SUSY Hunting at $\sqrt{s} = 13$ TeV

LPNHE HEP Seminar

Maximilian Swiatlowski[1]

[1] *Enrico Fermi Institute, University of Chicago*

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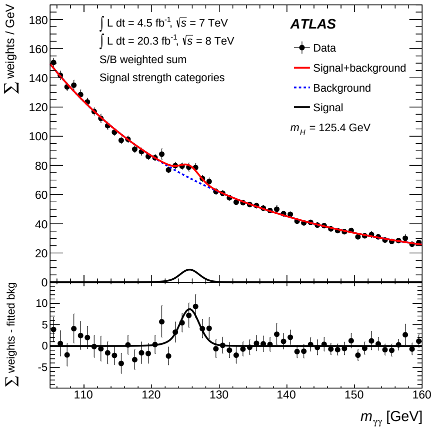
LHC Run 1 Legacy: The Higgs



What does the Higgs tell us about new physics around the corner?

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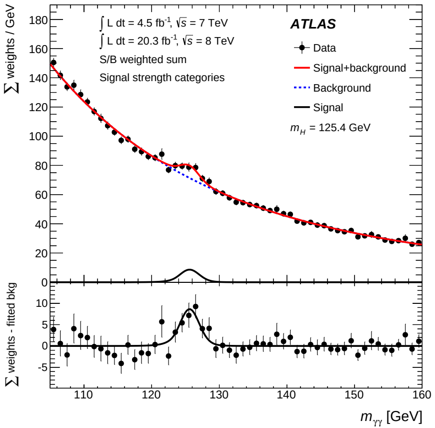

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Naturalness with SUSY

With the discovery of a 125 GeV Higgs, BSM physics is very well motivated!

Searches for (supersymmetric) top-partners are critical!

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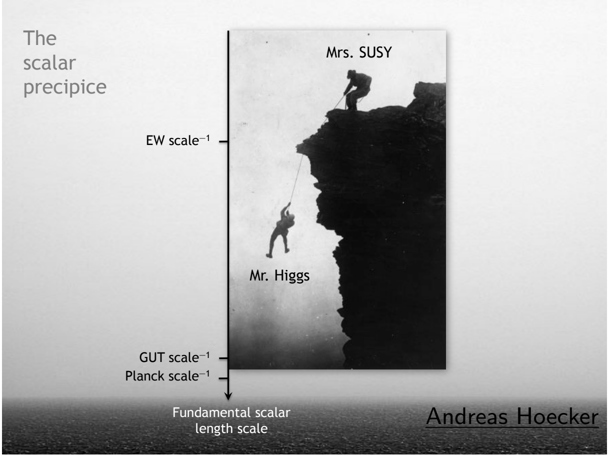

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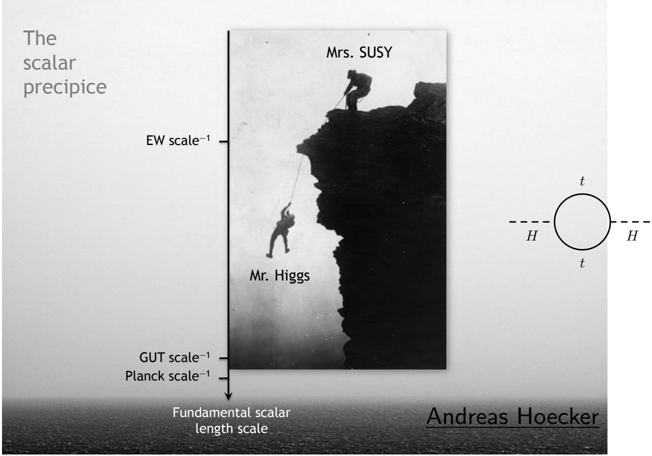

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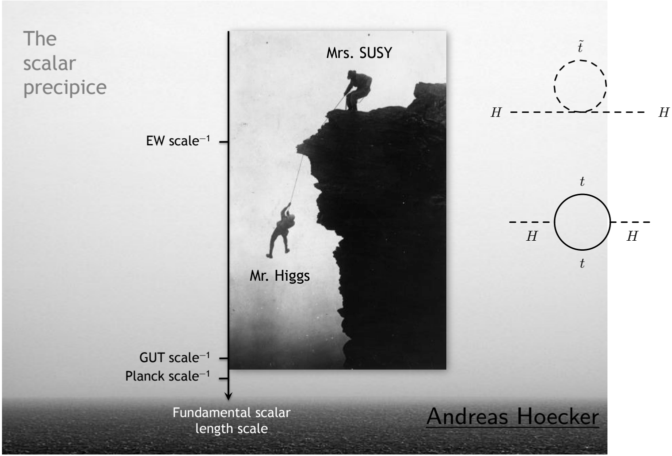

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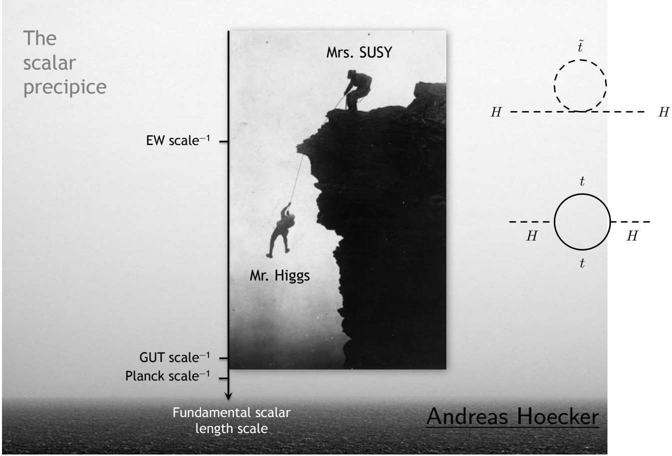

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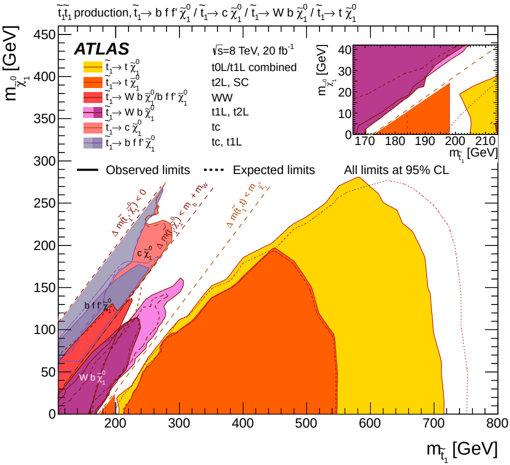
Natural SUSY: Direct Production

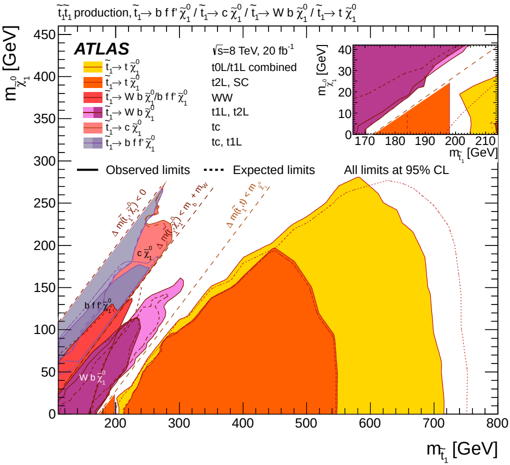


- Since the stop does the work of canceling top loops, stop production is a good place to look for natural SUSY
- Strong limits on direct production! But still lots of room for light stops

Where else can we search for signatures of naturalness?

How stable is Mrs. SUSY's footing?

Natural SUSY: Direct Production



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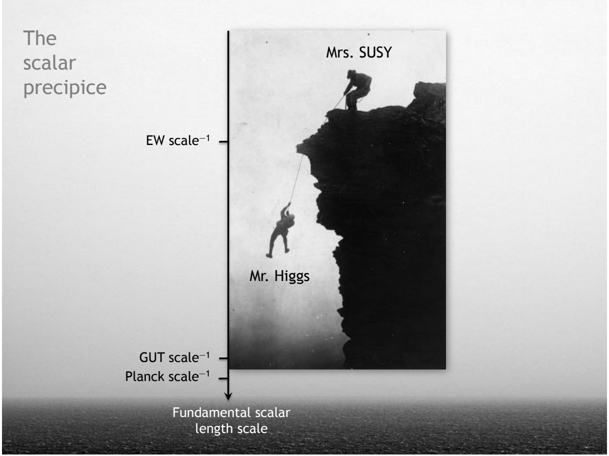
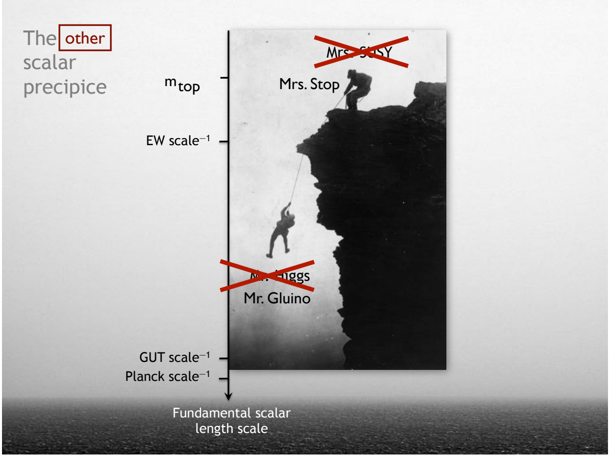
The Role of Gluinos



