CLICdp report

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on behalf of the CLICdp collaboration

SiD workshop 12-14 January 2015, SLAC

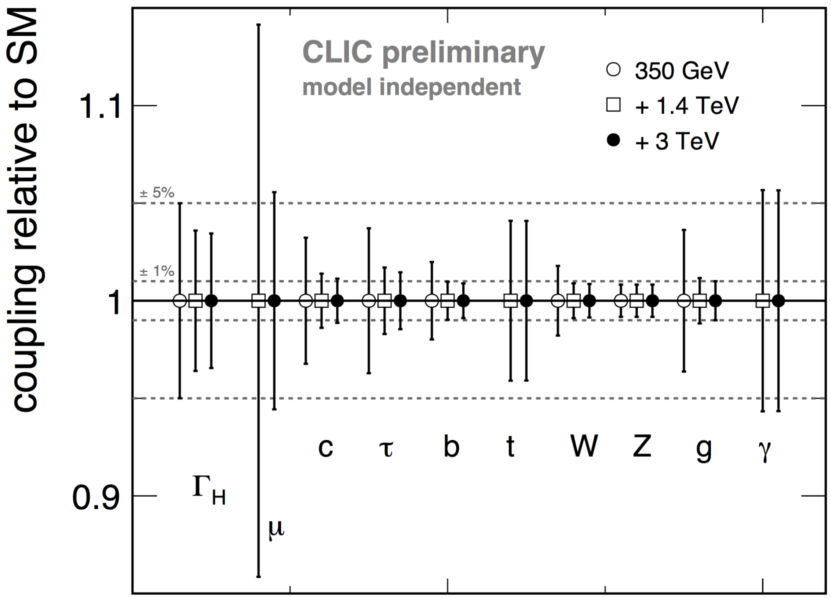
Outline

- Overview of physics studies
  - Summary of the Higgs results
  - BSM analyses planned
- Detector optimisation studies
  - Parameters for simulation models
- Vertex R&D
  - Test beam & simulation studies
  - Studies with mock-up
- W A-Hcal results
- Software
  - DD4Hep
  - Tracking code status

PHYSICS PROGRAM

CLIC Higgs physics

- Rich physics program in 3 energy stages: ~350 GeV, 1.4 TeV, 3 TeV
- In the last year focus on Higgs physics
  - Global fit: *Model independent* and *high precision* determination of the Higgs couplings and Higgs mass width

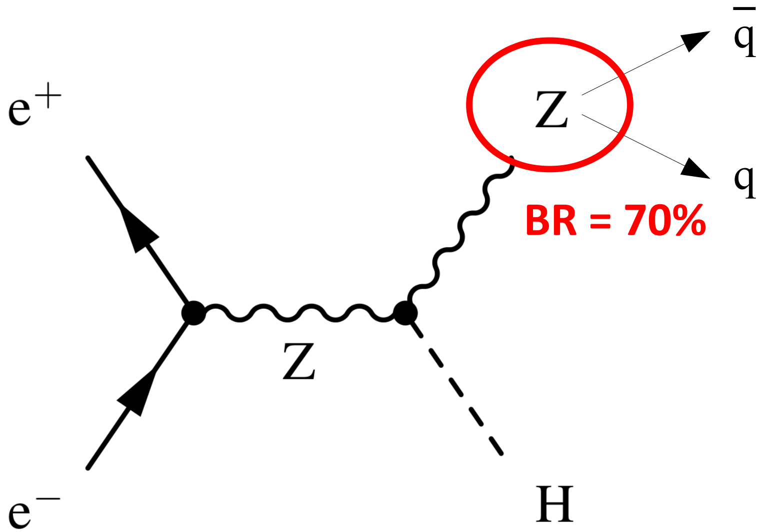


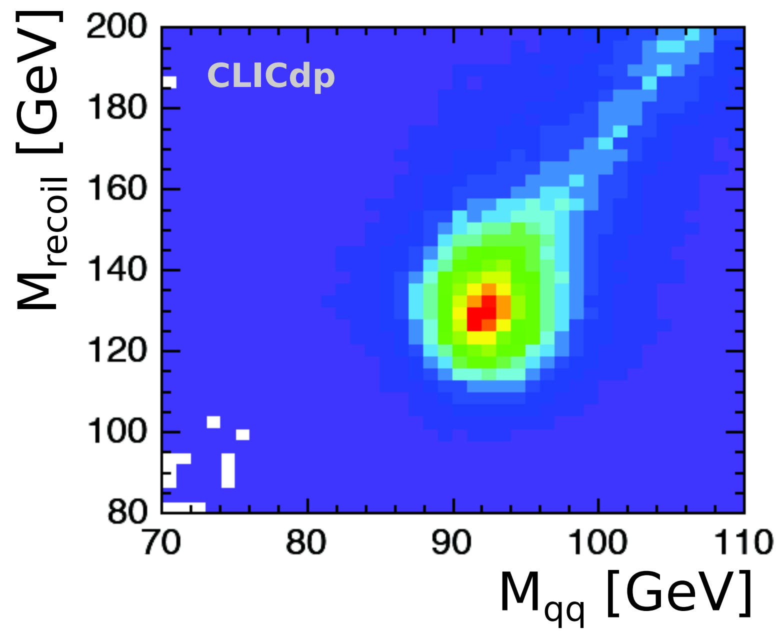
Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.8 %	0.9 %	0.9 %
g_{Hbb}	2.0 %	1.0 %	0.9 %
g_{Hcc}	3.2 %	1.4 %	1.1 %
$g_{H\tau\tau}$	3.7 %	1.7 %	1.5 %
$g_{H\mu\mu}$	–	14.1 %	5.6 %
g_{Htt}	–	4.1 %	$\leq$ 4.1 %
$g^{\dagger}_{Hgg}$	3.6 %	1.2 %	1.0 %
$g^{\dagger}_{H\gamma\gamma}$	–	5.7 %	< 5.7 %
Γ_H	5.0 %	3.6 %	3.4 %

Rare Higgs decay

- *Results limited by 0.8% on g_{HZZ}* from σ(HZ) measurement
  - Already included hadronic Z decays → substantial improvement (next slide)

Higgsstrahlung – hadronic Z decay





- Centre of mass energy 350 GeV, L = 500 fb^{-1}
- Large improvement in the precision measurement of g_{HZZ} including *hadronic Z decay*
  - $\Delta(g_{HZZ})/g_{HZZ} \approx 2.1\%$ only Z→ μμ and Z→ee events
  - $\Delta(g_{HZZ})/g_{HZZ} \approx 0.9\%$ Z→qq events
- Z→qq reconstruction *slightly depends on Higgs decay mode*
  - Careful choice of the selection variables
  - Extreme variation of the SM BRs lead to bias < 0.5 stat error

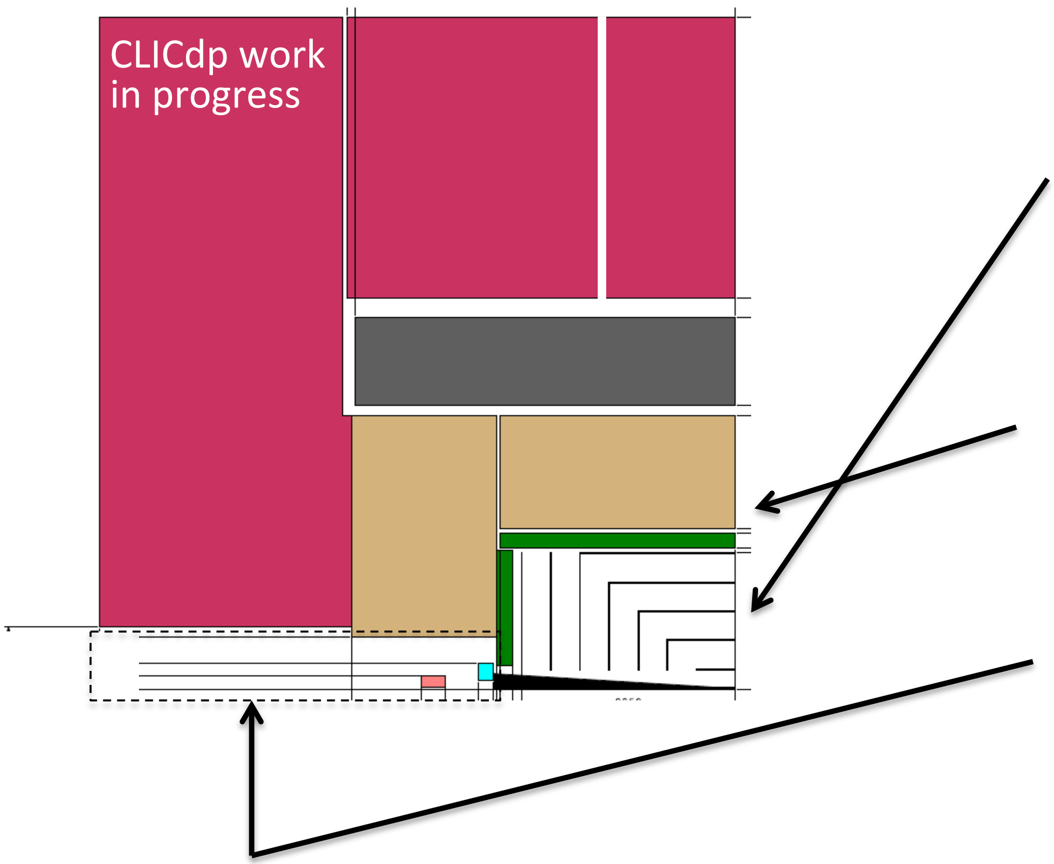
Physics workplan

- CLIC Higgs overview paper is being finalizing
- Next: Beyond SM physics
  - Benchmark studies*: SUSY*, *exotic* models (Z'), model-independent *Dark Matter* searches/exotics
  - High precision SM measurements: *top* physics (asymmetry, top quark couplings), *W* high precision measurements, *Higgs properties* measurements, reanalysis of double Higgs production (*Higgs self coupling* and quartic coupling)

→ Forward topologies → Requirements on detector layout to be taken in consideration in the detector optimisation effort

DETECTOR OPTIMISATION

Detector optimisation status



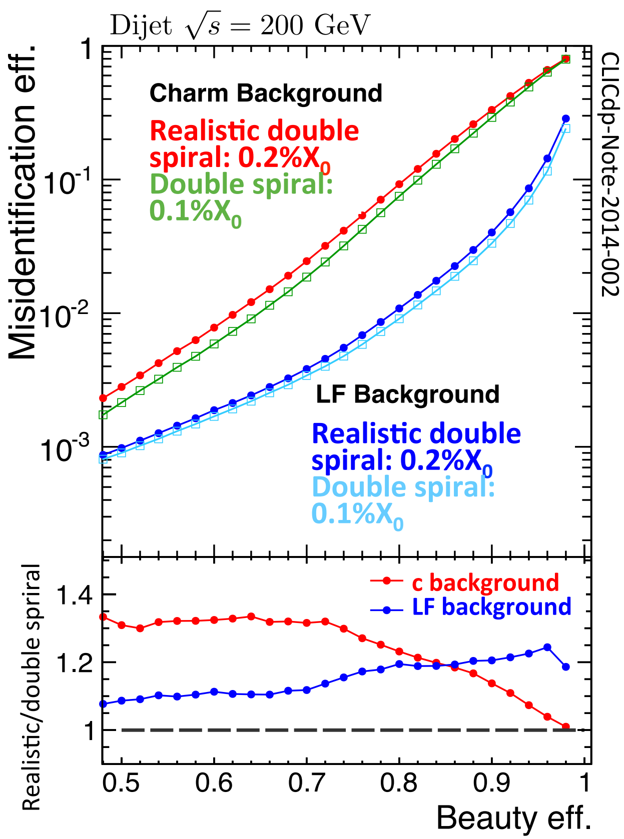
- **Vertex: double layers**
- **Full Si tracker**
  - Trk half length **2.3 m**
  - Trk outer radius **1.5 m**
  - **Trk layout –** *under study*
- **Ecal SiW** 25 layers
- **Hcal ScFe**
  - Hcal **cell size –** *under study*
  - Hcal **acceptance –** *under study*
- **B field 4 T**
- **QD0** and forward region configuration - *under study*

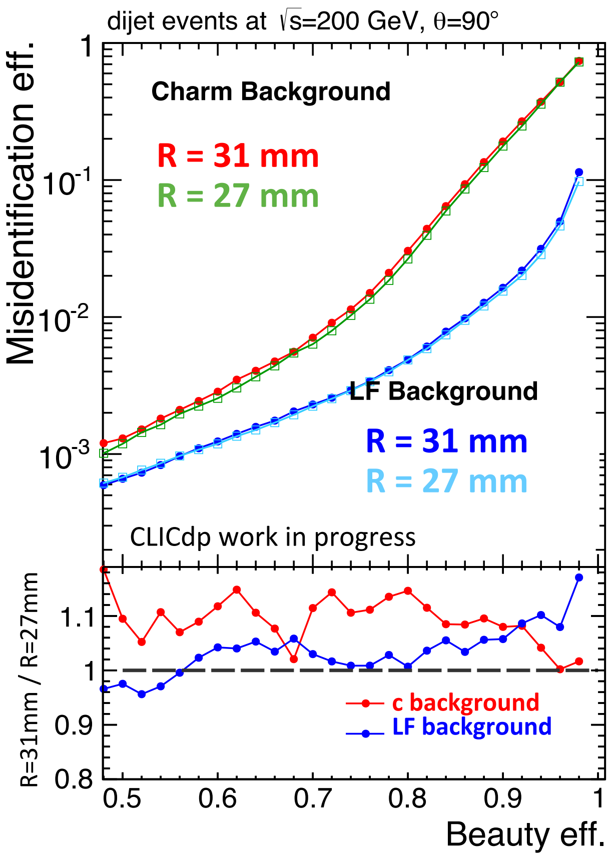
… and more studies on-going

*Finalize detector model (including software and validation) by **June 2015***

Vertex detector

- Requirements for vertex detector:
  - *Efficient heavy quark tagging* → used as performance metric
  - *Low material budget* → air cooling through spiral geometry. Realistic model: 0.2%X_0 per single layer
  - *Occupancy* of few %→ first layer layout
    → increase *R to 31 mm* to compensate the lower B



