PERFORMANCE OF THE CELLULAR AUTOMATON (CA) SEED FINDER IN TPC TRACKING

Tracking Focus Group

Abstract

We present a summary of performance evaluations of a new track–seed finder in STAR TPC tracking. The new seed finder is based on Cellular Automaton (CA) techniques. The seed finder feeds the standard STAR TPC tracking software (Sti) for track fitting and extrapolation to inner detectors. The resulting hybrid code is called StiCA here and it is compared to standard Sti, which uses its own seed finder. We used Data and Simulations to evaluate and compare performance for both Au+Au 200 GeV and p-p 500 GeV collisions in different luminosities. We also used targeted analysis of (relatively) small data samples for D^0 and W-boson reconstruction performance. In all cases StiCA consistently outperforms Sti in a significant and luminosity dependent way without significant drawbacks. Our conclusion and recommendation would be to deploy StiCA in all future productions in STAR.

Contents

1 Introduction

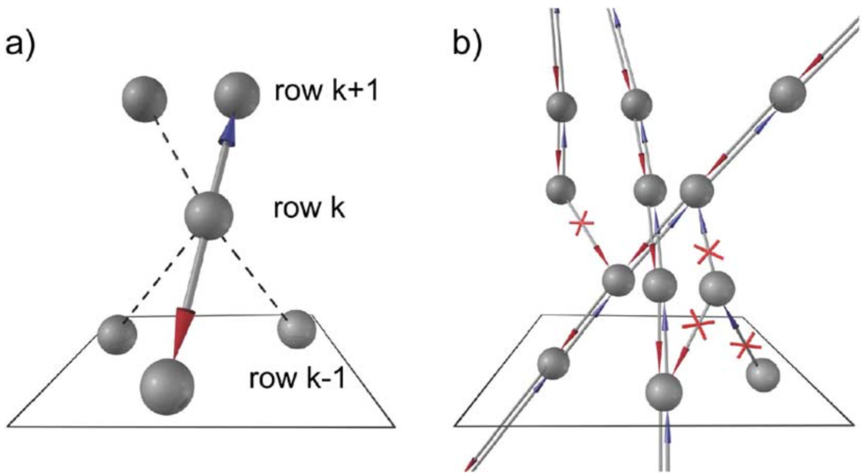
A new track-seed finder has been proposed and developed by the Frankfurt/GSI group based on Cellular Automaton (CA)[1], [2] concept: The seed-finding is done in two steps: a) small segment formation by connection neighboring hits and, b) segment fusion and selection based on track length. There are two important features that distinguish CA from traditional seed formation. One is that the track segment formation in CA can start in any place inside the TPC volume, not necessarily the outer padrows where the hit density is typically lower and therefore easier to identify them. The CA randomness has the advantage of finding tracks never reaching the outer TPC limits and are well hidden inside the bulk volume of TPC. The other advantage is that CA is directionally blind and not requiring the track to come from ”around the center of the TPC volume”, something typical in follow-your-nose algorithms. Instead it allows the track to grow naturally in any direction. An important ingredient of the CA method is that it is allowing up to 10% of the hits to participate in several segments (”hit sharing”) thus removing possible biases due to the given starting point. This feature is not available in the standard Sti seed finder. Recent tests with hit sharing in standard Sti seed finder in a p-p (W) sample showed, if anything, no difference, so the main advantage of CA comes from the other algorithmic strategies of the method.

Figure 1 shows the two steps (segment and track formation) of the CA algorithm in a graphical way. More details about the method can be found in the reference mentioned above.

In the following sections we show efficiencies for both Data and Simulations. For Data absolute efficiency estimation is not possible so we quote instead the so called Scanning Efficiency[3] or relative efficiency. In our case we have two trackers reconstructing the same event sample with total reconstructable number of track N_T. Lets say they find $n_1 = e_1 N_T$ and $n_2 = e_2 N_T$ tracks in a given event where the scanning efficiency for each tracker is e_1 and e_2, respectively. If these efficiencies are independent then the common set of different tracks found by both trackers is $N_{12} = e_1 e_2 N_T$. Then the scanning efficiency for each tracker is $e_1 = N_{12}/n_2$ and $e_2 = N_{12}/n_1$ respectively. Typically N_T is less than N_{TRUE}, the real total number of tracks in the event (since both trackers can miss some tracks), so the scanning efficiency tends to overestimate the real efficiency.

For Simulations the efficiency definition is straightforward $\text{Eff}_{SIM} = \frac{Reconstructed}{Reconstructable}$ tracks, so comparisons and performance are absolute. A few more definitions in the case of Monte Carlo (MC) simulations follow. Simulated (MC) and reconstructed (RC) tracks are considered if:
* Good-MC track: has number of TPC MC hits ≥ 15 (reconstructable), i.e. no geometrical acceptance in efficiency

[1] http://web-docs.gsi.de/~ikisel/reco/HERA-B/cats_vds.pdf
[2] http://web-docs.gsi.de/~ikisel/Kisel_Habil_thesis.pdf
[3] Statistical methods in experimental physics, Frederick James, p. 14



a) Neighbors finder. b) Evolution step of the Cellular Automaton.

Figure 1: The two basic steps of the CA seed finder. In the first step (left panel) track seeds are formed from neighboring hits. The starting point is random inside the TPC volume (i.e. not necessarily its outer part). Also the finder is directionally blind, i.e. there is no bias towards the center of the TPC. In the second step (right panel) segments compete where the longest tracks win.

