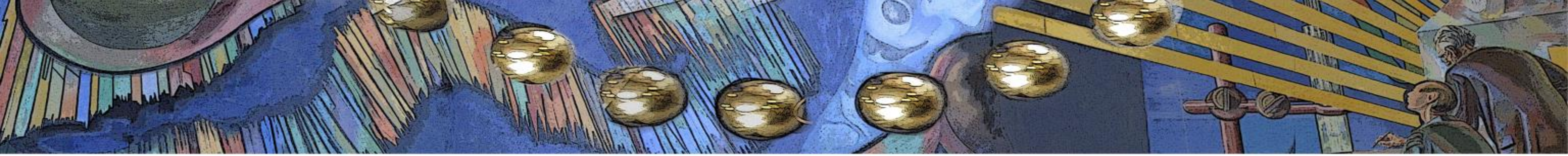
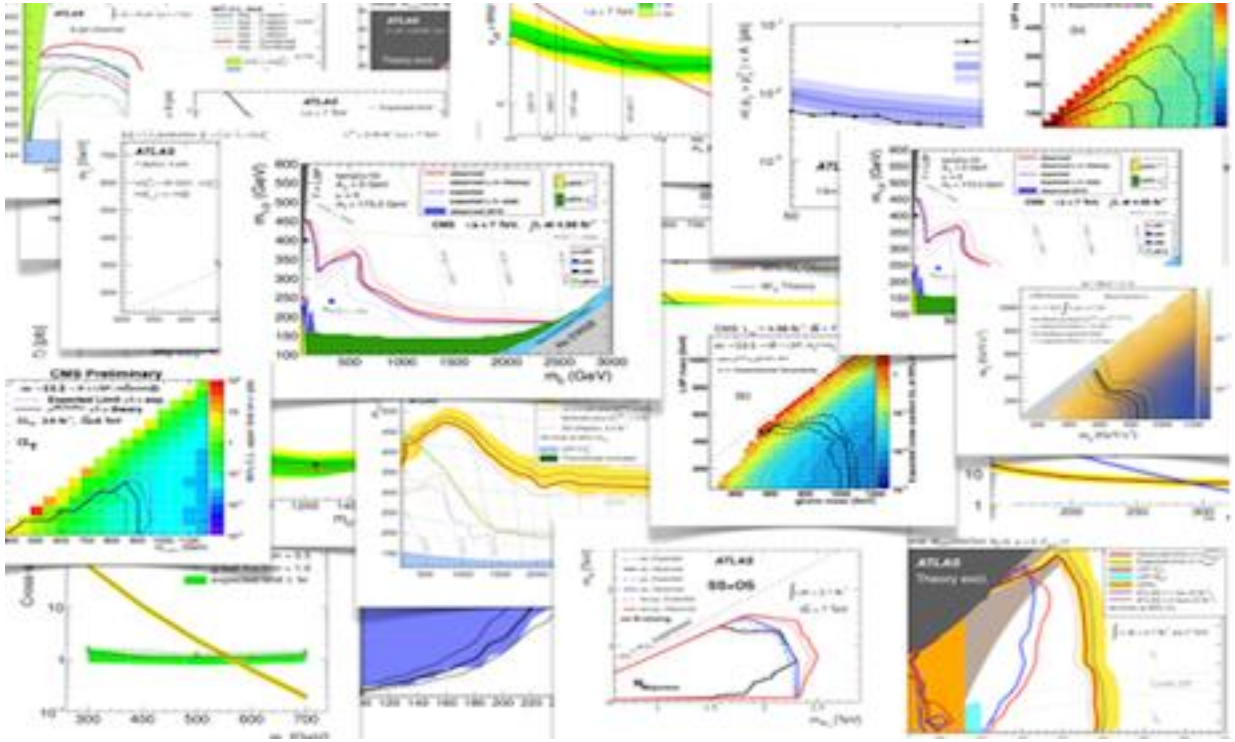


UiO : Department of Physics
University of Oslo

Reconstruction techniques in supersymmetry searches in the ATLAS experiment

Eirik Gramstad
University of Oslo
on behalf of the ATLAS Collaboration

DIS 2018 – XXVI International Workshop on Deep Inelastic Scattering and Related Subjects

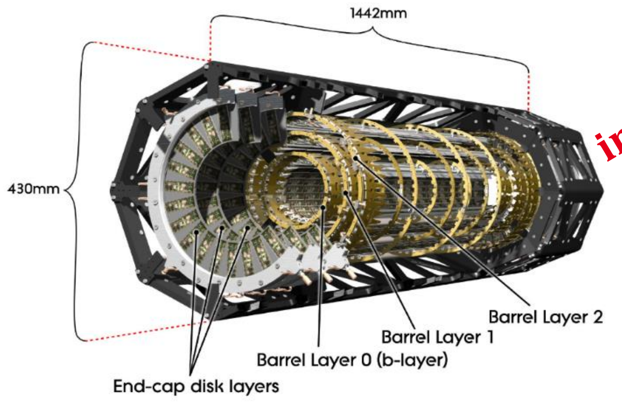


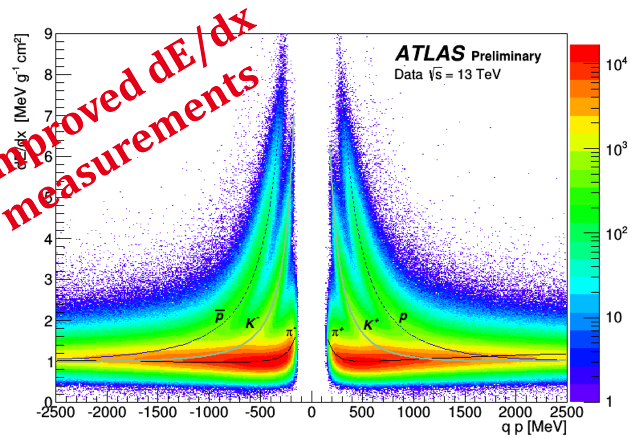
Will not show a lot of limit plots, I'll refer to the coming talks for all the nice limits from the various analyses

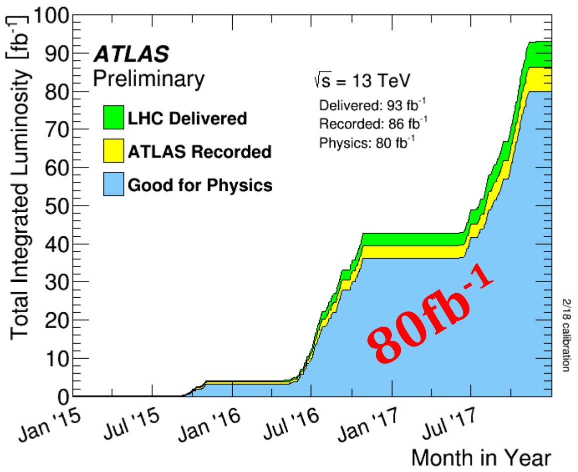
The ATLAS detector at the LHC

Tracking Detector

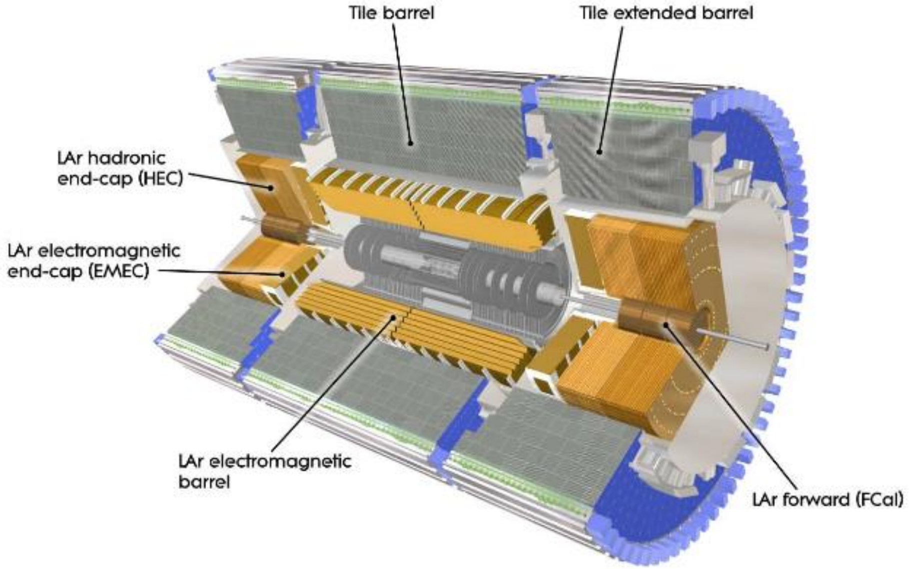
Since Run 1 a new, Insertable B-layer (IBL), has been installed inside the existing b-layer with a mean sensor radius of 3.3 cm







Calorimeters



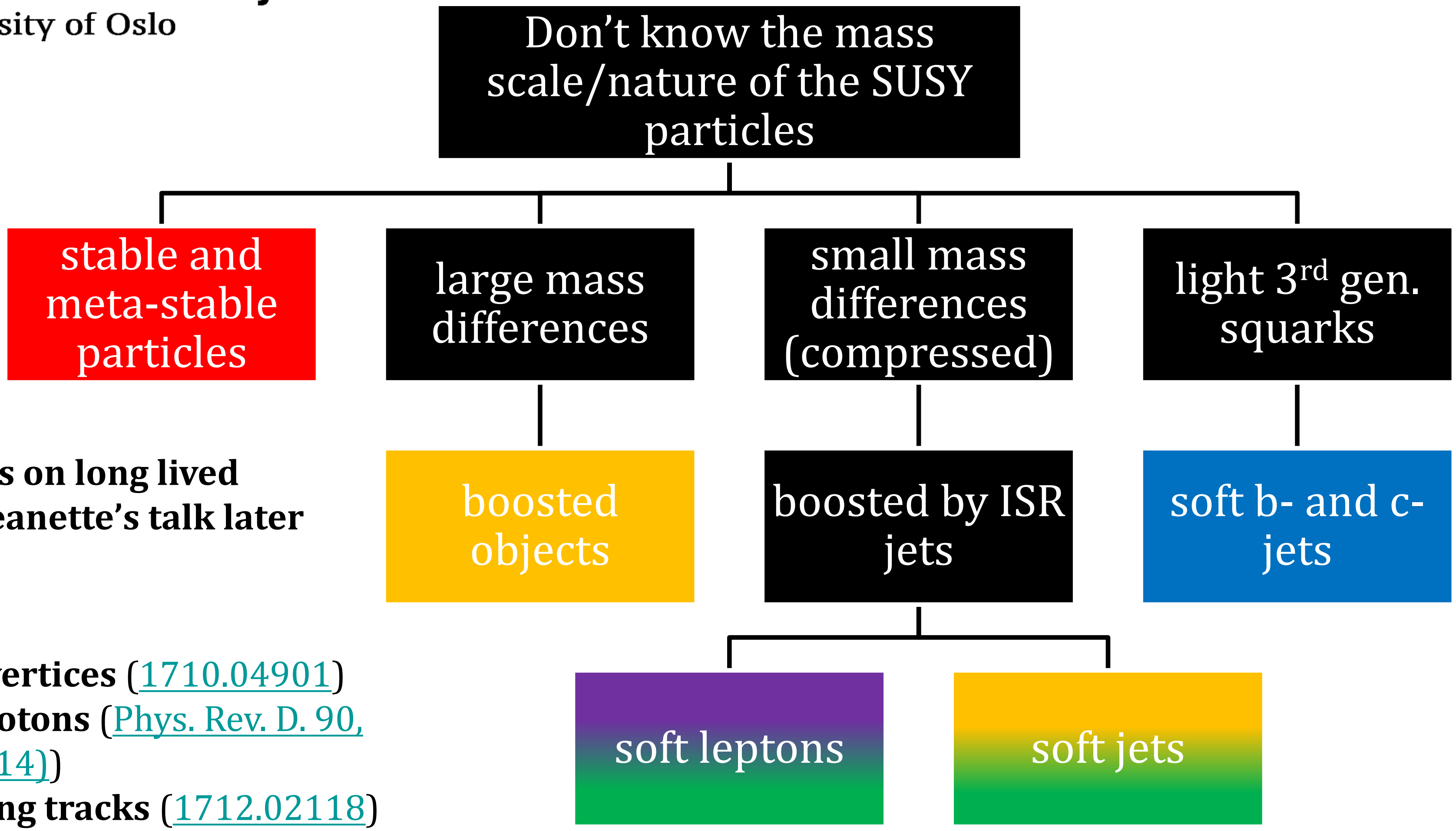
Covers the range $|\eta| < 4.9$

Jets are reconstructed by applying a jet-clustering algorithm to topological clusters from the calorimeter signal

Supersymmetry (SUSY) searches in ATLAS

SUSY provides an extremely rich model space

Reflected in the many ongoing analyses targeting various SUSY models



For more results on long lived sparticles see Jeanette's talk later today

- **Displaced vertices** (1710.04901)
- **Delayed photons** (Phys. Rev. D. 90, 112005 (2014))
- **Disappearing tracks** (1712.02118)
- **Large ionization losses** (Phys. Rev. D 93, 112015 (2016))
- **Slow Propagation Velocities** (1606.05129)

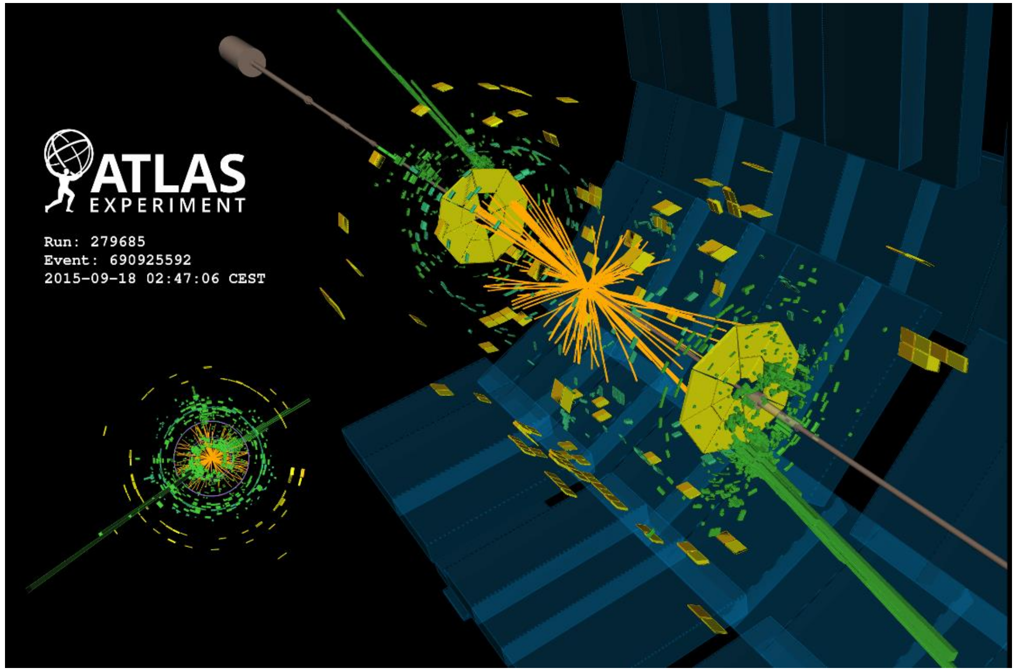
Jet re-clustering

Recursive Jigsaw Reconstruction

b- and c-tagging

Phys. Rev. D 97 (2018) 052010

Jets and jet re-clustering



- The standard jet algorithms in ATLAS use a predefined radius parameter, R, to build jets
  - R is roughly the size of the jet in the (η,Φ)-space