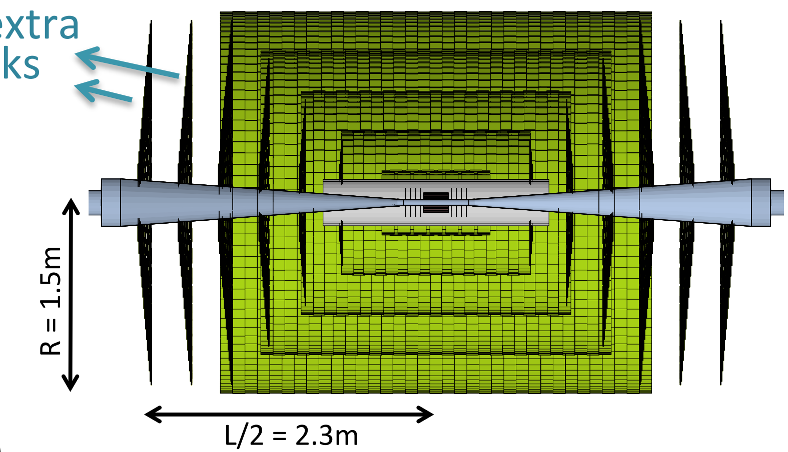


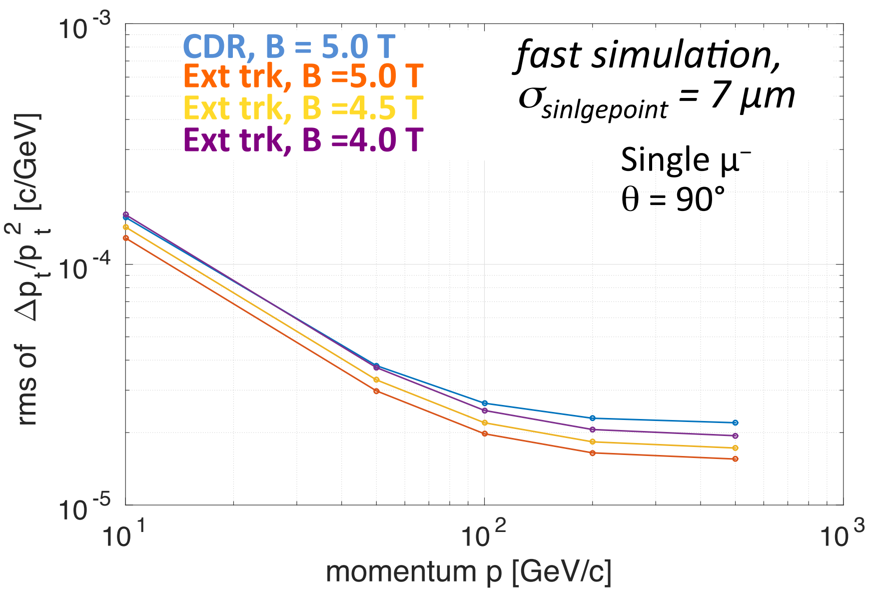
Main tracker and B choice

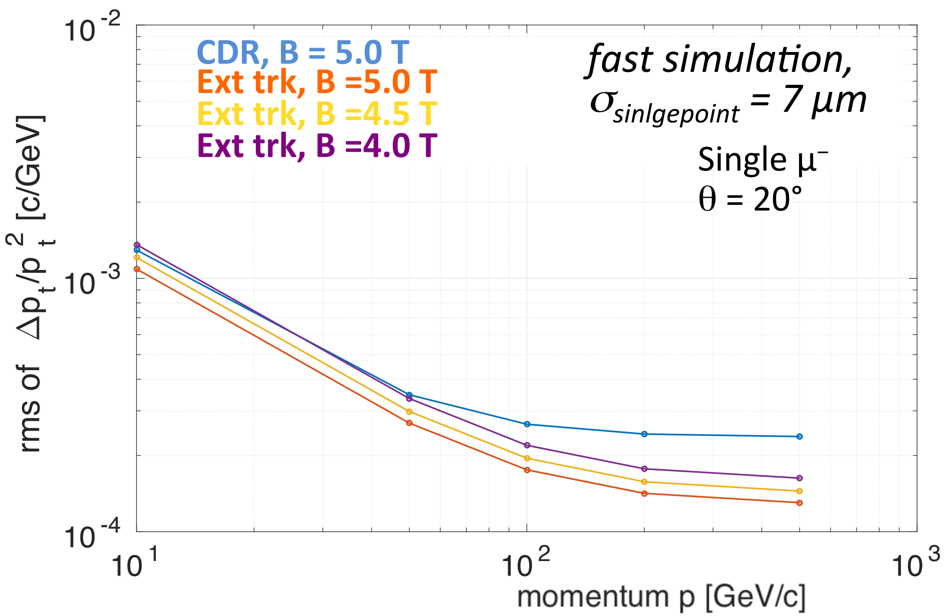
- Gluckstern's formula

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

- Improvement *extending tracker size*
  - R = 1.25 m → *R = 1.5 m*
  - L/2 = 1.6 → *L/2 = 2.3 m* (add disks)
- Worsening *decreasing B* (~10% for each 0.5 T)
  - For *B = 4T*, after trk extension similar or still better performance than CDR case





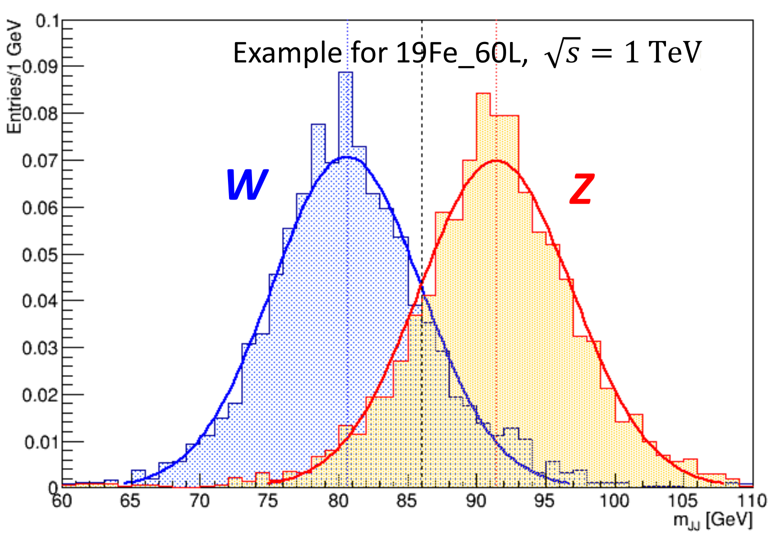


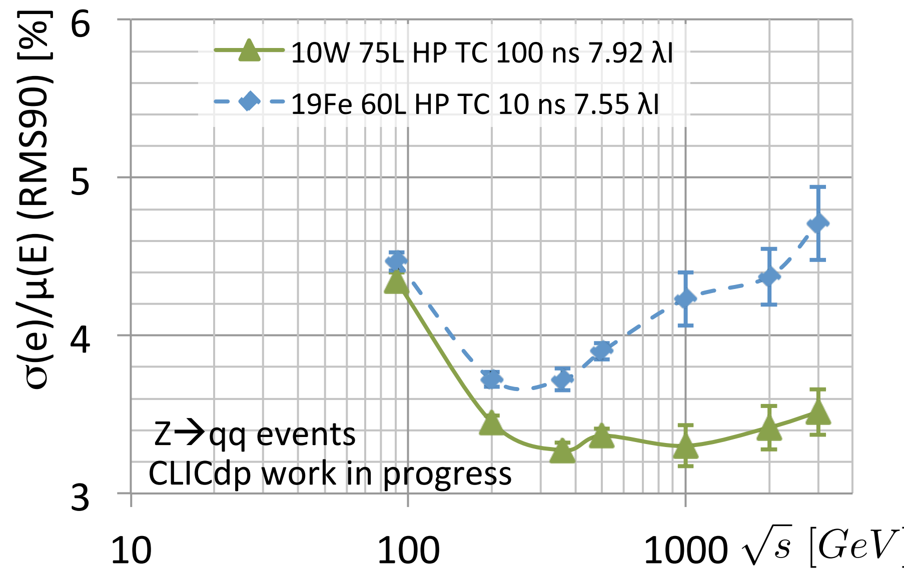
Hcal barrel: absorber material

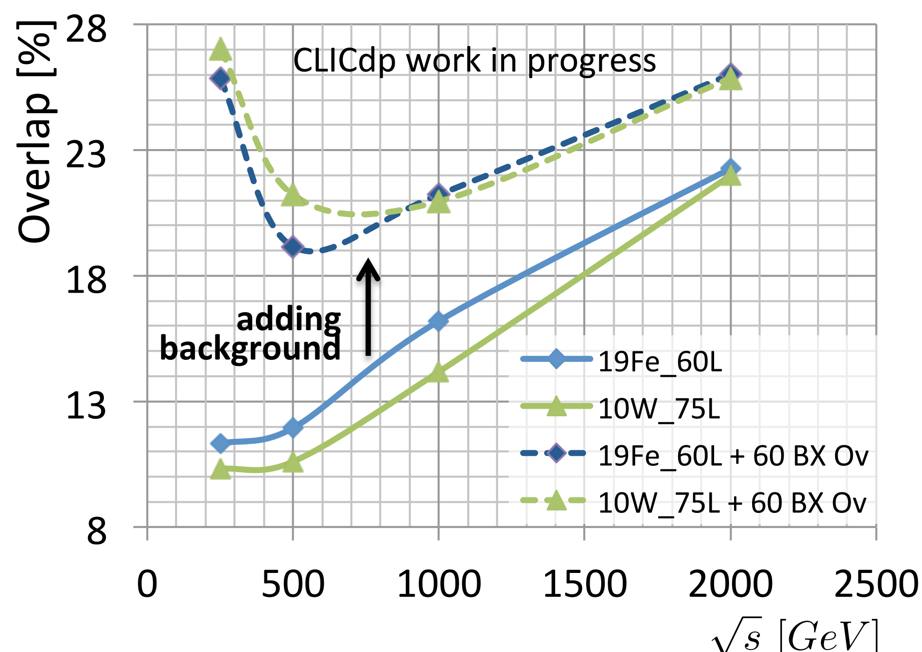
	# L	Abs Thick	Tot Depth	Tot Thick	TC
W	75	10 mm	7.92 λI	1322.5 mm	100 ns
Fe	60	19 mm	7.55 λI	1609 mm	10 ns

- Realistic Fe cassette included
- Jet energy resolution study
- W/Z separation study
  - $ZZ \rightarrow \nu\nu\boldsymbol{dd}$ and $WW \rightarrow \nu l\boldsymbol{ud}$ events

→ *Fe as absorber material in simulation*
cheaper, easy to work with,
similar performance as W

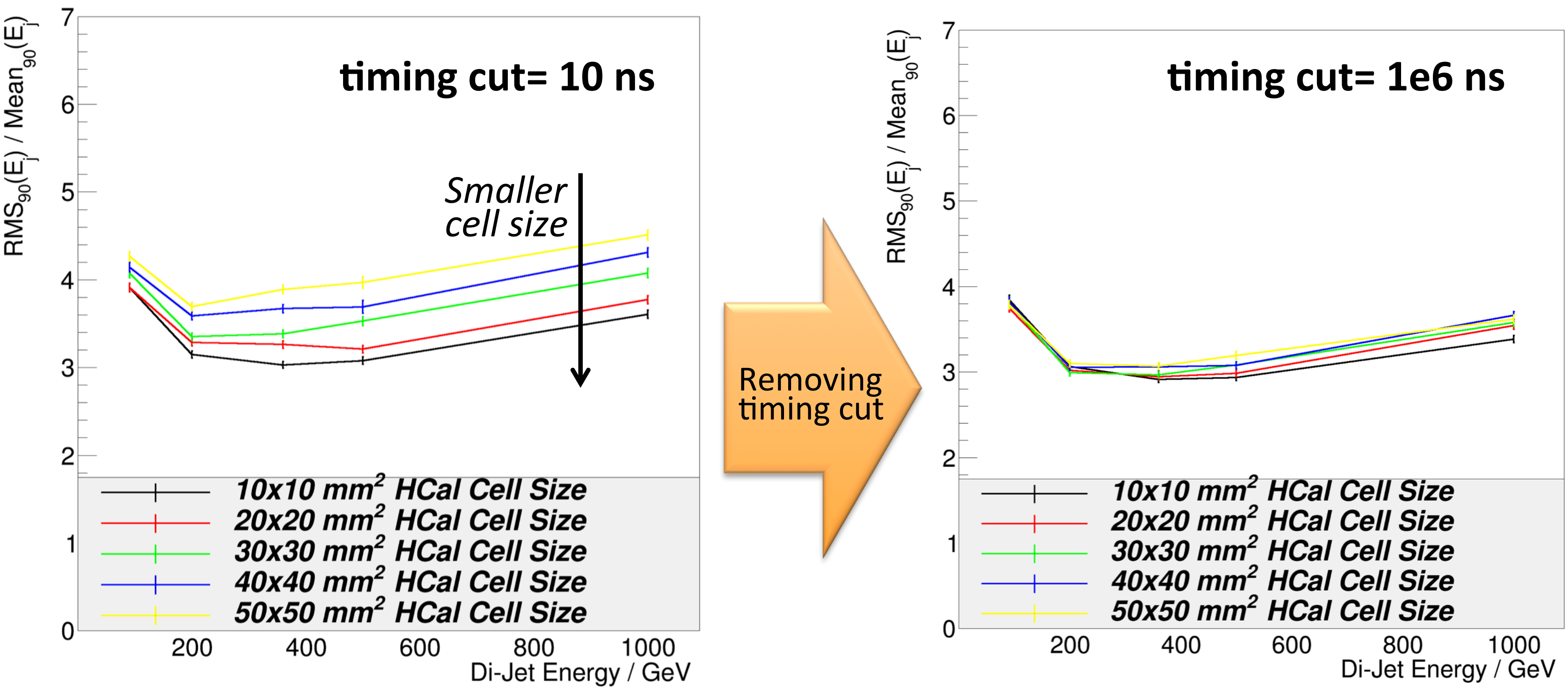






Hcal cell size optimisation

- Jet resolution dominated by *confusion term* for high energy jets.
- Confusion term increases with *cell size* when 10 ns timing cut is applied
  → improvement of the jet resolution for small cell size
  → dependence on timing cut under investigation

