Unconventional Tracking Techniques for Long-Lived Particle Searches in ATLAS

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on behalf of the ATLAS Collaboration

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UNIVERSITY OF CALIFORNIA
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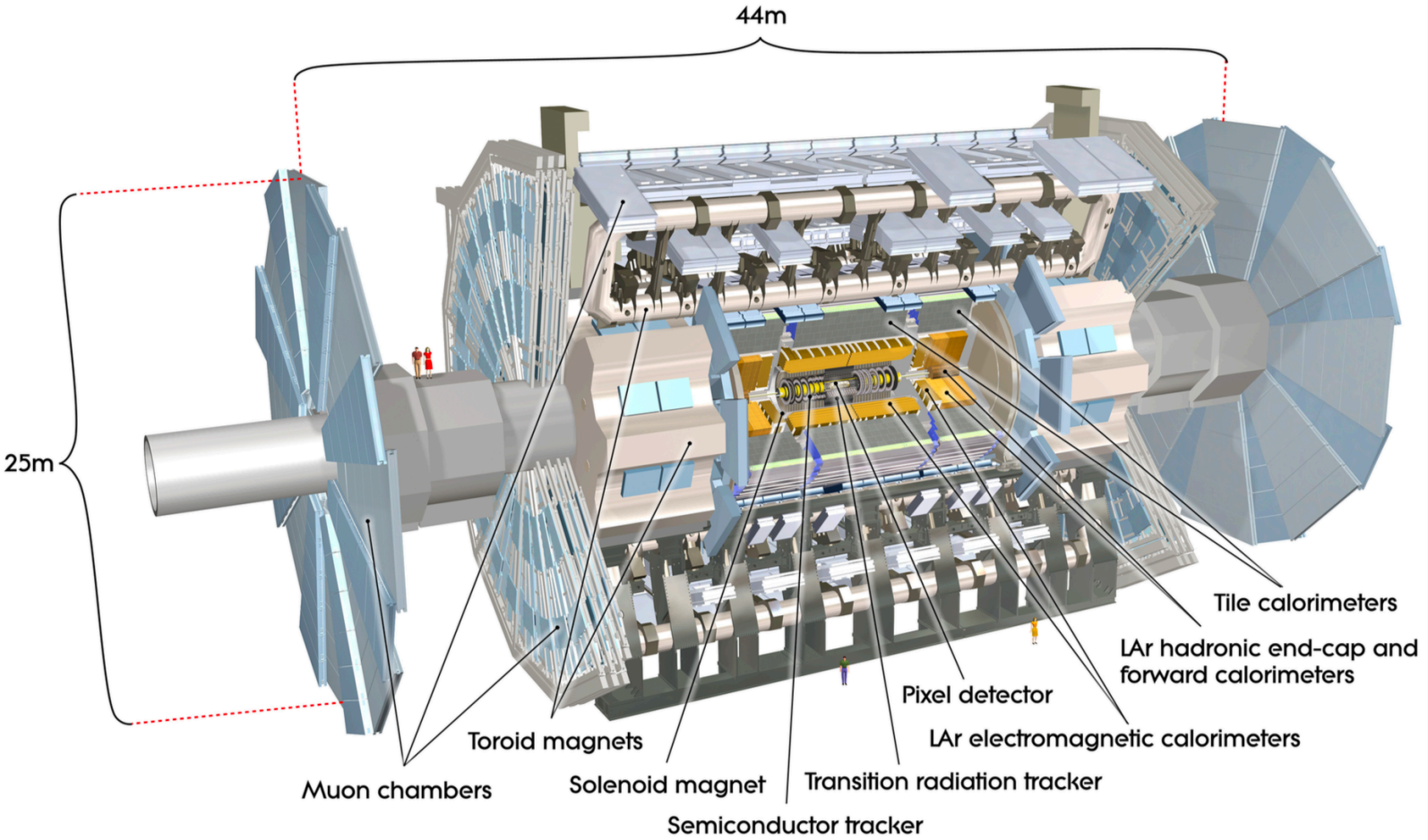
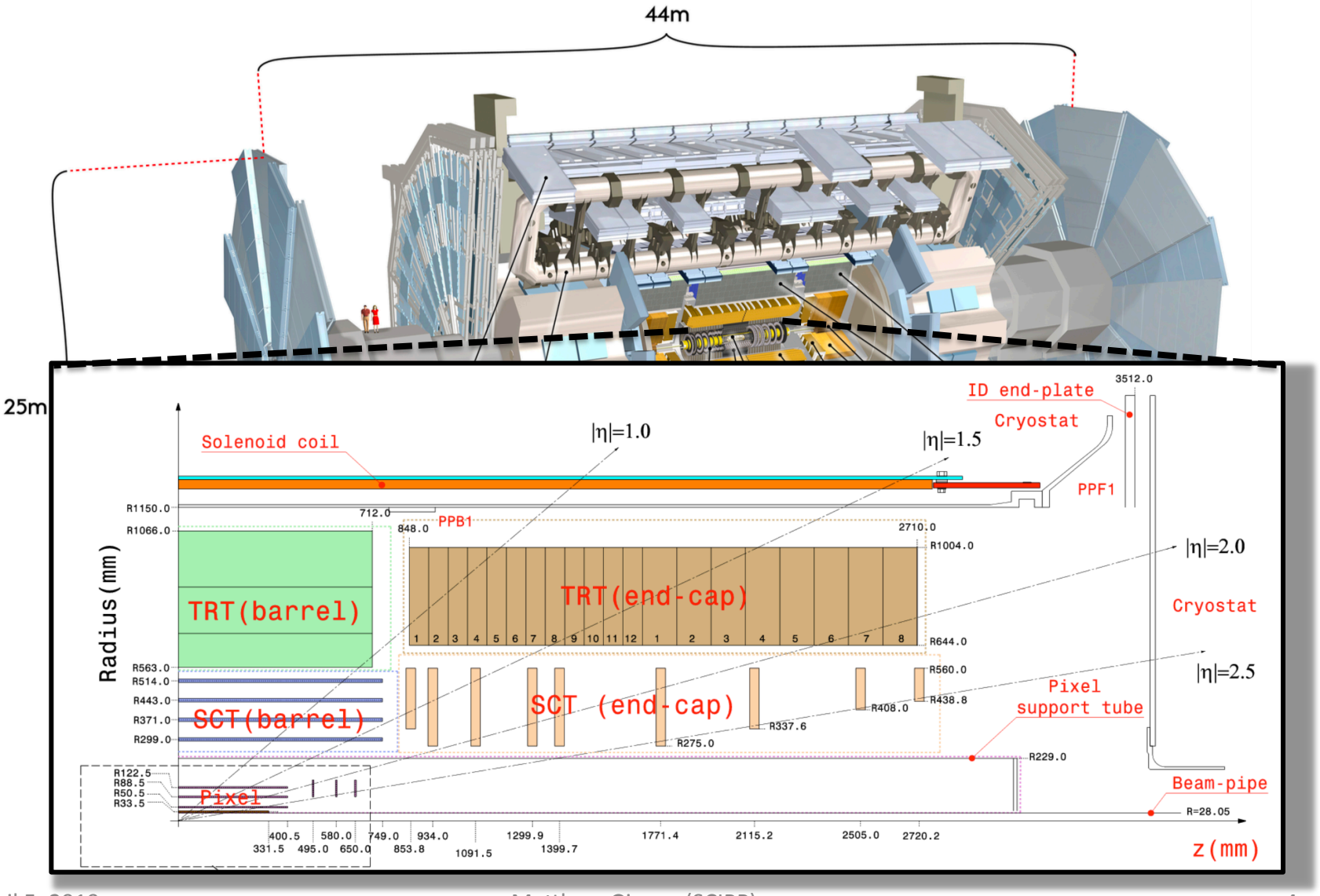
Introduction

- ⇨ Searches for long-lived particles require special tracking techniques
  - Particles produced during the decay of long-lived particles in the inner detector don't point back to the primary interaction region
  - Charged particles produced from the primary interaction region that decay before traversing the inner detector typically don't leave enough hits to be reconstructed by conventional techniques
- ⇨ Performance of algorithms targeting the above scenarios released for this workshop
  - *Performance of vertex reconstruction algorithms for detection of new long-lived particle decays within the ATLAS inner detector*
    - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-013/
  - *Performance of tracking and vertexing techniques for a disappearing track plus soft track signature with the ATLAS detector*
    - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-011/

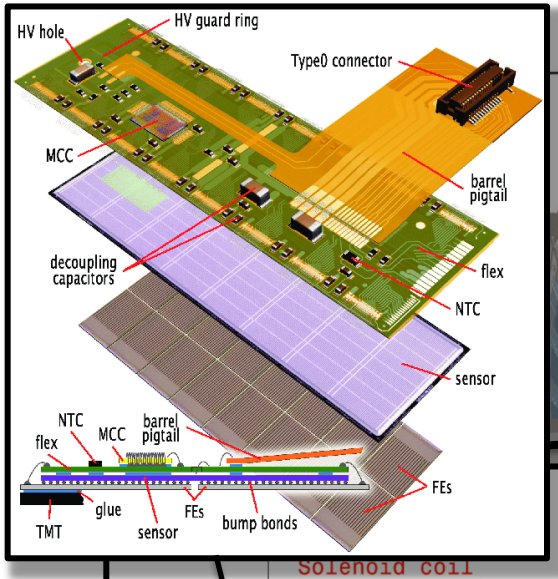
ATLAS detector

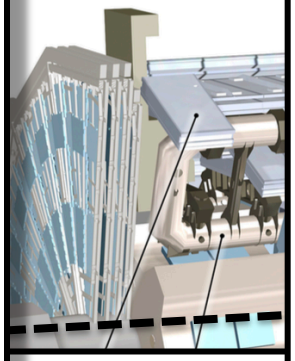


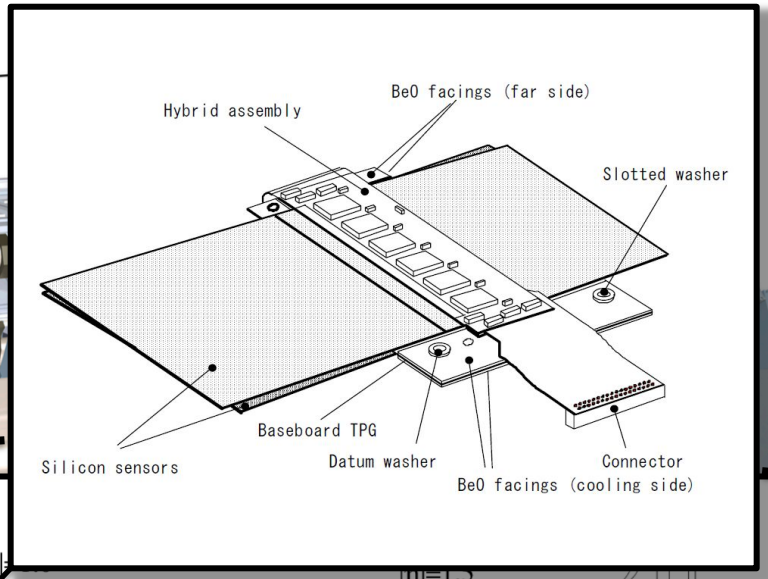
ATLAS detector

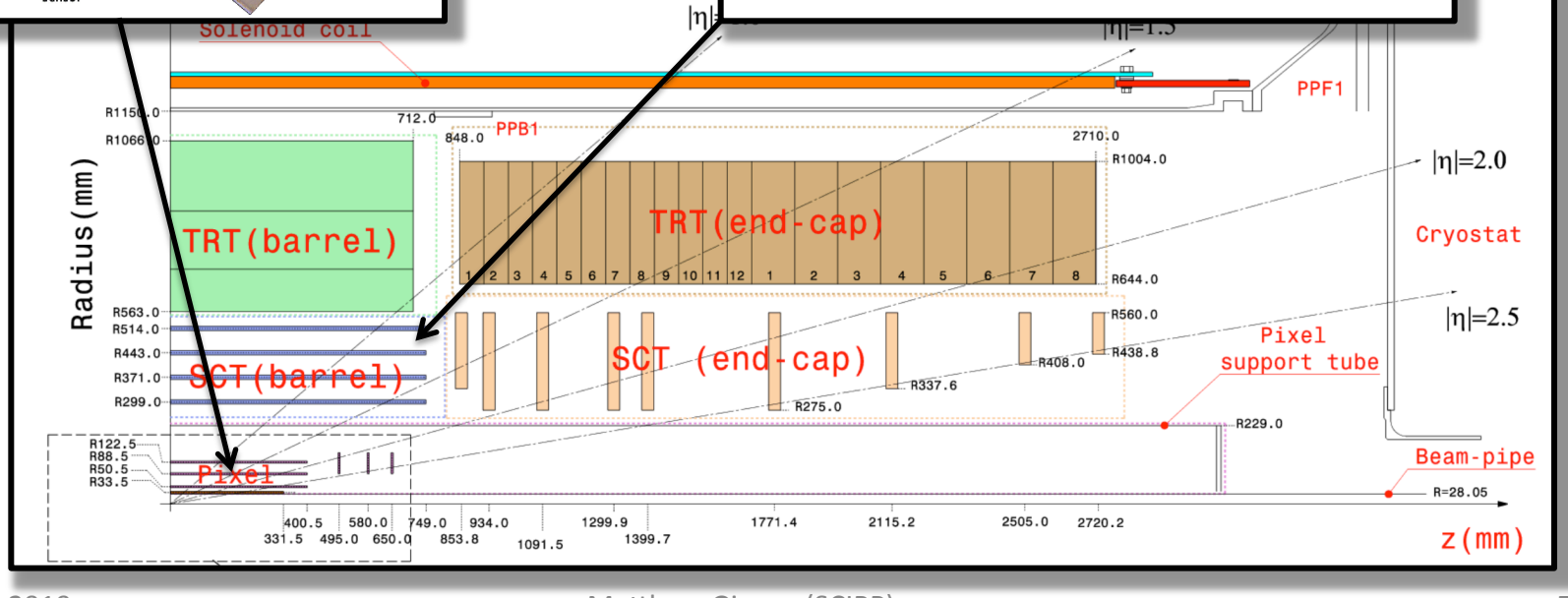


ATLAS detector



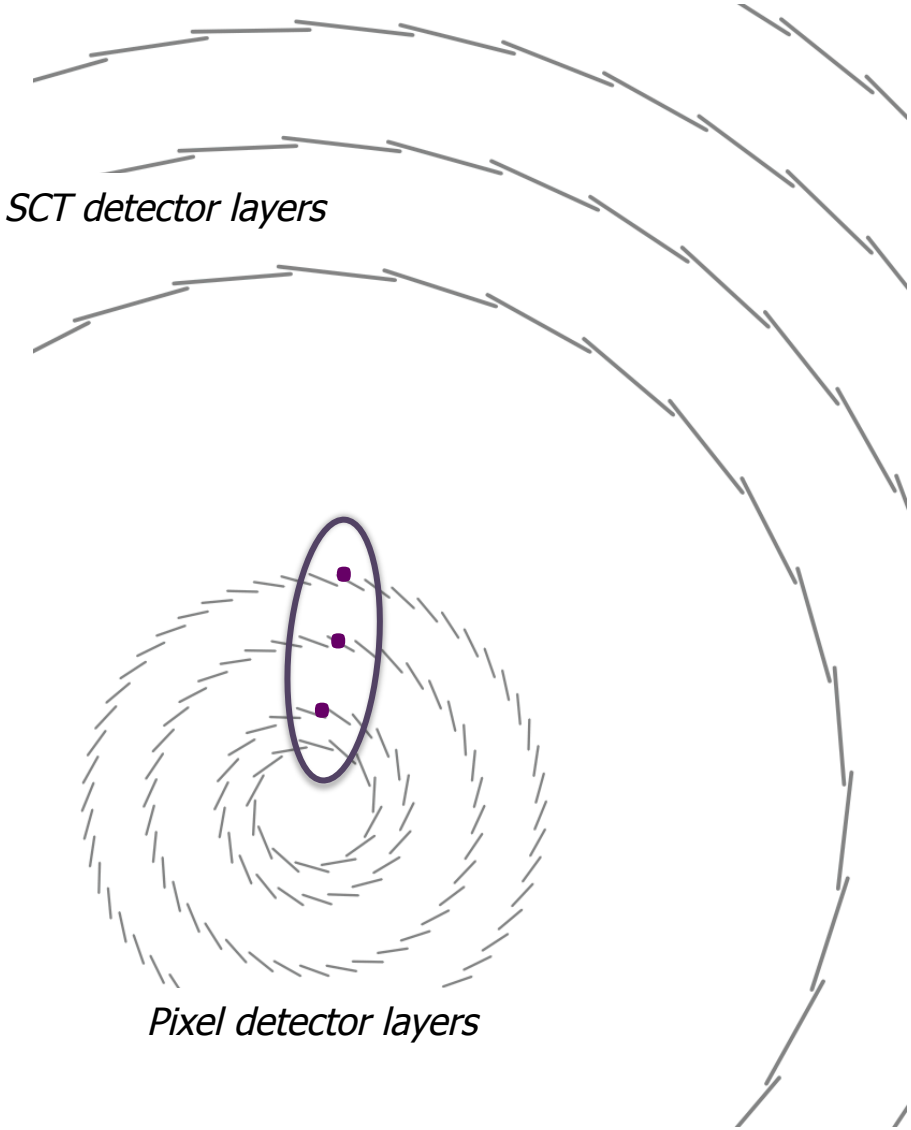






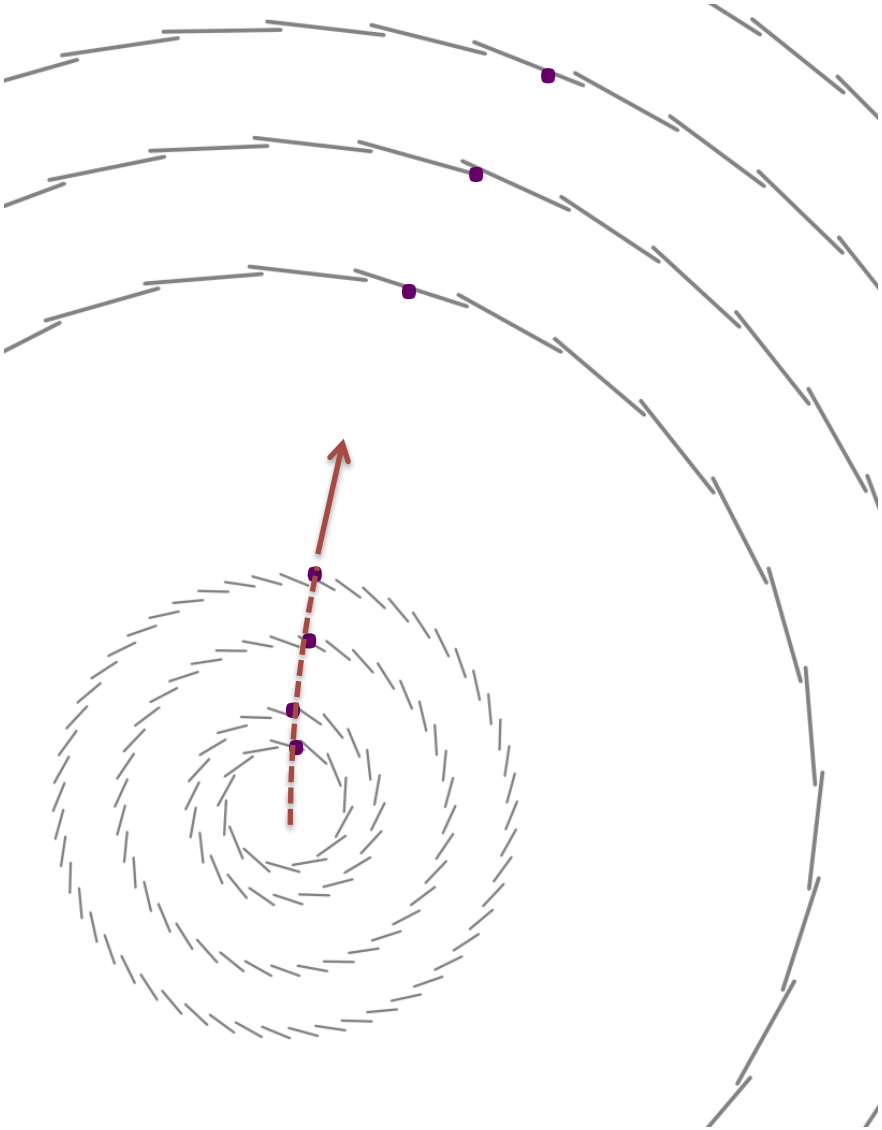
How do we go from measurements on our detector layers to tracks used for physics analysis?

