Searches for squarks and gluinos in all-hadronic final states with ATLAS

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On behalf of ATLAS collaboration

ATLAS in LHC

Large Hadron Collider (LHC) has been successfully operated at $\sqrt{s}$ = 13 TeV.

A total integrated luminosity of 36.1 fb^{-1} of proton-proton collision data was collected by the ATLAS experiment with good detector conditions and data quality during 2015 and 2016.

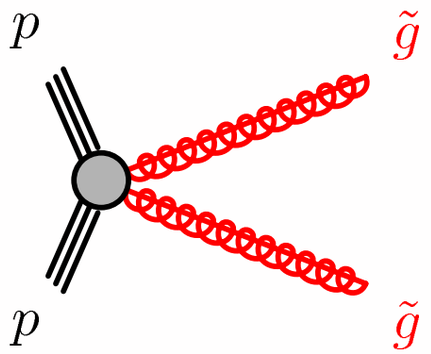
Upgrade of ATLAS detector before 13 TeV data taking to improve sensitivity:

- ➡ Insertable B-Layer
  (Ave. 3 cm from the beam axis)
  - ✓ improved tracking, especially b-tagging
- ➡ ATLAS High Level Trigger system
  - ✓ larger acceptance, while enhancing rejection
    - ◉ Improved E_T^{miss} trigger
    - ◉ Improved jet energy scale

SUSY production at LHC

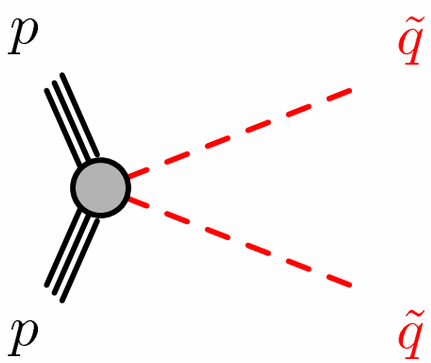
Supersymmetry (SUSY) is an extension of Standard Model (SM)

- A solution of hierarchy problem



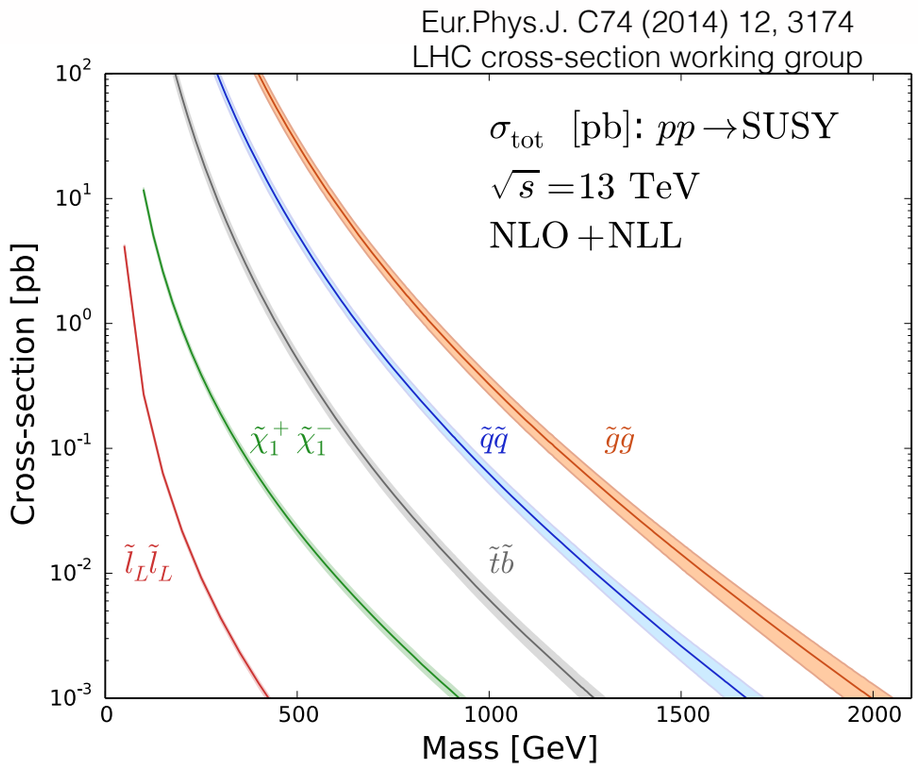
Assuming R-parity is conserved (RPC),

- SUSY particles are pair-produced
- Decay to SM particles and the lightest SUSY particle (LSP).
- LSP is stable and weakly interacting.
  - ➡ Missing transverse momentum: E_T^{miss}



At LHC, a pair of SUSY particles can be dominantly produced with strong interactions.

- large cross-sections for gluino and squark productions



Search channels

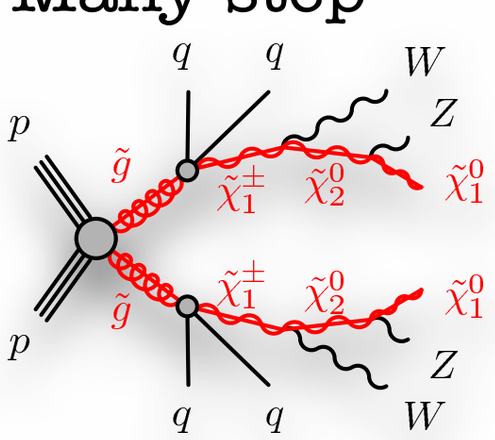
RPC
0 lepton

squarks/gluinos pair productions
+
full hadronic decays

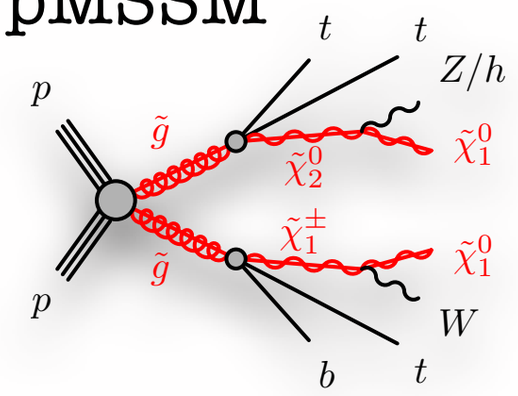
Searches for 3rd generations are in another talks

Multi-jets

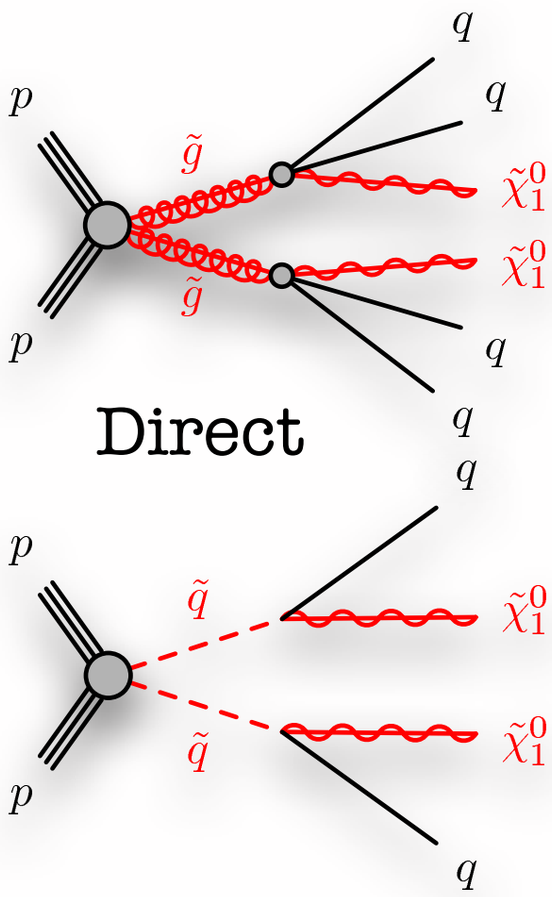
Many-step



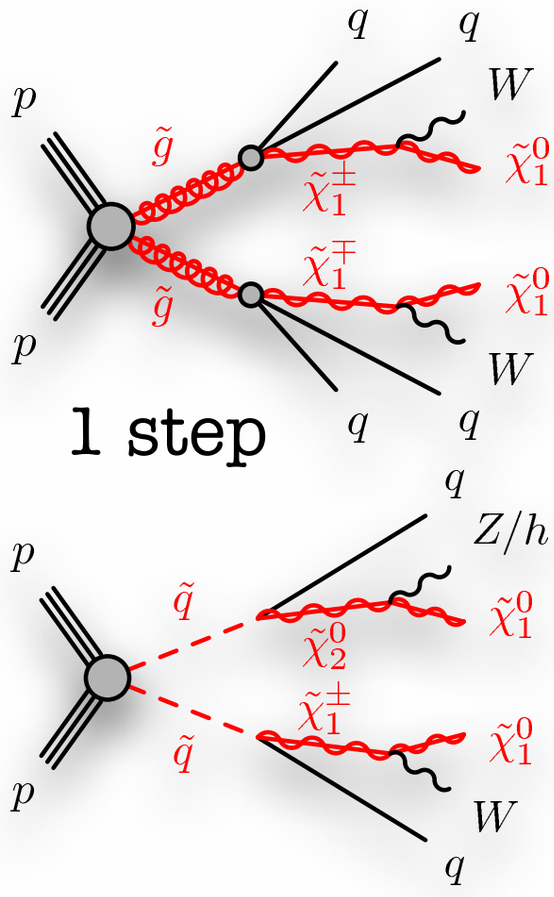
pMSSM



2-6 jets



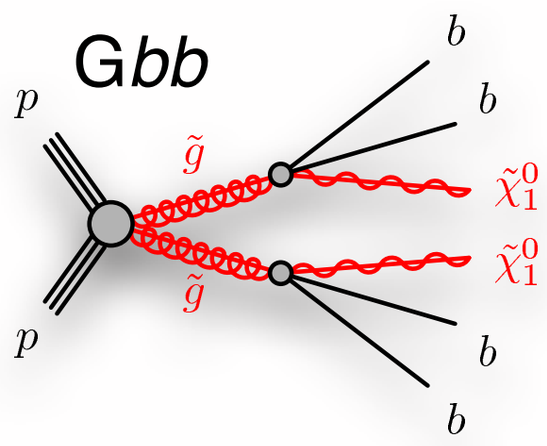
Direct



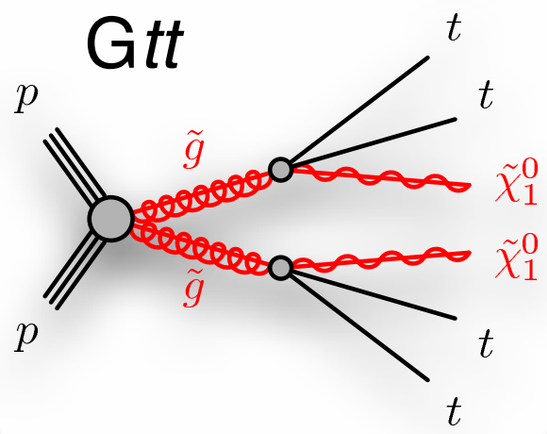
1 step

G*tt*/G*bb*

G*bb*



G*tt*



Search strategies

Signal Regions (SR)

- Many dedicated SRs constructed by target signatures using discriminating variables, for example,
  - E_T^{miss}, N_{jet}, $N_{b\text{-}jets}$, p_T^{Jet}, M_{EFF}, M_J^{Σ},

    $E_T^{miss}/\sqrt{H_T}$, ISR Jet, $(\vec{p}_T^{\,jet}, \vec{E}_T^{miss})_{min}$
  - Event level variables by Recursive Jigsaw Reconstruction (RJR)

Targets of searches

- "Simplified Model"
  - ✓ 1 step
  - ✓ Many-step
  - ✓ Gtt, Gbb
- particular decay modes
  - ✓ phenomenological MSSM (pMSSM)

Control Regions (CR)

- Orthogonal to SR, small contamination of signals
- Enriched a particular BKG
- Evaluate BKG MCs' normalisation factors with BKG only fit

Validation Regions (VR)

- Close to SR, limited potential signal contamination
- Validate background modelling

2-6jets channel

RPC
0 lepton

squarks/gluinos pair productions
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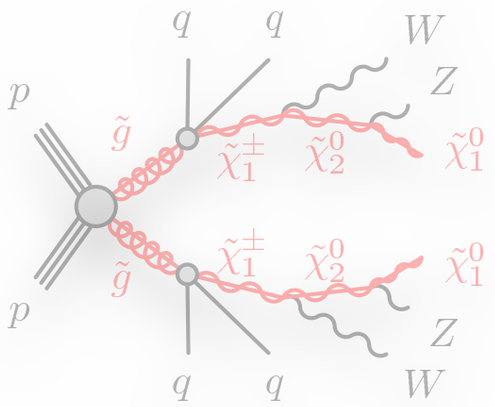
Searches for 3rd generations are in another talks

Multi-jets

Many-step



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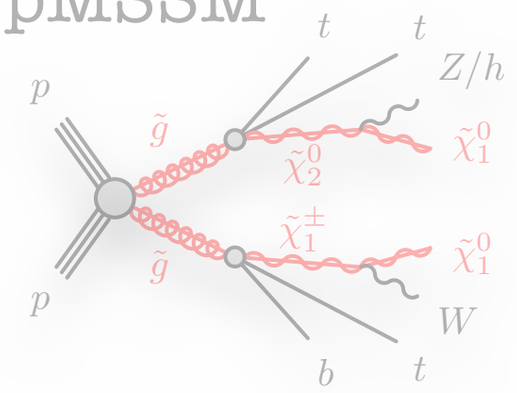
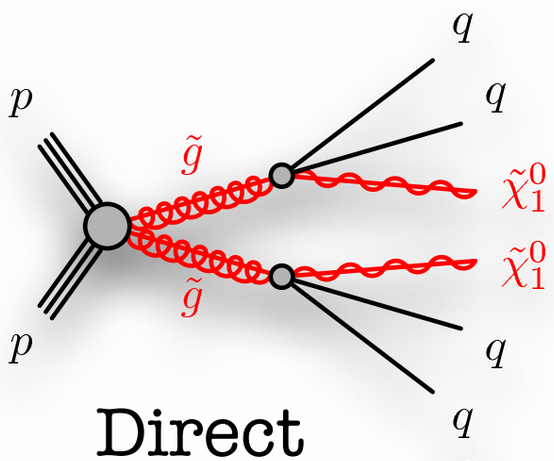


2-6 jets



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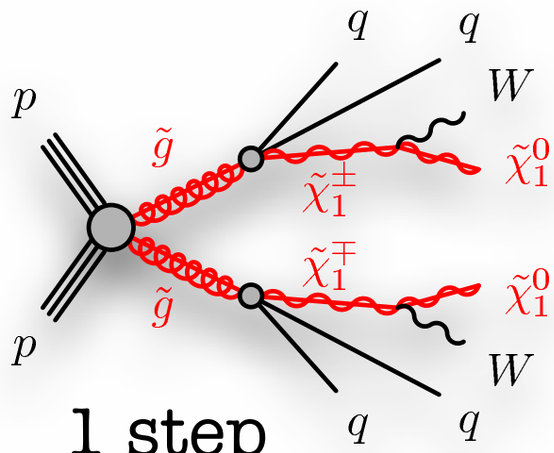
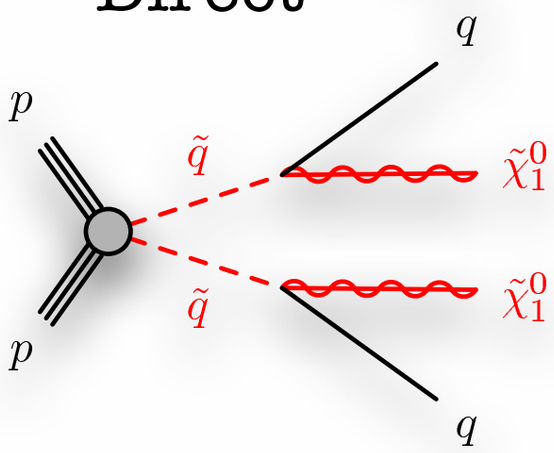
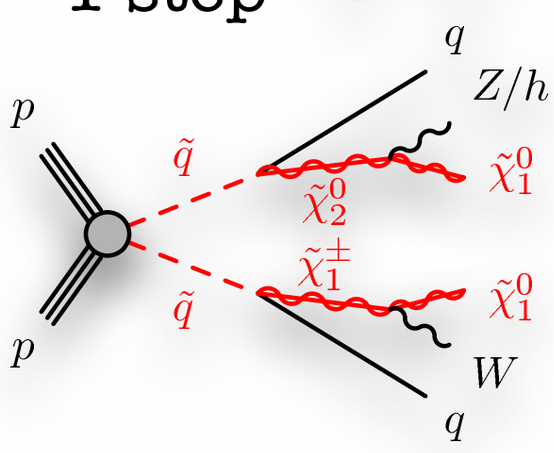