- Stop is a scalar: natural mass value of *stop itself* set by gluino mass
  - "Gluinos suck" (Savas)
- Naturalness implies a *light gluino* as well as light stops

The Role of Gluinos



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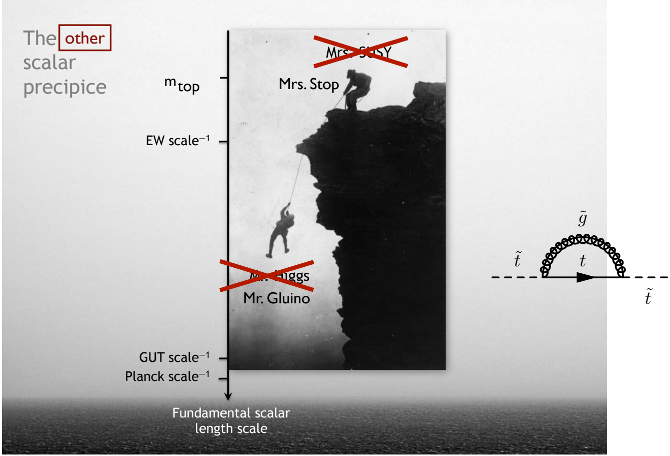

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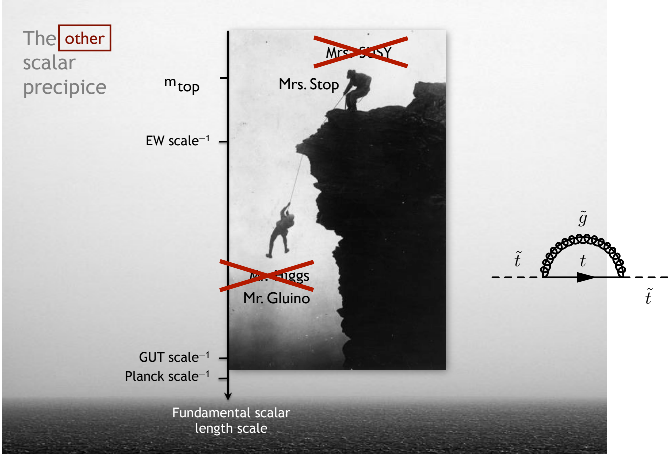

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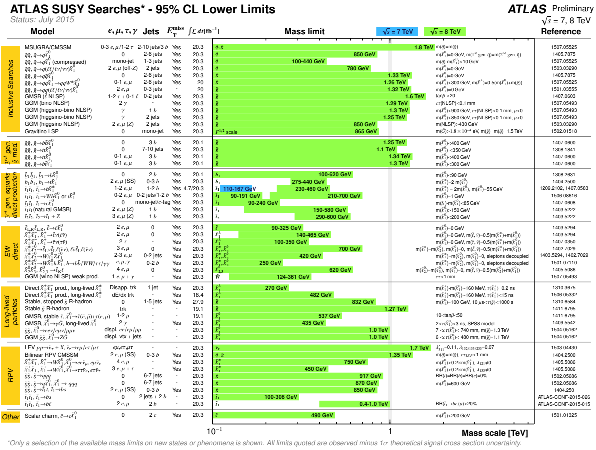
The Status of SUSY After $\sqrt{s} = 8$ TeV

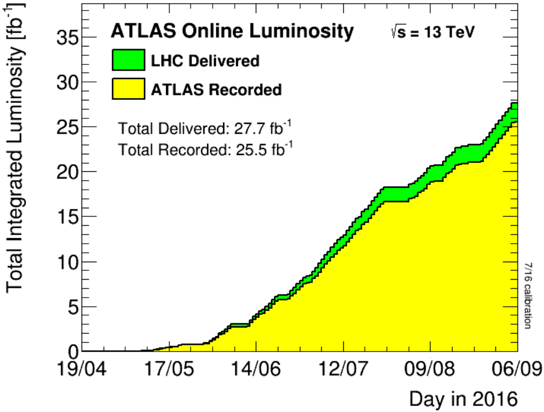


Strong limits already exist, but room yet for gluinos and stops!

And Now, $\sqrt{s} = 13$ TeV

Breaking its own energy records!

Luminosity

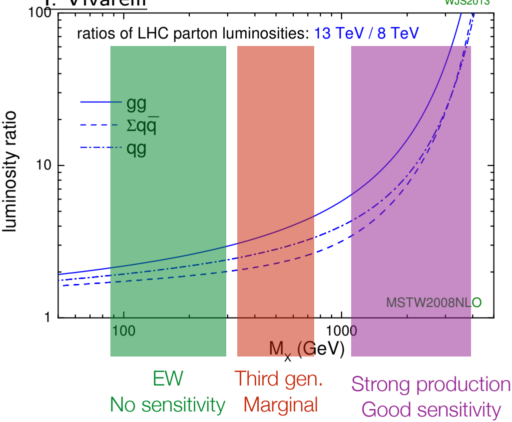


- Challenging start to LHC operations: simultaneous transition to higher $\sqrt{s}$ and smaller bunch spacing ($50 \rightarrow 25$ ns) was difficult!
- Large dataset delivered to experiments: 3.2 fb^{-1} usable by ATLAS

Where to Look First?

- New $\sqrt{s} = 13$ TeV data means exciting new prospects!
- Cross-section for higher-mass particles grows *dramatically*
  - Lighter particles, like third-gen squarks and electroweakinos, see a much smaller increase

I. Vivarelli



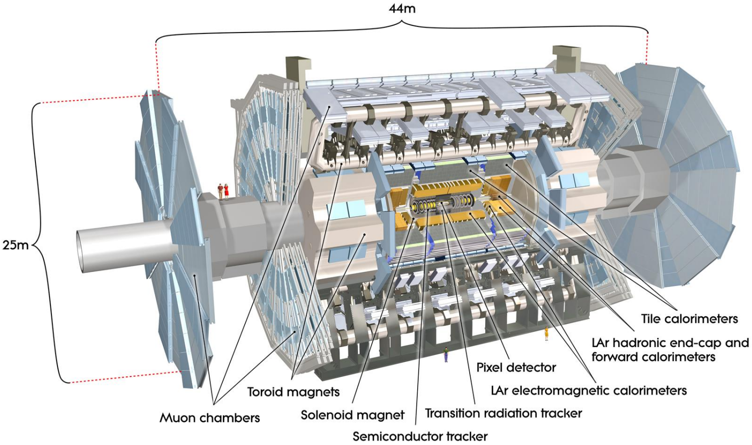
First SUSY analyses should cover the territory with the most potential gain: the most room for discovery!

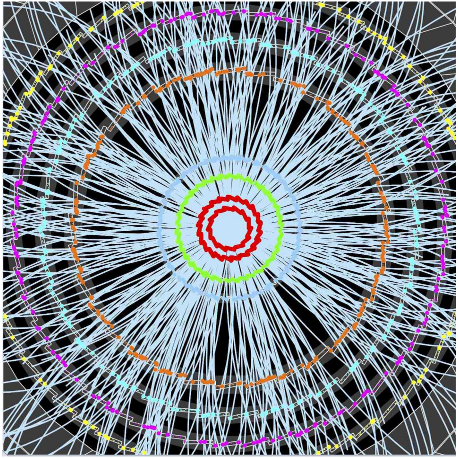
Outline

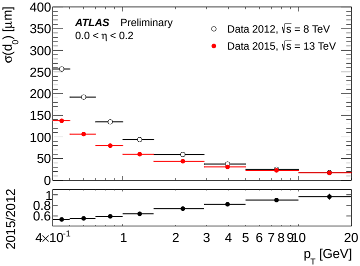
- ATLAS released 17 SUSY results for ICHEP: too many to cover in one seminar!
- Will try to cover just 3 of the most interesting (targeting gluino production) today:
  1. 0/1 lepton, ≥ 3 b-jets
  2. 0 lepton, 2-6 jets
  3. 0 lepton, RPV multijets
- Will (mostly) not discuss exact cuts, control region definitions, etc.
  - Instead, trying to give a broad overview of the strategy, techniques, and results
  - If you have more questions on a particular analysis, please do ask!

A Few Words on ATLAS

The ATLAS Detector



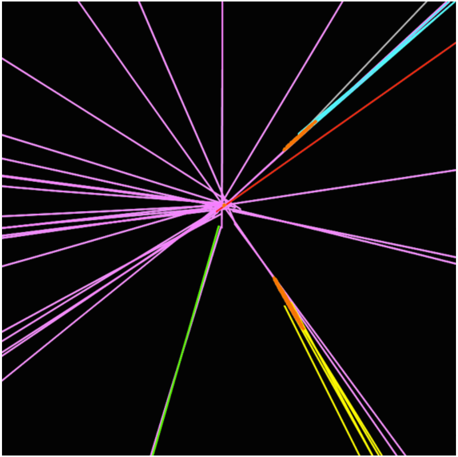


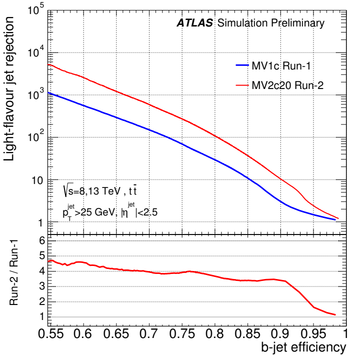


Huge improvement in track d_0 resolution!

