CLIC tracking studies

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LCWS 2014, Belgrade

Outline

- Introduction and motivations
- Extended full Si tracker:
  - Implementation
  - Performance results
  - Brief comparison between full and LDT (Linear collider Detector Toy) fast simulation
- Inhomogeneous B field
  - Implementation
  - Performance results and software limitations
- Plans for a new tracking code
  - ILD vertex code and cellular automaton

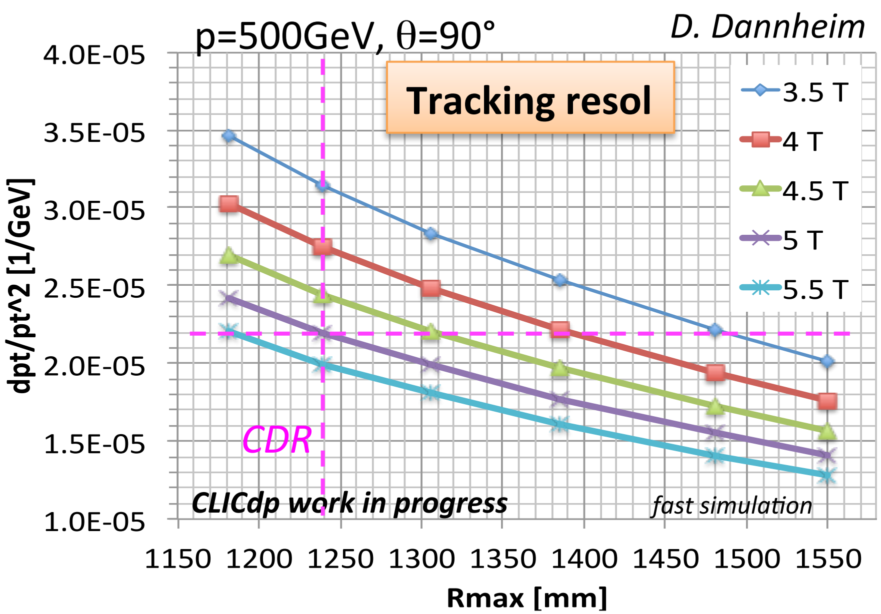
Introduction

- Excellent tracking performance is essential for the CLIC physics program
  - Particle flow measurement
  - CDR tracking resolution goal: **$\sigma(\Delta p_T)/p_T^2 \sim 2 \cdot 10^{-5}$ GeV^{-1}**

- *Detector model for simulation under optimization*
  - ***R=1.25m → 1.5m:*** track resolution depends stronger on R than on B

$$\frac{\sigma(p_T)}{p_T^2} \propto \frac{\sigma}{\sqrt{N+4}BR^2}$$

  - ***L/2=1.6m → 2.3m:*** improvement in track resolution and in forward acceptance (Hcal moved forward)



- ***Inhomogeneous B*** field causes distortion in particle trajectories
  - Study the impact on performance
  - Mapping of the B field
  - Implementation in the *software (currently under revision)*