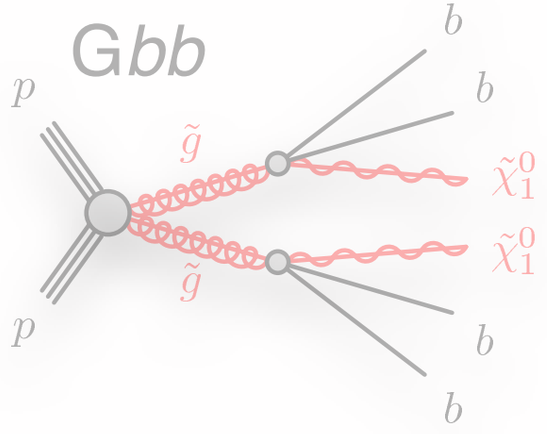
1 step



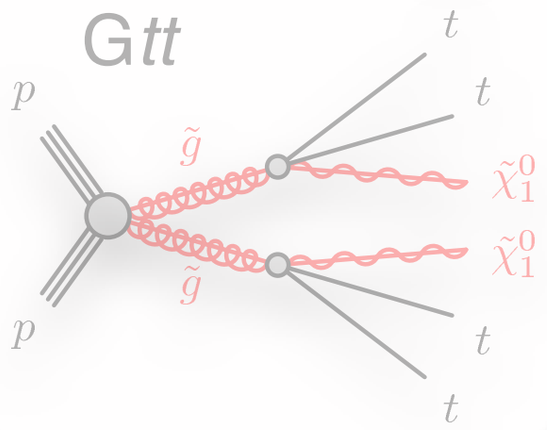


G*tt*/G*bb*

G*bb*

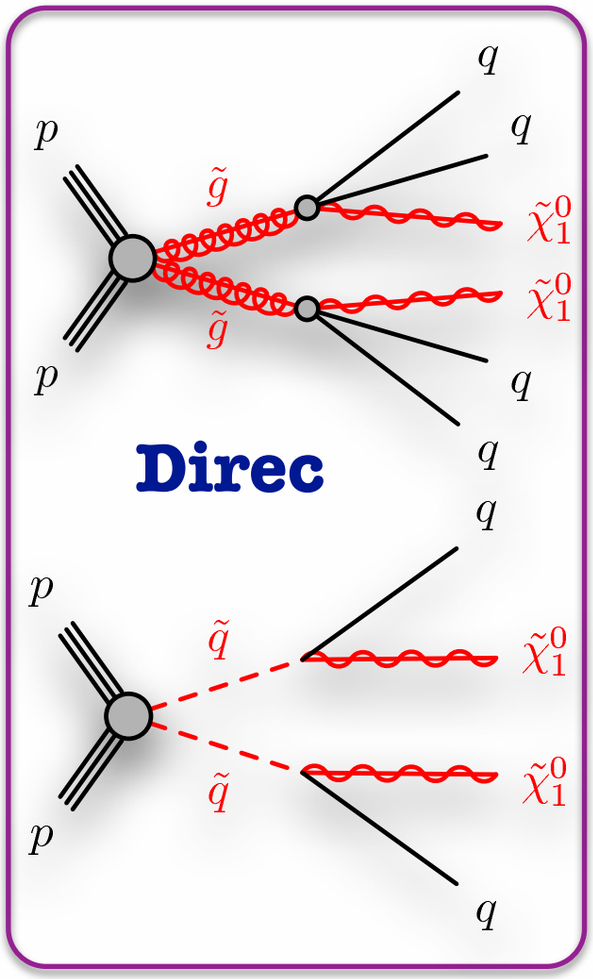


G*tt*



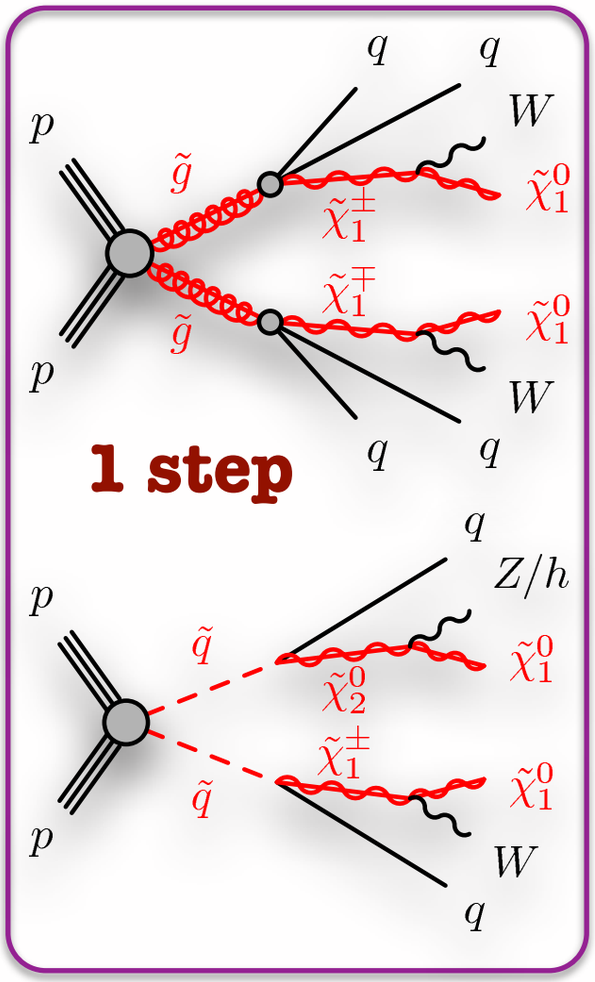
2-6j: Search strategies

https://arxiv.org/abs/1712.02332



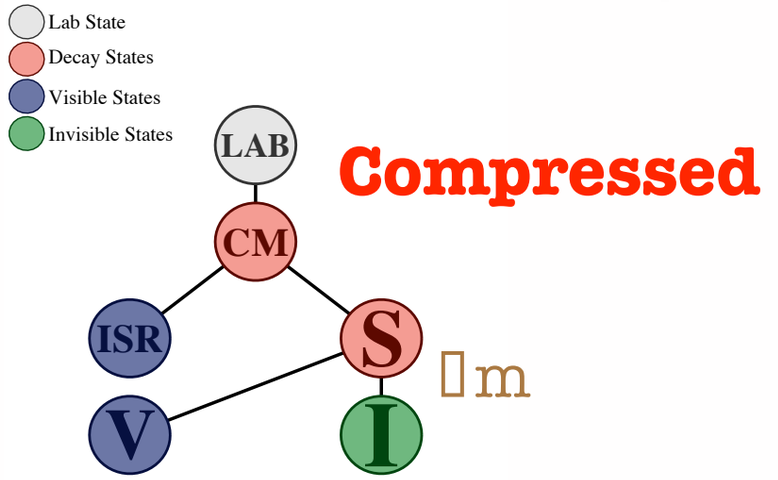
Effective mass (M_{EFF})-based search

- $M_{EFF} \equiv \sum p_T^{Jet} + E_T^{miss}$
  - ✓ M_{EFF} ≈ parent sparticle mass
- 24 SRs: sparticle mass and final states
  - ➡ ≧ 2, 3, 4, 5 jets: **direct** decays to LSP
  - ➡ ≧ 5,6 jets: **1 step** cascade decay with hadronically decaying W/Z/h bosons
  - ➡ ≧ 2 re-clustered large-R jets (R=1.0): **1 step** cascade decay with **boosted** W/Z/h bosons



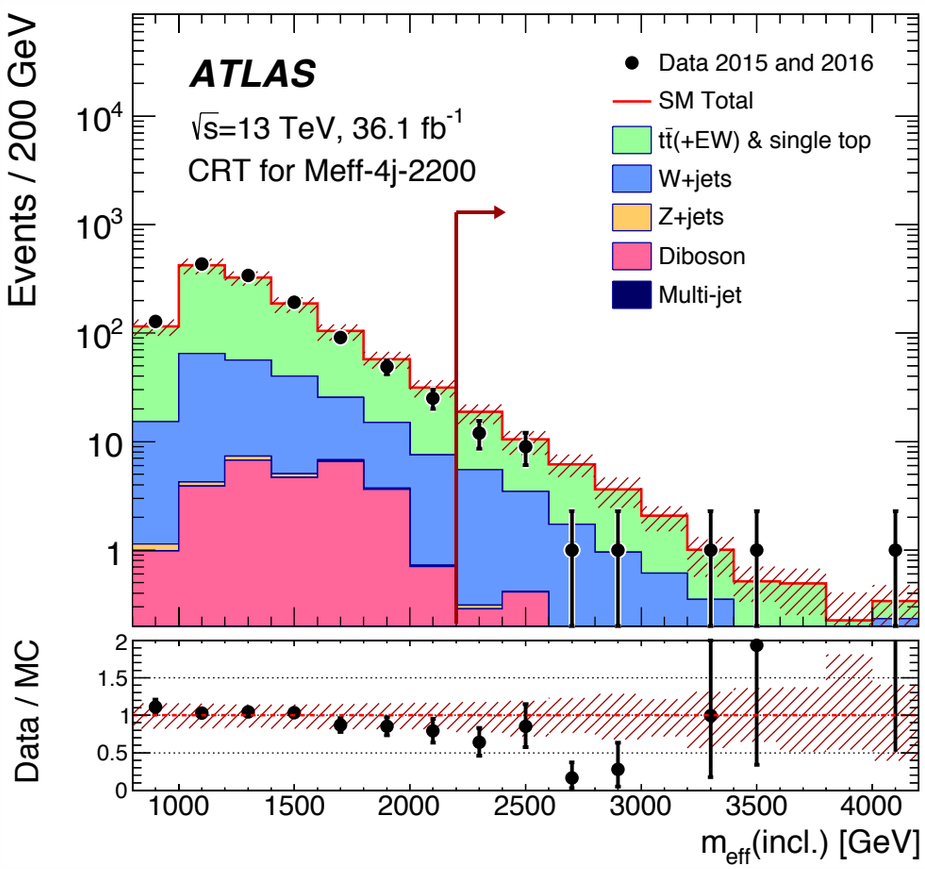
RJR-based search

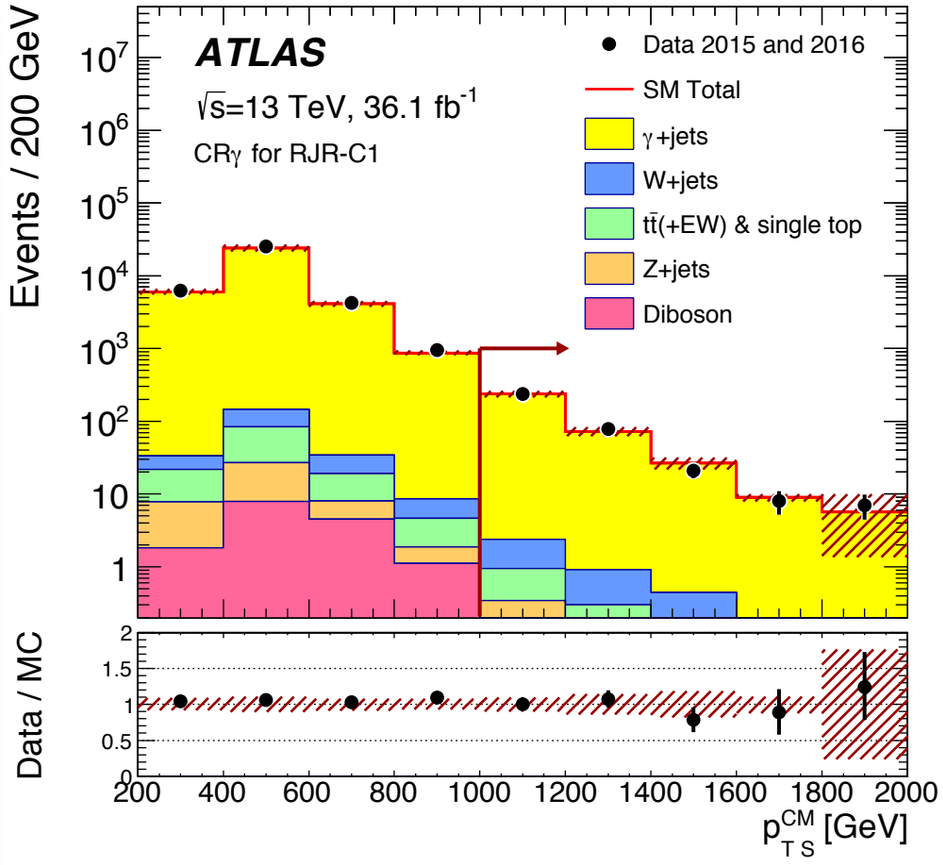
- 19 SRs:
  - ➡ $\Delta m \equiv m_P - m_I$
  - ➡ **squark**/**gluino**/**compressed** decay models
  - ➡ RJR-variables defined by decay models



2-6j: Background Estimation

Z + jets	Z→*νν*	CR with γ + jets
W + jets	W→*lν*	CR with 1 lepton + b-jet veto
Top quark pair	Semi-leptonic decays	CR with 1 lepton + b-jet tagging
single top		
di-boson production		MC normalised to NLO cross-section
QCD multi-jet		a data driven method with jet smearing

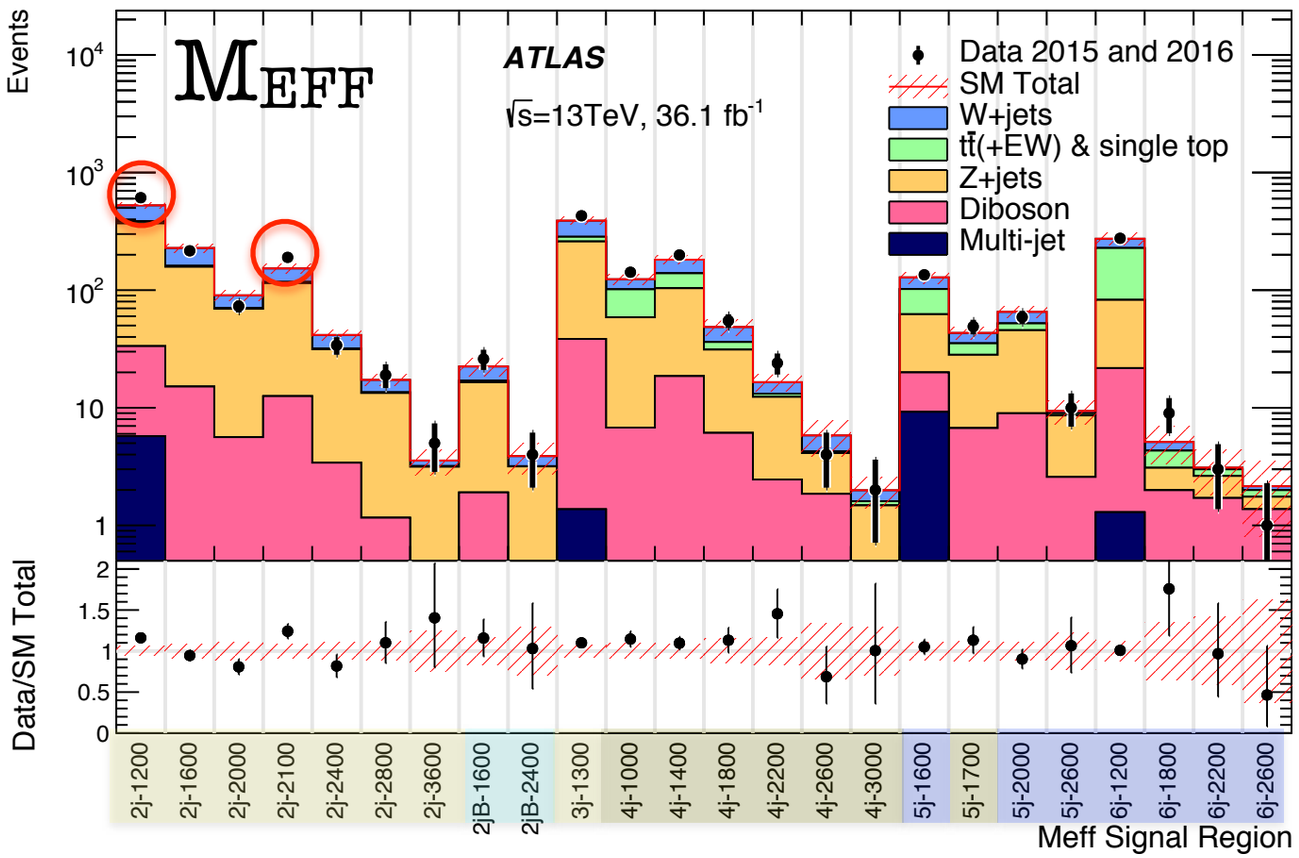


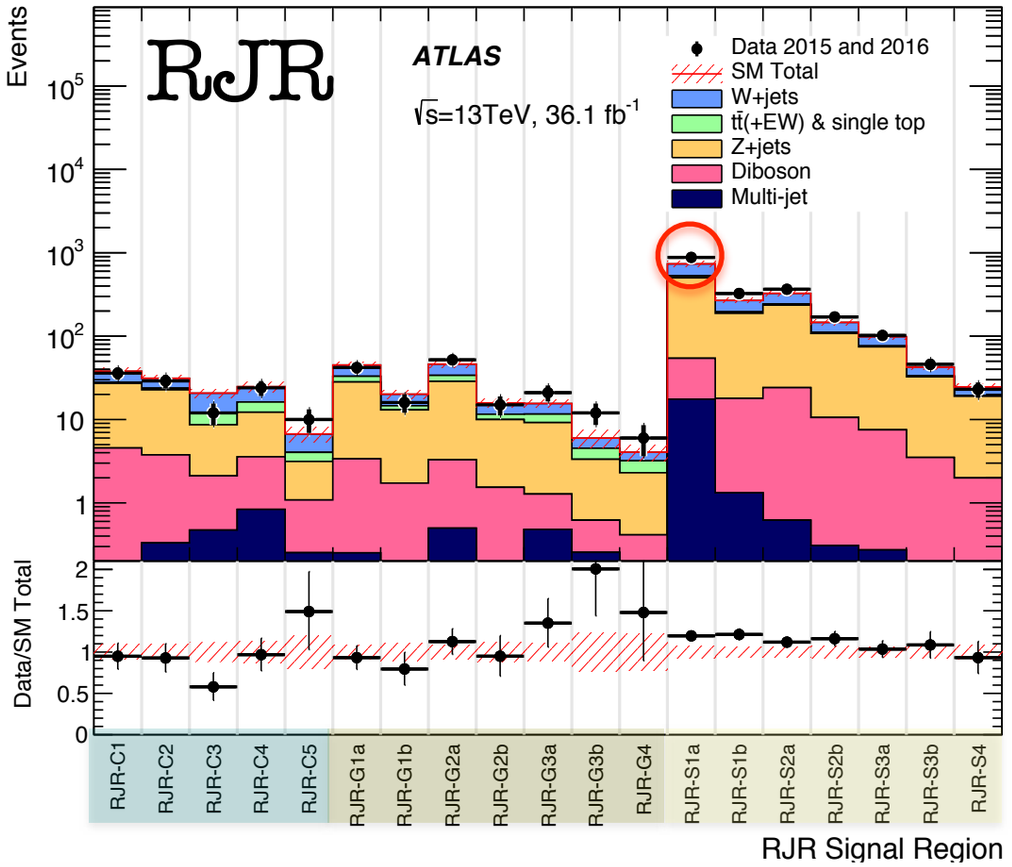


2-6j: Results

No significant excess

The largest excesses are 2 × 2.0σ in M_{EFF} and 2.5σ RJR (red circles)





