Rescuing *VBF H→Invisible* Events with Novel Vertex Selection

Connecting The Dots 2020

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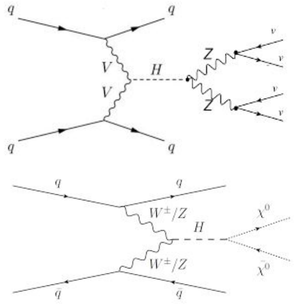
On behalf of the ATLAS Experiment

Current state of Primary Vertex Identification in ***VBF H→Invisible***

Example topologies



Default — Exploit high transverse momentum (p_T) tracks → Pick vertex with largest Σp_T^2

Challenging for Vector Boson Fusion *(VBF) Higgs→Invisible* topology

- Vertex Selection efficiency (VSE) much lower than other topologies (~80%)

Primary Challenges for *VBF H→Invisible* :

- Low visible p_T interaction due to invisible particles in final state
- Forward Hard Scatter jets outside tracker acceptance, reducing visible p_T further
- Merged Pileup (PU) vertices, which have a large resulting Σp_T^2 from the tracks of all the merged uncorrelated interactions

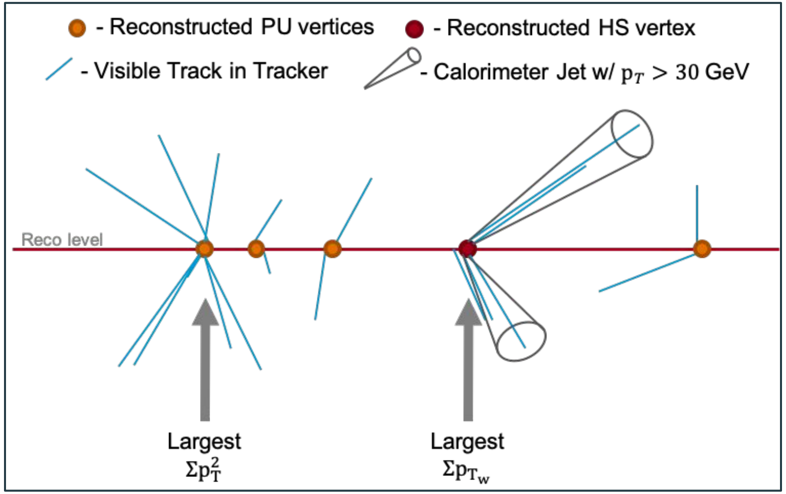
Can we improve it?

Tackling the low visible p_T and merged PU vertex challenge

$\cancel{\text{Maximize } \Sigma p_T^2}$

Combine jet and tracking information + Favor tracks going into HS jets to enhance visible HS p_T

Maximize $\sum p_{T_w} = \sum_{tracks} p^2_{T(track)} \frac{p^2_{T(closest\ jet)}}{\Delta R^1} \mathbb{1}(\Delta R < 0.4)\, \mathbb{1}(p_{T(jet)} > 30\ GeV)$



Tackling the low visible p_T and merged PU vertex challenge

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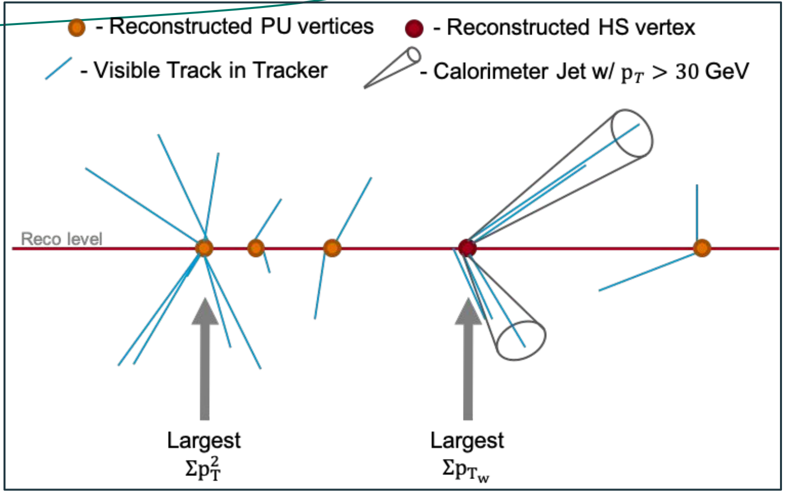
Maximize $$\sum p_{T_w} = \sum_{tracks} p^2_{T(track)} \boxed{\frac{p^2_{T(closest\ jet)}}{\Delta R^1}} \boxed{\mathbb{1}(\Delta R < 0.4)\, \mathbb{1}(p_{T(jet)} > 30\ GeV)}$$

