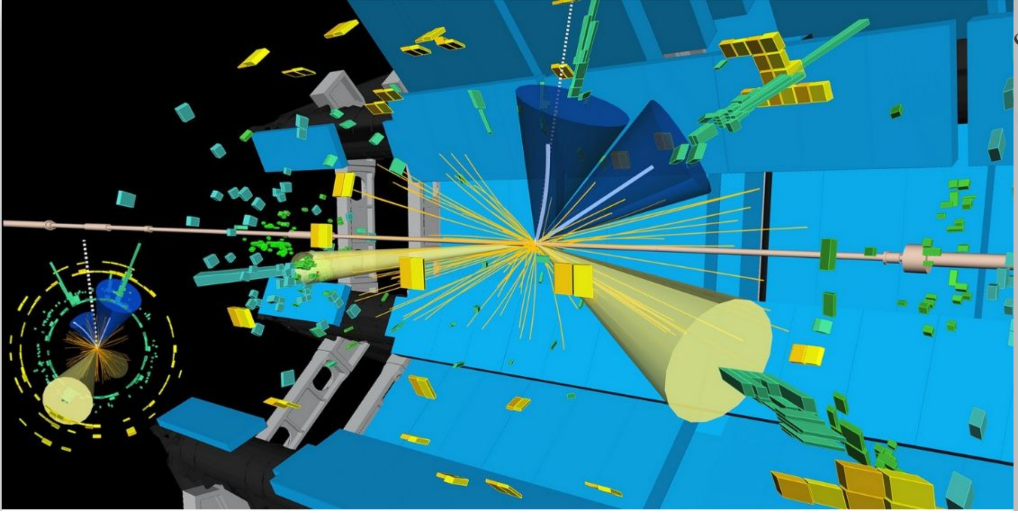
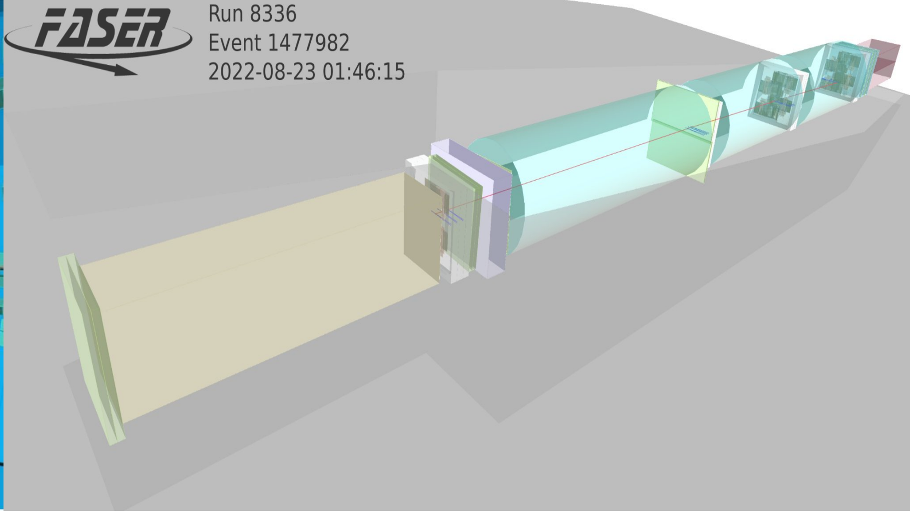




Reconstructing HEP particle trajectories:
from visible to 'invisible'

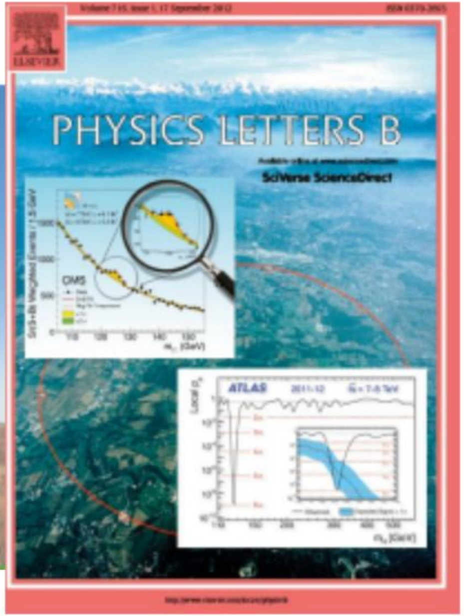
Xiaocong Ai (Zhengzhou University)