squark

gluino

1 step

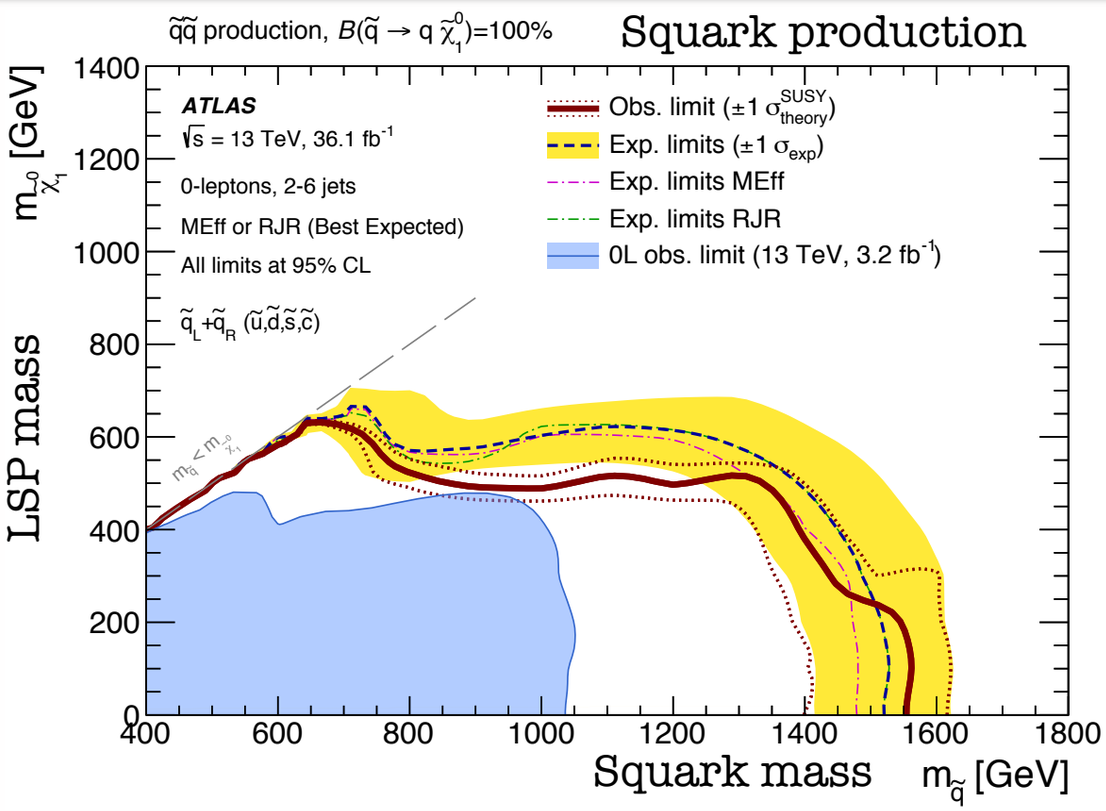
1step boosted

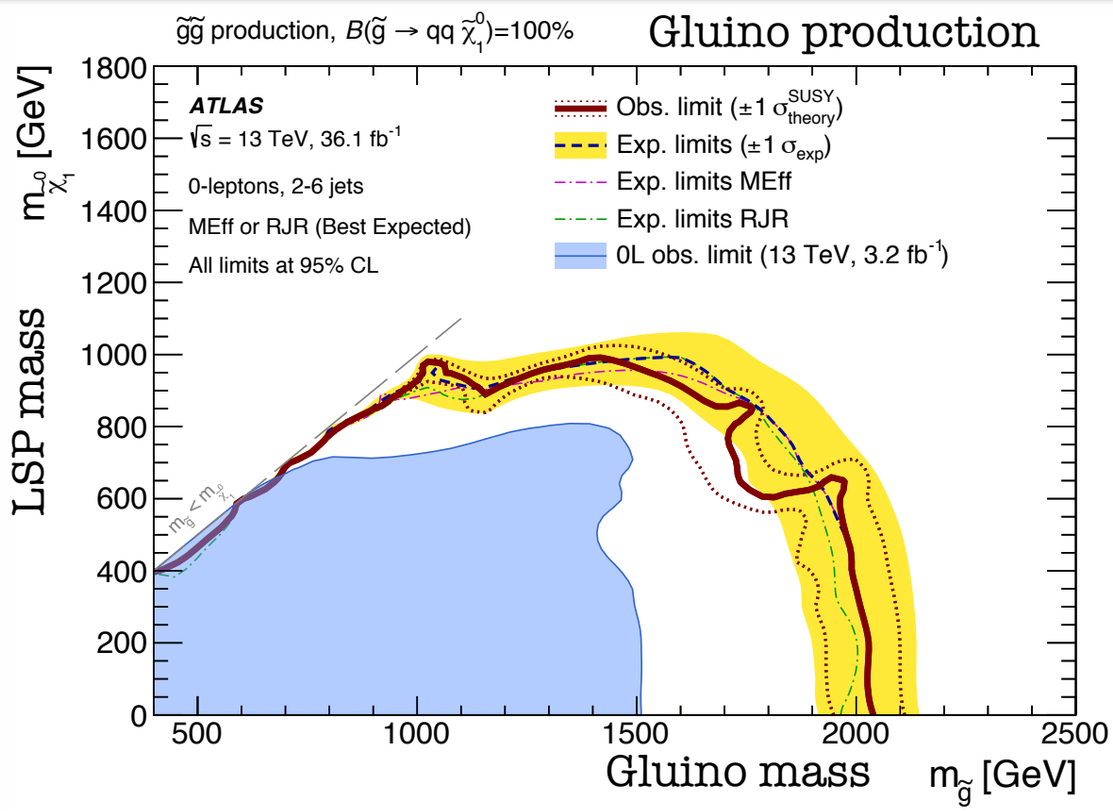
Compressed

squark

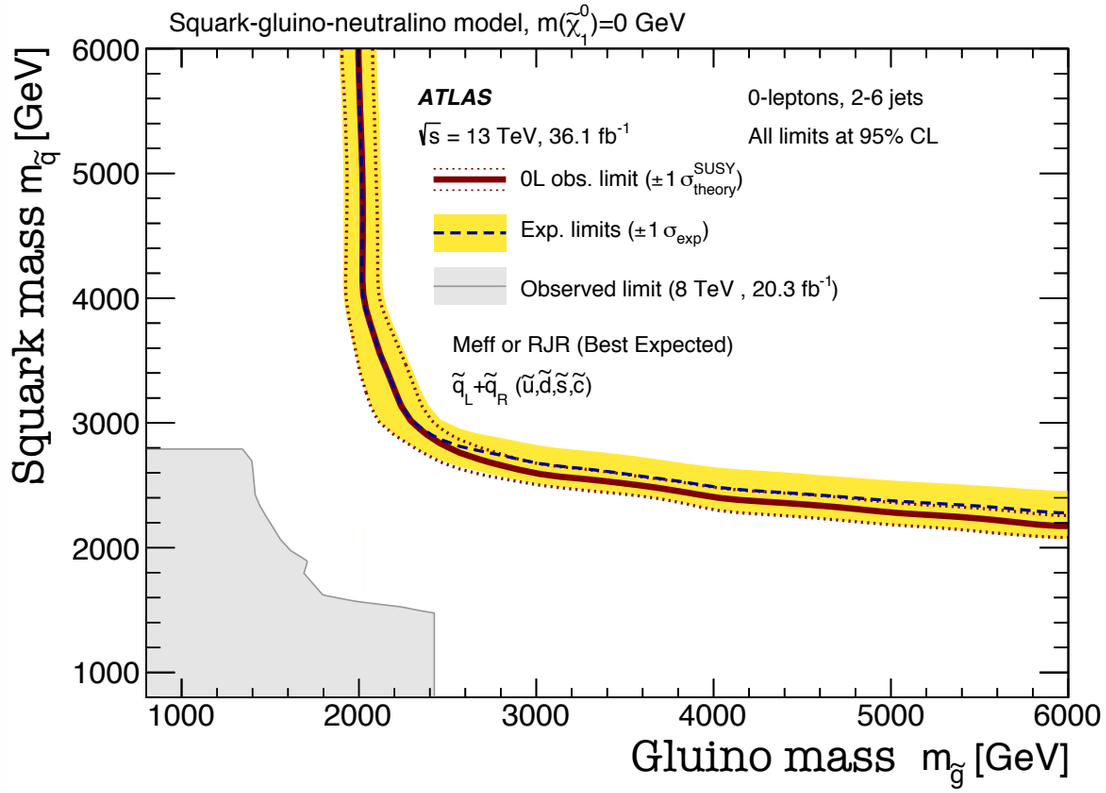
gluino

2-6j: Interpretations

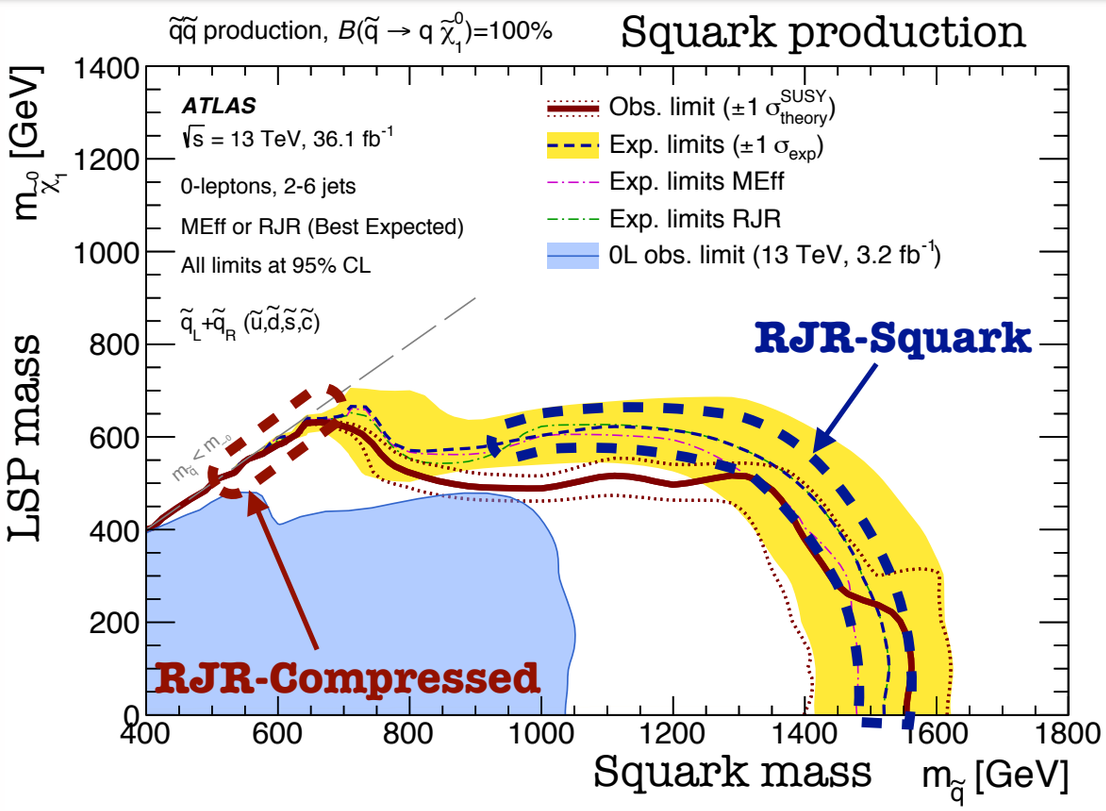


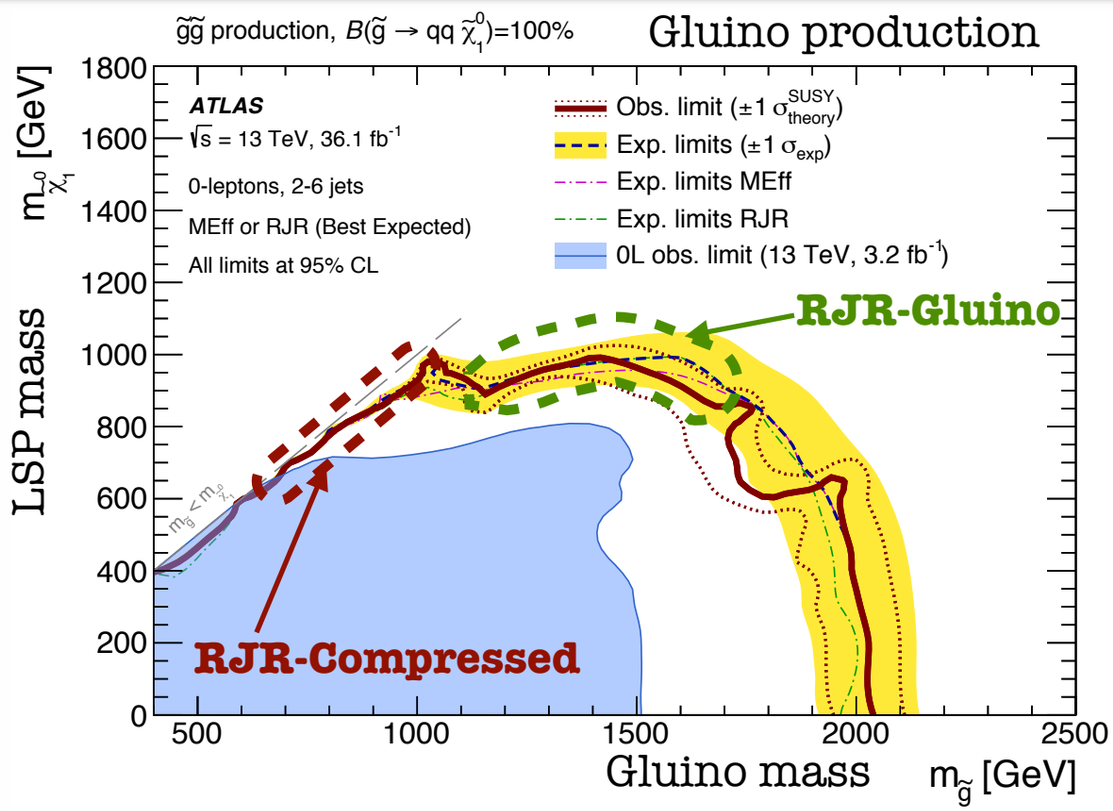


- Exclusion limit obtained with the SR with the best expected sensitivity at each mass point

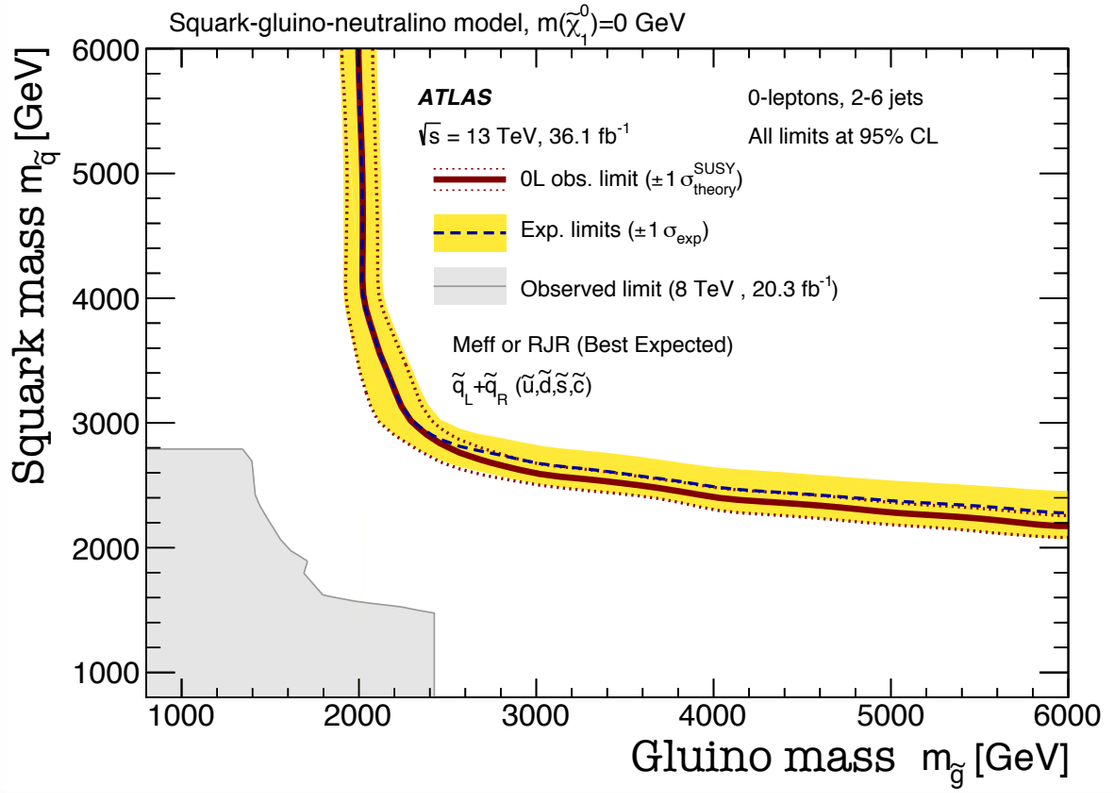


2-6j: Interpretations





- Exclusion limit obtained with the SR with the best expected sensitivity at each mass point
- RJR-based SRs improved limits in regions with very compressed spectra



Gtt/Gbb channel

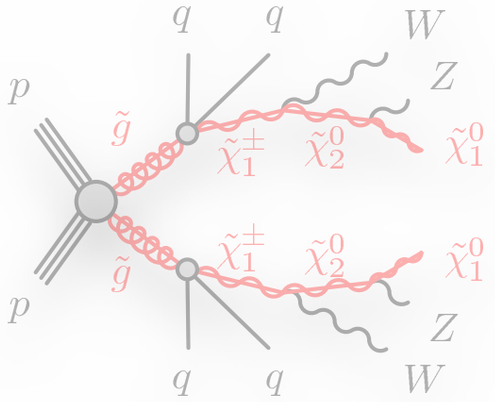
RPC
0 lepton

squarks/gluinos pair productions
+
full hadronic decays

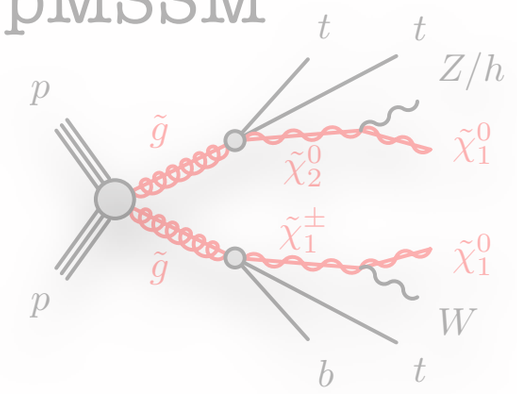
Searches for 3rd generations are in another talks

Multi-jets

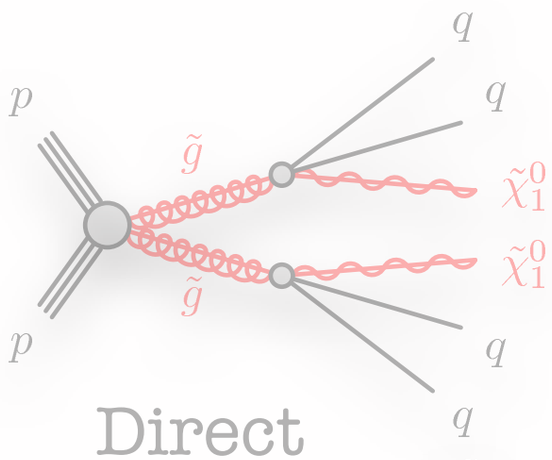
Many-step



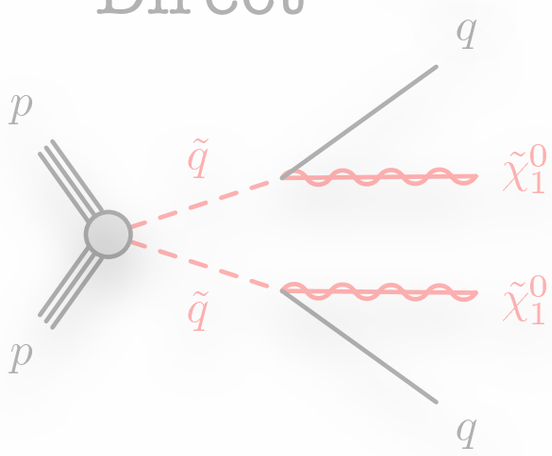
pMSSM

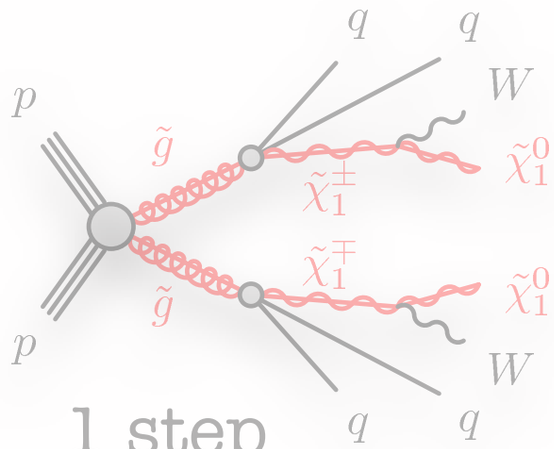


2-6 jets

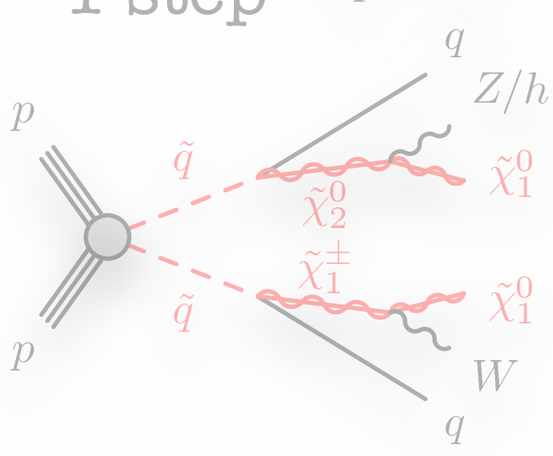


Direct



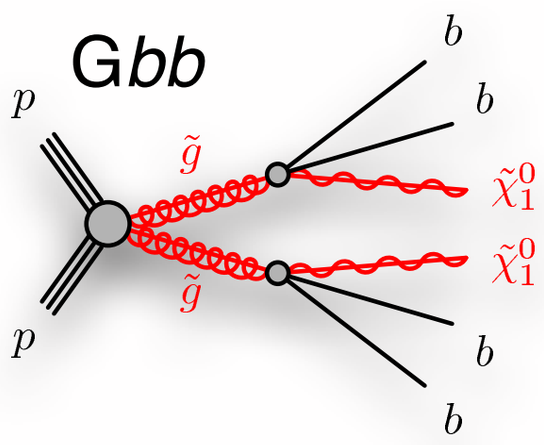


1 step

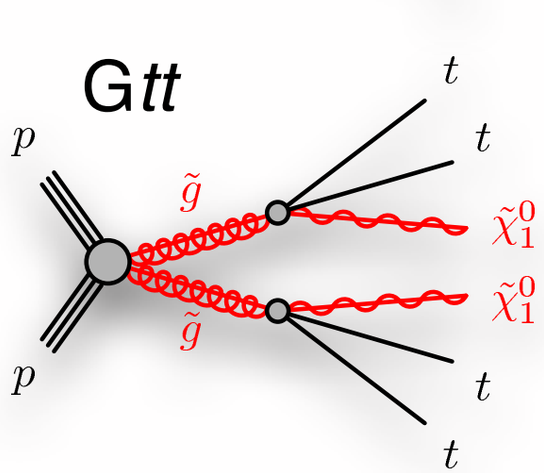


Gtt/Gbb

Gbb



Gtt



Gtt/Gbb: Introduction

https://arxiv.org/abs/1711.01901

A search for gluino mediated **stop** (G*tt*)/**sbottom** (G*bb*) productions

- Masses of stop and sbottom are expected to be light to solve the hierarchy problem.