Track Weighting:
Favor tracks centrally aligned to high p_T jets



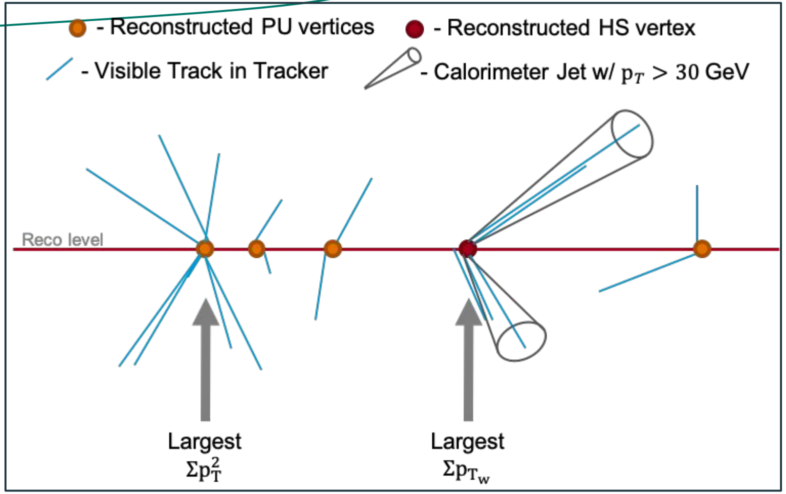
Vertex Grooming:
Consider tracks inside hard jets

Tackling the low visible p_T and merged PU vertex challenge

Combine jet and tracking information + Favor tracks going into HS jets to enhance visible HS p_T

$$\text{Maximize } \sum p_{T_w} = \sum_{tracks} p^2_{T(track)} \boxed{\frac{p^2_{T(closest\ jet)}}{\Delta R^1}} \boxed{\mathbb{1}(\Delta R < 0.4)\,\mathbb{1}(p_{T(jet)} > 30\ GeV)}$$

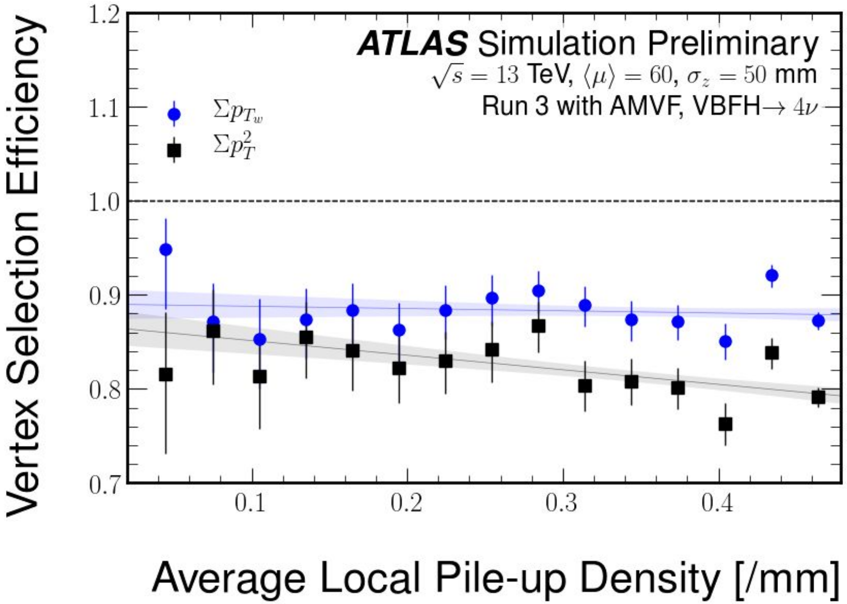
Track Weighting: Addresses the problem of low visible p_T by weighting with jet p_T. This enhances the visible HS p_T



