Reconstruction techniques in SUSY searches in the ATLAS experiment

SUSY2019 – Corpus Christi - Texas

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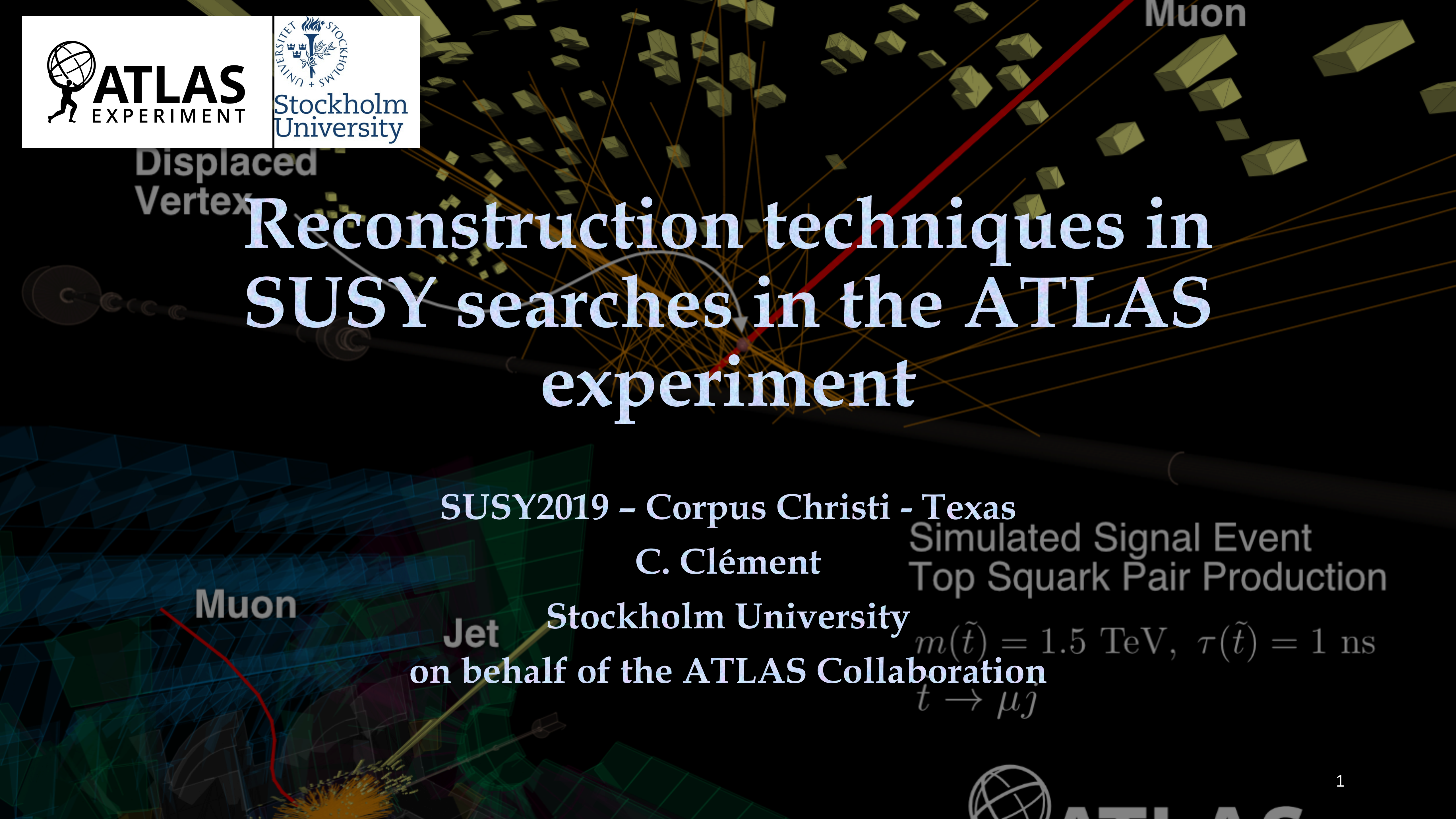
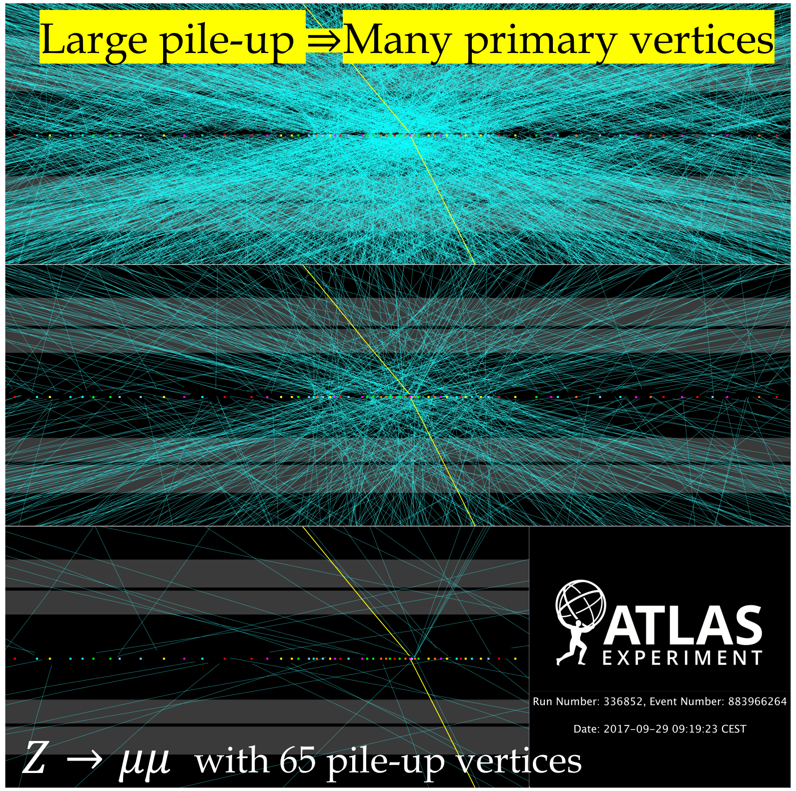
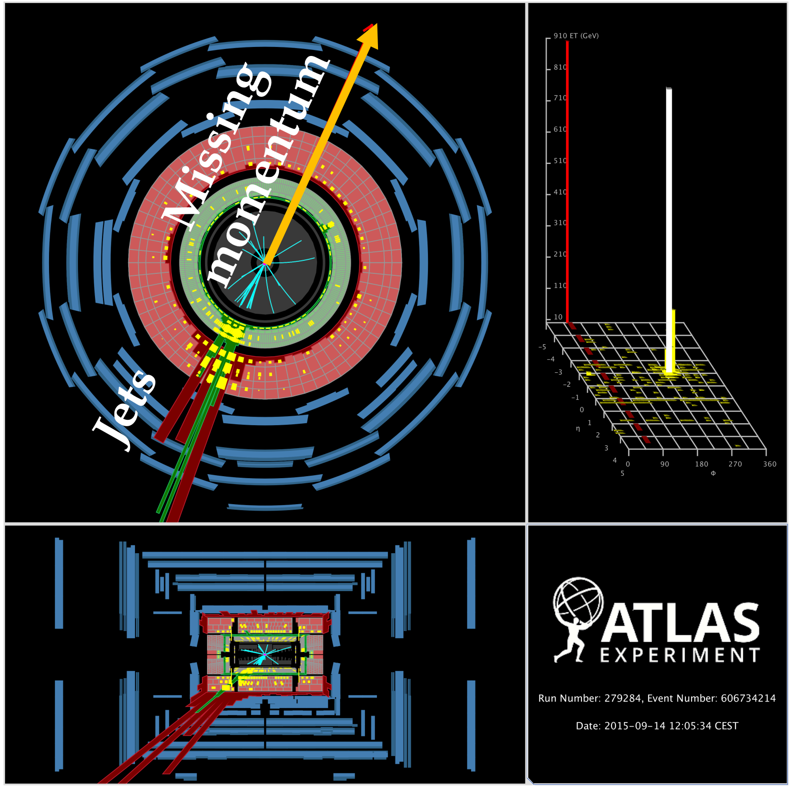
on behalf of the ATLAS Collaboration

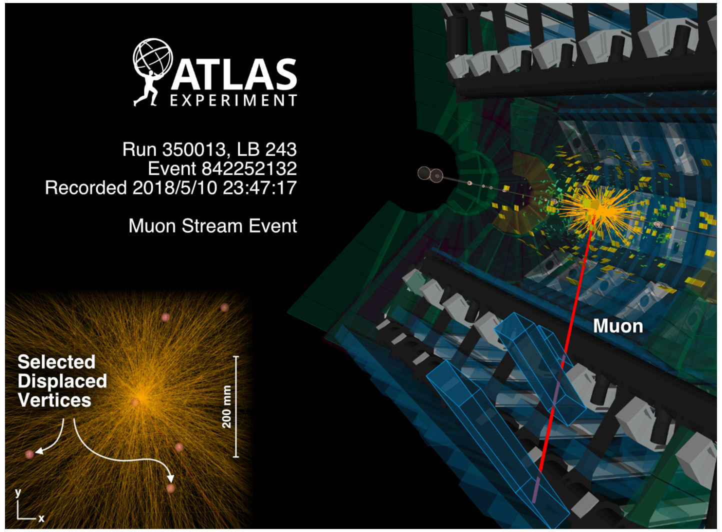


Signatures of SUSY

- Experimentally requires all classical collider signatures: leptons, jets, missing momentum, heavy flavor, ...
- Also large variety of less classical but very interesting & challenging signatures
- Compressed, boosted, R-parity violating scenarios
- Soft leptons, Missing momentum in presence of many objects, absence of jets, displaced vertices, boosted particles...







ATLAS Public event displays

Compressed Spectra SUSY and Very Low p_T Leptons

ATLAS-CONF-2019-014

Lighest sparticles $\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$

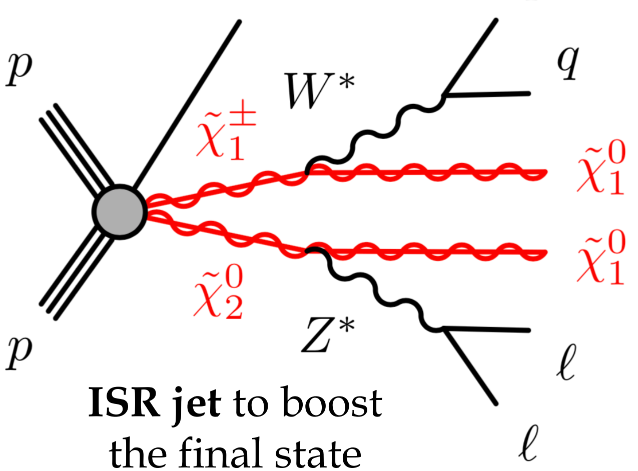
Scenario I "Higgsino" $\mu \ll |M1|, |M2|$

Triplet of Higgsino like gauginos

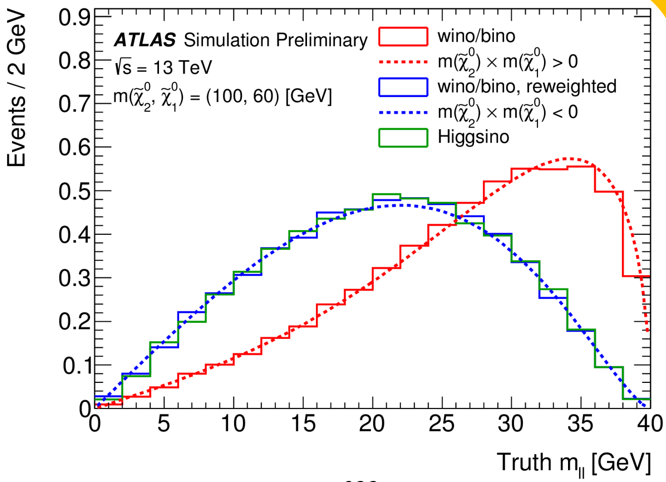
Scenario II "Wino" $|M1| < |M2| \ll \mu$

Key discriminating variable $m_{\ell\ell} < m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$