SRs are built by considering event signatures:

- $N_{jet} \geq 4$ with $p_T^{Jet} \geq 30$ GeV
- $N_{b\text{-}jet} \geq 3$
- Large E_T^{miss}
- $\Delta M = |M_{gluino} - M_{LSP}|$
- $M_{EFF} \equiv \sum p_T^{Jet} + \sum p_T^{Lepton} + E_T^{miss}$

For **G*tt***, followings are also considered

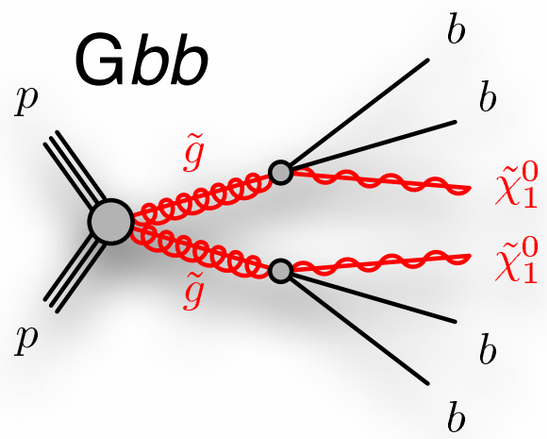
- Massive reclustered large-R jet (R=0.8) due to boosted top
- Isolated $e^{\pm}$ or $\mu^{\pm}$ from semi-leptonic top decay

Cut-and-count
- Maximise discovery power
- 6 Gtt & 4 Gbb SRs:
  Based on ΔM
  - ✓ four ΔM regions: High, Moderate, Low, Very low
  - ✓ partially overlapping

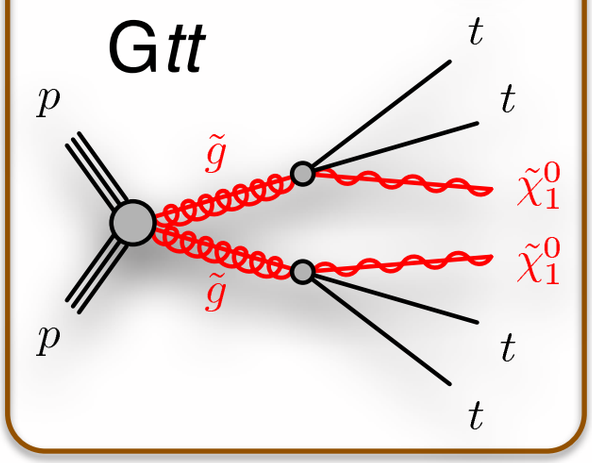
Multi-bin
- Strengthen the exclusion limit
- 14 SRs:
  Based on M_{EFF} and N_{jet}
  - ✓ non-overlapping

G*tt*/G*bb*

G*bb*

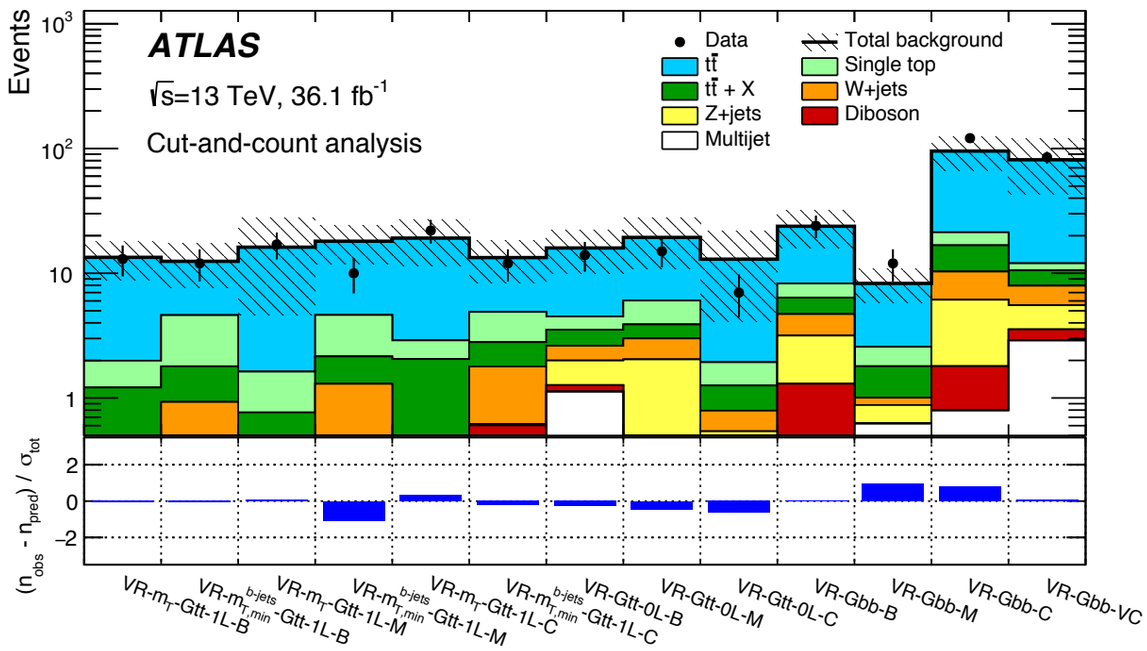


G*tt*

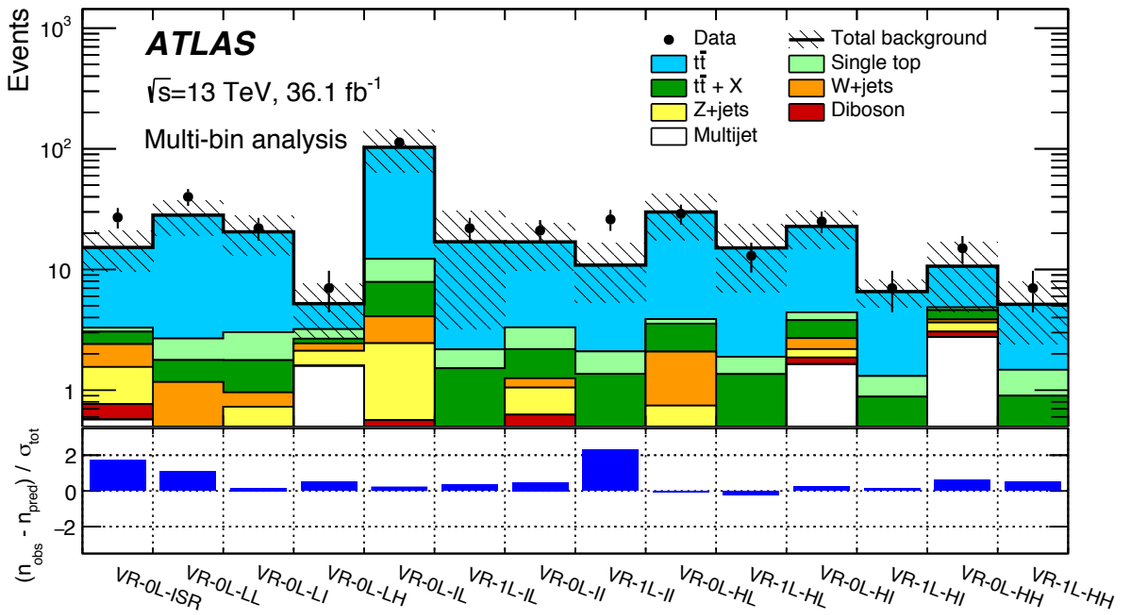


Gtt/Gbb: Background Estimation

top quark pair		MC normalised with top quark pair CR
single top, 4 tops		MC normalised to the best available cross-section
Z + jets	$Z \rightarrow \nu\nu$	
W + jets	$W \rightarrow l\nu$	
Top quark pair + W/Z/h		
di-boson production		
QCD multi-jet		a data driven method with jet smearing



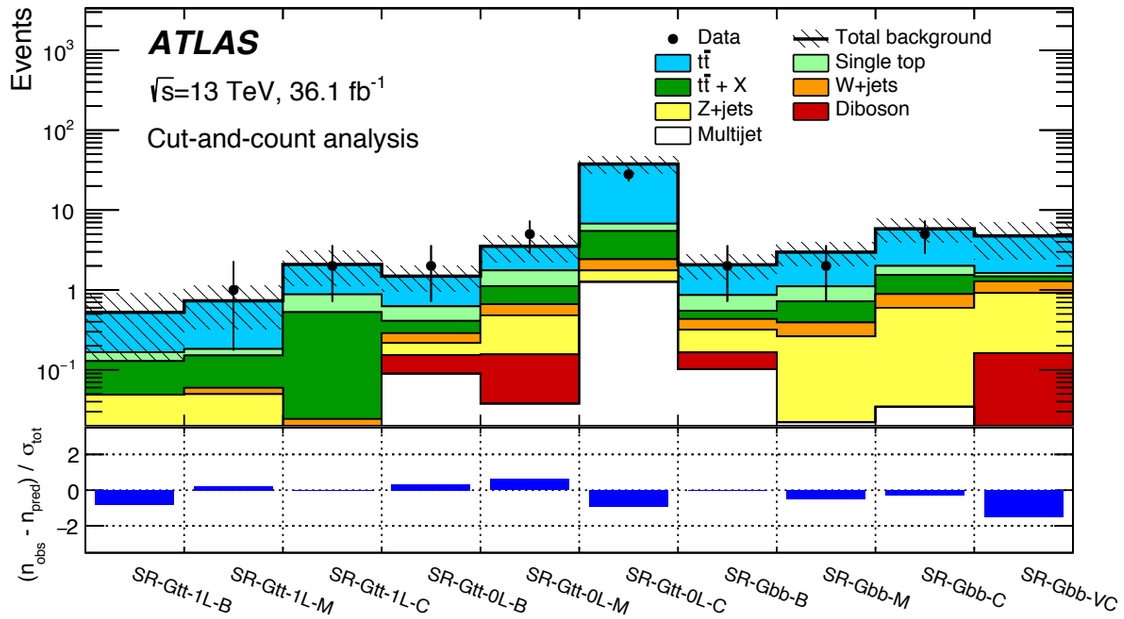
Cut-and-count VRs



Multi-bin VRs

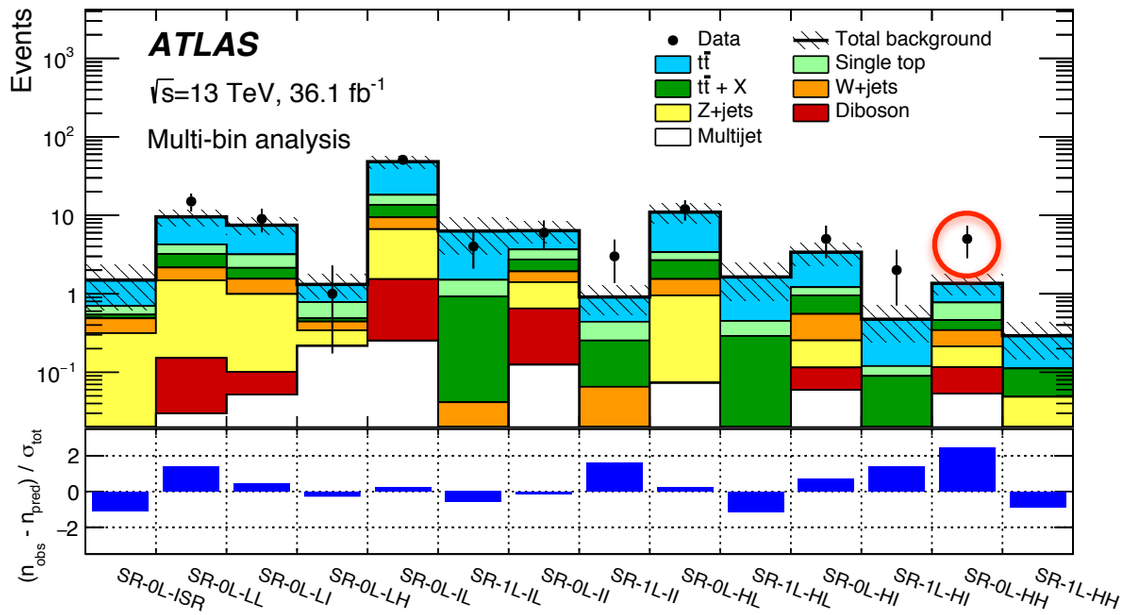
Gtt/Gbb: Results

No significant excess



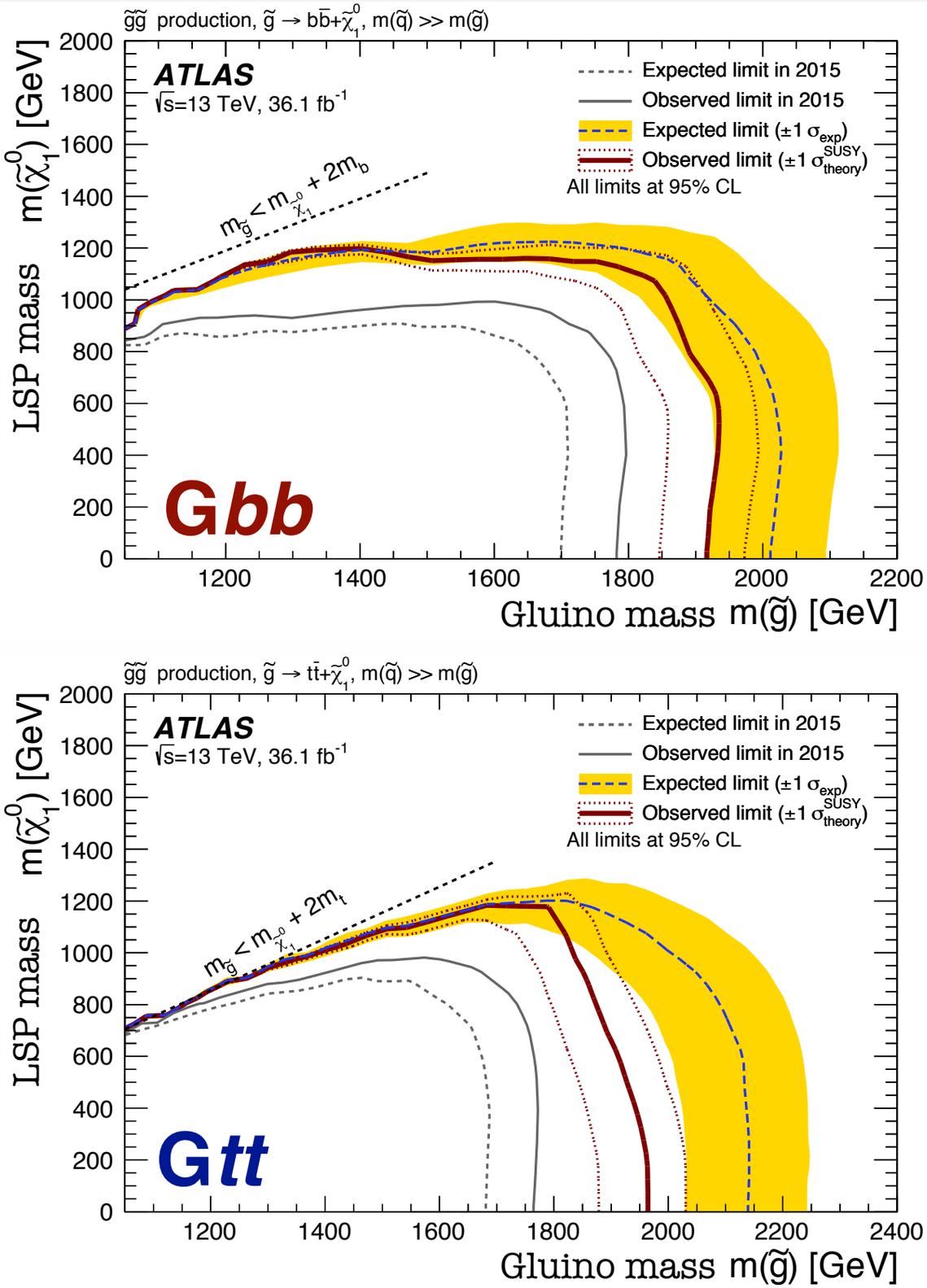
Cut-and-count SRs

The largest excess ≈ 2.3σ in a Multi-bin SR



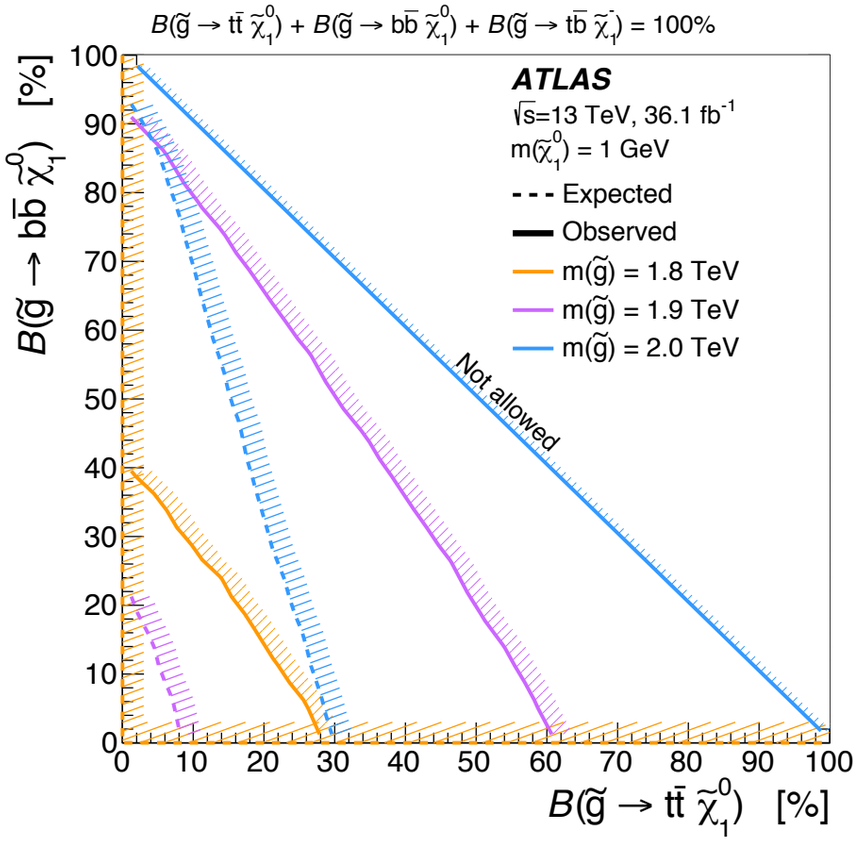
Multi-bin SRs

Gtt/Gbb: Interpretations



- Interpreted with the simplified model using multi-bin SRs
- New interpretation was done for gluino branching ratio plane Gtt vs Gbb

