Track reconstruction for LLP searches in ATLAS: challenges and opportunities

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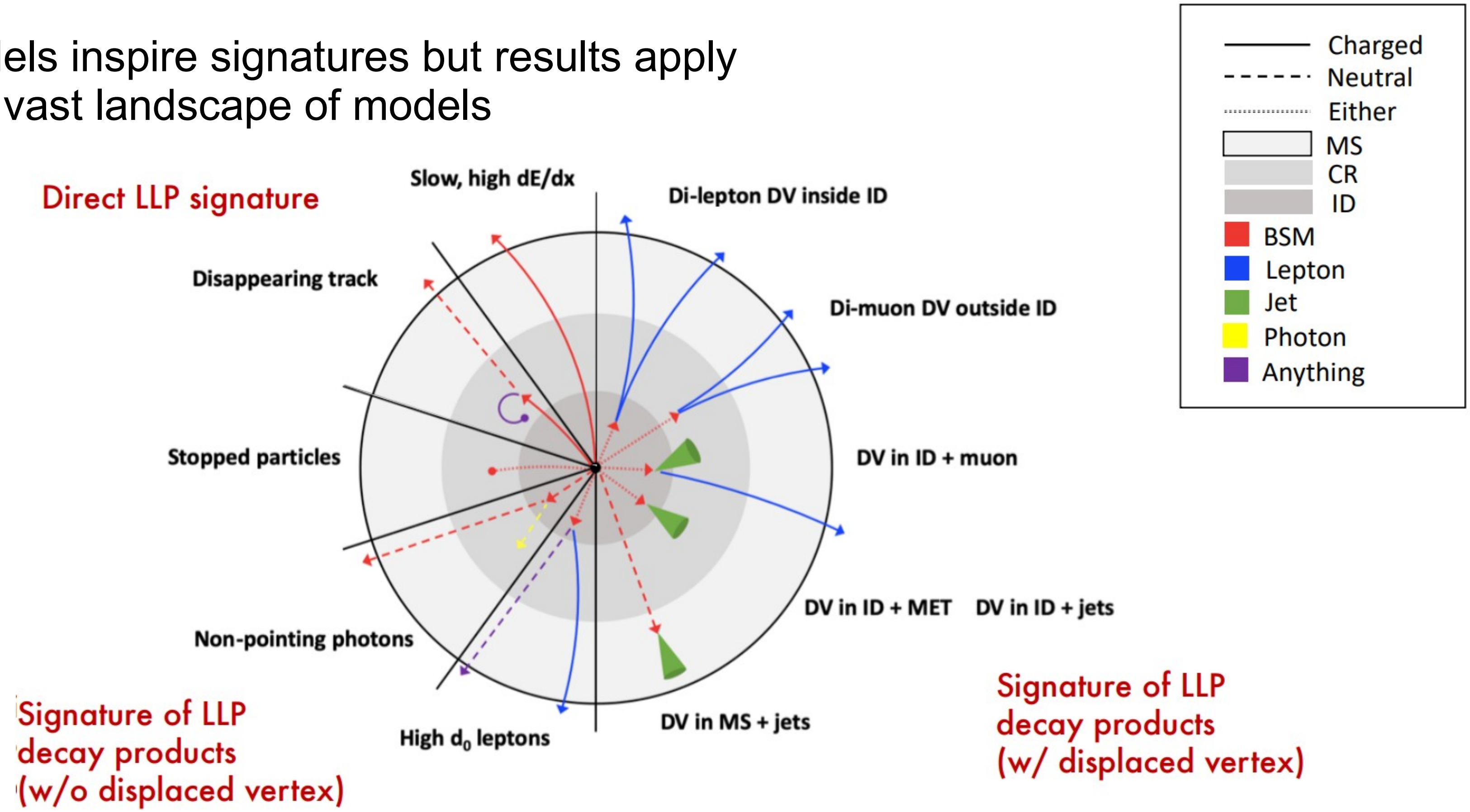
LLP landscape

Cartoon inspired by J. Antonelly, E. Thompson and many others

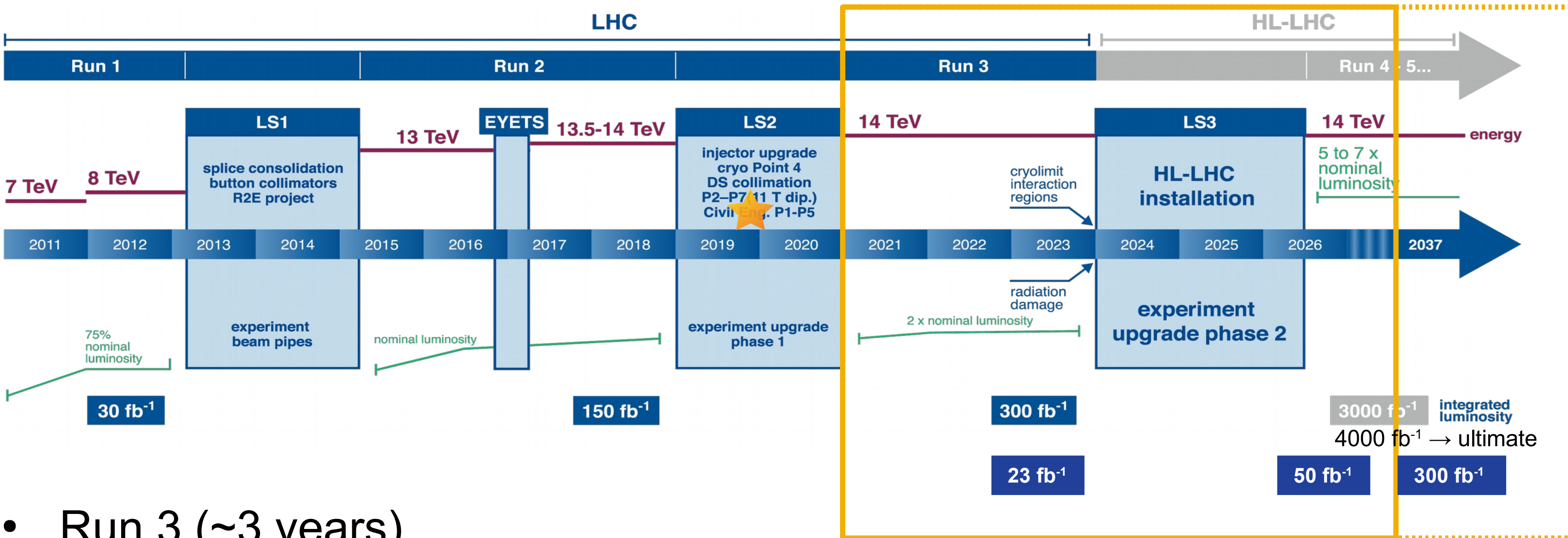
Signature driven searches

- Models inspire signatures but results apply to a vast landscape of models



- Not a comprehensive overview of LLP searches, rather I've picked just a couple that serve as good example of the challenges and opportunities ahead
- Highlights of dedicated reconstruction techniques for LLP searches

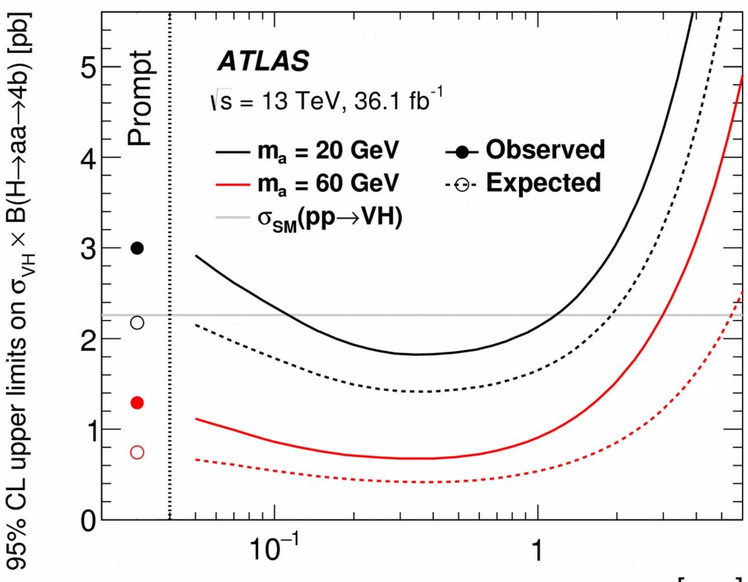
Timeline



- Run 3 (~3 years)
  - Overall at most small increase of energy and double of Run 2 dataset;
  - not extremely likely by itself to open the door to large new parameter space
- Run 4 (~2026)
  - First Run (3 years) of HL-LHC could give ~300/fb
- Mandatory to make best use of new detector capabilities and innovative analysis techniques to make the best use of data

First things first...

- Prompt analyses may have very significant sensitivity to LLPs
- Few technical details can boost prompt sensitivity
  - e.g. how much a jet is required to be prompt through explicit/implicit selections
  - More examples can be found. Room for "easy" extensions?
  - See also ATLAS RPC to RPV re-interpretation effort (link)
- Systematic uncertainties may become less standard to evaluate



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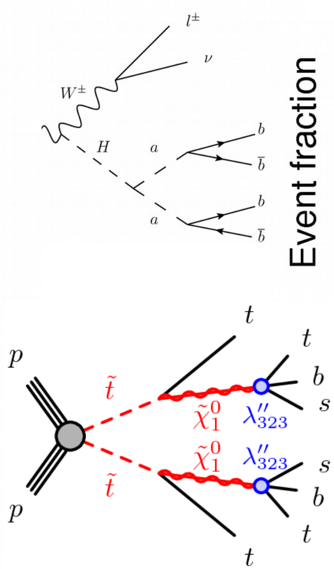
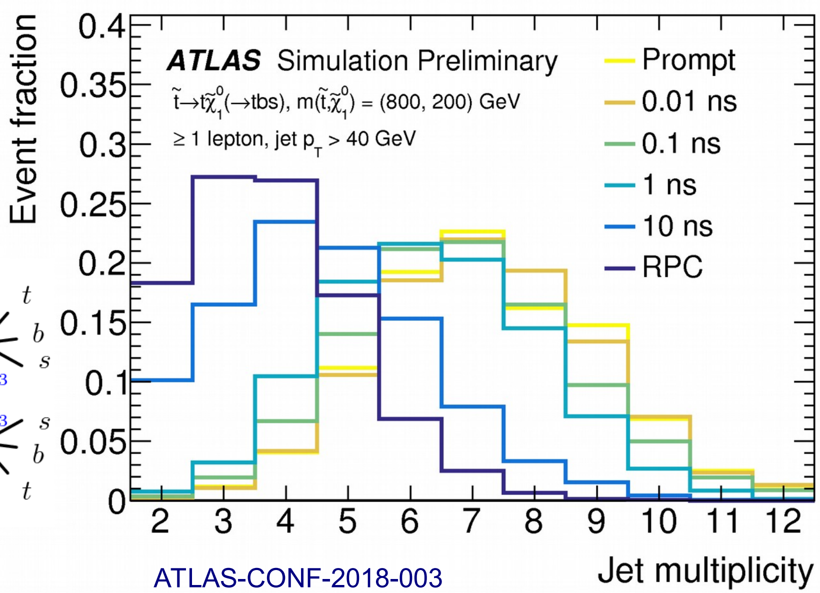
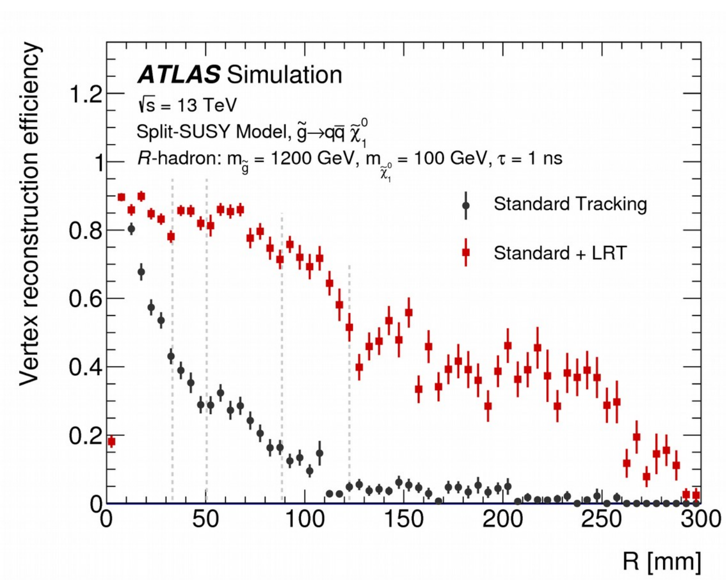


