BaBar Si Tracker Alignment

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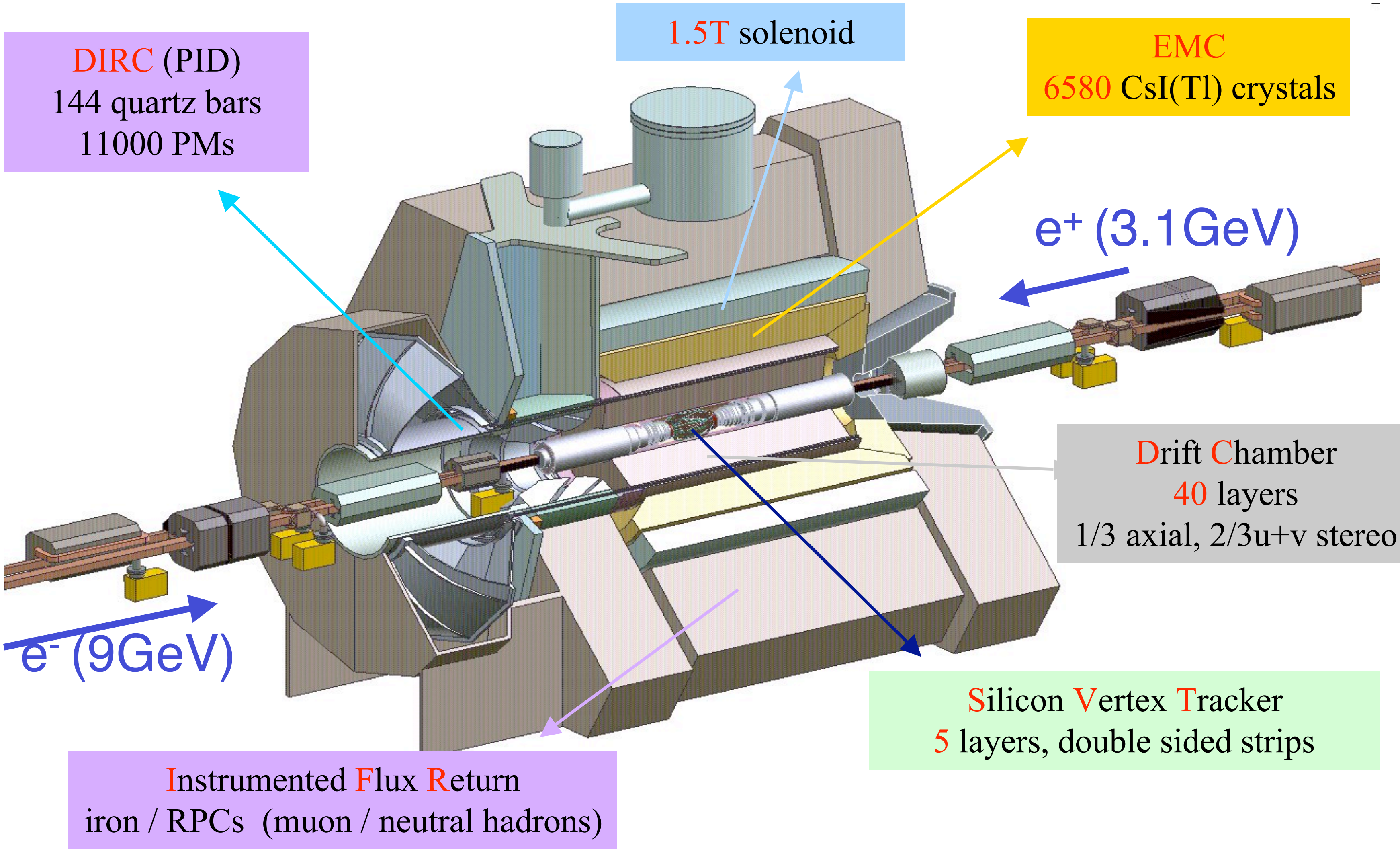
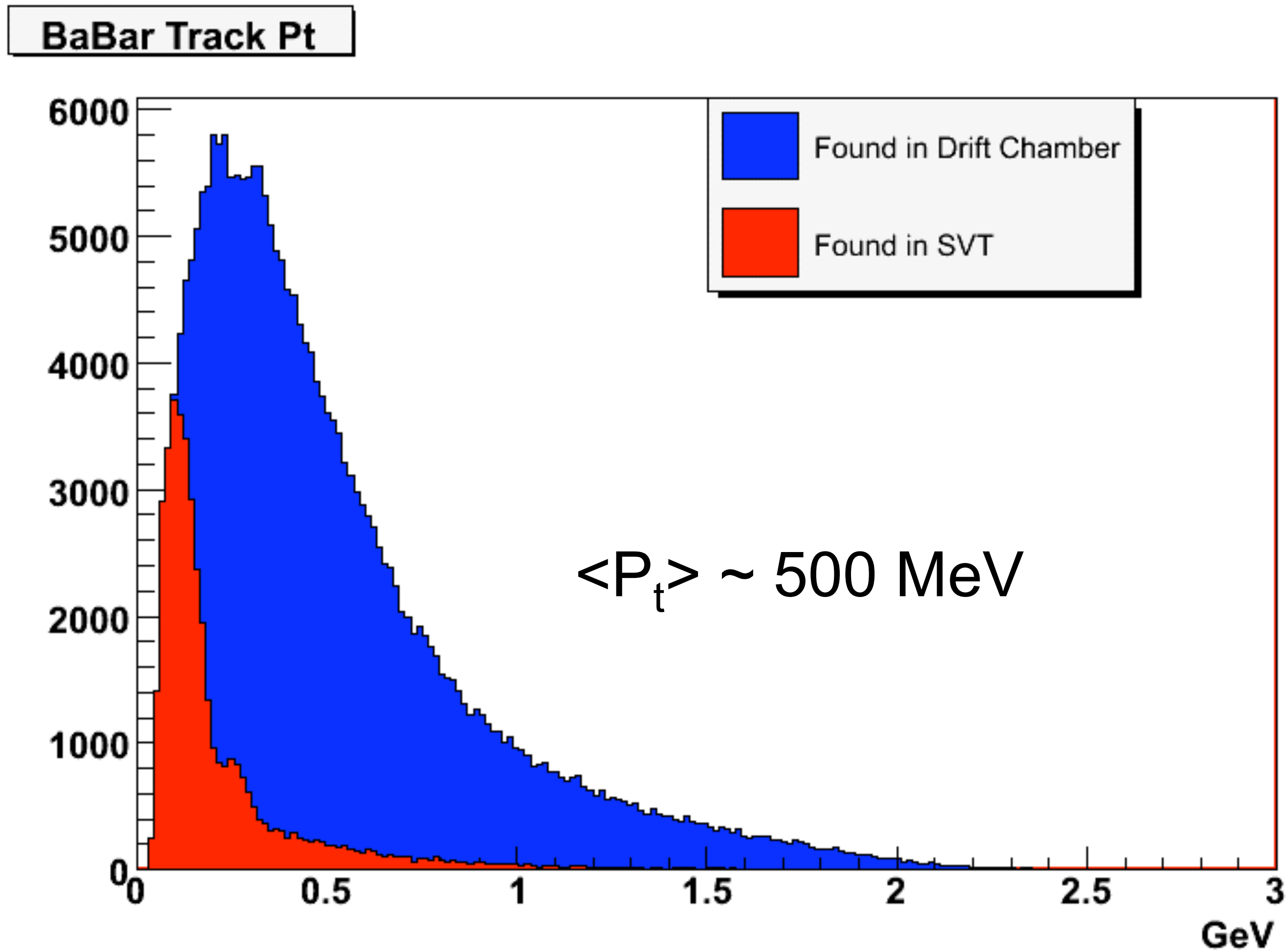
Representing the BaBar SVT alignment group

- **The BaBar experiment**
- **The BaBar Si Tracker alignment procedure**
- **Alignment procedure validation**
- **Results**
- **Lessons learned**

PEP-II and BaBar



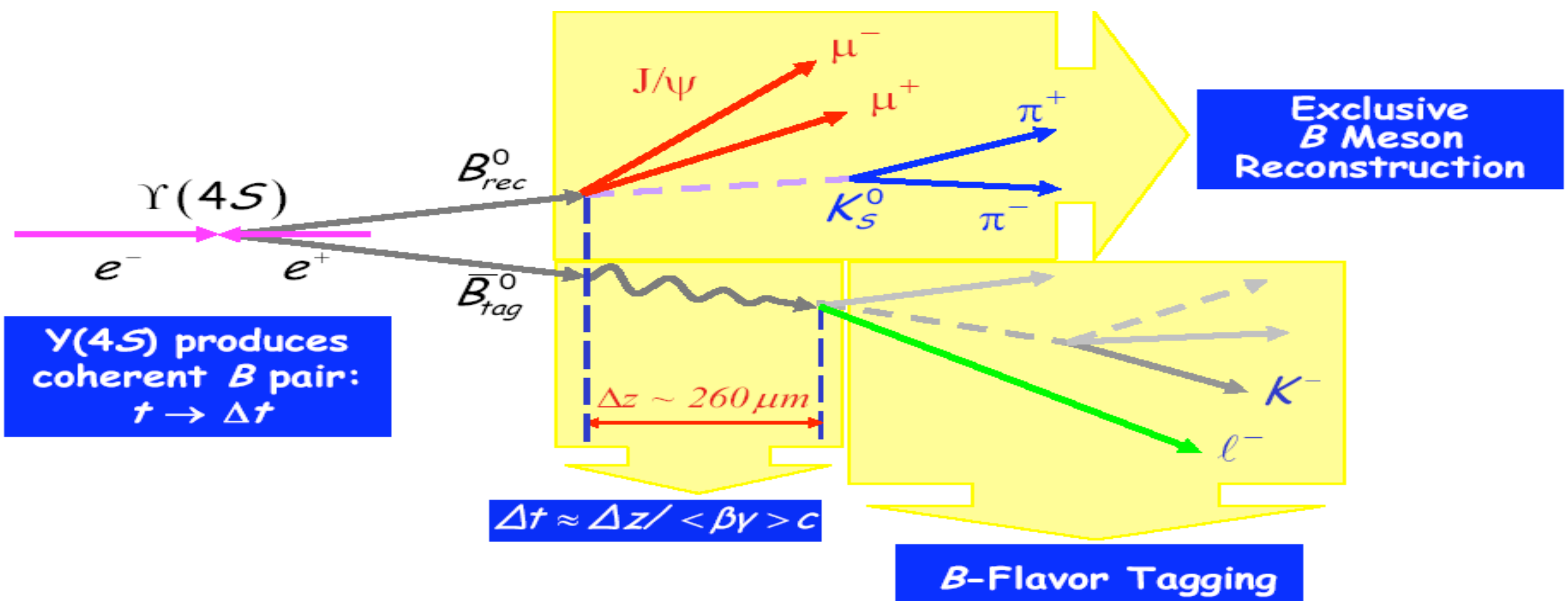
Track Momentum on the $\Upsilon(4S)$



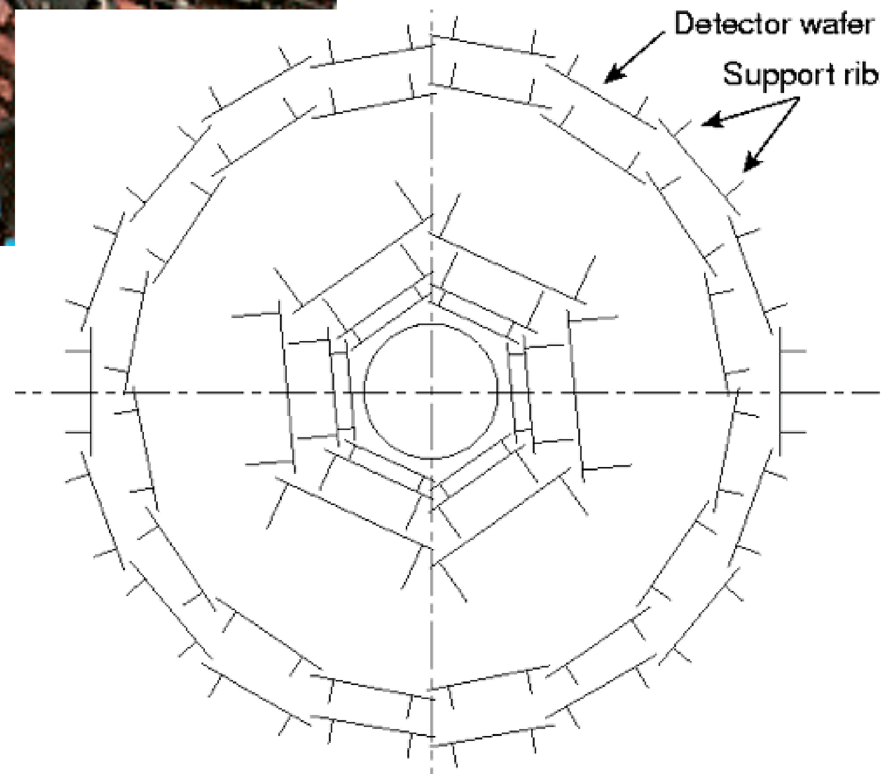
- **Scattering (material) largely dominates over point (hit) resolution in impact parameter resolution**

BaBar Physics Goals

- **Observe CP violation in B system**
  - **Time-dependent mixing (e.g. sin2β)**
  - **λ_z ~ 260 μm, $\sigma_z$vertex ~ 180μm, ⇒ 20μm point resolution**
- **PDG-competitive measurement of B, τ lifetimes**
  - **Control average alignment systematics to ~ 1 μm (0.5%)**
- **No B_s mixing, tertiary charm vertex separation, …**
  - **Modest requirements on material, resolution**

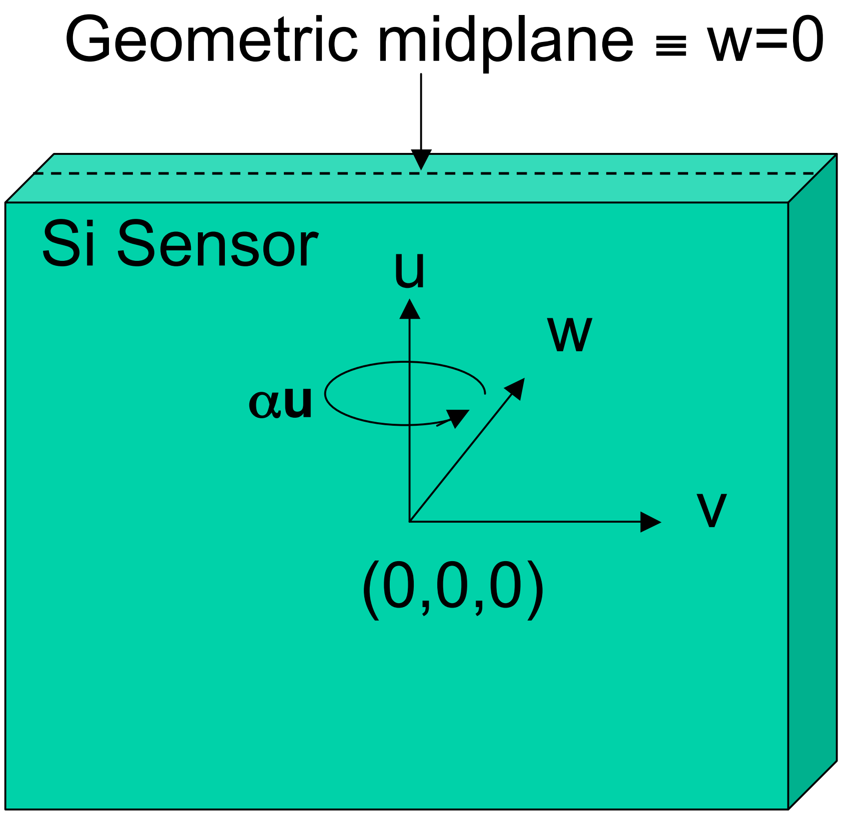


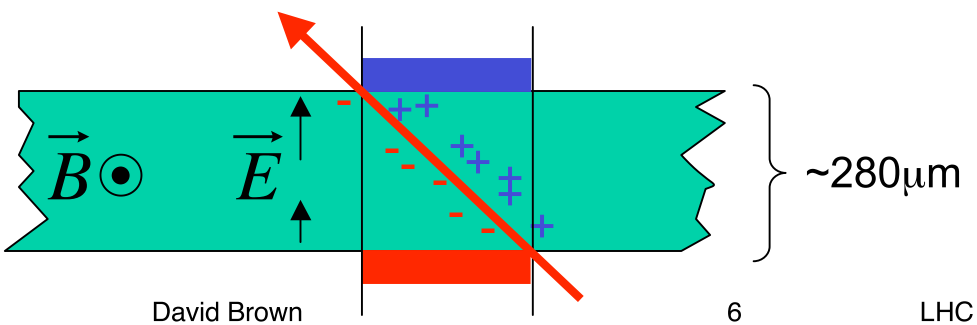
BaBar SVT



- 5 layers, 340 wafers
  - Radii from 3.3 to 15 cm
  - ‘Lampshades’ in layers 4 + 5
- Double sided readout
  - 90° strips
  - Kapton fanouts in active region
- ~2% X_0 total at normal
  - 1% X_0 Be beampipe
- No hardware alignment