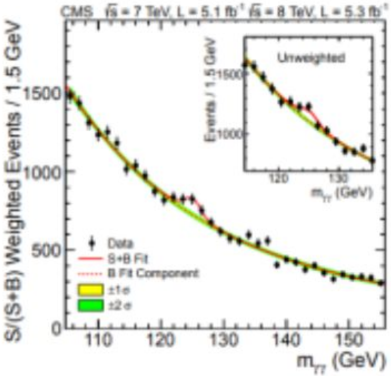
郑州大学
ZHENGZHOU UNIVERSITY

PKU HEP Seminar and Workshop, June 4, 2025

What is tracking

A long road to an exciting paper in particle physics





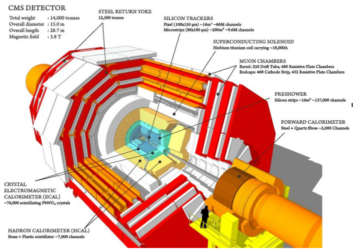
[Phys. Lett. B 716 (2012) 30]

Higgs discovery at CMS

The crucial role of HEP offline software

physics objects:

- Tracks, clusters, vertices,
- e, μ, τ/b/c/light-flavor jet, missing energy...

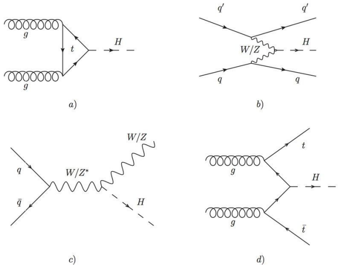


Trigger&DAQ

Reconstruction

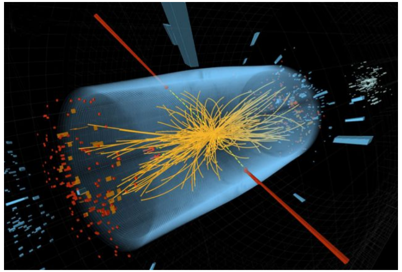
Analysis

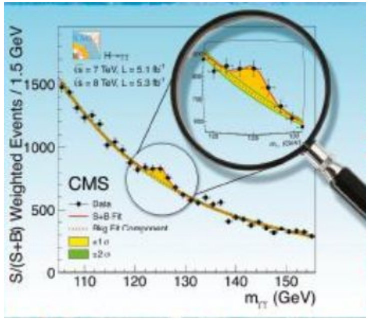
Ntuples



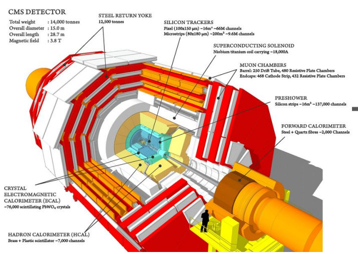
Simulation

Digitization





The crucial role of HEP offline software



Trigger&DAQ

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physics objects:

- Tracks, clusters, vertices,
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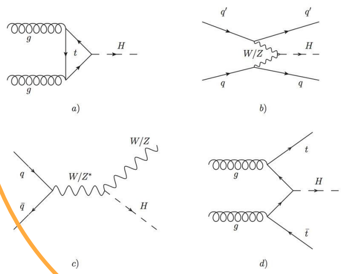
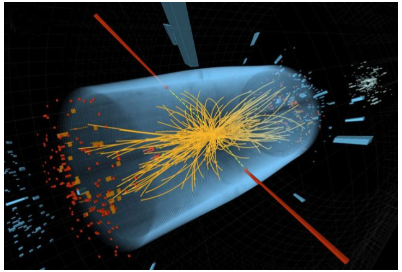
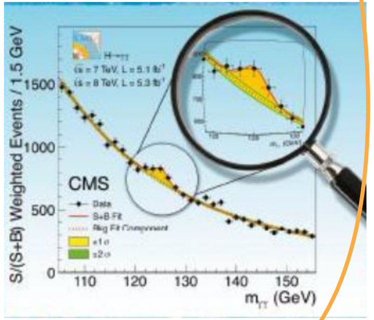


