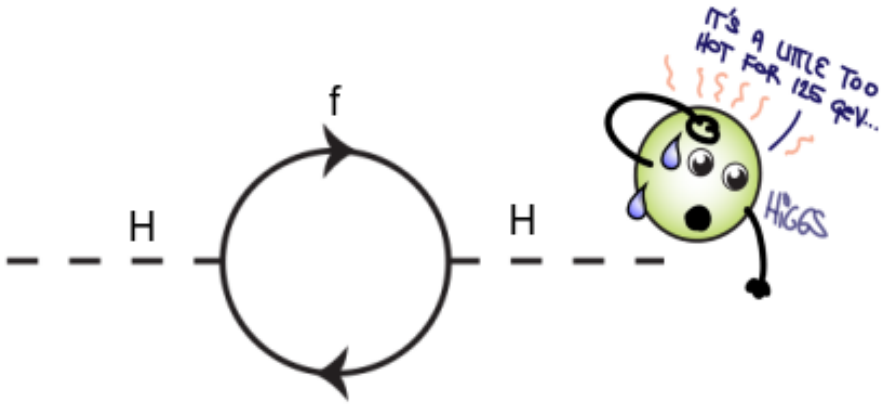
} mixing to form $\tilde{\chi}_i^0, \tilde{\chi}_j^{\pm}$



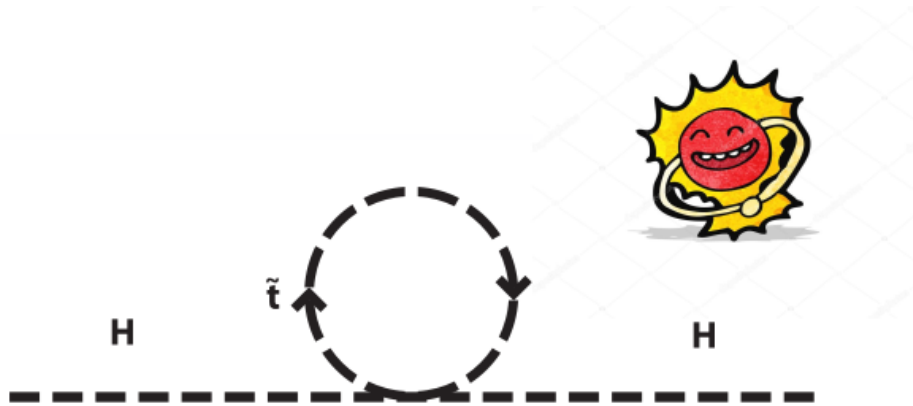
SUSY must be a broken symmetry $\rightarrow$ SUSY particles expected at high masses

Why the persistent interest in SUSY ?

⋆It provides possible solution to many shortcomings of the SM



- Hierarchy problem of the Higgs boson "lightness"



Why the persistent interest in SUSY ?

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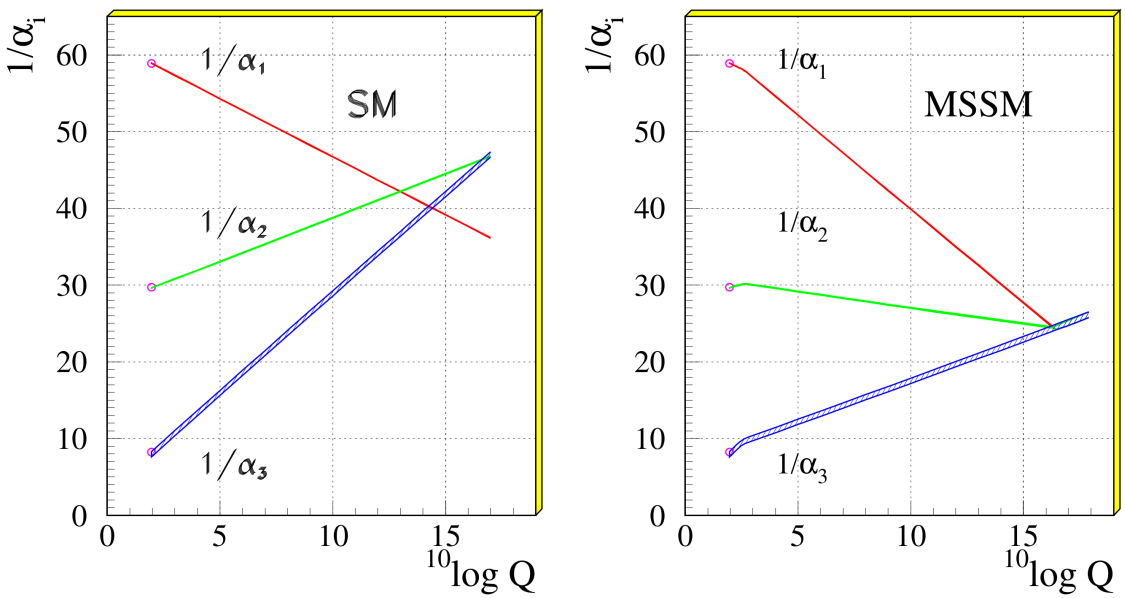
- Hierarchy problem of the Higgs boson "lightness"
- Grand unification

Unification of the Coupling Constants in the SM and the minimal MSSM



Supersymmetry in the standard model of particle physics

Why the persistent interest in SUSY ?

⋆It provides possible solution to many shortcomings of the SM

- Hierarchy problem of the Higgs boson "lightness"
- Grand unification
- In case of R-parity* conservation, it provides a WIMP-like dark matter candidate!

⋆ R-parity is an ad-hoc symmetry imposing that SUSY particles are produced and decay in pairs.

- Introduced to impose conservation of lepton/baryon number
- Lightest SUSY particle is neutral, stable and weakly interacting → excellent DM candidate

Supersymmetry in the standard model of particle physics

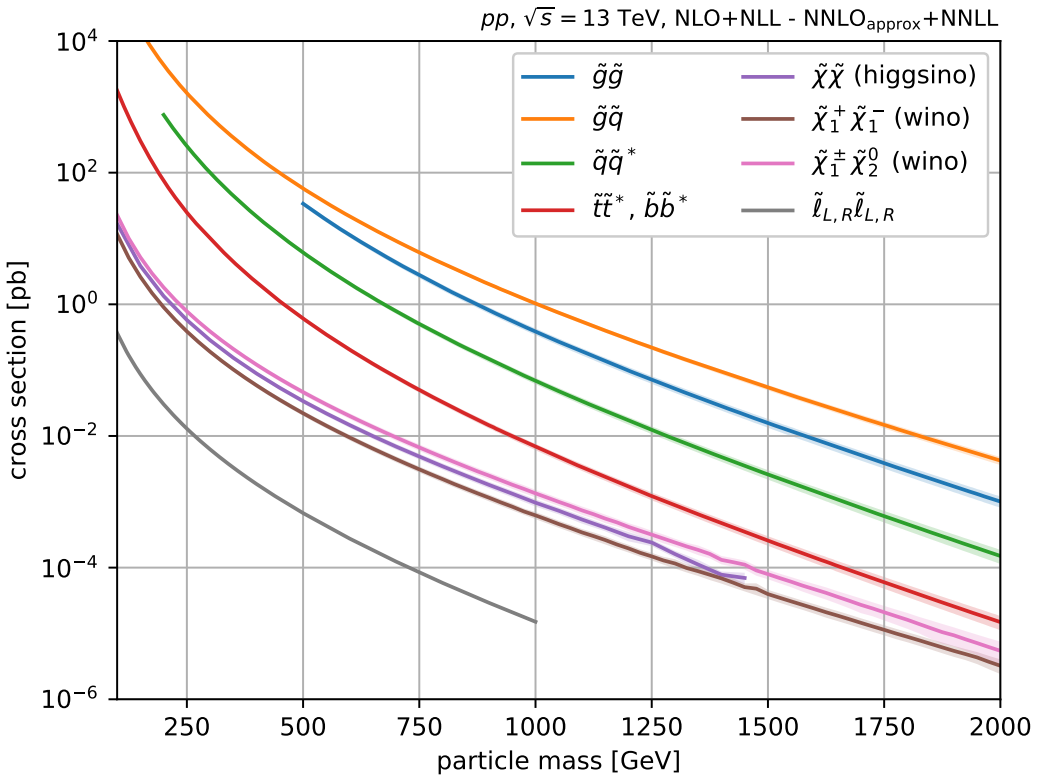
Why the persistent interest in SUSY ?

⋆It provides possible solution to many shortcomings of the SM

- Hierarchy problem of the Higgs boson "lightness"
- Grand unification
- In case of R-parity* conservation, it provides a WIMP-like dark matter candidate!
- it's a benchmark model !

Why search for squarks and gluinos?

- (Why not?)
- At the LHC, for a fixed mass squarks and gluinos have the highest expected production cross section



Let's simplify things

Even the minimal SUSY model (MSSM) has $\sim$ O(100) free parameters ! How can we constrain such a vast phase-space?

$\star$ simplified models!

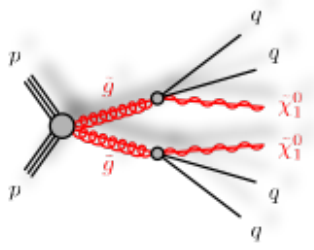
- most LHC analyses today target SUSY in this simplistic way
- 2/3 s-particles per model and rest of the SUSY spectrum effectively decoupled
- decay BRs to desired SM signatures often assumed to be 100%

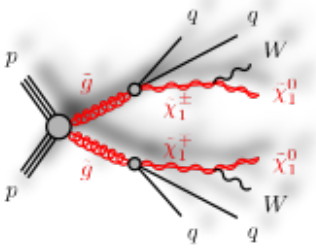
$\star$ Full picture much more complicated

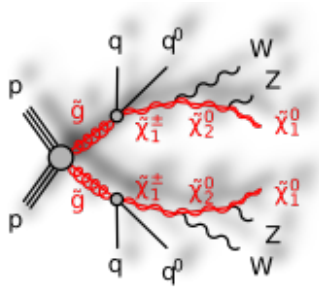
- coupling with extra s-particles + smaller BRs can reduce x-section
- simplified model limits should be taken with a grain of salt!

So many models.. How to group them?