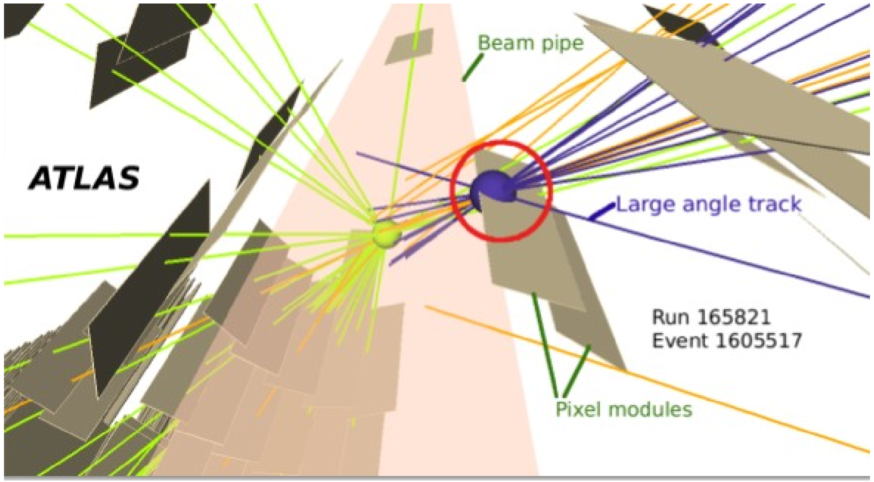


ATLAS-CONF-2018-003

Displaced Vertices

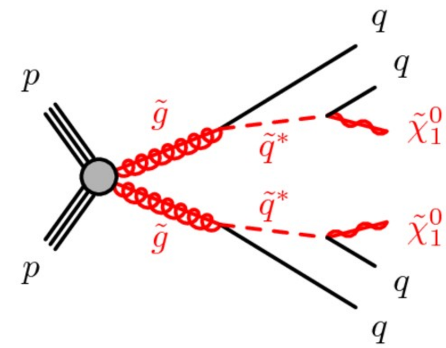
- Search for LLP decaying within the Inner Tracker (|r| < 300 mm)
- Events triggered/required to have either: MET, jets, or leptons
- Explicit reconstruction of displaced vertex via dedicated tracking/vertex
  - nTracks(DV) >= 5, m(DV) >= 10 GeV
- Main background from hadronic interactions plus “large angle tracks”

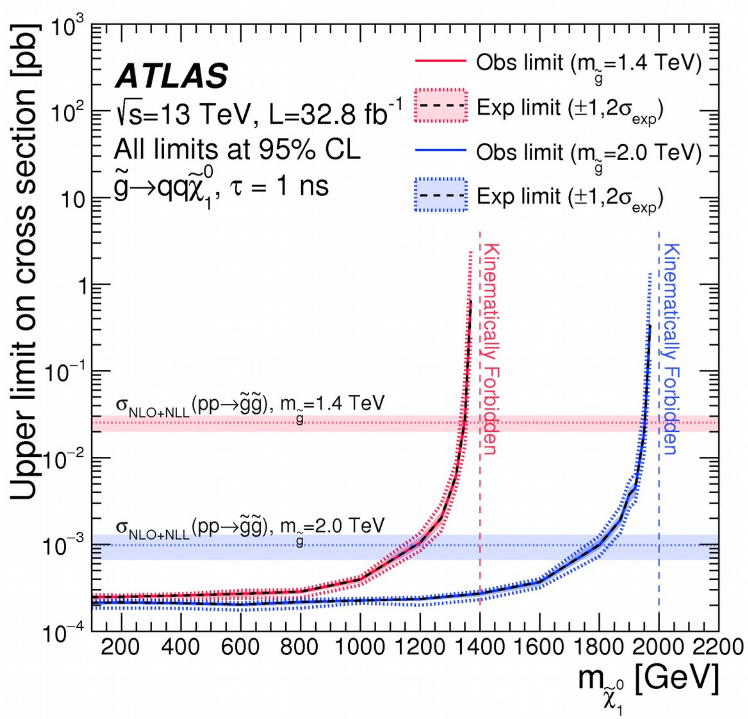


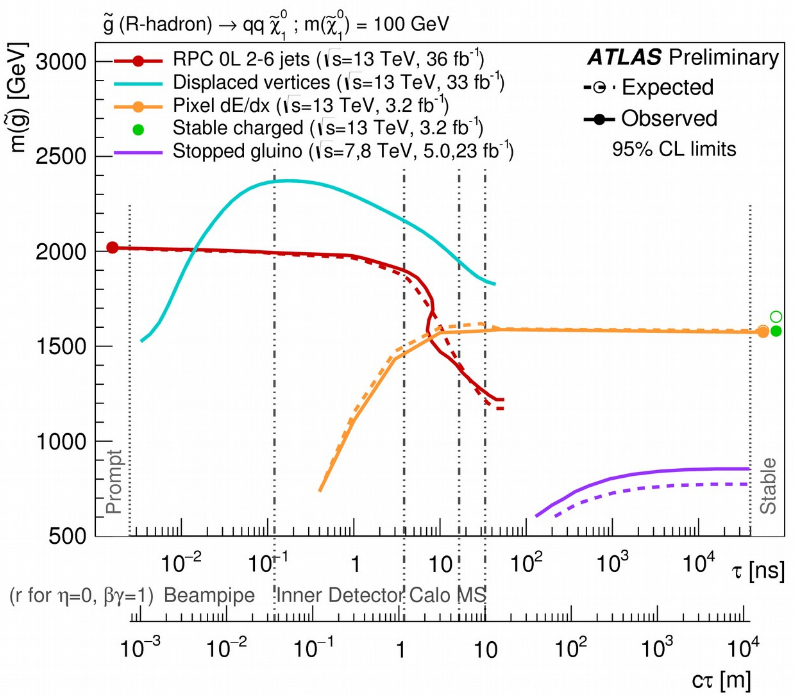


DV: results and next targets

- Focus of first run 2 results on e.g. strong production
- Larger dataset needed to unlock:
  - Electroweak production
  - Compressed spectra
- Ensure acceptance for low mass/multiplicity DV







Large radius tracking

- Dedicated track reconstruction using left-over hits from standard tracks

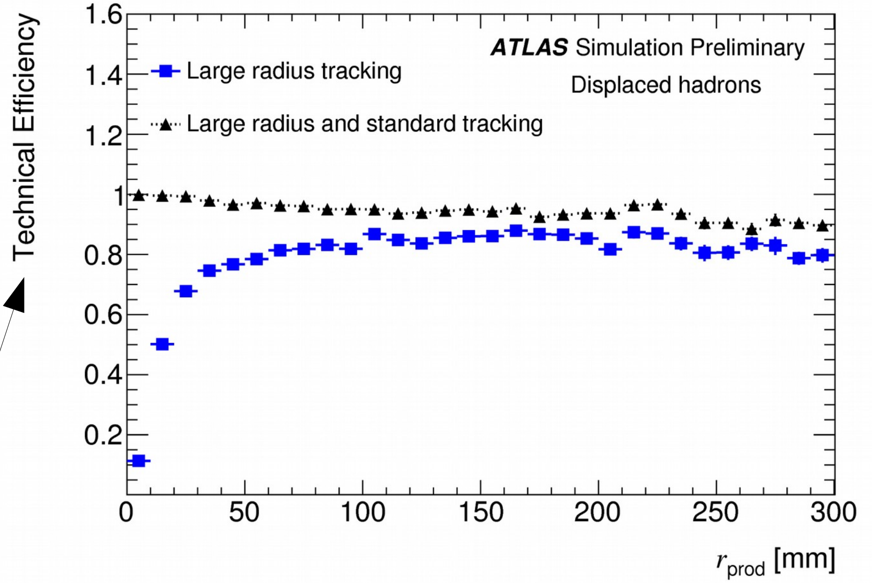
	Standard	Large radius
Maximum d_0 (mm)	10	300
Maximum z_0 (mm)	250	1500
Maximum $\|\eta\|$	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7
Seed extension	Combinatorial	Sequential

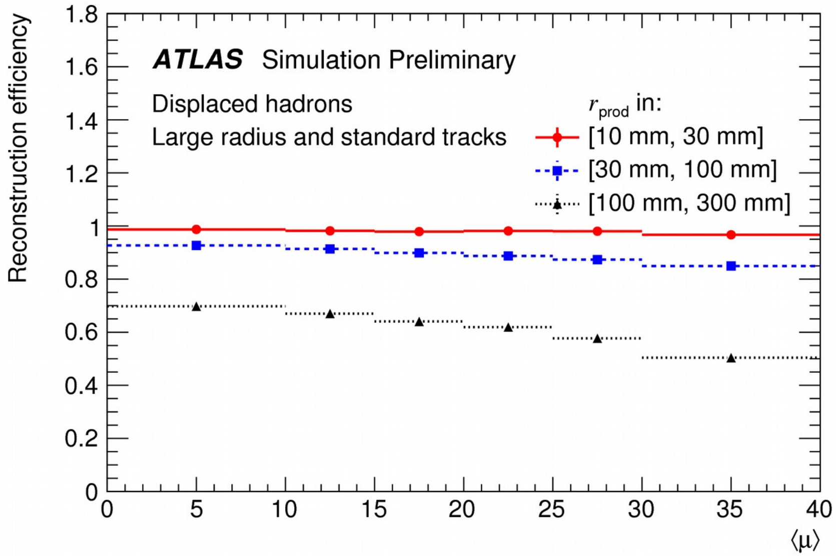
- Performed very well in Run 2!

$$\text{Eff} = \text{A} \times \text{eff}_{alg}$$

Based on charged truth particles that leave >= 7 energy deposits in active silicon elements

- Overall very efficient reconstruction
  - However large fake rate (not shown here)
- Significant pile-up effects call for fresh re-optimization for Run 3





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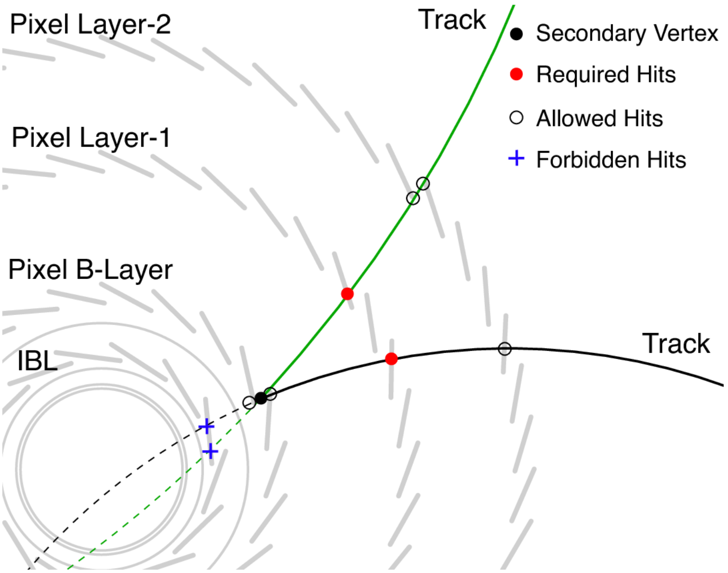
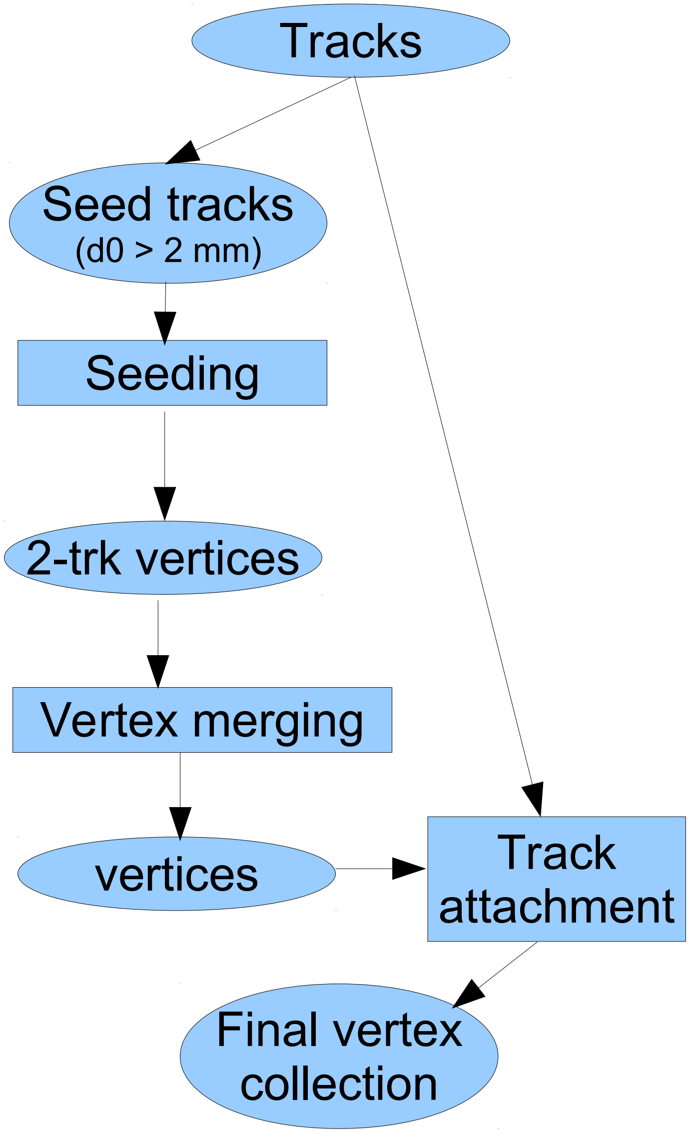
Displaced Vertices Reconstruction

- Based on incompatibility graph method
- Track selection based on hit pattern depending on vertex fit allows large fakes rejection
- Last step of track attachment aims at loosely attached tracks
  - Practically also recovers slightly displaced charged particles (e.g. b-jets..)