L=139 fb^{-1}



ISR jet to boost the final state

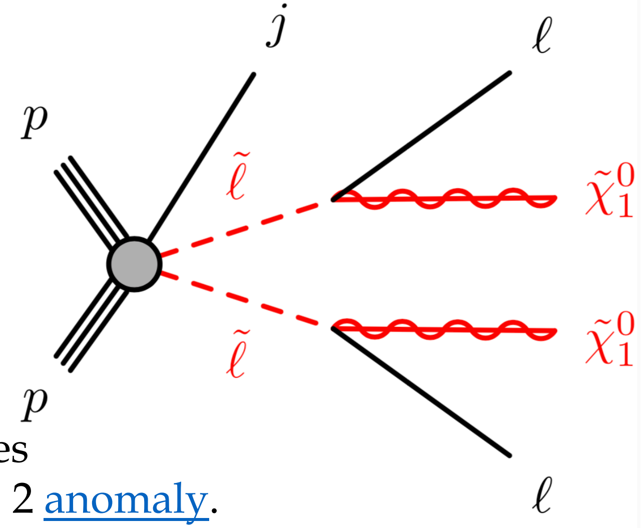


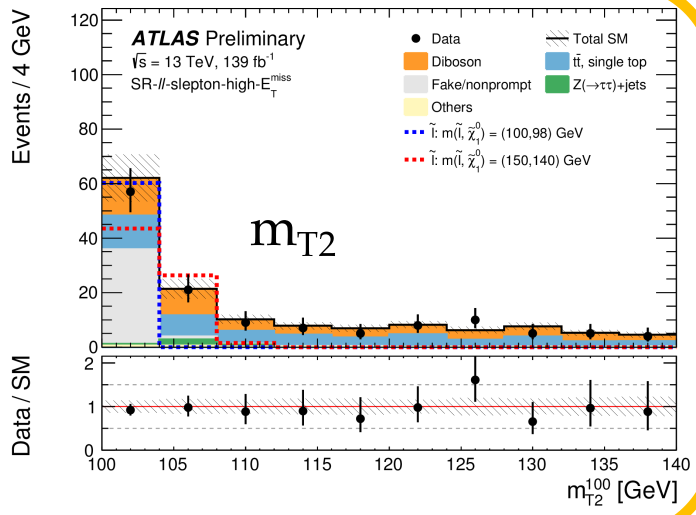
$m_{\ell\ell}$

Scenario III "Slepton" Lighest sparticles $\tilde{\chi}_1^0, \tilde{\ell}$

Slepton slightly heavier than a bino-like LSP

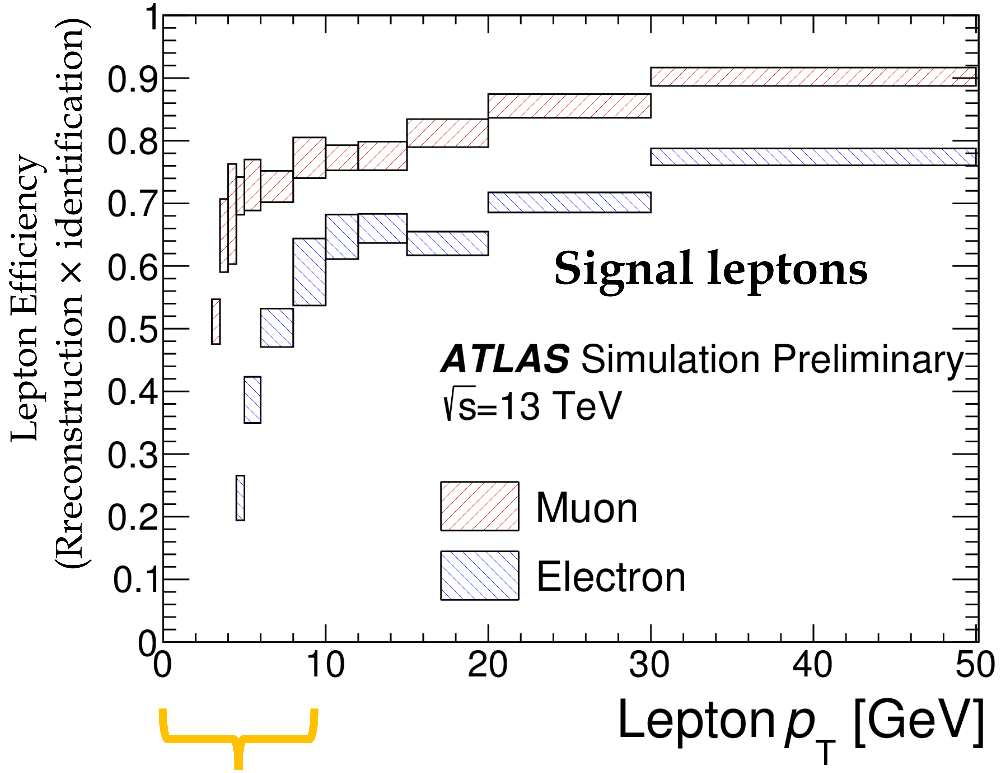
Key discriminating variable m_{T2}





Model can explain both dark matter thermal relic densities through coannihilation channels, as well as the muon g − 2 anomaly.

Extends sensitivity down to Δm ~2.6 GeV (Higgsino) ~2 GeV (Wino) and ~670 MeV (Slepton).



Very low efficiency

Signal leptons have very low efficiency at low lepton p_T
⇒ Define complementary signal region **SR1ℓ1T = 1 signal lepton+1 signal track**

Signal tracks

$p_T > 1$ GeV, $|\eta| < 2.5$, *Tight-Primary* working point.

Within $\Delta R < 0.01$ of e or μ failing signal lepton cuts.

Track and e/μ candidate p_T matching within 20%

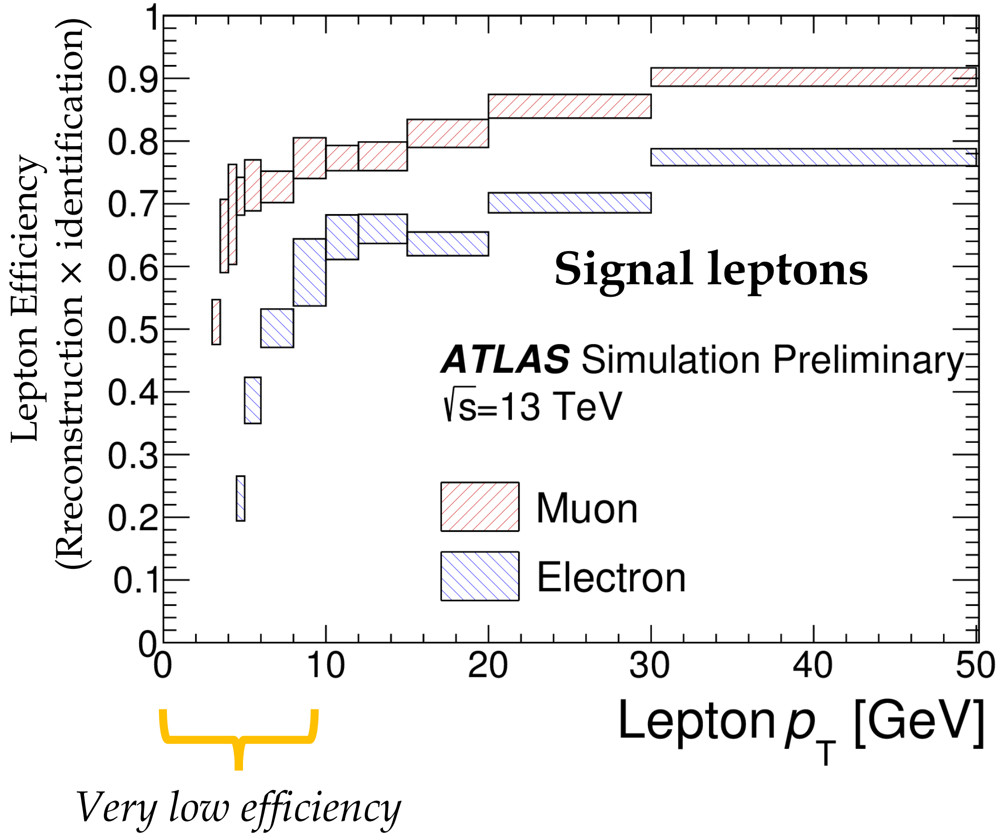
Isolation from jets and other activity:

$$\Delta R(track,jets) > 0.5$$

$$\sum_{\Delta R < 0.3} p_T \text{ (preselected track)} < 0.5$$

Track from Hard Scatter (HS) primary vertex:

$$d_0 \text{ significance} < 3 \ \& \ |z_0 \sin\theta| < 0.5 \text{ mm}$$



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Signal tracks provide

- +20% efficiency for e with $3 < p_T < 4$ GeV
- +35% efficiency for μ with $2 < p_T < 3$ GeV

Monte Carlo to Data Corrections rederived specifically for the signal tracks

Track-lepton matching efficiency measured in data with J/ψ events decaying to signal lepton + preselected track.

Track isolation corrections measured using Z events decaying to signal lepton+track matched to a reconstructed lepton candidate.

Track corrections compatible with 1.

ATLAS-CONF-2019-014

Background in SR1ℓ1T

Events with one prompt lepton + one track from hadrons, reconstructed from spurious hits...

Control sample

Same selections as SR1 ℓ 1T SR but **Same Sign**.
Data in SS sample used directly as the estimate of background.

Signal region 1ℓ1T

Variable	$1\ell 1T$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 200
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{lep}}$	> 30
$\Delta\phi(\mathrm{lep}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	< 1.0
Lepton or track p_{T} [GeV]	$p_{\mathrm{T}}^{\mathrm{track}} < 5$

Validation region 1ℓ1T

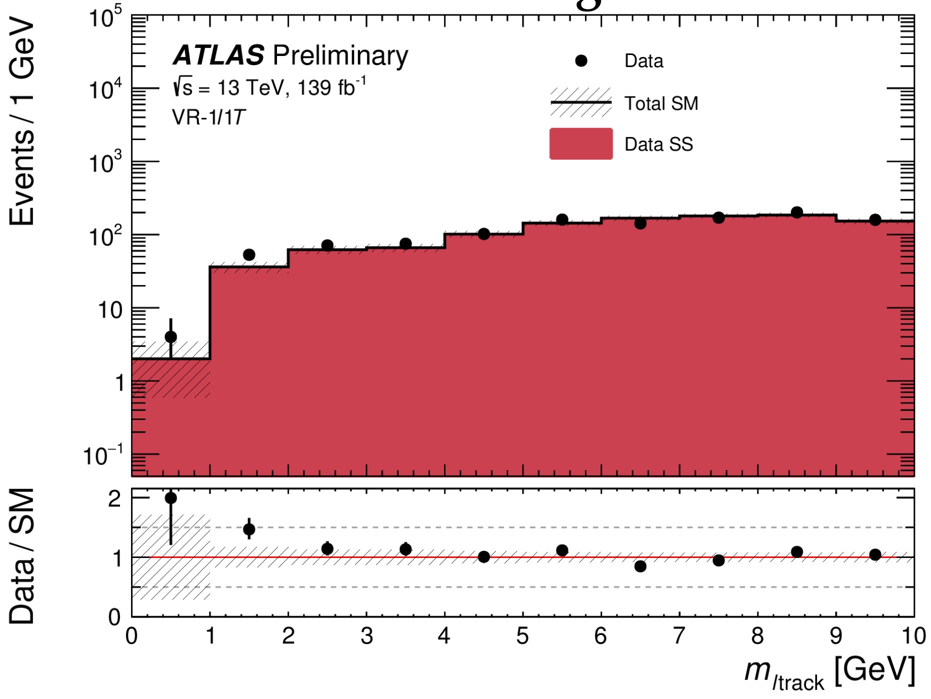
Derived from Signal region but

$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{lep}} > 15$

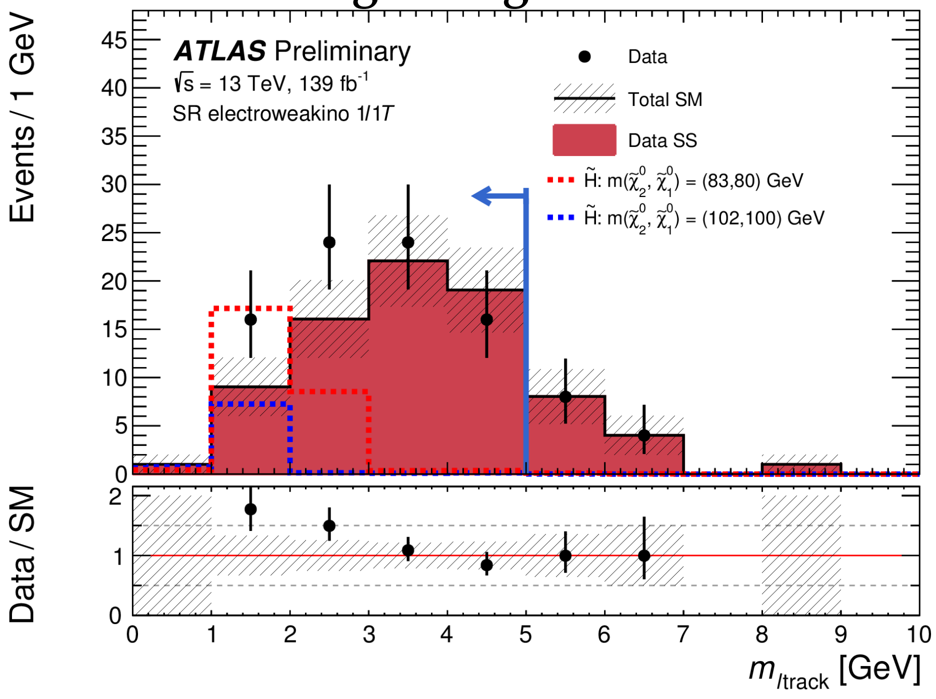
$\Delta\phi(\ell, p_{\mathrm{T}}^{\mathrm{miss}}) > 1.5$

No upper bound on $\Delta R_{\ell,\mathrm{trk}}$

Validation region 1ℓ1T



Signal region 1ℓ1T



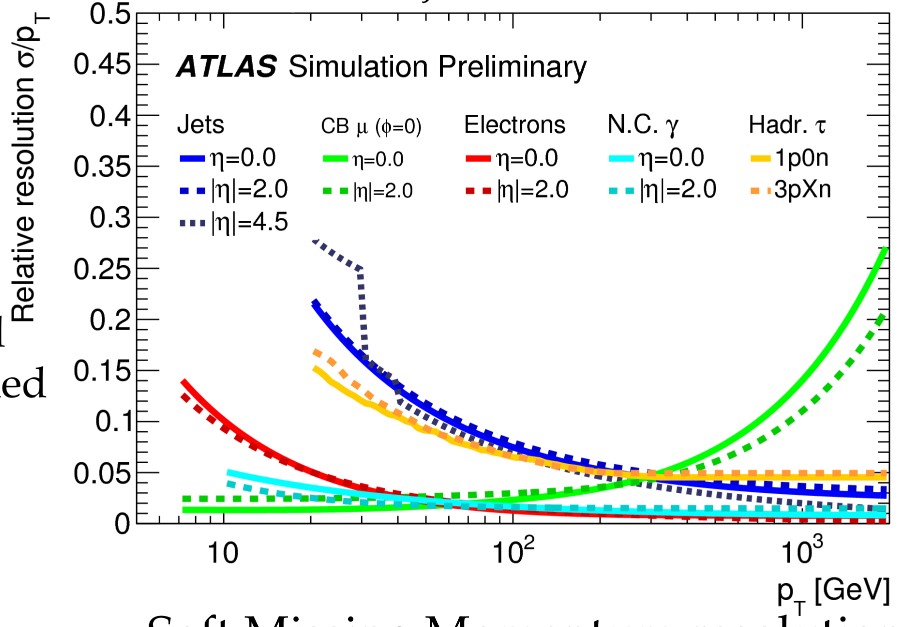
See also
Sezen Sekmen's talk tomorrow

ATLAS-CONF-2018-038

Object-Based Missing Momentum Significance

$$\boldsymbol{p}_T^{miss} = -\Big(\underbrace{\sum_{i\in\text{muons}} \boldsymbol{p}_\text{T}{}^i + \sum_{i\in\text{electrons}} \boldsymbol{p}_\text{T}{}^i + \sum_{i\in\text{photons}} \boldsymbol{p}_\text{T}{}^i + \sum_{i\in\text{hadronic }\tau} \boldsymbol{p}_\text{T}{}^i + \sum_{i\in\text{jets}} \boldsymbol{p}_\text{T}{}^i}_{\text{Hard objects}} + \underbrace{\sum_{i\in\text{Soft Term}} \boldsymbol{p}_\text{T}{}^i}_{\text{In ATLAS computed from Tracks not assigned to a hard object}}\Big)$$

Hard object resolutions



Each object has its own p_T- and η-dependent resolution.
⇒ how significant is the missing momentum wrt. all known object resolutions in the particular topology of a given event?