- b-tagging and vertex identification benefit greatly from this upgrade

New to ATLAS: The Inner-B-Layer



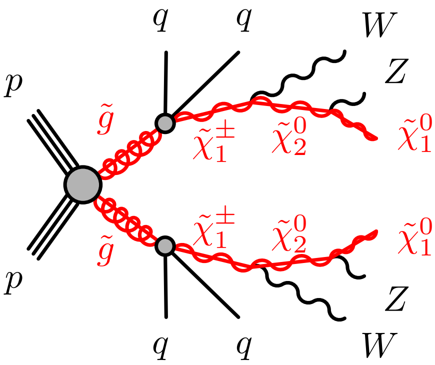


Factor of ≈ 4 gain in light jet rejection!

- *b*-tagging and vertex identification benefit greatly from this upgrade

General Analysis Strategies

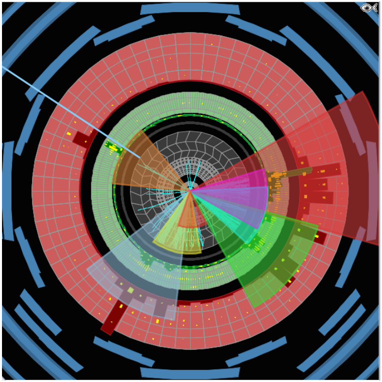
SUSY Signatures



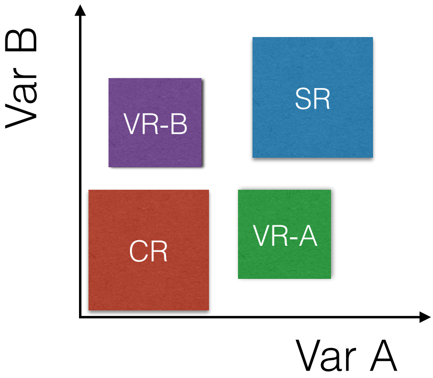
- Look for *pair-production* of gluinos
  - Highest cross-section particles, pair production guaranteed by *R*-parity
- Various forms of cascades decay gluino to SM particles and "LSP"
  - LSP is weakly interacting only: does not interact with detector
- SM particles like W, Z, t decay to leptons and quarks

General Note on Signal Regions

- Non-interacting LSPs give rise to dramatic *missing energy* signatures
  - Most powerful single handle: suppresses all forms of background!
- Many other effective handles shared by analyses– to name a few:
  1. H_T: sum of p_T of “analysis objects”
  2. m_{eff}: sum of E_T^{miss} and H_T
  3. $E_T^{miss}/\sqrt{H_T}$: $\sigma(E_T^{miss}) \approx \sqrt{H_T}$, so “significance” can improve power
  4. $m_T = \sqrt{2p_T^{\ell}(1 - \cos(\Delta\phi(E_T^{miss}, \ell)))}$: transverse mass of lepton and E_T^{miss}



General Note on Background Estimation

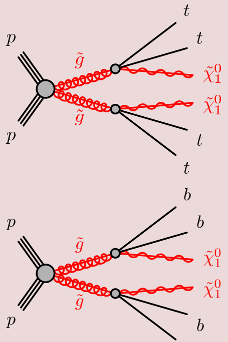


- Background estimates are usually done with a control region strategy:
  1. Invert cuts from SR to find background dominated region
  2. Derive normalization factor for background in this region
  3. Validate each inverted cut with validation region
- Each large background gets a control region: typically $t\bar{t}$, Z+jets, W+jets, etc.
- More sophisticated methods also used, but this is the most common approach

0/1L, 3-4 *b*-Jets

Multi-b: Overview

Targeted Processes



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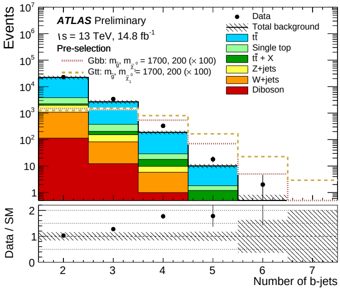
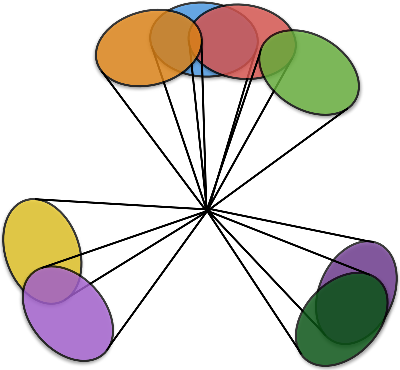
- Study two models: $\tilde{g}$ production, decaying through $\tilde{t}$ or $\tilde{b}$
- Final state targets 0/1 leptons, 4-8 jets, 3/4 b-tags, significant E_T^{miss}
- Use E_T^{miss}, m_{eff}, and $m_T^{b,min}$ as discriminating variables



Accidental Substructure



- High multiplicity leads to **significant "accidental" overlaps**

→ We can use **large jets** to capture these overlaps: jets have **mass**

- We can use this structure to search for new physics!

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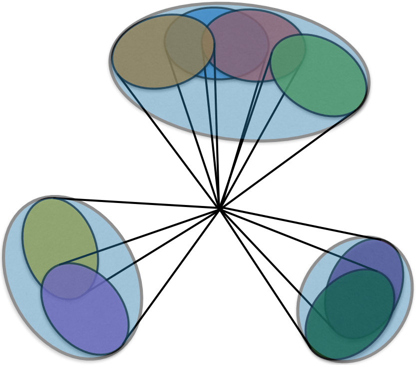

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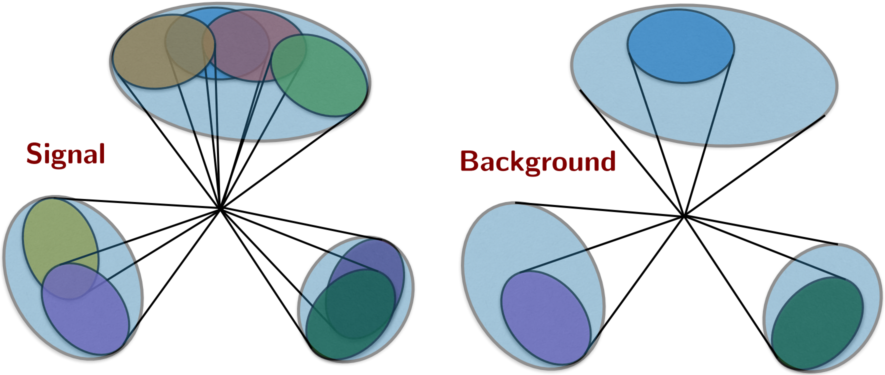

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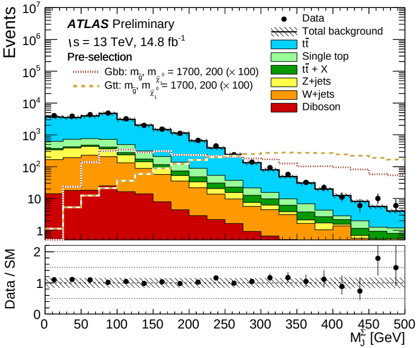
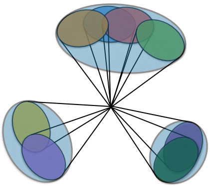
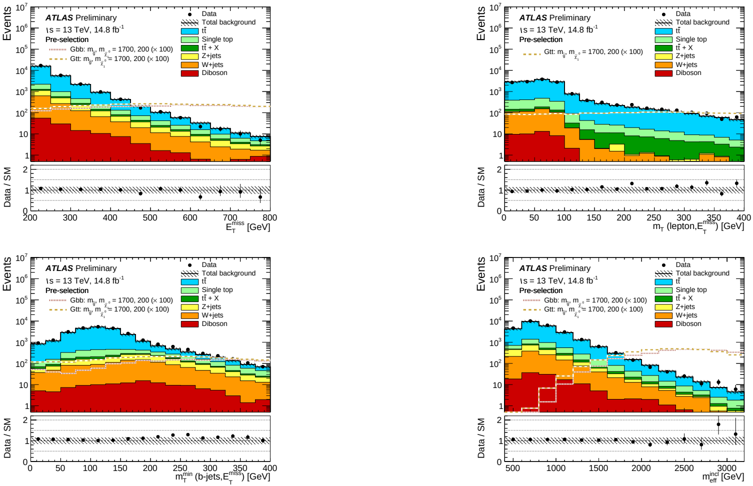
Total Jet Mass





- Identify large-R jets with *re-clustering* approach
  - Run a clustering algorithm on already-reconstructed jets, but with large size ($R = 0.8$)
  - Naturally groups jets close to each other
- Form M_J^{Σ} from sum of leading 4 large-R jet masses
  - In signal, many tops overlap, *add mass* to jets, though not necessarily forming clean ‘top jets’
  - Both 0L and 1L regions use this very effectively!