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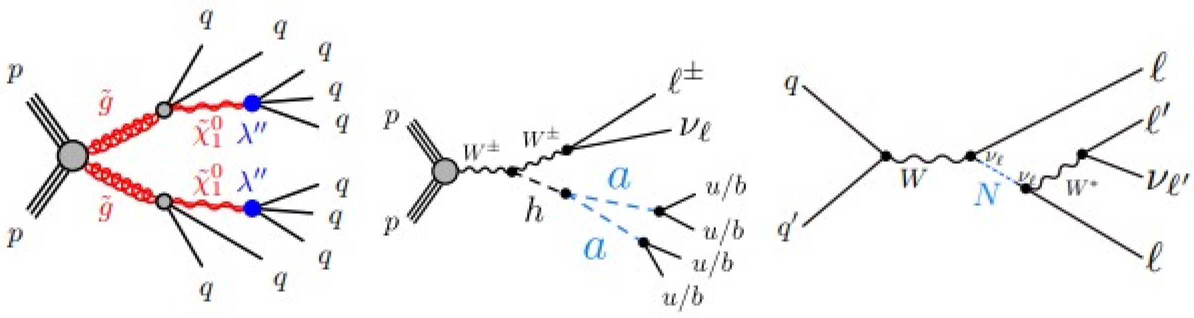
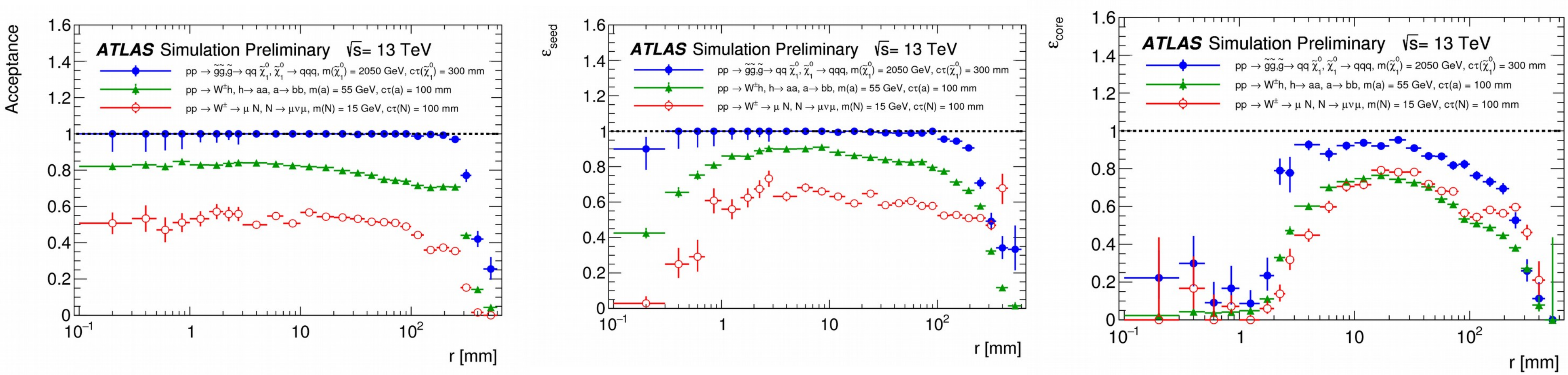
Displaced Vertices: performance

$$\varepsilon^{\mathrm{tot}}_{\vec{x}} = \mathcal{A}_{\vec{x}} \cdot \varepsilon^{\mathrm{alg}}_{\vec{x}} = \mathcal{A}_{\vec{x}} \cdot \varepsilon^{\mathrm{seed}}_{\vec{x}} \cdot \varepsilon^{\mathrm{core}}_{\vec{x}} \,.$$

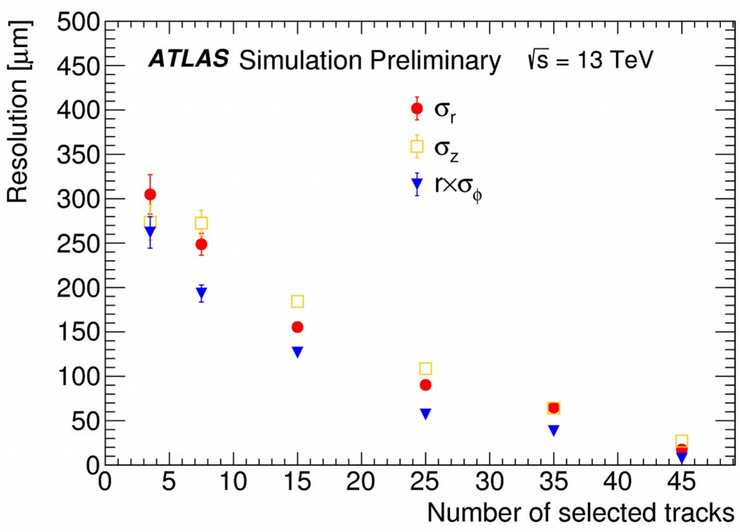


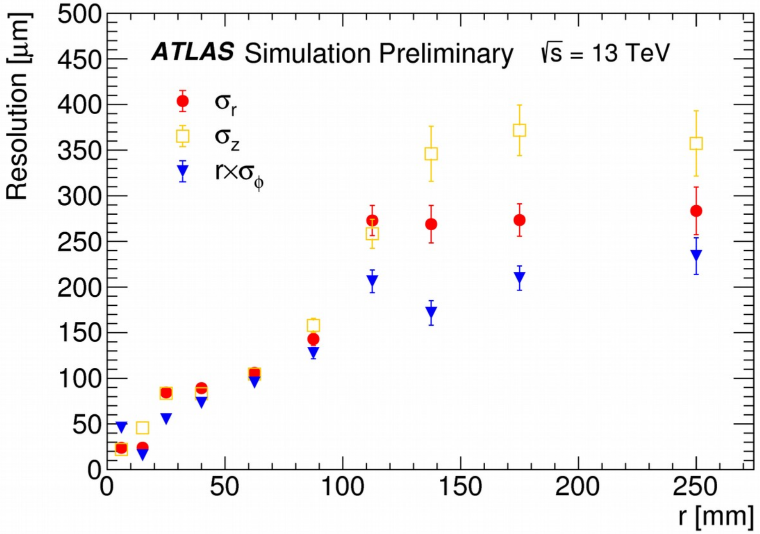
(a) Long-lived neutralino (b) Higgs portal (c) Heavy neutral lepton

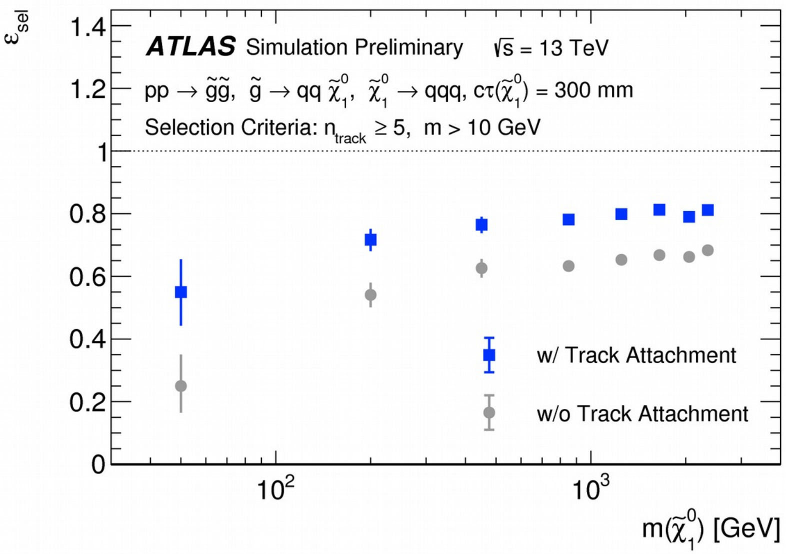


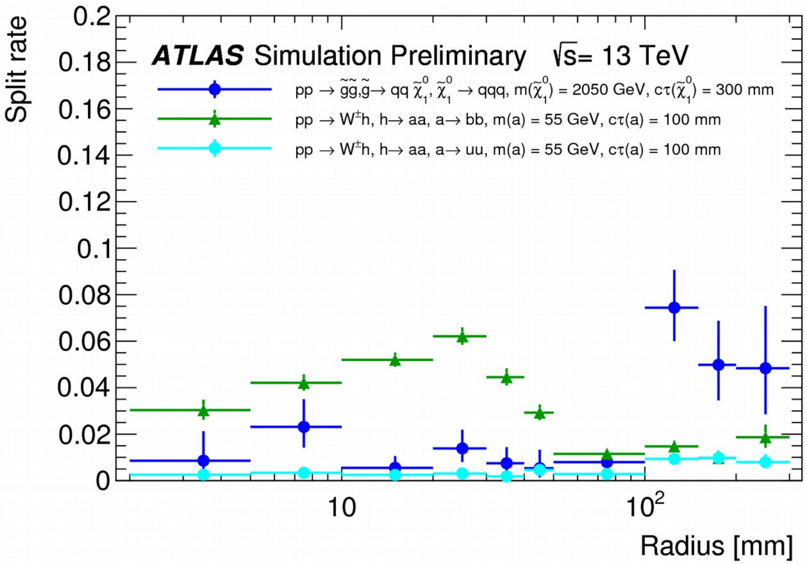
Note: performance metrics designed with re-interpretation needs in mind!

Displaced Vertices: performance



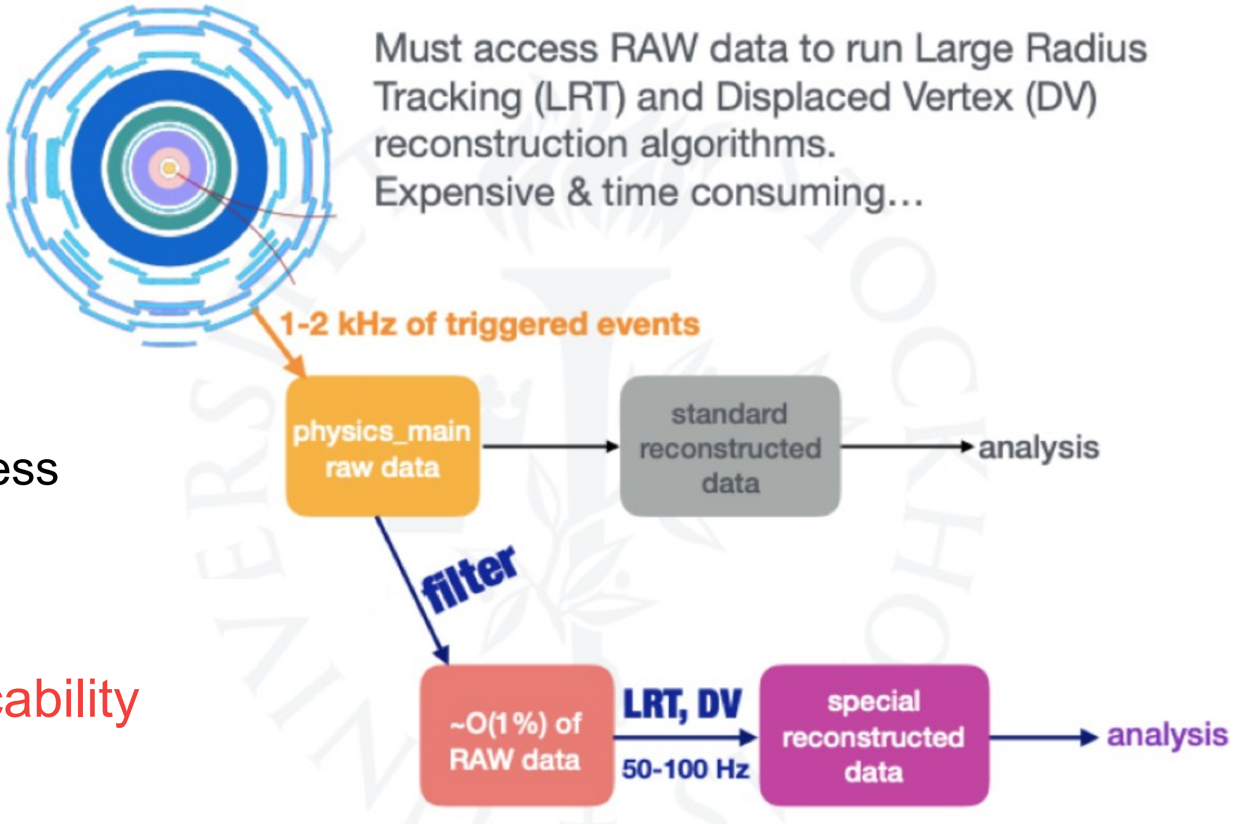






Dedicated data streams

- ATLAS implementation of large-radius tracking does not run by default
  - Too expensive both in terms of CPU as well as disk space
- Pre-select events based on normal reconstruction
  - Reduced requirements on reconstruction algs
  - in fact other custom algorithms are run on these events as well
- Gives flexibility in
  - What information to access
  - Resources
- However pre-selection of events limit its applicability i.e. extra “trigger”