* Good-RC track: has number of reconstructed hits ≥ 15
Tracks are classified as following:
- Matched track: 1 RC track corresponds to only 1 MC track,
- Clone track: 2 or more RC tracks correspond to 1 MC track,
- Lost track: no RC track corresponds to the MC track,
- Ghost track: a RC track does not correspond to any MC track.

The track reconstruction efficiency is the sum of Matched and Clone tracks (1– Lost).

2 StiCA Performance in p-p 500 GeV collisions for different luminosities

We present first the results for p–p 500 GeV collisions for both Data and Simulations. Two Data samples were used: one from Run-9 and one from Run-13. The difference between the two is that Run-13 had a factor of 8–10 higher luminosity than Run-9. Run-9 had peak luminosities up to 750 kHz while Run-13 luminosity peaked at about 6 MHz.

Figure 2 shows the scanning efficiency for Global tracks. Shown are Sti (black squares) and StiCA (black circles) efficiency as a function of p_T (upper row) and azimuthal angle ϕ (lower row). An average net gain of about 6-7% with StiCA is shown. Also some structure

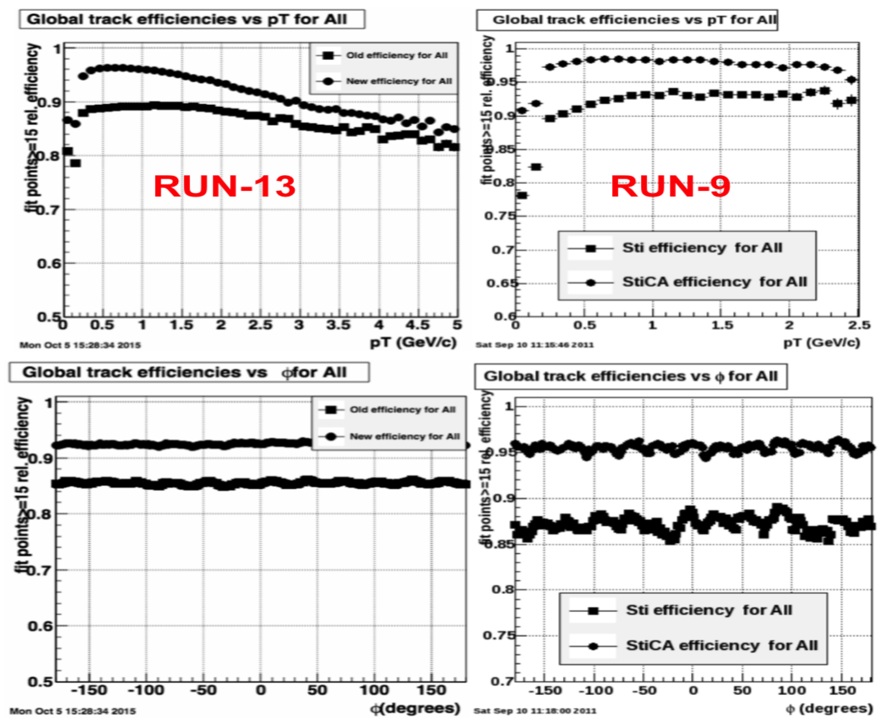


Figure 2: [Data] Global track scanning efficiency in p–p 500 GeV collisions for high (Run-13) and low (Run-9) luminosity.

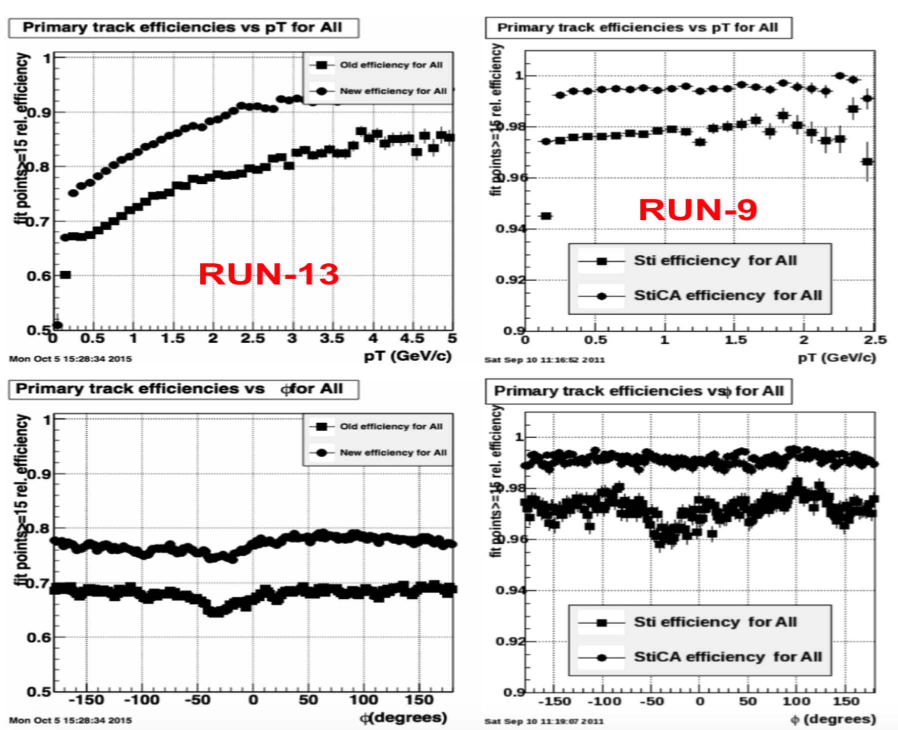


Figure 3: [Data] Primary track scanning efficiency in p–p 500 GeV collisions for high (Run-13) and low (Run-9) luminosity.