Wafer Alignment Description

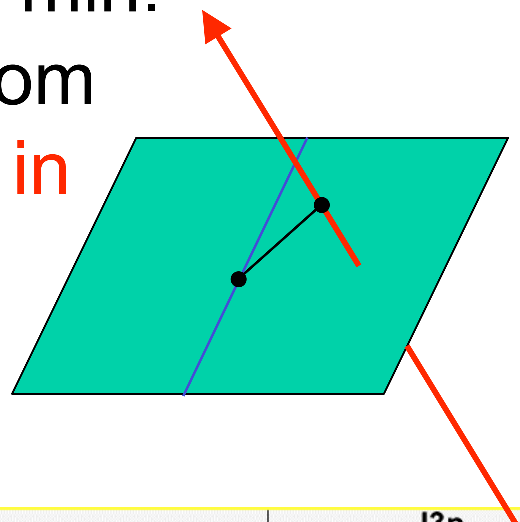


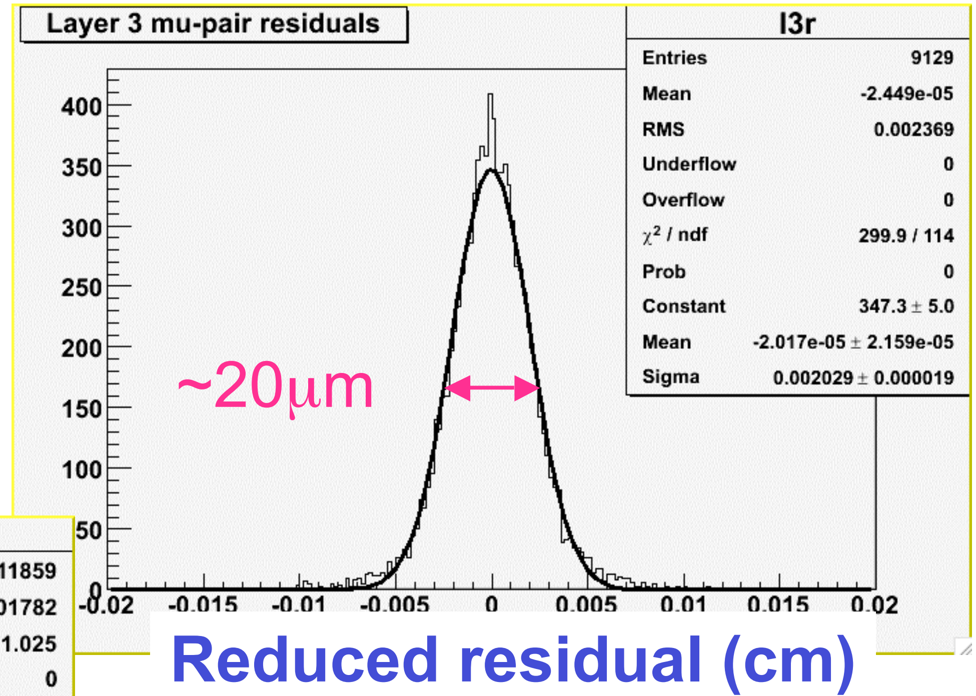


- **Sensor local coordinates**
  - ✦ **u≈φ, v≈beam, w≈radial outward**
- **6 alignment parameters**
  - ✦ **Deviation WRT nominal**
  - ✦ **3 translations δu δw δv**
  - ✦ **3 (small) rotations αu αw αv**
- **Total system has 6 redundant Global alignment DOFs**
- **Internal DOFs**
  - ✦ **Charge drift asymmetry (=0)**
  - ✦ **Lorentz shift (estimated)**
  - ✦ **Non-planar distortions**

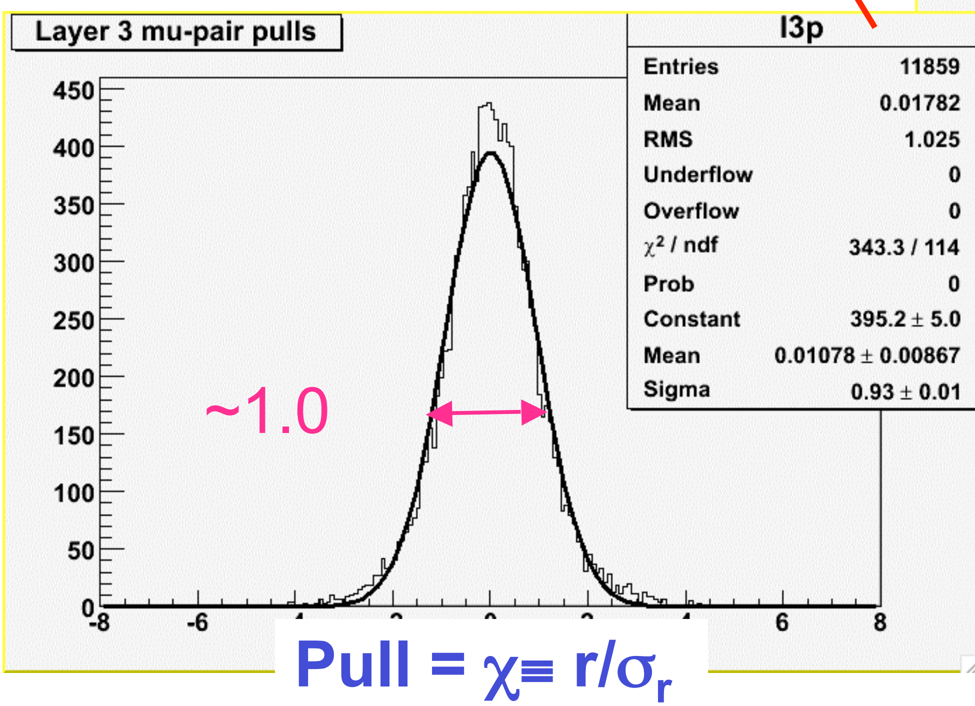
Track Residuals

Residual ≡ min. distance from track to hit in space





- Reduced residual excludes the hit from the track fit



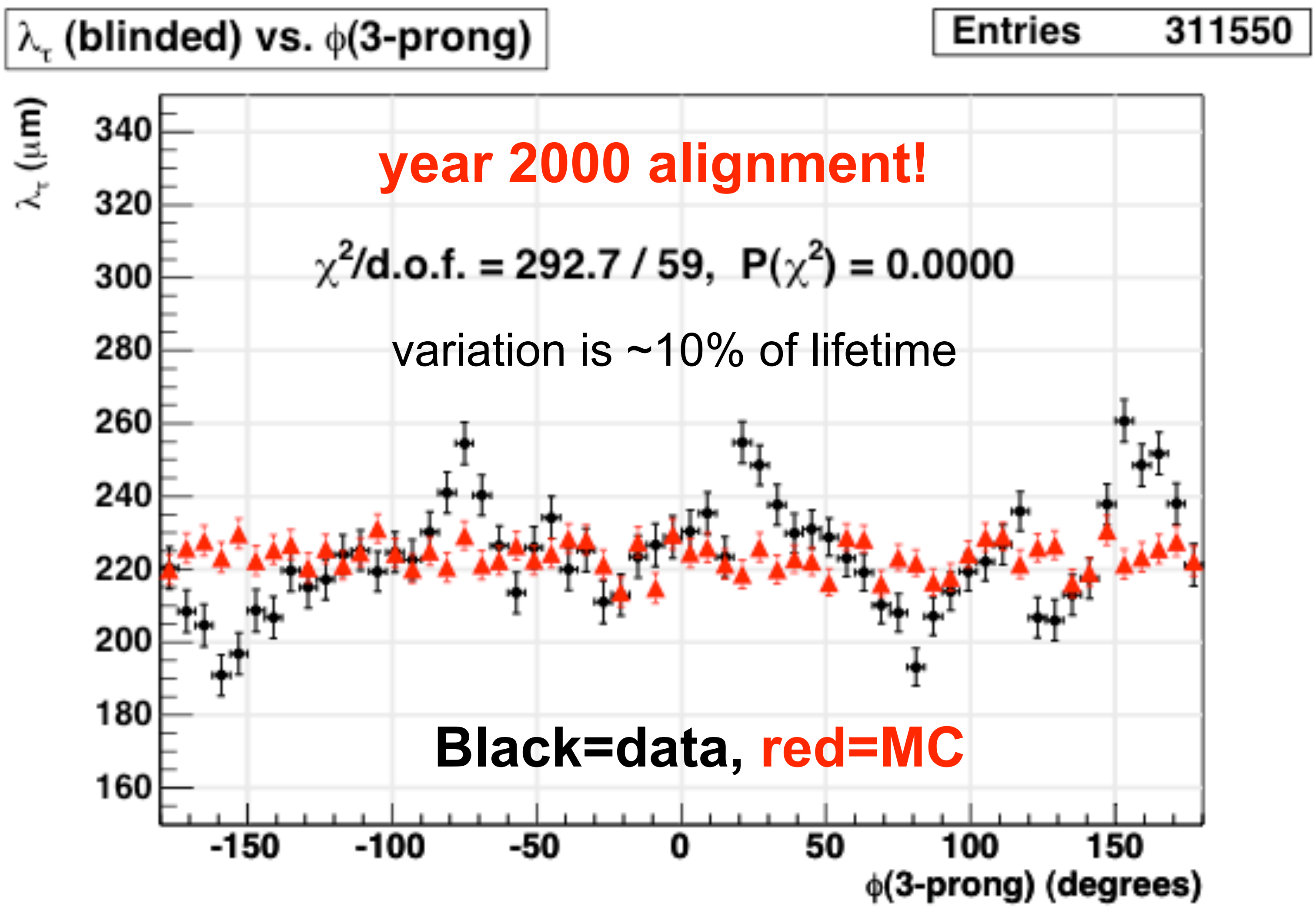
$$\chi^2 = \sum_{residuals} \left(r / \sigma_r \right)^2$$

BaBar Alignment History

- **BaBar design and construction: 1995→1999**
  - **Alignment is considered (overlaps) but not studied**
- **First data and commissioning in 1999**
  - **Used Optical Survey wafer alignment + cosmics**
- **1st Alignment procedure development 1999→2000**
  - **Based on (primarily) $e^+e^- \rightarrow \mu^+\mu^-$ events**
  - **1.5 FTE for development and operation**
  - **Procedure was manpower, cpu and data intensive**
    - ~1 month turnaround time
  - **Visible systematic errors remained**
    - Early BaBar physics results were not compromised!
- **Complete rewrite of alignment procedure 2001→2002**
  - **3 FTE development effort over 1 year**
  - **Separate operations effort of 0.5 FTE**
  - **Designed coherently with a new BaBar Data Model**
  - **Deployed in 2002, we are still using this procedure today**

BaBar τ lifetime in year 2000

Average τ 1-3 decay distance



Alignment Design Principles

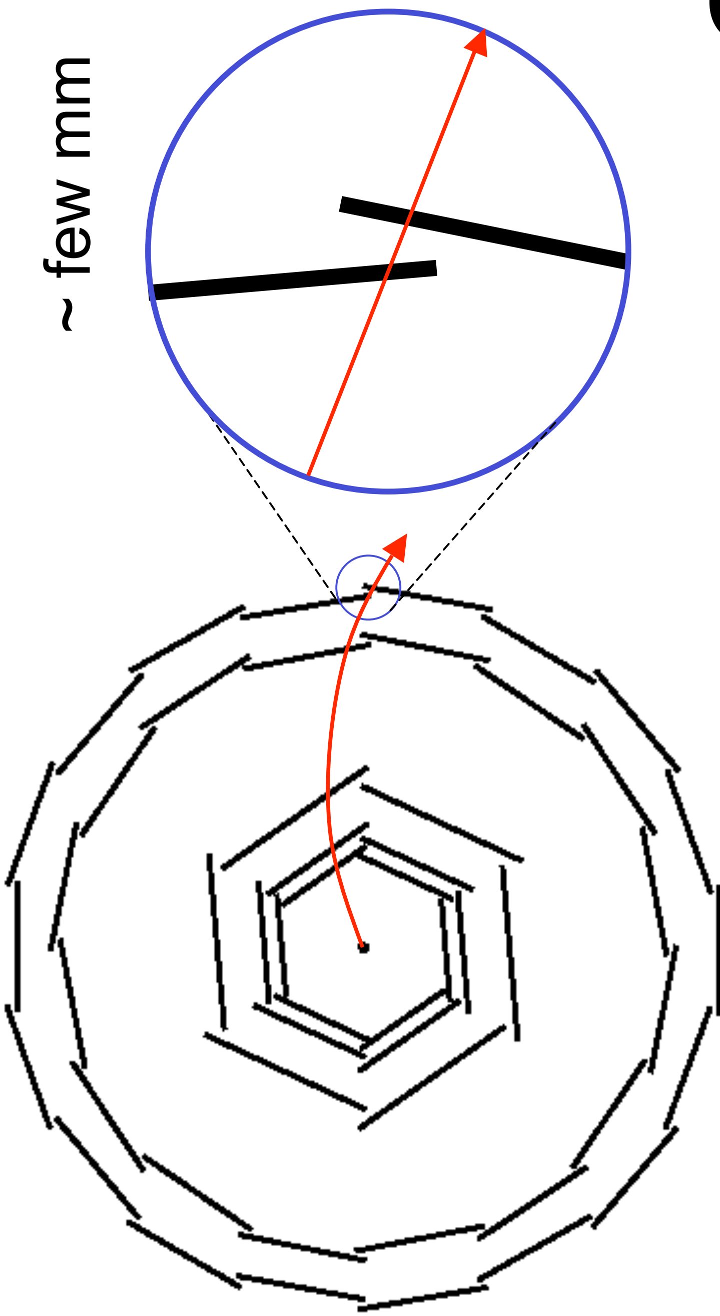
- **Combine complementary constraints**
  - ✦ **Use lots of tracks to cover all wafer DOFs**
  - ✦ **Use different event triggers and track geometries to balance systematic biases**
  - ✦ **Relate wafers across the detector to control global distortions**
  - ✦ **Incorporate lab-based optical survey information**
- **Select data to provide uniform constraints**
  - ✦ **Make detector coverage more uniform**
  - ✦ **Select events uniformly over (short) time period**
  - ✦ **Equilibrate statistical errors**
  - ✦ **Minimize statistical correlations between wafers**

Global Distortions

- **Small relative changes between adjacent wafers that add up coherently across the detector**
  - **Residuals work 'locally'**
- **Can introduce significant physics bias**
- **Choose alignment constraints which control these**