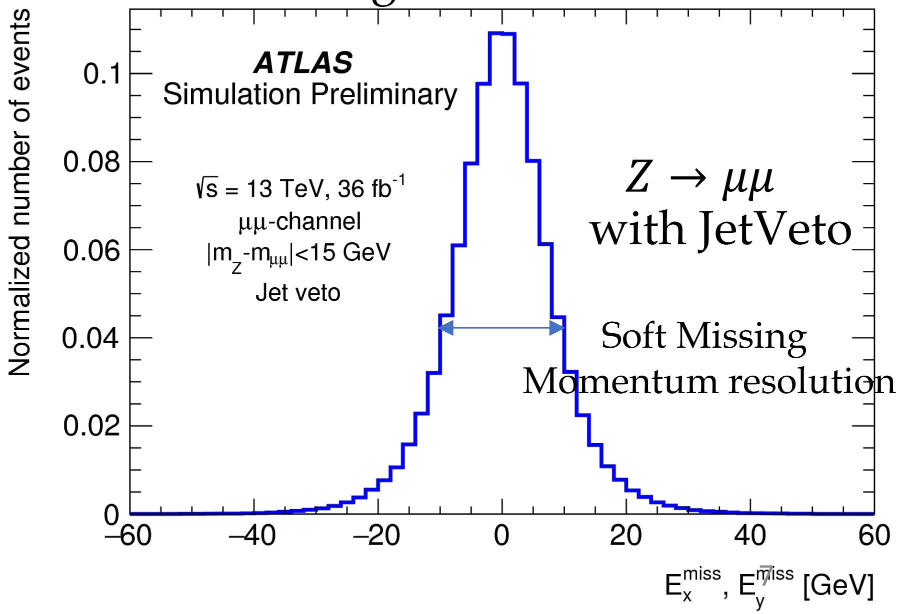
Object-based Missing Momentum Significance, can be derived from first principles

$$\mathcal{S} = \sqrt{\frac{|\mathbf{p}_\text{T}^\text{miss}|^2}{\sigma_\text{L}^2(1-\rho_\text{LT}^2)}}$$

σ_L^2 total object resolution along the direction of $\boldsymbol{p}_\text{T}^\text{miss}$

ρ_LT^2 correlation between the longitudinal and transverse direction resolutions

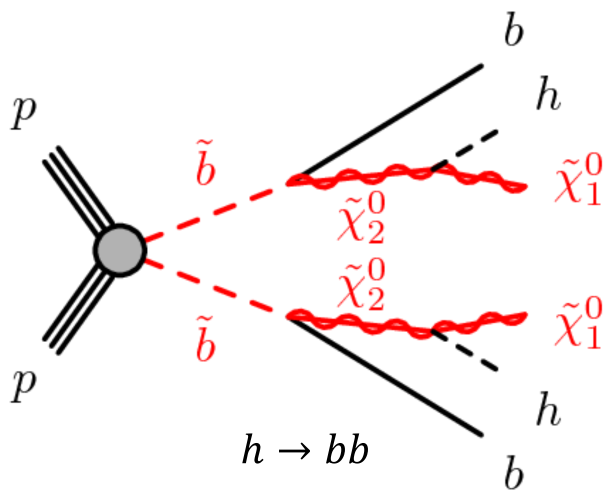
Soft Missing Momentum resolution

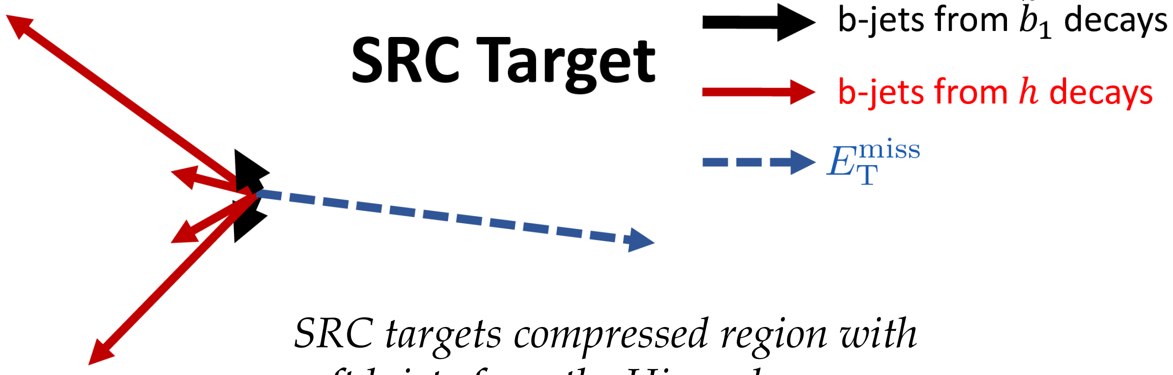


More details see also:
Xuanhong Lou's talk A key variable: Missing Transverse Energy - reconstruction, pile-up and its significance

Missing Momentum Significance & Sbottom Search

ATLAS-CONF-2019-011



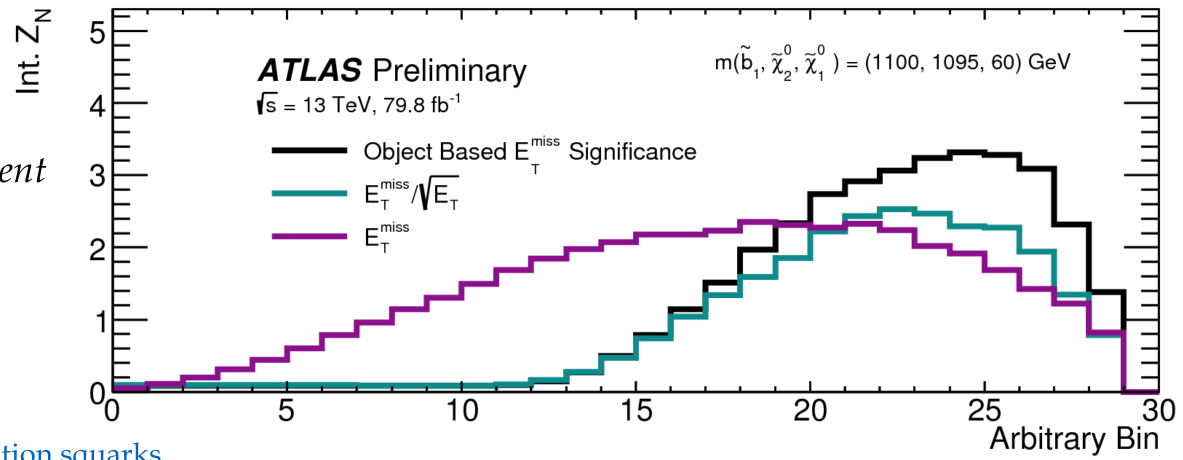


SRC targets compressed region with soft b-jets from the Higgs decays.

Higgs-pole annihilation scenarios with $m_{\tilde{\chi}_1^0} \sim m_h/2$ - Here work with $m_{\tilde{\chi}_1^0} = 60$ GeV (Dark Matter relic density motivated)

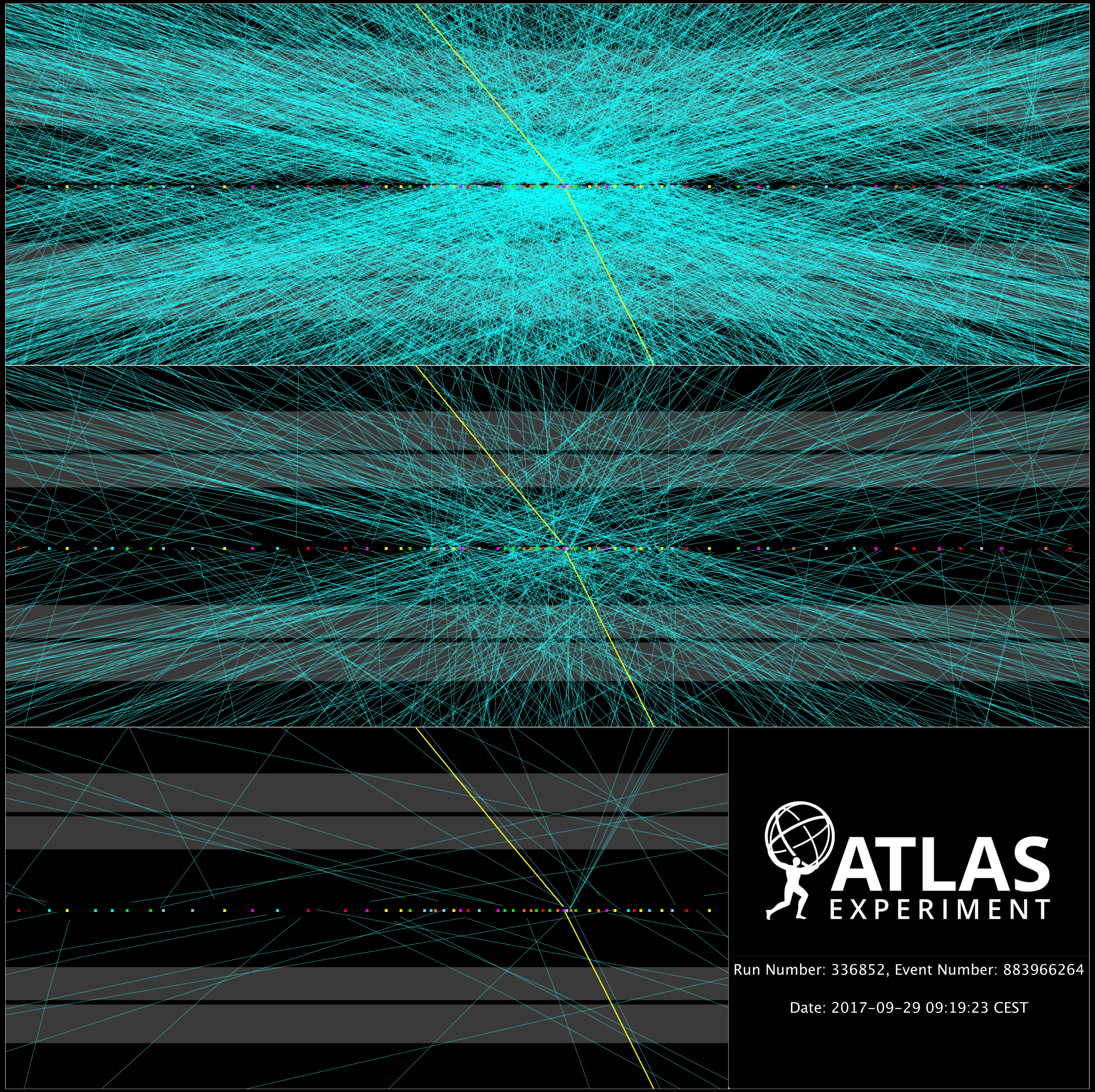
ATLAS-CONF-2018-040

Significant discrimination improvement with the object-based significance



More details see also John Anders' talk on Searches for direct pair production of third generation squarks

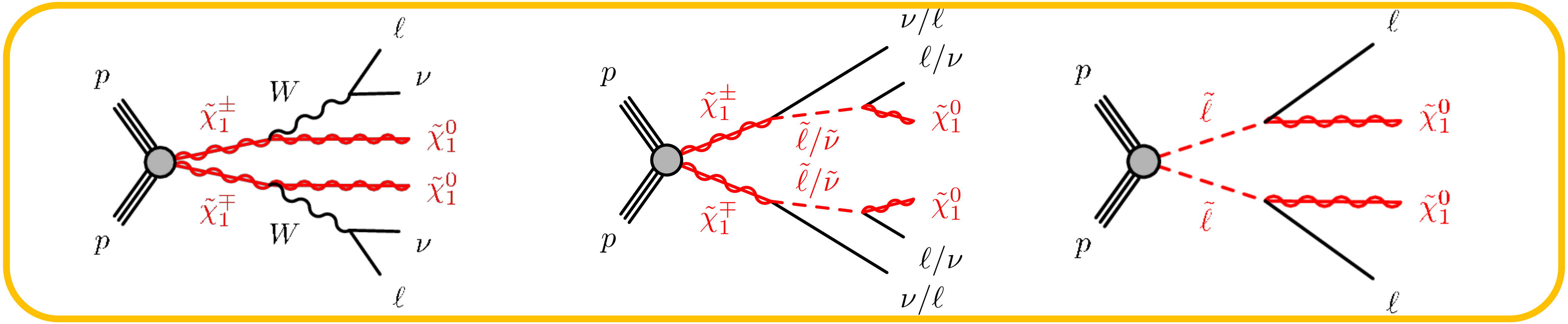
Pile-up Jet Suppression or "*knowing your hard scatter jets*"...



Many p-p collisions...

Hard Scatter "HS" PV defined by PV with highest Σp_T^2 of the tracks

Pile-up Jet Suppression or "*knowing your hard scatter jets*"...

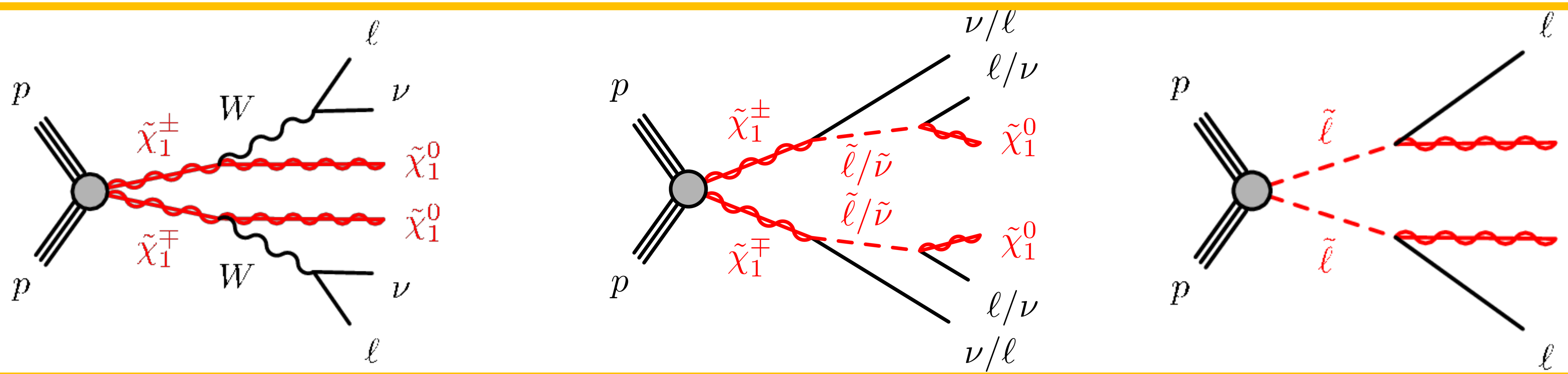


No hard scatter jets expected in final state $\Rightarrow$
Naively perform analysis with a jet veto. Extend to dedicated SR bin with 1 HS jet for additional sensitivity.

$\Rightarrow$ Need to make sure that we are counting jets from the **hard-scatter** PV and not pile-up jet...

$\Rightarrow$ Must suppress jets arising from pile-up vertices.
Also important and used when computing the Missing Transverse Momentum.

Pile-up Jet Suppression or "*knowing your hard scatter jets*"...