Standard Track Reconstruction



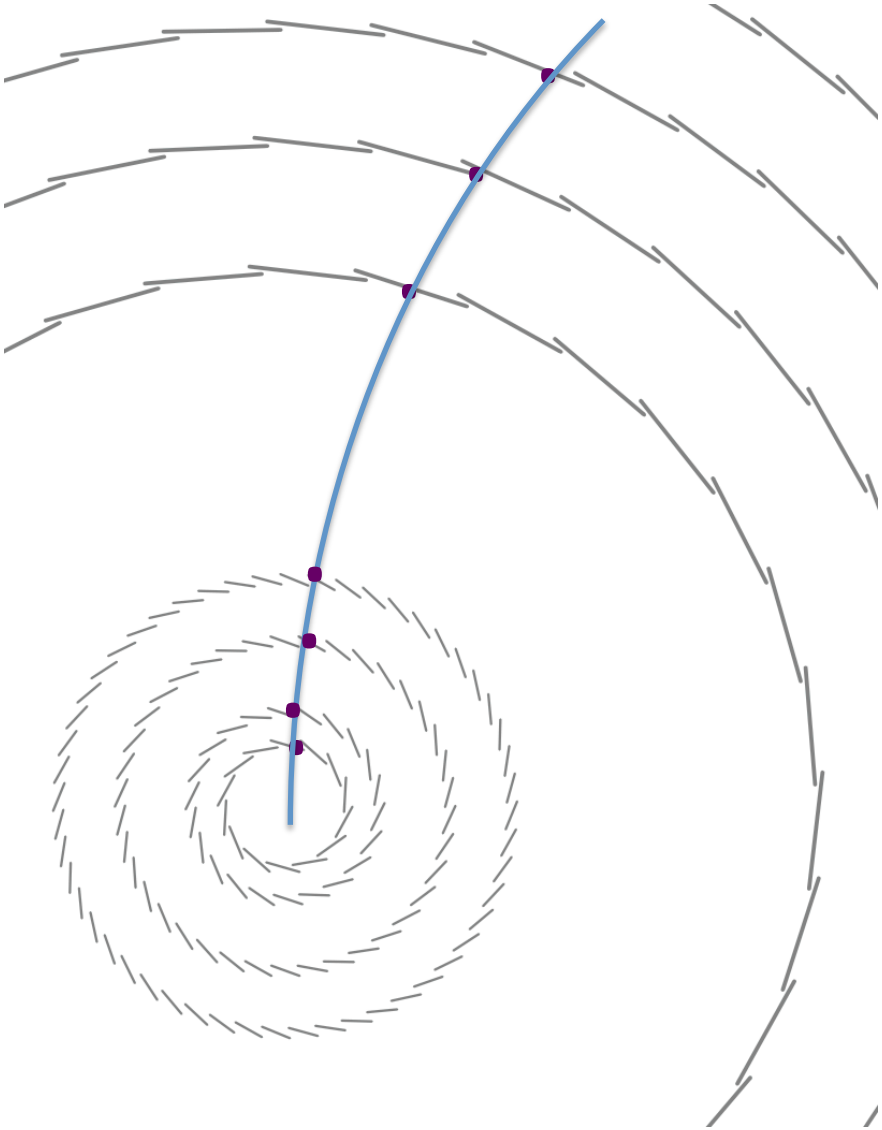
1. Combinations of three space-points used to form track seeds

Standard Track Reconstruction



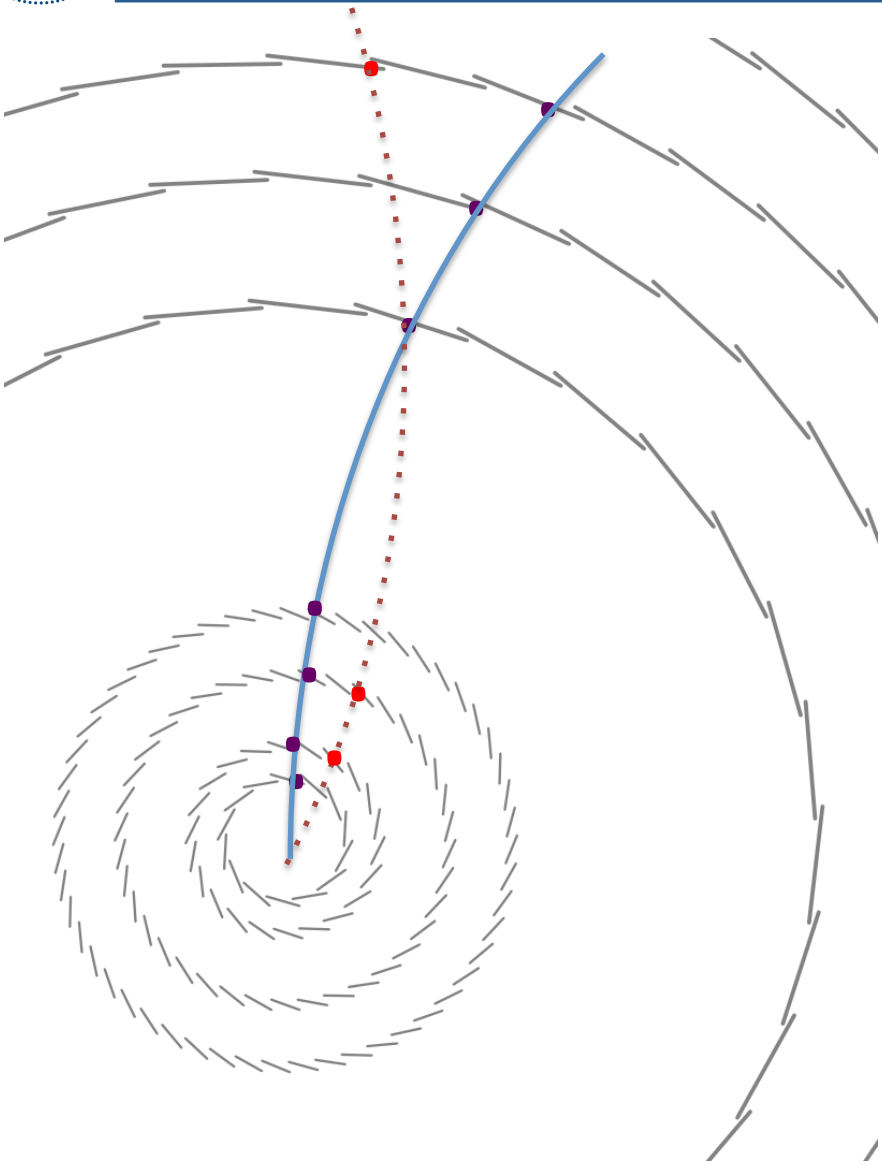
1. Combinations of three space-points used to form track seeds
2. Track parameters from seeds are used to initiate a search for additional hits → track extension

Standard Track Reconstruction



1. Combinations of three space-points used to form track seeds
2. Track parameters from seeds are used to initiate a search for additional hits → track extension
3. Track candidates are formed when they have at least 7 silicon hits

Standard Track Reconstruction



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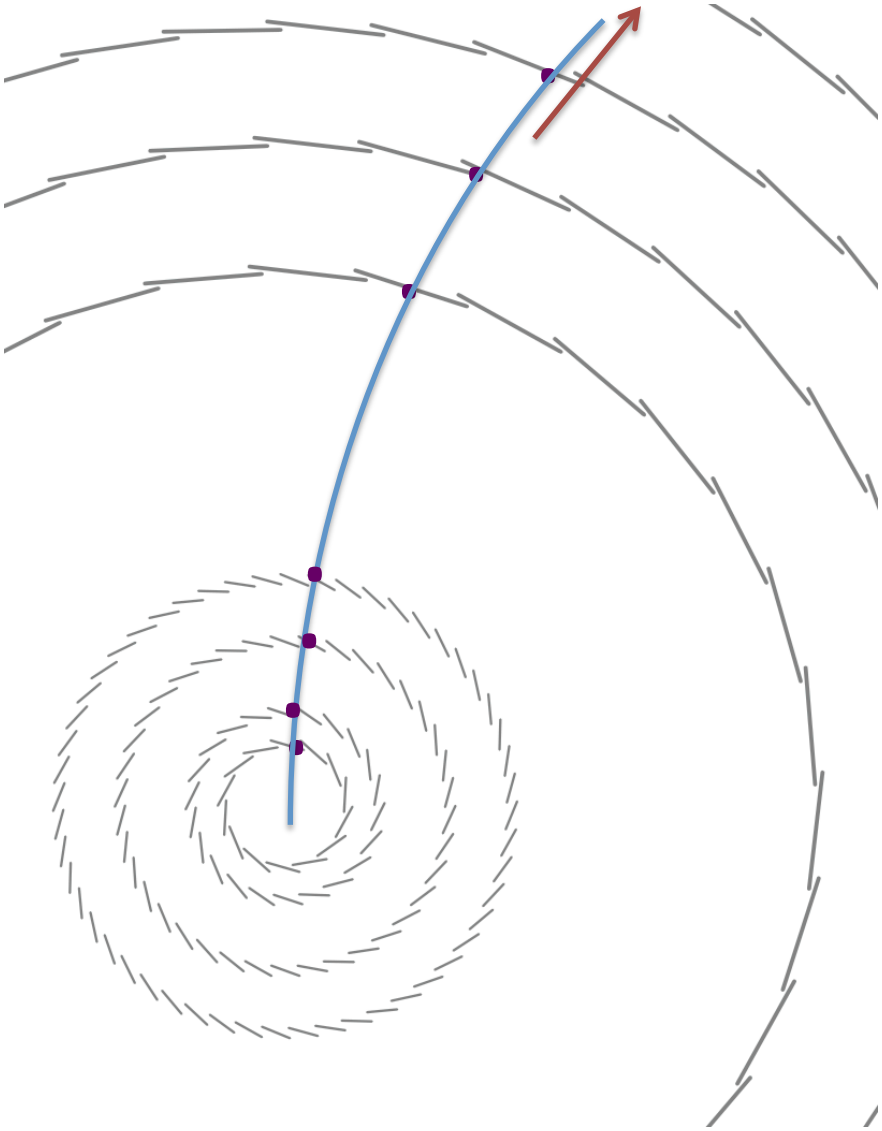
4. Ambiguity algorithm run to resolve shared hits among different tracks

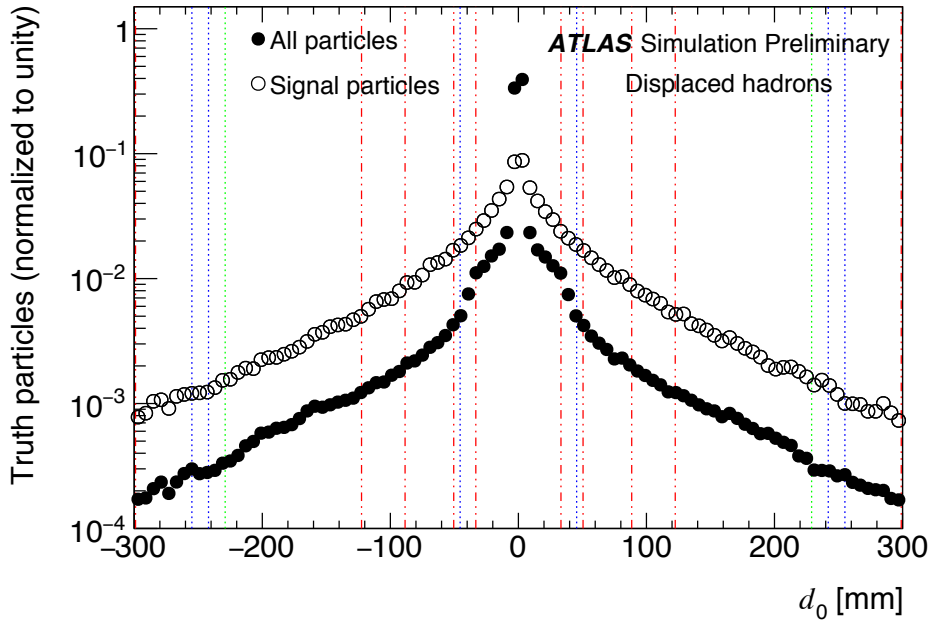
Standard Track Reconstruction



1. Combinations of three space-points used to form track seeds
2. Track parameters from seeds are used to initiate a search for additional hits → track extension
3. Track candidates are formed when they have at least 7 silicon hits
4. Ambiguity algorithm run to resolve shared hits among different tracks
5. Combined chi-squared fit
6. Tracks are extended into the TRT detector and refit

Standard Track Reconstruction

- The standard track reconstruction is optimized to select tracks originating from the primary pp interaction region.
- Tracks originating from LLP decays can have large impact parameters, and would be missed by the standard track reconstruction algorithms!



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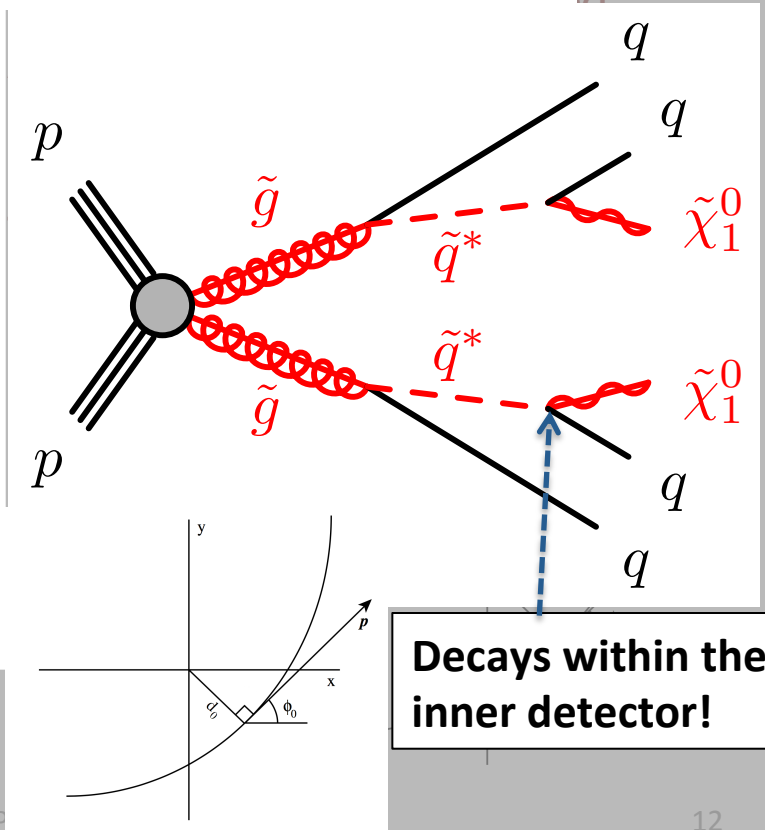
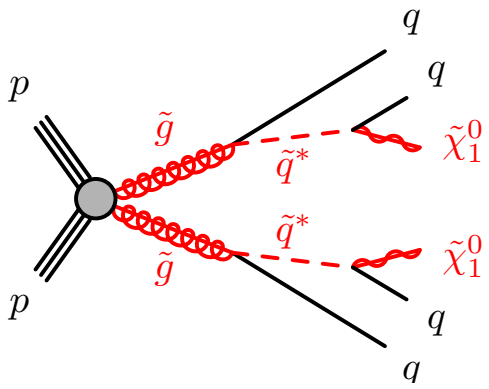


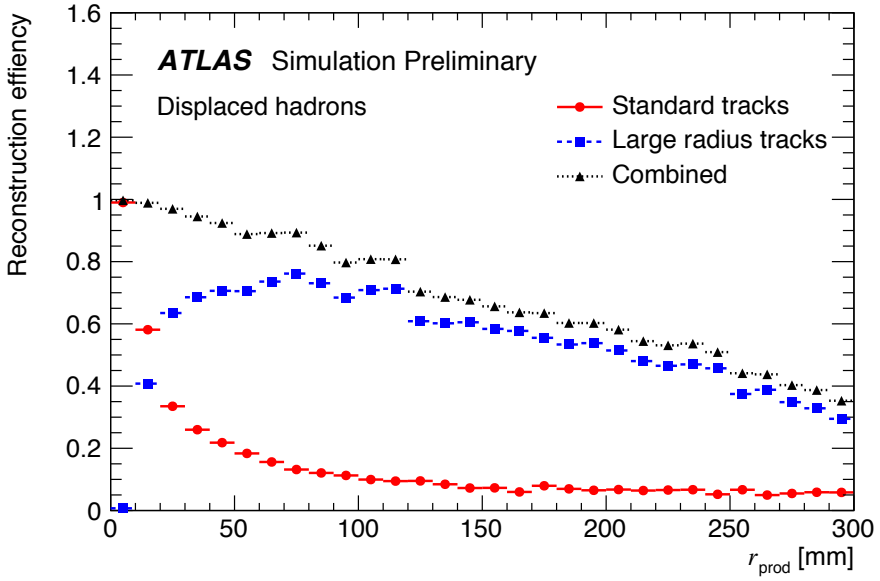
Decays within the inner detector!

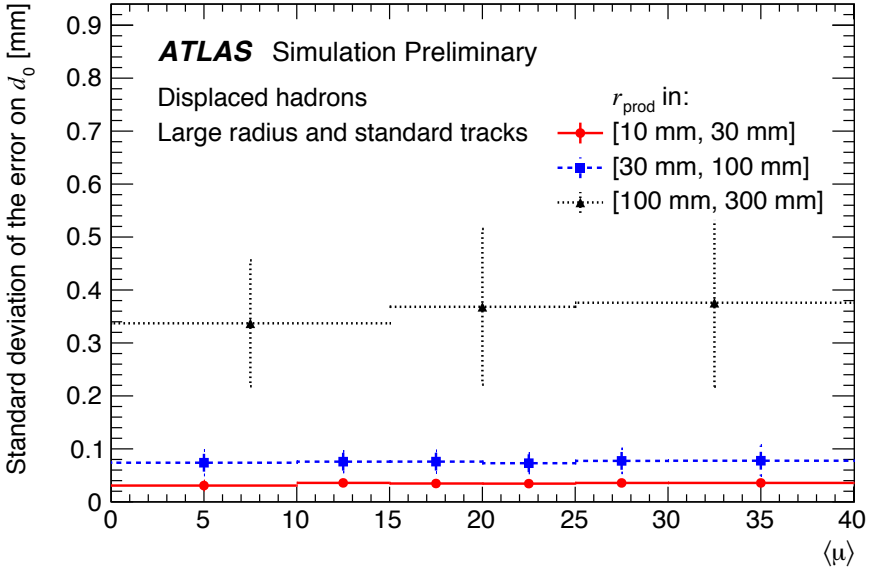
Large Radius Tracking (LRT)

⇨ Second pass tracking performed on unused hits to recover these "large radius" tracks

	Standard	Large radius
Maximum d_0 (mm)	10	300
Maximum z_0 (mm)	250	1500
Maximum $\|\eta\|$	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7
Seed extension	Combinatorial	Sequential







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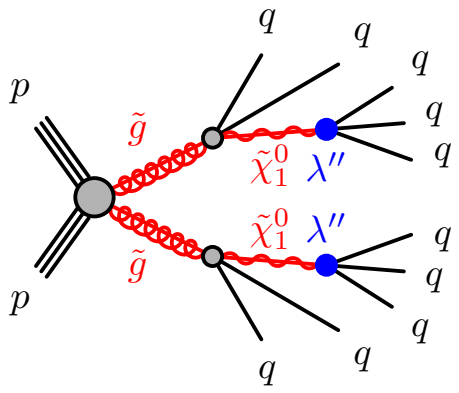
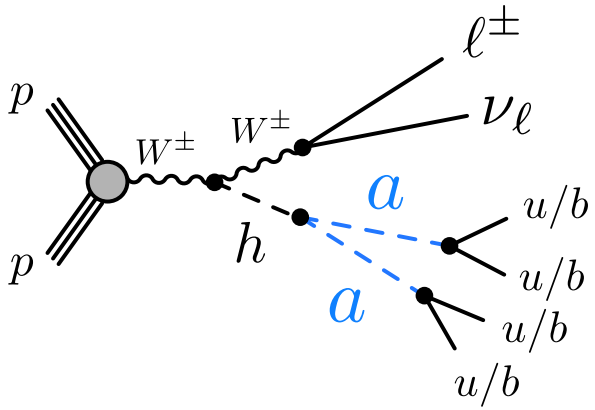
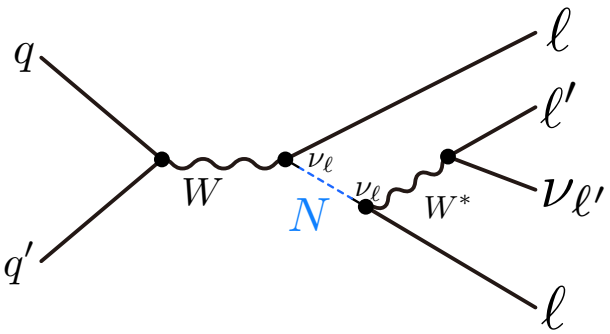
Secondary vertexing

- ⇨ A secondary vertexing algorithm is developed to reconstruct long-lived particles decaying throughout the inner detector
- ⇨ Standard and large radius tracks are used as input to form vertices