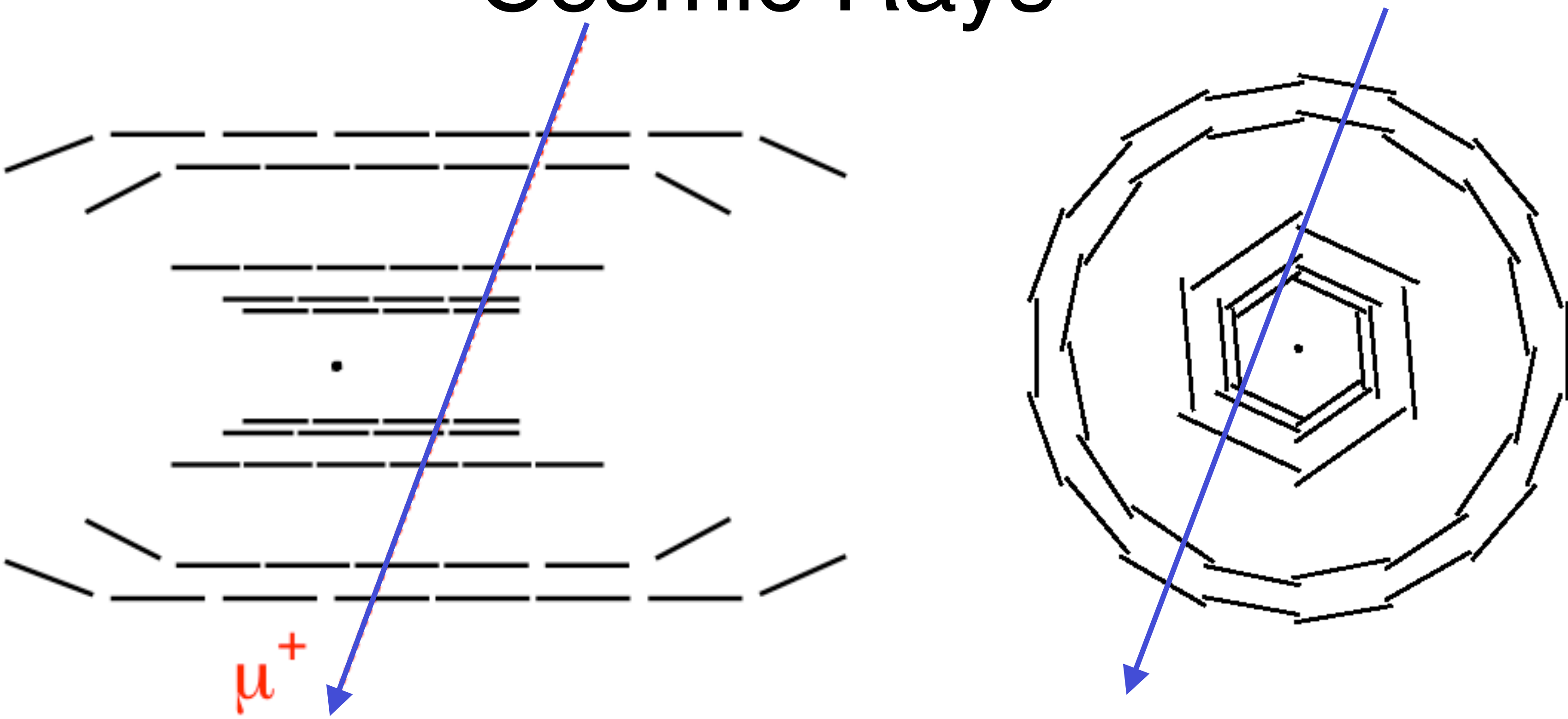
	ΔR	$\Delta\phi$	ΔZ
R	**Radial expansion (distance scale)**	**Curl (charge asymmetry)**	**Telescope (COM boost)**
ϕ	**Elliptical (vertex mass)**	**Clamshell (vertex displacement)**	**Skew (COM energy)**
Z	**Bowing (COM energy)**	**Twist (CP violation)**	**Z expansion (distance scale)**

Overlaps



- **Active Si overlap between adjacent wafers in the same layer**
- **Small gap between overlapping wafers**
  - **Constrains adjacent wafers**
  - **Not as effective in hex geometry**
- **Overlaps cumulatively provide a circumference constraint**
  - **Relies on precise knowledge of wafer size**
  - **Constrains *radial expansion, clamshell distortions***
- **Small fraction of tracks**
  - **Between 1% and 3%**

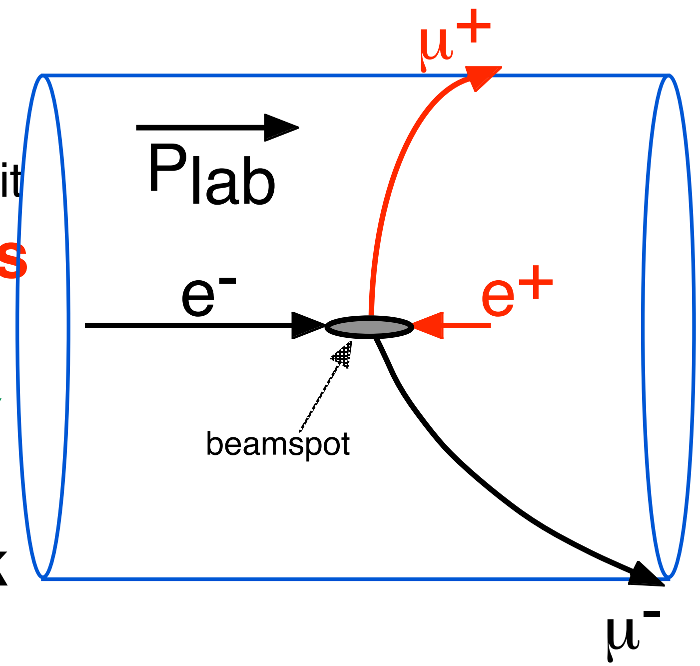
Cosmic Rays



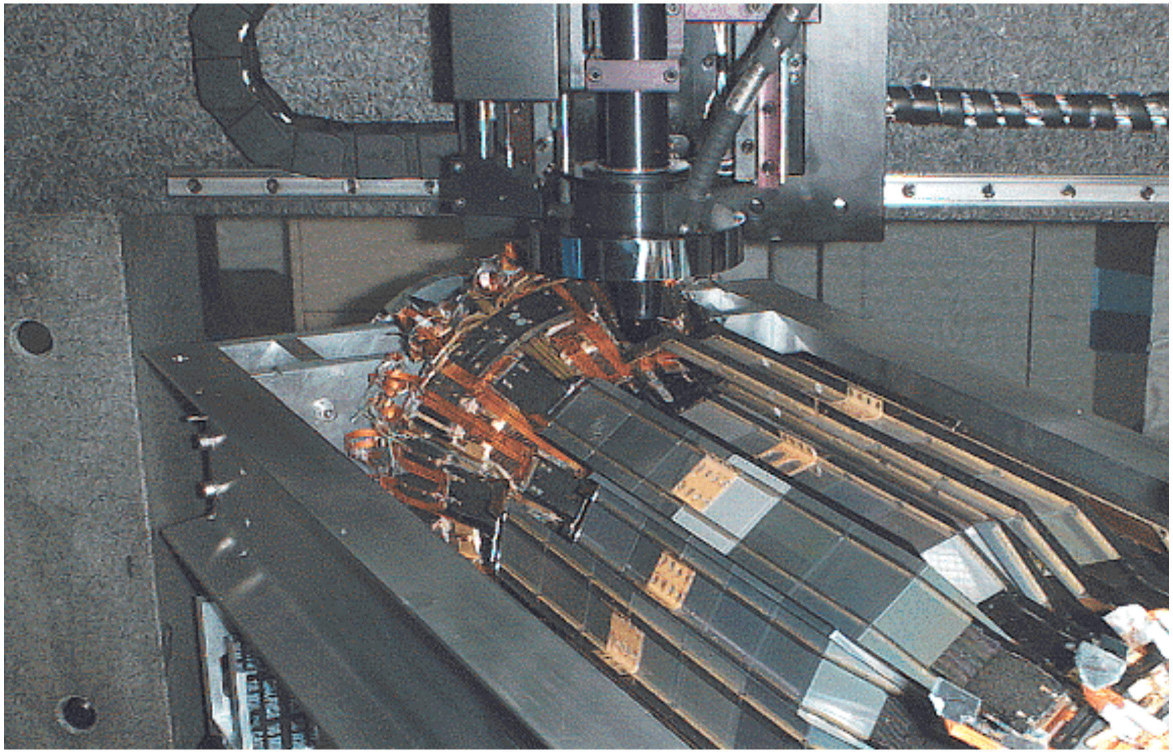
- High-momentum tracks (> 1Gev)
- Relates opposite side wafers ⇒ constrains *telescope distortion*
- Off-axis ⇒constrains *twist, elliptical distortions*
- Low rate, non-uniform illumination

Pair Fit

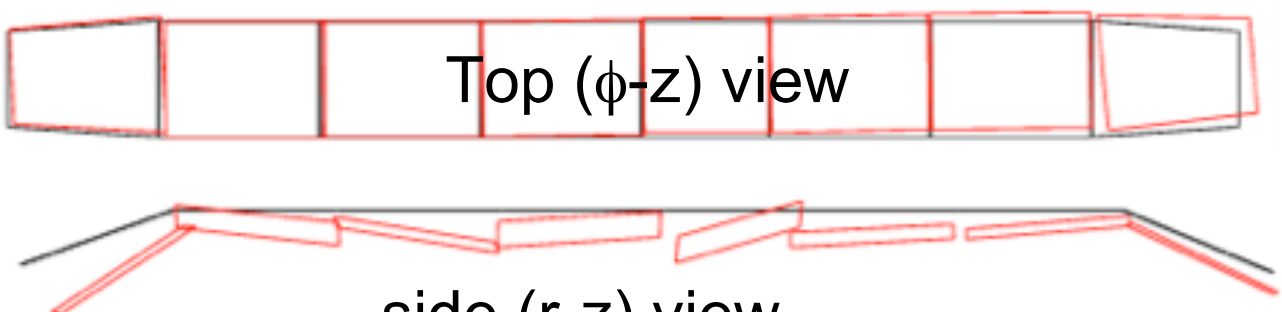
- **Fit 2 tracks from $e^+e^- \rightarrow \mu^+\mu^-$ (and $e^+e^- \rightarrow e^+e^-$) simultaneously**
  - **Constrained to a common origin**
  - **Constrain Σ momentum to 'known' CM 4-momentum**
    - Scale errors for beam uncertainties
    - Implemented in the BaBar Kalman track fit
- **Provides pair-constrained residuals**
  - **Not just a mass-constrained vertex fit!**
- **Constrains *curl, bowing, and skew distortions***
- **Technique can work for other track pairs (ie $\psi \rightarrow \mu^+\mu^-$)**
- **Depends on initial beam parameter knowledge**



Optical Survey



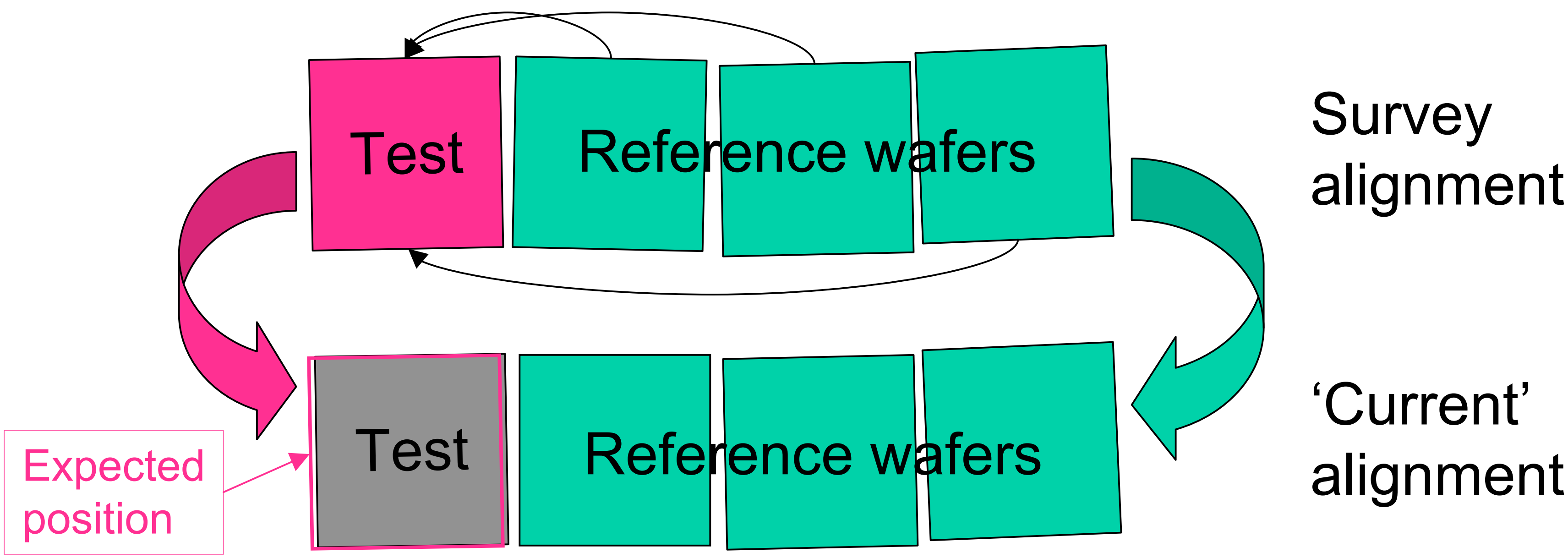
- **Use combination of Module Survey (lab bench) + Assembly Survey**
- **Constraint of wafers within a module complementary to tracks**
- **Constrains *Z expansion distortion***



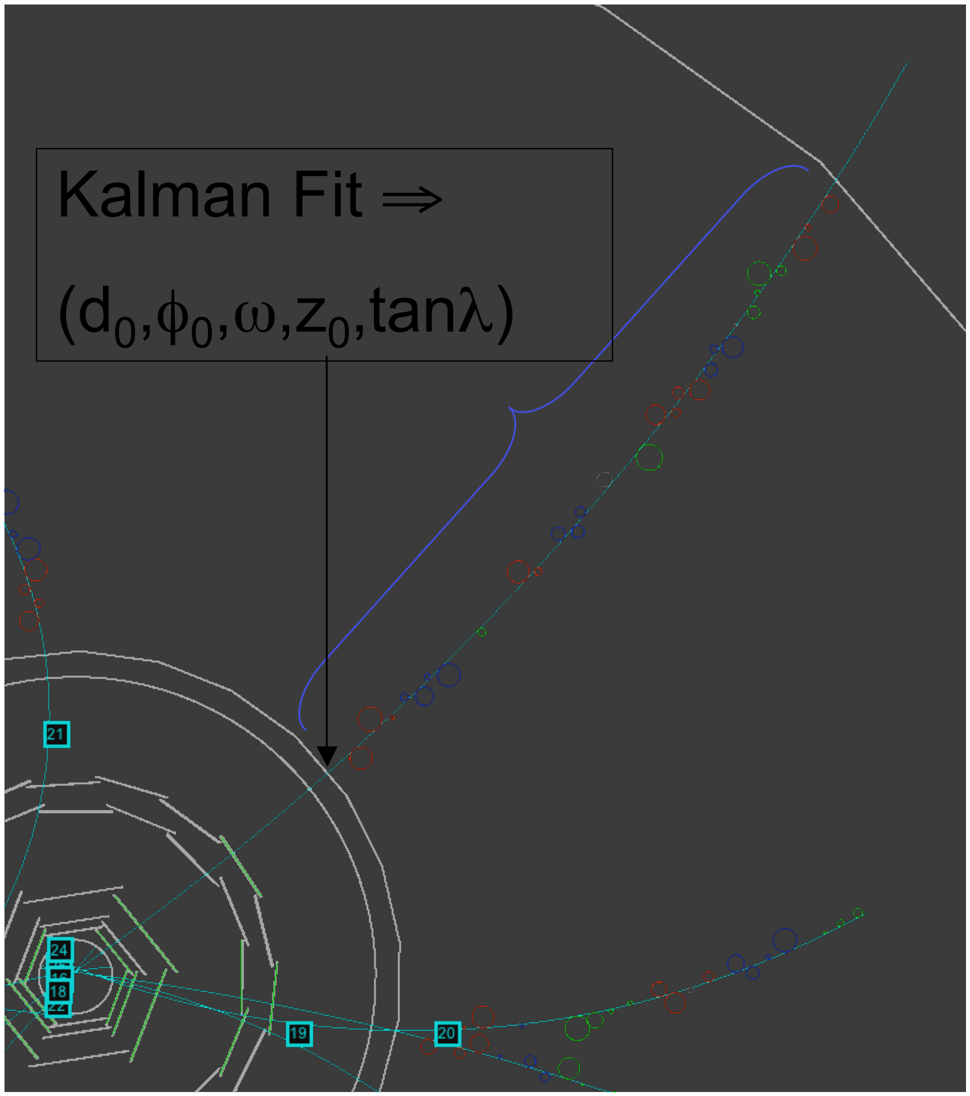
(distortions X 50)