Simulation

Digitization

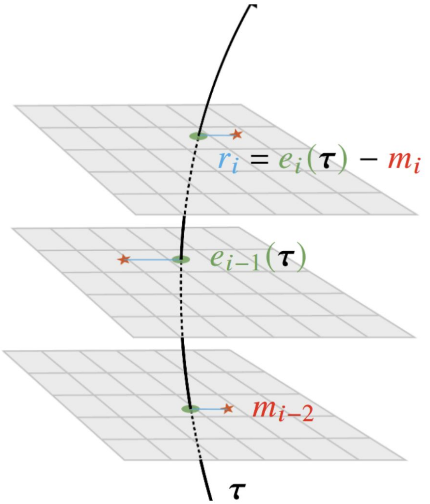


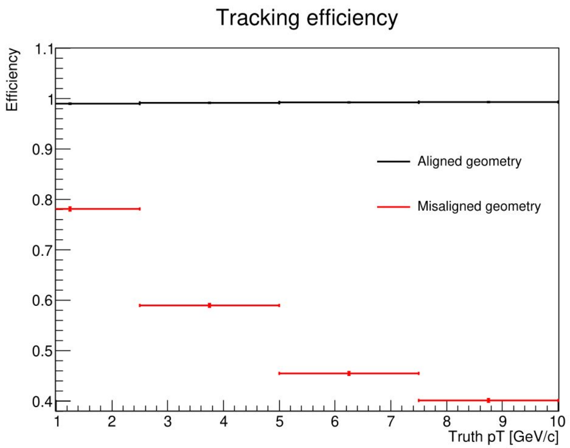


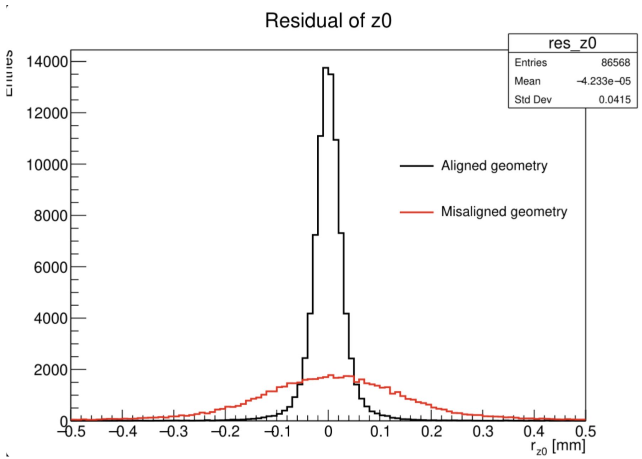
The offline software is the "**converter**" from detector data to physics data to make physics discoveries (basically all physics analysis) possible!

HEP offline software is about detectors

- To **guide** the design of often very sophisticated detectors
- To **exploit** (i.e. not to spoil) the maximum performance of the detectors
- To **detect** possible defects, malfunction, aging … of the detectors

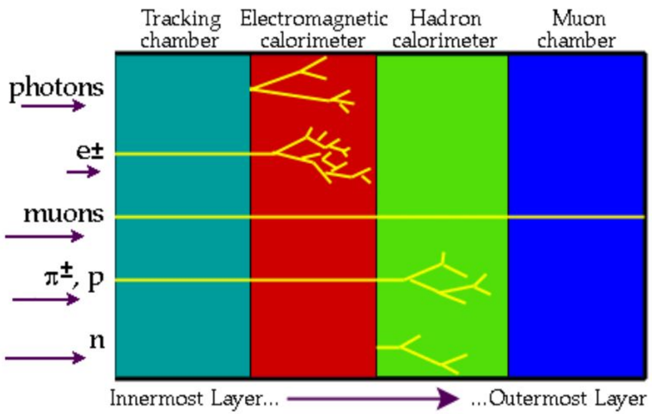


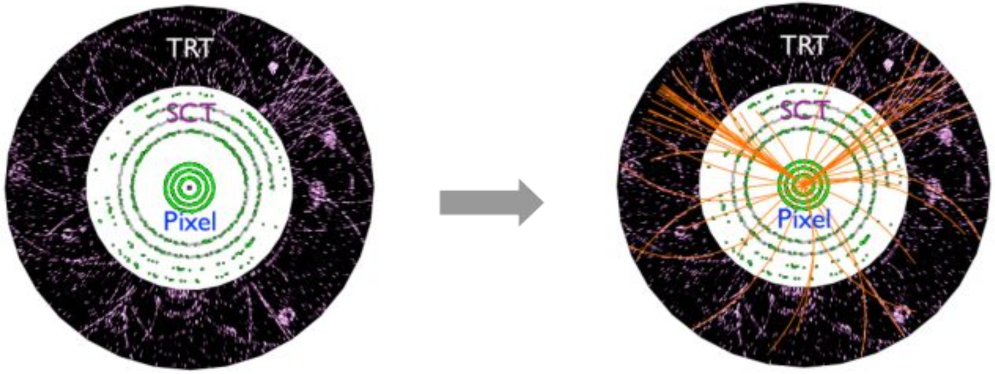




What is track reconstruction (a.k.a. tracking)?