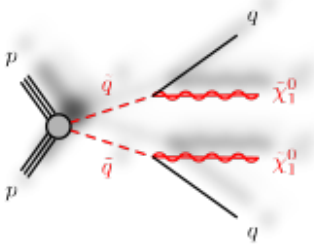
Gluinos

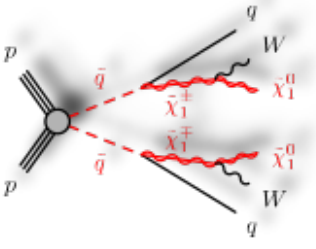




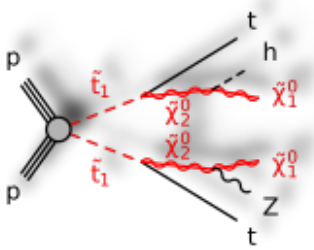


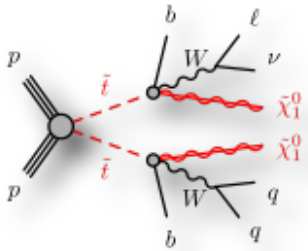
Squarks

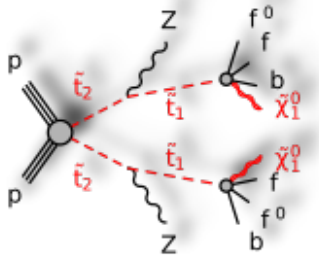


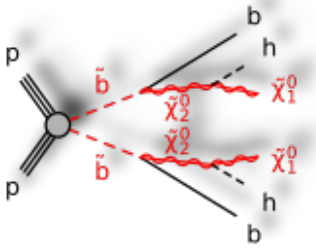


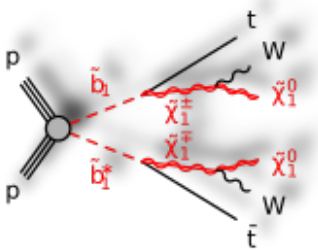
3rd Generation



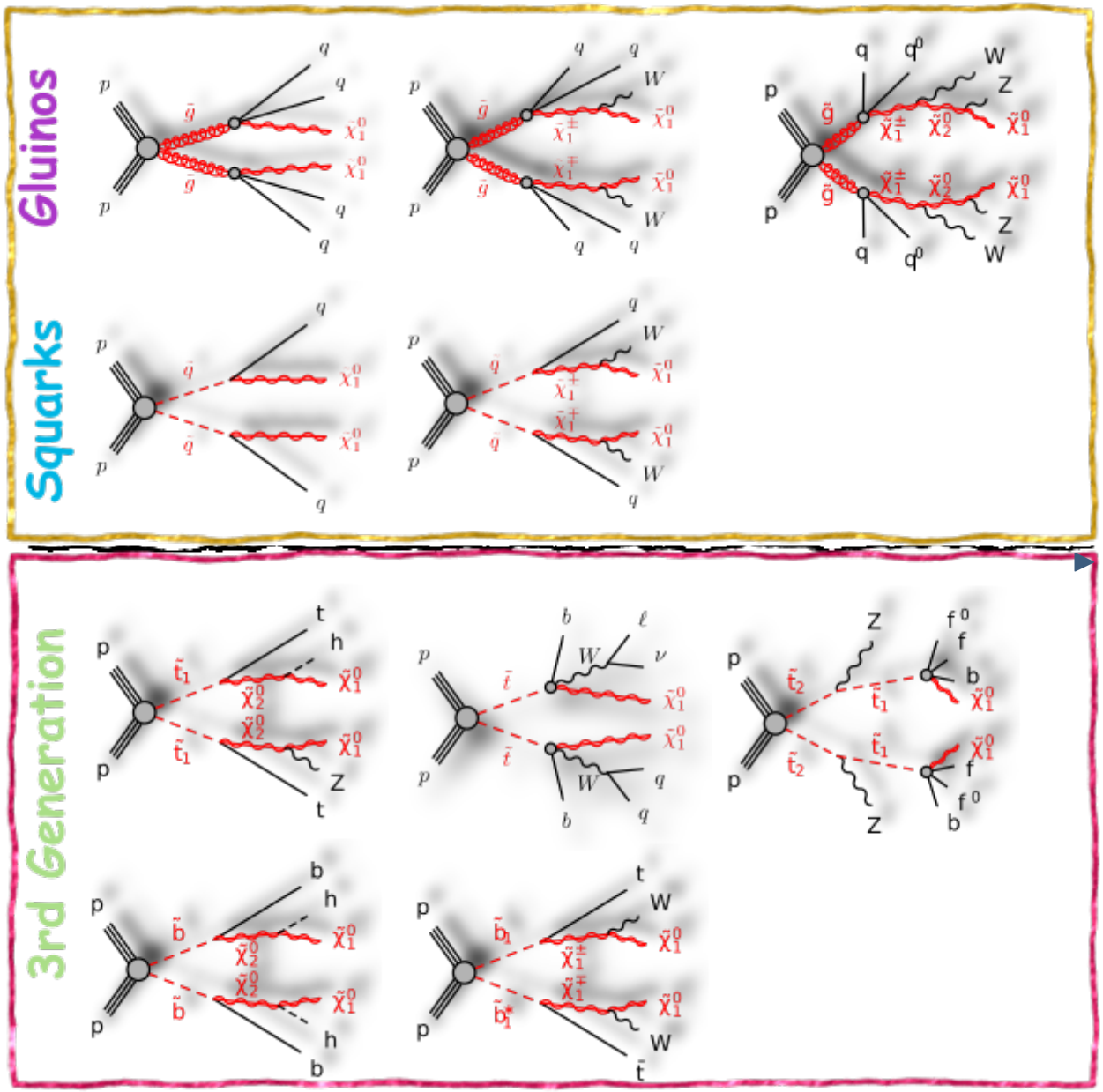






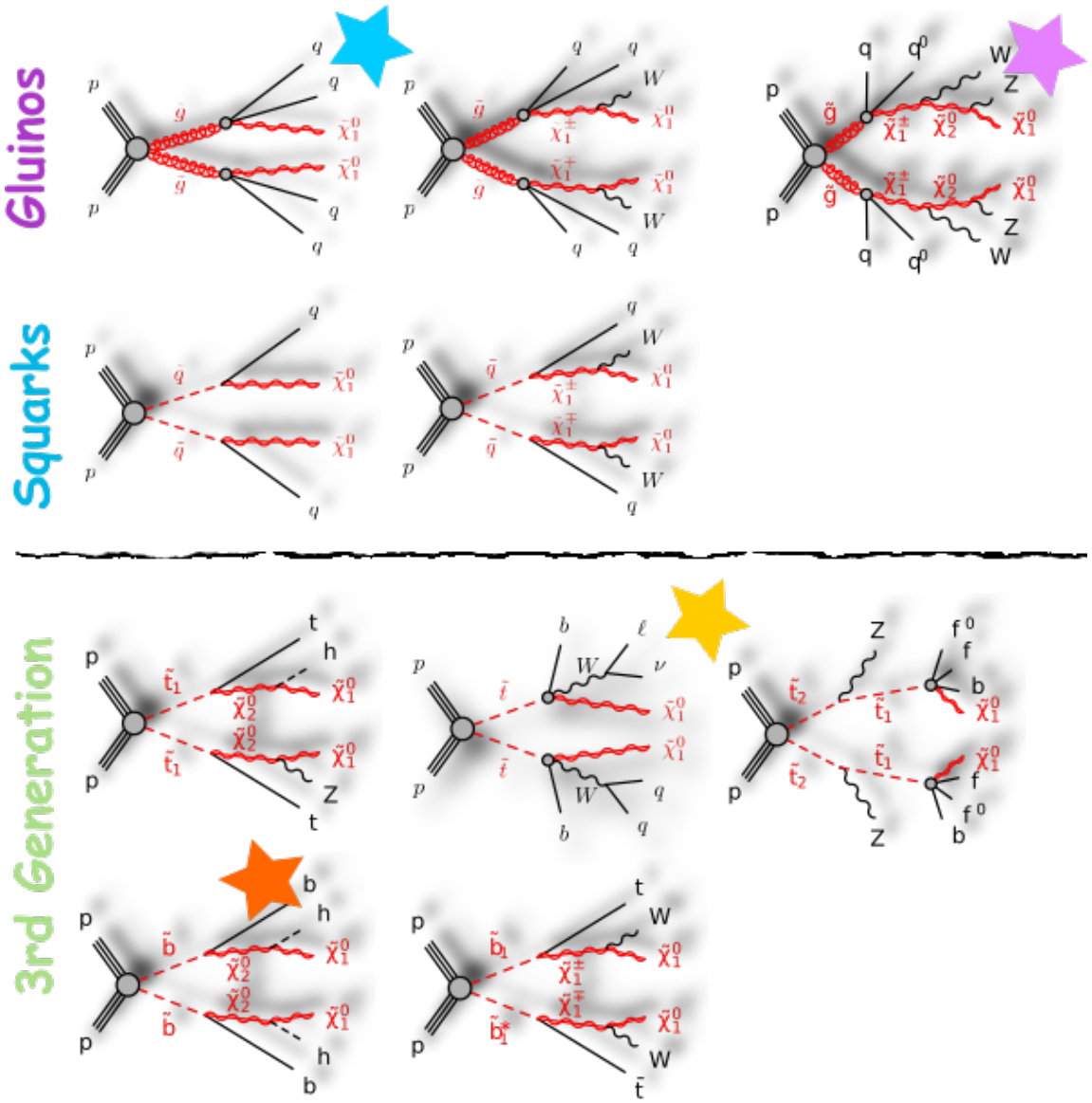


So many models.. How to group them?



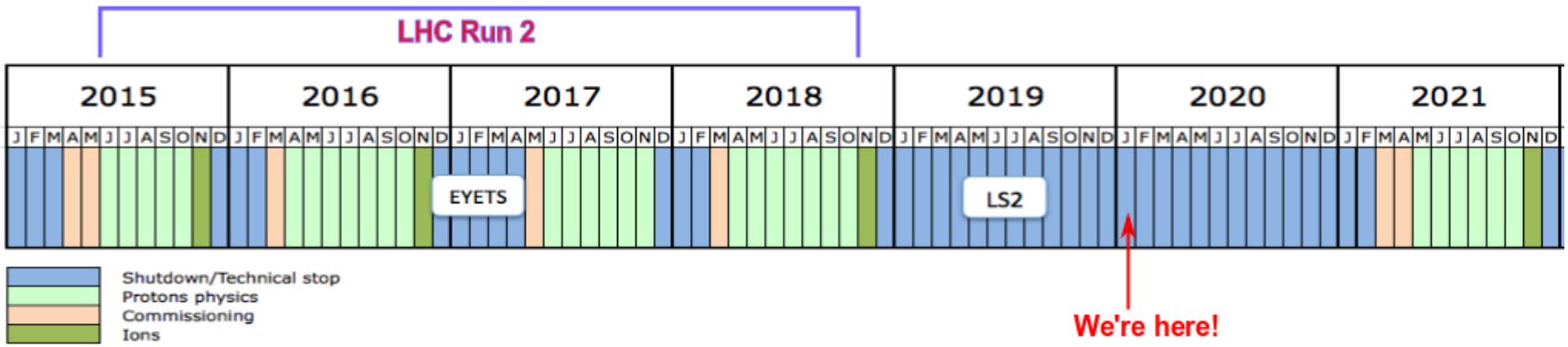
Inclusive vs targeted

So many models.. How to group them?

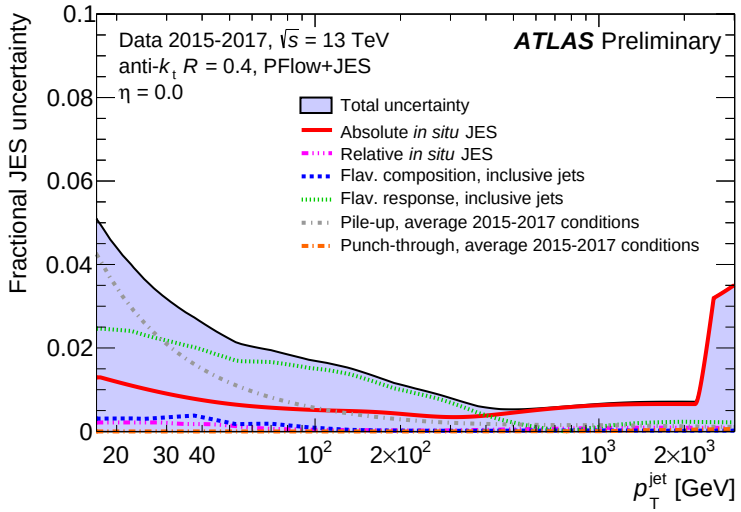


- Inclusive vs targeted
- Specific final state:
  - hadronic activity (jets)
  - number of leptons
  - V bosons
  - 3rd generation specifics (b-jets, top id)
  - Higgs boson
  - ...

The Run2 program of LHC



- both ATLAS and CMS recorded $\sim$ 140 fb^{-1} of physics-worthy data
- luminosity and detector performances exceeded expectations
- many SUSY analyses published mid-Run with partial datasets $\rightarrow$ no significant deviations from the SM were observed :(



⋆ **Disclaimer: only analyses using the full Run 2 datasets are shown in this presentation**

The time for innovation

Taking advantage of the large amount of collected data, new analysis techniques can be tried out!

CMS public results

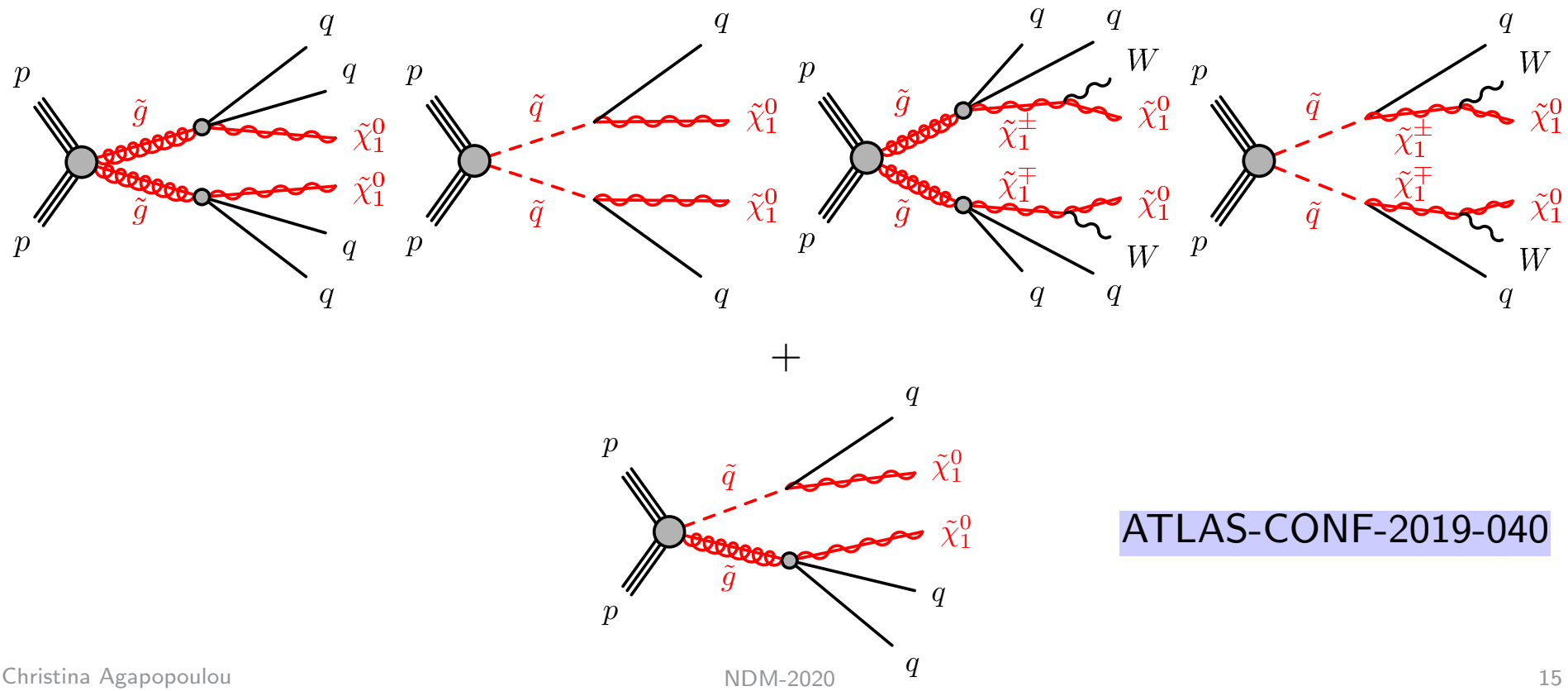
ATLAS public results

Inclusive searches

A case study: 0L, jets + $\mathrm{E_T^{miss}}$ from ATLAS

RPC search for gluinos and squarks (1st + 2nd generation only)