Survey Constraint

- **Compute 'survey to current' transform using reference wafers**
  - **Minimize difference between position of fiducials on the wafers**
- **Predict position of 'test' wafer position in 'current' alignment**
- **Compute $\Delta\chi^2$ = difference between current and survey position**
  - **Multiply out-of-plane errors X 10 to accommodate motion since survey**
- **Add survey $\Delta\chi^2$ to track residual χ^2**

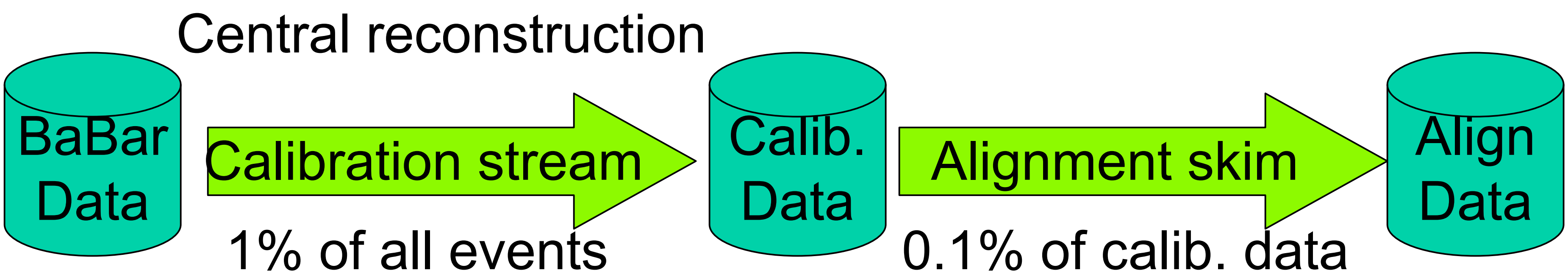


Outer Tracking Constraint



- **Tracks are split at boundary**
  - **Each half fit separately**
- **Outer track fit used to constrain the inner track fit**
  - **Can select which parameters to propagate**
  - **Improves precision while controlling propagation of outer tracker systematics**
  - **Standard feature of BaBar Kalman track fit**
- **μ-pair + cosmic (high p)**
  - **Constrain only curvature**
- **Isolated high-P hadrons**
  - **Constrained to full outer track fit (5 parameters)**
- **Keeps relative (global) alignment from drifting**

Alignment Data Reduction

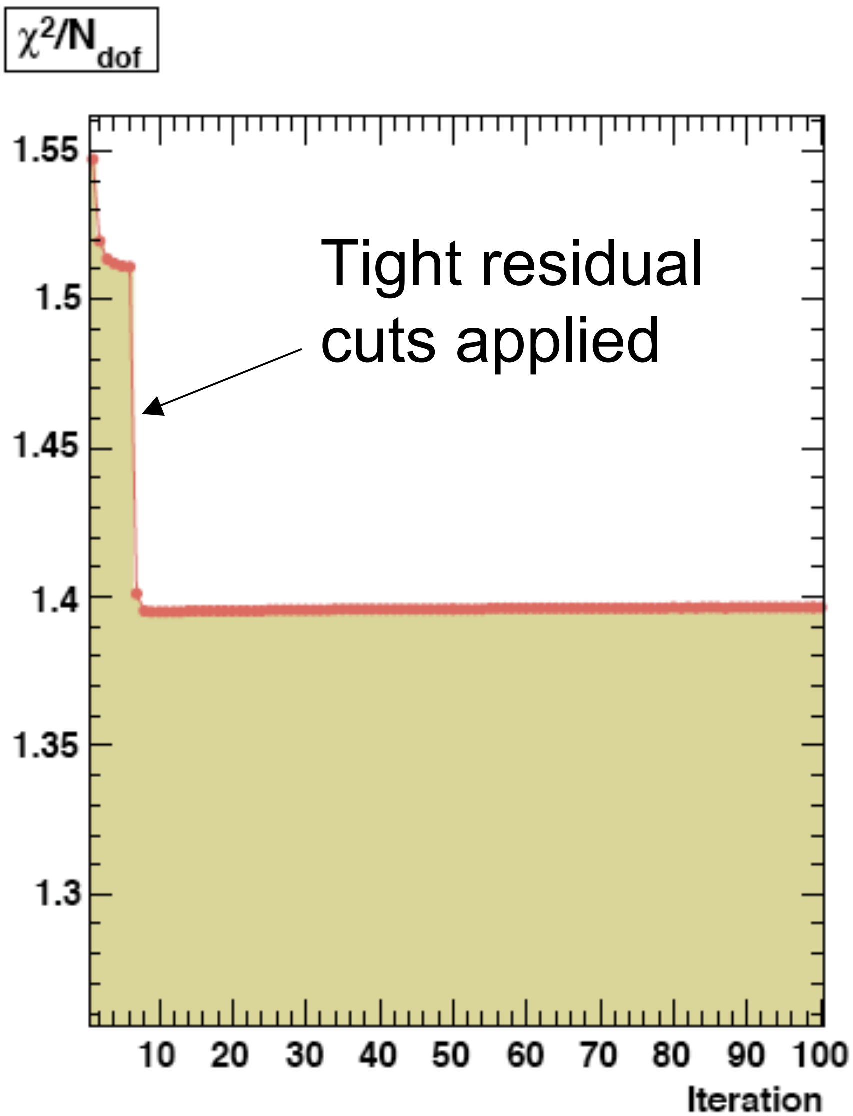


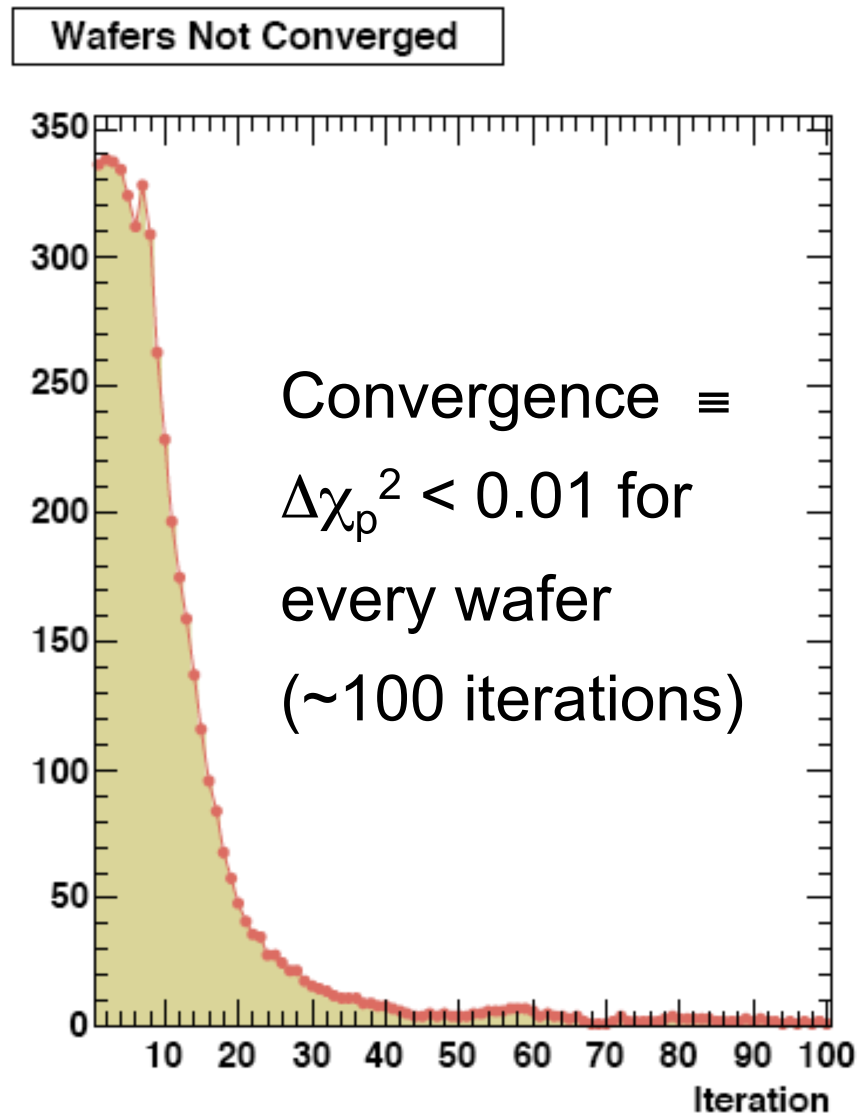
- **A dedicated sample is selected during reconstruction**
  - **μ pairs, cosmics, prescaled hadronic events with high P tracks, …**
  - **Written to a dedicated stream (file)**
- **From ~ 2 days accumulation we extract an alignment sample**
  - **Events are prescaled by type and polar angle coverage**
    - Timescale driven by cosmics
  - **Only selected tracks are kept, all other data is removed**
    - Outer tracker info is kept as a fit constraint, reduces track size by 1/3
  - **Hits are prescaled for uniform coverage, selected hits are flagged**
    - Defines fixed selection of hits used across iterations
    - Greatly reduces statistical correlation between wafers
- **Customizations are built in to the BaBar Data Model**

Alignment Iteration

- **Iteration factorizes the alignment problem**
  - **No need for huge matrix inversion (6X6 vs 1440X1440)**
  - **No need to compute distant derivatives**
- **1 iteration = loop over all wafers**
- **Minimize $\Sigma\,\chi^2$ (closed form) for each wafer**
  - **Sum $\Delta\chi^2$ + associated derivatives wrt alignment parameters**
  - **Solve for the change in this wafers alignment parameters**
- **Wafer positions are updated only after a full iteration**
  - **Parallelizable (if wall-clock time were an issue)**
- **Initialize using previous, survey, nominal, test configuration, …**
- **Tighten residual cuts after partial convergence**
  - **Reduces the effect of outliers without biasing alignment**
  - **Requires re-writing alignment dataset (reflagging hits)**
- **Convergence ≡ when wafers stop moving**
  - **$\Delta\,\chi_p^2 \equiv (\Delta P/\sigma P)^2/6 < 0.01$ for every wafer in 1 iteration**
  - **~100 iterations, <24 hours real-time (single processor)**

Alignment Convergence





Alignment Operations

- **Alignment computed every 2 weeks (or as necessary)**
  - **Fully automated (except validation!)**
  - **2-day turnaround**
  - **Upload to database only if changes are significant (by a human)**
- **So far we have ~40 alignment periods, separated by**
  - **Detector interventions**
  - **Humidity effects**
    - Carbon fiber is hygroscopic
- **Detector has been stable for the past ~2 years**

History of outer layer relative radial position vs Z for 2001→2003

http://dnbmac3.lbl.gov/~brownd/alignment/SvtChange_dr

Global Distortion Tests

- **Validate the procedure against global distortions**
  - **Small, coherent relative wafer displacement**
- **Use undistorted MC sample composed as data**
  - **Cosmics, μ-pairs, hadronic decays, …**
- **Align starting with a distorted initial condition**
  - **50 μm scale, smooth dependence on either R, ϕ, or Z**

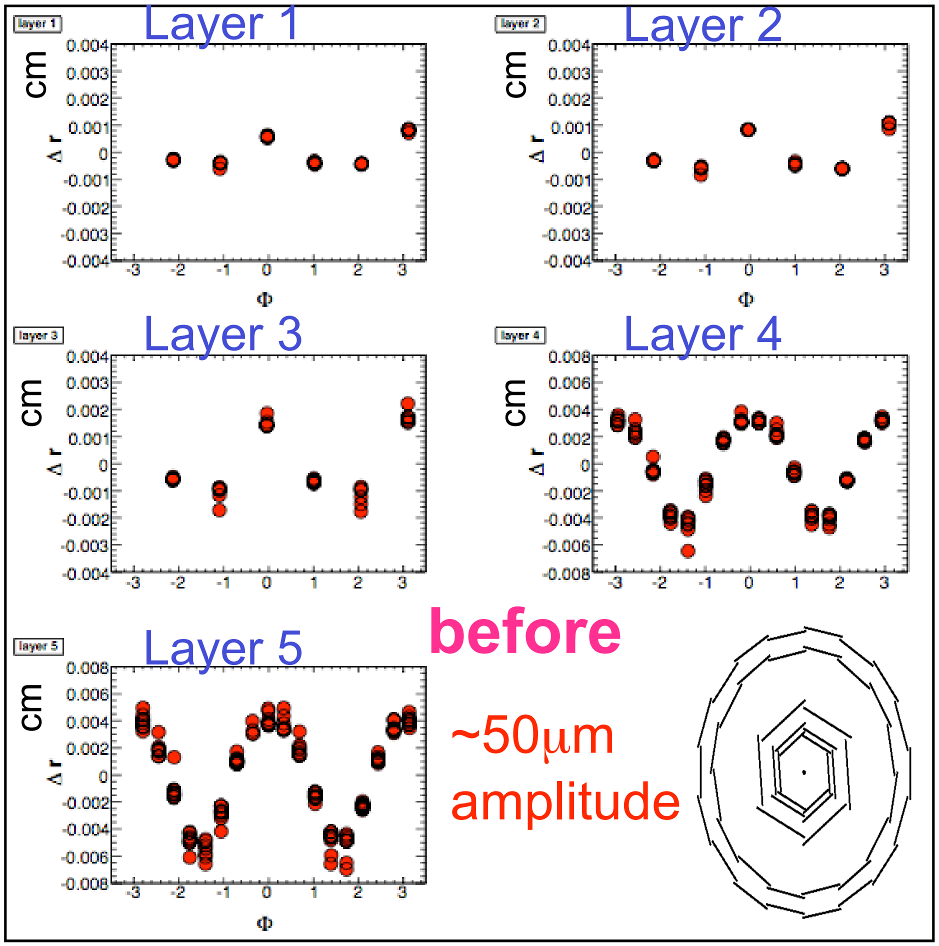
	ΔR	$\Delta\phi$	ΔZ
R	**Radial expansion (distance scale)**	**Curl (charge asymmetry)**	**Telescope (COM boost)**
ϕ	**Elliptical (vertex mass)**	**Clamshell (vertex displacement)**	**Skew (COM energy)**
Z	**Bowing (COM energy)**	**Twist (CP violation)**	**Z expansion (distance scale)**