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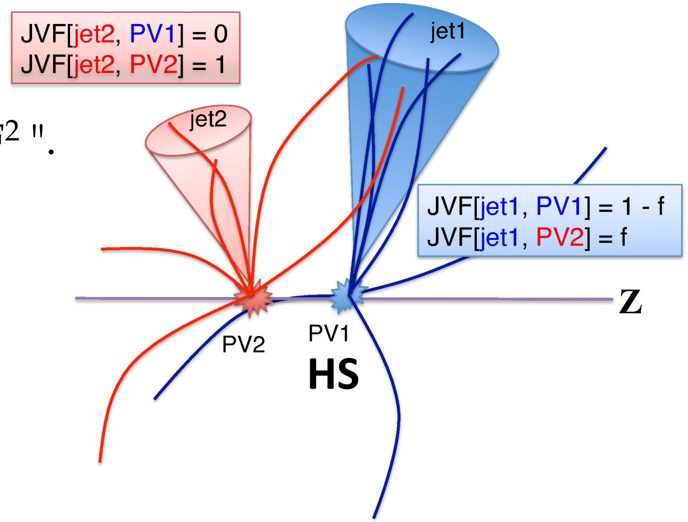
⇒ Must suppress jets arising from pile-up vertices.
Also important and used when computing the Missing Transverse Momentum.

Until recently all analyses applied pile-up removal up to p_T of 60 GeV.

⇒ Now extend to 120 GeV in **139 fb^{-1}** SUSY analyses, eg. in sbottom+higgs

Central pile-up jets removal: use Tracking



Compute fraction of total track momentum inside jet that is associated to the HS PV[1] = "corrJVF[2] ".

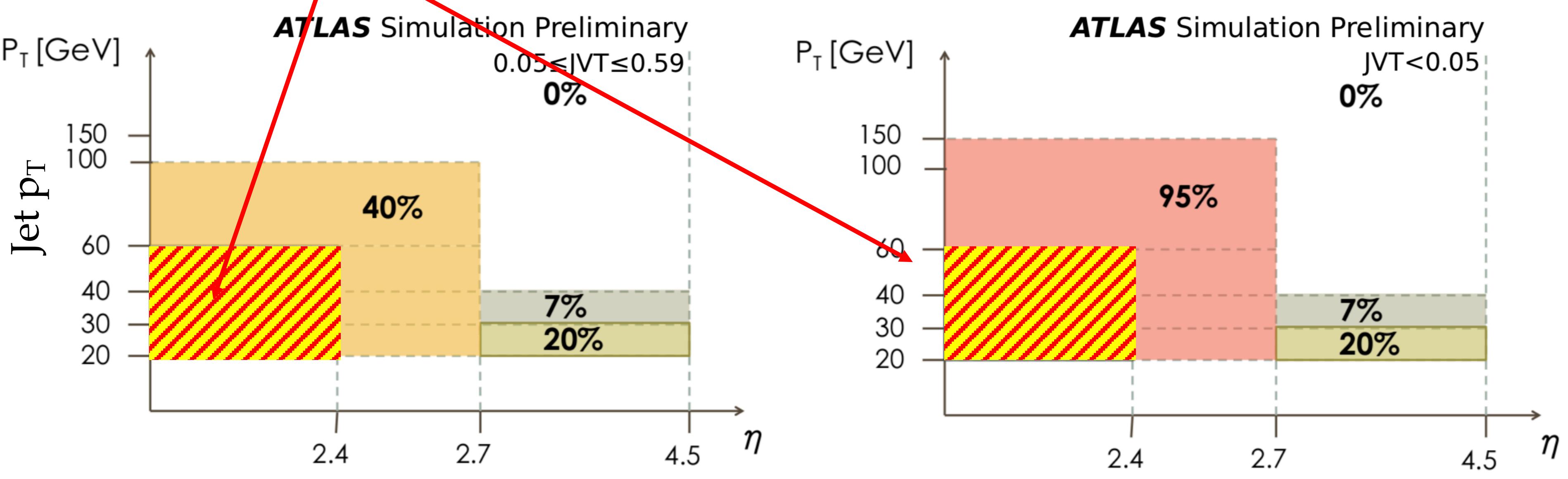
Compute total HS track momentum inside jet over calibrated jet p_T (R_{pT})

Jet Vertex Tagger = 2D-likelihood with R_{pT} and corrJVF

Old Standard: **remove jets with p_T< 60 GeV and JVT<0.59 and $|\eta|$<2.4**

arXiv:1510.03823

JVT<0.59



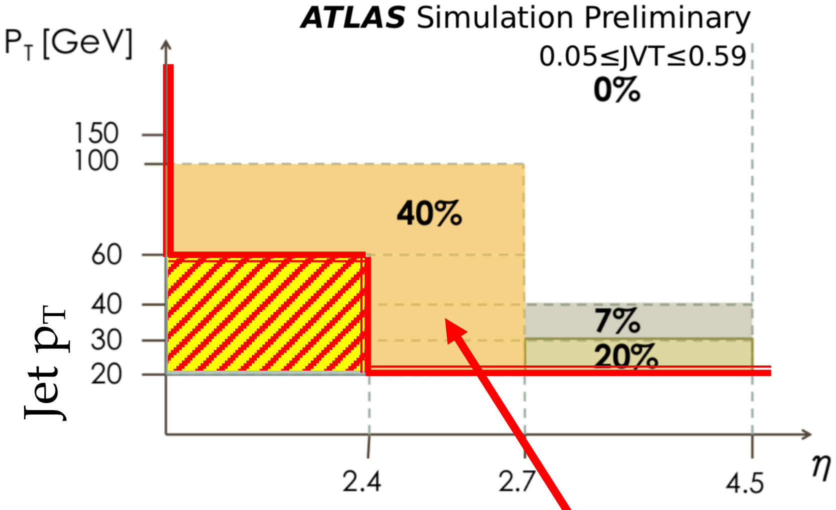
[1] Hard Scatter PV defined by highest Σp_T^2

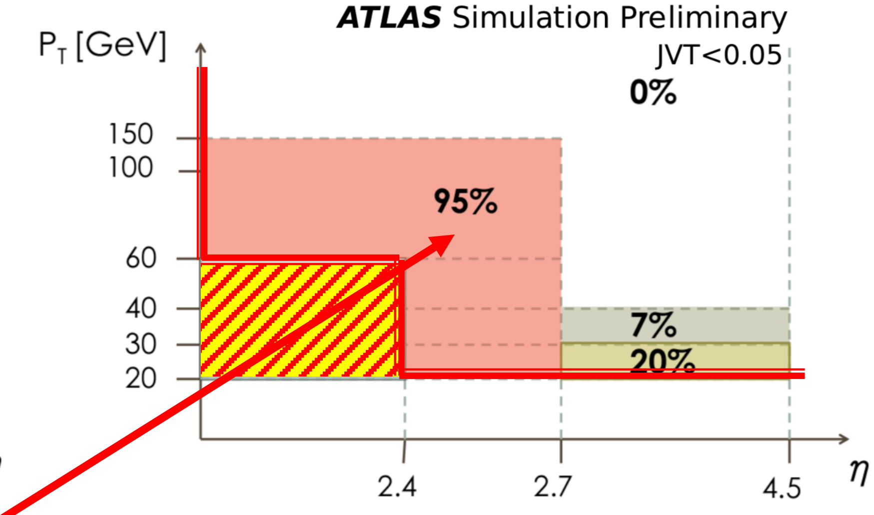
Percents indicate fraction of pile-up jets in Z+1 jet Monte Carlo

[2] Corrected Jet Vertex Fraction

$$\text{corrJVF} = \frac{\sum_m p_{T,m}^{\text{track}}(\text{PV}_0)}{\sum_l p_{T,l}^{\text{track}}(\text{PV}_0) + \frac{\sum_{n\geq 1}\sum_l p_{T,l}^{\text{track}}(\text{PV}_n)}{(k\cdot n_{\text{track}}^{\text{PU}})}}$$

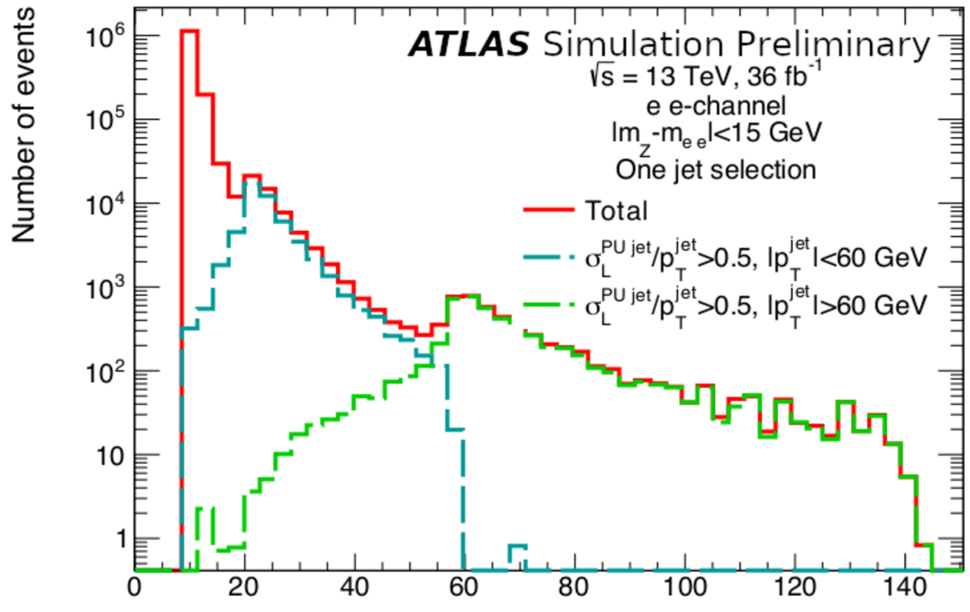
ATLAS-CONF-2018-038



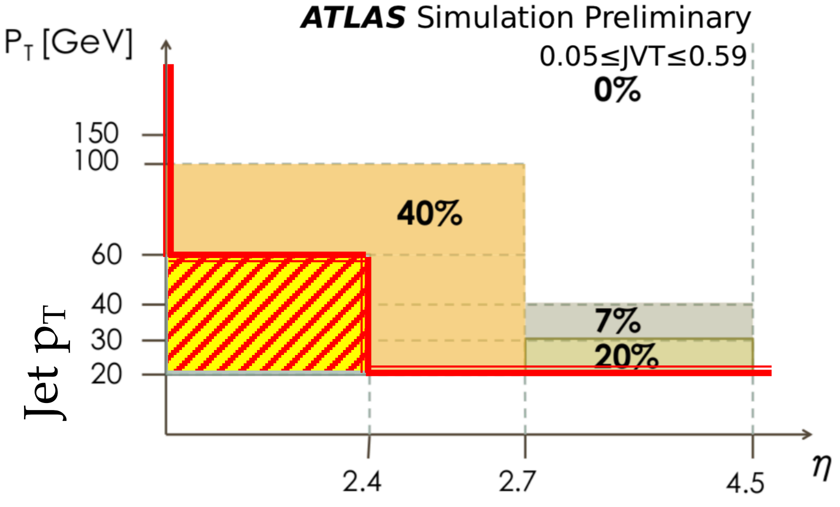


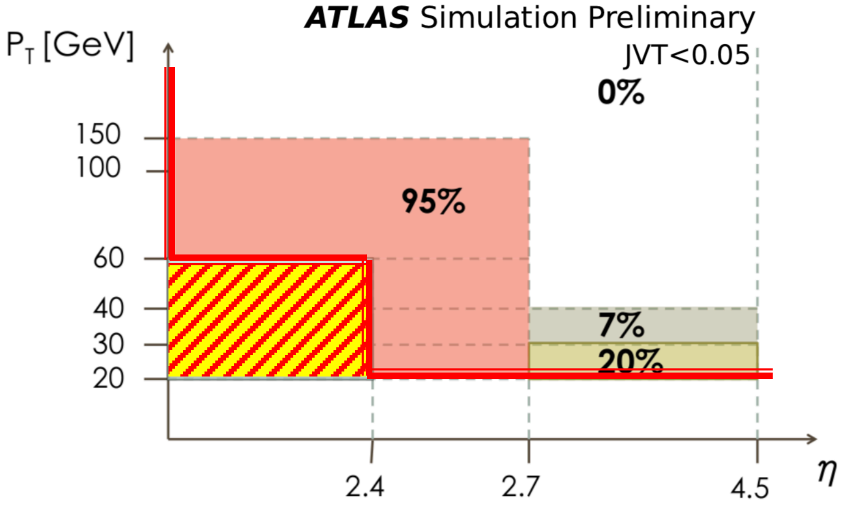
Jet resolution used in Missing Momentum Significance for jets.

Now studied in more details jets surviving standard cut:
Can have significant probability to arise from pile-up.