- neutralino is LSP
- 2-6 jets
- no leptons
- large E_T^{miss} from the escape of the neutralino



ATLAS-CONF-2019-040

A case study: 0L, jets + $\mathrm{E_T^{miss}}$ from ATLAS

Key variable

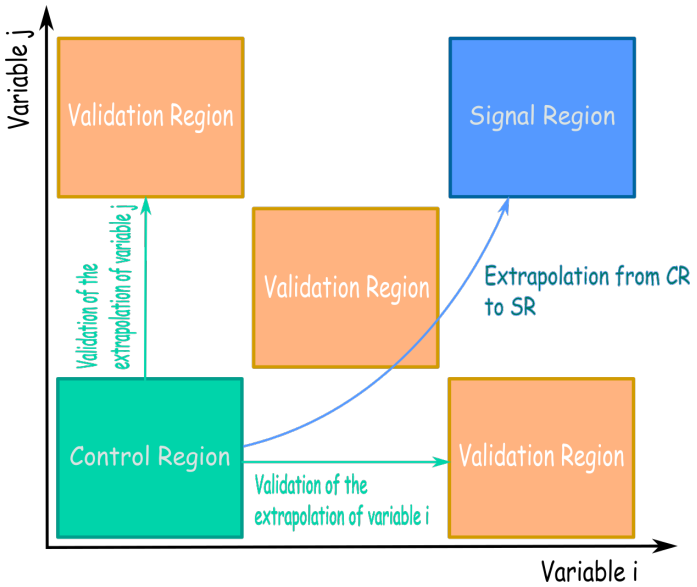
$$\mathrm{m_{eff}} = |\mathrm{E_T^{miss}}| + \sum_{\mathrm{j=1}}^{\mathrm{n}} |\mathrm{p_T^j}| + \sum_{\mathrm{l=1}}^{\mathrm{n}} |\mathrm{p_T^l}|$$

Analysis strategy: 2 complementary approaches

- ⋆ Multi-bin fit based on "traditional" variables
  - takes advantage of signal / bkg shape
  - 3-D binning in N_j, $\mathrm{m_{eff}}$, $\mathrm{E_T^{miss}}/\sqrt{\mathrm{H_T}}$ → O(100) bins
  - 3 separate strategies for direct squark, direct gluino and compressed spectrum
- ⋆ Boosted Decision Tree (BDT)
  - cut & count approach
  - introduce BDT variable built from ∼ 10 kinematic variables
  - targetting gluino direct/one-step decays

A case study: 0L, jets $+E_T^{miss}$ from ATLAS

Main backgrounds: Z+jets, W+jets, $t\bar{t}$ + single-t, multi-jet QCD

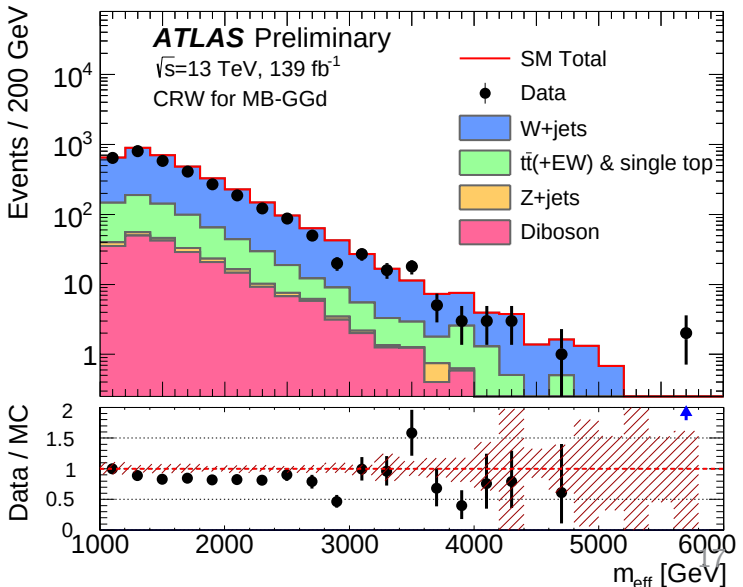


⋆ For most backgrounds, MC simulation is used

- mismodelling / detector effects can bias MC estimate
- build dedicated Control Regions (CRs)
  - pure in target SM background + no signal
  - orthogonal to SRs
  - comparison of MC to data in CRs → correction factors

⋆ The extrapolation from CR to SR can be validated

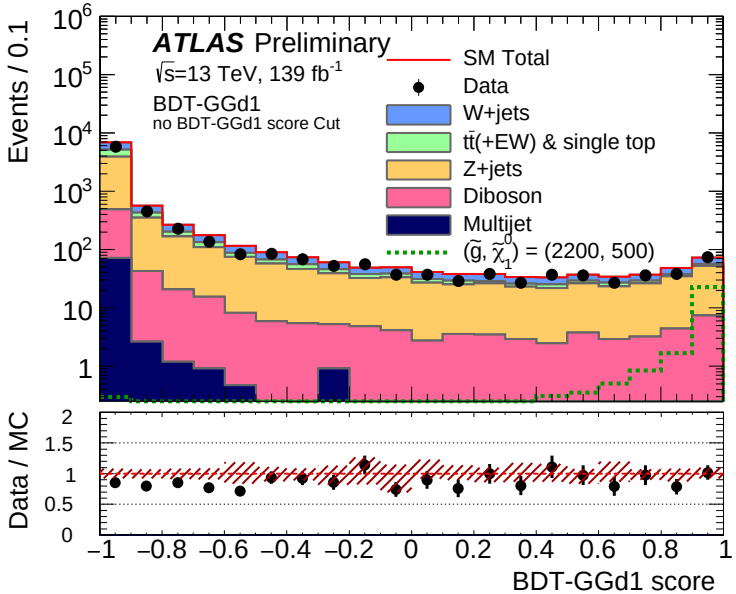
- in "intermediate" regions (VRs)

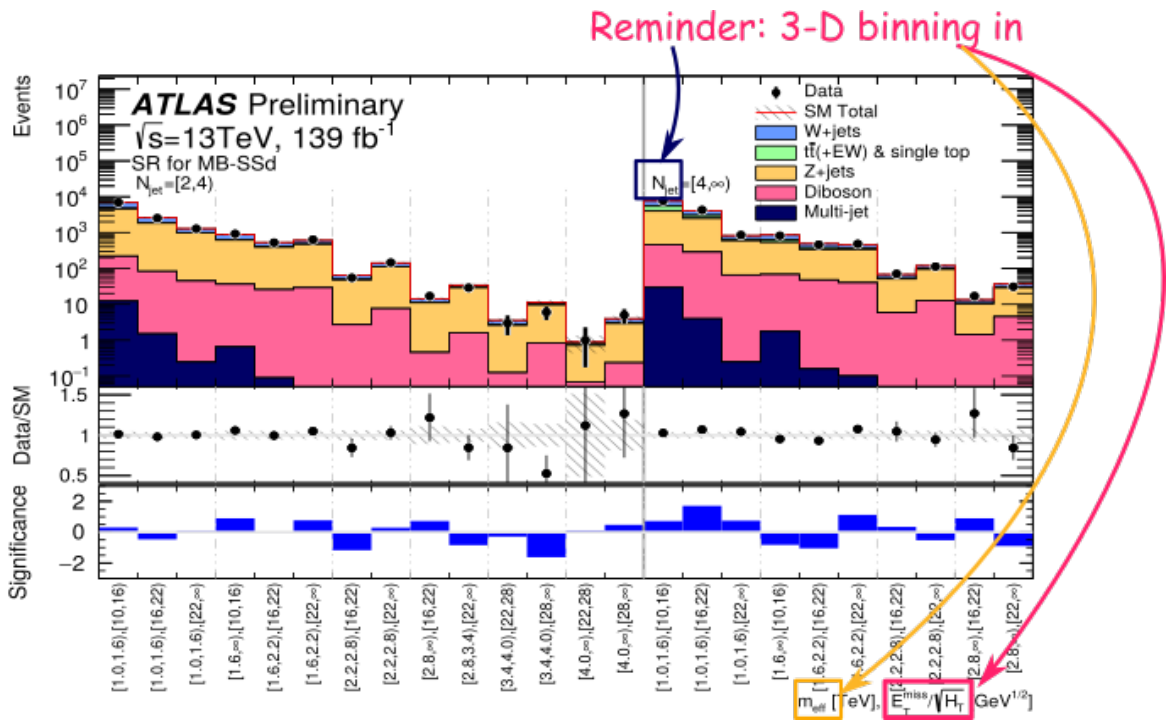


A case study: 0L, jets + E_T^{miss} from ATLAS

⋆ Results:

- no significant excess from SM prediction :(

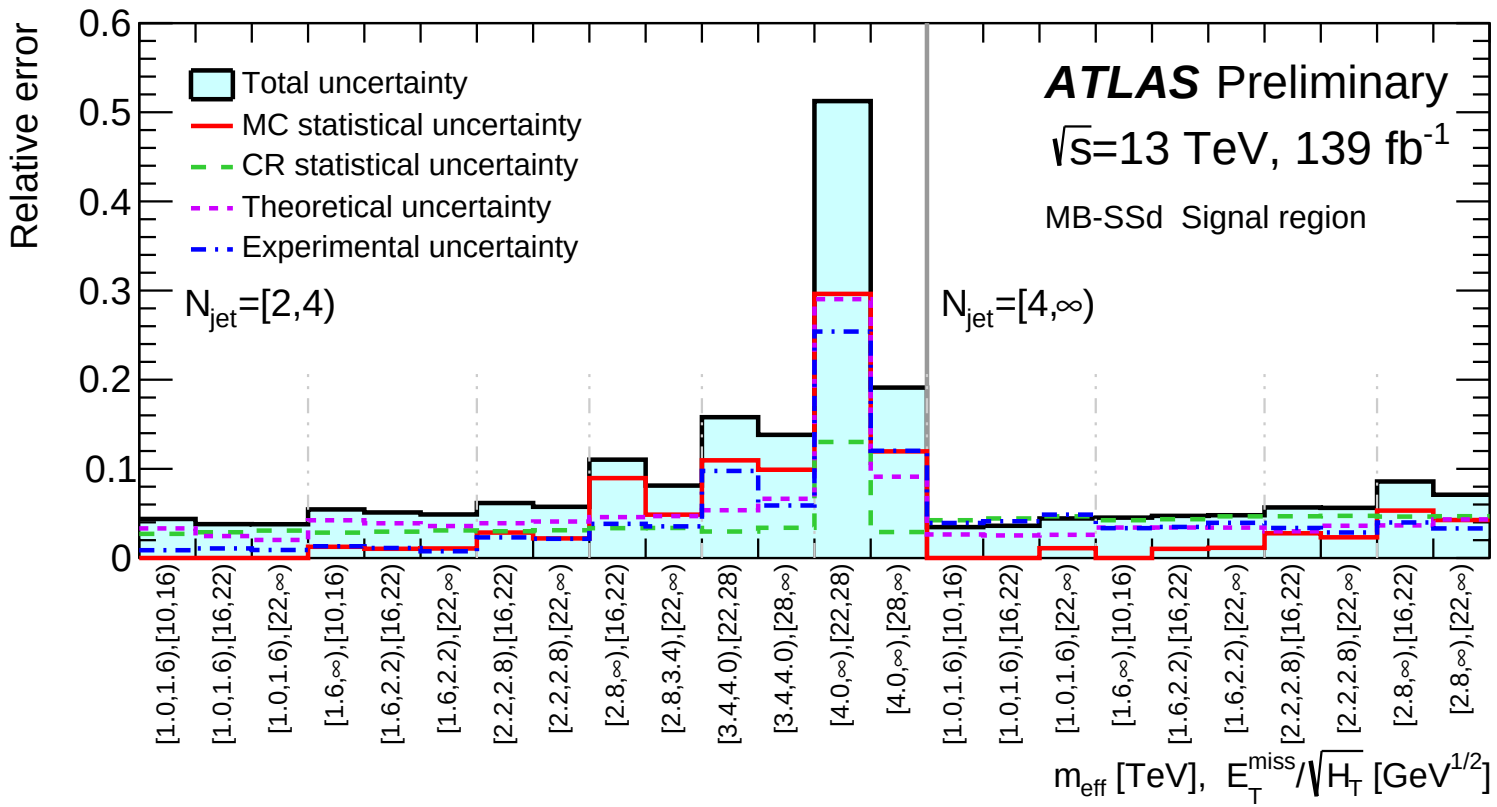




A case study: 0L, jets + $\mathrm{E_T^{miss}}$ from ATLAS

⋆ In many cases, dominant sources of systematic uncertainty are:

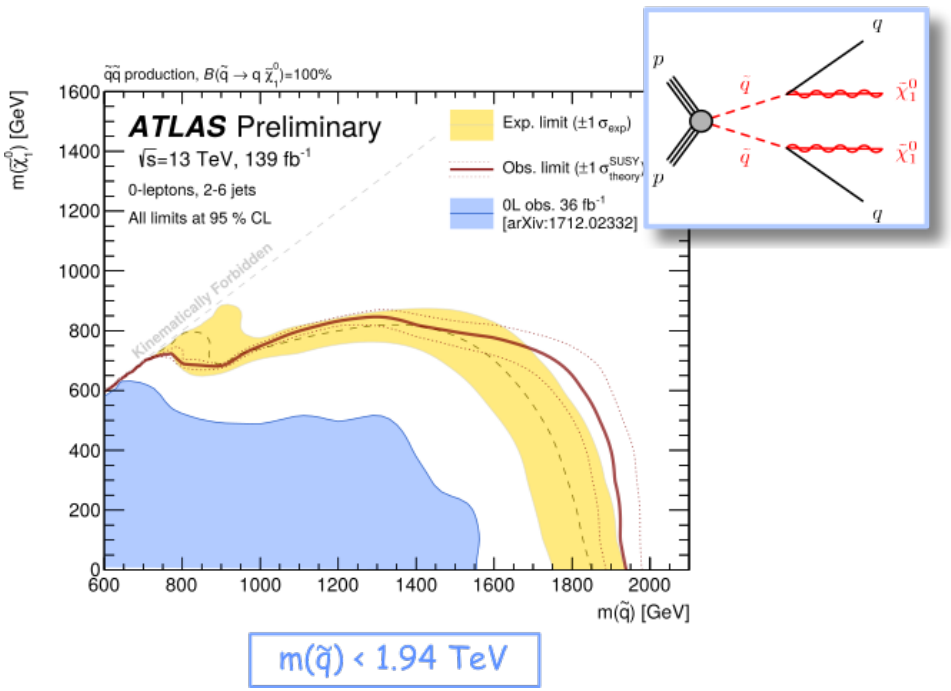
- CR/MC sample statistical uncertainty
- modelling of SM backgrounds
- JES/JER

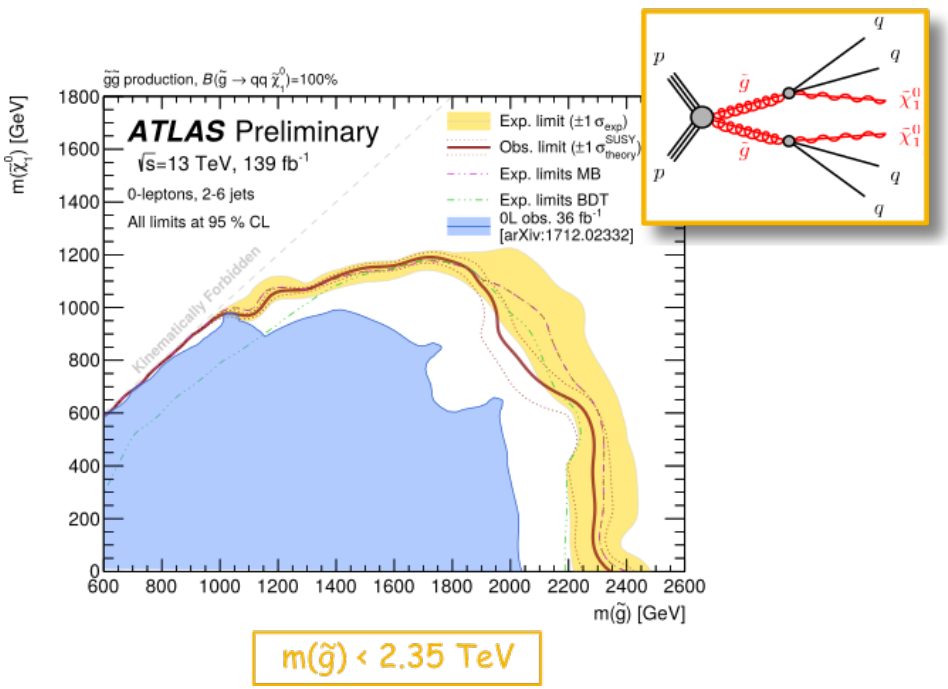


A case study: 0L, jets + $\mathrm{E_T^{miss}}$ from ATLAS

No excess in SRs $\rightarrow$ limits on potential models can be placed!

- exclusion limits from best SR per SUSY mass point
- for $\tilde{q}\tilde{q}$ grid, 8-fold $\tilde{q}$ degeneracy is assumed





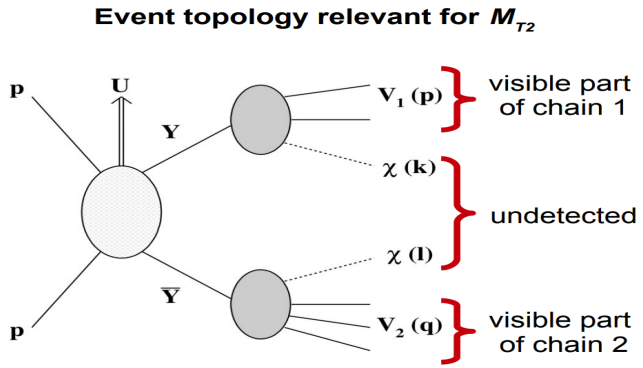
0L, jets + $\mathrm{E_T^{miss}}$ from CMS: CMS-SUS-19-006

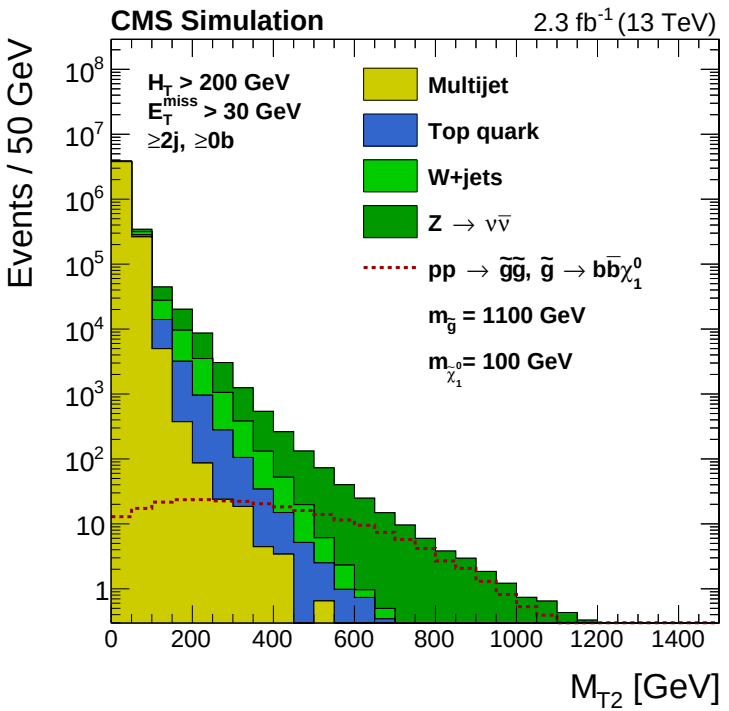
0L, MT2 + disappearing tracks CMS

the M_{T2} variable:

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

- group jets until two stable large-R jets are constructed
- decompose $\vec{p}_T^{\,miss}$ to take into account the 2 neutralinos
- compute transverse mass $M_T^{(i)}$* from pairing either of the two jets to either of the two p_T^{miss} components
- $M_{T2} \leq m_{SUSY}$
- low values for multijet events





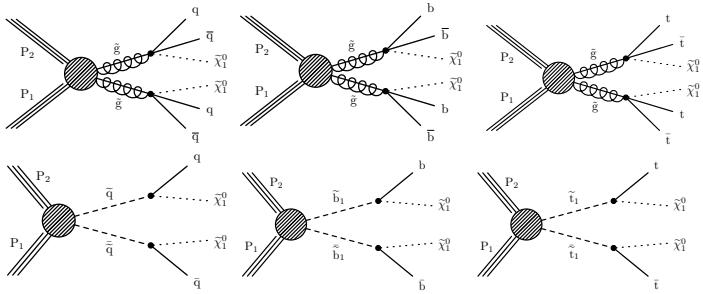
$$*M_T = \sqrt{2 p_T^J p_T^{miss} [1 - \cos(\Delta\phi_{J,p_T^{miss}})]}$$

0L, MT2 + disappearing tracks CMS

CMS-SUS-19-005

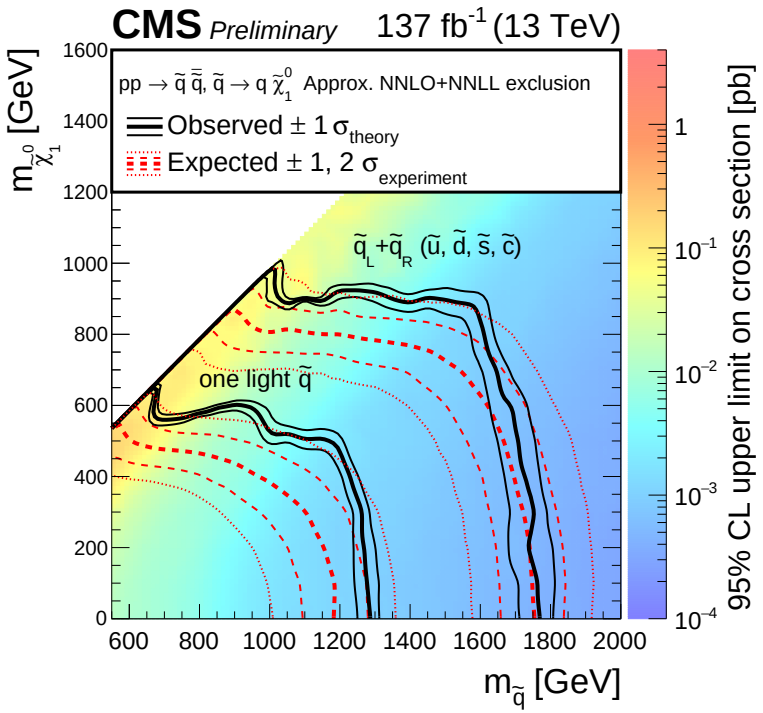
2 searches for $\tilde{g}$,$\tilde{q}$ (all generations):

- inclusive 0l + jets with M_{T2} variable
- long-lived $\tilde{\chi}_1^{\pm}$ based on disappearing tracks



M_{T2} inclusive:

- ⋆ SRs binned in Nj, N$_b$, H$_T$ and M_{T2} (or p_T^{jet} for N$_j$=1)
- ⋆ SM Background
  - lost lepton: estimated from 1L CRs
  - Z$\rightarrow \nu\nu$: from Z$\rightarrow ll$
  - QCD: data driven technique (rebalance and smear)



0L, MT2 + disappearing tracks CMS

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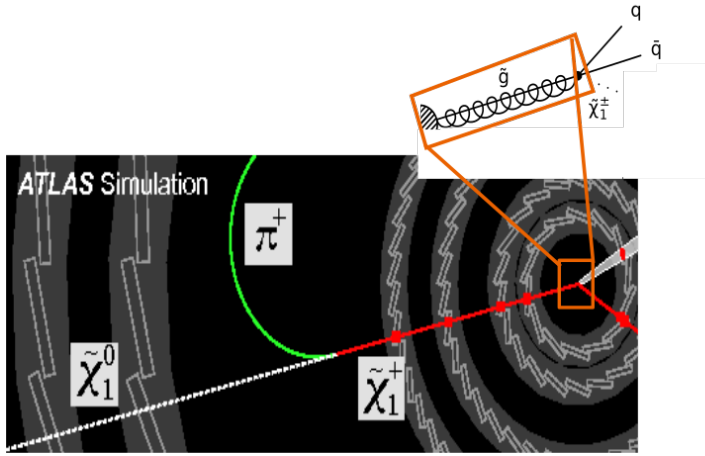