Cartoon by Rebecca Carney

Dedicated data stream

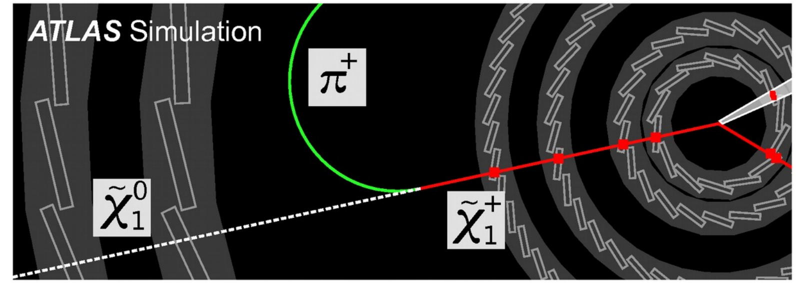
- Alternative is to work on faster algorithms that can run over all events
  - CMS has a version of large radius tracking ran on all events
  - Hard to compare performance unfortunately based on existing plots
  - Implementation in ATLAS more challenging (B-field, geometry) but should not be ruled out

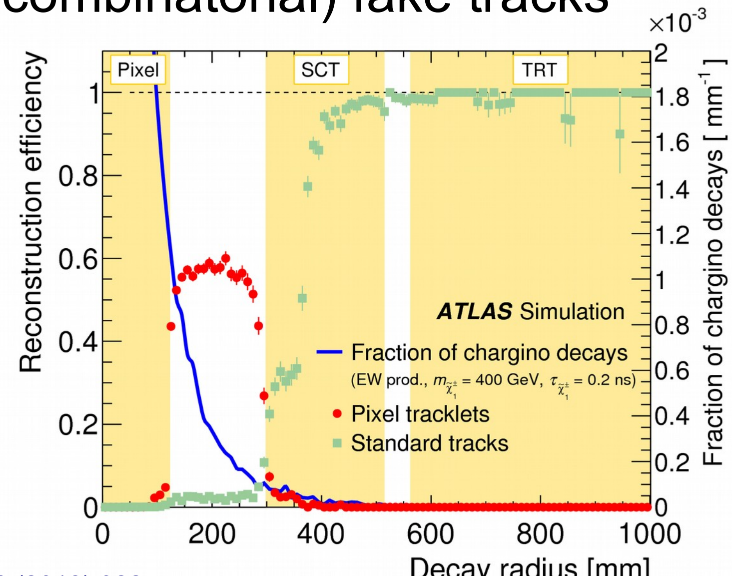
- As often it's the case, try to get the best of either approaches
  - Fast algorithms on all events to select as inclusively as possible interesting physics
  - Accurate (slower) algorithms to get as accurate/powerful as possible sensitivity

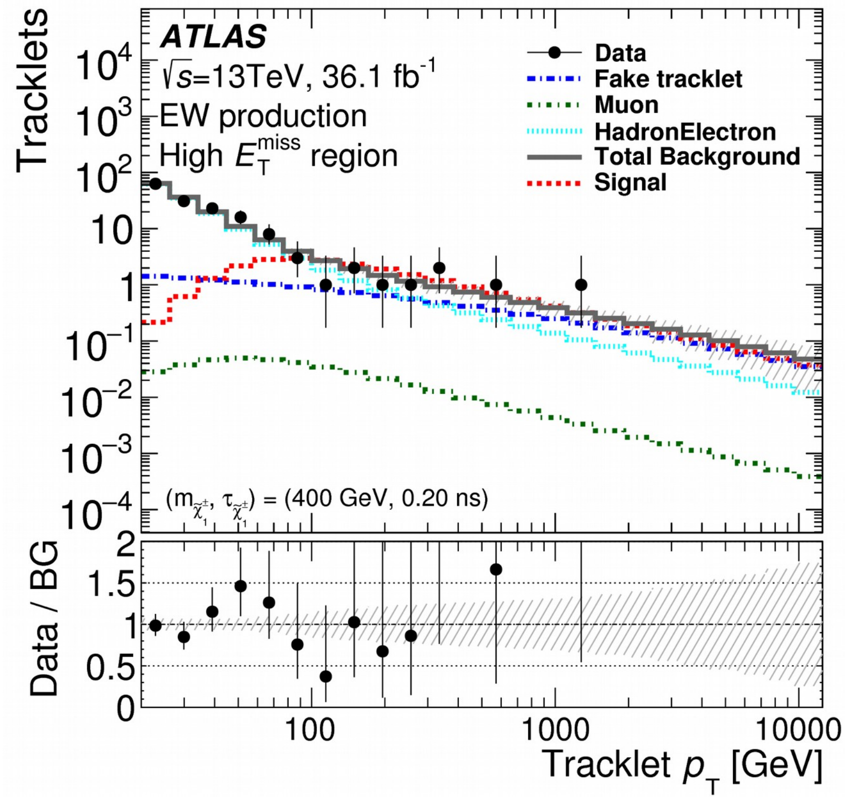
<u>Take-away messages</u>:
@Exp: need to address these challenges to have the most flexibility
@Exp+Theoriests: we can think of more complex algorithms as well

Short (disappearing) tracks

- Requires dedicated reconstruction when looking at very short tracks
  - Four pixel hits required in this version
  - Run for all events (fast for p_T > 5 GeV)
  - Longer lifetime also interesting! Not yet pursued in ATLAS in Run 2
- Main background coming from (combinatorial) fake tracks







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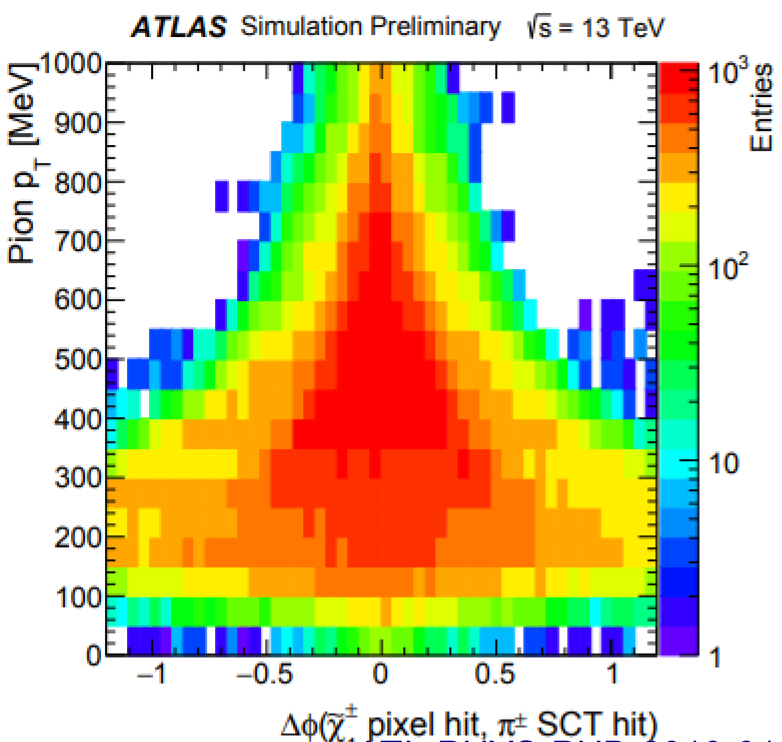
Soft-pion reconstruction

- Push even more towards short tracks and reduce main background
- Aim to reconstruct soft pion in chi decay!
- Second pass tracking seeded by high-pT pixel tracklets
  - DR = 0.8 from the direction of PV and last tracklet measurement
  - Use SCT hits to seed track finding with momentum as low as 200 MeV
- Vertex soft-pion candidate track with tracklets to assess compatibility

Seed property	Requirement
Number of space-points	= 3
Transverse impact parameter	$\|d_0\| < 10$ mm
Longitudinal impact parameter	$\|z_0\| < 250$ mm
Minimum transverse momentum	$p_T > 5$ GeV
Maximum pseudorapidity	$\|\eta\| < 2.2$



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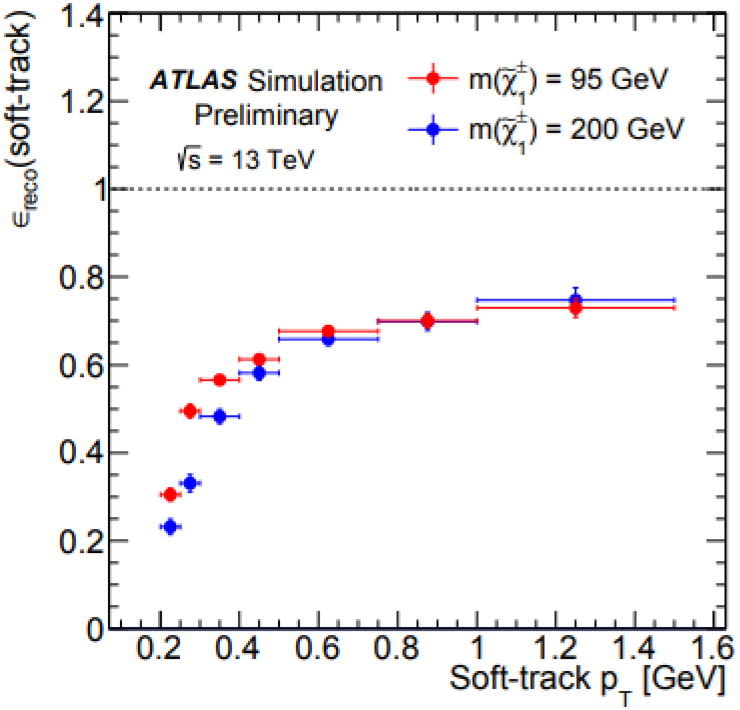
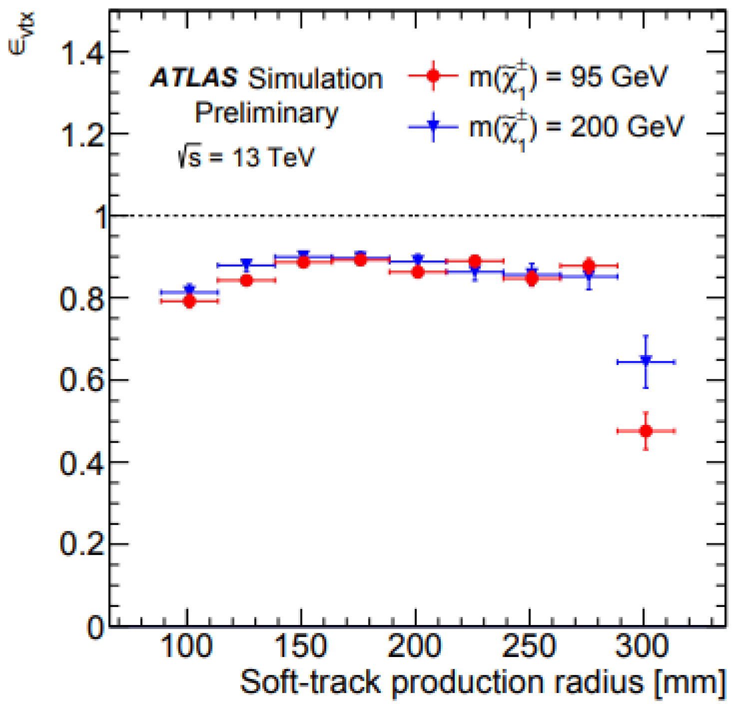
Soft-pion: reducing backgrounds..