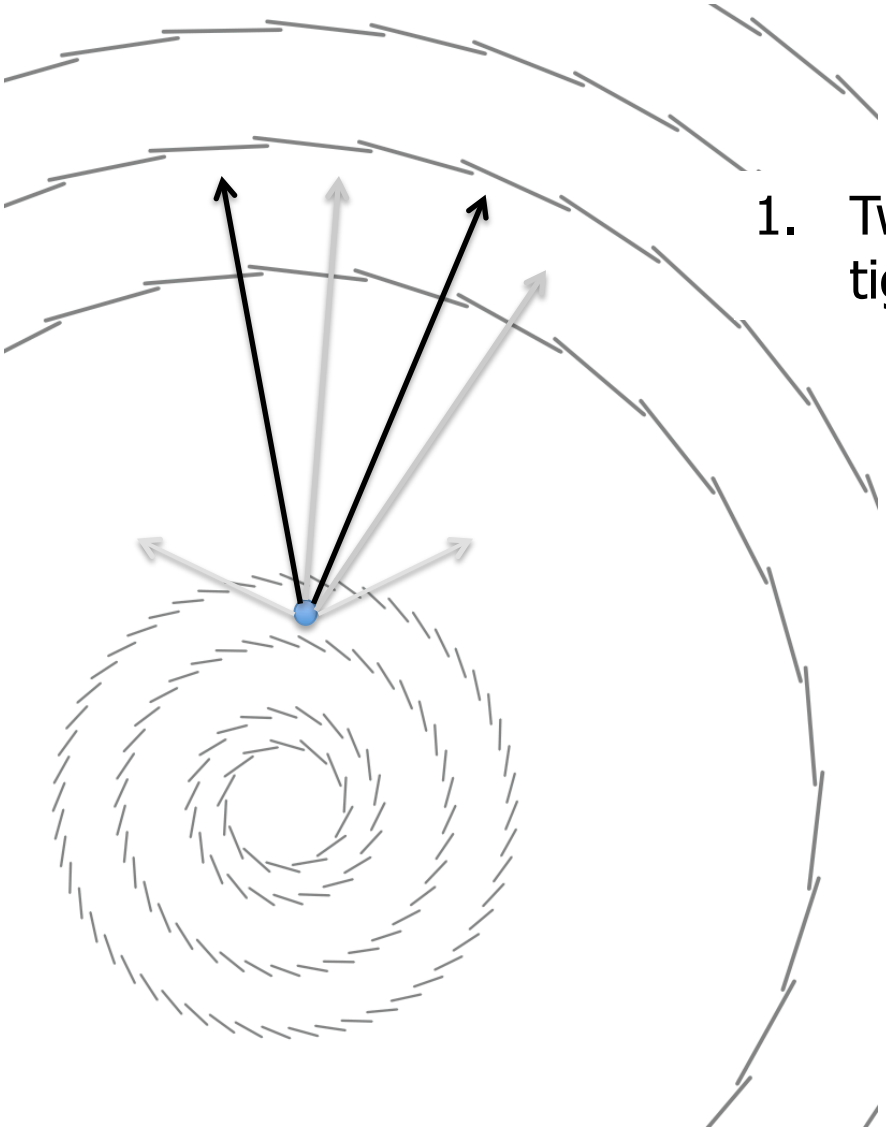






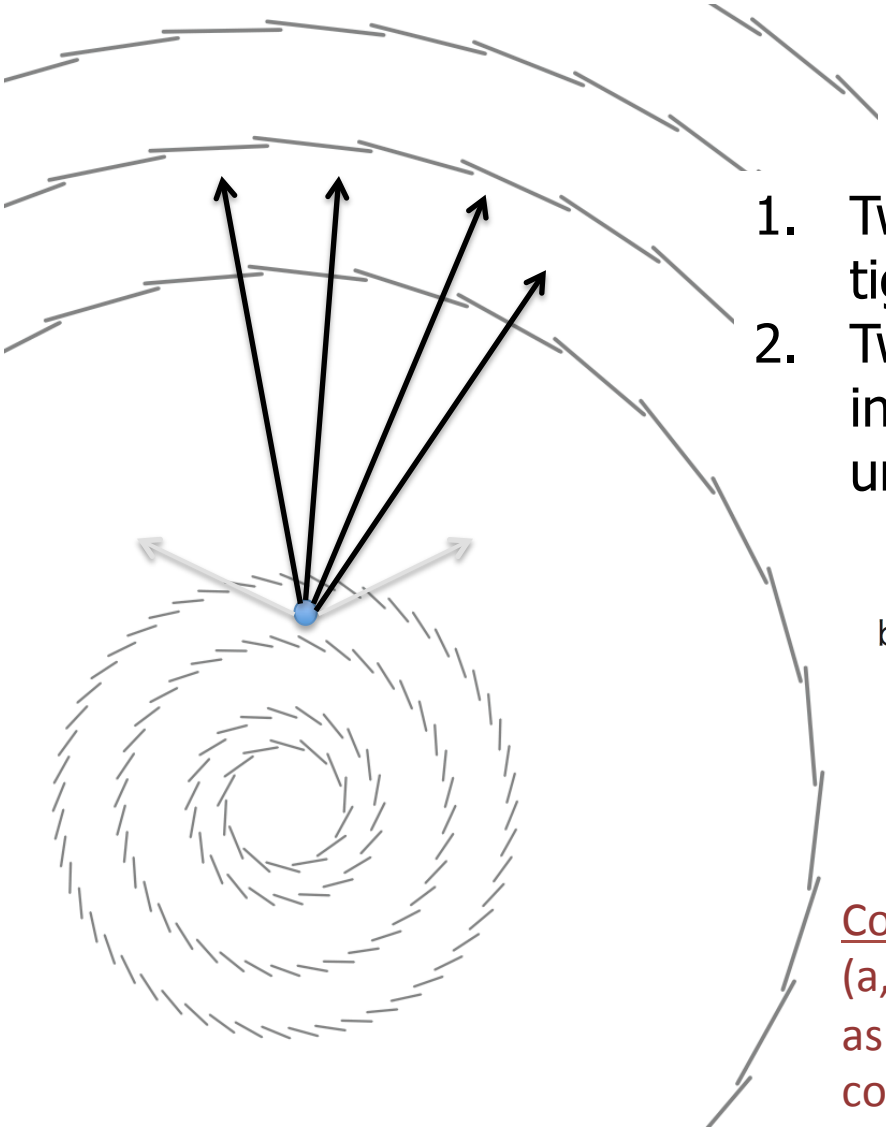
Process	LLP	Secondary vertex type	LLP mass [GeV]	LLP mean proper lifetime	Other params.
$pp \to \tilde{g}\tilde{g},\ \tilde{g} \to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to qqq$	$\tilde{\chi}_1^0$	hadronic (light flavor)	50–2350	1 ns	$m(\tilde{g}) = 2400$ GeV
$pp \to W^\pm h,\ h \to aa,\ a \to bb/uu$	a	hadronic (heavy and light flavour)	55	100 mm/c	
$pp \to W^\pm \to \ell^\pm N,\ N \to \ell^\pm \nu' \ell'^\mp$	N	leptonic	15	100 mm/c	

Vertex reconstruction (1)

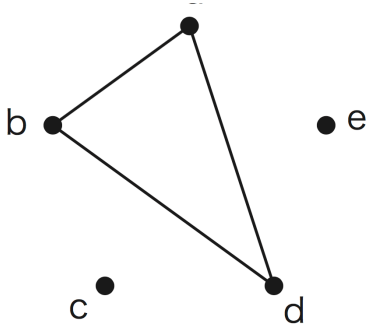


1. Two track seed vertices are formed from tightly selected tracks

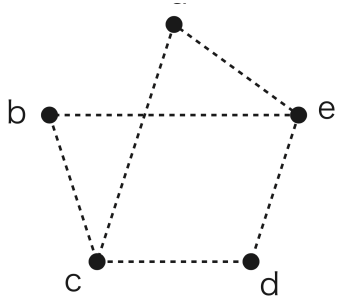
Vertex reconstruction (2)



1. Two track seed vertices are formed from tightly selected tracks
2. Two-track seed vertices are expanded into multi-track vertices using an undirected graph network

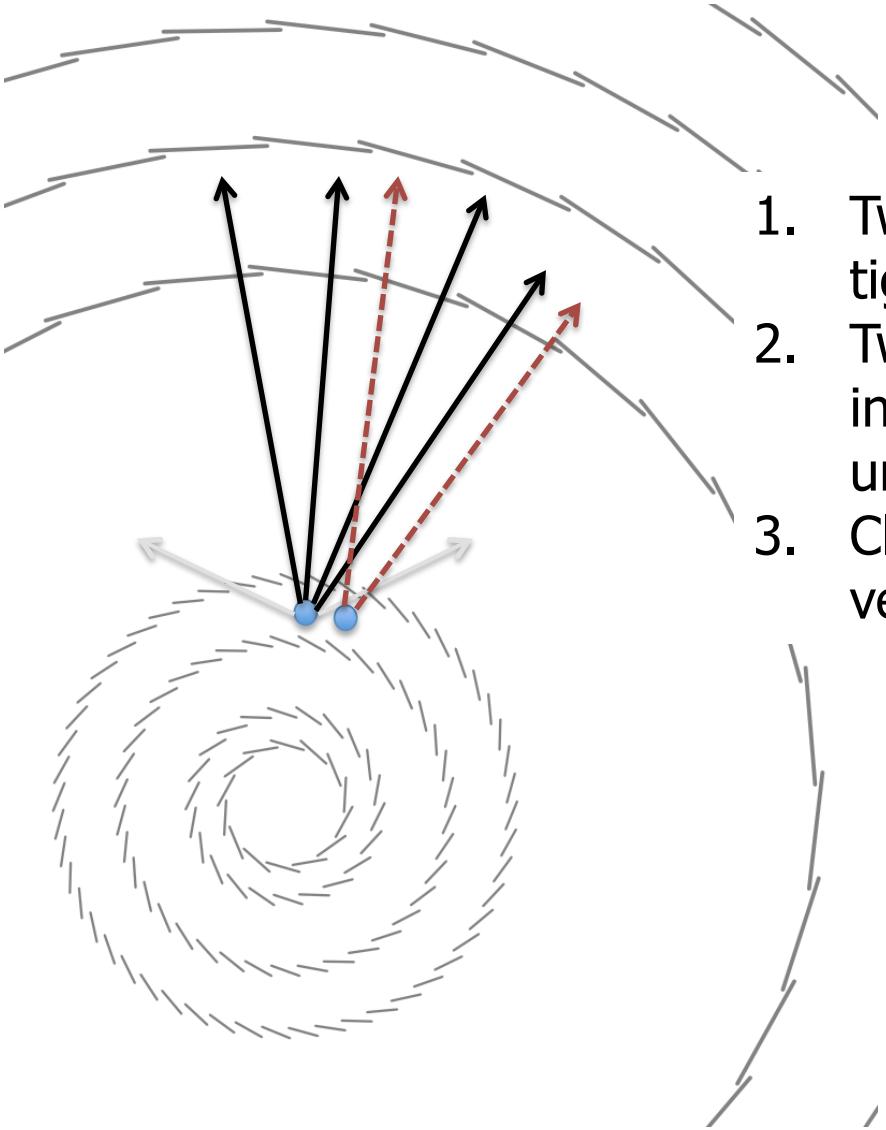


Compatibility graph: (a,b,d) are identified as originating from a common vertex



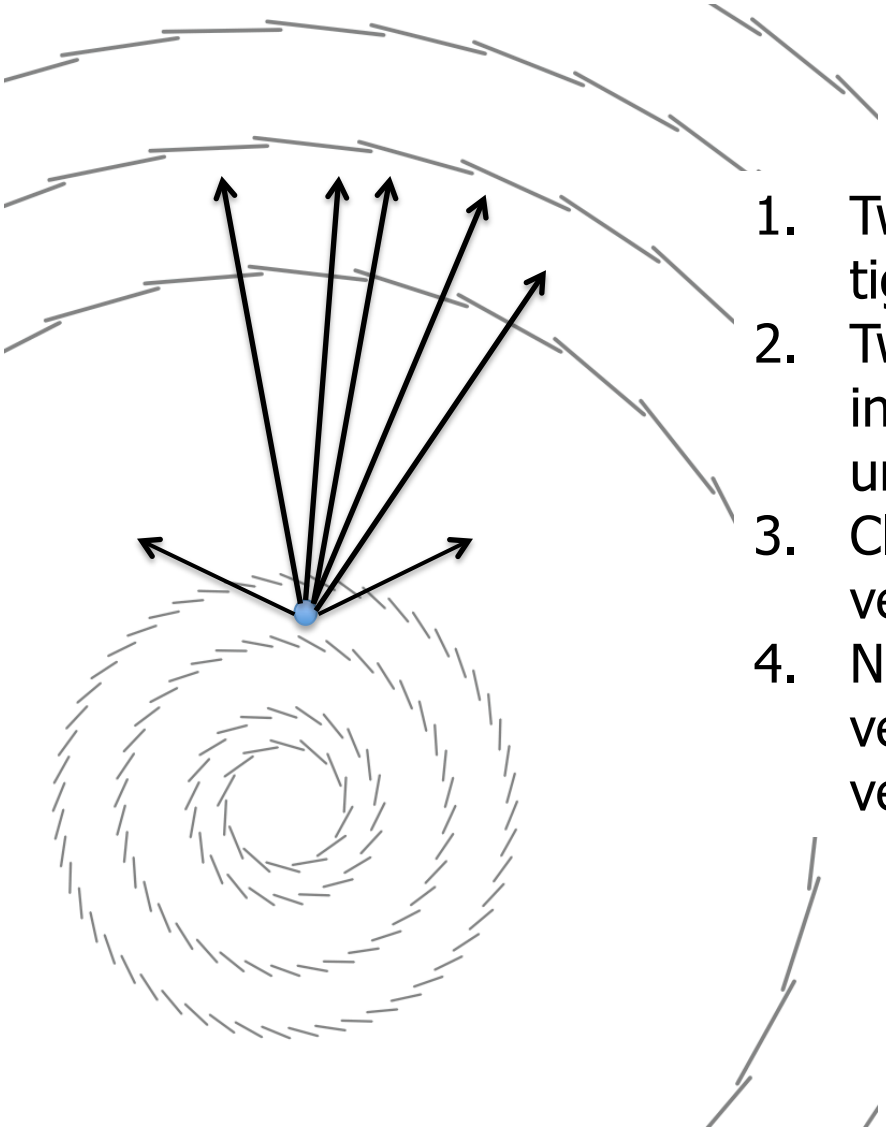
Incompatibility graph: removing nodes/lines from (c,e) makes (a,b,d) isolated and identified as a common vertex

Vertex reconstruction (3)



1. Two track seed vertices are formed from tightly selected tracks
2. Two-track seed vertices are expanded into multi-track vertices using an undirected graph network
3. Close-by vertices are merged into single vertex candidates

Vertex reconstruction (4)



1. Two track seed vertices are formed from tightly selected tracks
2. Two-track seed vertices are expanded into multi-track vertices using an undirected graph network
3. Close-by vertices are merged into single vertex candidates
4. Non-associated tracks are attached to vertices with loosened criteria, and the vertex is refit

Performance

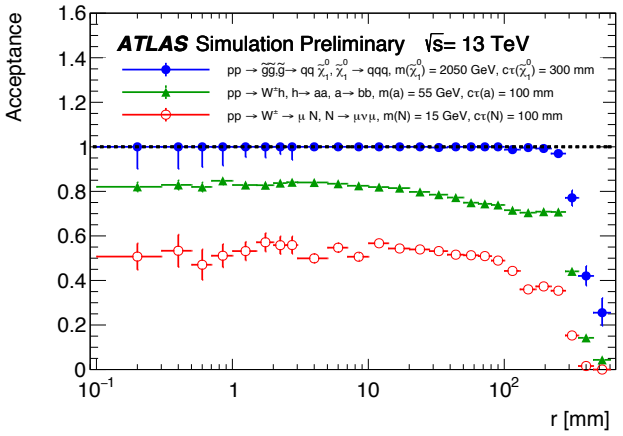
⇨ Tracking and vertexing performance is factorized into independent terms:

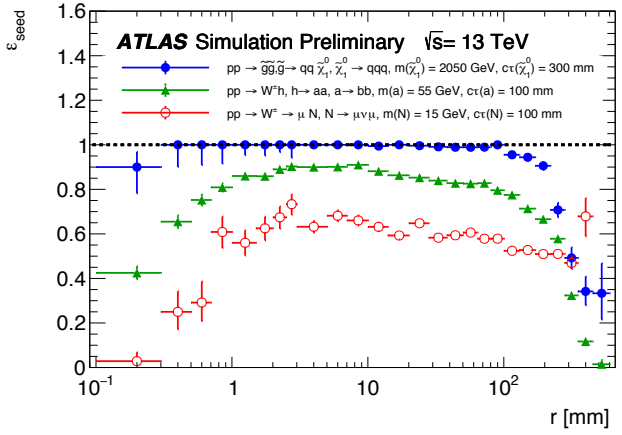
$$\varepsilon_{\vec{x}}^{\text{tot}} = \mathcal{A}_{\vec{x}} \cdot \varepsilon_{\vec{x}}^{\text{alg}} = \mathcal{A}_{\vec{x}} \cdot \varepsilon_{\vec{x}}^{\text{seed}} \cdot \varepsilon_{\vec{x}}^{\text{core}}$$

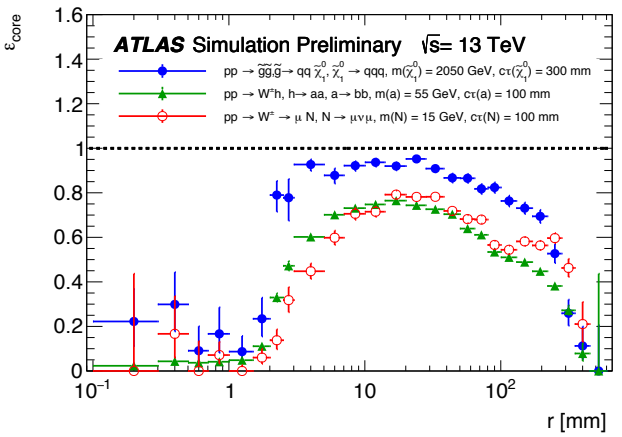
Tracking efficiency: requirement that at least two tracks from the LLP decay are reconstructed

Track selection efficiency: requirement that at least two tracks are selected given they are reconstructed

Vertex performance: requirement that vertex is successfully formed, given tracks are selected

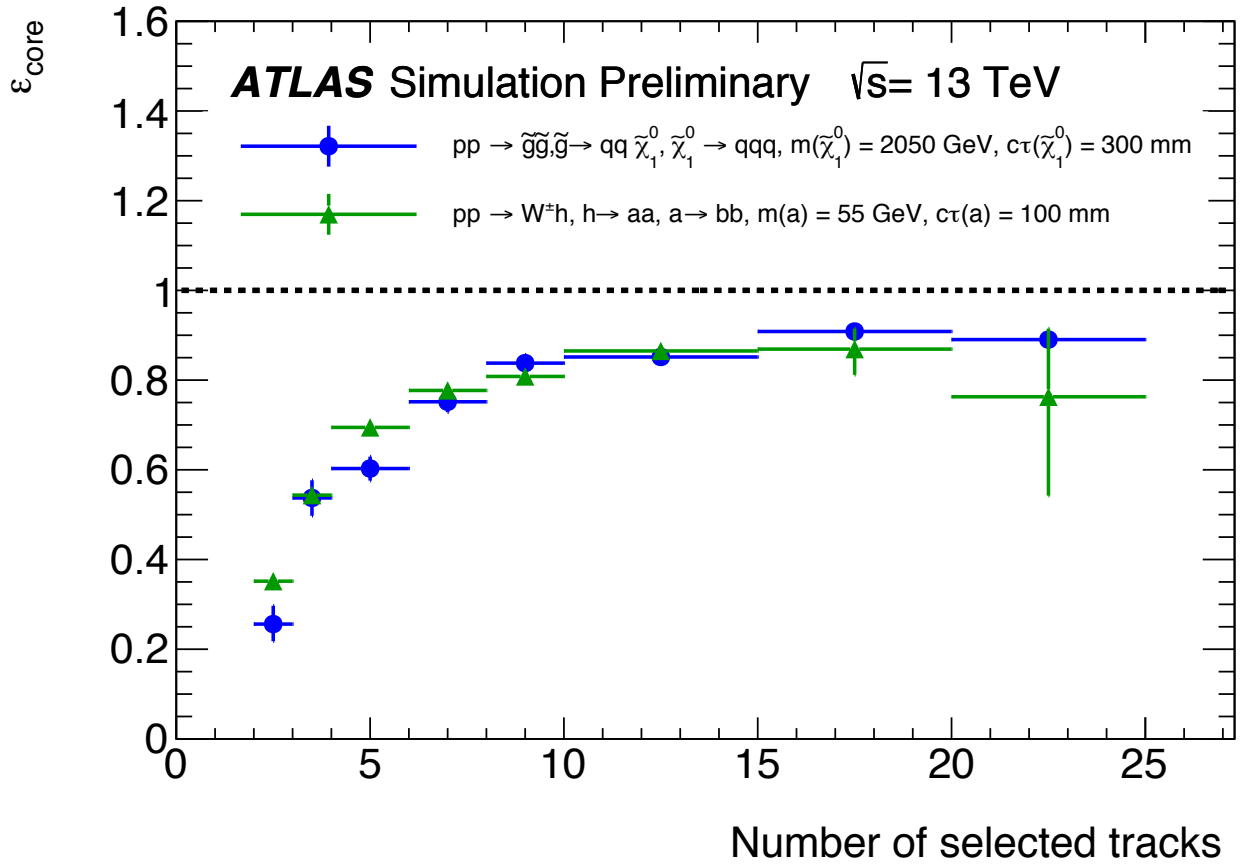






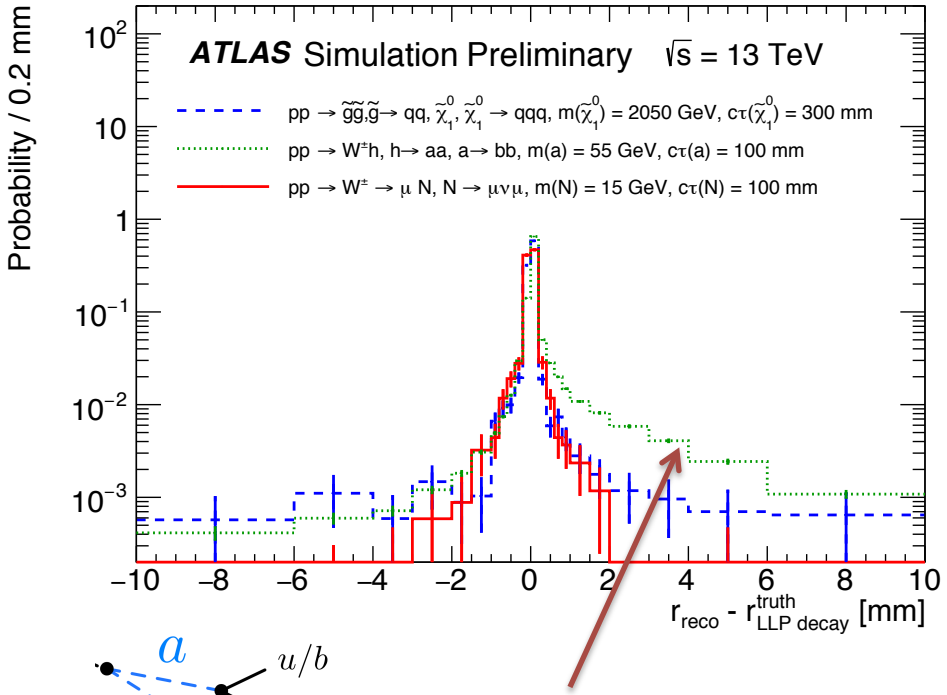
Track multiplicity

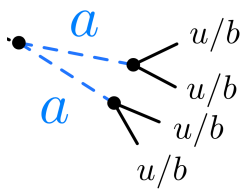
- ⇨ The efficiency is highest for large multiplicity final states
- ⇨ Reflects the redundancy of two-track vertex seed forming



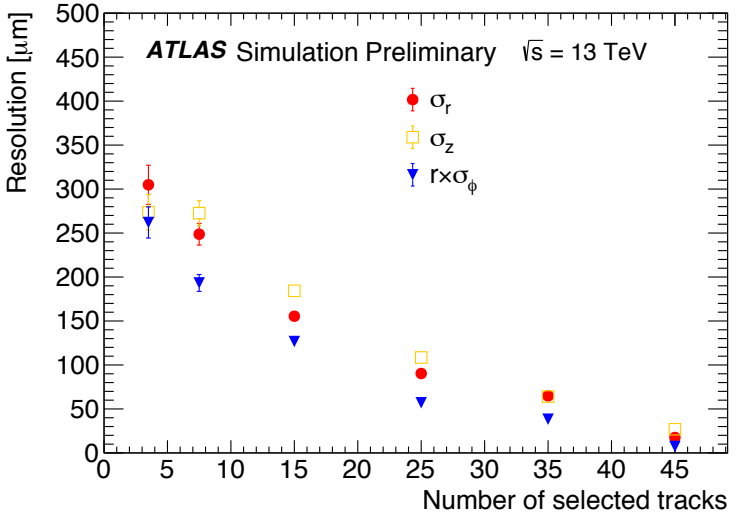
Vertex position resolution

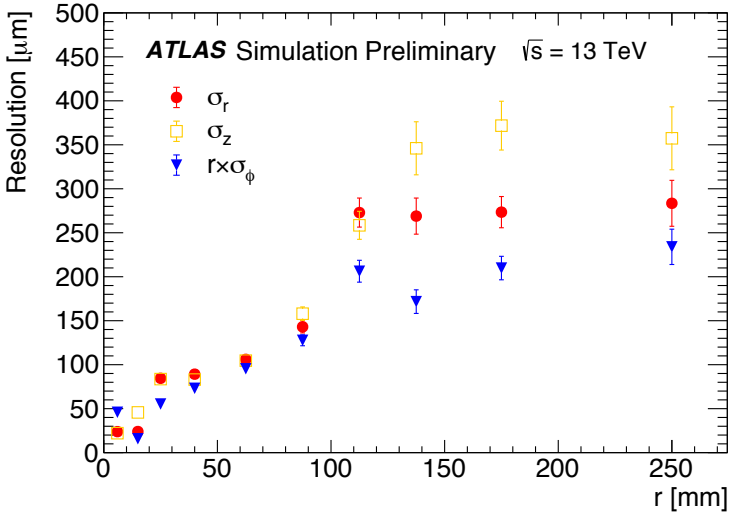
- Position resolution ~150 μm
- Depends strongly track multiplicity and vertex radius → precision of track parameters important (better in pixel)!