➡ Assuming three decay gluino's modes: Gtt, Gbb, Gtb
and
Br(Gtt) + Br(Gbb) + Br(Gtb) = 100%



Multi-jet channel

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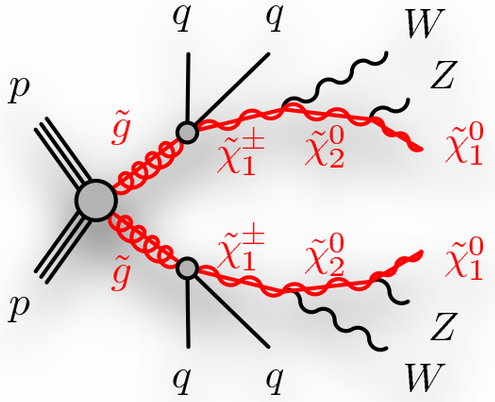
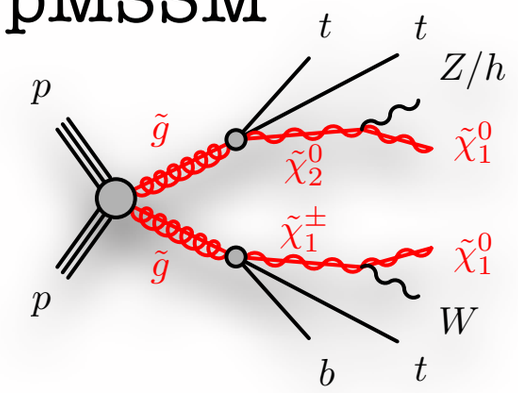
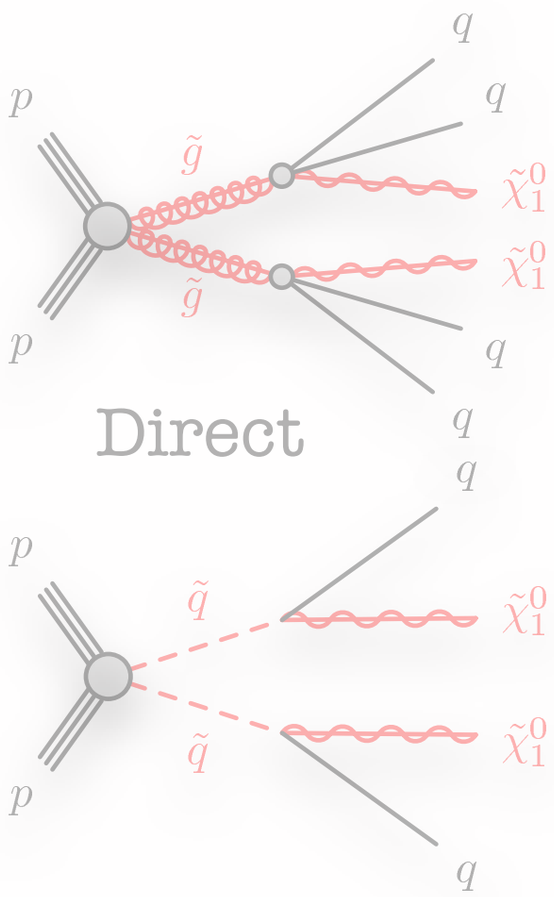
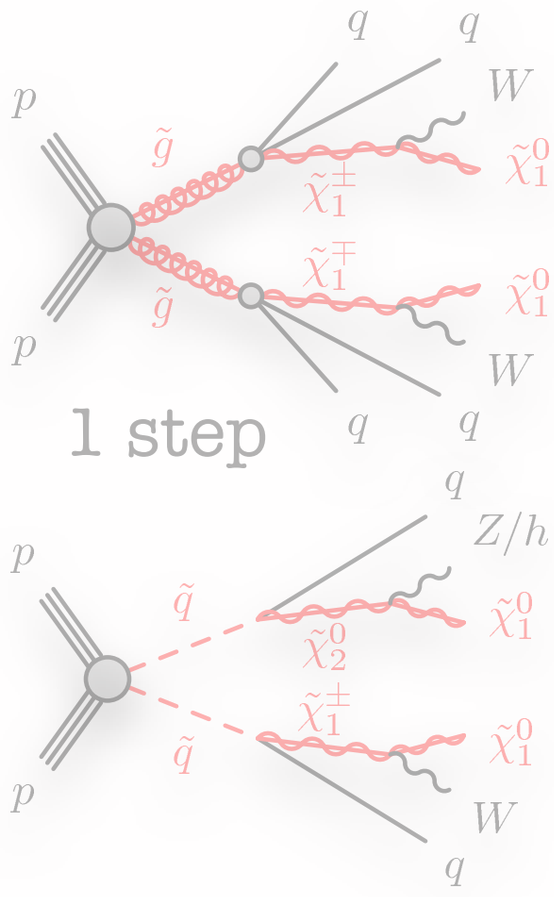


pMSSM

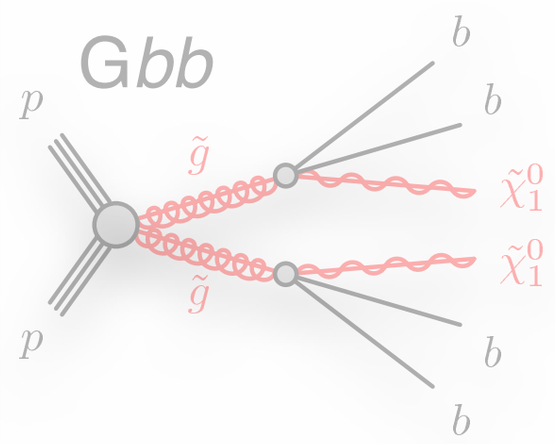


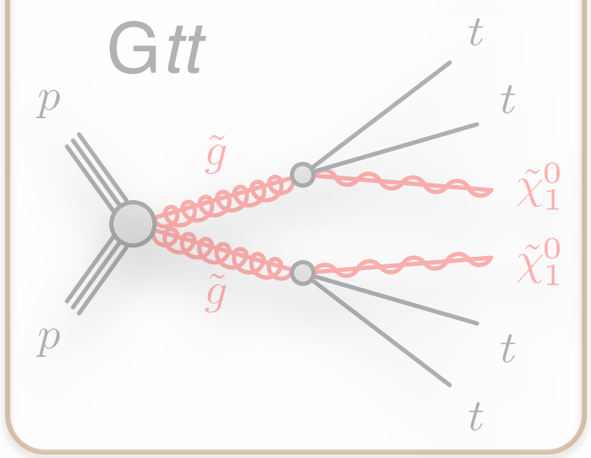
2-6 jets





G*tt*/G*bb*



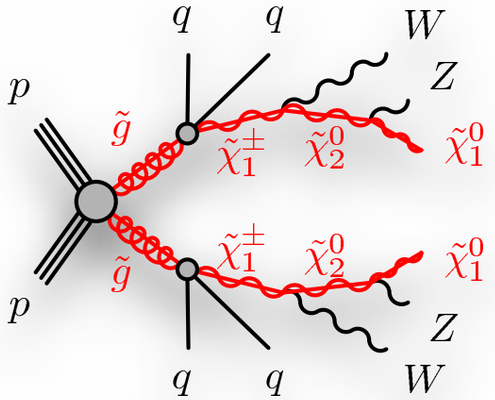


Multi-jet

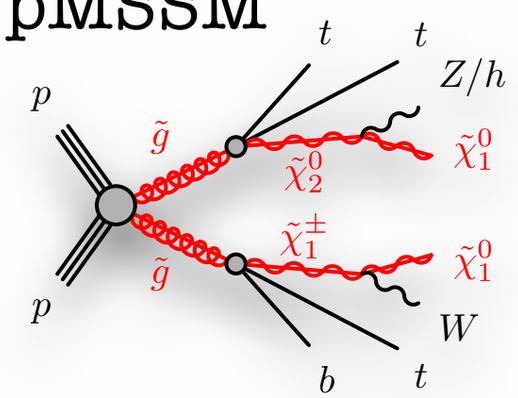
https://arxiv.org/abs/1708.02794

Multi-jets

Many-step



pMSSM



Motivation

- Many-step cascade decay of SUSY particles can produce high N_{jet}
- Unique sensitivity to some slices in pMSSM

The final state is characterised with

- Moderate E_T^{miss}
- $N_{jet} \geq 8$ (7) with $p_T^{jet} \geq 50$ (80) GeV
  - ➡ E_T^{miss} Significance: $E_T^{miss}/\sqrt{H_T} \geq 5\ GeV_{1/2}$

Final state with top quarks are considered in Jet mass stream

- Sum of mass of re-clustered large-R jet (R=1.0): $M_J^{\sum} \equiv \sum m_j^{R=1.0}$

Heavy flavour stream

- 21 SRs:
  $N_{jet} \geq 8, 9, 10, 11$ (7, 8, 9)
  with $p_T^{jet} > 50$ (80) GeV
  $N_{b\text{-}jet} \geq 0, 1, 2$

✓ Good sensitivity to signal with high LSP mass regions

Jet mass stream

- 6 SRs:
  $N_{jet} \geq 8, 9, 10$ with $p_T^{jet} > 50$
  $M_J^{\sum} > 340, 500$ GeV

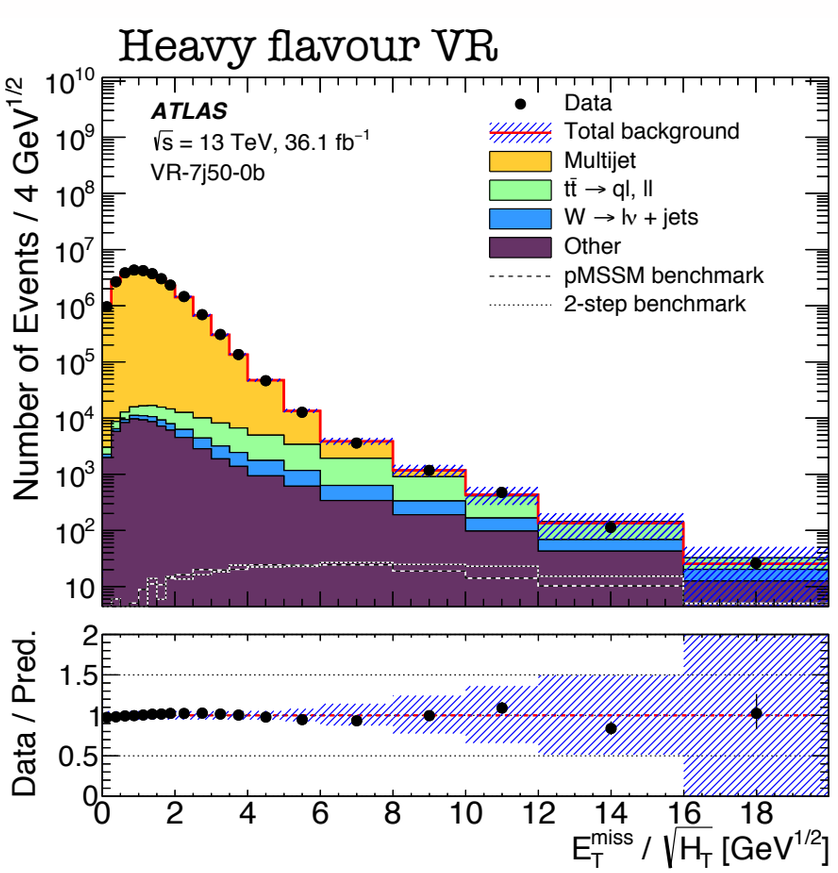
✓ Good sensitivity to signal with high gluino mass regions

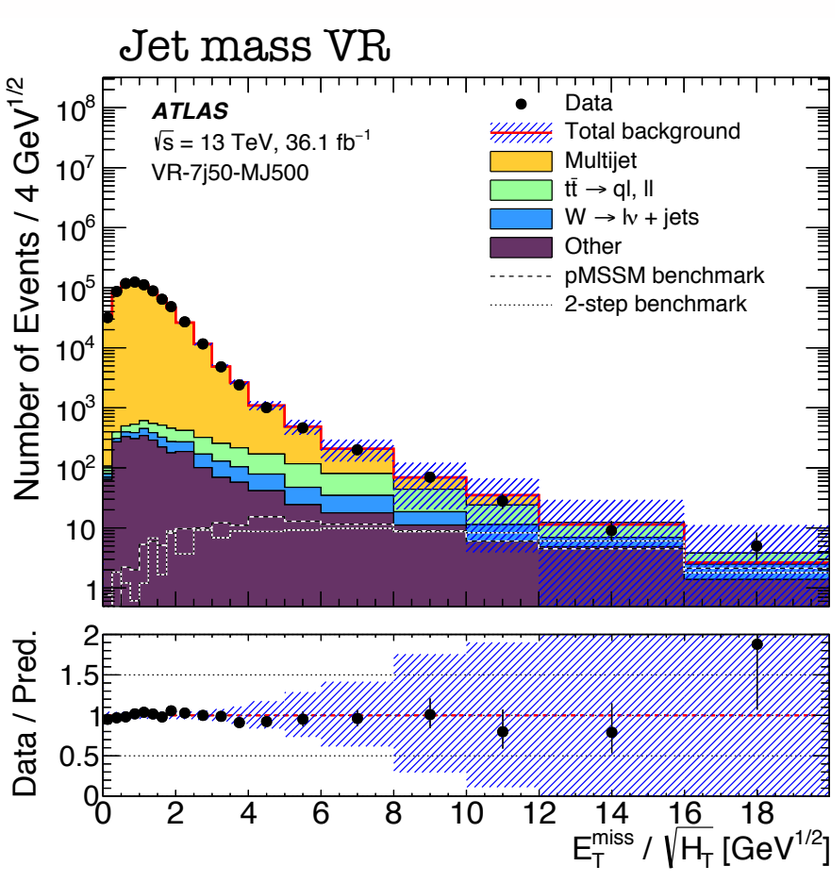
Multi-jet: Background Estimation

QCD multi-jet		data driven with “template” method
Semi-leptonically decaying top quark pair		MC normalised with top quark pair CR
W + jets	$W \to l\nu$	MC normalised with W + jets enriched CR
Z + jets	$Z \to \nu\nu$	MC normalised to the best available cross-section
single top		
di-boson production		

MJ-Template ≡
Data – Normalised BKG MC in MetSig distribution at N_{jet}=6

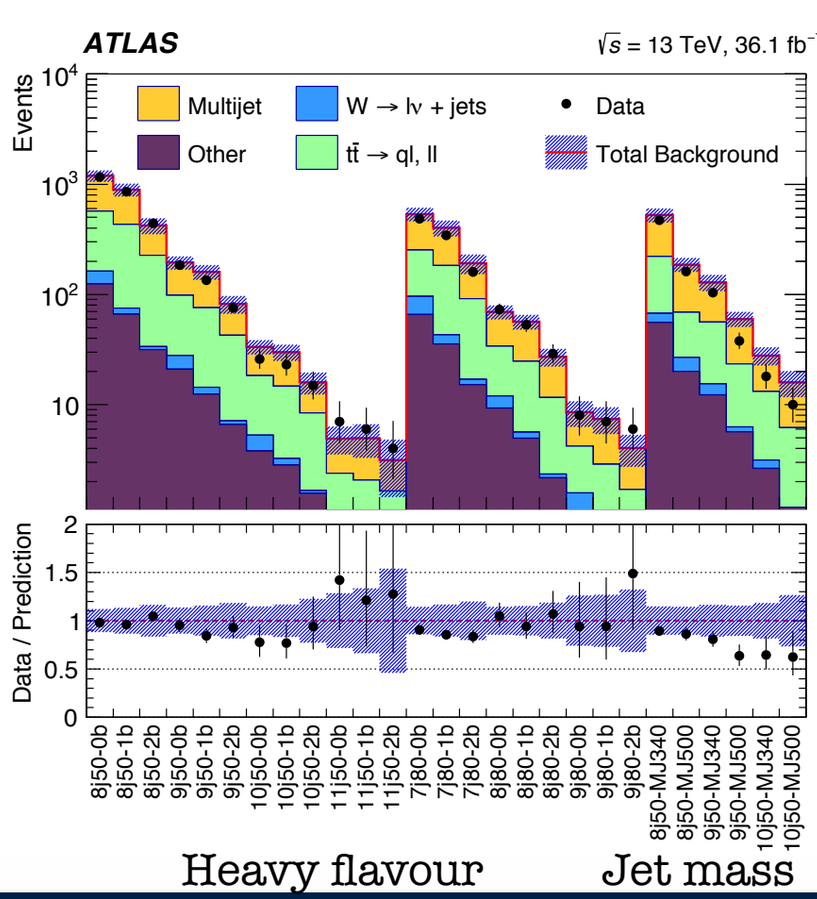
MJ-BKG@“k jets” ≡
MJ-Template × Ratio of N_{event}^{QCD} in low MetSig (<1.5) between N_{jet}=6 and k