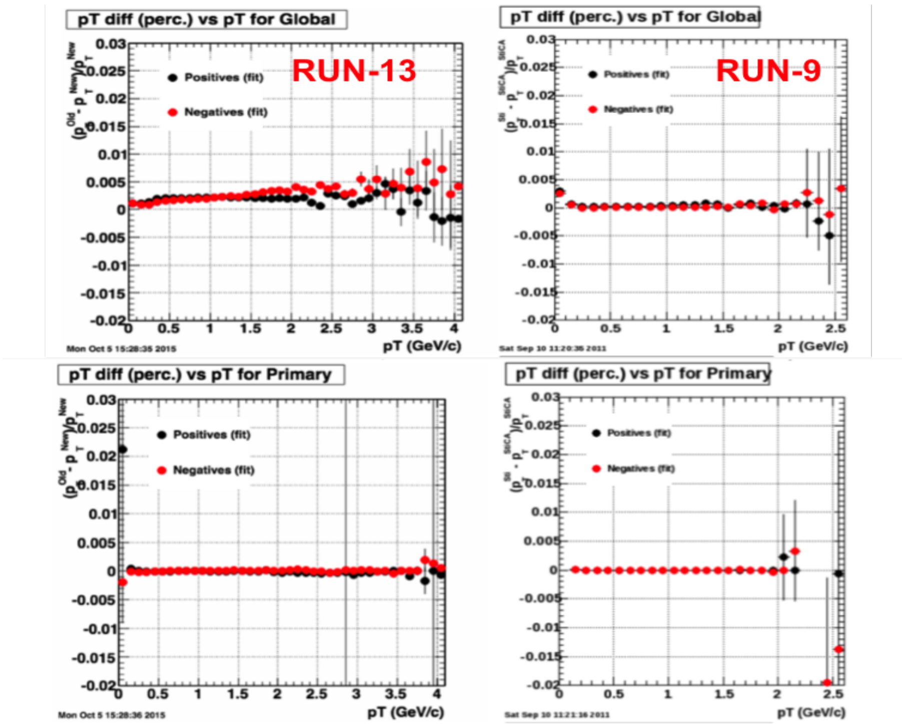


Figure 4: [Data] Track-by-track difference in reconstructed p_T shown as percentage. Global tracks in upper row and Primary tracks in lower row.

in ϕ in the Sti case (TPC sector boundaries) is less with StiCA.

Figure 3 shows the scanning efficiency for Primary tracks. Shown are Sti (black squares) and StiCA (black circles) efficiency as a function of p_T (upper row) and azimuthal angle ϕ (lower row). An average net gain of about 6-7% with StiCA is shown. Also some structure in ϕ in the Sti case (TPC sector boundaries) is less with StiCA. There is a striking difference between the p_T shape of efficiencies between Global and Primary tracks for Run-13 with the primary track efficiency dropping rapidly at low p_T. Apparently the high-luminosity environment of Run-13 (high pile-up) makes the task of track/event-vertex association more difficult.

Figure 4 shows the track-by-track difference in reconstructed p_T in Sti and StiCA. The difference is shown as percentage of reconstructed value. Global tracks (upper row) show a general agreement with a difference not exceeding half a percent for the bulk of the tracks. Primary tracks (lower row) show no difference for both luminosity samples. This is not a surprising result since both methods use the same Sti engine for track fitting.

Figure 5 summarizes MC studies of events with Run-13 luminosity conditions. It shows the percentage of Lost (not reconstructed but Good MC tracks) for primary tracks as a function of p_T for both positive (black) and negative (red) tracks. The vertical axis is mis-labelled as "efficiency" where it should say "in-efficiency". For the bulk of the tracks ($p_T > 0.2$ GeV/c) StiCA shows a difference of about 10-12%. Thus StiCA found (1-0.32)/(1-

