Recent results from searches for Supersymmetry at ATLAS

Boosting the sensitivity with the **full 13 TeV dataset**

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on behalf of the **ATLAS Collaboration**

Seminar at **Laboratoire Leprince-Ringuet**
École Polytechnique, Université Paris-Saclay

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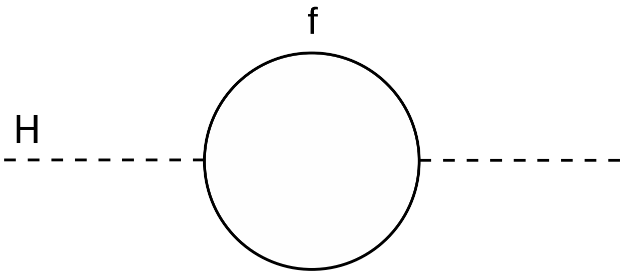
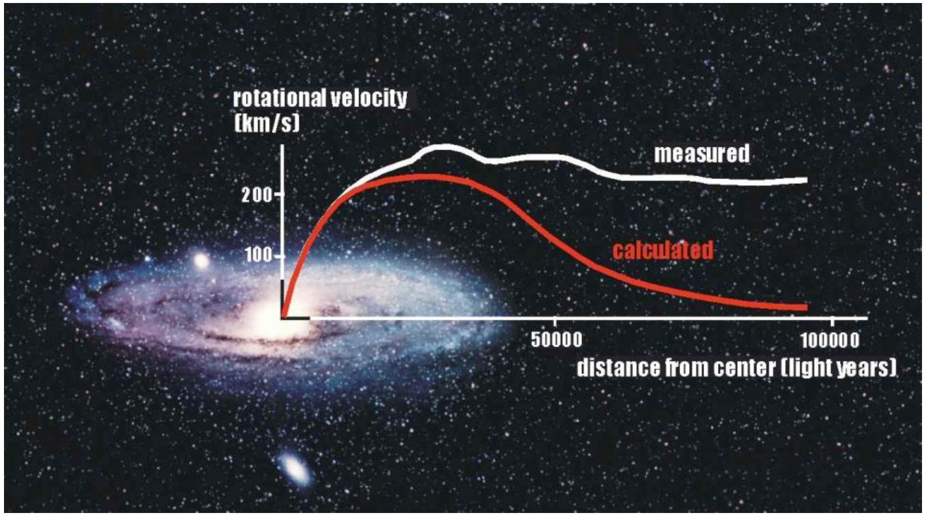
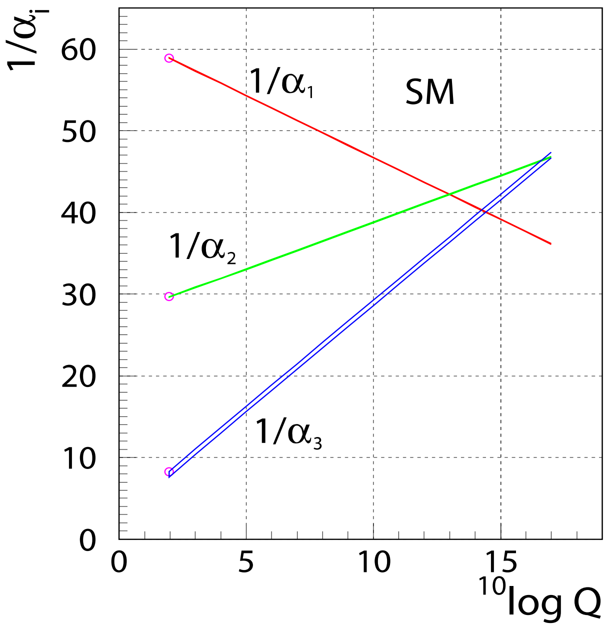
Open Questions of the Standard Model

- **Hierarchy problem**: Higgs mass subject to quadratically divergent loop corrections.
  → Incredible fine-tuning





- **Dark matter:** Cosmological data suggest presence of dark matter → No explanation within Standard Model



- **Grand unification:** Standard Model coupling constants do not unify at high scales.
  → SM does not imply a Grand Unified Theory

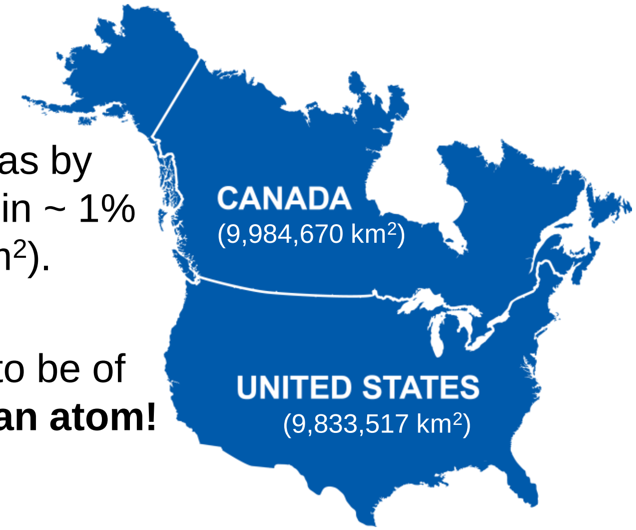
Never tired of analogies…

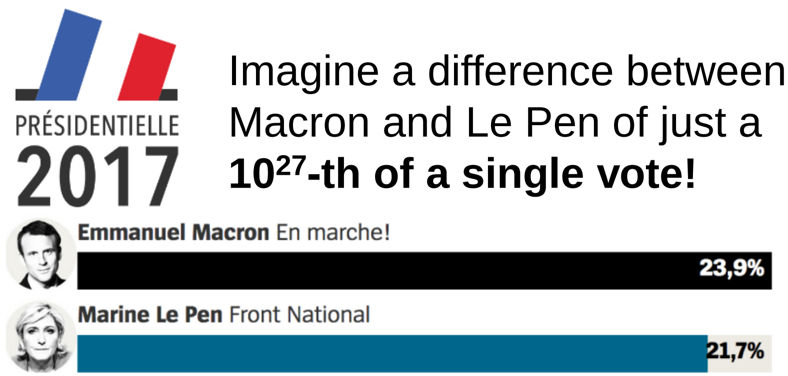
[source: http://www.quantumdiaries.org]

"The Higgs has a snowman's chance in hell"

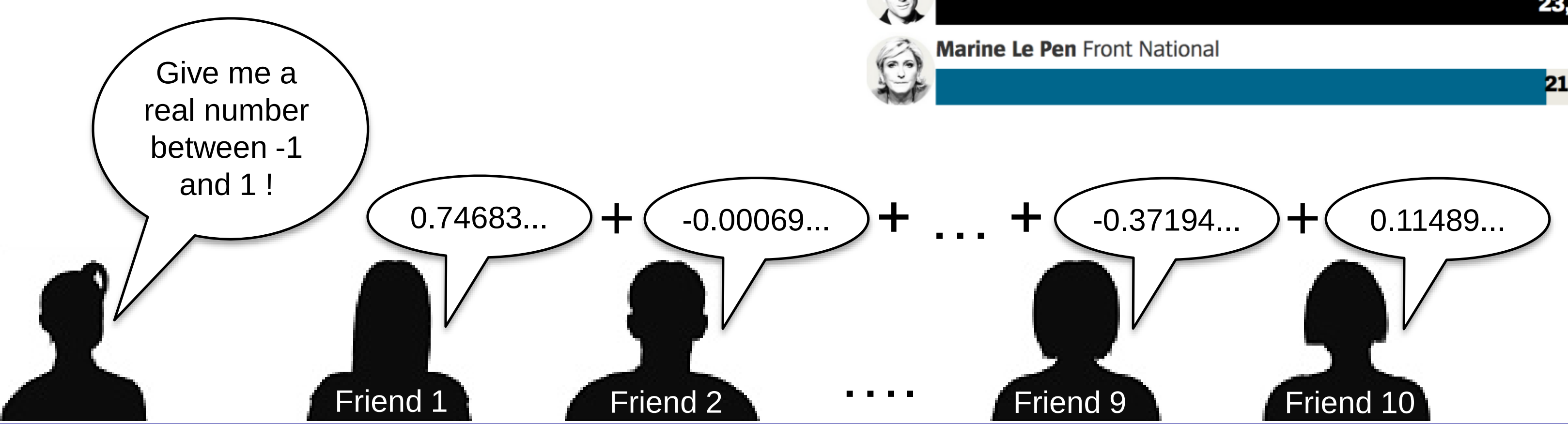
Surface areas by chance within ~ 1% (151,153 km²).

Imagine the **difference** to be of the **size of an atom!**





Imagine a difference between Macron and Le Pen of just a **10^{27}-th of a single vote!**



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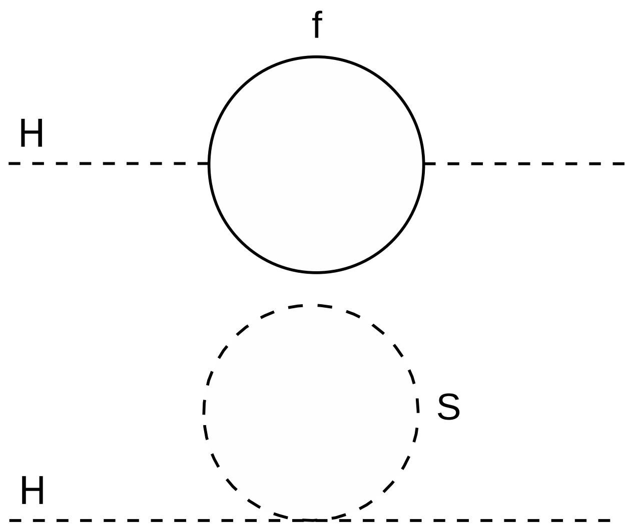
[source: link]

Analogies only for illustration. No liability for quantitative interpretation.

Never tired of analogies…

We need… Supersymmetry (SUSY)

- Fundamental symmetry between fermions and bosons introducing a set of new partner particles to the SM particles with half-spin difference.

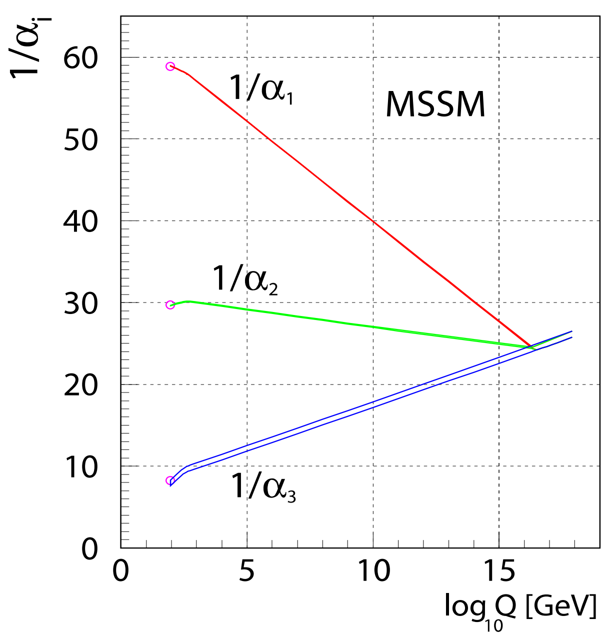


✓ Opposite-sign loop corrections from SUSY particles. Quadratic divergencies cancel. → No (little) fine-tuning.

✓ If R-parity conserved: Lightest SUSY Particle (LSP) stable. → Natural candidate for dark matter.

R-parity = $(-1)^{3(B-L)+2s}$
- SM particles: +1
- SUSY particles: -1

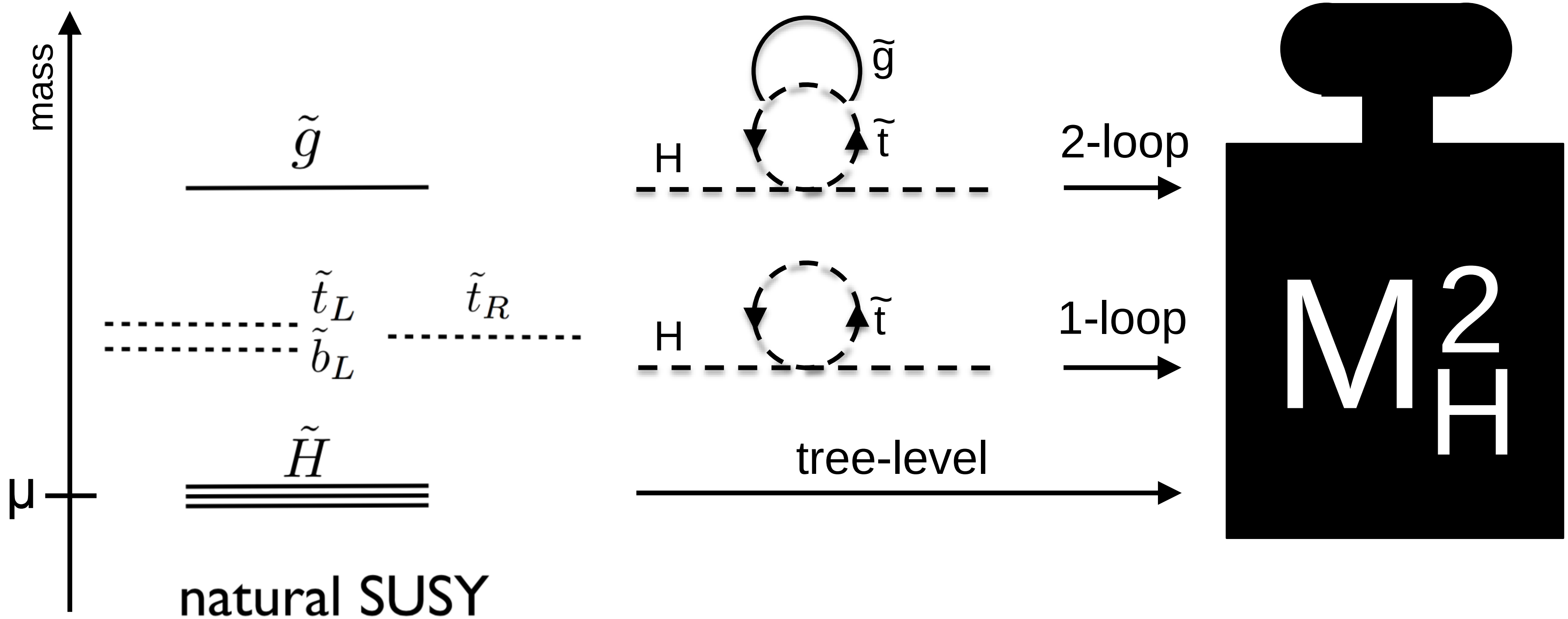
✓ Unification of gauge couplings at $M_{GUT} \approx 10^{16}$ GeV



Not just any SUSY…

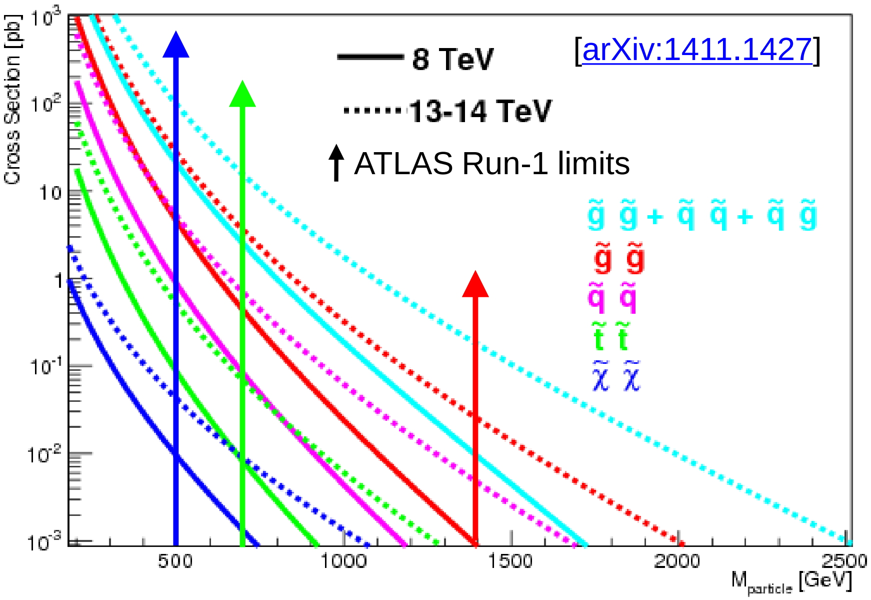
- Higgs boson discovery and strong experimental bounds have put vanilla SUSY under pressure
- Within the MSSM stop and gluino masses enter at **1 and 2 loop level** into the Higgs mass matrix, the Higgsino mass parameter μ **at tree level**

→ Search effort focus around "**Natural SUSY**" (e.g. arXiv:1110.6926) with relatively **light gluinos, stops, higgsinos** (remaining SUSY particles can be decoupled at high masses)

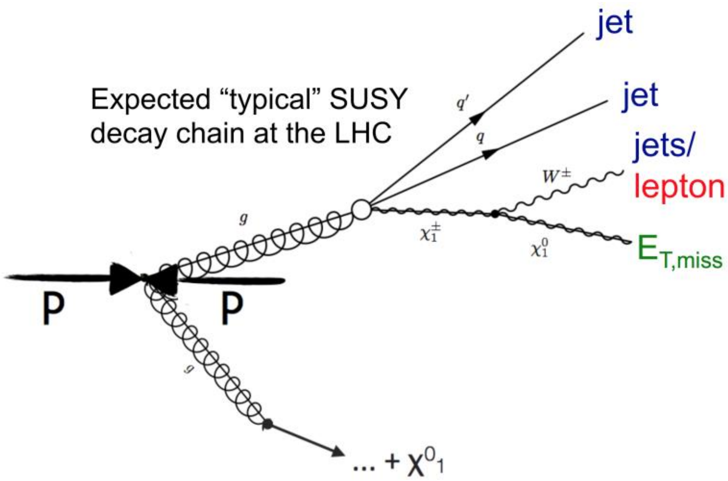


How to search for SUSY at the LHC

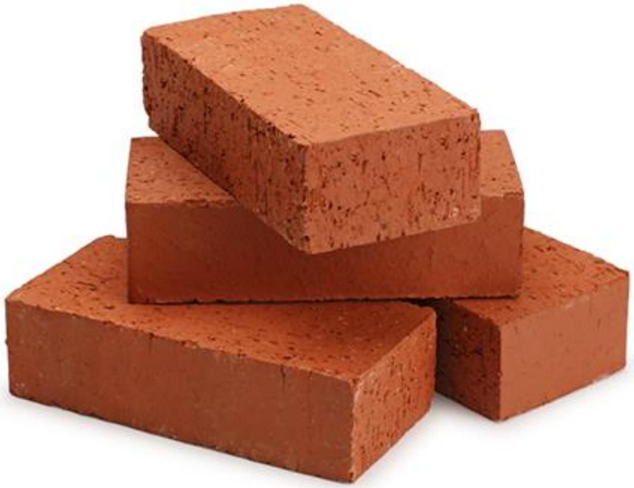
- If SUSY particles exist at LHC accessible energies:
  1. **R-parity conservation**
     - Pair-production via strong / EW interaction
     - Direct or cascade decays to the stable lightest SUSY particle (LSP).
     - Many high p_T SM decay products + large $E_{T,miss}$ (depending on the mass spectrum)
  2. **R-parity violation**
     - Multi-jets / multi-leptons signatures from LSP decay to SM particles
     - Displaced vertices from late LSP decays
  3. **Long-lived particles**
     - Sparticles produced with long lifetimes due to mass degeneracy, small couplings, virtuality
     - Secondary decay vertex



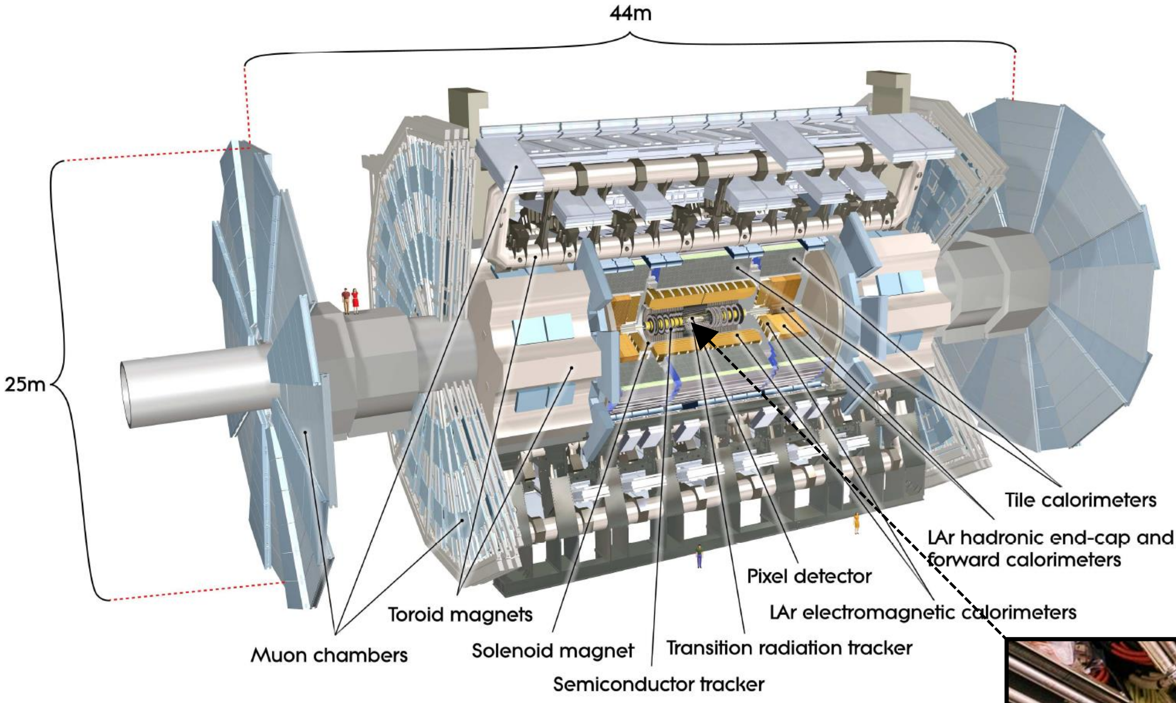
- Search strategy @ 13 TeV:
  - → Early data: **Gluino & 1st/2nd generation squark** searches have the largest potential due to enhanced cross-sections
  - → Beyond ~10 fb^{-1}: Searches for **3rd generation squarks** and **EW production** start to exceed Run-1 sensitivity



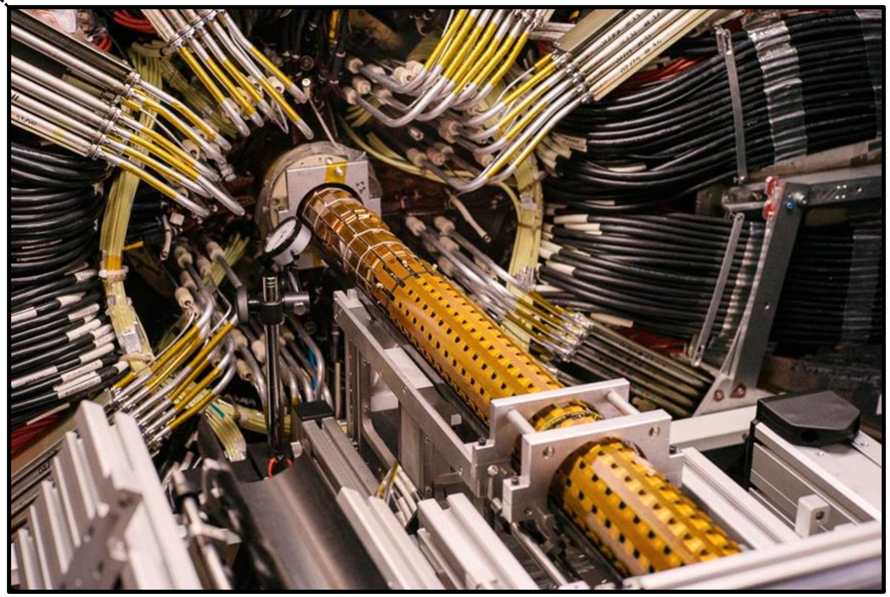
Tools & building blocks…



The ATLAS Experiment in Run-2



+ **New innermost pixel layer (IBL)** @ 3.3 cm from the beam line → additional 4th space-point measurement

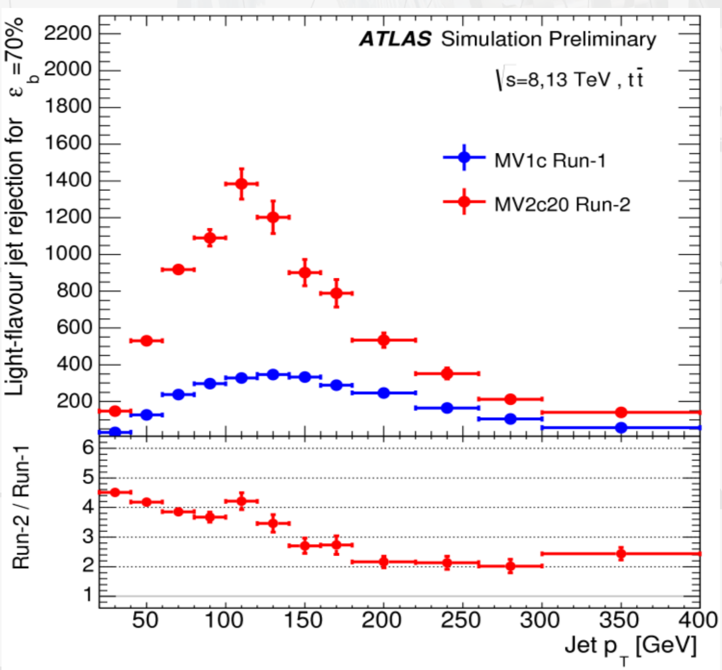


+ Upgraded **trigger/DAQ system** (improved bandwidths 75 kHz →100 kHz @ L1 & 1-1.5 kHz @ HLT)

+ Improved offline **reconstruction & analysis software**

+ …

- SUSY searches rely strongly on new **IBL**:
  - b-tagging crucial for many SUSY analyses: Improvements of a factor of 2 and more in light-flavour / c-jet rejection
  - Searches for long-lived particles: Improved track / secondary vertex reconstruction



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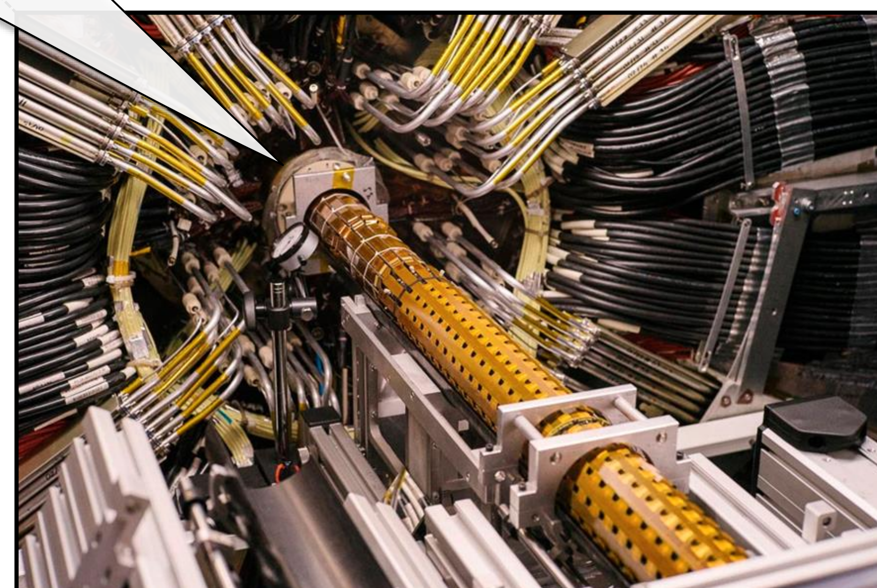
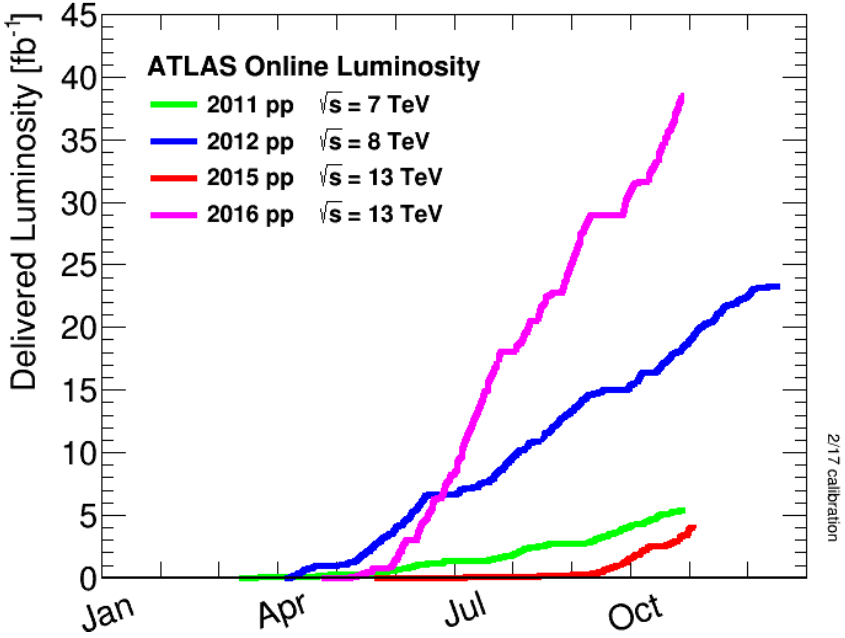
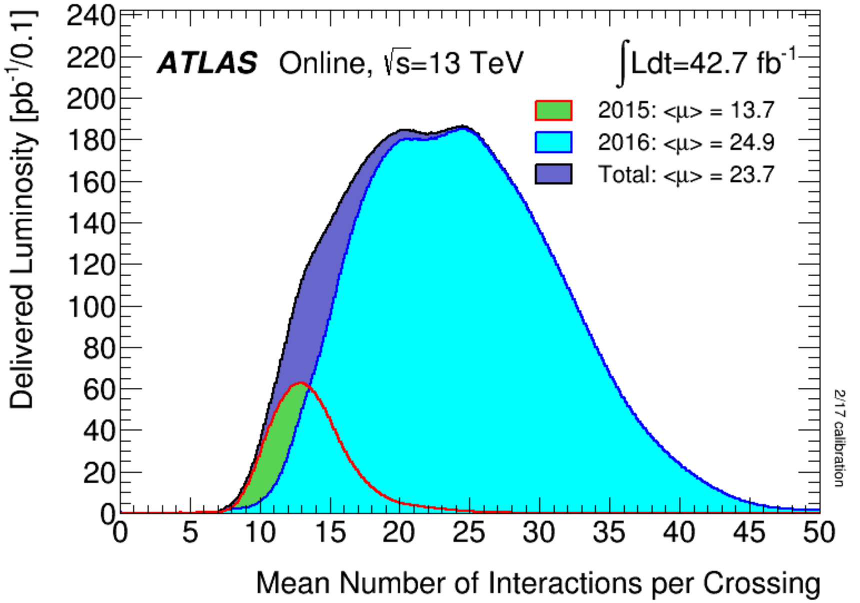


Data-taking 2015/2016

- Record performance of the LHC in 2016:
  - **1680 hours** of **13 TeV** stable beams data-taking in 2016!
  - Peak instantaneous luminosity of **1.38 x 10^{34} cm^{-2} s^{-1}**
  - Pile-up of up to **50** interactions per crossing

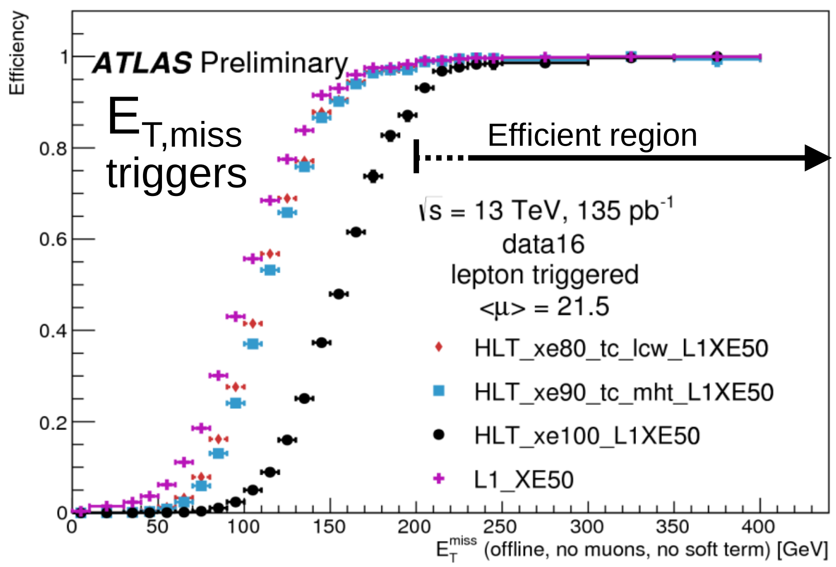
- Excellent Run-2 data-taking campaign for ATLAS:
  - **3.9 fb^{-1} + 35.6 fb^{-1}** recorded in 2015 + 2016
  - In total **36.1 fb^{-1}** (i.e. 91.4%) *good* for **SUSY searches**!