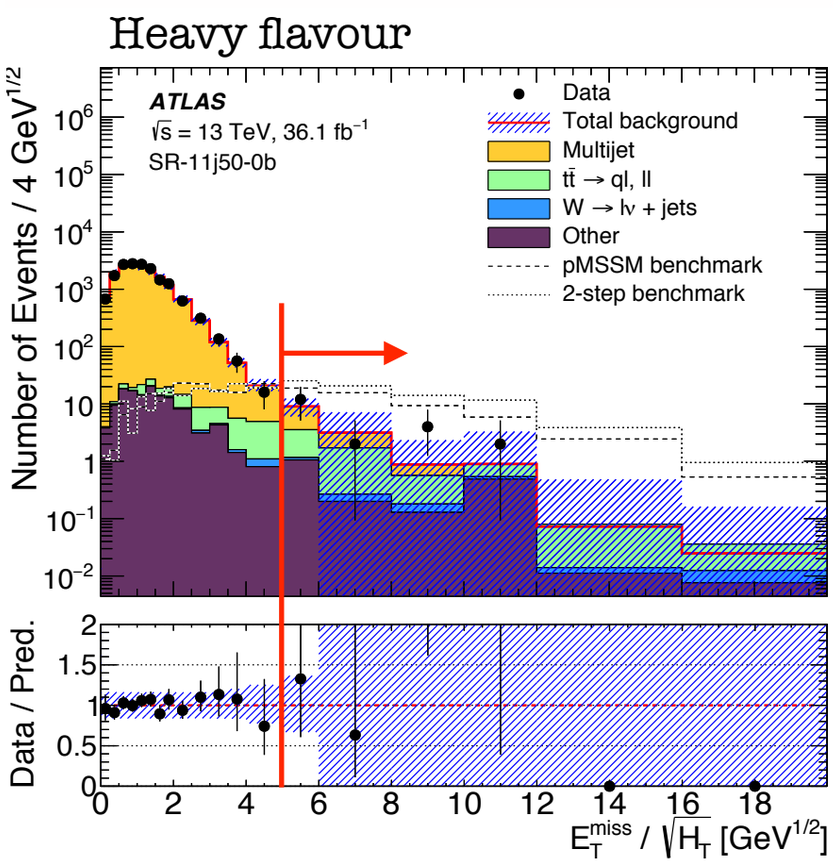
Multi-jet: Results

No excess was observed in any SRs

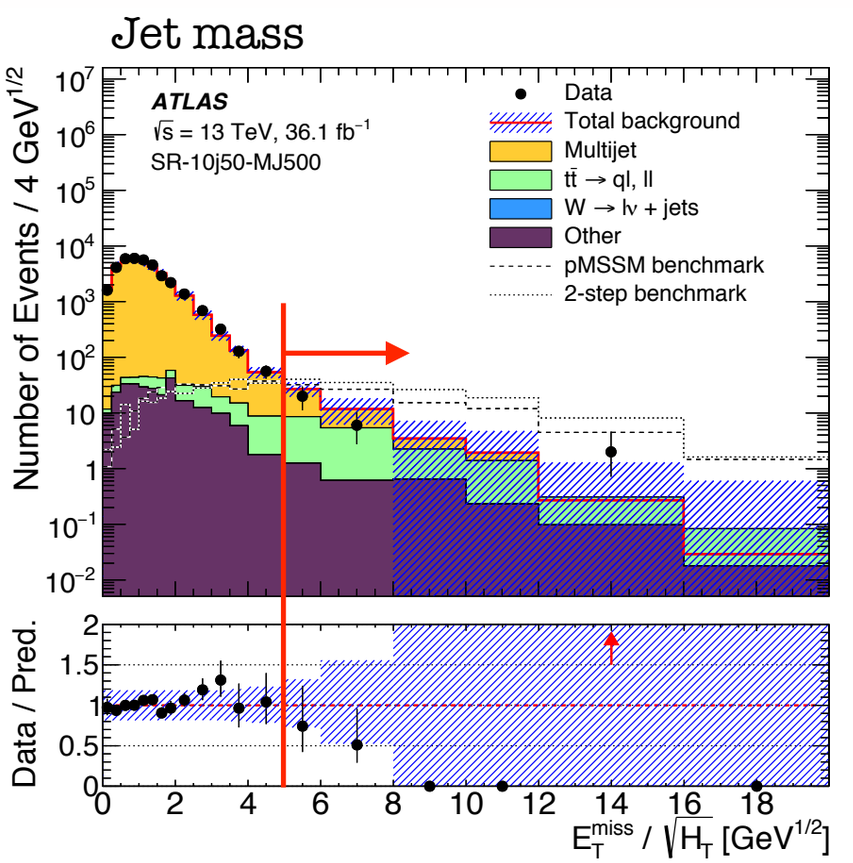


Heavy flavour Jet mass

Heavy flavour

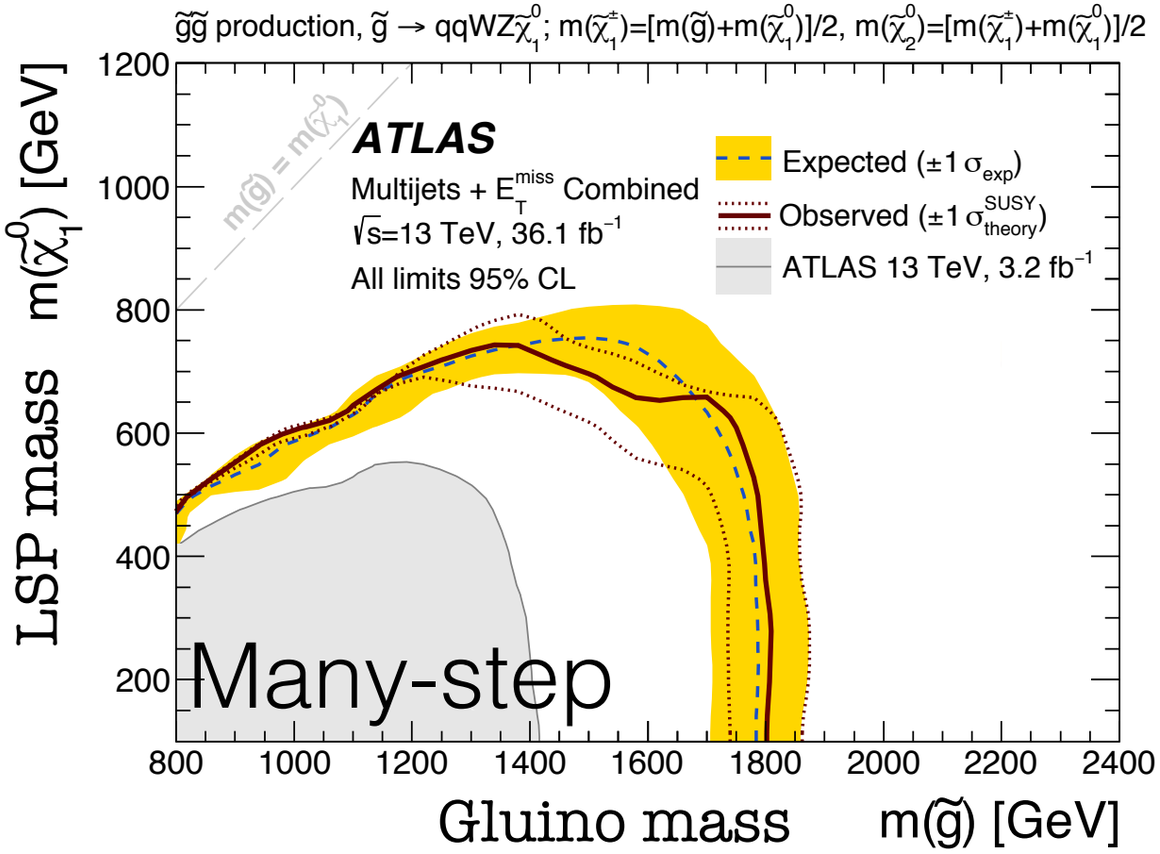


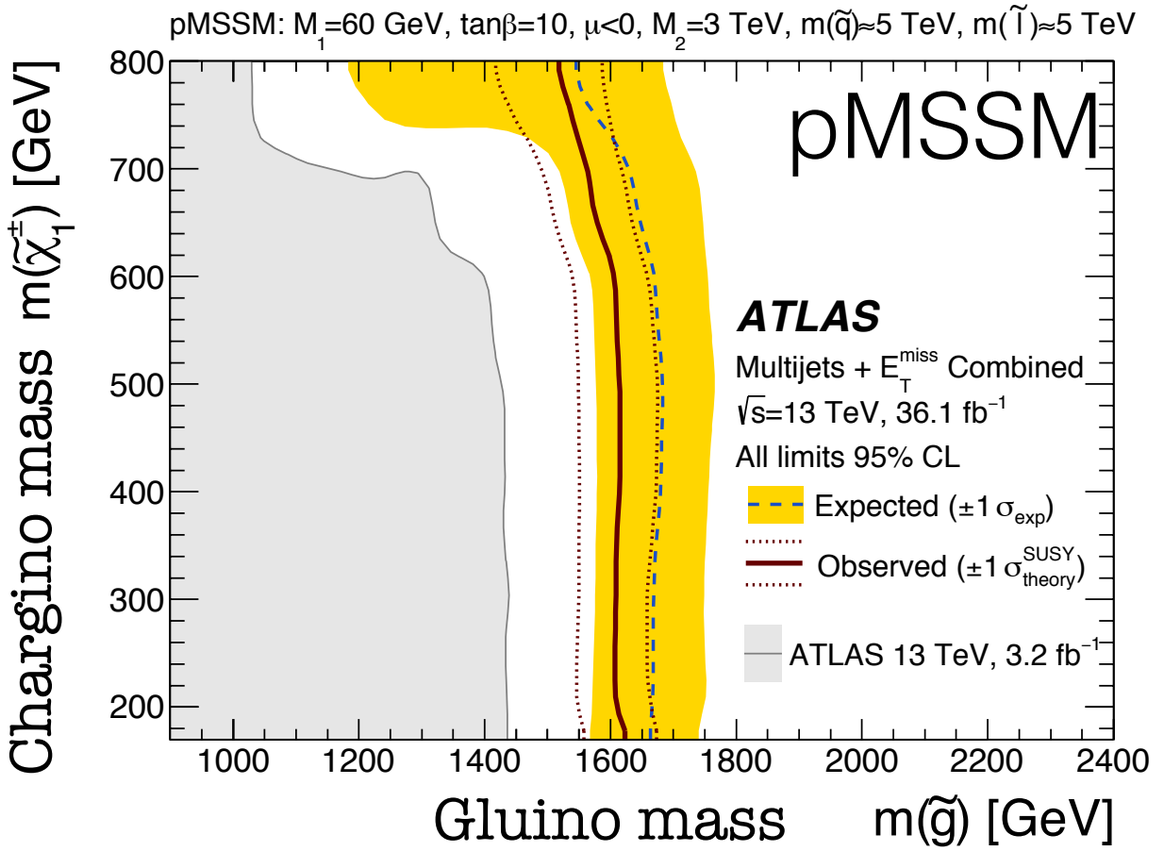
Jet mass



Multi-jet: Interpretations

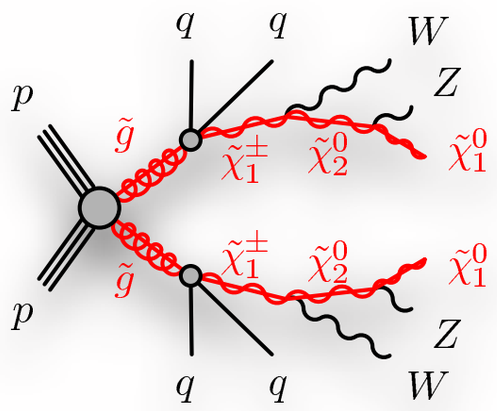
Exclusion limit obtained with the SR with the best expected sensitivity at each mass point