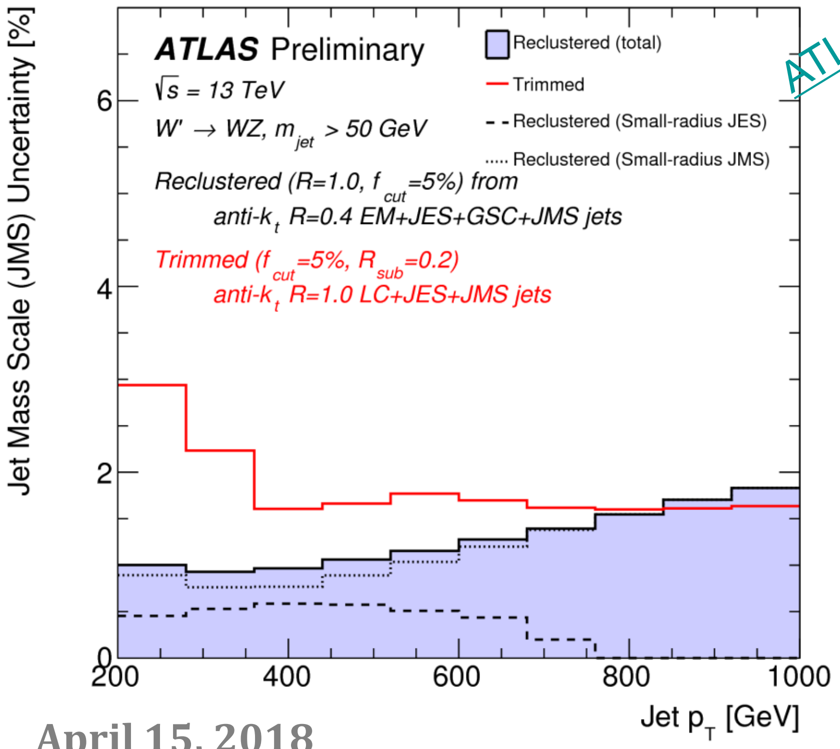
- The optimal R is process dependent and scales with the inverse of the momentum under consideration
  - ideally the R parameter would be optimised for each analysis
    - however, each jet configuration must be calibrated, in situ, to account for detector response, pile-up suppression and other experimental effects
      - reason why only a few choices of R (**0.4**) are used in most analyses in ATLAS
  - a solution is to re-cluster large R jets using the smaller R jets as input
    - the fully calibrated small R jets can make the calibration of the re-clustered large R jets automatically

$$\Delta R \sim \frac{2m}{p_T}$$

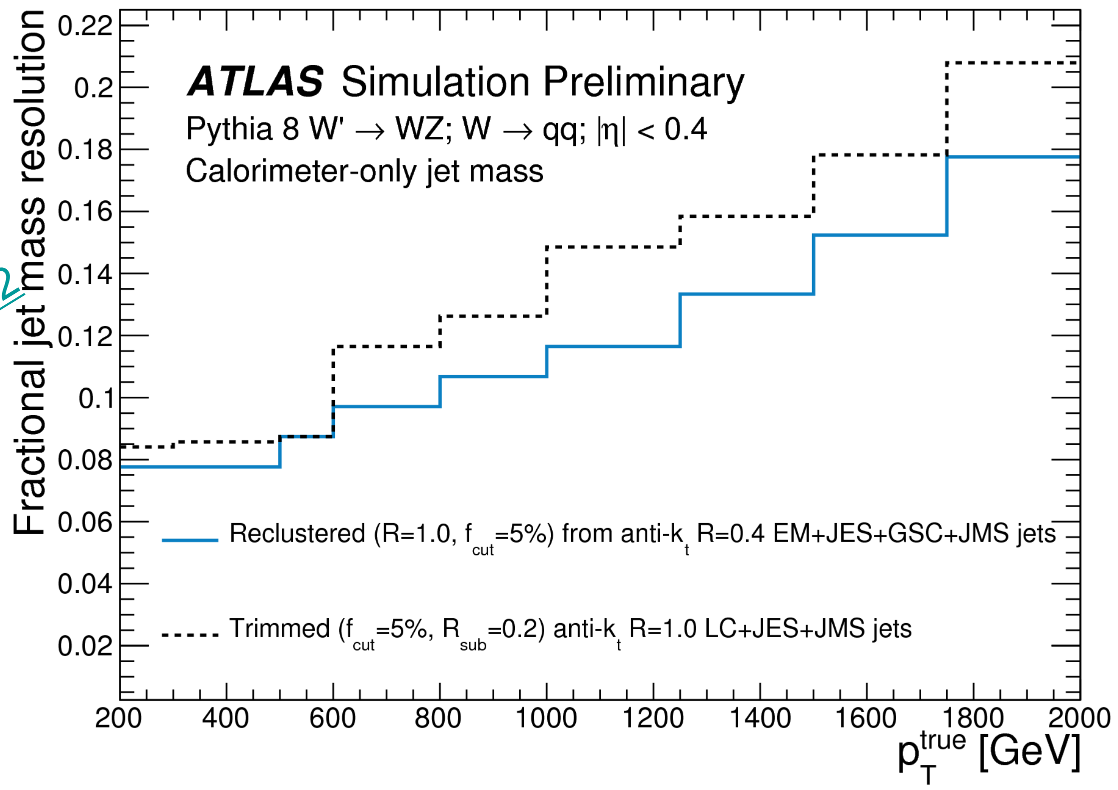
See Jason Veatch's talk from yesterday for more on jet re-clustering

Re-clustering

- large-R jets (R=1.0) built directly from topoclusters from calorimeter cells are available in ATLAS
  - calibrations and corrections done as for small-R jets



ATLAS-CONF-2017-062



large-R jets re-clustered from small-R jets show comparable or better jet mass resolution and uncertainties than **calibrated large-R trimmed jets!**

1712.02332
1711.11520

Use of large R-jets in SUSY analysis

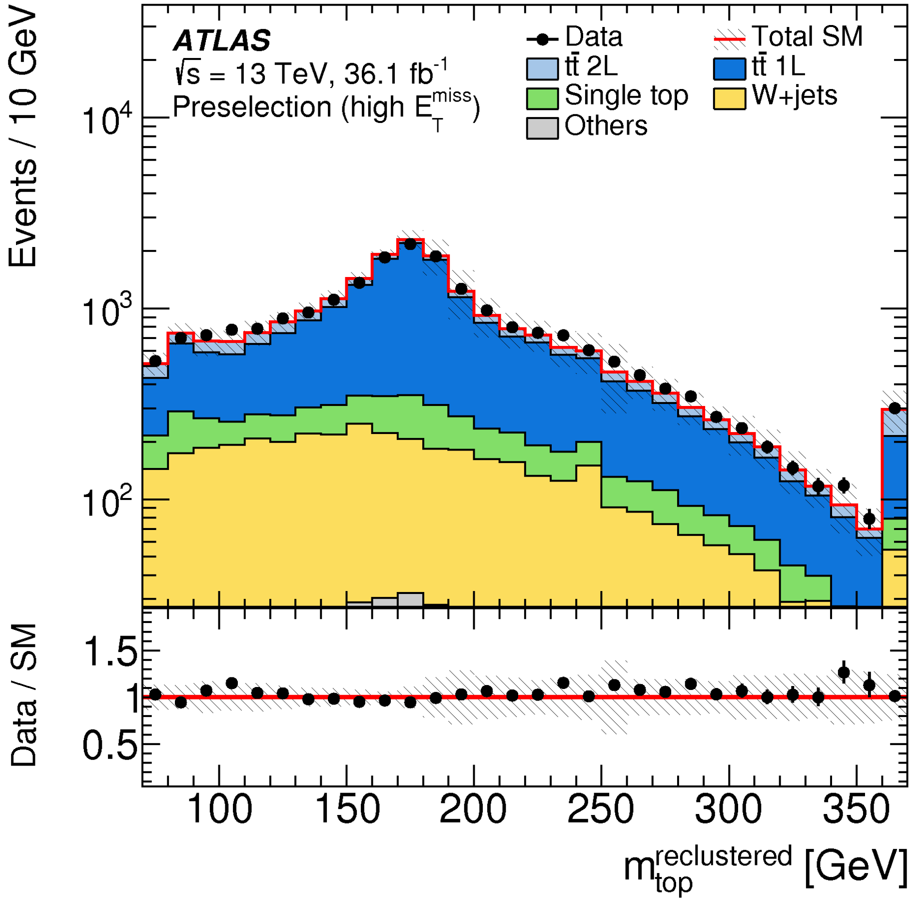
Top-tagging of boosted tops

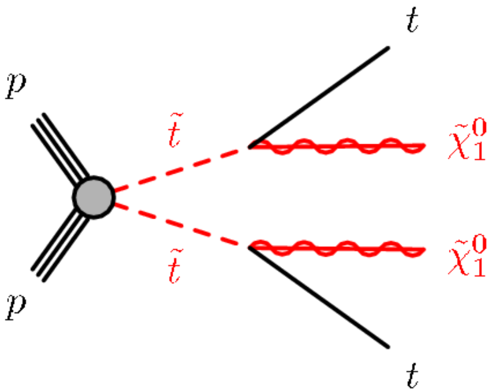
- reconstructing the hadronic top-quark decay can provide discrimination against di-leptonic $t\bar{t}$ events
- large R-jets is used to target events where the top quark is produced with a significant boost
  - re-clustering small-R jets into large-R jets with R = 3.0
    - radius of each jet is iteratively reduced to an optimal radius to match the p_T

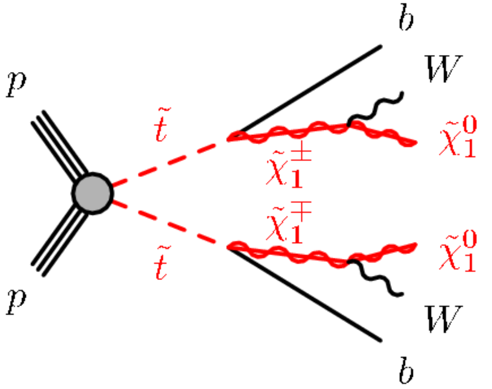
$$\boxed{R(p_T) = 2\frac{m_{top}}{p_T}}$$

jet mass: $$\boxed{M_J = \left(\sum_{i\in jet} E_i\right)^2 - \left(\sum_{i\in jet} \vec{p}_i\right)^2}$$