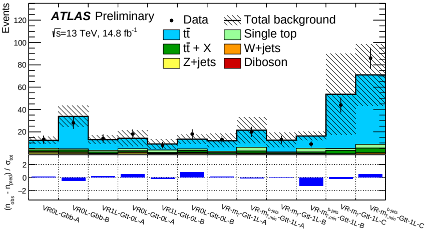
Other Handles



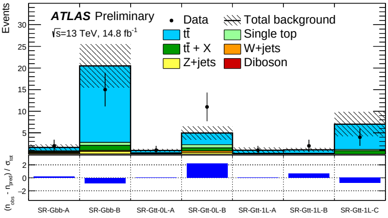
- Huge space of variables provide effective discrimination
  - Dramatic final state with 4 tops provides many handles!

Results

Validation Region Yields

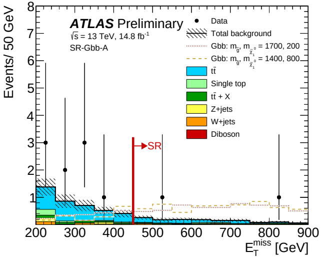


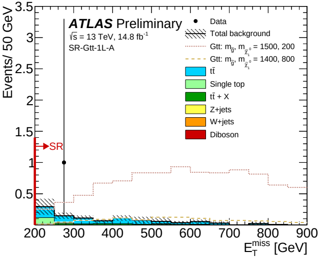
Signal Region Yields

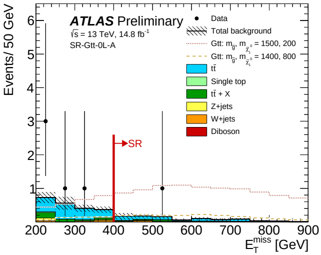


- Dominant background is $t\bar{t}$: normalized in data in 1L control regions
- Validation regions and signal region predictions both agree well with observation
  - Slight excess in one 0L signal region with moderate m_{eff}^{incl} and M_J^{Σ}

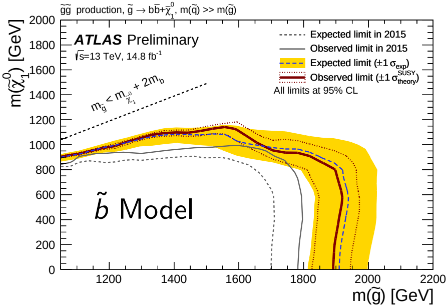
Results in Signal Regions

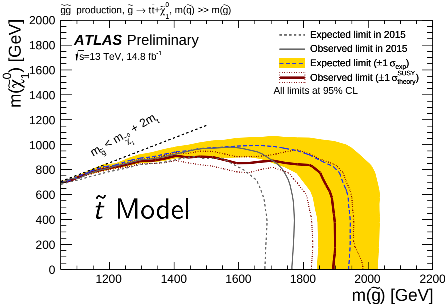






- Examples of $\tilde{b}$ and 0/1L $\tilde{t}$ regions here
- No signs of significant excesses over SM expectation



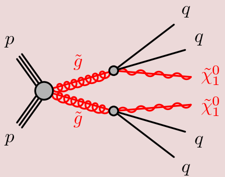


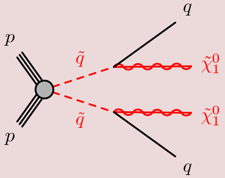
- Limits expand significantly earlier Run 2 sensitivity
- Statistical combination of 0L and 1L analyses provies $\approx$ 100 GeV gain in $\tilde{t}$ models
    - All signal/control/validation regions designed to be independent to allow for straightforward combination

0L, 2-6 Jets

0L, 2-6 Jets: Overview

Targeted Processes





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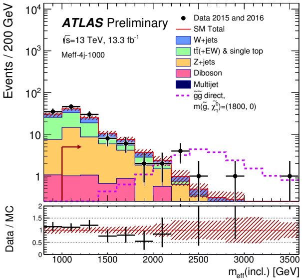
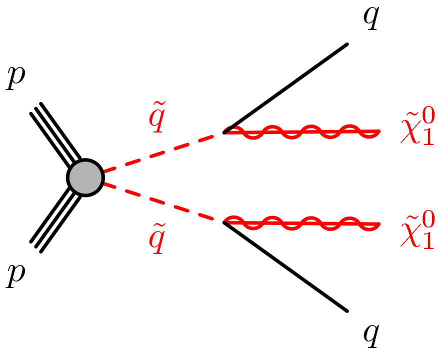
- Final state targets 0 leptons, 2-6 jets, significant E_T^{miss}
- Study both direct $\tilde{q}$ and $\tilde{g}$ production
  - → Seven signal regions target various production and phase space possibilities
- Standard analyses uses $m_{eff} = \sum p_T^{jets} + E_T^{miss}$ as main discriminant

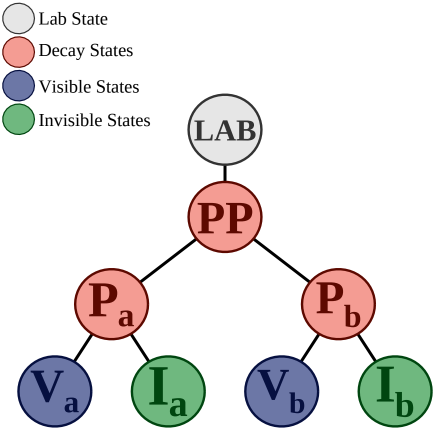


An Aside: What Makes SUSY Searches Difficult?



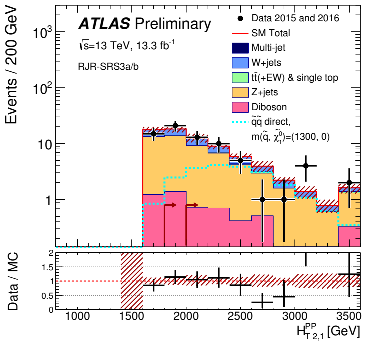
- SUSY searches with weakly interacting LSP's *cannot be fully reconstructed*
- The power of analyses is therefore always limited
  - $\rightarrow$ Can search for excesses in E_T^{miss}, but cannot reconstruct sparticles
- In the system above, no way to reconstruct $m_{\tilde{q}}$: $\tilde{\chi}_1^0$ are not measured

One Solution: "Recursive Jigsaws"

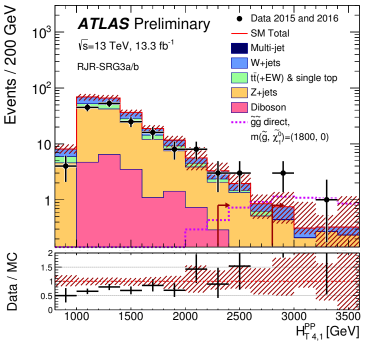


- If we impose a particular decay hypothesis, some headway can be made!
- The *recursive jigsaw* algorithm attempts to fully reconstruct the event by making *simple assumptions* about the decay topology:
  1. Form groups of "visible" objects (jets) by *minimizing masses of the groups*
  2. Divide E_T^{miss}, and assign longitudinal boost and masses to "invisible" objects, by *minimizing masses of intermediate states*

- $H^{F}_{n,m}$: sum of all momenta where F is frame choice, n is number of visible groups, m is number of invisible groups

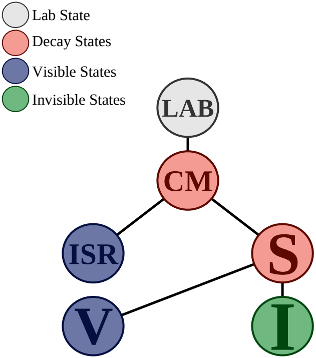


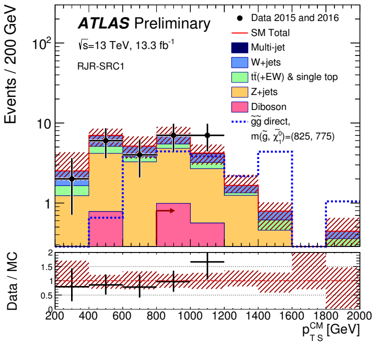
$H^{PP}_{2,1}$: sparticle frame, with two visible groups and 1 invisible: H_T like variable constructed for squarks



$H^{PP}_{4,1}$: sparticle frame, with four visible groups and 1 invisible: H_T like variable constructed for gluino decays

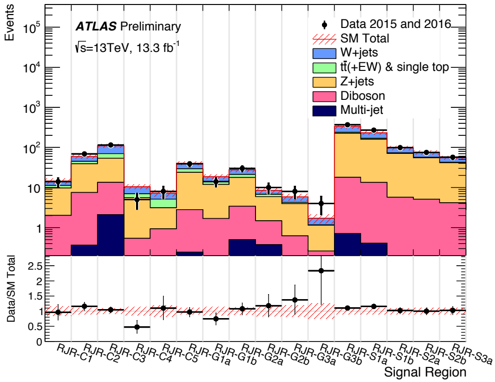
ISR Observables





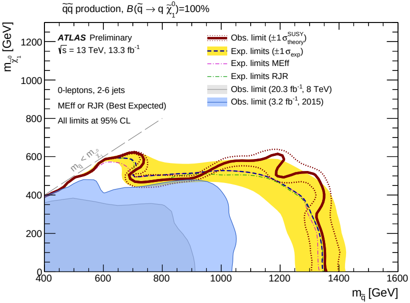
- Can use an alternate decay tree to identify ISR candidates
- p_{TS}^{CM} is the p_T of the non-ISR system: strong discrimination in otherwise challenging compressed scenarios