- Reconstruction (i.e. track finding) of charged tracks and measurement (i.e. track fitting) of their quantities, using the signals of trackers (usually in magnetic field):
  - Position
  - Momentum
  - Charge
  - Vertex
  - Velocity (dE/dx)



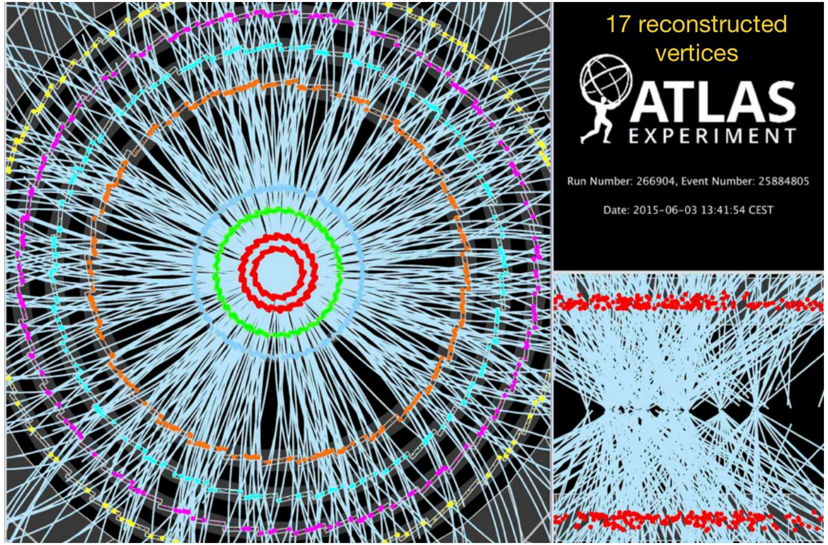


e.g. ATLAS Tracking

Why tracking matters?

Tracking is about vertex reconstruction

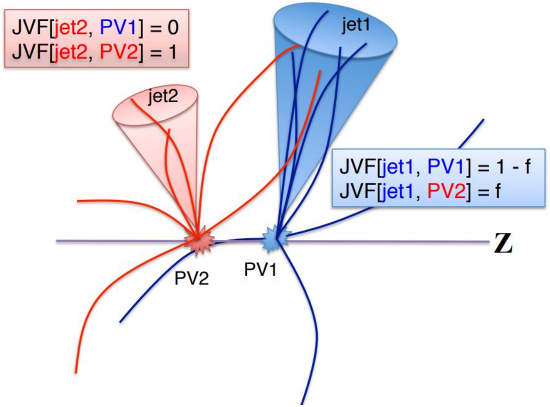
- Primary vertex reconstruction uses estimated track parameters of charged particles as inputs for:
  - Vertex finding
    - Associate tracks to vertices
  - Vertex fitting
    - Estimate vertex position

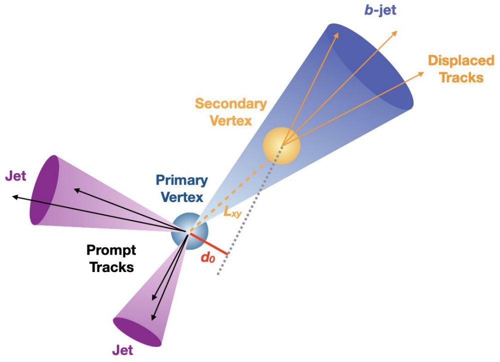


Tens to hundreds of additional proton–proton collisions accompanying the hard-scatter interaction, i.e. pile-up (μ)

Tracks/vertices are not just about charged particles

- Jets and missing energy reconstruction
  - Better p_T resolution for low pT tracks and angular resolution provided by tracker
  - Tracks/vertices are crucial for pile-up mitigation (needs precise jet-vertex association)
- Jet flavor-tagging (b, c or light-flavor jet)
  - Impact parameters, secondary vertices and length of flight
- Reconstruction of photon conversion vertex
  - Important input for e/γ discrimination
- Pivotal to track-based detector alignment

