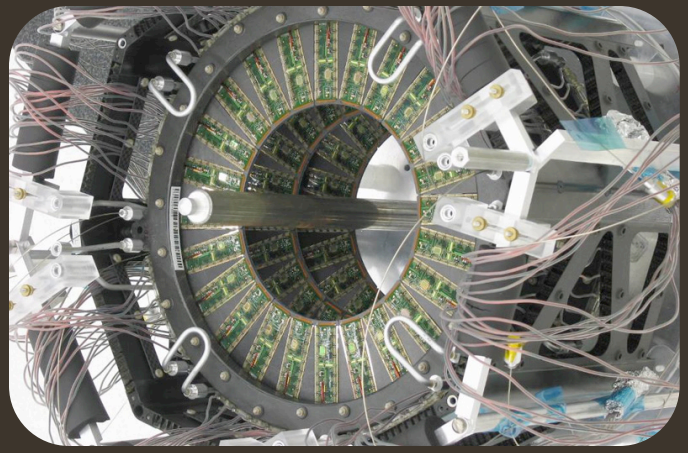
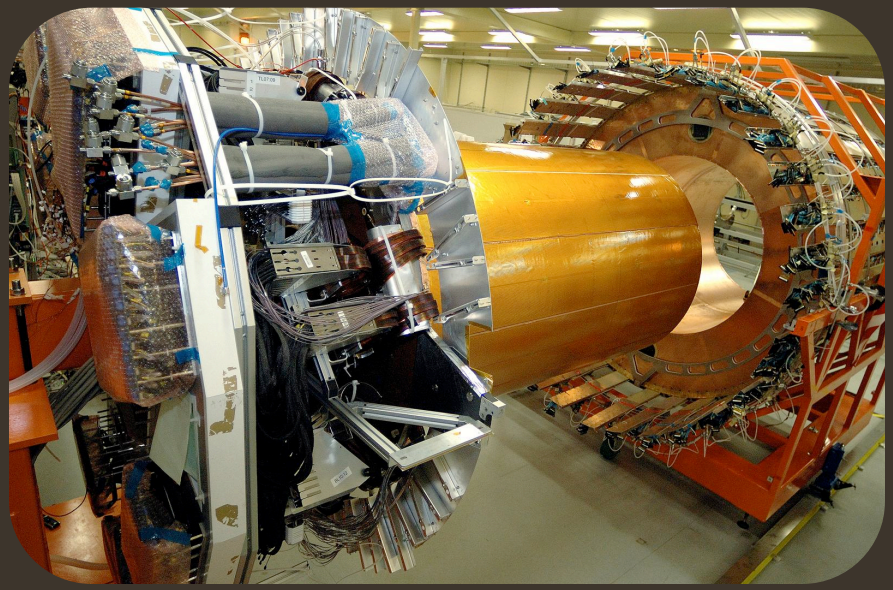
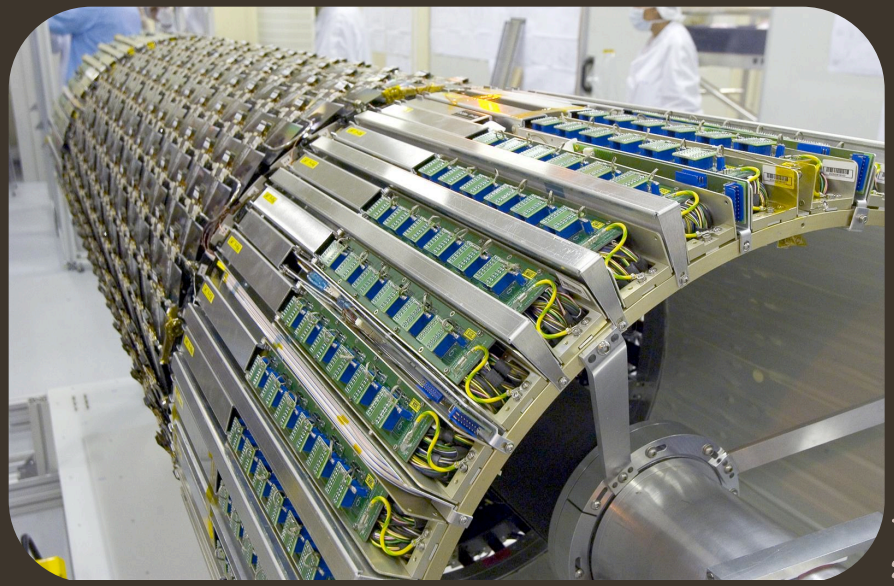


EPS HEP 2009 – Kraków



Alignment of the ATLAS Inner Detector Tracking System

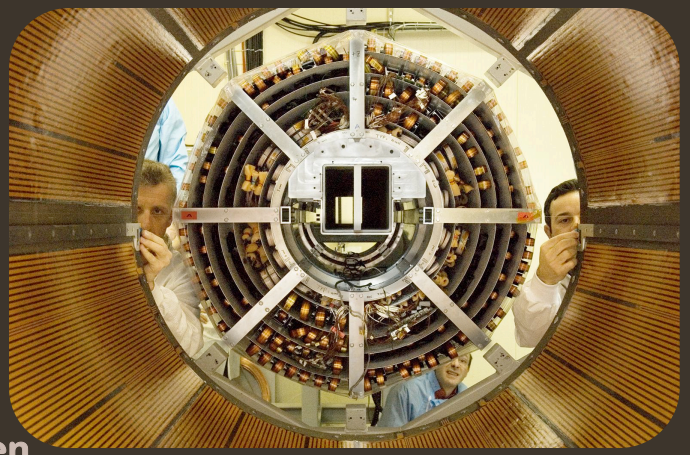


Oleg Brandt[1,2]

on behalf of the

ATLAS Collaboration

[1]Univ. of Oxford
[2]Univ. of Göttingen

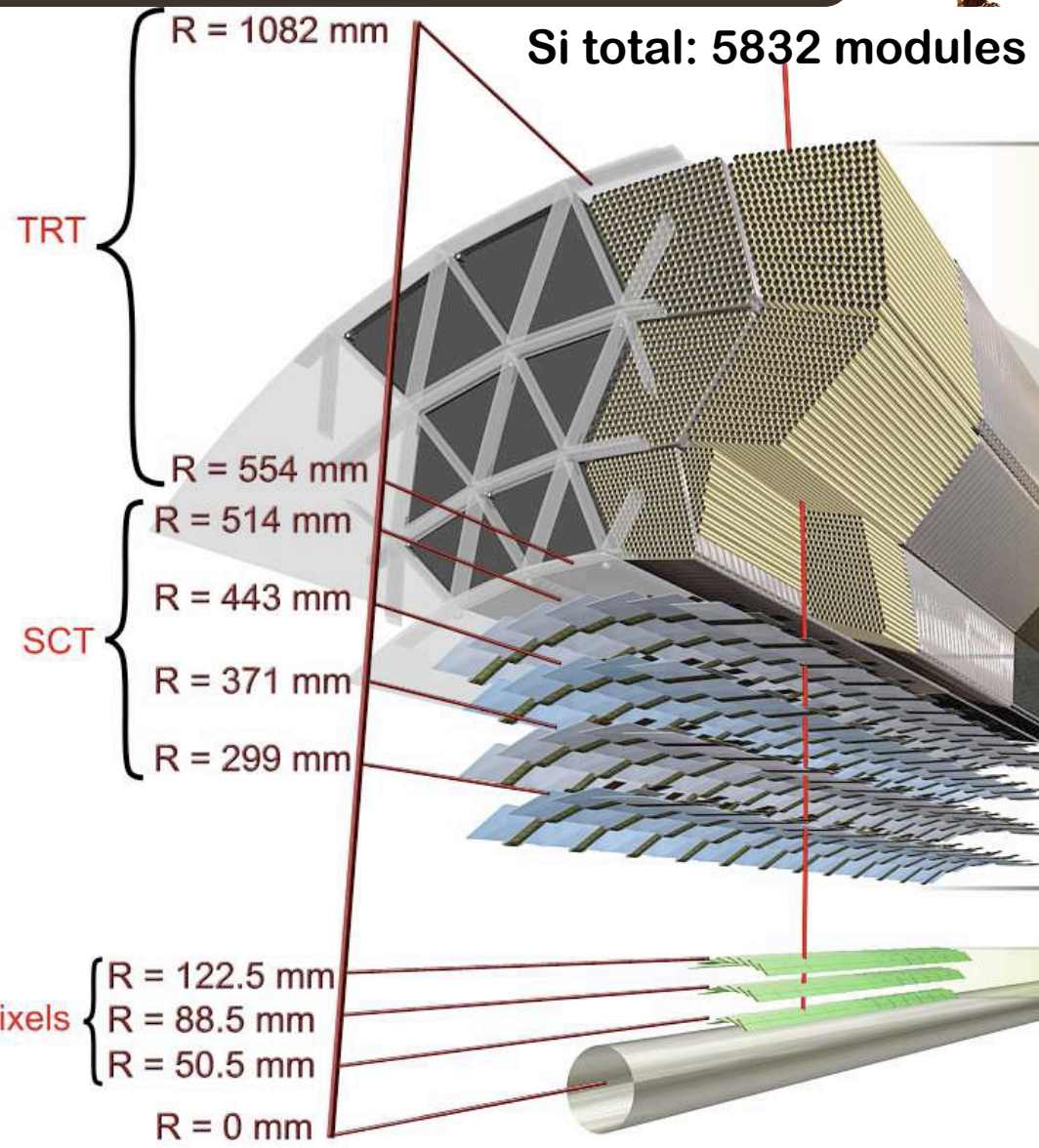


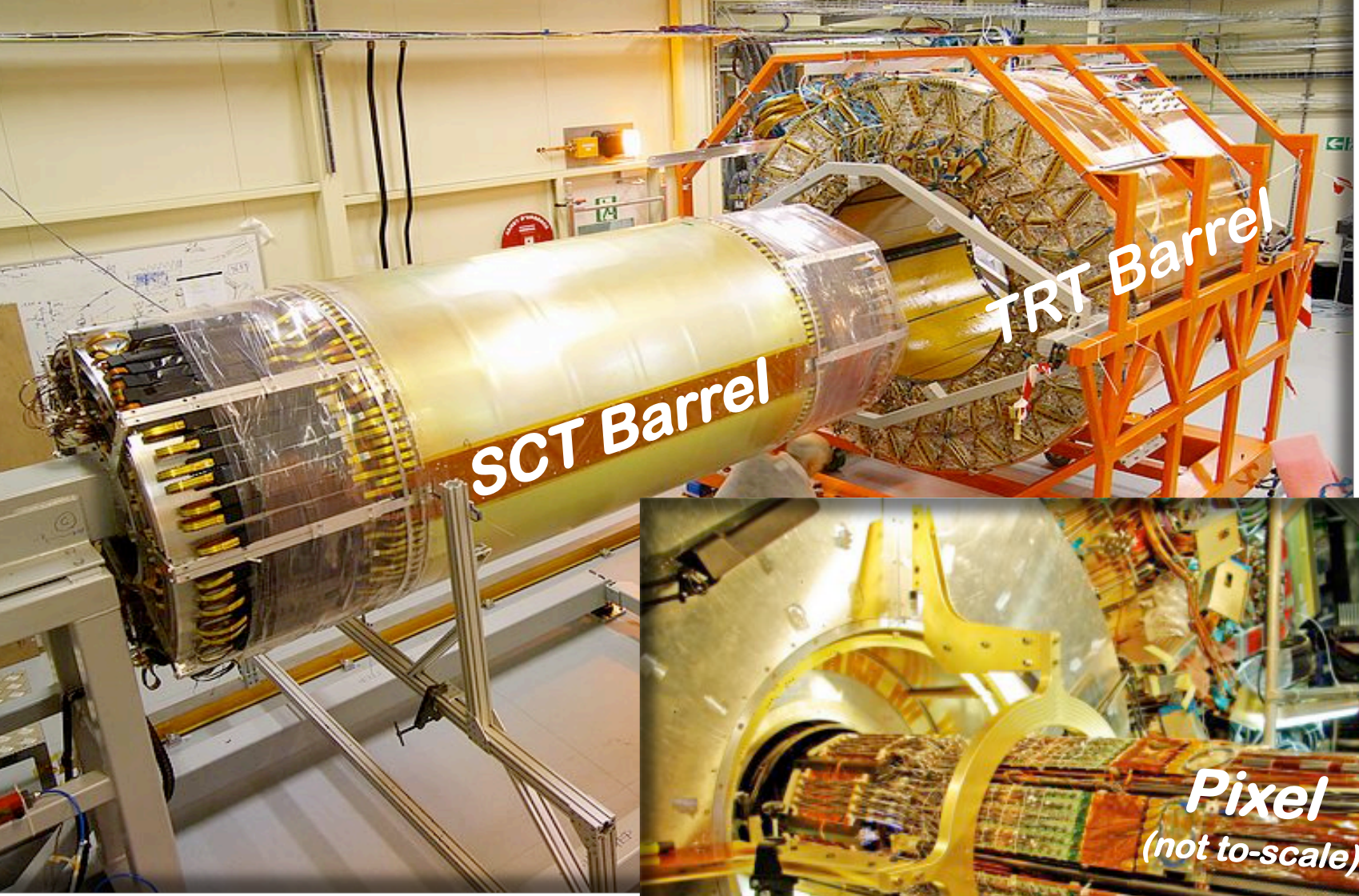
Today's Menu

- The Inner Detector (ID) of ATLAS:
  - Intrinsic resolutions
- The track-based alignment procedure
- Alignment with cosmic rays (autumn 2008):
  - Main results
- Alignment prospects for 2009+:
  - Impact of misalignments on physics
- Summary + Outlook
- Bonus slides:
  - (Fixing the momentum scale, monitoring, etc.)

ATLAS Inner Detector
Intrinsic Resolutions

- **TRT:**
  - Polyimide drift tubes
  - 992 modules:
    - Barrel: 3 rings, Σ 96 modules
    - ECs: 2x20 8-plane wheels
  - Intrinsic resolution: 130 μm (*R*–φ)
- **SCT:**
  - 40 mrad stereo p-n Si microstrips:
    - Nominal pitch: 80 μm
  - 4088 modules à 2 sides & 4 wafers:
    - Barrel: 4 layers, Σ 2112 modules
    - ECs: 2 x 9 rings, Σ 2 x 988 modules
  - Nominal resolution per module:
    - 17 x 580 μm² (*R*–φ x *z*)
- **Pixel:**
  - n-type oxygenated Si pixels:
    - Nominal size: 50 x 400 μm²
  - 1788 modules à 2 wafers:
    - Barrel: 3 layers, Σ 1456 modules
    - ECs: 2 x 3 rings, Σ 2 x 144 modules
  - Nominal intrinsic resolution:
    - 10 x 115 μm² (*R*–φ x *z*)



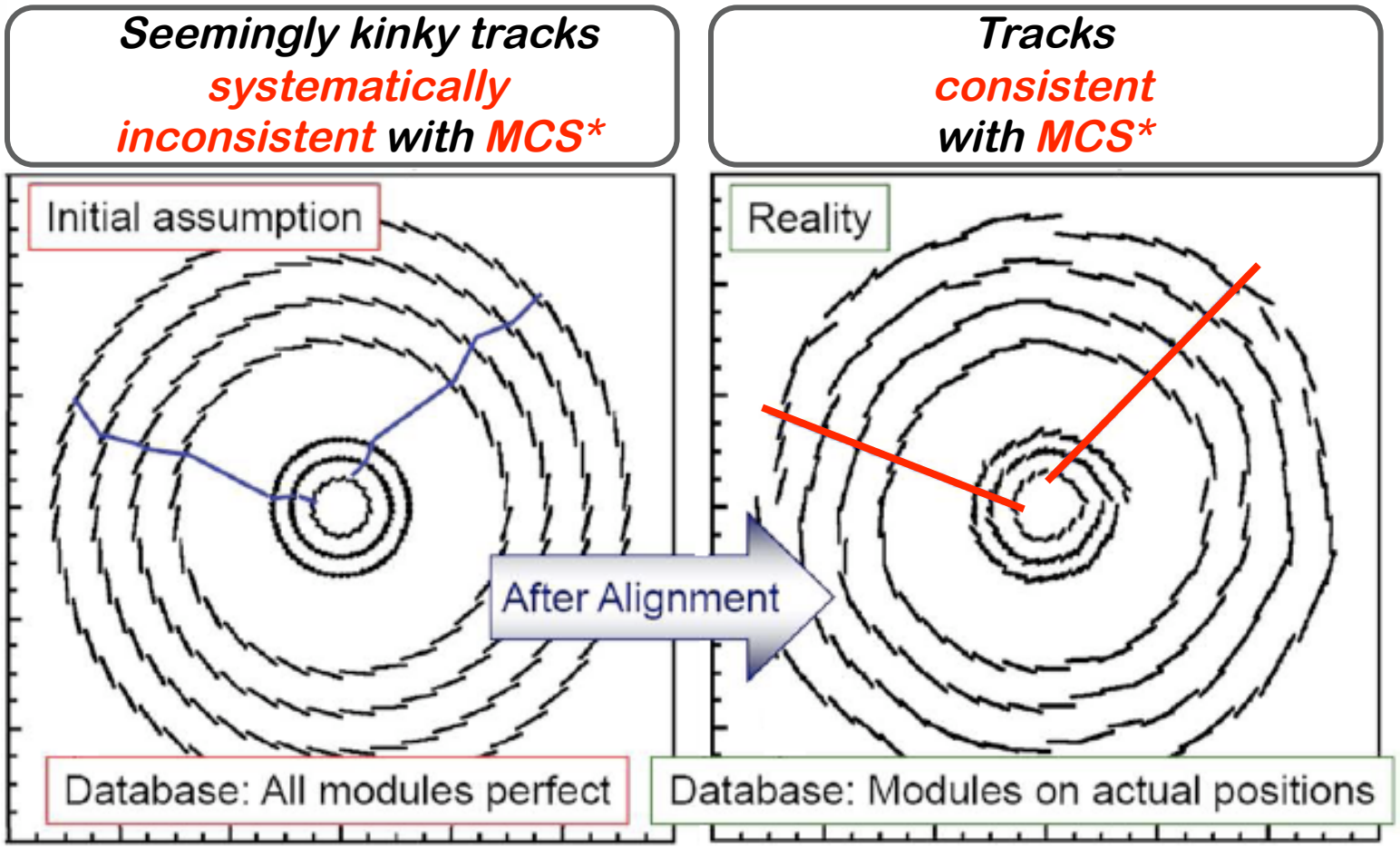

SCT Barrel
TRT Barrel

Pixel
(not to-scale)

Alignment Procedure @ ATLAS

- **References** *(+references therein)*:
  - **Si Global χ^2:** http://cdsweb.cern.ch/record/835270
  - **Si Local χ^2:** http://publications.mppmu.mpg.de/2005/MPP-2005-174/FullText.pdf
  - **Si Robust Alignment:** http://cdsweb.cern.ch/record/1061129
  - **TRT global χ^2:** http://cdsweb.cern.ch/record/1039585

Why Alignment?