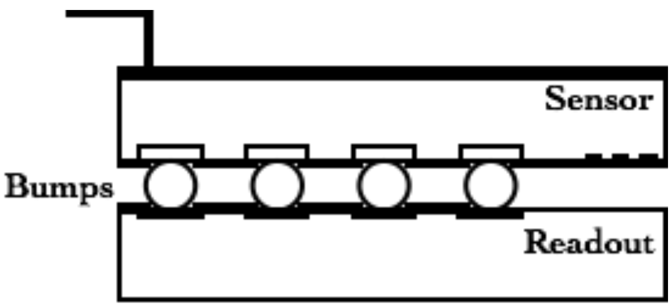


VERTEX R&D

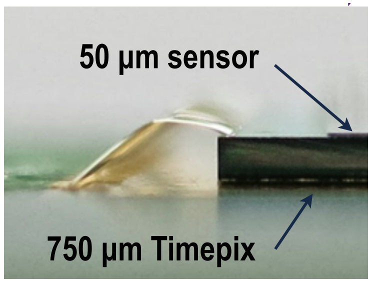
Hardware requirements

- ***Excellent single point resolution:*** σ = 3µm → pixel pitch 25 µm
- ***Low material budget:***
  sensor + readout 0.1%X_0 → 50µm sensor on 50 µm ASICs
  supports/cabling/others 0.1%X_0
- ***Fast readout:*** 10 ns slicing time

→ *Intense R&D*

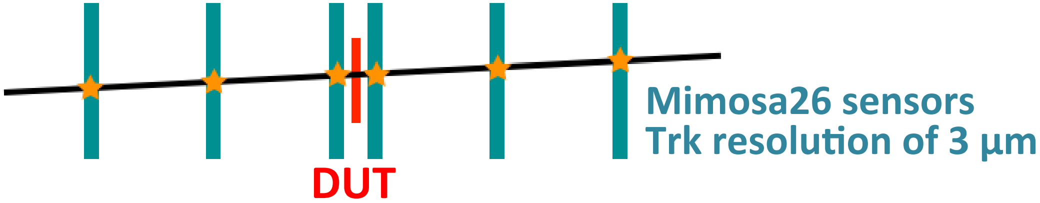


Bump-bonded assembly

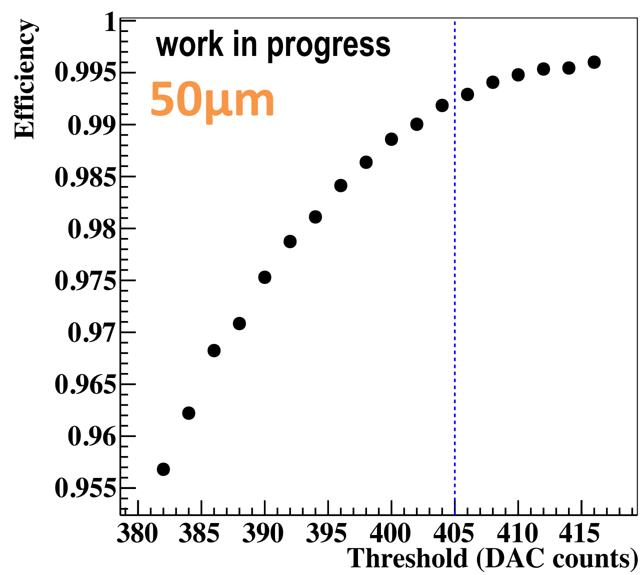


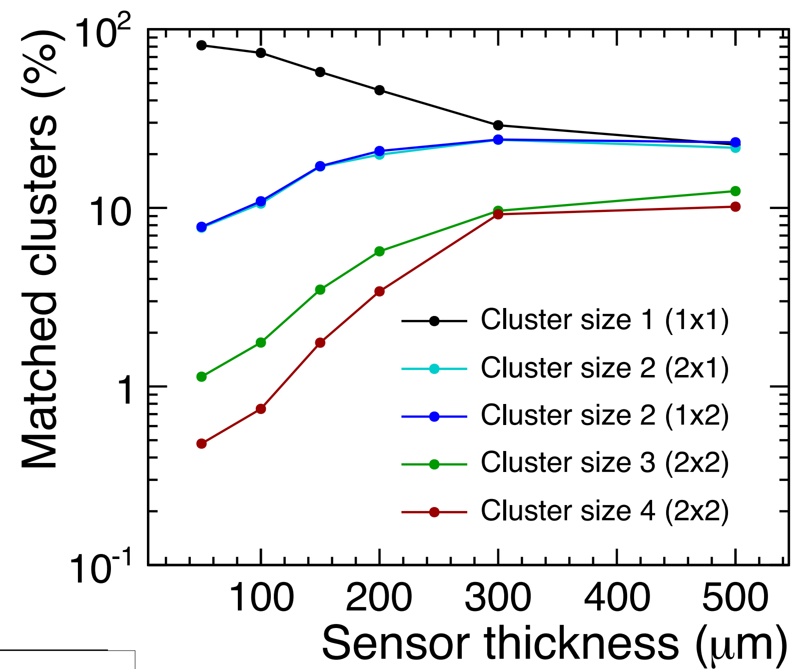
Timepix

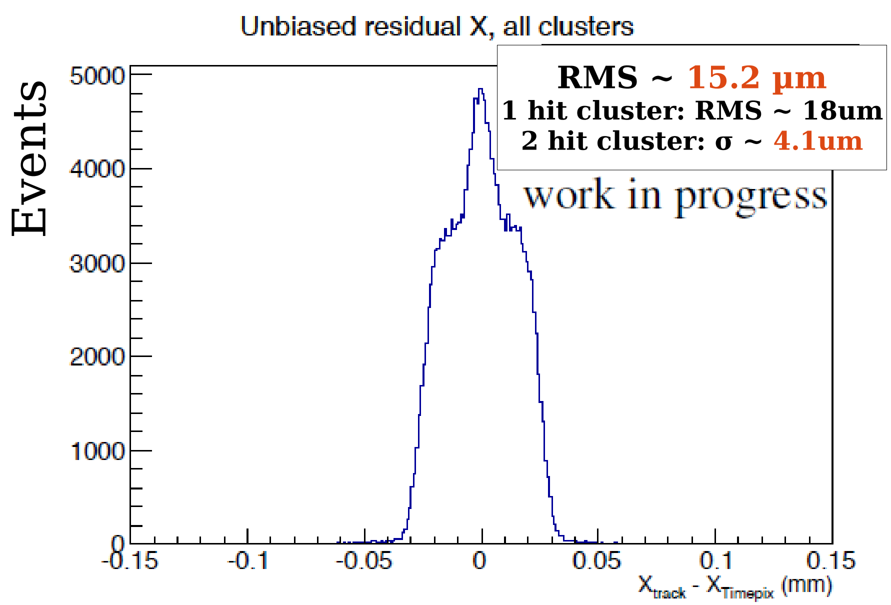
- *50-300 µm sensor bump-bonded to Timepix chips, 55 µm pixel pitch* → DESY test beam (5.6 GeV e) and CERN PS test beam (10 GeV π), EUDET telescope
- DC-coupling with amplifier input on the readout chip



Results for thin sensors

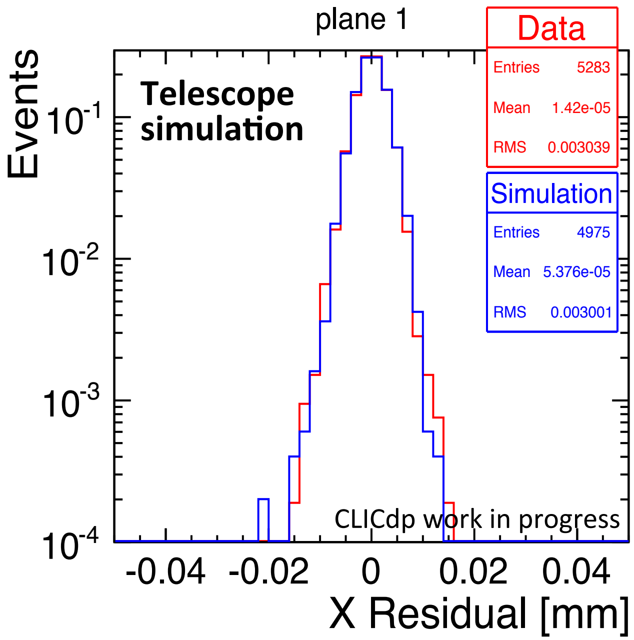






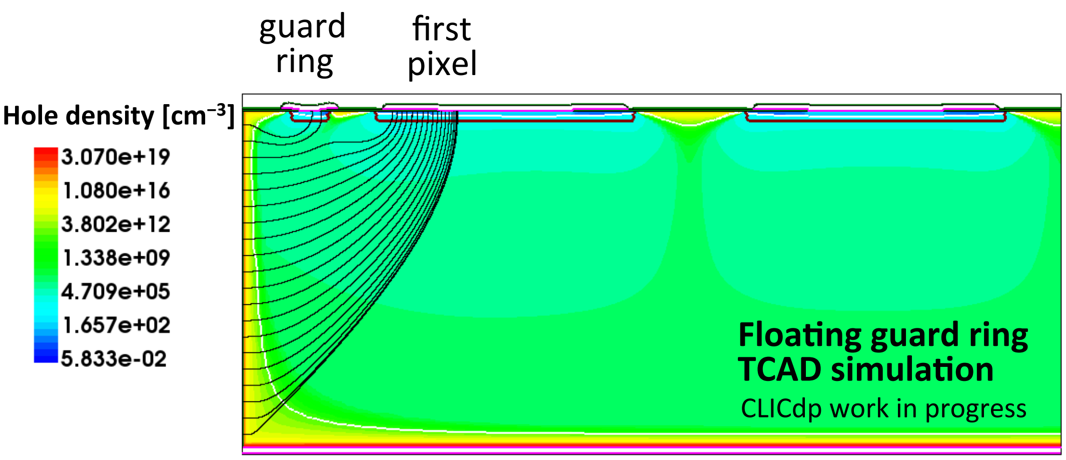
- Using *charge sharing information* (for cluster size > 1) it is possible to *gain up more than factor of 3 in single-point resolution*
- For *50 µm* thick sensor and 55µm pixel size this represent only 20% of the data *→ smaller pixel size is needed*

Pixel sensor simulation

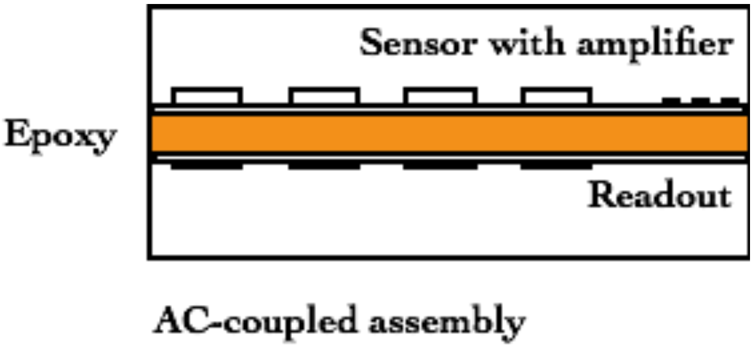


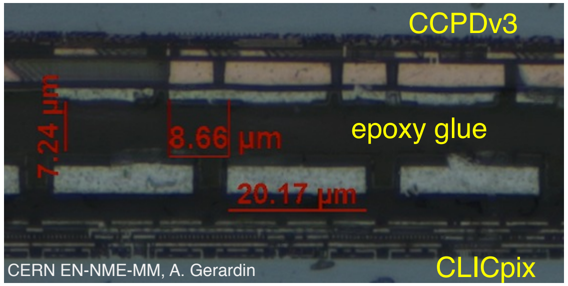
- *Allpix* simulation framework based on GEANT4
- Configuration of Si response and readout chip
- *Telescope and DUT simulation*
- Data and simulation in good agreement but for charge sharing → under investigation