Long asymmetric tail visible from b-hadron decays!

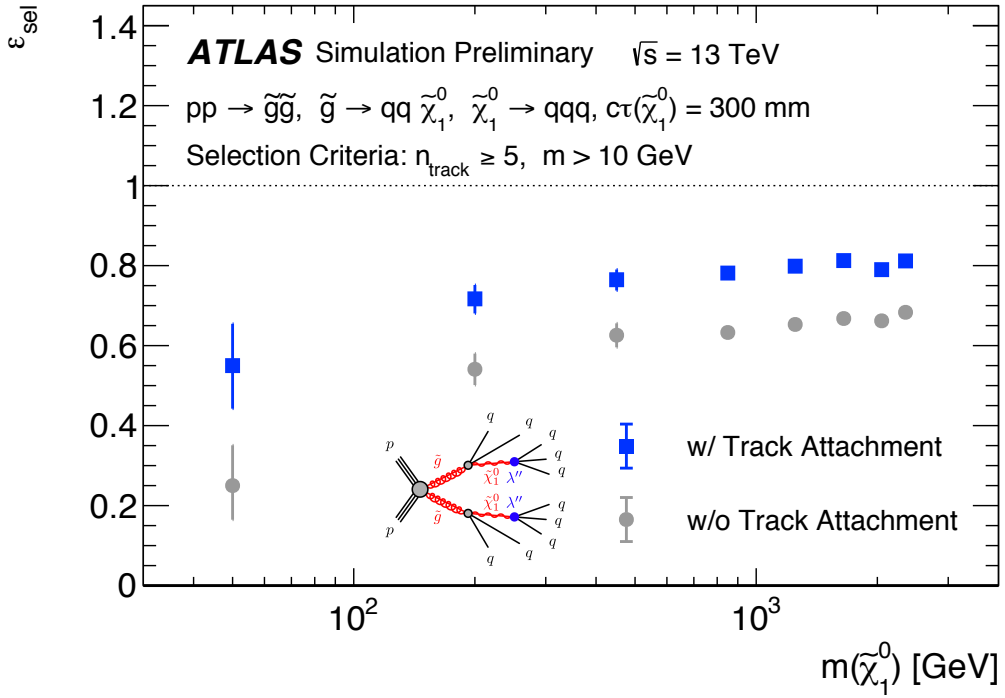




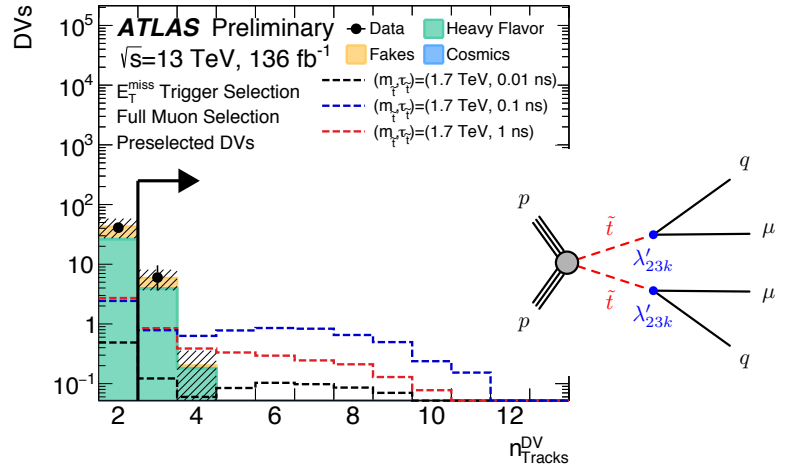
Fewer measurements in pixel detectors

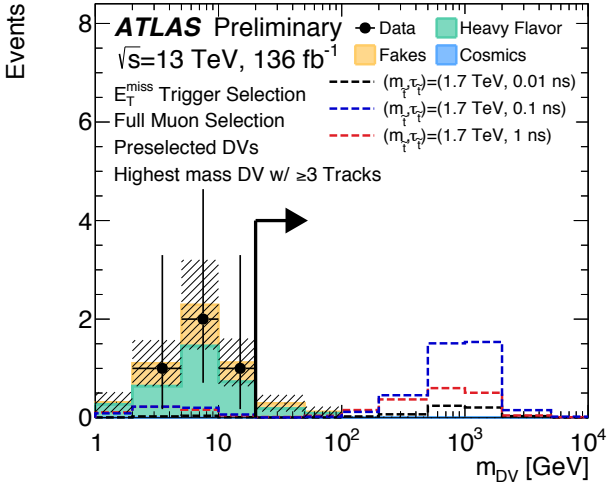
Attached track: selection efficiency

- ⇨ At analysis level, the vertex multiplicity and visible vertex mass can be used as extremely powerful discriminates
- ⇨ Attached track feature significantly improves analysis observables!



Selection efficiency: fraction of events passing $n_{track} \geq 5$ and $m_{vertex} > 10$ GeV over total number of reconstructed vertices from LLP





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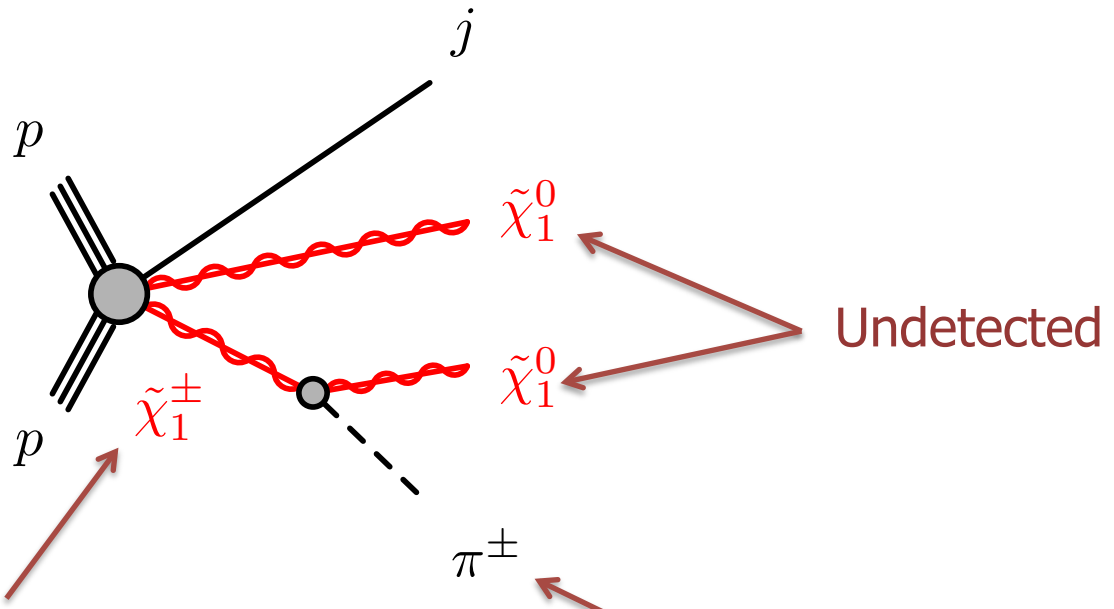
Disappearing track plus a soft-track signature

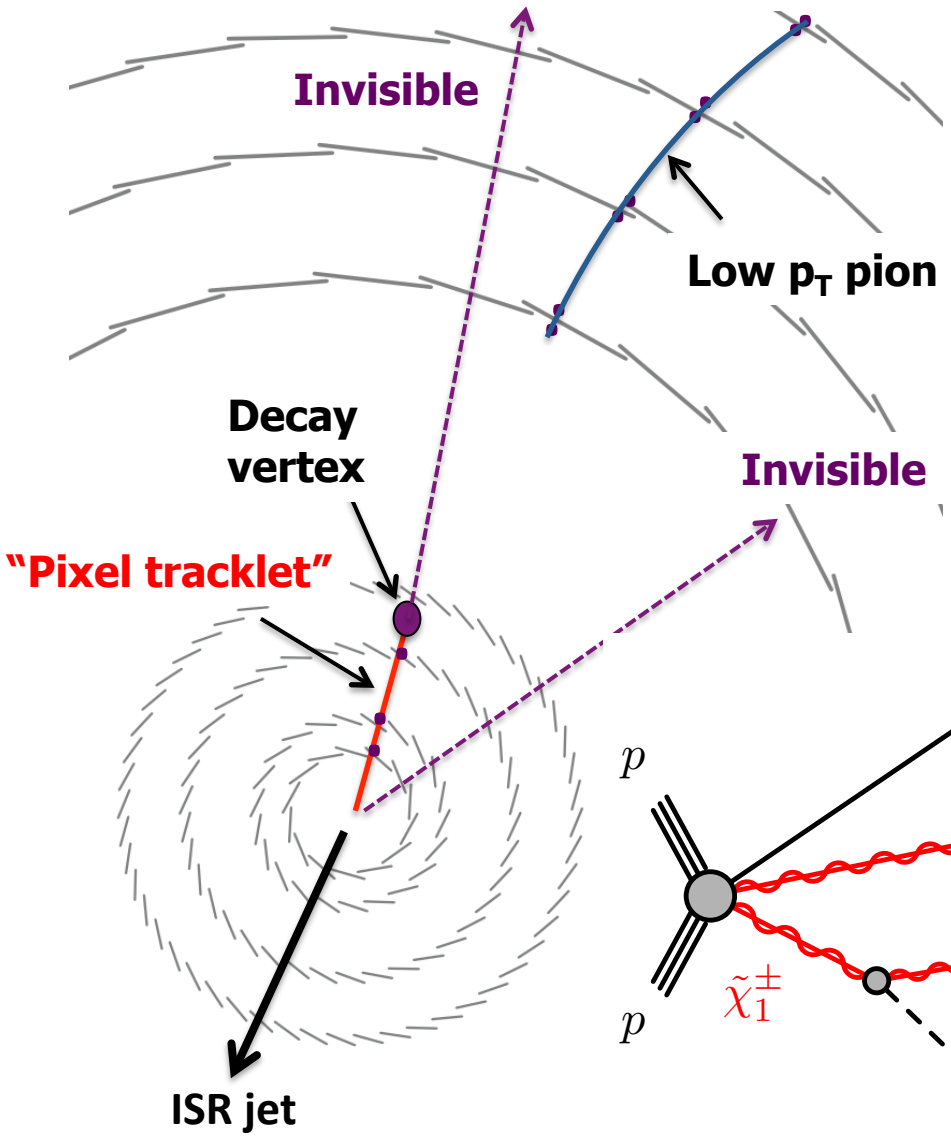


Long-lived charged state
from compressed mass spectrum

$\Delta m\left(\tilde{\chi}_1^\pm, \tilde{\chi}_{1,2}^0\right)$ ~ 300 MeV

Extremely low momentum
p_T ~ 300 MeV

Targeted physics scenario

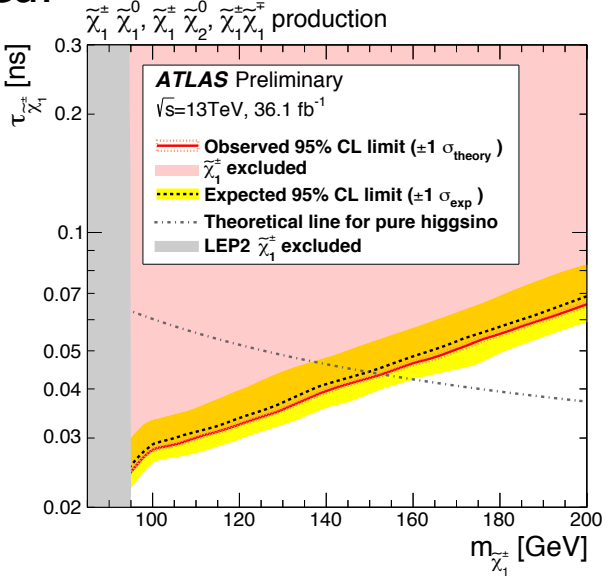


⇨ In a pure higgsino scenario, the mean lifetime of the chargino given by

$$c\tau[\text{mm}] \sim 7 \times \left[\left(\frac{\Delta m\left(\tilde{\chi}_1^\pm, \tilde{\chi}_{1,2}^0\right)}{340\ \text{MeV}}\right)^3 \sqrt{1 - \frac{m_{\pi^\pm}^2}{\Delta m\left(\tilde{\chi}_1^\pm, \tilde{\chi}_{1,2}^0\right)^2}}\right]^{-1}$$

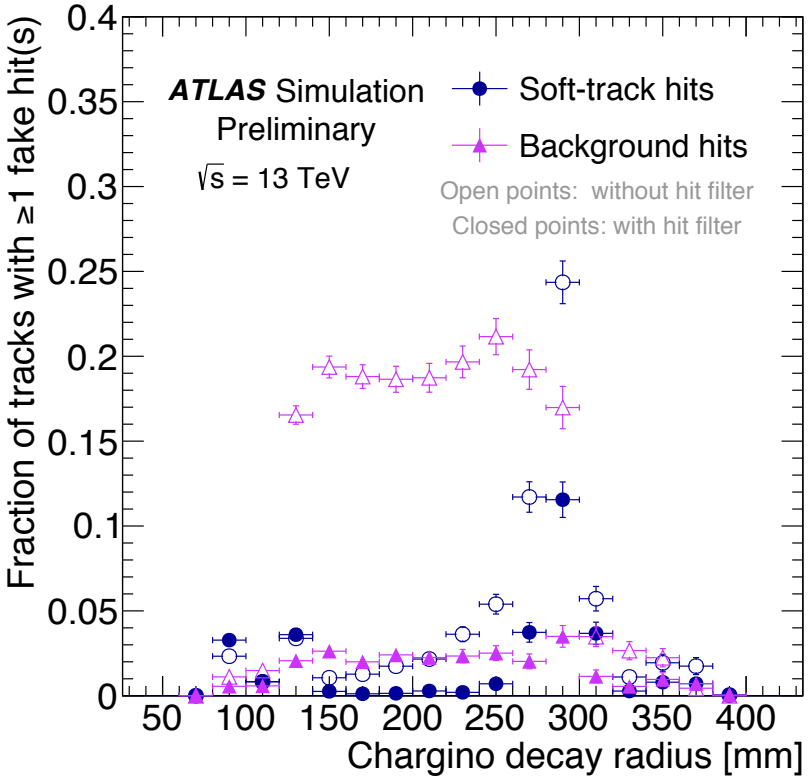
⇨ Leading to tracks with ~7 to 14 mm for masses accessible at the LHC

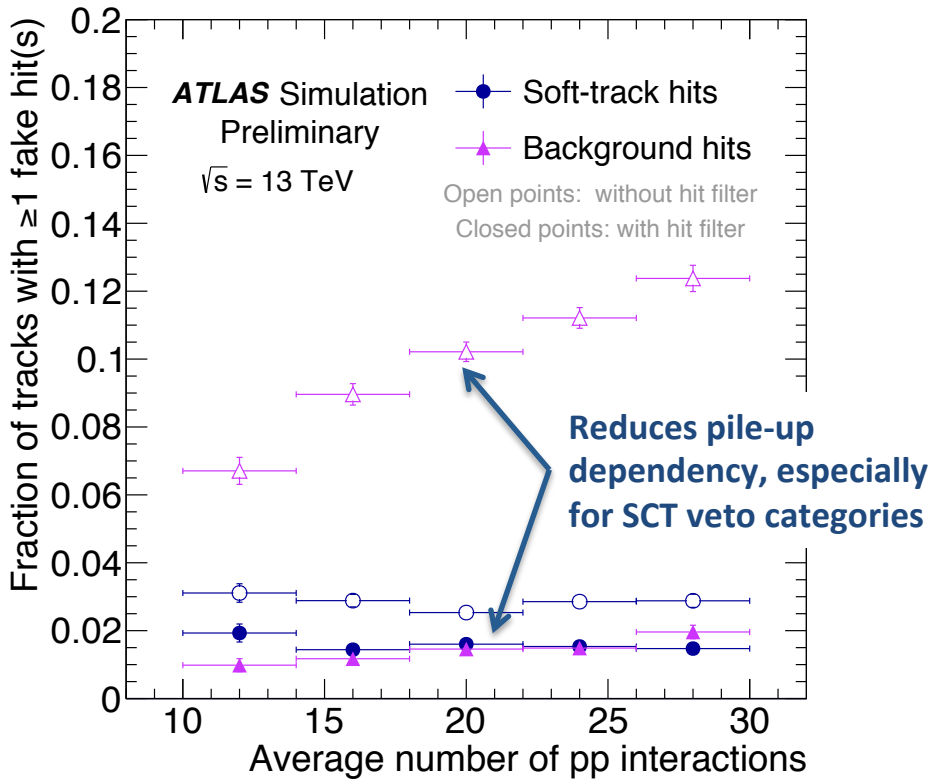
⇨ The shortest possible "pixel tracklet" is desired!