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



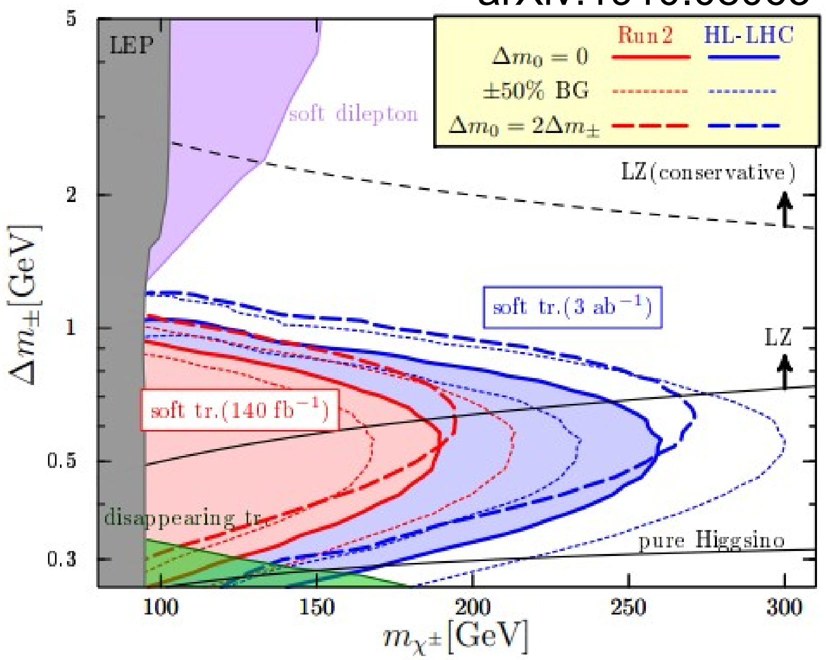


- While clear don’t want to take a hit on efficiency overall, can define a higher purity signal region with much reduced background (stay tuned!)

.. and pushing boundaries

- Just as additional teaser, suggested recently that similar techniques tailored in reconstructing soft displaced tracks can be employed to push our sensitivity in the "gap" of DeltaM(chi+-,chi0)

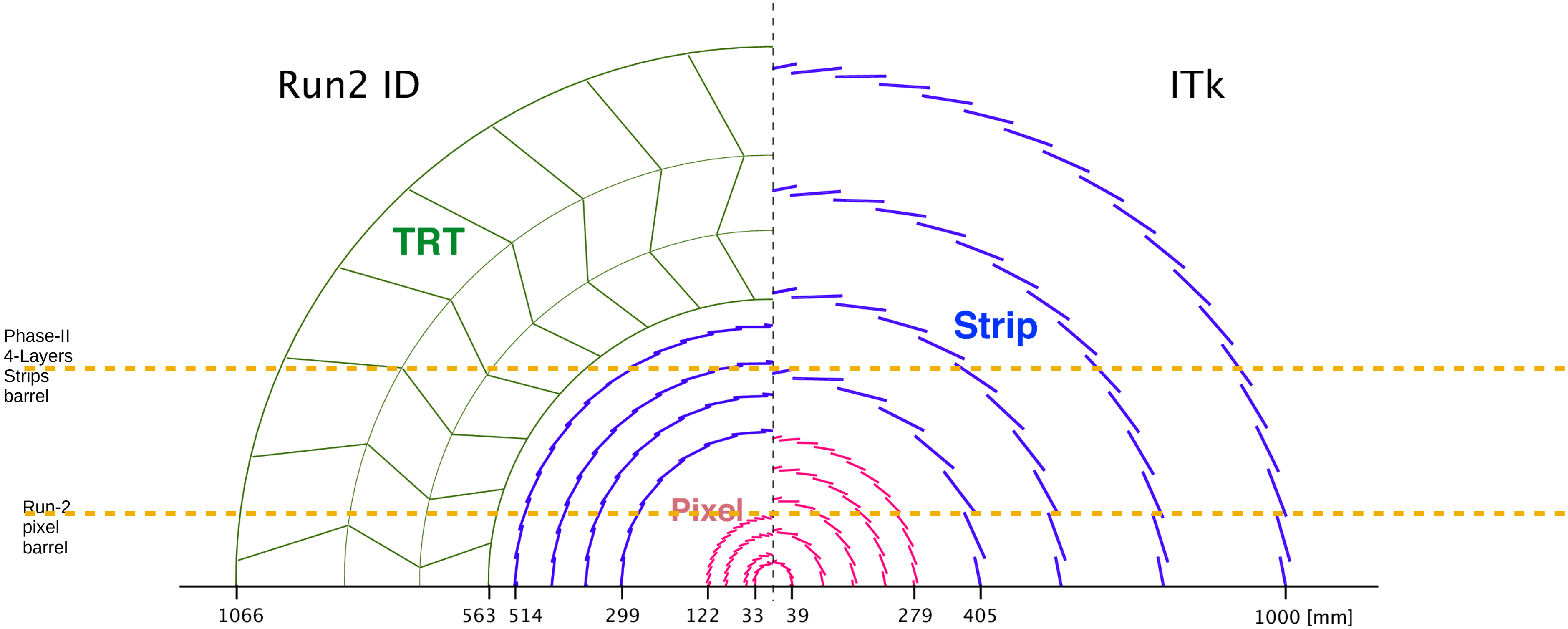
arXiv:1910.08065



- Many more obvious extensions awaiting people to be excited about this physics and ready to embrace technical challenges

Phase-II ATLAS Inner Tracker

- New all-Silicon tracker (ITk): 5 pixel and 4 strip barrel layers
- ATLAS Phase-II inner tracker has non-trivial implications for LLPs:
  - "Expanded" (in radius) barrel layers
  - Extended coverage $|\eta| < 2.5 \rightarrow 4.0$
  - Reduced material budget
  - Coarser charge measurement in pixels

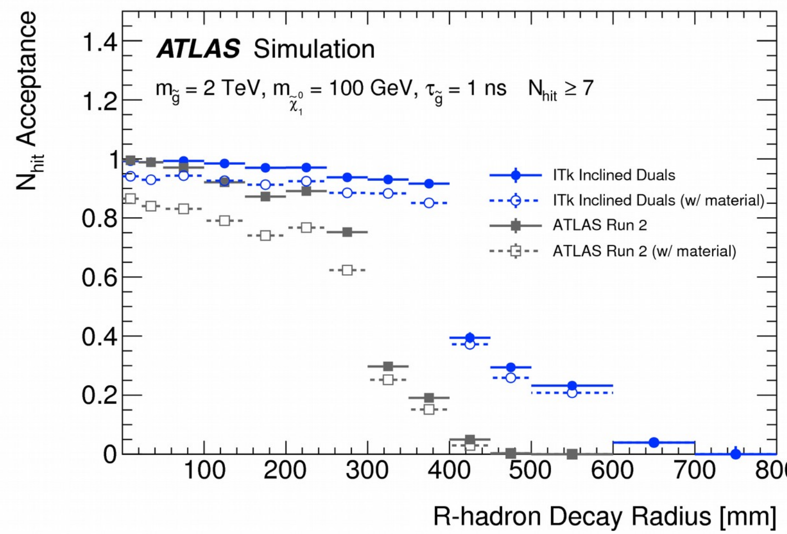


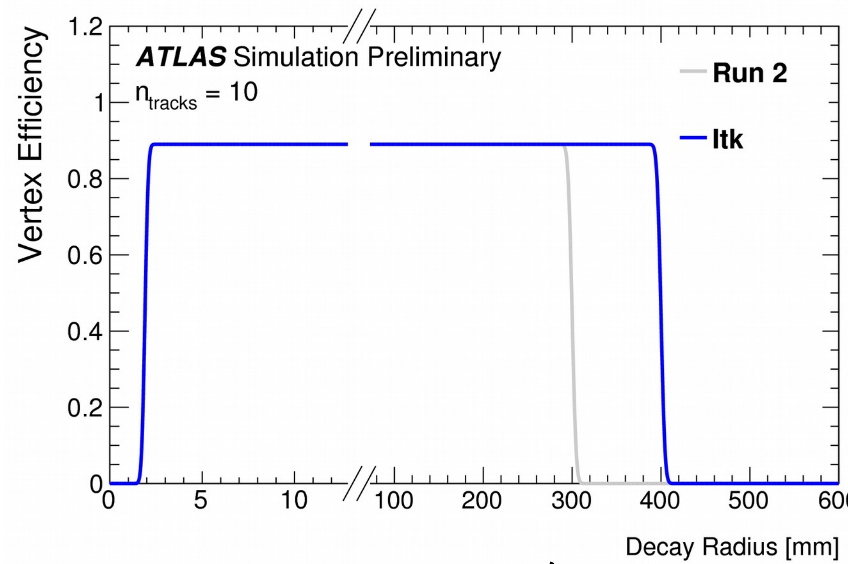
Displaced Vertices in the ID

- Tiny background after selections
  - hadronic interactions, accidental crossing
- Dedicated tracking and vertexing setup
  - Tacking efficiency driven by geometric acceptance and interactions with material

Opportunities
- Layout design
  - Access to longer lifetime
  - Geometric coverage
- Lower material budget

Challenges
- Keep tracking and vertexing efficiency high with large combinatorics





- e.g. for gluino R-hadrons expect ~1-1.5 TeV better sensitivity @ 14 TeV,3/ab w.r.t. now for DV+$\not{E}_T$

Speeding up tracking

- Based on popular request..

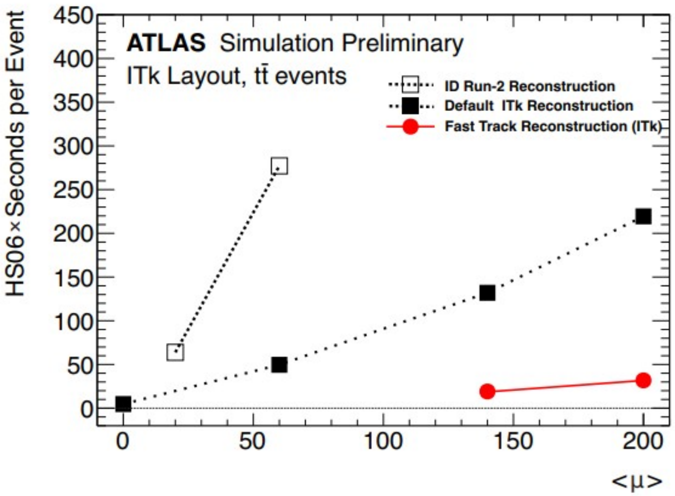
Detector	$\langle\mu\rangle$	Cluster Finding	Space Points	Si Track Finding	Ambiguity Resolution	TRT+Back Tracking	Primary Vertex	Total ITk/ID
ITk Layout	200	22	6.5	78	97	-	6	219
Run-2	20	1.5	0.7	23	15	19	0.5	64

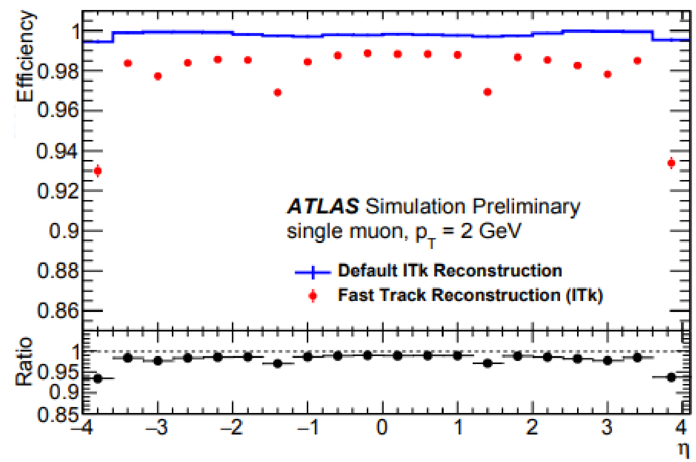
- Recent studies looked into speeding up track reconstruction for HL-LHC
  - Pixel-only seeding (5 pix layers vs 4 now..)
  - Avoid re-doing what hardware does already (e.g. some clustering)
  - Trade-off accuracy in Ambiguity solving with speed (fast cleaning)
  - Several technical “tricks” to reduce or eliminate steps that yield small imrprovements

$\langle\mu\rangle$	Tracking	Byte Stream Decoding	Cluster Finding	Space Points	Si Track Finding	Ambiguity Resolution	Total ITk
140	default	$1.2^{(*)}$	17.1	6.0	41.1	58.2	123.6
	fast		4.5	0.9	12.4	-	19.0
200	default	$1.6^{(*)}$	26.3	8.6	85.8	92.0	214.3
	fast		6.3	1.2	22.6	-	31.7

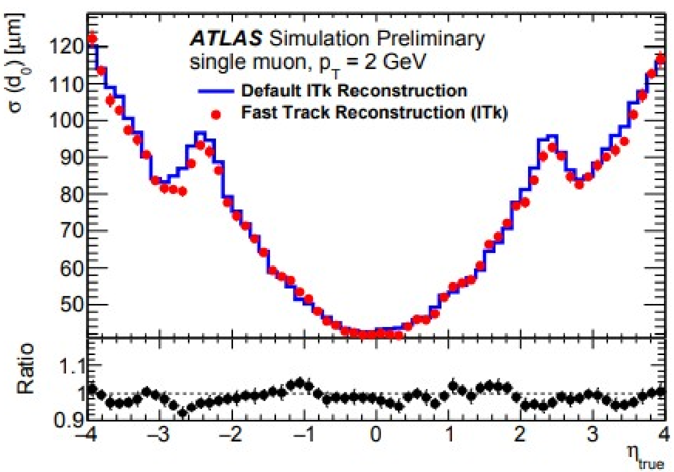
(∗) Scaled from Run-2, see text.