- same method is used to define boosted hadronically decaying W-boson candidates







1711.01901

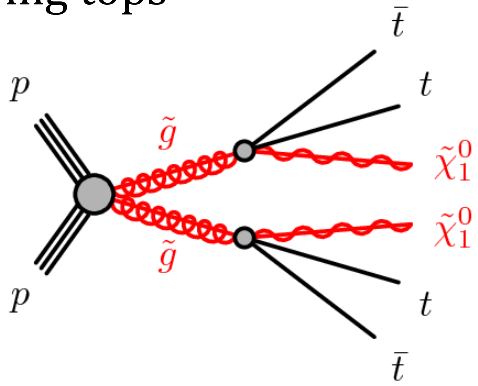
Use of large R-jets in SUSY analysis

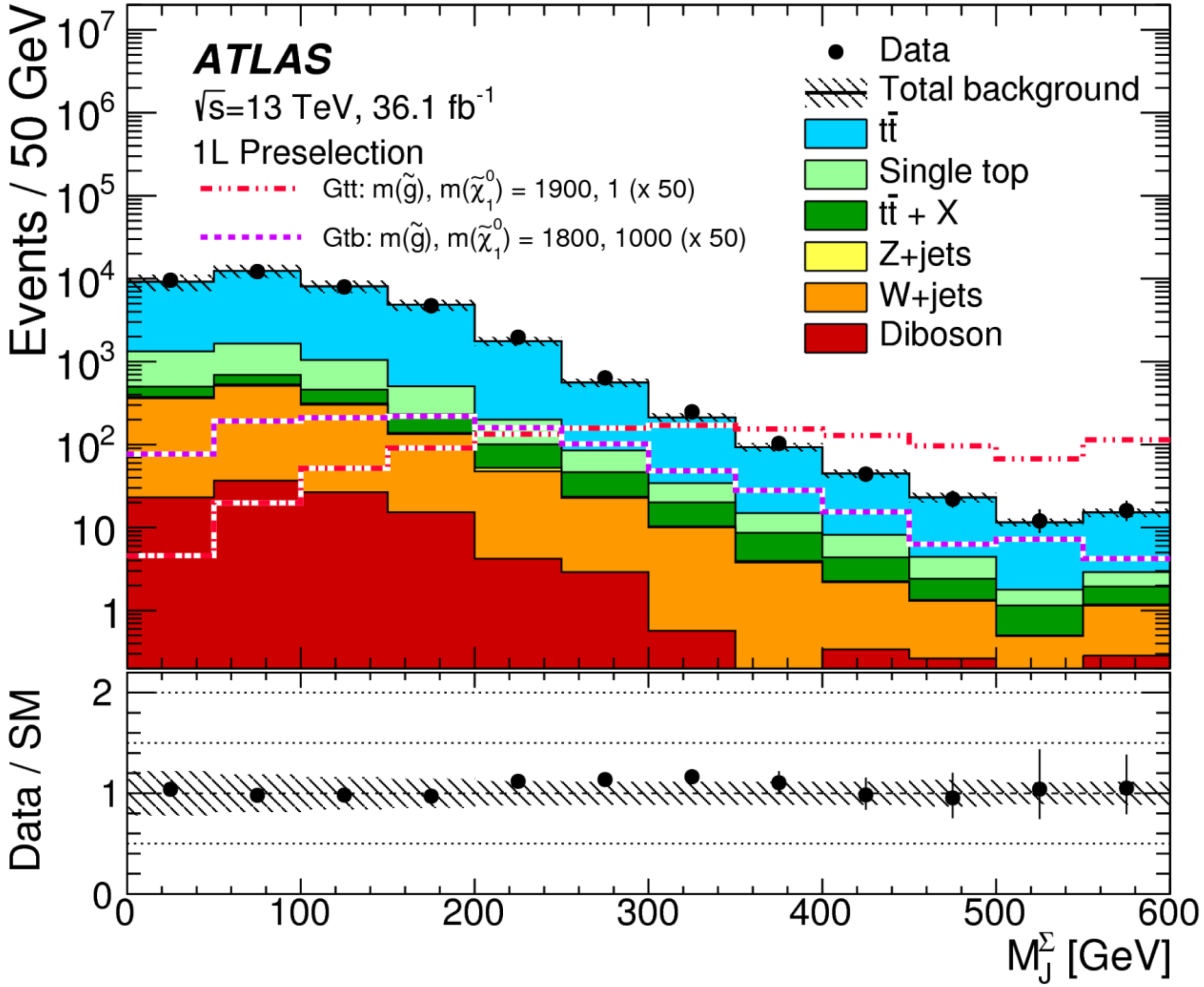
Total jet mass

$$M_J^{\Sigma} = \sum_{n \leq x} M_{j,n}$$

A sum over all the large-R re-clustered jets in the event

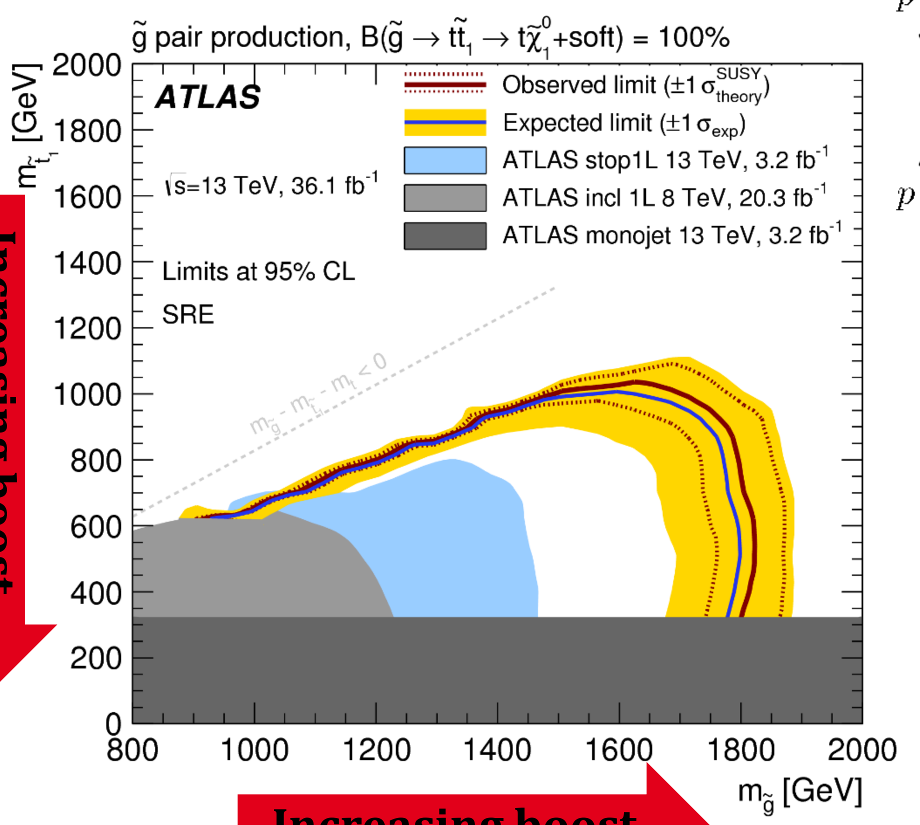
Typically large in events with as many as four top quarks while the main background is dominated by $t\bar{t}$ events with one or two hadronically decaying tops





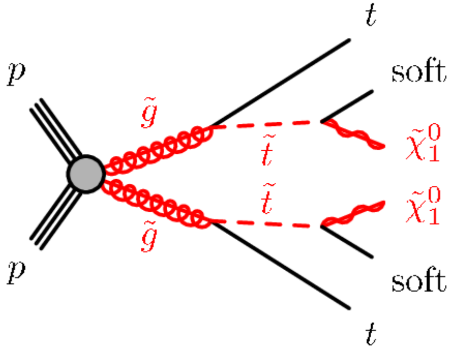
Some selected results

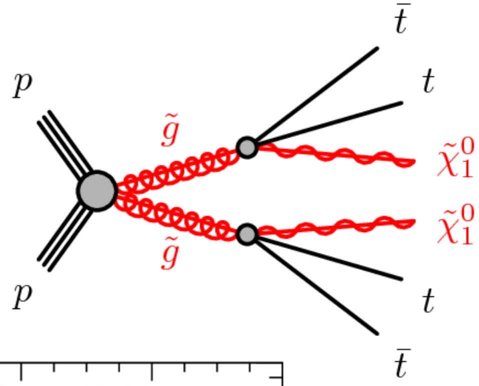
For more results on searches for gluinos and squarks see Matt LeBlanc's talk later today

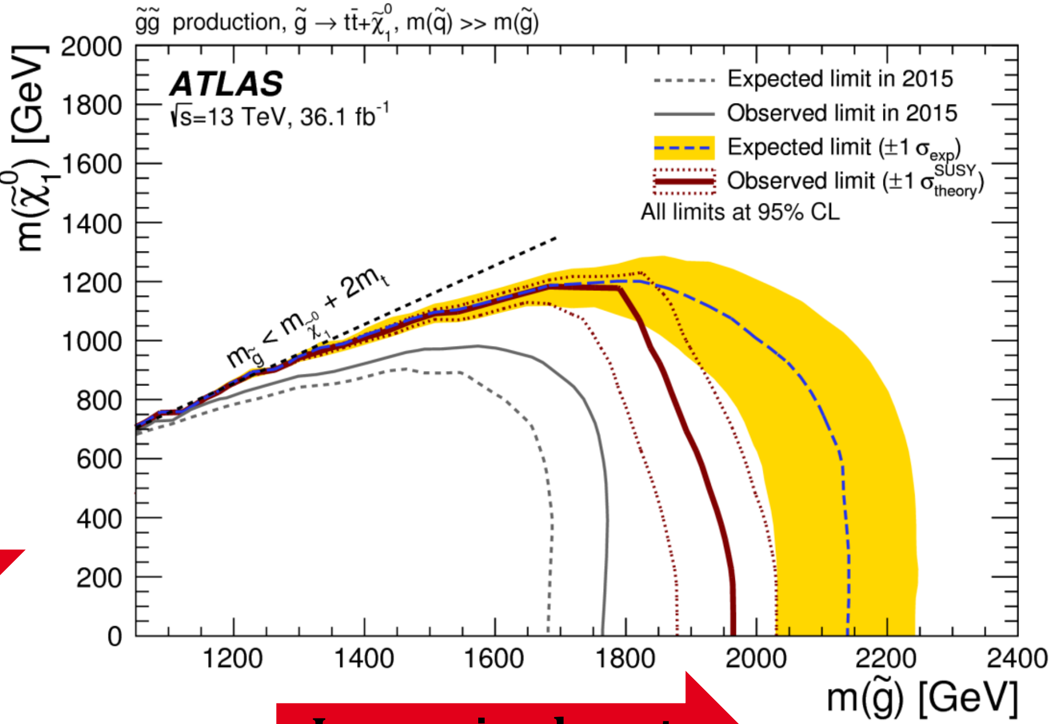


Increasing boost

Increasing boost







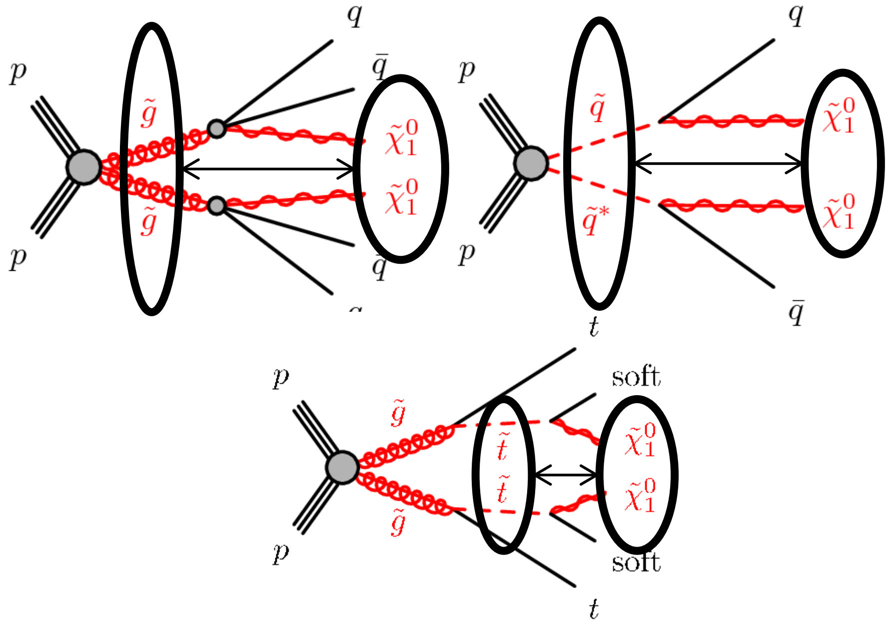
Increasing boost

Increasing boost

Use of large R-jets in SUSY analysis

SUSY Production	Final State	Radius Parameter	Data and Energy	Reference	Used for
$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$	0-lepton, jets, E_T^{miss}	1.0	$36fb^{-1}$@13TeV	1712.02332	To select hadronically decaying W and Z
$\tilde{t}\tilde{t}$	1 lepton, jets, E_T^{miss}	3.0	$36fb^{-1}$@13TeV	1711.11520	W- and Top-tagging (2-top events))
$\tilde{g}\tilde{g}$	0-1 leptons, b-jets, E_T^{miss}	0.8	$36fb^{-1}$@13TeV	1711.01901	Top-tagging (4-top events)
$\tilde{t}\tilde{t}$, $\tilde{g}\tilde{g}$	0 lepton, b-jets, jets, E_T^{miss}	1.2/0.8	$36fb^{-1}$@13TeV	JHEP 12 (2017) 085	Top and W-tagging
	1 lepton, b-jets, jets, E_T^{miss}	1.2/1.0	$3.2fb^{-1}$@13TeV	Phys. Rev. D 94 (2016) 052009	Top-tagging

Recursive Jigsaw Reconstruction (RJR)



For compressed scenarios :

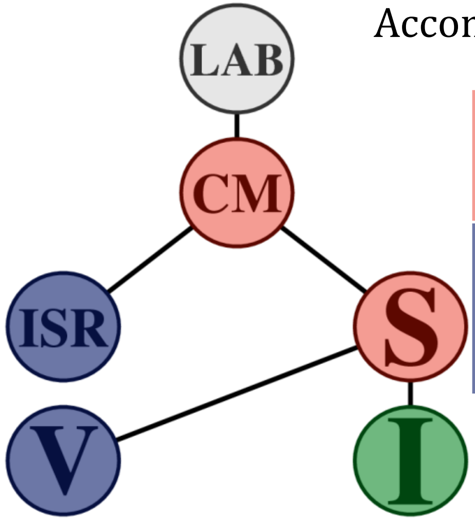
$$0 < \Delta m(\tilde{g}/\tilde{q}/\tilde{t}, \tilde{\chi}_1^0) < 200 \text{ GeV}$$

E_T^{miss} does not come from the large momentum of WIMPS received from decays, but rather from recoiling against Initial State Radiation (ISR) jets

Rather than relying on «mono-ISR»-signal, RJR tries to separate ISR objects from the sparticle objects

SUSY Production	Final State	Data and Energy	Ref.
$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$	0-lepton, jets, E_T^{miss}	36fb^{-1}@13TeV	1712.02332
$\tilde{t}\tilde{t}$	1 lepton, jets, E_T^{miss}	36fb^{-1}@13TeV	1711.11520
$\tilde{g}\tilde{g}, \tilde{t}\tilde{t}$	0 lepton	36fb^{-1}@13TeV	JHEP 12 (2017) 085

Recursive Jigsaw Reconstruction (RJR)



Accomplished with a simple decay view of the event

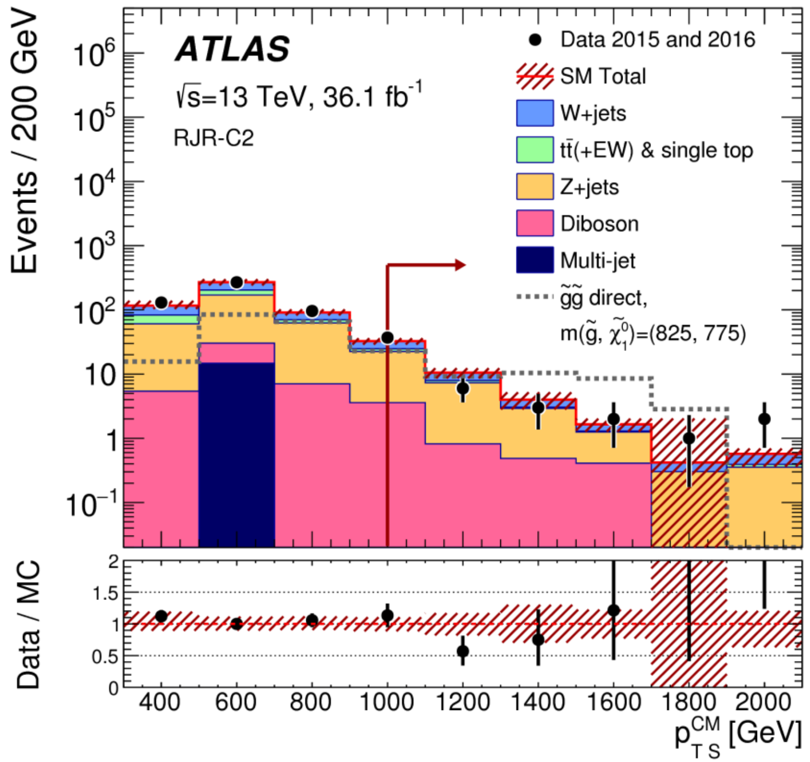
CM
centre-of-mass system incl. all visible objects and E_T^{miss}