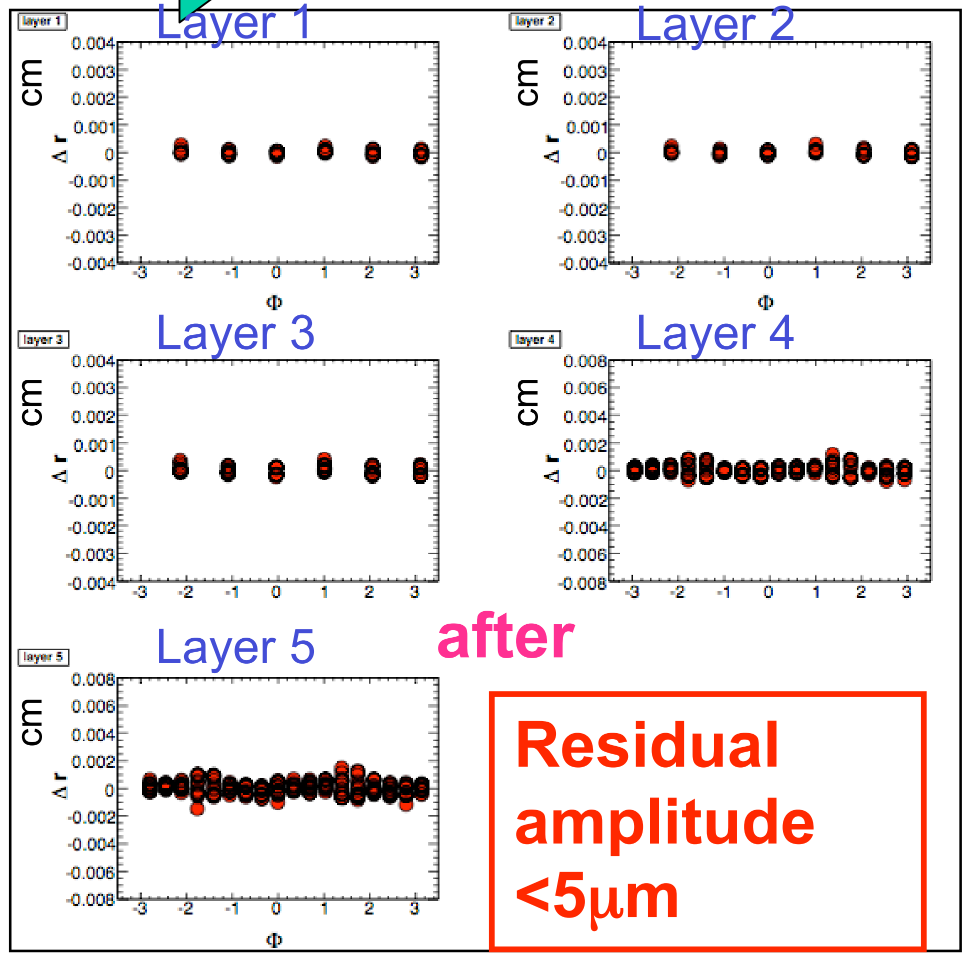
Example: Elliptical Distortion

Apply 0.1% elliptical distortion (~50μm amplitude in layer 5)

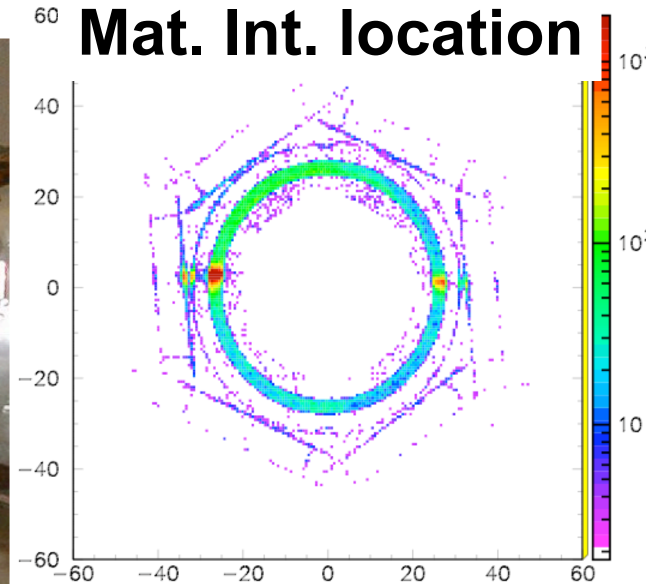
ΔR vs φ by layer

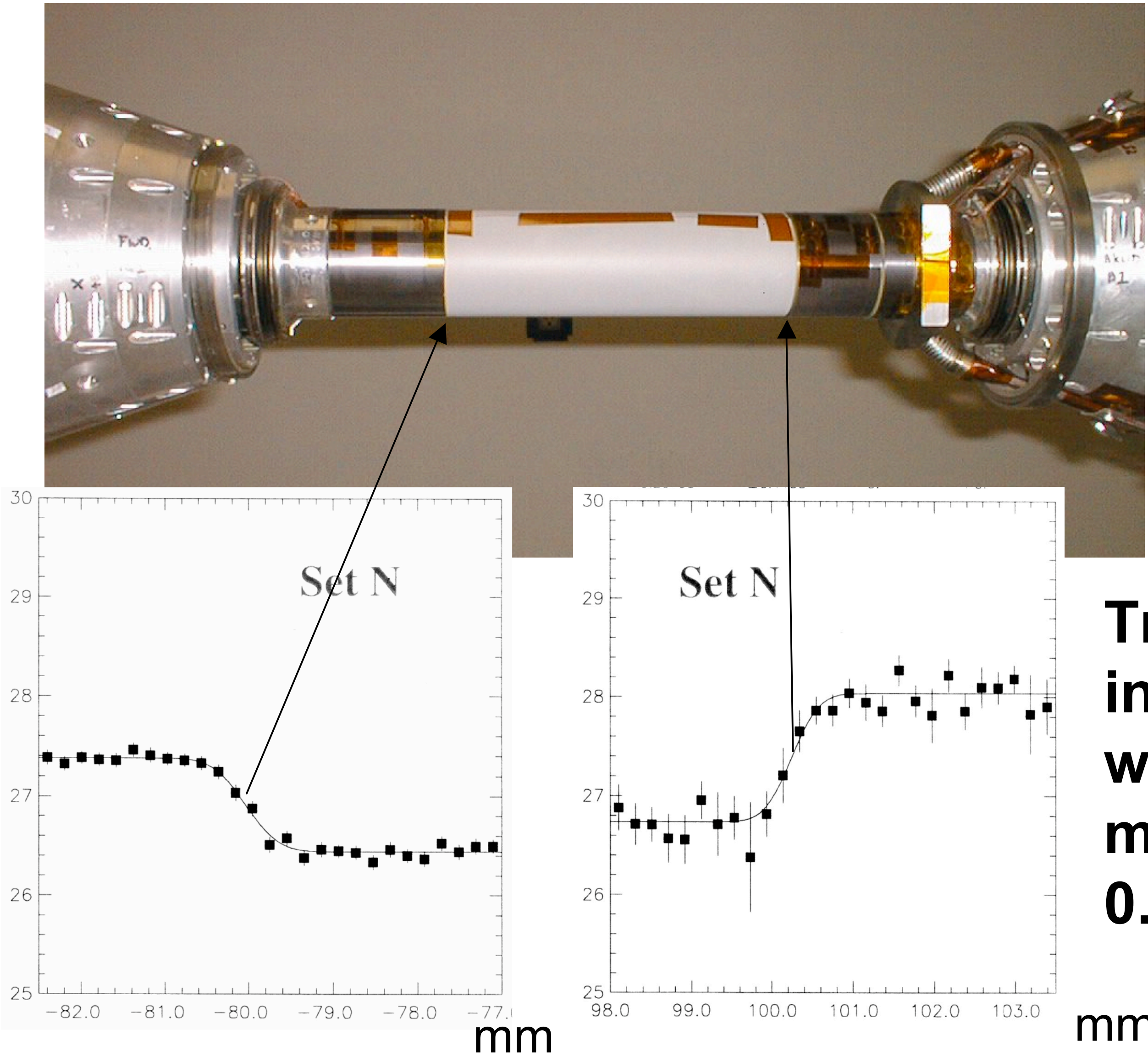
100 Iterations





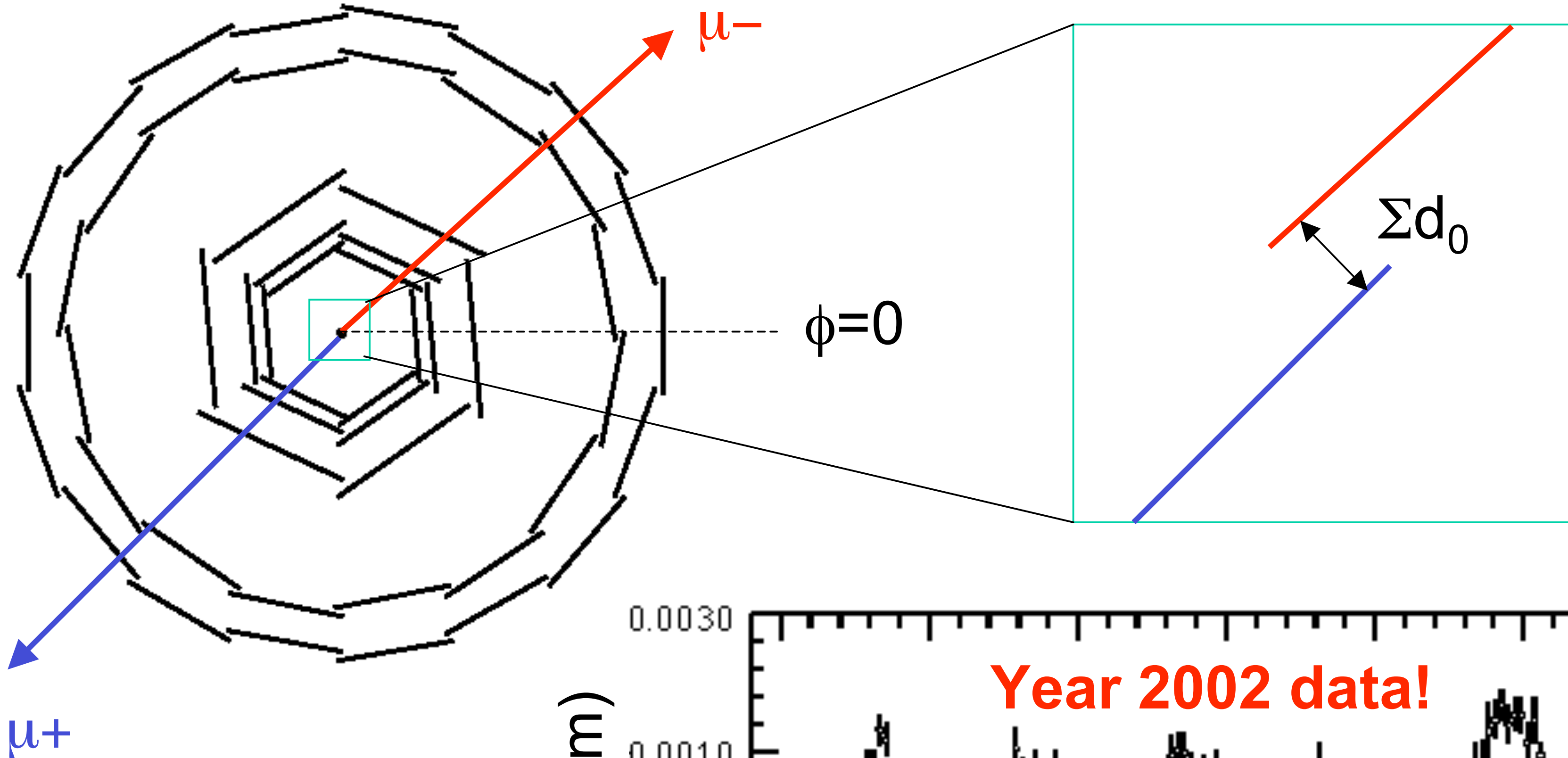
Z Scale Validation



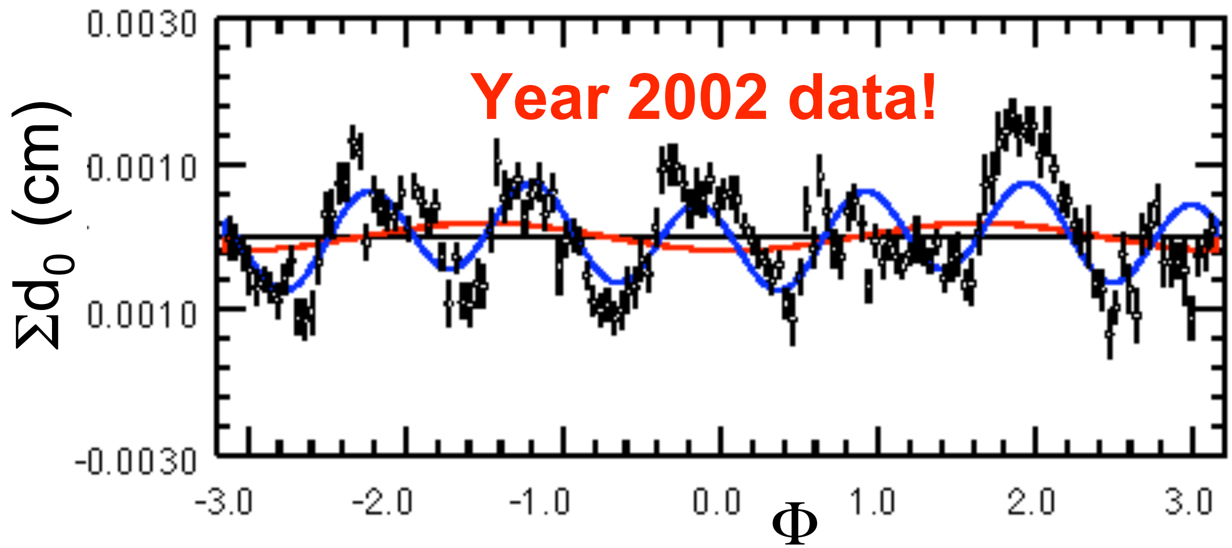


Tracks from material interactions agree with bench measurements to 0.03 ± 0.05 %

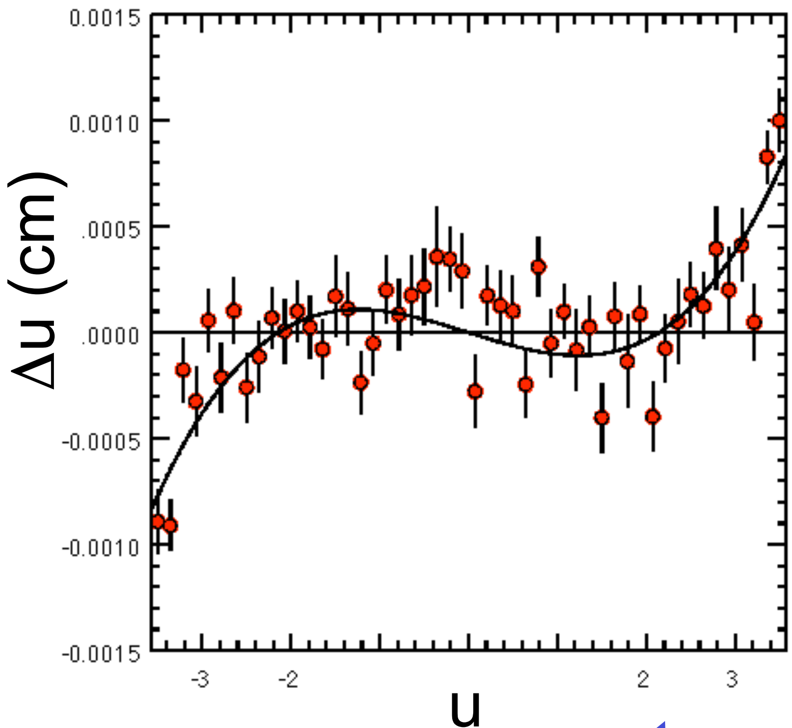
μ-pair miss distance

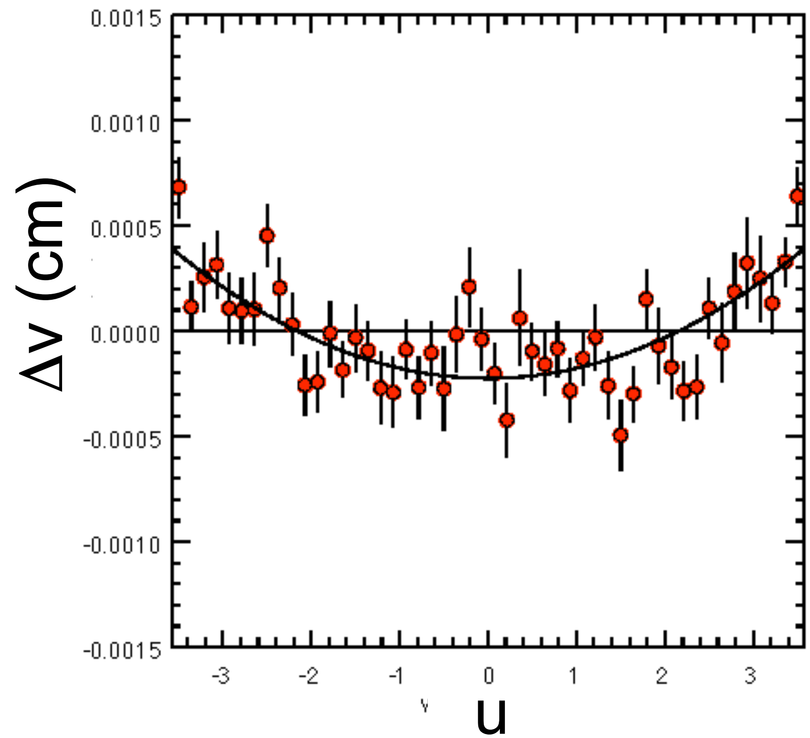


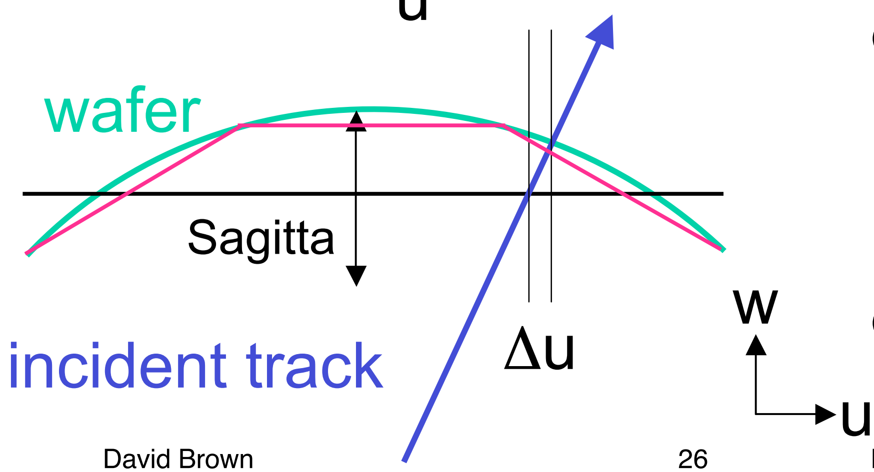
After alignment, we observed a strong 6-fold symmetry