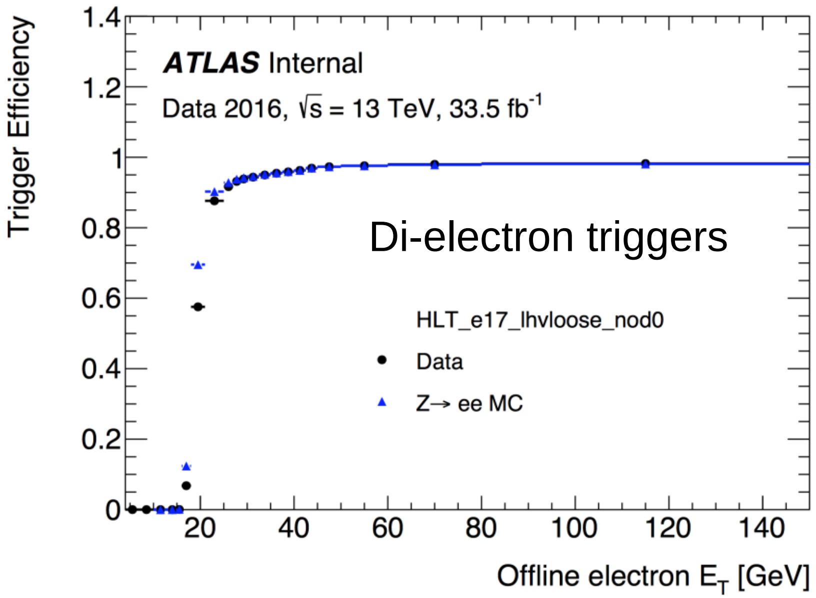


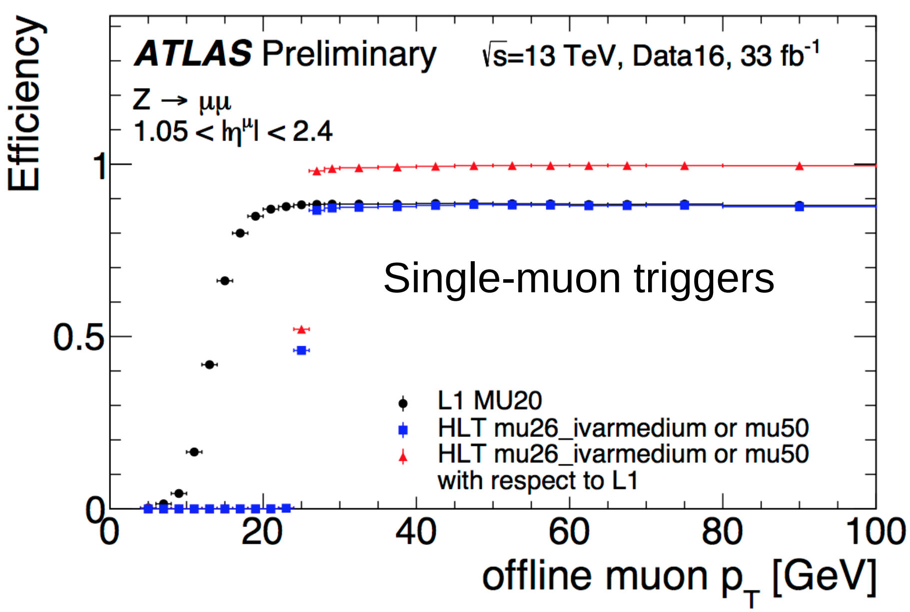


Trigger Performance Highlights

- **ATLAS trigger and DAQ** systems form the basis for a successful data-taking
- Major **challenge** in 2016: **Maintain trigger performance** in fierce luminosity & pile-up conditions
- Main physics triggers for SUSY searches: Generic **$E_{T,miss}$, jet, lepton triggers**

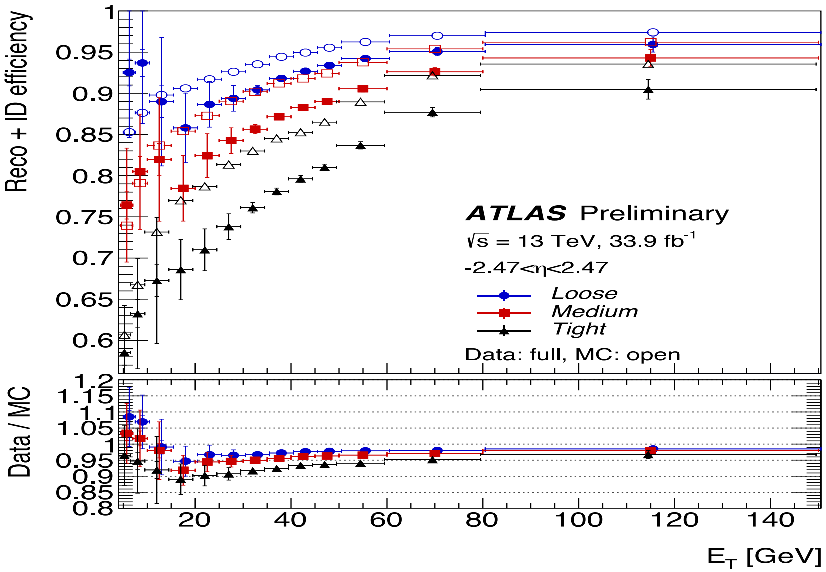




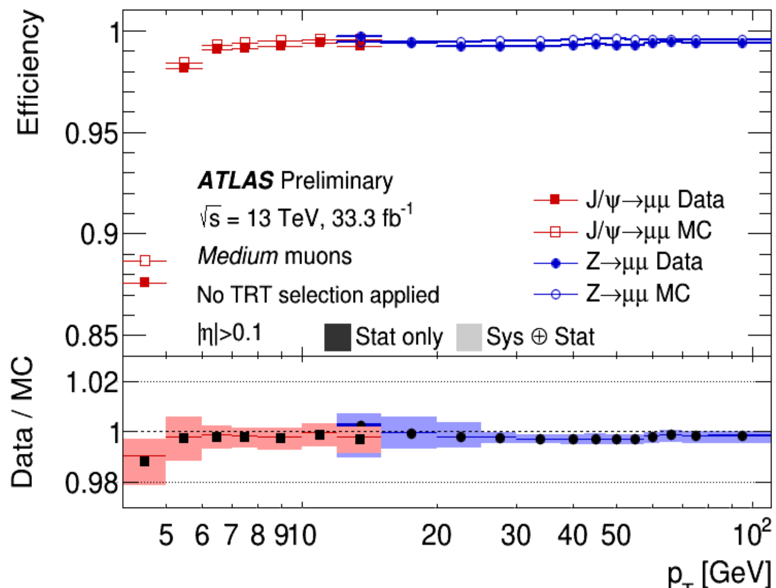


Detector Performance Highlights

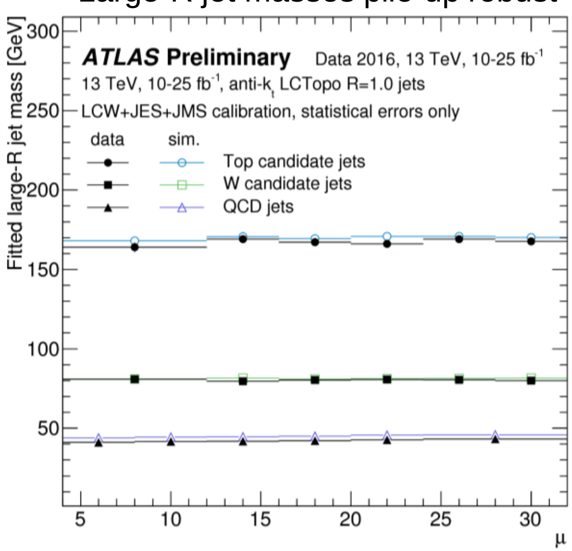
Electron performance measured down to 4.5 GeV



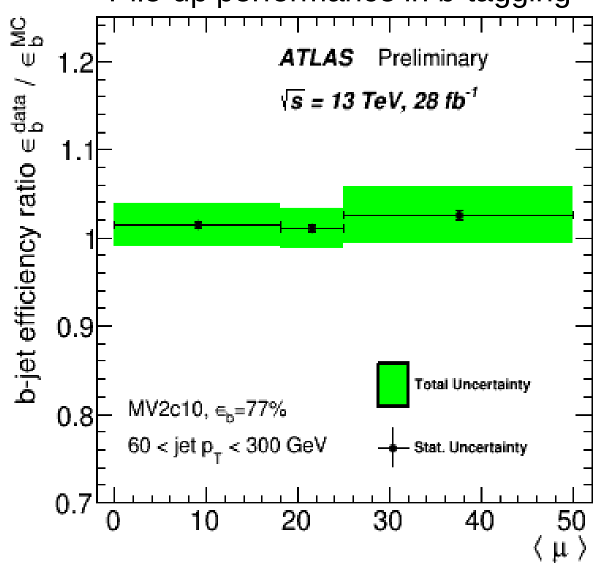
Muon performance measured down to 4 GeV



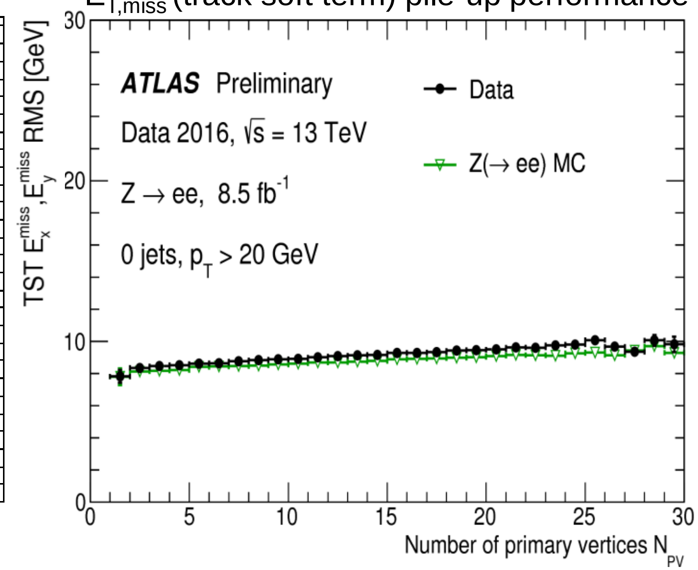
Large-R jet masses pile-up robust



Pile-up performance in b-tagging



$E_{T,miss}$ (track soft term) pile-up performance



Blueprint of a vanilla SUSY search

① Build signal regions (**SR**s) based on requirements on signal / background discriminating variables to target specific SUSY event topologies. Optimised for discovery & exclusion.

② Determine Standard Model background in the SRs:

Irreducible Backgrounds

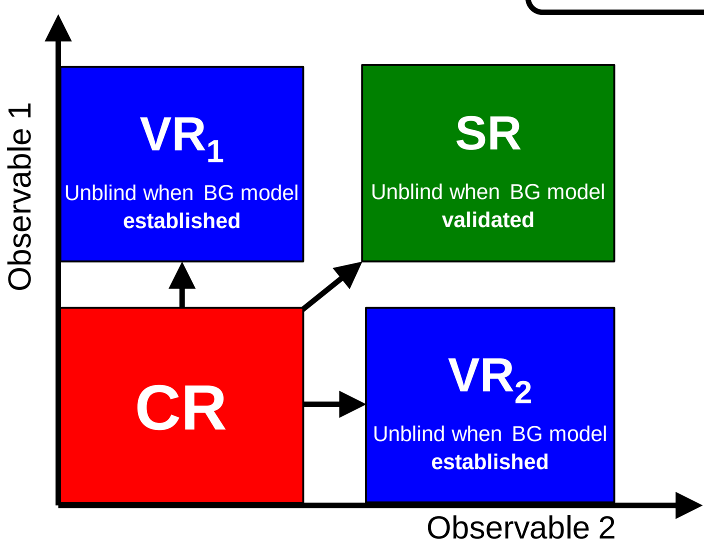
- Dominant processes:
  - MC normalised to data in process-enhanced control regions (**CR**s)
  - Extrapolation to validation regions (**VR**s) & **SR**s
- Subdominant processes: Pure MC predictions

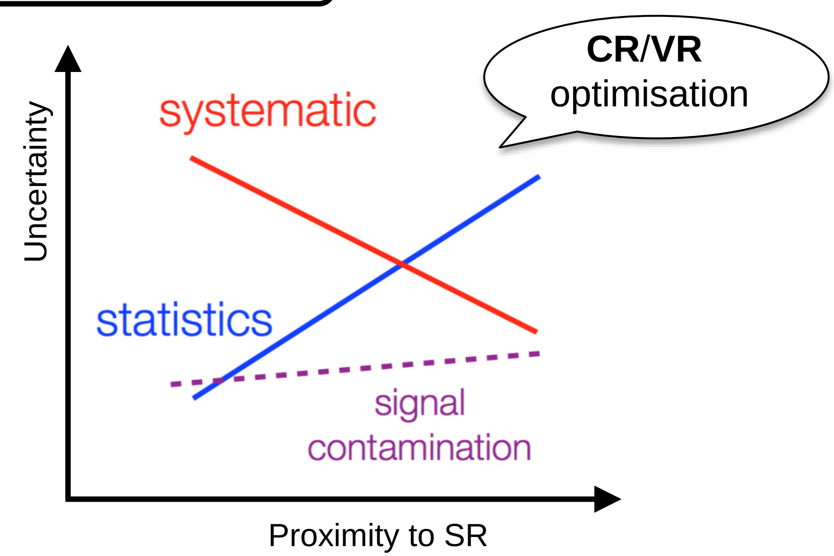
Reducible Backgrounds

- Fake $E_{T,miss}$, fake leptons backgrounds: Pure data-driven estimates
- Validation in **VR**s

Combined Fit

- Simultaneous fit of all components in **CR**s (and **SR**s for exclusion)





Discriminating variables in a nutshell

- Plethora of observables used by SUSY searches to maximally exploit event information:

complexity

Reconstructed object multiplicities, momenta, energies, e.g. $\mathbf{N_{jet/b\text{-}tag/\ell/\gamma}}$, $\mathbf{p_T}$, $\mathbf{E_{T,miss}}$, …

Scale variables, e.g. $\mathbf{m_{eff}} = \Sigma p_T + E_{T,miss}$,

Angular variables, e.g. **min** $\mathbf{\Delta\Phi}$(jet, $E_{T,miss}$), …

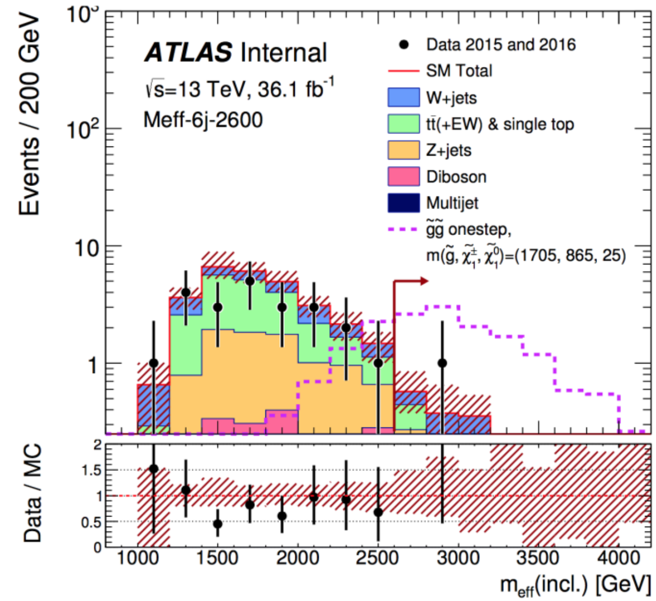
Mass variables, e.g. $\mathbf{m_{\ell\ell}}$, $\mathbf{m_T^{b/\ell/j}}$, $\mathbf{\Sigma m_{fat\text{-}jet}}$, …

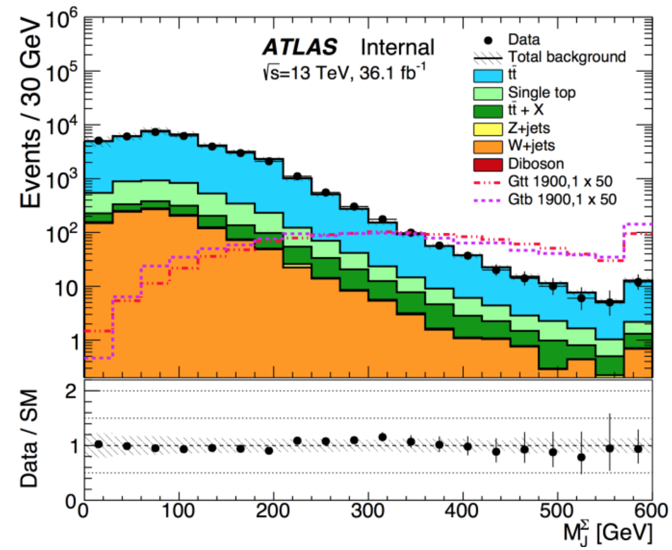
Event shape variables, e.g. **Aplanarity**, …

Hypothesis-based event variables e.g. $\mathbf{m_{T2}}$, …

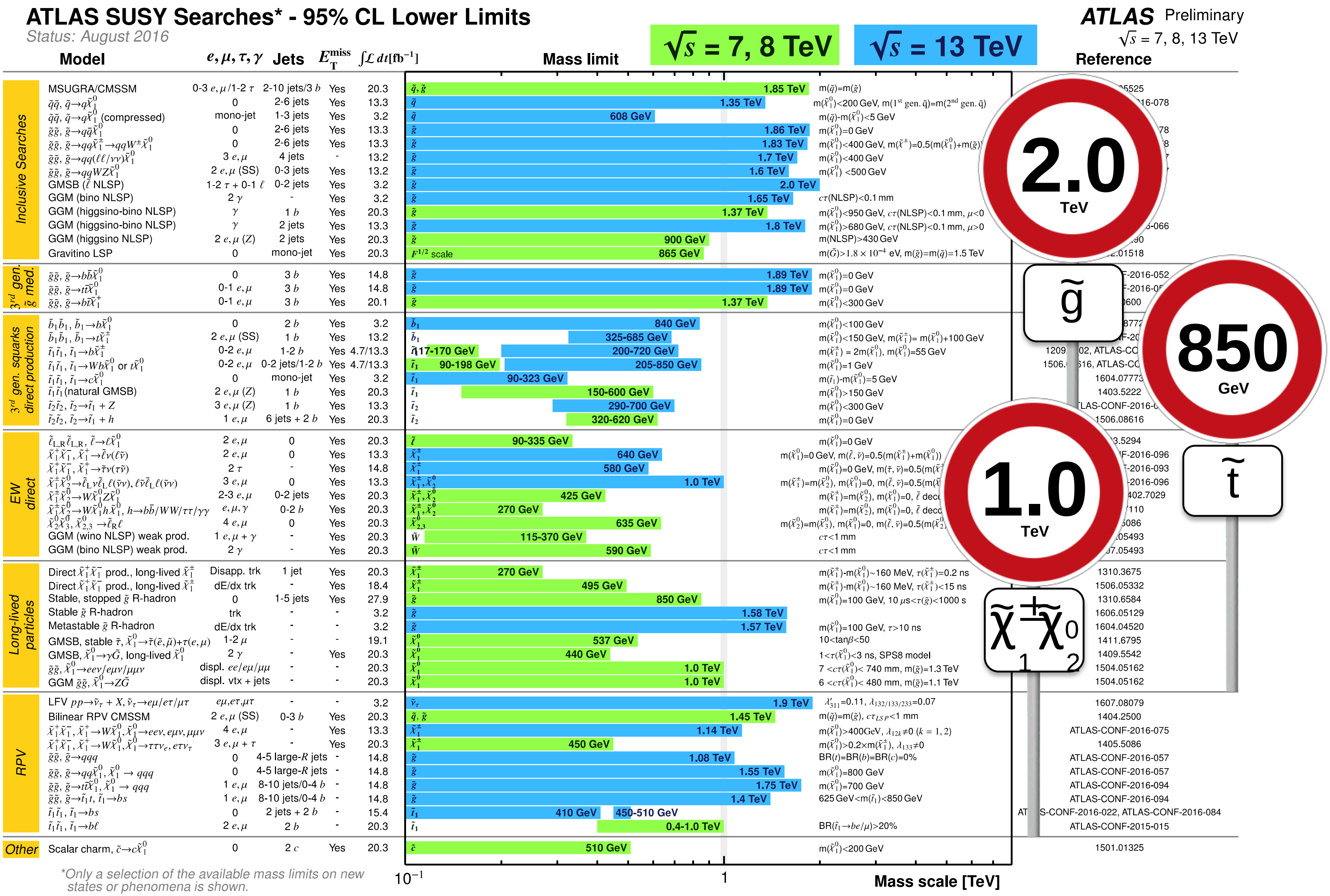
⋮

More complex methods, e.g. new **recursive jigsaw reconstruction** [arxiv:1607.08307], …





ATLAS SUSY Searches: Status August '16



New SUSY results with full 2015/2016 dataset

① **Inclusive searches for gluinos and squarks:**

- 0-ℓ + 2-6 jets + $E_{T,miss}$ [ATLAS-CONF-2017-022]
- 0/1-ℓ + 3-4 b-jets + $E_{T,miss}$ [ATLAS-CONF-2017-021]

① **Searches for direct production of 3rd generation squarks:**

- 0-ℓ + b-jets + $E_{T,miss}$ [ATLAS-CONF-2017-029]
- 1-2-ℓ or 3-ℓ + b-jets + $E_{T,miss}$ (h/Z bosons in decay chain) [ATLAS-CONF-2017-019]

① **Searches for RPV scenarios and long-lived particles:**

- Stop resonance search [ATLAS-CONF-2017-025]
- 1-ℓ + 8-12 jets + no $E_{T,miss}$ [ATLAS-CONF-2017-013]
- Displaced vertex search [ATLAS-CONF-2017-026]
- Disappearing track signature (search for long-lived charginos) [ATLAS-CONF-2017-017]

- All results available on the ATLAS SUSY public webpage:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

Part 1 of 3

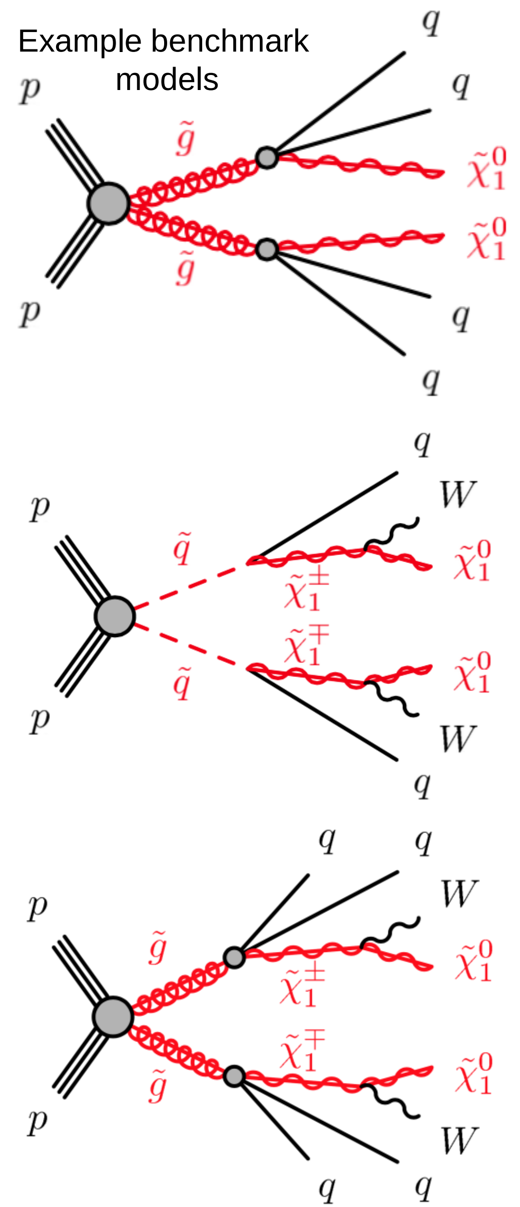
Inclusive searches for gluinos and squarks

Inclusive 0-l Search: Overview

- Final state: **2-6 Jets + E_{Tmiss} (no leptons!)**

$\mathbf{H_T} = \Sigma p_T^{jet}$,
$\mathbf{m_{eff}} = H_T + E_{T,miss}$

Example benchmark models



m_{eff}-based Analysis Stream

- **24 inclusive SRs** using the *effective mass* as final discriminant:
  - ≥2/3 jet regions → **direct** squark decays
  - ≥4/5 jet regions → **direct** gluino decays
  - ≥5/6 jet regions → gluino/squark decays **via χ±** with W bosons
  - ≥2 **large-R** jets → gluino/squark decays with **boosted** W bosons
  - → Scans **of m_{eff}, $E_{T,miss}/m_{eff}$ or $E_{T,miss}/\sqrt{H_T}$** to cover variety of mass spectra