ISR
particles not from the sparticle decays

S
sparticle system

V
visible decay products

I
WIMP

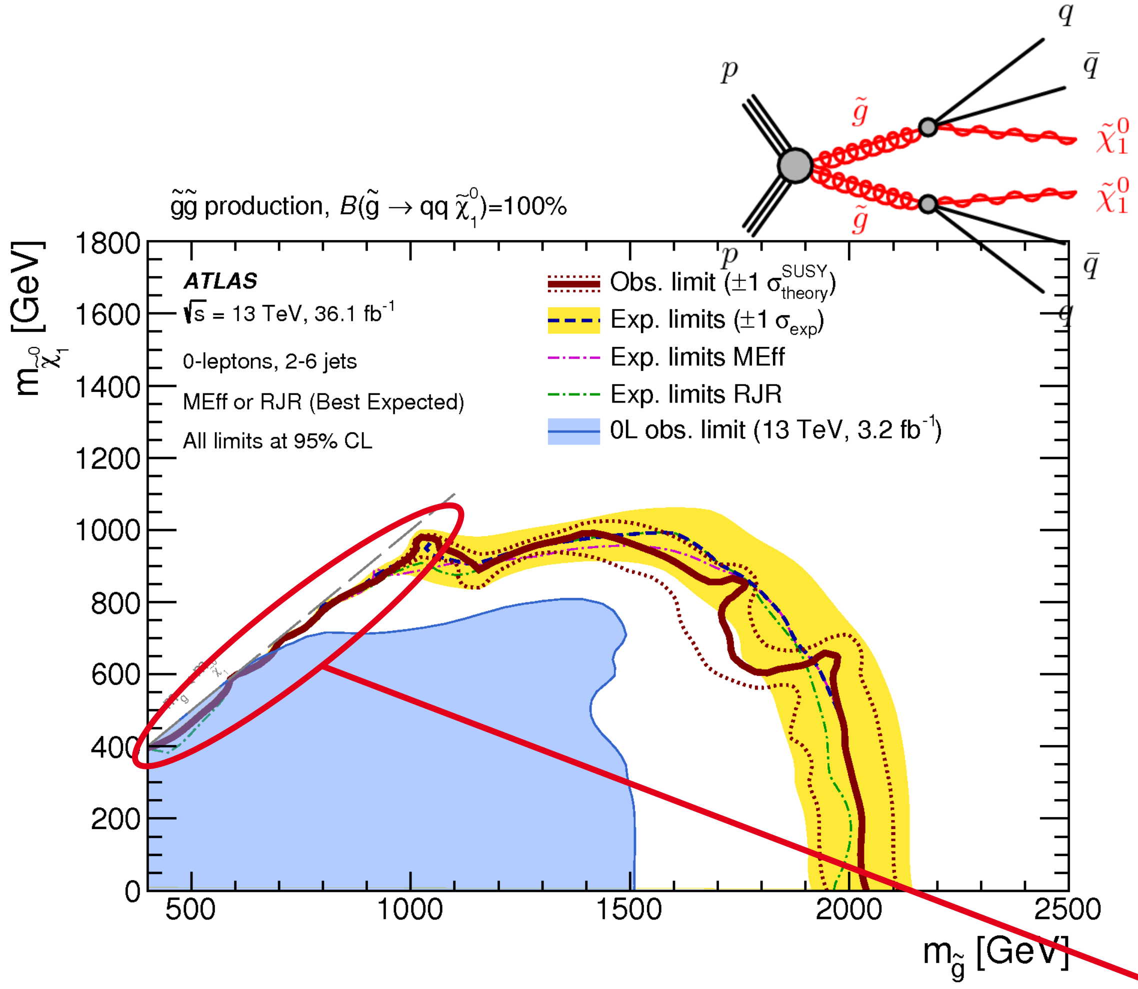


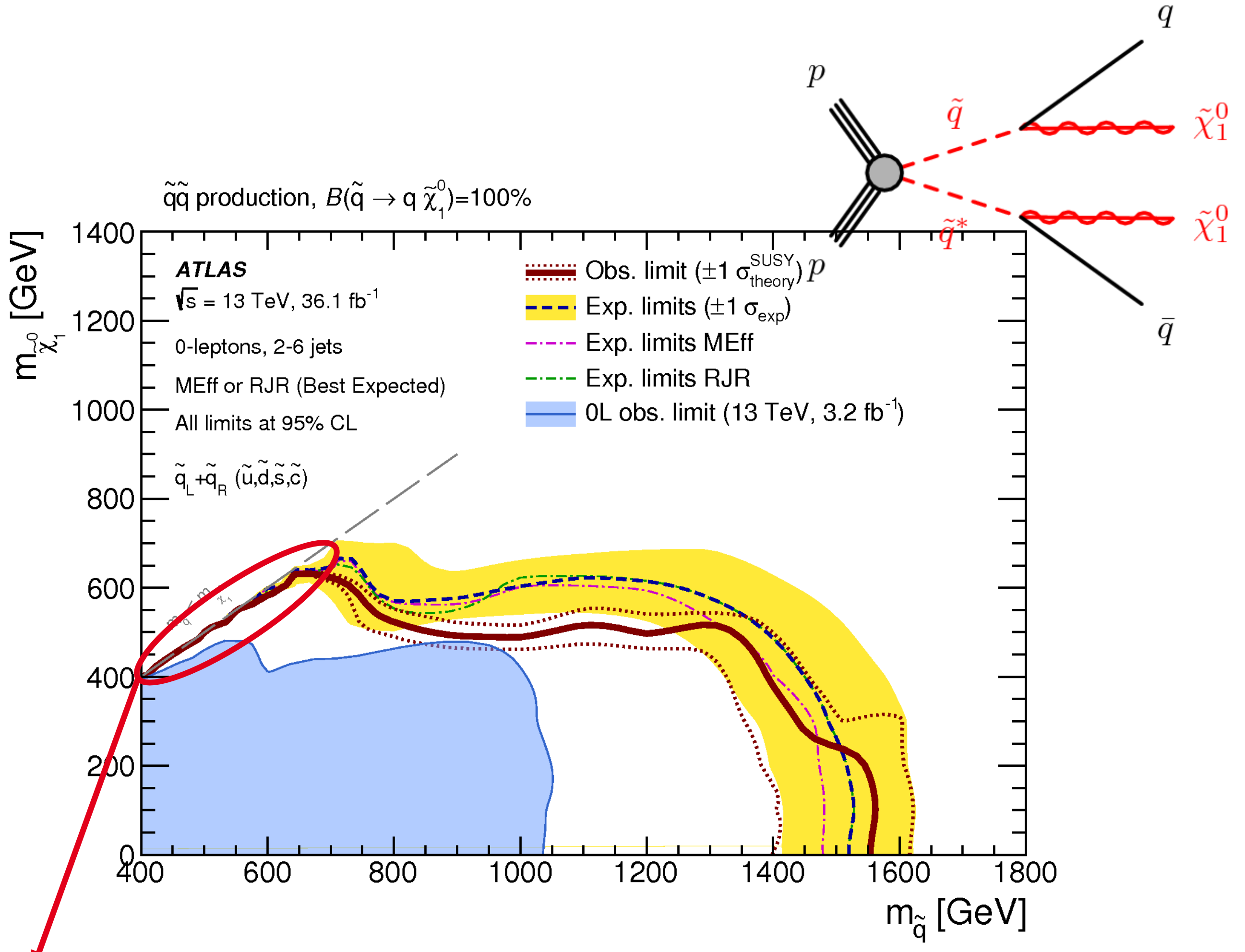
Each event is reconstructed by:

1. ignoring the longitudinal momenta of all jets
2. treat E_T^{miss} as the transverse momentum of I (with zero mass)
3. partition all jets into ISR and V by minimizing the mass of the ISR and S systems
4. Analyse the event kinematics in the transverse view

p_{TS}^{CM}: magnitude of the vector summed transverse momenta of all S-associated jets and E_T^{miss} - evaluated in the CM frame

Recursive Jigsaw Reconstruction (RJR)

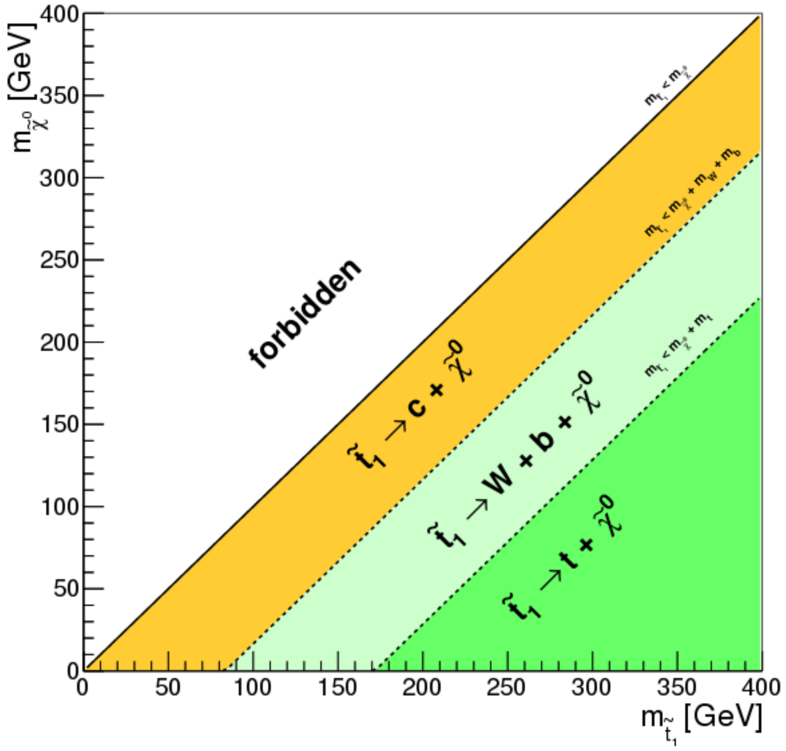


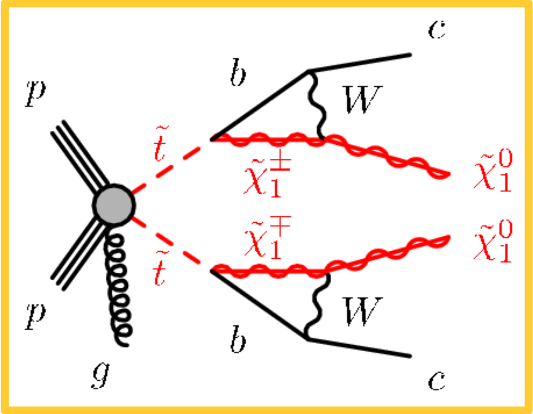


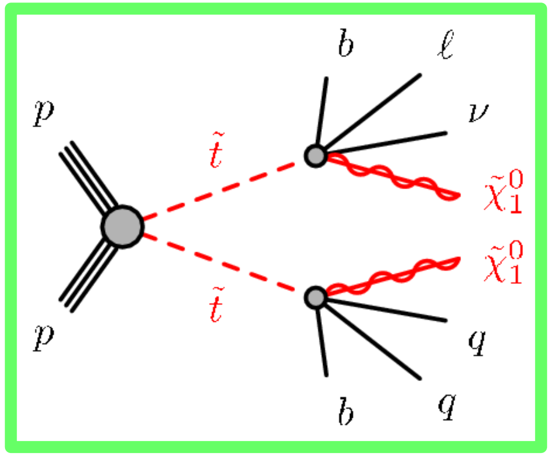
The RJR signal regions provides the best sensitivity in regions where $\Delta m(\tilde{g}/\tilde{q}, \tilde{\chi}_1^0) < 50$ GeV
Squark masses up to **650 GeV** and **gluino** masses up to **1 TeV** are excluded

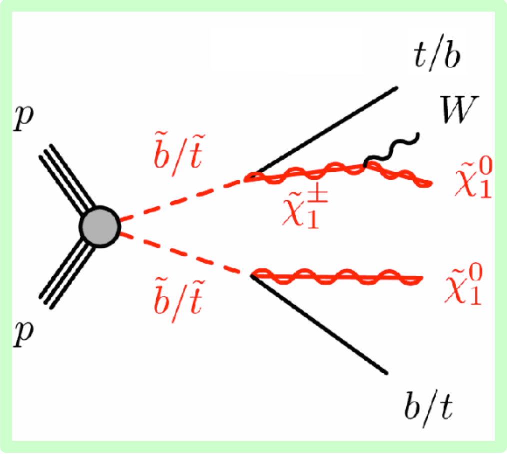
SUSY searches with b/c-tagged jets

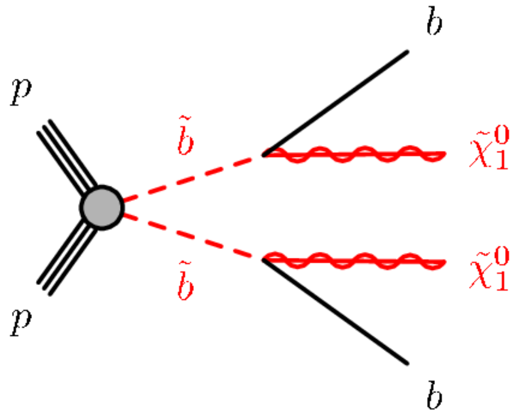
- Naturalness considerations suggest that the superpartners of the third generation quarks are the lightest coloured supersymmetric particles
  - may lead to light $\tilde{b}$ and $\tilde{t}$ squarks and therefore produced with relatively large cross-sections at the LHC
  - results in final states with **b-** or **c-jets**











SUSY searches with b/c-tagged jets

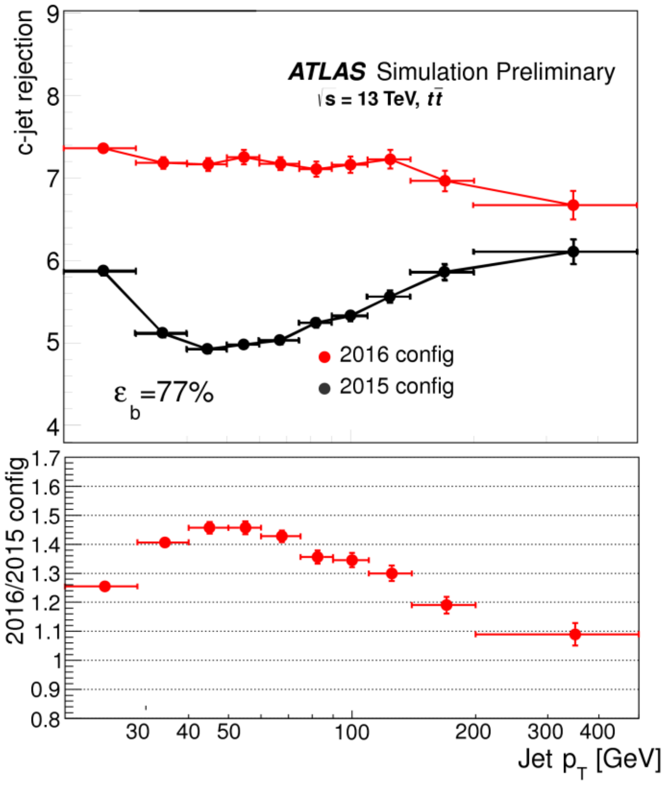
B-tagging in ATLAS is based on three distinct strategies

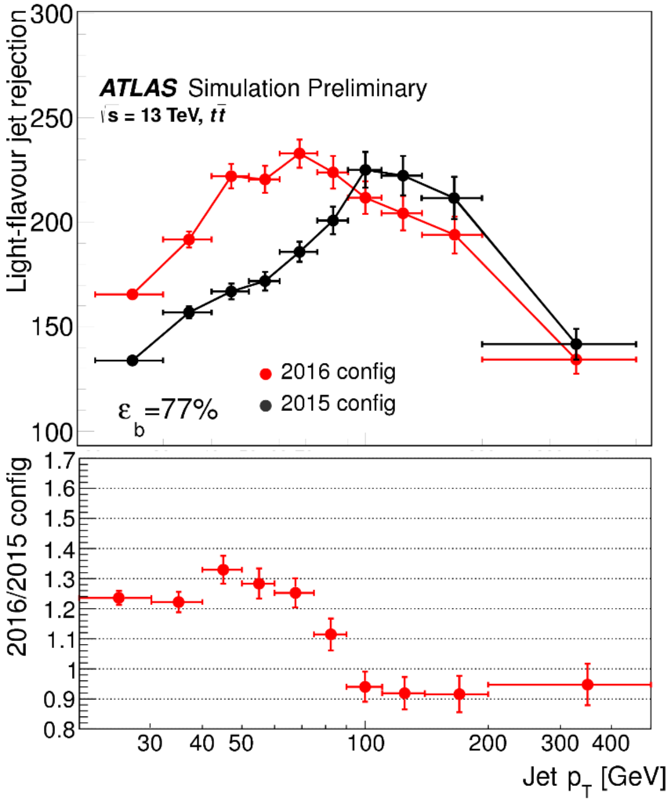
1. **Impact Parameter**: exploiting the relatively large life times: ~1.5 ps, cτ ~450μm by measuring impact parameters of tracks
2. **Secondary Vertex Finding**: builds secondary vertices within the jets
3. **Decay Chain Multi-Vertex**: exploits the topological structure of weak b- and c-hadron decays inside the jet (reconstruct the full b-hadron decay chain)