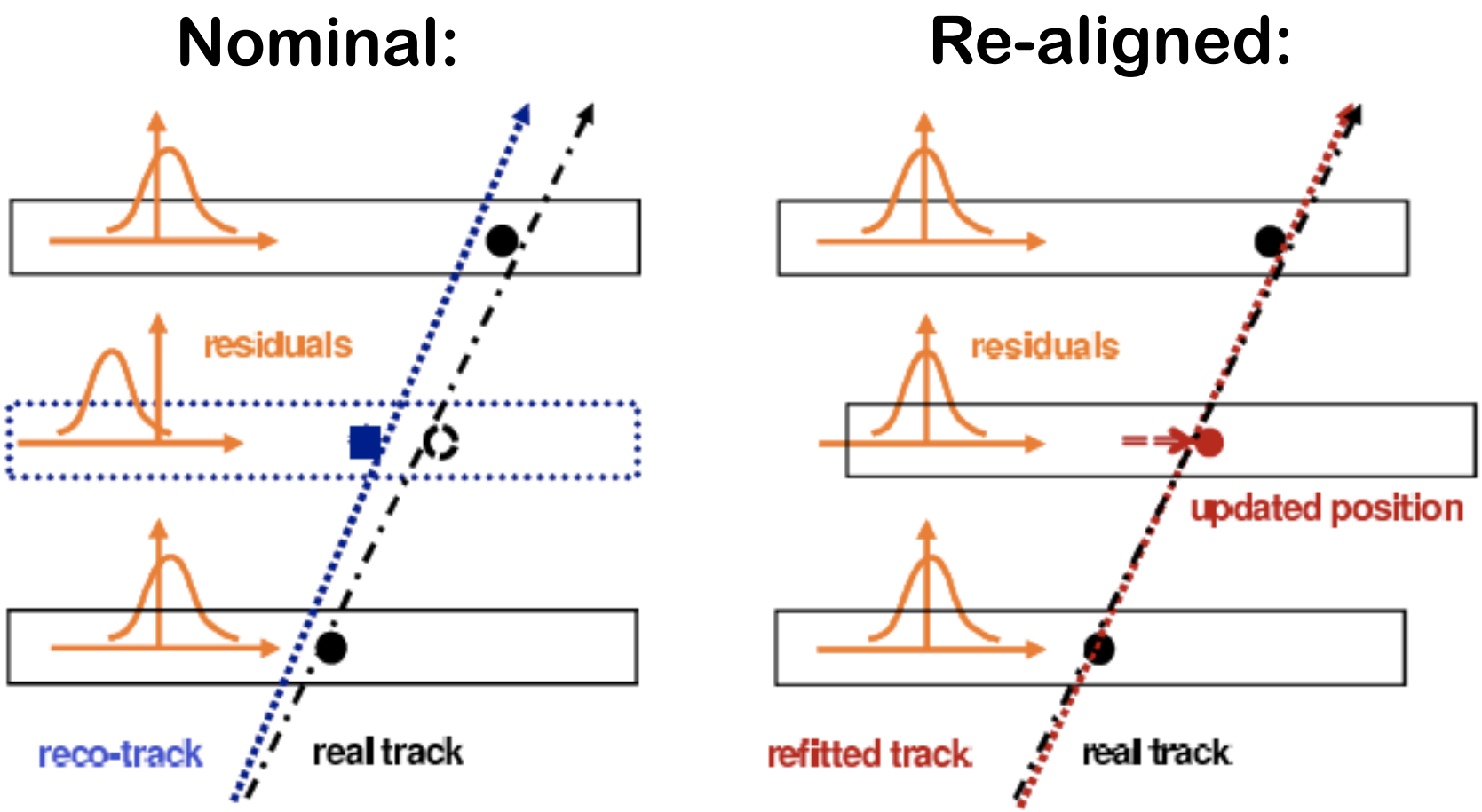


Cartoon: 100x exaggerated

- **Determine the position of modules:**
  - **Hardware-based methods (e.g. optical survey)**
  - **Track-based approaches**

* MCS: Multiple Coulomb Scattering

Track-Based Alignment: Residuals



Track-based alignment:
Optimisation of residual distributions!

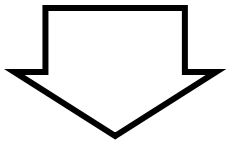
Alignment Goals

- Declared goal for alignment:
  - Degradation of tracking parameter resolution by < 20 % due to misalignments!
- Resulting alignment precision for random misalignments:
  - Pixels: *O*(7 μm)
  - SCT: *O*(12 μm)
  - TRT: *O*(30 μm)
- Initial misalignments at individual module level (barrel):
  - Pixels: *O*(500 μm)
  - SCT: *O*(100 μm)
  - TRT: *O*(100 μm)

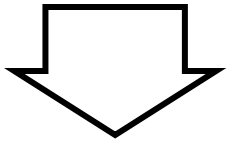
ATL-INDET-97-16035

Alignment Procedure

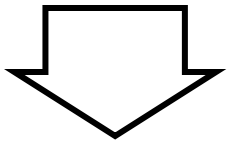
Beam Spot (first-pass) ← ALIGNMENT STREAM



Si Alignment



TRT Alignment



Beam Spot (final) ← PHYSICS STREAM

Constants to database?

Full loop: multiples of 24 h
Cross-checks on shorter time scale

Alignment Procedure

Beam Spot (first-pass)

ALIGNMENT STREAM

Si Alignment

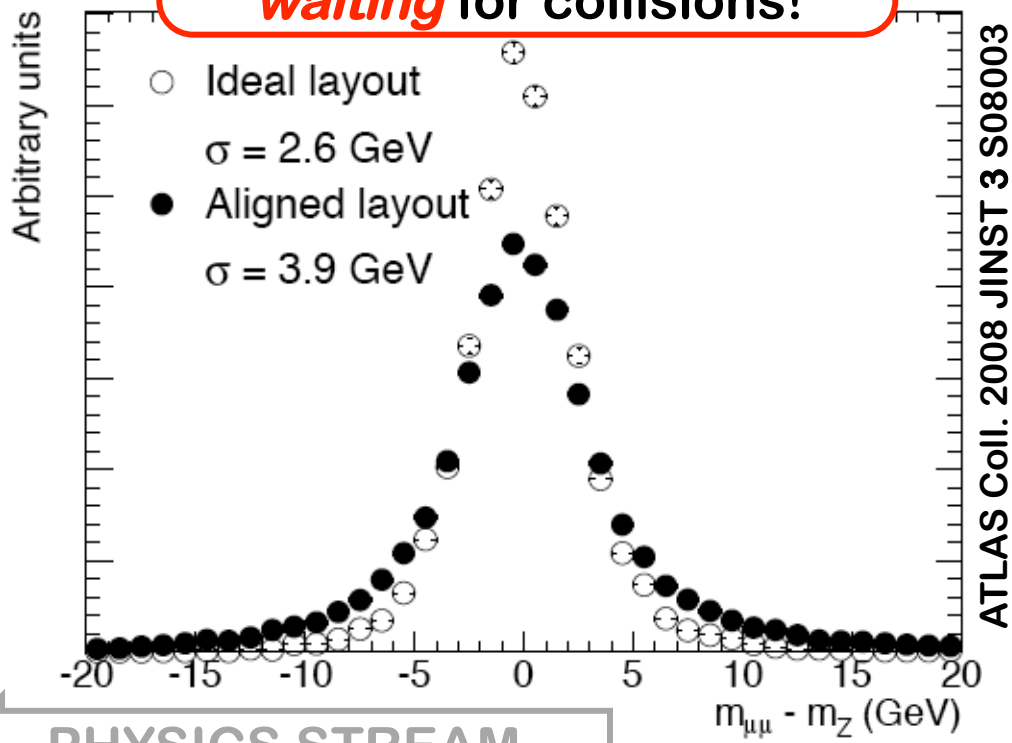
TRT Alignment

Beam Spot (final)

PHYSICS STREAM

Full loop: multiples of 24 h
Cross-checks on shorter time scale

Alignment procedure *validated* with MC and *waiting* for collisions!



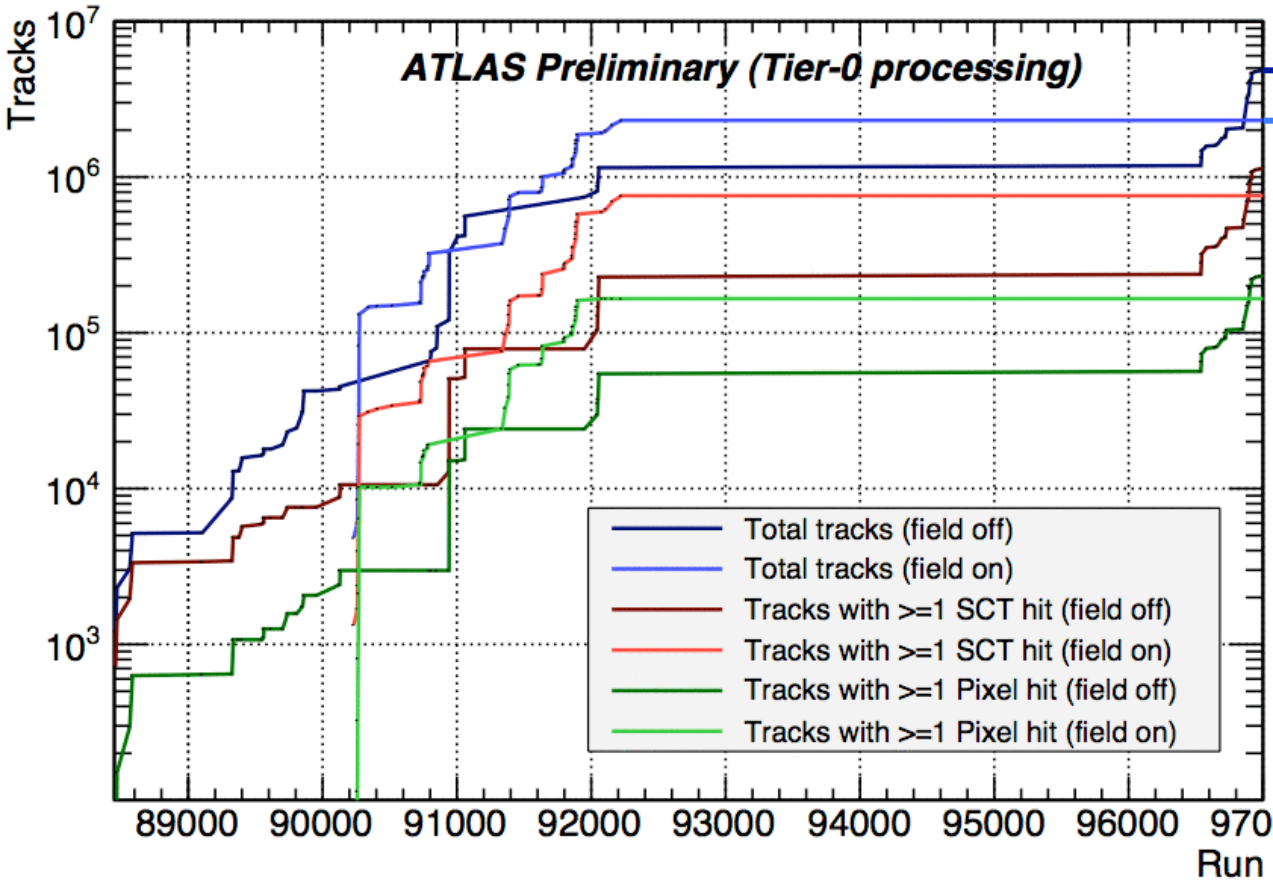
Constants to database?

Alignment with M8+ Cosmic Ray Real Data

- References *(+bonus slides)*:
  - http://indico.cern.ch/conferenceDisplay.py?confId=50502

Alignment with M8+ Cosmic Ray Data

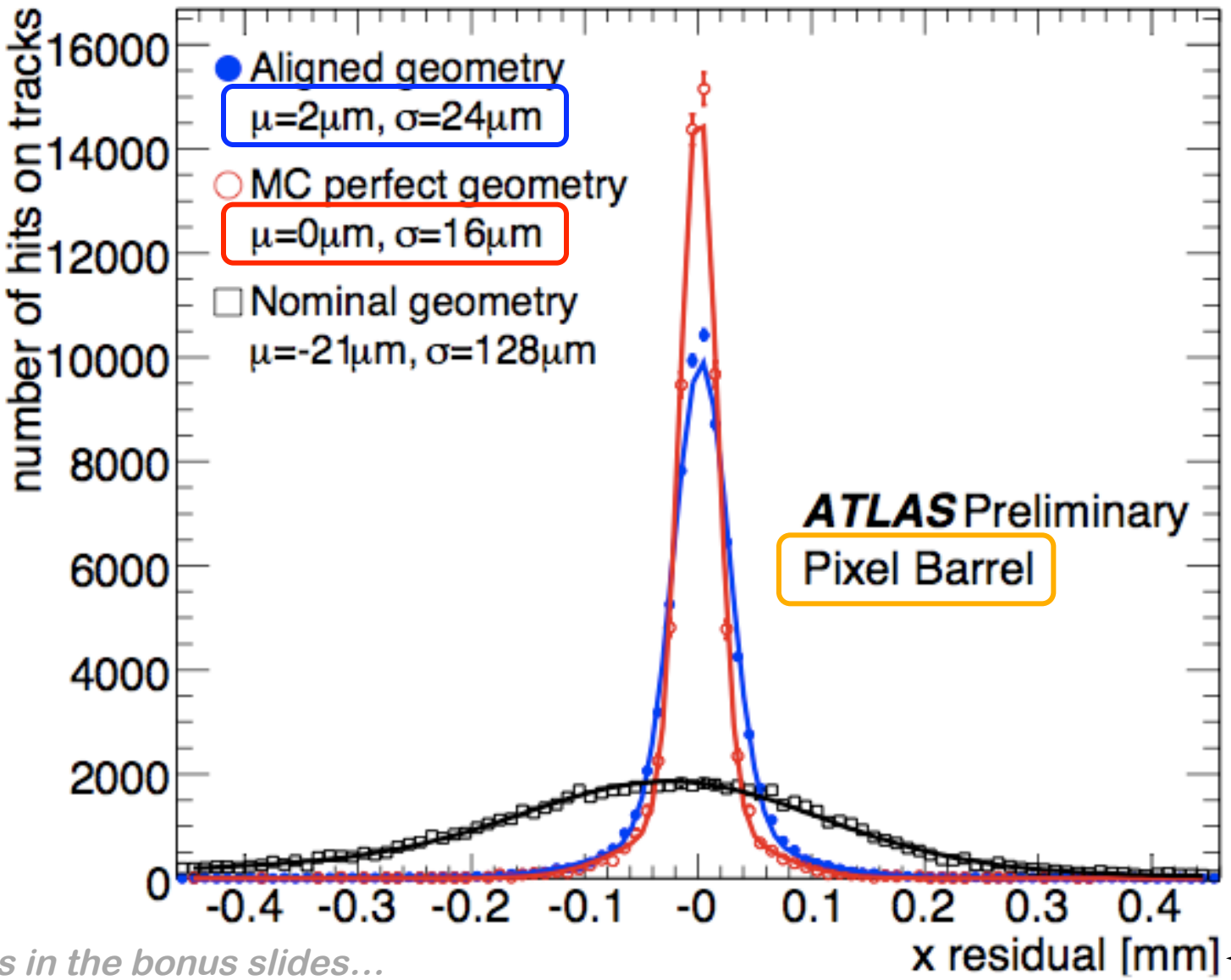
- **M8+**: ATLAS in 24/7 full operation mode Sept.-Dec. 2008!
  - Took cosmic ray data
  - Many lessons learnt (trigger, timing, noise, DAQ, calibration)



solenoid OFF
solenoid ON

- **Solenoid OFF:**
  - 5M ID tracks
  - 2M with SCT hits
  - 230k with Pixel hits
- **Solenoid ON:**
  - 2.6M ID tracks
  - 880k with SCT hits
  - 190k with Pixel hits

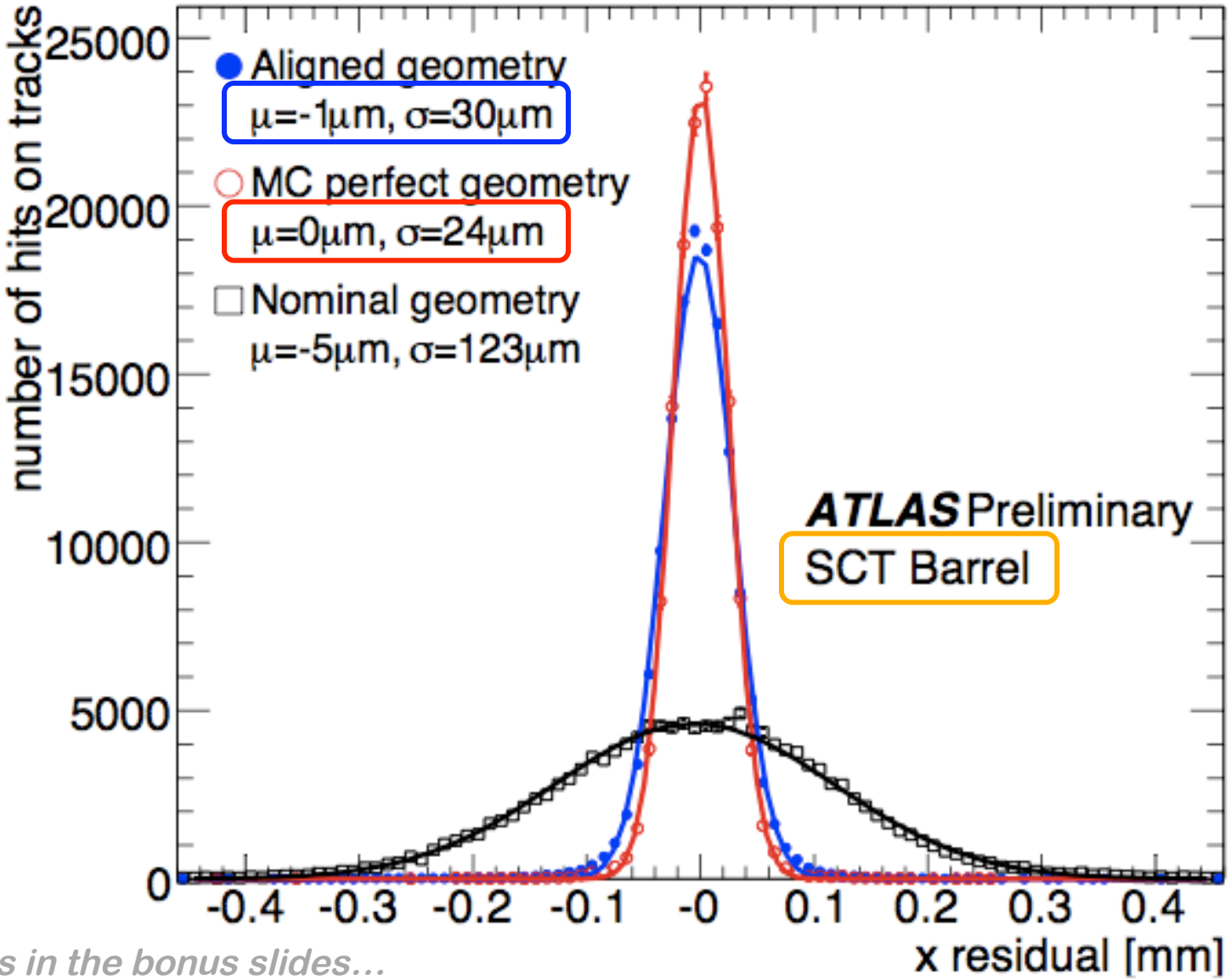
M8+ Alignment: Residuals (Pixel)