Vertex Grooming: Addresses the problem of merged PU vertices by neglecting “background” PU tracks that are uncorrelated to hard jets

Tackling the low visible p_T and merged PU vertex challenge

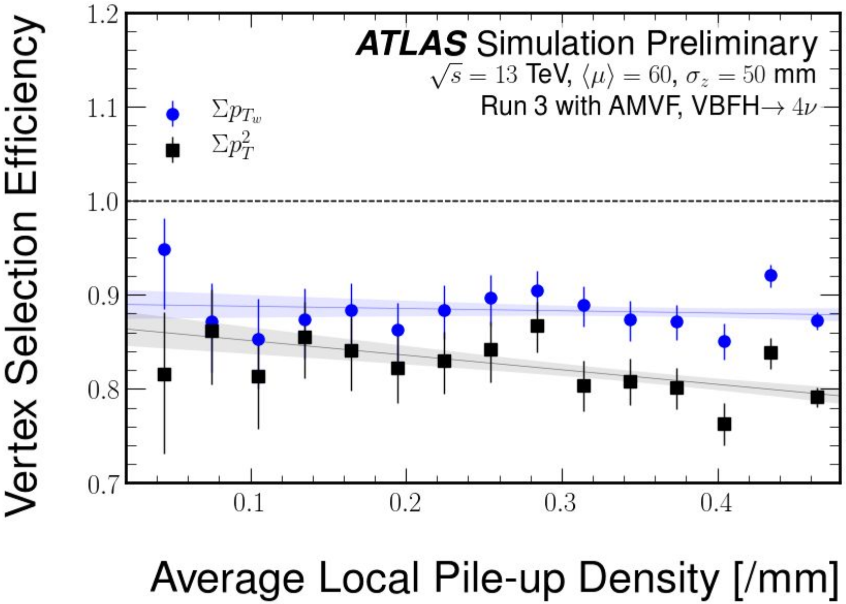
Vertex selection efficiency as a function of Pileup density.
Pileup density is the local density of vertices at the Primary Vertex in the event.
Default sumPT selection method (square) is compared with sumPTw selection (circle).
Error bars are statistical errors. Best fit linear functions are drawn through the sets of points with 1-sigma error bands to visualize the slopes with Pileup density.
AMVF refers to the Adaptive Multi-Vertex Finder algorithm used to reconstruct vertices[1].



[1]: Development of ATLAS Primary Vertex Reconstruction for LHC Run 3 [ATL-PHYS-PUB-2019-015]

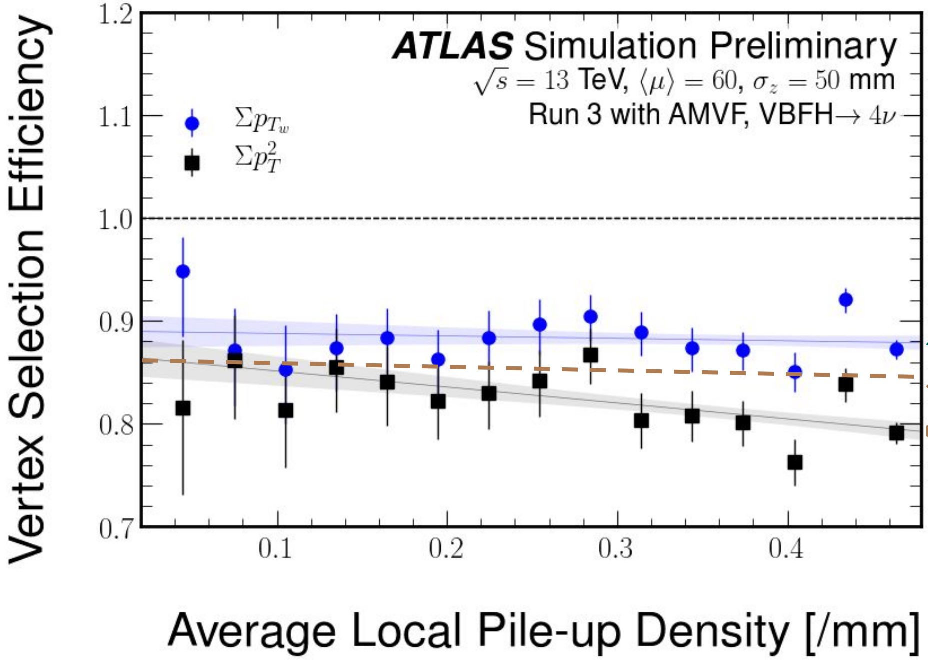
Tackling the low visible p_T and merged PU vertex challenge