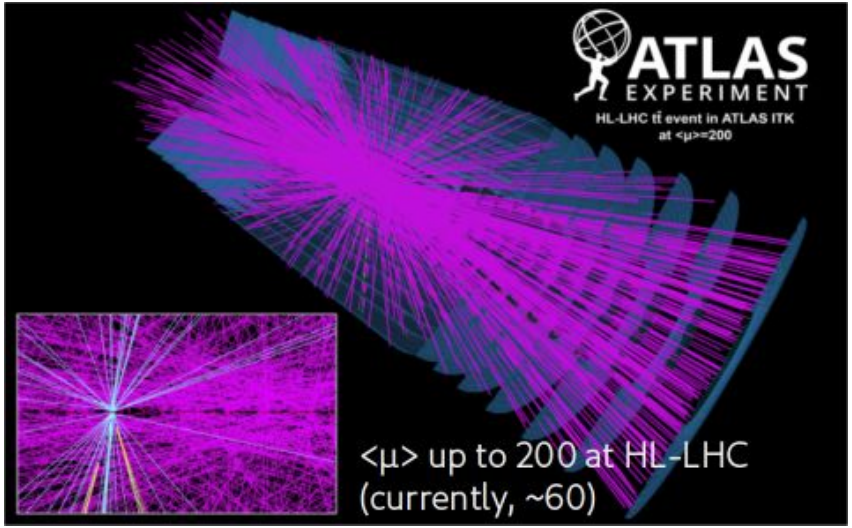


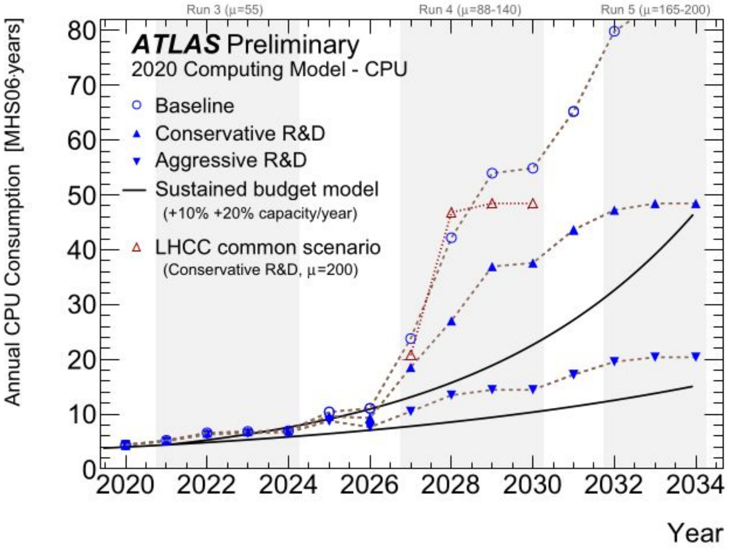


Tracking is challenging

Much more dense environment

- Future colliders tend to have much increased luminosity => higher pileup
  - e.g. <μ> = 200 at HL-LHC, <μ> = 1000 at FCC-hh
- Much increased combinatorics, data rate and CPU needs
  - ~7k particles/event at HL-LHC