In *local* module frame

MORE plots in the bonus slides…

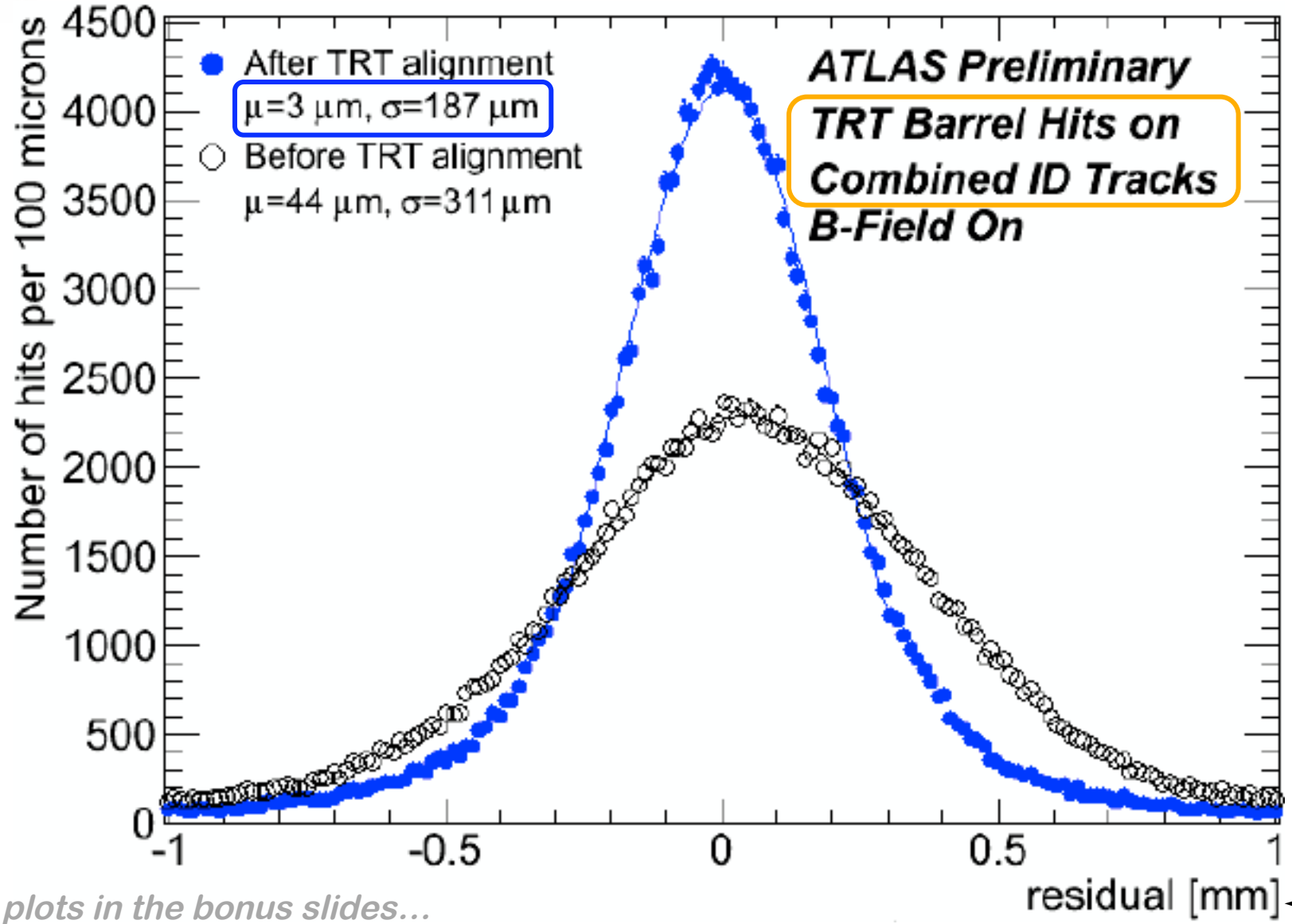
M8+ Alignment: Residuals (SCT)



In *local* module frame

MORE plots in the bonus slides…

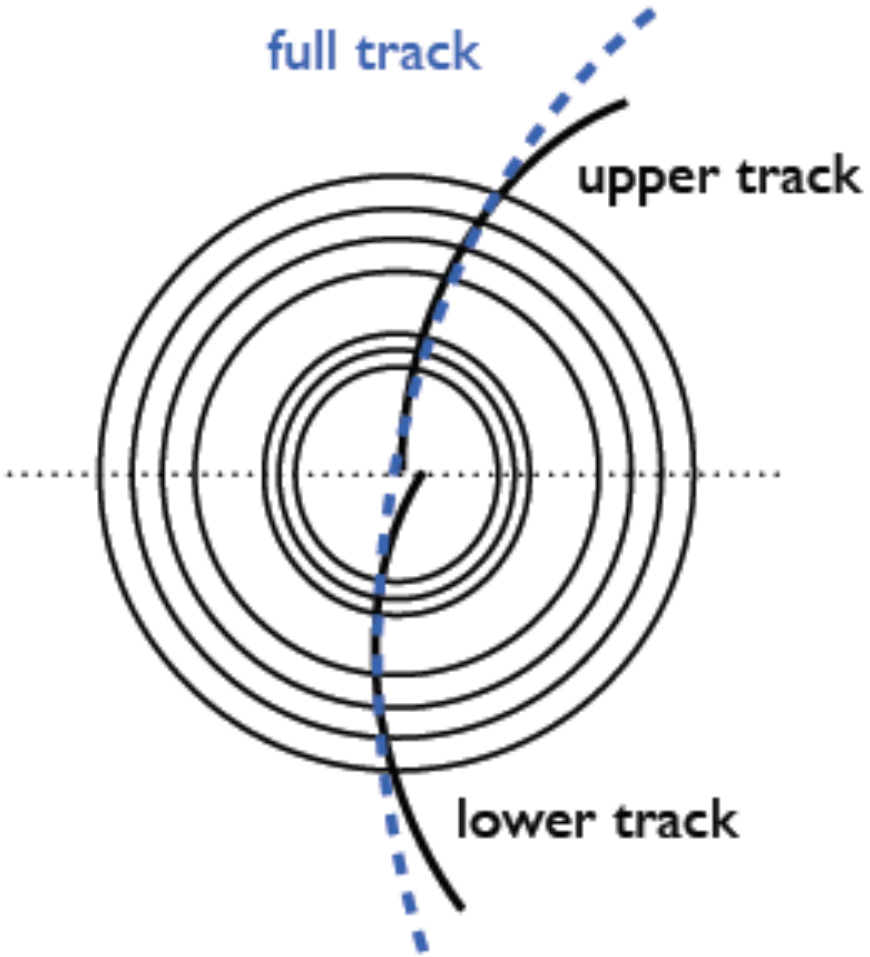
M8+ Alignment: TRT-SCT



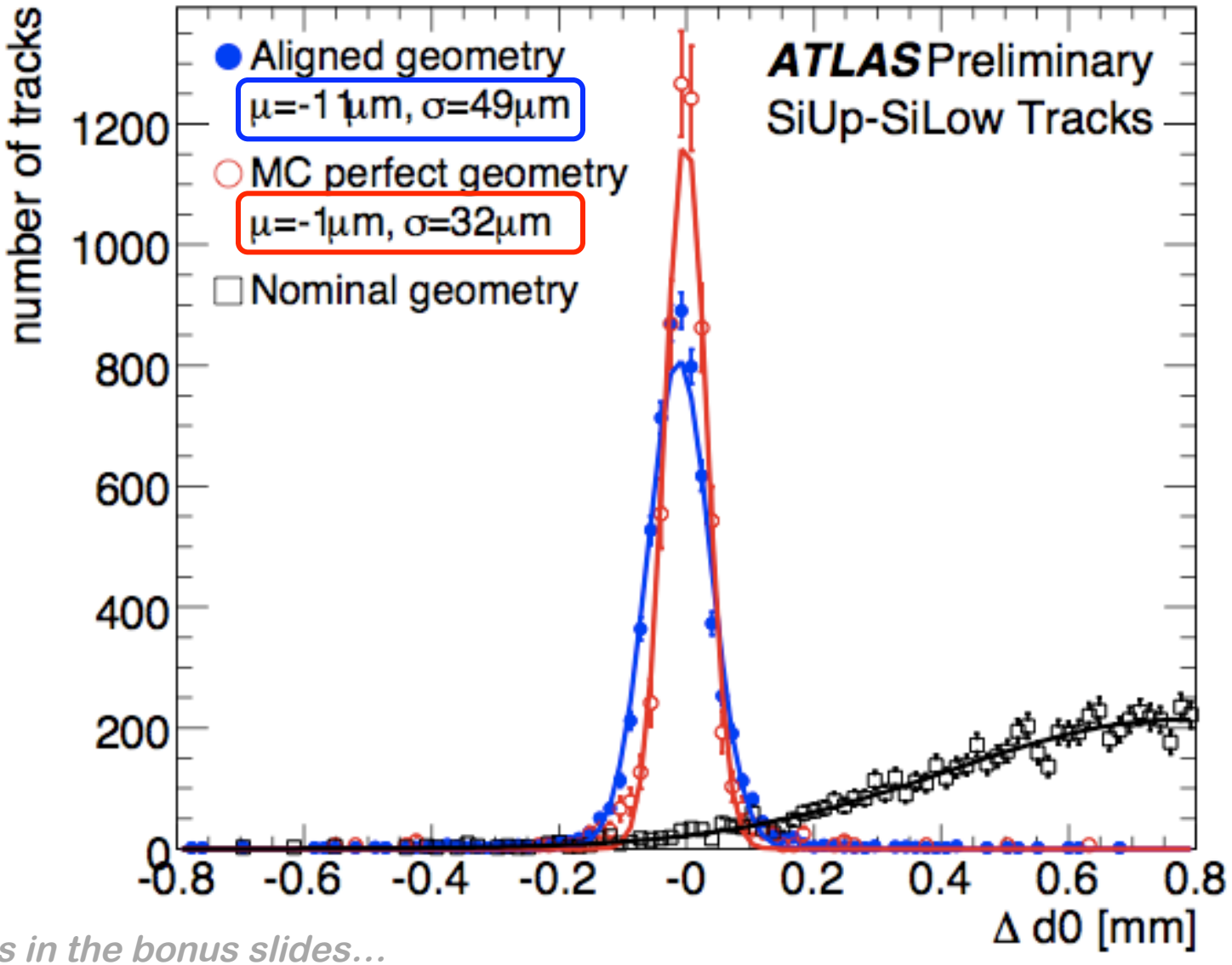
MORE plots in the bonus slides…

M8+ Cosmics Alignment: Performance

- Use track segment matching for alignment validation
- Estimate uncertainty and bias in track parameter reco:
  - Split track in 2 halves
  - Refit each
  - Compare track parameters:
    - d_0, z_0, ϕ, θ, q/p