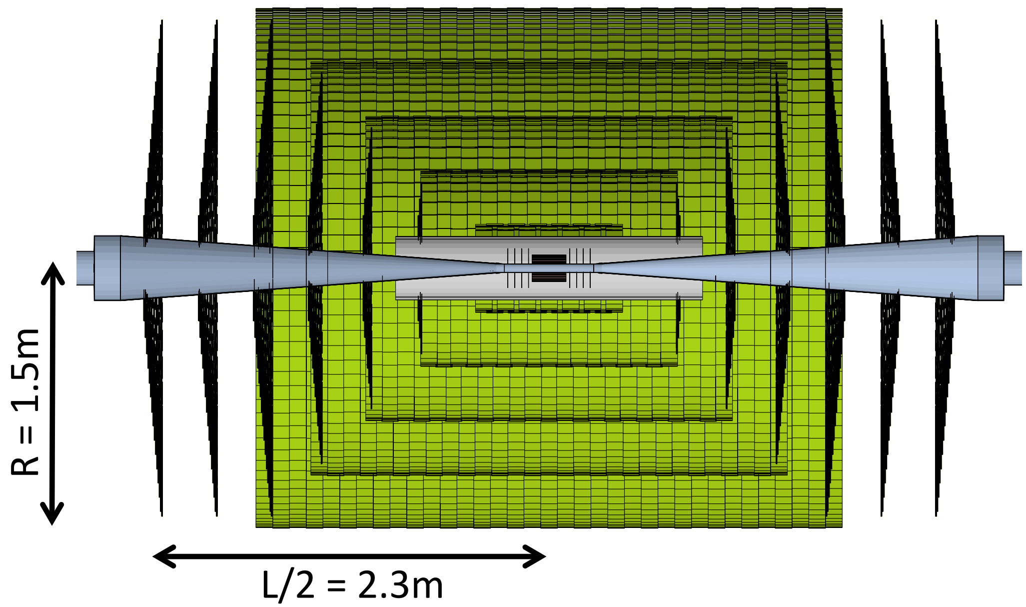
Implementation

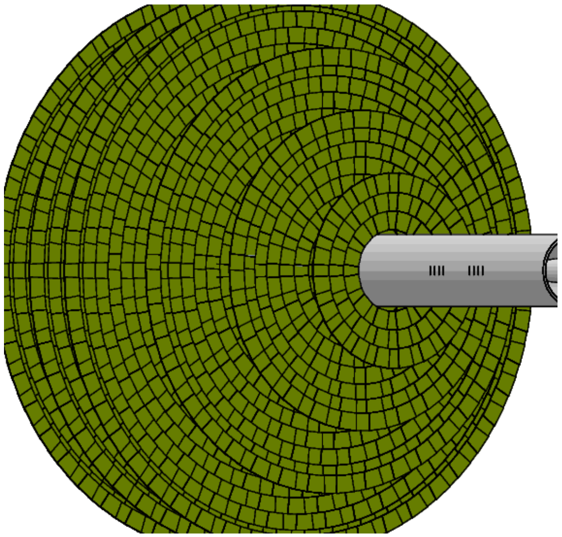
Performance results

Comparison between fast and full simulation

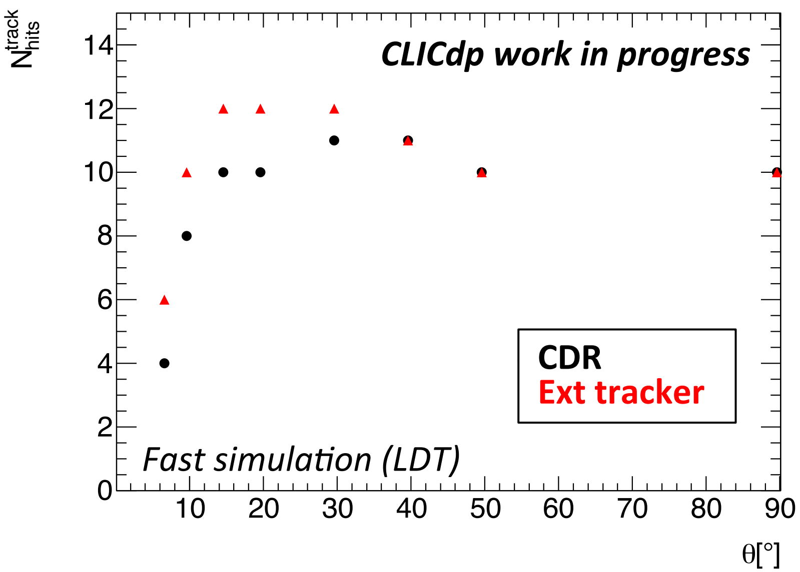
EXTENDED TRACKER GEOMETRY

Implementation

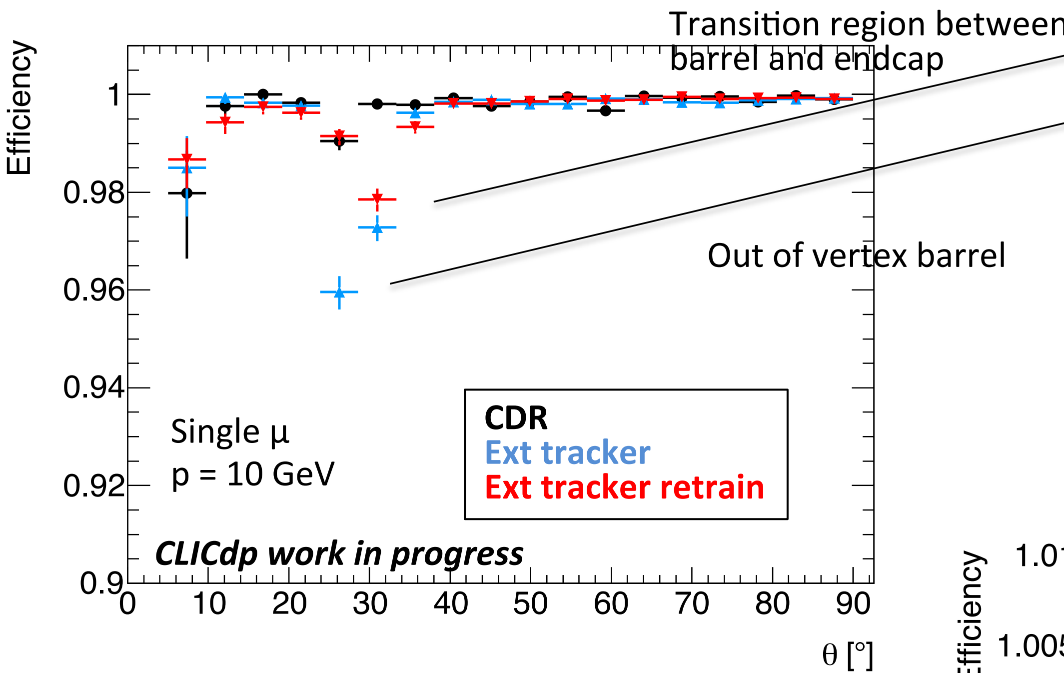


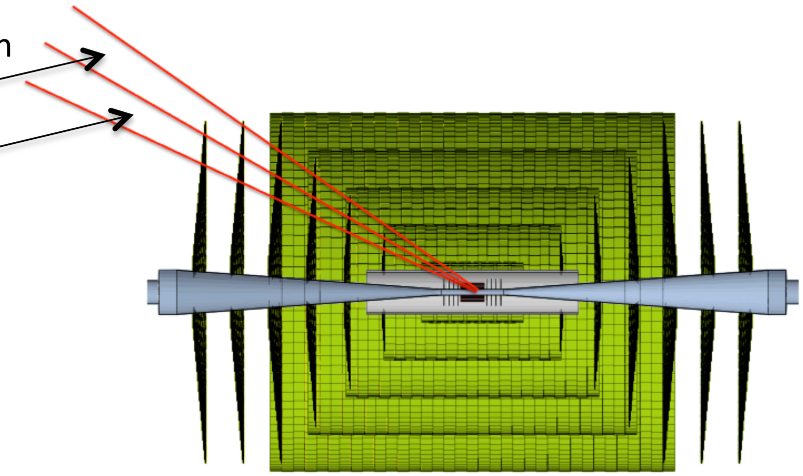


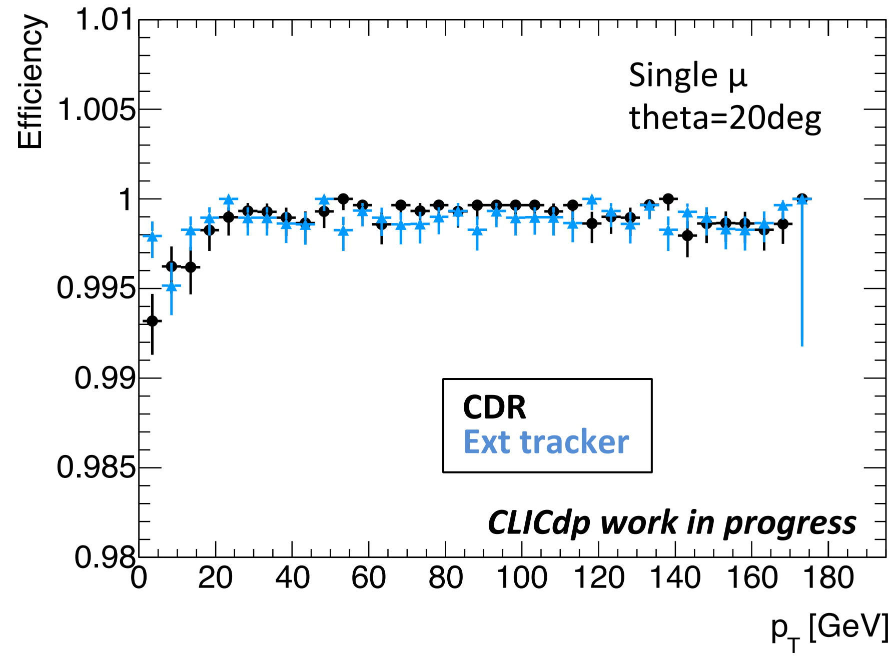
- *Extended tracker* implemented in simulation
  - added 2 forward disk w.r.t. to SiD → **L/2 = 2.3m**
  - radial dimension extended to **R = 1.5 m**
  - pointing transition regions (but not at the IP)
- No optimization for modules overlap in rings and at the edges of layers
- No optimization for layers position → equispaced
- All *overlaps solved* in the tracker region



Performance - efficiency



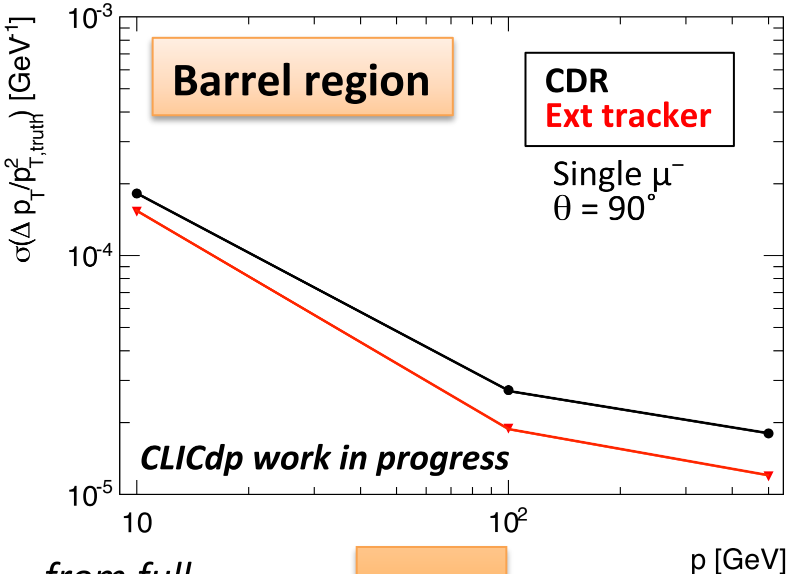


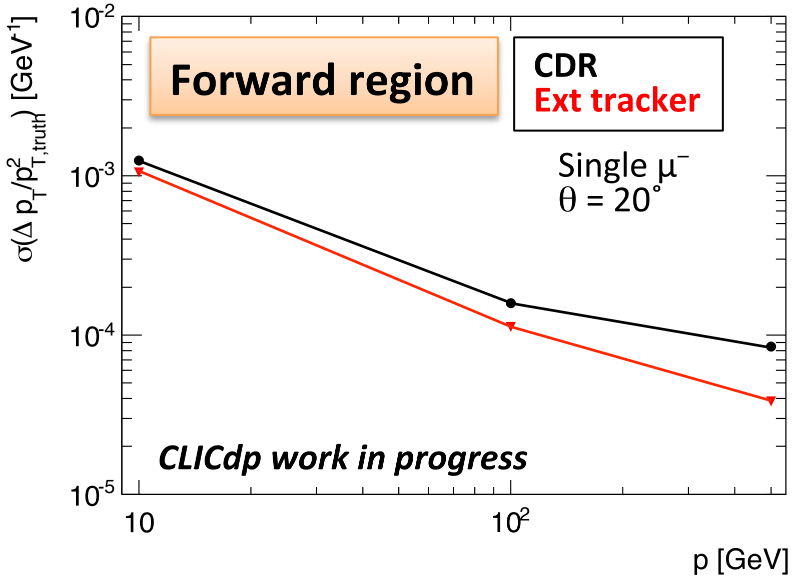


- Full simulation
- Stable performance as a function of p_T even in the forward region (θ<20°)
- After retraining, good eff performance also as a function of θ. *~2% drop in efficiency in the transition region between barrel and endcap*

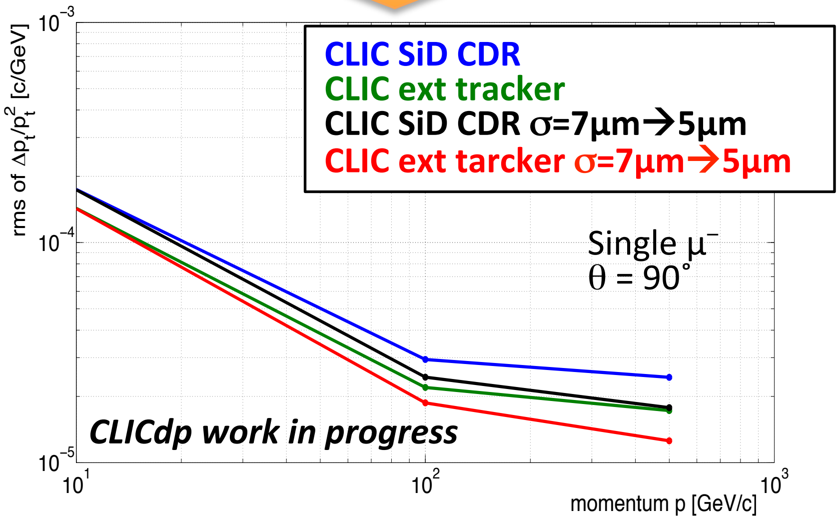
Performance – p_T resolution

Single μ, p = 10, 100, 500 GeV





from full to fast sim



- According to Gluckstern's formula expected improvement in p_T resolution:

$$\sigma_{\mathrm{new}} = \left(L_{\mathrm{old}}/L_{\mathrm{new}}\right)^2 \sigma_{\mathrm{old}}$$

→ *20-50% improvement*: OK

- Same improvement in full and fast sim
  - In full sim too optimistic charge sharing (no gauss smear at digitization level) → *retuning of the parameters needed*