- **Inclusive Vertex Selection Efficiency improved from 80% to 88%**
- Performance limited by charged particles outside tracker acceptance due to forward jets
- **Solved challenge of merged PU vertices** (with high Σp_T^2) by utilising correlations between HS tracks and HS jets
  - PU tracks from merged PU vertices are uncorrelated to jets hence don't contribute to Σp_{Tw}



Tackling the low visible p_T and merged PU vertex challenge

Inclusive VSE improved from 80% to 88%

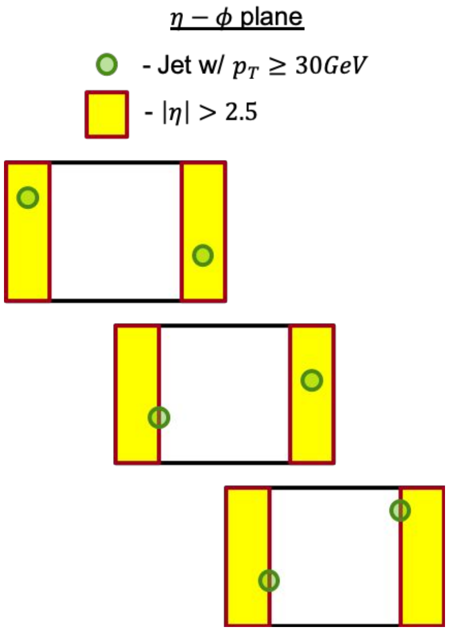


Enhance HS vertex with track weighting

Solve PU merging with vertex grooming

Tackling Jets outside tracking acceptance

- Vertex selection limited due to charged particles beyond acceptance, $|\eta|>2.5$
- **Concretely identify cases of significant activity beyond tracking acceptance** $\rightarrow$
- Case of 2 jets completely outside tracking acceptance ($|\eta|>2.5$) can only be addressed at HL-LHC[1] where the tracking coverage is extended to $|\eta|<4.0$
- Partially contained jets can be accounted for by matching tracks to calorimeter jets



[1]: ATLAS PIXEL TDR: [CERN-LHCC-2017-005 ; ATLAS-TDR-025] [CERN-LHCC-2017-021 ; ATLAS-TDR-030]

How to define cases with significant activity beyond tracker acceptance ?

- We can exploit the PU jet distribution (Most events have either 0 PU jets or 1 central PU jet)

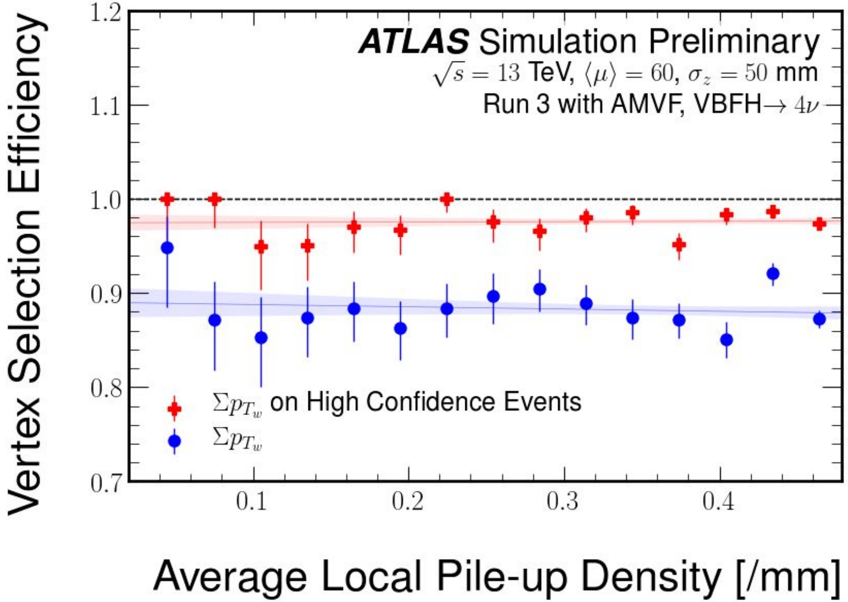
- **Low Confidence Event**: An Event with significant activity (p_T) *beyond* tracker acceptance
  - ≥ 2 jets with $p_T > 30\ GeV$ and $|\eta| > 2.1$ with RpT < 0.1 w.r.t. any vertex