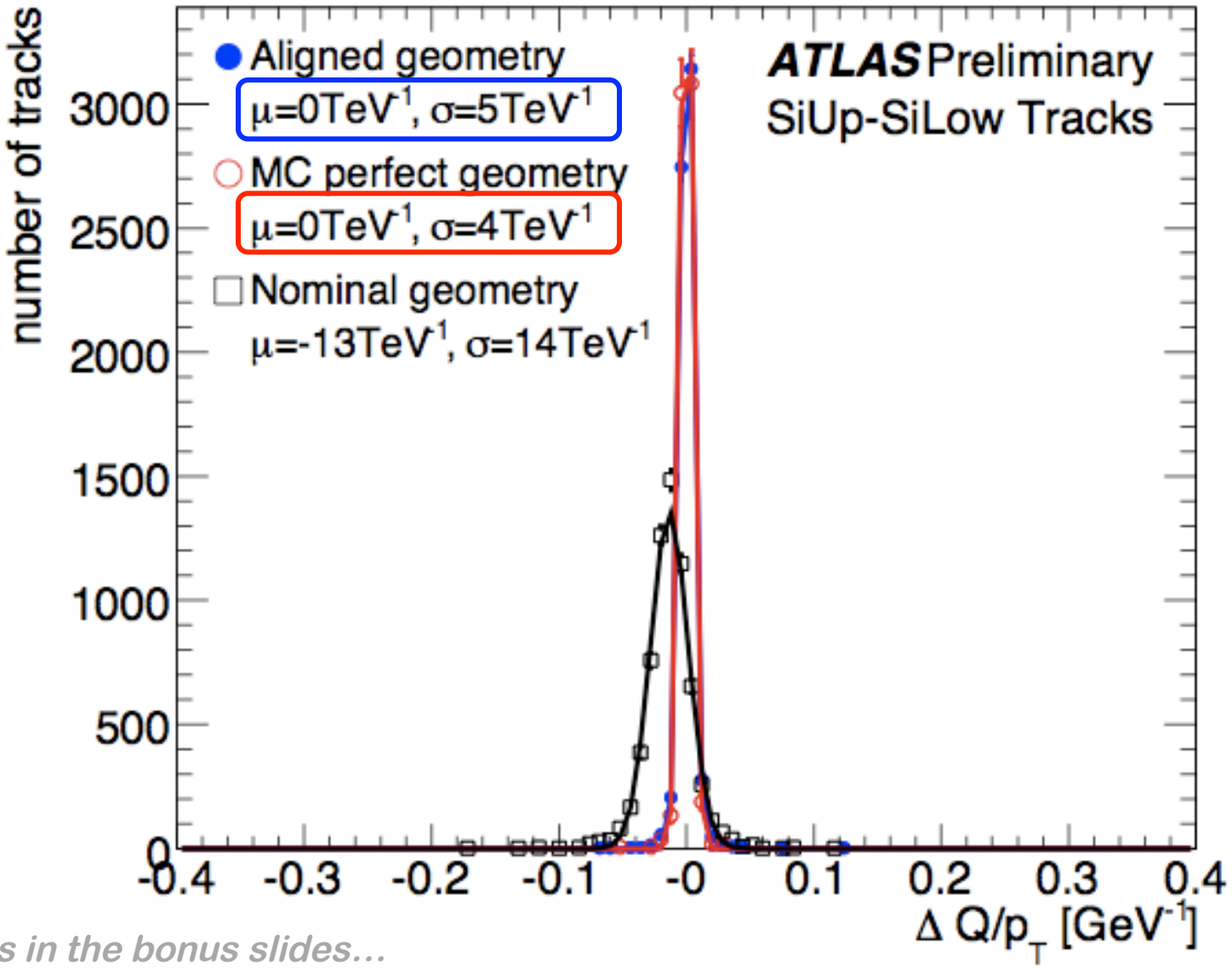


M8+ Alignment: Impact Parameter



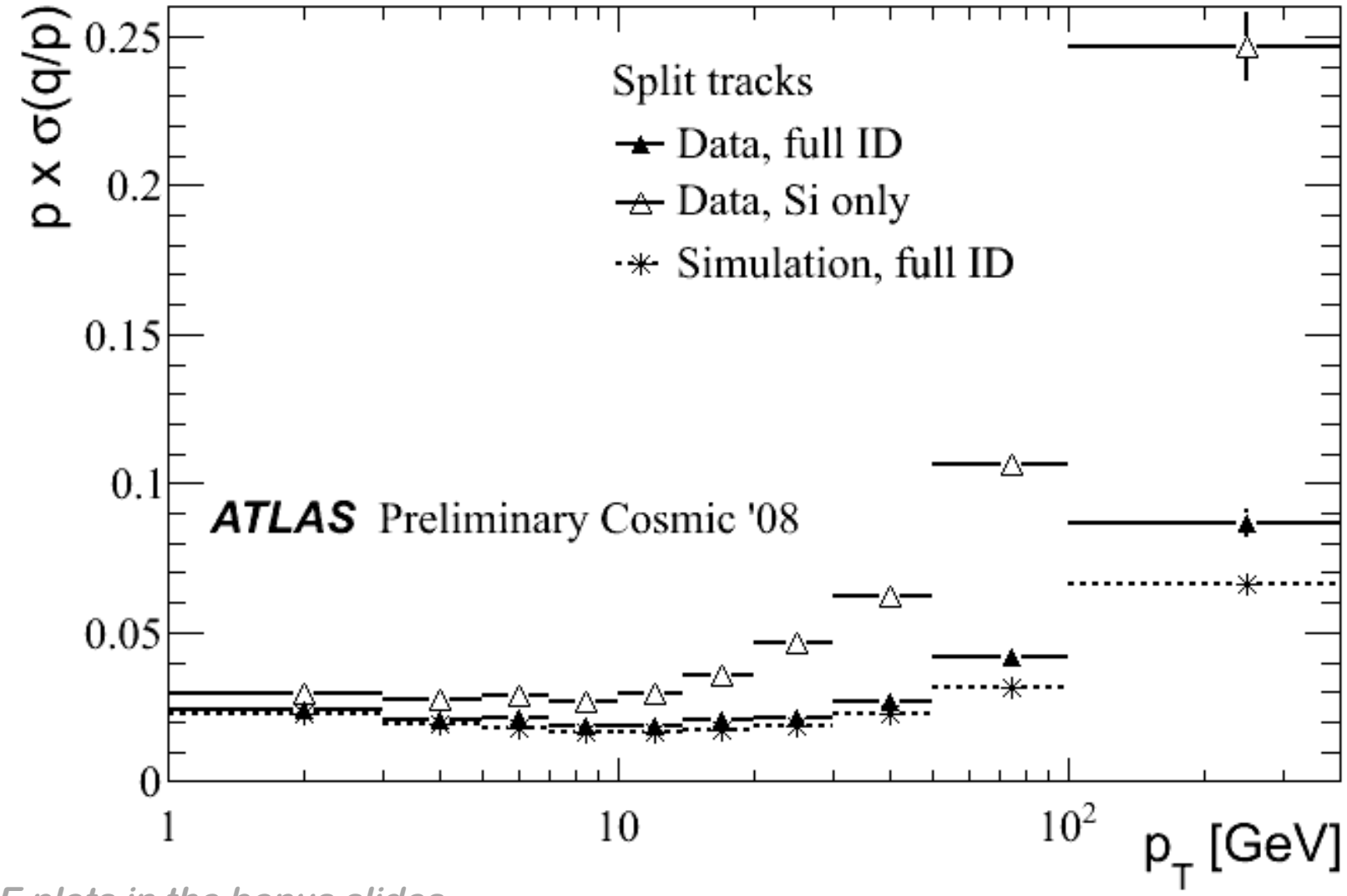
MORE plots in the bonus slides…

M8+ Alignment: q/p_T



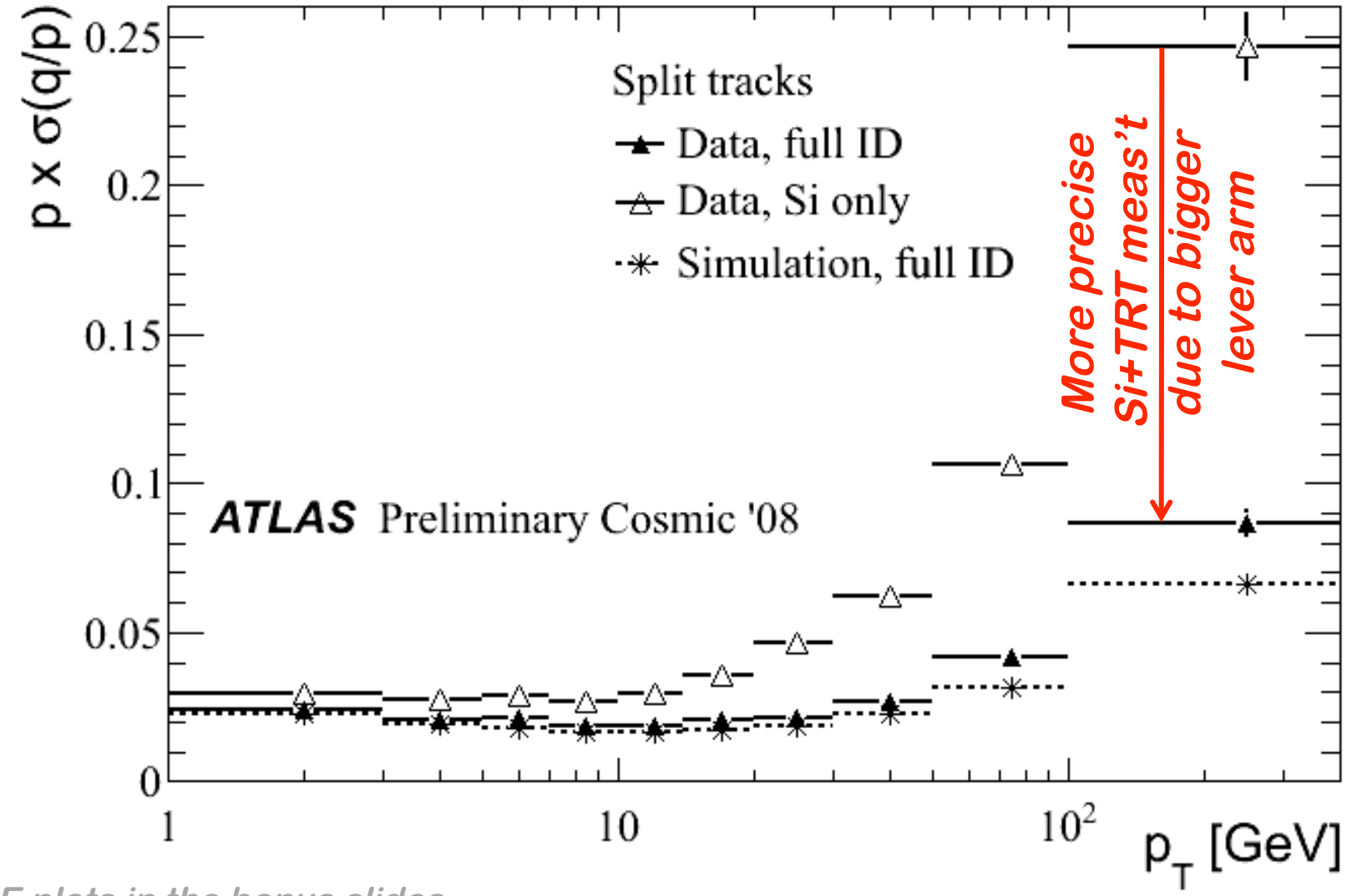
MORE plots in the bonus slides…

M8+ Alignment: $p.\sigma(q/p)$ vs. p_T



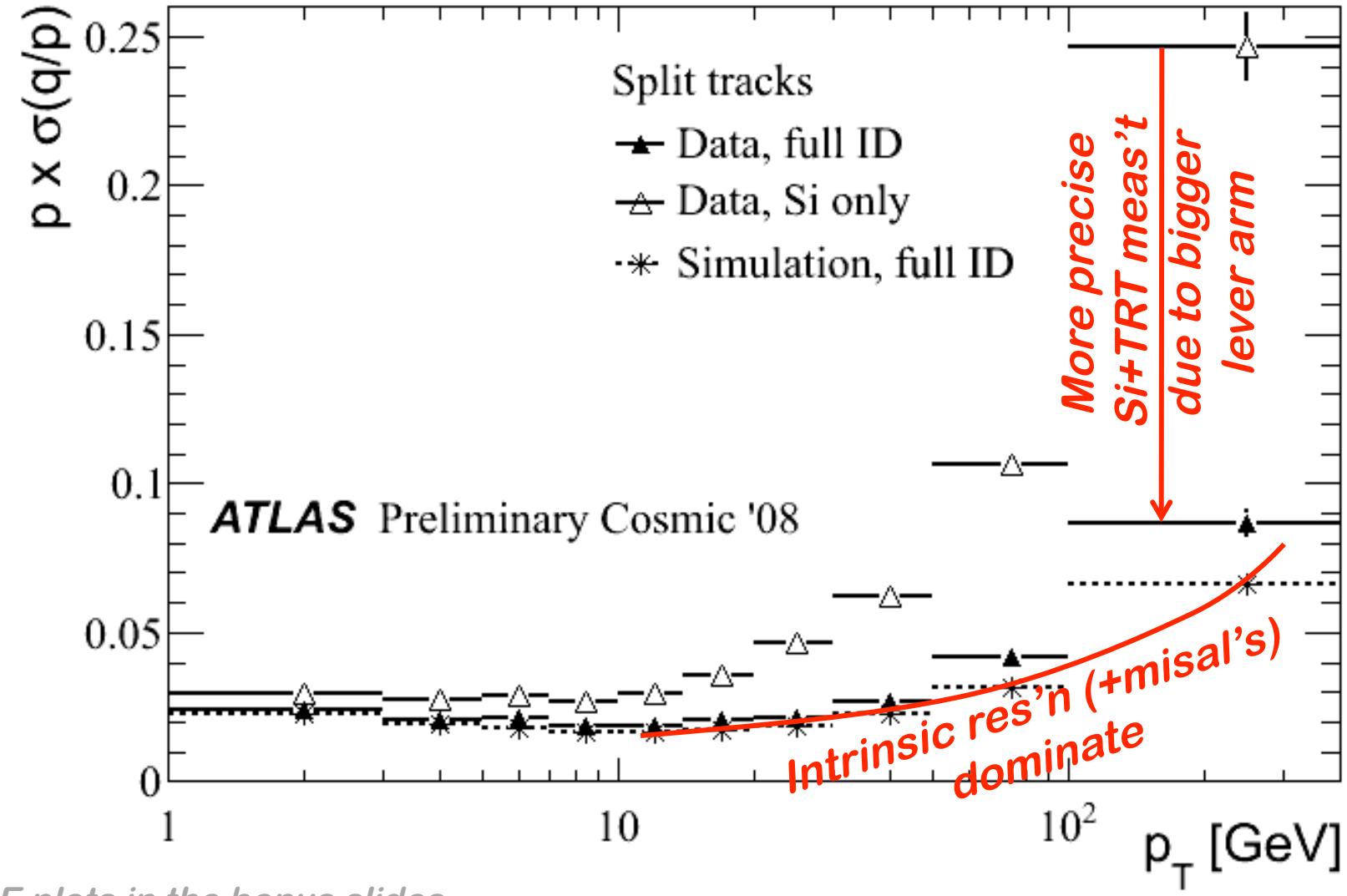
MORE plots in the bonus slides…

M8+ Alignment: $p.\sigma(q/p)$ vs. p_T



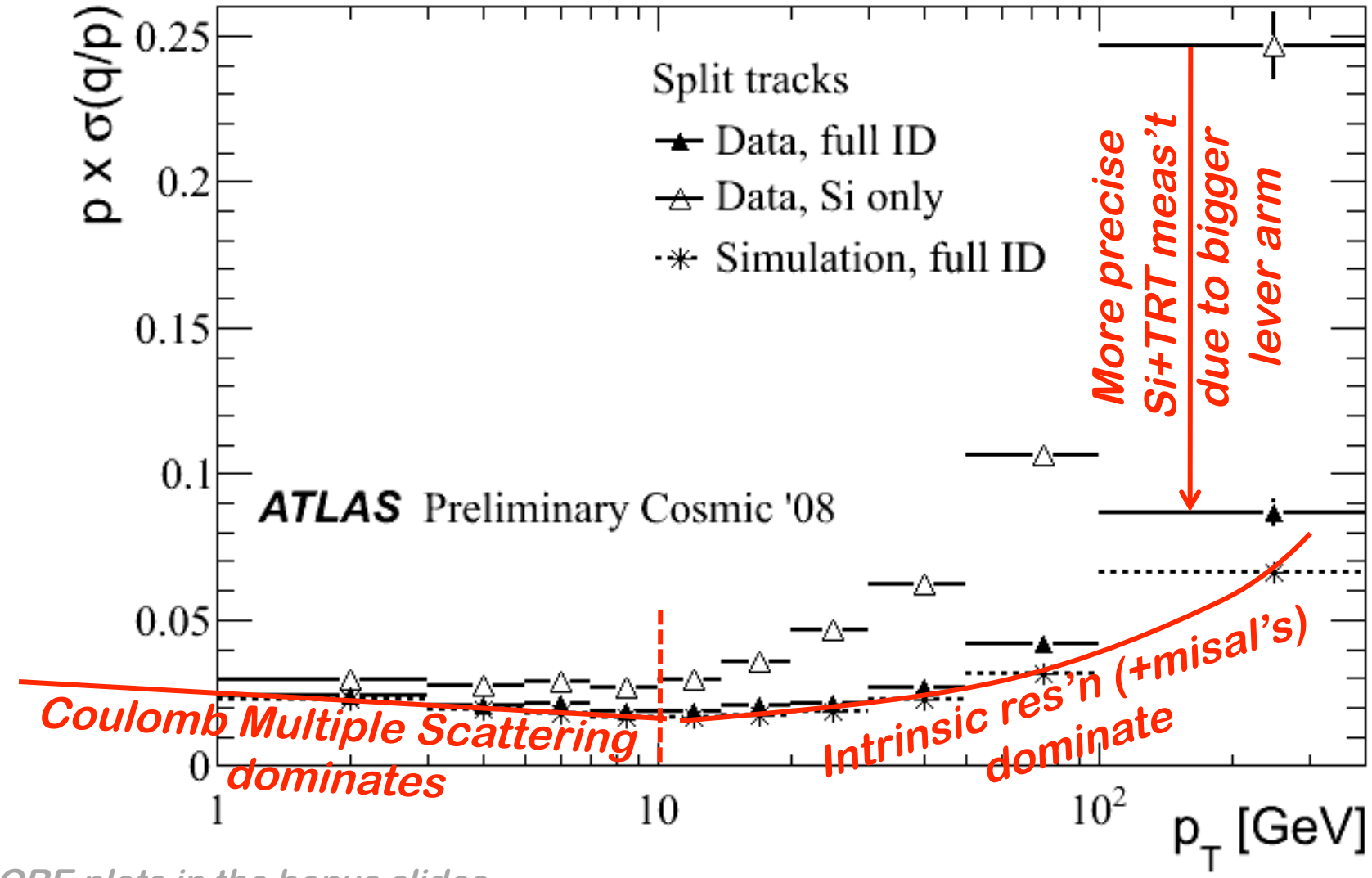
MORE plots in the bonus slides…

M8+ Alignment: $p.\sigma(q/p)$ vs. p_T



MORE plots in the bonus slides…

M8+ Alignment: $p.\sigma(q/p)$ vs. p_T



MORE plots in the bonus slides…

M8+ Alignment: Quintessence

- We have a good alignment set from M8+ for the ID!
  - Alignment uncertainty in the barrel:
    - Consistent with random misalignments of ~20 μm
- Some beware-s:
  - Validated and well-understood in barrel only
  - Best alignment: upper and lower quadrant of the barrel
  - Performance not directly transferrable to collision data:
    - Well-aligned parts of the detector are the ones with much statistics ➔ they have a (statistically) bigger influence on the width of performance distributions!
    - Typical angle of impact different

Alignment Prospects for 2009

- **Disclaimer:**
  - **The following is what we *believe* to be a *possible scenario* for Inner Detector alignment in 2009…**

2009: Expected Alignment Performance

- Define two alignment sets:
  - Day 1:
    - Based on M8+ experience
  - Day 100:
    - Initial physics performance

2009: Expected Alignment Performance

- Define two alignment sets:
  - Day 1:
    - Based on M8+ experience
  - Day 100:
    - Initial physics performance
- Gaussian smearing:

	Day-1 Barrel	Day-1 Endcap
Pixel	20 μm	50 μm
SCT	20 μm	50 μm
TRT	100 μm	100 μm

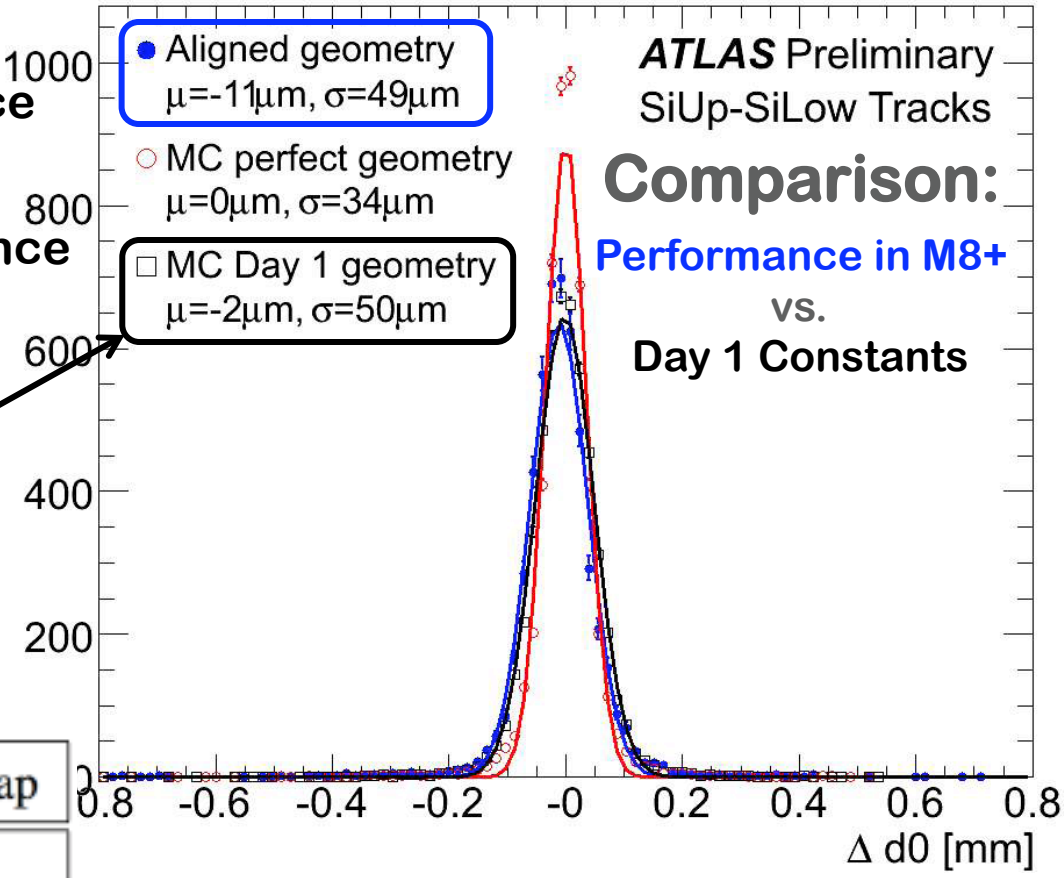
	Day-100 Barrel	Day-100 Endcap
Pixel	10 μm	10 μm
SCT	10 μm	10 μm
TRT	50 μm	50 μm

2009: Expected Alignment Performance

- Define two alignment sets:
  - Day 1:
    - Based on M8+ experience
  - Day 100:
    - Initial physics performance
- Gaussian smearing:

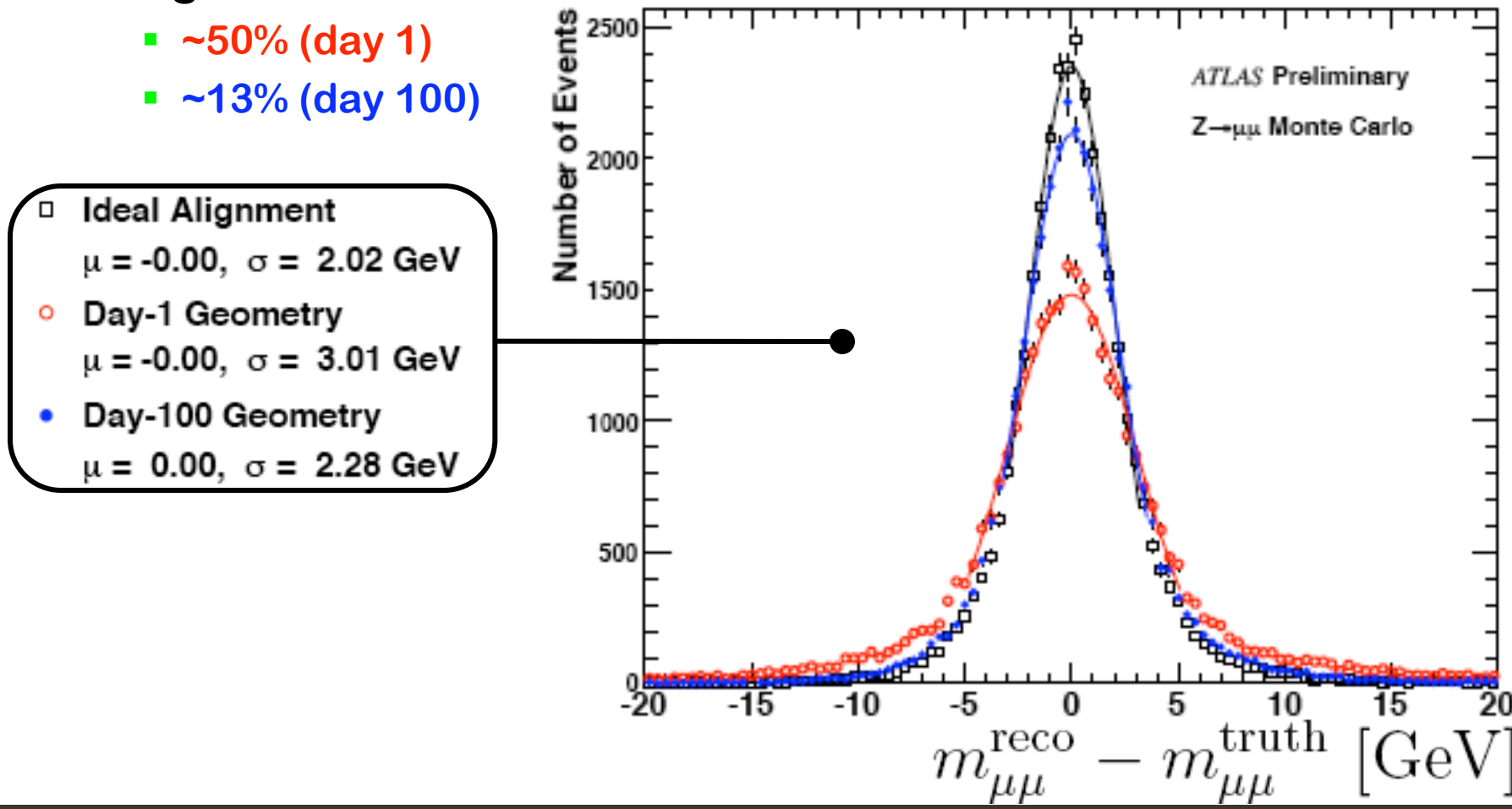
	Day-1 Barrel	Day-1 Endcap
Pixel	20 μm	50 μm
SCT	20 μm	50 μm
TRT	100 μm	100 μm