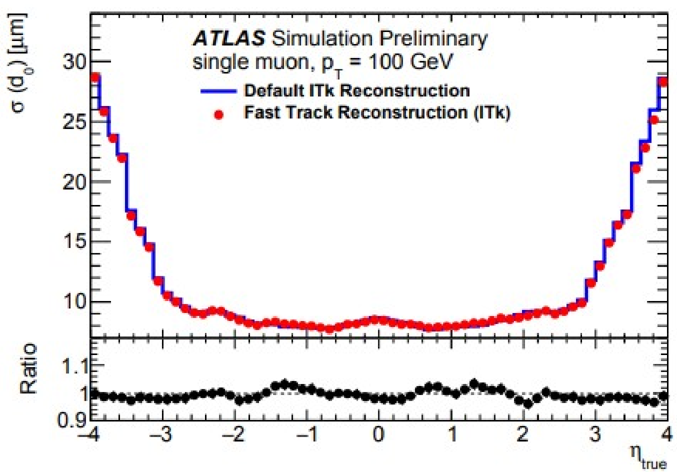
Fast tracking: performance





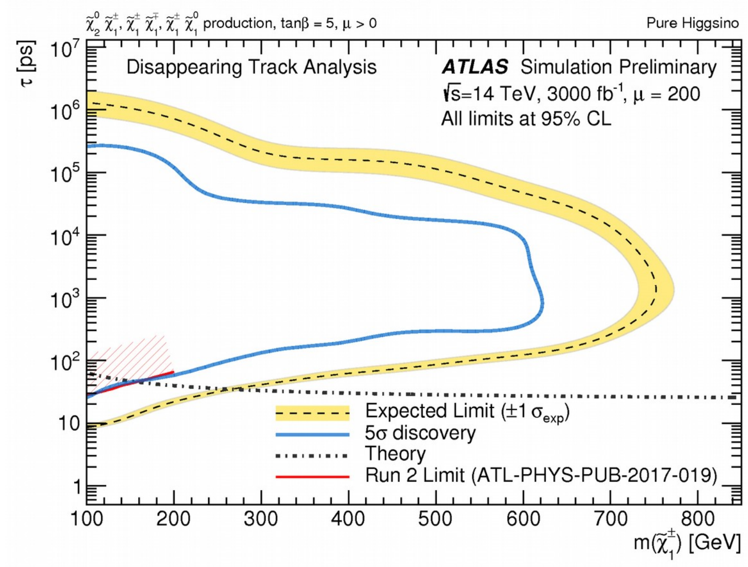
- For a slight reduction of efficiency (at low pT only) and little to no impact on parameter resolution can achieve a huge speed up for prompt tracking → large radius?
- This is all tuned / studied for HL-LHC phase-II detector. Some concepts apply Run 3





Opportunities

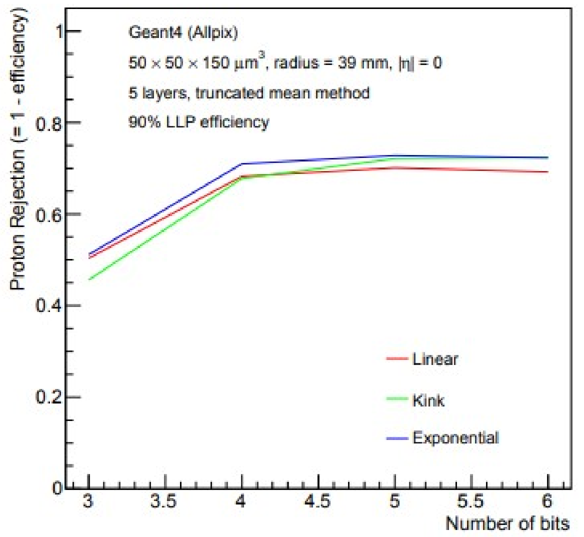
- Lower fake rate and better accuracy
- Low x-section → profit from large luminosity
- Higher masses sensitivity call for using dE/dx information too (non-MIP particle, measured by pixel detector)



Challenges

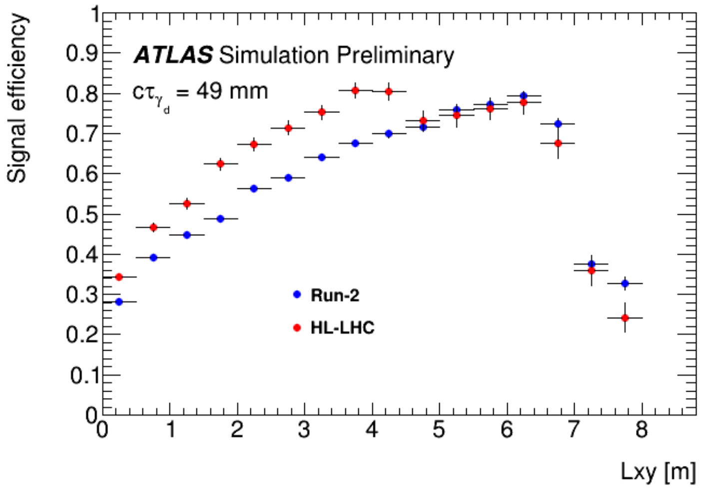
- Only 2-pixel layers in first 12 cm
  - need aggressive R&D and creativity
- Impact of coarser pixel charge measurements can be minor

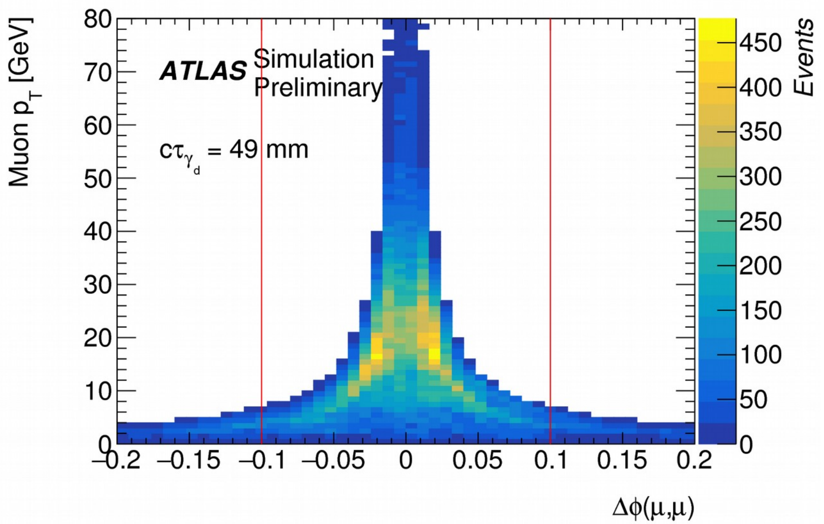
arXiv:1710.02582

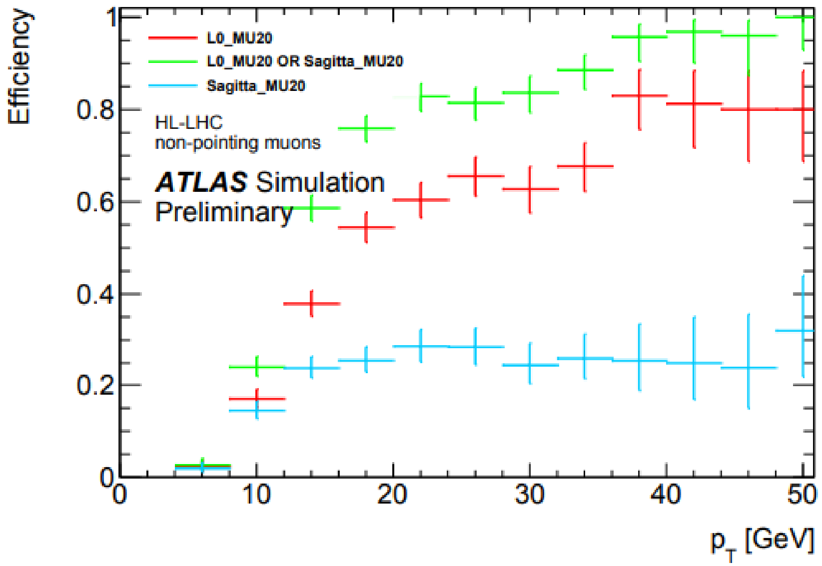


Decays in the Muon system

- Dedicated trigger to select decays of neutral particles in the MS already now
- Phase-II upgrades offer new improvements
  - Benefit from usage of high-resolution MDT measurement already at L0/L1 trigger
  - Increased coverage (75% → 95%)
- Collimated decays challenge the 1μ ↔ 1RoI
- Proper p measurement for non-prompt μ at Level-1 (CMS too, see Michail)







Beyond pp..

- Exclusive production in Heavy-Ion ultra-peripheral collisions
  - Competitive since x-sec can scale as much as Z^4

- Clean event!! Should be able to reconstruct a lot of interesting stuff that pile-up may make hard to tackle?

Quasistable charginos in ultraperipheral proton-proton collisions at the LHC

S. I. Godunov, V. A. Novikov, A. N. Rozanov, M.I. Vysotsky, E. V. Zhemchugov

(Submitted on 20 Jun 2019)

We propose an approach for the search of charged long-lived particles produced in ultraperipheral collisions at the LHC. The main idea is to improve event reconstruction at ATLAS and CMS with the help of their forward detectors. Detection of both scattered protons in forward detectors allows complete recovery of event kinematics. Though this requirement reduces the number of events, it greatly suppresses the background.

Long Lived Particles Searches in Heavy Ion Collisions at the LHC

Marco Drewes, Andrea Giammanco, Jan Hajer, Michele Lucente

(Submitted on 23 May 2019)

We show that heavy ion collisions at the LHC provide a promising environment to search for new long lived particles. A main advantage lies in the possibility to operate the main detectors with lower triggers, which can increase the number of observable events by orders of magnitude if the long lived particles are produced with low transverse momentum. If the LHC is operated with Pb nuclei this is insufficient to overcome the suppression due to the lower instantaneous luminosity compared to proton runs, but for lighter nuclei a higher sensitivity per running time can be achieved than in proton collisions. We illustrate this explicitly for heavy neutrino searches in the Minimal Neutrino Standard Model. In less minimal models with complicated event topology the absence of pile-up provides another key advantage of heavy ion collisions because it

A Heavy Metal Path to New Physics

Marco Drewes, Andrea Giammanco, Jan Hajer, Michele Lucente, Olivier Mattelaer

(Submitted on 22 Oct 2018)

We show that heavy ion collisions at the LHC provide a promising environment to search for signatures with displaced vertices in well-motivated New Physics scena
with very loose triggers. For scenarios in which long-lived particles are produced in the decay of light particles, this can increase the number of observable events by
ion community for unrelated reasons, this can lead to a higher sensitivity per time of running than in pp collisions. We illustrate that explicitly for heavy neutrinos in th
no pile up, i.e., the average number of simultaneous interactions per bunch crossing is well below unity. This entirely removes the problem of mis-identifying the loca

Conclusions

- Signatures coming from LLP can often evade common assumptions made in event reconstruction
- Sometimes, a little bit of care is enough to unlock sensitivity to a huge new parameter space
- Sometimes, dedicated reconstruction techniques are needed

- While some of these techniques have been now around for quite some time, their evolution is still in a phase where either
  - Large gains are still possible with more R&D
  - Significant challenges ahead will need us to rethink some of our strategy

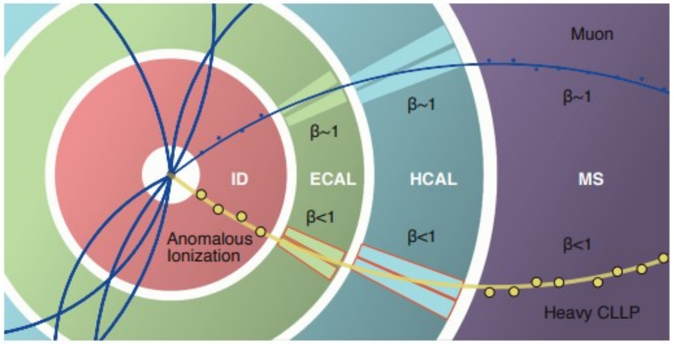
- Within the US we start having quite a critical mass of people interested and involved in searches with these signatures

BACKUP

Background characterization

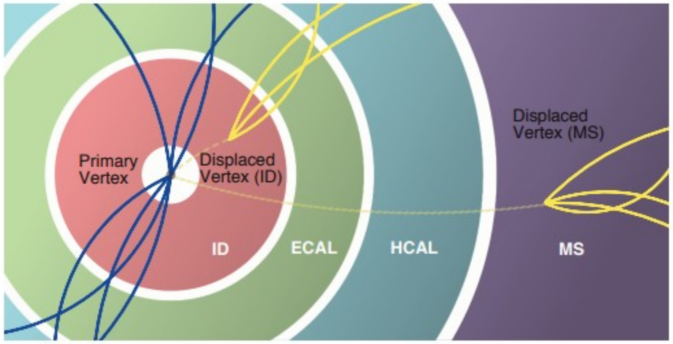
LLP searches have often “hard” backgrounds to project

- Instrumental → depend on operation, stability, …
- Machine-related → uncertainty on LHC machine configuration, simulations
  - e.g. Unpaired/empty bunches unique as source for data-driven estimate
  - Especially a concern in MS and Calorimeter
- Hadronic interaction in very high pile-up
  - Very sensitive to final distribution of material within the upgraded detector
  - Timing distribution?? [can discuss more during next talk as well]
    - Many different nuclear interactions/excitations possible
    - Modeling in Geant-4??
    - Current test-beam data could already give us a clue!!