Implementation & B field map

Results with current fit model and code

Plans for a new tracking software

INHOMOGENEOUS B FIELD

Workflow & B field map

1) Geometry definition: compact.xml + GeomConverter

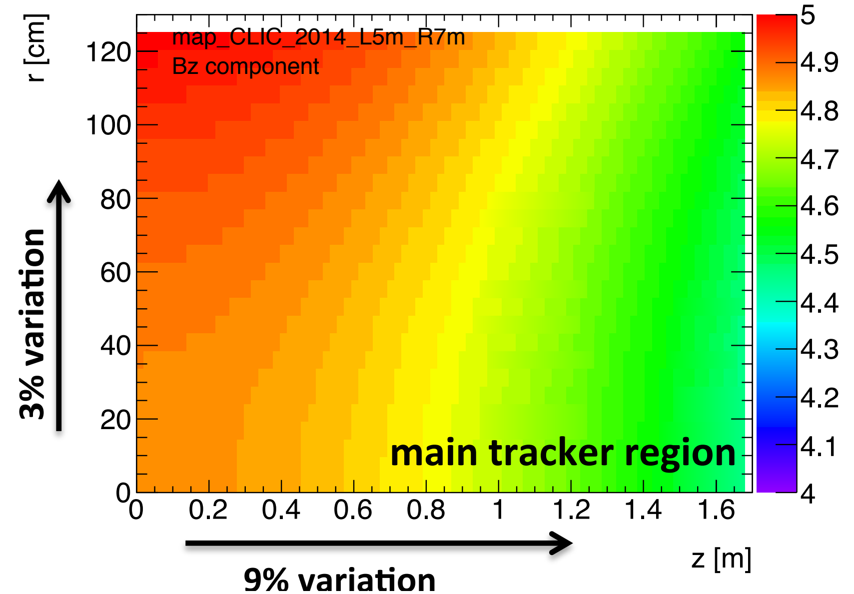
→ ***Non-homogeneous*** *B field introduced by a map with position coordinates and field values*

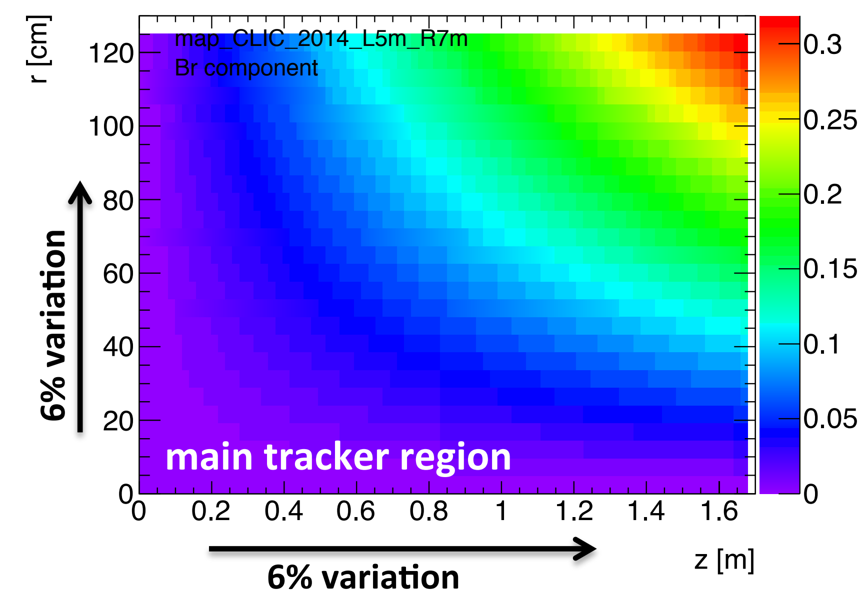
2) Simulation: SLIC (based on Geant4 → interaction of particle in matter)

→ *Tracker hits are simulated according the* ***non-homogeneous*** *B field*

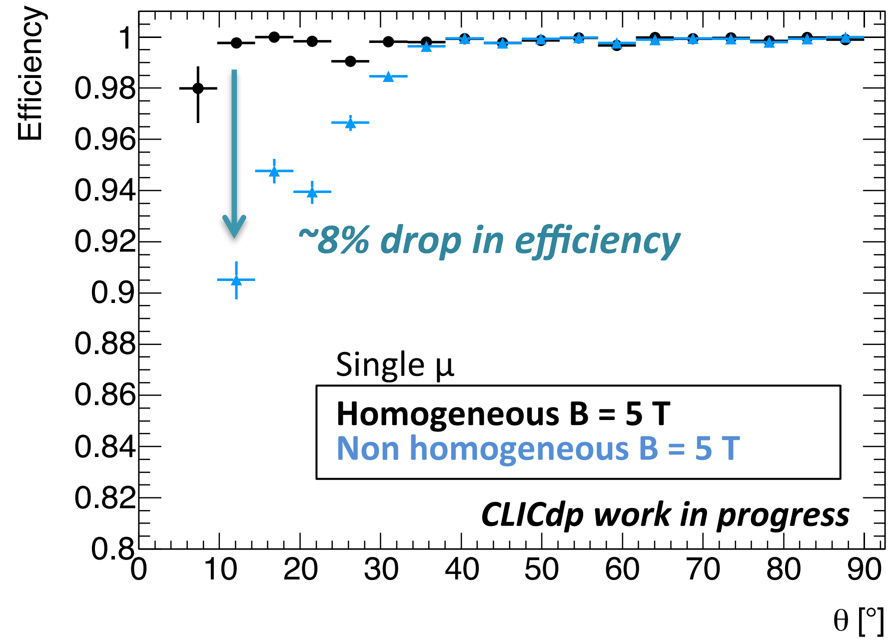
3) Reconstruction: LCSim (at the moment)

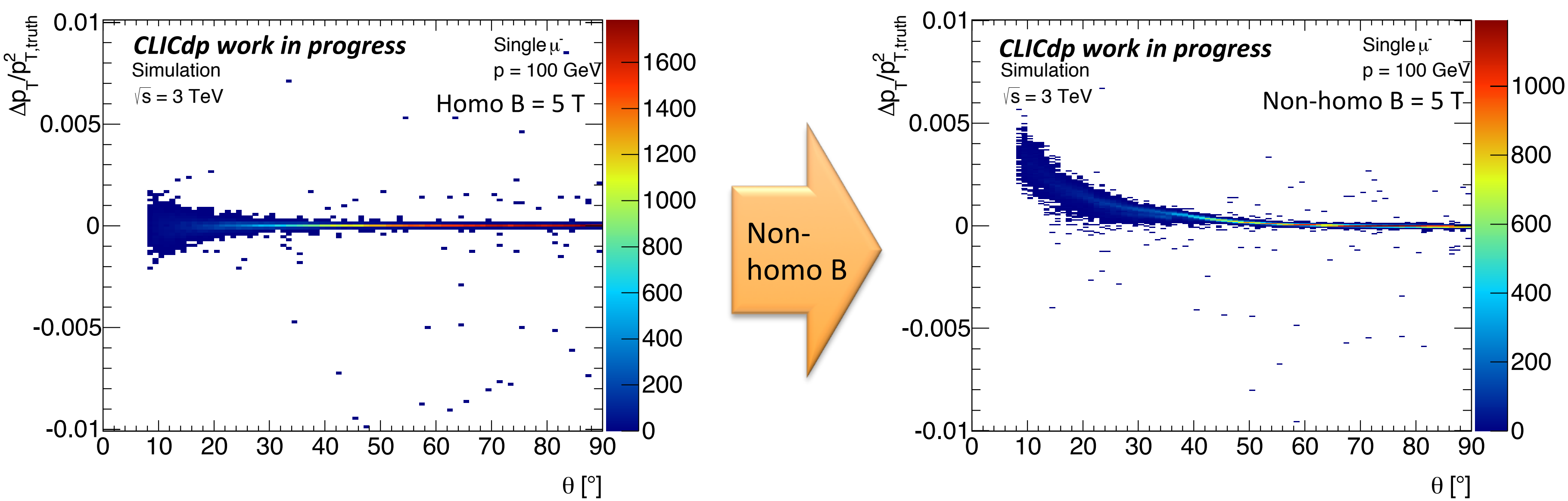
→ ***Homogeneous*** *B field (value at the IP):*
- need to move from the global helical fit: work on going for the tracking software



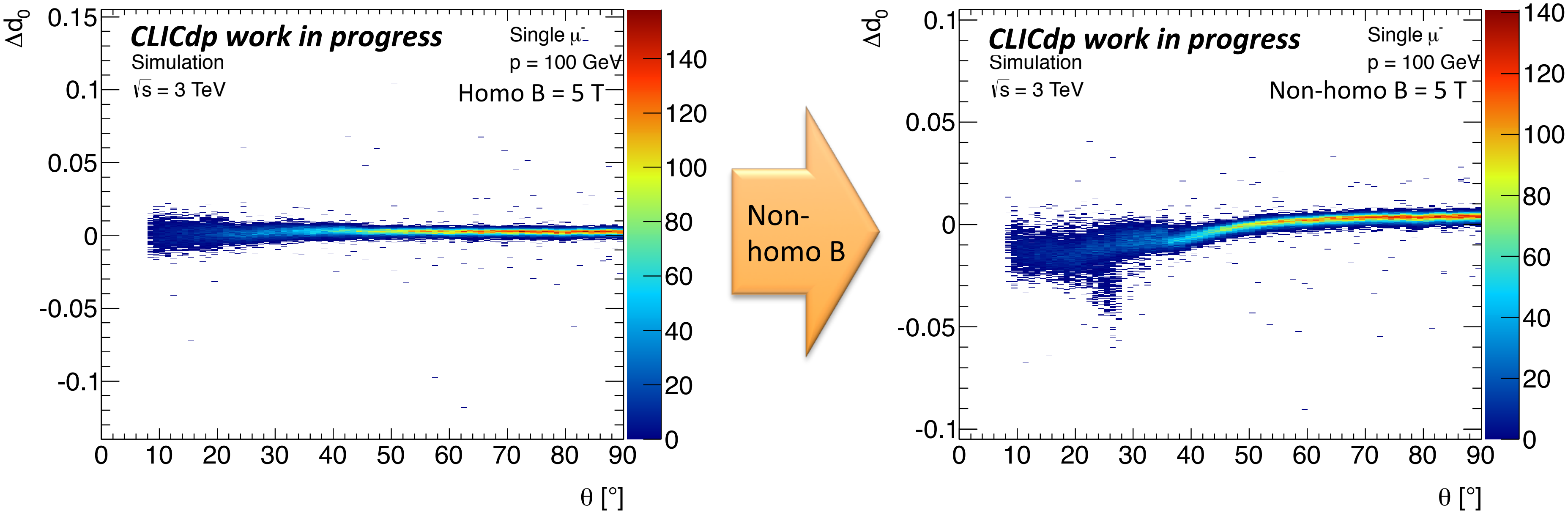


- Geometry used: *CLIC_2014_L5m_R7m* (CLIC_SiD with reduced endcaps)
- Degradation in reco efficiency and bias in the p_T reco due to the *assumption of **homogeneous field in the reconstruction***
  - In CLIC_SiD *helical* extrapolation and fit
  - In ATLAS use of *numerical integration method* (Runge-Kutta)