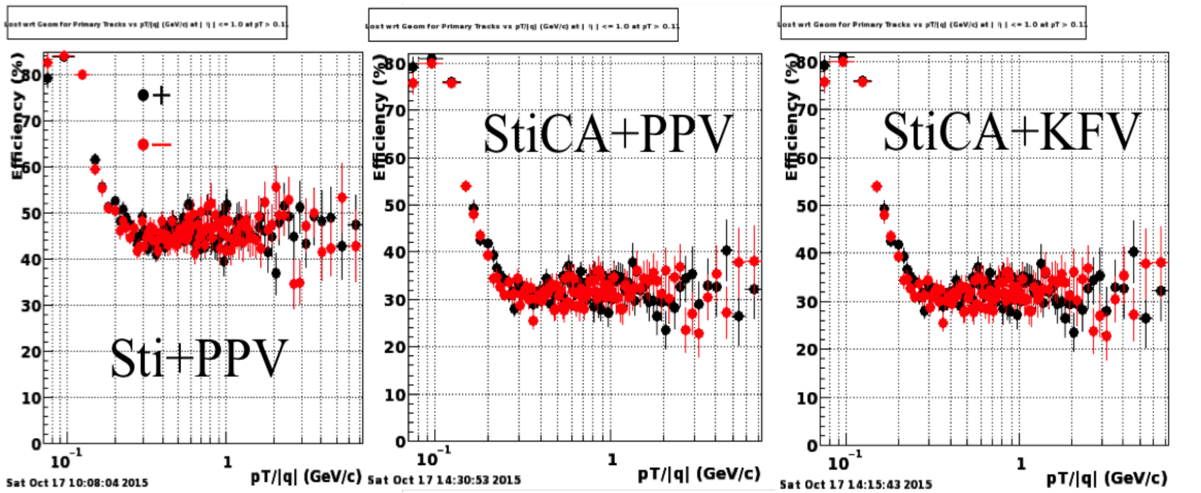


Figure 5: [Simulation] Summary plots showing the percentage of Lost primary tracks in simulated p–p 500 GeV events as a function of p_T. The luminosity (pile-up) conditions are similar to Run-13 ones (high luminosity).

0.45) = 1.24 or about 24% more tracks in the triggered vertex than standard Sti. This result seems to be independent of the event vertex finder/fitter package used as shown in the middle and right plots where two very different event vertex finders were used. We note here that the MC efficiency difference of about 10% is about the same as the scanning efficiency for the same luminosity sample (10%) but there is a difference in the absolute magnitudes of efficiency; in Figure 3 the absolute efficiency for Sti/StiCA at 1 GeV/c p_T is 73/83% whereas in Figure 5 the same numbers (1-lost) are 55/65%. This confirms that scanning efficiency tends to overestimate absolute efficiencies but it is an excellent estimator for efficiency differences.

More details can be found here[4,5].

3 StiCA Performance in Au+Au 200 GeV collisions

In this section we compare the tracking efficiencies of Sti/StiCA in a heavy ion environment: Au+Au 200 GeV collisions. Both Data and Simulations were used to that end. The Data sample is from Run-14, day-89 (high) and day-94 (medium) luminosity. Details about the data sample and the obtained results can be found here[6].

Figure 6 shows the scanning efficiency for Run-14 Au+Au 200 GeV data as a function of p_T (first row) and azimuthal angle ϕ (middle row). The bottom row shows track-by-track p_T difference as a fraction of the original p_T (percentage). No significant difference is seen as expected since both methods use the same Sti track fitting engine. The difference between

[4] https://drupal.star.bnl.gov/STAR/event/2015/12/10/tracking-focus-group-bnl-meeting/stica
[5] http://www.usatlas.bnl.gov/~fisyak/star/MuMc/2013/
[6] http://www.usatlas.bnl.gov/~fisyak/star/TbyT/2014_P15ic_StiCA/

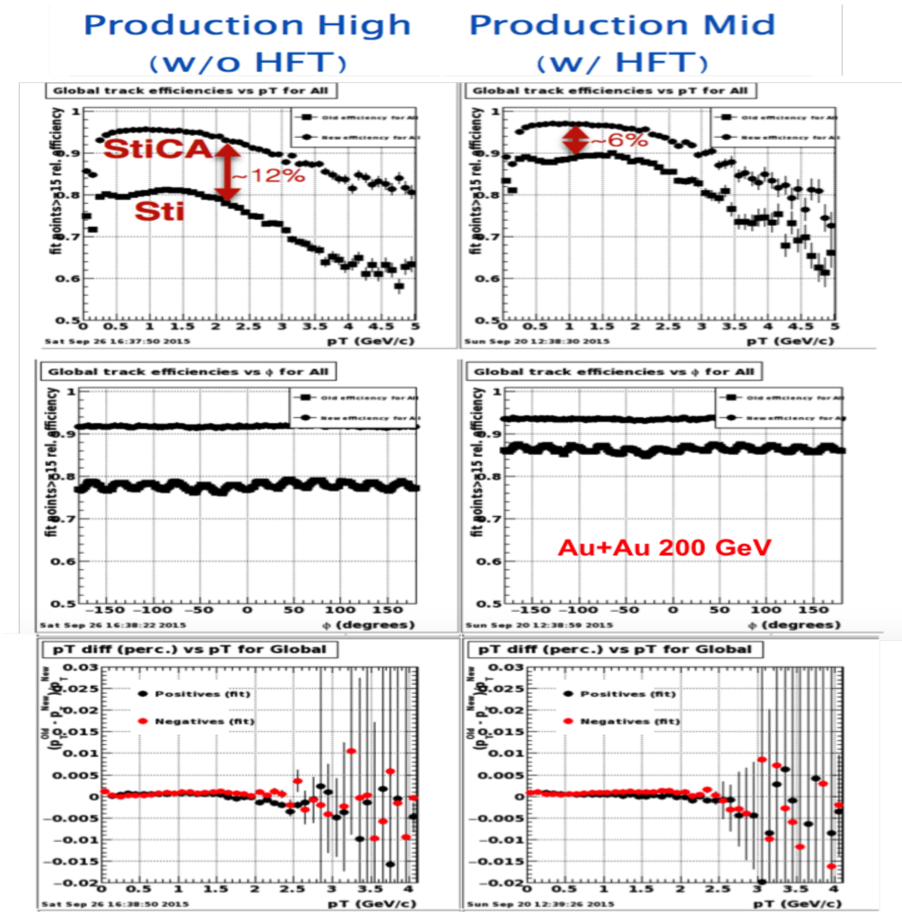


Figure 6: [Data] Global track scanning efficiency in Run-14 Au+Au 200 GeV collisions for two luminosities and with or without the HFT included in tracking.

the left/right column besides luminosity is the inclusion of the HFT vertex detector hits in tracking (right column) or not (left column). The StiCA/Sti comparison is done exclusively within the TPC therefore the inclusion or not of the HFT hits in tracking should not affect it. In general the same behavior that was observed in p–p collisions is seen here too. An average net gain of about 6-12% with StiCA is found. Also the structure in ϕ in the Sti (TPC sector boundaries) is absent in the case of StiCA. Note that the StiCA gain increases with the beam luminosity.

