Overview of the Inner Silicon detector alignment procedure and techniques in the RHIC/STAR experiment

Yuri Fisyak, Jerome Lauret, Gene Van Buren, Victor Perevoztchikov (Brookhaven National Laboratory, USA),

Spyridon Margetis (Kent State University, USA),

Jonathan Bouchet(Subatech, France),

Ivan Kotov (Ohio State University, USA),

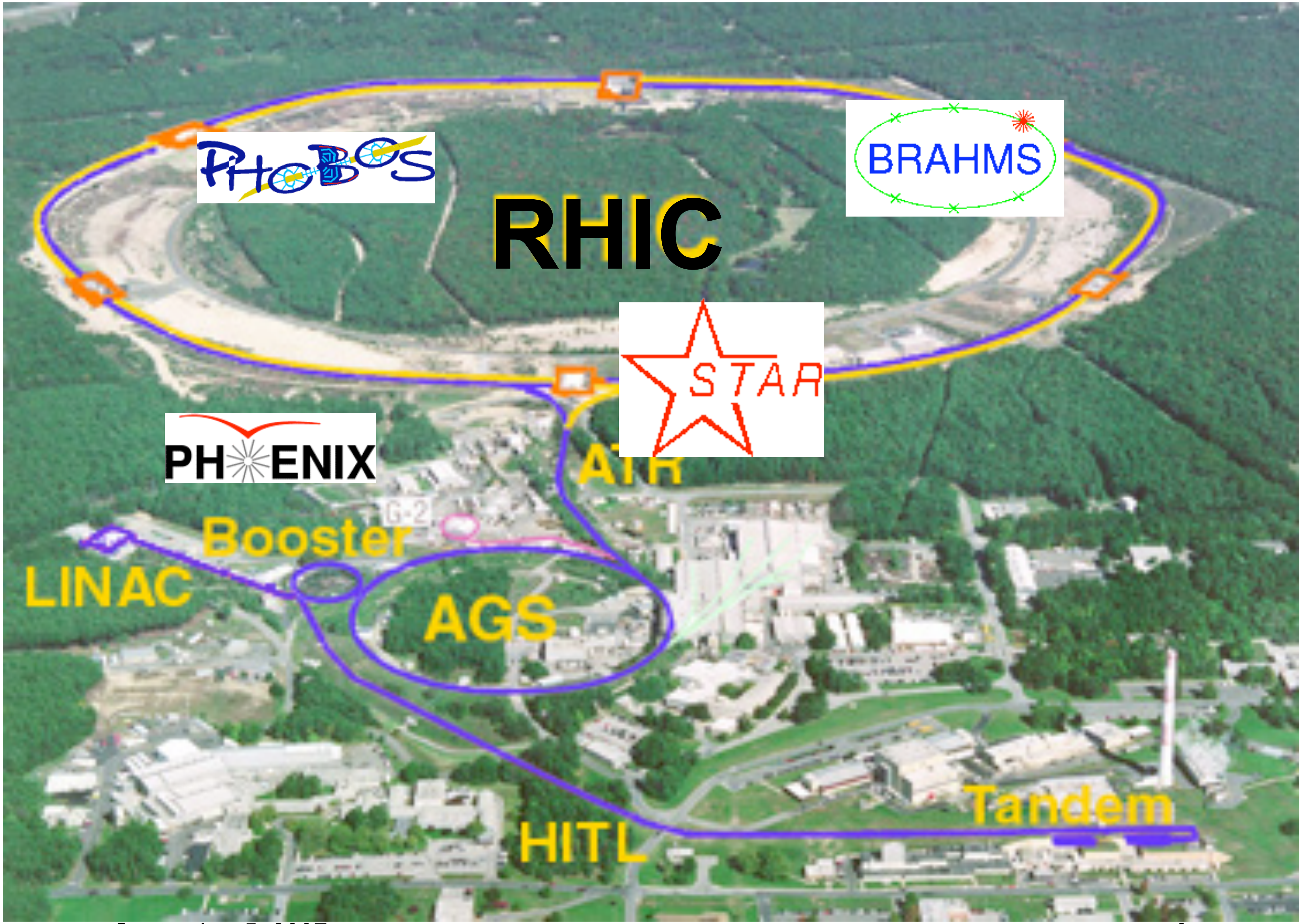
Rafael Derradi de Souza (Universidade Estadual de Campinas)