$$RpT = \sum_{tracks}^{in\ vertex} (p_{T(track)}/p_{T(jet)} \cdot \Theta(\Delta R_{(track-jet)} < 0.4\,)$$

- **High Confidence Event**: An Event with significant activity (p_T) *within* tracker acceptance
  - < 2 jets with $p_T > 30\ GeV$ and $|\eta| > 2.1$ with RpT < 0.1 w.r.t. any vertex

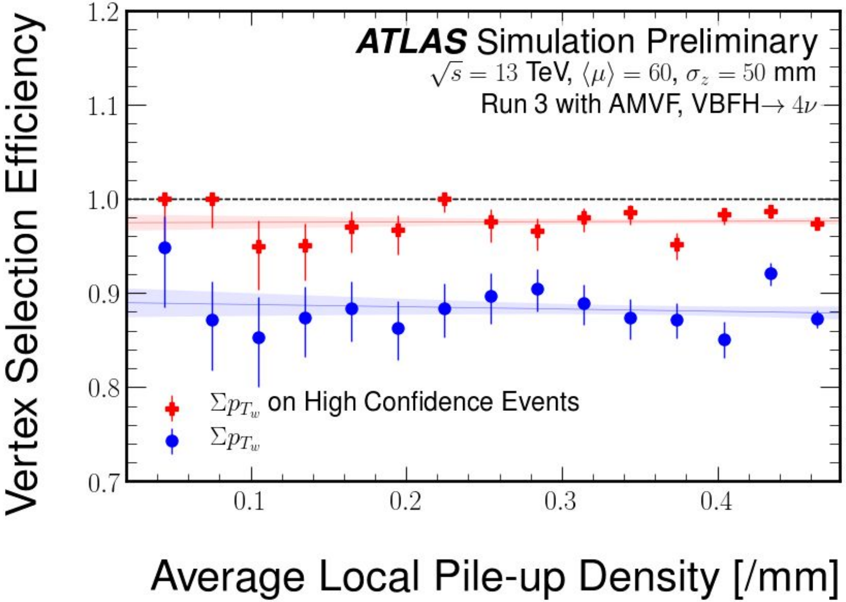
Tackling Jets outside tracking acceptance

Vertex selection efficiency as a function of Pileup density. sumPTw selection on all events (circle) is compared with sumPTw selection on High Confidence Events (cross).
Every High Confidence Event has sufficient tracks inside forward Hard Scatter jets, leading to a very high vertex selection efficiency with sumPTw.
Error bars are statistical errors. Best fit linear functions are drawn through the sets of points with 1-sigma error bands to visualize the slopes with Pileup density.