SCT hit filter

- ⇨ Single pile-up associated to tracklets trajectory spoil the disappearing track condition (veto on SCT hits)
- ⇨ Require SCT hits on both axial and stereo layers → significant reduction in fake rate, and improves disappearing track condition

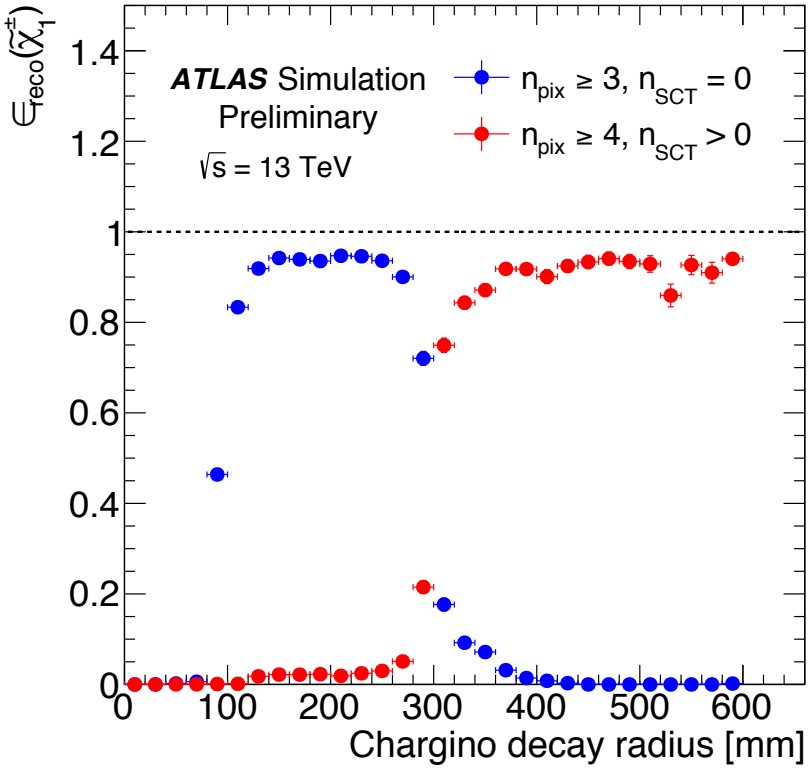


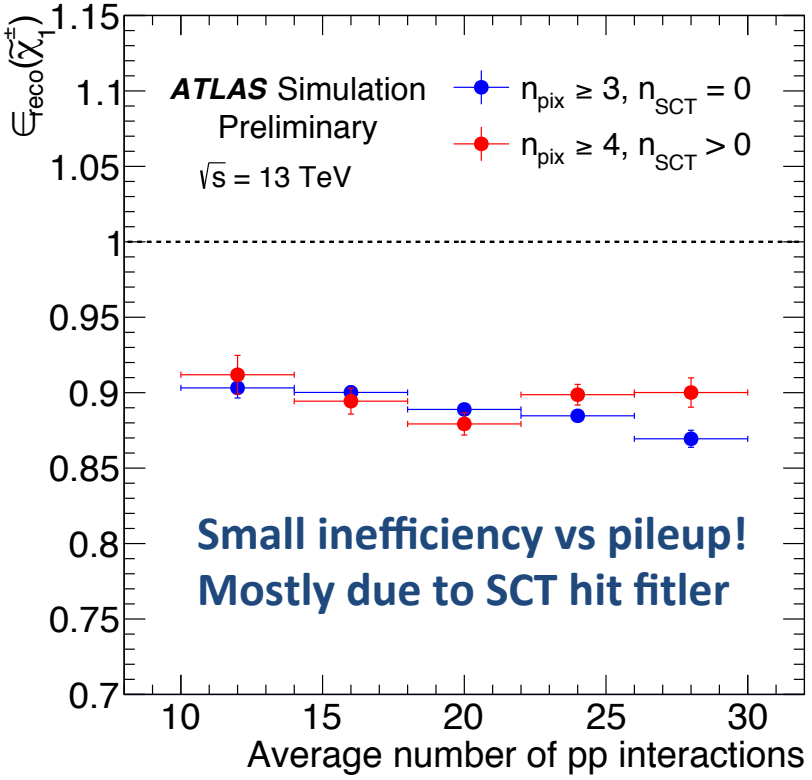


Tracklet reconstruction

⇨ Reconstruction efficiency better than 90% beyond r ~88 mm

$$\epsilon_{\text{reco}}(\tilde{\chi}_1^{\pm}) = \frac{\text{number of charginos matched to a reconstructed track}}{\text{number of generated chargino particles}}$$





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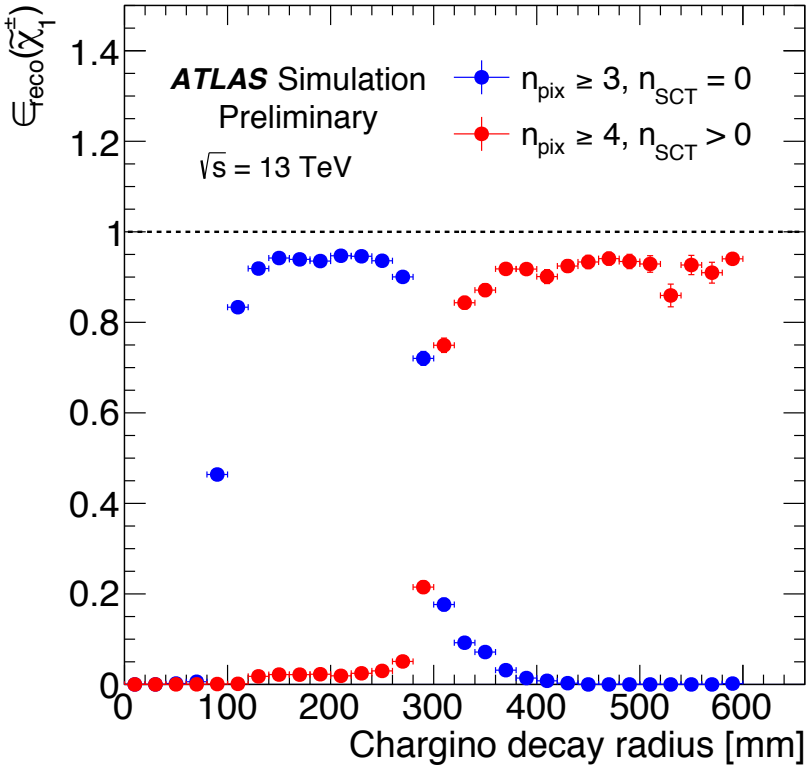
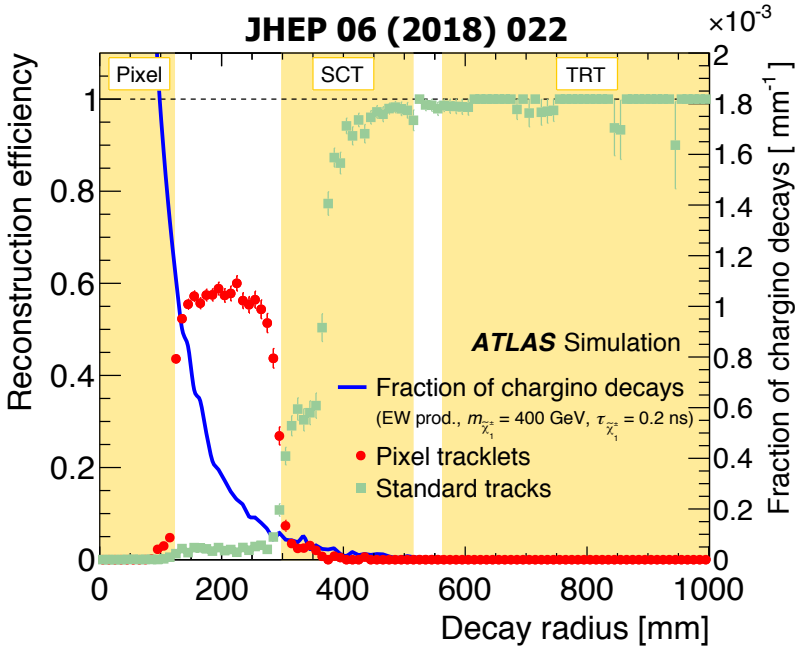
⇨ Reconstruction efficiency better than 90% beyond r ~88 mm

$$\epsilon_{\text{reco}}(\tilde{\chi}_1^{\pm}) = \frac{\text{number of charginos matched to a reconstructed track}}{\text{number of generated chargino particles}}$$

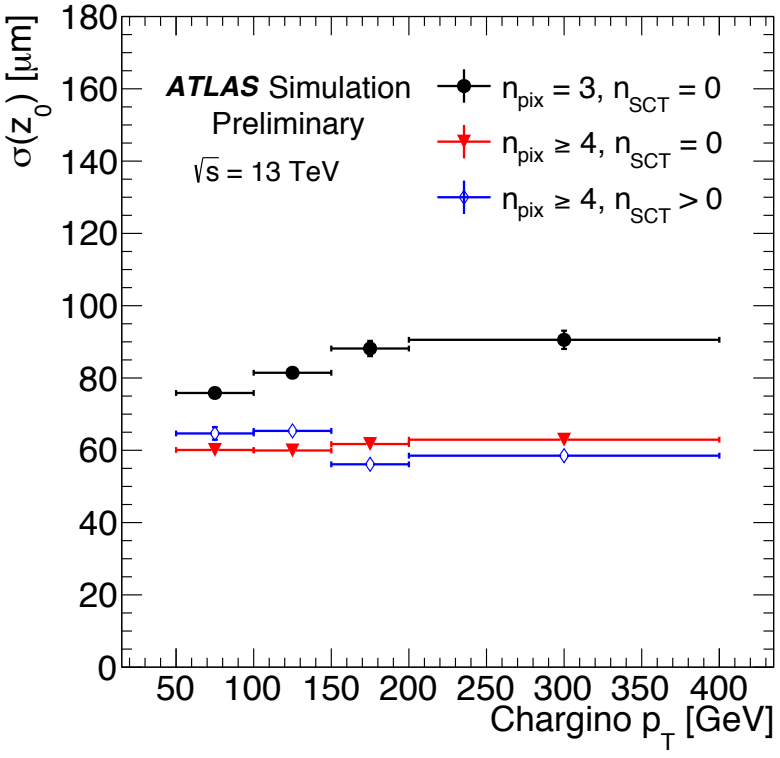


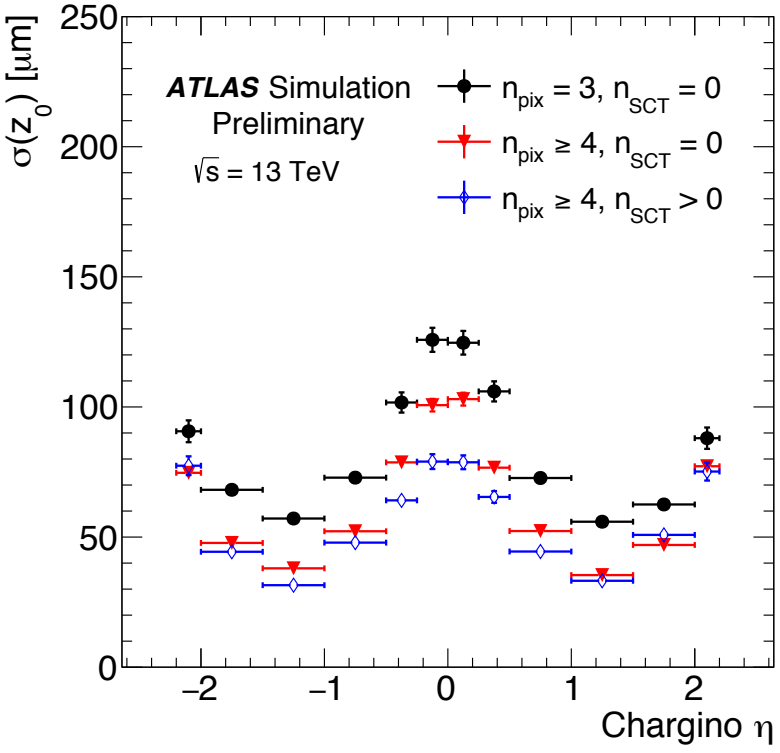


Significant improvements in overall efficiency and towards shorter track lengths compared to previous ATLAS reconstruction algorithms !!

Tracklet IP resolution

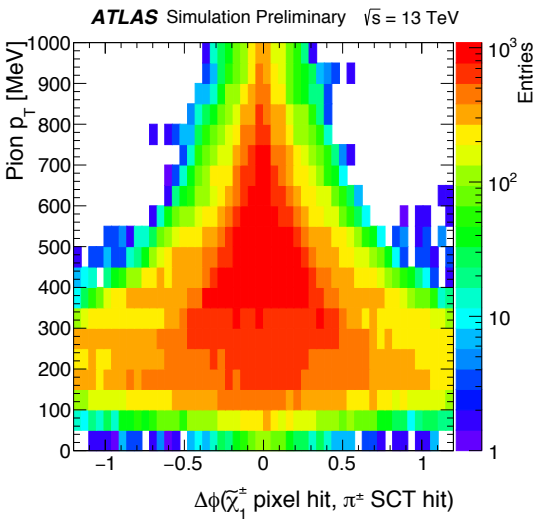
- Impact parameter resolution with respect to the beam spot
  - Small differences between 4-pixel and 4-pixel plus SCT hit categories → z_0 resolution main driven by presence of pixel hits
  - Resolution of z_0 IP depends highly on incident angle → cluster sharing in the forward regions improves the single hit resolution

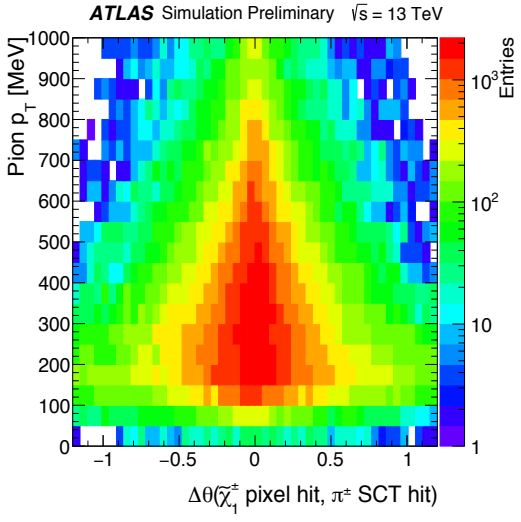


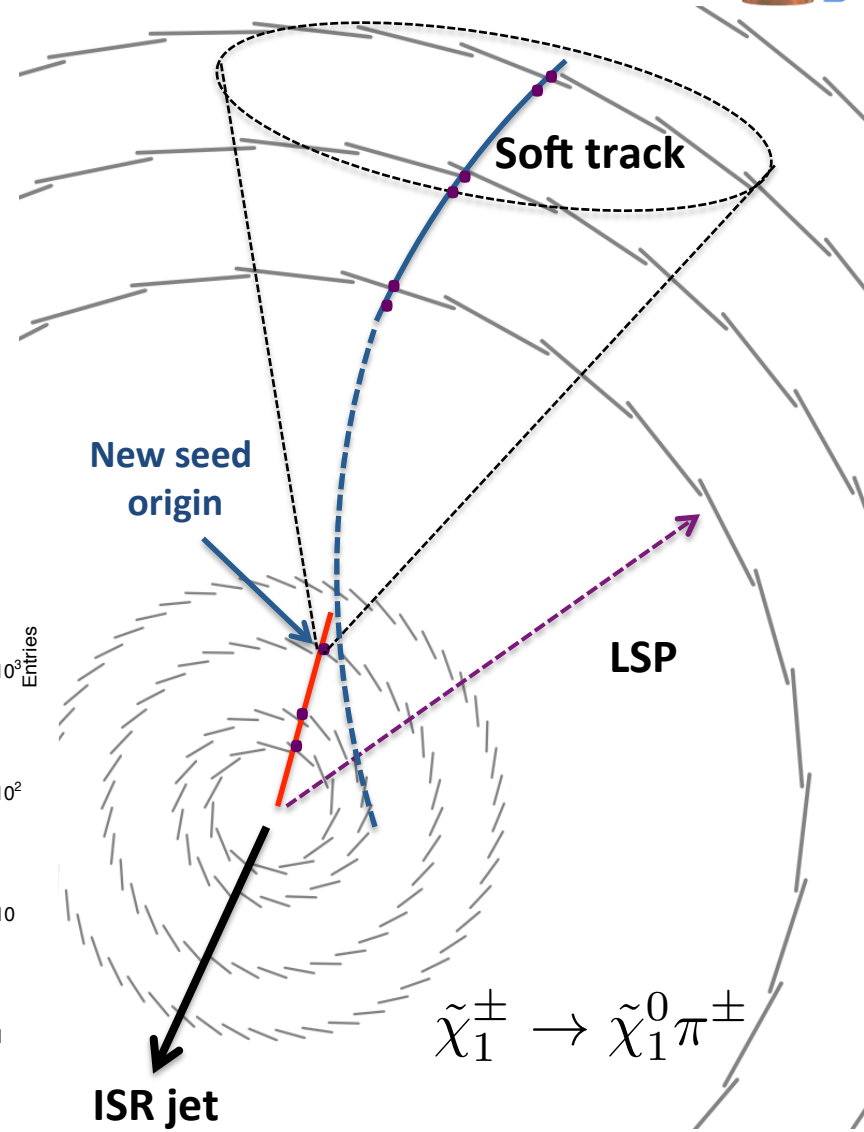


RoI soft-track seeding

- ⇨ A Region of Interest (RoI) technique developed to reconstruct soft-track
  - Tracklets define a RoI to search for seeds
  - Dynamically set the origin in each RoI to the last pixel tracklet measurement
  - Apply impact parameter requirements relative to this new origin
  - Perform track finding using SCT hits only
- Reduces execution times by over an order of magnitude: ~30 s/evt → 1-2 s/evt

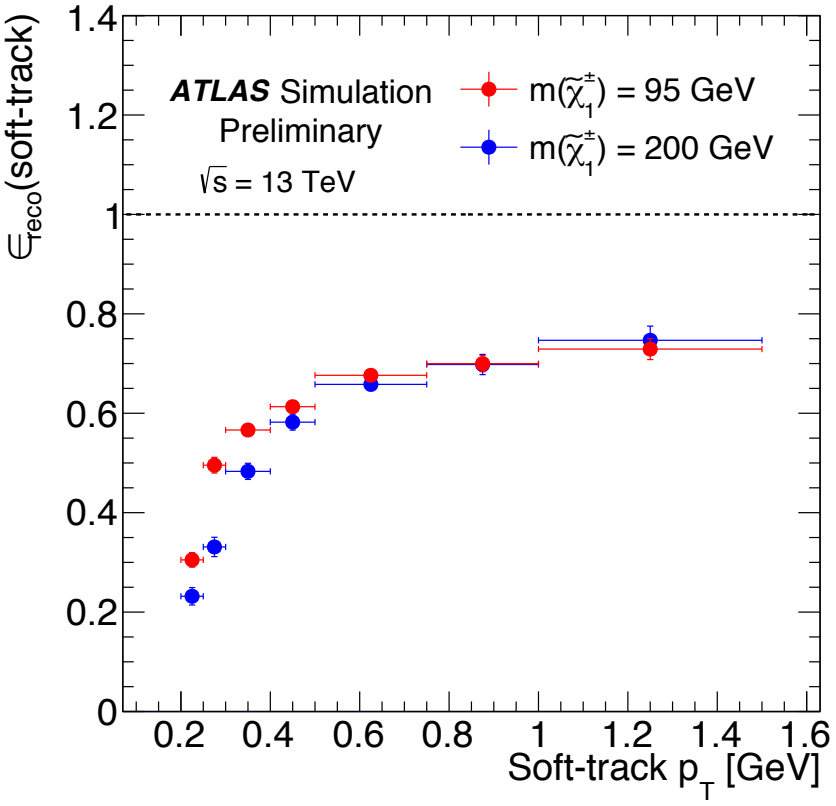


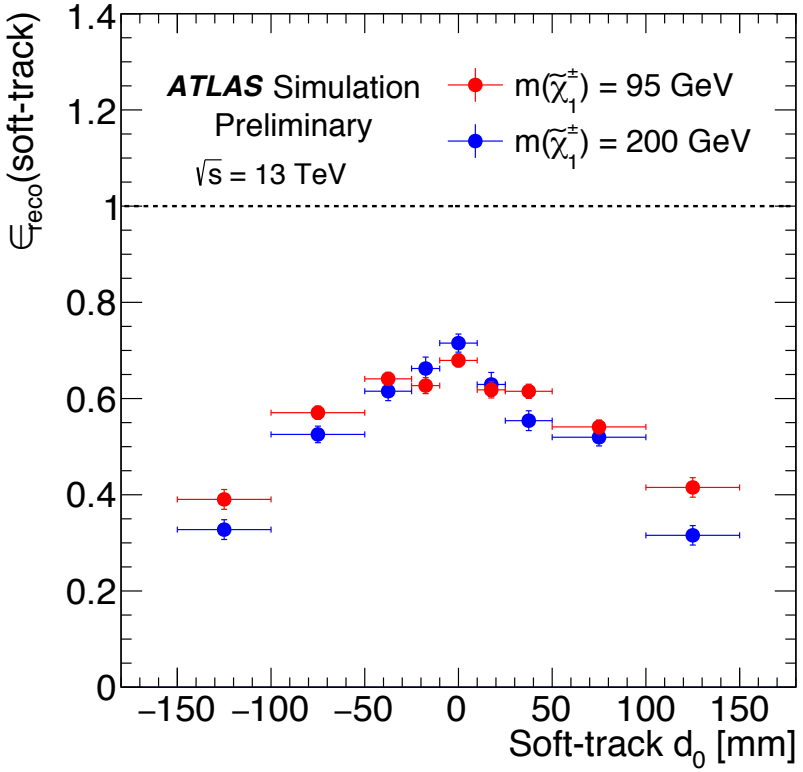




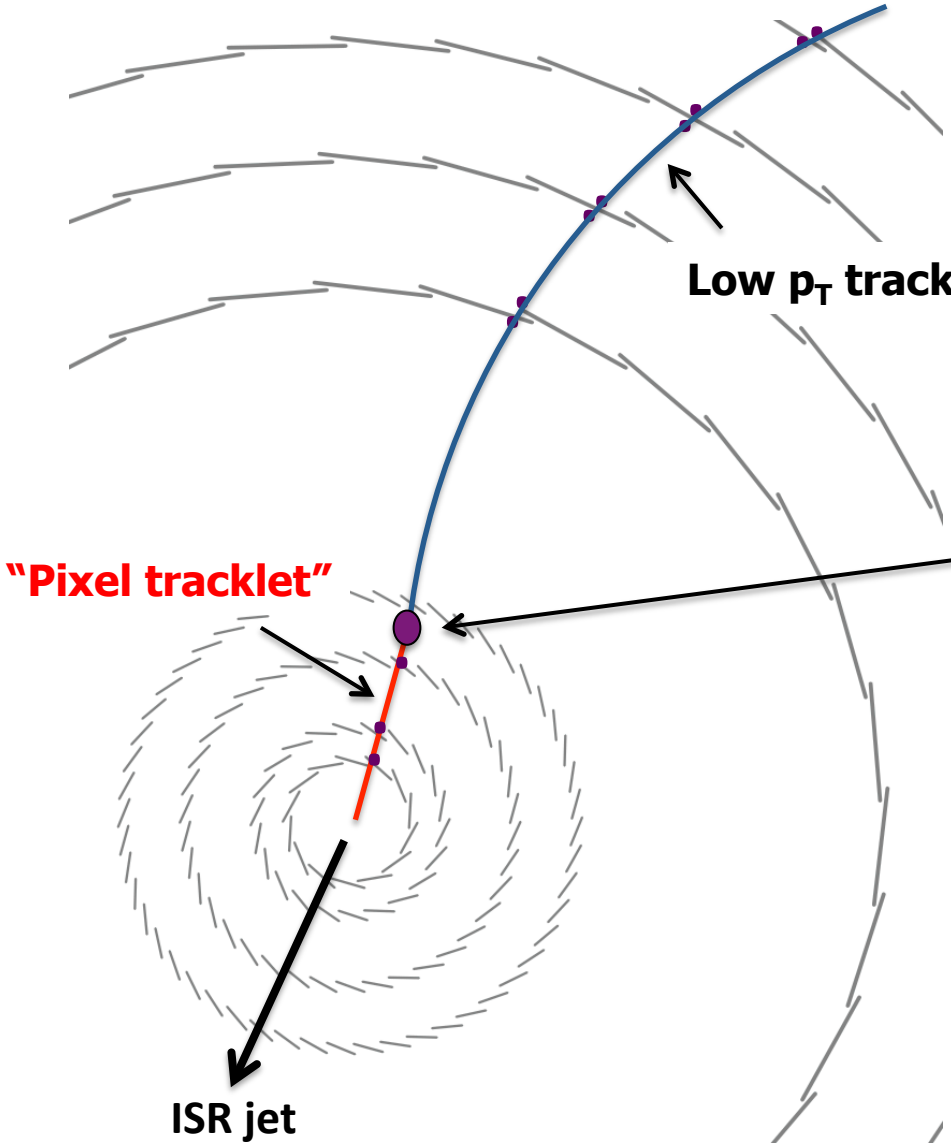
Soft-track reconstruction efficiency

- ⇨ Efficiency evaluated after successful reconstruction of a tracklet with the same criteria used during the soft-track seeding stage
- ⇨ Achieve ~50-60% for tracks with p_T > 300 MeV