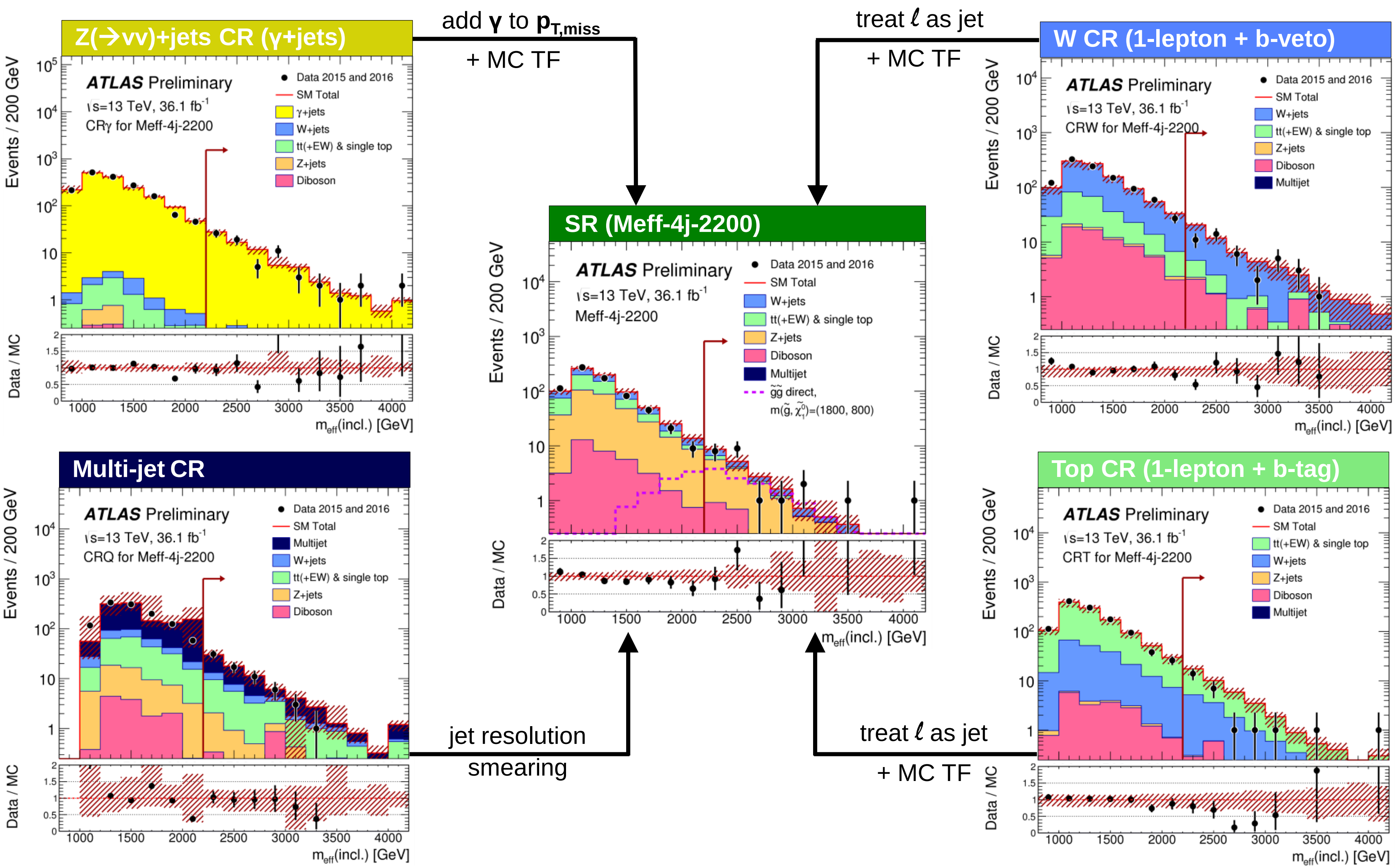
not orthogonal but complementary

Recursive Jigsaw Analysis Stream

- **19 inclusive SRs** based on the *recursive jigsaw* reconstruction technique:
  - Impose specific decay hypothesis on event and assign four-momenta to invisible states.
  - Compute kinematic variables in the frames of the intermediate hypothesized particles

Inclusive 0-l Search: Backgrounds

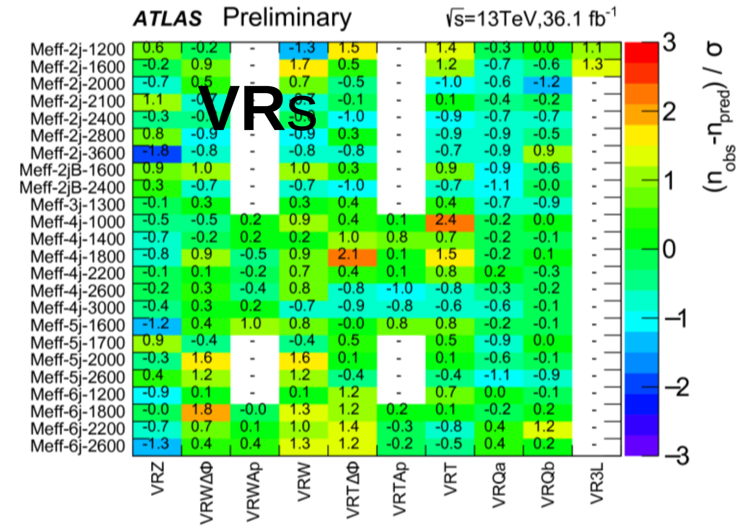
- Dominant backgrounds estimated in 4 CRs for each SR → extrapolation to VRs/SRs with transfer factors (TFs)

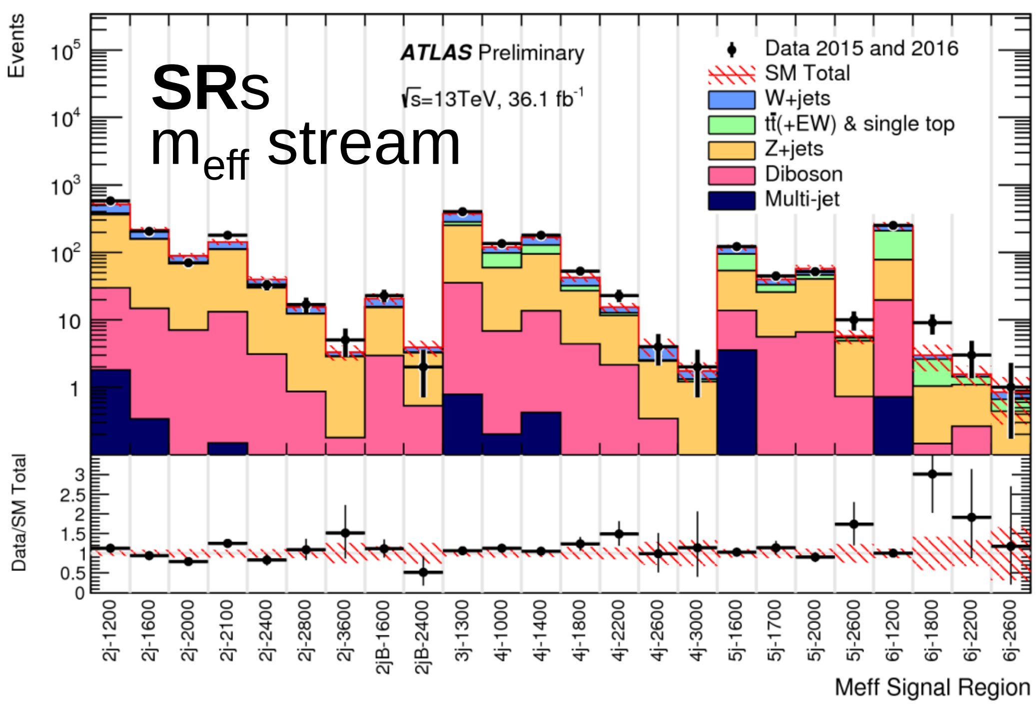


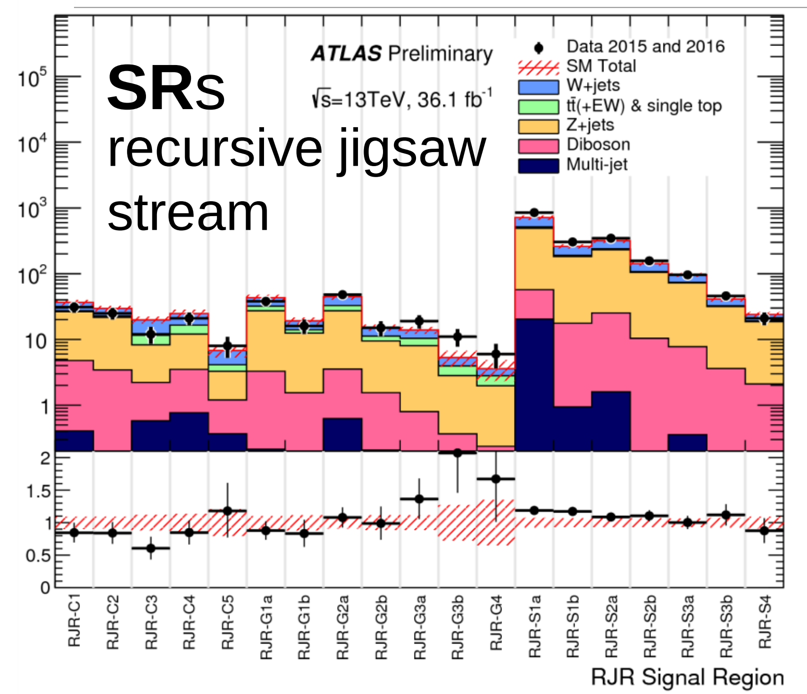
Inclusive 0-l Search: Results

- Background estimates validated in **large amount of validations regions** for the major background processes

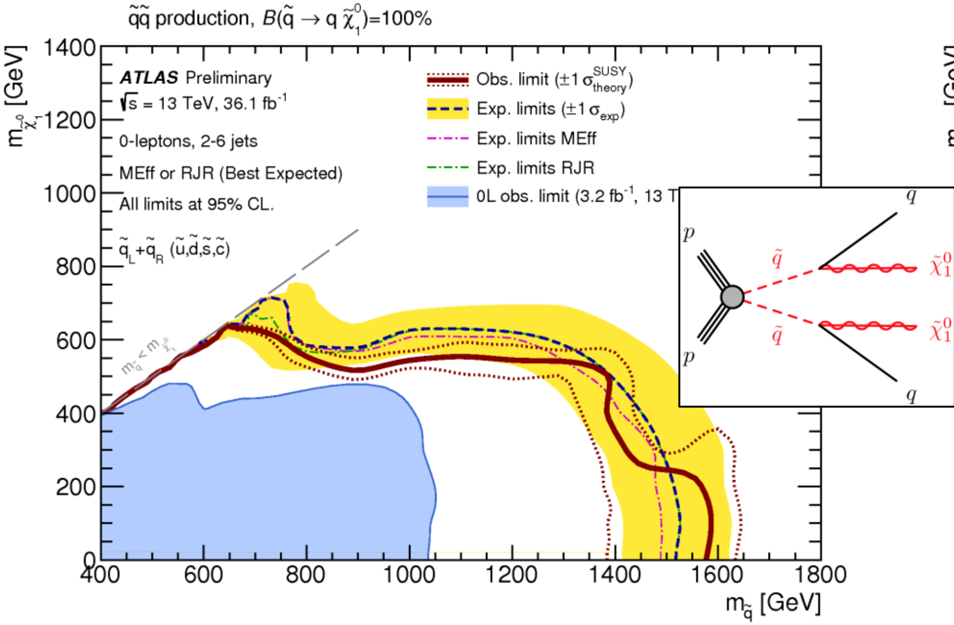
- **No significant deviations** from the Standard Model expectation in both streams

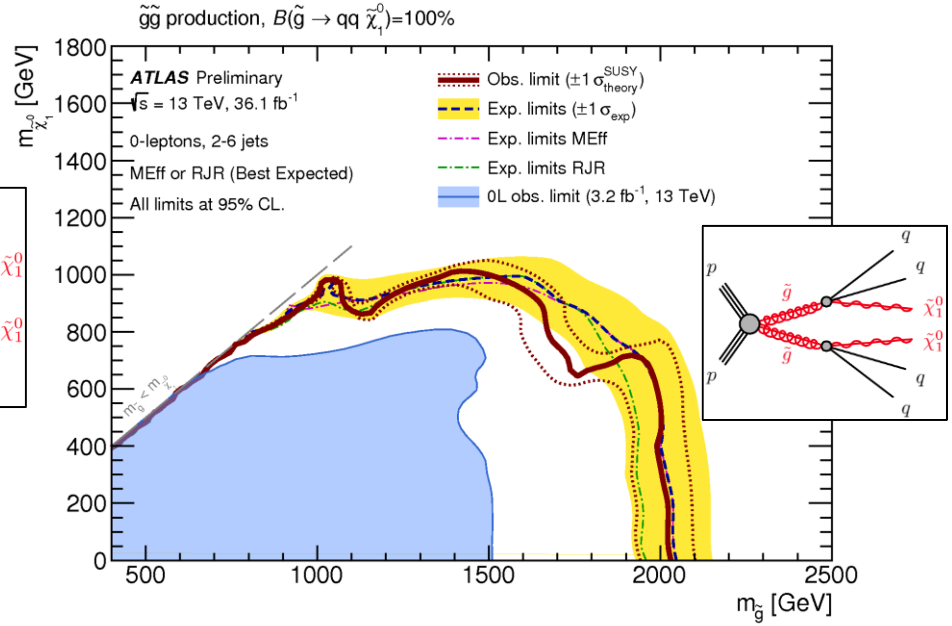


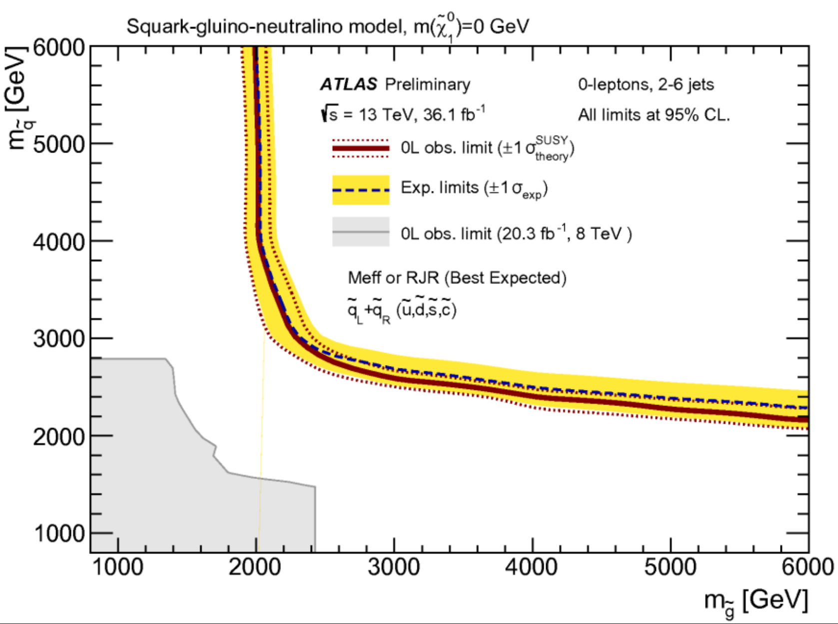


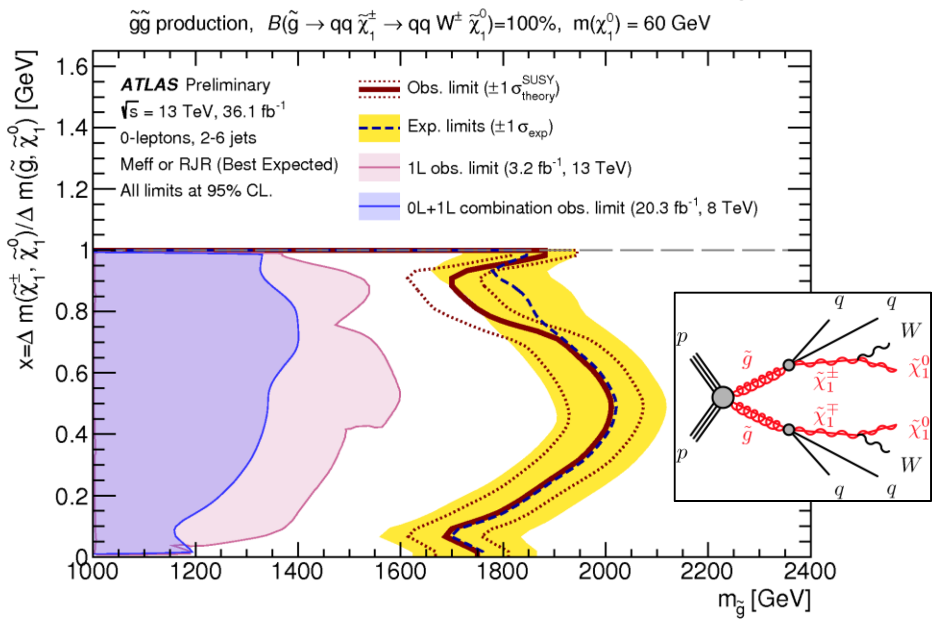


Inclusive 0-l Search: Interpretations









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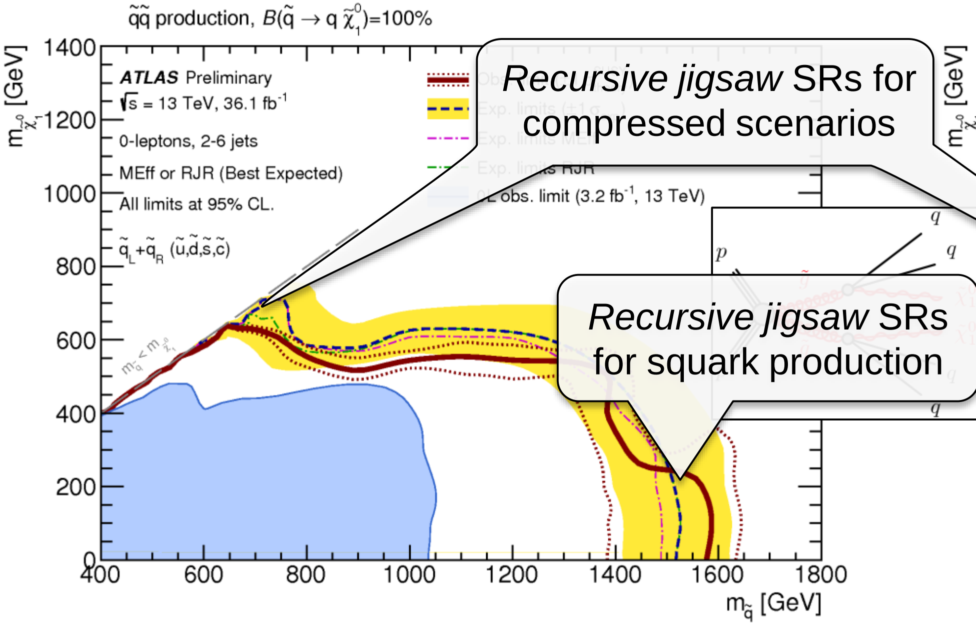
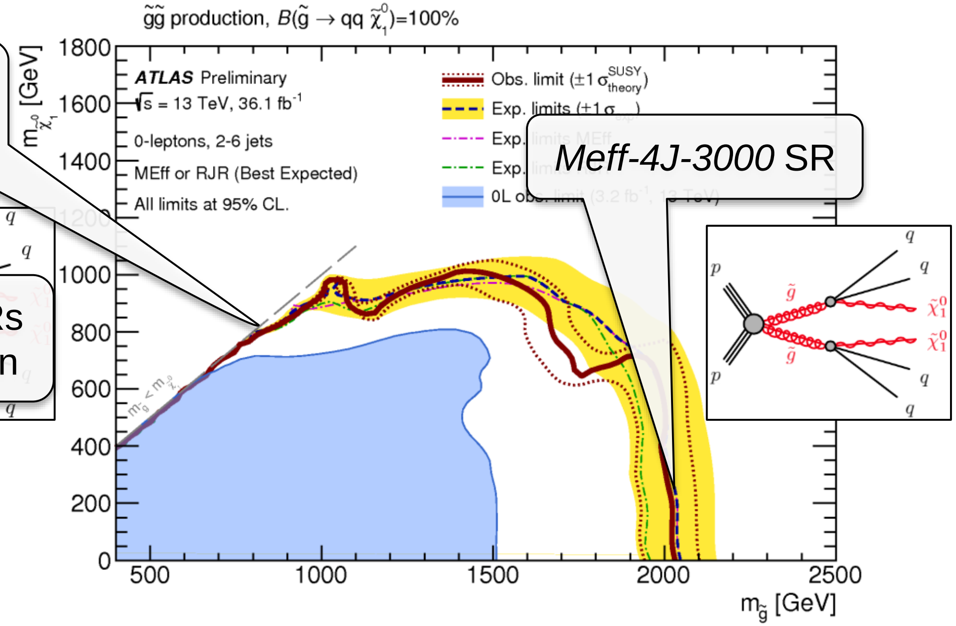
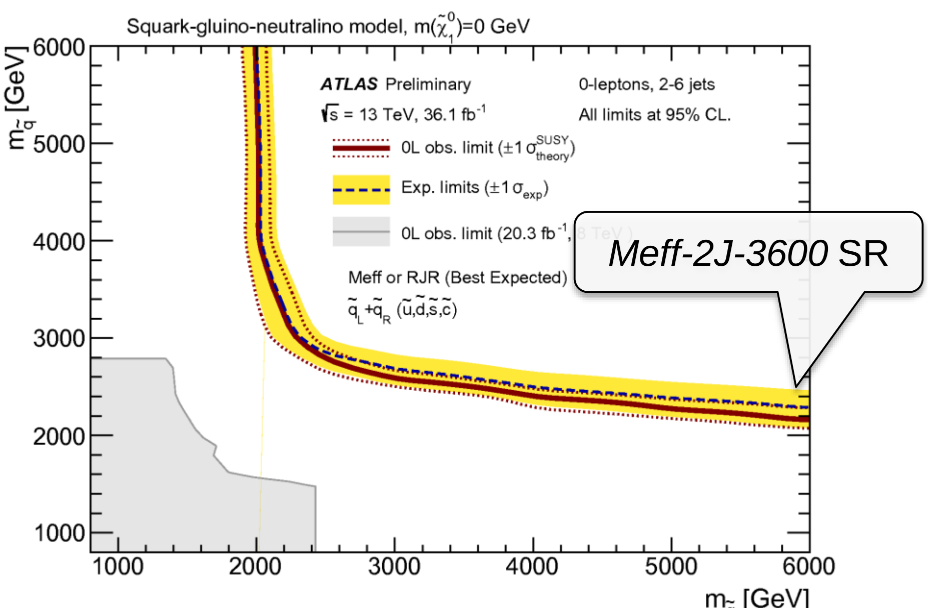
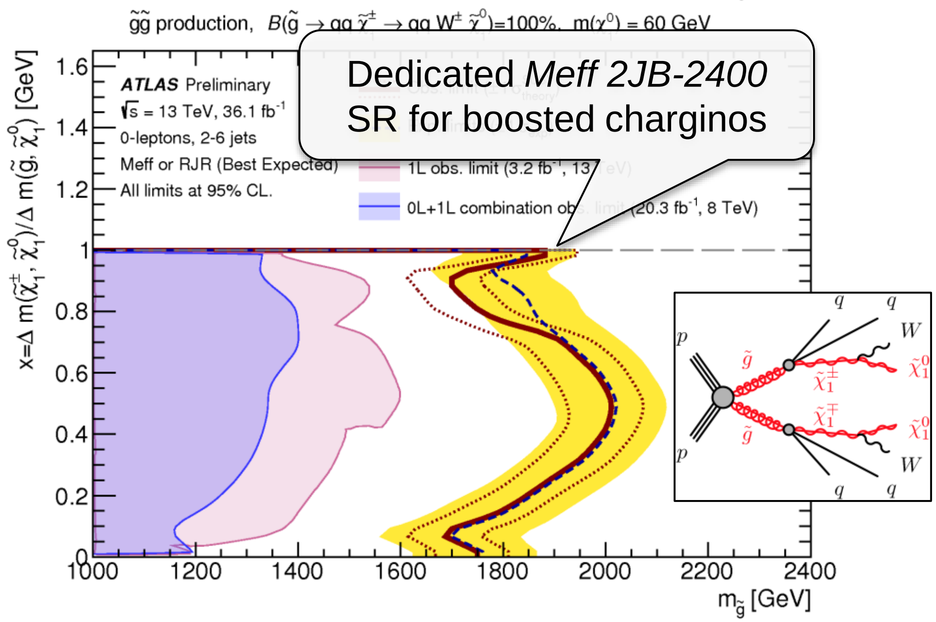


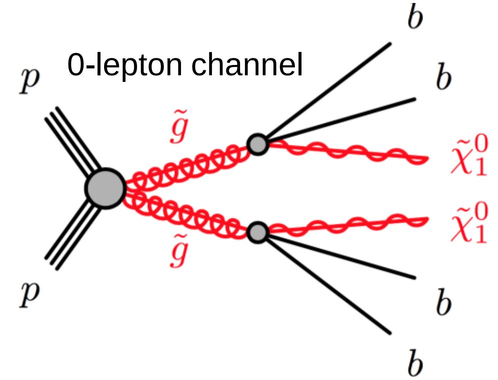






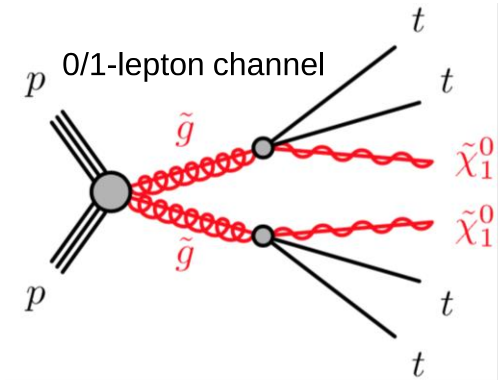
Multi b-jet Search: Overview

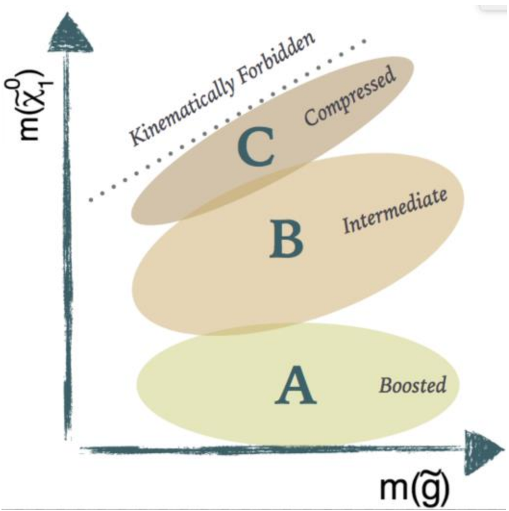
- Defining feature: **≥ 3 b-jets + 0/1 lepton + $E_{T,miss}$** final state
- Main benchmarks are gluino-mediated stop/sbottom production

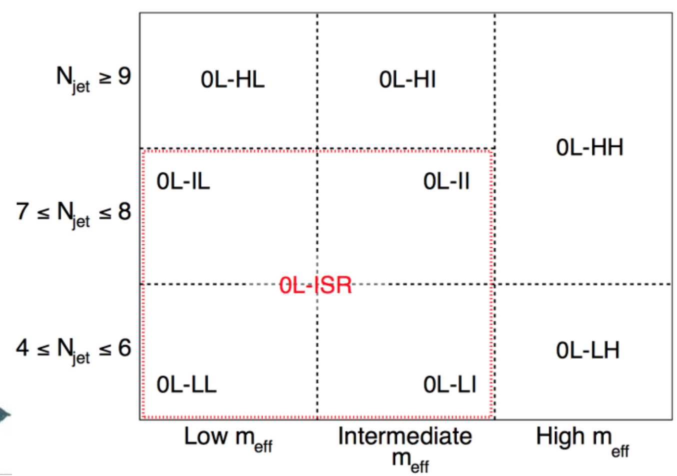


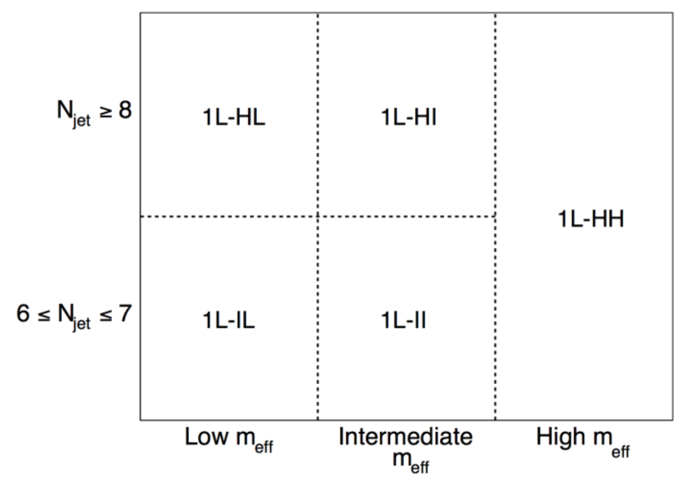
① 10 Inclusive signal regions optimised for discovery:
  - Selection: ≥ 3-8 jets using $N_{b\text{-tag}}$, m_{eff}, m_T, $E_{T,miss}$, $\Sigma m_{\text{large-R jets}}$ to target compressed, intermediate, & large mass splittings