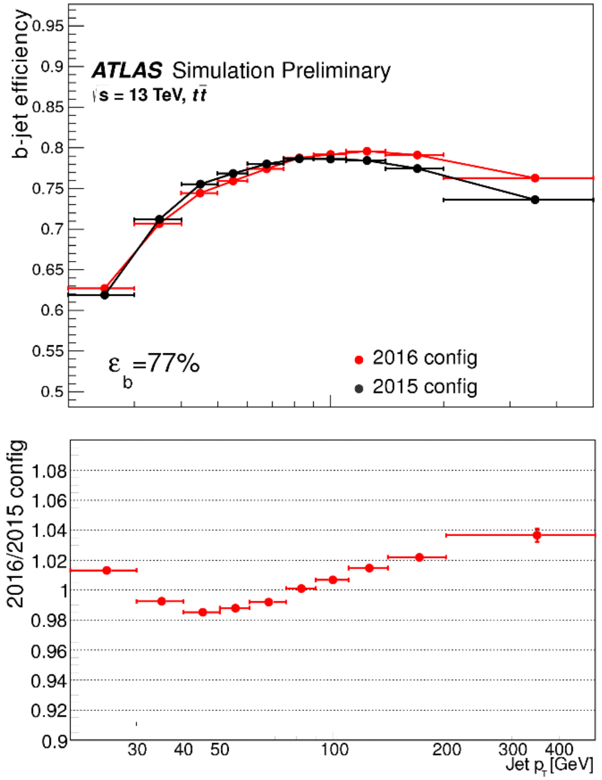
Output from each is combined into a Boosted Decision Tree algorithm

The inclusion of the IBL has significantly improved the b-tagging performance in Run 2

Major improvement in c-jet rejection since 2015



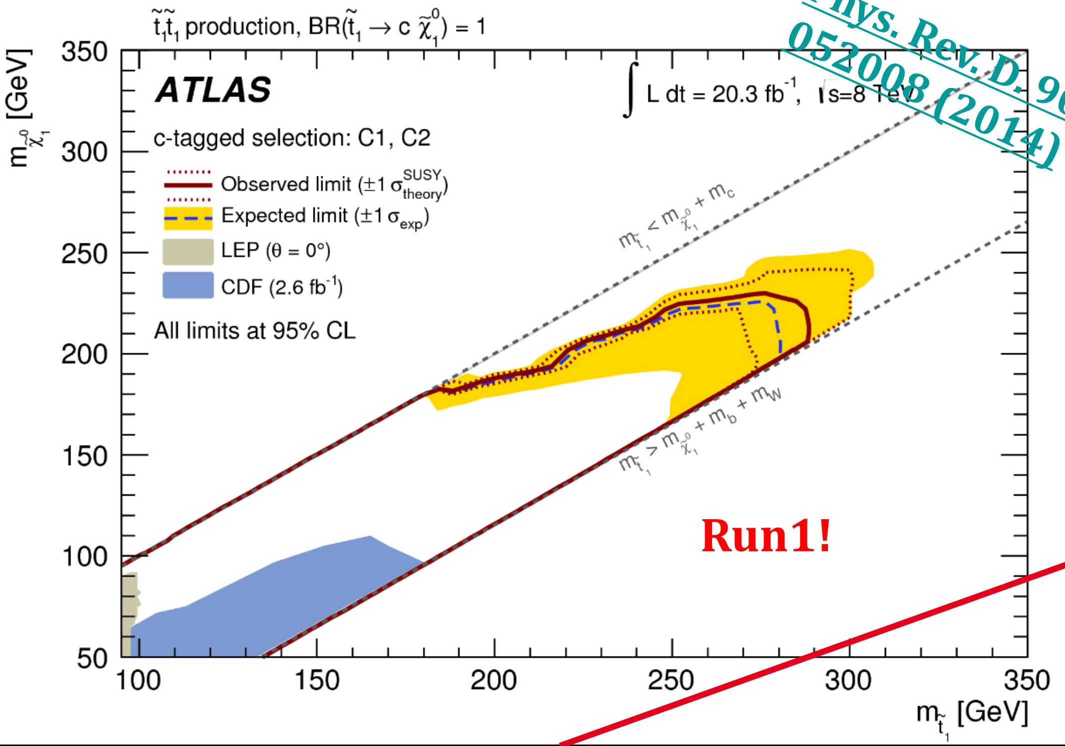




For more results on 3rd generation squarks see Jovan's talk later today

SUSY searches with b/c-tagged jets

Phys. Rev. D. 90, 052008 (2014)



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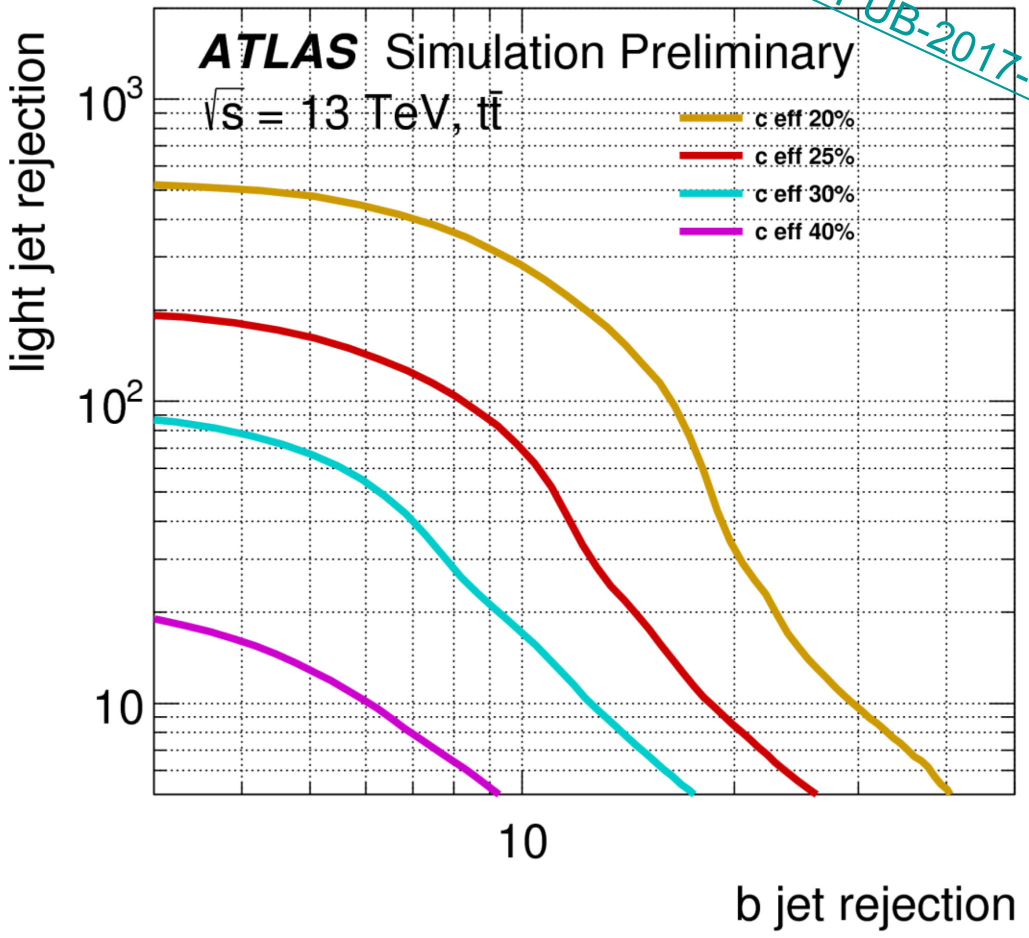


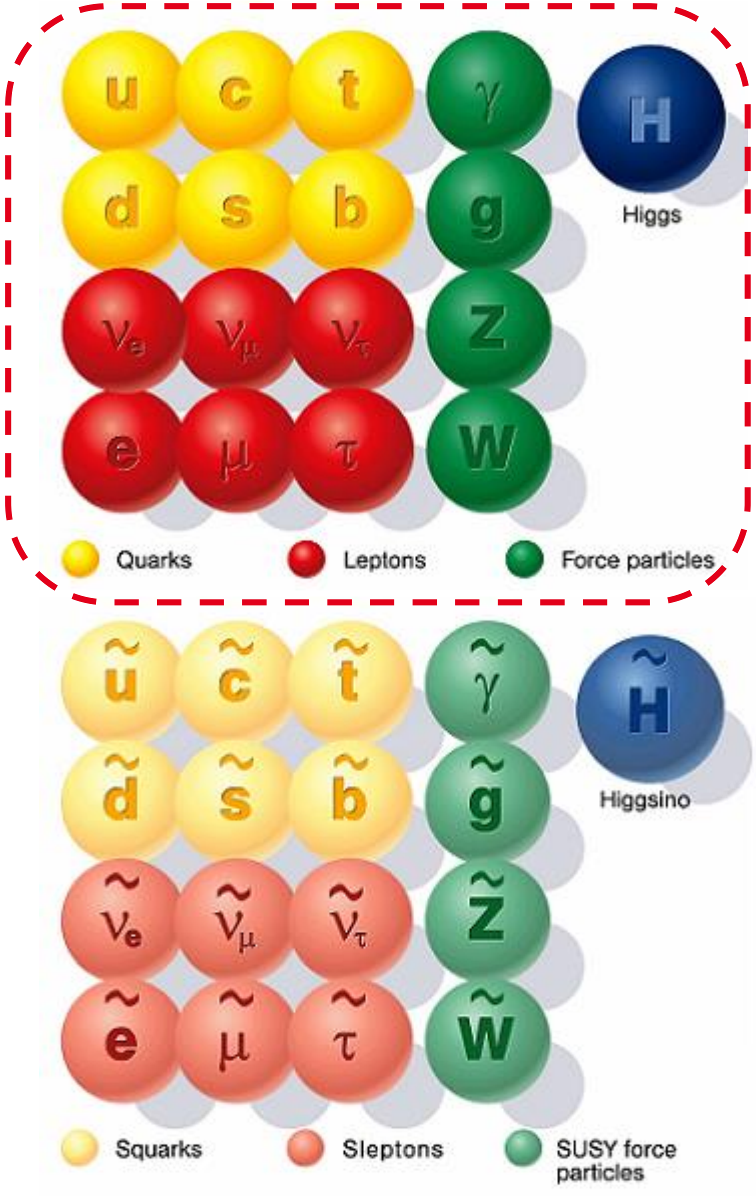
Operating point	c-tagging eff.	b-jet rejection	light-jet rejection	τ-jet rejection
medium	20%	8	200	10
loose	95%	2.5	-	-

Improvements also in the b-tagging efficiency by exploiting new approaches to multivariate analysis and training samples

Conclusions

- supersymmetry as an extension to the Standard Model is very well motivated
  - solves the hierarchy problem
  - provides a natural candidate for Dark Matter…
- only drawback is that there has not yet been any significant evidence for it’s existence
- however, SUSY is still alive, we just need to
  - develop more clever methods in the analyses
    - several improvements and new techniques have been developed since LHC Run 1
  - start looking into new territory
    - with more and better understanding of the data we become more sensitive to new regions of phase space

Supersymmetry particle content



BACKUP

Jets and jet re-clustering

- The jet clustering algorithms in ATLAS uses sequential recombination
  - defines distance metrics d_{ij} (between object *i* and *j*) and d_{iB} (object *i* and beam direction)
    - *i* and *j* combined into protojet if $d_{ij} < d_{iB}$
    - protojet *i* defined as jet if $d_{ij} > d_{iB}$
    - process continues until no protojets left

$$d_{ij} = \min\left(k_{ti}^{-2}, k_{tj}^{-2}\right)\frac{\Delta_{ij}^2}{R^2}$$

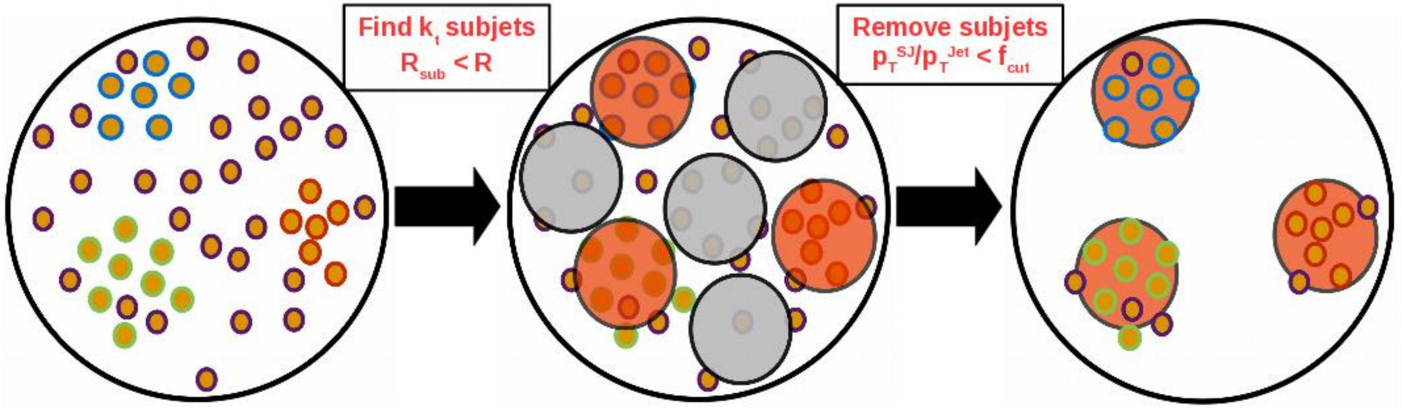
$$\Delta_{ij} = \sqrt{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}$$

radius parameter, size of the jet

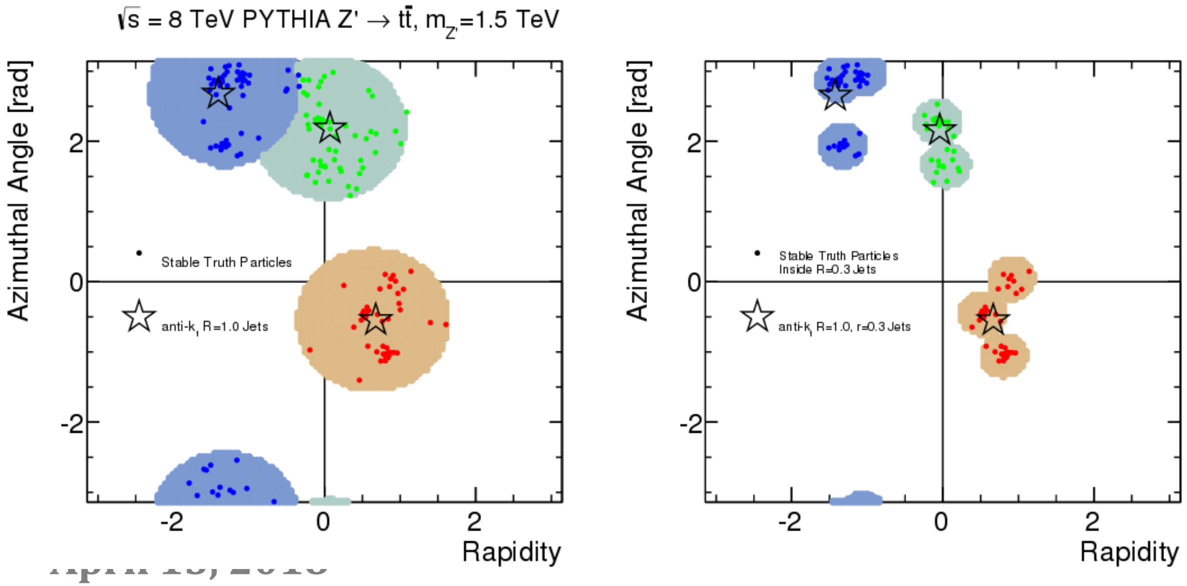
transverse momenta of particle *i* and *j*