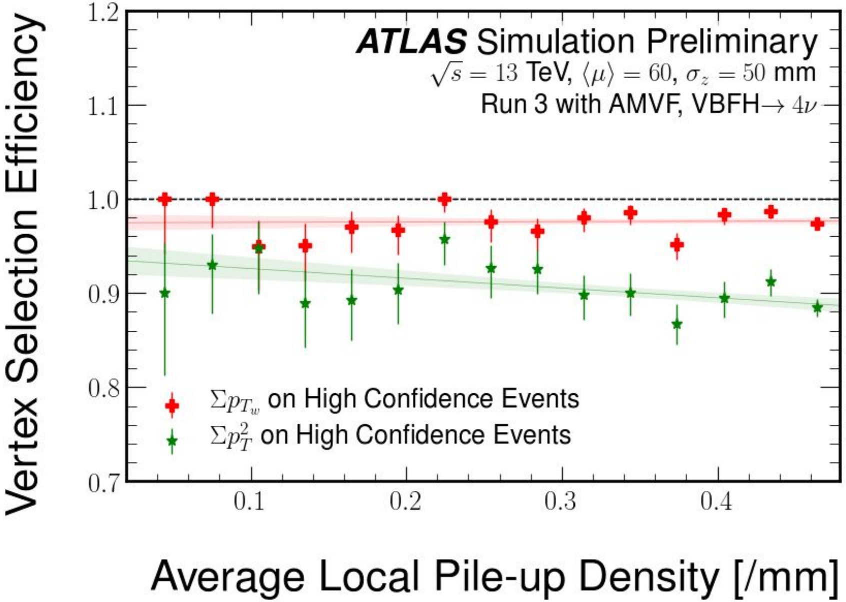
Tackling Jets outside tracking acceptance

- Handle events differently based on presence of hard jets with tracks outside acceptance
- *High confidence events* should be utilized for vertex selection
    - **Significantly improved VSE ~98%**
    - Remaining 2% inefficiency comes from events with a Hard QCD PU interaction that has larger Σp_{Tw} than the $VBF\ H \rightarrow Invisible$ vertex
- *Low confidence events* can be retained for Physics
    - Contain useful jets (with no tracks)



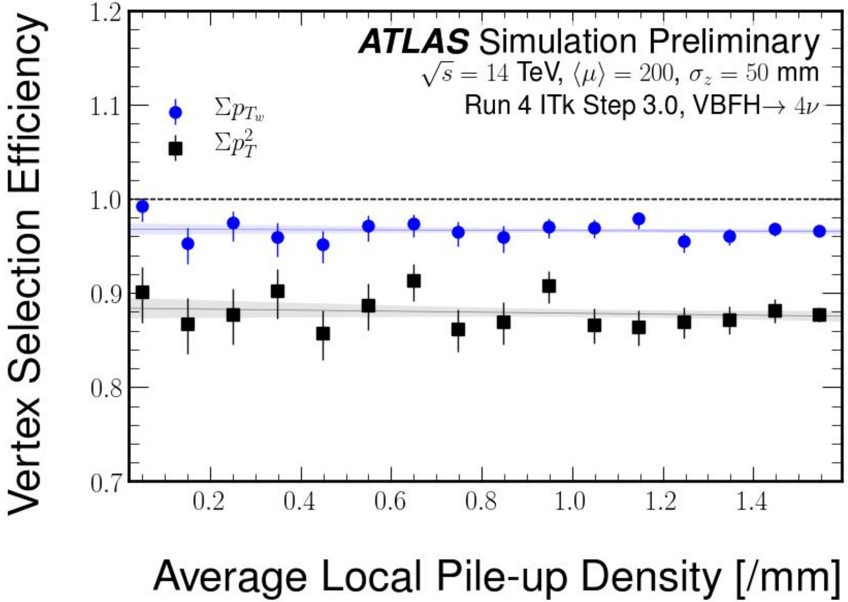
Tackling Jets outside tracking acceptance

- Compare Σp_{Tw} and $\Sigma p_T^{\,2}$ on High Confidence Event category
- **Inclusive VSE improved from 89% to 98%**
- Primarily limited by
    - Merging of PU vertices
    - Hard QCD PU interactions



What would this look like at HL-LHC?

Vertex selection efficiency as a function of Pileup density. Pileup density is the local density of vertices at the Primary Vertex in the event.
Default sumPT selection method (square) is compared with proposed sumPTw selection (circle).
Note: Efficiencies are larger than the values from current primary vertex identification due to increased tracking acceptance at the HL-LHC[1] (Run 4); PU merging is less prominent due to improved tracking resolution at HL-LHC.
Error bars are statistical errors. Best fit linear functions are drawn through the sets of points with 1-sigma error bands to visualize the slopes with Pileup density.