The Explanation: Wafer Bowing



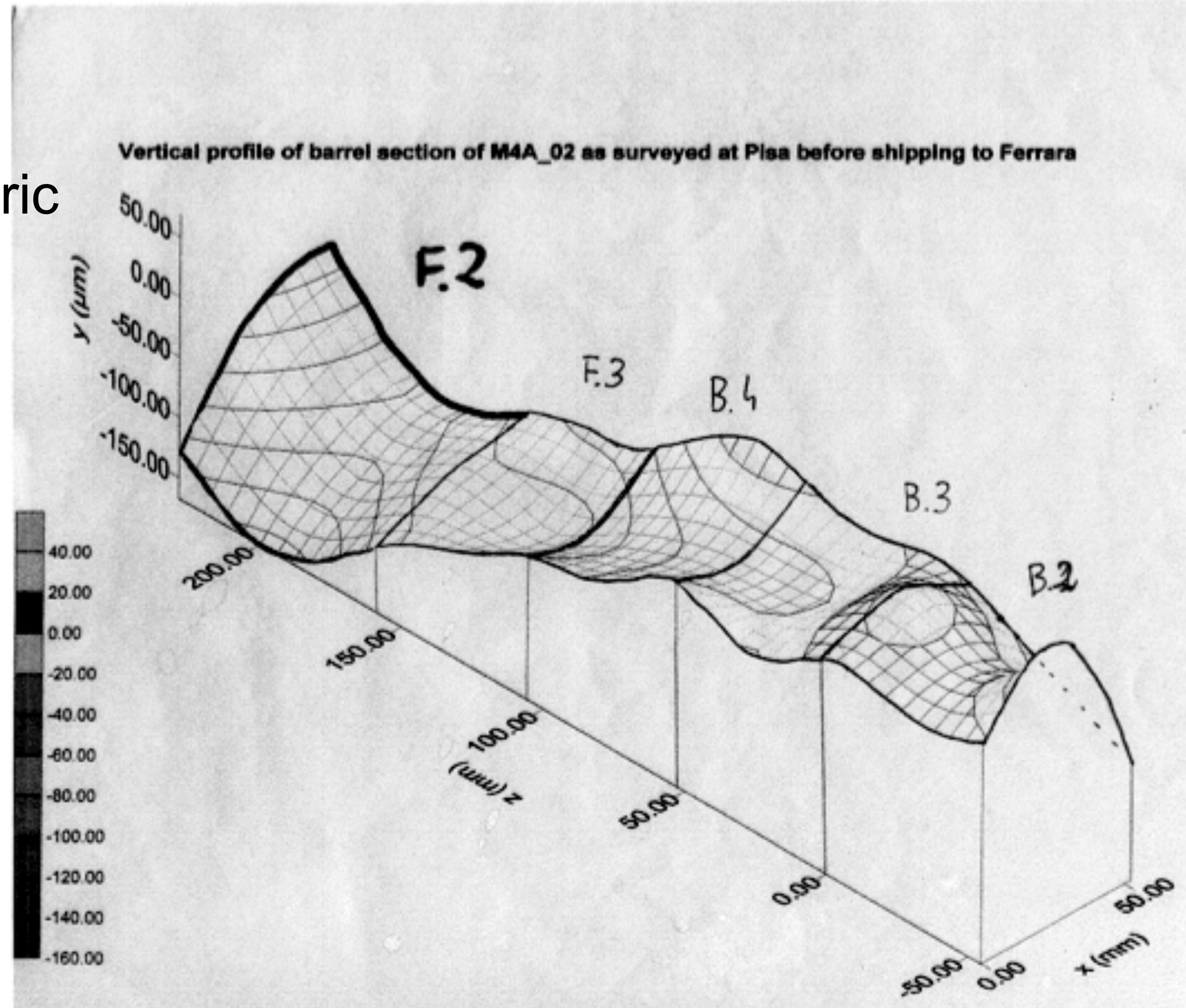




- **Fit wafer sagitta**
  - **Use both u and v residuals**
  - **Iterate with normal alignment**
  - **Mostly affects layers 1,2 + 3**
- **Correct in reconstruction**
  - **Model v strips as 3 linear pieces**

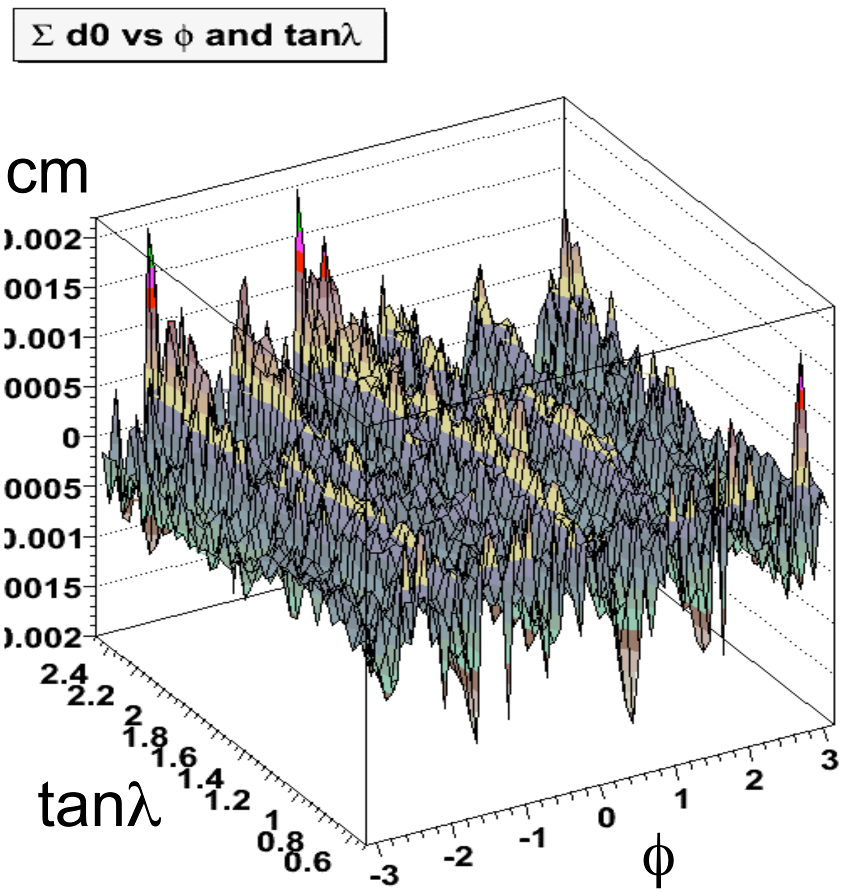
Wafers are not planes (or cylinders)!

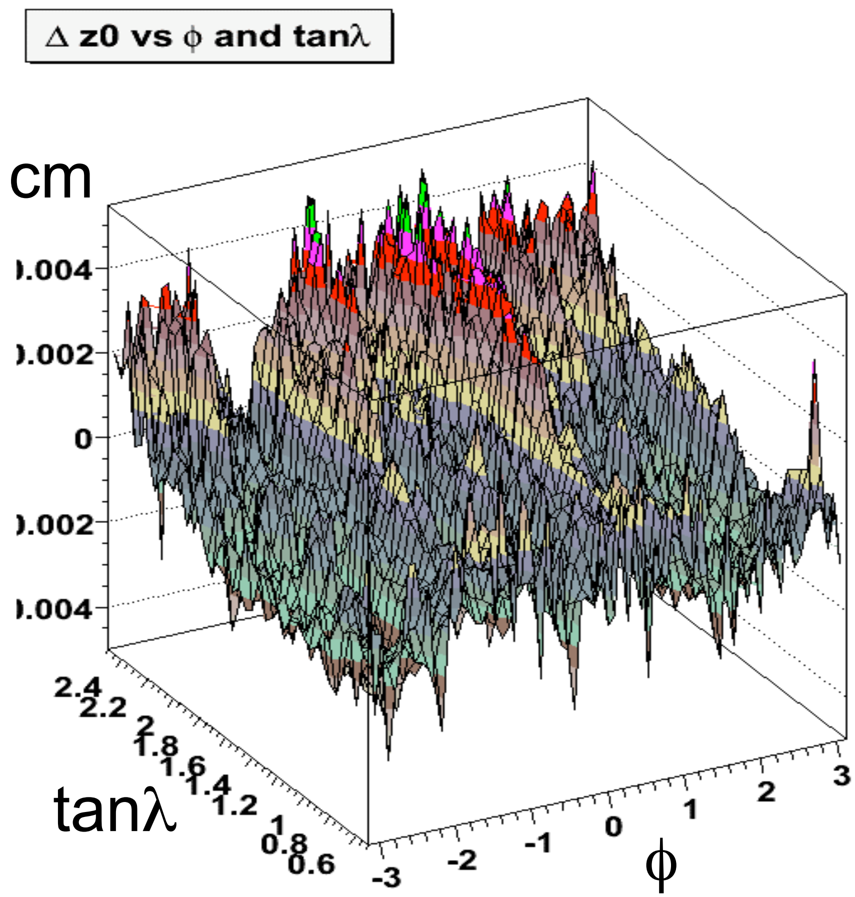
3-D Interferometric survey of 1 module before installation



μ-pair Miss Distance

- **Average variation of <2 μm in Σd_0, <10 μm in Δz_0**
- **With 10X standard alignment sample, structure is seen**
  - **More general non-planar distortions**



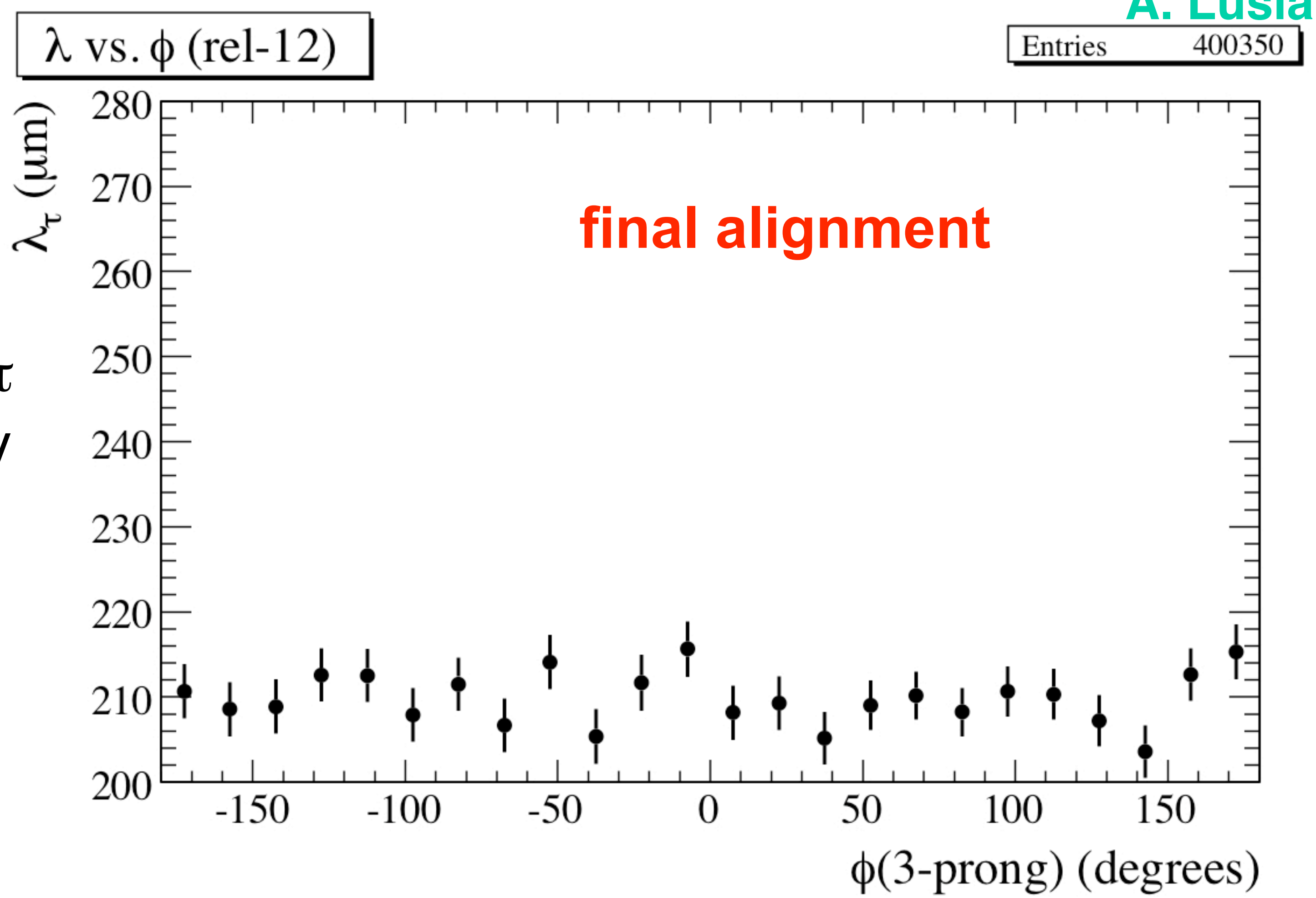


τ Lifetime Revisited (2005)