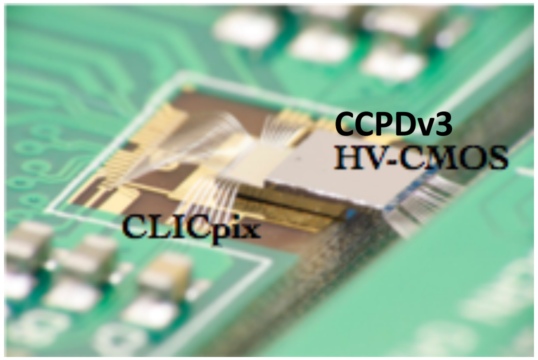
- *TCAD* simulation of field behaviour at the edge of a sensor
- *Active edge sensors* to reduce material budget and dead areas
- Voltage drop between the edge and the first pixel → Floating guard ring



HV-CMOS active sensors

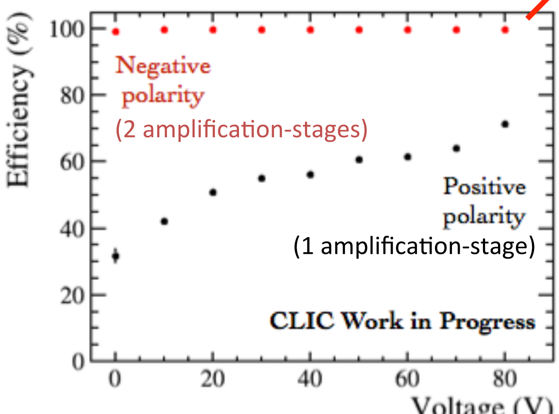


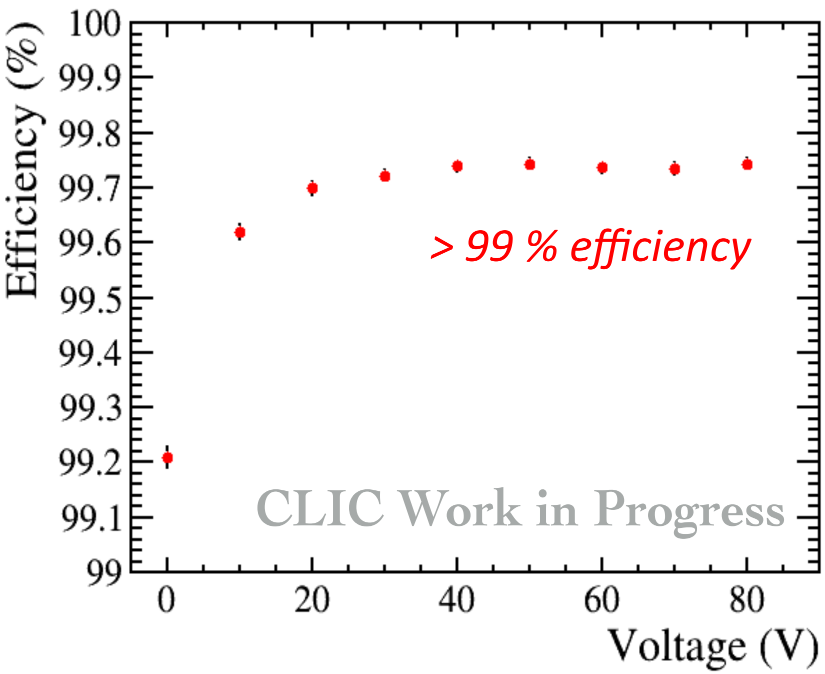




- *HV-CMOS sensor glued on CLICpix ASIC, 25 µm pixel pitch*
- AC-coupling → amplification of the signal on the sensor side to allow measurable signal on the readout ASIC
- Power consumption and pulse shape studies on-going

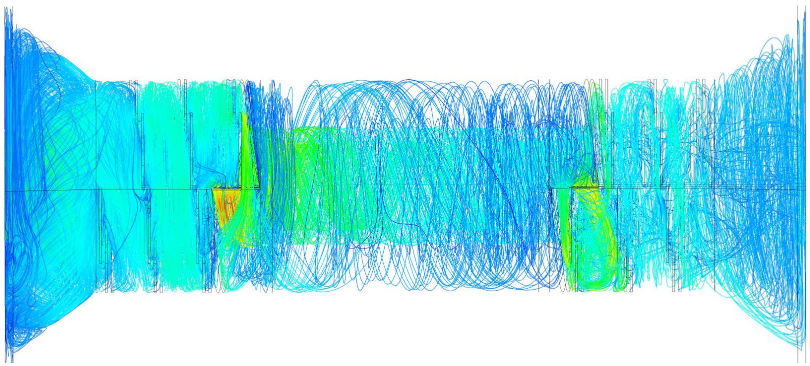
CERN SPS test beam results

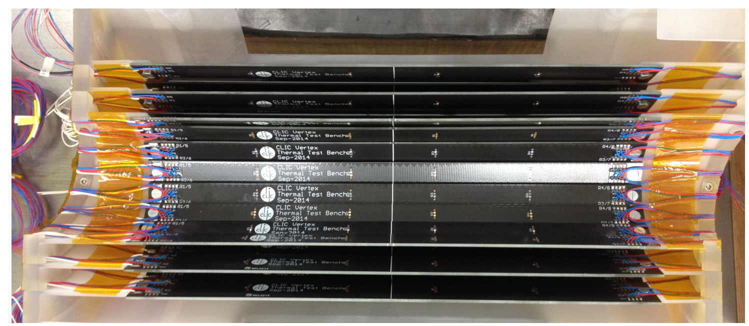


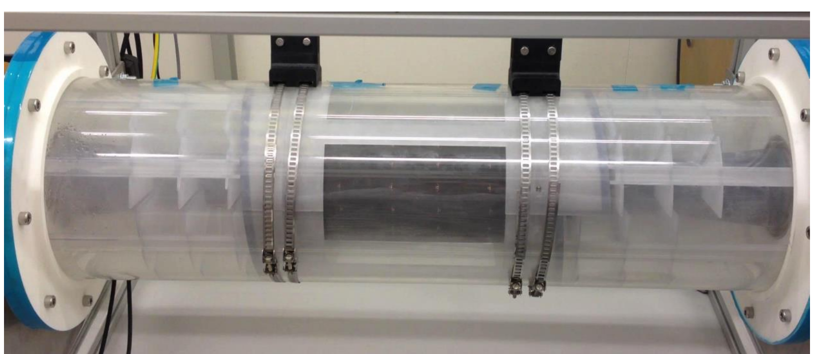


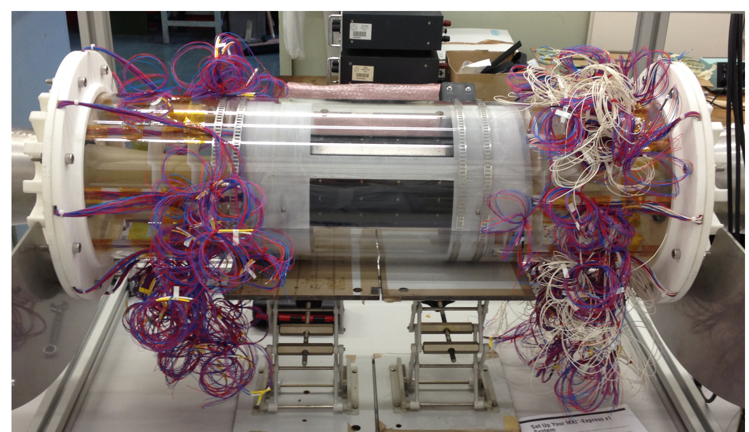
Forced-air and thermal mock-up

- Real-size mock-up to verify simulation and study air-flow feasibility, vibrations and temperature
  - ~500 W heat load to extract (50mW/cm^2) → T^{Si} < 40°C after power pulsing
  - Vibration acceptable at 1-2 µm RMS amplitude
- Bending/stiffness of low mass supports (0.05%X_0)



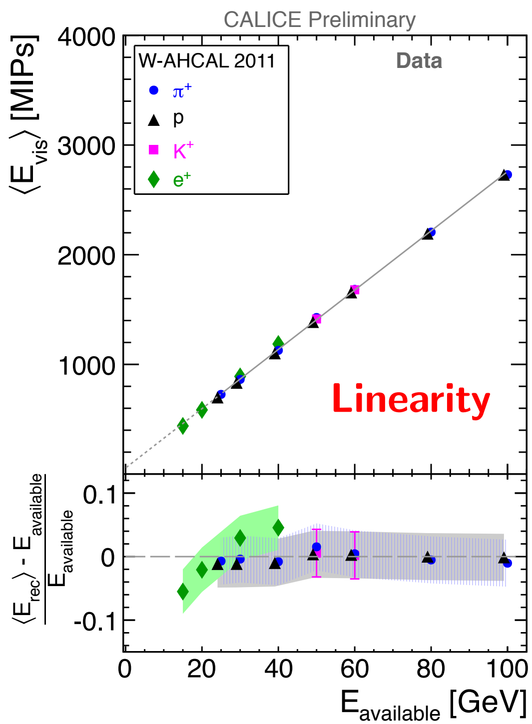


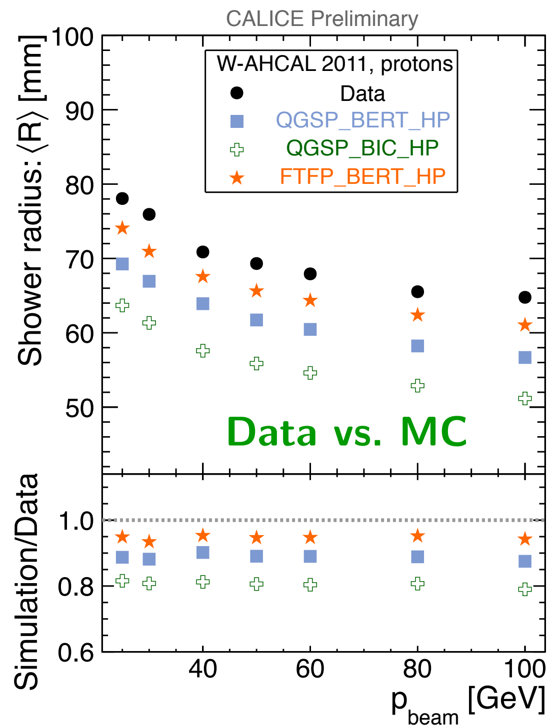


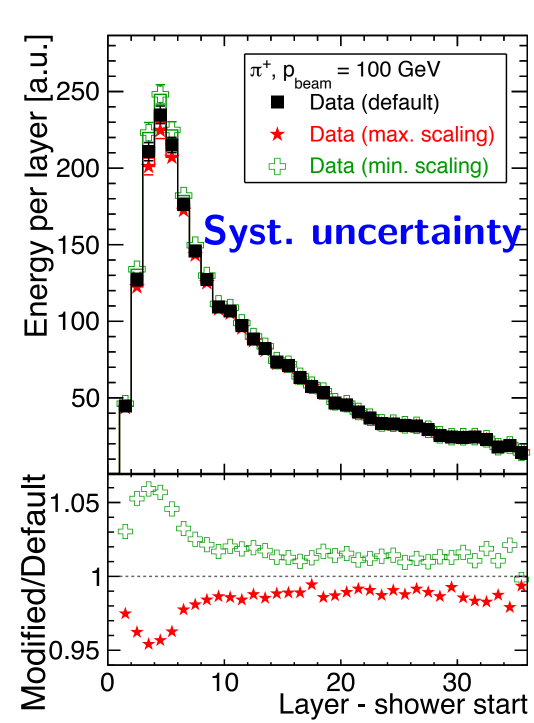


W A-HCAL STATUS

CALICE Tungsten Analogue Hcal







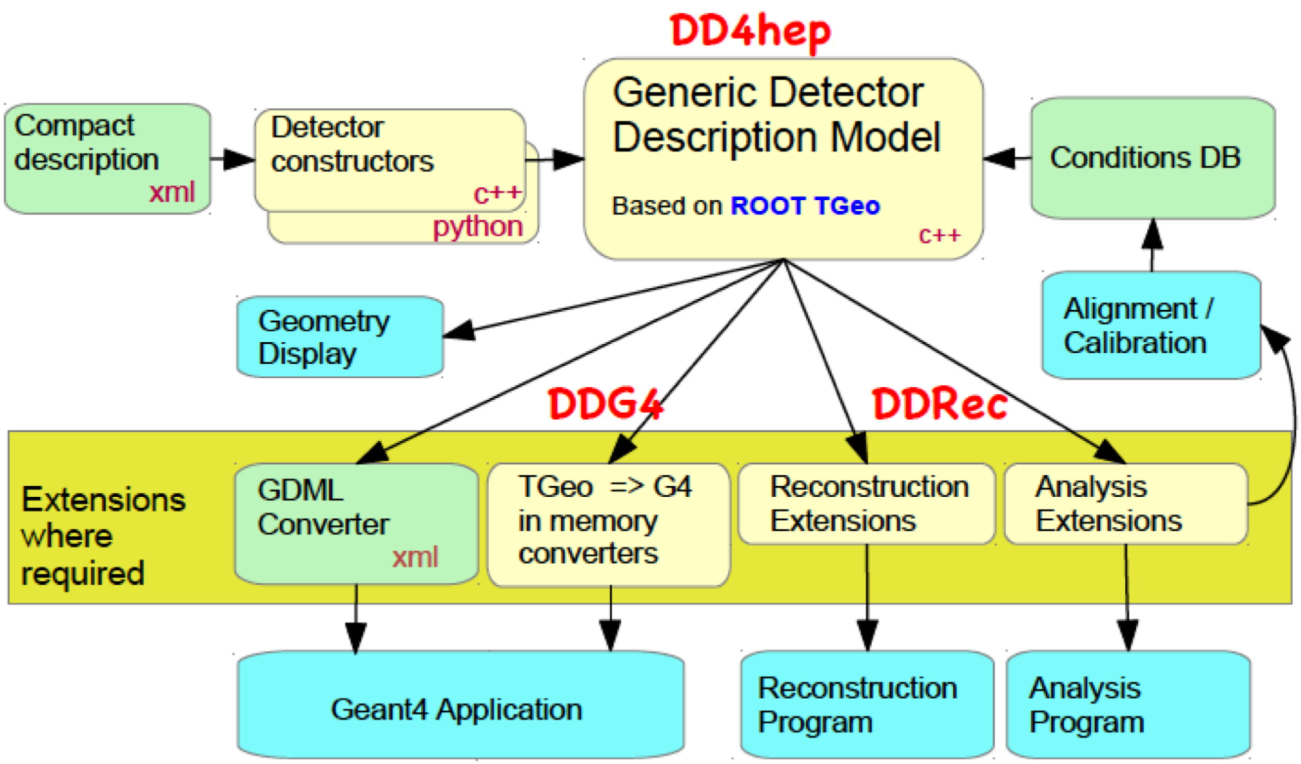
- Test beam data : e, π, K and p at 1-300GeV
- *Good linearity, resolution:* $\frac{\sigma_E}{E}(\pi^+, E = 3-10GeV) = \frac{(61.8 \pm 2.5)\%}{\sqrt{E[GeV]}} \oplus (7.7 \pm 3.0)\% \oplus \frac{0.070GeV}{E[GeV]}$
- *Data-simulation* in general in *agreement*
  - room for improvement in shower shape description
- Comprehensive study of all relevant *systematic uncertainties*