	Day-100 Barrel	Day-100 Endcap
Pixel	10 μm	10 μm
SCT	10 μm	10 μm
TRT	50 μm	50 μm



Effect of Misalignments: M_Z

- *Z* is standard candle of the SM!
  - Using only Inner Detector for p_T reco
  - Degradation in width:
    - ~50% (day 1)
    - ~13% (day 100)

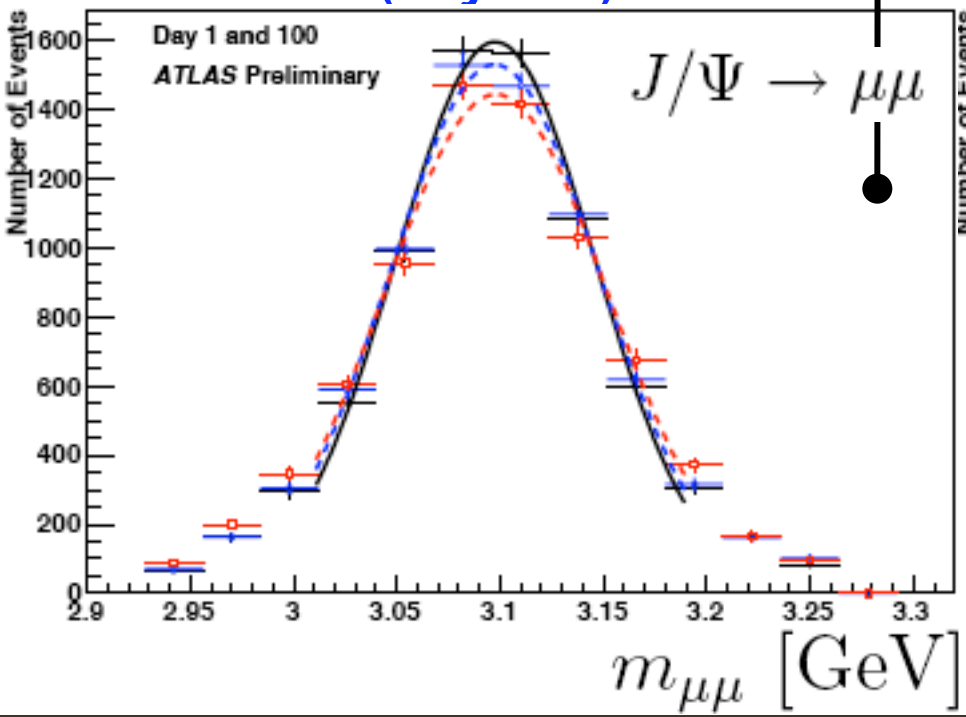


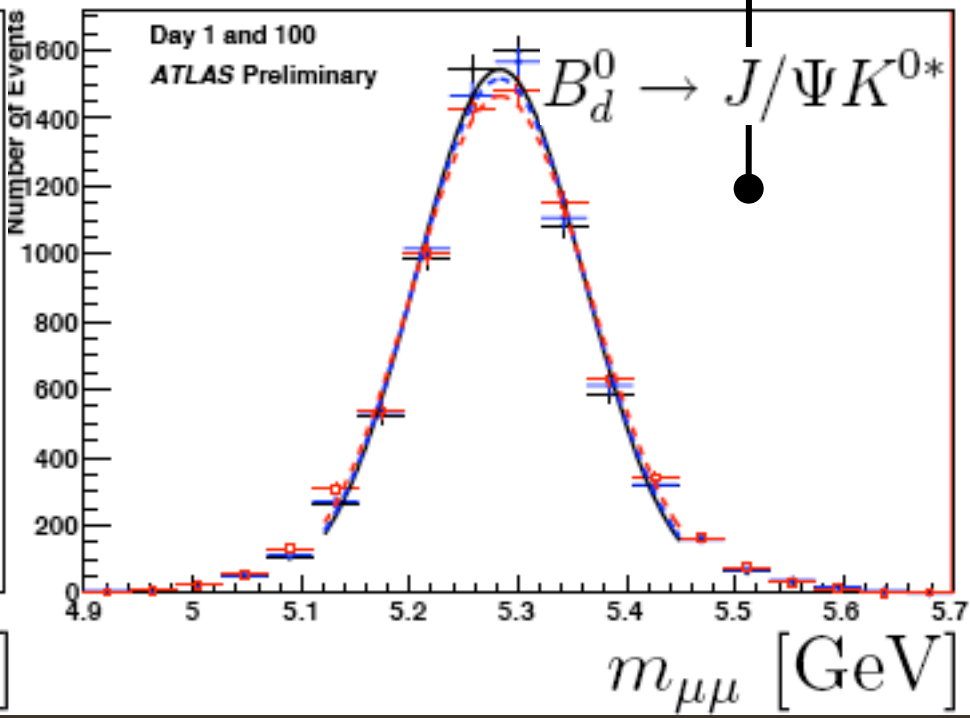
Effect of Misalignments: *B*-physics

- $J/\Psi \rightarrow \mu\mu$
- $B_d^0 \rightarrow J/\Psi K^{0*}$
- Impact small (MCS dominates):
  - ~10% (day 1)
  - ~5% (day 100)

- Ideal
  μ: 3.098 σ: 0.048 [GeV]
- Day 100
  μ: 3.097 σ: 0.051 [GeV]
- Day 1
  μ: 3.098 σ: 0.054 [GeV]

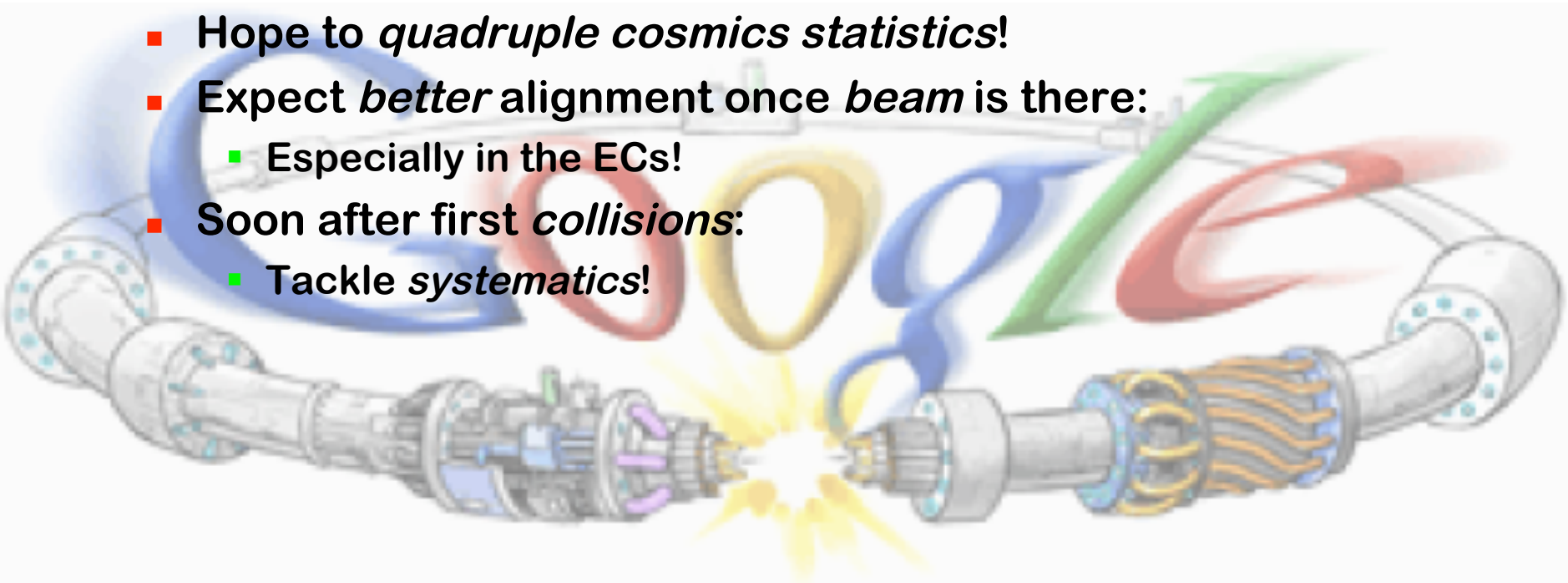
- Ideal
  μ: 5.283 σ: 0.077 [GeV]
- Day 100
  μ: 5.283 σ: 0.079 [GeV]
- Day 1
  μ: 5.284 σ: 0.082 [GeV]





Summary / Outlook

- ATLAS Inner Detector alignment is in ready for collisions:
  - *Alignment algorithms validated* thoroughly with MC
  - *Alignment infrastructure* works well
  - *Impressive alignment* quality achieved with *2008 cosmics*!
  - Estimated *misalignment impact* on early SM physics *limited*
- Great alignment prospects for 2009+:
  - Hope to *quadruple cosmics statistics*!
  - Expect *better* alignment once *beam* is there:
    - Especially in the ECs!
  - Soon after first *collisions*:
    - Tackle *systematics*!



Bonus slides

- For more details:
  - Bonus slides
  - https://twiki.cern.ch/twiki/bin/view/Atlas/ApprovedPlotsID
  - LHC Alignment Workshop (June 2009)
    - http://indico.cern.ch/conferenceDisplay.py?confId=50502

Alignment Algorithms at ATLAS

- **References** *(+references therein)*:
  - **Si Global χ^2:** http://cdsweb.cern.ch/record/835270
  - **Si Local χ^2:** http://publications.mppmu.mpg.de/2005/MPP-2005-174/FullText.pdf
  - **Si Robust Alignment:** http://cdsweb.cern.ch/record/1061129
  - **TRT global χ^2:** http://cdsweb.cern.ch/record/1039585

Alignment Algorithms at ATLAS

- There are 3 Si + 1 TRT alignment algorithms:
  - Global χ^2:
    - Minimise $\chi^2 \equiv \sum_{\text{tracks}} r^T V^{-1} r$
    - w/r/t alignment parameters:

$$\delta a = -\left(\sum_{\text{tracks}} \frac{dr^T}{da} V^{-1} \frac{dr}{da}\right)^{-1} \sum_{\text{tracks}} \frac{dr^T}{da} V^{-1} r\,, \quad \text{with} \quad \frac{dr}{da} = \frac{\partial r}{\partial a} + \frac{\partial r}{\partial \pi}\frac{d\pi}{da}$$

  - Local χ^2:
    - Similar to Global χ^2, but with $\frac{dr}{da} = \frac{\partial r}{\partial a}$
    - $\frac{dr^T}{da} V^{-1} \frac{dr}{da}$ in block-diagonal form, easy soluble, more iter's
  - Robust Alignment:
    - Topological distributions of residuals for subdetector alignment
    - Residual and overlap residual distributions for module align't
  - TRT Alignment:
    - Similar to the Global χ^2 algorithm
- References: past talks + proceedings are listed in:
  - https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasIDAlignPresentations

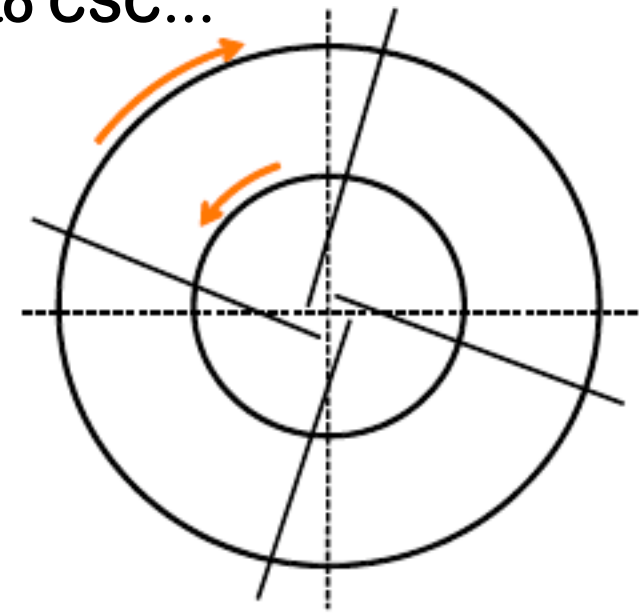
Eliminating "Weak Mode" deformations

- References:
  - Write-up available soon!

After First Beam:
Improving Alignment Performance

- Very soon *O*(day):
  - Decent EC alignment (L1, L2)
- Soon *O*(week):
  - Vertical / horizontal modules: similar alignment performance
  - Decent EC alignment (L3)
- Fairly soon *O*(month):
  - Alignment of somewhat similar quality to CSC…
- Reach limit: systematics dominating:
  - Not understood detector effects:
    - e.g. depletion depth?
  - "Weak Mode" deformations:
    - Leave the χ^2 (almost) unchanged
    - Bias track parameters
    - E.g. "curl" around *Z*

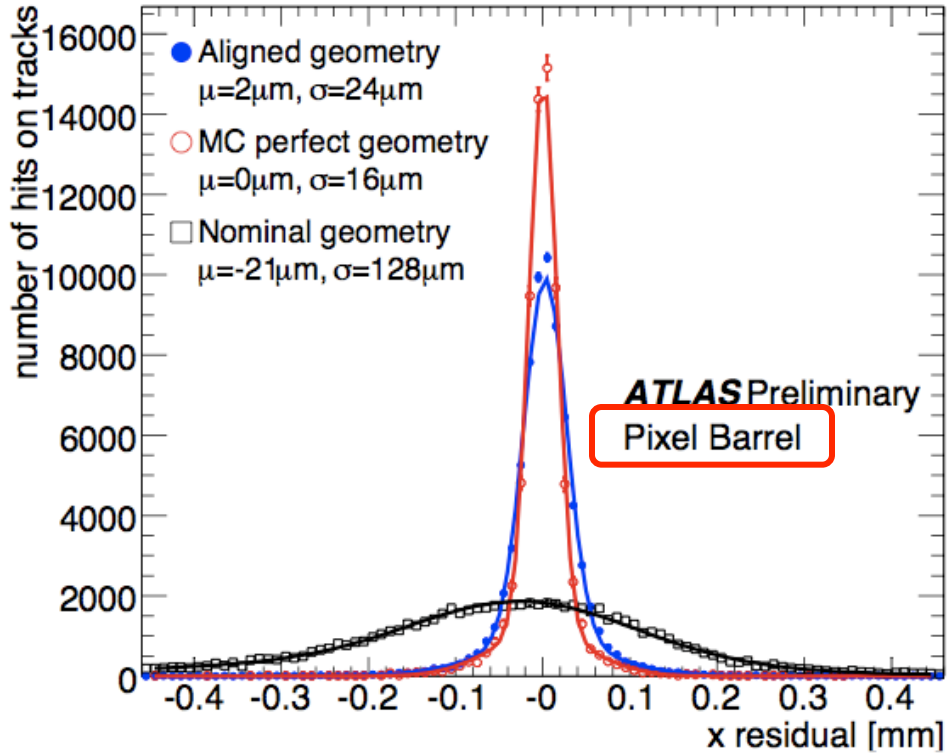
log time

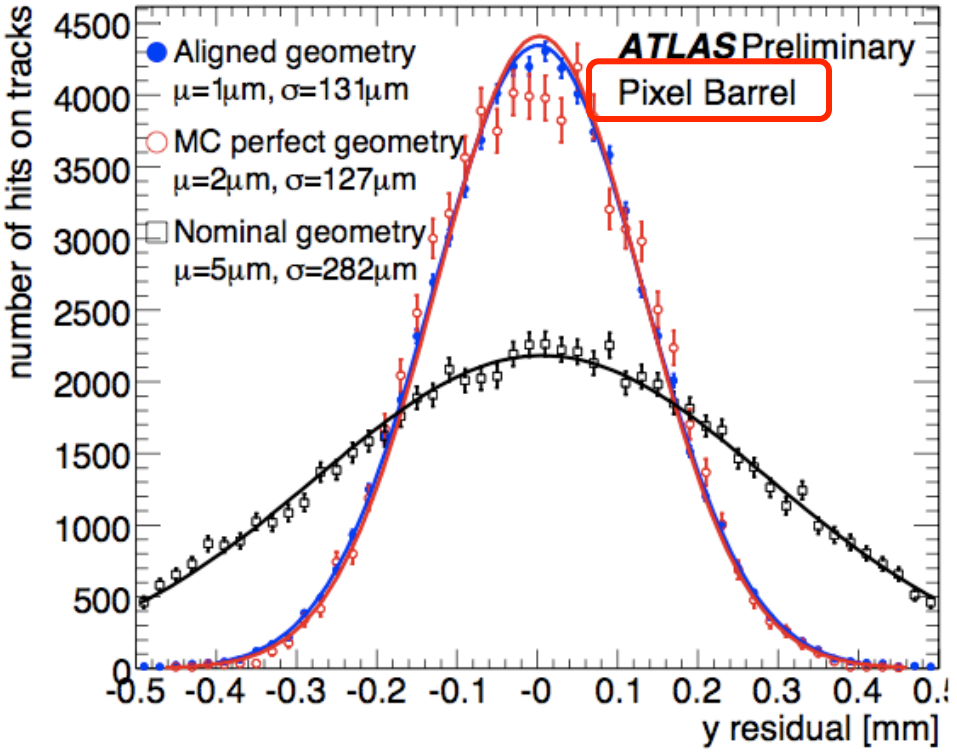


Residual and Track Parameter Monitoring

M8+ Alignment: Residuals (Pixel)

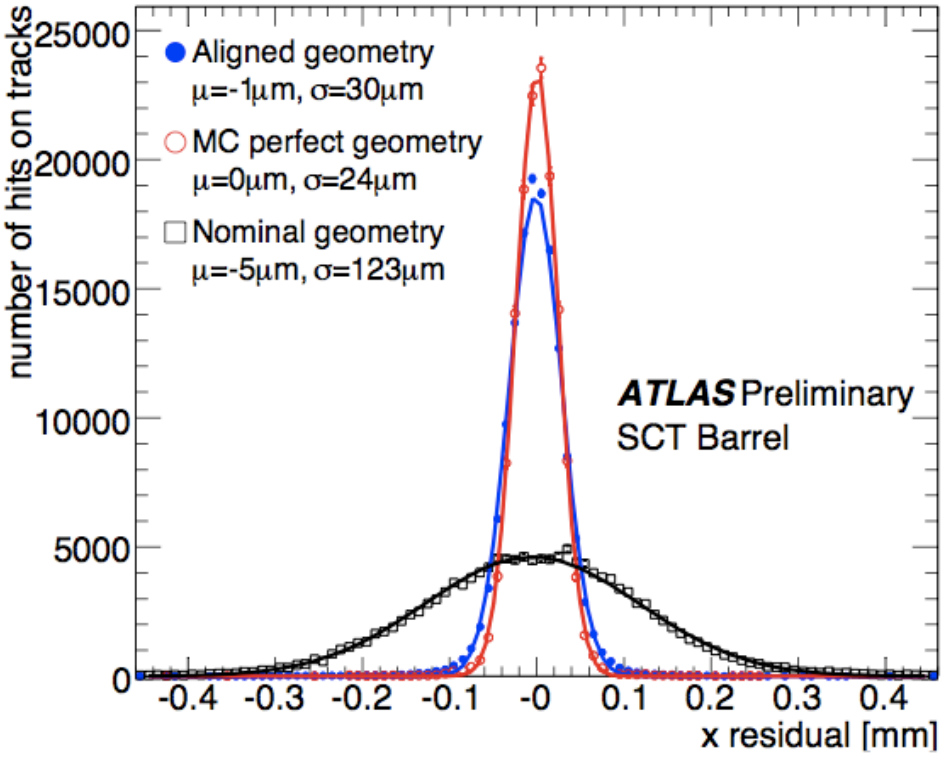
- In all following plots for Si:
  - p_T > 2 GeV, $|d_0|$<50mm, $|z_0|$<400mm (through pixel *b*-layer)
  - "Golden" runs: 91885, 91888, 91890, 91891, 91900, NewT