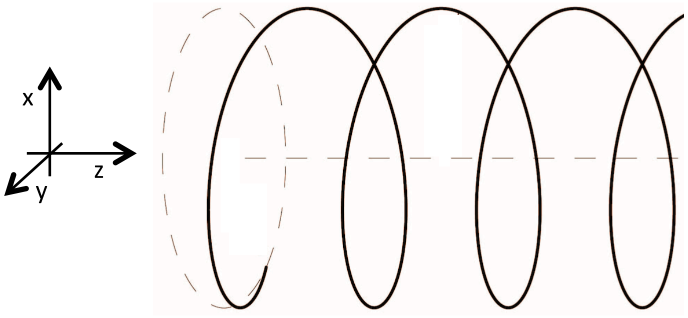


Impact parameter resolution



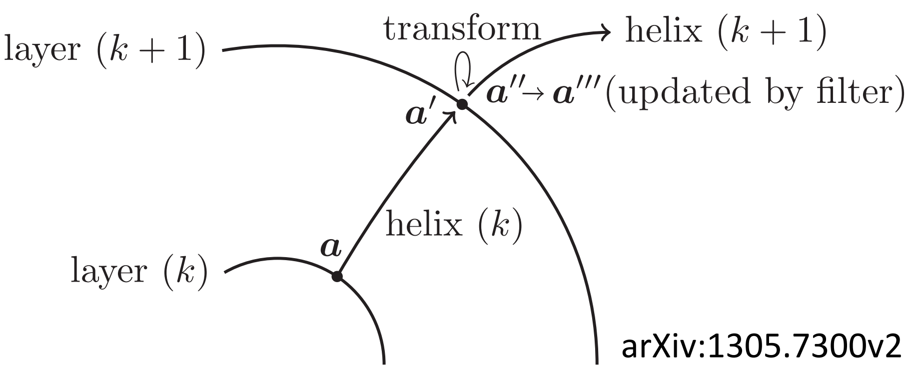
- Similar conclusion: bias in d_0 resolution due to reconstruction bias
- z_0 not affected (see backup)

Tracking extrapolation



- **Global helical model:**
  - Homogeneous B
  - Circumference in rφ plane
  - Straight line in Sz plane
  - 5 parameters $(\kappa, d_0, z_0, \phi_0, tan\lambda)$

- **Wise-segmented helix:**
  - Helix from layer to layer (homo B)
  - At every measurement update the B field and the reference frame
  - Impose a "sufficient" number of these steps (not only on measurement plane)
  - Kalman filter implementation



arXiv:1305.7300v2

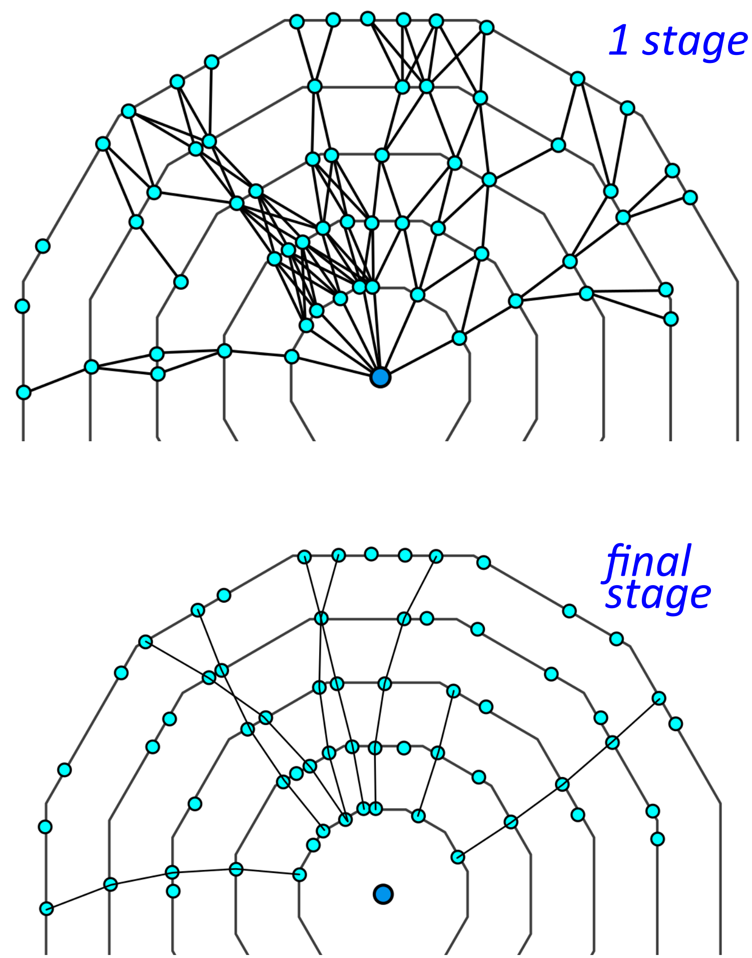
soft-pub-2007-005

$$\frac{d^2\mathbf{r}}{ds^2} = \underbrace{\frac{q}{p}\left[\frac{d\mathbf{r}}{ds} \times \mathbf{B}(\mathbf{r})\right]}_{\text{Lorentz force}} + \underbrace{g(p,\mathbf{r})}_{\text{energy loss function}}\frac{d\mathbf{r}}{ds}$$

- **Runge-Kutta based extrapolator:**
  - General method, any assumption about B
  - Solve second order differential equation of motion to compute the intersection of the trajectory with the destination plane

Plans for the tracking software

- Current SiD tracking software has shown some limitations for our user case:
  - No implementation of Kalman filter (important for low p_T tracks)
  - Global helical tracking extrapolator
- ILD software `SiliconTracking_MarlinTrk` has shown poor performance in terms of efficiency when the TPC is not included
- *Start to work to extended the ILD vertex tracking software based on **cellular automaton** (Y. Voutsinas, F. Gaede, R. Glattauer) and on **mini-vectors** idea*
  - ✓ Kalman filter implemented (KalDet/KelTest)
  - ✓ Promising performance
  - ✓ Accounts for double layers
  - → Extend to the full Si tracker
  - → Interface to DD4hep (now use of gear file)
  - → Study the case of B decay



from R. Glattauer's thesis

Summary

- ***Extended tracker*** geometry implemented in simulation:
  - *Stable efficiency* performance w.r.t. CDR
  - Up to *20-50% improvement* in *p_T resolution*

  → *On going implementation also in DD4hep (M. Frank, N. Nikiforou, A. Sailer)*

- Results with realistic B field ***with homogeneous B assumption in reco***:
  - *Degradation* in the tracking *efficiency* in the forward region (θ>30°)
  - *Bias and degradation in the p_T and d_0 resolution* → assumption of homogeneous B (helix) in the reconstruction

  → *Confident of restoring good performance considering inhomogeneous B in reco*

- Start working on a new tracking software:
  - Starting point: *ILD vertex/Si tracking software* based on cellular automaton

  → *Work just started!*

Thanks for your attention!