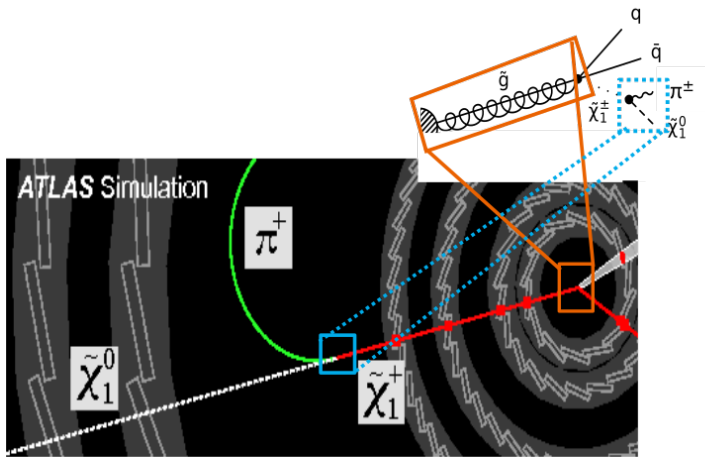

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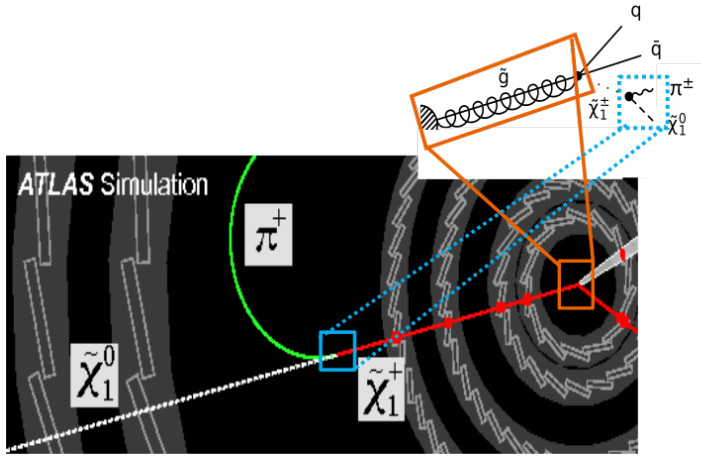
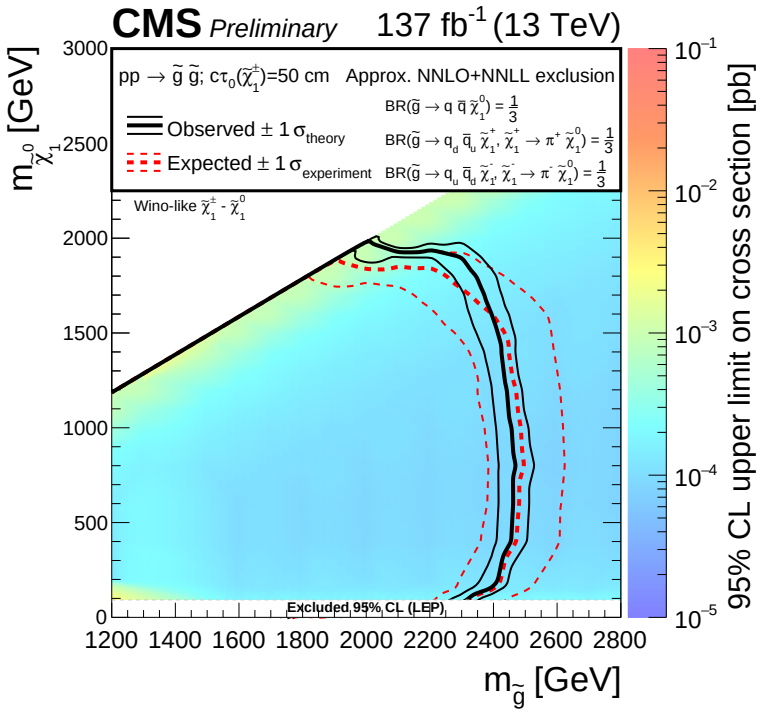


Disappearing tracks:

★ Event selection
- tracks with no outer-layer hits and no calo deposit
- SRs split to various track lengths to probe different life times

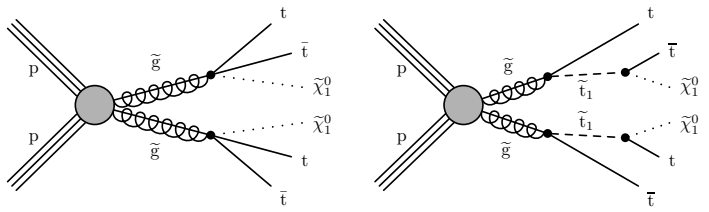
★ SM Background
- poorly reconstructed objects
- incorrect combinatorics



1L, large radius jets, CMS

CMS-SUS-19-007

search for $\tilde{g}$ in final states with 1l, p_T^{miss} and high N_j



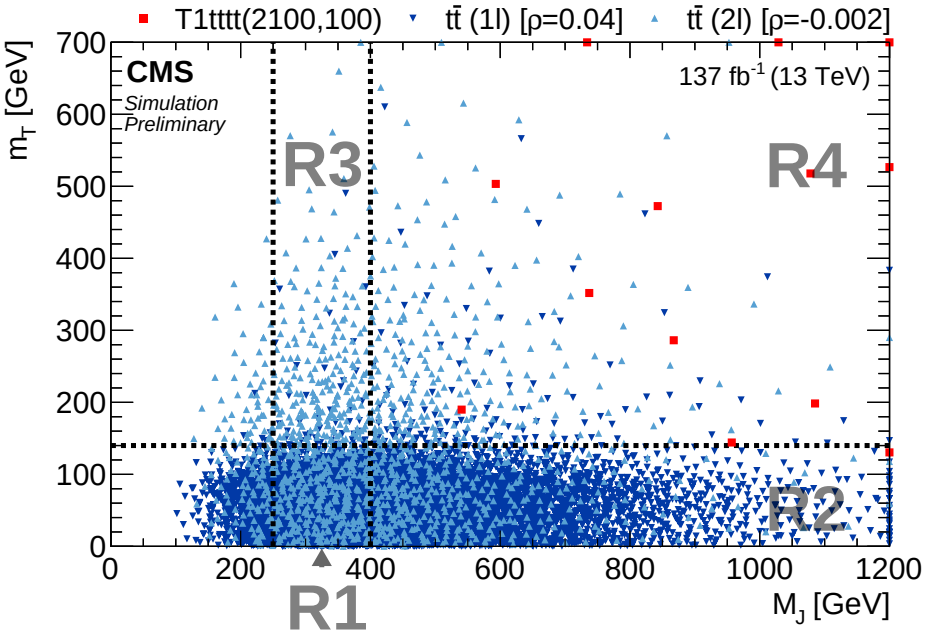
Analysis strategy: 2 key variables

$$m_T = \sqrt{2 p_T^l p_T^{miss} [1 - \cos(\Delta\phi_{l,p_T^{miss}})]}$$

$$M_J = \sum_{J_i = \text{large-R jets}} m(J_i)$$

Main background: SM $t\bar{t}$

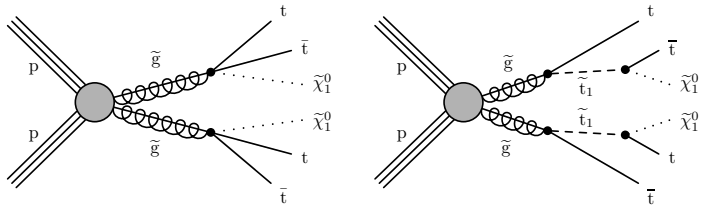
- ⋆ m_T and M_J uncorrelated for SM $t\bar{t}$
- ⋆ correlated for signal



1L, large radius jets, CMS

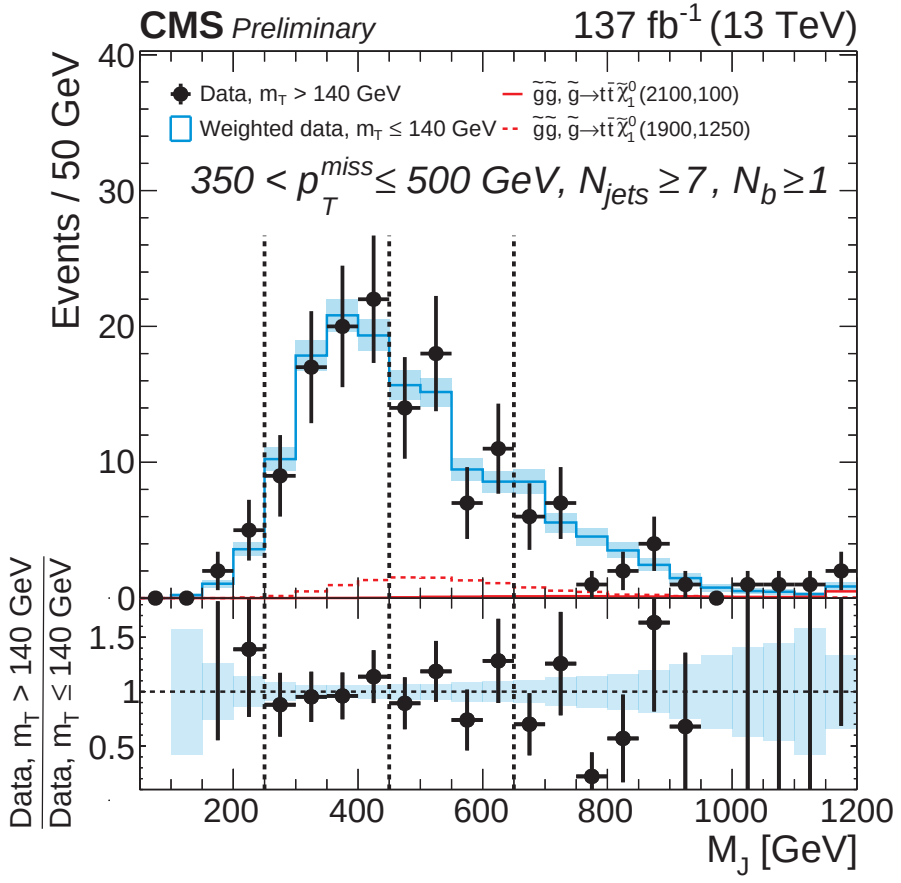
CMS-SUS-19-007

search for $\tilde{g}$ in final states with 1l, p_T^{miss} and high N_j



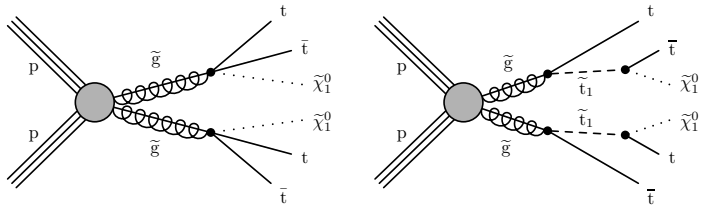
Signal regions:

- ⋆ binning of $\mathrm{M_J}$-$\mathrm{m_T}$ plane in N_j, N_b, p_T^{miss}
- ⋆ background from dedicated CRs
- ⋆ No significant deviation from SM



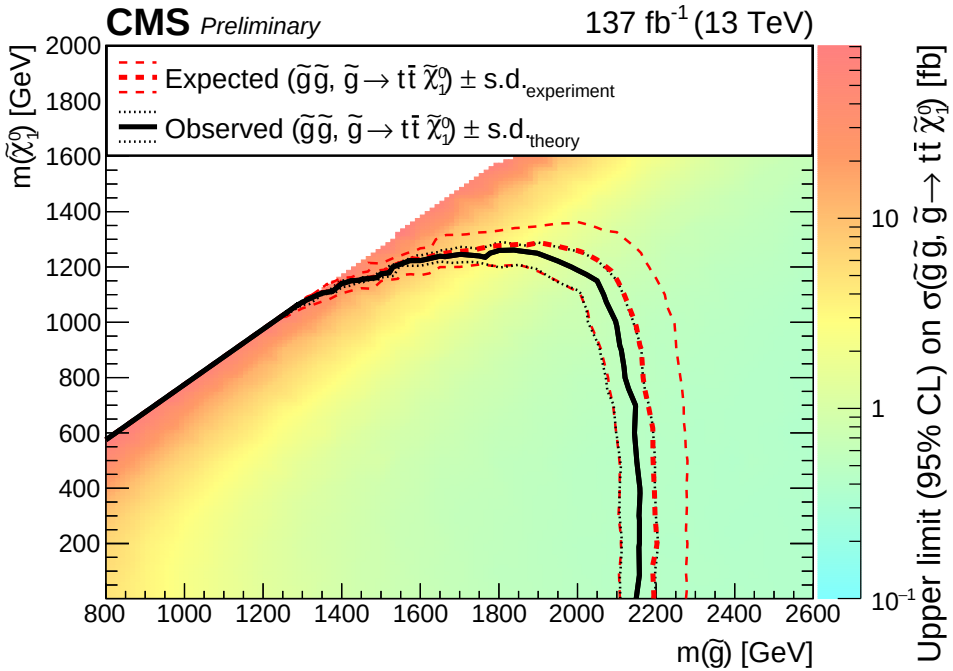
1L, large radius jets, CMS

search for $\tilde{g}$ in final states with 1l, p_T^{miss} and high N_j



No significant deviation from SM

- ⋆ exclusion limits
- ⋆ m($\tilde{g}$)>2150 GeV

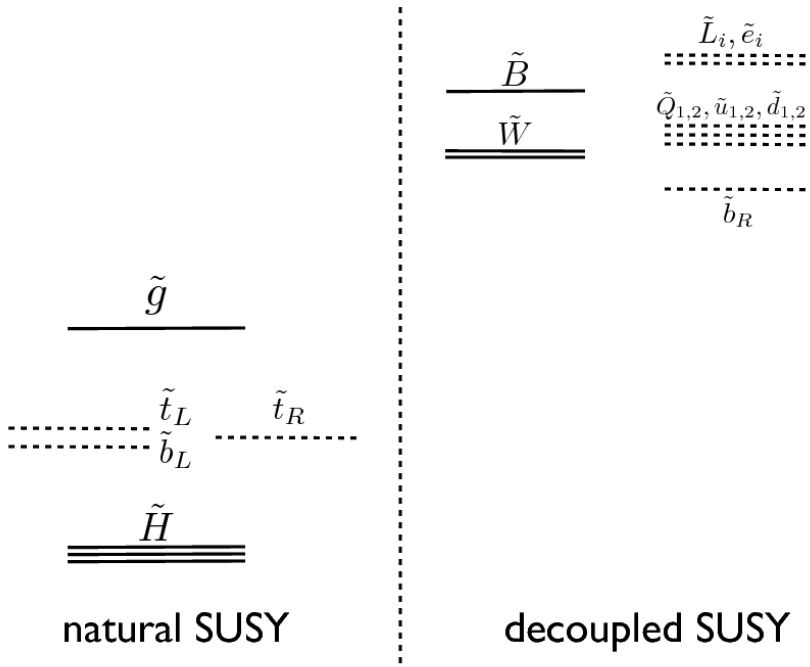


3rd Generation searches

Why is 3rd generation special - natural SUSY

Natural SUSY: scenario with minimum fine-tuning to obtain m_H (hierarchy problem)