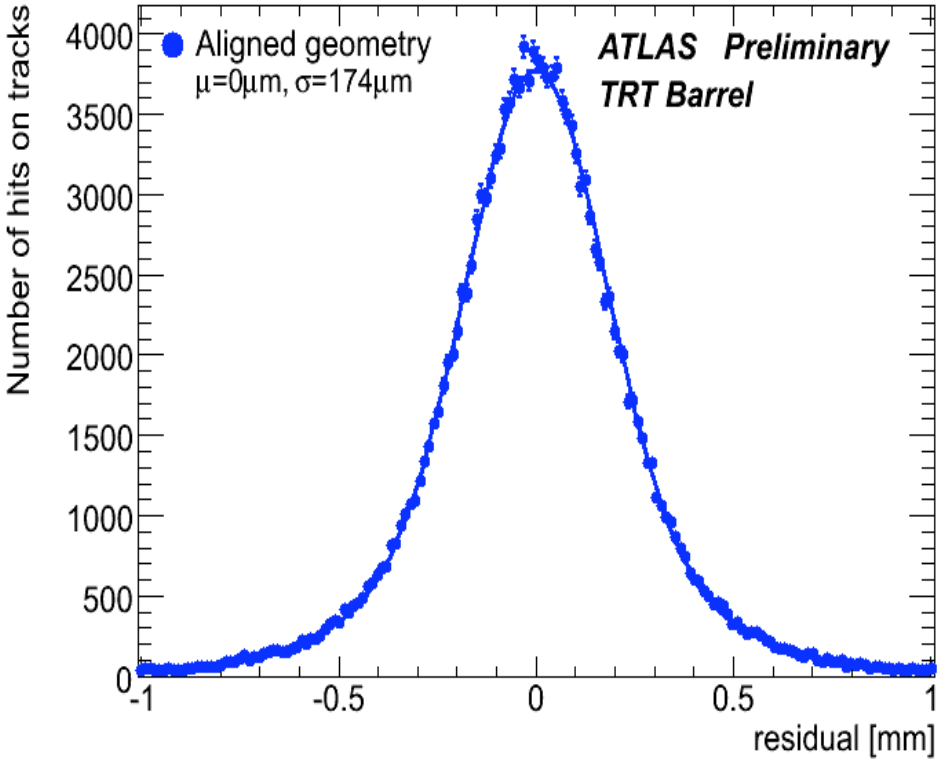




M8+ Alignment: Residuals (SCT, TRT)

- In all following plots for Si:
  - p_T > 2 GeV, $|d_0|$<50mm, $|z_0|$<400mm (through pixel *b*-layer)
  - "Golden" runs: 91885, 91888, 91890, 91891, 91900, NewT

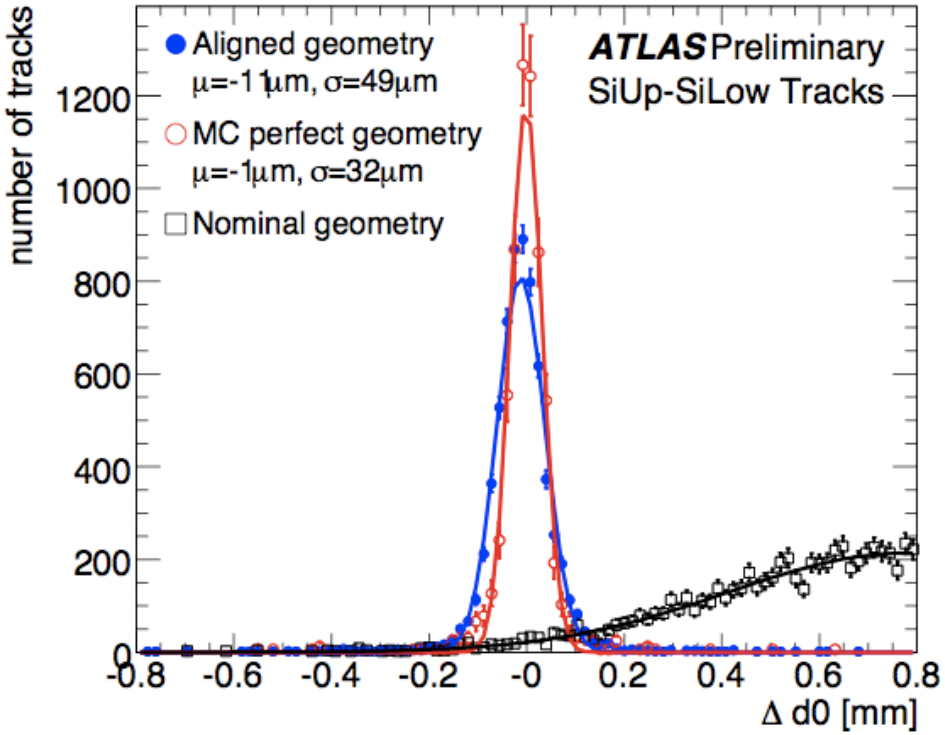


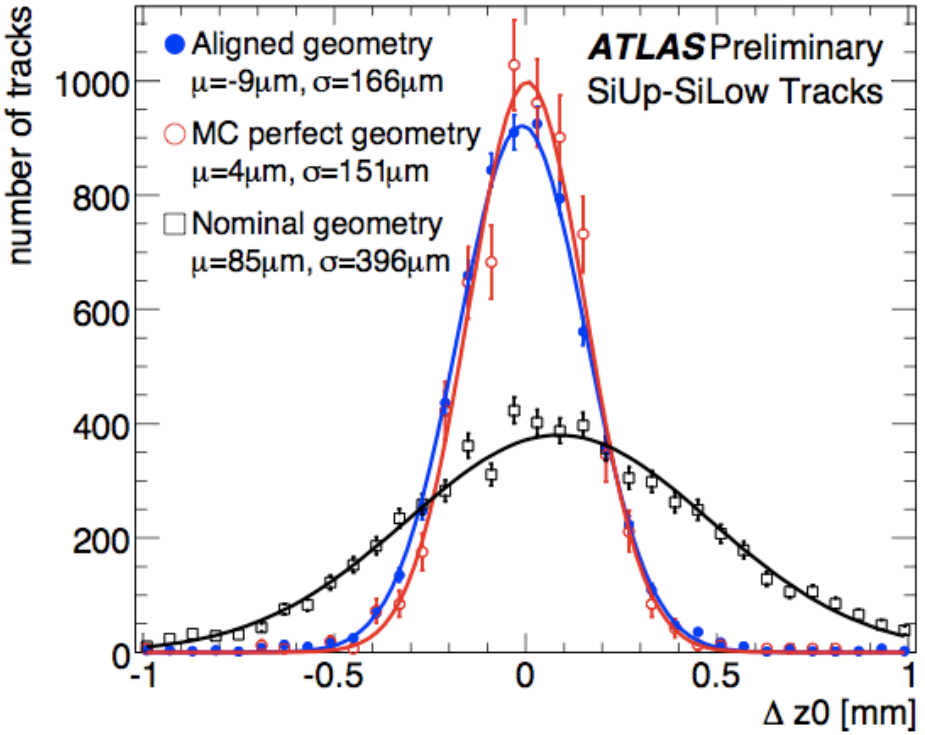


- For TRT:
  - no min. p_T, $|d_0|$<100 mm (through pixel), >45 TRT hits

Alignment with M8+ Cosmics: Results

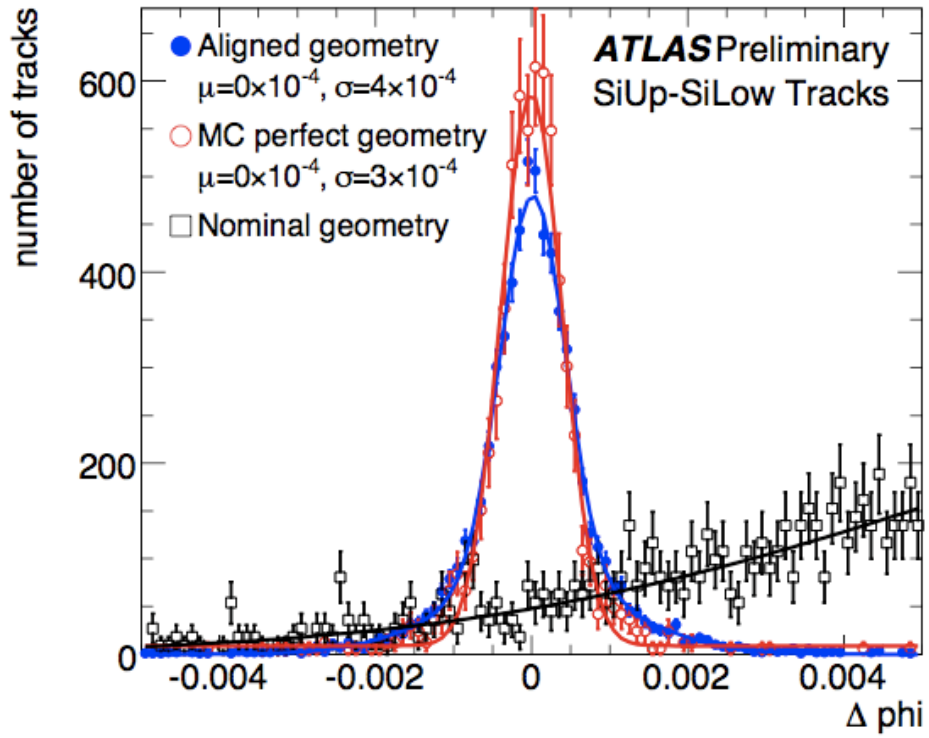
- In all following plots for Si:
  - p_T > 2 GeV, $|d_0|$<50mm, $|z_0|$<400mm (through pixel *b*-layer)
  - "Golden" runs: 91885, 91888, 91890, 91891, 91900, NewT
  - 7 SCT hits, 3 pixel hits, 1 *b*-layer hit

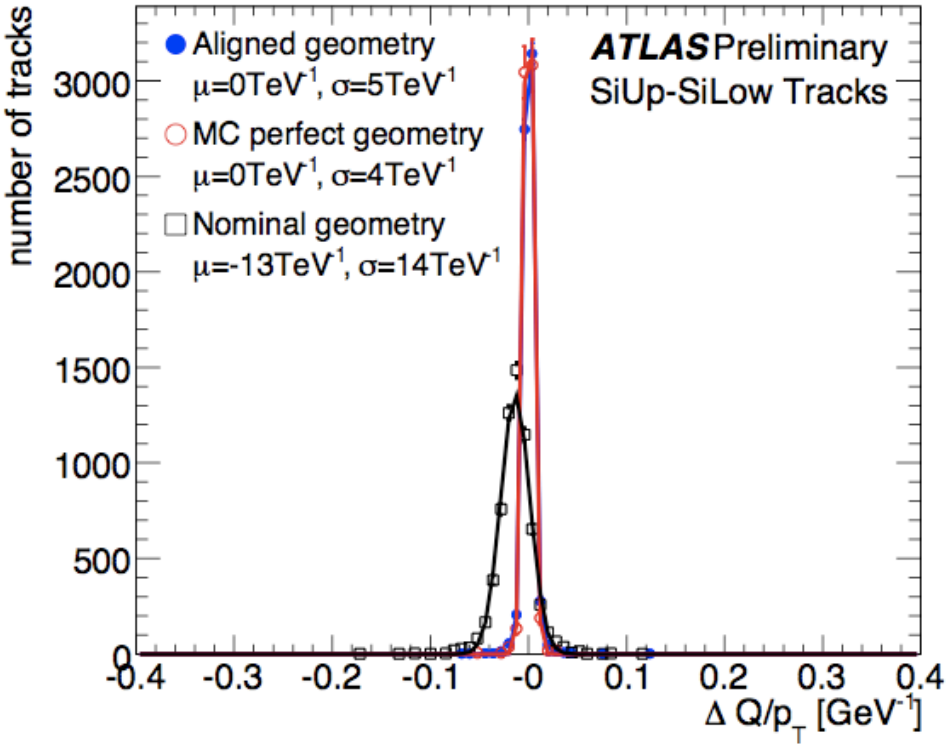




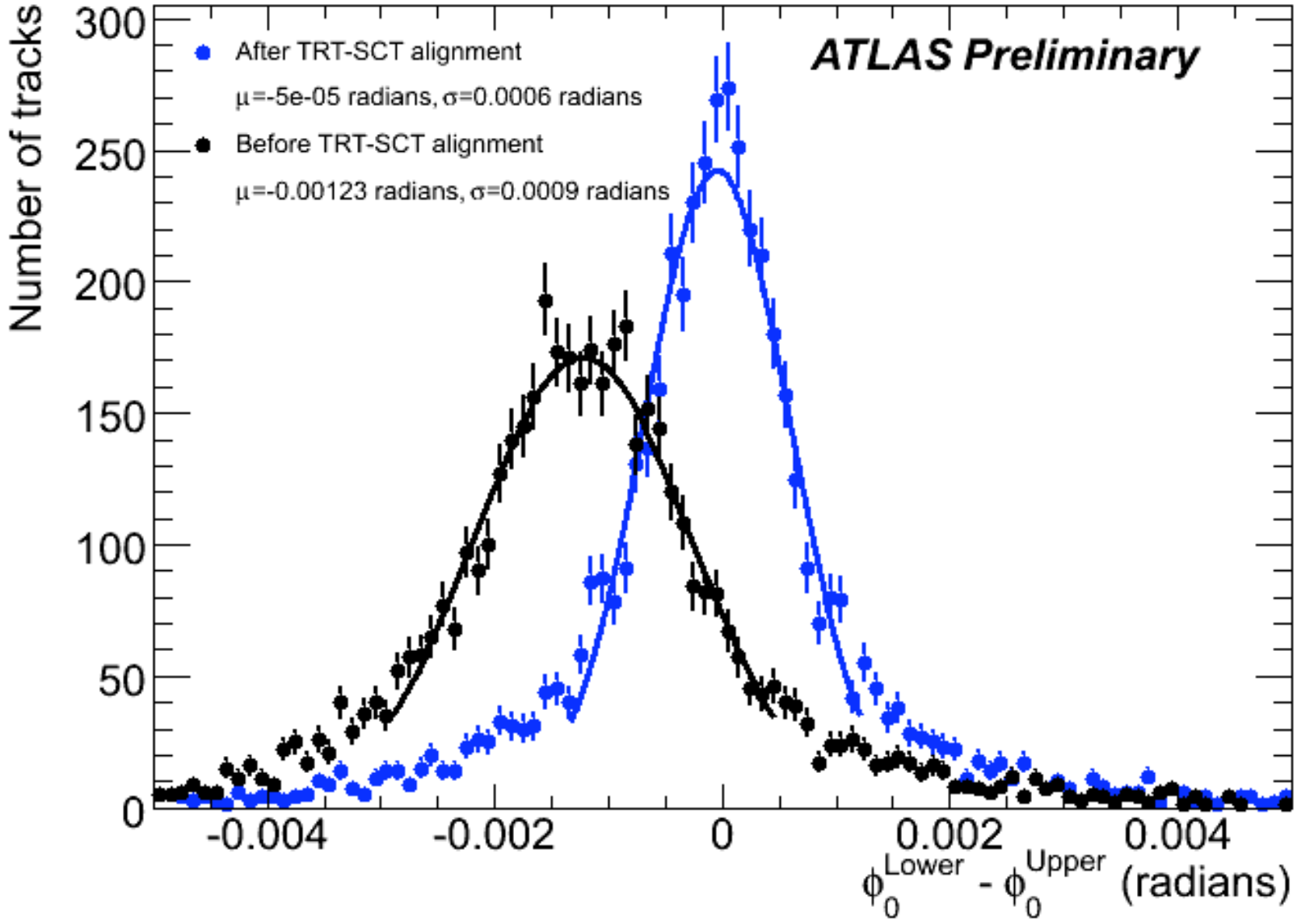
Alignment with M8+ Cosmics: Results

- In all following plots for Si:
  - p_T > 2 GeV, $|d_0|$<50mm, $|z_0|$<400mm (through pixel *b*-layer)
  - "Golden" runs: 91885, 91888, 91890, 91891, 91900, NewT
  - 7 SCT hits, 3 pixel hits, 1 *b*-layer hit