BACK-UP

LCSim software version

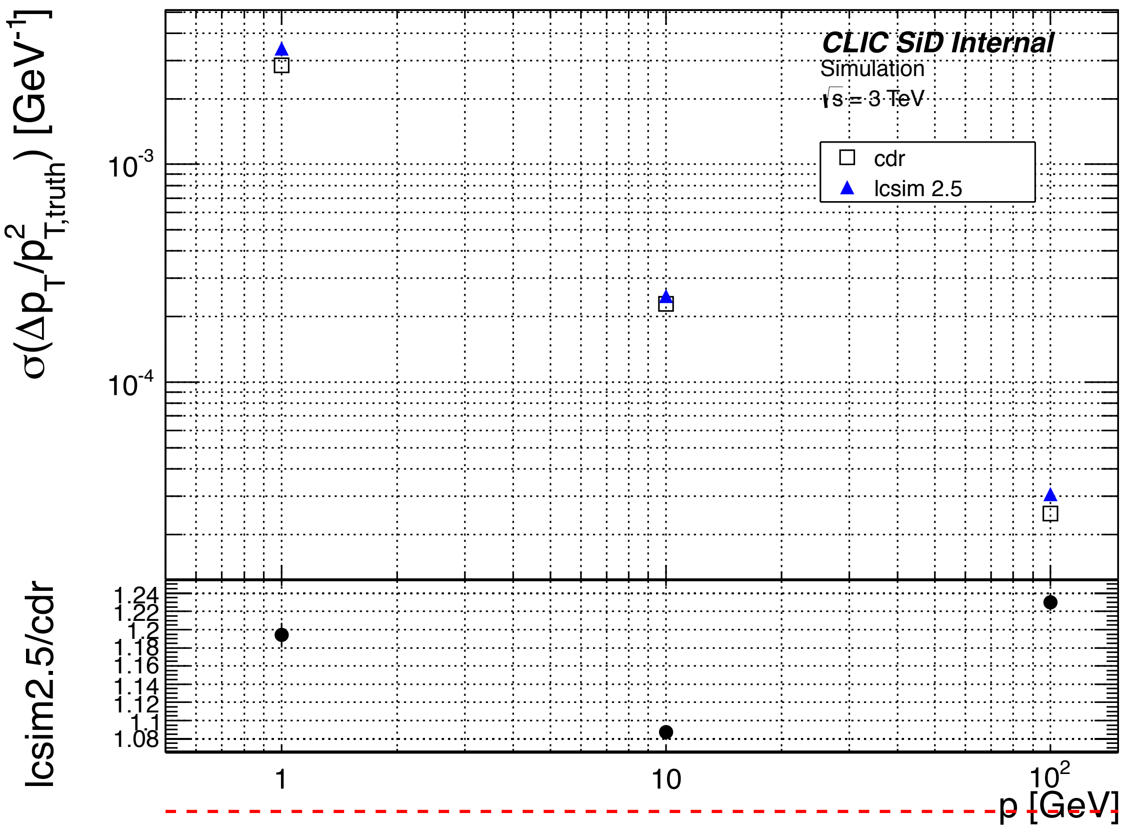
- Some discrepancies observed between LCSim CDR, LCSim 2.5, LCSim 2.8 for the tracking performance *(agreement with Nilou's studies):*
  - *from LCSim CDR to LCSim 2.5* (used for DBD):
    - ~20% worsening of the momentum resolution
    - improvements in the pull distributions (better estimation of the uncertainties) and less theta dependence
  - *from LCSim 2.5 to LCSim 2.8* ("Norman's patch")
    - restore of CDR performance but d0 resolution → 10% worsening at p=10GeV
    - worsening again in the pull distributions

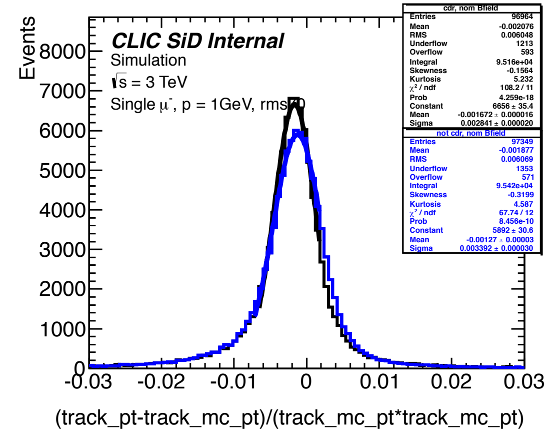
    → probably attempt to restore as much as possible CDR without removing the changes introduced for the HPS

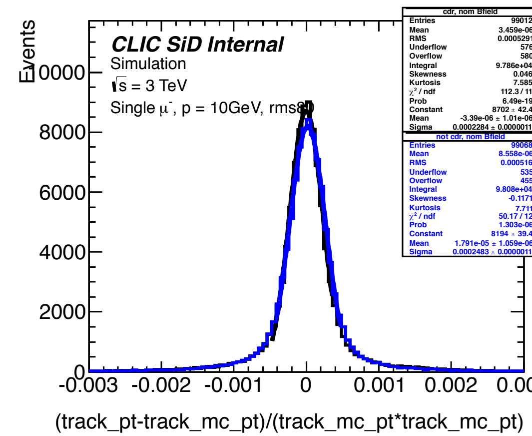
- Plan to migrate to a new tracking code
  - *decision to **use LCSim 2.5***

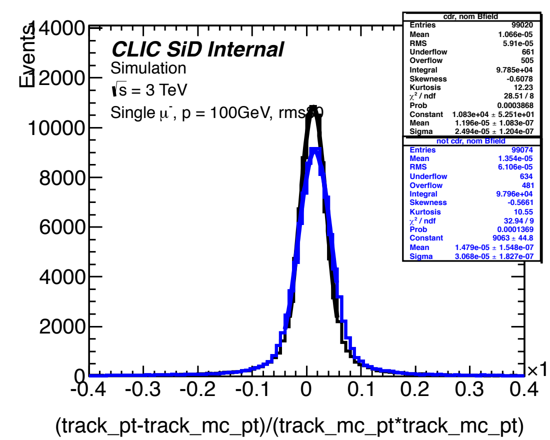
Comp LCSim CDR and 2.5

Single μ, inclusive in theta









Better resolution (~20%) for CDR (LCSim 1.18) version.
But CDR version gives results better than expectation.

FROM ATLAS NOTE soft-pub-2007-005:
(A. Salzburger)

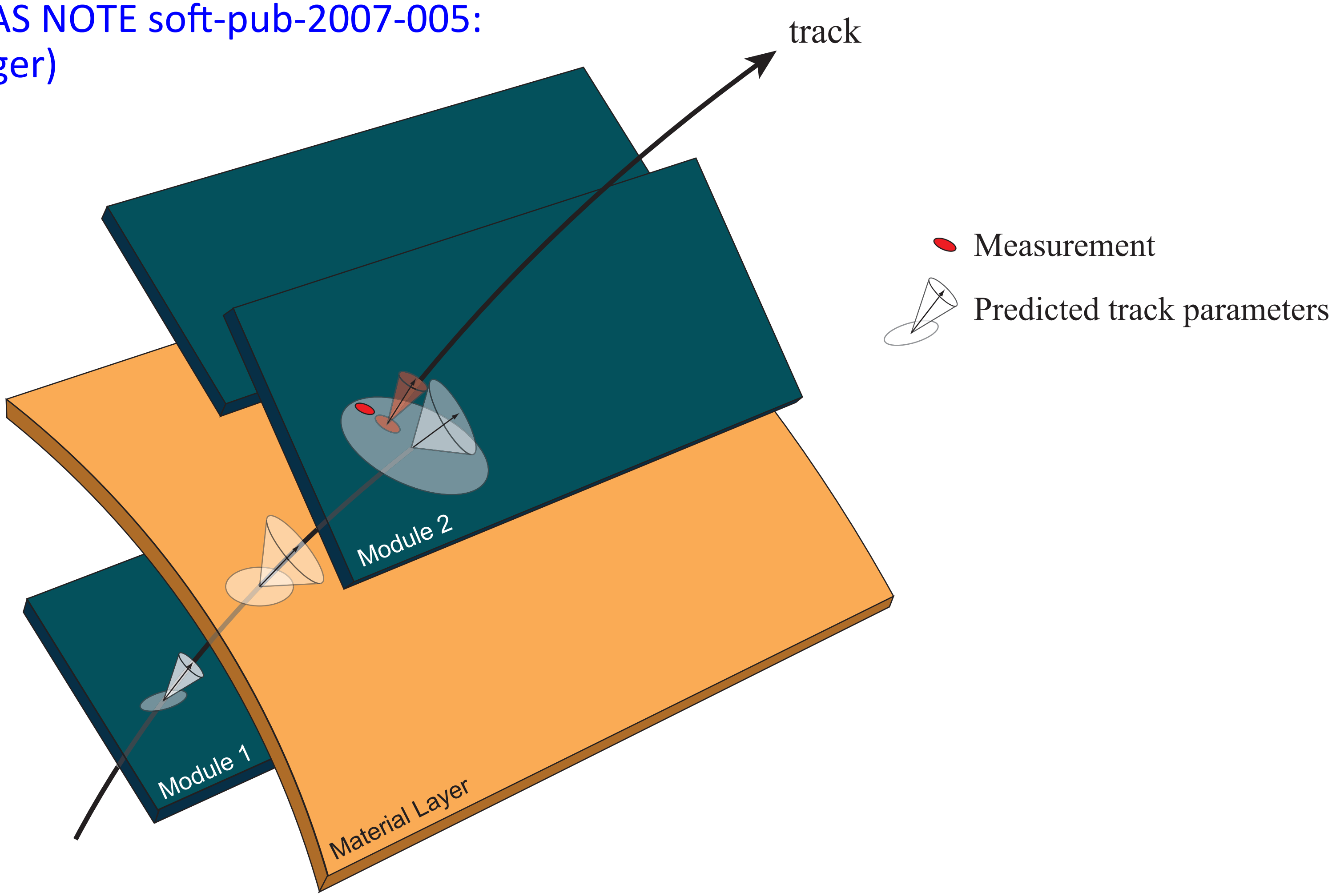
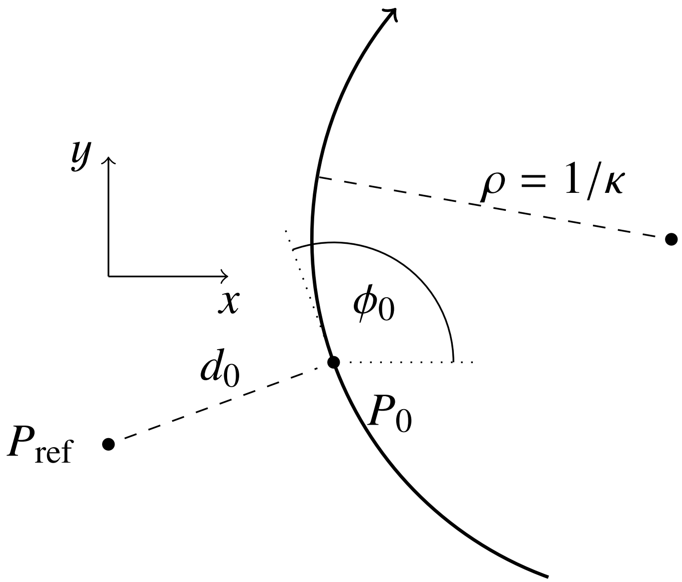