Direct Detection

Measure interactions of SM-charged LLP with detector



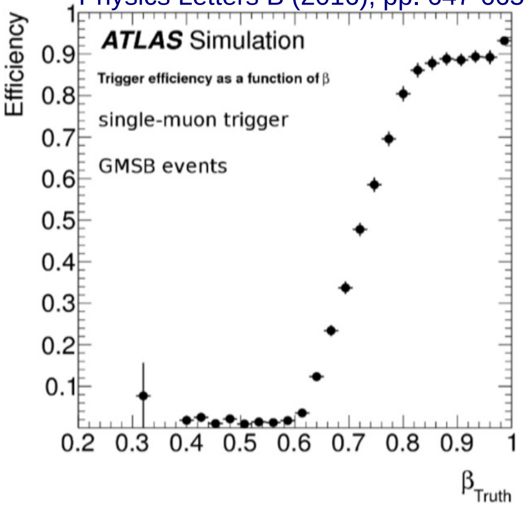
Indirect Detection

Measure displaced decay products

Run-3: triggering

- Flexibility to implement custom triggers for dedicated signatures
  - Possibility of more “elaborated” calo-based selections at L1 could reduce rate enough for dedicated more time-consuming algorithms on full detector at HLT
  - Trigger strategies that allow objects to be delayed by > 25 ns (1 bunch x-ing) with L1-Topological requirements on MET or Jets

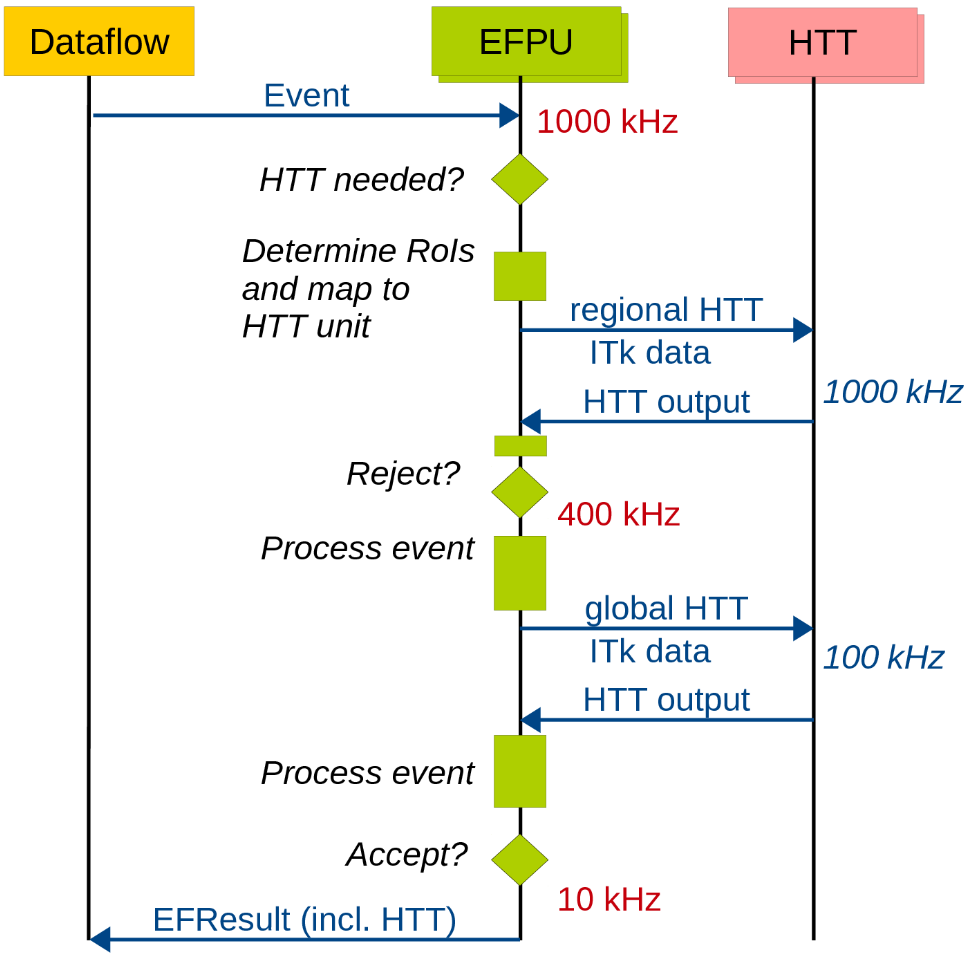
Physics Letters B (2016), pp. 647-665



- Need to retain high efficiency while fighting against pile-up
  - e.g. non prompt leptons, MET!

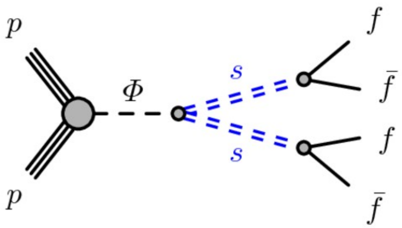
Triggering on Inner Detector

- Two-phases upgrade
- Outer part of Inner Detector will be read-out @ 1MHz (regional based on L0)
- Could be sensitive to fairly displaced tracks if tuned properly
- Other dedicated algorithms or hardware could also be possible if designed early enough
  - Either for Run-4 or later..
  - Need to still keep a low rate in a challenging and busy environment



- Note: MS+Calo info combined at L0/L1 very flexibly (evolution from Run-3)

- Neutral particles decaying in the ATLAS calorimeter



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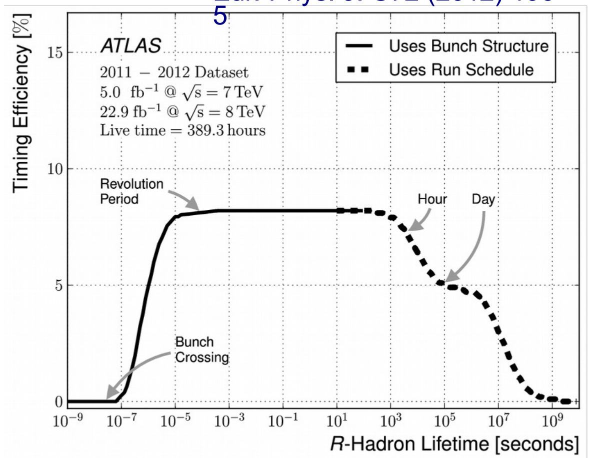
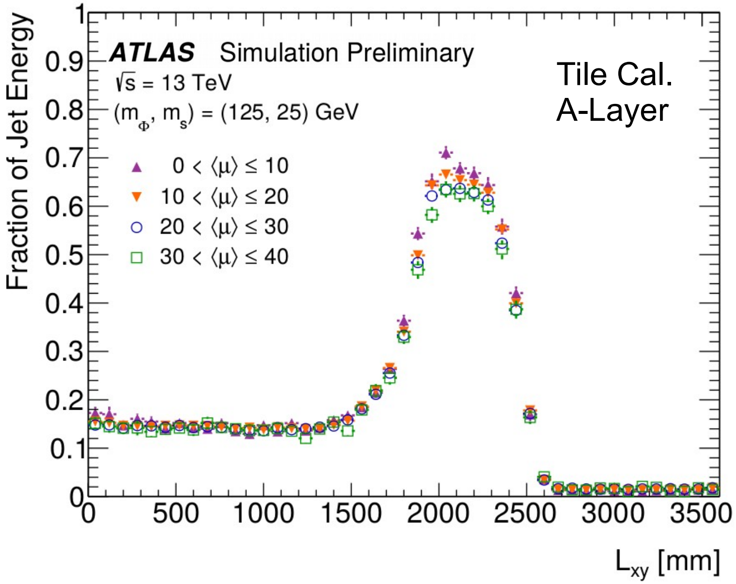


- Dedicated trigger strategies
  - "isolated" and narrow energy deposits in Tile calorimeter vetoing other activity
  - very delayed signature on non-colliding bunch crossings and no-beam periods are sensitive to lifetimes up to ~years



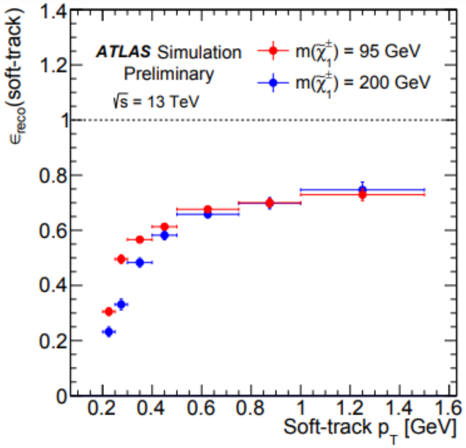
- Need to ensure pile-up robustness and high efficiency in rejecting non-collision backgrounds
  - take advantage of calorimeter segmentation
- Upgraded L1 Trigger L1 with increased granularity will help in background rejection

Run-3: offline

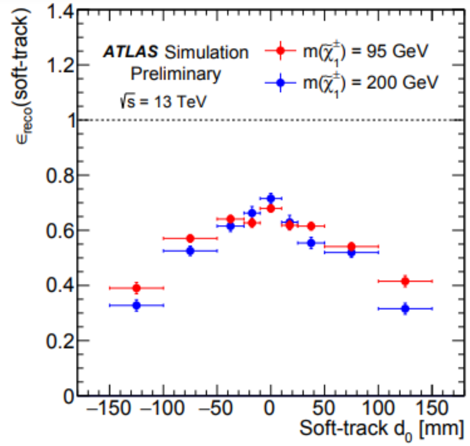
- Continuously optimizing/fighting against computing resources
- Two apparently competing needs:
  - Streamline data analysis and reduce information as much/early as possible
  - Increase flexibility to allow more complex algorithms using low-level information
- Non-trivial implications for the experiment's internal organization
- ATLAS already using different data-processing paths for some LLP and other exotic searches
  - Filtering data early based on standard reconstruction
  - Dedicated reconstruction on subset of data (relaxed CPU constraints)
- Such model could potentially be vital to add complexity to analysis
- Other approaches for adding flexibility even later in the analysis "lifetime cycle" are being investigated as well (let's be creative!)