M8+ Alignment: TRT-SCT



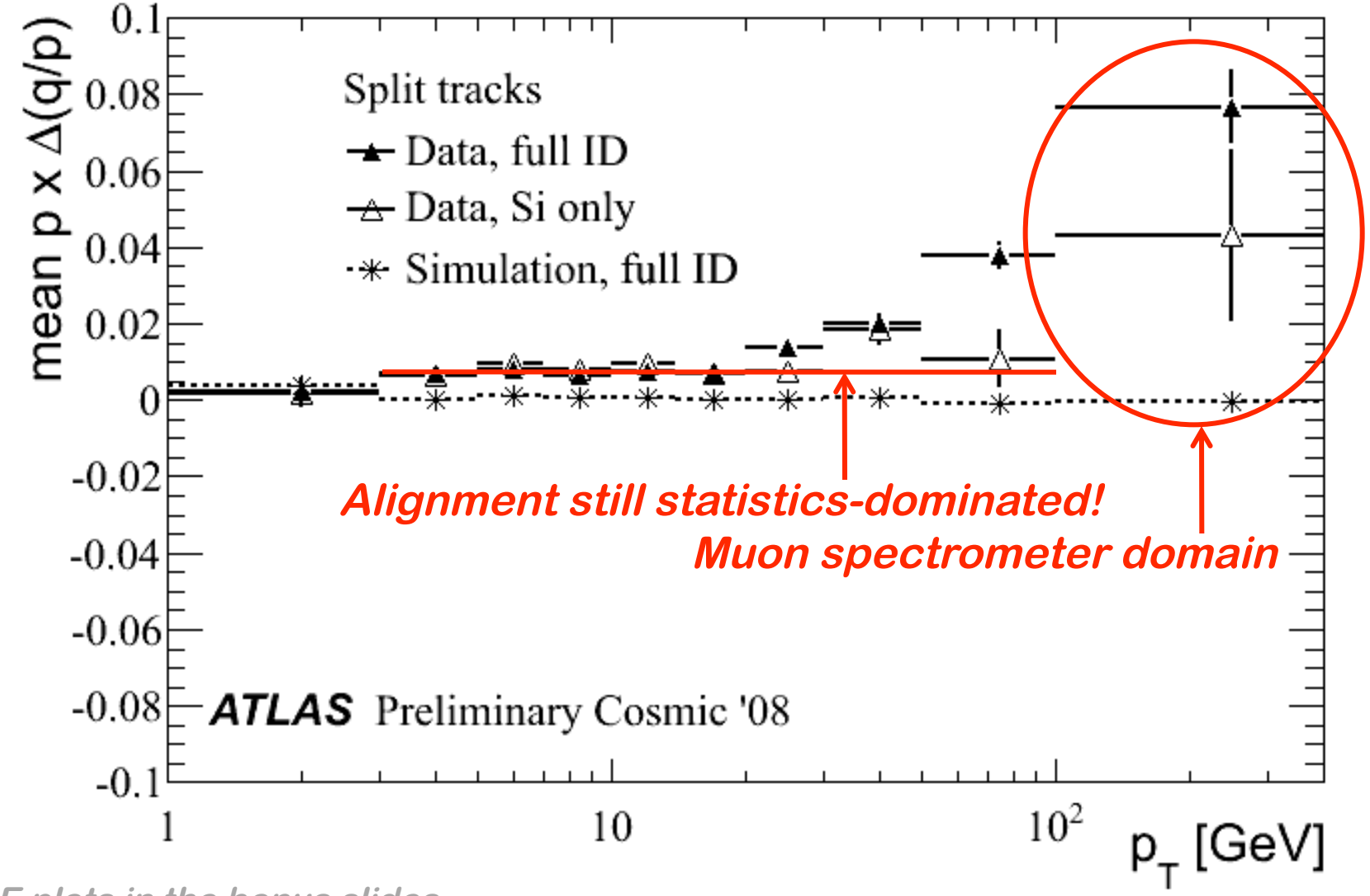
MOR

Topological Track Parameter Monitoring

Topological Track Parameter Distr'ns

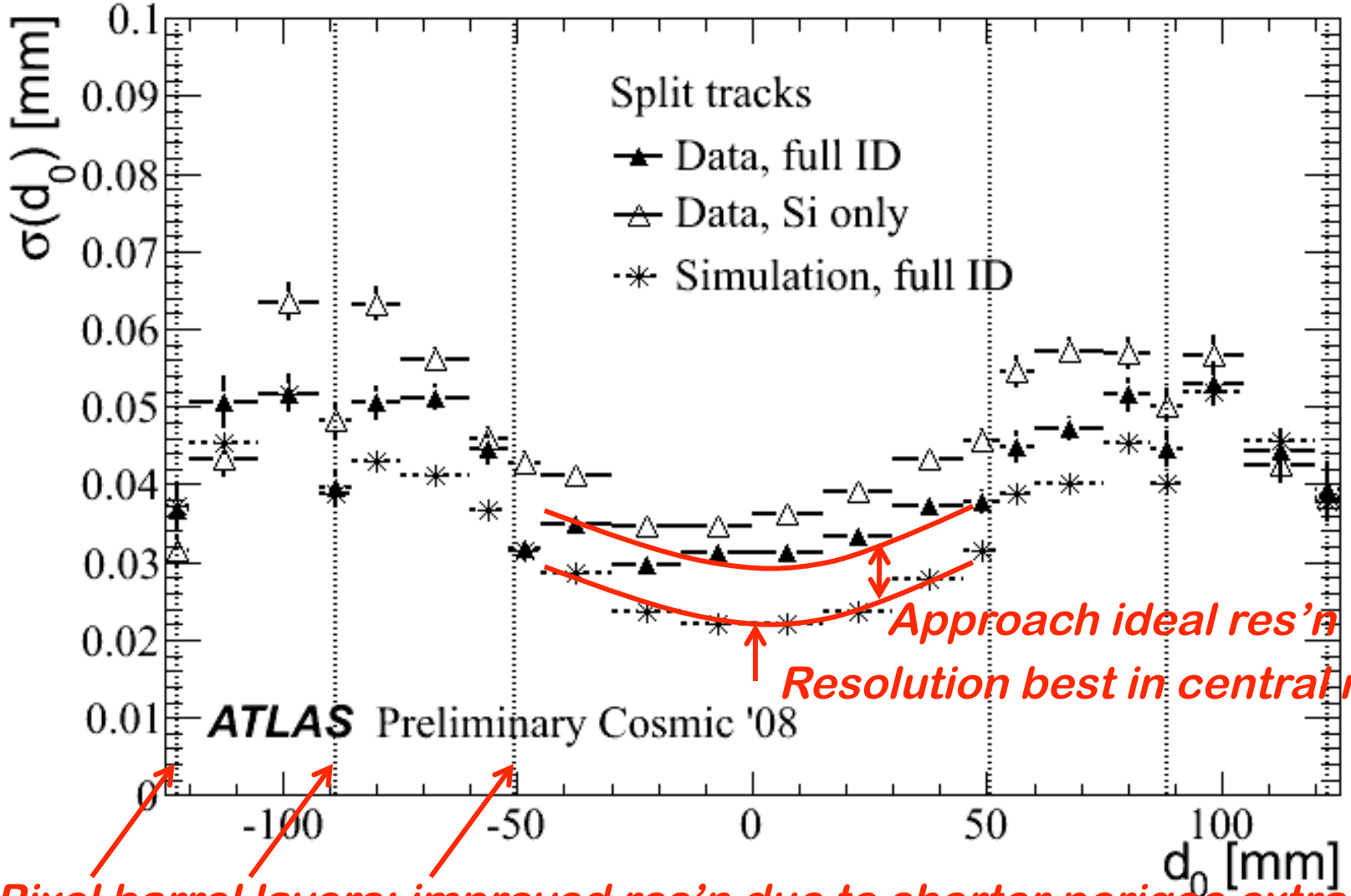
- In all following plots:
  - "Golden" runs: 91885, 91888, 91890, 91891, 91900, NewT
  - >1 pixel barrel hits
  - >5 SCT barrel hits
  - >25 TRT barrel hits (except Si only tracks)
  - $|d_0| < 40$ mm (through pixel *b*-layer)
  - $p_T > 1$ GeV
  - 5 ns < event phase (timing) < 30 ns
  - quoted resolution is the RMS of the residual distribution of the particular track parameter divided by $2^{-1/2}$

M8+ Alignment: $\langle p \rangle . \Delta(q/p)$ vs. p_T



MORE plots in the bonus slides…

M8+ Alignment: $\langle d_0 \rangle$ vs. d_0

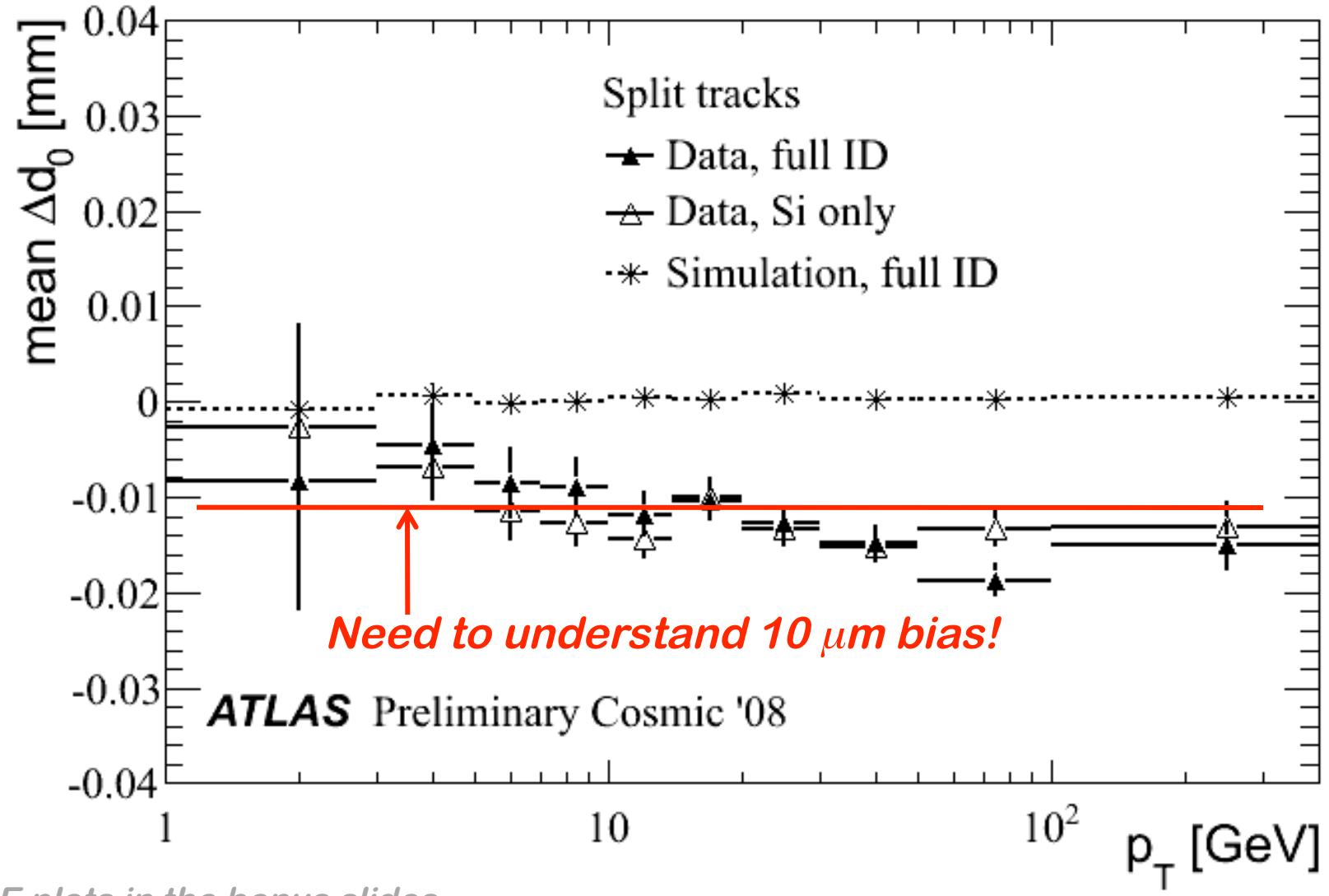


Approach ideal res'n to ~20%

Resolution best in central region

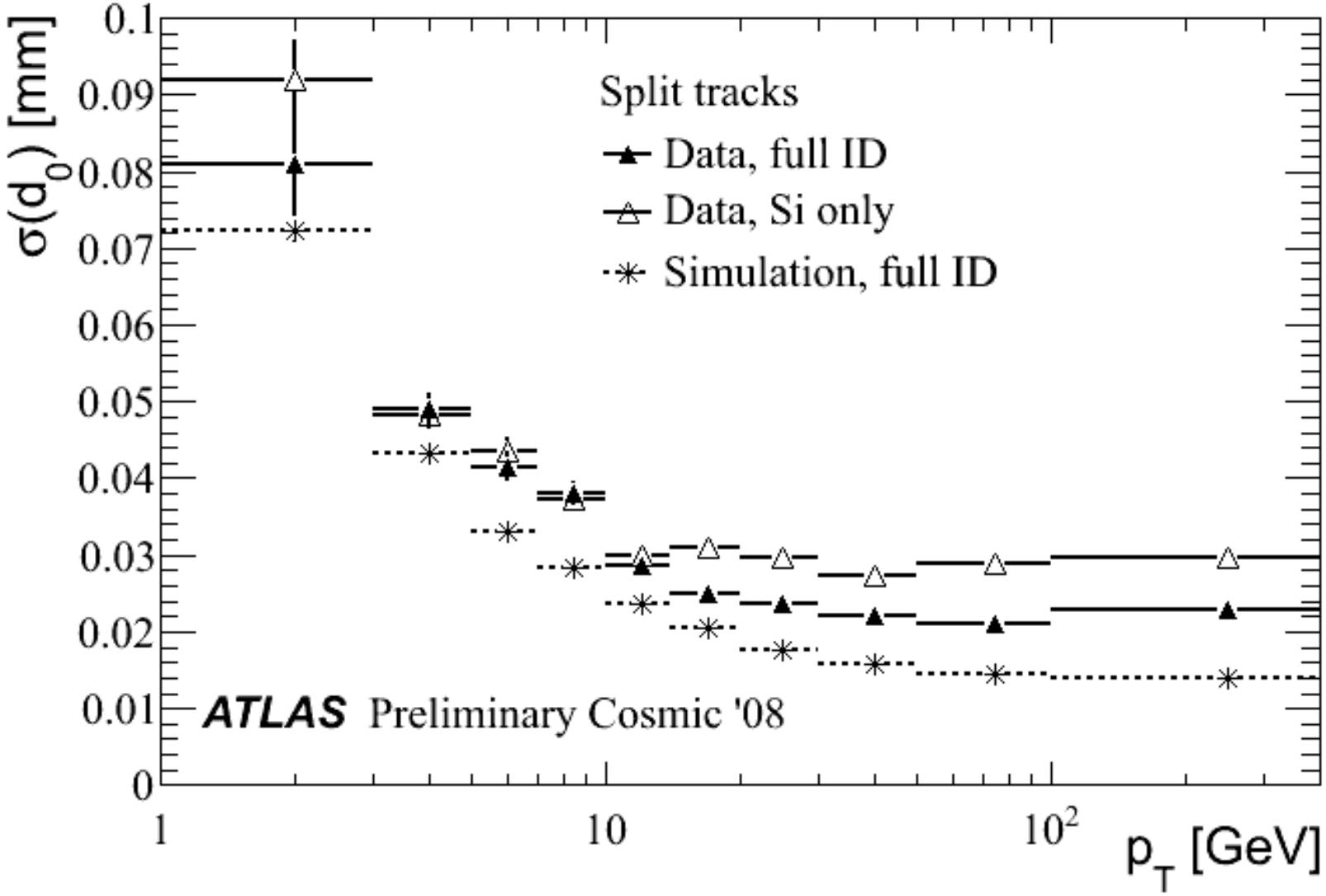
Pixel barrel layers: improved res'n due to shorter perigee extrapol'n