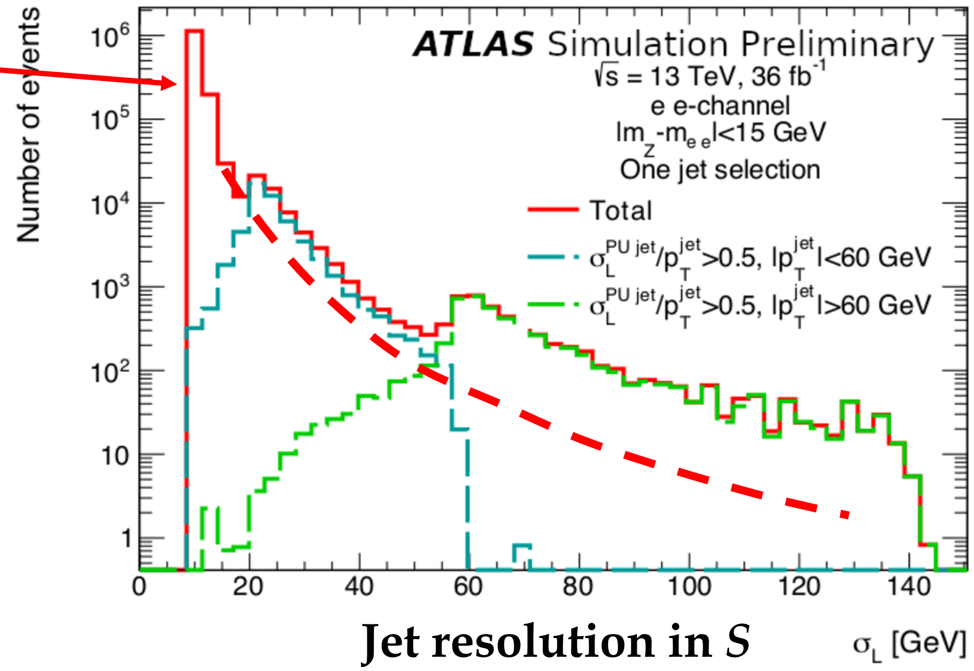
Jet resolution in *S*

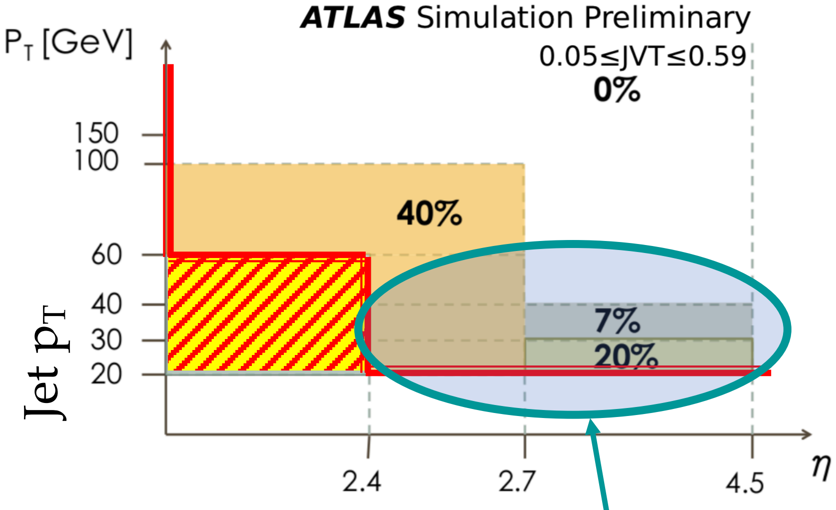


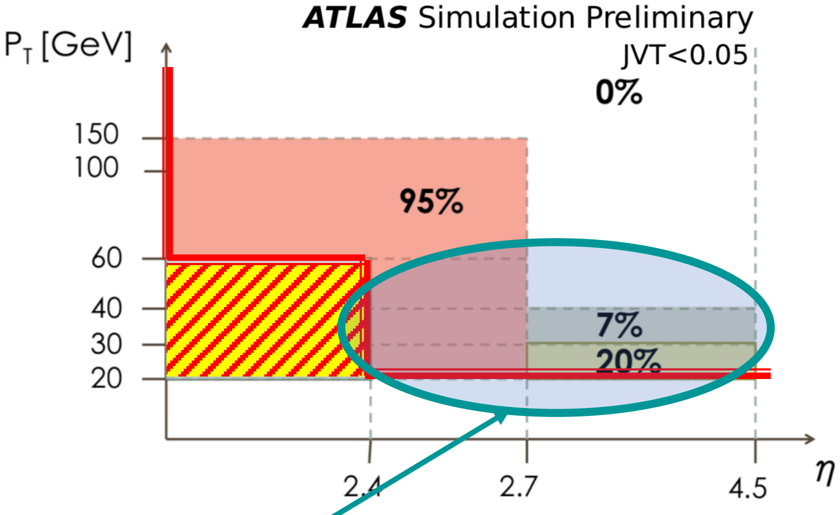


Jet resolution used in Missing Momentum Significance for jets.

Bulk of the jets, from HS PV, have resolution scaling as standard ${}^{1}/_{\sqrt{E}}$







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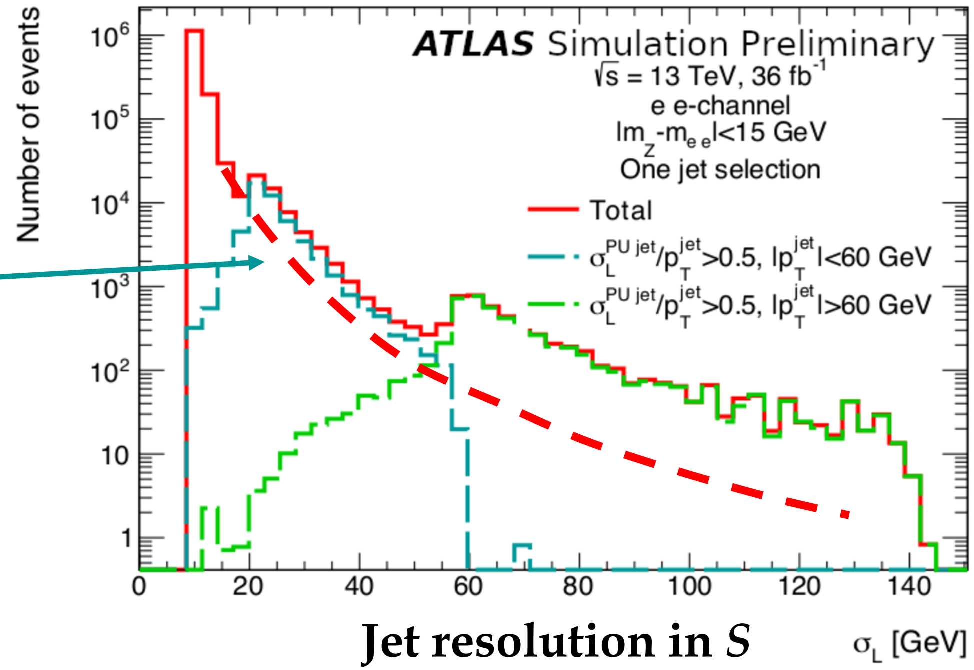
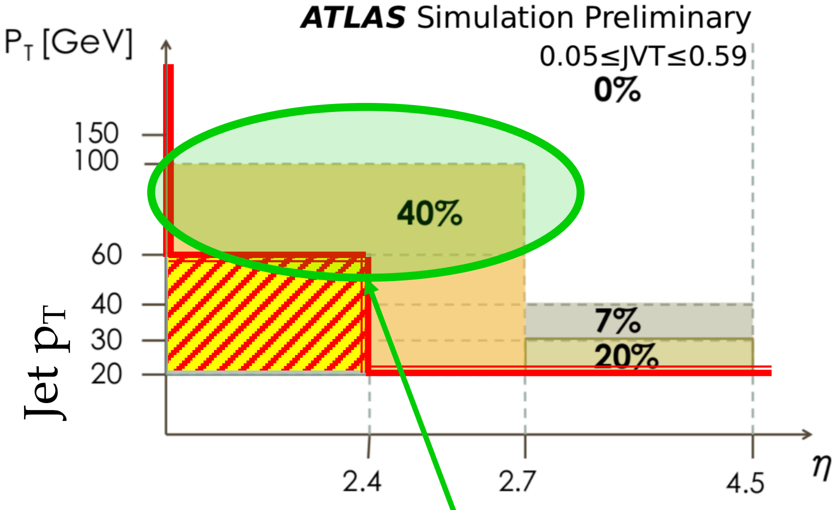
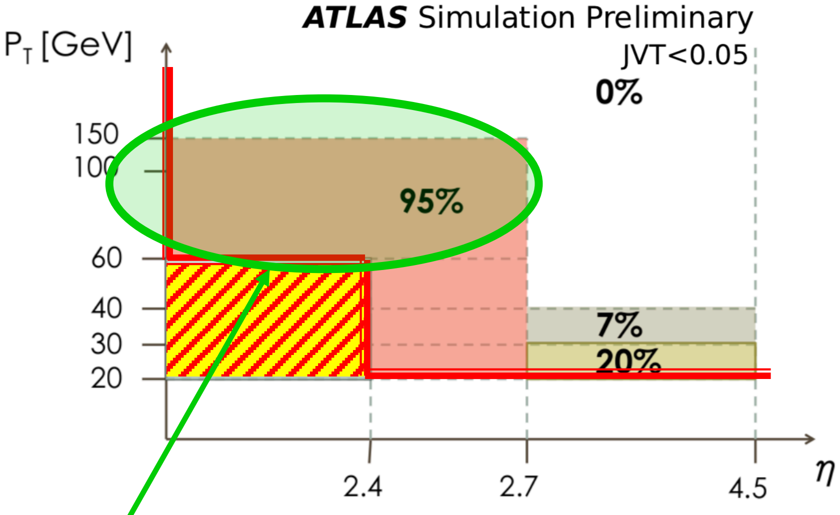


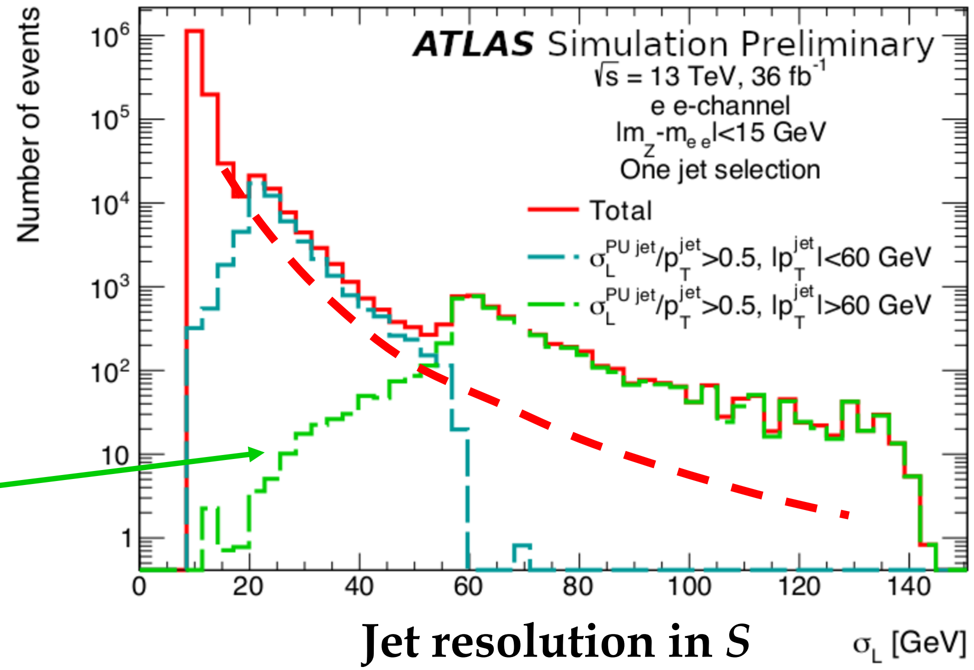
Jet resolution in *S*

Intermediate resolution term in Object based missing momentum significance: pile-up jets at $20 < p_T < 60$ GeV but $|\eta| > 2.4$.





Jet resolution used in Missing Momentum Significance (S) for jets.

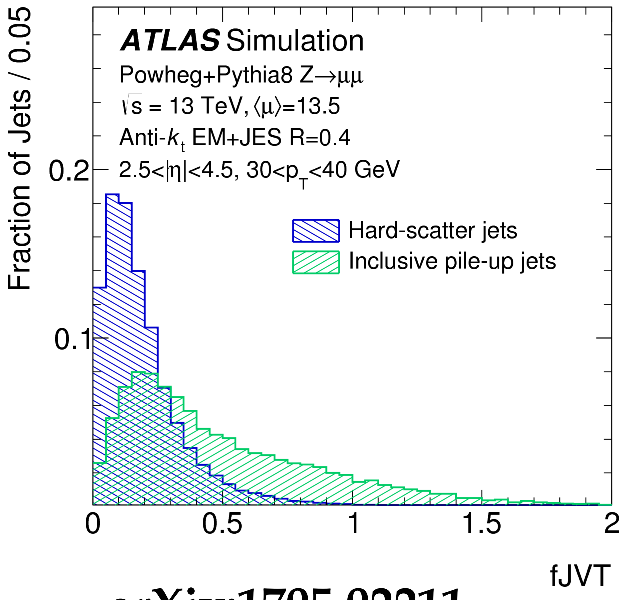


Jet resolution in S

In the worst resolution region: large contribution from pile-up jets with p_T > 60 GeV at all η.

⇒ Apply additional loose JVT selection for jets between 60 and 120 GeV
Reduces pile-up jet contamination to <1%, at 90% efficiency for HS jets.

How to suppress forward pileup jets without tracking?



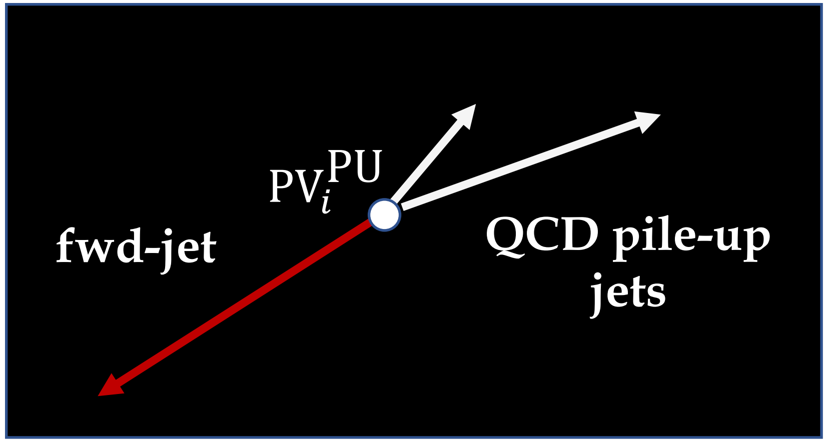
arXiv:1705.02211

For Central jets the tracking is able to confirm that jets come from the HS PV.

Forward region does not have precision tracking

Particularly important for physics channels involving forward jets, VBF signatures…

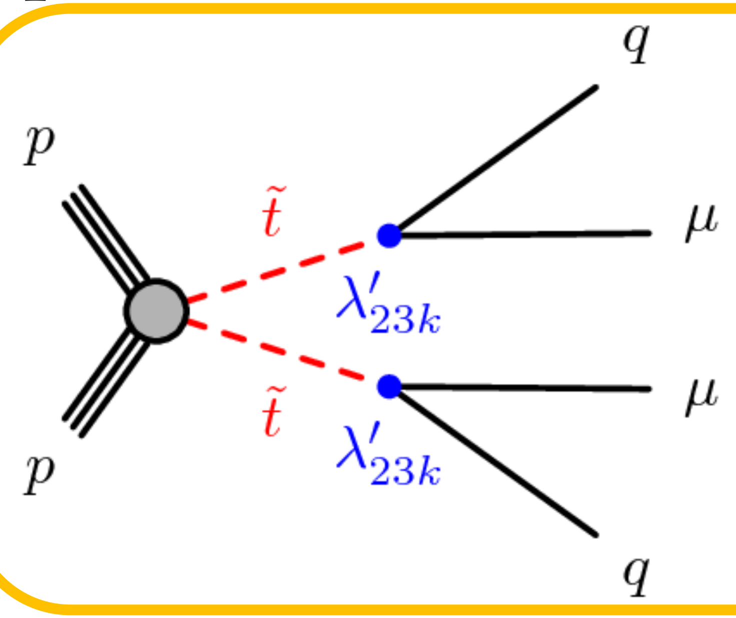
1) Assign central pile-up jet to their respective pile-up PV_i^{PU} using tracks.
2) Determine the missing momentum per pile-up PV.
3) Define a metric **fJVT** that quantities how well a forward jet matches the missing momentum from a pile-up vertex.



Forward pile-up jets can be identified if they balance the momentum associated to a PV_i^{PU}

<u>Remove jets with high values of fJVT from the Missing Momentum calculation</u>
(tight Missing Momentum Working Point)

Special Reconstruction for Long-Lived Particles



Long lived — stop quark decaying via RPV coupling λ'_{23k} can yield Displaced Dertex (DV) with a muon and a jet.