→ *Publication including beam momenta up to 150 GeV in early 2015*

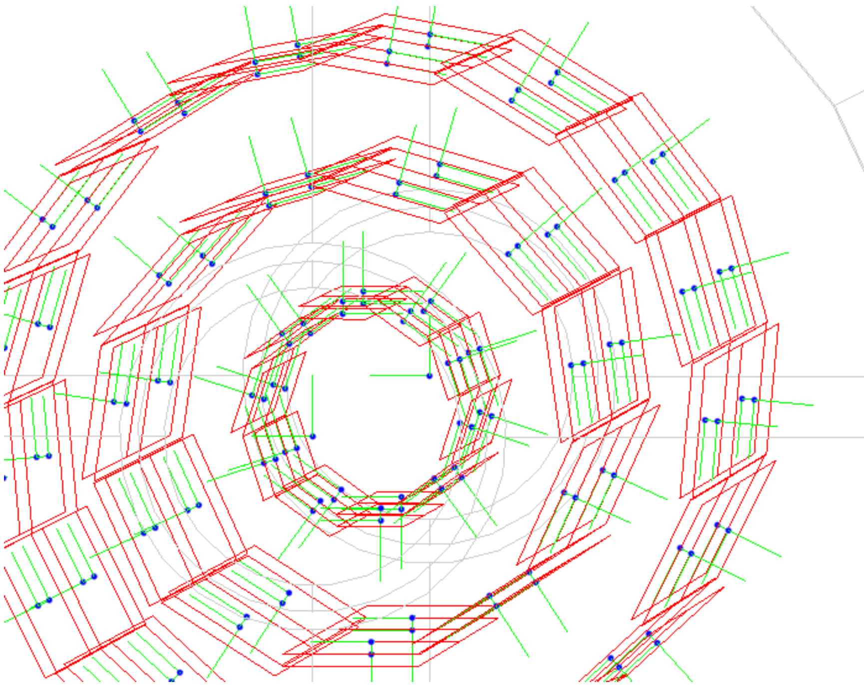
SOFTWARE

DD4Hep

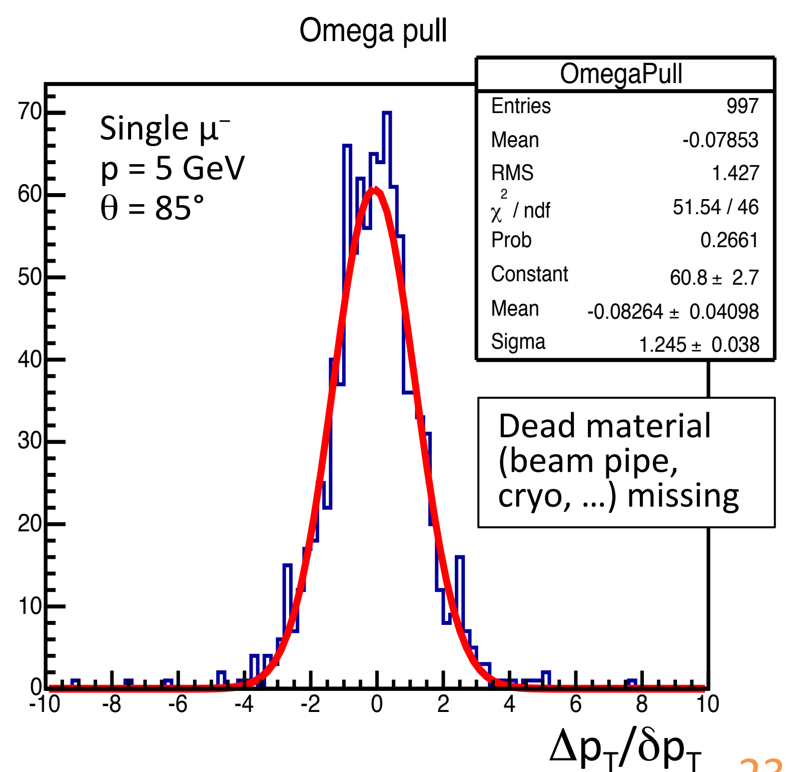
- *Full detector description*: geometry, materials, visualization, parameters for readout, alignment, calibration, etc.
- *Consistent Description*: Single source of detector information for display, simulation, reconstruction, analysis, alignment, etc.
- Detector Palette for CLIC based on SiD model → example detector model for testing and to be updated with the most recent subdetectors
- *Validation* of simulation and reconstruction interface on-going



DDRec: Surfaces for tracking



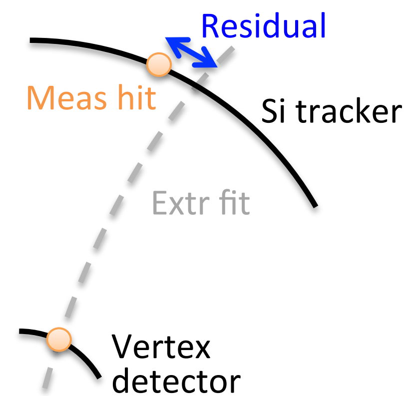
- *Tracking code* needs a special interface to geometry for track extrapolation and Kalman filter
- Measurements and dead material *surfaces* attached to volumes:
  - local coordinates
  - Inner and outer material and thickness

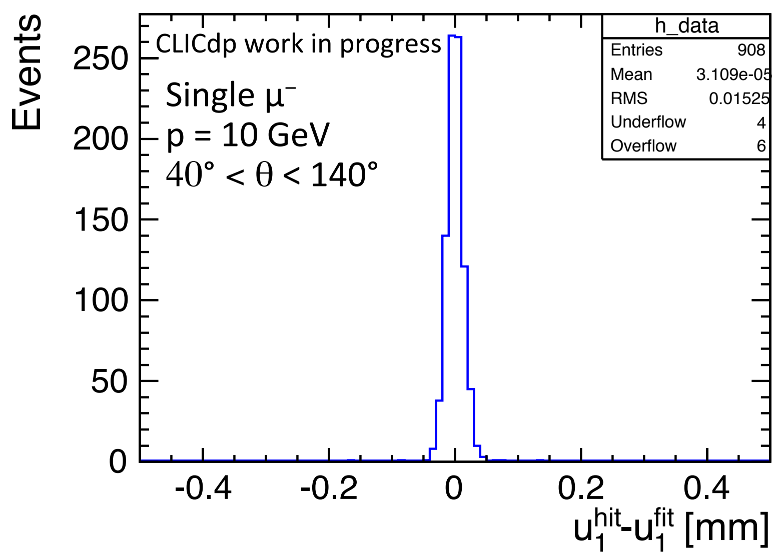


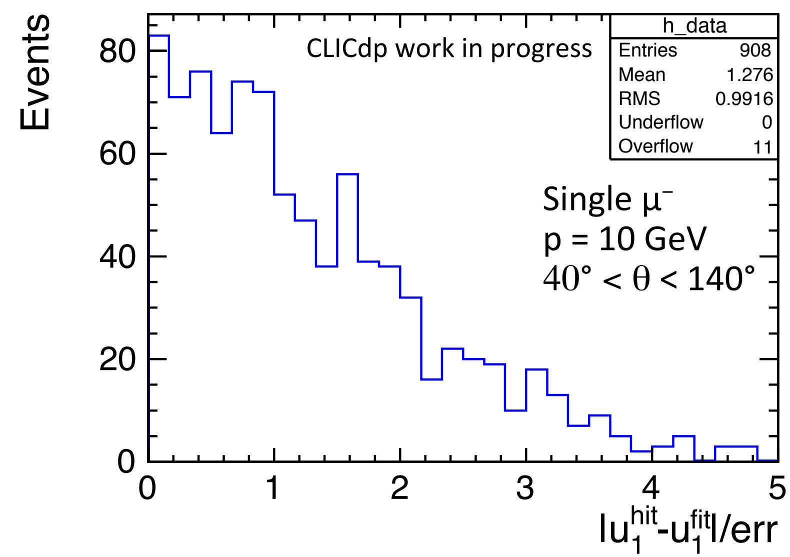
- Use material properties (A, Z, ρ, X_0, λ_I) to compute effects of *energy loss* and *multiple scattering* along path length between surfaces
- Run existing reconstruction code with the new simulation model

Tracking code

- ILD vertex software based on *cellular automaton* and on *mini-vectors*
  - Accounts for double layers
  - Kalman filter implemented
- *Extend* to full Si tracker
  - Promising results for single μ
  - Next: performance tracking in jets (Z→qq)
  - Currently use of ILD detector model (extension to SIT)
  - Next: use CLIC detector through DD4Hep

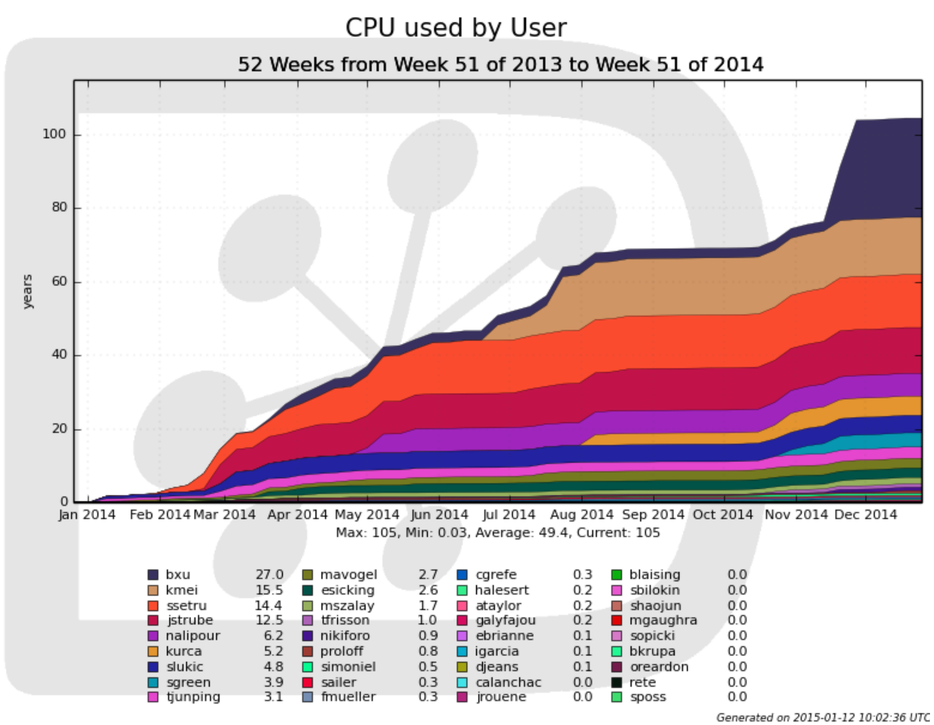


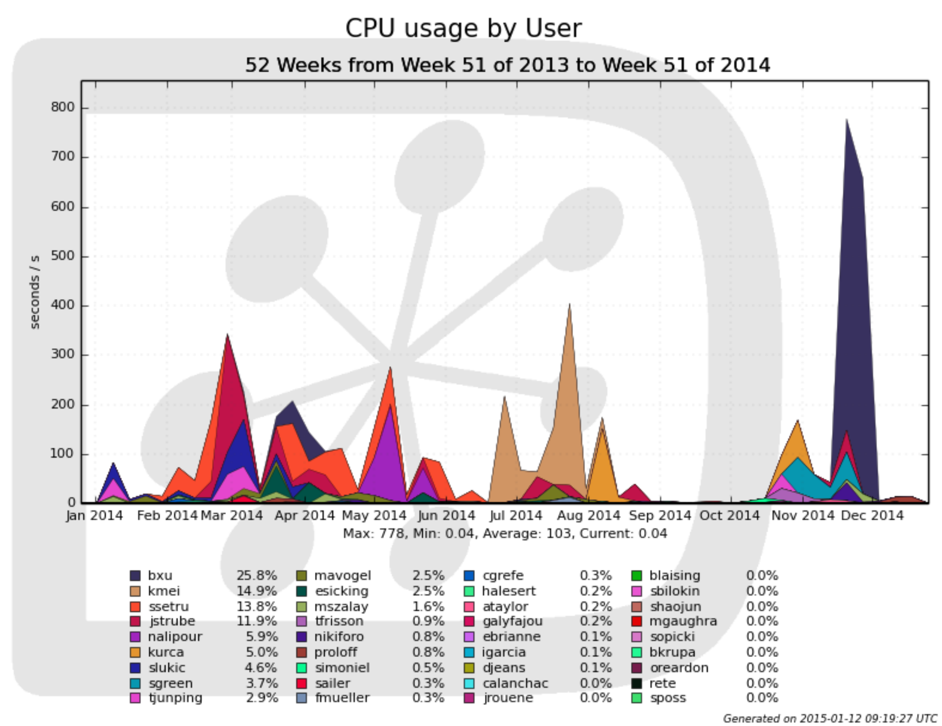




ILCDirac

- ILCDirac: Complete Grid Solution
- Workload management, data storage, production system, bookkeeping
- Used by CLICdp, SiD, ILD, CALICE
  - Grid interface for users and production to run any LC software
- https://twiki.cern.ch/twiki/bin/view/CLIC/DiracUsage





Collaboration

CLICdp collaboration keeps growing ☺
25 institutes

- CLICdp web site: http://clicdp.web.cern.ch/
- CLICdp next workshop 27-30 January: https://indico.cern.ch/event/336335/
- We are close and we have links with ILC community

Conclusion

- Higgs paper being finalised!
- Good progress in the detector model optimisation:
  - Only few parameters missing
  - Software starting to come together → validation ongoing, encouraging results
- Intensive vertex R&D
  - Test beam results from DESY, CERN PS, CERN SPS campaigns
- A-Hcal analysis of 2011 test beam data is being finalised

Thanks for your attention!