② Binned orthogonal signal regions optimised for exclusion:
  - Selection: Ranging from low to high (m_{eff} & N_{jet}) to cover broad range of mass spectra
  - Combined fit over all bins to enhance exclusion power





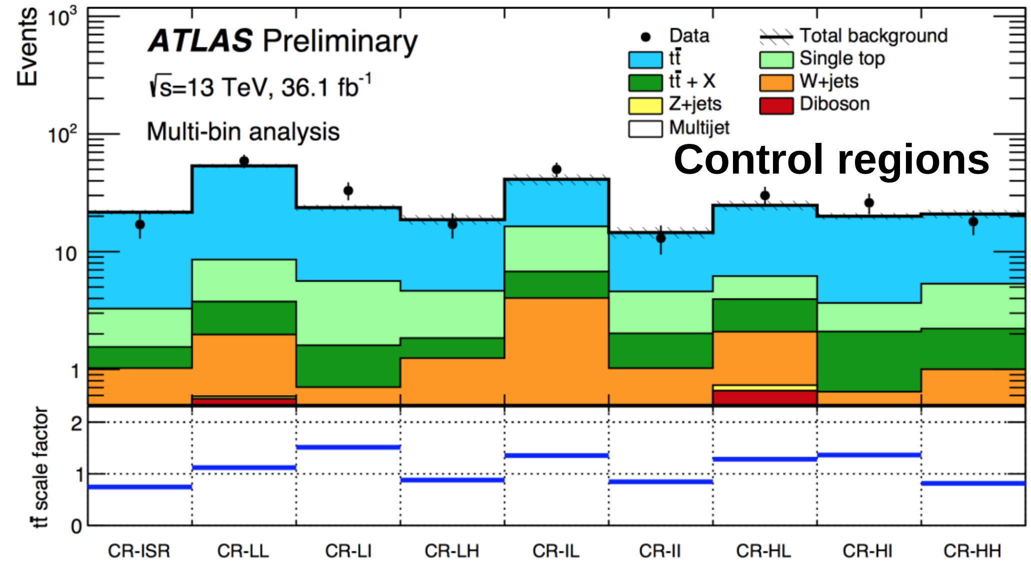


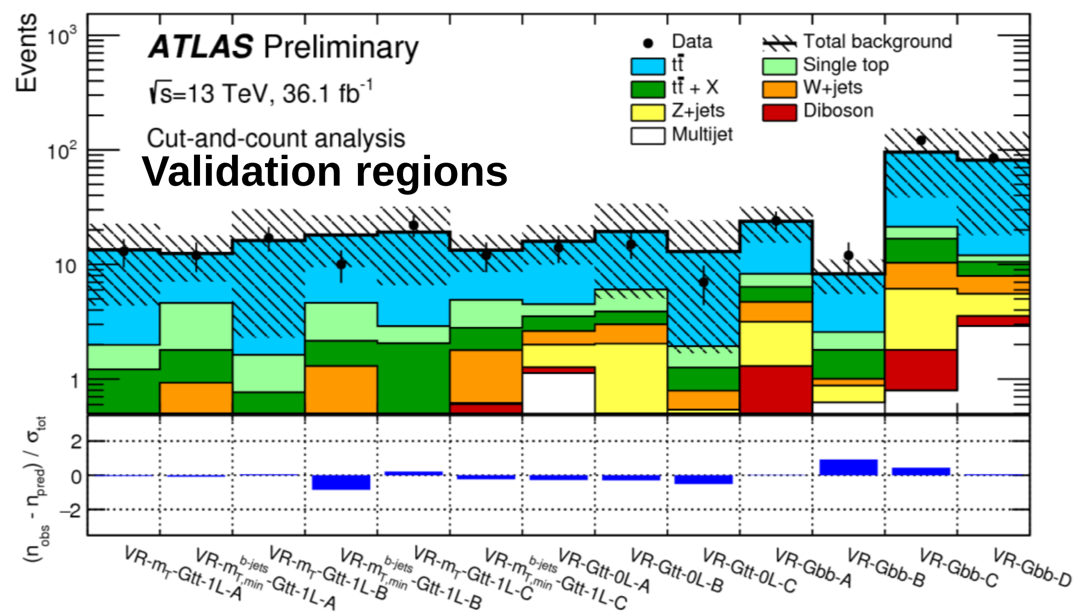


Multi b-jet Search: Backgrounds

- Dominant background **$t\bar{t}$+jets** estimated with semi data-driven approach in dedicated **1-lepton control regions** + extrapolation to validation and signal regions
- **Other backgrounds** ($t\bar{t}$+X, Z+jets, single-top, di-boson) **from simulation**
- Multi-jets background negligible

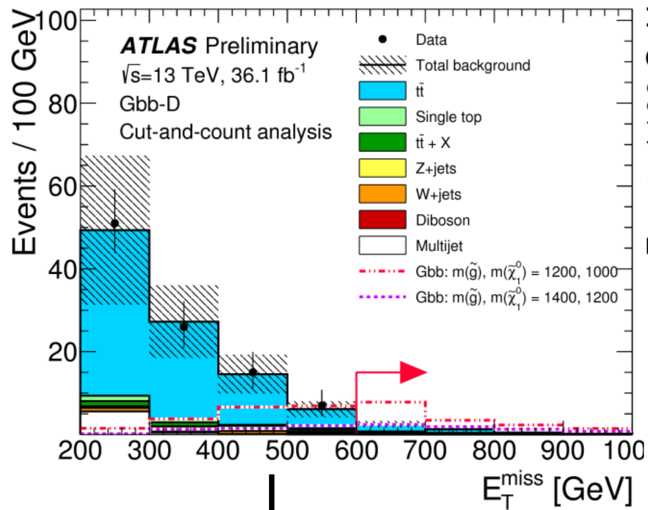
→ No evidence of significant background mis-modeling in the validation regions

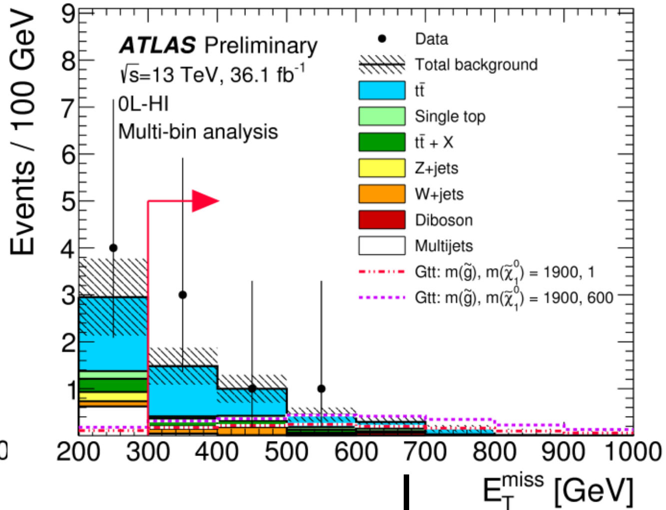


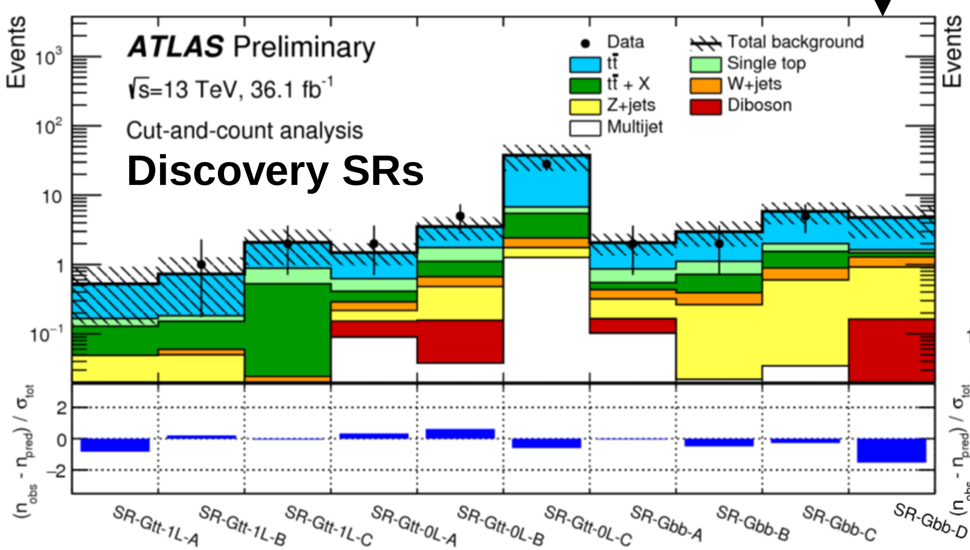


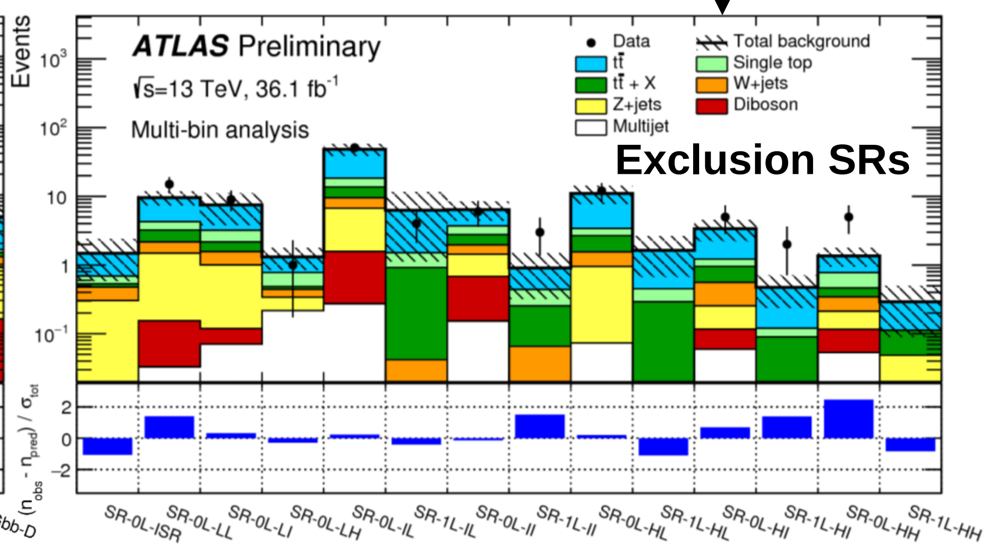
Multi b-jet Search: Results

- Generally **good agreement** between data and prediction in discovery and exclusion signal regions
- Small deviation in 0-lepton high-mass signal region ~ 2σ

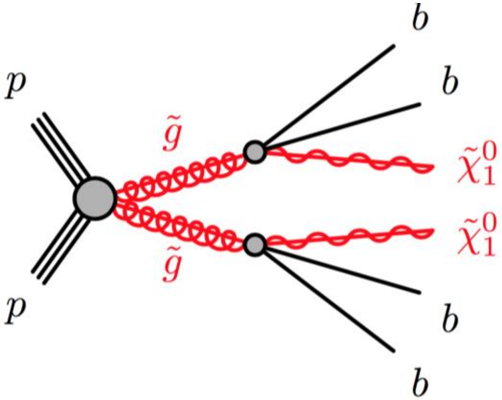


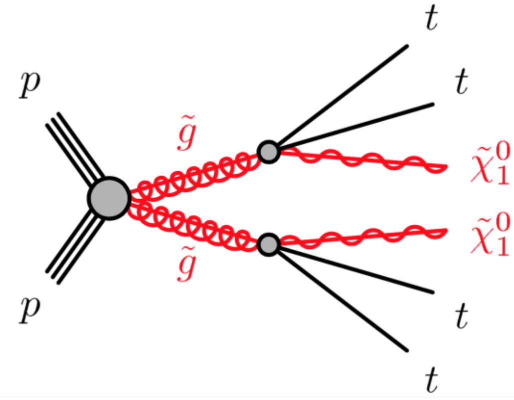


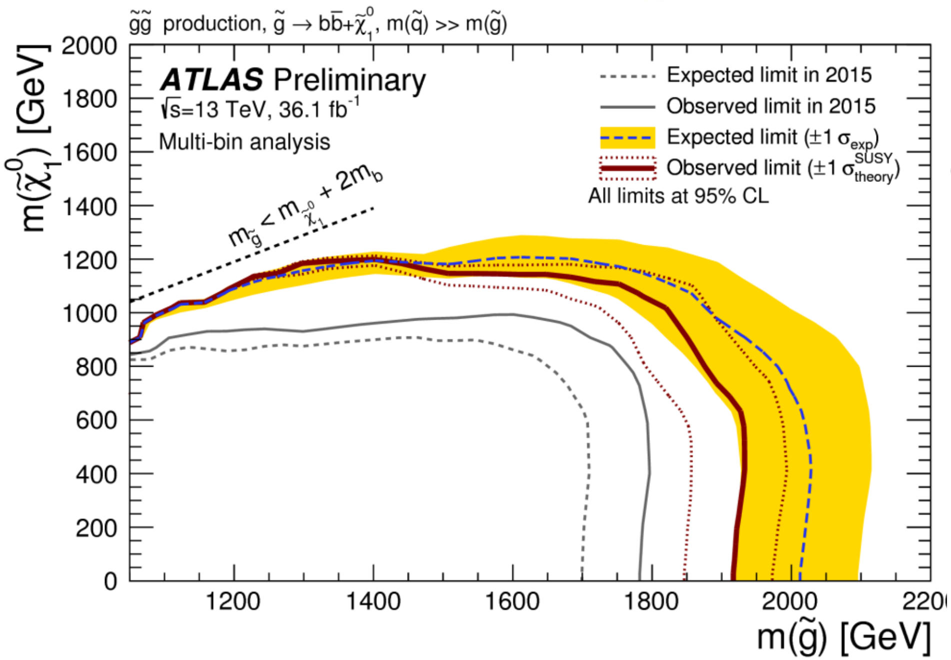


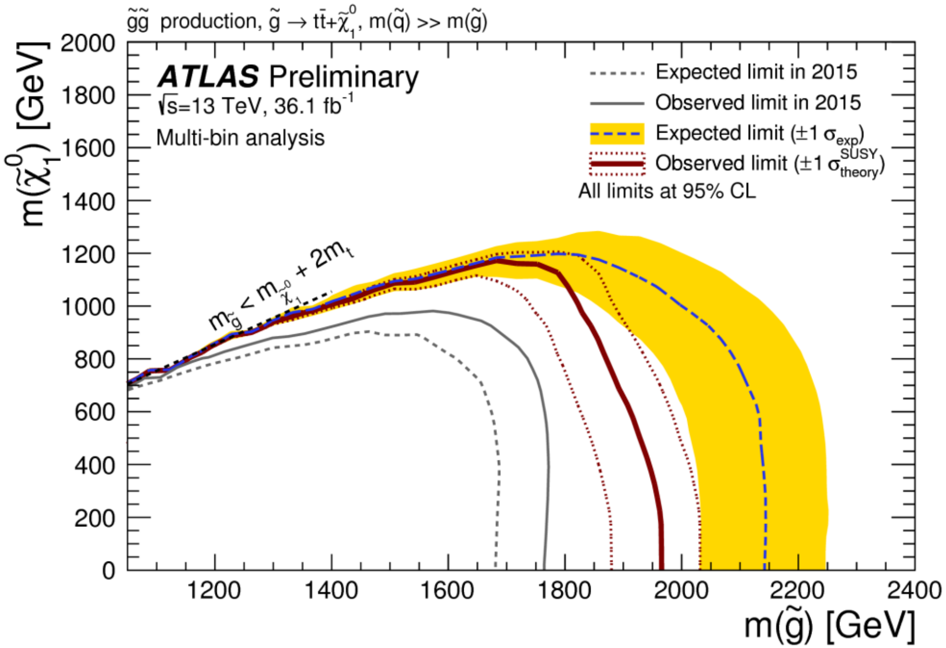


Multi b-jet Search: Interpretation









→ Sensitivity extended in g→bb+$\tilde{\chi}^0$ analysis extended by ~100 GeV w.r.t. 14.8 fb^{-1} analysis – observed **beyond 1.9 TeV**

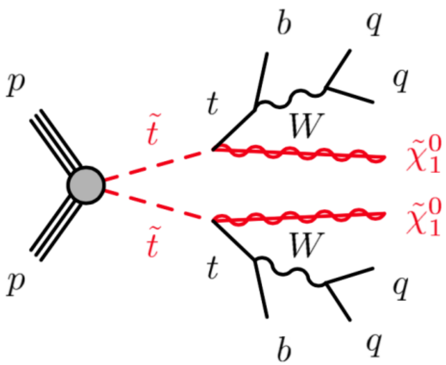
→ Sensitivity extended in g→tt+$\tilde{\chi}^0$ analysis extended by ~200 GeV w.r.t. 14.8 fb^{-1} analysis – observed limit **beyond 1.95 TeV**

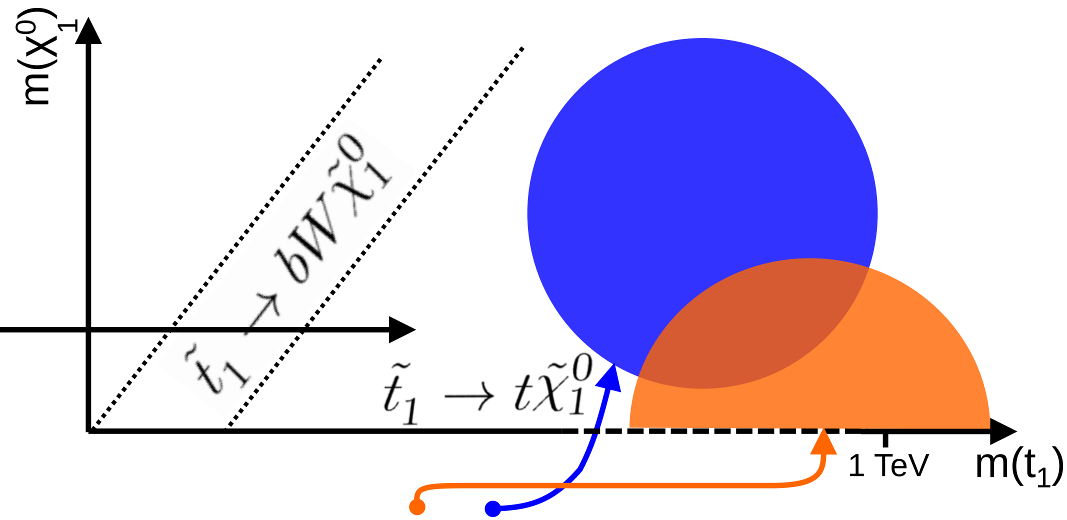
Part 2 of 3

Searches for 3rd Generation Squarks

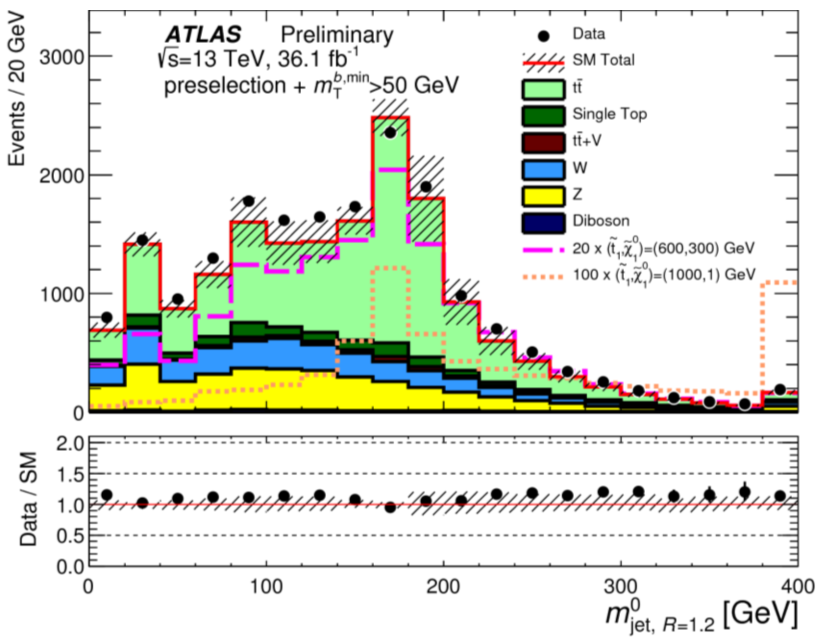
Stop 0-l Search: Overview

- **Final state:**
  - b-jets + E_{Tmiss} (no leptons!)





Signal Regions A & B



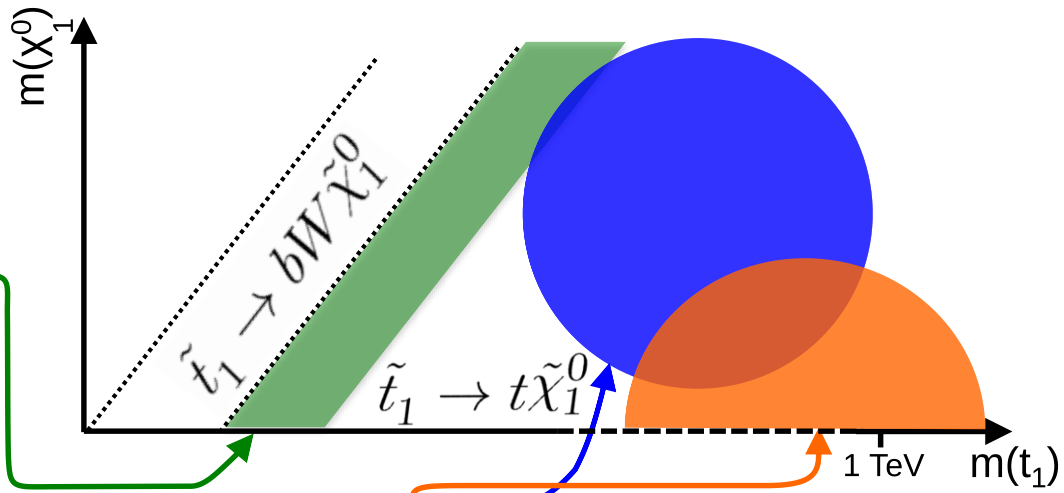
- **Boosted regime**: 3 orthogonal top reconstruction categories based on large-R jet mass requirements:
  1. **2 tops**
  2. **1 top + 1 W**
  3. **1 top only**

- Signal regions A:
  - **Tight requirements** $E_{T,miss}$ & m_{T2} to target high mass region

- Signal regions B:
  - **Looser requirements** to target intermediate mass region

Stop 0-l Search: Overview

- **Final state:**
  - b-jets + E_{Tmiss} (no leptons!)



Signal Regions C

- Exploit **initial state radiation** for sensitivity in near diagonal region (**$m_{stop} \sim m_t + m_{LSP}$**)
- Scan regions of R_{ISR} (ratio of $E_{T,miss}$ and p_T^{ISR} in CM frame)

$$R_{\mathrm{ISR}} = \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{p_{\mathrm{T}}^{\mathrm{ISR}}} \sim \frac{m_{\tilde{\chi}^0}}{m_{\tilde{t}}}$$

- Additional *recursive jigsaw* reconstruction based kinematic variables in the ISR and sparticle hemispheres

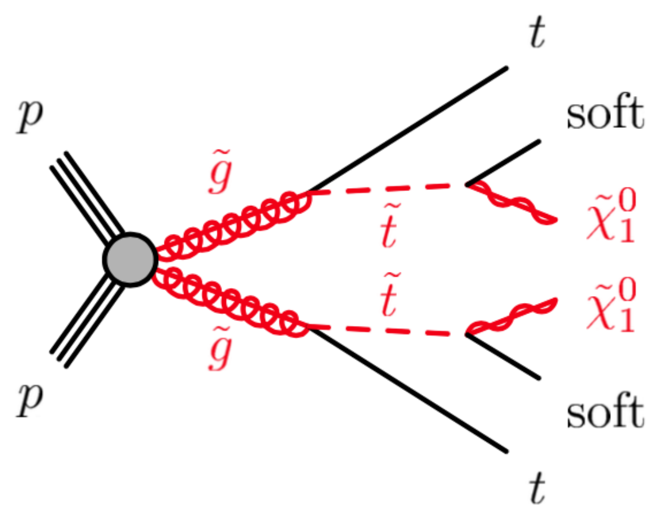
Signal Regions A & B

- Boosted regime: 3 orthogonal top reconstruction categories based on large-R jet mass requirements:
  1. **2 tops**
  2. **1 top + 1 W**
  3. **1 top only**
- Signal regions A:
  - **Tight requirements** $E_{T,miss}$ & m_{T2} to target high mass region
- Signal regions B:
  - **Looser requirements** to target intermediate mass region

Stop 0-l Search: Overview

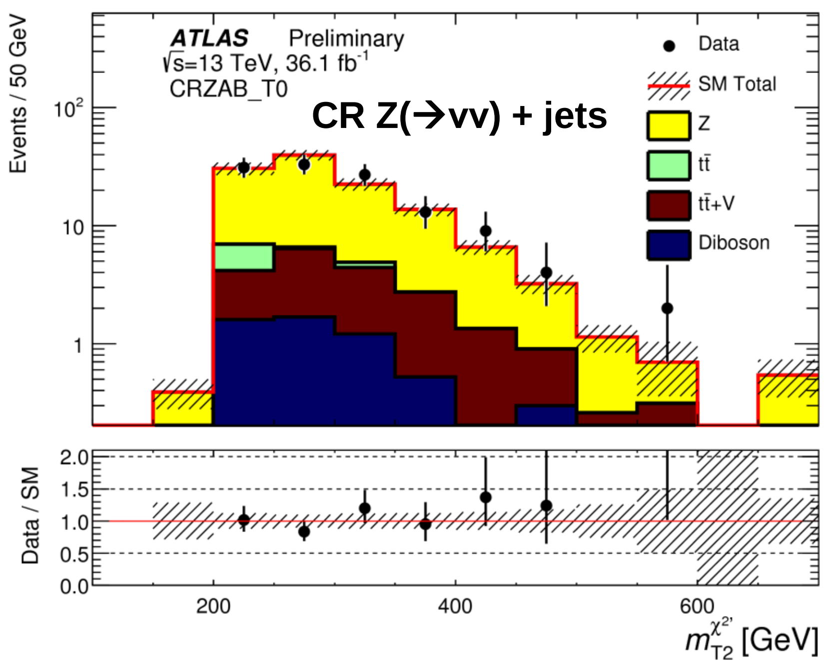
Signal Region E

- Targets **gluino-mediated** stop production with **highly boosted top quarks**
- Δm(gluino,stop) large, **Δm(stop,LSP)= 5 GeV**
- Requirements on 1st/2nd leading **large-R jet mass**
- Tight $E_{T,miss}$, H_T and $E_{T,miss}/\sqrt{H_T}$ selections

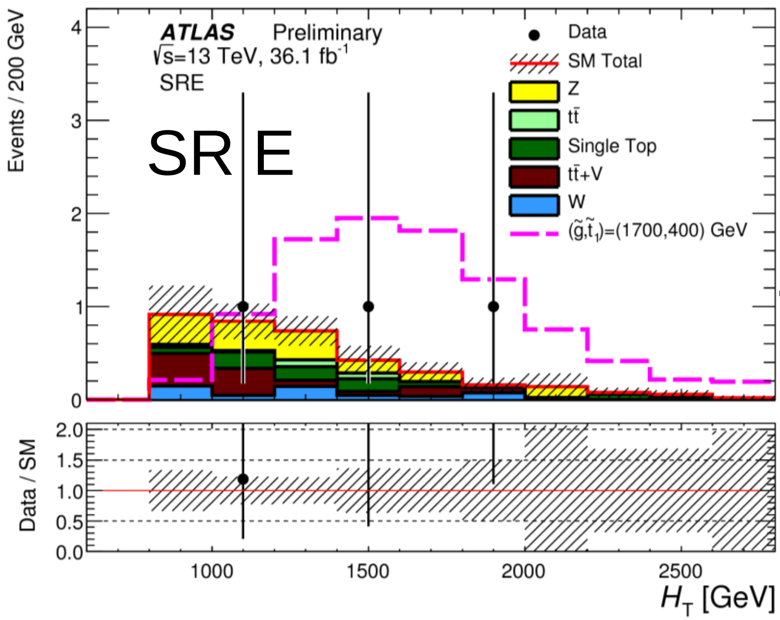


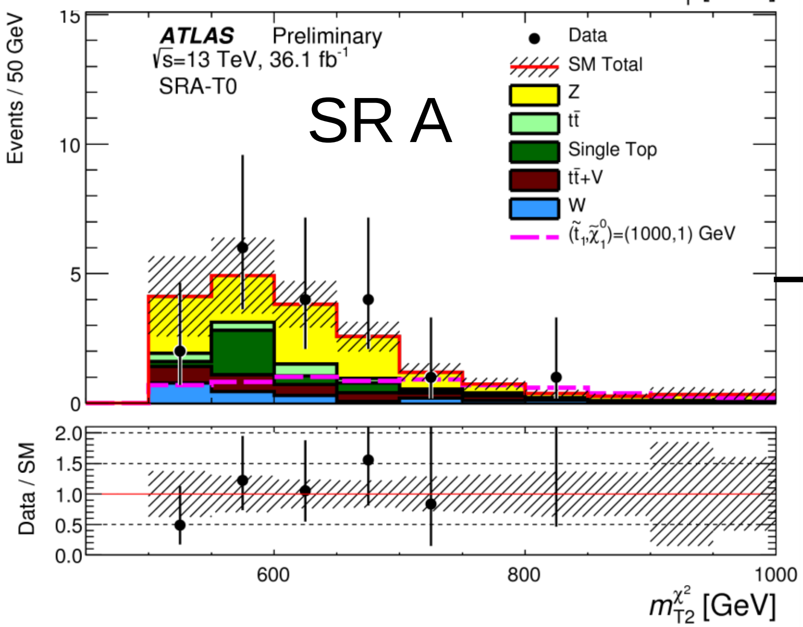
Background Estimation

- Dominant backgrounds:
  - **Z(→νν) + heavy flavour jets** [2ℓ CR]
  - **$t\bar{t}$** [1ℓ CR], **$t\bar{t}$+Z(→νν)** [1ℓ+1γ CR]
- Subdominant backgrounds:
  - **W + heavy flavour jets** [1ℓ CR],
  - **single-top** [1ℓ CR]
  - **Multi-jets** [Multi-jets CR]
- Semi data-driven background estimation with simulated based extrapolation to VRs & SRs
  - **Lepton** in **1ℓ CRs → jet**
  - **Leptons** in **2ℓ CR → p_{Tmiss}**
  - **Photon → p_{Tmiss}**