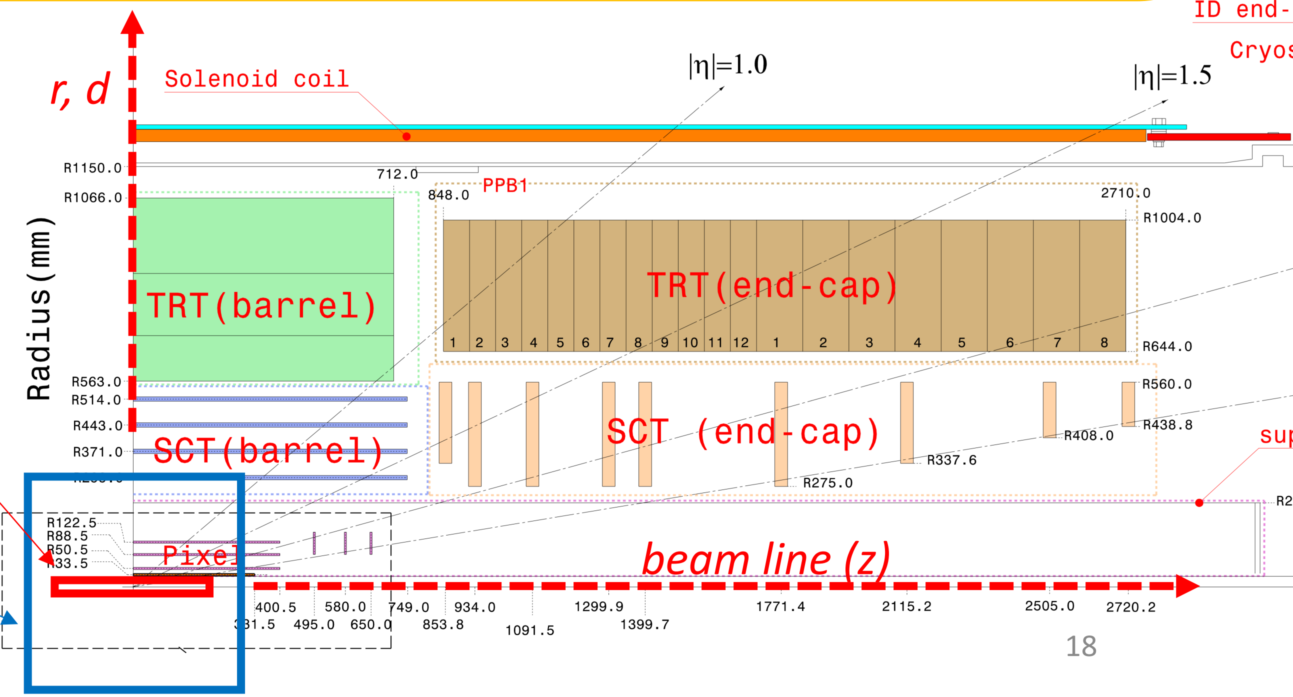
Other BSM models with this type of signature [ATLAS-CONF-2019-006]
Long-lived lepto-quarks, BSM particles in Higgs decays, right-handed neutrinos, long-lived electroweakino LSP...

Standard track reconstruction optimized for charged particles from beam interaction region or short-lived particles (b-hadrons,...)
$\Rightarrow$ Tracks with $|d_0| < 10$ mm and $|z_0| < 250$ mm

Need to look for DV with r_{DV} and $|z_{DV}|<300$ mm

Long-lived stop quarks search exploits

$\Rightarrow$ Dedicated Large Radius Tracking [ATL-PHYS-PUB-2017-014]



Long-Lived Particles and Large Radius Tracking

Large Radius Tracking ATL-PHYS-PUB-2017-014

Uses hits not already used by the standard tracking algorithm.

Track impact parameter selections are relaxed to $|d_0| < 10$ mm → 300 mm and $|z_0| < 250$ mm → 1500 mm.

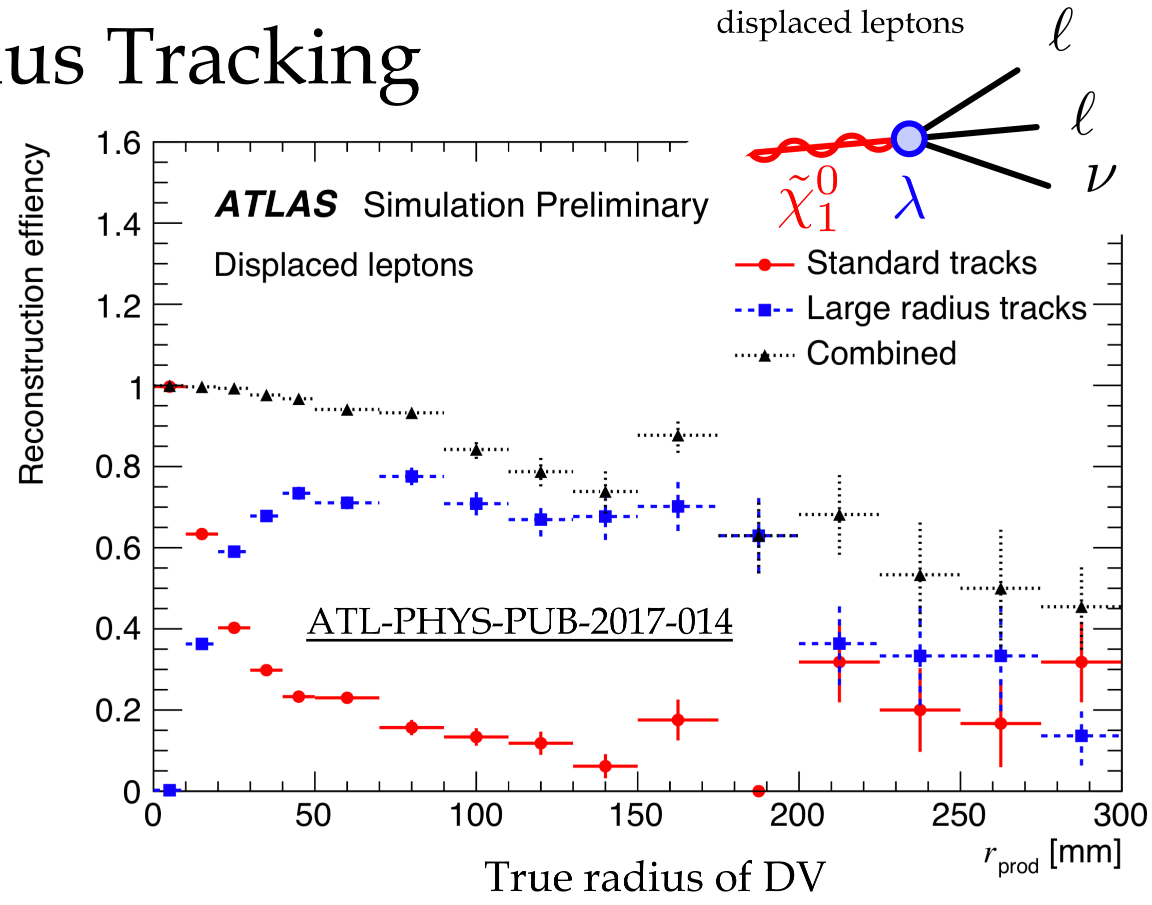
Requirements on the number of shared hits also relaxed.

Dedicated secondary-vertex reconstruction for LLP decays

Tracks $p_T > 1$ GeV and $|d_0| > 2$ mm (⇒ tracks from PV ignored).

Avoid contamination from fake tracks[1] by requiring:
⇒ Tracks with at least ≥6 SCT hits OR ≥ 1 Pixel hit.
⇒ Tracks rejected if (it has <2 pixel hits AND zero TRT hits)

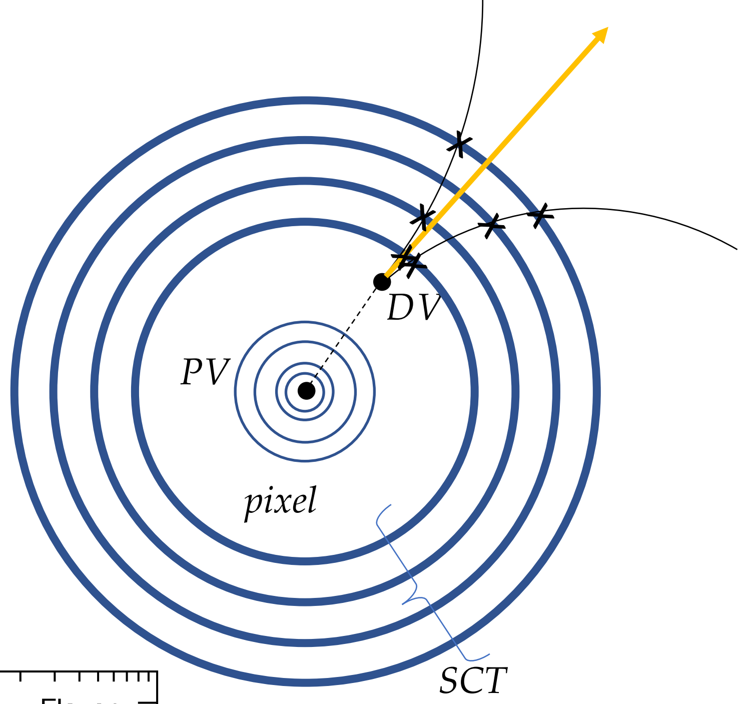
Additional requirements for tracks with $p_T < 25$ GeV



[1] Reconstructed from spurious combinations of hits

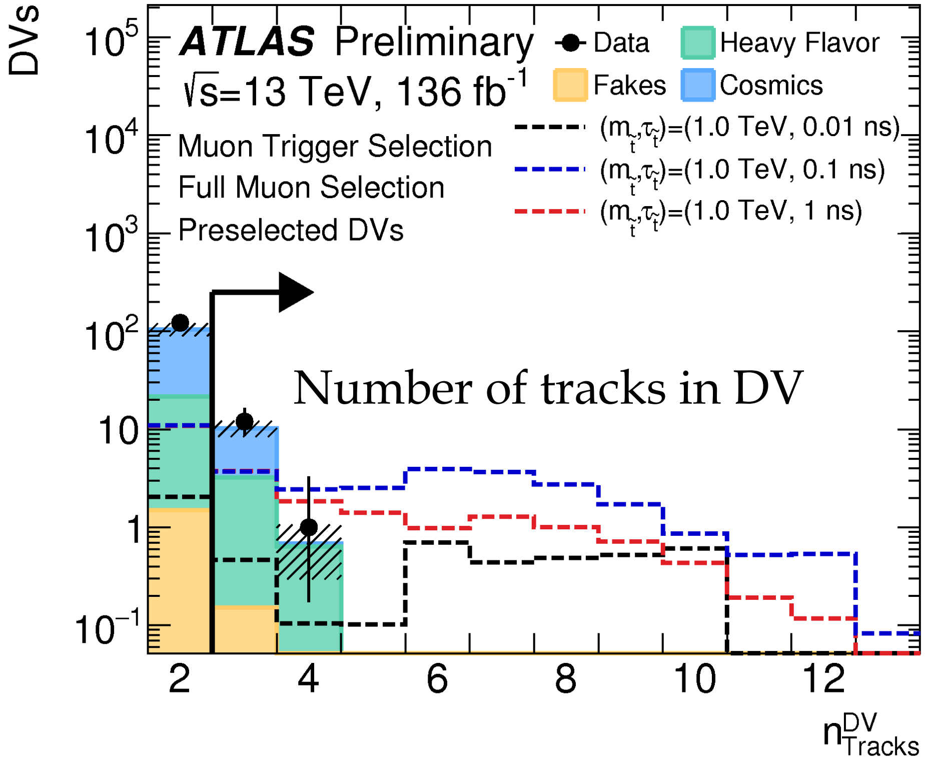
Displaced Vertex (DV) Reconstruction

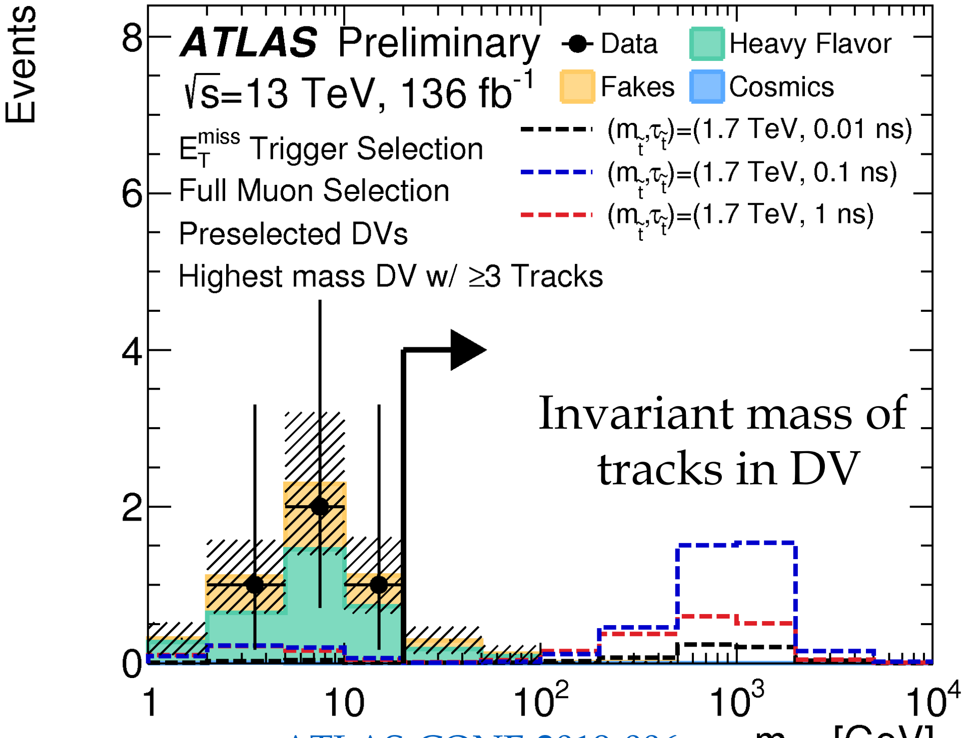
<u>Start from Seed vertices made from pairs of tracks</u>
No track hits at radii smaller than the DV.
With silicon hits at larger radius
Direction of the **vector sum of the momenta of the tracks** consistent with the vector from the PV to the DV.



<u>2) Iterative merging of seed vertices in to *n-track* vertices</u>

Do not consider DVs overlapping with detector elements (background from h-interactions)





[ATLAS-CONF-2019-006]

Boosted hadronic tops in stop searches and jet reclustering

Top decay products may be identified with separated standard Anti-k_t R=0.4 jets but top → daughter correspondance difficult (6 jets).
⇒ **Reclustered jets Anti-k_t jets R=1.2**

<u>Input constituents</u>
Already calibrated standard Anti-k_t jets R=0.4.