Similar results are seen in Figure 7 that shows the same distributions as Figure 6 but for Primary tracks. There are only minor differences in the shape details of the p_T dependence. Also the azimuthal dependence of the efficiency shows a more fluctuating structure than for global tracks.

We will now discuss the MC simulation results for Au+Au 200 GeV. Simulation was done using Hijing (trigger vertex restricted by $|Z| < 3\,\text{cm}$) with 75 kHz pileup of minimum biased events which is comparable to the High luminosity Data sample above. The HFT was not included in tracking. Details about the simulation and the results can also be found here[7]. Overall no significant differences were observed in the reconstructed track quality between the two methods.

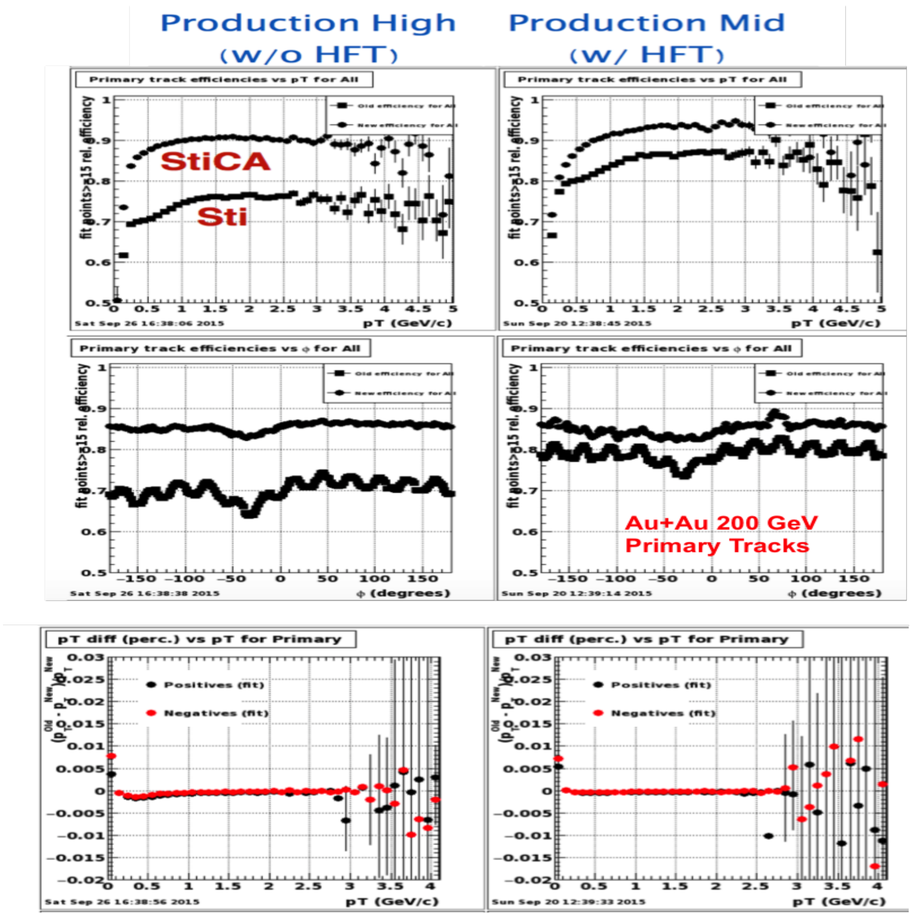


Figure 7: [Data] Primary track scanning efficiency in Run-14 Au+Au 200 GeV collisions for two luminosities and with or without the HFT included in tracking.

Figure 8 is a summary plot showing the percentage of Lost (not reconstructed but Good MC tracks) primary tracks as a function of p_T for both positive (black) and negative (red) tracks. The vertical axis is mis-labelled as "efficiency" where it should say "in-efficiency". For the bulk of the tracks ($p_T > 0.2$ GeV/c) StiCA shows a difference of about 10%. Thus StiCA found (1-0.25)/(1-0.35) = 1.15 or about 15% more tracks in the triggered vertex than standard Sti. This result seems to be independent of the event vertex finder/fitter package used as shown in the middle and right plots where two very different event vertex finders were used. We should note here that the scanning efficiency difference in Data (12%) is comparable with the absolute MC-based efficiency of 10%, as in p–p. In terms of absolute efficiency we see that the scanning efficiency from Figure 7 at 1 GeV/c for Sti/StiCA is

[7] http://www.usatlas.bnl.gov/~fisyak/star/MuMc/2014/

75/90% whereas the absolute efficiency in Figure 8 (1-lost) is 65/75% respectively. We see again that the scanning efficiency tends to overestimate absolute efficiencies but it is an excellent estimator for efficiency differences.