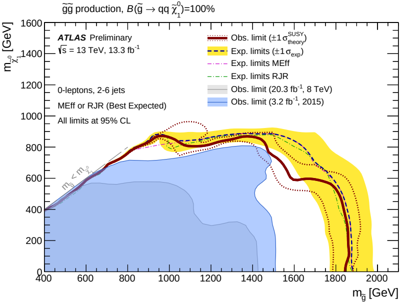
Signal Regions and Results



- Define signal regions targetting compressed scenarios, gluino models, and squark models
  - Magnitudes of cuts can change to cover full phase space
- Generally very good agreement with SM expectation: no strong hints of new physics

Limits

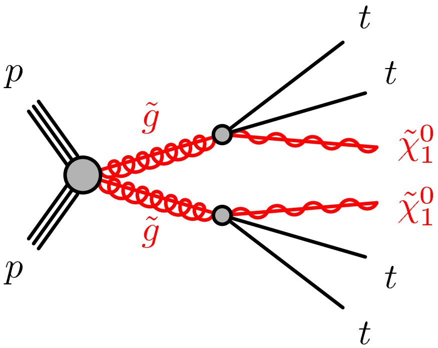




- Strong limits, with significant improvement over early run 2 results, set in both squark and gluino mass planes
- Jigsaw analysis outperforms standard m_{eff} approach in compressed and large mass-splitting scenarios

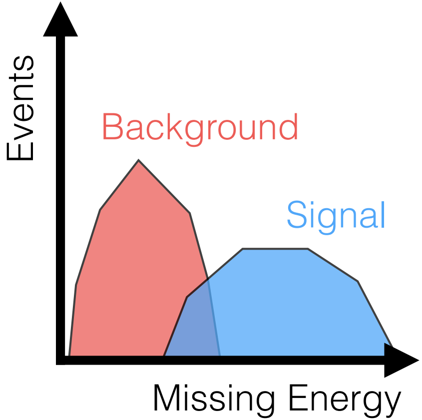
RPV Multijets

SUSY Signatures



- The key to all the searches discussed so far is **missing energy**
  - These models assume R-parity, which means the Lightest Supersymmetric Particle ($\tilde{\chi}_1^0$) **is stable**
  - This neutralino **does not interact**: escapes detection, appears as E_T^{miss}
- But what if the LSP decays? Existing searches will not work!

SUSY Signatures



- The key to all the searches discussed so far is **missing energy**
  - These models assume *R*-parity, which means the Lightest Supersymmetric Particle ($\tilde{\chi}_1^0$) **is stable**
  - This neutralino **does not interact**: escapes detection, appears as E_T^{miss}
- But what if the LSP decays? Existing searches will not work!

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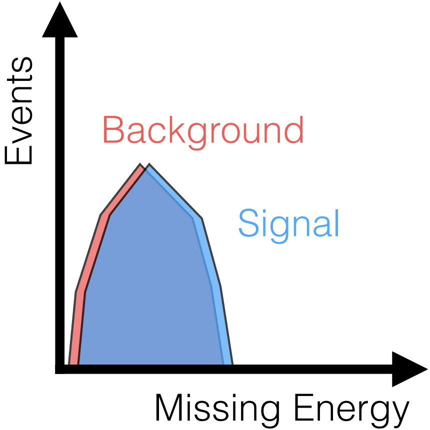

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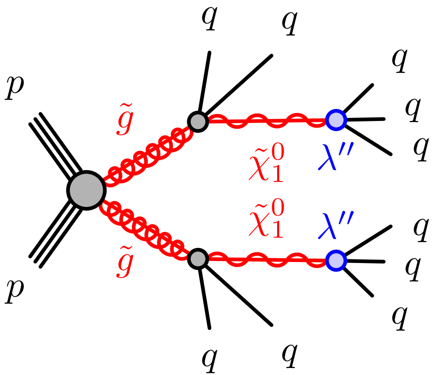
High Multiplicity RPV Signatures

- Consider $\tilde{g}$ pair production, decaying with $\tilde{g} \to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to 3q$: R-parity violating!



- Final state has huge number of quarks!
  - Between **10** (light quarks only) and **22** (top decays) partons
  - **Extremely difficult background estimation:** high-mass extremes of QCD are difficult to model
  - No source of E_T^{miss}: **need other discrimination handles**

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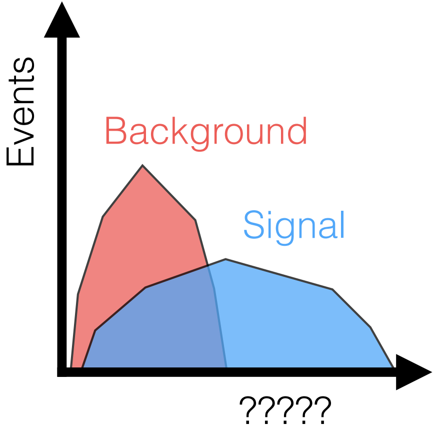

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  - Between **10** (light quarks only) and **22** (top decays) partons
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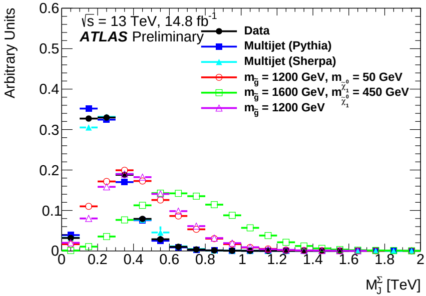
  - No source of E_T^{miss}: **need other discrimination handles**

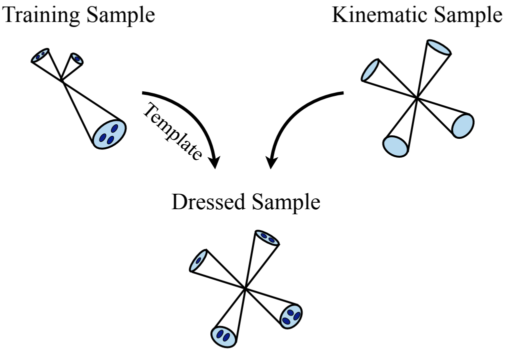
Total Jet Mass

- As used in the multi-B analysis and previous 8 TeV analyses, M_J^Σ can come to the rescue
- **Mass** comes when combining **widely spaced** particles
  - $\rightarrow$ Jets with substructure have **high mass**!
  - No individual jet corresponds to $\tilde{\chi}_0^1$ or $\tilde{g}$
- Many different signals look very different from **background**



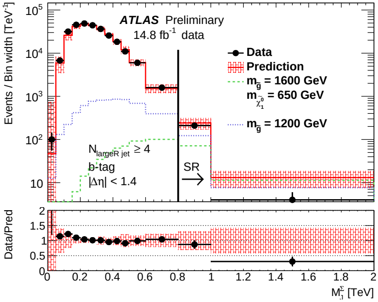
NB: use *trimmed* $R = 1.0$ jets with $p_T > 100$ GeV, $|\eta| < 2.5$

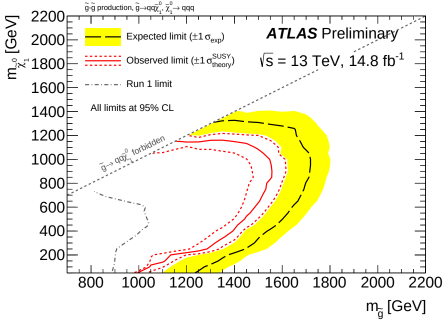
Background Estimation Strategy



- Use 3-jet region to build *jet mass templates*: $m(p_T, \eta)$
- Use kinematics of events from 4/5-jet region to build background
  - Even if signal is present, p_T distributions are very similar, but mass distributions would be very different

Results and Limits





- Several regions also require the presence of a *b*-tagged jet to increase sensitivity to heavy flavor
- No significant signal observed (1.5σ excess)
- Significant improvement over Run 1 analysis!

Conclusions

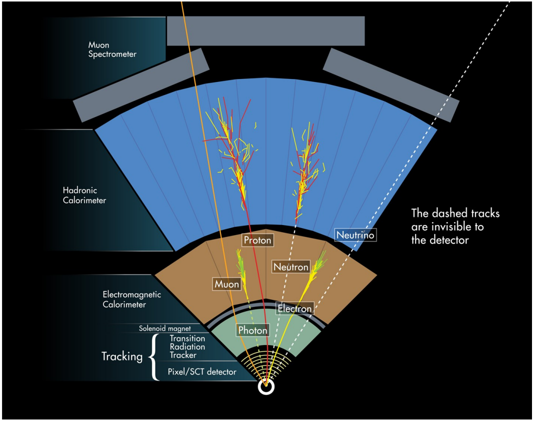
Conclusions

- Substantial amounts of $\sqrt{s} = 13$ TeV data are here, but SUSY is not (yet!)
- First searches optimized for discovery have not yet observed any significant deviation from the SM
- Run 2 has just begun, though: full 2016 dataset promises $\approx$3x the data, and even more coming in 2017!
  - $\tilde{g}$ sensitivity will likely extend to 2 TeV and beyond
- Many other signatures are being explored as well: direct stop, electroweak production,
  - SUSY is still hiding: which corner is it behind?

Thank you for your attention!