Cons

Does not use the fine granularity of the calorimeter

Does not allow use of fine substructure variable

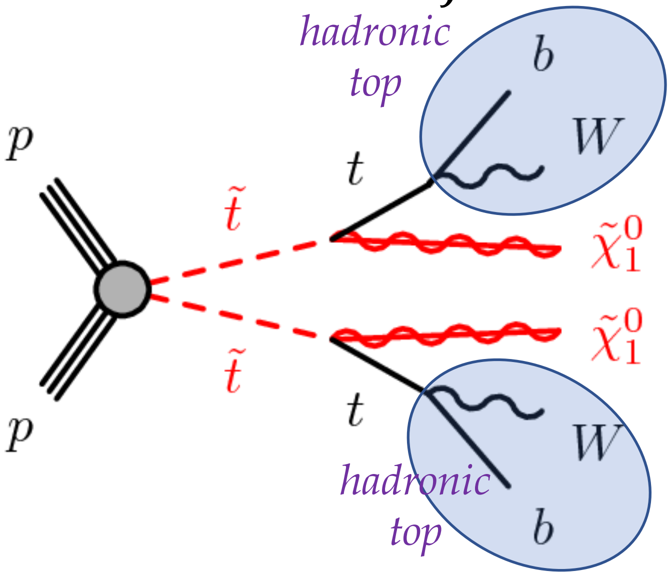
Loss of performance at very high p_T when the daughter jets start to merge $\Delta R \sim 2m/p_T$

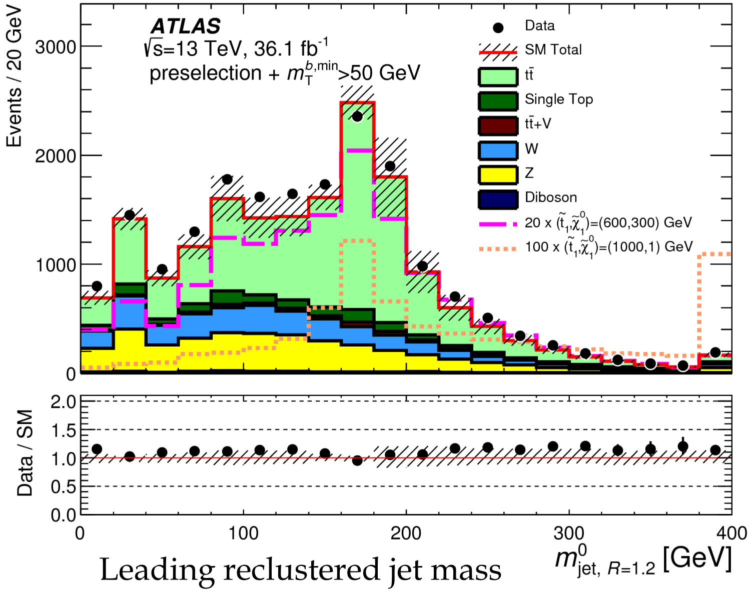
Pros

Relies on already calibrated standard R=0.4 jets.

Propagate uncertainties from R=0.4 jets to reclustered jets

Correlation between the reclustered jet and R=0.4 jets.





Leading reclustered jet mass

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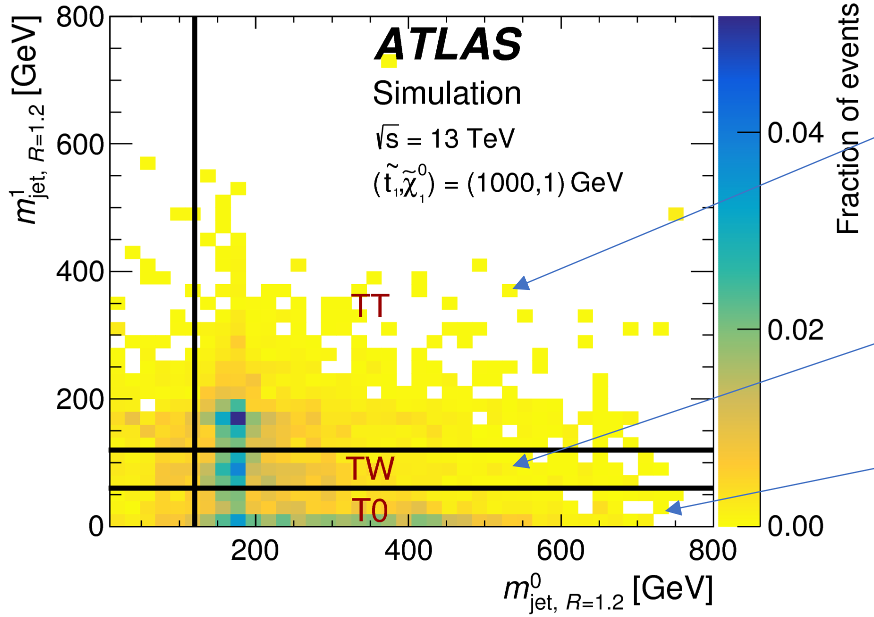


2 hadronic tops

1 hadronic top + 1 hadronic W

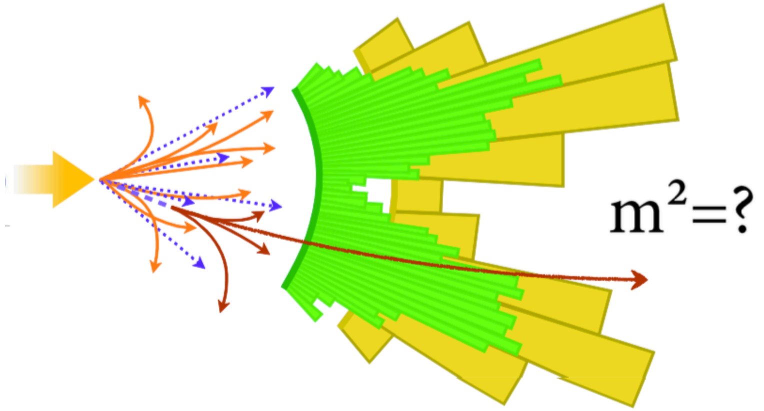
1 hadronic top

Large-R jet reconstruction

At high boost decay products not in well separated R=0.4 jets

$t \to bq\bar{q}'$ $W \to q\bar{q}'$ $\Delta R \sim {}^{2m}/_{p_\mathrm{T}}$

$t \to bq\bar{q}'$
$W \to q\bar{q}'$



Use single large Anti-k_t R=1.0 jets
Inputs constituents = locally calibrated calo clusters.
Suppress pile-up with trimming[1]

Pros
Capture substructure eg. $q\bar{q}'$ even at very high p_T
Access finest granularity of calorimeter since inputs are clusters.

⇒ Substructure variables eg. D_2 looking for 2 hard core substructure.

Cons
Requires dedicated large-R jet calibration

Difficult to correlate systematics with standard jets

Current SUSY search regime still have p_T(top) and p_T(W) only moderately boosted.

See also D. Miller's talk

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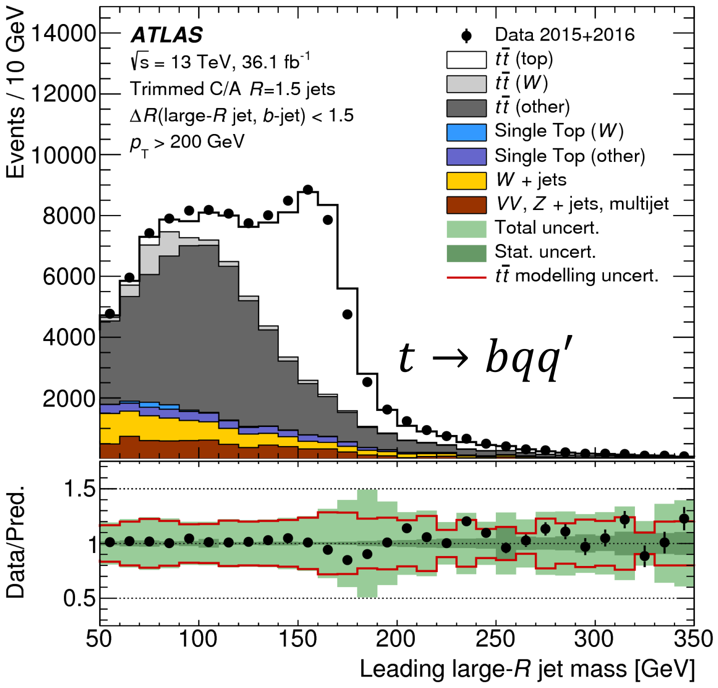
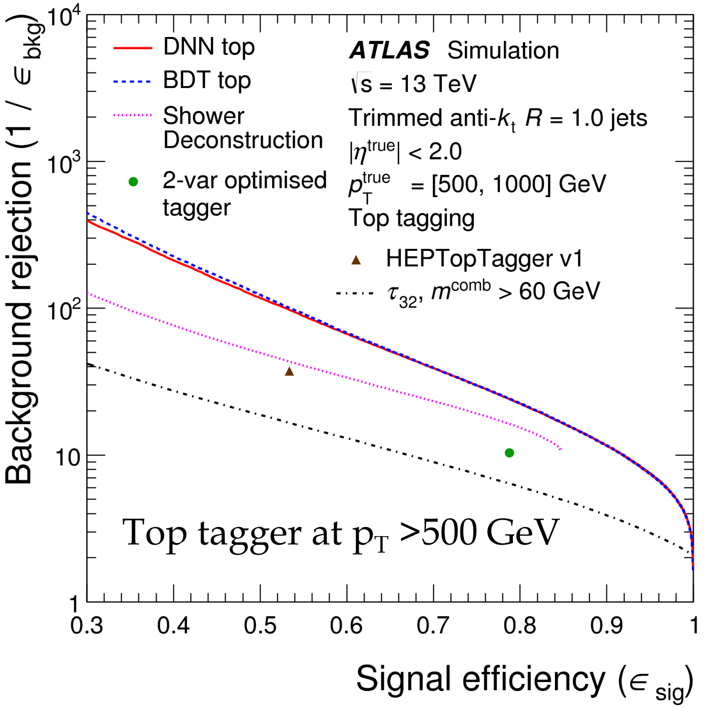




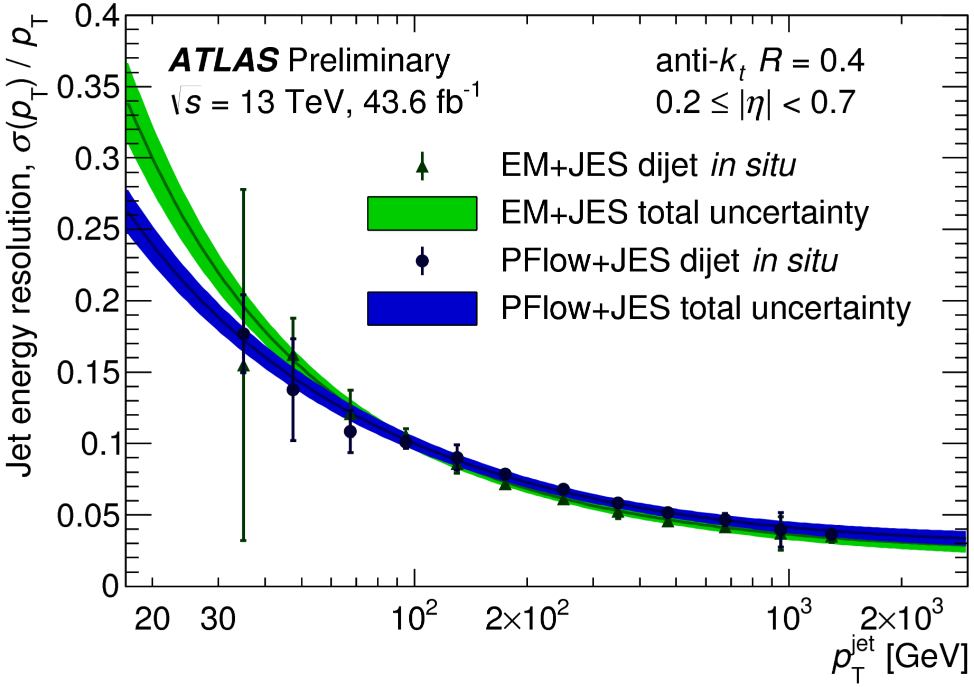
Top and W-taggers calibrated with top, W decays in data.

[1] Cluster the large jet constituents into k_t R=0.2 sub-jets, then remove sub-jets with p_T < 20% of large jet.

Conclusions & Outlook

- Large variety of signatures provided by SUSY
- Still coming up with new ways of using our ATLAS detector
- Continuous development of techniques to:
  - Mitigate effects of pile-up
  - Improve Missing Momentum resolution
  - Improve jet reconstruction and jet energy resolution
  - Identify very boosted hadronically decaying top and W/Z
  - ATLAS particle flow jets available, not yet applied to SUSY analyses
- Stay tuned!

[Jet energy resolution in 2017 data and simulation](#)



Backup

- Definition of soft Missing Momentum Term
- Definition of signal leptons
- Inner Tracker Layout
- Additional information on forward pile-up jet tagger

Definition of Soft Missing Momentum Term

The soft term introduced in Section 3.1 is a significant contribution to the $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction, in particular in events with low jet activity. The track-based soft term is exclusively reconstructed from ID tracks that are not associated with the hard objects [9]. Only those tracks associated with hard scatter primary vertex are included, and these are required to have:

- $p_{\mathrm{T}} > 400$ MeV;
- $|d_0|/\sigma(d_0) < 2$ and $|z_0 \sin(\theta)| < 3.0$ mm, where d_0 ($z_0 \sin(\theta)$) is the transverse (longitudinal) impact parameter;
- $\Delta\phi(\text{track}, e/\gamma) > 0.05$ or $\Delta\eta(\text{track}, e/\gamma) > 0.2$;
- $\Delta R(\text{track}, \tau) > 0.2$.

Mismeasured tracks are removed following the strategy described in Reference [9].