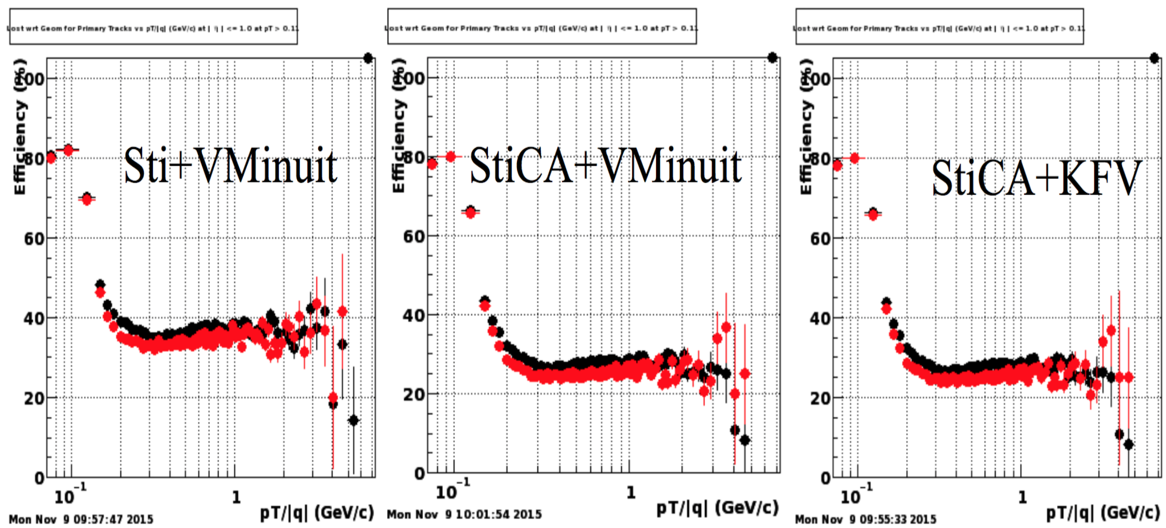


Figure 8: [Simulation] Summary plots showing the percentage of Primary Lost tracks in simulated Au+Au 200 GeV events as a function of p_T. The luminosity (pile-up) conditions are similar to high luminosity data sample without the HFT in reconstruction.

As a partial summary we observe that StiCA outperforms Sti in all scenarios (p–p or Au+Au) and estimators (Data or Simulations) in terms of reconstruction efficiency by a significant margin.

4 StiCA Timing Performance

We now move to the very important topic of reconstruction time since any possible big difference between the two methods will greatly influence deployment decisions in a given CPU-resource environment.

The left column in Figure 9 shows the CPU time needed for each method to reconstruct a full event as a function of the number of TPC hits (event size or event centrality) for Au+Au 200 GeV data. The upper panel shows the scatter plot and lower panel the averages for both Sti (black) and StiCA (red). It shows that StiCA needs a bit more time to reconstruct the same event than Sti needs but in order to quantify the difference we need to normalize to the total number of reconstructed tracks per event. In the previous sections we have shown that StiCA finds more tracks per event therefore it is reasonable to need more time to reconstruct them. The per-track CPU time needed by each method is shown is the right column of Figure 9. The upper panel shows the CPU time per track and the lower panel shows the ratio of StiCA/Sti. We see that on average StiCA needs about 10% less CPU time to reconstruct a track compared to Sti. This is a very important result showing that StiCA is not only more efficient in track reconstruction but also more efficient in CPU resources. More details about the timing studies can be found here[8].

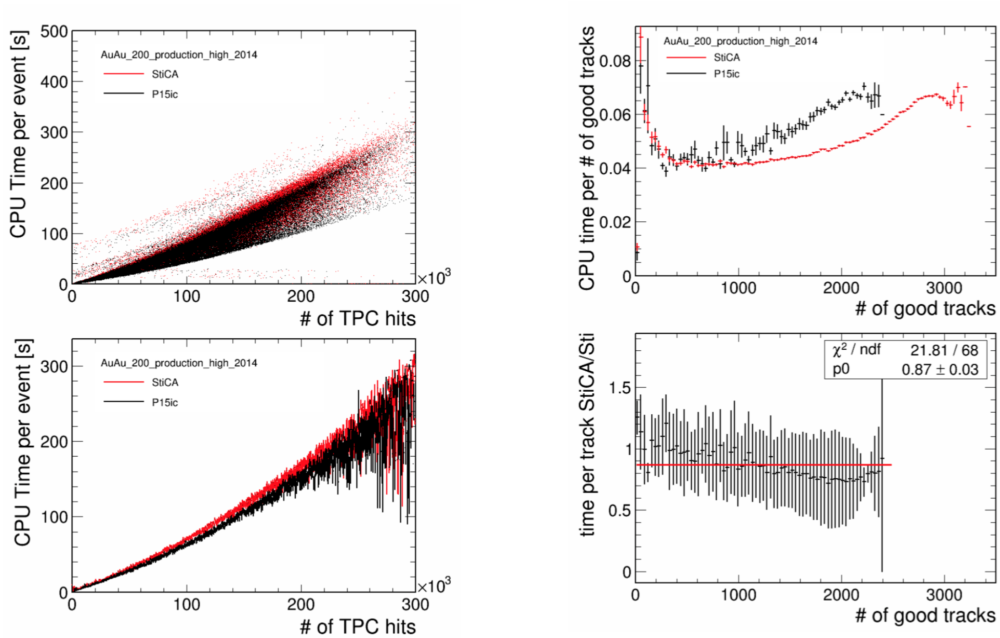


Figure 9: Actual CPU time per event (left column) and per reconstructed track (right column) as a function of event size for Sti (black) and StiCA (red).