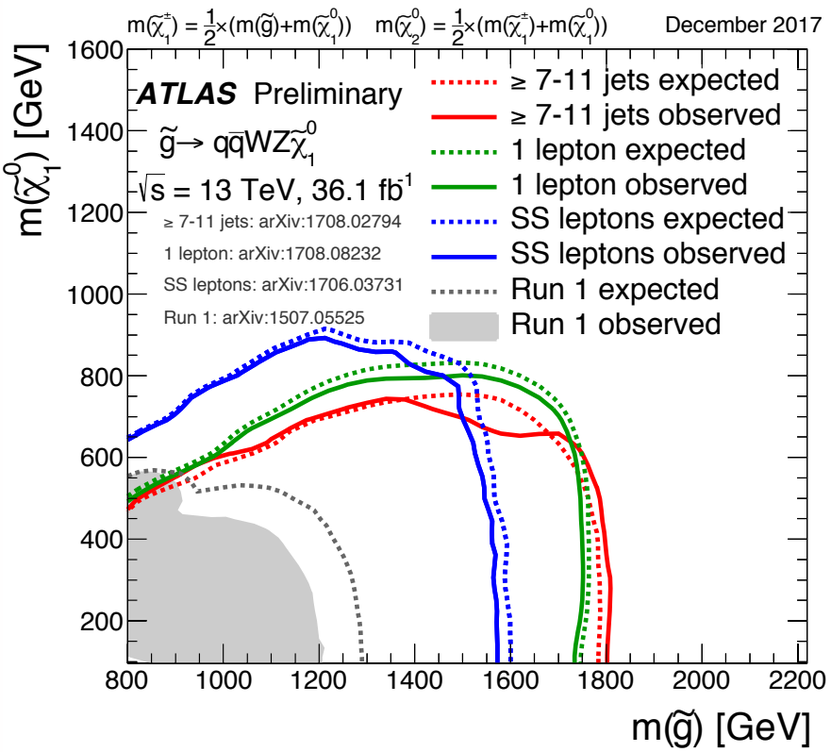




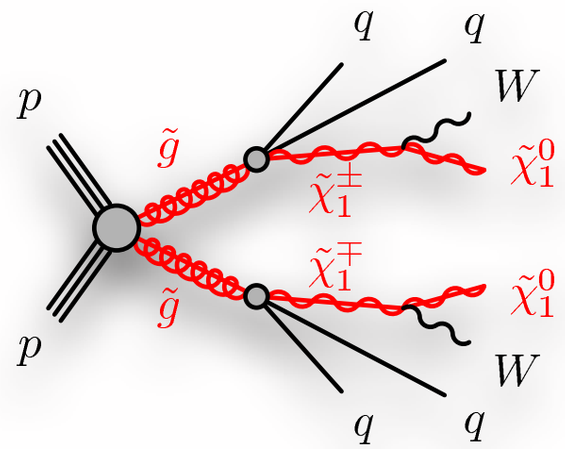
Interpretations

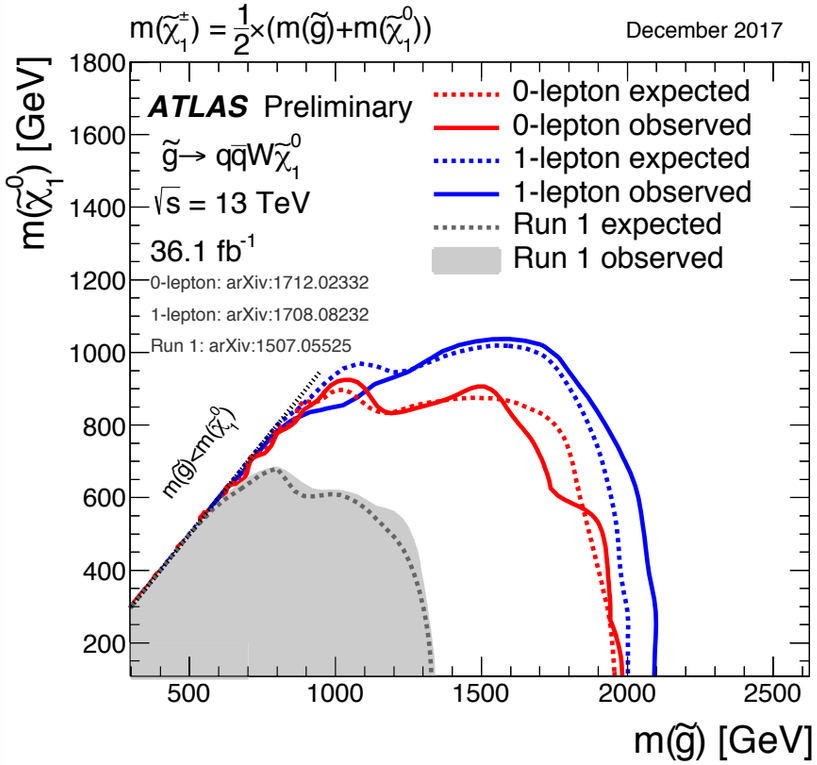
Multi-jet



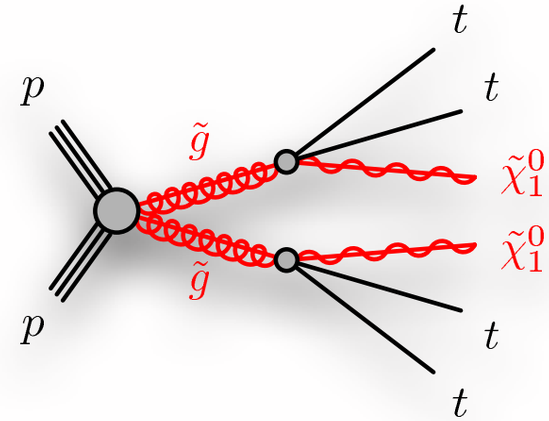


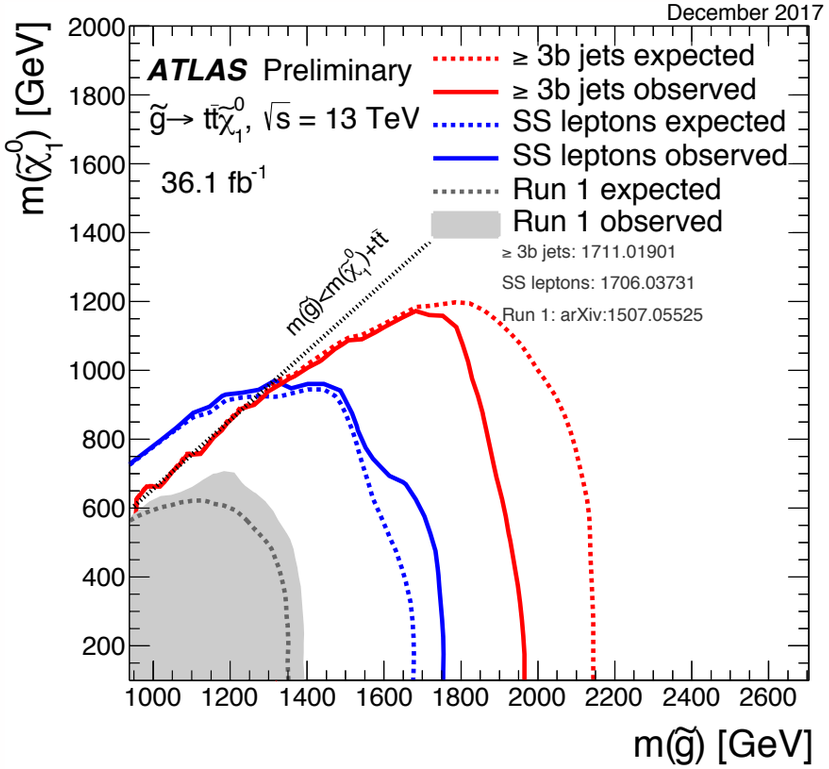
2-6 jets





G*tt*



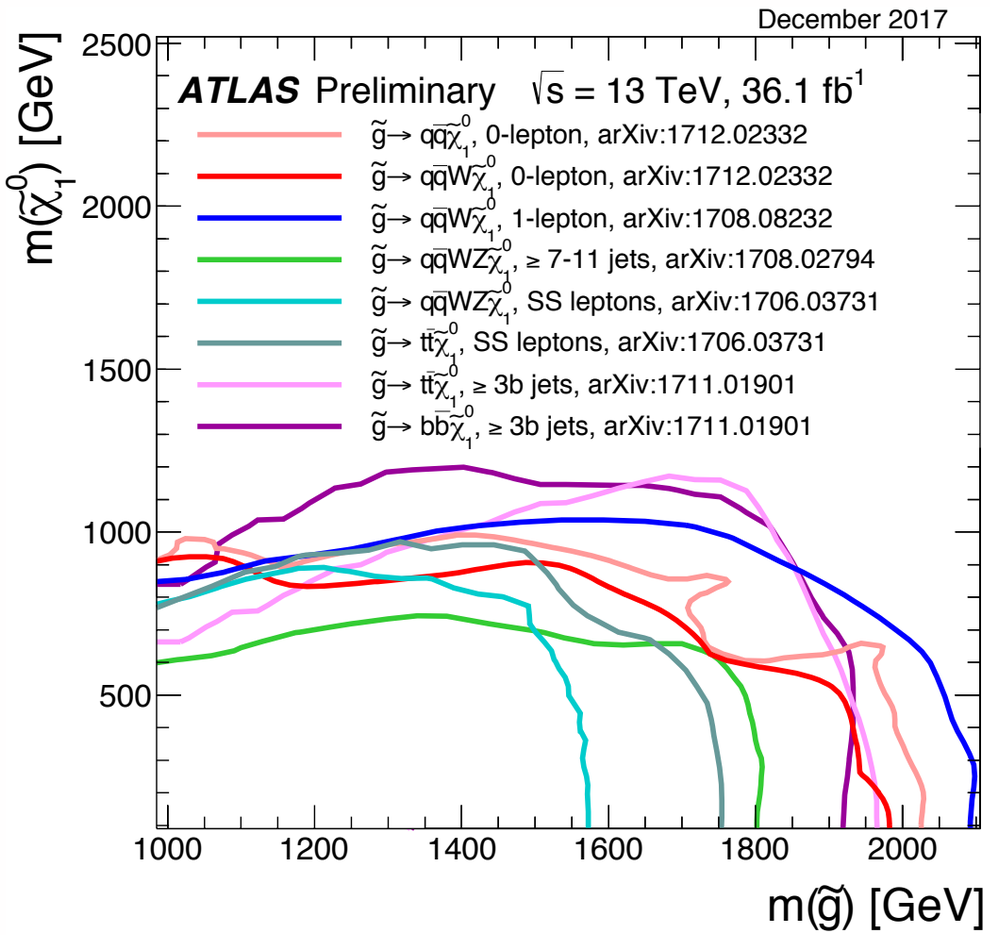


Conclusion

The proton-proton collision data in 2015 and 2016 collected by ATLAS, corresponding integrated luminosity of 36.1 fb^{-1}, are fully analysed and the results have been finalised.

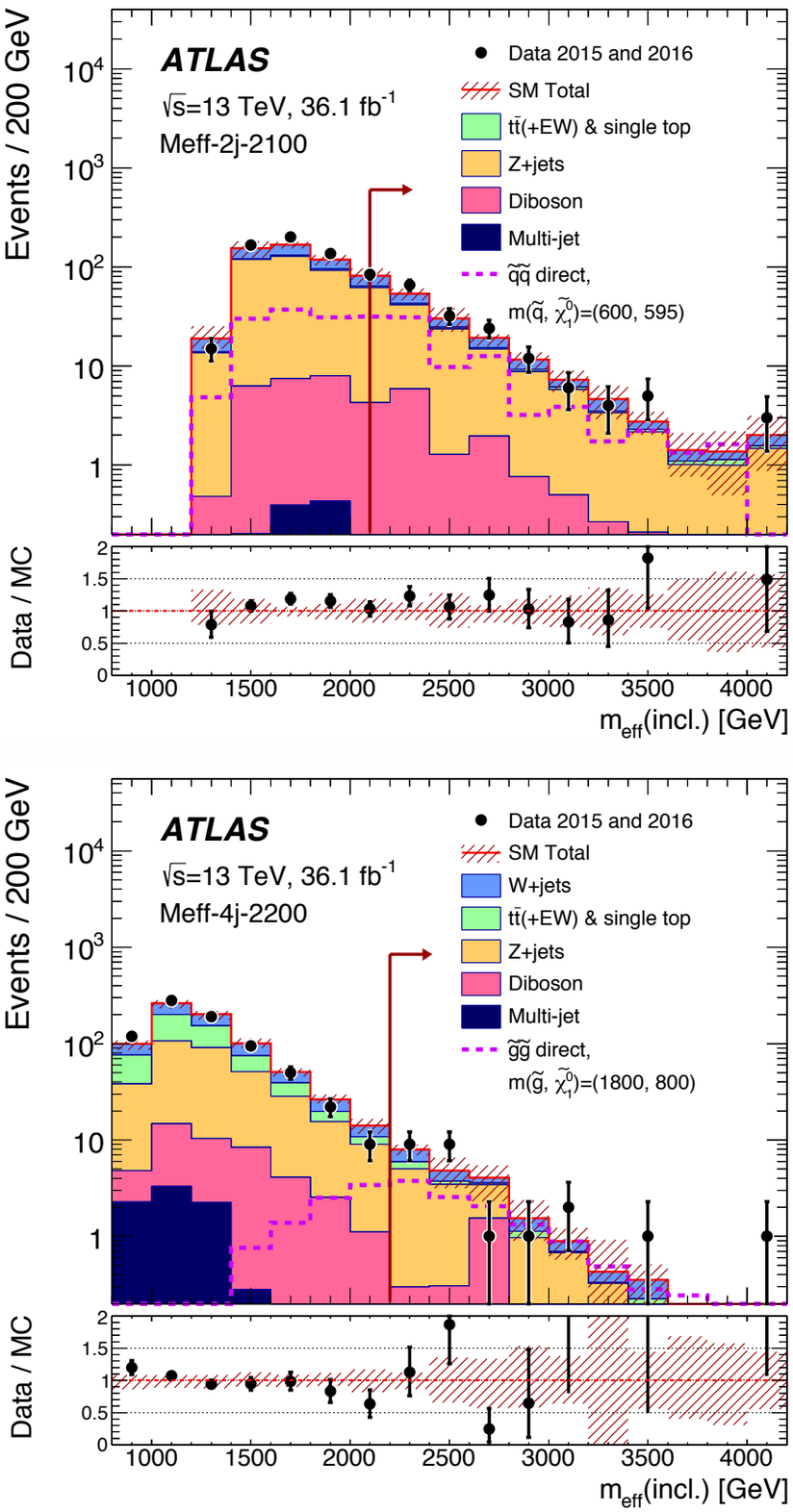
Not only relying increased statistics, but also analyses have been improved their sensitivity.

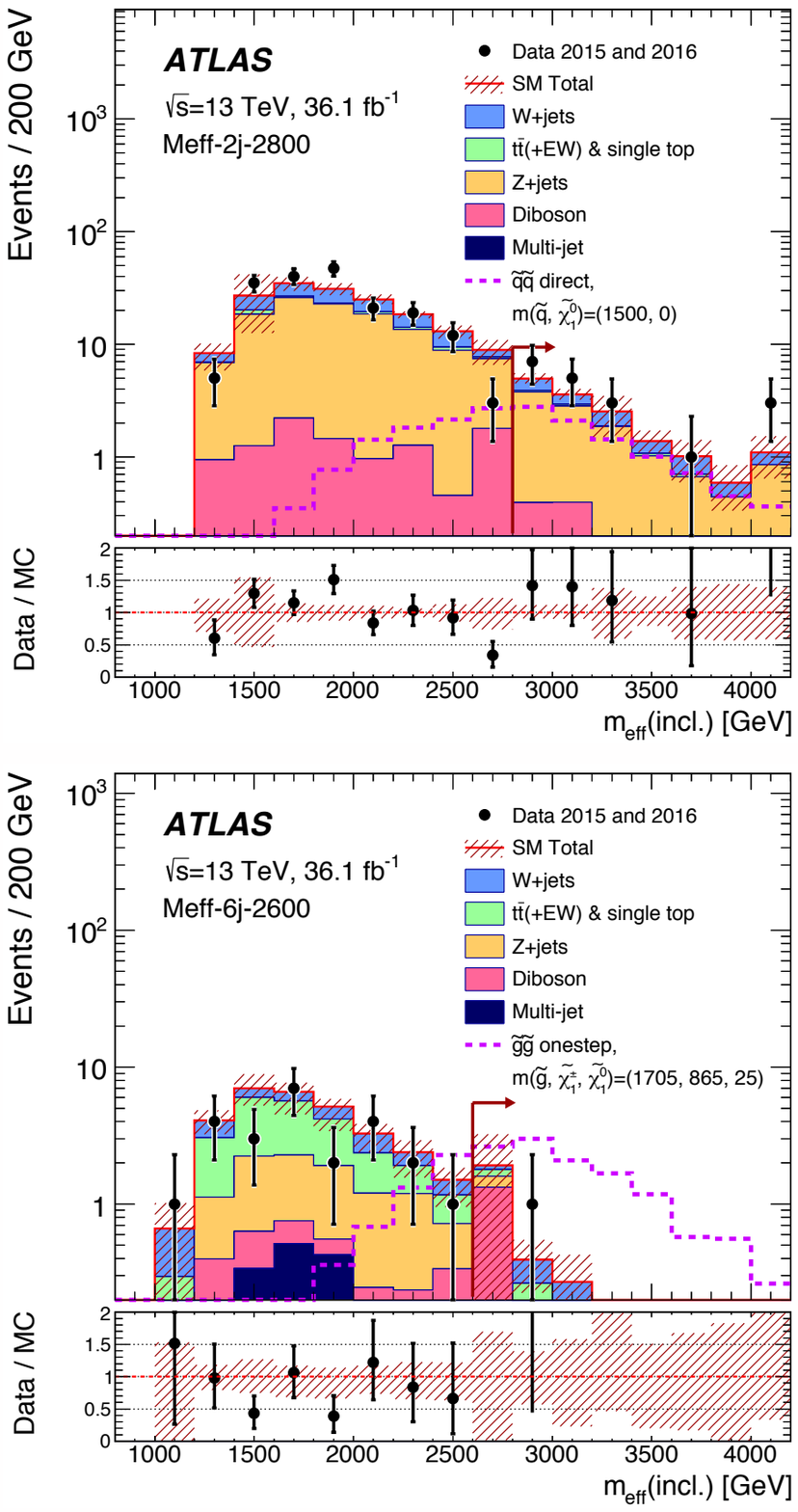
Despite outstanding efforts, the evidence of squarks/gluinos has not appeared yet.

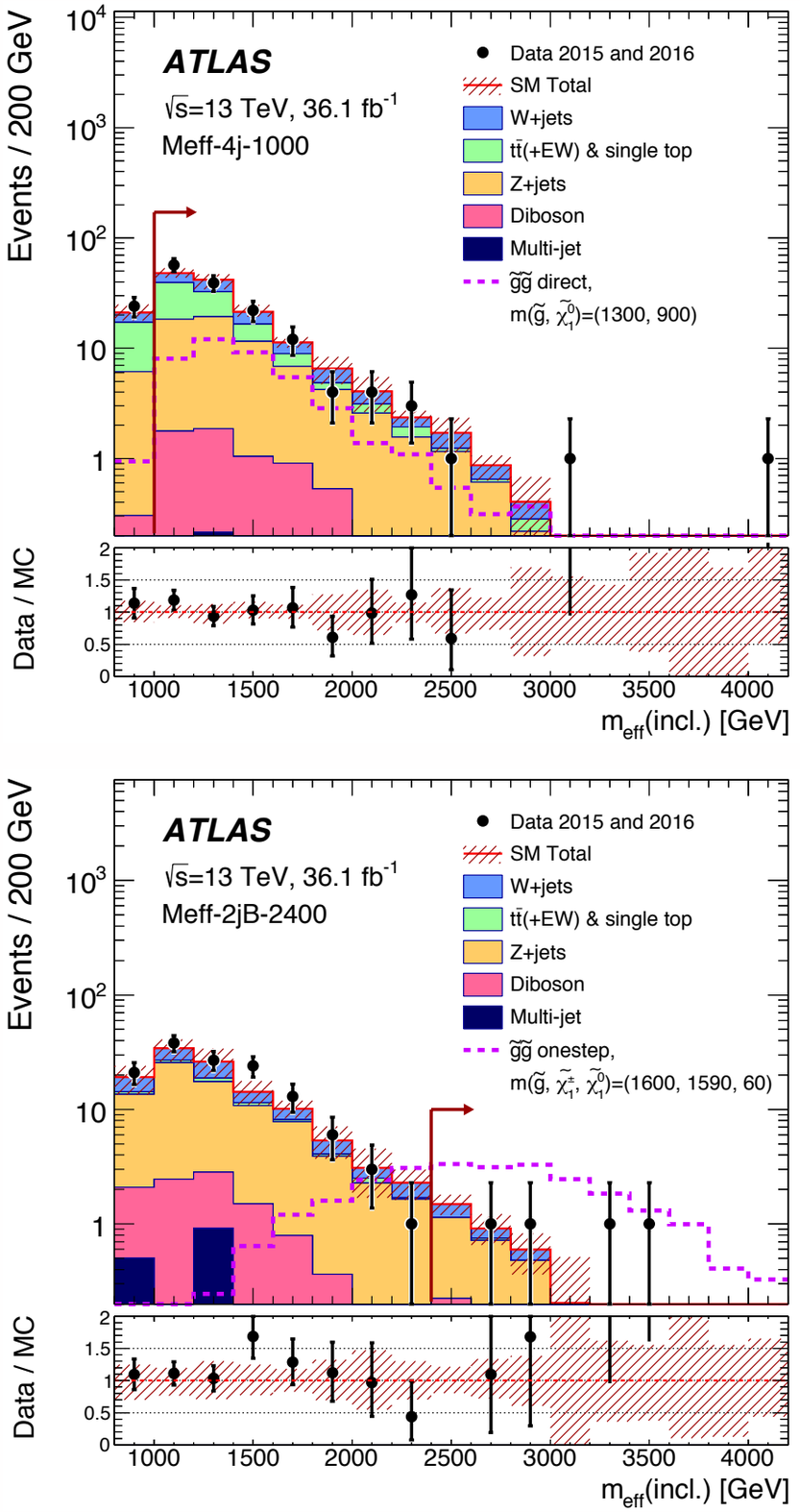


Backup

2-6j: Results


ATLAS
√s=13 TeV, 36.1 fb-1
Meff-2j-2100
Data 2015 and 2016
SM Total
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
q̃q̃ direct,
m(q̃, χ̃10)=(600, 595)
Events / 200 GeV
Data / MC
meff(incl.) [GeV]


ATLAS
√s=13 TeV, 36.1 fb-1
Meff-2j-2800
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
q̃q̃ direct,
m(q̃, χ̃10)=(1500, 0)
Events / 200 GeV
Data / MC
meff(incl.) [GeV]

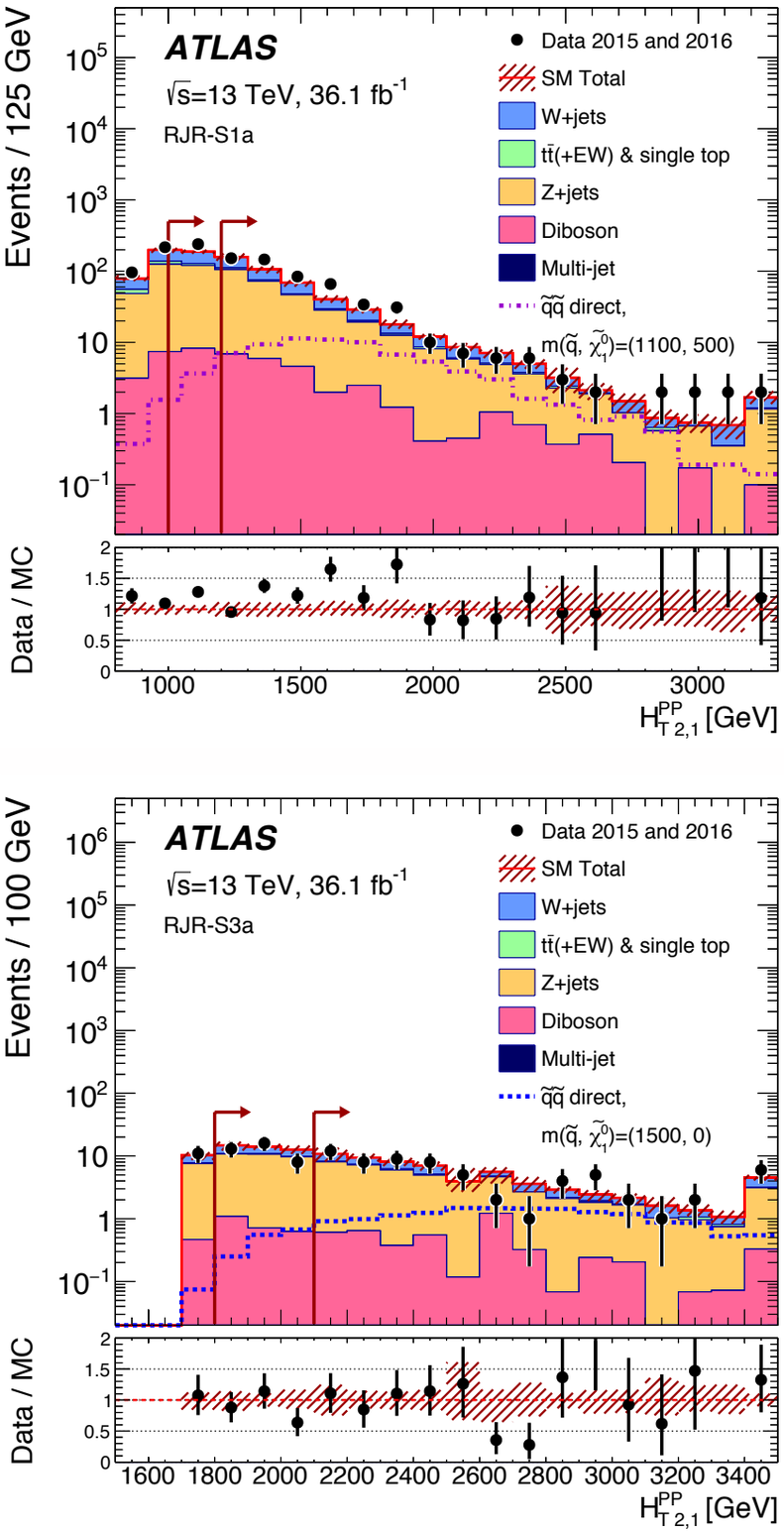

ATLAS
√s=13 TeV, 36.1 fb-1
Meff-4j-1000
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
g̃g̃ direct,
m(g̃, χ̃10)=(1300, 900)
Events / 200 GeV
Data / MC
meff(incl.) [GeV]