Backup

Raw detector measurements are reconstructed to particles or analysis objects



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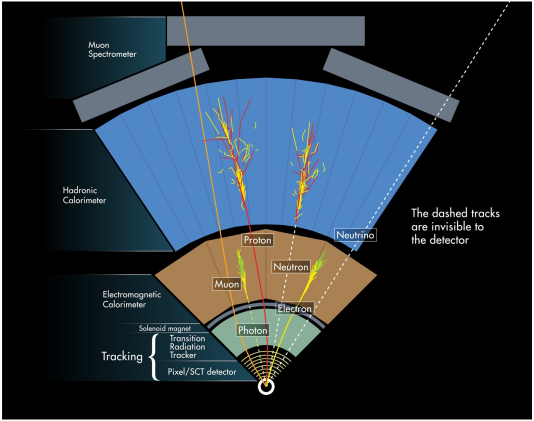
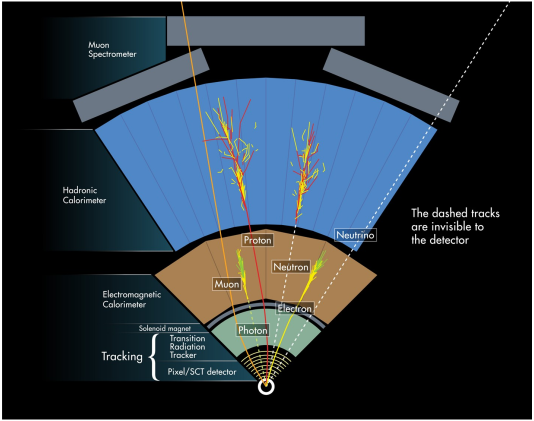


Electrons: inner detector track matched to EM calo deposit

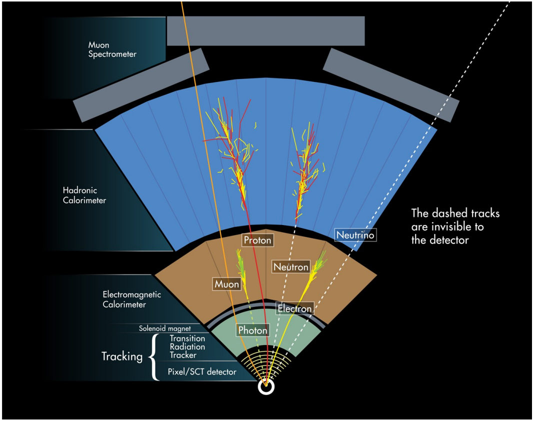
Doing Analysis

Raw detector measurements are reconstructed to particles or analysis objects



Muon: inner detector track matched to track in muon-spectrometer

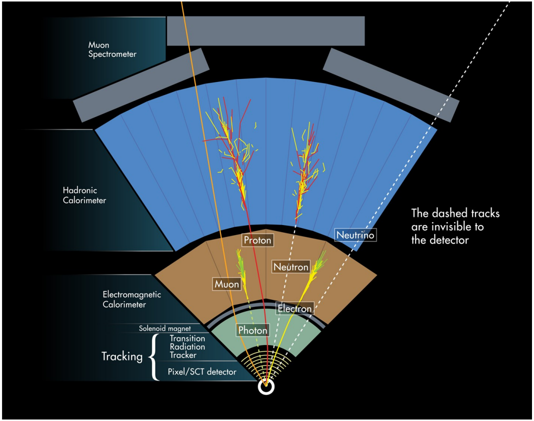
Raw detector measurements are reconstructed to particles or analysis objects



Photon: isolated EM calo deposit

Doing Analysis

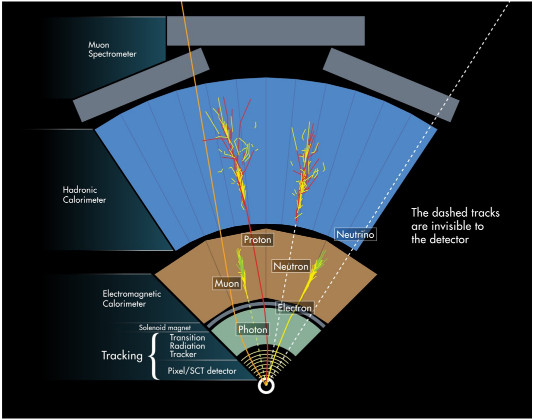
Raw detector measurements are reconstructed to particles or analysis objects



Jet: Collimated spray of protons, neutrons, and more

Doing Analysis

Raw detector measurements are reconstructed to particles or analysis objects



E_T^{miss}: Inferred missing energy, measured from energy misbalance

Unusual Variable Definitions

- $m_T = \sqrt{2p_T^\ell(1 - \cos(\Delta\phi(E_T^{miss}, \ell)))}$
  - Used in many single-lepton analyses
- $m_{CT} = [E_T(b_1) + E_T(b_2]^2 - [p_T(b_1) + p_T(b_2)]^2$
  - Used in direct $\tilde{b}$ analysis: kinematic endpoint on background
- $m_T^{b,min} = min_{i\leq 3}\left(\sqrt{2p_T^b(1 - \cos(\Delta\phi(E_T^{miss}, b)))}\right)$
  - Used in Gtt analyses: endpoint on background

0L, 2-6 Jets: RJR SR Definitions

Targeted signal	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$					
Requirement	Signal Region					
	RJR-S1		**RJR-S2**		**RJR-S3**	
$H_{1,1}^{\mathrm{PP}}/H_{2,1}^{\mathrm{PP}}\geq$	0.6		0.55		0.5	
$H_{1,1}^{\mathrm{PP}}/H_{2,1}^{\mathrm{PP}}\leq$	0.95		0.96		0.98	
$p_{\mathrm{PP,\ z}}^{\mathrm{lab}}/\left(p_{\mathrm{PP,\ z}}^{\mathrm{lab}}+H_{\mathrm{T\ 2,1}}^{\mathrm{PP}}\right)\leq$	0.5		0.55		0.6	
$p_{\mathrm{j2,\ T}}^{\mathrm{PP}}/H_{\mathrm{T\ 2,1}}^{\mathrm{PP}}\geq$	0.16		0.15		0.13	
$\Delta_{\mathrm{QCD}}>$	0.001					
	RJR-S1a	**RJR-S1b**	**RJR-S2a**	**RJR-S2b**	**RJR-S3a**	**RJR-S3b**
$H_{\mathrm{T\ 2,1}}^{\mathrm{PP}}$ [GeV] $>$	1000	1200	1400	1600	1800	2000
$H_{1,1}^{\mathrm{PP}}$ [GeV] $>$	1000		1400		1600	

Targeted signal	$\tilde{g}\tilde{g},\ \tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$					
Requirement	Signal Region					
	RJR-G1		**RJR-G2**		**RJR-G3**	
$H_{1,1}^{\mathrm{PP}}/H_{4,1}^{\mathrm{PP}}\geq$	0.35		0.25		0.2	
$H_{\mathrm{T\ 4,1}}^{\mathrm{PP}}/H_{4,1}^{\mathrm{PP}}\geq$	0.8		0.75		0.65	
$p_{\mathrm{PP,\ z}}^{\mathrm{lab}}/\left(p_{\mathrm{PP,\ z}}^{\mathrm{lab}}+H_{\mathrm{T\ 4,1}}^{\mathrm{PP}}\right)\leq$	0.5		0.55		0.6	
$\min\left(p_{\mathrm{j2\ T\ i}}^{\mathrm{PP}}/H_{\mathrm{T\ 2,1\ i}}^{\mathrm{PP}}\right)\geq$	0.12		0.1		0.08	
$\max\left(H_{1,\ 0}^{\mathrm{Pi}}/H_{2,\ 0}^{\mathrm{Pi}}\right)\leq$	0.95		0.97		0.98	
$\lvert\frac{2}{3}\Delta\phi_{\mathrm{V,P}}^{\mathrm{PP}}-\frac{1}{3}\cos\theta_{\mathrm{P}}\rvert\leq$	0.5		–			
$\Delta_{\mathrm{QCD}}>$	0					
	RJR-G1a	**RJR-G1b**	**RJR-G2a**	**RJR-G2b**	**RJR-G3a**	**RJR-G3b**
$H_{\mathrm{T\ 4,1}}^{\mathrm{PP}}$ [GeV] $>$	1000	1200	1500	1900	2300	2800
$H_{1,1}^{\mathrm{PP}}$ [GeV] $>$	600		800		900	

Targeted signal	compressed spectra in $\tilde{q}\tilde{q}$ ($\tilde{q}\rightarrow q\tilde{\chi}_1^0$); $\tilde{g}\tilde{g}$ ($\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$)				
Requirement	Signal Region				
	RJR-C1	**RJR-C2**	**RJR-C3**	**RJR-C4**	**RJR-C5**
$R_{\mathrm{ISR}}\geq$	0.9	0.85	0.8	0.75	0.70
$\Delta\phi_{\mathrm{ISR,\ I}}\geq$	3.1	3.07	2.95	2.95	2.95
$\Delta\phi(\mathrm{jet}_{1,2},\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}>$	-	-	-	0.4	0.4
M_{TS} [GeV] $\geq$	100	100	200	500	500
$p_{\mathrm{TS}}^{\mathrm{CM}}$ [GeV] $\geq$	800	800	600	600	600
$N_{\mathrm{jet}}^{\mathrm{V}}\geq$	1	1	2	2	3