September 5, 2007

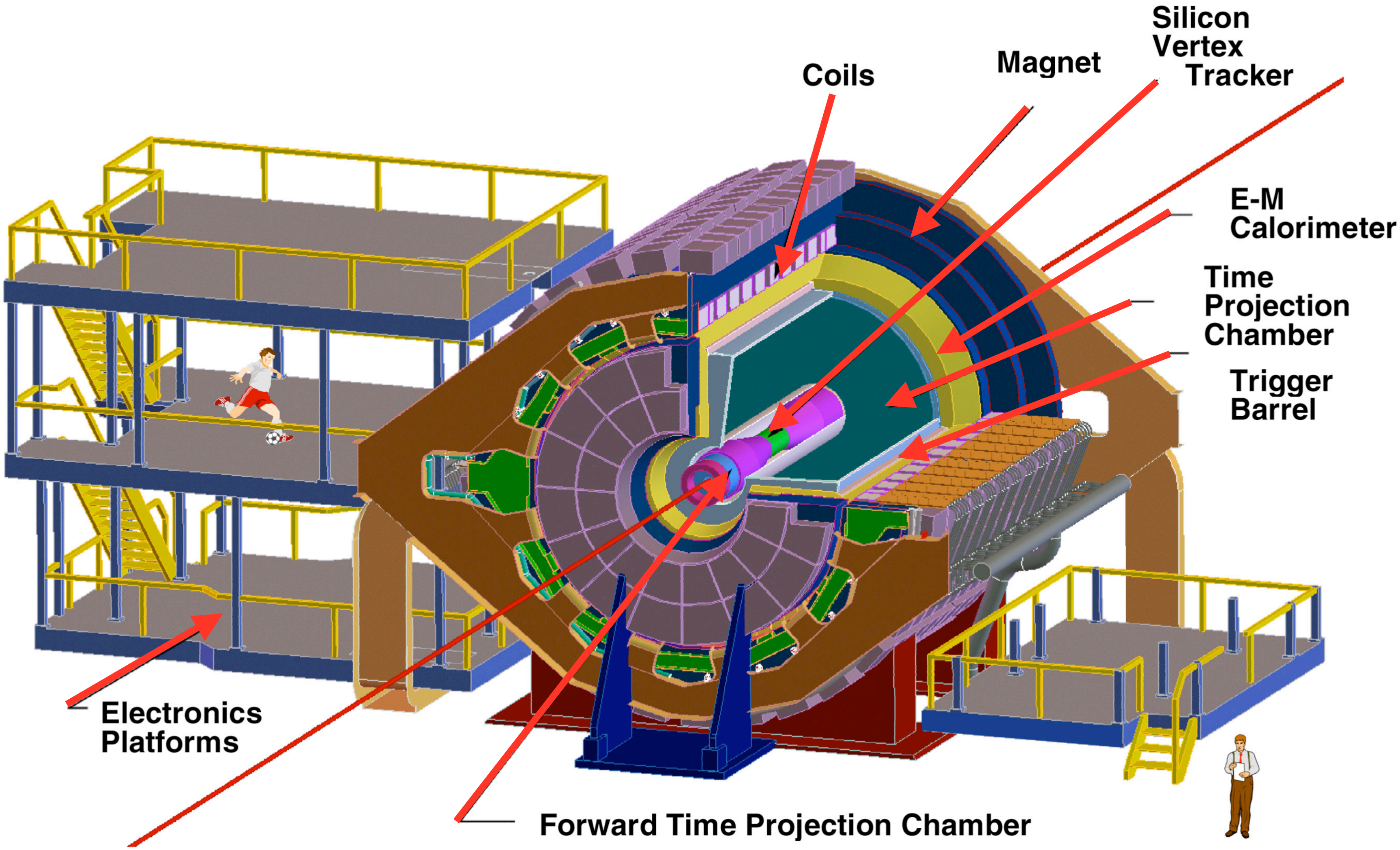
fisyak@bnl.gov

Outline

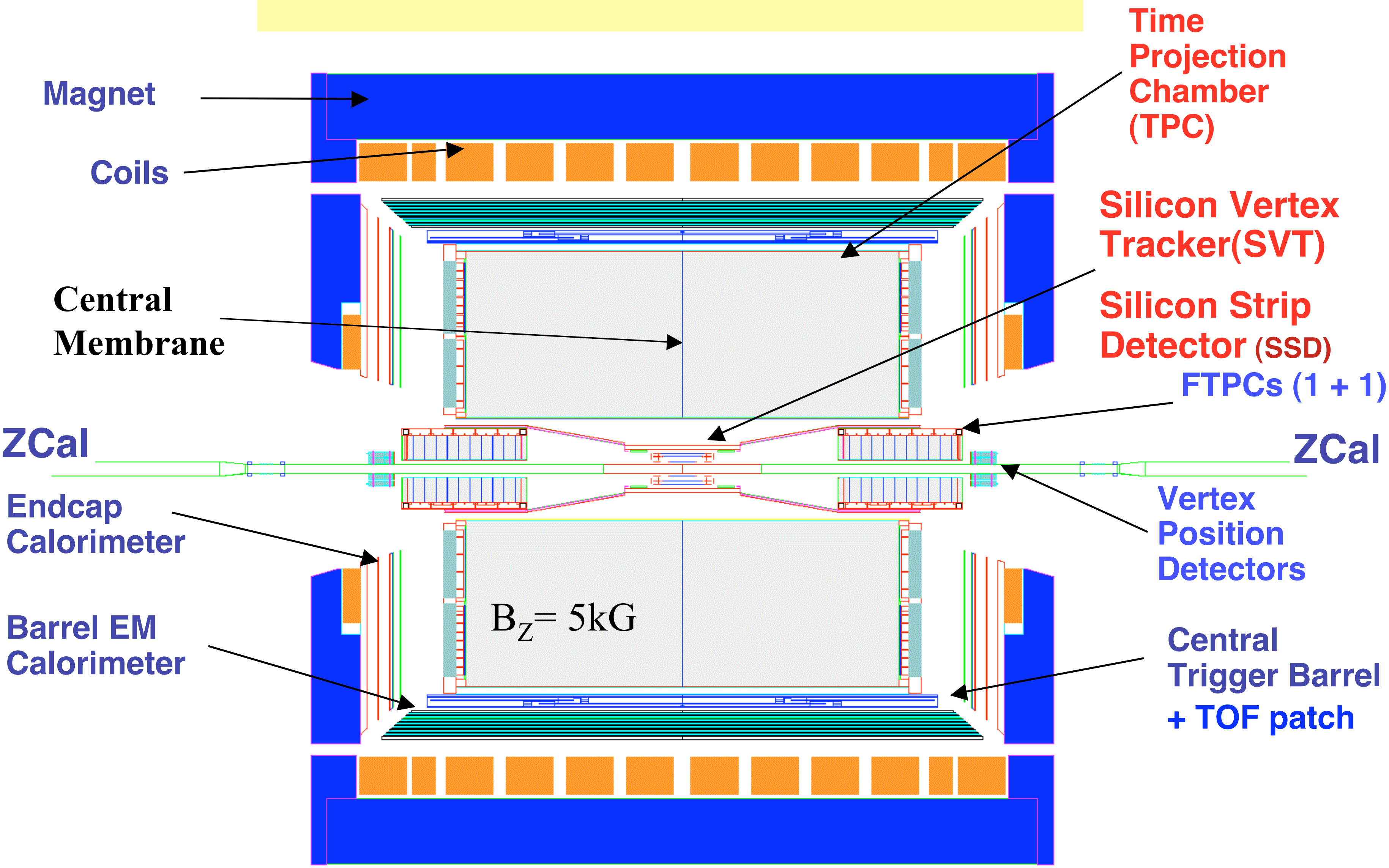
- STAR detector.
- STAR **tracking in barrel** region : TPC + SVT + SSD.
- Results of **two drift detectors** SVT and TPC **alignment** with respect **to each other** for run III and IV data.
- **Reiteration** with alignment procedure for run V (Cu+Cu 200 GeV) data and our plans for run VII (Au+Au 200 GeV):
  - Impact of SSD on alignment,
  - Interest in charm,
  - Limitations from Detector setup due to Multiple Coulomb Scattering,
  - Requirements on Silicon detectors alignment precision.
- Methods, Calibration and Alignment procedure.
- Results.
- Conclusion.


PHOBOS
BRAHMS
RHIC
STAR
PHENIX
ATR
G-2
Booster
LINAC
AGS
Tandem
HITL

STAR - **S**olenoidal **T**racker **A**t **R**HIC -
A multi-purpose detector for Heavy Ions Physics



The STAR Detector



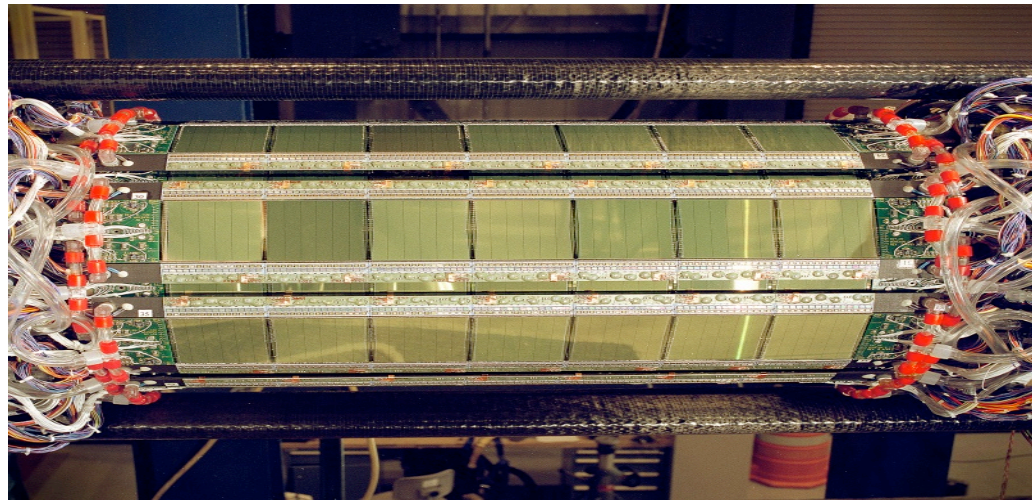
Time Projection Chamber

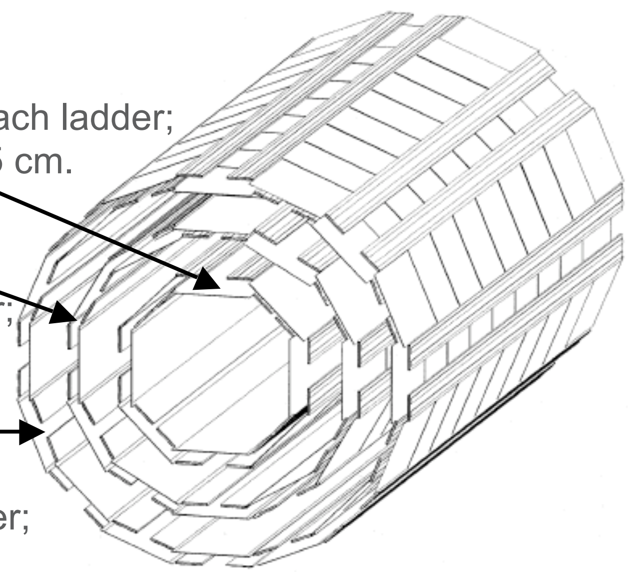
- **TPC is the main STAR tracking detector** [1] and working in STAR from day one (Run I, FY 2000).
- TPC is divided into halves by Central Membrane and contains 12 sectors in each half and each sector contains Inner (13 pad rows) and Outer (32 pad rows) sub sectors.
- Electrons produced by charge particles drift (in Z direction) from Central Membrane to end caps in almost parallel electric and magnetic fields where they are detected with 45 pad rows placed at radii in range [60,190] cm.
- **Drift velocity is monitored** by laser system[2] with **precision ~2 $\times 10^{-4}$** providing **systematic error in Z direction ~40 μm** at the maximum drift length (~ 2m).
- **Spatial resolutions:**
  - $\sigma_{\rho\phi} \approx$ **600 μm** and $\sigma_z \approx$ **1200μm** for Inner Sectors and
  - $\sigma_{\rho\phi} \approx$**1200 μm** and $\sigma_z \approx$ **1600μm** for Outer Sectors.
- **Distortions** due to non-perfect electric field and space charge collected in TPC are monitored by DCA (distance of closest approach) of the track at the primary vertex and kept on the level **better than ~100μm**[3].