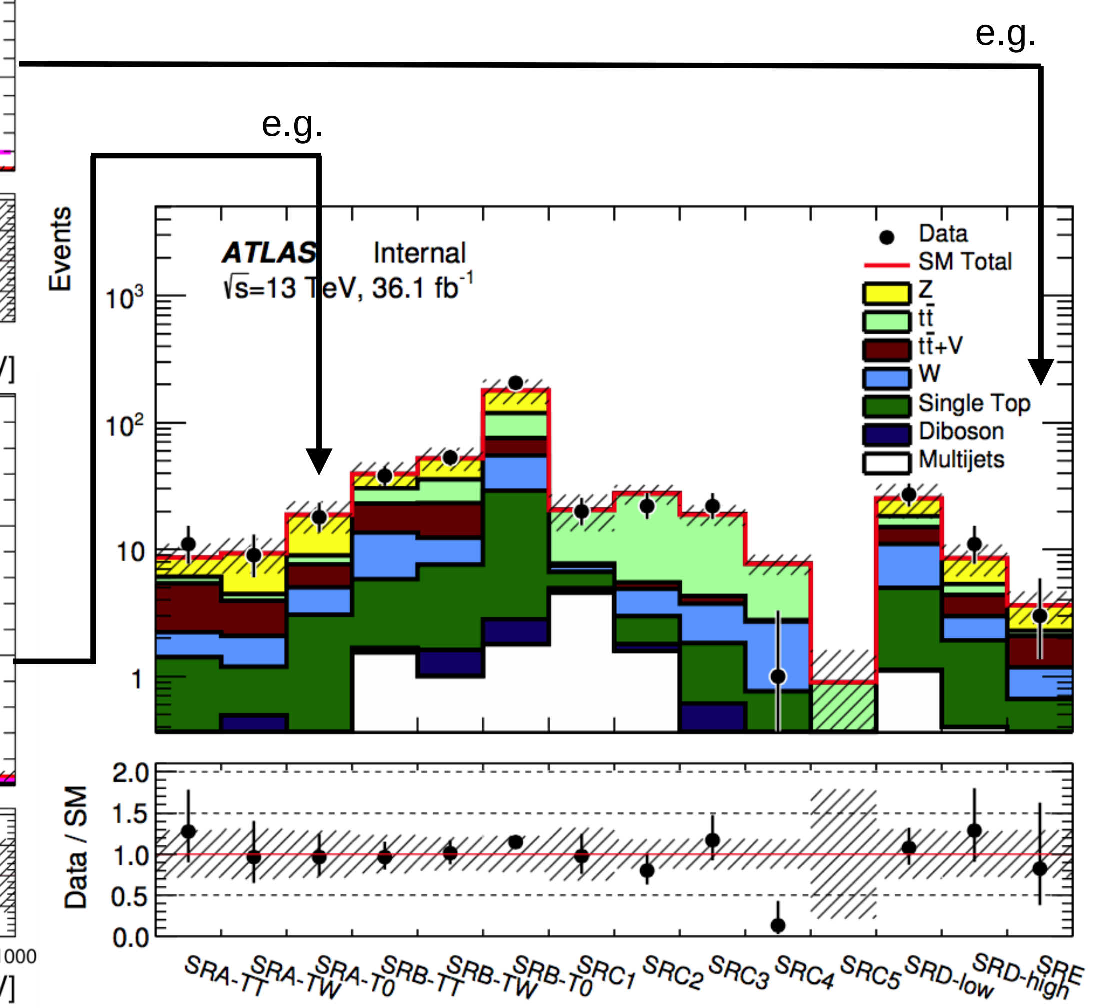


Stop 0-l Search: Results

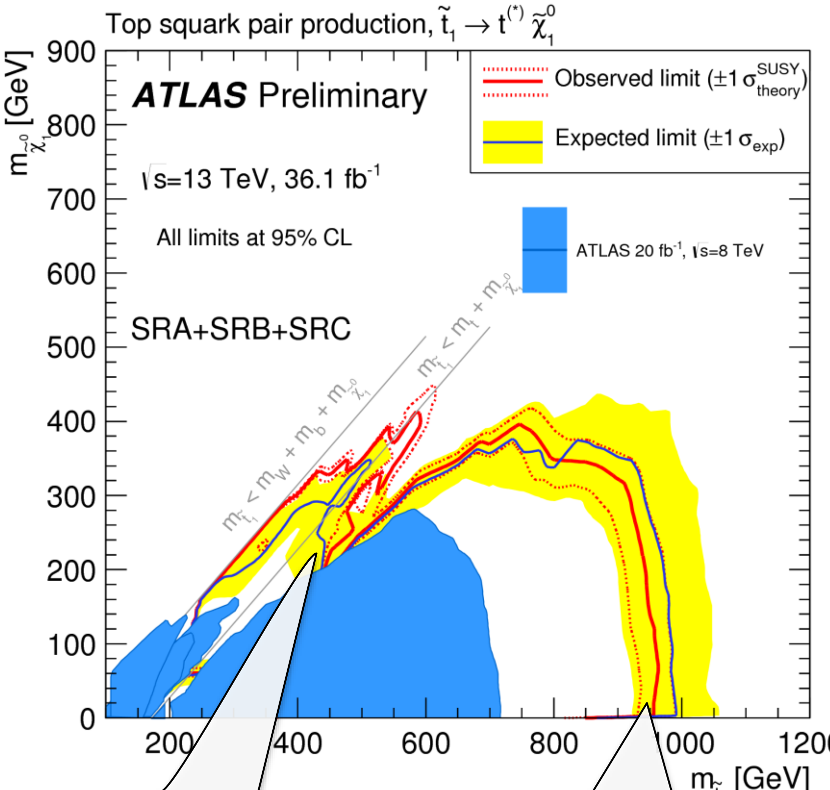


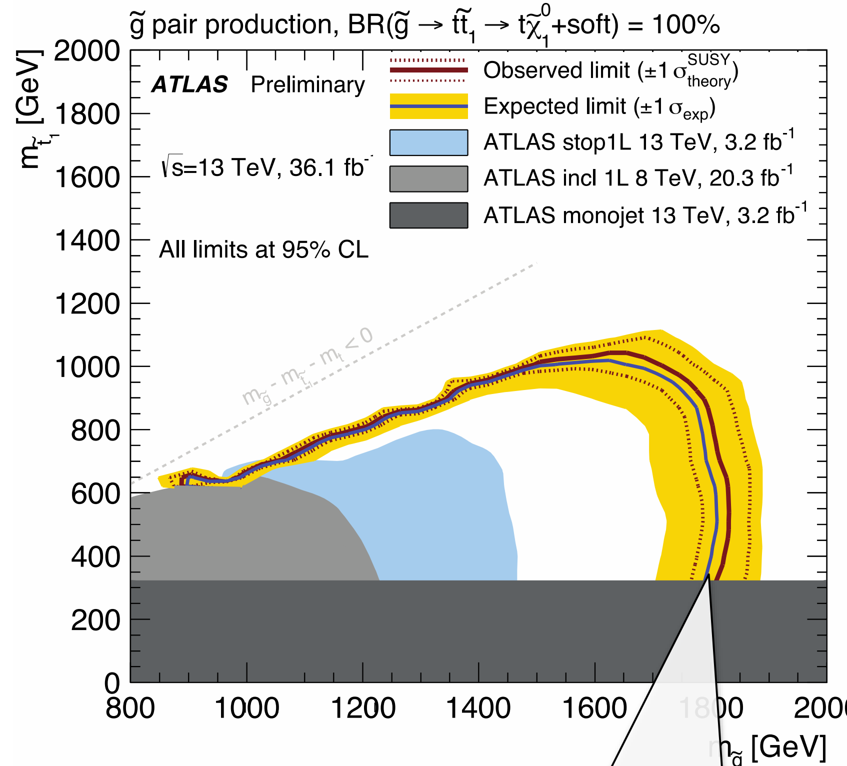


- **No significant deviations** in any of the signal regions



Stop 0-l Search: Interpretation

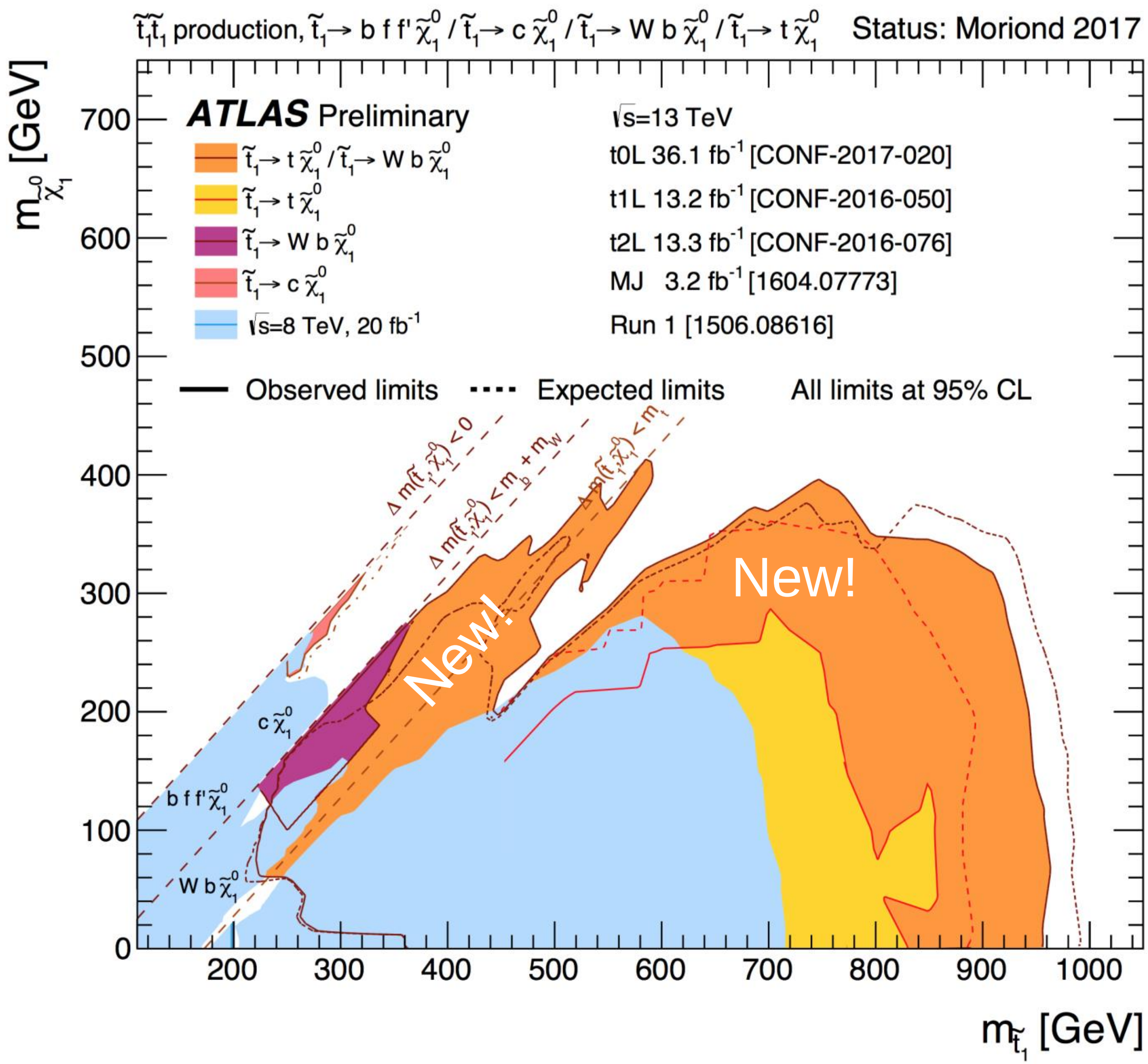




- Simplified model with 100% branching fractions to t → t + LSP:
  - Bounds up to $\mathbf{m_{stop}}$ **~ 940 GeV** @ low LSP masses
  - Stop mass range **250-430 GeV** excluded @ in diagonal region where $\mathbf{m_{stop} \sim m_t + m_{LSP}}$

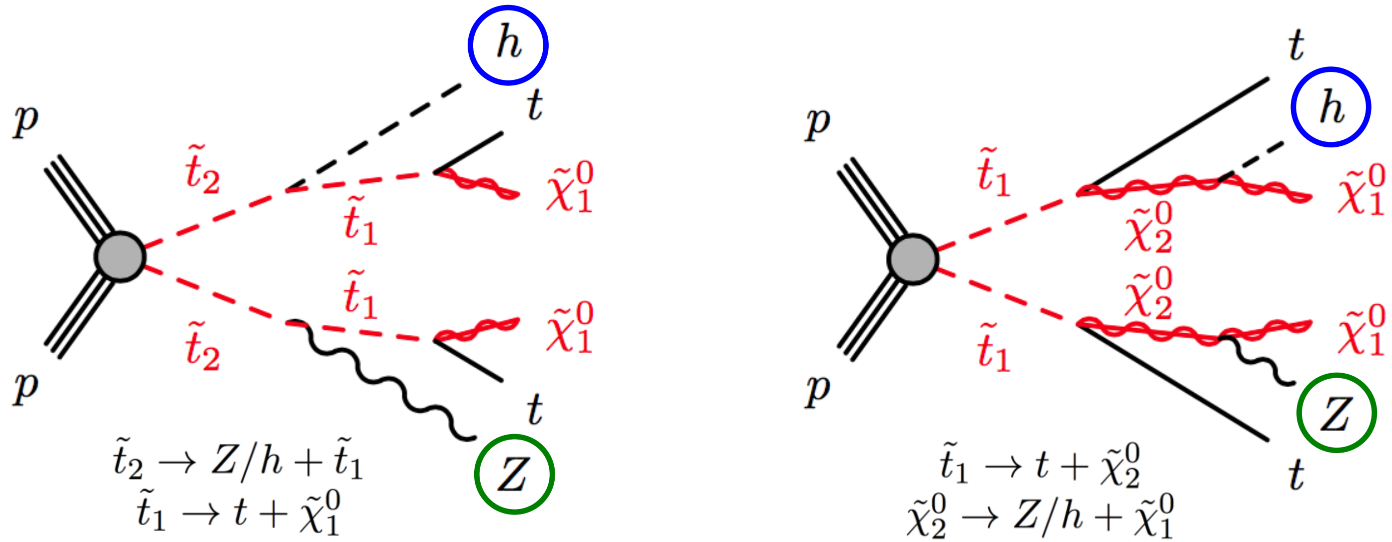
- Gluino-mediated stop production up to $\mathbf{m_{gluino}}$ **~1.8 TeV**

Putting it into context



Stop Z / Higgs Search: Overview

- Search targeting direct stop production with a **Z or Higgs bosons** in the decay chain:

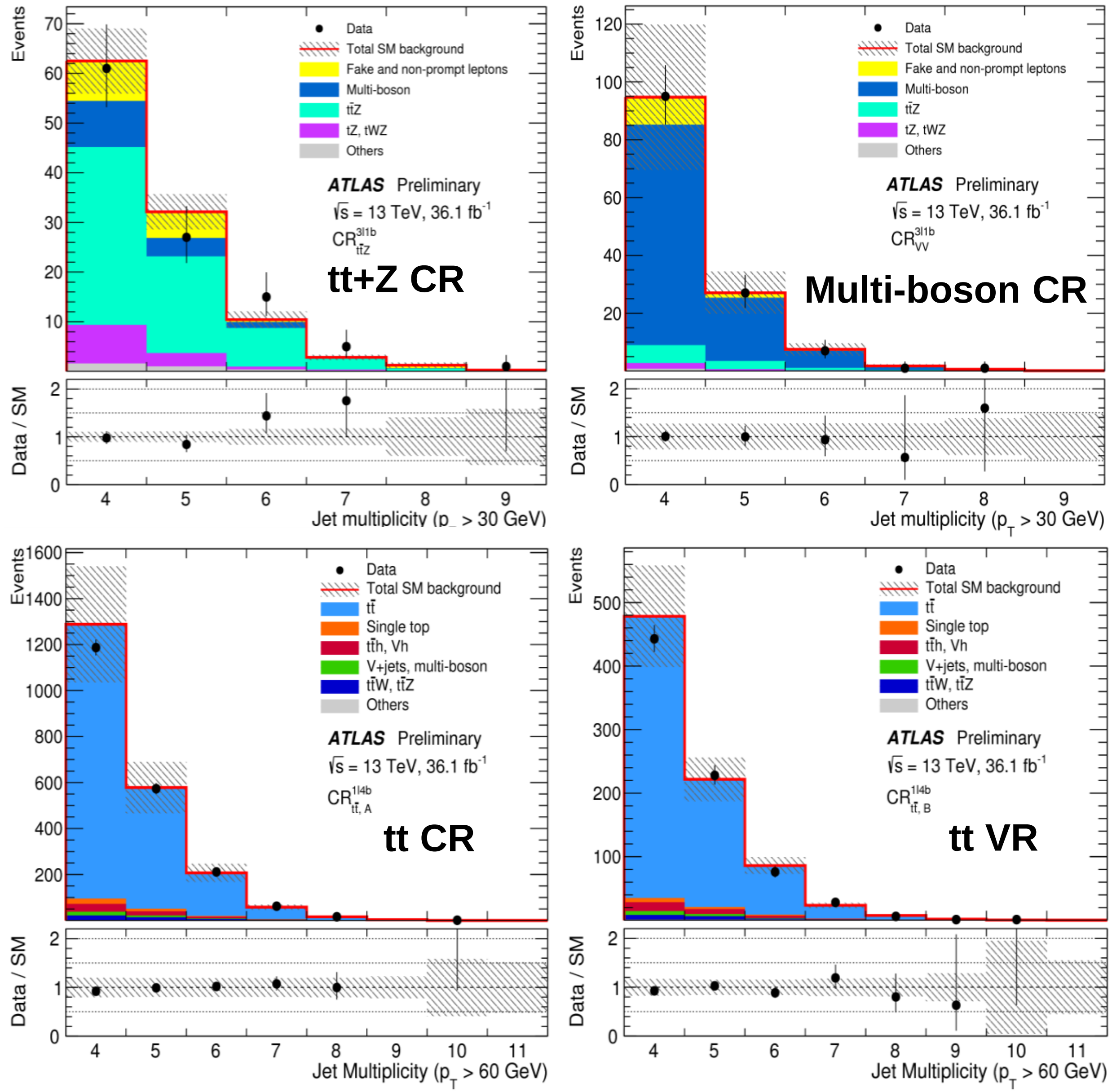


- Searches for t_2 can improve sensitivity in the regions $\mathbf{m_{stop,1} \sim m_t + m_{LSP}}$ → Difficult to access due to similarities with Standard Model tt production
- **2 analysis streams** with **3 signal regions each** to target large, intermediate, small mass differences:
  - 3-ℓ + 1 b-jet stream (targeting $Z \to \ell^+\ell^-$ decay): Use of Z boson with $p_T^{\ell\ell}$ requirements
  - 1/2-ℓ + 4 b-jets stream (targeting $h \to b\bar{b}$ decay): Use of p_T^{bb} and $m_{bb} \sim m_h$ requirements

Stop Z / Higgs Search: Backgrounds

- **3-ℓ + 1 b-jet stream:**
  - **$t\bar{t}$+Z & multi-boson** (dominant, dedicated CRs),
  - **multi-jets** (subdominant - data-driven matrix-method),
  - **$t\bar{t}$+W/H & rare SM processes** (minor, from simulation)

- **1/2-ℓ + 4 b-jets stream:**
  - **$t\bar{t}$** (dominant, dedicated CRs & VRs)
  - **single-t & $t\bar{t}$+H & rare SM processes** (minor, from simulation)

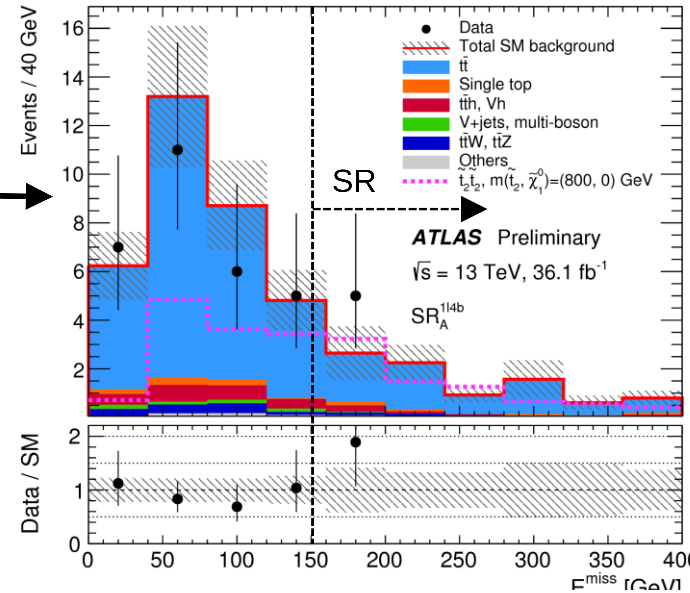


Stop Z / Higgs Search: Results

- **No significant deviations** in any of the signal regions

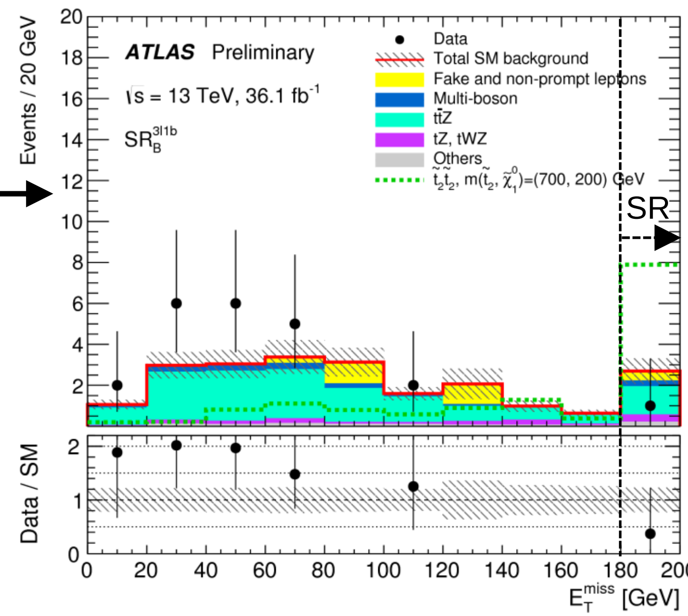
e.g.

	$SR_A^{1\ell 4b}$	$SR_B^{1\ell 4b}$	$SR_C^{1\ell 4b}$
Observed events	10	28	16
Total (constrained) SM events	13.6 ± 3.0	29 ± 5	10.5 ± 3.2
Fit output, $t\bar{t}$	11.3 ± 2.9	24 ± 5	9.3 ± 3.1
Single top	0.50 ± 0.18	1.7 ± 0.4	0.24 ± 0.07
V+jets, multi-boson	0.20 ± 0.15	0.23 ± 0.10	0.01 ± 0.01
$t\bar{t}h$, ggh, Vh	0.89 ± 0.16	1.19 ± 0.35	0.56 ± 0.13
$t\bar{t}W$, $t\bar{t}Z$	0.36 ± 0.21	1.09 ± 0.31	0.10 ± 0.10
Others	0.37 ± 0.20	1.33 ± 0.69	0.34 ± 0.18

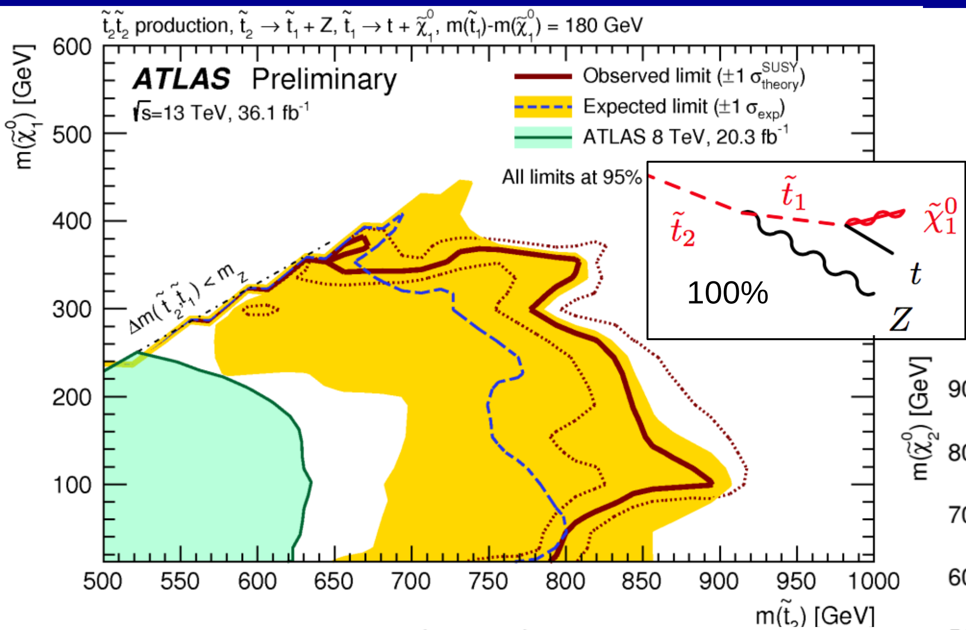


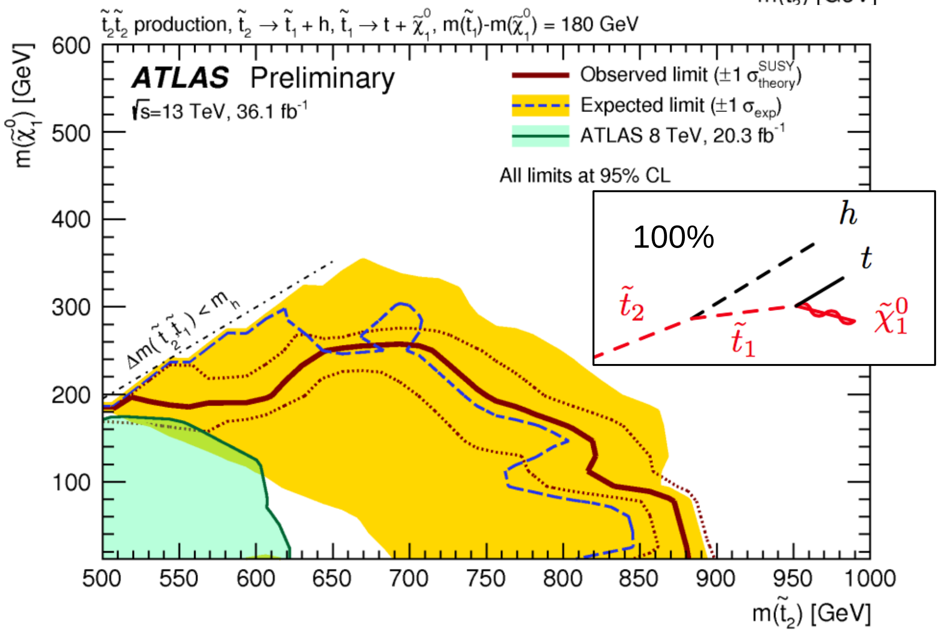
e.g.