0L, 2-6 Jets: m_{eff} SR Definitions

Targeted signal	$\tilde{q}\tilde{q}$, $\tilde{q} \rightarrow q\tilde{\chi}_1^0$				
Requirement	Signal Region				
	Meff-2j-800	**Meff-2j-1200**	**Meff-2j-1600**	**Meff-2j-2000**	**Meff-3j-1200**
E_T^{miss} [GeV] $>$	250				
$p_T(j_1)$ [GeV] $>$	200	250			600
$p_T(j_2)$ [GeV] $>$	200	250			50
$p_T(j_3)$ [GeV] $>$	–				50
$\lvert\eta(j_{1,2})\rvert <$	0.8	1.2			–
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_T^{miss})_{min} >$	0.8				0.4
$\Delta\phi(\text{jet}_{i>3}, \boldsymbol{E}_T^{miss})_{min} >$	0.4				0.2
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] $>$	14	16	18	20	16
m_{eff}(incl.) [GeV] $>$	800	1200	1600	2000	1200

Targeted signal	$\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$					
Requirement	Signal Region					
	Meff-4j-1000	**Meff-4j-1400**	**Meff-4j-1800**	**Meff-4j-2200**	**Meff-4j-2600**	**Meff-5j-1400**
E_T^{miss} [GeV] $>$	250					
$p_T(j_1)$ [GeV] $>$	200					500
$p_T(j_4)$ [GeV] $>$	100			150		50
$p_T(j_5)$ [GeV] $>$	–					50
$\lvert\eta(j_{1,2,3,4})\rvert <$	1.2	2.0			–	
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_T^{miss})_{min} >$	0.4					
$\Delta\phi(\text{jet}_{i>3}, \boldsymbol{E}_T^{miss})_{min} >$	0.4					0.2
Aplanarity $>$	0.04					–
$E_T^{miss}/m_{eff}(N_j) >$	0.25		0.2			0.3
m_{eff}(incl.) [GeV] $>$	1000	1400	1800	2200	2600	1400

Targeted signal	$\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	
Requirement	Signal Region	
	Meff-6j-1800	**Meff-6j-2200**
E_T^{miss} [GeV] $>$	250	
$p_T(j_1)$ [GeV] $>$	200	
$p_T(j_6)$ [GeV] $>$	50	100
$\lvert\eta(j_{1,\ldots,6})\rvert <$	2.0	–
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_T^{miss})_{min} >$	0.4	
$\Delta\phi(\text{jet}_{i>3}, \boldsymbol{E}_T^{miss})_{min} >$	0.2	
Aplanarity $>$	0.08	
$E_T^{miss}/m_{eff}(N_j) >$	0.2	0.15
m_{eff}(incl.) [GeV] $>$	1800	2200

Multi-b: 0L $\tilde{t}$ SR Definitions

Criteria common to all Gtt 0-lepton regions: ${p_{\mathrm{T}}}^{\mathrm{jet}} > 30$ GeV, $N_{b\text{-jets}} \geq 3$					
	Variable	Signal region	Control region	VR1L	VR0L
Criteria common to all regions of the same type	$N^{\mathrm{Signal\ Lepton}}$	$= 0$	$= 1$	$= 1$	$= 0$
	$\Delta\phi^{4j}_{\mathrm{min}}$	> 0.4	–	–	> 0.4
	$m^{b\text{-jets}}_{\mathrm{T,min}}$	> 80	–	> 80	> 80
	m_{T}	–	< 150	< 150	–
Region A (Large mass splitting)	N^{jet}	≥ 8	≥ 7	≥ 7	≥ 6
	$E_{\mathrm{T}}^{\mathrm{miss}}$	> 400	> 250	> 200	> 300
	$m_{\mathrm{eff}}^{\mathrm{incl}}$	> 2000	> 1750	> 1750	> 1300
	M_J^{Σ}	> 200	> 200	> 200	< 200
Region B (Small mass splitting)	N^{jet}	≥ 8	≥ 7	≥ 7	≥ 7
	$E_{\mathrm{T}}^{\mathrm{miss}}$	> 400	> 400	> 325	$\in (300, 400)$
	$m_{\mathrm{eff}}^{\mathrm{incl}}$	> 1250	> 1250	> 1250	> 1200

Multi-b: 1L $\tilde{t}$ SR Definitions

Criteria common to all Gtt 1-lepton regions: ≥ 1 signal lepton, $p_T{}^{jet} > 30$ GeV					
	Variable	Signal region	Control region	VR-m_T	VR-$m_{T,min}^{b\text{-jets}}$
Region A (Large mass splitting)	N^{jet}	≥ 6	$= 6$	≥ 5	≥ 6
	$N_{b\text{-jets}}$	≥ 3	≥ 3	≥ 3	≥ 3
	m_T	> 200	< 200	> 200	< 200
	$m_{T,min}^{b\text{-jets}}$	> 120	–	–	> 120
	E_T^{miss}	> 200	> 200	> 200	> 200
	m_{eff}^{incl}	> 2000	> 1500	> 1350	> 1500
	M_J^{Σ}	> 200	> 200	< 200	> 200
Region B (Moderate mass splitting)	N^{jet}	≥ 6	$= 6$	≥ 5	≥ 6
	$N_{b\text{-jets}}$	≥ 3	≥ 3	≥ 3	≥ 3
	m_T	> 200	< 200	> 200	< 200
	$m_{T,min}^{b\text{-jets}}$	> 120	–	–	> 120
	E_T^{miss}	> 350	> 300	> 250	> 300
	m_{eff}^{incl}	> 1500	> 1250	> 1100	> 1500
	M_J^{Σ}	> 150	> 150	< 150	> 150
Region C (Small mass splitting)	N^{jet}	≥ 6	$= 6$	≥ 6	≥ 6
	$N_{b\text{-jets}}$	≥ 4	≥ 4	≥ 3	≥ 4
	m_T	> 150	< 150	> 150	< 150
	$m_{T,min}^{b\text{-jets}}$	> 80	–	< 80	> 80
	E_T^{miss}	> 200	> 200	> 200	> 200
	m_{eff}^{incl}	> 500	> 500	> 500	> 500

Multi-b: $\tilde{b}$ SR Definitions

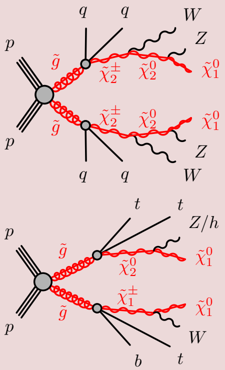
Criterion common to all Gbb regions: $N^{\text{jet}} \geq 4$				
	Variable	Signal region	Control region	Validation region
Criteria common to all regions of the same type	$N^{\text{Candidate Lepton}}$	$= 0$	–	$= 0$
	$N^{\text{Signal Lepton}}$	–	$= 1$	–
	$\Delta\phi^{4j}_{\text{min}}$	> 0.4	–	> 0.4
	m_{T}	–	< 150	–
Region A (Large mass splitting)	$p_{\text{T}}{}^{\text{jet}}$	> 70	> 70	> 70
	$N_{b\text{-jets}}$	≥ 3	≥ 3	≥ 3
	$E_{\text{T}}^{\text{miss}}$	> 450	> 350	> 450
	m_{eff}^{4j}	> 1900	> 1750	< 1900
Region B (Small mass splitting)	$p_{\text{T}}{}^{\text{jet}}$	> 30	> 30	> 30
	$N_{b\text{-jets}}$	≥ 4	≥ 4	≥ 4
	$E_{\text{T}}^{\text{miss}}$	> 300	> 300	> 275
	m_{eff}^{4j}	> 1000	> 1000	< 1000

RPV 0L: SR Definitions

n_{jet}	b-tag		b-veto	inclusive	
	$\|\Delta\eta_{12}\| > 1.4$	$\|\Delta\eta_{12}\| < 1.4$	-	$\|\Delta\eta_{12}\| > 1.4$	$\|\Delta\eta_{12}\| < 1.4$
$= 3$	3jCRb1_4j	-	3jCRb0_4j	3jCR_5j	
≥ 4	4jVRb1	4jSRb1	-	4jVR	4jSR
≥ 5	5jVRb1	5jSRb1	-	5jVR	5jSR

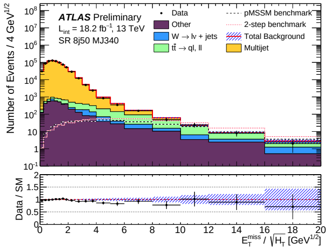
0L, 7-10 Jets

Targeted Processes

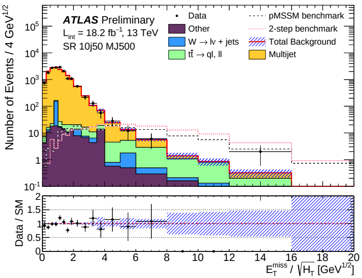


ATLAS-CONF-2015-077

- Final state targets 0 leptons, 7-10 jets, significant E_T^{miss}
- Multijet background estimated *from data*
- Study two step decay chain and pMSSM inspired model
  - 6 SR: $\geq$ 8, 9, 10 jets, with $M_J^{\Sigma} > 340, 500$
- Use $E_T^{miss}/\sqrt{H_T}$ as main discriminant: total jet mass provides additional power!