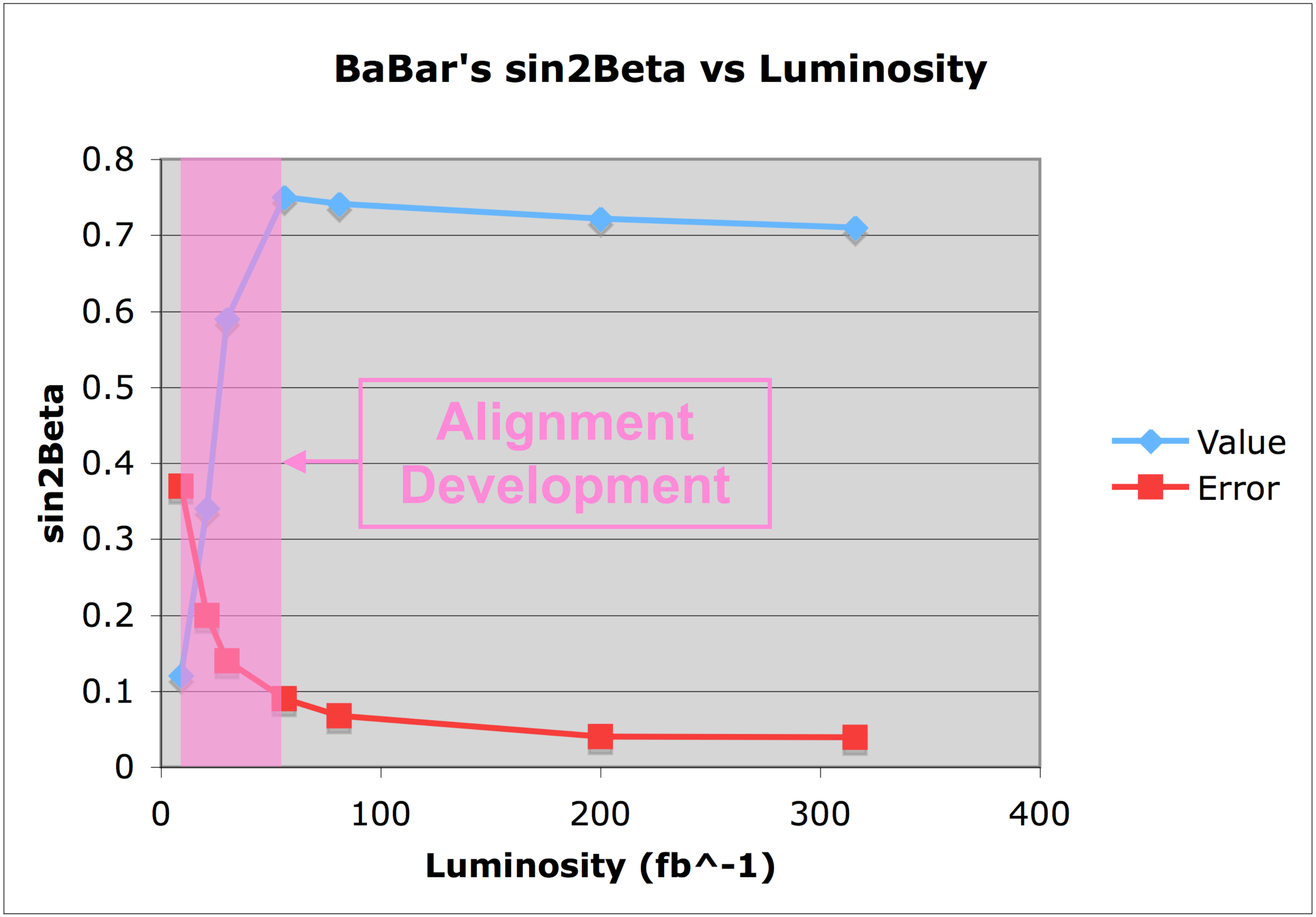
- **"The peak to peak variation of the reconstructed decay length vs ϕ is consistent with just natural lifetime fluctuations."**

A. Lusiani

Average τ 1-3 decay distance



BaBar's sin2β History



Si Alignment Lessons Learned

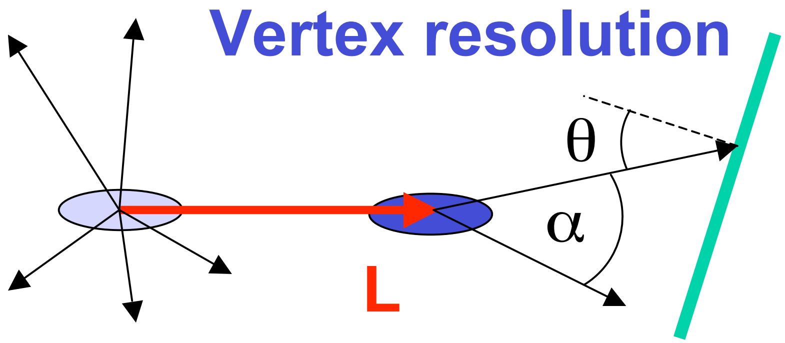
- **Detector Design**
  - **Prioritize material, resolution, stability**
  - **Simulate alignment to optimize overlap, layer coverage, …**
- **Construction**
  - **Make Lab-bench measurements of all components**
    - Survey aggregate sensor units (module, ladder, …) in 3-D
    - Measure material properties of all active-region components
      - Si thickness, material of hybrids, location of masking, …
  - **Assembly survey as a cross check (if practical)**
- **Software Design**
  - **Data model support for alignment**
    - Custom event selection, hit flagging, parameter constraints
  - **Kalman track fit alignment-specific features**
    - Pair fit, parameter constraint
  - **Allocate adequate manpower to alignment development**
- **Operations**
  - **Allocate dedicated processing and storage for alignment**

Lessons Learned (continued)

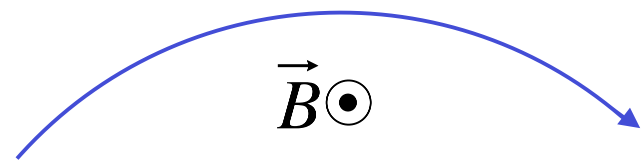
- **Procedure**
  - **Accurately represents the true DOFs**
    - Consider non-planar distortions!
  - **Use complementary event types and external constraints**
  - **Prescale events to create a uniform, consistent data sample**
  - **Prescale and flag hits**
    - Reduce statistical correlations
    - Consistent and stable χ^2 calculations
  - **Validate against realistic distortion scenarios**
  - **Don't get hung up on mathematical details**
    - Any well-behaved, additive measure will probably work
    - Any minimization technique that converges will probably work
- **Physics Use**
  - **Plan for providing an early (preliminary) alignment**
  - **Provide analysts with a misalignment estimate**
- **Be prepared for the unexpected!**

Backup Slides

How Well To Align?



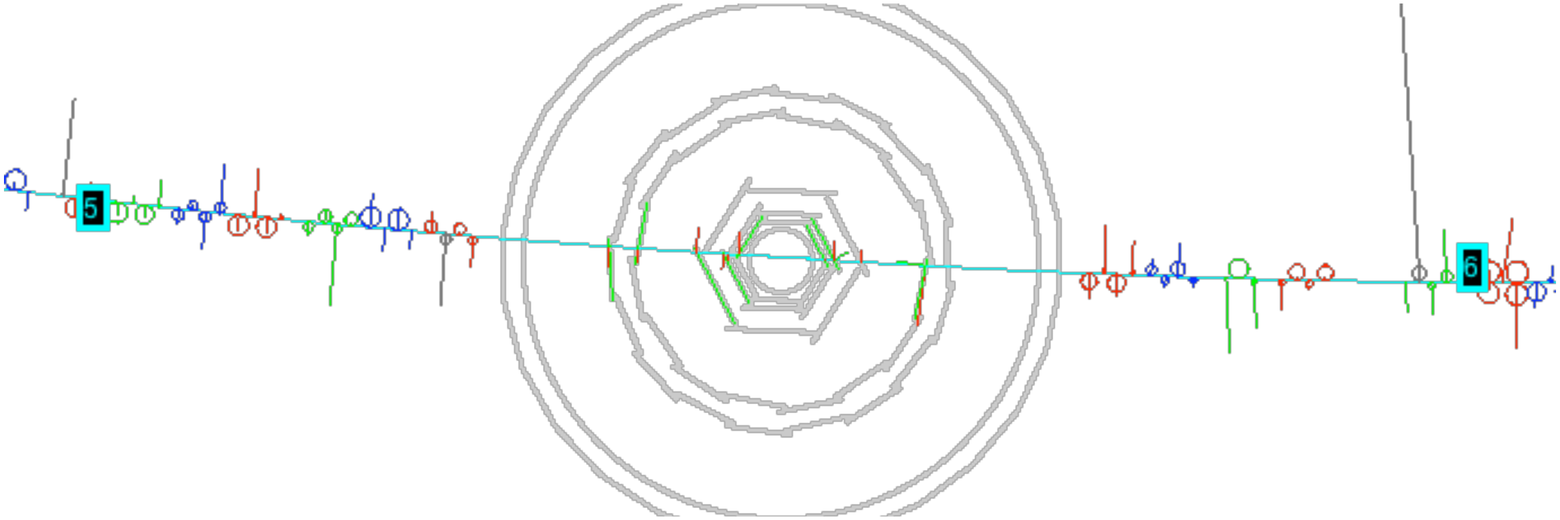
$$\delta L \approx \frac{\dfrac{\delta_x}{0.7\sqrt{N}} \oplus \dfrac{R_{\min} 14\,Mev\sqrt{\Delta / X_0}}{P\sin^{3/2}\theta}}{\alpha}$$



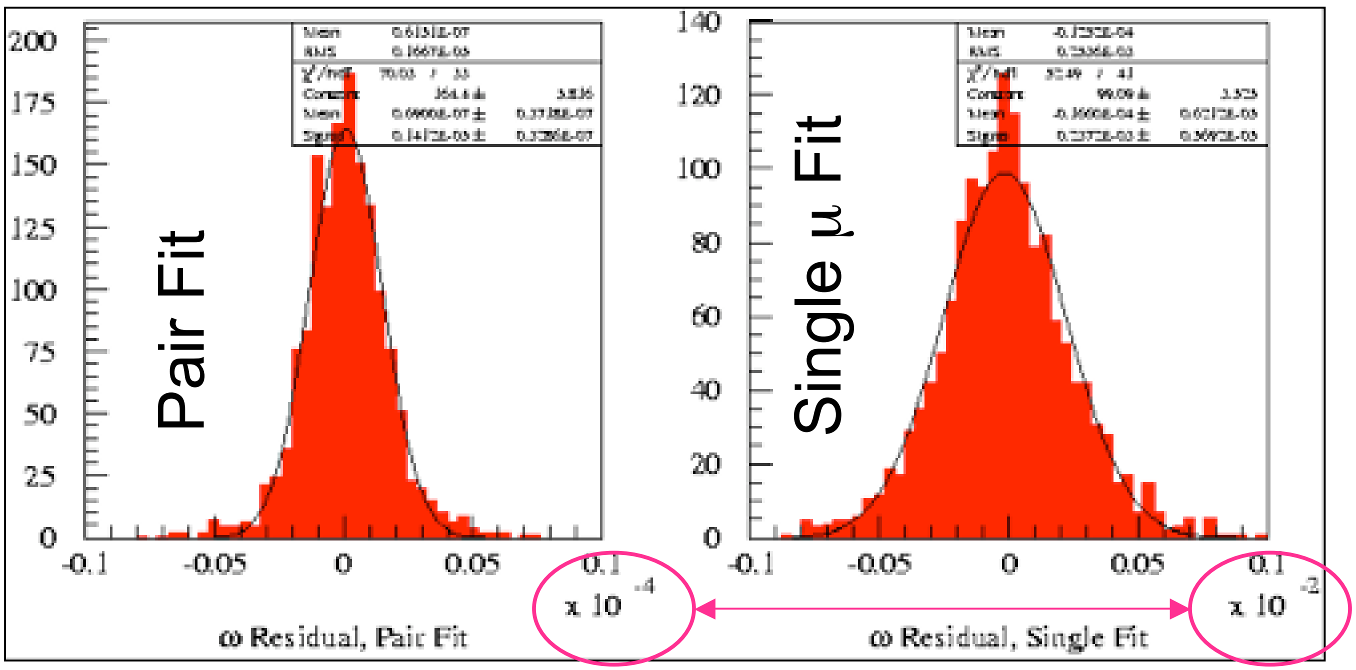
$$\frac{\delta P_t}{P_t^2} \approx \frac{\delta_x\sqrt{720/(N+5)}}{0.3L\int \vec{B}\times\overrightarrow{dL}} \oplus O(1/P)$$

- **Statistical (< 5% from alignment)**
  - **$\delta_{in\text{-}plane} < \delta_x/3$**
  - **$\delta_{out\text{-}of\text{-}plane} \sim \delta_{in\text{-}plane}/\theta$**
- **Systematic (no visible biases)**
  - **Roughly 3-times better than statistical *on average***

Pair Fit Results

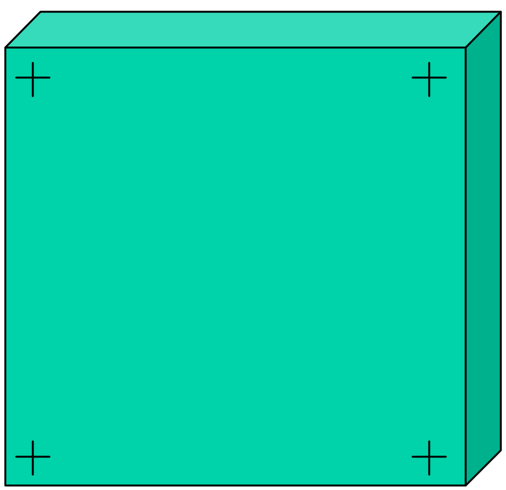


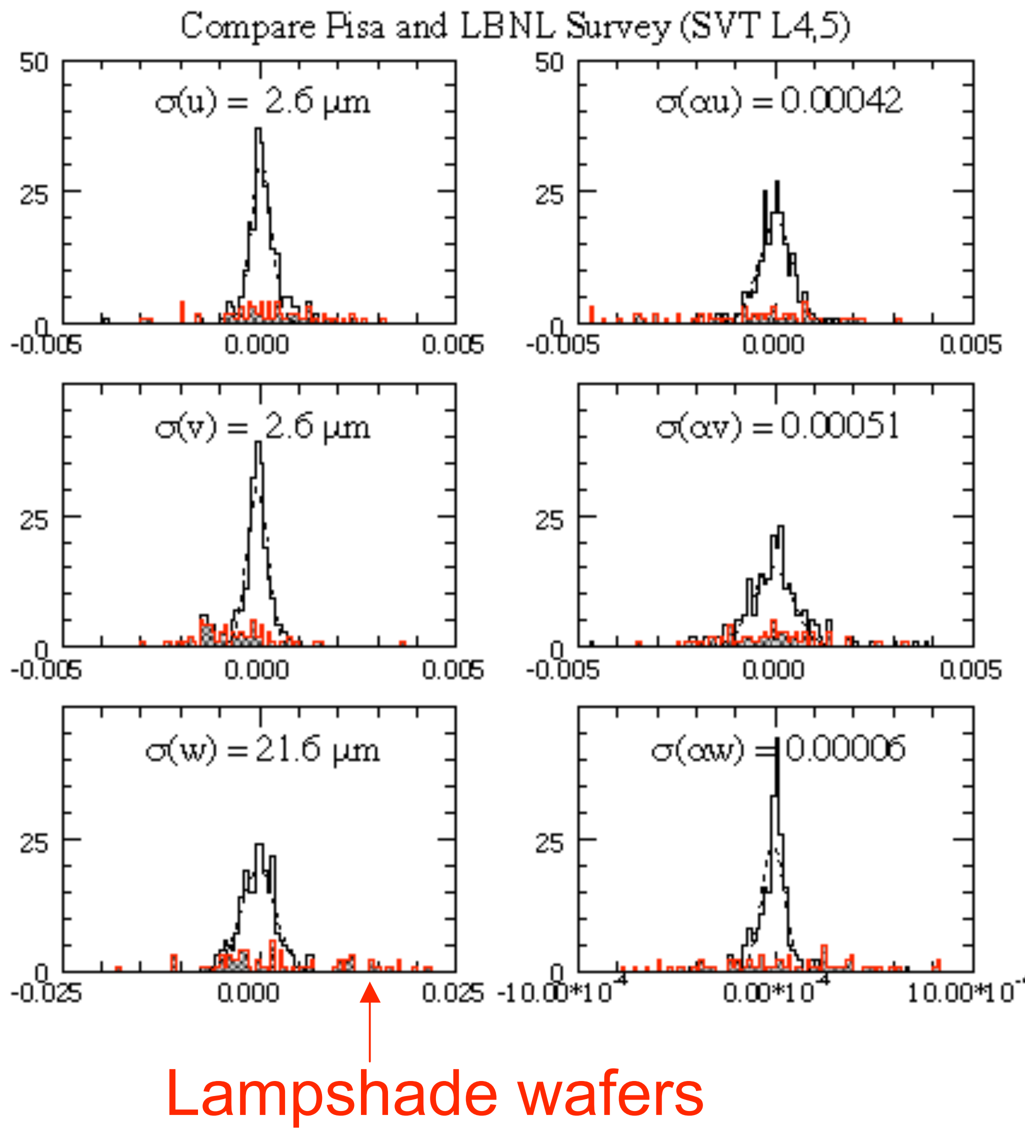
- **Curvature resolution improves >2 orders of magnitude!**
- **Constrains relative dip angle (through boost)**