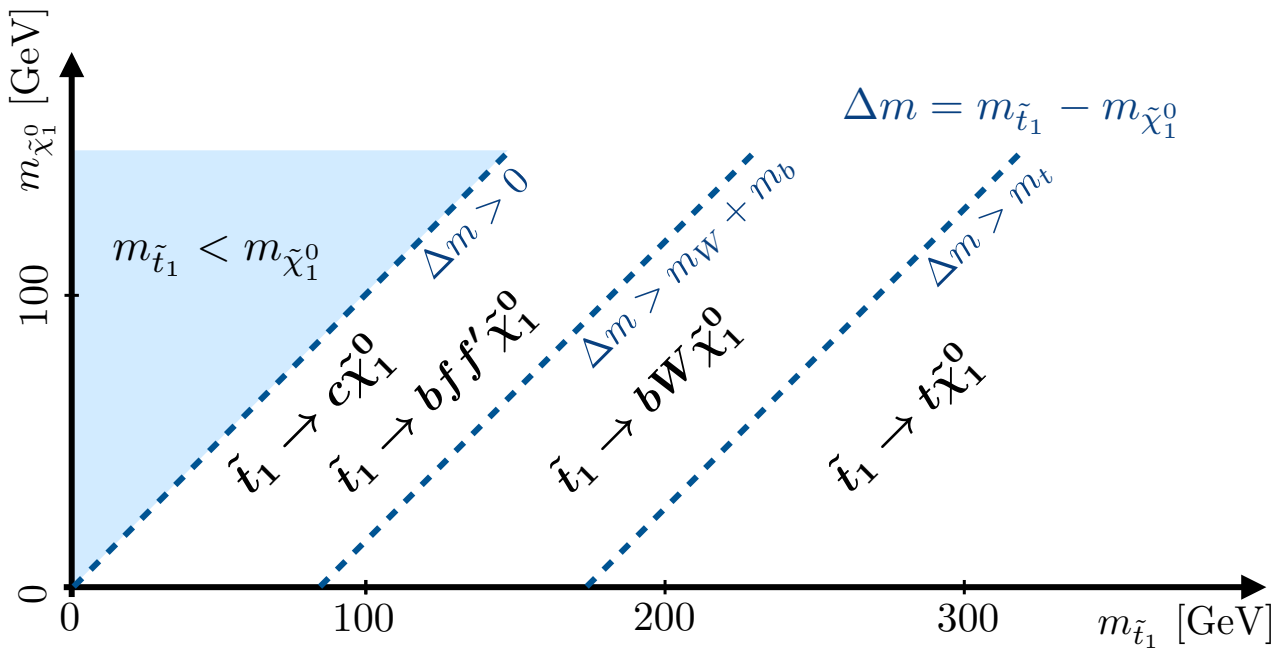
- s-particles with significant radiative contributions to Higgs potential should not be too heavy!
- stops,sbottoms, gluinos and higgsinos
- rest of the s-particles effectively decoupled



Why is 3rd generation special - natural SUSY

Assuming lightness of s-top, we get very interesting - and sensitive - phenomenology!

Decay topologies of $\tilde{t}_1$ in the m($\tilde{\chi}_1^0$)-m($\tilde{t}_1$) plane
(rest of s-particles decoupled)

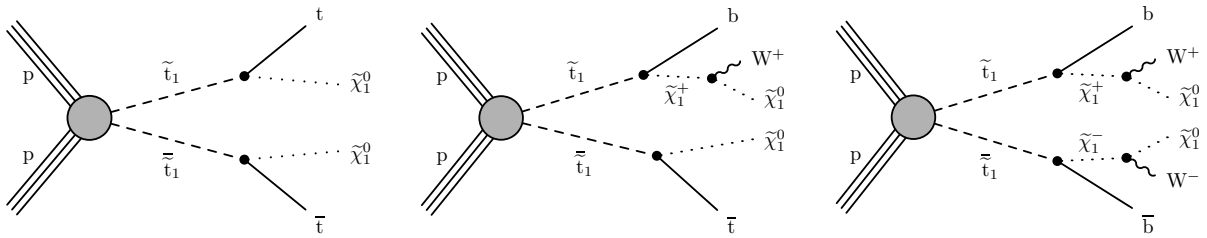


Search for 1l(e/μ) + high missing transverse energy

CMS-SUS-19-009

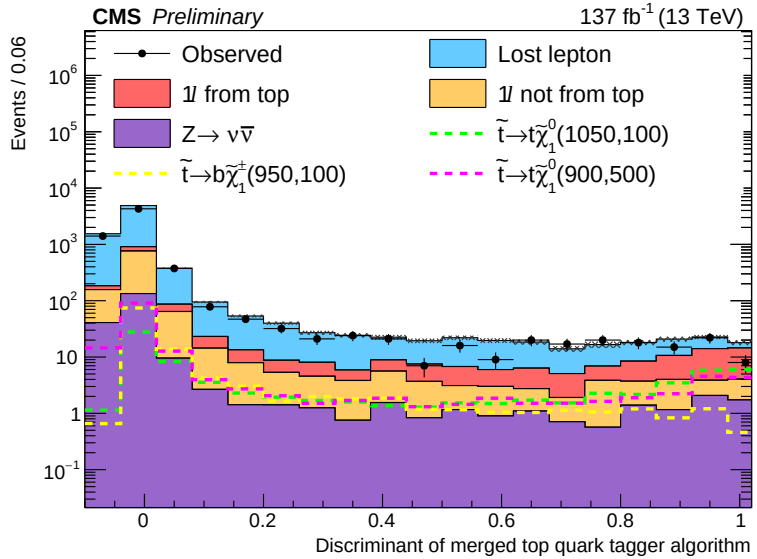
⋆ Signal selection

- DNN to identify and categorize hadronically decaying t
- Standard selection: SRs defined by selections on N_j, N_t, E_T^{miss}, M_{lb}
- search regions targeting compressed mass spectra based on ISR
  - Two mass splittings: $\Delta m(\tilde{t}, \tilde{\chi}_1^0) \sim m_t$, $\Delta m(\tilde{t}, \tilde{\chi}_1^0) \sim m_W$



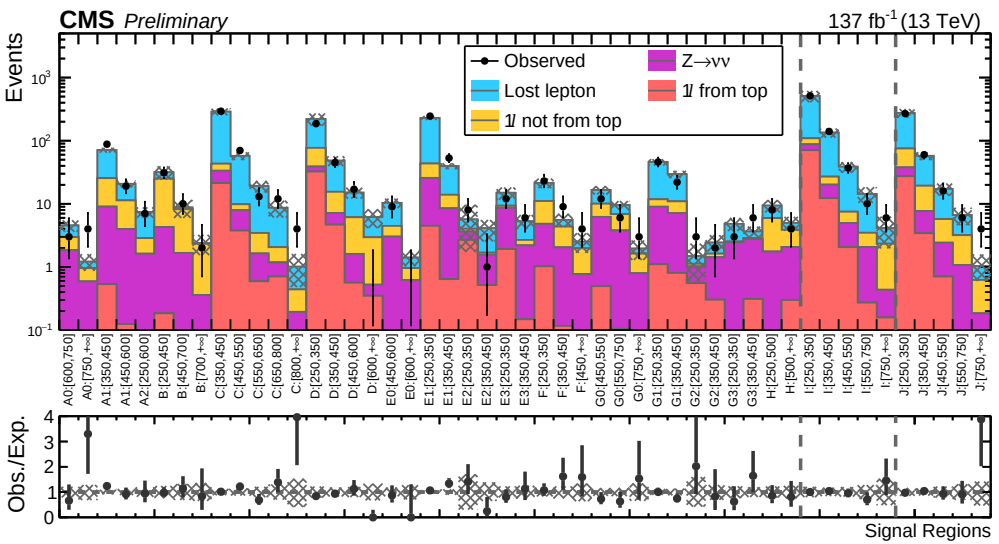
⋆ Main backgrounds

- lost lepton: di-lepton CR
- one lepton: mainly from W+jets → 0b CR
- Z+jets: estimated from simulation



⋆ No excess from SM → exclusion + interpretation

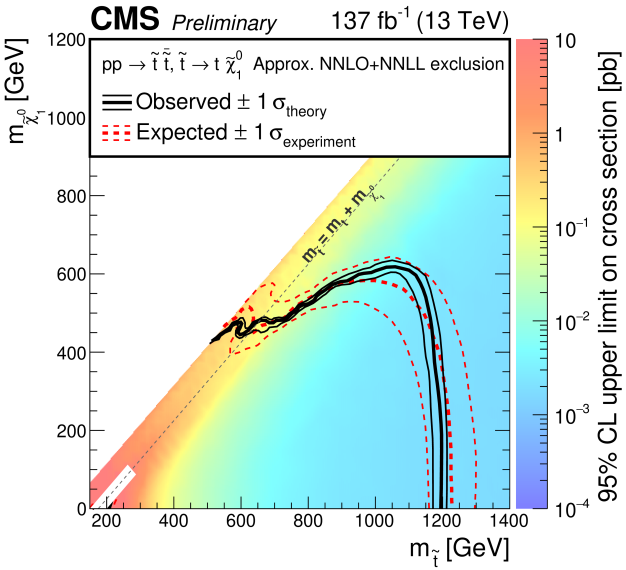
- $m_{\tilde{t}} < 1.2$ TeV excluded
- exclusion in compressed region of the $\tilde{t} \to t\tilde{\chi}_1^0$ channel improved by x5



	N_J	t_{mod}	M_{lb} [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

X0: Inclusive
X1: Untagged
X2: Boosted top
X3: Resolved top

I: $N_J \geq 5$, $N_{b,med} \geq 1$
J: $N_J \geq 3$, $N_{b,soft} \geq 1$

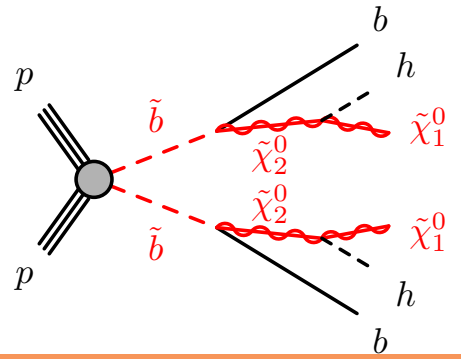


stop+1L from ATLAS, targeting 3-body decay: ATLAS-CONF-2019-017

sbottom+H, ATLAS

unique signature: high # (b)-jets, E_T^{miss}, 0 leptons + **h** $\rightarrow b\bar{b}$

[arXiv:1908.03122]

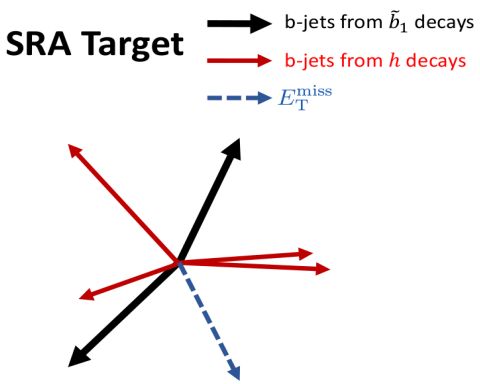


⋆ Analysis strategy: 3 SR groups to target 3 mass hierarchies

- each taking advantage of special kinematic properties
- try to reconstruct higgs boson - low efficiencies

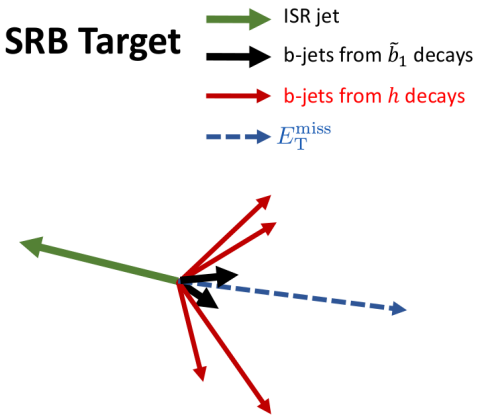
moderate/high $\Delta m(\tilde{b}_1, \tilde{\chi}_2^0)$