7-10 Jets: Multijet Estimation

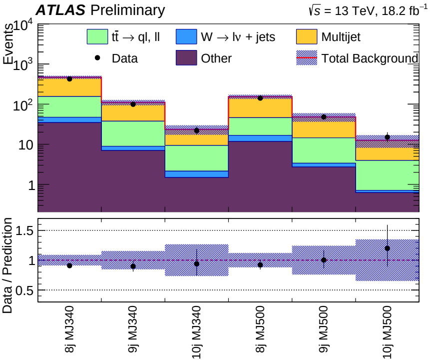


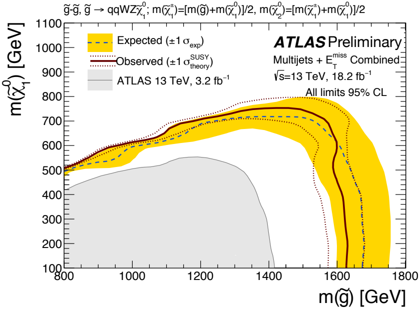
- Cannot trust MC modelling of complicated multijet background: instead use data-driven technique
- Source of E_T^{miss} from multijet events is *calorimeter mismeasurement*
  - Variance in calorimeter measurements is proportional to H_T: therefore $E_T^{miss}/\sqrt{H_T}$ distributions are approximiately invariant across jet multiplicity

→ Measure $E_T^{miss}/\sqrt{H_T}$ in low-multiplicity events: use as template in SR

→ Normalize template in $E_T^{miss}/\sqrt{H_T} < 1.5$ region: search in $E_T^{miss}/\sqrt{H_T} > 4$ region

7-10 Jets: Results



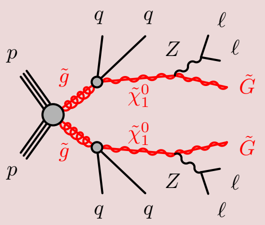


- Data agrees very well with SM prediction in all SR's
- Two step decays show significantly improved limits!

2L + Jets

2L-Z: Overview

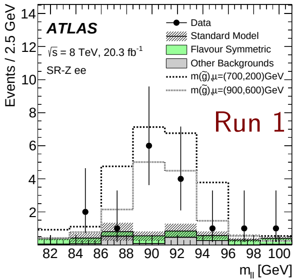
Targeted Processes



Run 1 analysis (arXiv:1503.03290) saw a 3.0σ excess, mostly in electron channel!

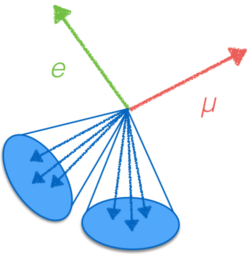
ATLAS-CONF-2015-082

- Final state has with on-shell Z (leptonic), jets, E_T^{miss}
  - Use SR identical to Run 1 analysis: confirm or deny the excess quickly!
- Require $E_T^{miss} > 225$ GeV, $H_T > 600$ GeV, $81 < m_{\ell\ell} < 101$, $\Delta\phi(jet_{12}, E_T^{miss}) > 0.4$

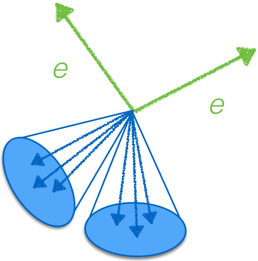


Run 1 Result

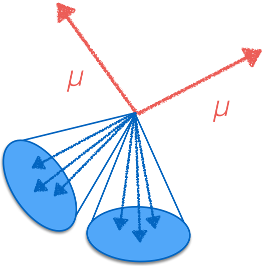
2L: Flavor Symmetric Backgrounds



Signal depleted



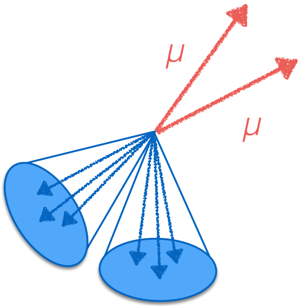
Signal region



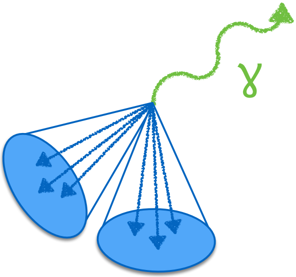
Signal region

- Backgrounds like $t\bar{t}$, Wt, WW are *flavor symmetric*: decay to $ee/\mu\mu/e\mu$ are all equally likely
- $e\mu$ sample has no real Z: can measure this with no signal contamination
- Double the rate (after adjusting for efficiency, reconstruction effects) to get background estimate in signal region!

2L: Z+jet Backgrounds



SR-like events

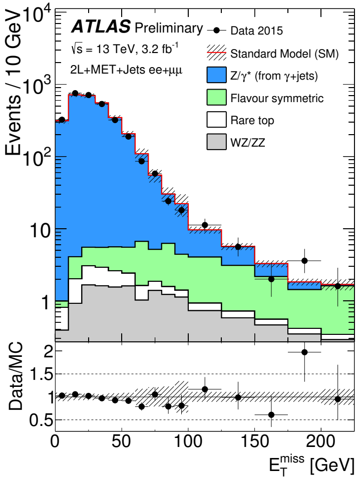


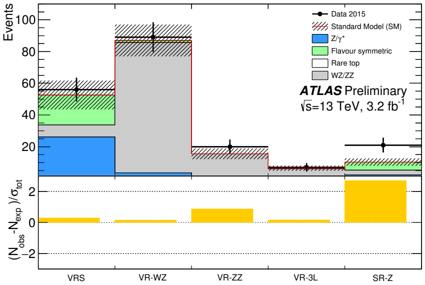
CR-like events

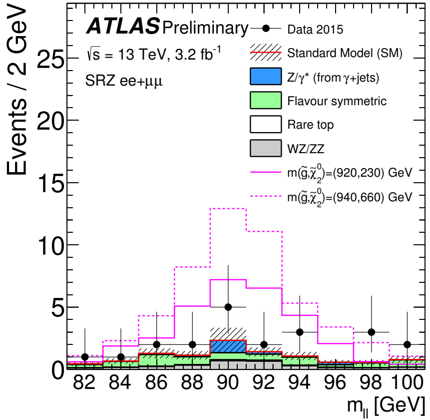
- Z+jet events should be very rare: high E_T^{miss} requirement supresses backgrounds
  - However, since background could give $m_{\ell\ell}$ peak, important to model!
- Use γ+jet events, smeared to take into account resolution differences between γ and e/μ and adjust for p_T distributions, to develop prediction

2L: Other Notes on Backgrounds

- Z+jet estimate agrees very well in validation region, shown here!
  - NB: prediction drops to 0 at $E_T^{miss} > 200$ GeV: SR has > 250 GeV requirement
- One more background, WW/WZ: τ decays and missed leptons can contribute to SR
  - Use background from MC, but validate in dedicated VR

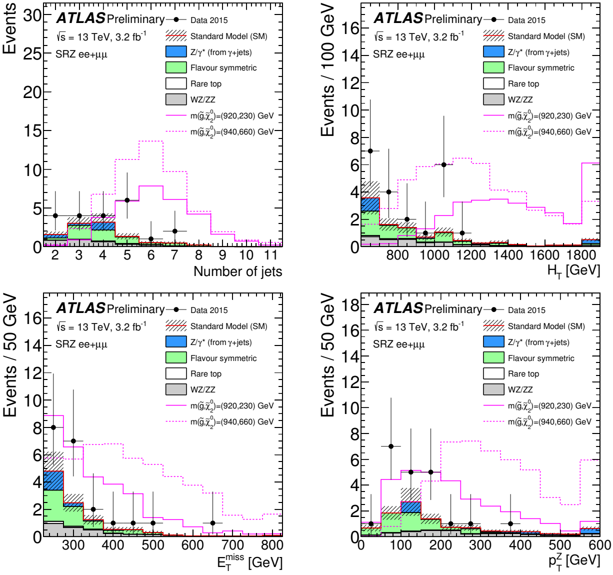






- Rather good agreement in all validation regions observed
- However, an intriguing 2.3σ excess is measured in the SR (again!)
  - 21 events observed, 9.7 expected
  - Flavor symmetric this time: 11 in $\mu\mu$, 10 in ee

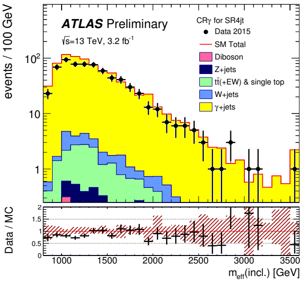
2L: Signal Region Distributions

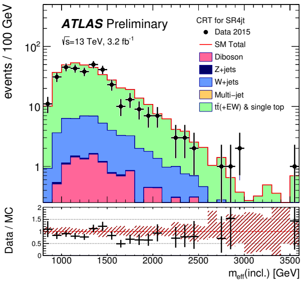


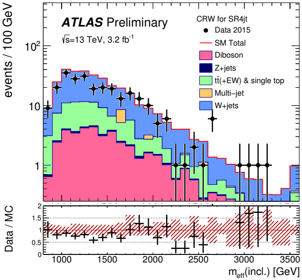
- No strong signal-like features in other distributions
- Clearly an interesting target for 2016 data!

0L + 2-6 Jets

0L, 2-6 Jets: Control Regions







- Three separate control regions normalize largest backgrounds
  1. CRγ normalizes Z: transfer factor measured with $Z \to \ell\ell$
  2. CRW normalizes W: select lepton and veto *b*-jets
  3. CRt normalizes top: select lepton and select *b*-jets