SVT- A 3 Layer Silicon Drift Detector[4].

SVT is the inner tracking-detector in STAR and it is located near the interaction point. Two hybrids form a wafer, and wafers form a ladder, ladders are arranged in 3 barrels on two rigid Clam-Shells. The detector consists of 216 wafers in total.

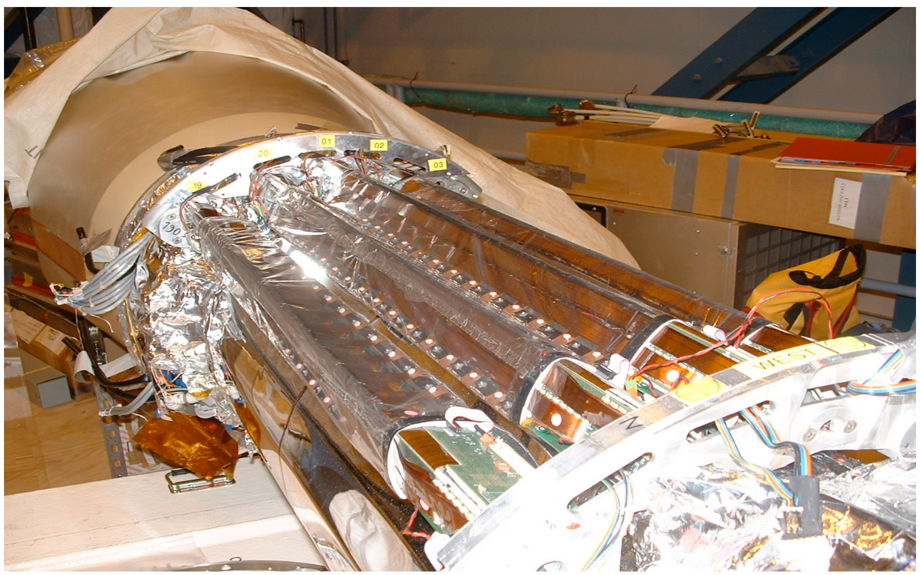
- A new technology at the time.
- **Primarily designed to do multi-strange particle physics.**
- Electrons drift in $\rho\phi$ direction (perpendicular to TPC drift direction).
- Strips (=anodes) are placed along Z (beam axis).
- Size of pixel $\rho\phi \times Z$ = 250 μm (time bin) $\times$ 250 μm (strip pitch).
- The intrinsic spatial resolution (accounting for charge sharing):
  - **$\sigma_{\rho\phi}$ < 80μm** and
  - **σ_z < 80μm**.
- **Relatively thick** (~1.5% X_0 per layer).
- Relatively far from beam.
- Installed in STAR since Run II, and became **fully functional since Run III**.

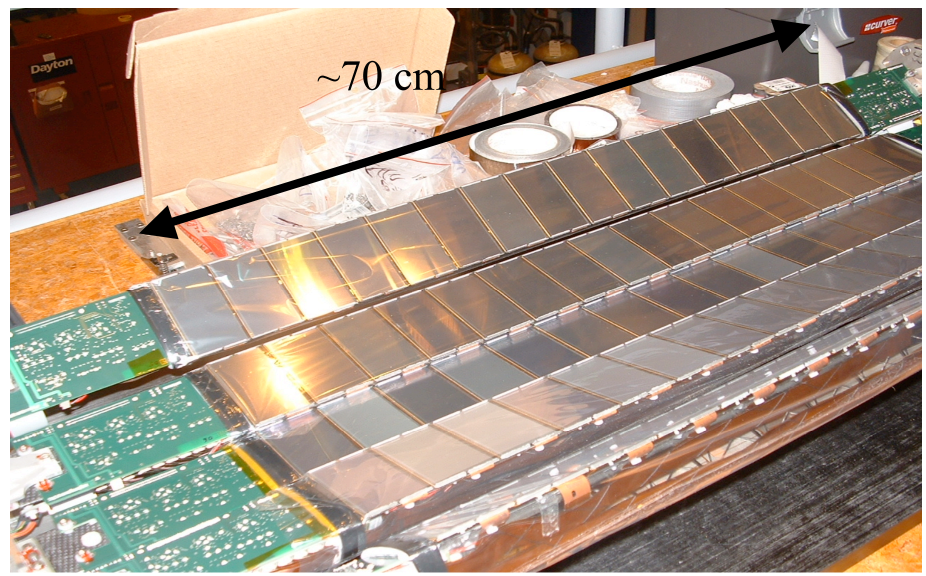




SSD - A single layer of 2-side Silicon Strip Detector[5]

- It wraps around the SVT as a fourth layer.
- Its primary **purpose** is to provide an **intermediate (non-drifting) point** for track matching **between TPC and SVT**.
- 20 ladders with 16 wafers each mounted on 4 rigid Sectors at ~23 cm from the beam.
- Installed in STAR for Run IV, became **fully functional in Run V**.
- Strip pitch: 95 μm. Strip length: 4 cm. Stereo angle between p- and n-strips is 35 mrad.
- Intrinsic **resolution** should be better than **~30 μm** ($\rho\phi$) × 860 μm (Z).
- **Big Advantage: Non-drifting** technology.
    - Of course there is a Lorentz shift of holes and electrons in $\rho\phi$ direction due to our 5 kG magnetic field (with Lorentz θ_{holes} = 4.4° → 4.4μm and $\theta_{electrons}$ = 1.6 ° → 1.6 μm) which produces a sizable effect in Z direction (~ 200μm) due to the stereo angle. But it is clear how to account for this effect.





Alignment and Calibration of SVT with TPC for Run III-IV data

- **Analysis** of the first SVT data with respect to TPC
  - has showed rather **weak correlation** between the data and SVT **calibration** and **alignment** done on **test bench** and
  - clearly **required recalibration** and **realignment in situ**.
- These recalibration and alignment efforts for these **two drifting detectors** gave rather **modest results**: spatial resolution (including alignment) $\sigma_{\rho\varphi} \approx \sigma_Z \approx 200\ \mu m$.
- However these **modest results could not be used** in heavy ion collision high track multiplicity environment due to a **high ghosting level**.
- We had to **revisit this problem** when the **SSD** came into the game.

New goals

- The **initial goal** for the SVT was to **measure Ξ, Ω particles**, but this task pretty much has been done with TPC only analysis.
- But there is much interest in **direct charm** measurements now.
  - In Cu+Cu 200 GeV interactions (Run V) we have already observed ~4 standard deviations of D^0 signal.
  - Thus it looks very attractive to set a worthy **task to reduce background** and **enhance significance** of the **charm** signal by a **factor of ~3-5** through use of the Silicon Vertex Detector.
- A renewed effort started with SSD coming online.
- Alignment and drift velocity calibrations were re-visited to see if we are able to do ‘some/any’ direct D-meson measurement and/or B-meson tagging.
- I have to stress:
  - **Heavy Ion collisions** are the **toughest environment** for this kind of work: about 2000 tracks in a single event !

Figures of merit for SVT/SSD precision.

- **Pointing accuracy**, aka **Impact parameter** resolution**:**
  - **DCA** resolution (in bending XY $\equiv \rho\phi$ plane: σ_{DCA}) and
  - Resolution in non-bending plane: σ_z,

is **figure of merit** for charm decay ($c\tau \sim 100 \mu m$) registration with a vertex detector:

- $\sigma^2_{DCA} = \sigma^2_{vertex} + \sigma^2_{track} + \sigma^2_{MCS}$ (the same for non-bending plane),
- **primary vertex resolution**: $\sigma_{vertex} \sim 600\ \mu m / \sqrt{N_{good\ tracks}}$, for central Au+Au collisions turns out to be **better than 20 μm** (for minimum biased events ~100 μm),
- **track pointing resolution**: $\sigma_{track} \sim 2\ \sigma_{XY}$ in our case, where σ_{XY} is intrinsic detector precision $\oplus$ alignment errors,
- **Multiple Coulomb Scattering** (MCS): $\sigma_{MCS} \sim 170 \mu m / p(GeV/c)$ (from simple analytic estimations)
- from **requirement** that the **track pointing resolution** should be **comparable with MCS @ 1 GeV/c** then **detector resolution** (including alignment) should be **σ_{XY} < 80 μm** and **σ_z < 80 μm** for both bending and non-bending planes.