5 StiCA Physics Performance

We used two sensitive physics probes to test the performance of StiCA relative to Sti. We chose the D^0 charm meson and Run-14 data sample with HFT in tracking plus the W particle in the Run-13 p–p data sample. To make the comparison reliable and valid the specific runs analyzed were identical for both methods. Also in both cases the analysis was done by independent experts using identical offline optimizations cuts and code. Below we present a summary of their findings.

5.1 D^0 reconstruction

The result on D^0 reconstruction is summarized in Figure 10 that shows the invariant mass distribution in a Run-14 Au+Au 200 GeV sample of 25 million events. The left plot is for Sti and is the result of the official production. The right plot is the StiCA result. The HFT hits

[8]https://drupal.star.bnl.gov/STAR/blog/kehw/sti-and-stica-performance-comparison

were included in both cases and their inclusion, or not, on a track was exclusively handled by Sti since StiCA was only applied to TPC hits in this analysis. We stress here the fact that identical cuts and analysis was followed in both cases.

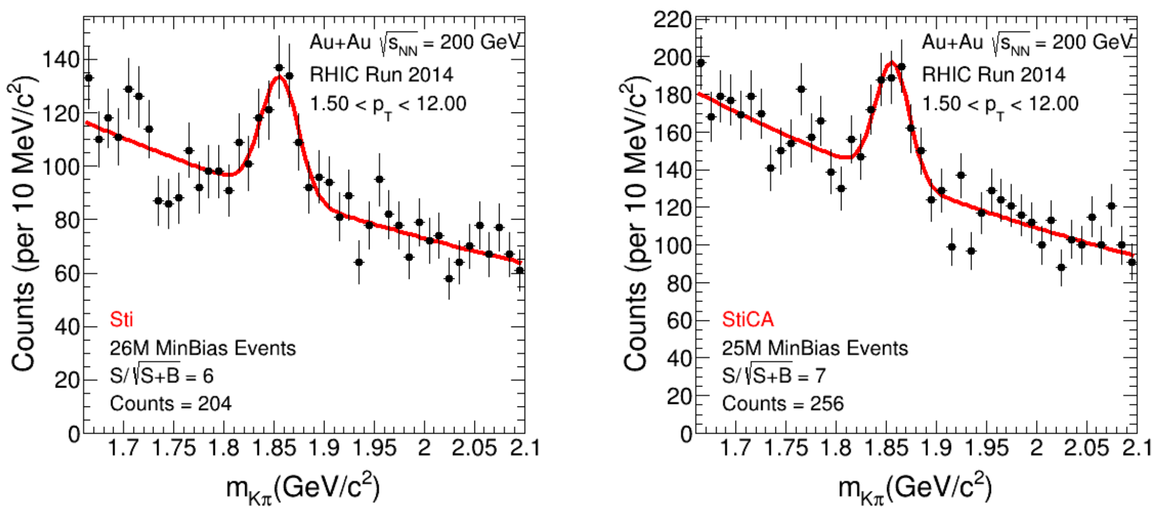


Figure 10: [Data] Reconstructed D^0 invariant mass distribution in Run-14 Au+Au 200 GeV collisions for Sti (left) and StiCA (right)

We make several observations. The first is that the integrated D^0 counts under the peak is about 25% more in the case of StiCA. At the same time we also observe that the number of combinatorial background under the D^0 mass peak increased from 100 (Sti) to about 140 (StiCA). Obviously more reconstructed tracks per event (StiCA) will lead to more combinatorial background but one has to watch this and perform a detailed quantitative study and analysis of the causes. In cases like this the final arbiter is the signal significance (Significance= $S/\sqrt{S+B}$). The result shows a significance of 6 for Sti and 7 for StiCA which is an improvement of about 15% in the case of StiCA over Sti. Larger samples and detailed optimization will be able to further quantify the differences between the two methods but this initial study shows results that are in agreement with our efficiency studies.

5.2 W reconstruction

Several tests were performed using the Run-13 p–p W-stream data where the official production result (Sti) is compared to StiCA. There were two productions with StiCA: one done by Y. Fisyak's codes setup and one done in an officially setup "evaluation" area where the production was administered by S&C group after codes were checked for show stoppers. There was also a production using the Sti part in the "evaluation" area to perform an apples-to-apples comparison between to two packages.

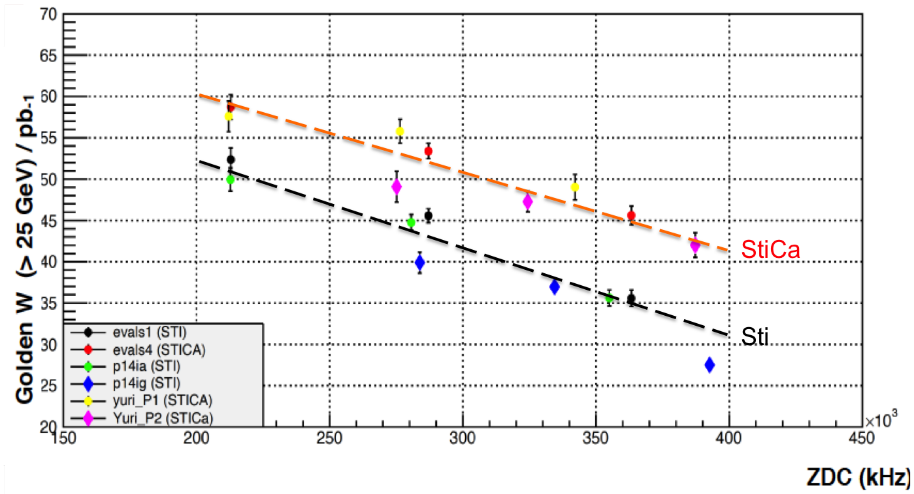


Figure 11: [Data] Reconstructed number of ”Gloden W” particles as a function of ZDC rate (luminosity). The black and orange dashed lines represent fits to the Sti and StiCA numbers respectively.