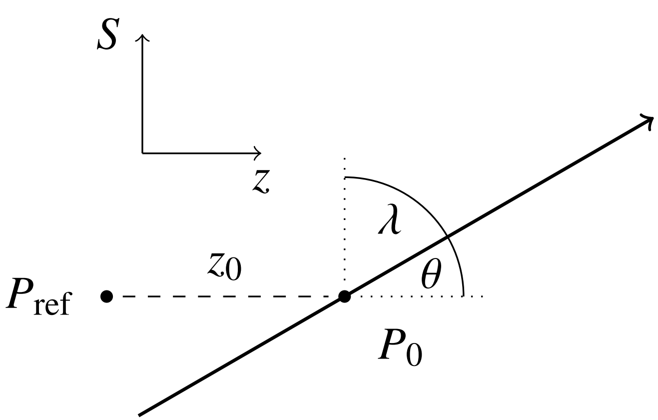
Figure 1: Simplified illustration of a typical extrapolation process within a Kalman filter step. The track representation on the detector module 1 is propagated onto the next measurement surface, which results in the track prediction on module 2. The traversing of the material layer between the two modules causes an increase of the track direction uncertainties and thus — by correlation — an increased uncertainty of the predicted track parameters. In the Kalman filter formalism, the weighted mean between prediction and associated measurement build the updated measurement which builds the start point for the next filter step; this leads to the illustrated non-continuous track model.

Helix tracking model (homo B)

FROM C. GREFE'S THESIS:



(a) xy plane



(b) $S\,z$ plane

starting point $P_0 = (x_0, y_0, z_0)$

$d_0 = \sqrt{x_0^2 + y_0^2}$

$$p_T = \frac{k\,B}{|\kappa|}$$

$$p_x = p_T\ \cos\phi_0,$$

$$p_y = p_T\ \sin\phi_0,$$

$$p_z = p_T\ \tan\lambda,$$

$$p = \frac{p_T}{\cos\lambda} = p_T\sqrt{1+\tan^2\lambda},$$

$$q = \frac{\kappa}{|\kappa|}.$$

Change of coordinate frame

FROM ILD NOTE arXiv:1305.7300v2:
(Bo Li, Keisuke Fujii, Yuanning Gao)

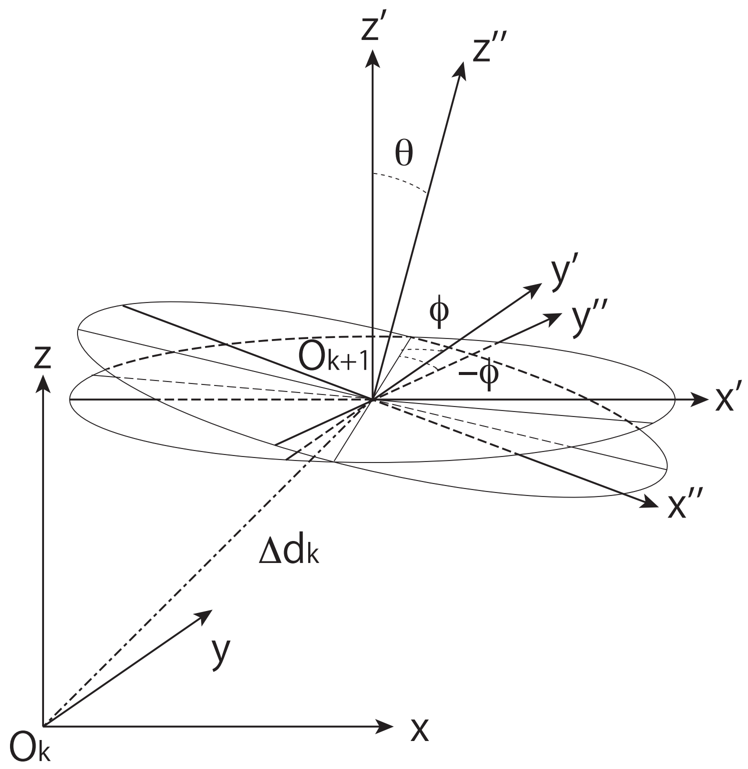


Figure 4: Transformation from one frame to the next. The θ and ϕ angles are determined by the magnetic field directions at the position $\boldsymbol{O}_k$ and $\boldsymbol{O}_{k+1}$.

Cellular automaton criteria

FROM R. Glattauer's THESIS

Table 2.1.: The different criteria available in the `KiTrack` package
(The time is given relative to the fastest criterion)

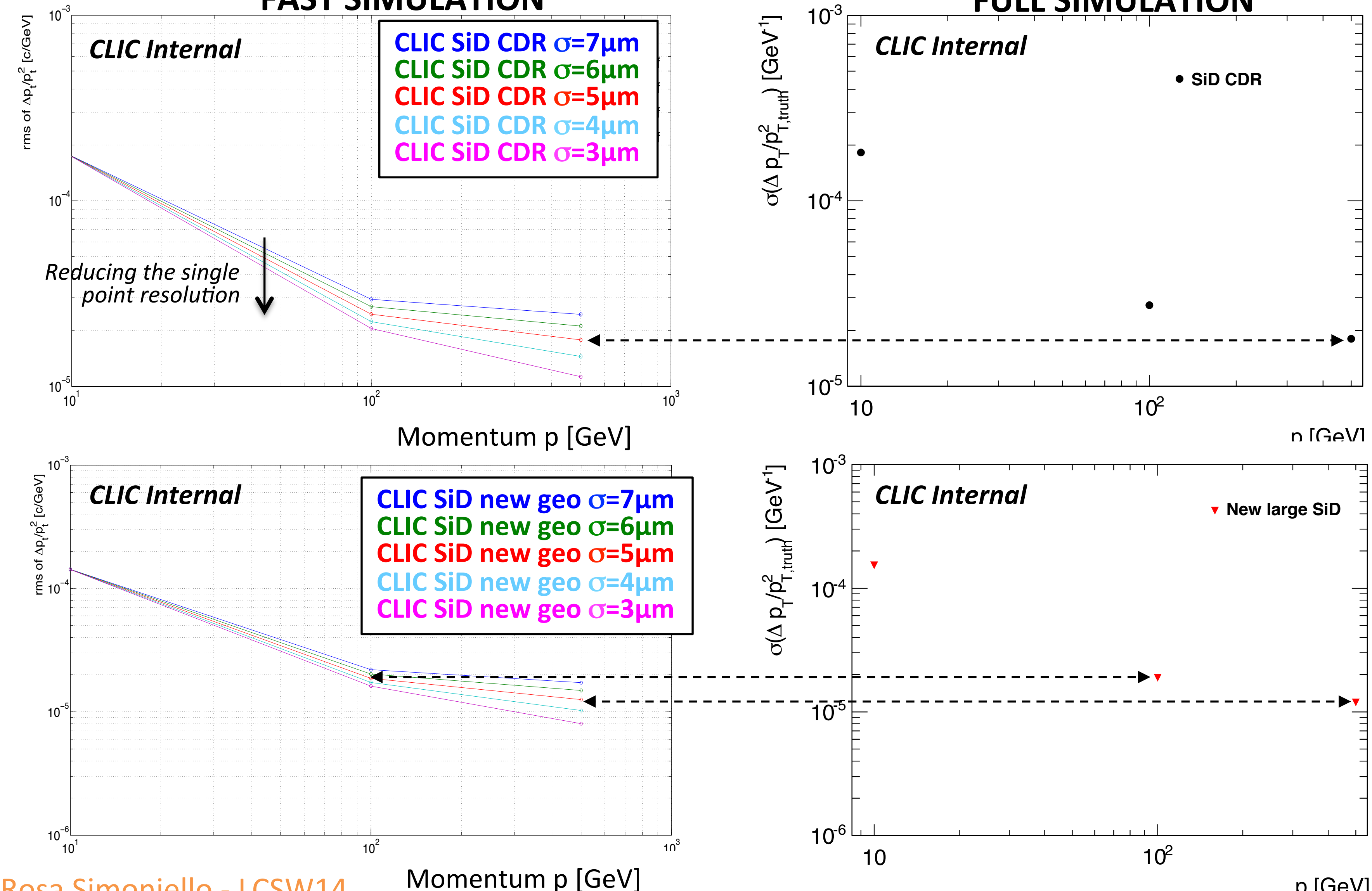
name	hits	time	description
DeltaRho	2	1.00	The difference of the distances to the z-axis: $\Delta\rho = \sqrt{x_2^2 + y_2^2} - \sqrt{x_1^2 + y_1^2}$.
RZRatio	2	1.00	The distance of two hits divided by their z-distance: $\frac{\sqrt{\Delta x^2+\Delta y^2+\Delta z^2}}{\lvert\Delta z\rvert}$
StraightTrackRatio	2	1.04	Best suited for straight tracks: if the line between the two hits points towards IP. Calculated is $\frac{\rho_1}{z_1}/\frac{\rho_2}{z_2}$, where $\rho = \sqrt{x^2 + y^2}$. Is equal to 1 for completely straight tracks.
DeltaPhi	2	1.30	The difference between the ϕ angles of two hits in degrees. ϕ is the azimuthal angle in the x-y plane w.r.t. the positive x axis: $\phi = \text{atan2}(y, x)$.
HelixWithIP	2	1.43	Checks if two hits are compatible with a helix through the IP. A circle is calculated from the two hits and the IP. Let α be the angle between the center of the circle and two hits. For a perfect helix $\frac{\alpha}{\Delta z}$ should be equal for all pairs of hits on the helix. The coefficients for the first and last two hits (including the IP) are compared: $\frac{\alpha_1}{\Delta z_1}/\frac{\alpha_2}{\Delta z_2}$. This is 1 for a perfect helix around the z-axis.
ChangeRZRatio	3	1.23	The coefficient of the RZRatio values for the two 2-hit-segments. Ideally this would equal 1.
2DAngle	3	1.23	The angle between two 2-hit-segments in the x-y plane.
2DAngleTimesR	3	1.46	The 2DAngle, but multiplied with the radius of the circle the segments form, in order to get better values for low momentum tracks.
3DAngle	3	1.25	The angle between two 2-hit-segments.
3DAngleTimesR	3	1.48	3DAngle times the radius of the circle.
PT	3	1.30	The transversal momentum as calculated from a circle in the x-y plane. This criterion includes knowledge about the magnetic field and in this way differs from the rest. A more basic version would be to either use the radius of the circle or its inverse Ω. Using p_T was chosen for reasons of readability.
IPCircleDist	3	1.30	From the 3 hits a circle is calculated in the x-y plane and the distance of the IP to this circle is measured.
IPCircleDistTimesR	3	1.30	Distance of the IP to the circle multiplied with the radius of the circle to take into account higher deviations for low transversal momentum tracks.
DistOfCircleCenters	4	1.66	Circles are calculated for the first and last 3 hits. The distance of their centers is measured.
RChange	4	1.66	The coefficient of the radii of the two circles.
DistToExtrapolation	4	2.21	From the first 3 hits the relation of α to Δz is calculated. This is used to predict x and y of the fourth hit for the given z-value. The distance of this prediction to the actual position in x and y is measured.
NoZigZag	4	2.30	A criterion to sort out tracks that make a zig zag movement. The 2-D angles are measured for the first and the last three hits. Then they are transposed to the area of $-\pi$ to π and multiplied. A zig-zagging track would give angles with different signs and therefore a negative multiplication result.
2DAngleChange	4	2.30	The coefficient of the 2-D angles.
3DAngleChange	4	2.41	The coefficient of the 3-D angles.
PhiZRatioChange	4	2.50	The coefficient of the PhiZRatio of the first 3 and the last 3 hits.