- The optimal radius parameter, R, is process dependent and scales with the inverse of the momentum under consideration
  - ideally the R parameter would be optimised for each analysis
    - however, each jet configuration must be calibrated, in situ, to account for detector response, pile-up suppression and other experimental effects
      - reason why only a few choices of R (0.4 and 0.6) are used in most analyses in ATLAS
  - a solution is to re-cluster large R jets using the smaller R jets as input
    - the fully calibrated small R jets can make the calibration of the re-clustered large R jets automatically

Jet Grooming



ATLAS trimming parameters: R_{sub} = 0.2, f_{cut} = 0.05



calibrated large-R jets removes subjets if

$$p_T^{subjet} < f_{cut} * p_T^{jet}$$

re-clustering algorithms removes any small radius jet constituent j of a large R re-clustered jet J if

$$p_T^{j} < f_{cut} * p_T^{J}$$

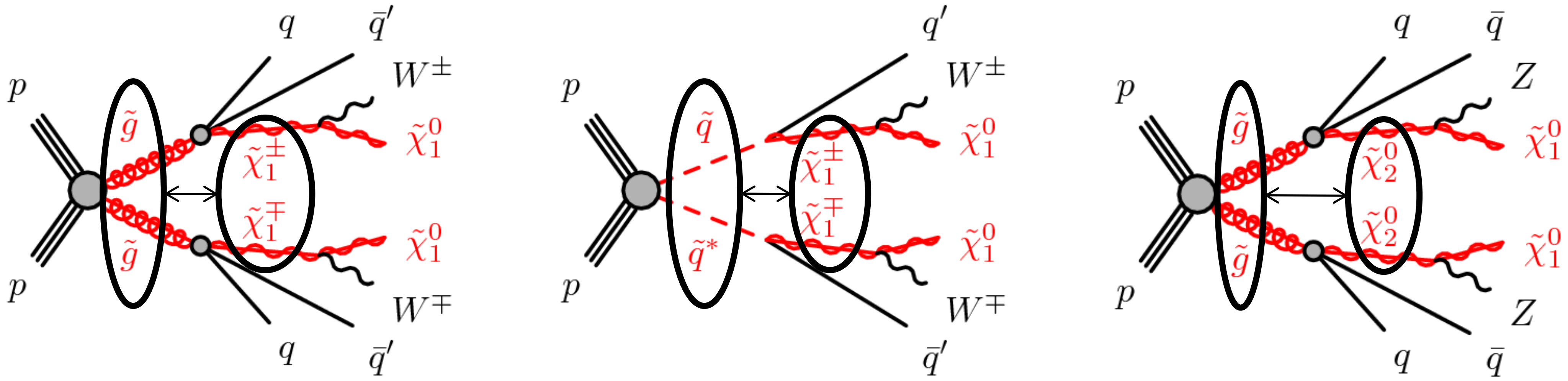
1712.02332

Use of large R-jets in SUSY analysis

W- and Z-tagging

- small mass difference between parent SUSY particle and intermediate chargino/neutralino can cause W and Z to have significant p_T
  - decay products appear as a single high-mass jet

$$M_J = \left(\sum_{i \in jet} E_i\right)^2 - \left(\sum_{i \in jet} \vec{p}_i\right)^2$$



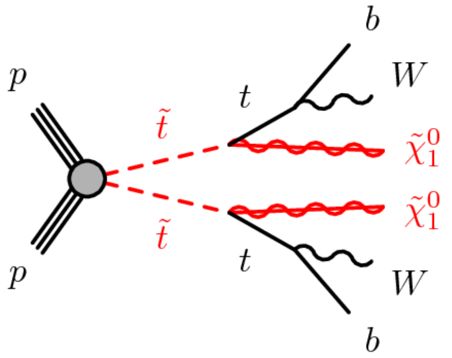
Phys. Rev. D 94 (2016) 052009 (3.2fb^{-1})

JHEP 12 (2017) 085 (36.1fb^{-1})

Use of large R-jets in SUSY analysis

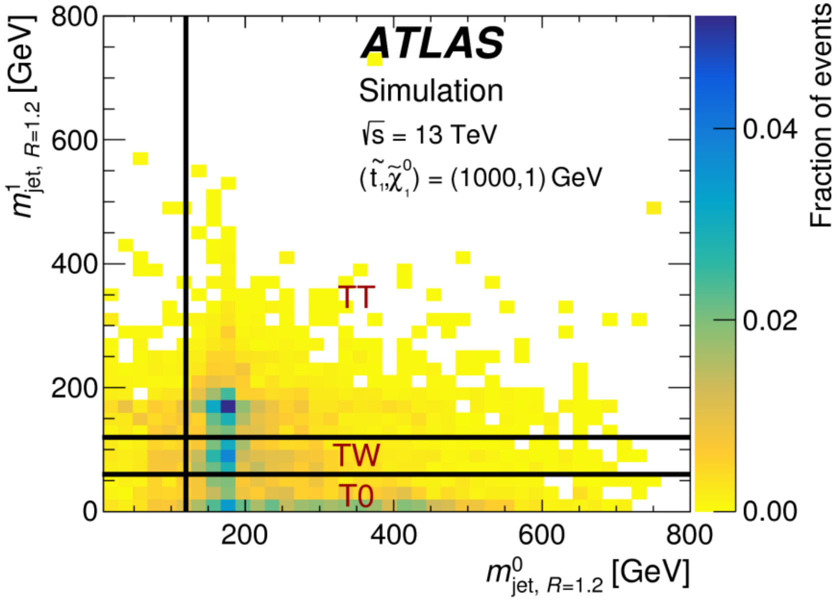
Top-tagging of boosted tops

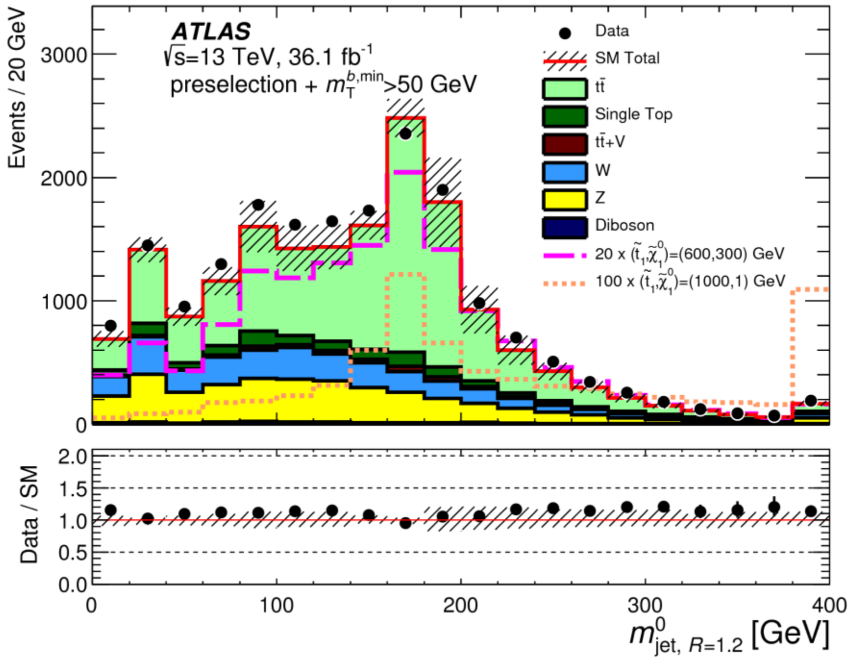
High top squark masses



$m_{\tilde{t}} \sim O(1000\ \mathrm{GeV})$

Highly boosted requires two large-R jets (R = 1.2)





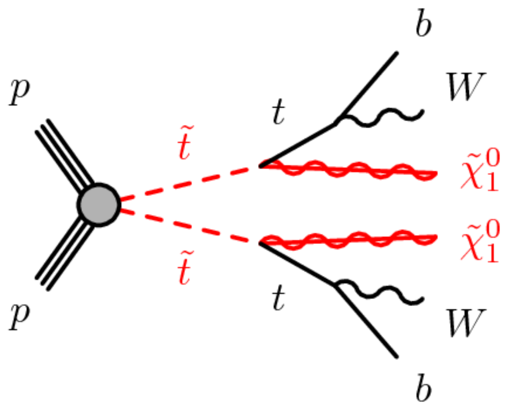
Use of large R-jets in SUSY analysis

Top-tagging of boosted tops

JHEP 12 (2017) 085

Phys. Rev. D 94 (2016) 052009

High (1000 GeV) top squark masses

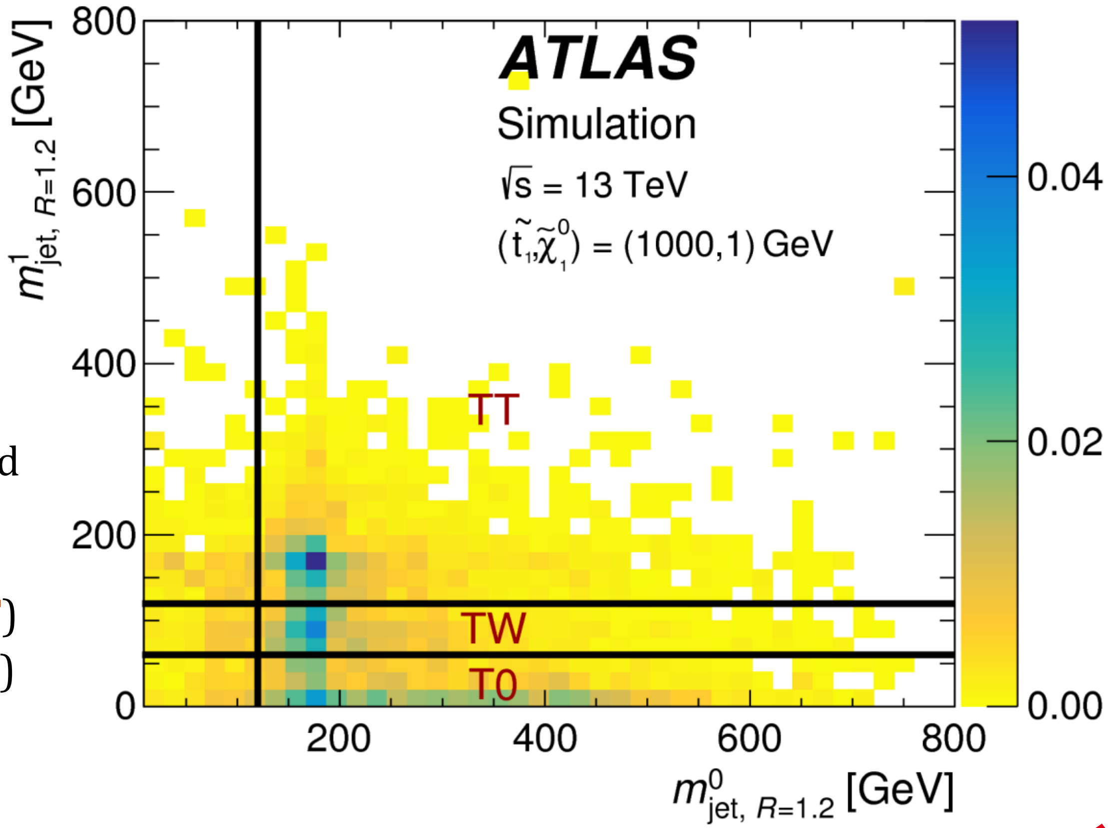


two R = 1.2 re-clustered jets are required and events classified based on jet mass:

$m_{jet} > 120$ GeV : top candidate (T)

$60 < m_{jet} > 120$ GeV : W candidate (W)

$m_{jet} < 60$ GeV: unclassified (0)



$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \sim m_t$

High p_T jets from Initial State Radiation (ISR) jets boost the di-top-squark system

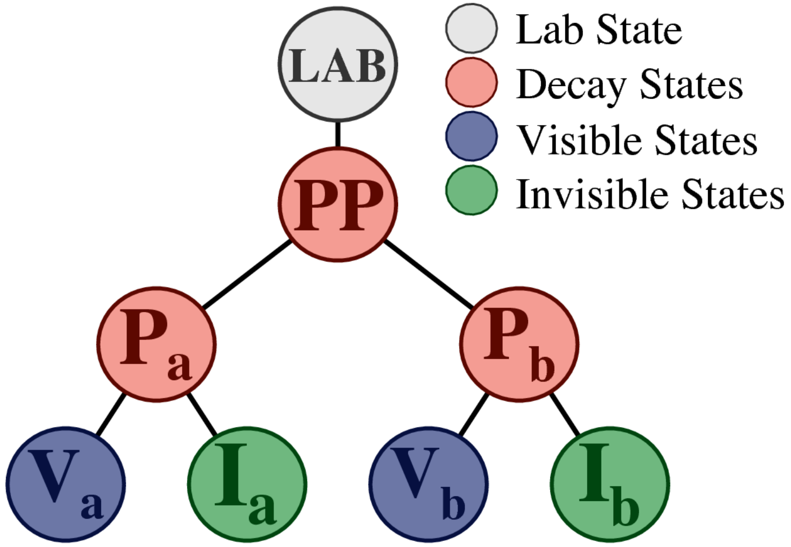
requires also two large-R jets (R = 0.8)

High p_T jets from Initial State Radiation (ISR) jets boost the di-top-squark system

requires also two large-R jets (R = 0.8)

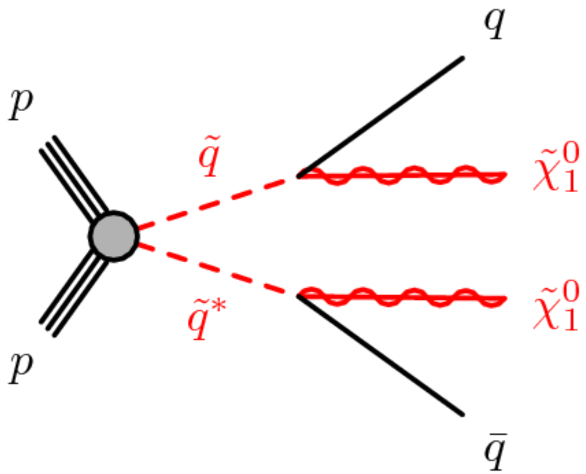
Recursive Jigsaw Reconstruction (RJR) Analyses

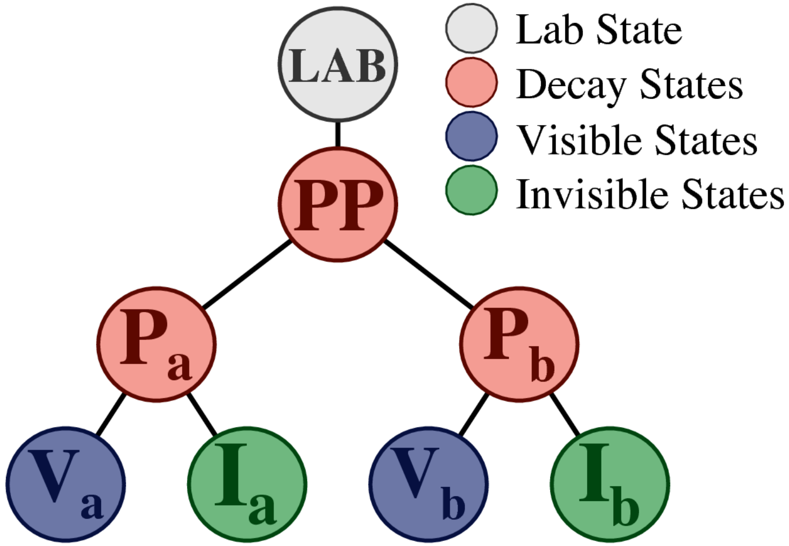
- a method for decomposing measured properties event by event to provide a basis of kinematic variables
- events involving invisible weakly interacting particles present a challenge, as their four-momenta are only partially constrained
- this loss of information from escaping particles constrains the kinematic variable construction
- the RJR technique partially mitigates this loss of information by determining approximations of the rest frames of intermediate particle states in each event



- **PP**: initially produced sparticles
  - **P_a P_b**: assigned to two hemispheres (a and b) and decays to the particles observed in the detector:
    - **V**: visible objects
    - **I**: invisible objects

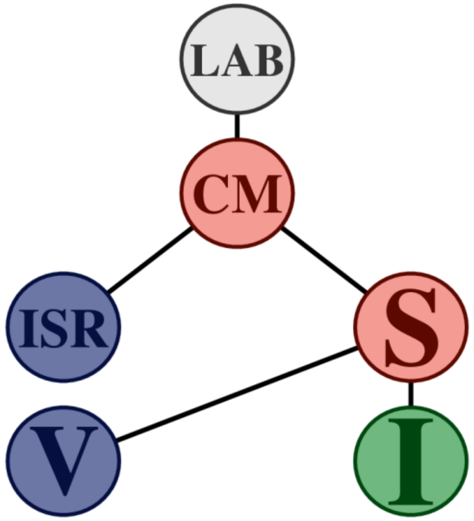
Recursive Jigsaw Reconstruction (RJR) Analyses





- the jets are partitioned into the two hemispheres **a** and **b** by choosing the grouping which minimizes the masses of the two systems
- the remaining unknowns in the event are then associated with the neutralinos ($\mathbf{I_a}$ and $\mathbf{I_b}$):
    - masses
    - longitudinal momenta
    - how each contribute to the $\vec{p}_T^{miss}$
  - determined through subsequent minimizations of the intermediate particle masses appearing in the decay tree

- constructs several rest frames for which all relevant momenta are defined and can be used to construct variables (invariant masses, angles between objects etc.)