M8+ Alignment: $\langle d_0 \rangle$ vs. p_T

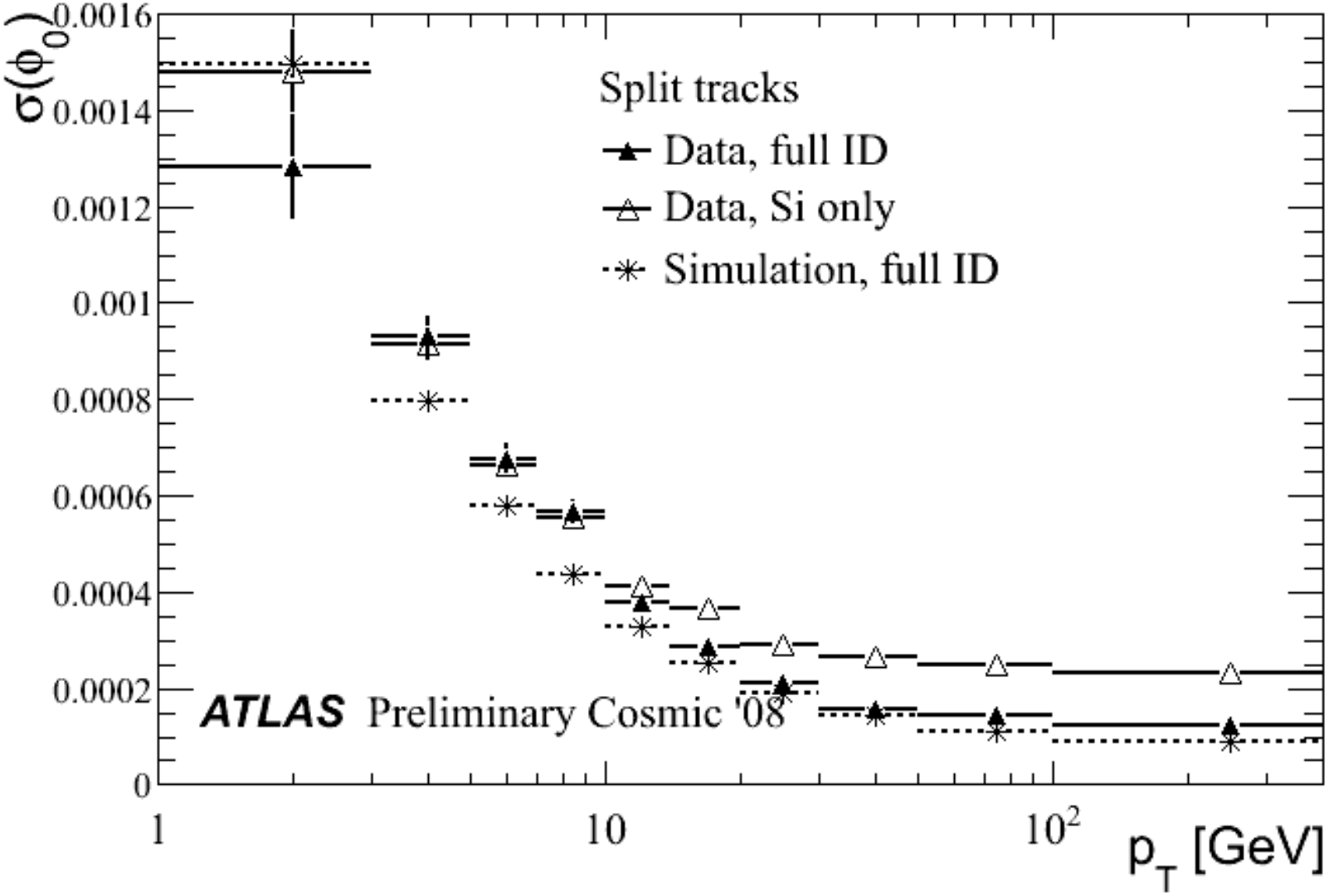


MORE plots in the bonus slides…

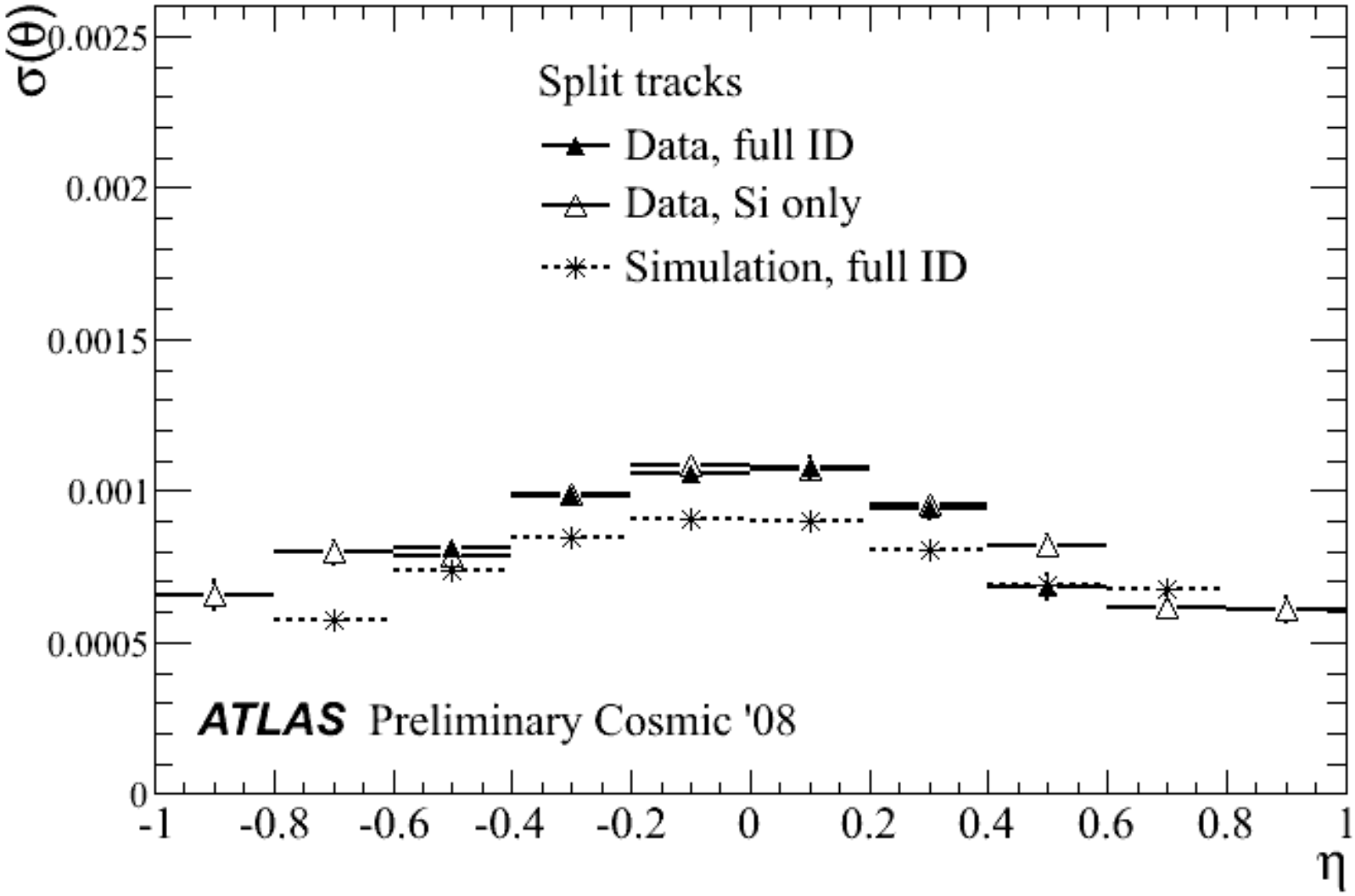
M8+ Alignment: $\sigma(d_0)$ vs. p_T



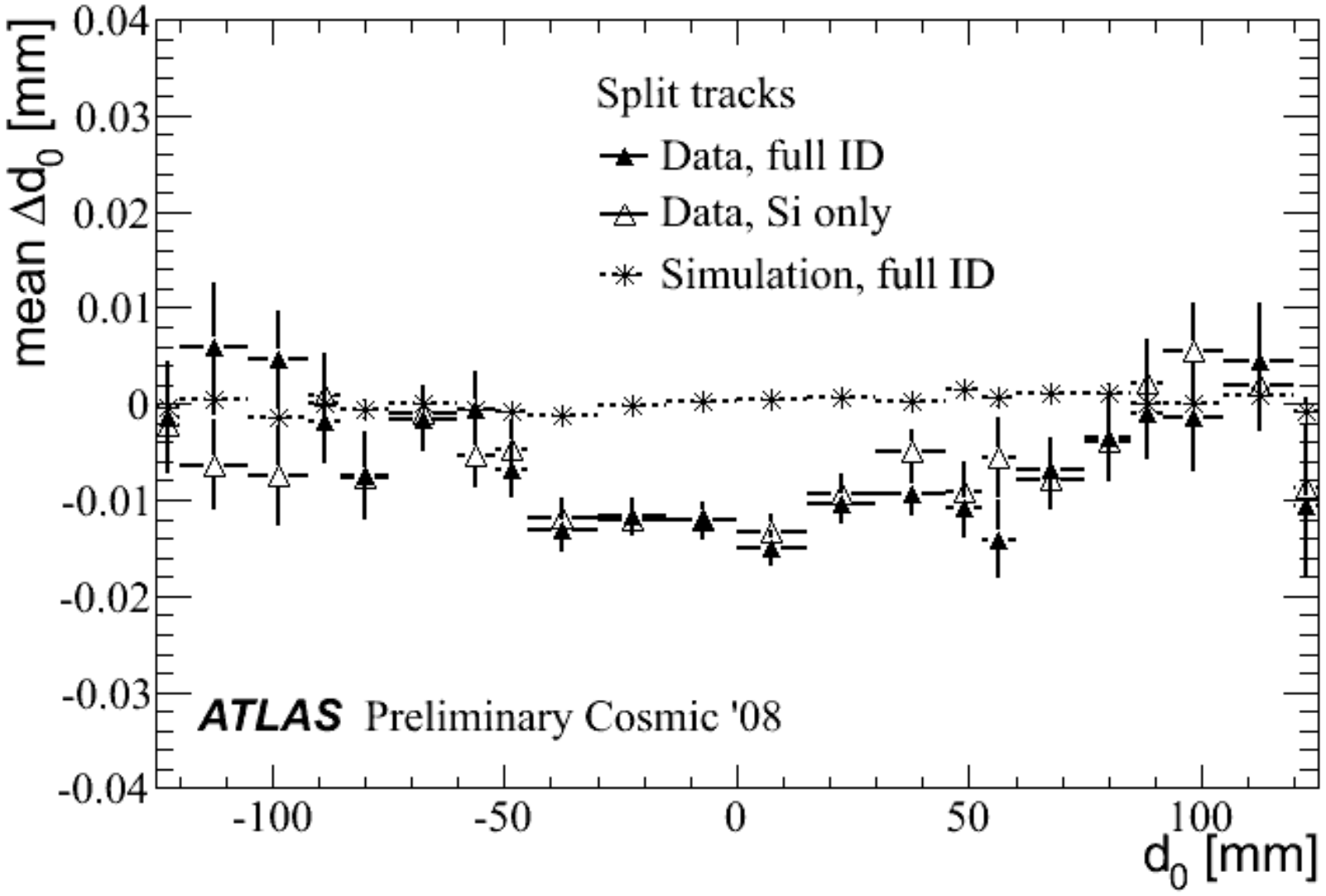
M8+ Alignment: $\sigma(\phi_0)$ vs. p_T



M8+ Alignment: σ(θ) vs. η



M8+ Alignment: $\langle \Delta d_0 \rangle$ vs. d_0

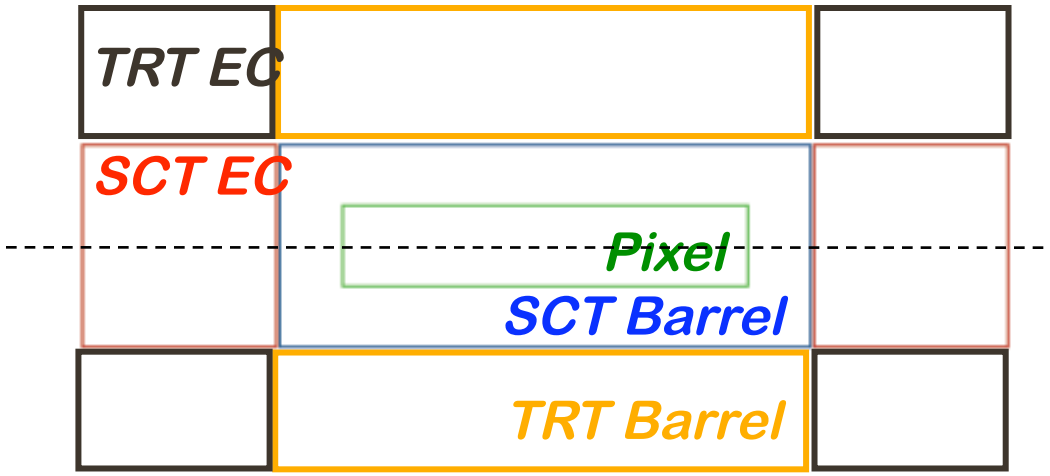


Alignment Superstructures ("Levels")

Alignment "Superstructures": Level 1

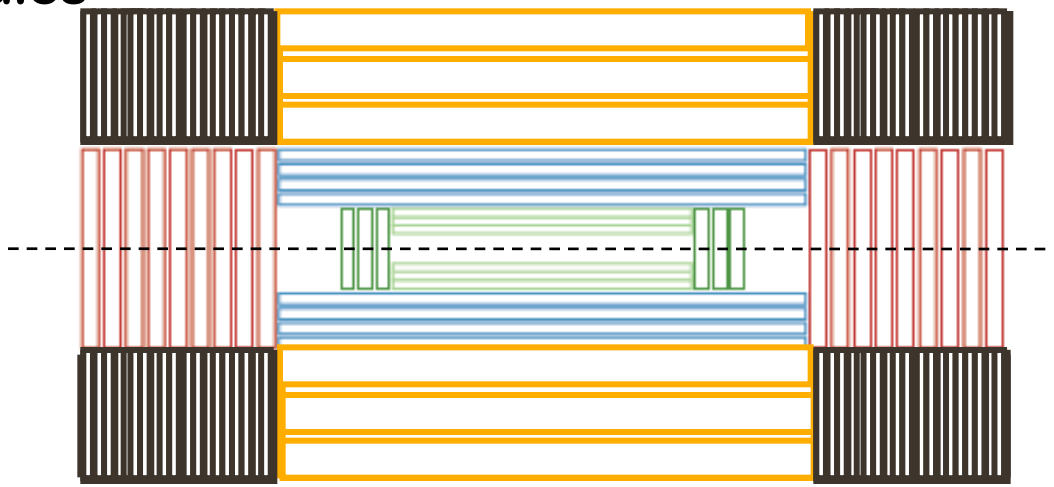
- Define superstructures of modules:
  - Reflecting the detector geometry + build specifications
  - Typically: superstructure misalignments large!
- Level 1:
  - Pixel detector
  - SCT barrel
  - SCT EC A
  - SCT EC C
  - TRT Barrel (5 DoF)
  - TRT ECs

  - Σ: 7 superstructures
  - Σ: 41 DoF



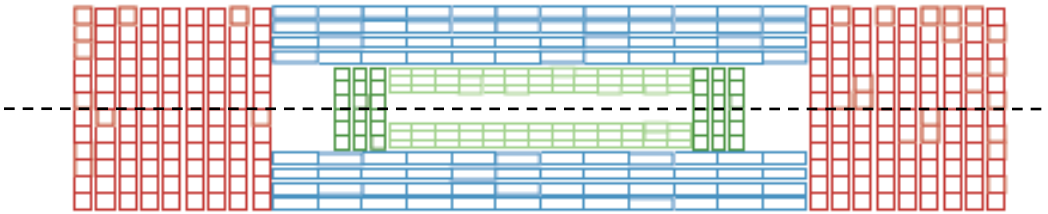
Alignment "Superstructures": Level 2

- Define superstructures of modules:
  - Reflecting the detector geometry + build specifications
  - Typically: superstructure misalignments large!
- Level 2:
  - Pixel Barrel: 3 layers
  - Pixel ECs: 2 x 3 disks
  - SCT barrel: 4 layers
  - SCT ECs: 2 x 9 disks
  - TRT barrel: 32 x 3 modules
  - TRT ECs: 2 x 40 disks
  - Σ: 207 superstructures
  - Σ: 1146 DoF



Alignment "Superstructures": Level 3

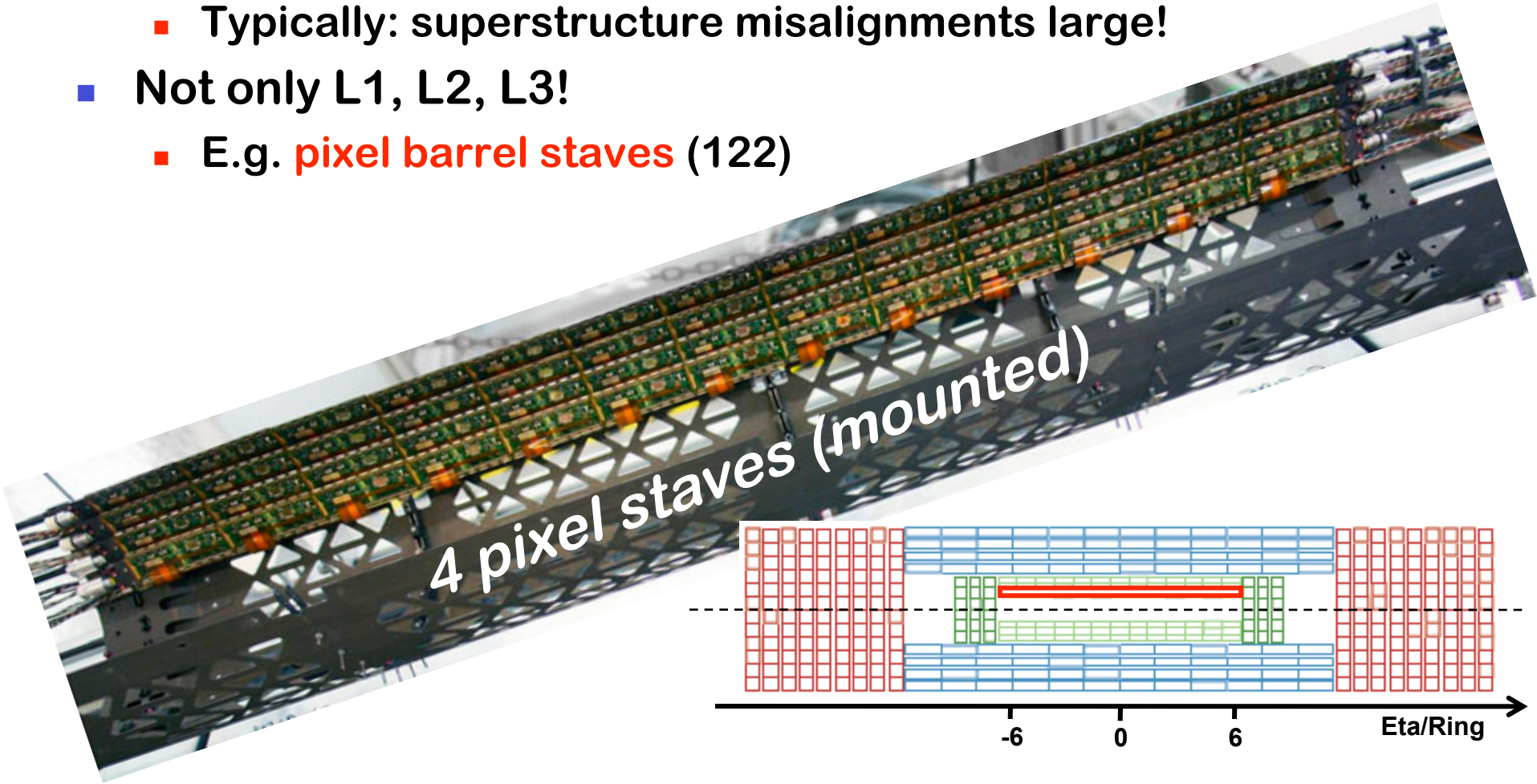
- Define superstructures of modules:
  - Reflecting the detector geometry + build specifications
  - Typically: superstructure misalignments large!
- Level 3:
  - Pixel Barrel: 1456 modules
  - Pixel ECs: 2 x 144 modules
  - SCT barrel: 2112 modules
  - SCT ECs: 2 x 988 modules
  - (no TRT structures at L3)*
  - Σ: 5832 modules
  - Σ: 34992 DoF



* L3 for TRT: individual straw alignment. Not planned in the near future…

Alignment Levels: "Superstructures"

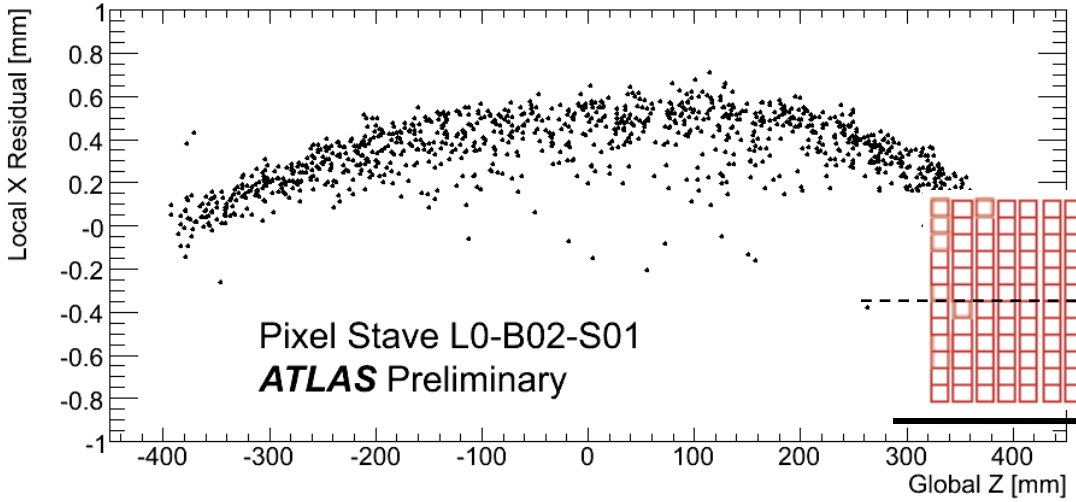
- Define superstructures of modules:
  - Reflecting the detector geometry + build specifications
  - Typically: superstructure misalignments large!
- Not only L1, L2, L3!
  - E.g. pixel barrel staves (122)

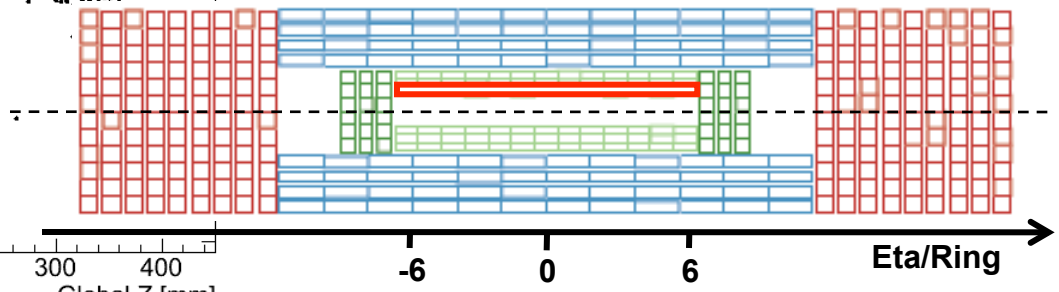


Alignment Levels: "Superstructures"

- Define superstructures of modules:
  - Reflecting the detector geometry + build specifications
  - Typically: superstructure misalignments large!
- Not only L1, L2, L3!
  - E.g. pixel barrel staves (122)

- Parabolic displacement of modules in local x plane of *O*(500 μm)
  - Corrections implemented





Alignment Levels for Si and TRT

Silicon Alignment Levels					
Geometry Level	Structures (DoFs)	Pixel	Pixel Structures (DoFs)	SCT	SCT Structures (DoFs)
1	4 (24)	complete pixel detector	1 (6)	1 barrel + 2 endcaps	3 (18)
1.5	7 (42)	2 barrel half-shells + 2 endcaps	4 (24)	1 barrel + 2 endcaps	3 (18)
1.6	11 (66)	3*2 barrel half-shells + 2 endcaps	8 (48)	1 barrel + 2 endcaps	3 (18)
2	31 (186)	3 barrel layers + 2*3 endcap discs	9 (54)	4 barrel layers + 2*9 discs	22 (132)
2.1	- (-)	-	- (-)	-	- (-)
2.3	- (-)	-	- (-)	-	- (-)
2.5	- (-)	-	- (-)	-	- (-)
3	5832 (34992)	1456 barrel + 2*144 endcap	1744 (10464)	2112 barrel + 2*988 endcap	4088 (24528)

TRT Alignment Levels			
Geometry Level	TRT	TRT DoFs	comments
1	1 barrel + 2 endcaps	17	no alignment correction around the global Z-coordinate in the barrel
2	32*3 barrel modules+ 40*2 endcap wheels	(32x3) x 5 Dof + (40x2) x 6 Dof = 960	