BACK-UP

Cooling: simulations

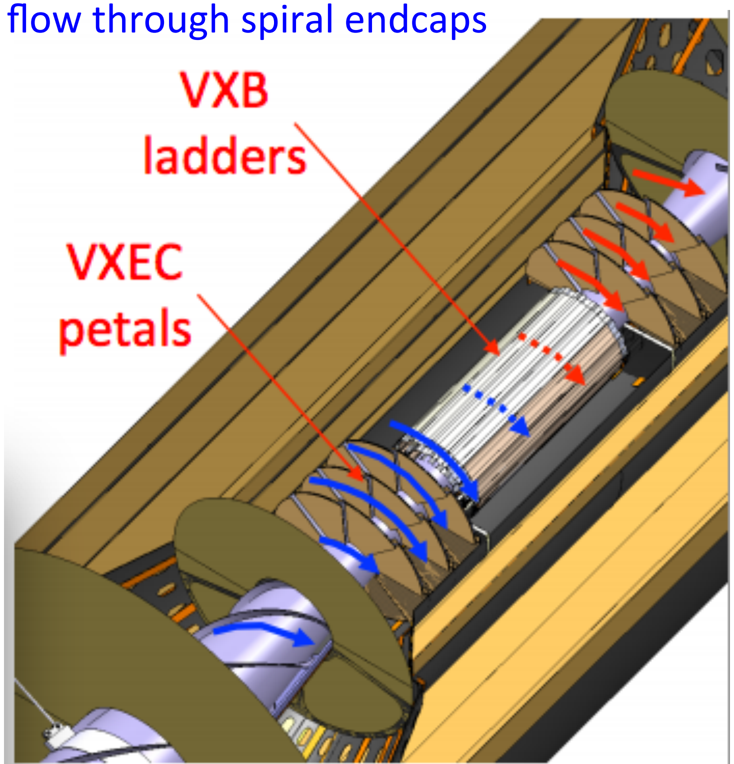
Cooling studies for CLIC vertex detector

- ~500 W power dissipation in CLIC vertex area
- spiral disks allow air flow through detector
- ANSYS Computational Fluid Dynamic (CFD) finite element simulation

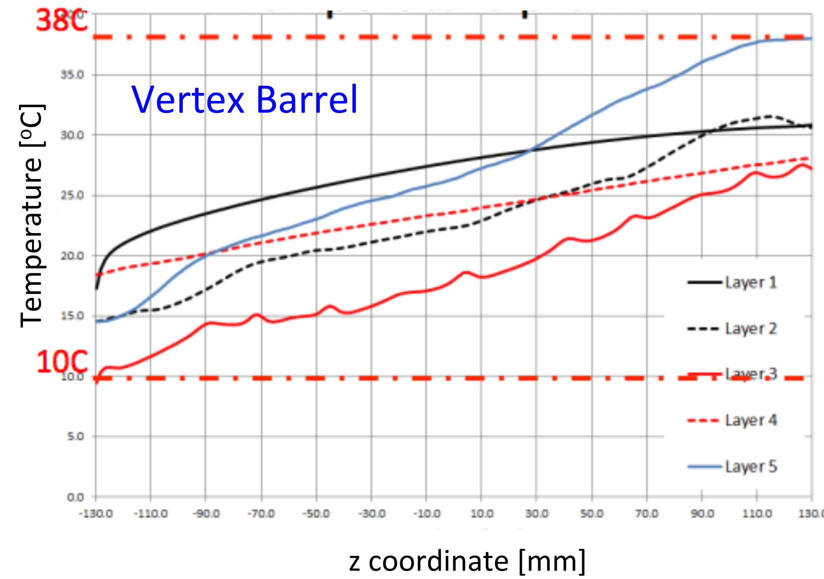
→ air cooling seems feasible

- 5-10 m/s flow velocity, 20 g/s mass flow

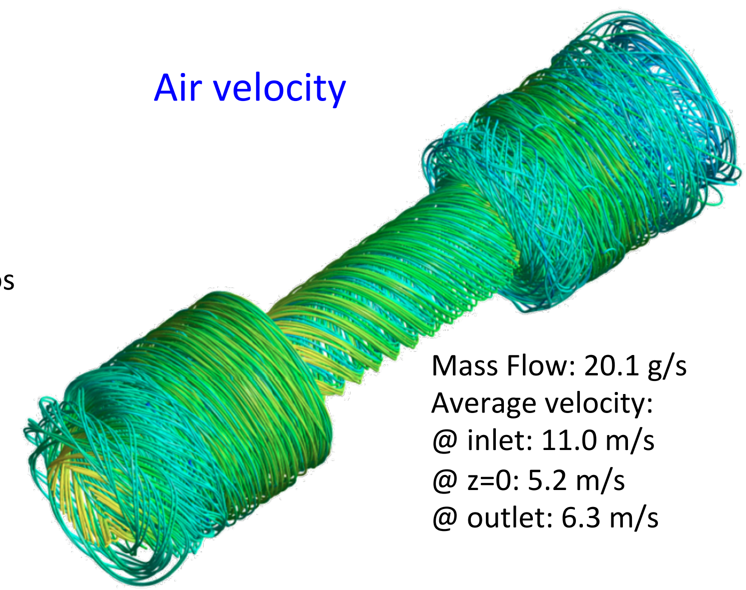
Air flow through spiral endcaps



Temperature profile (FE simulations)



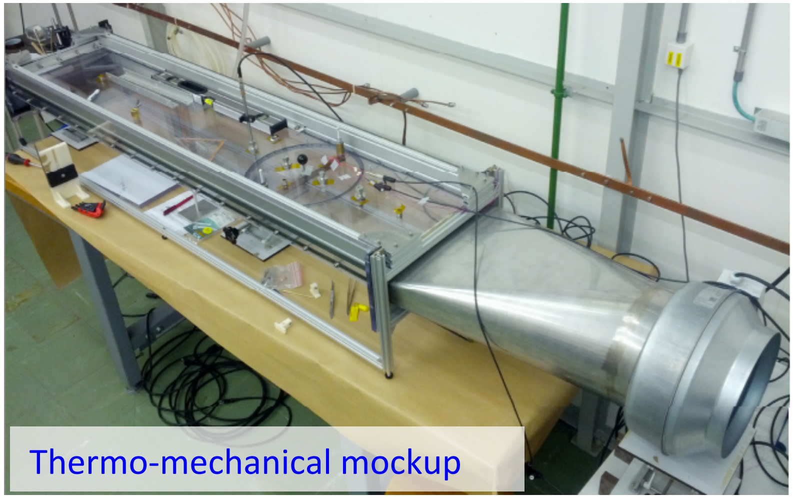
Air velocity



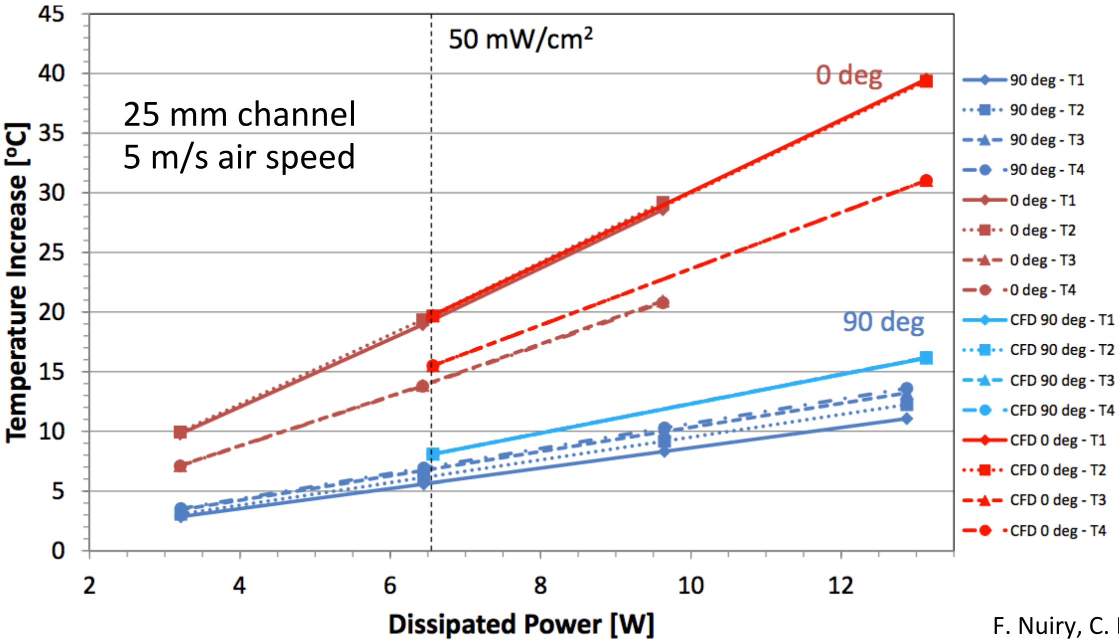
F. Duarte Ramos

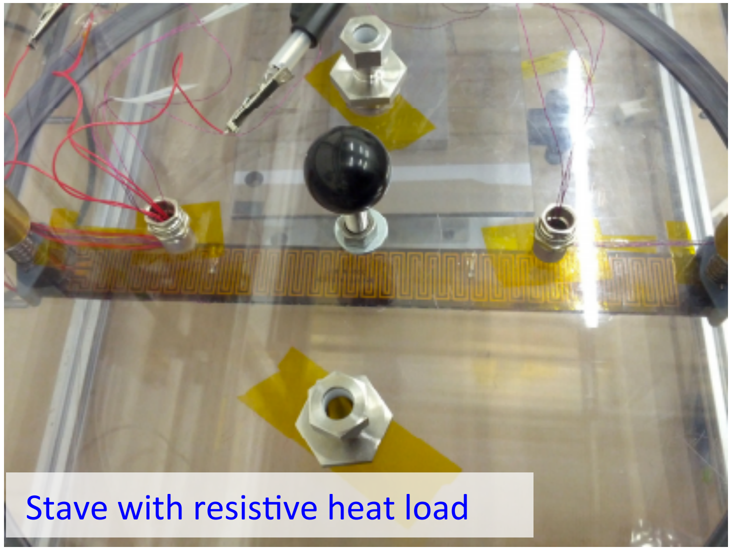
Cooling: experimental verification

- built mock-up to verify simulations (temperature, vibrations)
- measurements on single stave equipped with resistive heat loads:
  - air flow
  - temperature
  - vibrations (laser sensor)
- comparison with simulation



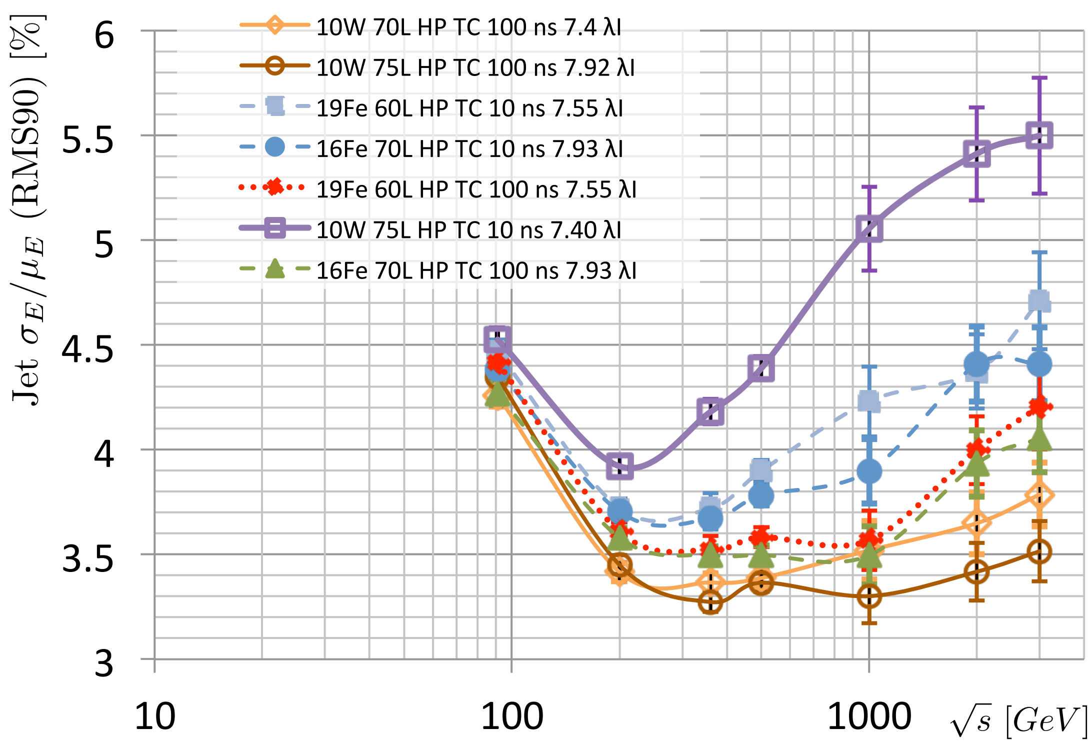
Temperature increase: measurement + CFD simulation