If $\tilde{q}$,$\tilde{g}$ are nearly mass degenerate with the $\tilde{\chi}_1^0$

$$E_T^{miss} \sim -\vec{p}_T^{ISR} \times \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{q},\tilde{g}}}$$

Rather than relying on «mono-ISR»-signal, RJR tries to separate ISR objects from sparticle objects

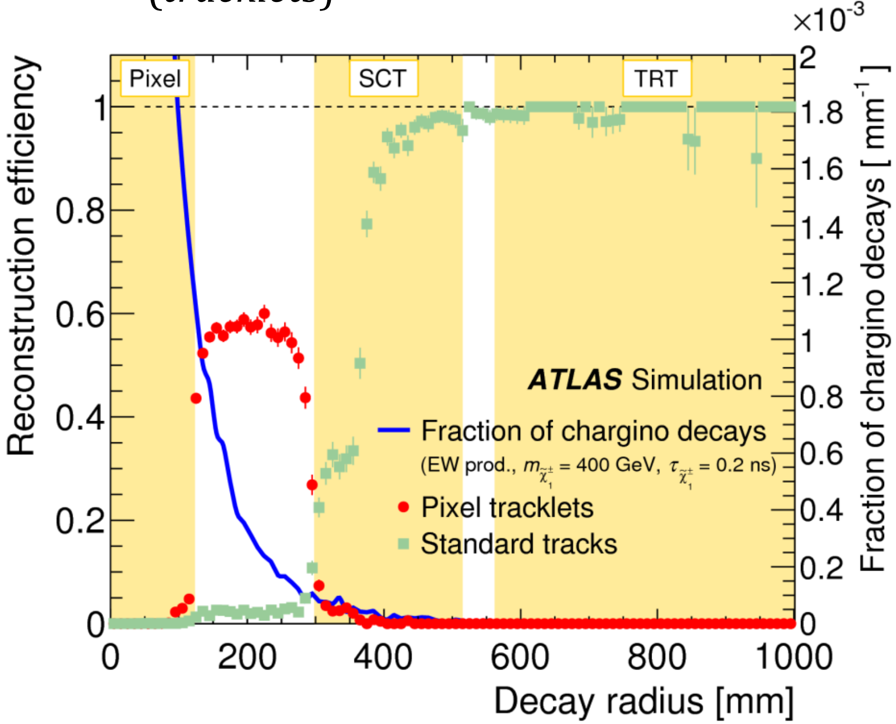
- $p_{\mathrm{T}\,S}^{\mathrm{CM}}$: the magnitude of the vector-summed transverse momenta of all S-associated jets ($|\vec{p}_{\mathrm{T}\,S}^{\mathrm{CM}}|$) and $E_{\mathrm{T}}^{\mathrm{miss}}$ evaluated in the CM frame.
- $R_{\mathrm{ISR}} \equiv \vec{p}_I^{\,\mathrm{CM}} \cdot \hat{p}_{\mathrm{T}\,S}^{\mathrm{CM}} / p_{\mathrm{T}\,S}^{\mathrm{CM}}$: serves as an estimate of $m_{\tilde{\chi}}/m_{\tilde{g}/\tilde{q}}$. This is the fraction of the momentum of the S system that is carried by its invisible system I, with momentum $\vec{p}_I^{\,\mathrm{CM}}$ in the CM frame. As $p_{\mathrm{T}\,S}^{\mathrm{CM}}$ grows it becomes increasingly hard for backgrounds to possess a large value in this ratio – a feature exhibited by compressed signals.
- $M_{\mathrm{T}\,S}$: the transverse mass of the S system.
- N_{jet}^{V}: number of jets assigned to the visible system (V) and not associated with the ISR system.
- $\Delta\phi_{\mathrm{ISR},\,I}$: the azimuthal opening angle between the ISR system and the invisible system in the CM frame.

(Meta-)Stable SUSY particles

Reconstruction technique	SUSY scenario(s)	Data and Energy	Ref.
Non-pointing and delayed photons	Gauge-Mediated Symmetry Breaking (GMSB)	$20fb^{-1}$@8TeV	Phys. Rev. D. 90, 112005 (2014)
Displaced vertices	R-hadron models	$33fb^{-1}$@13TeV	1710.04901
Large ionization losses and slow propagation velocities		$3.3fb^{-1}$@13TeV	1606.05129
Disappearing tracks	Anomaly-Mediated Supersymmetry Breaking (AMSB)	$36fb^{-1}$@13TeV	1712.02118
Large ionization losses	mini-split SUSY, AMSB	$3.3fb^{-1}$@13TeV	Phys. Rev. D 93, 112015 (2016)

Disappearing Tracks

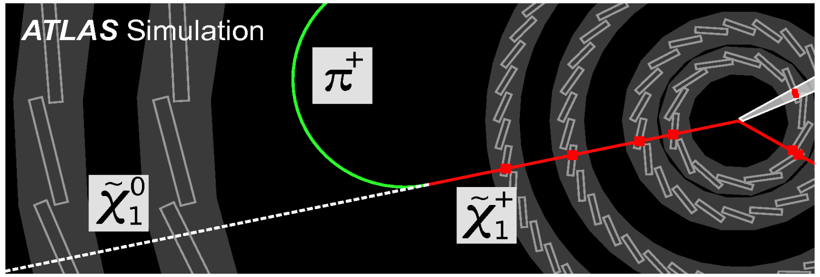
- Large improvements in analysis compared with Run1 thanks to the new IBL
  - Run1: sensitive to charginos decaying at radii > 30 cm. (*short tracks*)
  - Run2: sensitive down to radii of ~12 cm. (*tracklets*)



For more results on long lived sparticles see Jeanette's talk later today

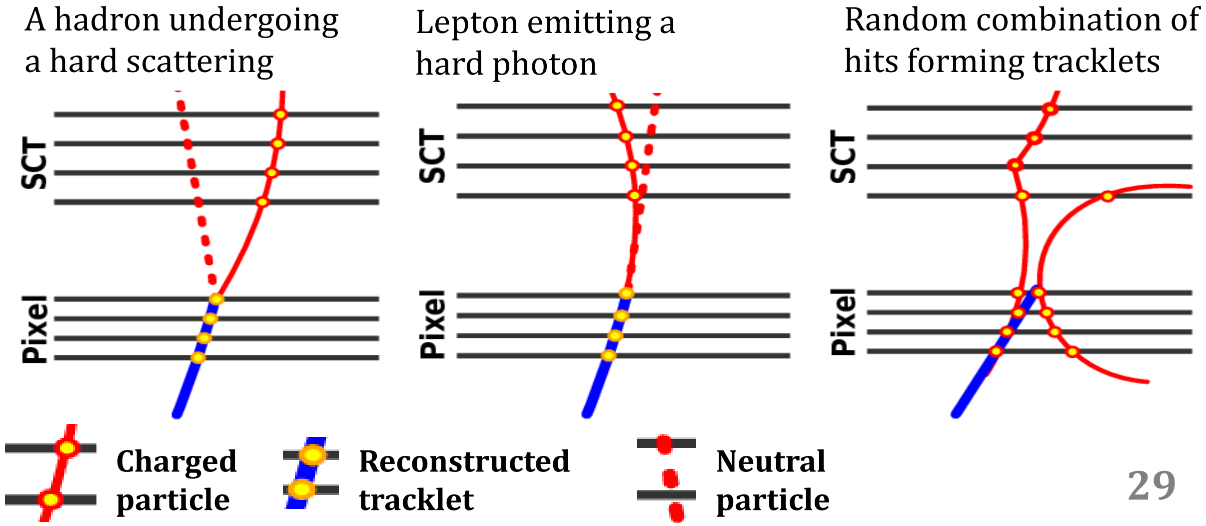
Track/tracklets:

1. **tracks**: reconstructed using standard algorithms (> 7 hits in silicon detectors)
2. **tracklets**: track reconstruction is rerun with looser criteria (≥ 4 hits in Pixel) using only hits not associated to any tracks
   - extrapolated to SCT and TRT and any compatible hits are assigned to the tracklet
   - required to have $p_T > 5$ GeV and $|\eta| < 2.2$



Signal: a chargino decaying a measurable distance (> 12 cm) from the interaction point

Backgrounds:

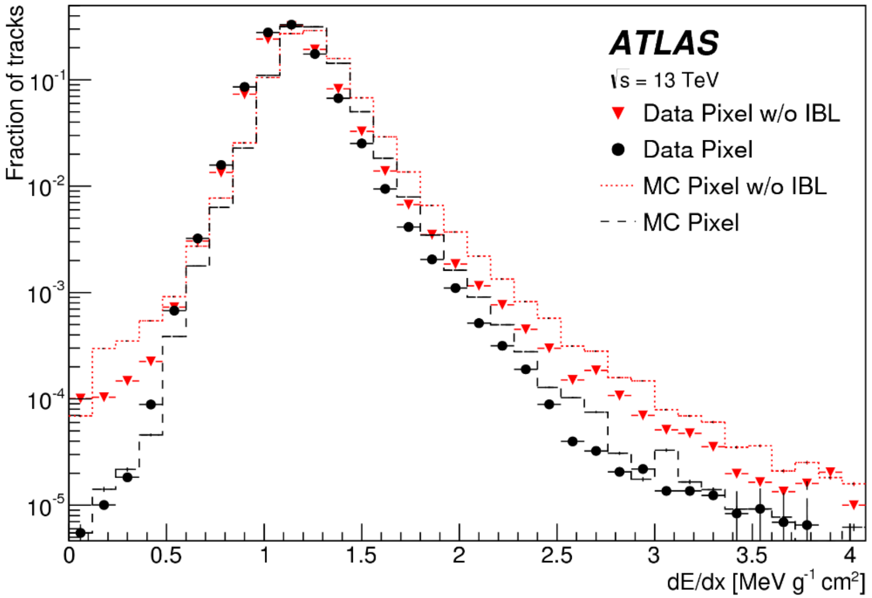


Large Ionizations Losses

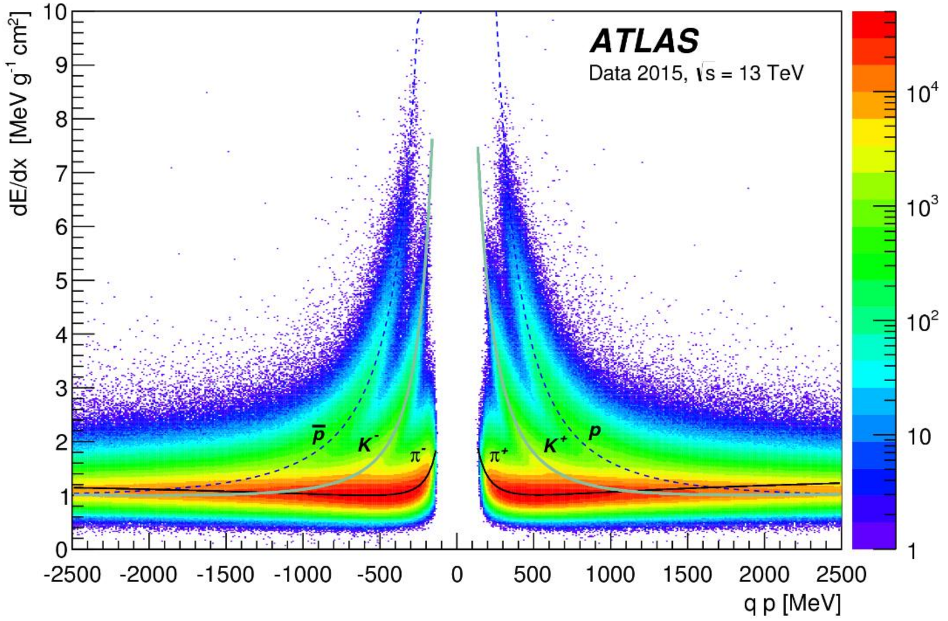
- the average energy loss of a massive, charged particle in matter is expected to follow the Bethe-Bloch distribution
  - from measurements of dE/dx, βγ can be estimated from…

$$\boxed{\frac{dE}{dx}(\beta\gamma)_{MPV} = \frac{p_1}{\beta^{p_3}}\ln(1 + [p_2\,\beta\gamma]^{p_5}) - p_4}$$

  - … and mass found through $m = \frac{p}{\beta\gamma}$
  - valid in $0.3 < \beta\gamma < 1.5$
    - overlaps the expected range of long lived particles produced at the LHC (100 – 1600 GeV)
  - $p_1,\ldots,p_5$ are calibration constants measured in data using low-momentum pions, kaons and protons



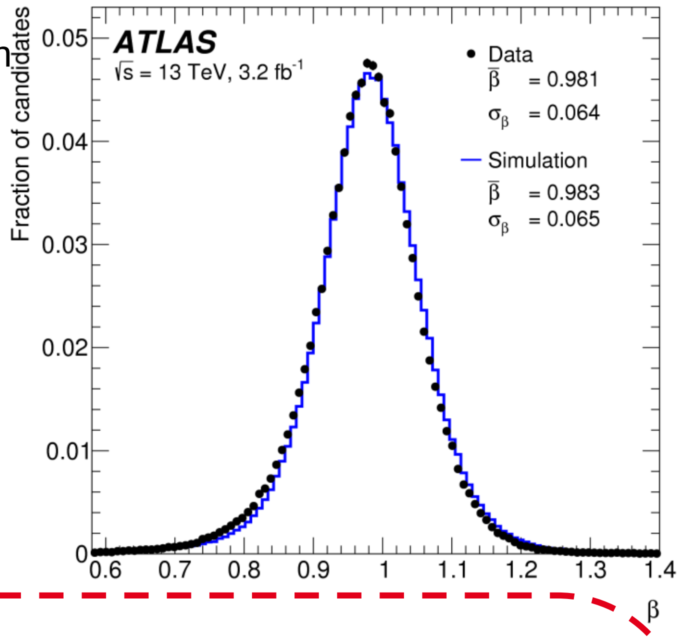
the search sensitivity has been considerably extended since Run1 thanks to the new pixel layer (IBL)