Two-track vertex fit

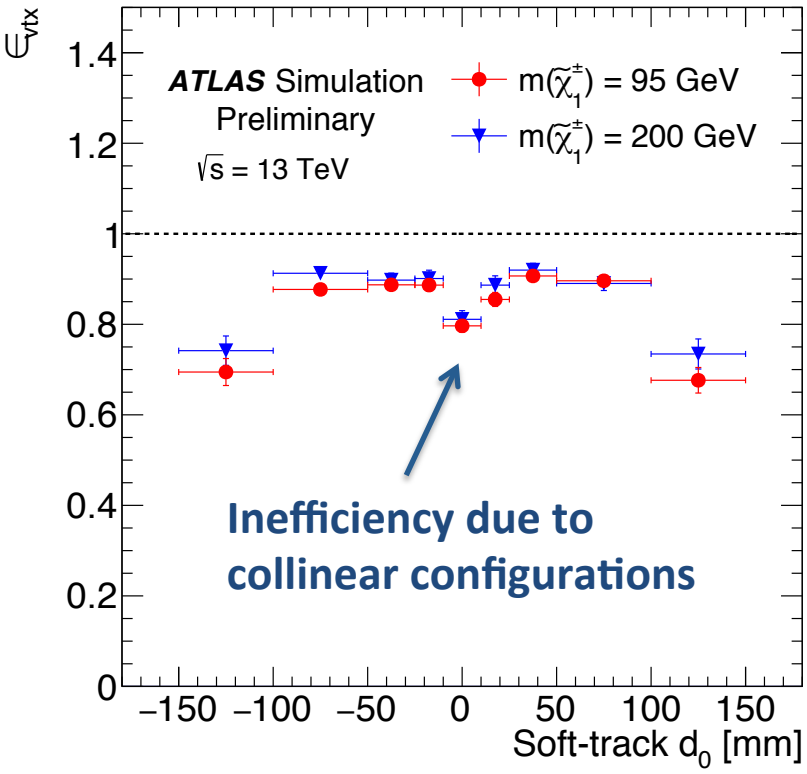


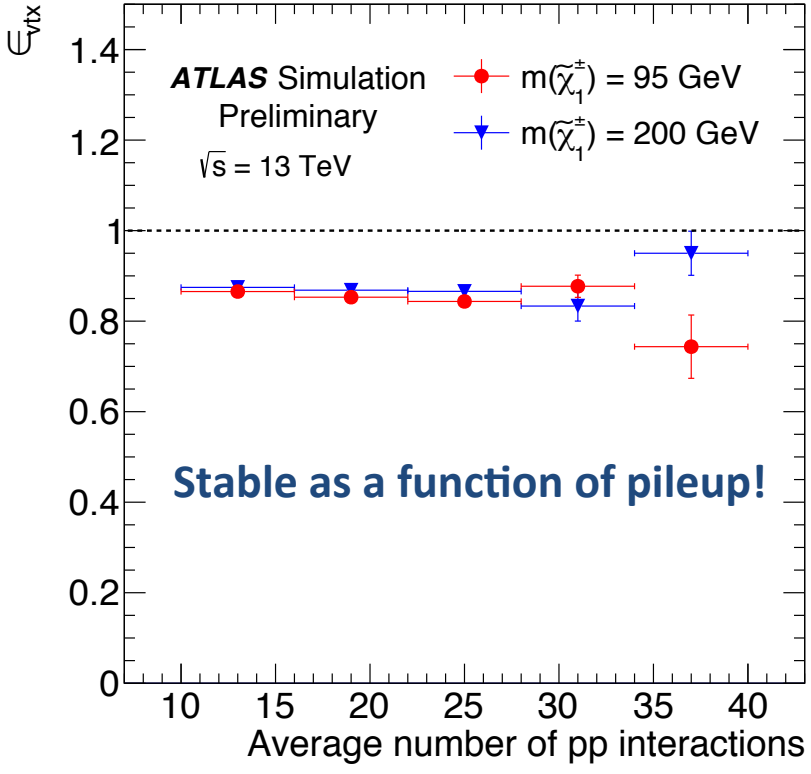
Two-track vertex fit performed to estimate decay position of the pixel tracklet

Vertex efficiency

- Two-track vertex fit performed with pixel-tracklet and soft-track
- Tracking efficiency factored out from vertex efficiency:

$$\epsilon_{\text{vtx}}(x) = \frac{N_{\text{truth}}(\text{vertex reconstructed} \mid \text{seed tracks reconstructed})}{N_{\text{truth}}(\text{seed tracks reconstructed})}$$

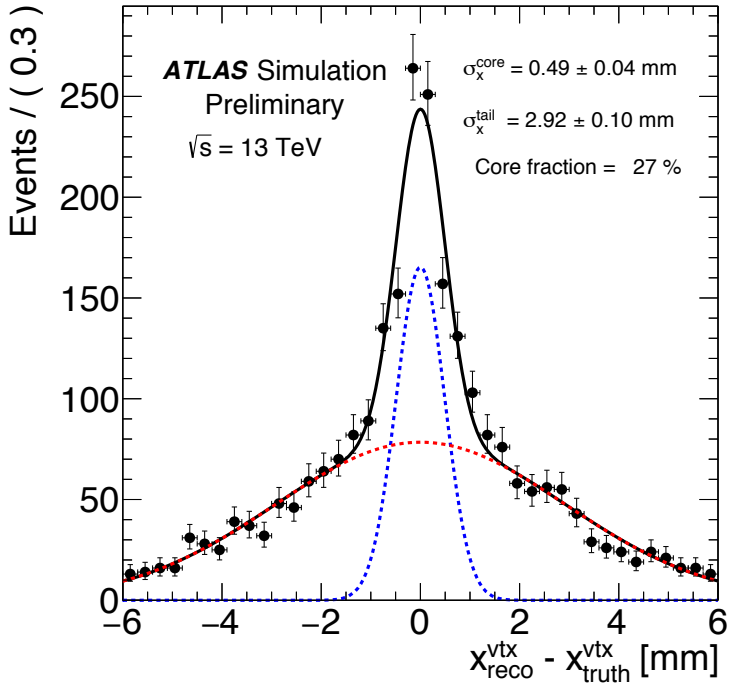


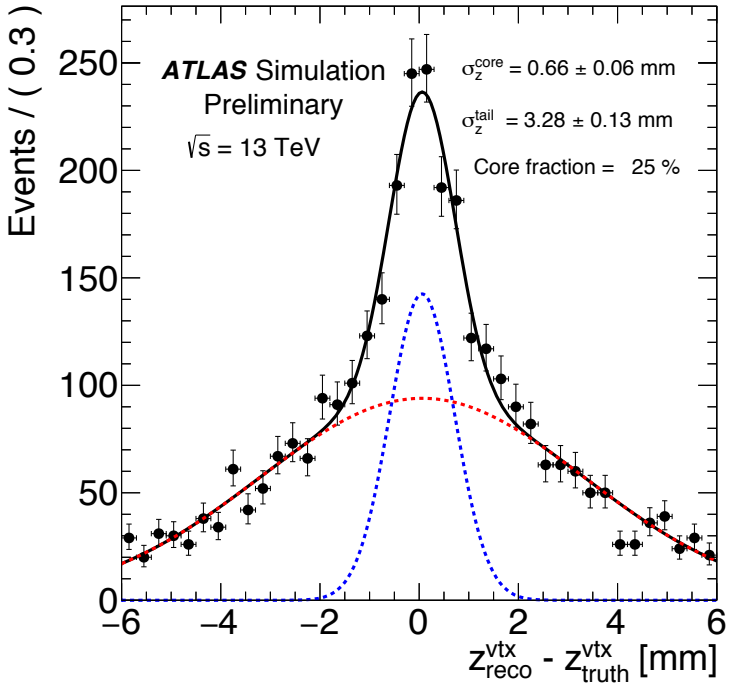


Vertex Position Resolution

- Position resolution studied in signal by taking difference between reconstructed and generated decay position
- Extract resolution with double gaussian model for the "core" and "tails"
- Resolution dominated by the tails

	$r < 150$ mm	150 mm $< r <$ 300 mm
σ_x^{core}	0.49 ± 0.04 mm (27%)	0.52 ± 0.03 mm (38%)
σ_x^{tail}	2.92 ± 0.10 mm (73%)	2.41 ± 0.06 mm (62%)
σ_y^{core}	0.49 ± 0.07 mm (22%)	0.52 ± 0.03 mm (33%)
σ_y^{tail}	2.86 ± 0.10 mm (78%)	2.36 ± 0.05 mm (67%)
σ_z^{core}	0.65 ± 0.08 mm (18%)	0.66 ± 0.06 mm (25%)
σ_z^{tail}	3.69± 0.20 mm (82%)	3.28 ± 0.13 mm (75%)



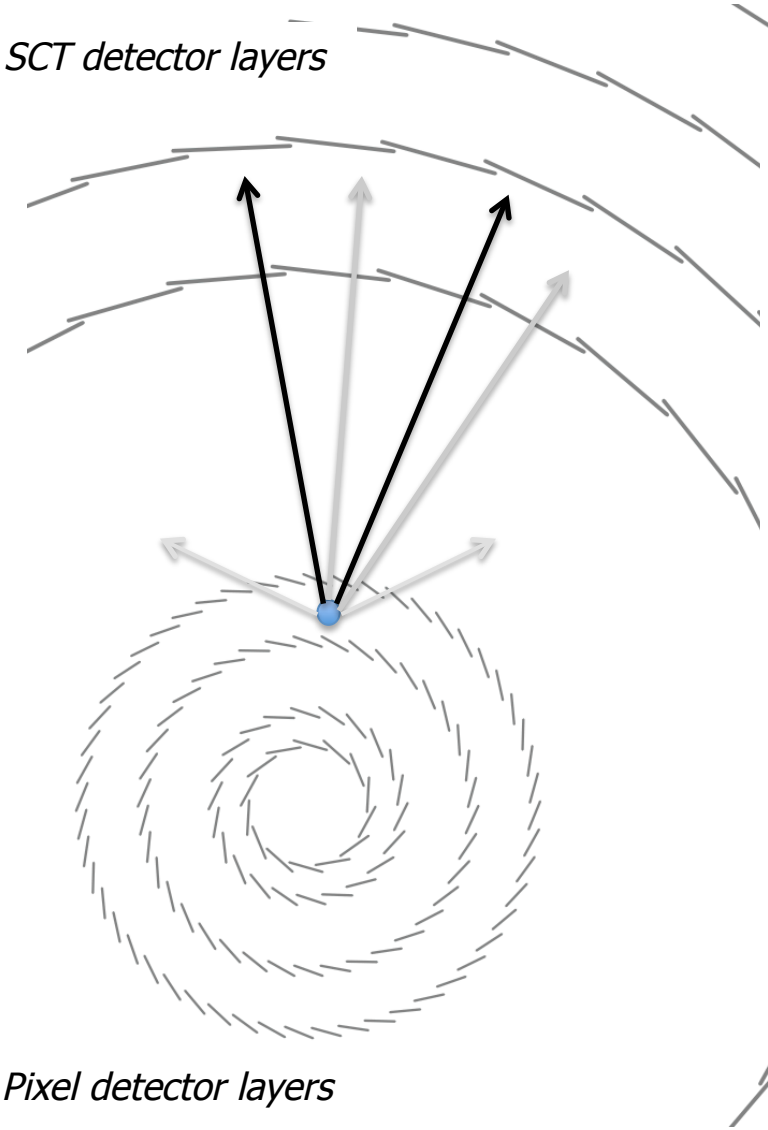


Conclusions

- ⇨ Techniques for the reconstruction of "unconventional" signatures with the ATLAS detector were presented
- ⇨ An inclusive vertexing algorithm was described
  - Efficient reconstruction of vertices decaying throughout the ATLAS inner detector
  - Attached track feature improves analysis selection efficiency by over 20%
  - Position resolution of vertices O(150) μm → highly dependent on track multiplicity and the track parameters entering the vertex
- ⇨ Extended techniques for a disappearing track signature
  - Efficient reconstruction of tracklets with as few as three pixel hits
  - Improved efficiency in high pile-up environment with a dedicated hit filter
  - Targeted the low momentum charged particle from the decay of the chargino
  - Developed two-track vertexing methods to estimate decay position of the chargino with a position resolution O(1) mm

Additional slides

Two-track vertex seeding

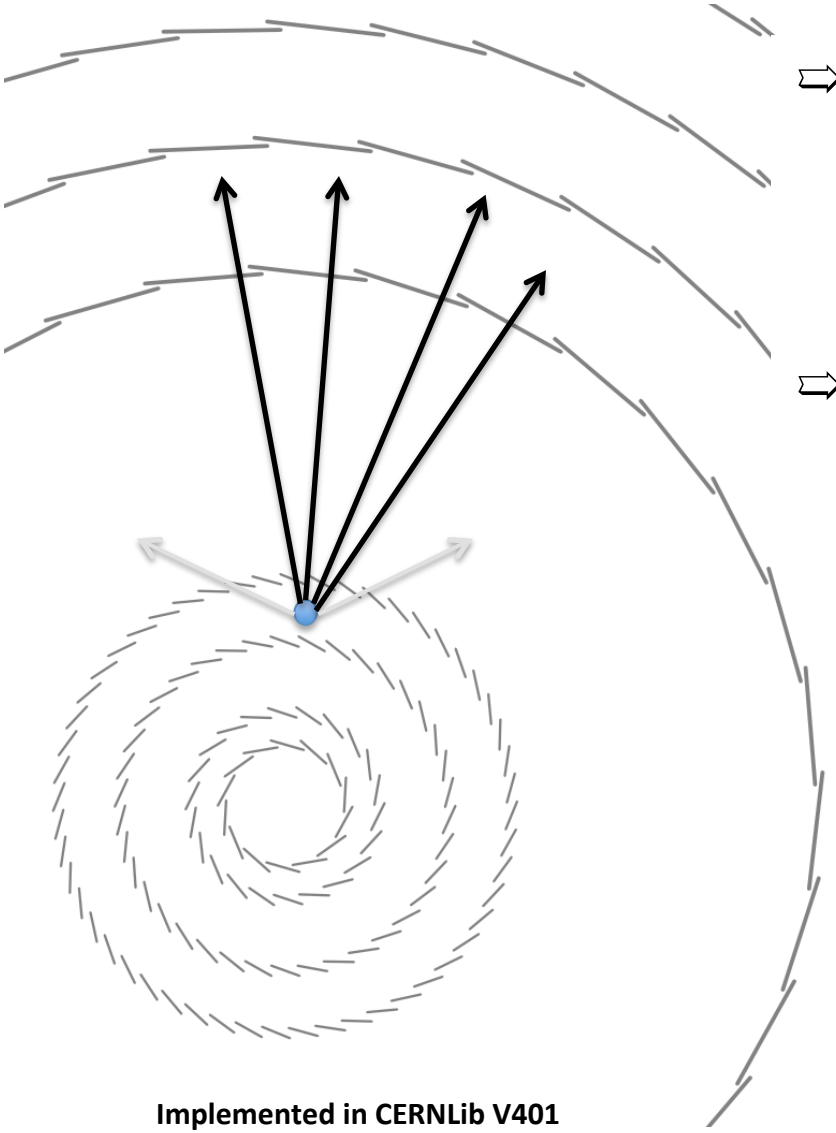


⇨ Two track seed vertices are formed from selected tracks with d_0 > 2mm
- Fast estimation of initial vertex position performed using an approximate fit
- Tracks required to have hits consistent with an outward propagating track coming from the vertex

⇨ Impact parameters relative to estimated vertex calculated
- Tracks are required to have compatibility with originating from the seed vertex position: impact parameters of d_0<100 mm and z_0<50mm from seed vertex position

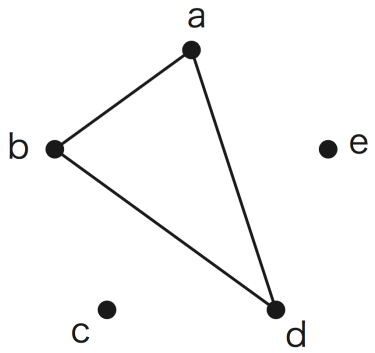
⇨ Full vertex fit performed to form two track vertex candidates

Multi-track vertex finding

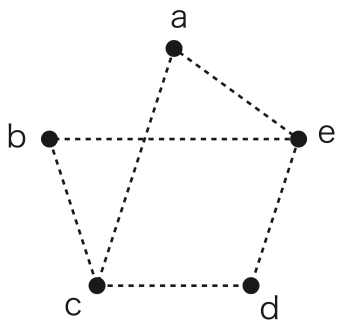


Implemented in CERNLib V401

- ⇨ Two track seed vertices are extended into multi-track vertices using an undirected graph network
  - Tracks mapped as nodes
  - Two-track vertices mapped as edges
- ⇨ Identified tracks from a common vertices fit as a multi-track vertex

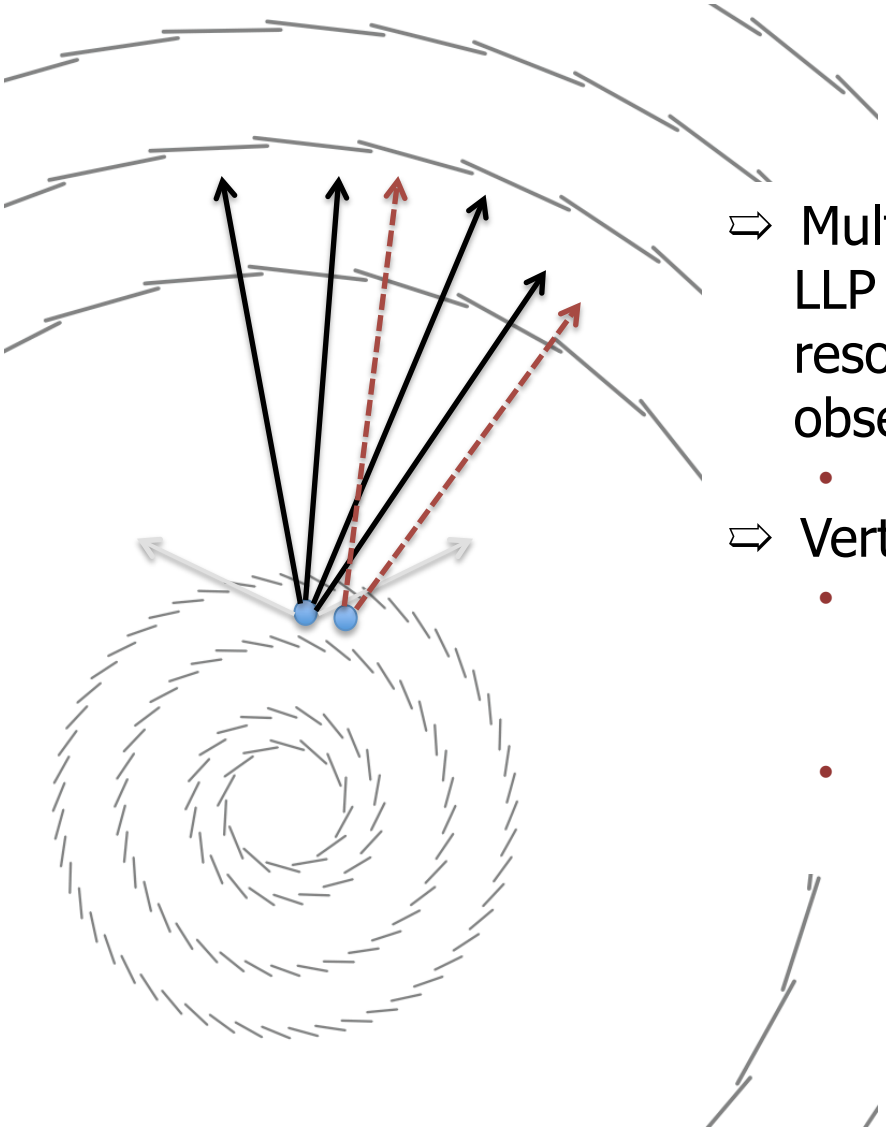


Compatibility graph: (a,b,d) are identified as originating from a common vertex



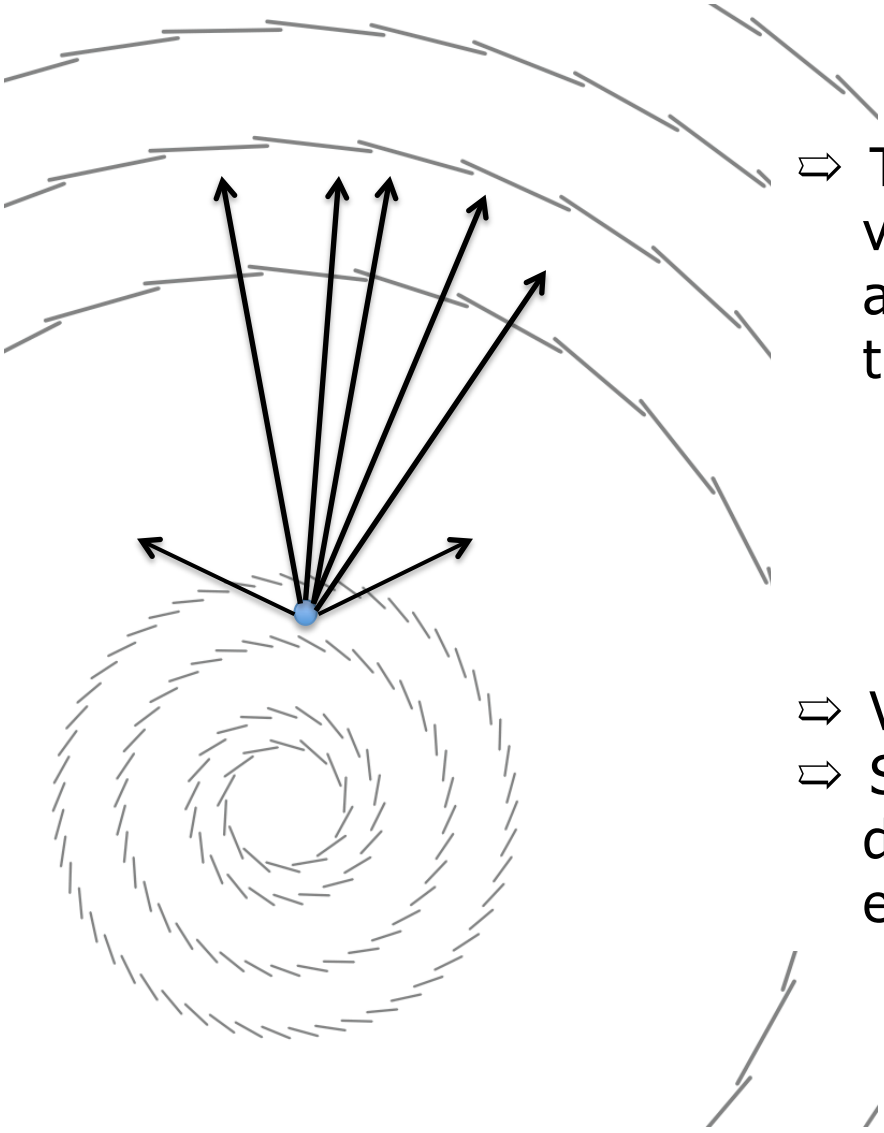
Incompatibility graph: removing nodes/lines from (c,e) makes (a,b,d) isolated and identified as a common vertex