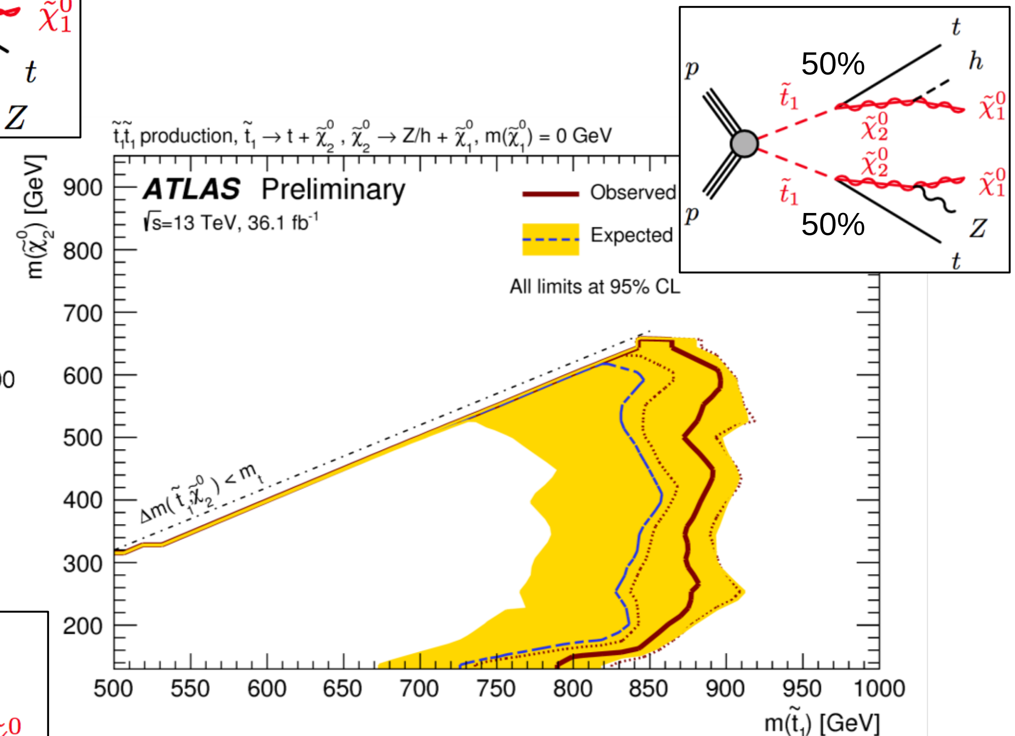
	$SR_A^{3\ell 1b}$	$SR_B^{3\ell 1b}$	$SR_C^{3\ell 1b}$
Observed events	2	1	3
Total (constrained) SM events	1.9 ± 0.4	2.7 ± 0.6	2.0 ± 0.3
Fit output, multi-boson	0.26 ± 0.08	0.28 ± 0.10	0.23 ± 0.05
Fit output, $t\bar{t}Z$	1.1 ± 0.3	1.4 ± 0.5	1.2 ± 0.3
tZ, tWZ	0.43 ± 0.23	0.36 ± 0.19	0.19 ± 0.10
Fake and non-prompt	$0.00^{+0.30}_{-0.00}$	0.45 ± 0.19	$0.00^{+0.30}_{-0.00}$
Others	0.09 ± 0.02	0.23 ± 0.06	0.36 ± 0.06



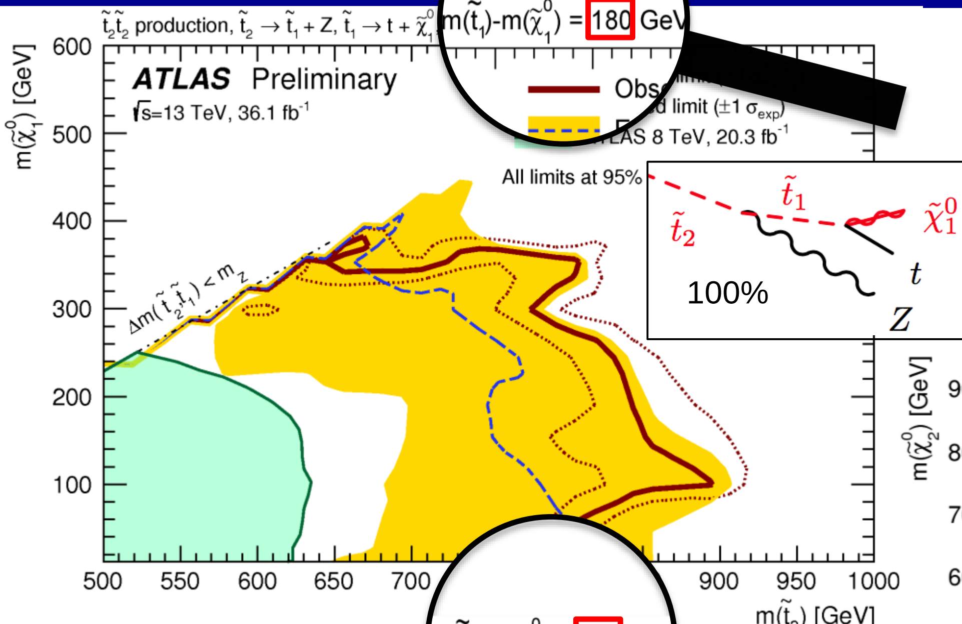
Stop Z / Higgs Search: Interpretation

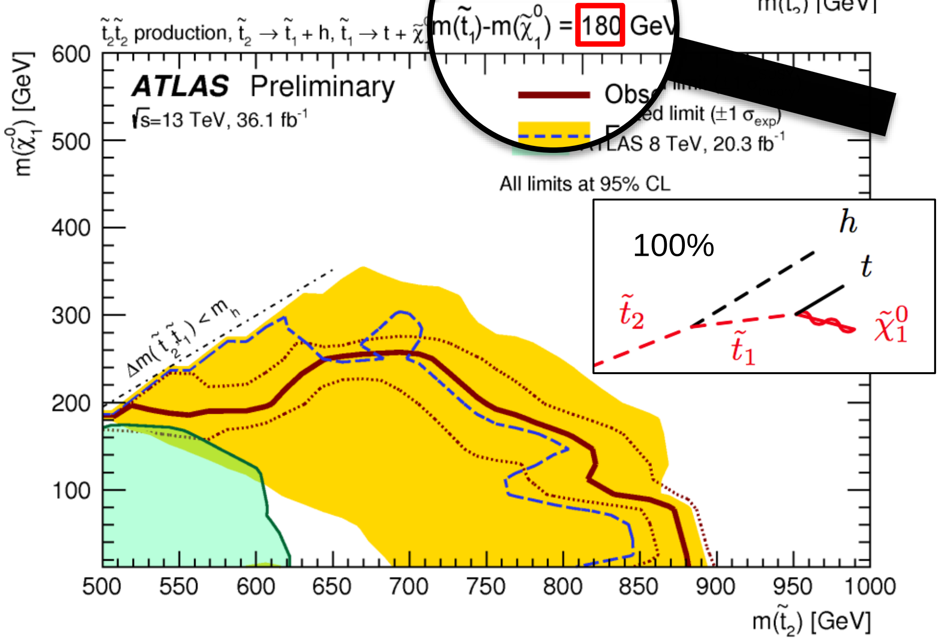


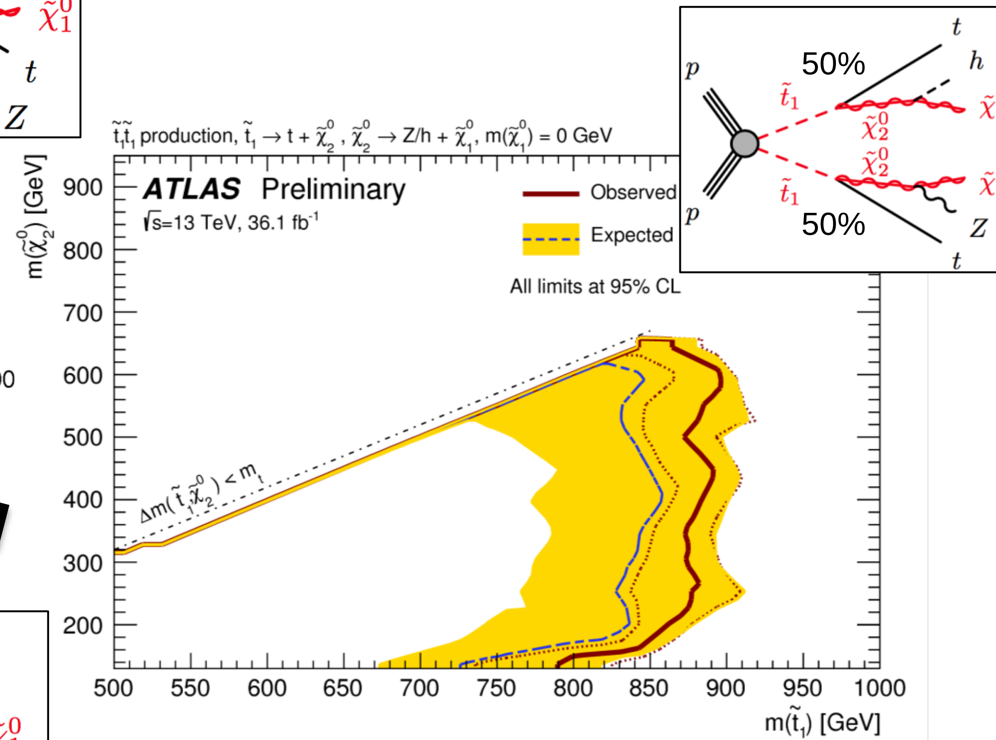




Stop Z / Higgs Search: Interpretation





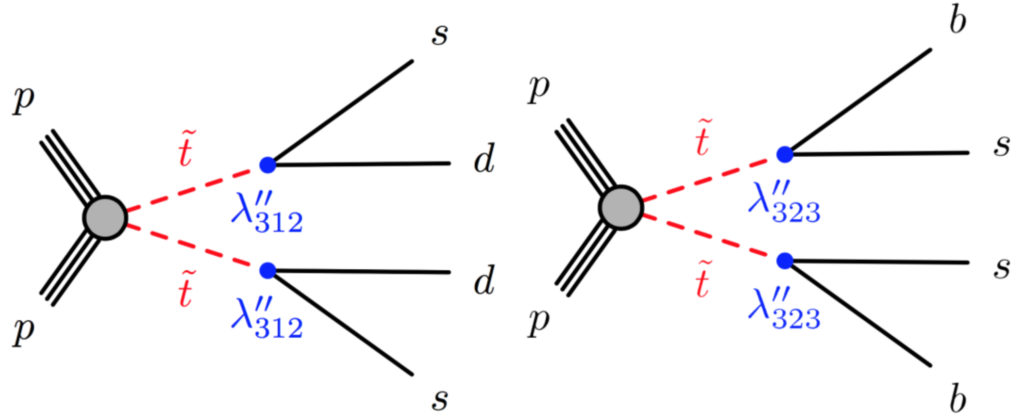


Part 3 of 3

Searches for RPV SUSY & Long-lived Particles

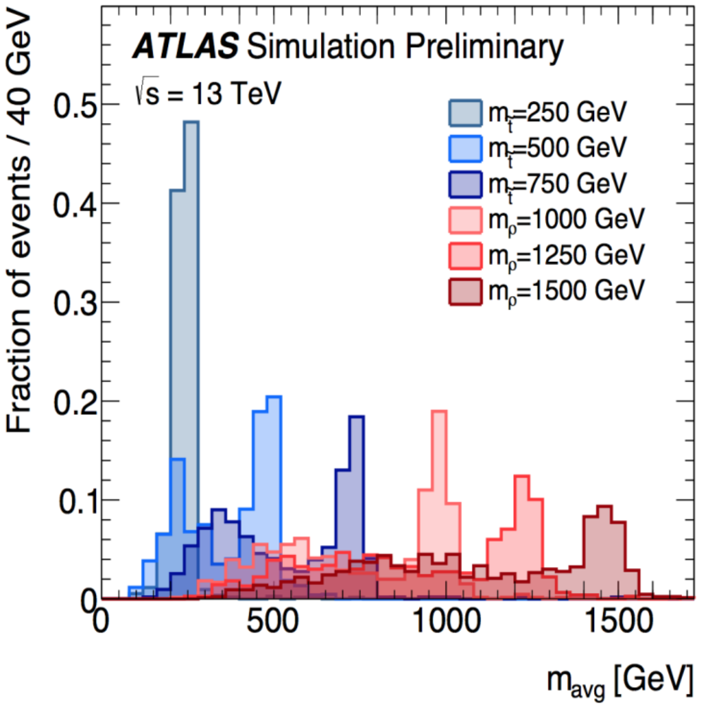
Stop RPV Search

- Motivation: If stops have R-parity violating decays (e.g. stop → jj) no / little sensitivity from $E_{T,miss}$-based searches → **stops could still be light**
- Dedicated search for 2 resonances in 4-jet final states targeting decays of stop to a pair of jets

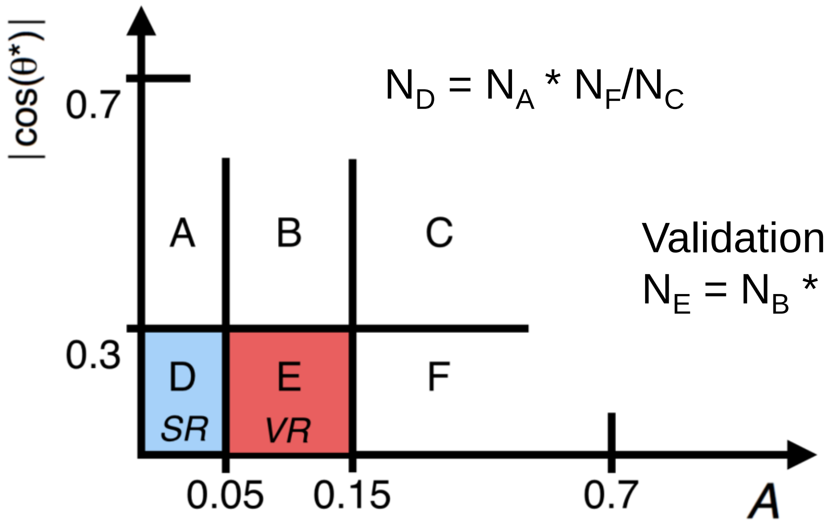


Signal region selections

- Two resonance candidates built by pairing the four leading jets (p_T > 120 GeV) according to their angular separation
- **Inclusive** and **two b-tag selection** (one b-tag in each pair)
- Final discriminant: **Average mass** of candidate resonances: $m_{avg} = 0.5*(m_1 + m_2)$



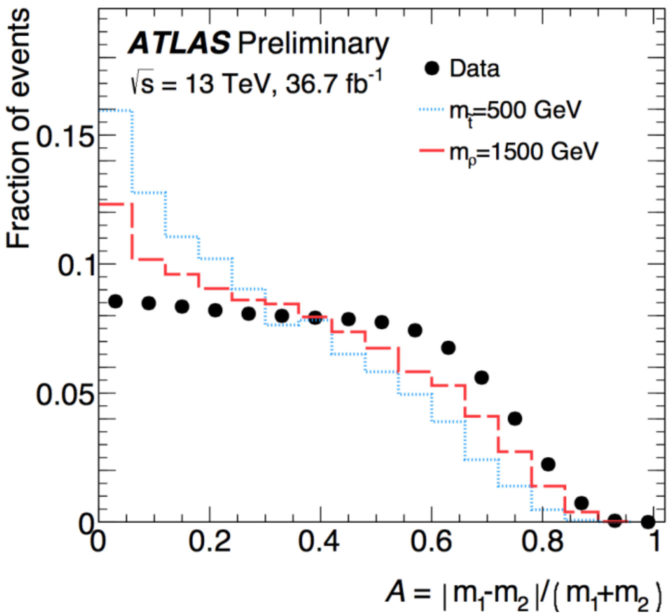
- Major background: **Multi-jets** production
- Reduced by further requirements using e.g.:
  - mass asymmetry: $A = |m_1 - m_2| / (m_1 + m_2)$
  - Angle θ* of jet pairs with beamline in rest-frame
- "ABCD-method" in A and |cosθ*| to estimate shape & normalisation in a data-driven way

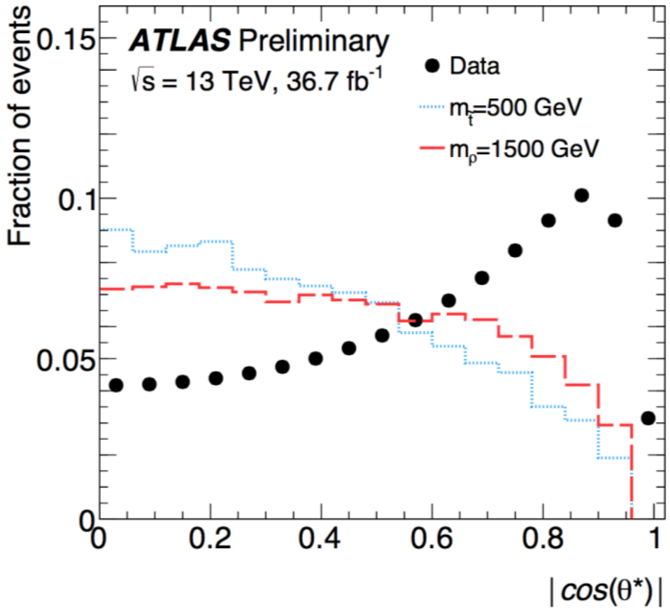


$N_D = N_A * N_F/N_C$

Validation with
$N_E = N_B * N_F/N_C$

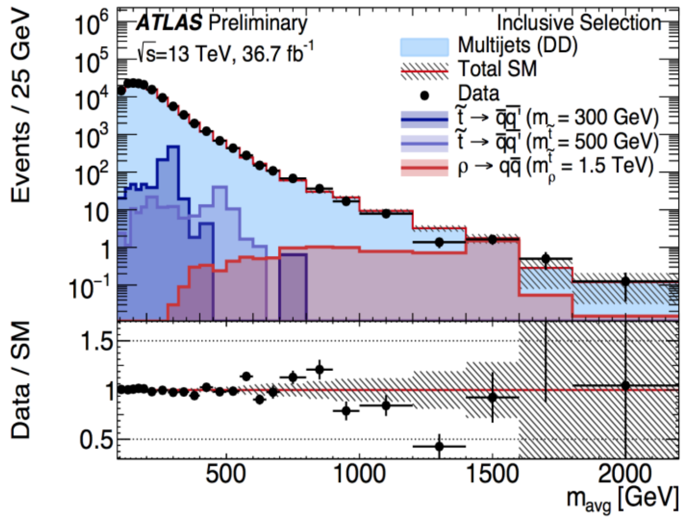
- **tt background** dominant in two b-tag region → taken from simulation

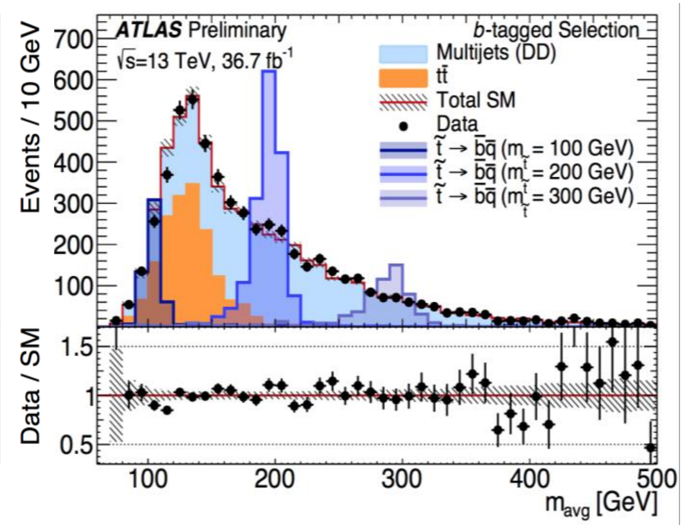


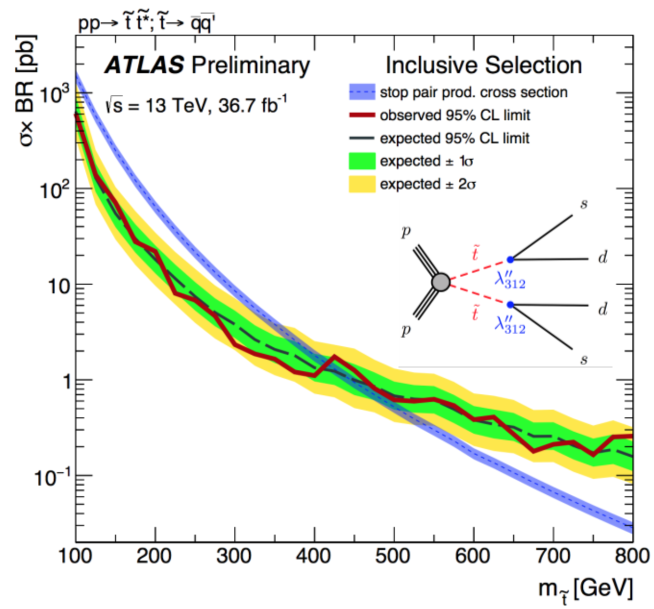


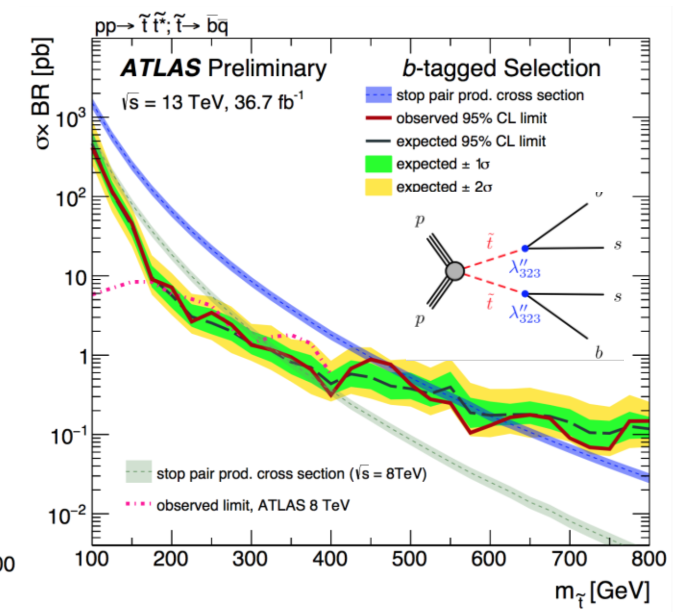
Stop RPV Search - Results

- **No evidence for resonances** in average di-jet mass
- **Stop decays to two quarks** excluded between **100 - 410 GeV** stop mass
- **Stop decays to bs** quark pair excluded between **100 - 610 GeV** of stop mass







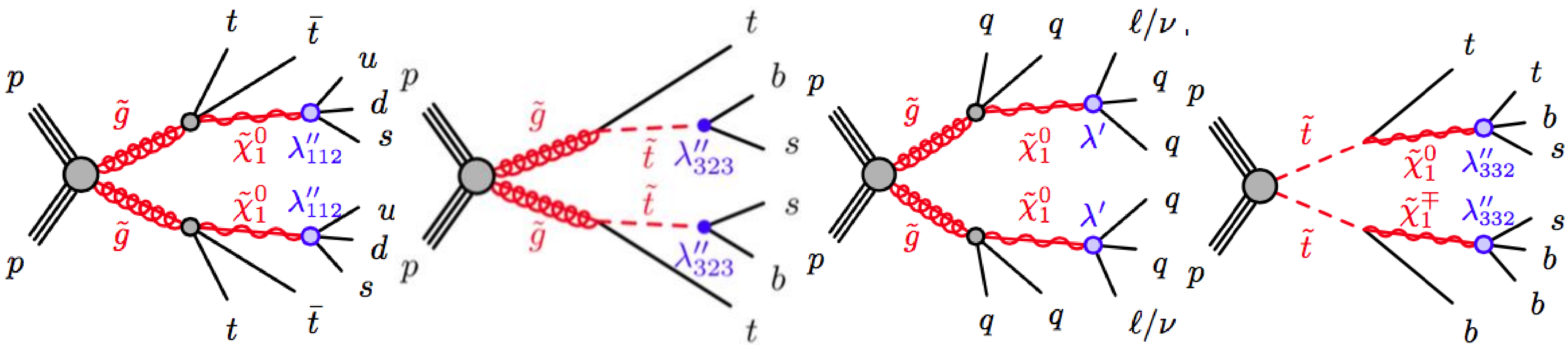


RPV 1l Search – Overview

- Search for new physics in lepton + multi-jets (up to **≥12 jets**) final state
- Defining feature: **No m_T or $E_{T,miss}$ requirements**

→ Final state has been actively asked for by the theory community, e.g. [arXiv:1310.5758]

- RPV SUSY simplified models with gluino and stop pair production used as benchmark:

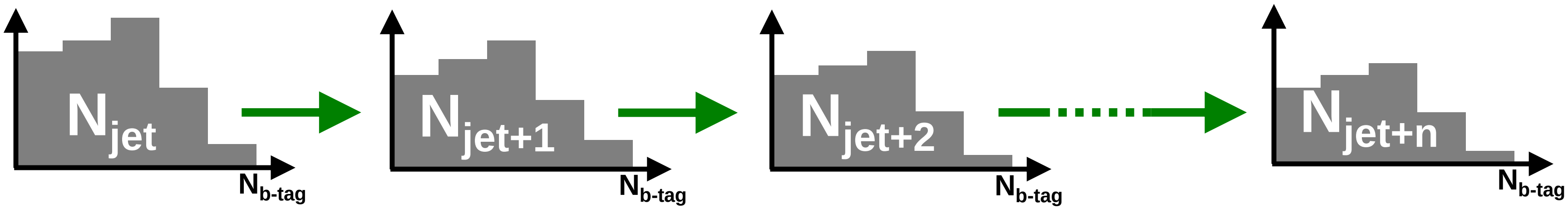


1-lepton + multi-jets selections

- 1 e / μ > 30 GeV with **tight ID and isolation** requirements (to counter fakes)
- **3 analysis streams** with jet p_T > 40/60/80 GeV
- Events in each stream categorized:
  1. N_{jets}: **5-7 jets** used to *build background model* only, **8 - ≥12 jets** used as *signal regions*
  2. $N_{b\text{-tags}}$: **0,1,2,3,≥4**

RPV 1l Search: Backgrounds

- Dominant backgrounds: **$t\bar{t}$+jets** @ high $N_{b\text{-jet}}$ and **V+jets** @ low $N_{b\text{-jet}}$ → data-driven estimate
- Basic concept: **Parameterised extrapolation** of $N_{b\text{-tag}}$ spectrum from medium to high N_{jet}



$N_{b\text{-tag}}$	tt+jets	V+jets
Shape	• Initial shape from **5-jet** selection + evolution to higher N_{jet} parameterised with fixed probabilities of additional jets to be b-jets	• From MC for each N_{jet} slice
Normal-isation	• N_{jet}-evolution predicted with parameterised model based on combination of **staircase** and (extended) **Poisson scaling** of N_{jet} ratios $\mathbf{r_j = N_{j+1}/N_j}$ with scaling parameters $\mathbf{c_i}$ $r_j = c_0 + c_1/(j + c_2)$	

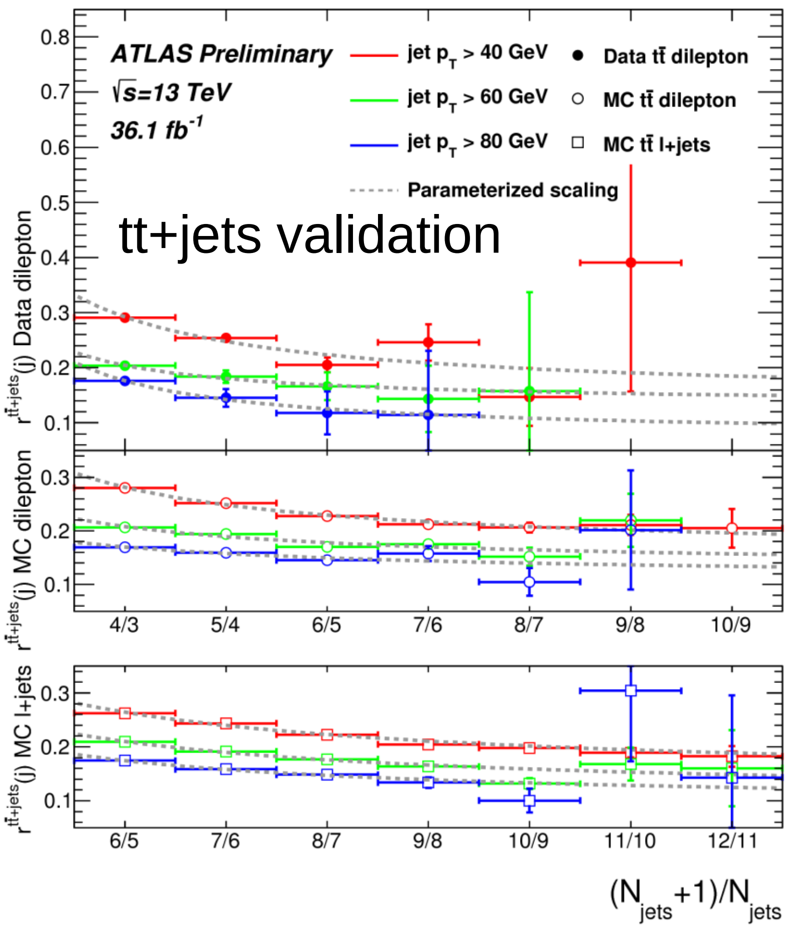
→ **Simultaneous fit** of shape & normalisation in all considered bins:

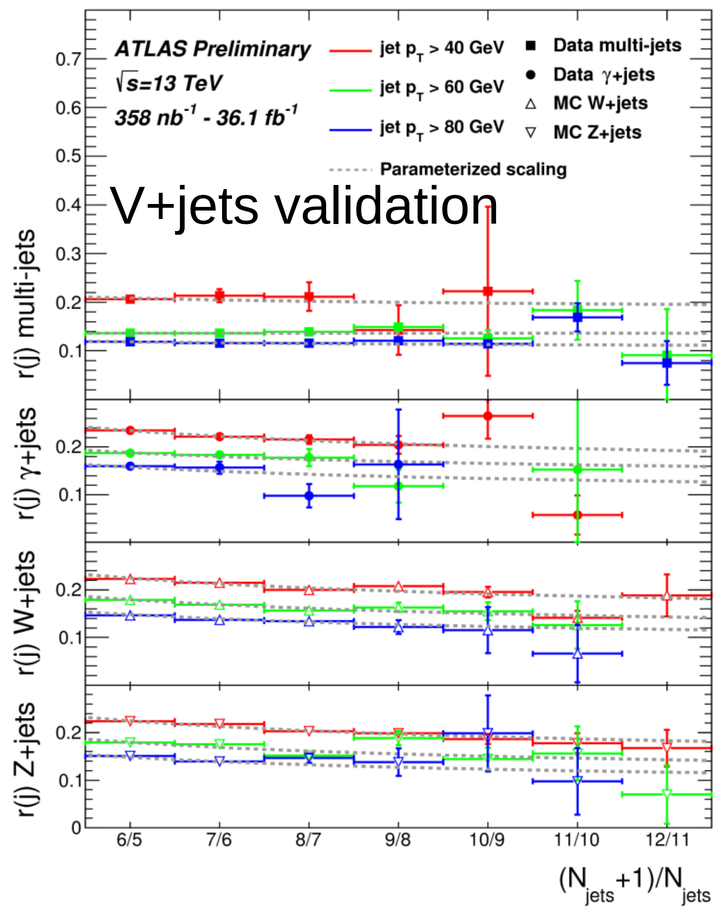
- **Discovery setup**: **Only $N_{b\text{-tag}}$ ==0, ≥3 bins** considered as SRs. Orthogonal bins with small signal contamination used to constrain background model.
- **Exclusion setup**: **All N_{jet} / $N_{b\text{-tag}}$ bins** used to constrain model.