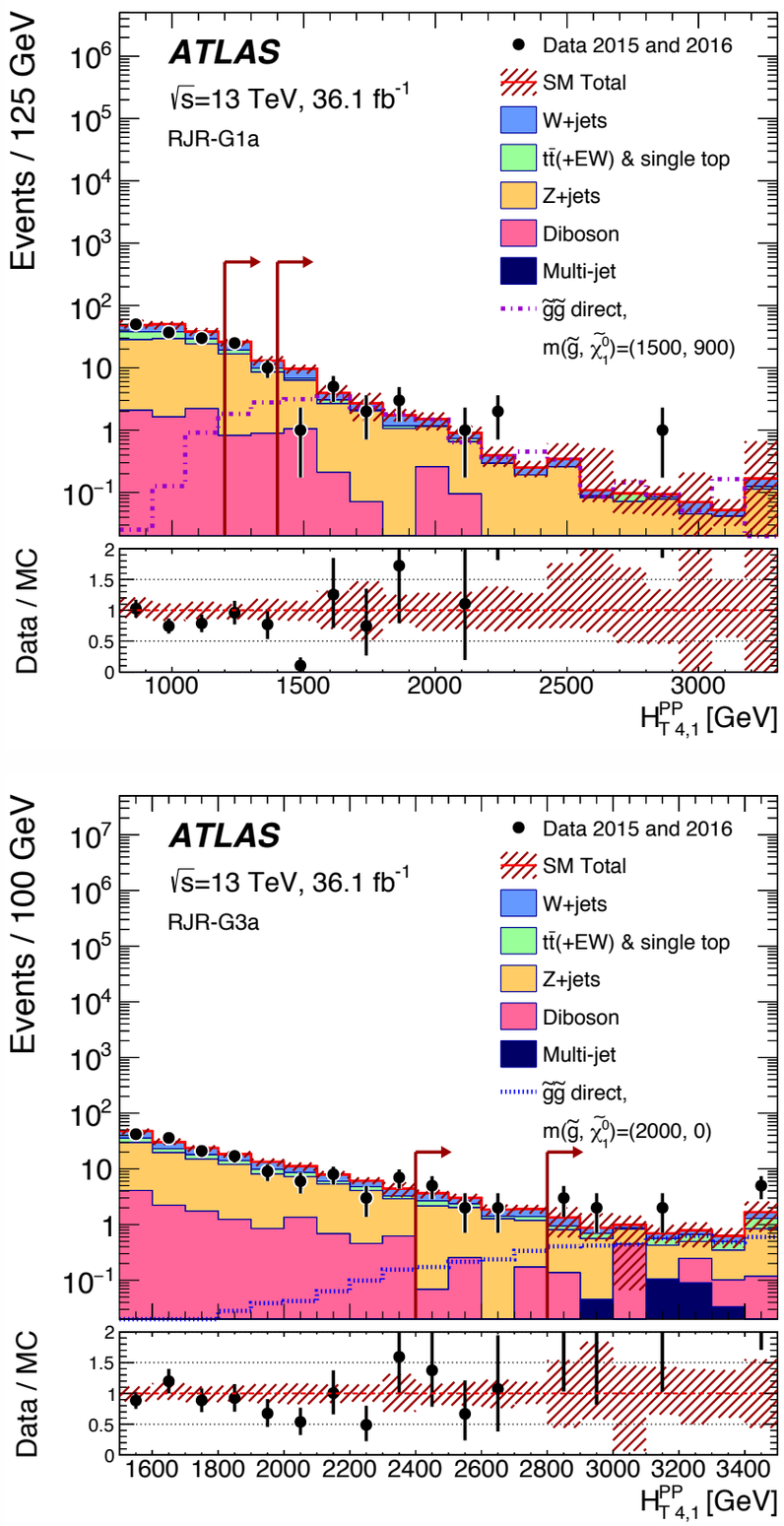
ATLAS
√s=13 TeV, 36.1 fb-1
Meff-4j-2200
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
g̃g̃ direct,
m(g̃, χ̃10)=(1800, 800)
Events / 200 GeV
Data / MC
meff(incl.) [GeV]

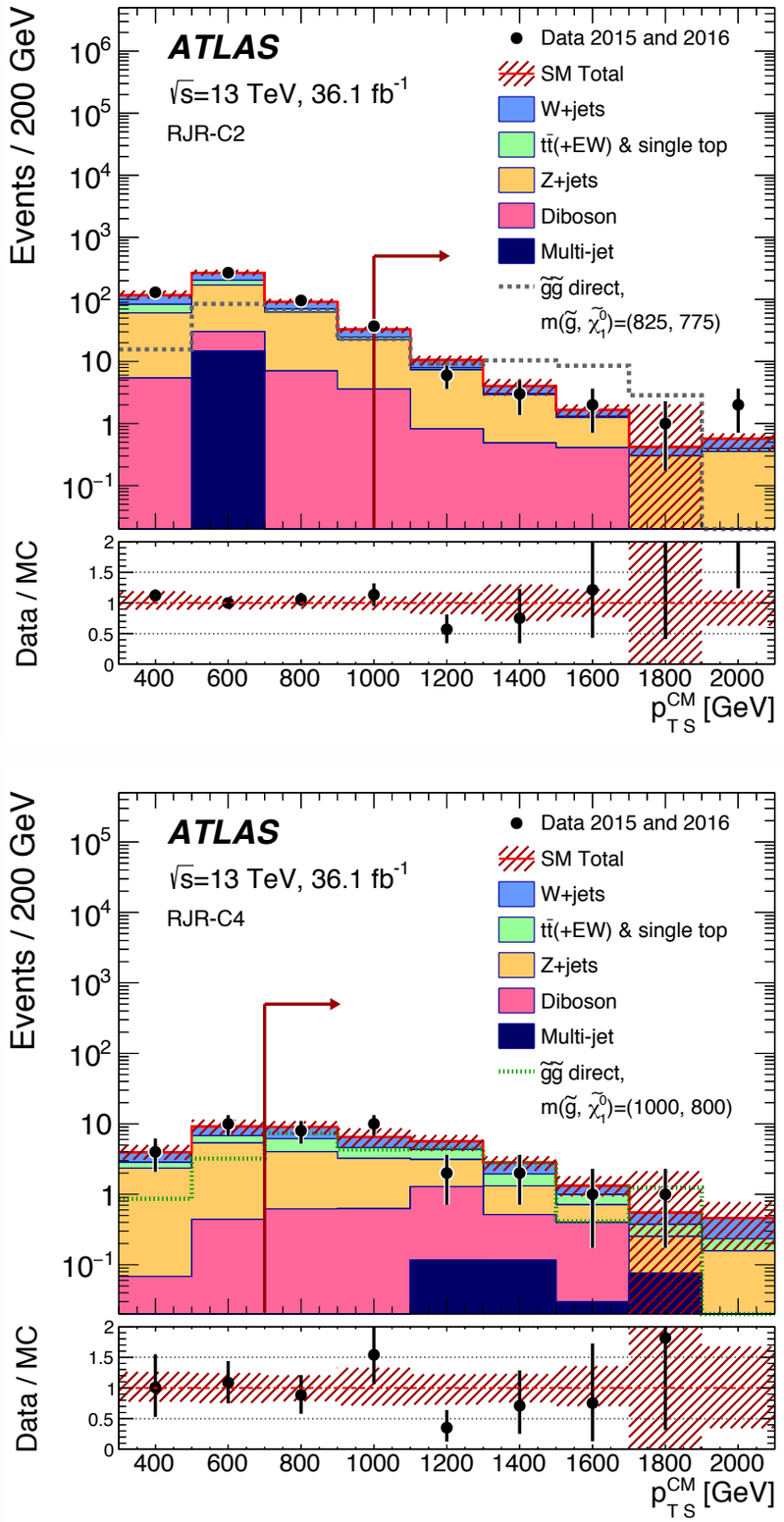
ATLAS
√s=13 TeV, 36.1 fb-1
Meff-6j-2600
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
g̃g̃ onestep,
m(g̃, χ̃±1, χ̃01)=(1705, 865, 25)
Events / 200 GeV
Data / MC
meff(incl.) [GeV]

ATLAS
√s=13 TeV, 36.1 fb-1
Meff-2jB-2400
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
g̃g̃ onestep,
m(g̃, χ̃±1, χ̃01)=(1600, 1590, 60)
Events / 200 GeV
Data / MC
meff(incl.) [GeV]

2-6j: Results


ATLAS
√s=13 TeV, 36.1 fb-1
RJR-S1a
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
q̃q̃ direct,
m(q̃, χ̃10)=(1100, 500)
Events / 125 GeV
Data / MC
H PP T 2,1 [GeV]


ATLAS
√s=13 TeV, 36.1 fb-1
RJR-G1a
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
g̃g̃ direct,
m(g̃, χ̃10)=(1500, 900)
Events / 125 GeV
Data / MC
H PP T 4,1 [GeV]

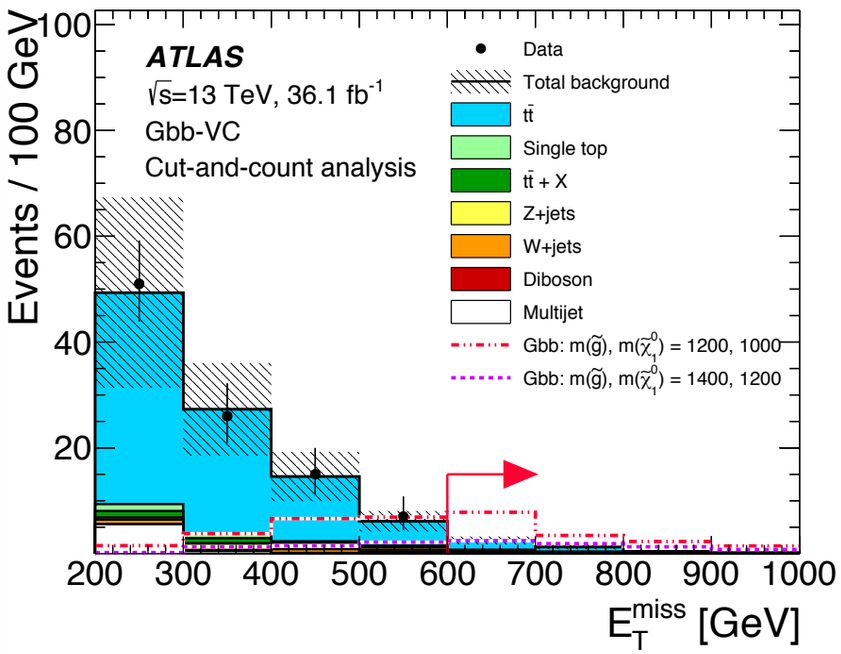

ATLAS
√s=13 TeV, 36.1 fb-1
RJR-C2
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
g̃g̃ direct,
m(g̃, χ̃10)=(825, 775)
Events / 200 GeV
Data / MC
p CM T S [GeV]

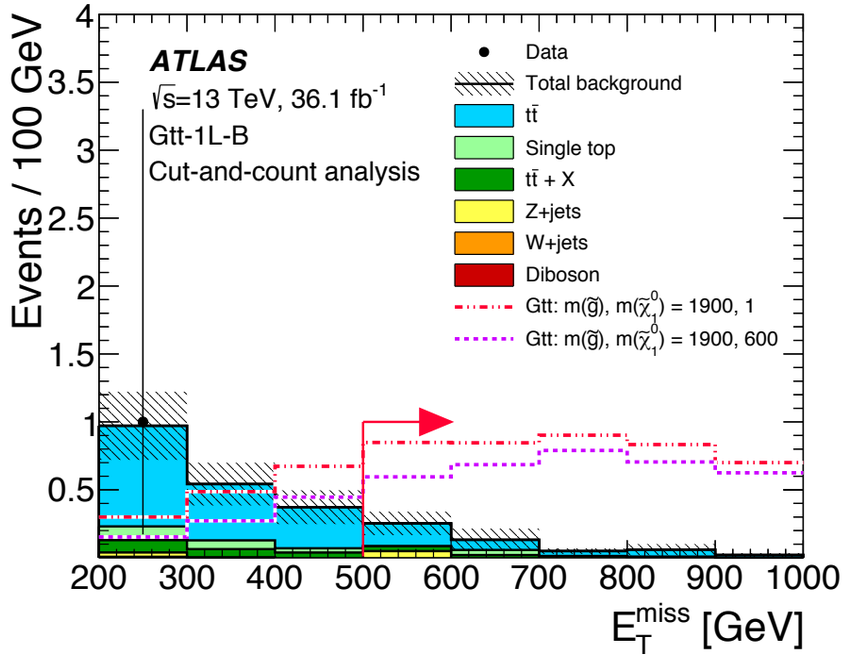
ATLAS
√s=13 TeV, 36.1 fb-1
RJR-S3a
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
q̃q̃ direct,
m(q̃, χ̃10)=(1500, 0)
Events / 100 GeV
Data / MC
H PP T 2,1 [GeV]

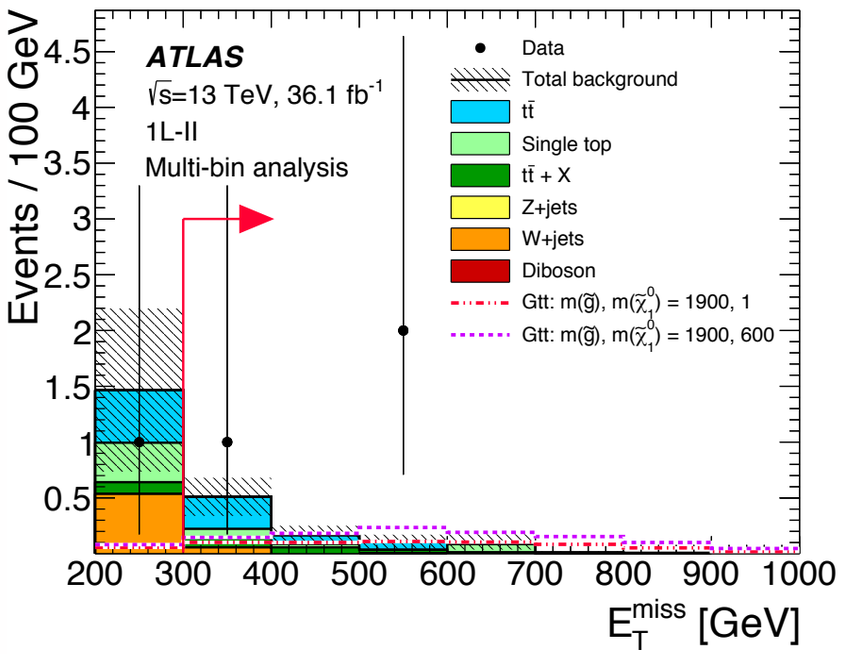
ATLAS
√s=13 TeV, 36.1 fb-1
RJR-G3a
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
g̃g̃ direct,
m(g̃, χ̃10)=(2000, 0)
Events / 100 GeV
Data / MC
H PP T 4,1 [GeV]

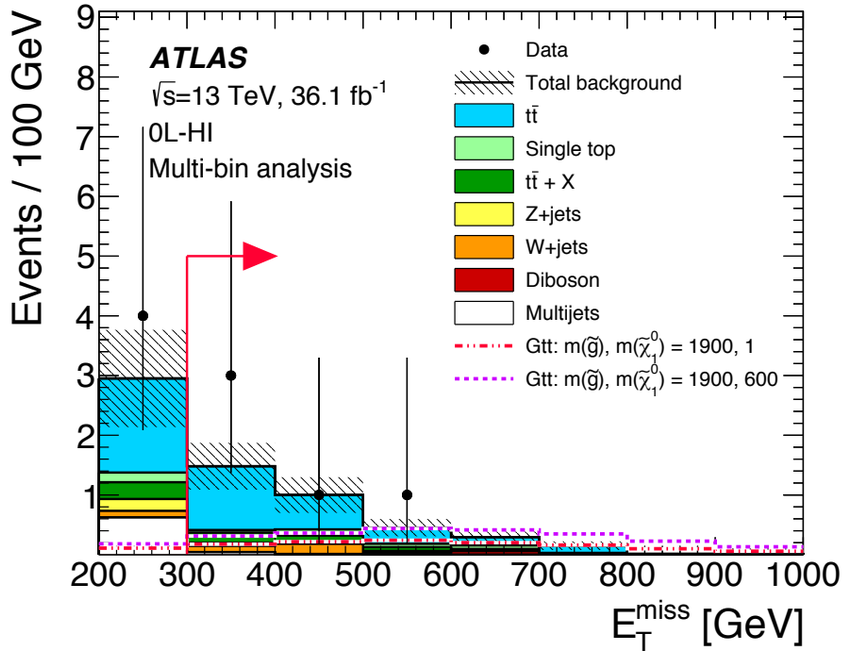
ATLAS
√s=13 TeV, 36.1 fb-1
RJR-C4
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multi-jet
g̃g̃ direct,
m(g̃, χ̃10)=(1000, 800)
Events / 200 GeV
Data / MC
p CM T S [GeV]

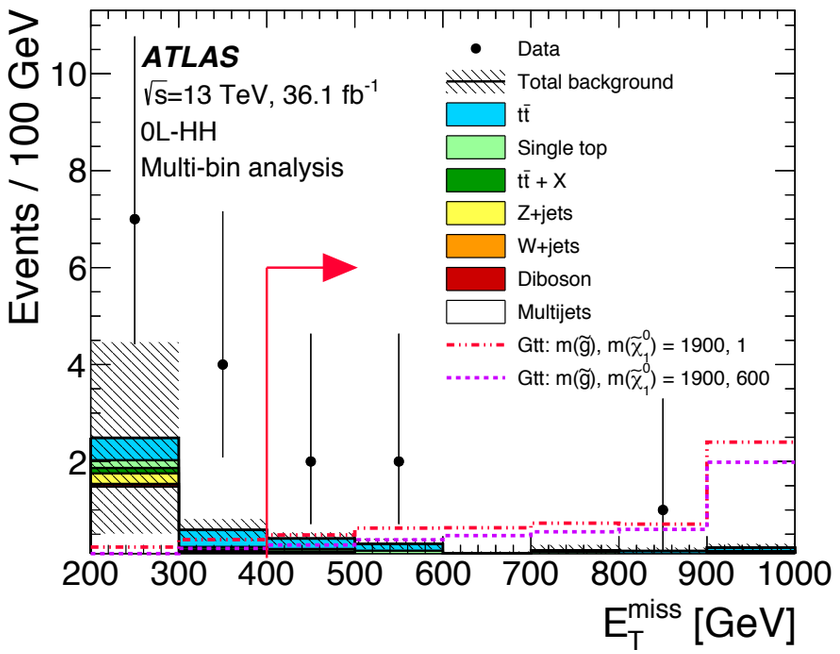
Gtt/Gbb: Results











Multi-jet: Interpretations

Exclusion limit obtained with the SR with the best expected sensitivity at each mass point