The results are summarized in Figure 11 that shows the reconstructed number of the so-called ”Golden W” as a function of the luminosity (ZDC rate). The Sti/StiCA each has three sets of points, one from each analysis. All are clustered, and fitted, along the two lines (also shown in the figure). We observe that StiCA gives a gain of about 20% at low luminosities to more than 30% at higher ones.

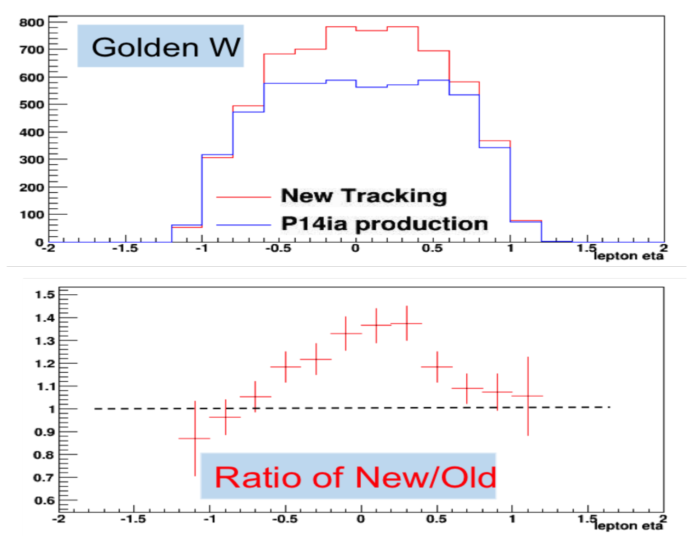


Figure 12: [Data] The pseudorapidity dependence of the reconstructed Ws (upper panel) and the gain ratio (lower panel).

Figure 12 shows the pseudorapidity dependence of the reconstructed Ws (upper panel) for both Sti (blue) and StiCA (red). Clearly the gain is significant around midrapidity. This can be seen in the lower panel of the same figure where we show the ratio of the two efficiencies. Values close to 40% are reached around midrapidity.

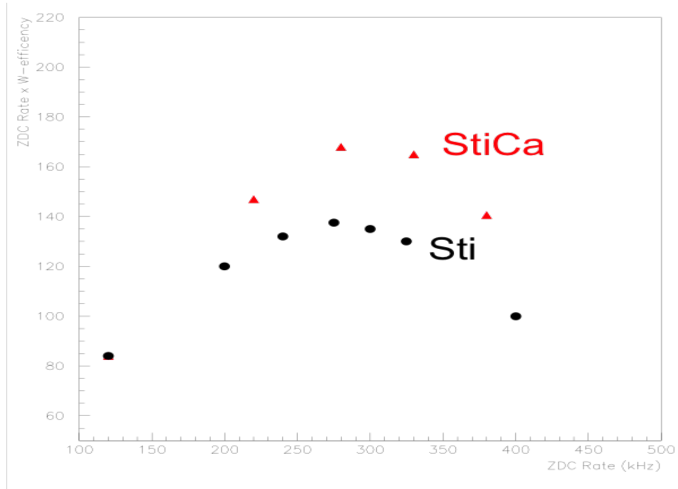


Figure 13: [Data] The ZDC Rate*W-efficiency as a function of the ZDC Rate for both Sti and StiCA.

Another way to look at Figure 11 data is to multiply the event rate by the W-efficiency which is proportional to the total number of reconstructed Ws in a given number of events. This is shown in Figure 13 for both StiCA (red) and Sti (black). For Sti we observe that at a ZDC rate $>$ 300 kHz (or 1.285x $10^{32}\,cm^{-2}s^{-1}$ luminosity) we start loosing Ws rapidly despite the increased luminosity. But for StiCA we only start loosing at a ZDC rate $>$ 350 kHz. This suggests to use this number for Run-17 which is a luminosity of 1.57 x $10^{32}\,cm^{-2}s^{-1}$.

6 Summary

We presented a summary of performance evaluations of a CA-based track–seed finder in STAR TPC tracking. The seed finder feeds the standard STAR TPC tracking software (Sti) for track fitting and extrapolation to inner detectors. The resulting hybrid code, StiCA, was then compared to standard Sti, which uses its own seed finder. We used Data and Simulations to evaluate and compare performance for both Au+Au 200 GeV and p-p 500 GeV collisions at different luminosities. We also used targeted analysis of (relatively) small data samples for D^0 (Au+Au 200 GeV) and W (p–p 500 GeV) reconstruction performance. In all cases StiCA consistently outperforms Sti in a significant and luminosity dependent way without any significant drawbacks. Our conclusion and recommendation to STAR management would be to deploy StiCA in all future productions in STAR after finishing the currently underway code compliance review and cleanup.