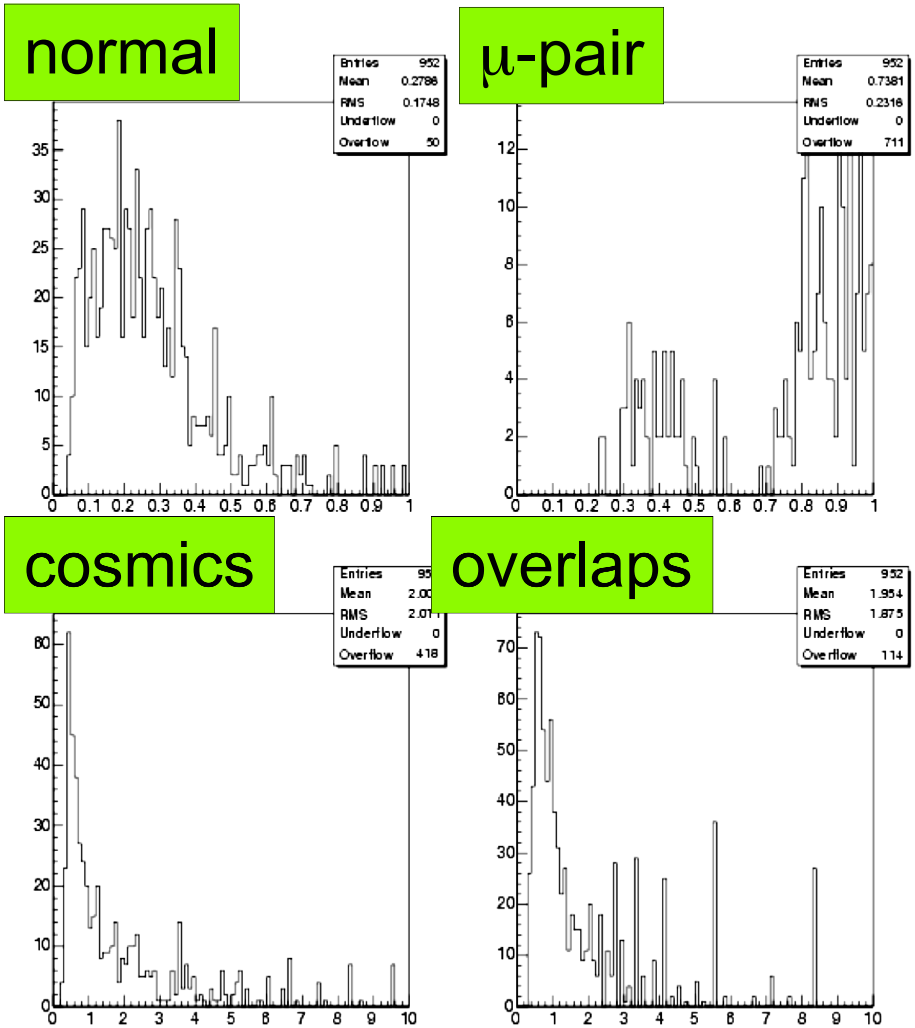
Lab⇔Assembly Survey Comparison

- **Compare at fiducials**
  - ✦ **Remove global DOFs**
- **<3μm in plane**
  - ✦ **~1μm statistical**
- **~20μm out of plane**
  - ✦ **~10μm statistical**
- **Average these when used in alignment**



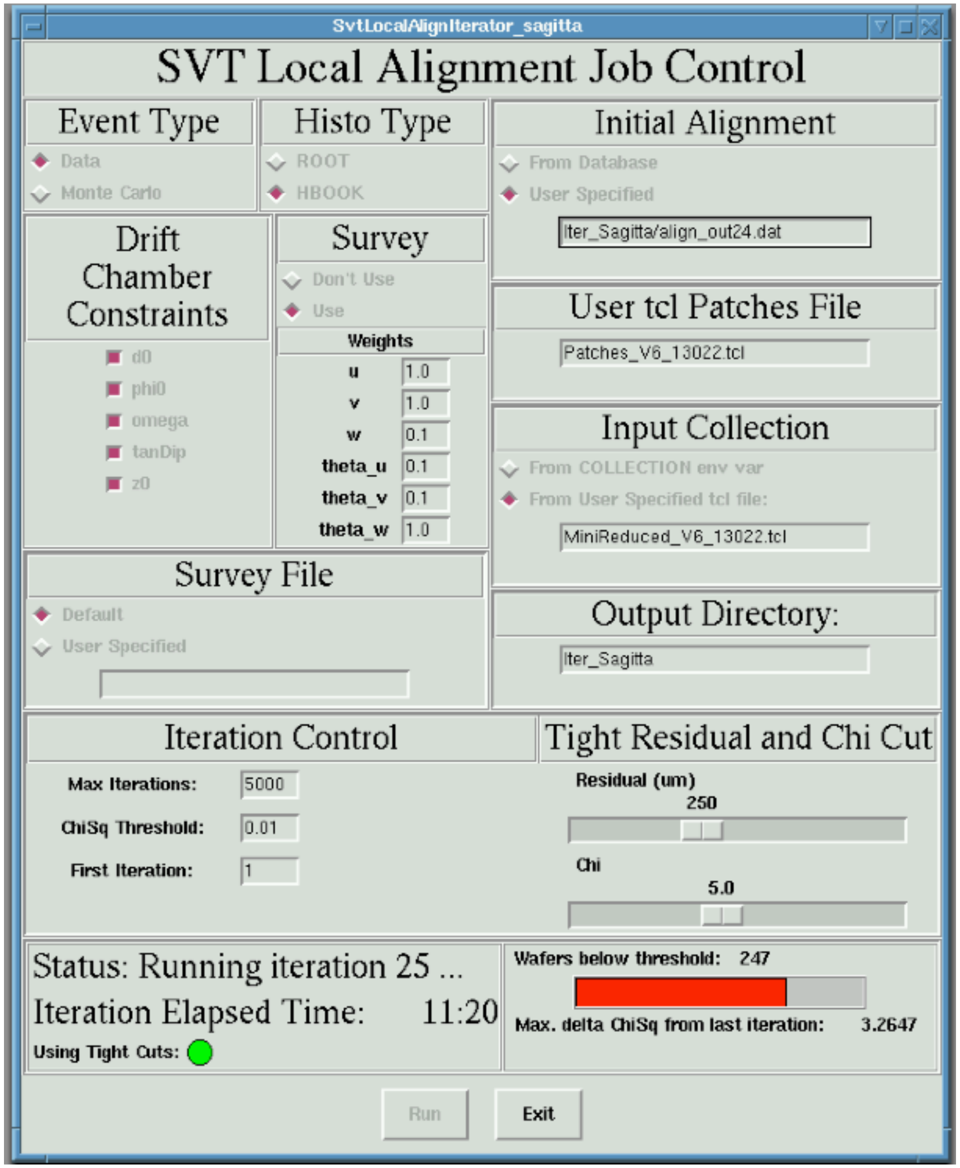


Event and Hit Prescaling



- **Prescale events by category**
  - **$\mu^+\mu^-$, cosmic, overlap track, …**
- **Prescale hits on each track**
  - **Uniformly populate wafers**
  - **Sample data period uniformly**
  - **Balance different event types**
  - **Eliminate statistical correlation between wafers**
- **Flag selected hits**
  - **The exact same hits are used to calculate χ^2 every iteration**
  - **Can (anti-)select hits when validating**
  - **Written into the data**
- **Overlaps are under-populated**
  - **1.5% nominal overlap in layer 4**

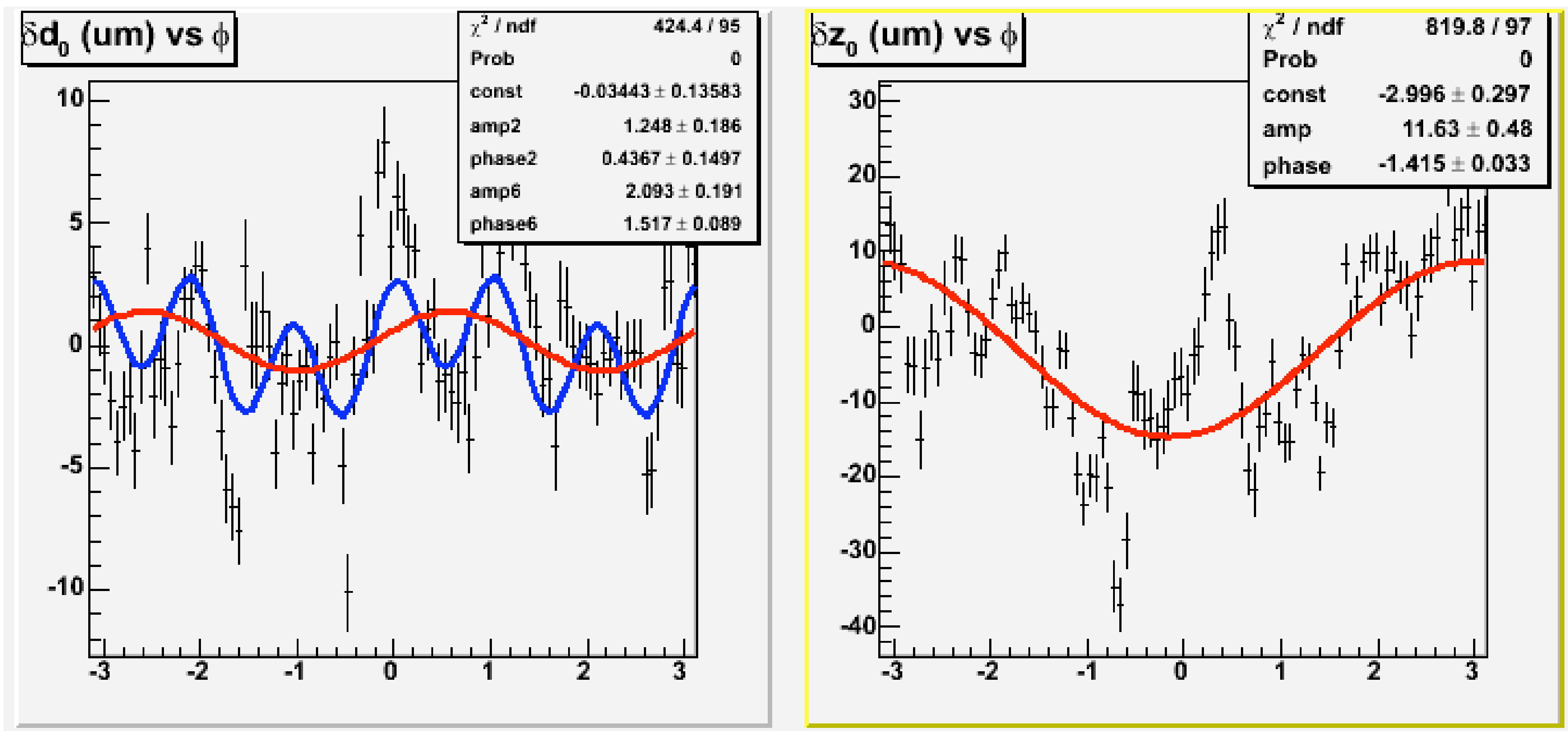
Iteration Control



- Iteration is controled by tcl scripts with tk window
  - Parameters can be adjusted
  - Job progress is monitored
- Typical job converges in ~100 iterations and takes ~ 24 hours

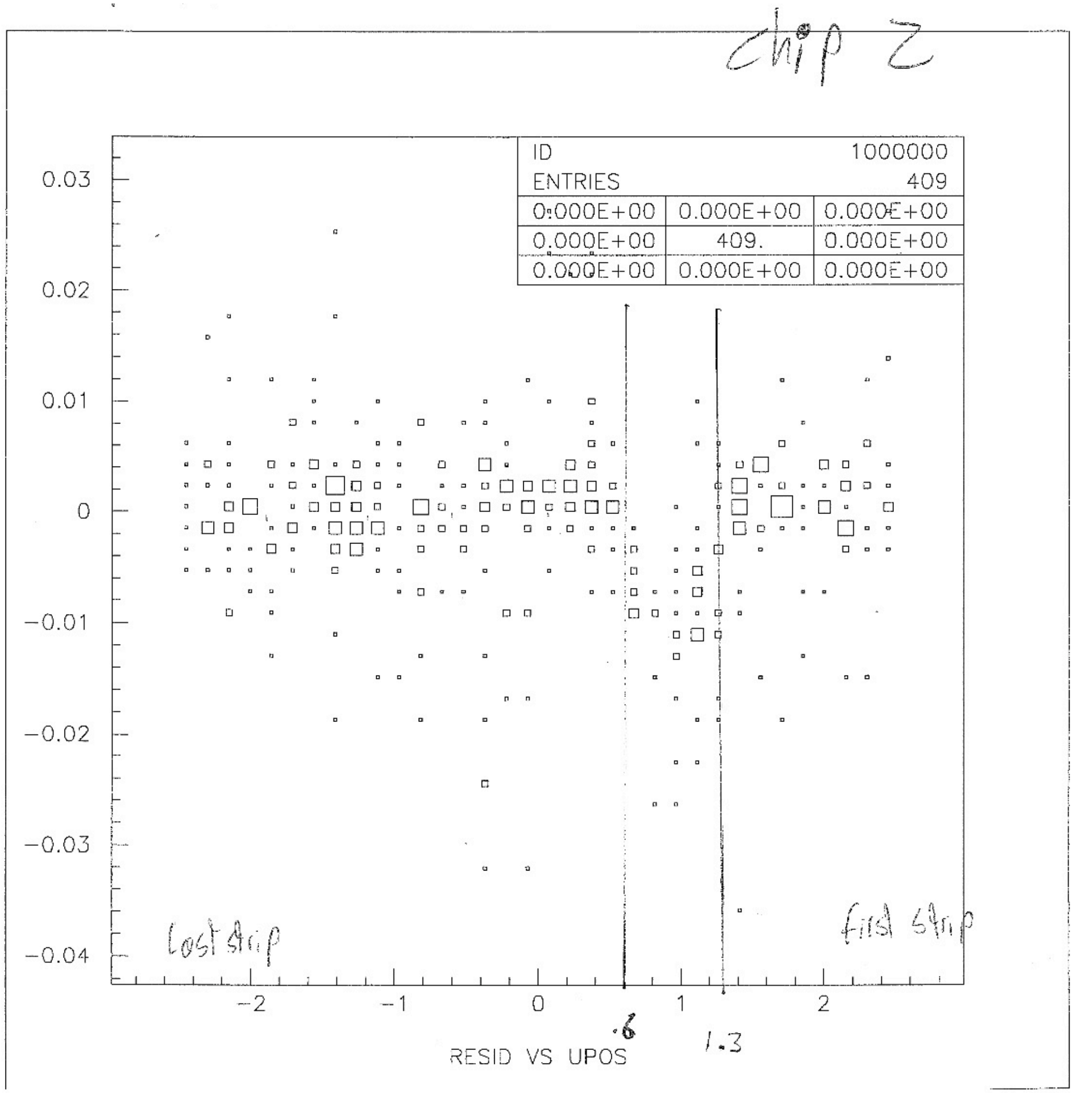
μ-pairs after Curvature Correction

- **Average distortion reduced to ~2 μm in Σd_0, ~10 μm in Δz_0**
- **With 10X data, structure is seen!**



Σd_0 Δz_0

Aleph VDET bonding error



Residual (cm)

Track position on wafer (cm)