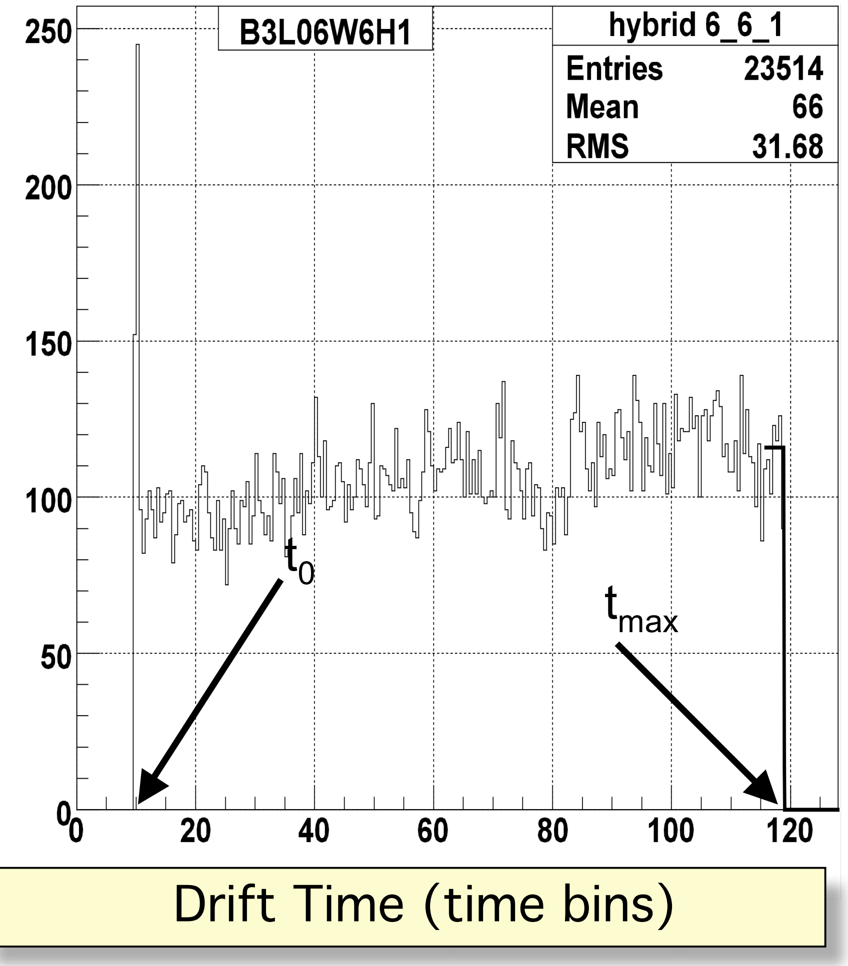
Methods

- Methods can naturally be split into two parts:
  - Calibration of SVT Drift velocities on hybrid level, and
  - Alignment of detectors:
    - **Assumed:**
      - Frozen **wafer position** on ladder from **survey data**, i.e. **ladder** is the **lowest level** degree of freedom.
      - **Rigid body** model: ignore possible twist effects, gravitational/stress sagging etc.

- The methods are **interconnected** and this supposes **iterative** procedure i.e.
  - using average drift velocities to do alignment and
  - after the alignment, check and correct drift velocities
  - …and iterate

Methods (average drift velocities)

- As the **first approximation** we are using **average** (constant) **drift velocity per hybrid** from **charge step** method:
  - clean up noisy strips,
  - from **drift time** distribution for each **hybrid** we have reasonably sharp cut offs at t_0 and t_{max},
  - from these numbers and the total drift length (L) we can estimate average drift velocity $v_D = L/(t_{max} - t_0)$.
  - These hybrids' v_D should be **correct in average per ladder**; this is the sample which we are using for alignment.



Methods (alignment) I

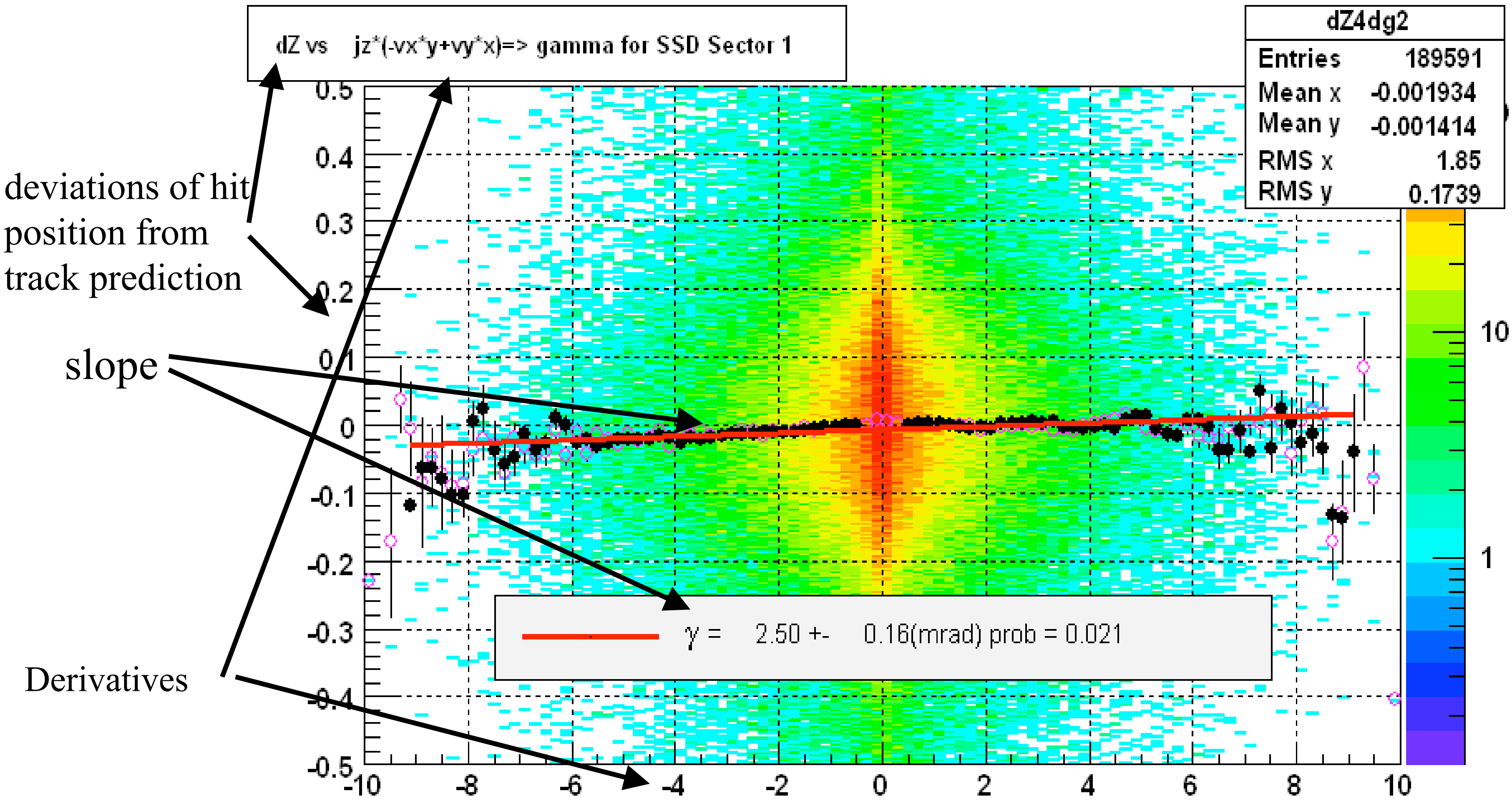
- For small misalignments, we can assume a model where the **hit position deviations** from tracks are **linearly proportional to the misalignments** through **derivatives** of track projections to measurement planes with respect to misalignment parameters (e.g. first order of a Taylor expansion)
  - The derivatives take as a condition that both a track prediction and a hit stay on a measurement plane after applying the correction (see Appendix for details)
  - Global alignment:
    - Vector of misalignment parameters: Δ (shift+rotation = 6 parameters)
    - Coordinates: **X** = (x,y,z)
    - $\mathbf{X}_{hit} - \mathbf{X} = \partial X / \partial \Delta \times \Delta \equiv \mathbf{G} \times \Delta$, where $\mathbf{X}_{hit}$ and **X** are hit position and track prediction on measurement plane, respectively
  - Local alignment:
    - Vector of misalignment parameters: δ
    - Coordinates: **u** = (u,v,w≡0)
    - $\mathbf{u}_{hit} - \mathbf{u} = \partial \mathbf{u} / \partial \delta \times \delta \equiv \mathbf{L} \times \delta$, where **u** is prediction of track on measurement plane [6].