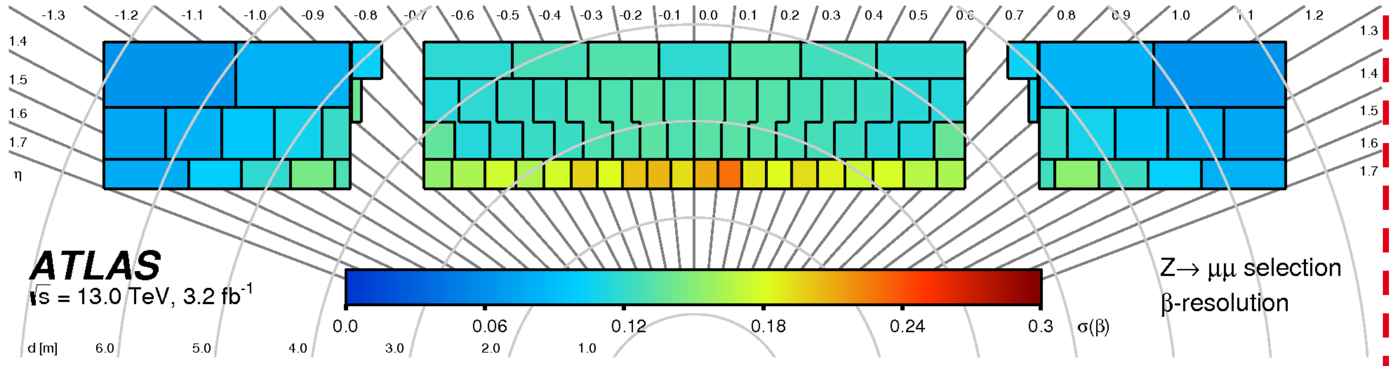
dE/dx versus charged signed momentum for minimum bias event tracks

Slow Propagation Velocities

Distribution of β for data and simulation in a $Z \to \mu\mu$ selection



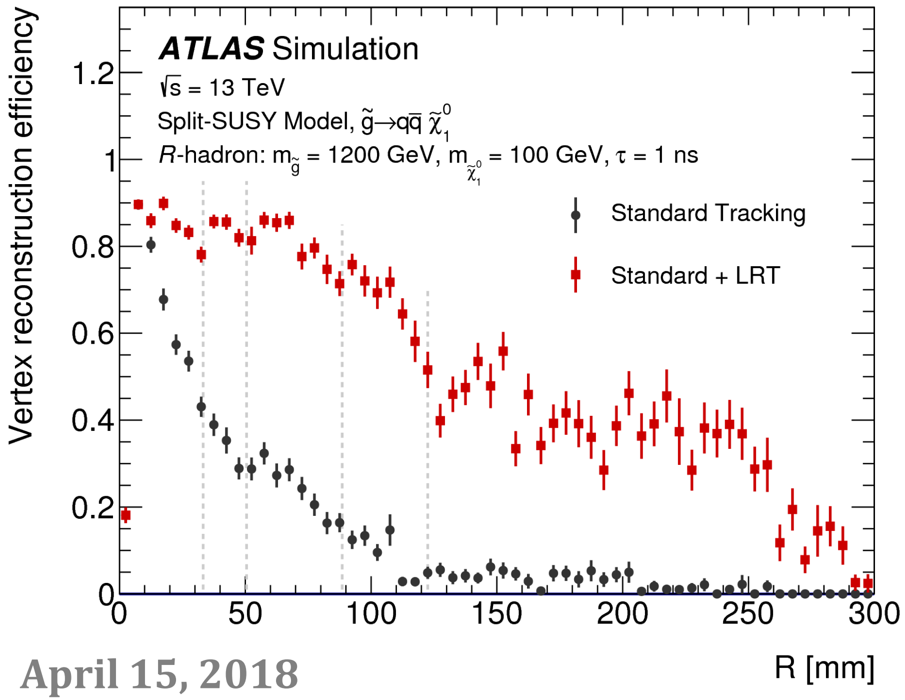
- charged particles with a speed measurably slower than c can be identified and their mass determined from their measured speed (β) and momentum, using the relation $m = \frac{p}{\beta\gamma}$
  - estimation of β from time-of-flight measurements relies on timing and distance information from the tile-calorimeter cells crossed by the extrapolated candidate track
- five cell-by-cell β corrections are applied
  1. minimise the η dependence of β within each cell (shifts of ~0.05 in β at high η)
     - actual trajectory of the extrapolated track in each calorimeter cell is used to re-calculate the distance-of-flight
  2. correction on MC to account for timing mismodelling due to imperfect simulation (shifts of ~0.1 in β at high η)
  3. compensate for the fact that the readout of the tile calorimeter is optimised for in-time signals (shifts of ~0.05 in β at high η)
  4. cell-time smearing to adjust the cell-time resolution in simulation to that in data
  5. uncertainty in the single β measurements is scaled up by ~12% based on the requirement that the pull distribution to be a unit Gaussian



finally the β associated with the particle is estimated as a weighted average, using the β measurement in each traversed cell and its uncertainty, σ_β

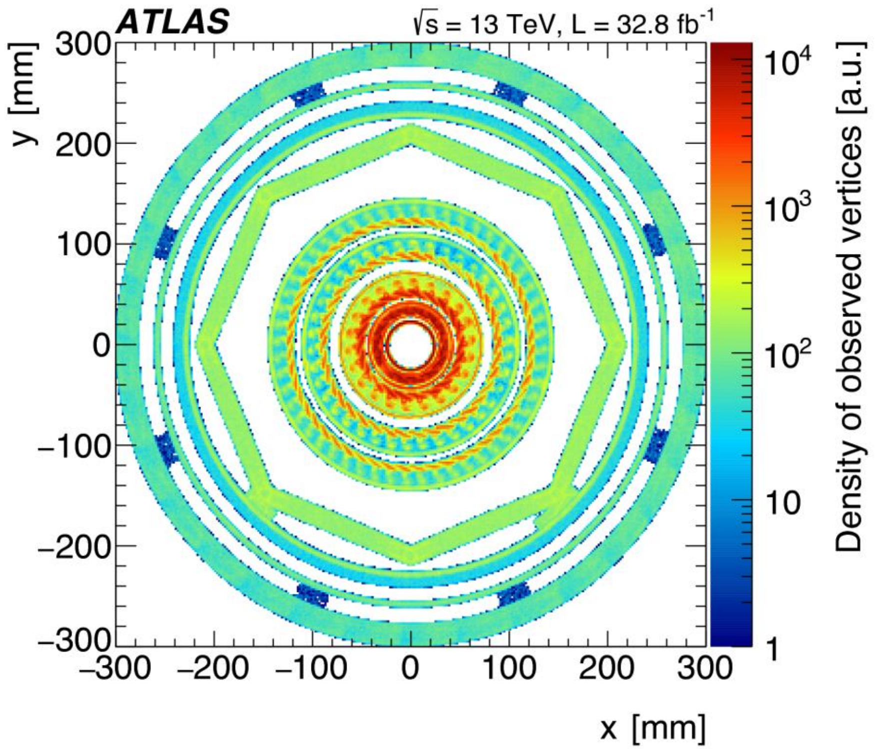
Displaced Vertices (DV)

- massive particles with lifetimes in the ps to ns range could decay in the inner tracker volume of ATLAS
  - the decay products often contain several electrically charged particles, which can be reconstructed as tracks
  - a displaced vertex can be reconstructed by using dedicated tracking and vertexing techniques



Displaced tracks and vertices:

- standard track reconstruction puts relatively tight constraints on the transverse (d_0) and longitudinal (z_0) impact parameters (IP) of track candidates
  - $|d_0| < 10$ mm and $|z_0| < 250$ mm
- an additional *large-radius tracking* (LRT) algorithm with looser criteria is used to reconstruct DV
  - using hits not associated to track reconstructed by standard algorithms
  - increased IP cuts: $2 < |d_0| < 300$ mm and $|z_0| < 1500$ mm
  - relaxed criteria of hits shared with several tracks



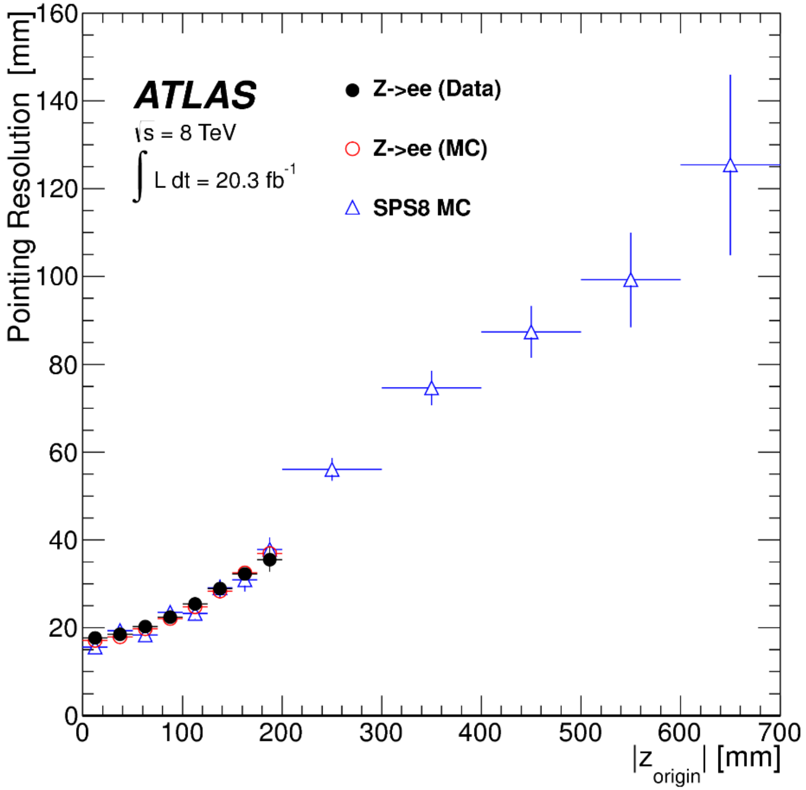
Backgrounds:

- hadronic interactions in material rich regions – excluding 42 % of the fiducial detector volume
- veto vertices matching track multiplicities and reconstructed masses expected from K_S^0 and Λ^0 decays

Non-Pointing and Delayed Photons

- photons stemming from long lived particle decays may show up in many SUSY scenarios
  - these photons may then be *non-pointing* and/or *delayed*

non-pointing photons:

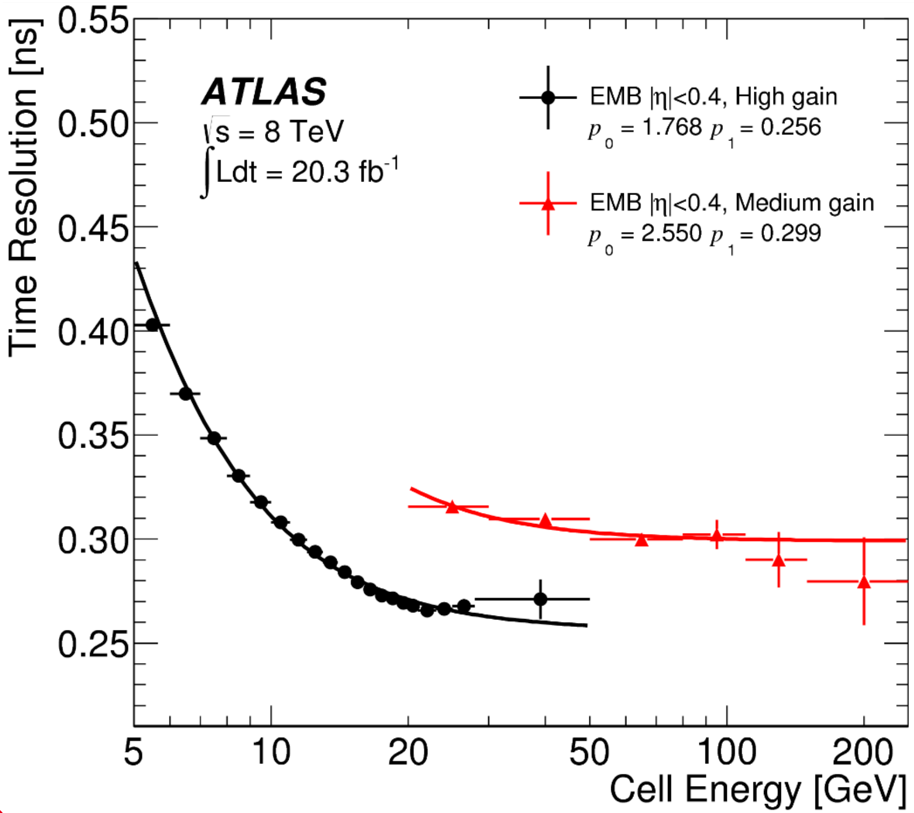


- the flight direction of photons are measured precisely using the three different longitudinal segments of the LAr EM calorimeters
- the direction is compared with the direction back to the PV
  - separation of the direction along the beamline defines $|\Delta z_\gamma|$

The expected pointing resolution as a function of $|z_{origin}|$ for MC (using MC gen. level information to determine z_{origin}) and $Z \rightarrow ee$ events (using z_{PV} as z_{origin})

delayed photons:

- arrival time of the photon can be measured by the LAr calorimeter and defined as the the arrival time t_γ of a photon
  - t_γ = 0: expected from prompt photons
  - t_γ > 0: photons from non-prompt LLP decays



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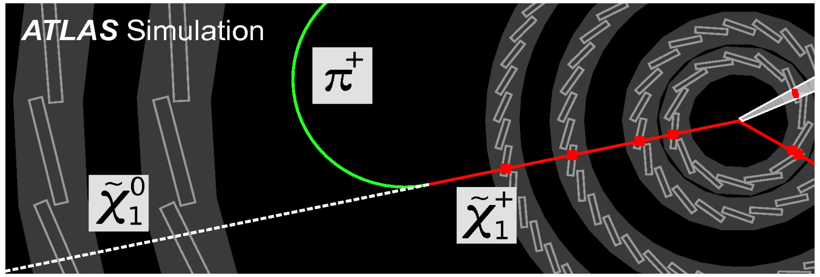
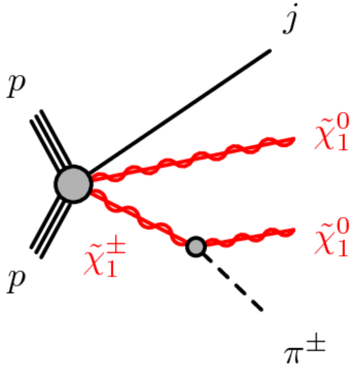
Disappearing Tracks





In a pure wino LSP model, for $\tau_{\tilde{\chi}_1^\pm} \sim 0.2$ ns, i.e. $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim 160$ GeV, charginos of a mass up to 460 GeV are excluded