Take-away messages:
@Exp: need to address these challenges to have the most flexibility
@Exp+Theoriests: we can think of more complex algorithms as well

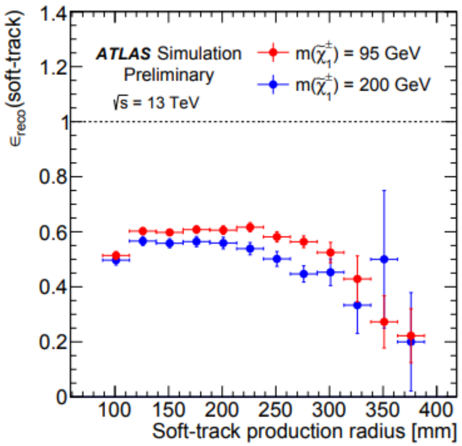
Soft-pion reco efficiency



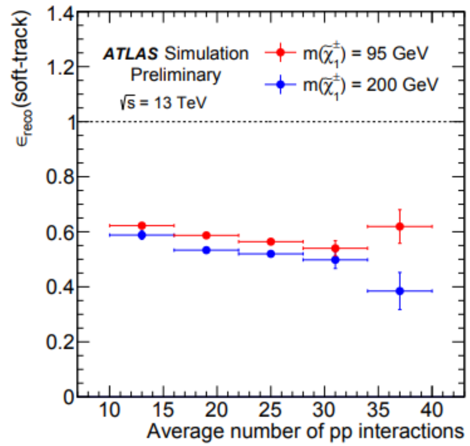
(a)



(b)

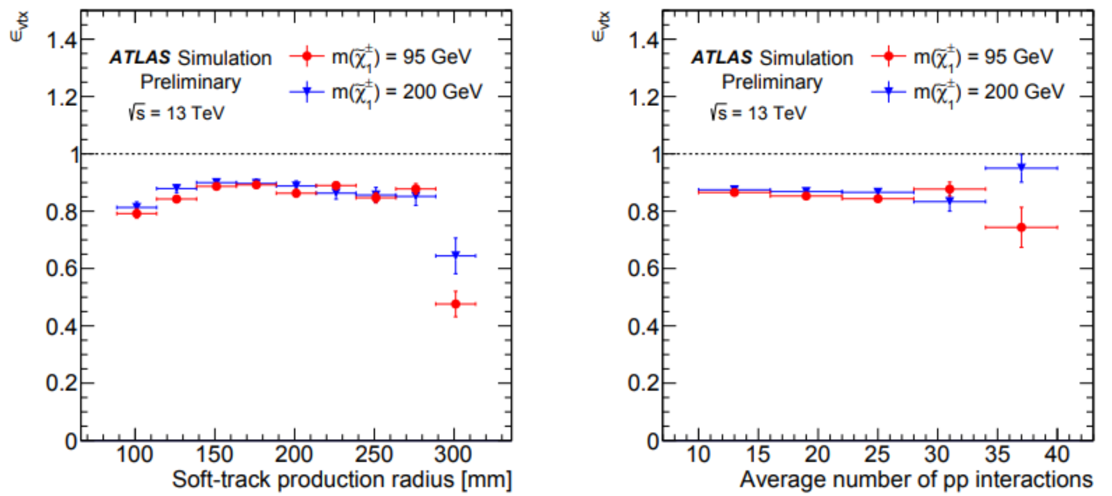


(c)

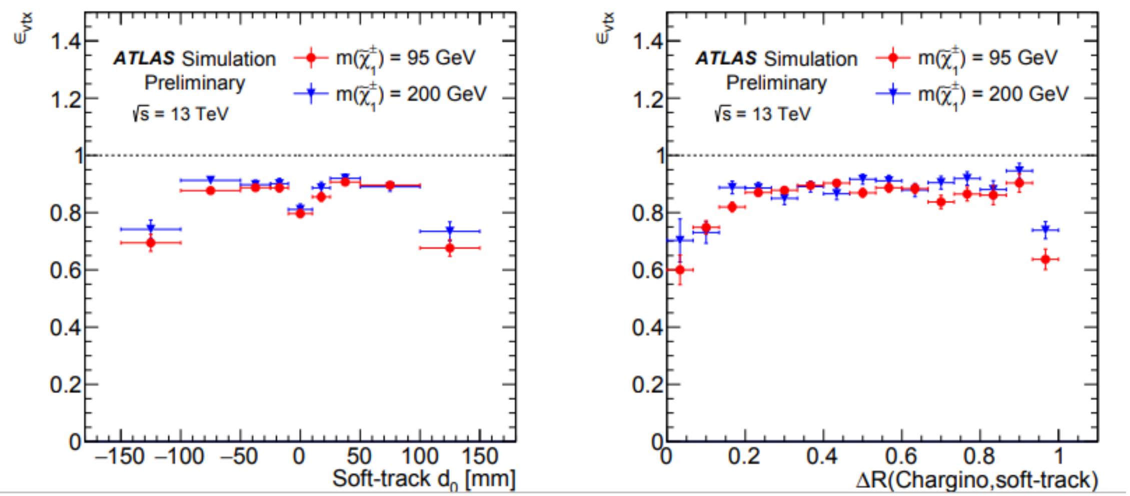


(d)

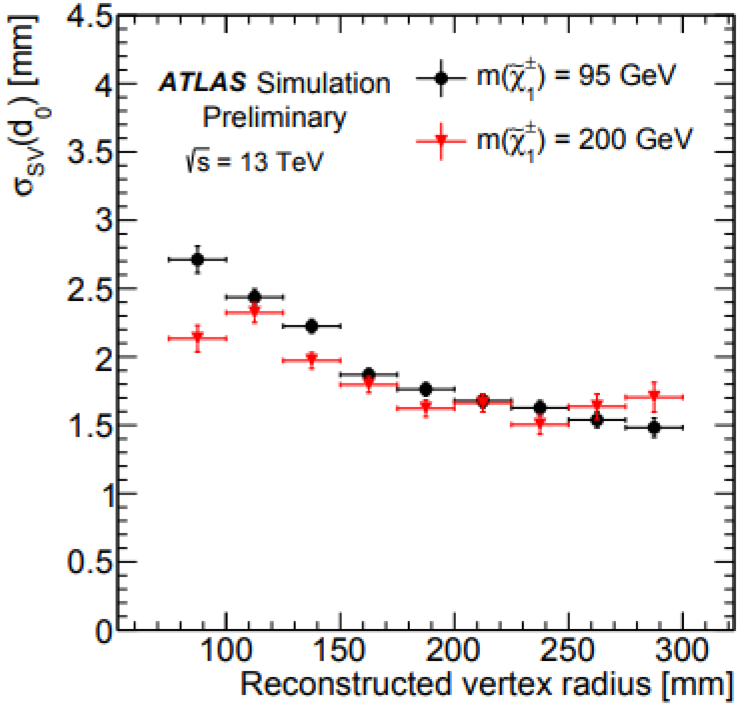
Soft pion vertex efficiency

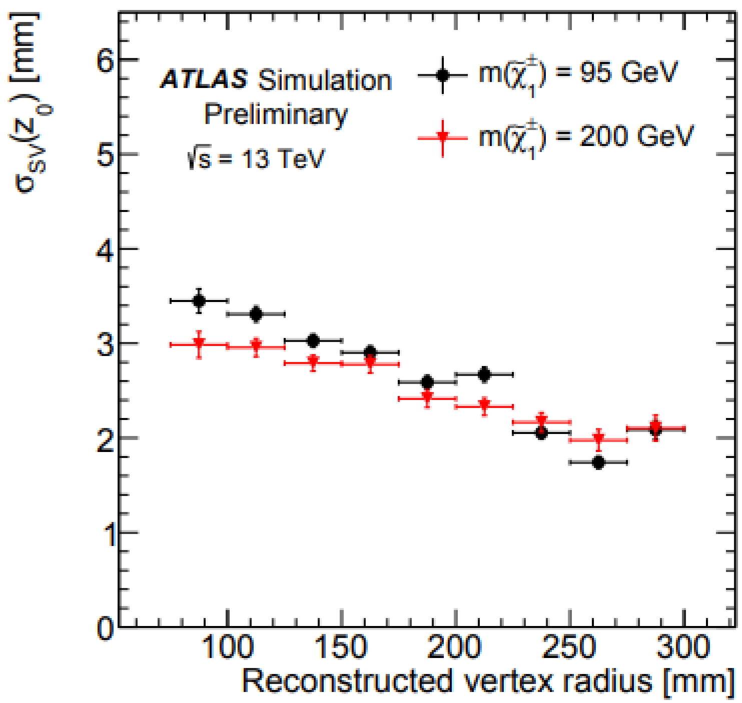


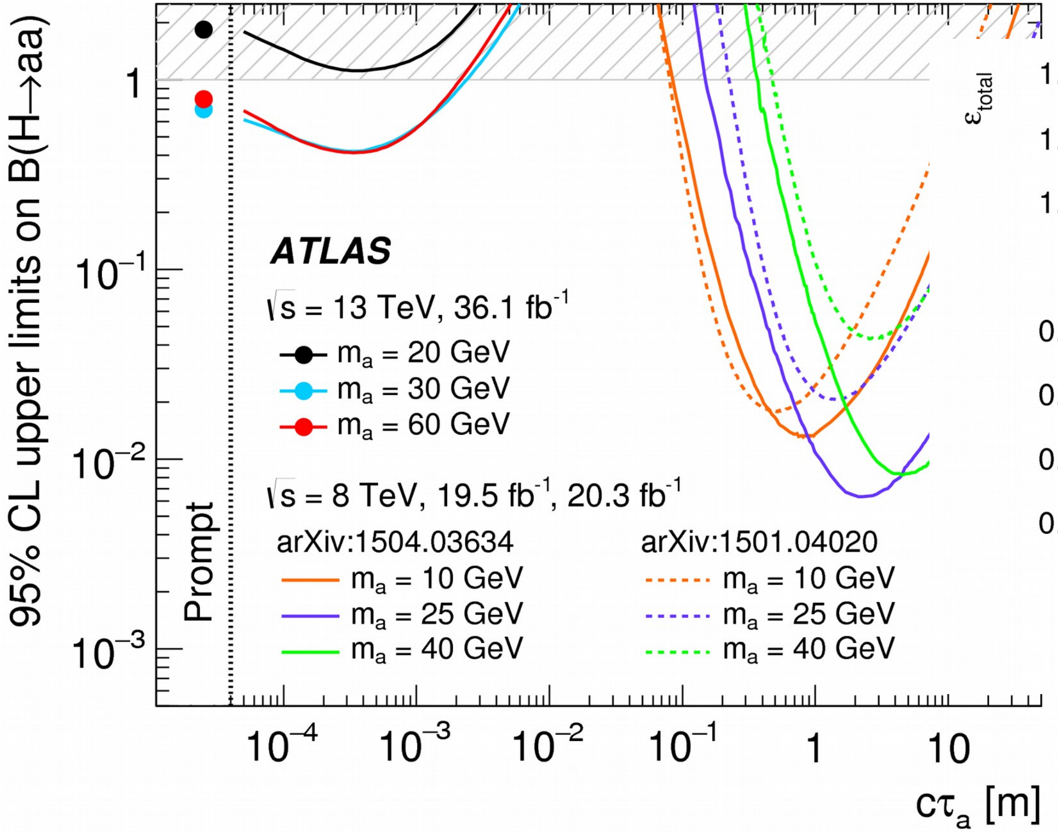
(a) (b)

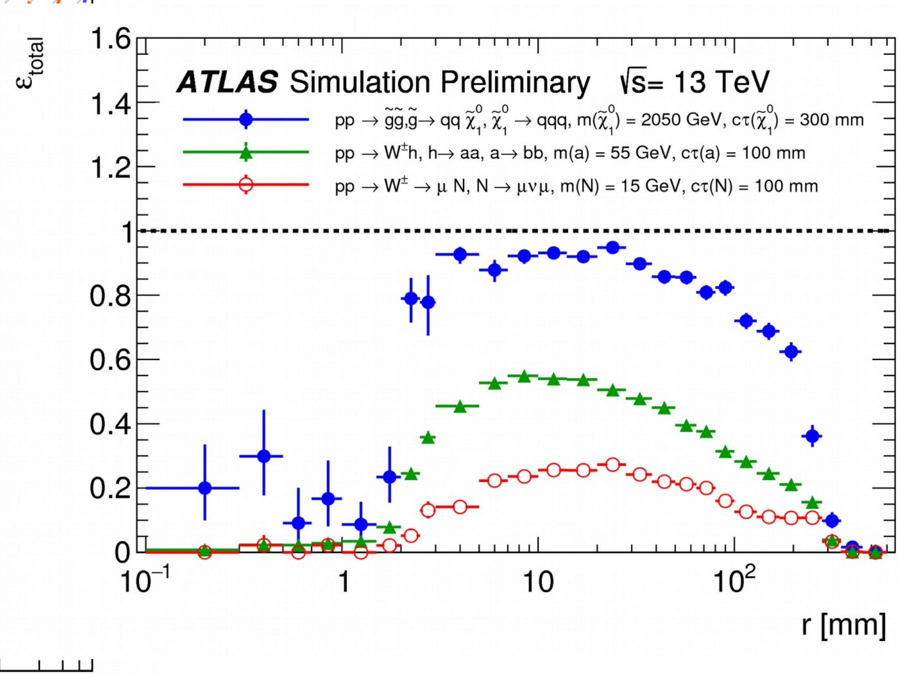


Soft pion DV resolution






95% CL upper limits on B(H→aa)
ATLAS
√s = 13 TeV, 36.1 fb-1
ma = 20 GeV
ma = 30 GeV
ma = 60 GeV
√s = 8 TeV, 19.5 fb-1, 20.3 fb-1
arXiv:1504.03634
ma = 10 GeV
ma = 25 GeV
ma = 40 GeV
arXiv:1501.04020
ma = 10 GeV
ma = 25 GeV
ma = 40 GeV
Prompt
cτa [m]


εtotal
ATLAS Simulation Preliminary √s= 13 TeV
pp → g̃g̃,g̃→ qq χ̃⁰₁, χ̃⁰₁ → qqq, m(χ̃⁰₁) = 2050 GeV, cτ(χ̃⁰₁) = 300 mm
pp → W±h, h→ aa, a→ bb, m(a) = 55 GeV, cτ(a) = 100 mm
pp → W± → μ N, N → μνμ, m(N) = 15 GeV, cτ(N) = 100 mm
r [mm]