Scan for matching full sim (barrel)

Single μ, p = 10, 100, 500 GeV, theta=90deg – *Resolution in Rφ,z coord*

Single point resolution needed for matching the full sim perf: 5μm

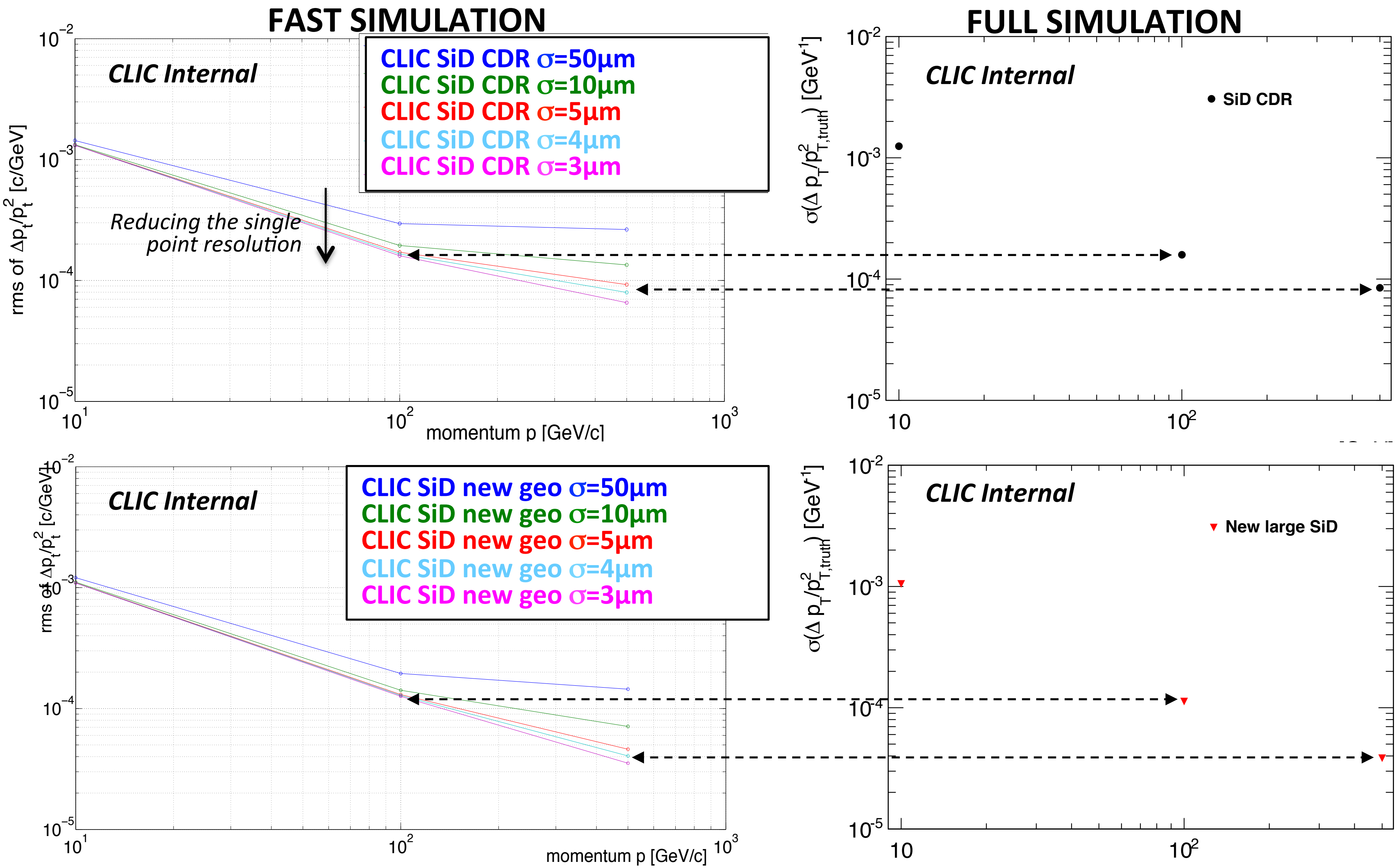
FAST SIMULATION **FULL SIMULATION**



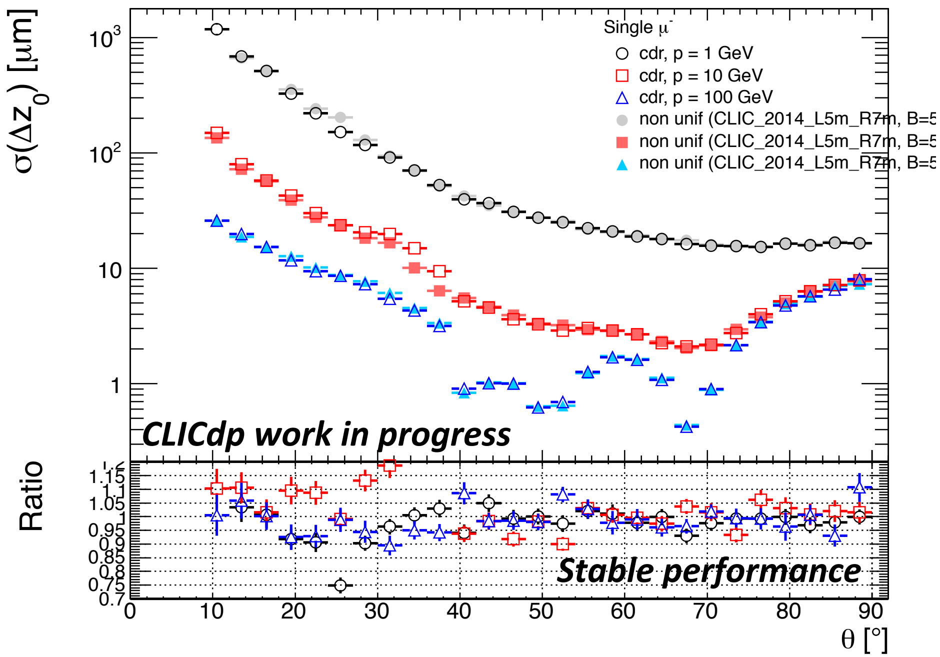
Scan for matching full sim (forward)

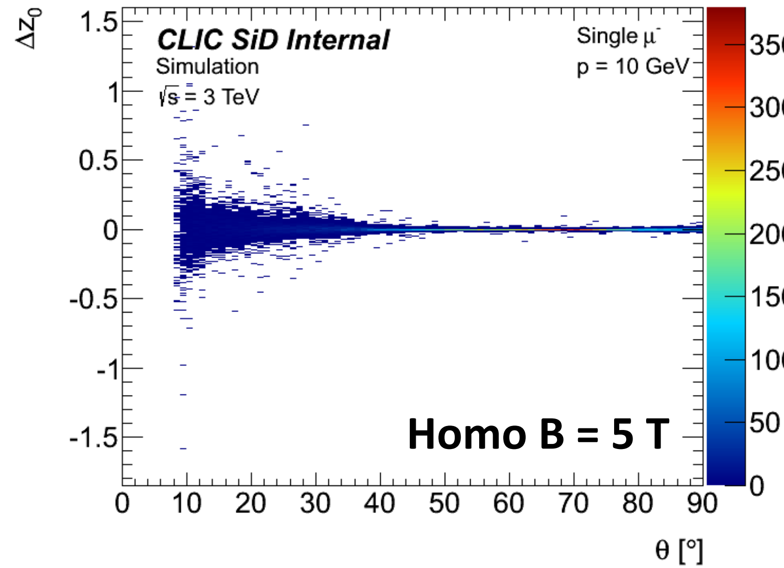
Single μ, p = 10, 100, 500 GeV, theta=20deg – *Resolution in u-v coord*