- $n_b \geq 4$
- at least one reco h
- multi-bin in m_{eff}



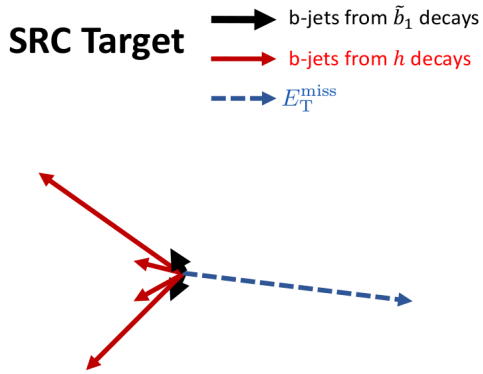
small $\Delta m(\tilde{b}_1, \tilde{\chi}_2^0)$, $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130\text{GeV}$

- ISR jet
- $n_b \geq 5$
- both h



small $\Delta m(\tilde{b}_1, \tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 60\text{GeV}$

- object-based E_T^{miss}-significance S
- $n_b \geq 4$

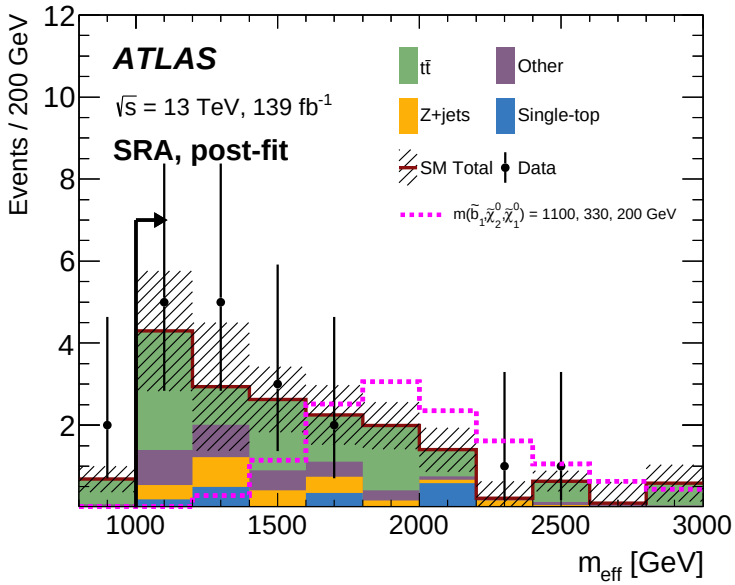


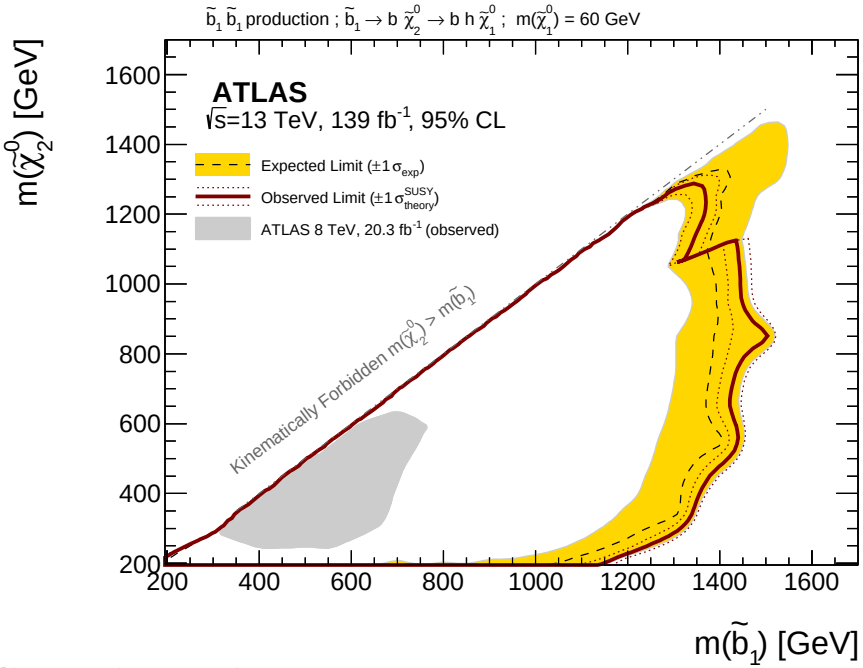
sbottom+H, ATLAS

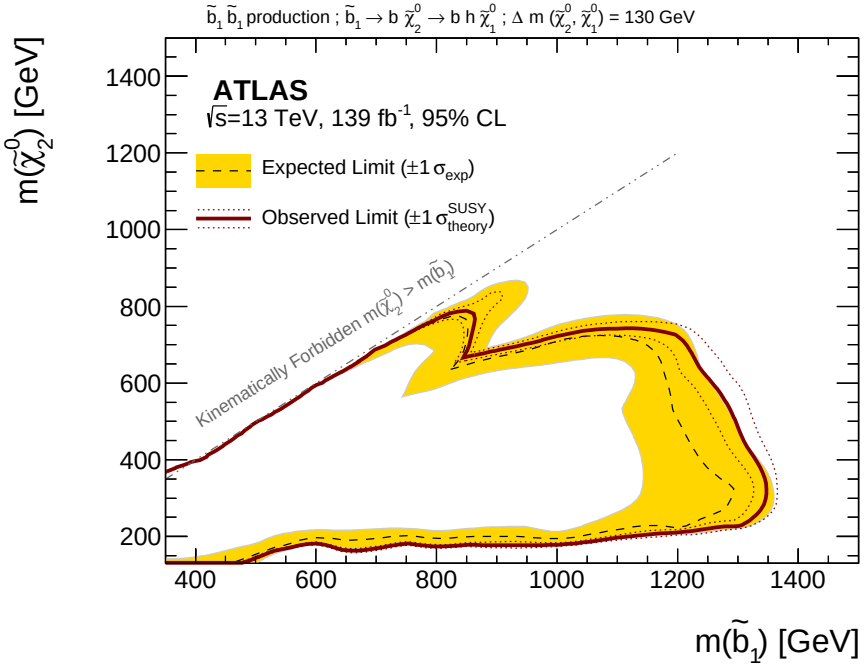
⋆ Interpretation in two mass-splitting scenarios:

- $m(\tilde{\chi}_1^0) = 60$ GeV
- $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV

$\rightarrow m(\tilde{b})$ excluded up to 1.5 TeV



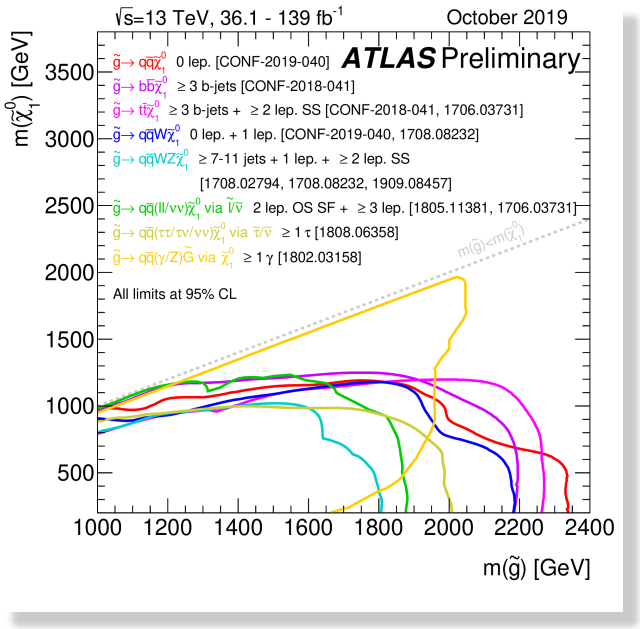


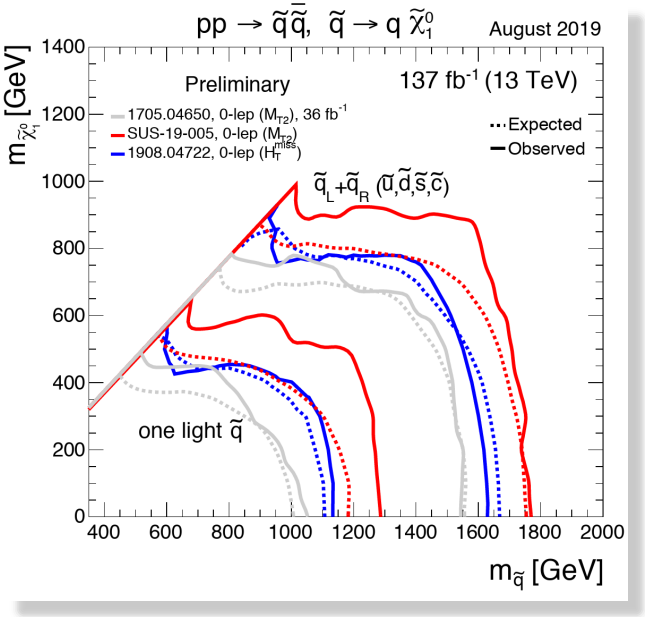


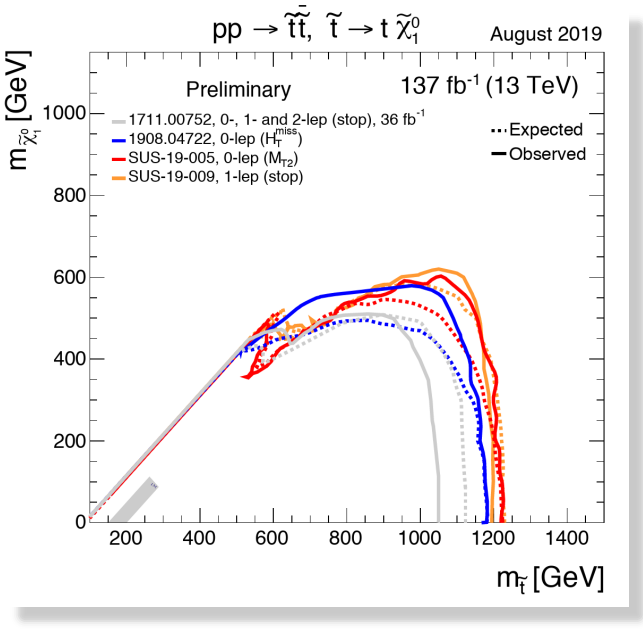
Summary limits

⋆ Most partial limits extended by a few 100 GeV with full Run2 data

⋆ Many analyses targeting challenging regions







Conclusions

- Run 2 of the LHC finished at the end of 2018 and was an undeniable success
- Most SUSY analyses are now updating their partial results with the full dataset
- Systematic use of simplified models
- So far, no evidence of squarks and gluinos in RPC SUSY :(
- Most limits increased a few 100 GeV from partial results
- Limit highlights:
  - $\tilde{g}\tilde{g} \rightarrow qqqq\tilde{\chi}_1^0\tilde{\chi}_1^0$: m($\tilde{g}$) excluded up to **2.4 TeV**
  - $\tilde{q}\tilde{q} \rightarrow qq\tilde{\chi}_1^0\tilde{\chi}_1^0$: m($\tilde{q}$) excluded up to **1.9 TeV** (assuming 8-fold degeneracy)
  - $\tilde{t}\tilde{t} \rightarrow tt\tilde{\chi}_1^0\tilde{\chi}_1^0$: m($\tilde{t}$) excluded up to **1.2 TeV**
- A lot more analyses to come! + reinterpretations, pMSSM scans

Thank you
for your
attention!