Methods (alignment) II

- Misalignment parameters have been calculated as **slopes** of straight line fits to histograms of the most probable deviations (**X_{hit} - X** or **u_{hit} - u)** versus the corresponding derivative matrix (G_{ij} or L_{ij}) component [7]
  - See examples on following slides
- For alignment we use "good" (with well defined parameters) tracks fitted with the primary vertex.
  - Use of primary tracks significantly improves precision of track predictions in Silicon detectors and reduces influence of systematics.
- Precision of the method is checked with simulation
  - Accuracy ~10 μm in detector position and ~0.1 mrad in its rotation.
- There is a **problem** when we start **far from minimum** because there are significant **correlations** among alignment parameters.
- To solve this problem as a starting point we use **Least-Squares Fit** with above derivatives to get first approximation for the parameters.
  - The precision of this method is less than slopes method but it does provide a reasonable approximation to use slopes.

An example of Global alignment of the first SSD sector:

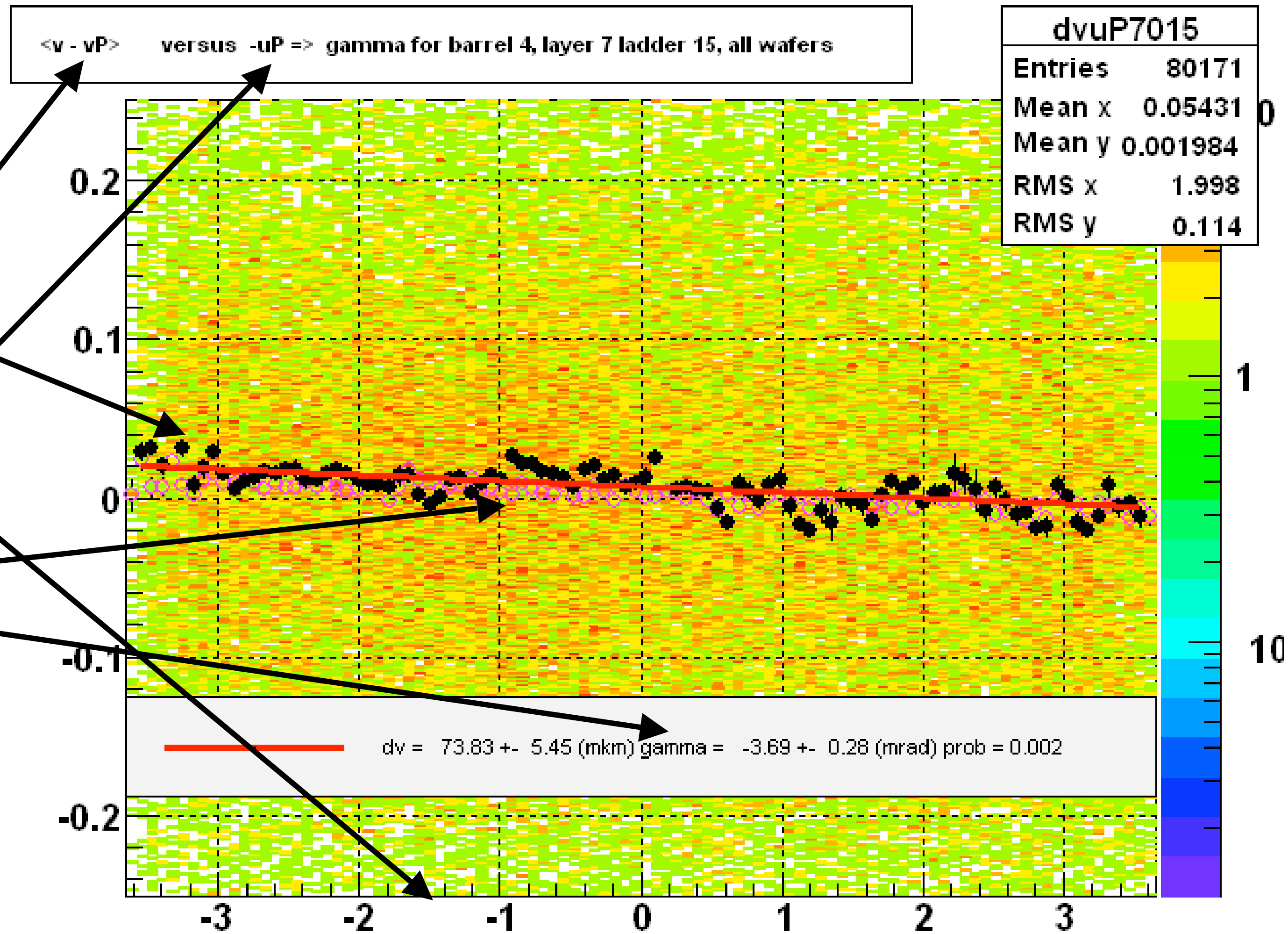
γ is rotation around Z axis



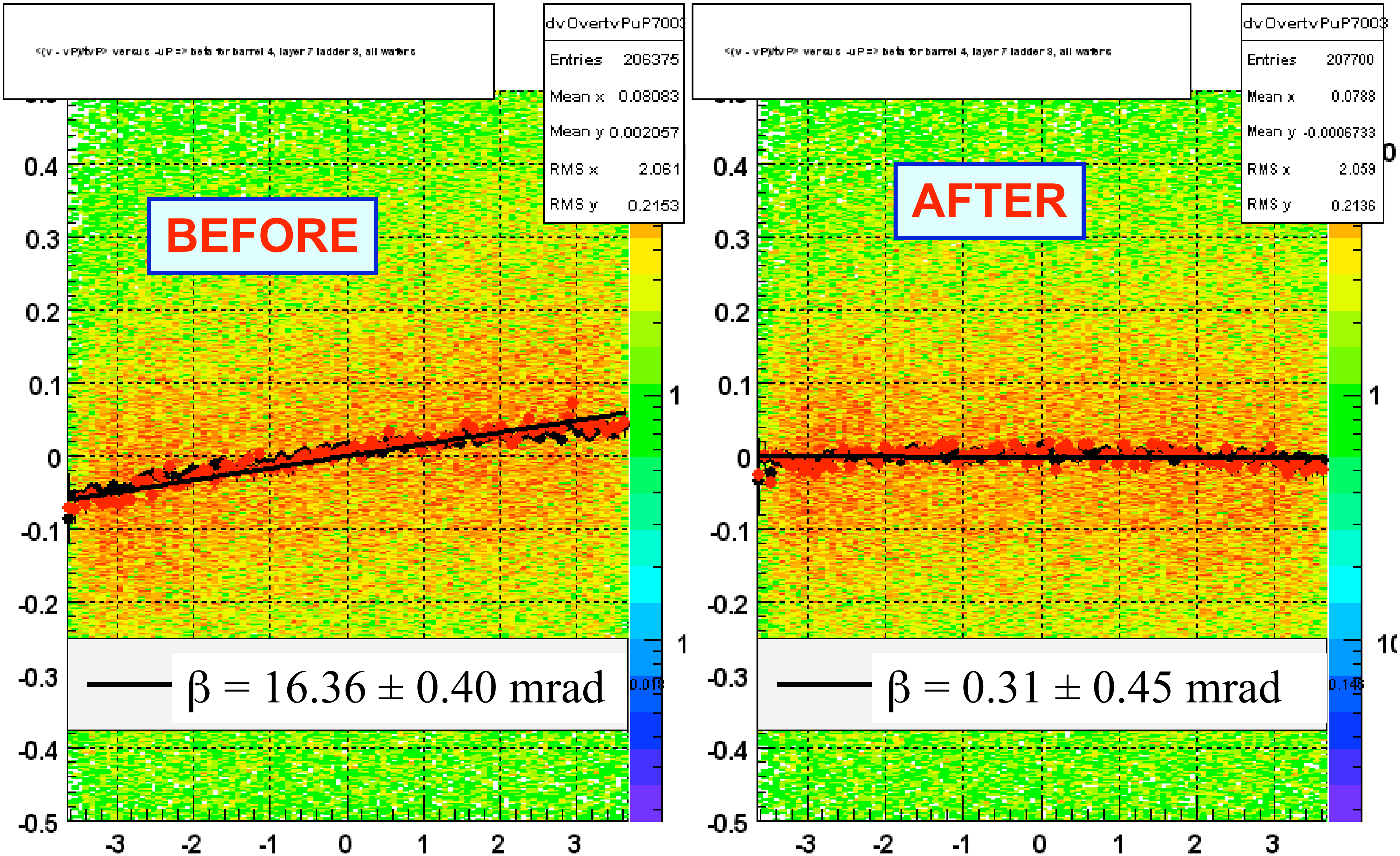
An other example of local alignment:

γ is rotation around w ($\equiv$local Z) axis

- hit position deviations
- Derivative
- slope



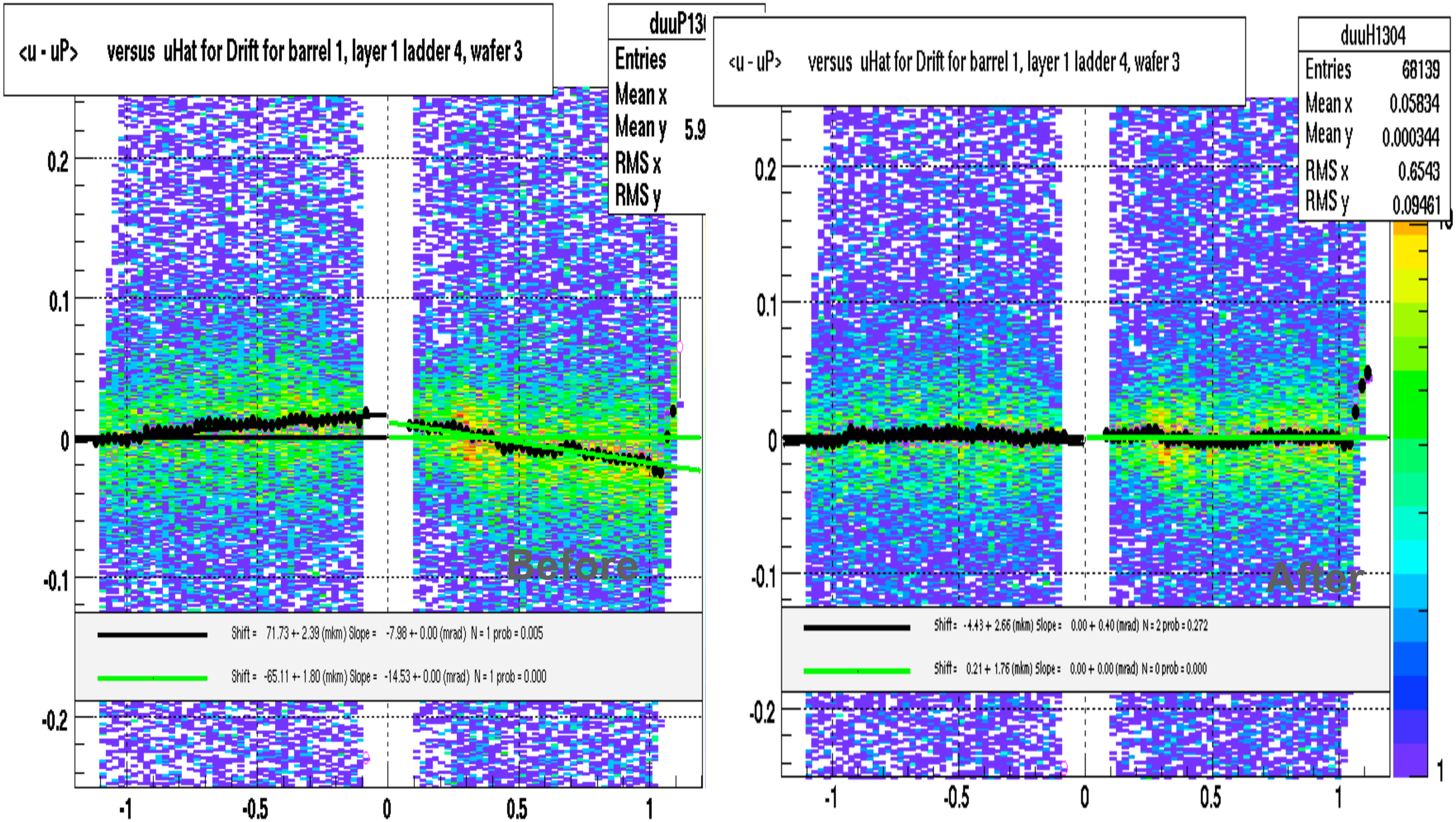
Example of correcting a SSD individual ladder rotation around the v-axis (local Y) (β).



Procedure includes 4 steps:

1. **Average SVT drift velocity:** as the first approximation, average drift velocity for SVT is obtained from charge step method for each hybrid.
2. **TPC only tracks**
   - Global alignment of SSD with respect to TPC as whole
   - Global alignment of SSD sectors
   - Local Alignment of SSD ladders:
     - Individual Ladders showed translations up to ~200 μm and rotations (especially around y-axis) of up to ~20mrad.
     - After the SSD Ladder fine tuning, the majority of ladders had translational alignments calibrated to under 20 μm, and rotational alignment calibrated to within 0.5 mrad, both of which were within errors of the calibration method.
3. **TPC + SSD tracks**
   - Global Alignment of SVT as whole
   - Global Alignment of SVT Clam Shells
   - Local Alignment of SVT ladders
   - Correction to SVT drift velocities.
     - SVT drift velocities have been refitted including extra dependence on drift distance and anode (up to 3rd degree Tchebyshev, see next slide). This fit reduced hit residuals from ~100 μm to ~10 μm.
4. **TPC + SSD + SVT tracks**
   - Check consistency
   - Reevaluate SVT & SSD hit errors

An example of drift residual (cm) versus drift distance before and after the correction (typical wafers)



± (Drift Distance / max Drift Distance + 0.1) for left / right hybrid

SVT/SSD resolutions after Calibration/Alignment

- A quality of calibration/alignment procedure for Run V has been estimated from hit pull analysis in track fit, and
- Spatial resolution estimated by requirement to have pull standard deviation equal to 1 (averaged over 3 samples: 62 GeV Forward Magnetic Field, 200 GeV Reverse and Forward Magnetic Field) is as follows:
  - SVT:
    - $\sigma_{\rho\phi}$ = 49±5 μm, and
    - σ_Z = 30±7 μm.
  - SSD resolution:
    - $\sigma_{\rho\phi}$ = 30 μm (set to design value since << MCS),
    - σ_Z = 742 ± 41 μm.

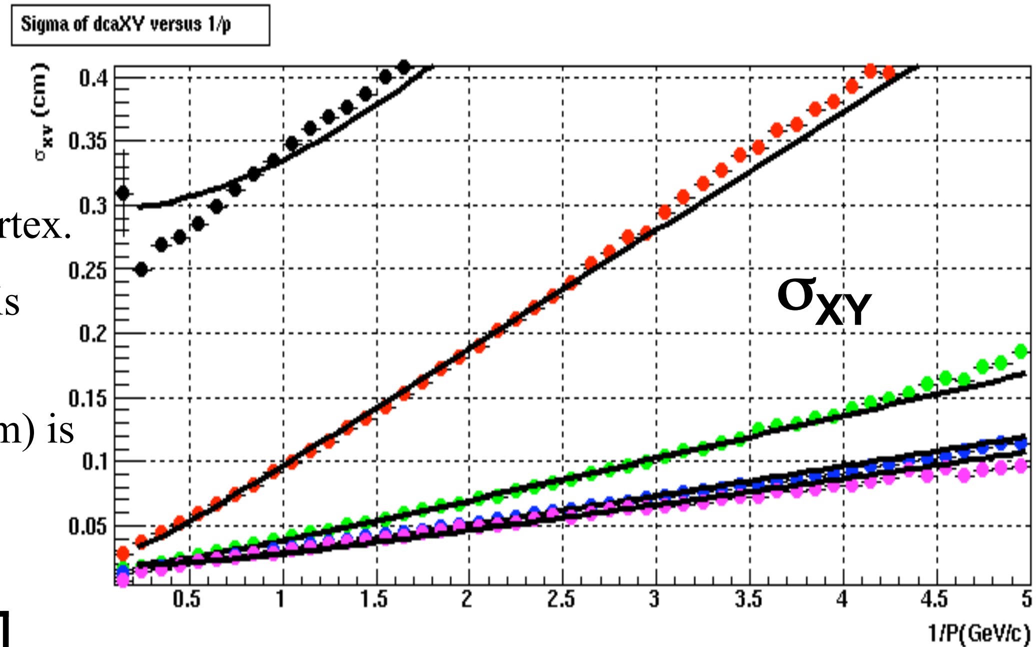
DCA resolution

•Pointing (DCA) resolution has been estimated as standard deviation of global track DCA with respect to the primary vertex.