Vertex merging



- ⇨ Multiple separate vertices from a common LLP decay degrade vertex position resolution and can deteriorate vertex observables
  - Vertex track multiplicity and visible mass
- ⇨ Vertices are merged and refit:
  - Assume the higher multiplicity vertex is correct, and shuffle tracks from close by low track multiplicity vertices and refit
  - Force the merging of the two vertices if they are with 10σ or 1mm of each other

Track attachment

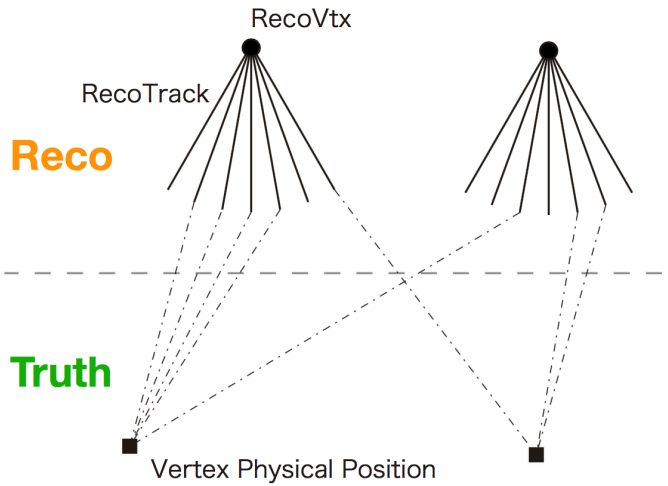


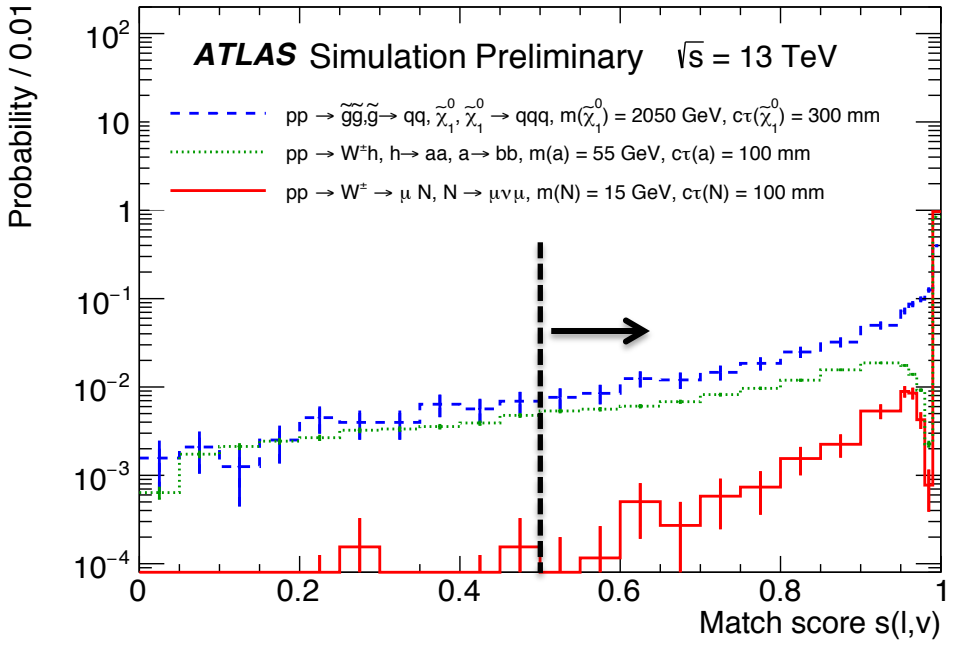
- ⇨ Tracks not used to form multi-track vertex candidates are used to associated to vertices with loosened track selection criteria
  - Tracks not required to pass outward hit pattern requirement
  - Tracks impact parameter significance with respect to secondary vertex required to be less than 5σ
- ⇨ Vertices refit with attached vertices
- ⇨ Significantly improve final analysis discriminates and analysis selection efficiencies!

Vertex Truth Matching

- LLP decay can have cascade decays of descendent particles around to original LLP decay (e.g. b-hadron decays)
  - Position-based matching of the vertex can bias performance
- Reconstructed vertices are matched to generator-level vertices using a p_T weighted score of the constituent tracks

$$s(v,l) \equiv \frac{\sum_{i \in \text{tracks} \in v} \left(p_T^{(i)} \mid \text{descendent of LLP decay } l \right)}{\sum_{i \in \text{tracks} \in v} p_T^{(i)}}$$



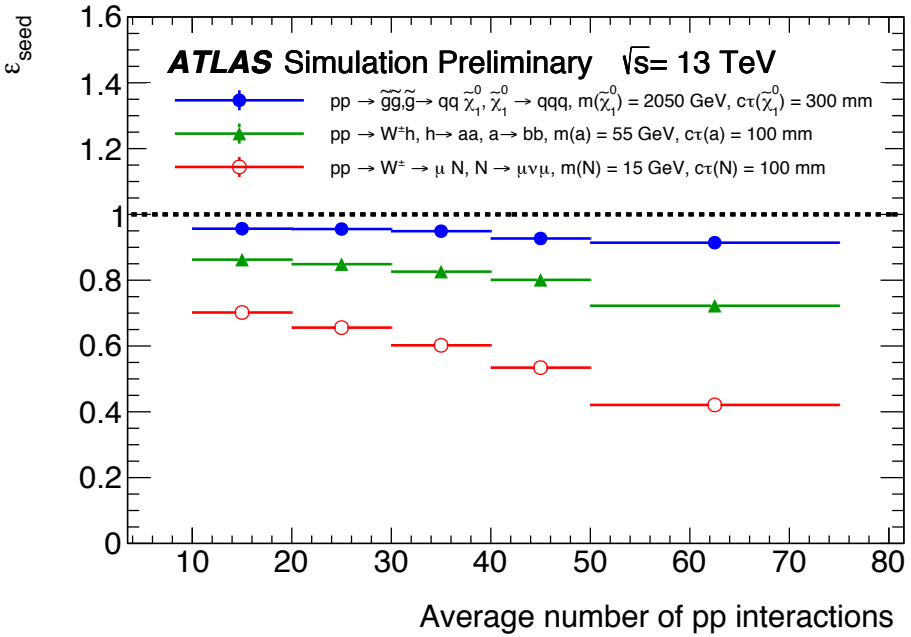


Vertices are considered reconstructed if s(l,v) > 0.5

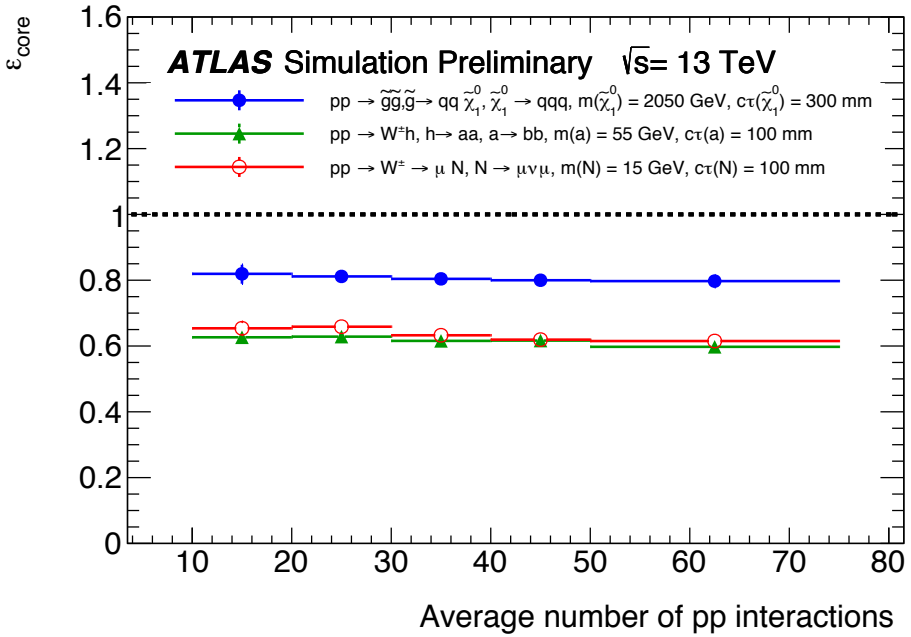
Multiple pp interactions

- ⇨ Multiple interactions per bunch crossing can degrade performance
- ⇨ Track selection efficiency affected at very high values
  - Loosing efficiency from shared hits, choose the wrong tracks, etc
- ⇨ Vertexing formation efficiency very robust against pile-up!

Two-track selection efficiency

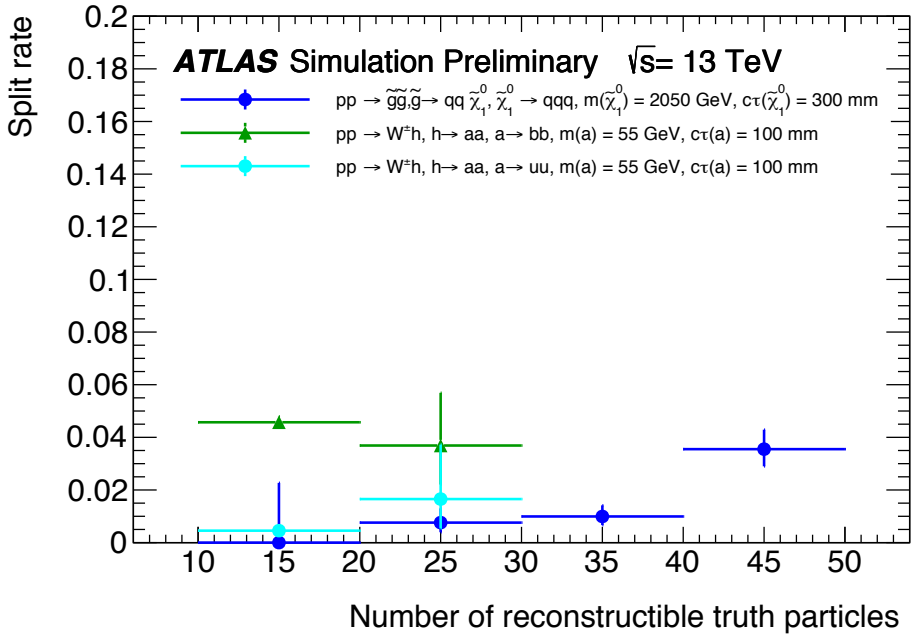


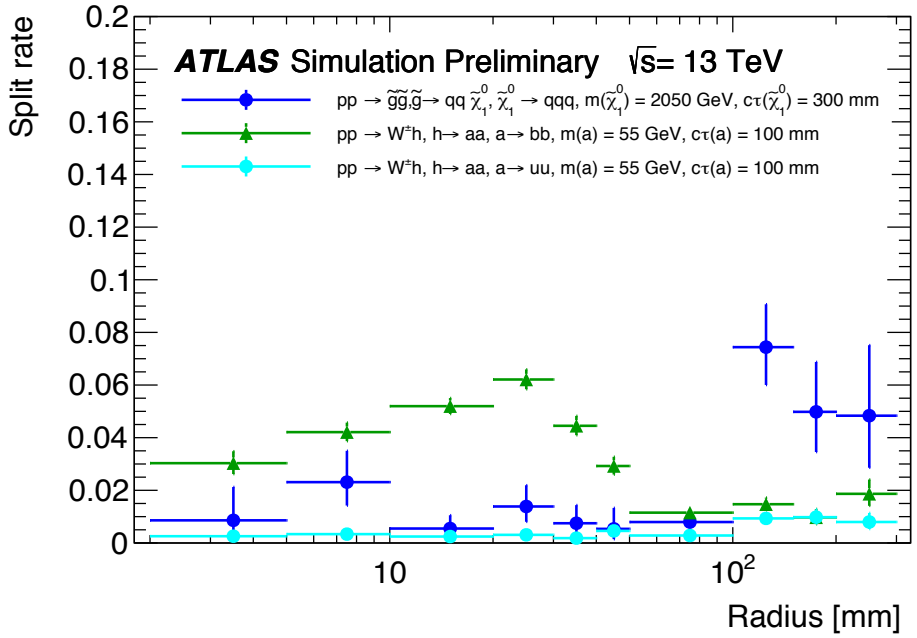
Vertex formation efficiency



Split rate

- ⇨ Probability that a single LLP decay vertex is reconstructed into two separate reconstructed vertices (algorithm tunes to minimize this)
- ⇨ Highest for a→bb sample due to non-negligible b-decay length
- ⇨ Grows with track multiplicity, and when constituent track parameters of the vertex don't have pixel hits





Pixel tracklet reconstruction

- ⇨ Tracklets with as few as three pixel hits are reconstructed
- ⇨ Run as a second pass tracking after the standard tracking run
  - Small ~5% inefficiency with this choice, but speeds up execution times
- ⇨ Tracklet seeded from space-points in the pixel detector only:

Requirement	cut
Number of space-points	$= 3$
Transverse impact parameter	$\lvert d_0 \rvert < 10$ mm
Longitudinal impact parameter	$\lvert z_0 \rvert < 250$ mm
Minimum transverse momentum	$p_{\mathrm{T}} > 5$ GeV
Maximum pseudorapidity	$\lvert \eta \rvert < 2.2$

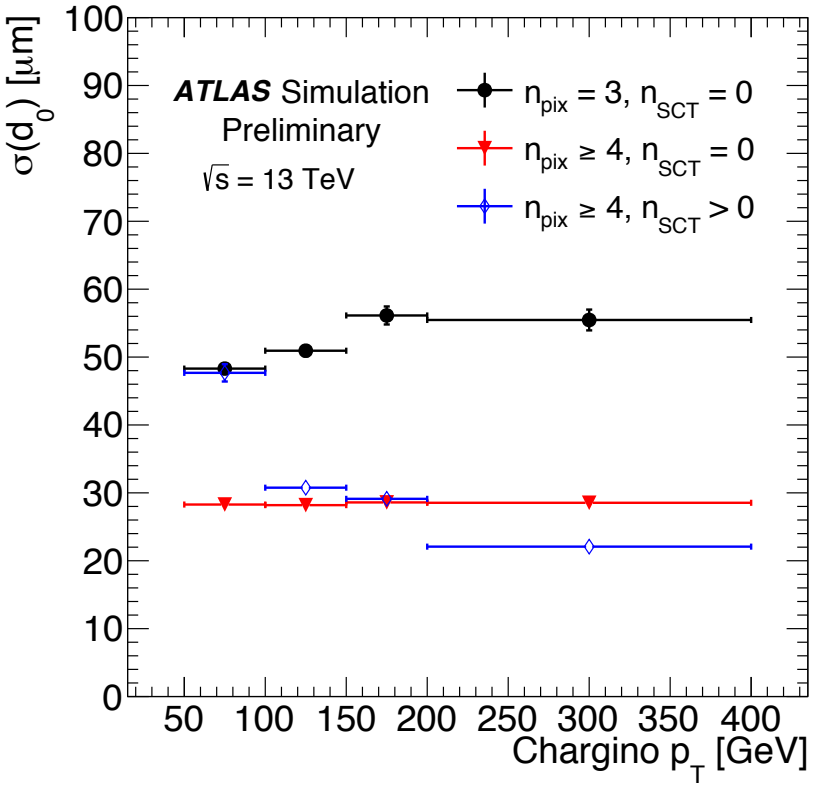
Same as standard tracking

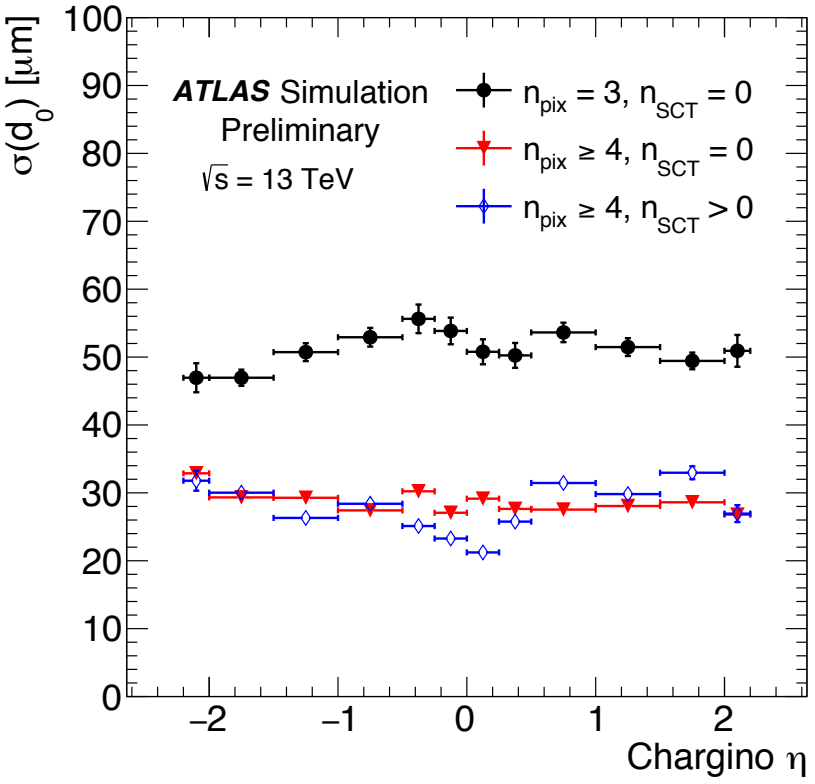
Fake rate explodes at low p_T and higher η regions

- ⇨ Forward search for addition silicon clusters performed
  - Efficiently reconstructs charginos across a wide decay range
  - Dedicated SCT hit filter developed to reduce fake SCT hits wrongly associated to the tracklets trajectory → recovers ~40% efficiency and reduces pile-up dependence