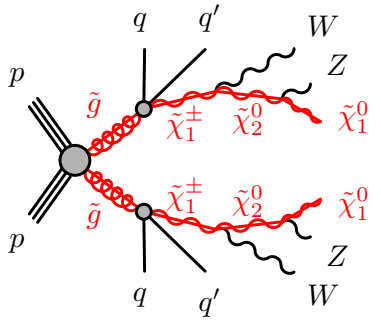
Backup

SS + 3L ATLAS

Search for $\tilde{q}$ and $\tilde{g}$ - signatures with same-sign (SS) or >= 3 leptons

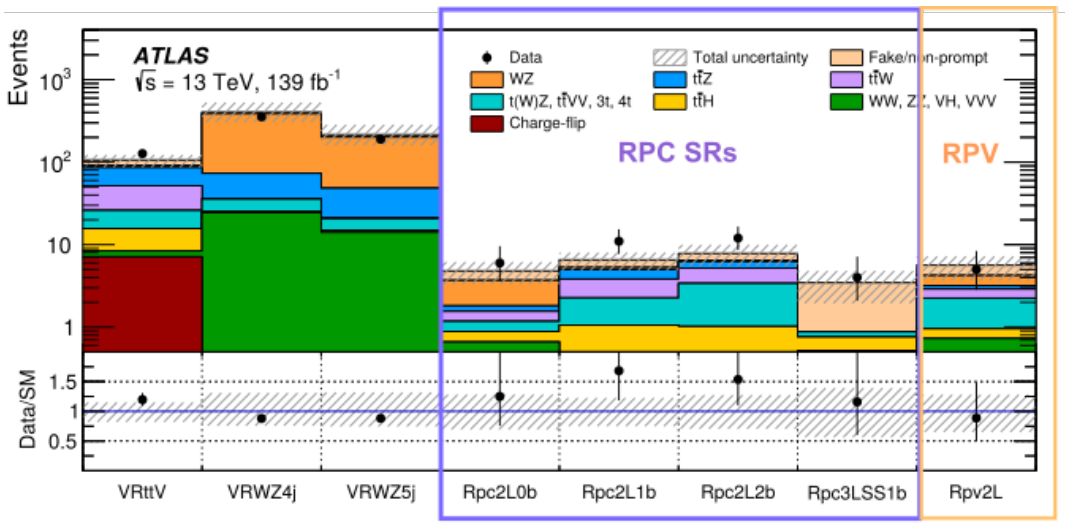
- selection based on n_l, N_j, E_T^{miss},m_{eff}
- + N_b to probe 3rd generation $\tilde{q}$

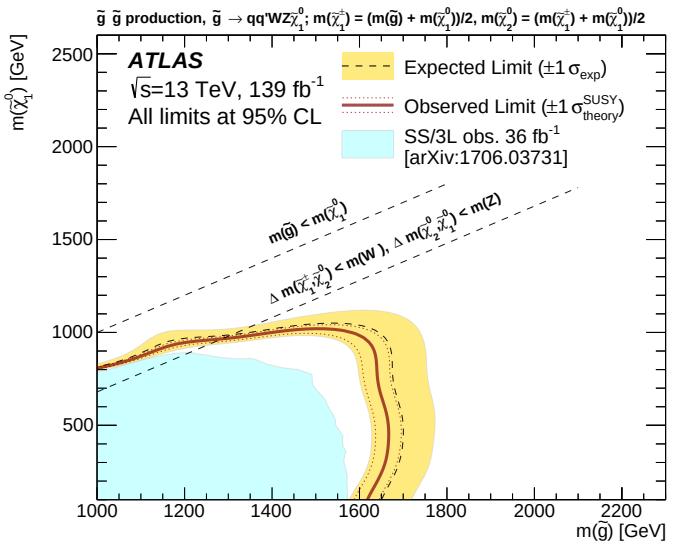
[arXiv:1909.08457]



★ SM Background:

- WZ+jets, $t\bar{t}V$,VV
- Reducible: charge flip, fake/non-prompt leptons





ss+3l from CMS : CMS-SUS-19-008

search for $\tilde{t}$ - signatures with E_T^{miss}, jets + 2 SF-OS l (Z-boson)

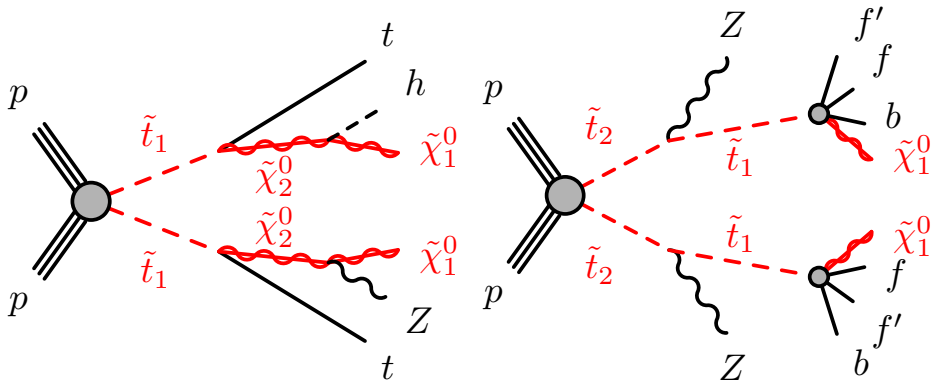
⋆ Event selection:

- 4 SRs for 2 mass splittings of the two models
- cuts on E_T^{miss}, N(b)$_{jets}$, p_T^{jet} ...

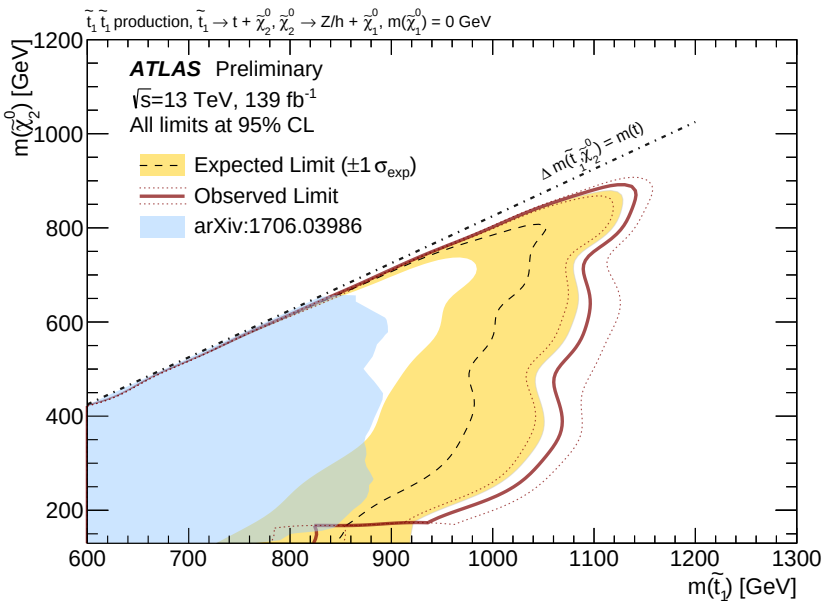
⋆ Background:

- main contributions from $t\bar{t}Z$ + multi-V
- estimated from dedicated CRs
- fake/non-prompt letpon → data driven

ATLAS-CONF-2019-016



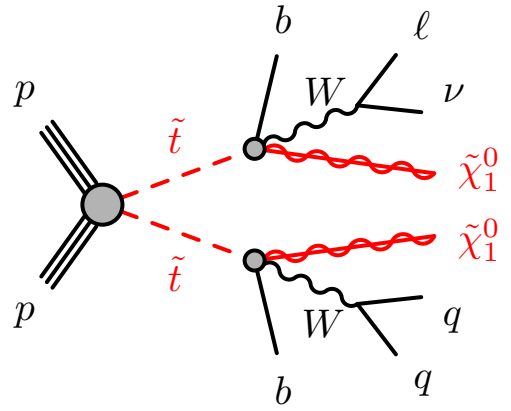
Requirement / Region	SR_{1A}	SR_{1B}	SR_{2A}	SR_{2B}
Third leading lepton p_T [GeV]	> 20	> 20	< 20	< 60
n_{jets} ($p_T > 30$ GeV)	≥ 4	≥ 5	≥ 3	≥ 3
$n_{b-tagged\,jets}$ ($p_T > 30$ GeV)	≥ 1	≥ 1	–	≥ 1
Leading jet p_T [GeV]	–	–	> 150	–
Leading b-tagged jet p_T [GeV]	–	> 100	–	–
E_T^{miss} [GeV]	> 250	> 150	> 200	> 350
$p_T^{\ell\ell}$ [GeV]	–	> 150	< 50	> 150
$m_{T2}^{3\ell}$ [GeV]	> 100	–	–	–



Targeting 3 - body decay with challenging mass splitting

$m_W + m_b < \Delta m(\tilde{t}, \tilde{\chi}_1^0) < m_t$

ATLAS-CONF-2019-017



⋆ Recurrent Neural network:

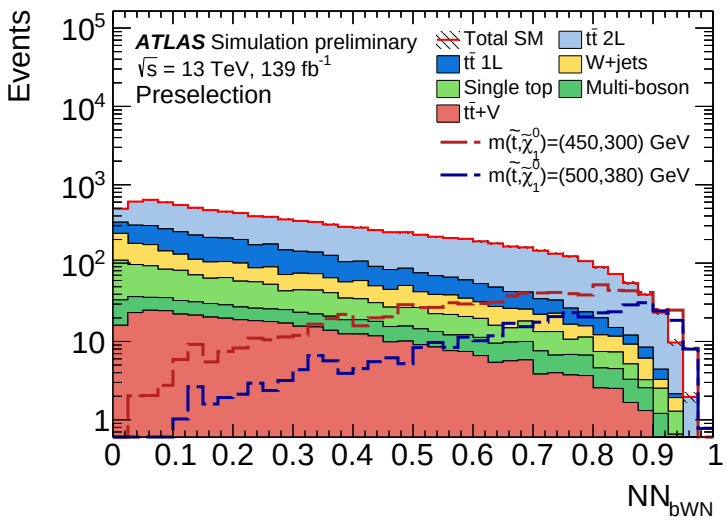
- classifier between signal and SM $t\bar{t}$
- analysis binned in NN score

⋆ SM Background:

- Main contribution from "lost lepton" $t\bar{t}$

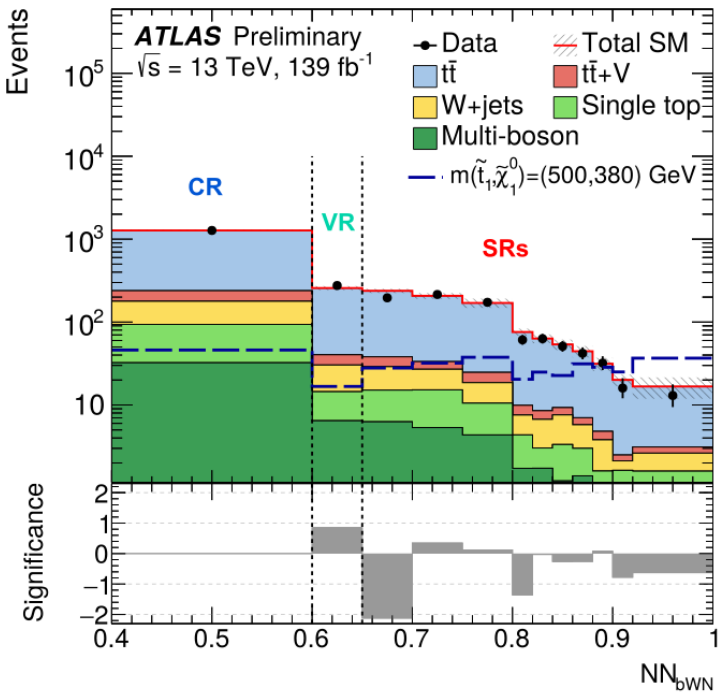
→ estimated from dedicated CR / extrapolation validated in VR

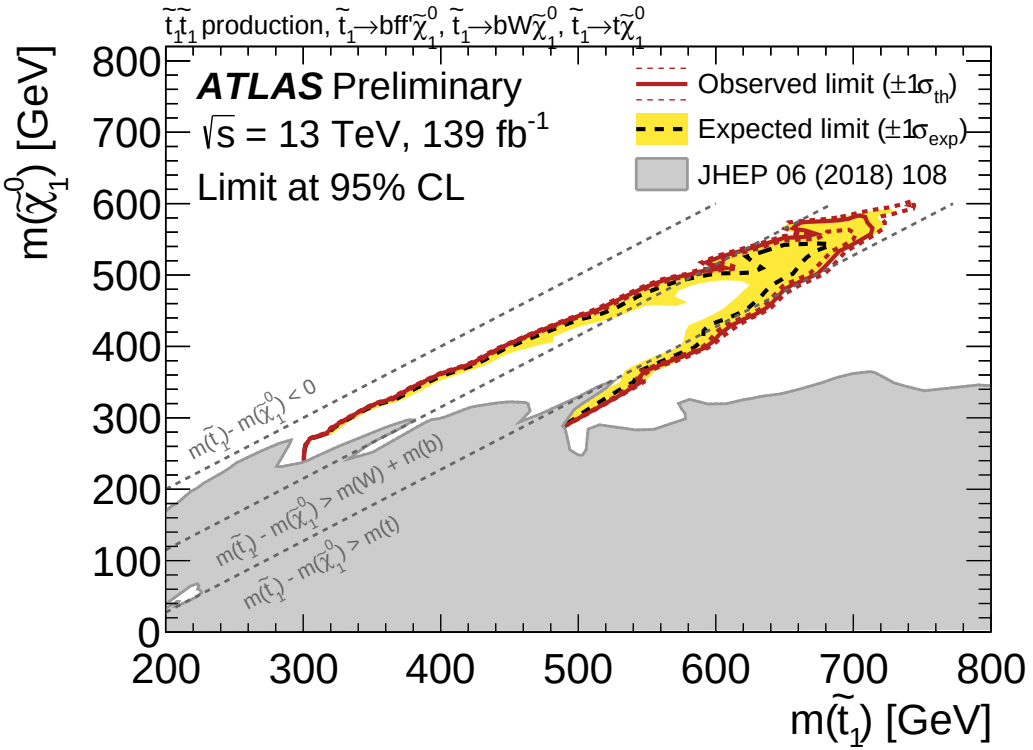
- residual backgrounds from MC estimates



stop 1L, ATLAS

⋆ Results: good SM / data agreement in VR and SRs





⋆ Interpretation in the full mass spectrum

- m($\tilde{t}$) excluded up to 720 GeV for m($\tilde{\chi}_1^0$) $\sim$ 580 GeV