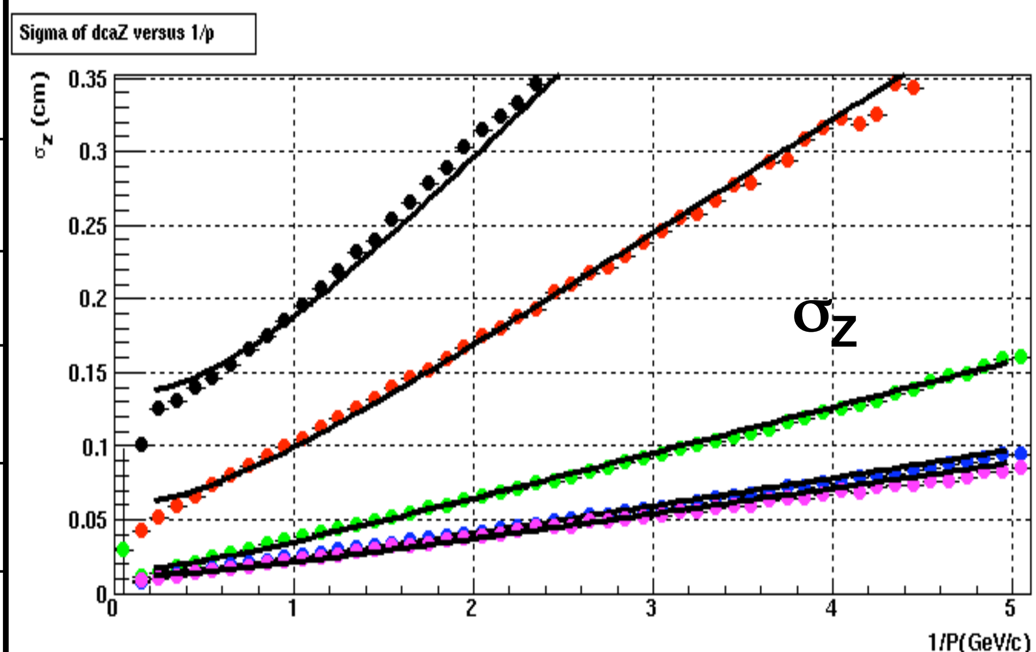
•With increasing no. of fitted Si points it is improved by ~ order of magnitude.

•Contribution from tracking (constant term) is comparable with MCS @ 1 GeV/c

•Thus we have **reached our desired goal !**

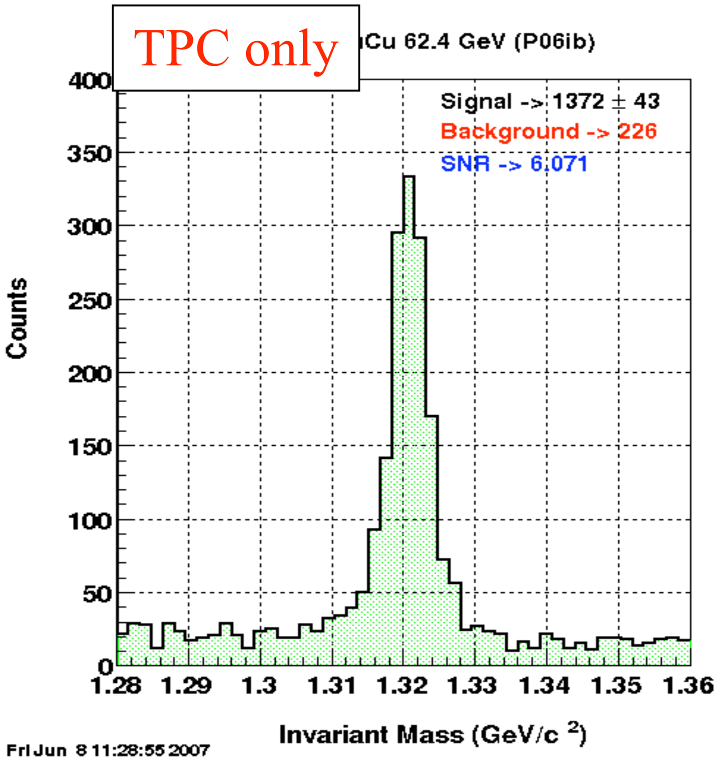


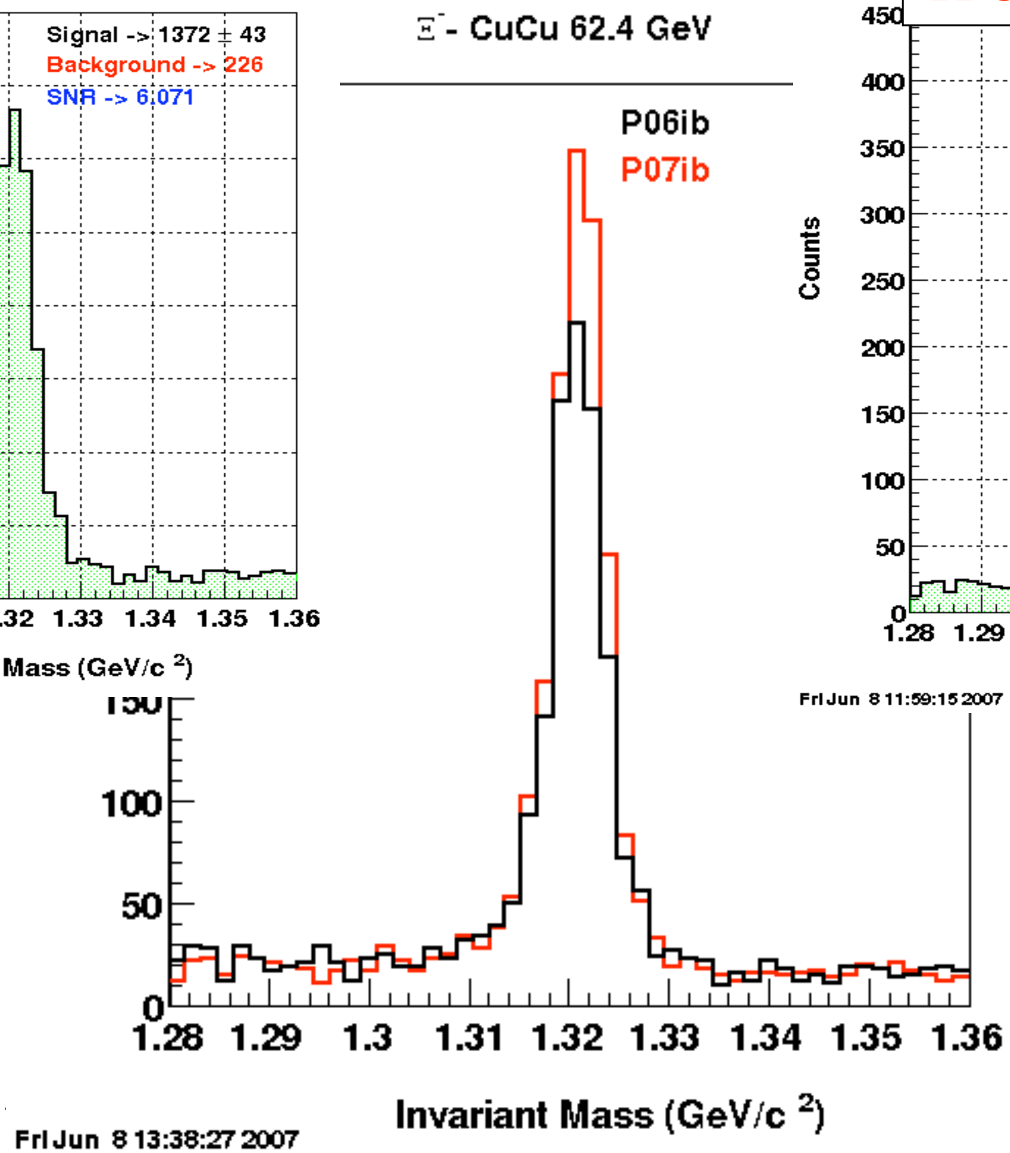
Number of Silicon Points fitted to track	σ_{XY} @1GeV/c (μm)	σ_Z @1GeV/c (μm)
0 - ● TPC only	3350	1184
1 - ● TPC+SSD	967	993
2 - ● TPC+SSD+SVT	383	351
3 - ● TPC+SSD+SVT	296	232
4 - ● TPC+SSD+SVT	281	212