Signal Leptons

Not public yet
https://cds.cern.ch/record/2673601

Preselected electrons

$p_T > 4.5$ GeV, $|\eta| < 2.47$
Calo+tracking-based *VeryLoose* likelihood
$|z_0 \sin\theta| < 0.5$ mm

Signal electrons

Preselected and
Medium identification criterion (88% efficiency)
d_0 significance < 5
Gradient isolation WP, uses both tracking & calo

Preselected muons

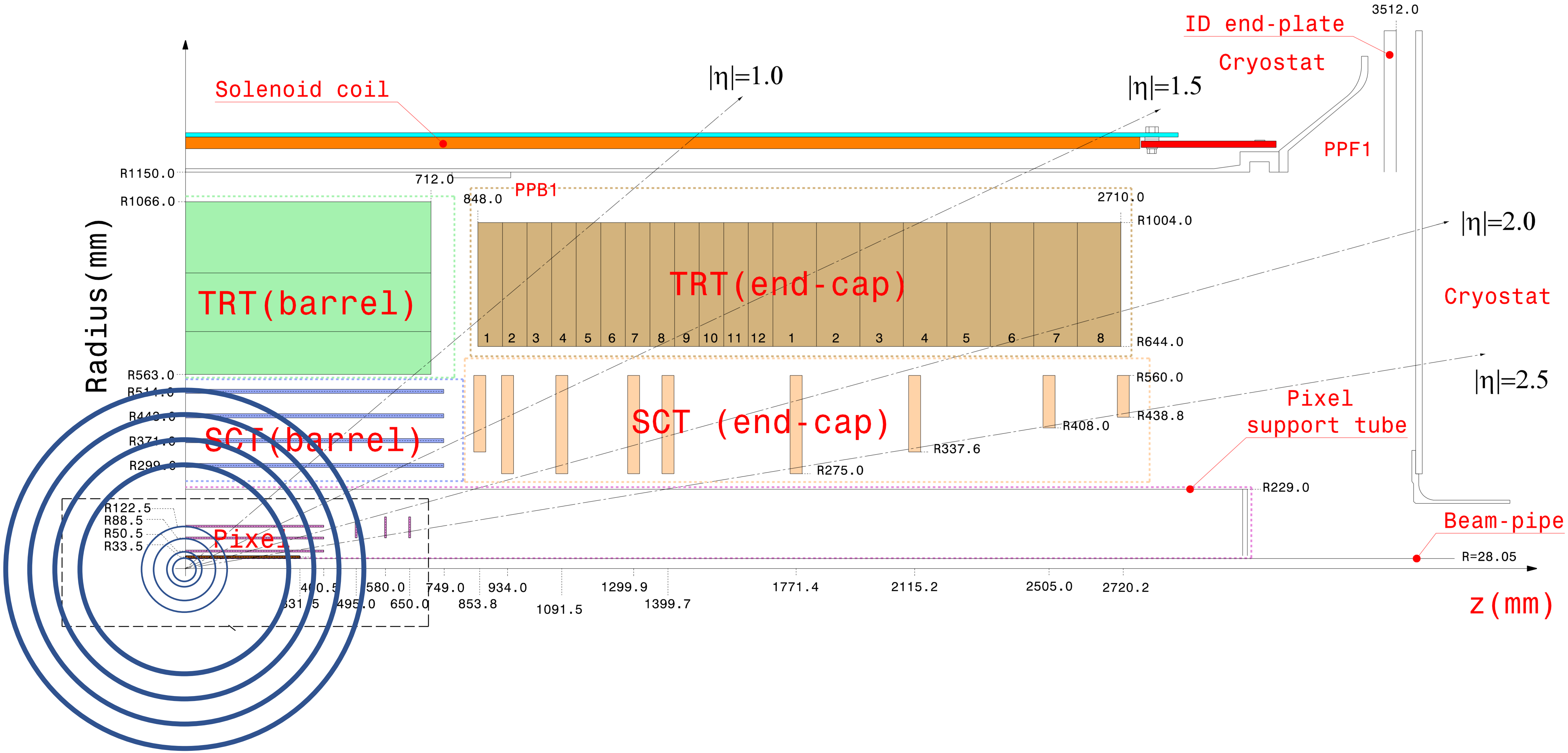
$p_T > 3$ GeV, $|\eta| < 2.5$
LowPt criterion, a re-optimized selection similar to those defined in Ref. [83] but with improved efficiency and background rejection for $p_T < 10$ GeV muon candidates.
$|z_0 \sin\theta| < 0.5$ mm

Signal muons

Preselected and
d_0 significance < 3
FCTightTrackOnly isolation working point, which uses only tracking information

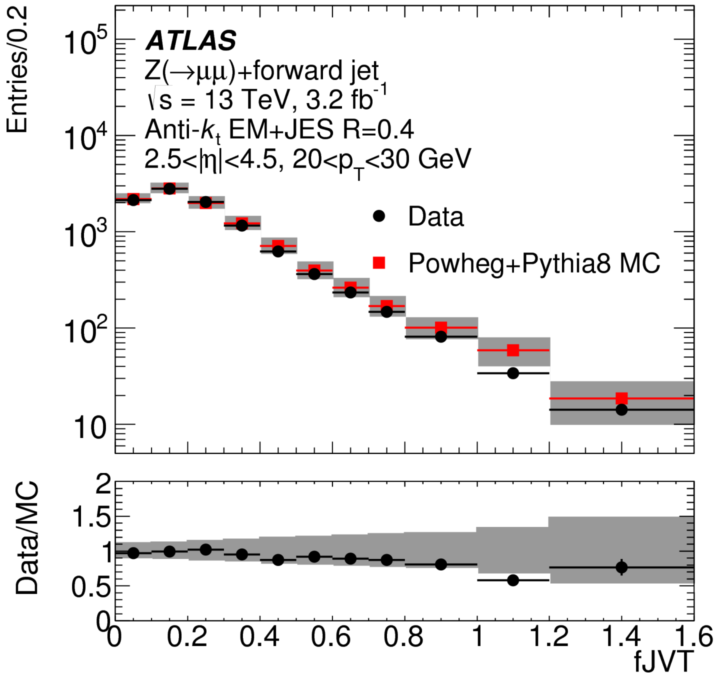
Very low or zero efficiency at low lepton p_T

$\Rightarrow$ Define a complementary signal region **SR1ℓ1T**

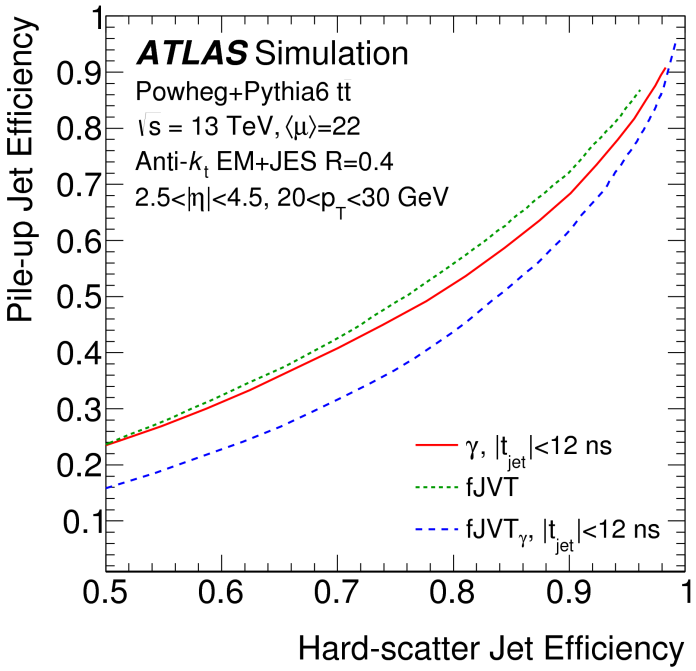


ID end-plate
3512.0
Cryostat
|η|=1.0
|η|=1.5
Solenoid coil
PPF1
R1150.0
712.0
PPB1
848.0
2710.0
R1066.0
R1004.0
|η|=2.0
Radius(mm)
TRT(barrel)
TRT(end-cap)
Cryostat
1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8
R644.0
R563.0
R560.0
|η|=2.5
Pixel
support tube
SCT (end-cap)
R438.8
SCT(barrel)
R408.0
R337.6
R275.0
R229.0
R122.5
R88.5
R50.5
R33.5
Pixel
Beam-pipe
R=28.05
580.0
749.0
934.0
1299.9
1771.4
2115.2
2505.0
2720.2
495.0
650.0
853.8
1091.5
1399.7
z(mm)

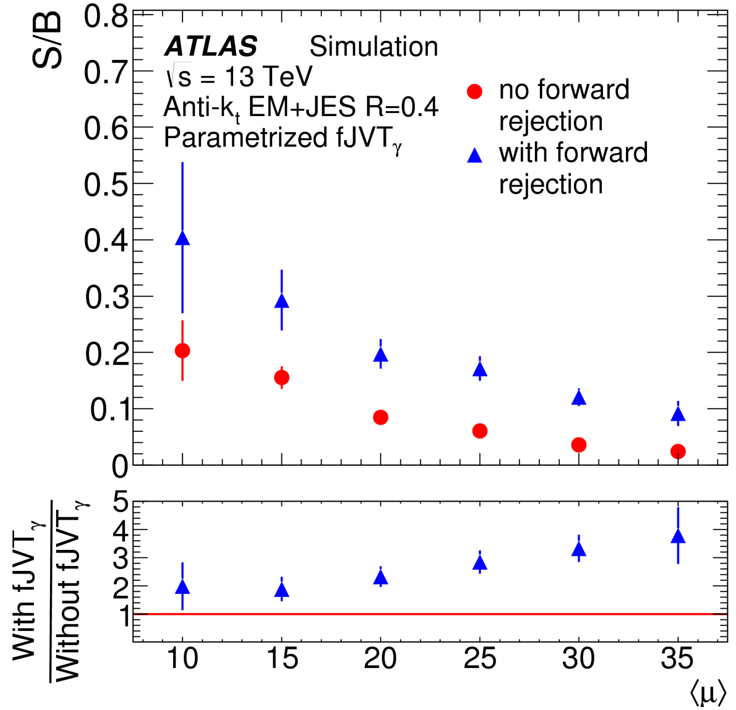
Improved performance with fJVT



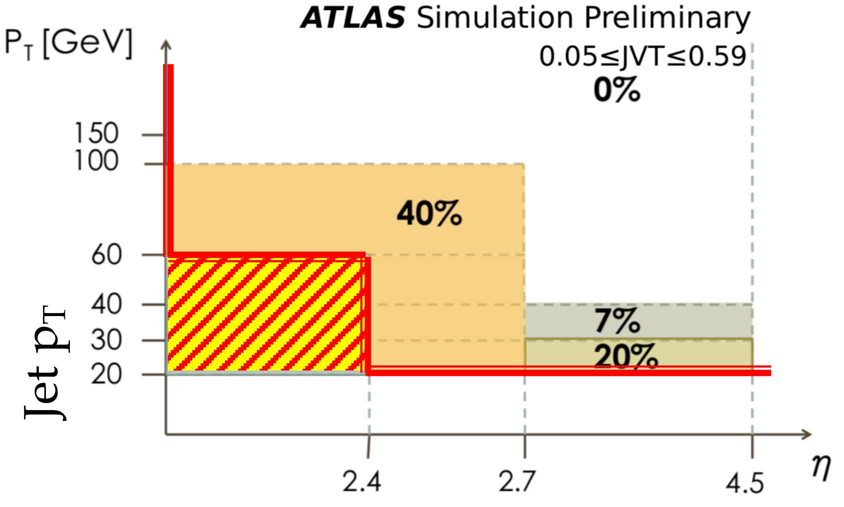
evaluation in data

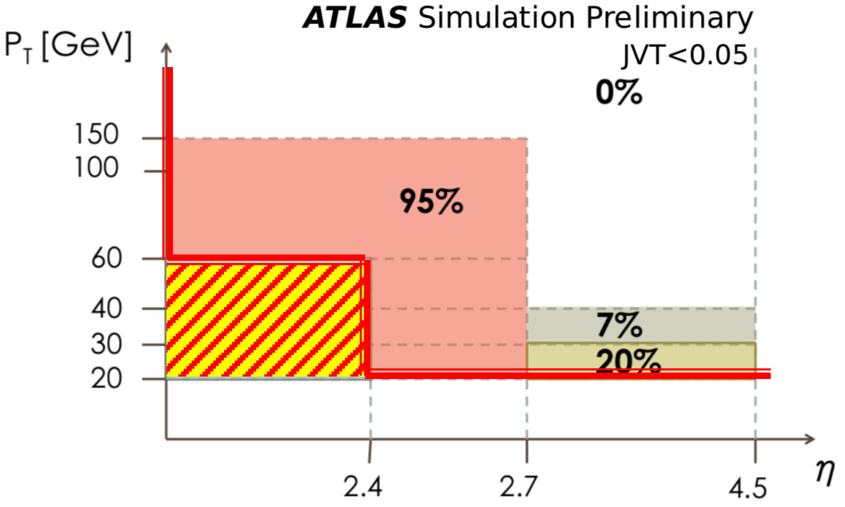


57% of forward pile-up jets are rejected @ hard-scatter efficiency of 85%



Evaluation in a simplified VBF H→ $\tau\tau$ → ll analysis background from Z→ ll
Significant improvement of S/B



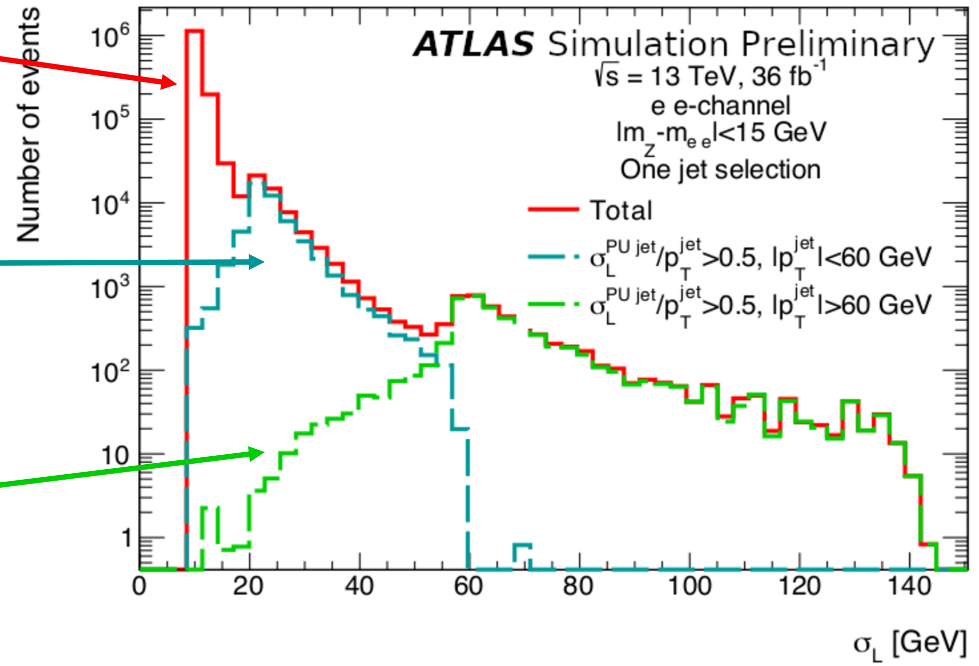


Jets resolution in Missing Momentum Significance.

Bulk of the jets have resolution scaling as ${}^{1}/_{\sqrt{E}}$

Higher resolution term in Object based missing momentum significance: pile-up jets at $20 < p_T < 60$ GeV but $|\eta| > 2.4$.

Higher resolution term in Object based missing momentum due to pile-up jets with $p_T > 60$ GeV at all η.



⇒ Apply additional JVT selection of > 0.11 for jets up to 120 GeV
Reduces pile-up jet contamination to <1%, at 90% efficiency for HS jets.