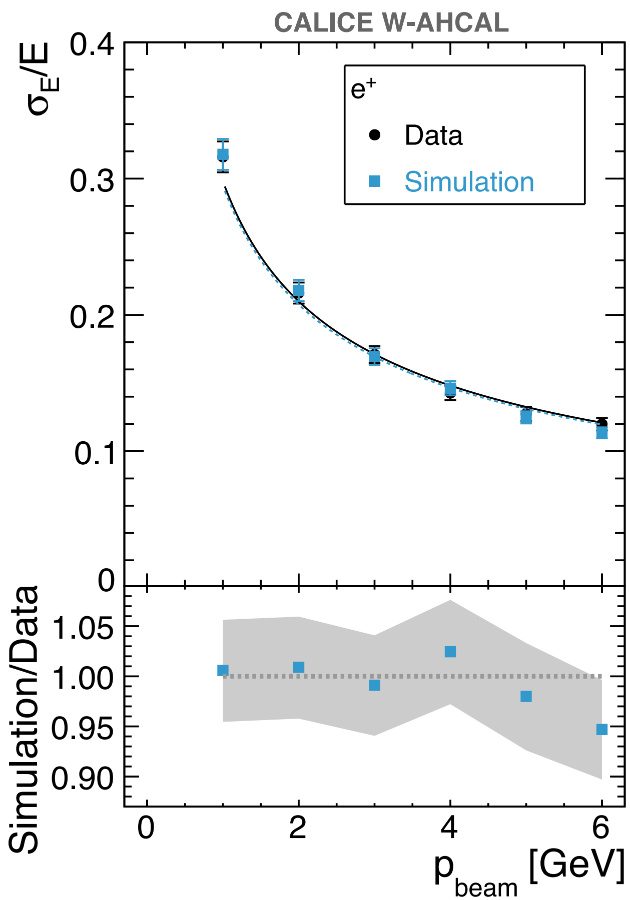
F. Nuiry, C. Bault, F. Duarte Ramos, M.-A. Villarejo Bermudez, W. Klempt

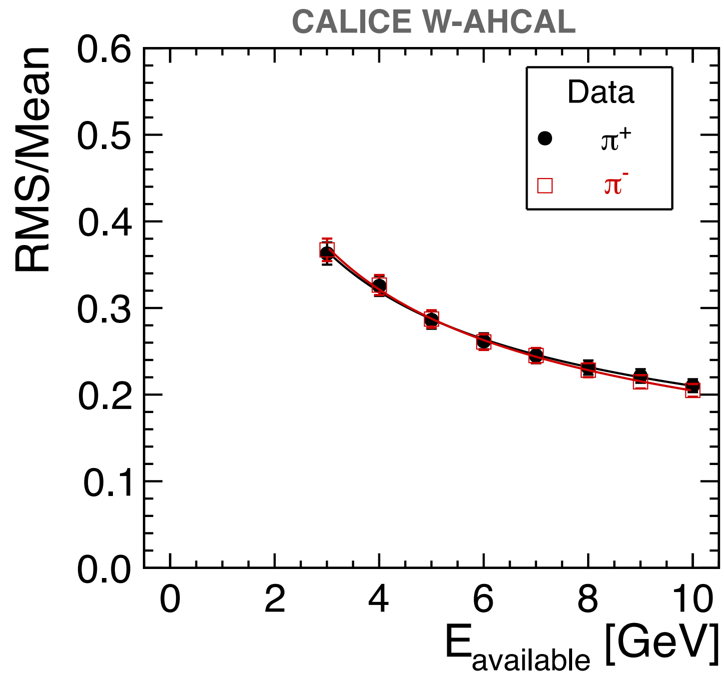
Detector	# Layers	Abs Thick	Cass. Thick	Air	Total Depth	Total Thickness	Inner R	Outer Face Position	Outer Radius
		mm	mm	mm	#λI	mm	mm	mm	mm
CLIC_ILD_CDR	75	10	5* (*Scint)	1.5	7.42	1237.5	2058	3295.5	3341.2
CLIC_SID_CDR						1237.5	1447	2684.5	2721.7
W + cassette	75	10	4.8	2.7	7.92	1322.5	1750	3072.5	3115.1
W + cassette	**70**	**10**	**4.8**	**2.7**	**7.40**	**1235**	**1750**	**2985**	**3026.4**
Fe + cassette	**60**	**19**	**4.8**	**2.7**	**7.55**	**1609**	**1750**	**3359**	**3405.6**
Fe + cassette	70	16	4.8	2.7	7.93	1661	1750	3411	3458.3



W A-Hcal resolution

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\mathrm{GeV}]}} \oplus b \oplus \frac{c}{E[\mathrm{GeV}]}$$

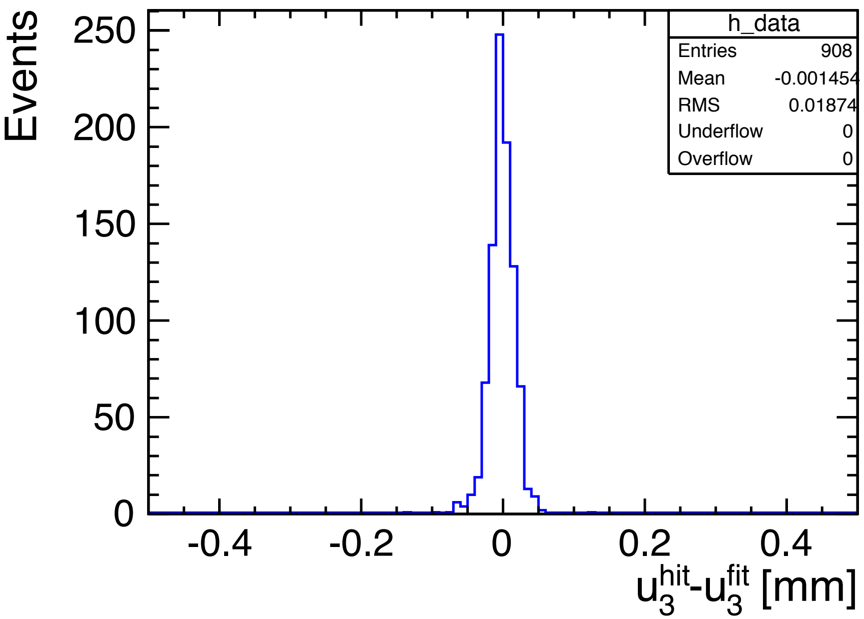


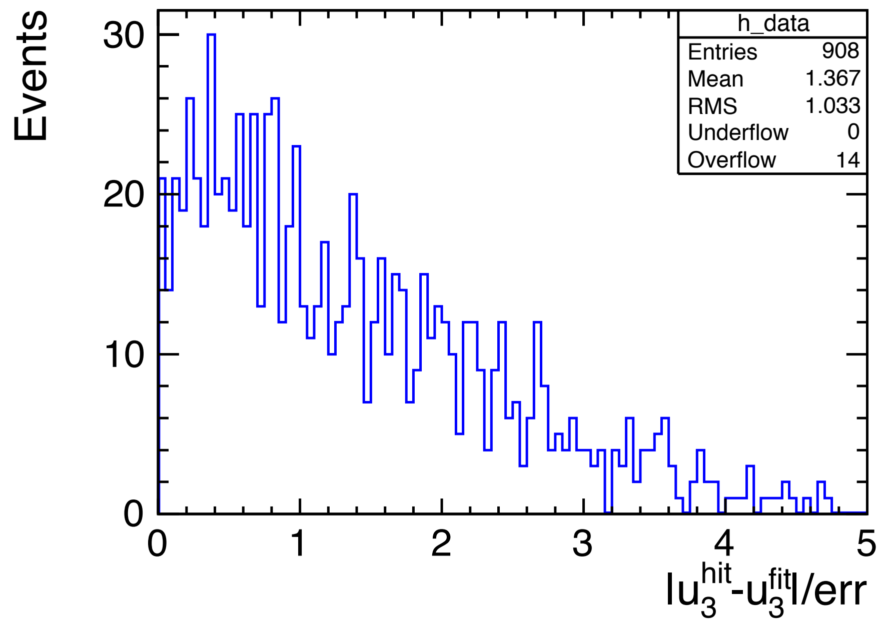


Data e+: a = (29.6 ± 0.5)% and b = (0.0 ± 2.1)%, c fixed to 36MeV
MC e+: a = (29.2 ± 0.4)% and b = (0.0±1.5)%, c fixed to 36MeV

Data π+: a = (61.8 ± 2.5)% and b = (7.7 ± 3.0)%, c fixed to 70MeV
Data π-: a = (63.9 ± 2.4)% and b = (3.2 ± 6.9)%, c fixed to 70MeV

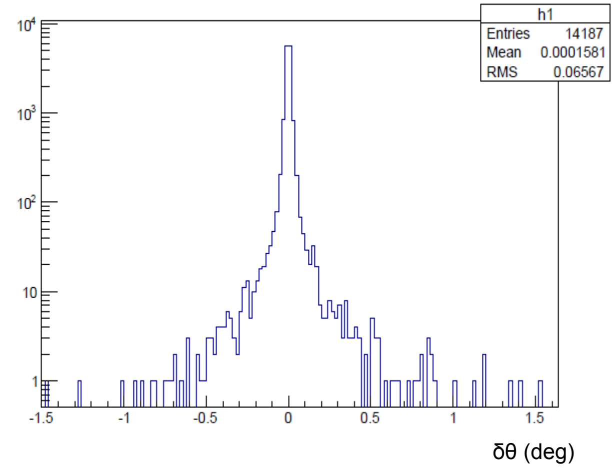
Ext to SIT 2 “double” layer



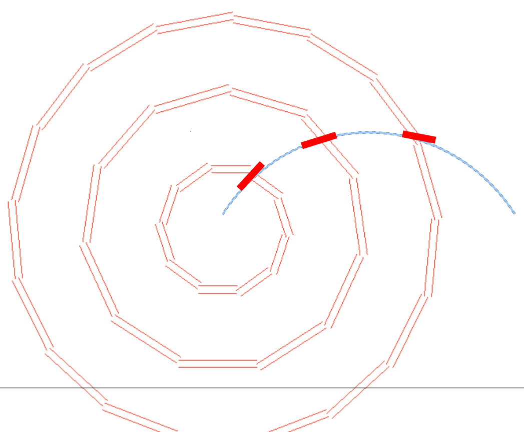


Mini – Vector Tracking

- Mini – vector formation
  1) Hits in adjacent layers (dist 2mm) with max distance 5mm
  2) Or δθ between hits in adjacent layers (cut can go up to 0.1^0)
- Divide VXD into θ, φ sectors
  - Try to connect mini – vectors in neighbouring sectors
- Cellular automaton criteria
  - φ, θ pointing direction of the mini – vectors
  - No zig-zag (2 MV segments)
- ttbar sample, pair bkg included for √s = 500GeV
- Fast CMOS vertex detector