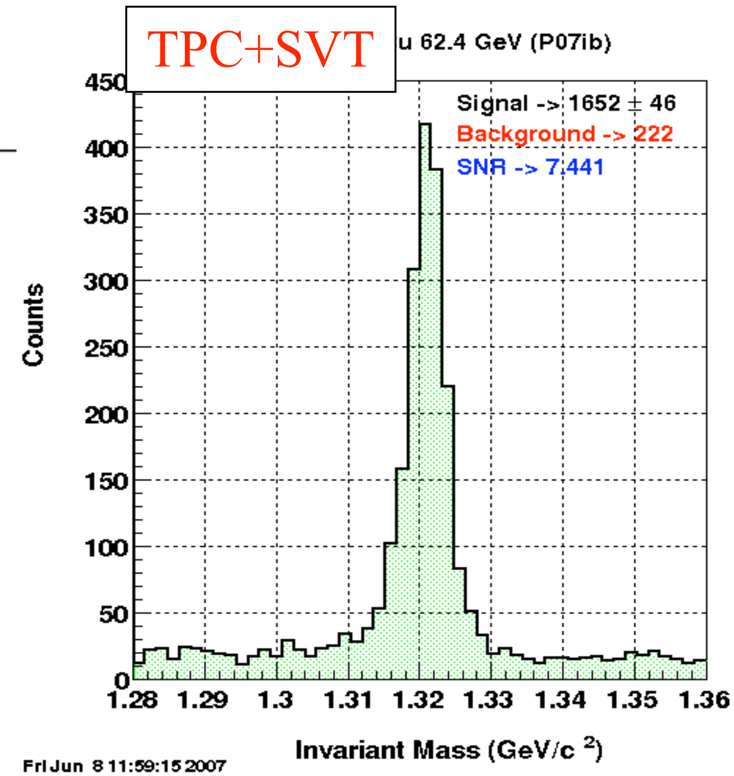


The SVT enhances physics signals.

(Ξ- Analysis Comparing TPC Only and TPC+SVT production for Cu+Cu 62 GeV, analysis done by Geraldo Magela S. Vasconcelos, UNICAMP -Brazil)







Zvert<30cm

We get 20% enhancement of Ξ signal.

Conclusions

- Recent interest in charm physics has re-focused STAR's interest in its vertex detectors.
- The presence of drift silicon (SVT) technology complicates the alignment task
  - but also presence of non-drifting detectors (like SSD) improve the situation drastically.
- Our alignment approach and techniques were successful to overall shifts better than 20 μm
  - which is sufficient for this device.
- Calibration/alignment procedure for Run V (Cu+Cu) has been completed, data has been re-processed, and data analyses is under way.
- Calibration/alignment procedure for Run VII (Au+Au 200 GeV) is under way.
- First physics checks (Run V) look fine. Silicon detectors:
  - improve momentum resolution for global tracks,
  - improve primary vertex resolution,
  - greatly improve track selection (based on DCA),
  - sharpen (multi-)strangeness physics, and
  - other non-physics side benefits:
    - Use of SVT (+SSD) as a high resolution microscope to undo TPC distortions and as a distortion monitor in high luminosity runs.
- STAR Silicon Vertex Detector (and Silicon Strip Detector) are sharpening our physics.

References

1. “The STAR time projection chamber a unique tool for studying high multiplicity events at RHIC”, M.Anderson et al., NIM A499: 652,2003.
2. “The laser system for the STAR time projection chamber”, J. Abele et al., NIM A499: 692,2003.
3. “Correcting for distortions due to ionization in the STAR TPC”, G. Van Buren et al.,NIM A566:22-25,2006.
4. “The STAR Silicon Vertex Tracker” A large area Silicon Drift Detector”, R.Bellwied et Al., NIM A499: 640, 2003.
5. “The STAR silicon strip-detector (SSD)”, L.Arnold et al., NIM 2003 A499: 652, 2003.
6. “Alignment Strategy for the SMT Barrel Detectors”, D.Chakborty, J.D.Hobbs, October 13, 1999. D0 Note (unpublished)
7. “Sensor Alignment by Tracks”, V.Karimaki et al.,CMS CR-2004/009 (presented at CHEP 2003)

Appendix

A. Appendix. Jacobian of measured hit position deviation from predicted track ones with respect to misalignment parameters.

1. *Misalignment of the detector in Global Coordinate System (GCS)*

- $\vec{j} = (j_x,\, j_y,\, j_z)$ - track direction cosinuses in GCS on measurement plane,
- $\vec{x} = (x,\, y,\, z)$ - track prediction in GCS on measurement plane,
- $\vec{x}_{hit} = (x_{hit},\, y_{hit},\, z_{hit})$ - hit position in GCS on measurement plane,
- $\vec{v} = (v_x,\, v_y,\, v_z)$ - direction of perpendicular to measurement plane in GCS,
- $\vec{\Delta} = (\Delta_x,\, \Delta_y,\, \Delta_z,\, \Delta_\alpha,\, \Delta_\beta,\, \Delta_\gamma)$ - misalignment parameters: shift and rotation with respect to X,Y,Z axises, respectively.
- $\vec{x}_{hit} - \vec{x} = \mathbf{G} \cdot \vec{\Delta} =$

$$\begin{pmatrix} -1 + j_x v_x & j_x v_y & j_x v_z & j_x(-v_y z + v_z y) & -z + j_x(v_x z - v_z x) & y + j_x(-v_x y + v_y x) \\ j_y v_x & -1 + j_y v_y & j_y v_z & z + j_y(-v_y z + v_z y) & j_y(v_x z - v_z x) & -x + j_y(-v_x y + v_y x) \\ j_z v_x & j_z v_y & -1 + j_z v_z & -y + j_z(-v_y z + v_z y) & x + j_z(v_x z - v_y x) & j_z(-v_x y + v_y x) \end{pmatrix} \vec{\Delta}$$

2. *Misalignment of the detector in Local Coordinate System (LCS)*

- $\vec{u} = (u,\, v,\, w \equiv 0)$ - track prediction in LCS on measurement plane.
- $(t_u,\, t_v)$ - track direction tangenses in Local Coordinate system (LCS) on measurement plane.
- $\vec{u}_{hit} = (u_{hit},\, v_{hit})$ - hit position in LCS on measurement plane,
- $\vec{\delta} = (\delta_u,\, \delta_v,\, \delta_w,\, \delta_\alpha,\, \delta_\beta,\, \delta_\gamma)$ - misalignment parameters, shift and rotation with respect to local u,v,w axises, respectively.
-
$$\vec{u}_{hit} - \vec{u} = \mathbf{L} \cdot \vec{\delta} = \begin{pmatrix} -1 & 0 & t_u & t_u v & -t_u u & v \\ 0 & -1 & t_v & t_v v & -t_v u & -u \end{pmatrix} \vec{\delta}$$
- $(u_{hit} - u) = -\delta_u + t_u(\delta_w + v\delta_\alpha - u\delta_\beta) + v\delta_\gamma;$
  $(v_{hit} - v) = -\delta_v + t_v(\delta_w + v\delta_\alpha - u\delta_\beta) - u\delta_\gamma;$