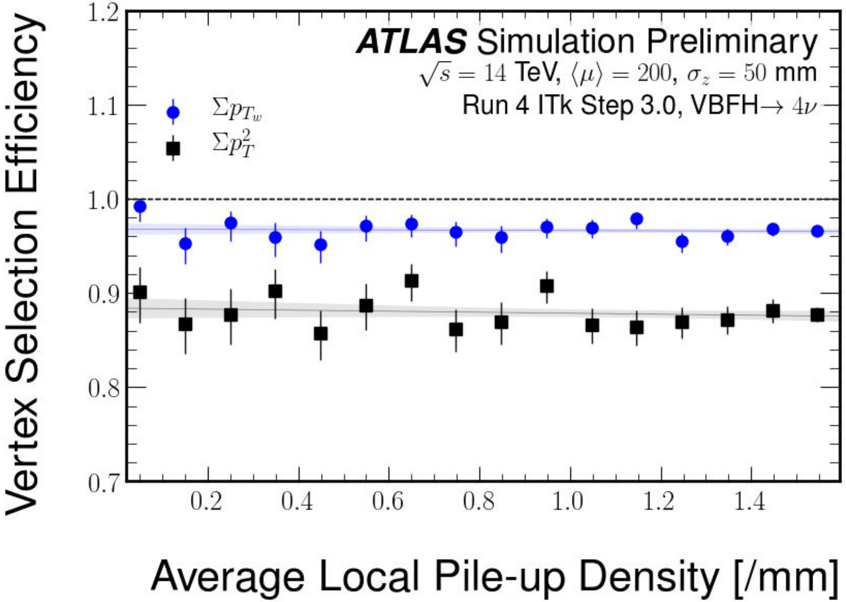


[1]: ATLAS PIXEL TDR: [CERN-LHCC-2017-005 ; ATLAS-TDR-025] [CERN-LHCC-2017-021 ; ATLAS-TDR-030]

What would this look like at HL-LHC?

- Tracking acceptance expanded to $|\eta| < 4$ [1]
- Low visible p_T challenge remains
- Increased incidences of PU Dijet events

- Maximising Σp_{Tw} aids with low visible p_T
- Hard QCD PU handled by event selection
- **Inclusive VSE improved to 97% (from 88%)**



[1]: ATLAS PIXEL TDR: [CERN-LHCC-2017-005 ; ATLAS-TDR-025] [CERN-LHCC-2017-021 ; ATLAS-TDR-030]

Conclusions

A novel vertex selection method Σp_{Tw} is introduced that exploits the correlation between HS tracks and jets to boost the visible p_T of the *VBF H→Invisible* vertex and remove the impact of uncorrelated PU interactions. A new event categorization is defined to identify the conditions under which the vertex selection algorithm is reliable, rescuing VBF invisible events that could be otherwise rejected due to a wrongly selected vertex.

Current Geometry (Run 3)

- Vertex Selection Efficiency improved from 80% to **88%**
- Impact of Pileup Merging rectified
- Restricting to High Confidence Events yields higher VSE at **98%**
- Low Confidence Events usable with good VBF jets but uncertain vertex

HL-LHC (Run 4)

- Vertex Selection Efficiency improved from 88% to **97%** by using Σp_{Tw} instead of Σp_T^2
- Increased track acceptance & improved track resolution gives boost in performance of both methods

Backup

Data used and Event Selection applied

Run 3

- Assuming Run 2 layout, beam optics, filing schemes etc
- Identifiable event:
  - 2 truth matched HS reconstructed jets
  - p_T >70,50 GeV, η <4.0
  - $\Delta\phi$ < 2.6, $\Delta\eta$ > 3.0

Run 4

- Step 3 layout
- Identifiable event:
  - 2 truth matched HS reconstructed jets
  - p_T >70,50 GeV, η <4.0
  - $\Delta\phi$ < 2.6, $\Delta\eta$ > 3.0

Gaussian assumption

To account for limited stats after Event Selection, We use average local PU vertex density, which is an approximation of the true local PU density

$$\text{Density}(z) = \frac{\mu}{\sqrt{2\pi\sigma^2}} \exp - \frac{z^2}{2\sigma^2}$$

How does vertex splitting manifest?