ttbar, δθ of hits belonging to a MV based on MC info

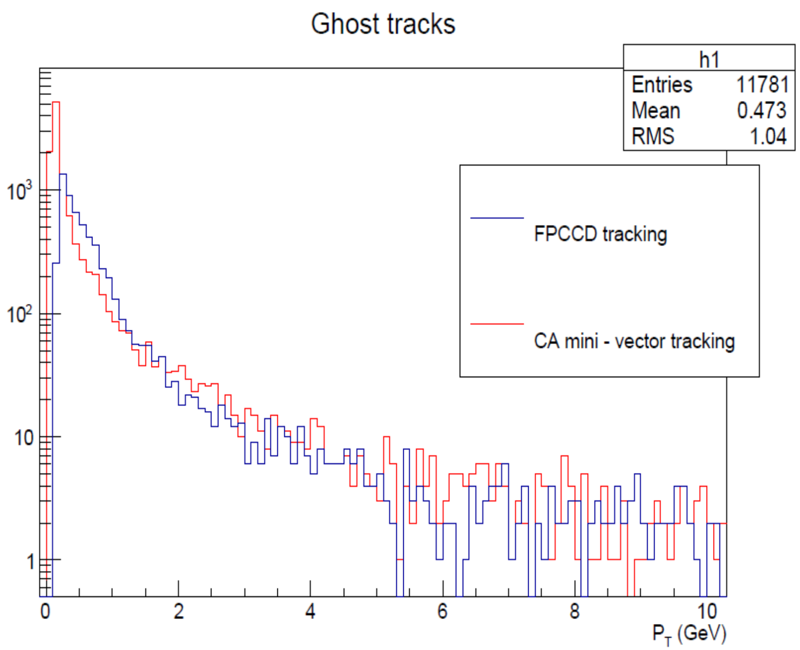


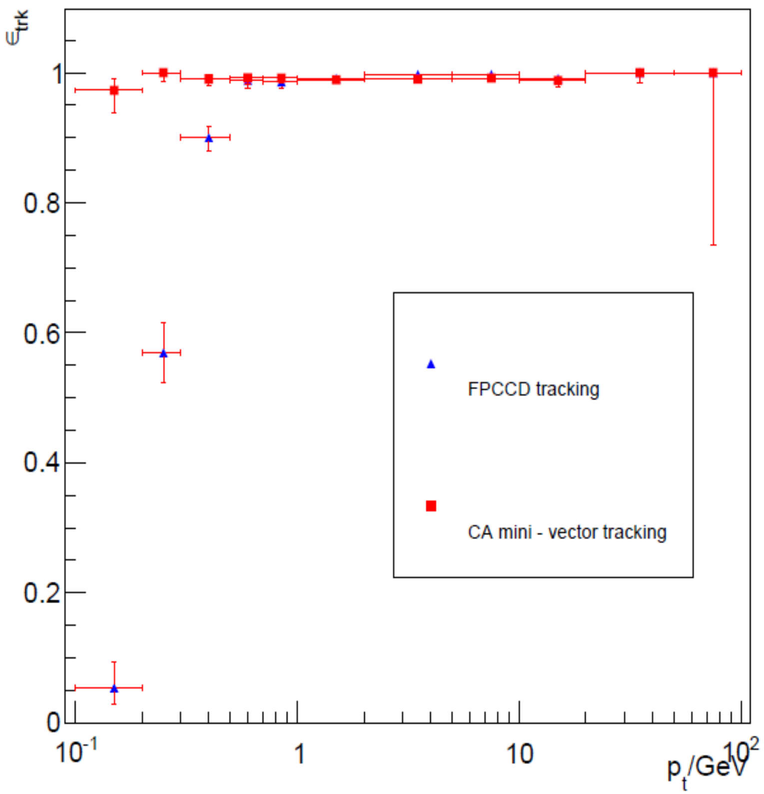
	Dist < 5mm	δΘ $<0.5^0$	δΘ $<0.3^0$	δΘ $<0.1^0$
VXD hits	10^5	10^5	10^5	10^5
MiniVectors	$3x10^5$	10^5	$6x10^4$	$2x10^4$
Connections	$O(10^5)$	$O(10^5)$	$< 10^5$	$\sim 10^4$
Raw tracks	$O(10^6)$	$O(10^6)$	$O(10^5)$	$< 10^5$
Time	~10min	~ 2min	~ 1min	~ 20 s

Comparison with FPCCD Tracking II

Sample: ttbar, √s = 500 GeV, fast CMOS VXD, pair bkg overlayed, 120 events

- Ghost tracks / evt (P_T > 1 GeV)
  - FPCCD: ~ 10
  - CA: ~ 11
- Time / evt
  - FPCCD: ~ 75 s
  - CA: ~ 25 s





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: $\phi = \mathrm{atan2}(y, x)$.
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.

Workflow & B field map

1) Geometry definition: compact.xml + GeomConverter

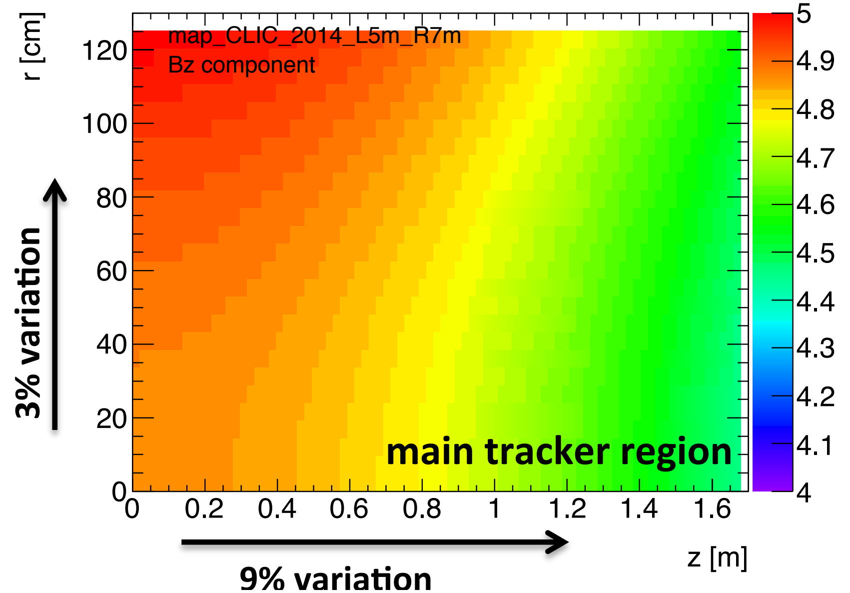
→ ***Non-homogeneous*** *B field introduced by a map with position coordinates and field values*

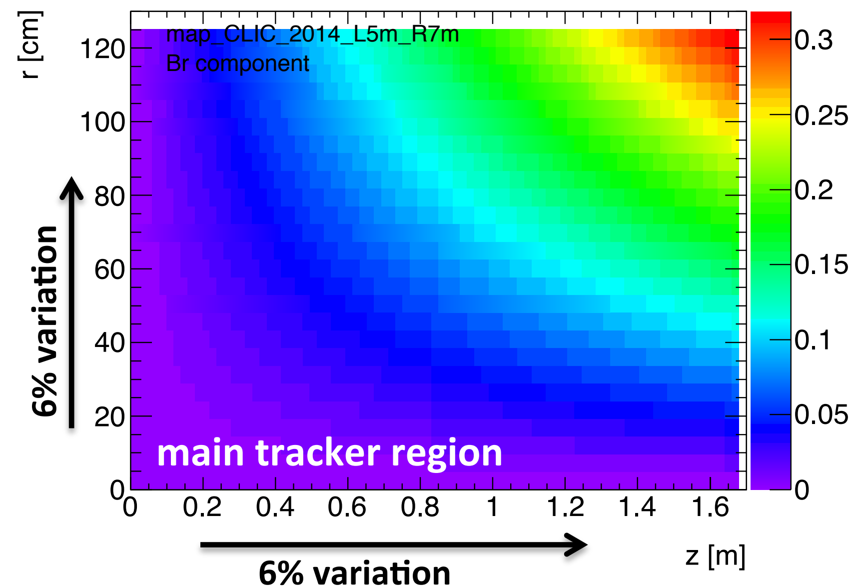
2) Simulation: SLIC (based on Geant4 → interaction of particle in matter)

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

3) Reconstruction: LCSim (at the moment)

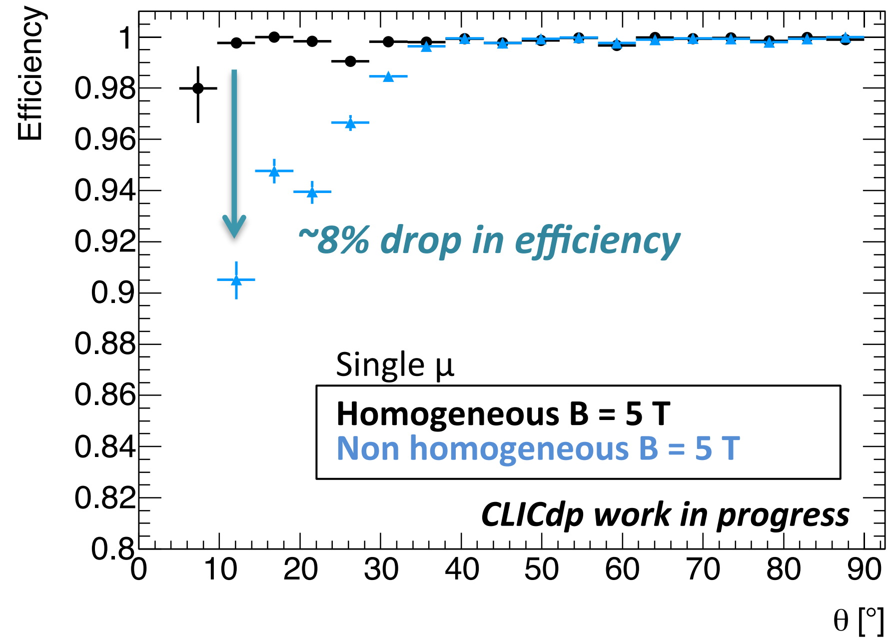
→ ***Homogeneous*** *B field (value at the IP):*
- need to move from the global helical fit: work on going for the tracking software

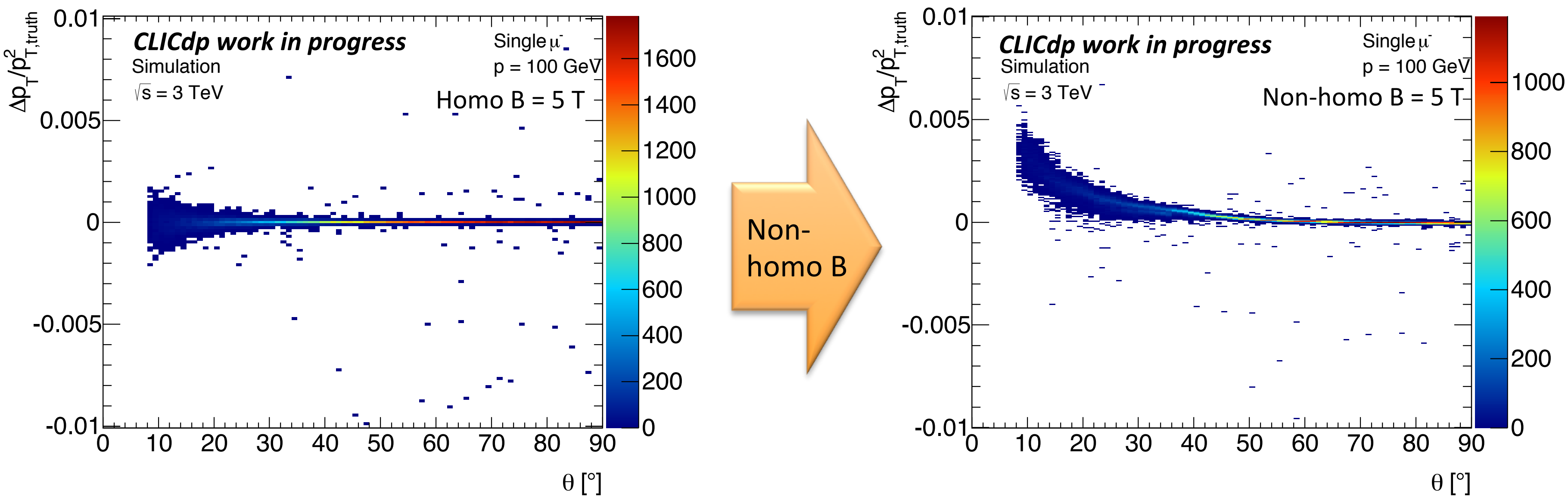




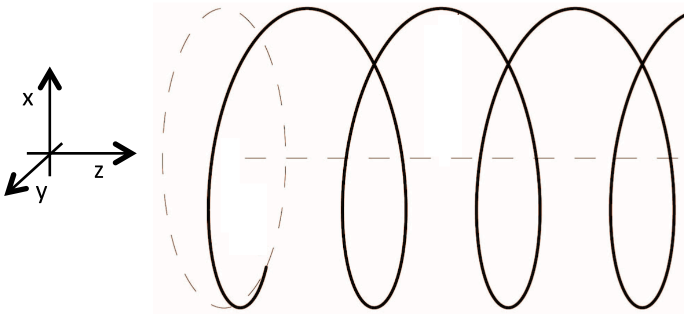
Efficiency and p_T resolution

- 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)



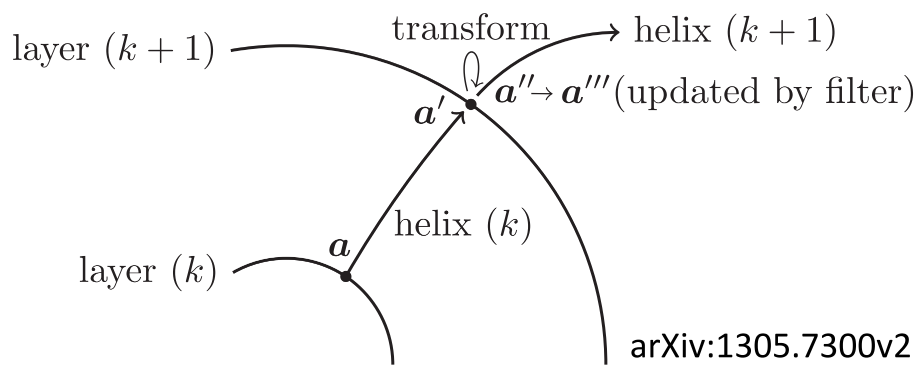


Tracking extrapolation



- **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

$$\frac{d^2\mathbf{r}}{ds^2} = \frac{q}{p}\left[\frac{d\mathbf{r}}{ds} \times \mathbf{B}(\mathbf{r})\right] + g(p,\mathbf{r})\frac{d\mathbf{r}}{ds}$$

Lorentz force energy loss function

- **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

QD0 and Yoke endcap

Two main configurations under study:

- *QD0 partially in the detector → L* = 4.5m*
- *QD0 out of the detector → L* = 6m*
  - Extended *HCAL acceptance*
    - Interest in high energy and t-channel physics
    - Quantitatively estimation of the gain for physics analysis on going
  - Loss in *luminosity* to be studied
  - *Reduce yoke* endcap: 2.8m → 1.4m
    - Add ring coils to reduce the stray
      - field < 3.2mT at R=15m
      - power consumption: 2 x 2260 kW
    - Inside the detector region:
      - 4% reduction of the B field
      - 23% increase of the B distortion