- Other backgrounds: **multi-jets** (data-driven matrix-method estimate), **diboson / single-top / tt+X** (from simulation - mostly < 10%)

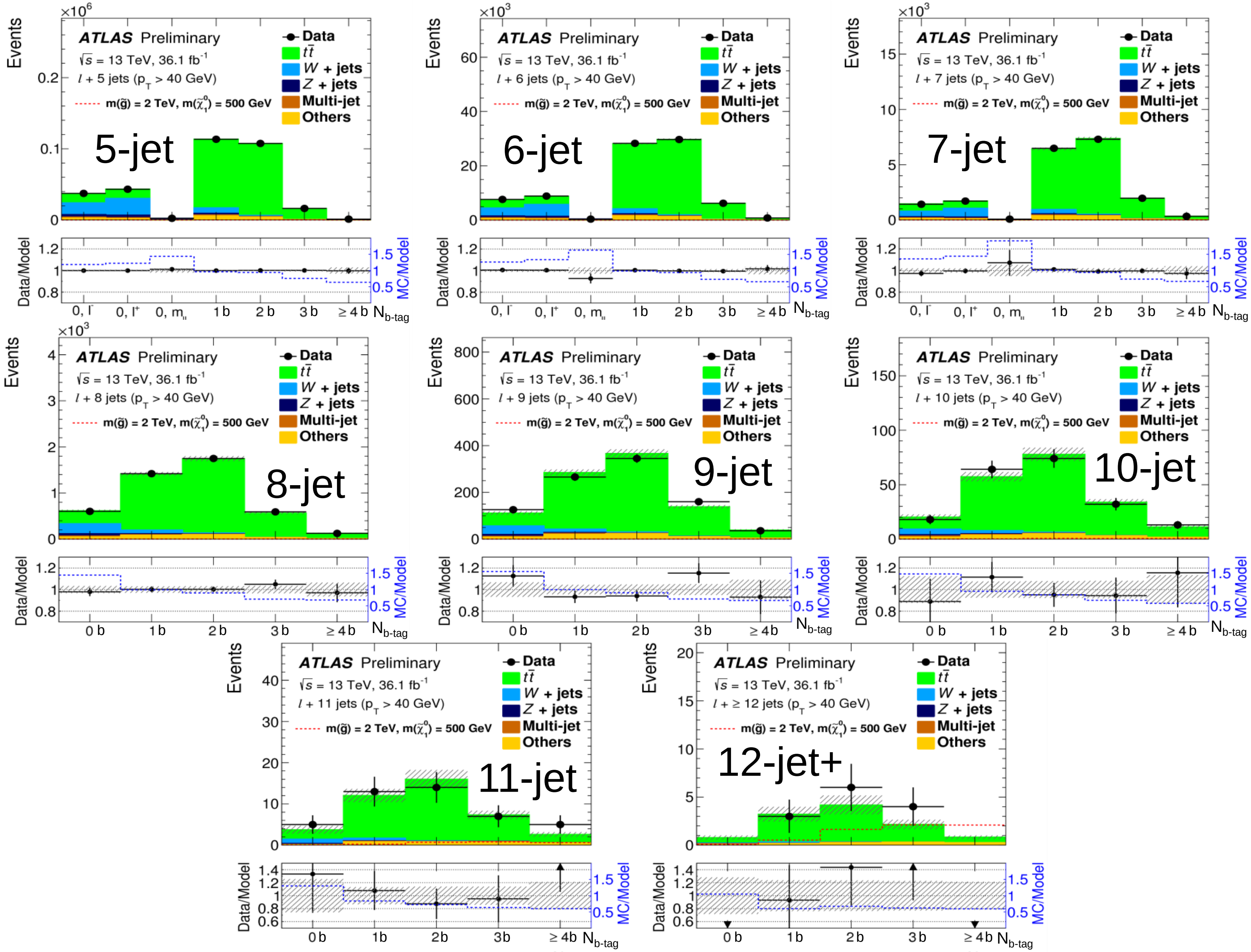
RPV 1l Search: Validation

- Scaling of N_{jets} normalisation **validated** in **data** and **simulation**:
  - ✓ $t\bar{t}$ di-lepton selection (data validation)
  - ✓ $t\bar{t}$ di-lepton selection (MC closure)
  - ✓ $t\bar{t}$+jets + lepton (MC closure)
  - ✓ γ+jets control selection (data validation)
  - ✓ multi-jets selection (data validation)
  - ✓ W+jets / Z+jets (MC closure)

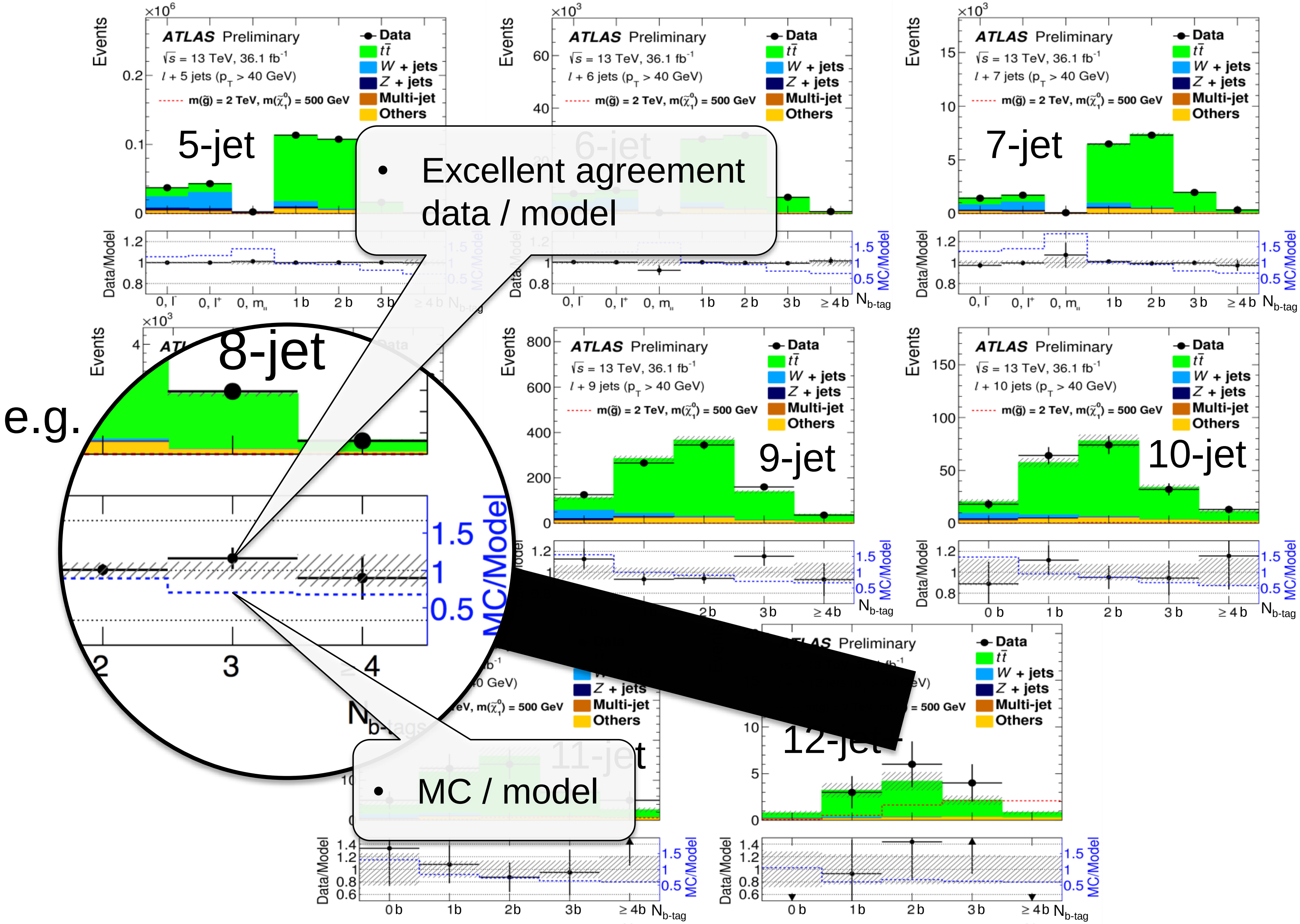




RPV 1l Search: Results

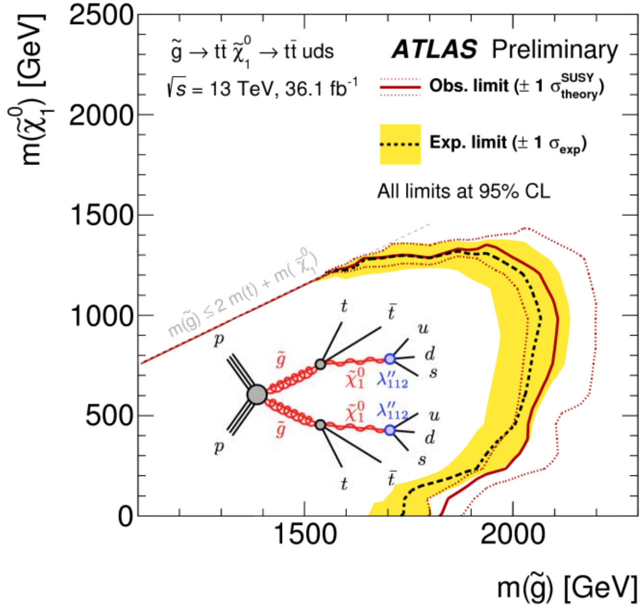


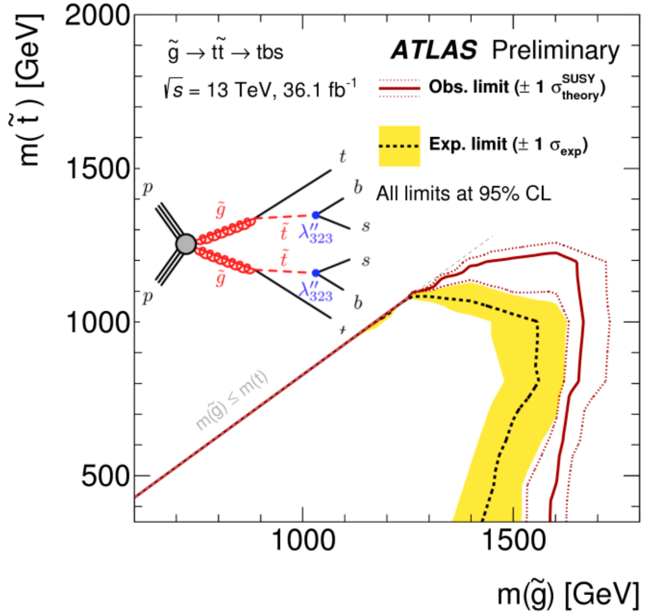
RPV 1l Search: Results

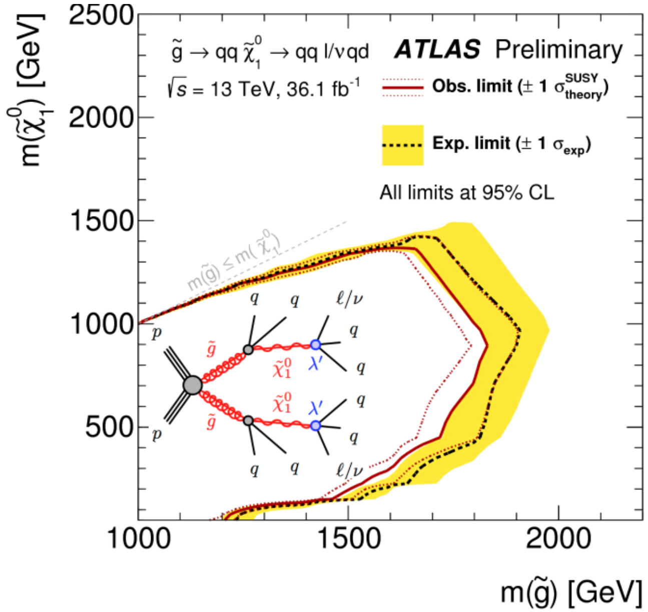


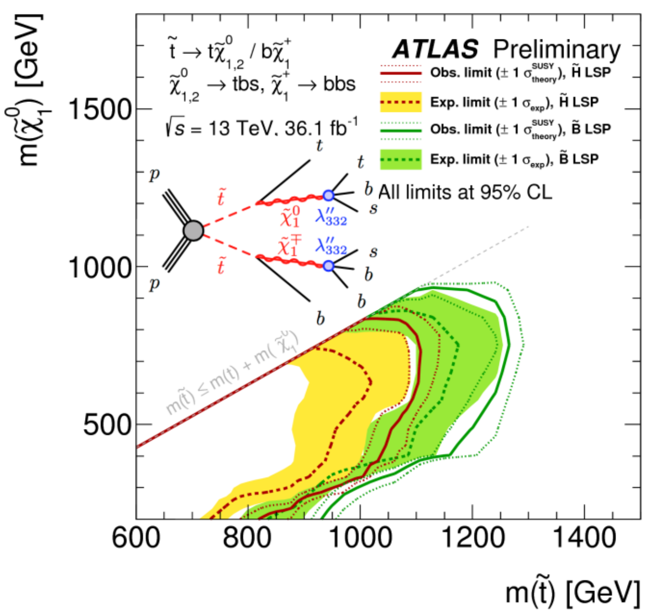
RPV 1l Search: Interpretation

- Limits on 4 RPV SUSY models
  - Up to ~**2.1 TeV gluino mass** depending on model
  - Up to ~**1.25 TeV stop mass**
- Limit on **SM 4-top production of 6.5 x SM** (9.1 expected)



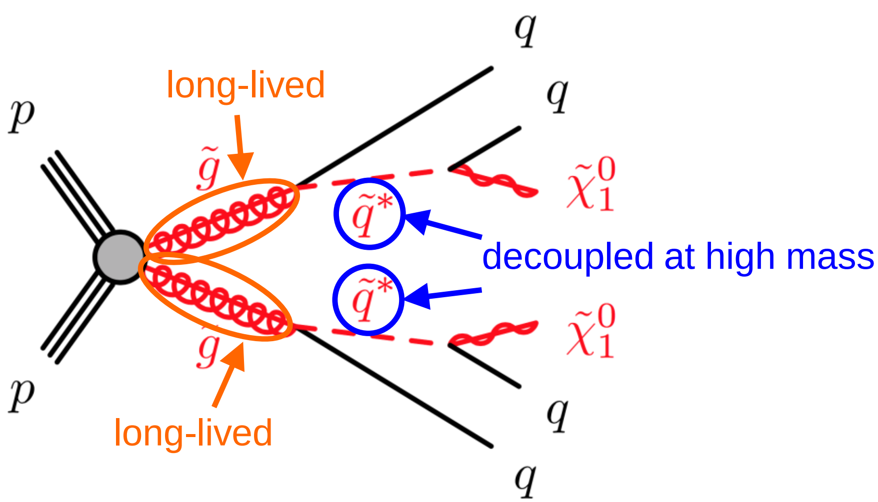






Displaced Vertex Search - Overview

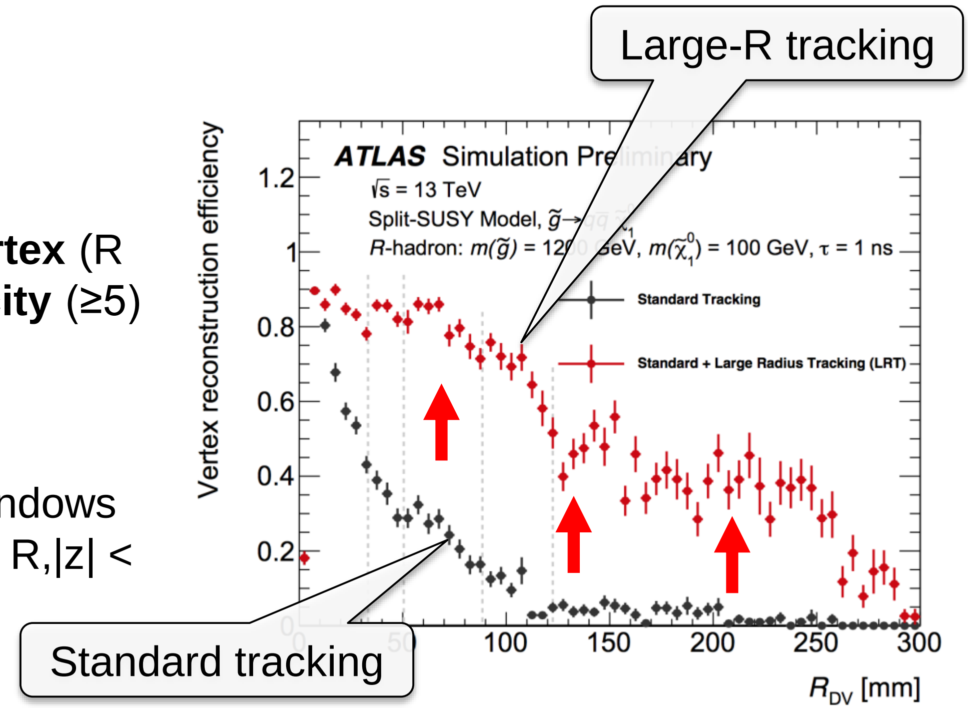
- Search for long-lived massive particles in the lifetime range O(10^{-2}) – O(10) ns
- Split-SUSY inspired simplified model as benchmark



- Long-lived gluinos form bound colour singlet states with SM particles (R-hadron) → decay in the inner tracker volume

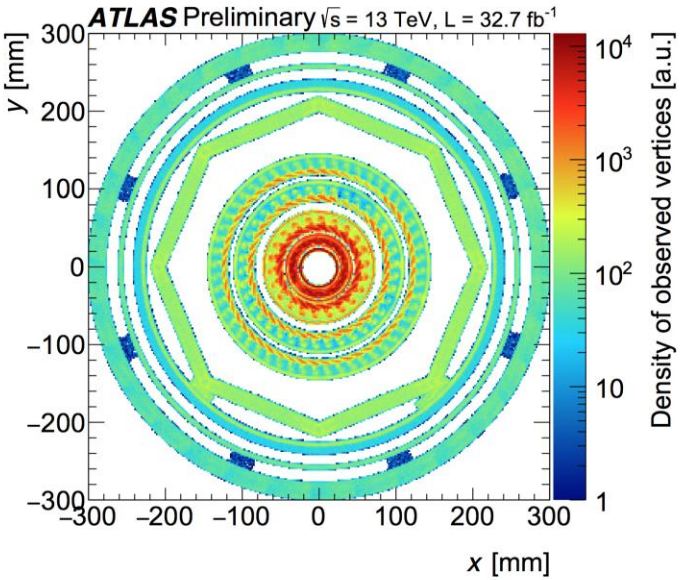
- Experimental signature: **Displaced vertex** (R ~ 1-100 mm) with **high track multiplicity** (≥5) and **high mass** (>10 GeV) + $\mathbf{E_{T,miss}}$

- Use of specialised **large radius track reconstruction** with extended d_0/z_0 windows to reconstruct displaced vertices within R,|z| < 30 cm



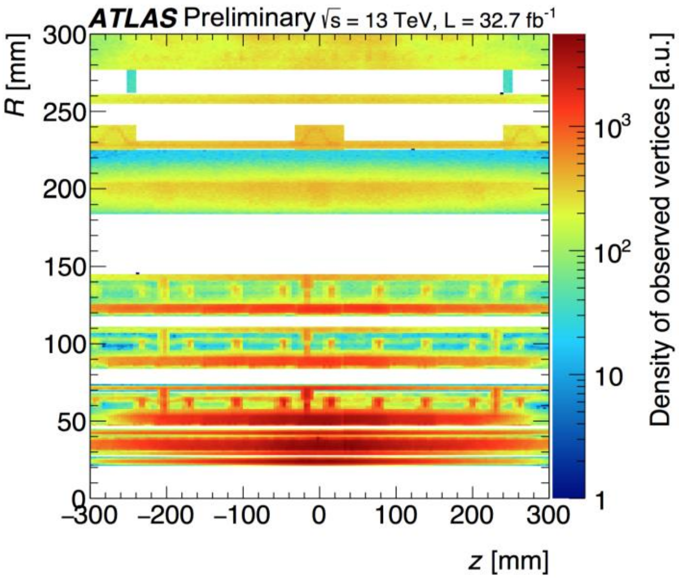
Displaced Vertex Search - Backgrounds

- **Hadronic interactions** with detector material → Produces displaced vertices:
  - Background significantly reduced by **removing material-rich regions** from fiducial volume (maps based on minimum bias data) → Discards **42% of detector volume**
  - Residual contribution estimated with exponential fit at low m_{DV} + extrapolation to high m_{DV}



- **Close-by short-lived SM particle decays** → Merge into common vertex thus passing N_{trk} and m_{DV} cuts
  - Estimated by merging vertices from distinct events randomly

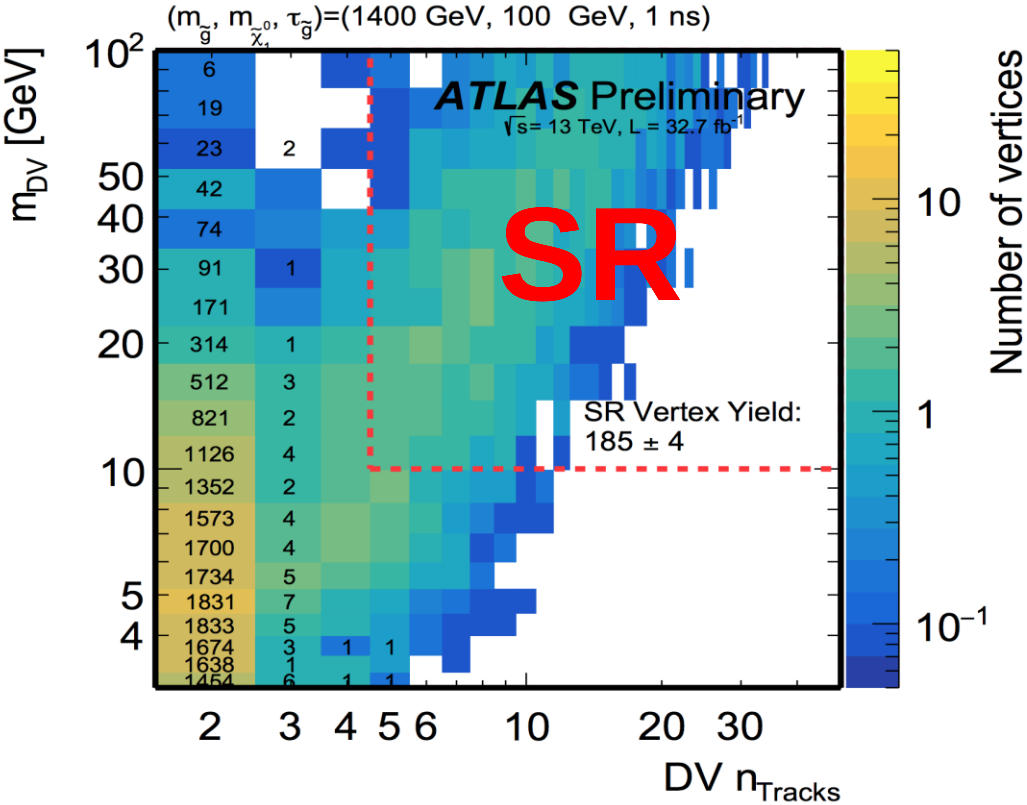
- **Accidental crossing** of low mass vertices and tracks → Used in vertex reconstruction thus passing N_{trk} and m_{DV} requirements
  - Estimate by adding pseudo-track to vertices in a control region

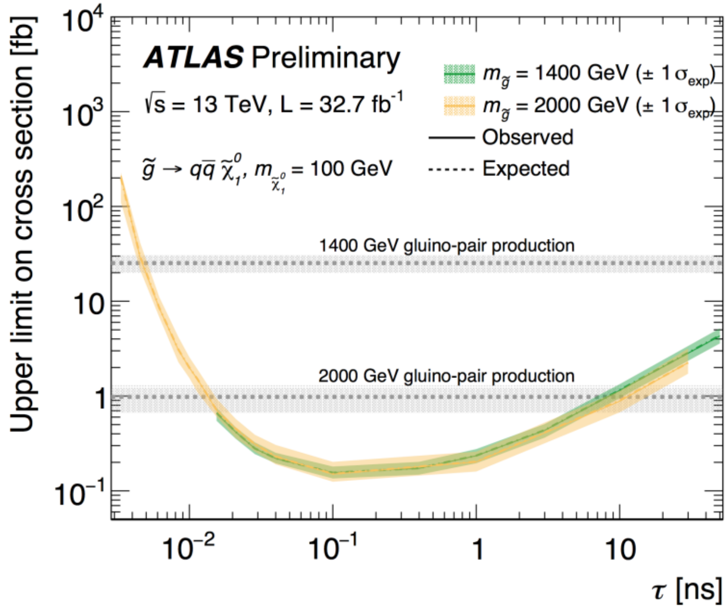


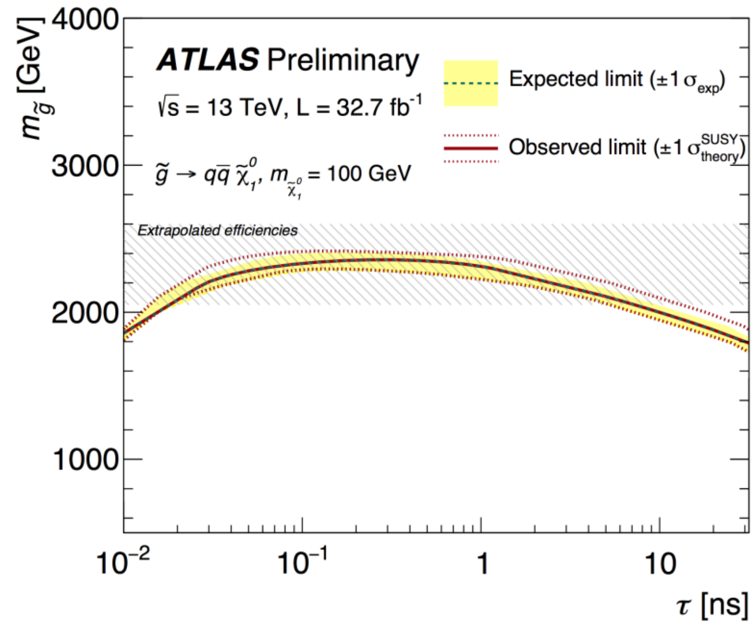
→ Several dedicated signal-depleted validation regions used for cross-checks

Displaced Vertex Search -Results

- **No event is observed** in the SR: Consistent with the background **expectation of 0.2 ± 0.2 events**
- Exclude long-lived gluinos up to **2.3 TeV** with lifetimes of ~ O(10^{-2}) - O(10) ns