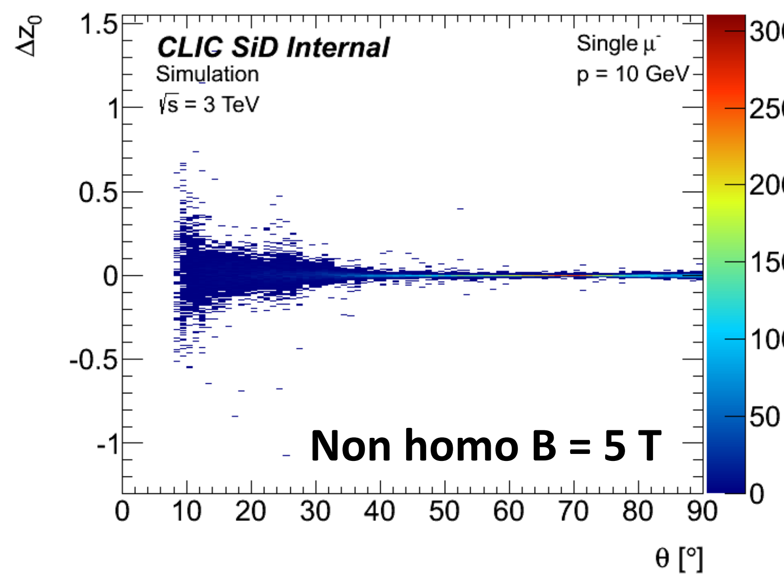
Single point resolution needed for matching the full sim perf: 4μm



z_0 resolution

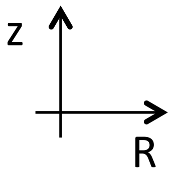


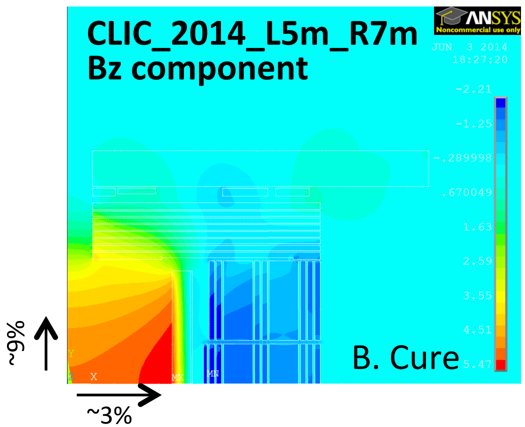


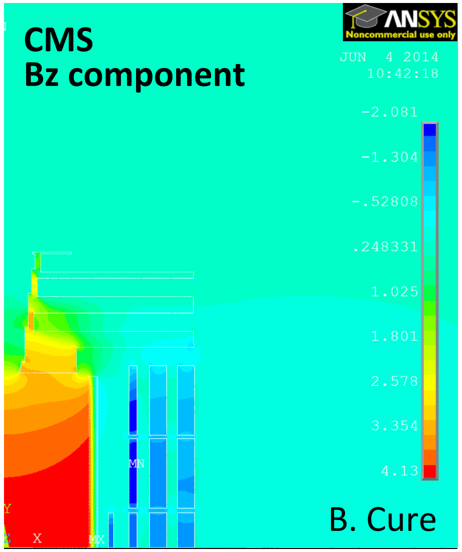


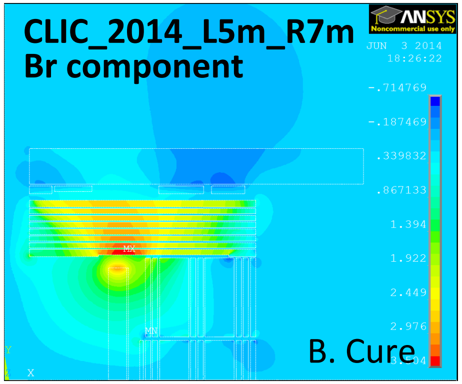
Comparison with CMS

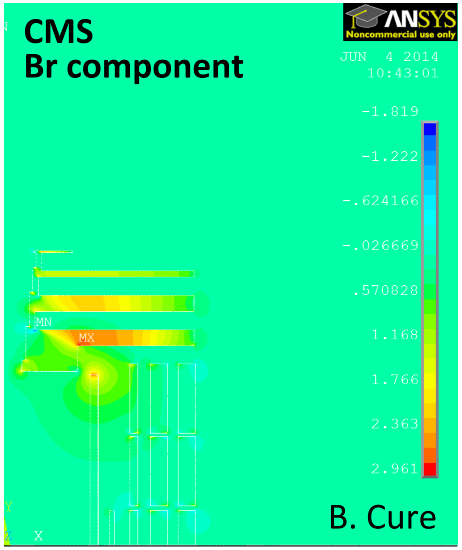
Thanks to Benoit Cure and Nicola Amapane









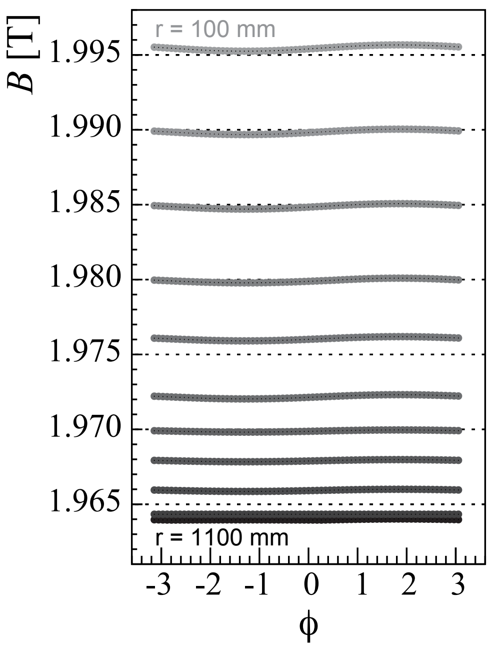


- CMS accurate study of field in the yoke (arXiv:0910.5530)
- Field inside the tracker region *pretty homo* (long solenoid)
  - Main inhomo from non-symmetry in z (different number of spires in the coil)
- Tracker field mapped with an *accuracy <0.1%* → important for physical analysis:
  - measurements of track parameters near the interaction vertex
  - to limit bias in the momentum scale (w.r.t. the momentum resolution)

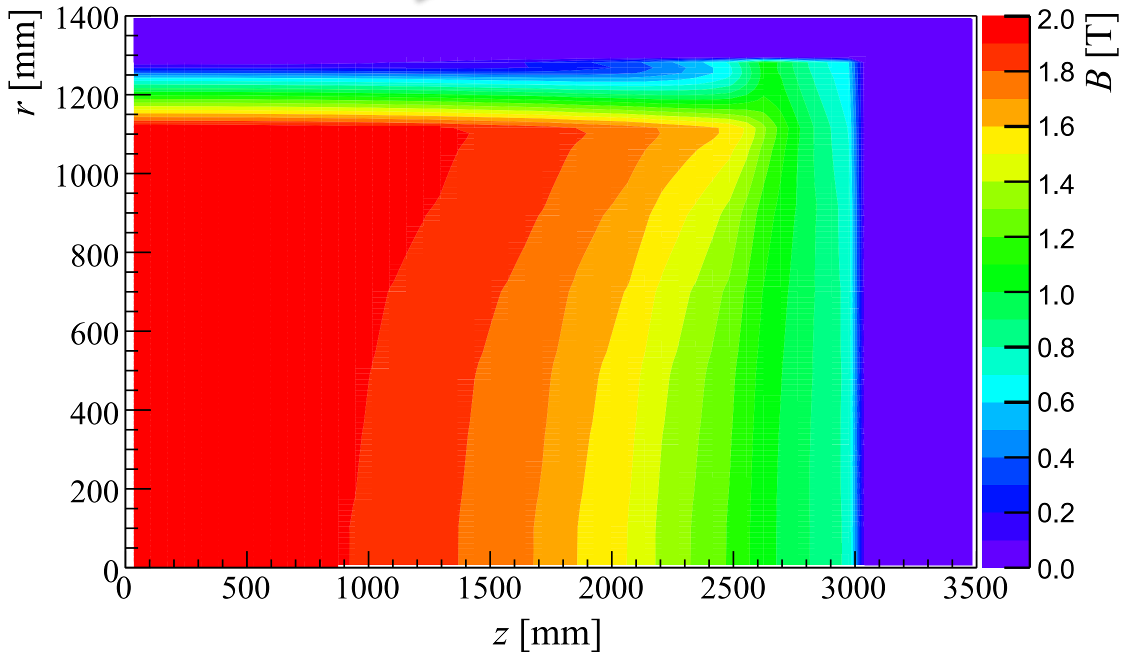
	CMS	CLIC_SiD
B [T]	3.8	5.0
L [m]	12.5	6.4
R [m]	3.0	5.4

FROM ATLAS NOTE
soft-pub-2007-005:
(A. Salzburger)

ATLAS case



~40% non-homo of B in the z direction



The first plot shows the ϕ-dependency of the magnetic field at different radii in steps of 100 millimeter at $z = 0$: the homogeneity of the field in the ID is broken in radial and azimuthal direction even in the very central part of the solenoid. The second plot shows the magnitude of the magnetic field shown within a quarter of the Inner Detector.