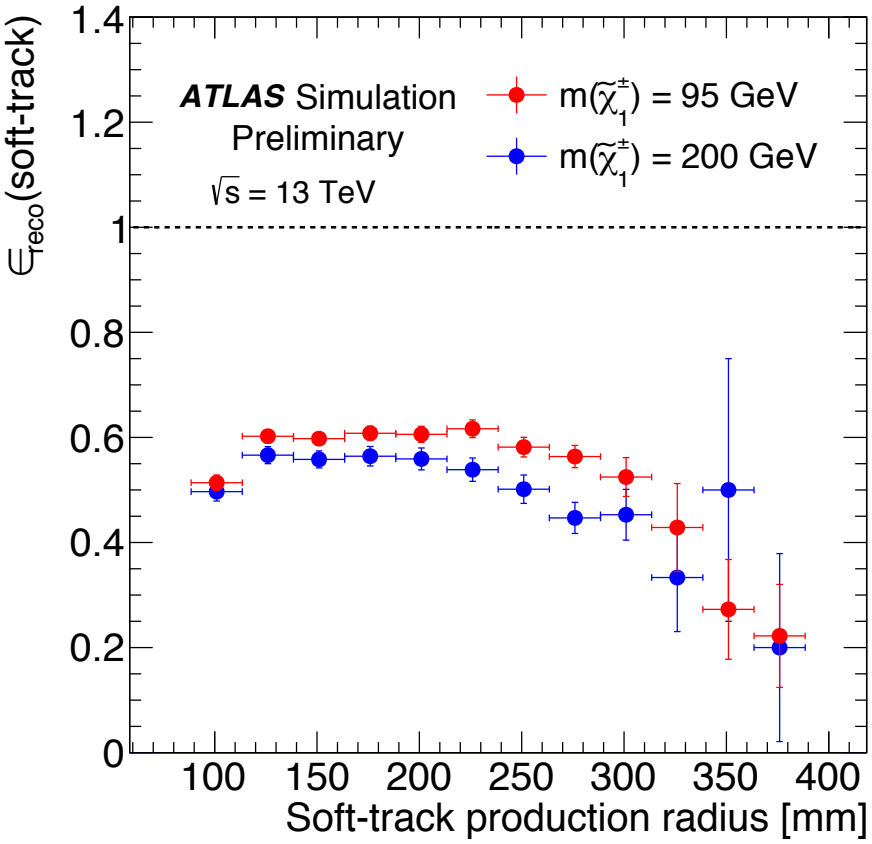
Pixel tracklet IP resolution

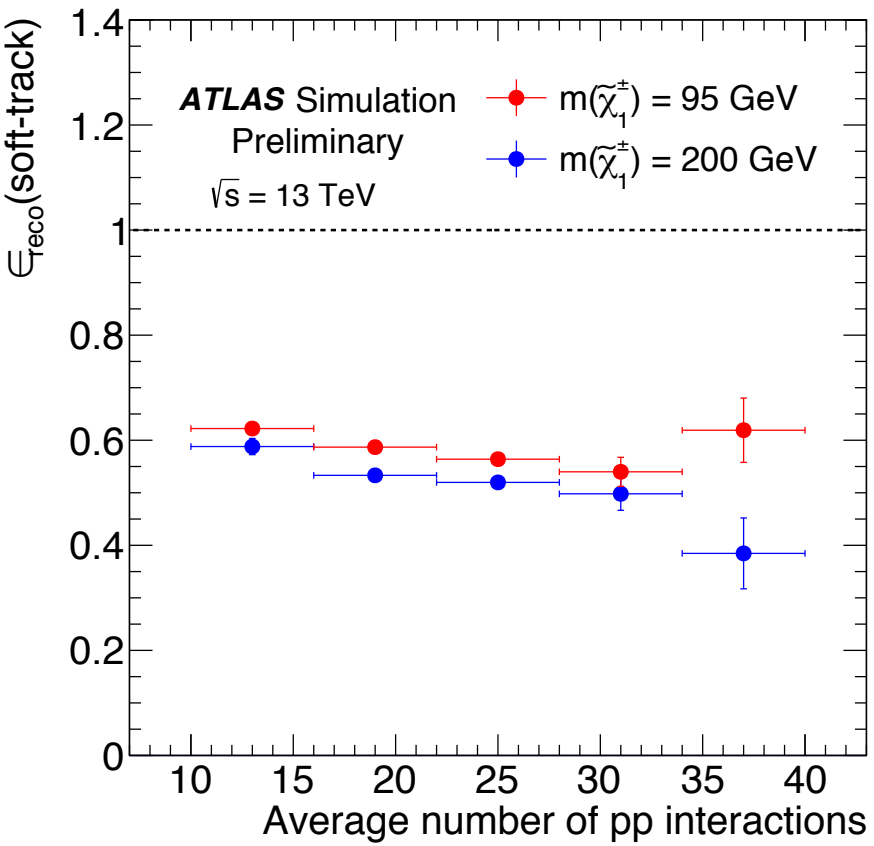
⇨ Transverse d_0 impact parameter resolution



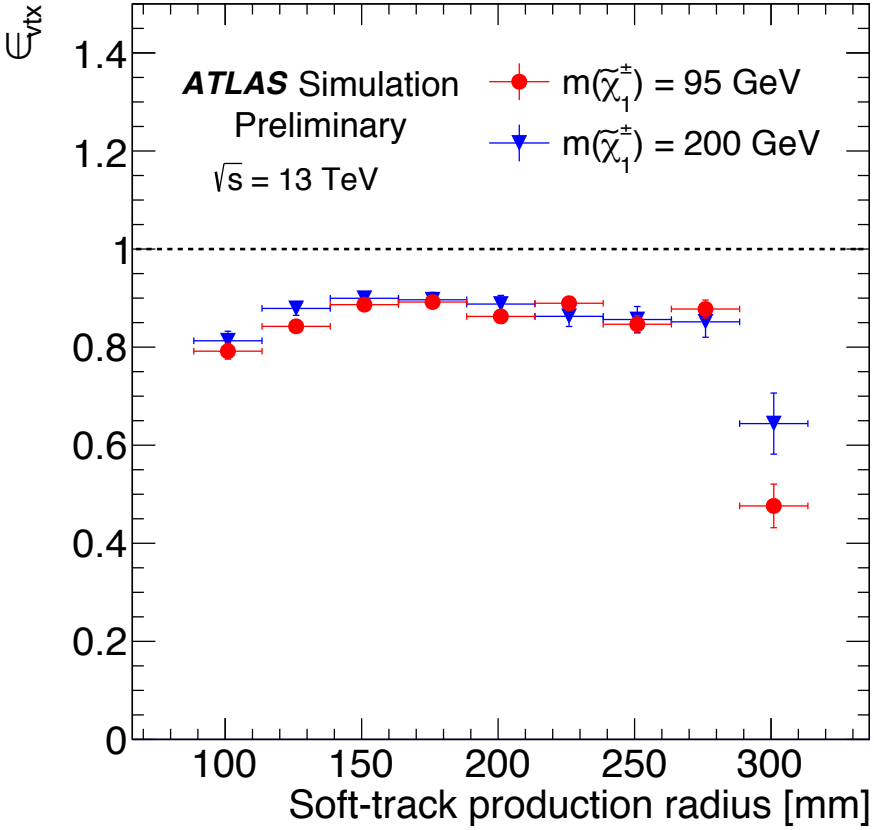


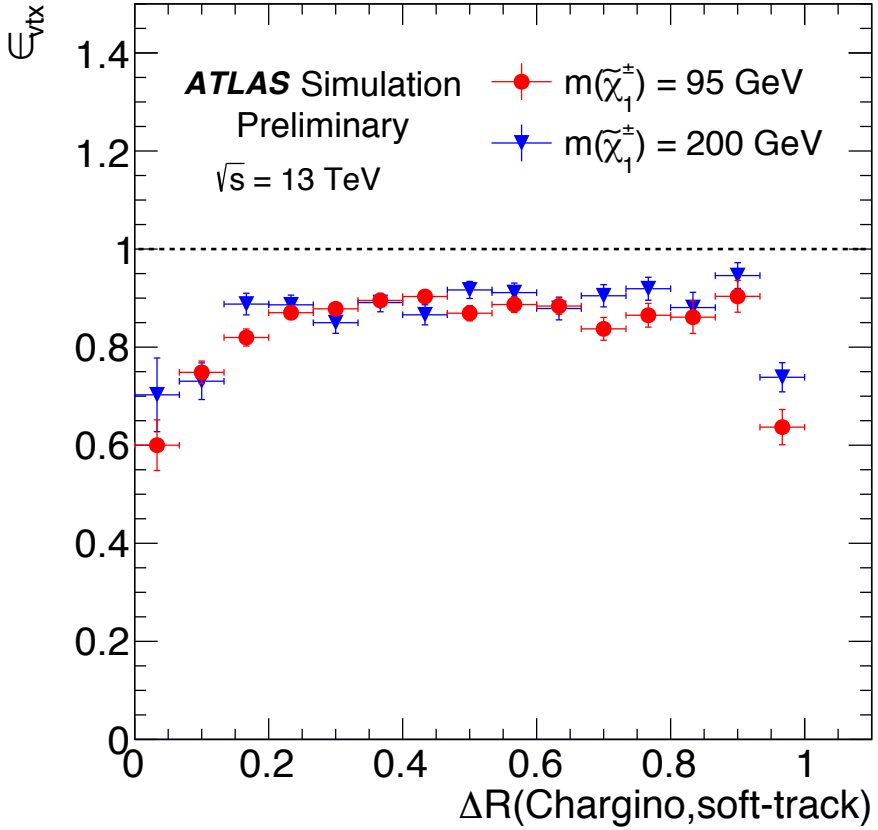
Soft-track reconstruction efficiency





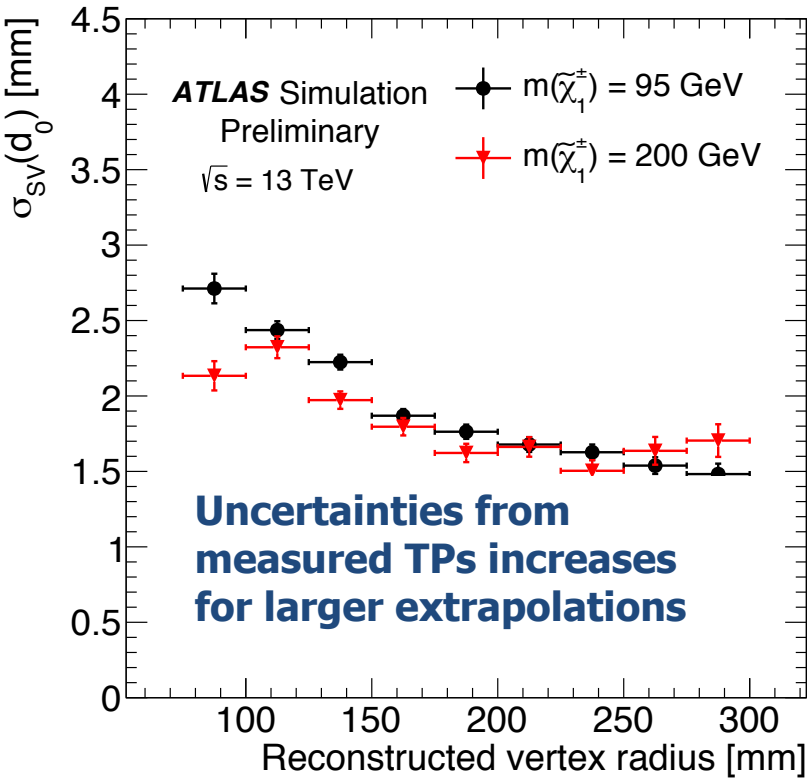
Vertexing efficiency

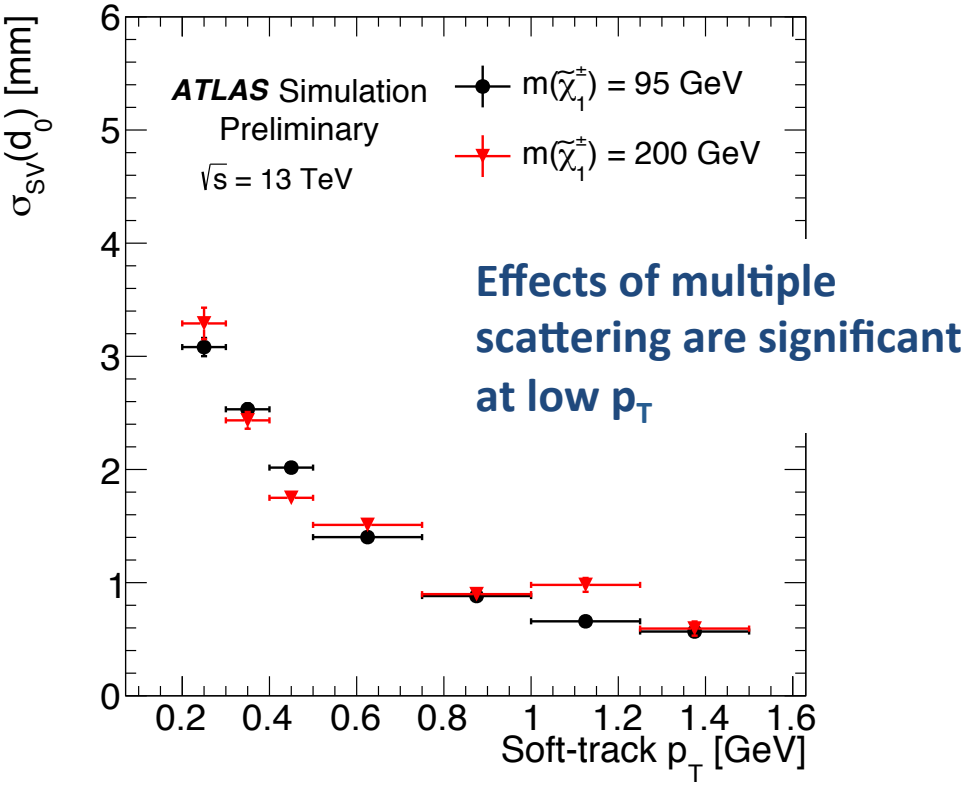




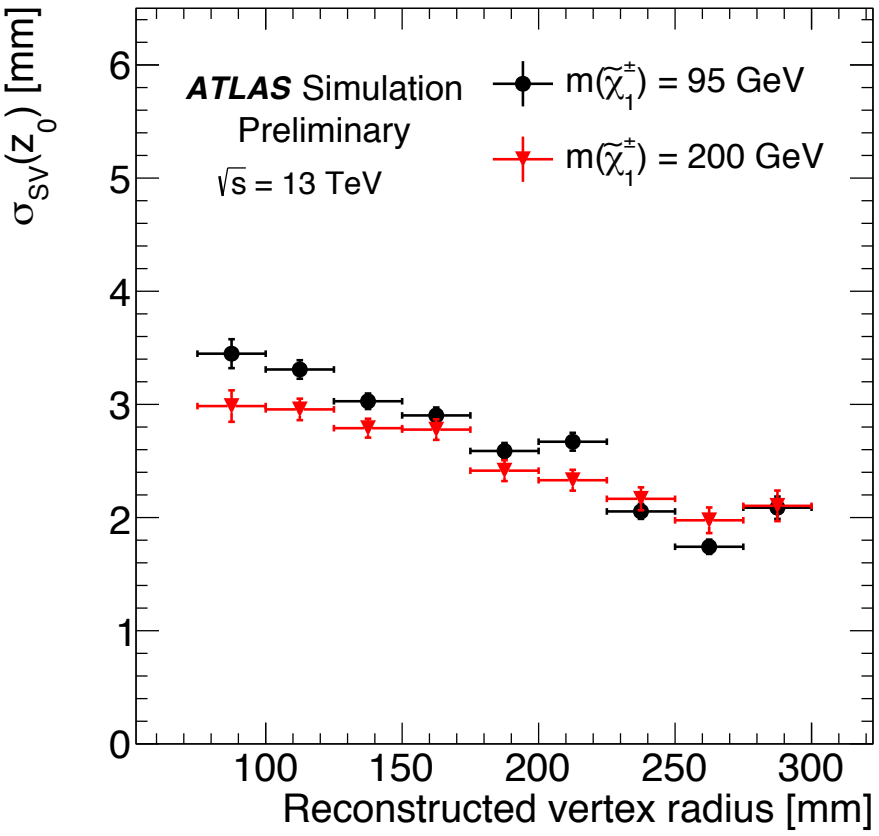
SV Impact Parameters

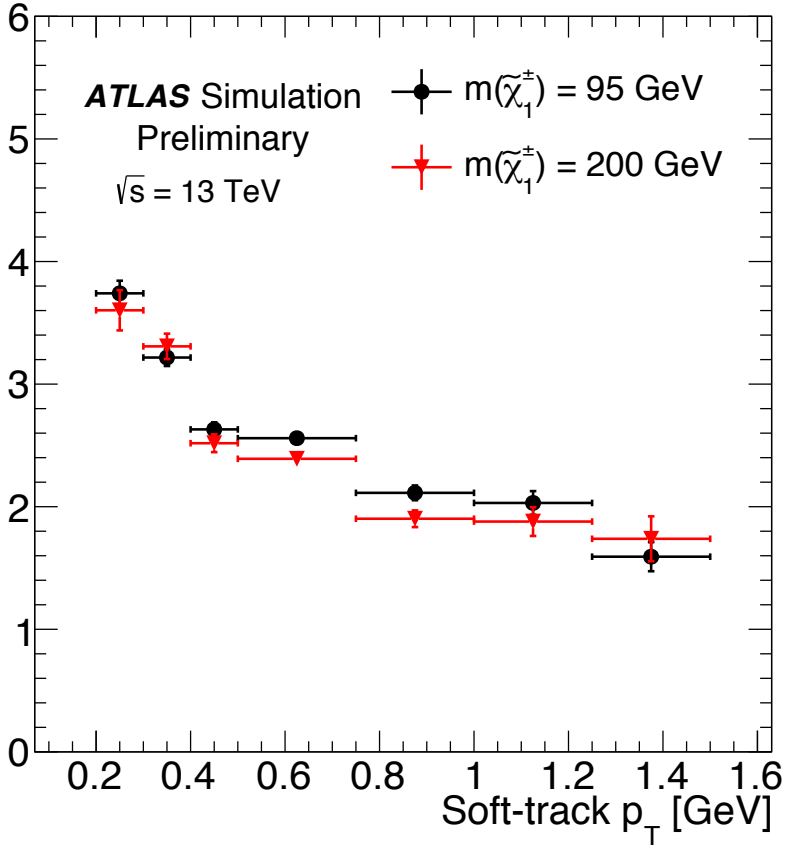
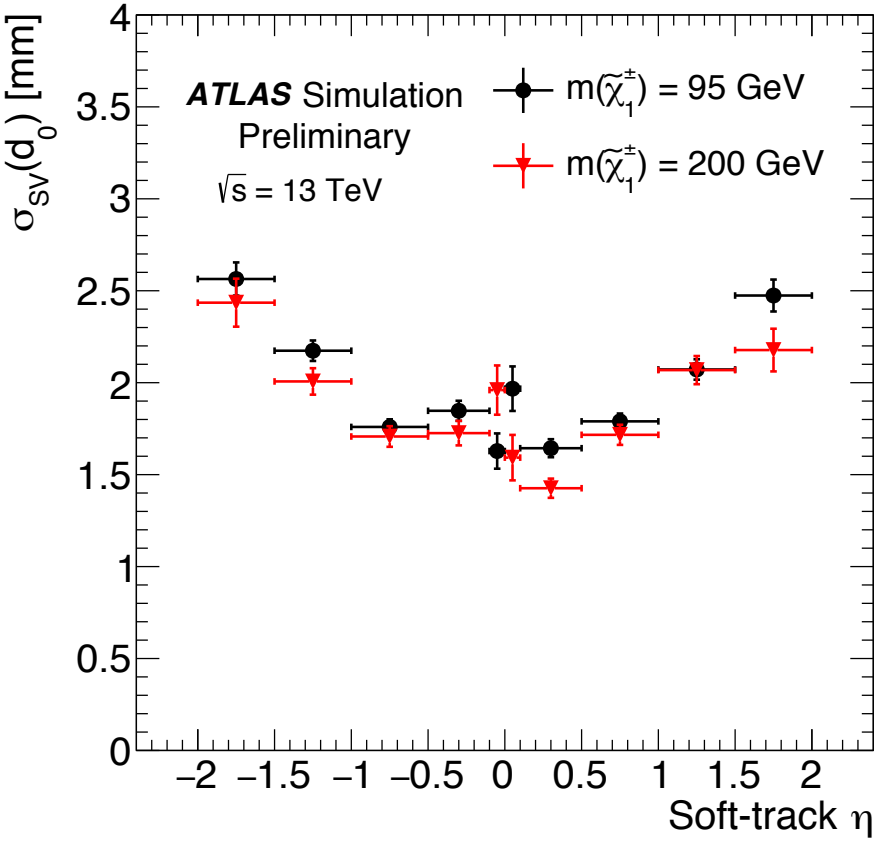
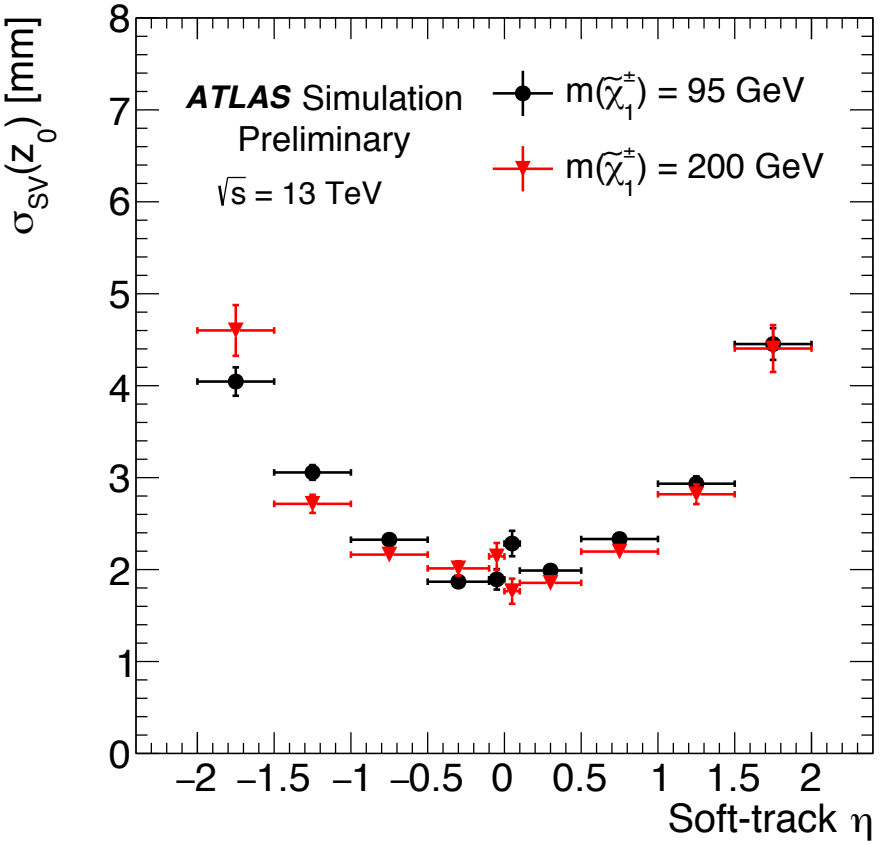
- ⇨ Impact parameter resolution relative to the fitted secondary vertex
- ⇨ Soft-track only use SCT measurements → degraded performance in pointing resolution further from the SCT detector





SV Impact Parameters





SV Impact Parameters