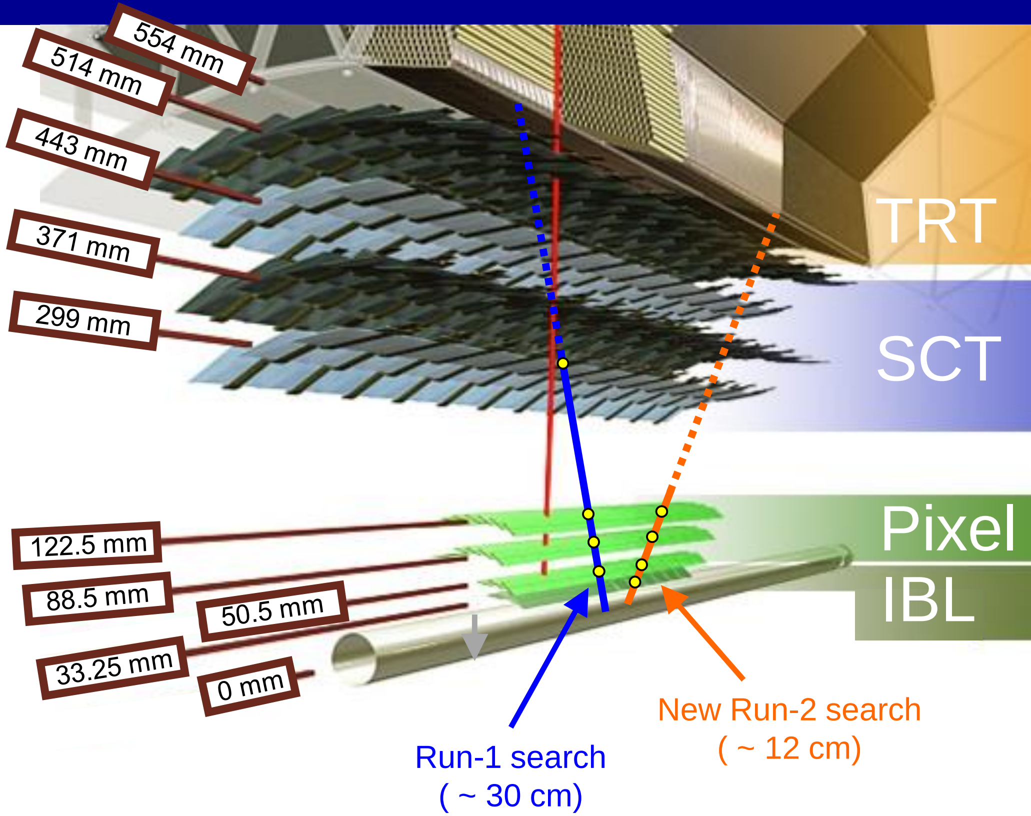




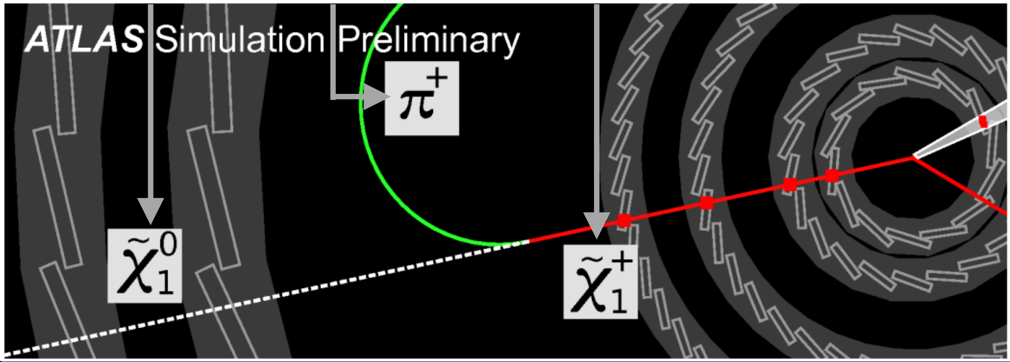
Disappearing Track Search: Overview

- If lightest chargino & neutralino are almost pure Wino (e.g. in **A**nomaly **M**ediated **S**USY **B**reaking)
  - **Mass degeneracy:** $\Delta m(\chi^{\pm}_1, \chi^0_1)$ ~ 160 MeV
  - **Chargino long-lived:** τ ~ 0.2 ns
  - **Sizable decay length:** cτ ~ 6 cm
- Chargino decays into ultra-soft pion and neutralino
- Experimental signature to discriminate against SM backgrounds:
  - **Disappearing track**
  - **Large $E_{T,miss}$** from LSP
- Run-1 search was sensitive to disappearing tracks with **decay lengths starting from 30 cm ~ 1 ns**

→ New insertable pixel B-layer (IBL) installed during long shutdown opens up window to shorter life-times (cτ ~ 12 cm) **for the very first time!**



$E_{T,miss}$ + pion (very soft) + disappearing track



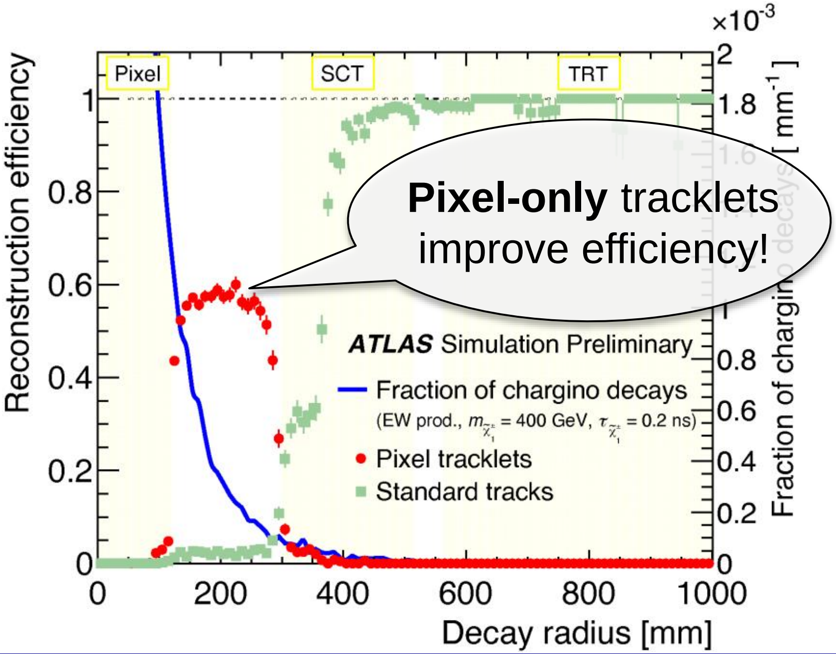
Disappearing Track Search: Overview

- **pMSSM reinterpretation** of 8 TeV ATLAS SUSY searches [JHEP 10 (2015) 134] showed that Run-1 analysis excluded **~30% of Wino-like models**

- **~70%** of the Wino-LSP models included in the pMSSM scan have **lifetimes of 0.15-0.25** ns

→ A **very generic lifetime range** in MSSM!

→ **Strong motivation** to search for disappearing track signals with **shorter decay lengths**!

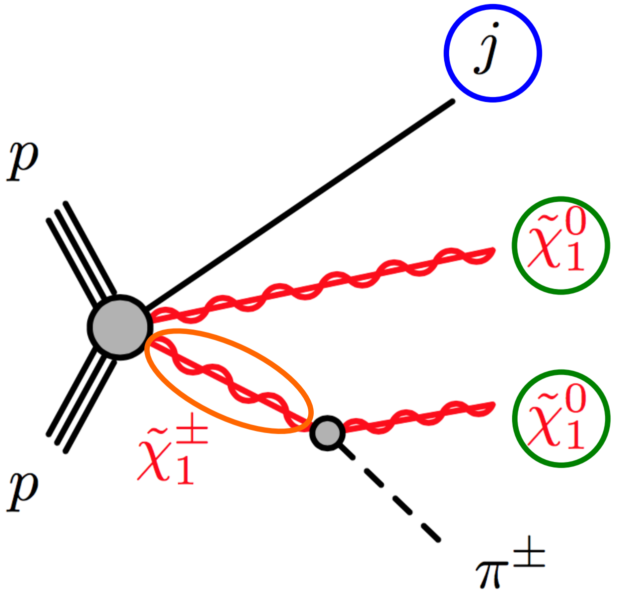


Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + E_T^{miss}	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + E_T^{miss}	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + E_T^{miss}	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + E_T^{miss}	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons + jets + E_T^{miss}	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + E_T^{miss}	3.0%	1.3%	2.9%	3.1%
0-lepton stop	9.4%	7.8%	8.2%	10.2%
1-lepton stop	6.2%	2.9%	5.4%	6.8%
2b-jets + E_T^{miss}	3.1%	3.3%	2.3%	3.6%
2-leptons stop	0.8%	1.1%	0.8%	0.7%
Monojet stop	3.5%	11.3%	2.8%	3.6%
Stop with Z boson	0.4%	1.0%	0.4%	0.5%
tb+E_T^{miss}, stop	4.2%	1.9%	3.1%	5.0%
ℓh, electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2-τ, electroweak	0.2%	0.3%	0.2%	0.2%
3-leptons, electroweak	0.8%	3.8%	1.1%	0.6%
4-leptons	0.5%	1.1%	0.6%	0.5%
Disappearing Track	11.4%	0.4%	29.9%	0.1%
Long-lived particle	0.1%	0.1%	0.0%	0.1%
$H/A \to \tau^+\tau^-$	1.8%	2.2%	0.9%	2.4%
Total	40.9%	40.2%	45.4%	38.1%

Most **powerful** search for Wino-LSPs !

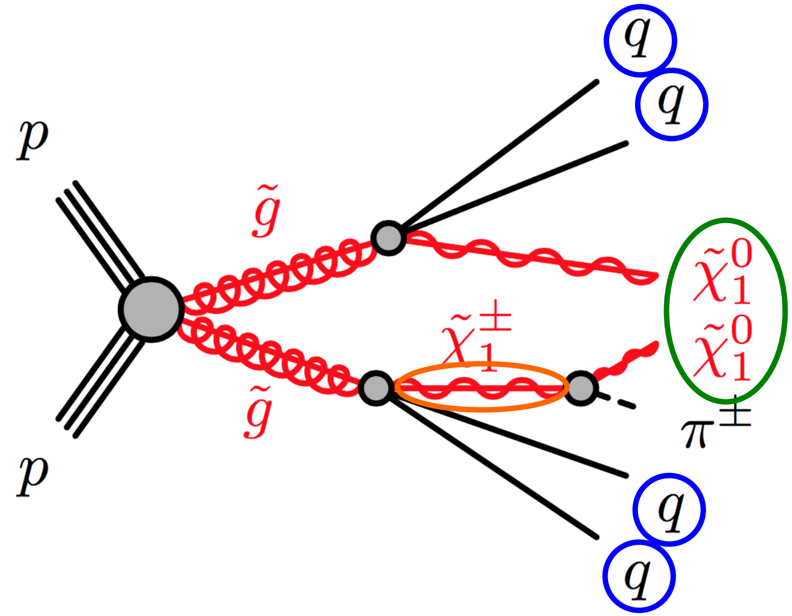
Disappearing Track Search: Overview

- Electroweak production channel



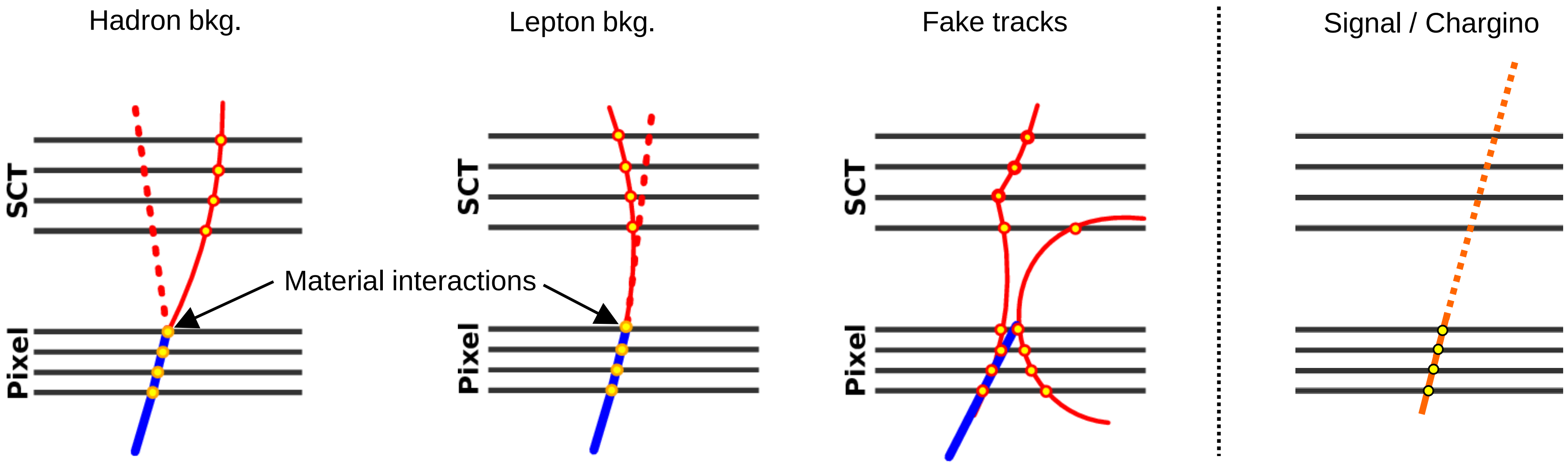
ISR jet + **$E_{T,miss}$** + **disappearing track**

- Gluino-mediated production channel



Multi-jet + **$E_{T,miss}$** + **disappearing track**

Disappearing Track Search: Backgrounds



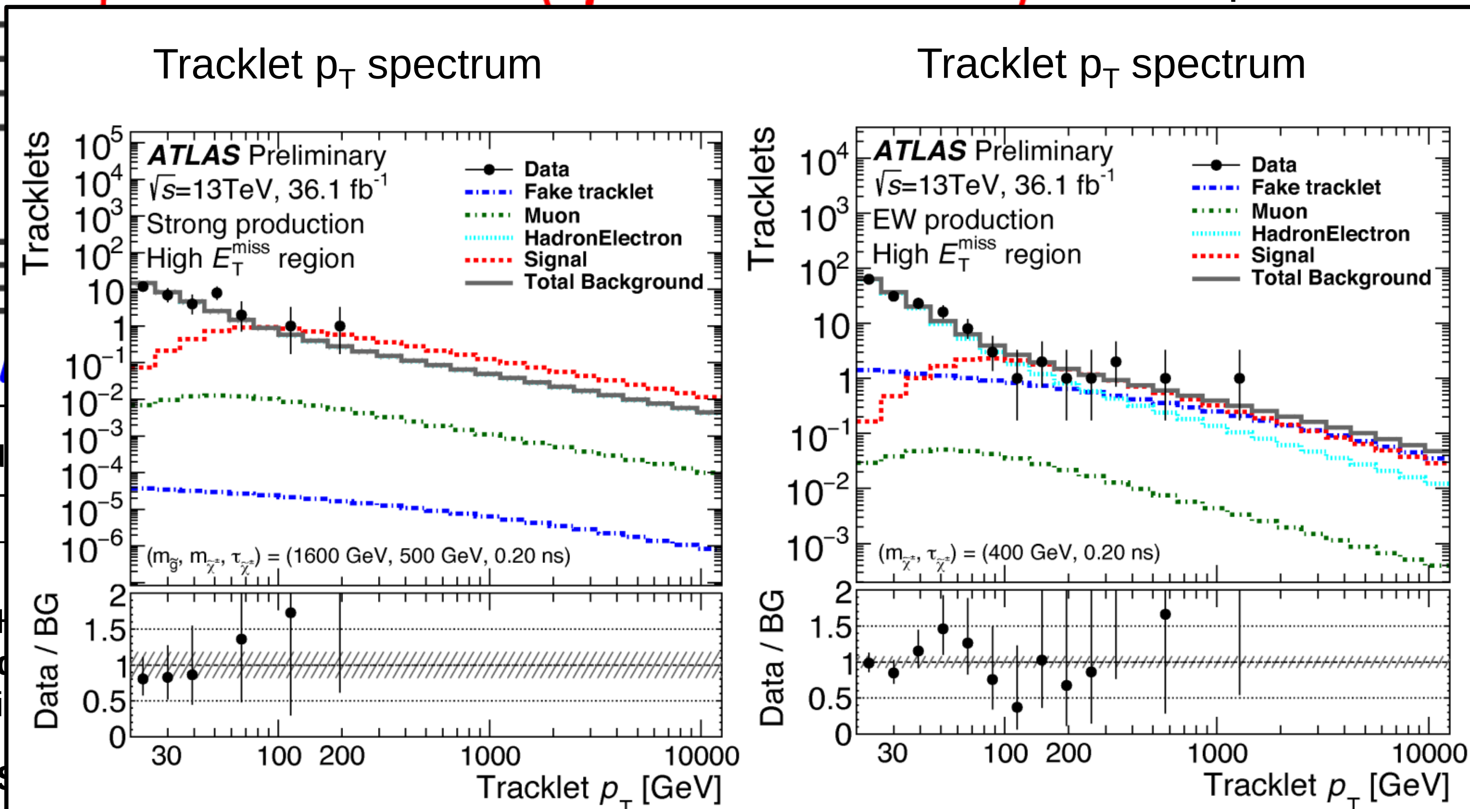
Simultaneous **fit of tracklet p_T** distribution using **templates** for the 3 backgrounds (+ signal)

- Hadron / lepton templates obtained from **data control samples** without material interaction
- **Smearing** with resolution function (from Z → μμ events) to match tracklet p_T spectrum

- Fake track template obtained from **data control region** with large d_0 significance + no $E_{T,miss}$ selection
- Extrapolation to large $E_{T,miss}$ checked

- Template from **MC smeared** with resolution function
- Smearing parameters from **muon data sample** corrected for muon / chargino differences in MC

Disappearing Track Search: Backgrounds



Simu

signal

→ pp events to match tracklet p_T spectrum

$E_{T,miss}$ selection

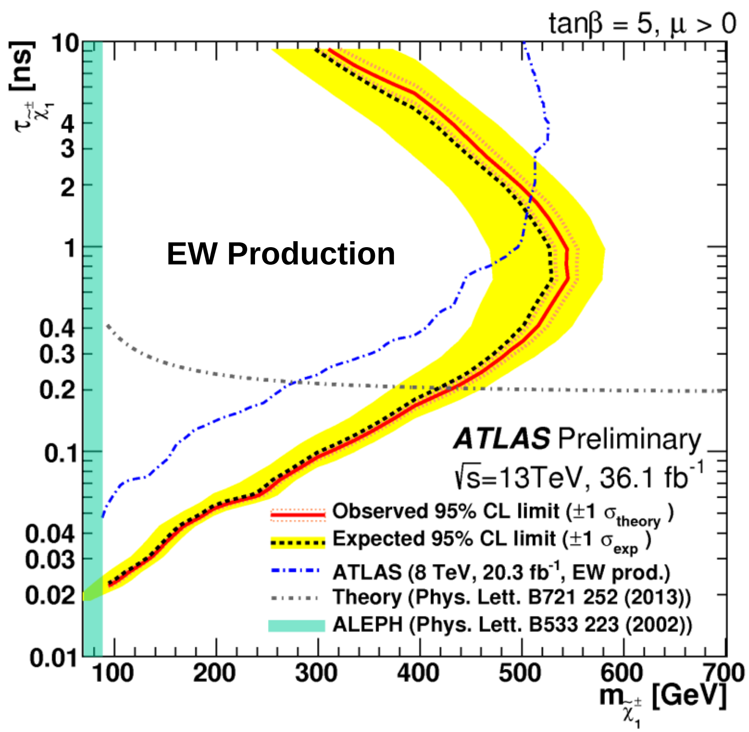
- Extrapolation to large $E_{T,miss}$ checked

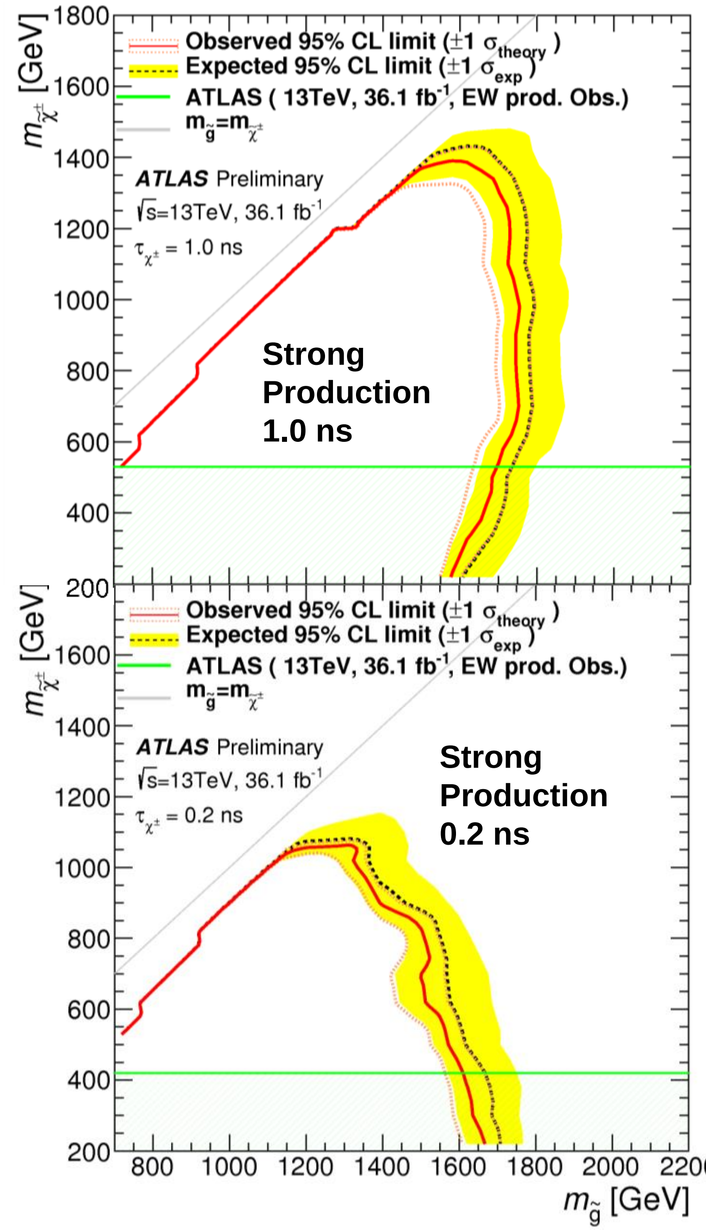
from **MC** with function

rs from **muon data sample** corrected for muon / chargino differences in MC

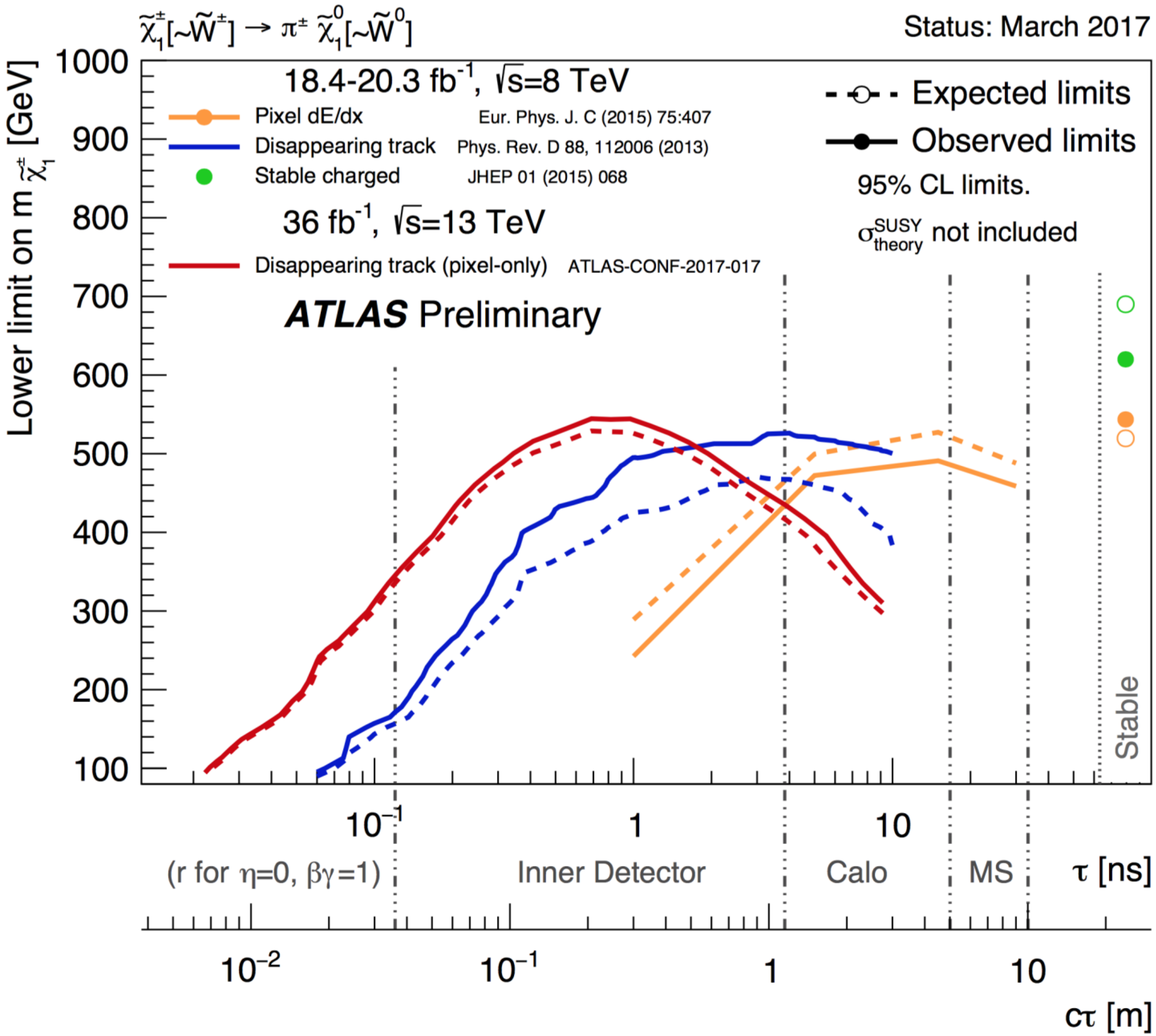
Disappearing Track Search: Results

- **No significant deviations** from the Standard Model expectation
- Limits set in EW and strong production channels:
  - **EW Production**: Significant improvement w.r.t. Run-1 at **lower lifetimes**
  - **Strong production**: Reaching to **1.4 (1.1) TeV in chargino** mass for lifetimes of 1.0 (0.2) ns



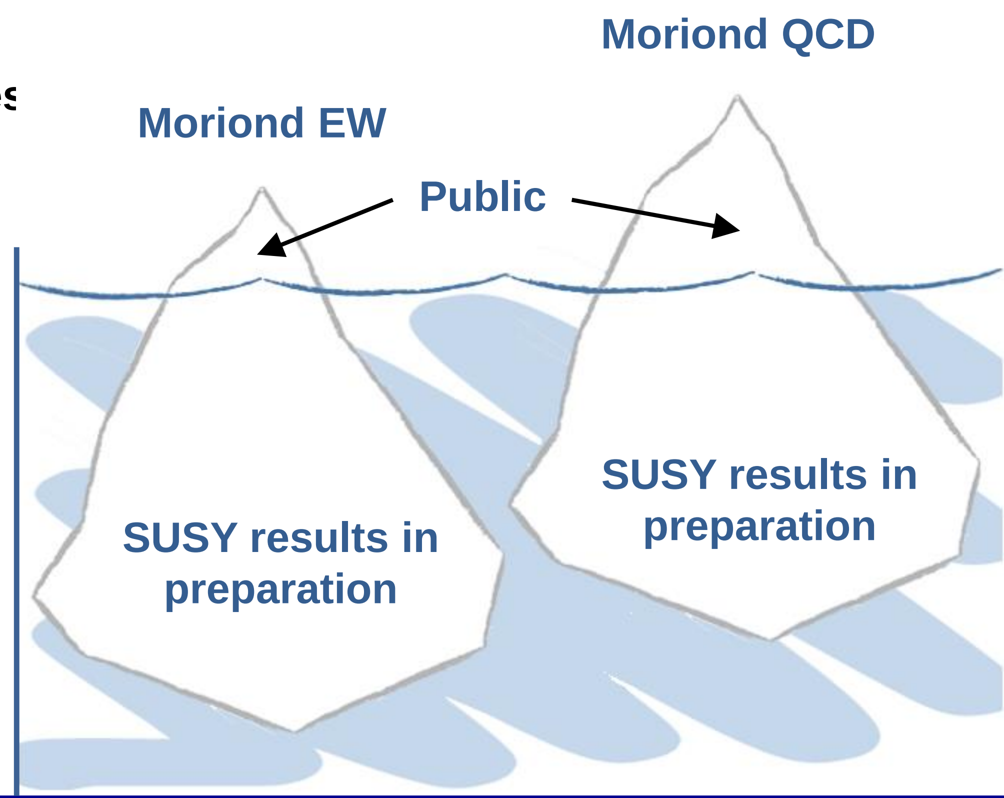


Putting it into context



Summary & Outlook

- Huge thanks to the LHC and injector teams for the **fantastic performance in 2016**
- ATLAS has produced 8 **new SUSY search results** using the full **2015 + 2016 dataset of up to 36.1 fb^{-1} at 13 TeV**:
  - 2 inclusive searches for **squarks and gluinos**
  - 2 searches for **3rd generation squarks**
  - 2 searches for **RPV SUSY**
  - 2 searches for **long-lived particles**
- **No significant deviations** from SM
- **Significant boost in sensitivity** excluding gluino masses in some scenarios beyond 2 TeV!
- Still only the **tip of the iceberg**
- Stay **fine-tuned** until further notice!



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