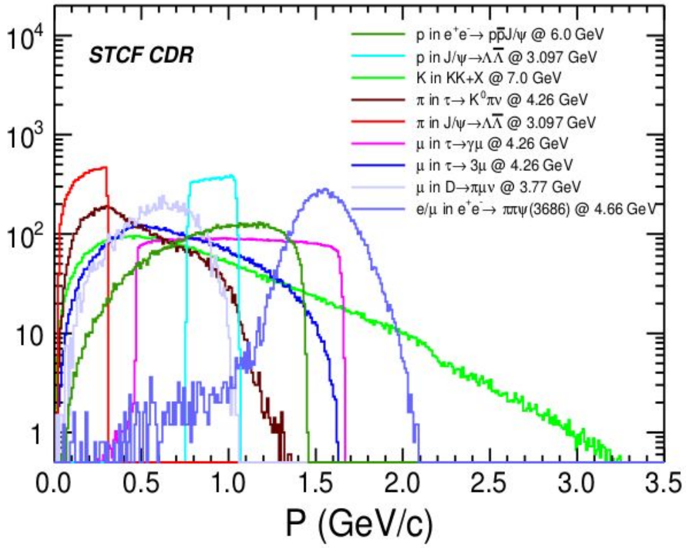




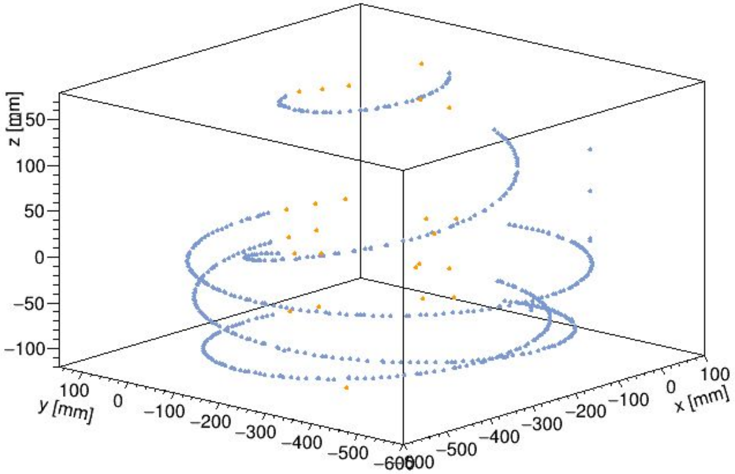
More challenging tracking requirements

- Tracking of low pT tracks is very important at future flavor factories
  - e.g. tracking eff. > 50/90/99 % with pt > 50/100/300 MeV at STCF (important to probe CPV in $\tau \rightarrow K_S \pi \nu_\tau$ and $J/\psi \rightarrow \Lambda$ anti-Λ)

Momentum distributions of charged particles at STCF

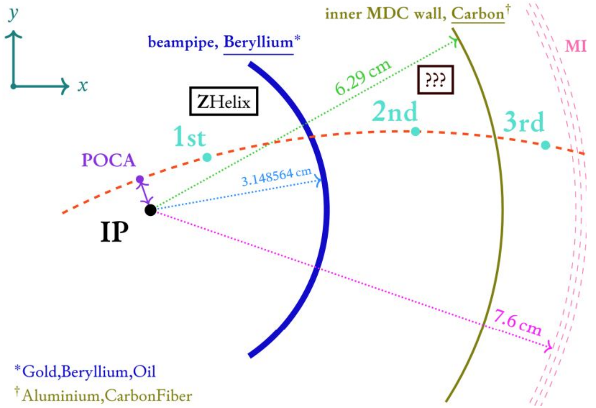


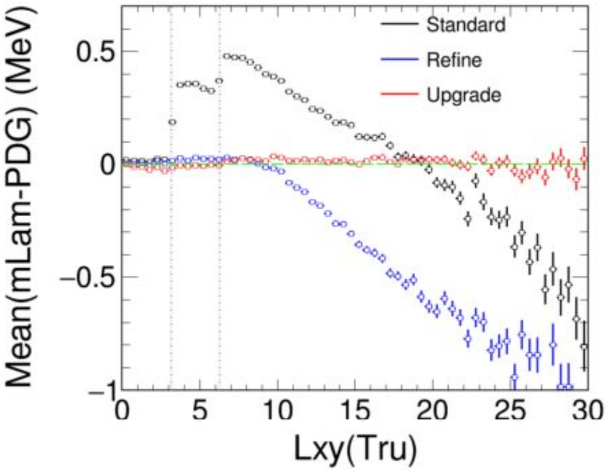
An example of low-p_T muon trajectory (p_T = 100 MeV, theta = 90) at STCF

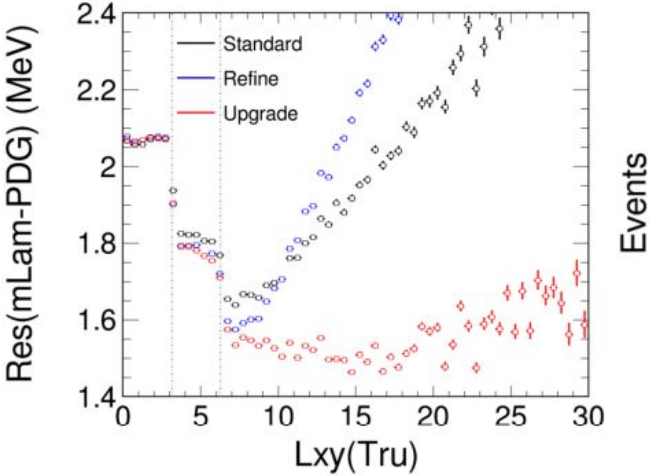


More complex tracking signatures

- Reconstruction of long-lived particles e.g. Λ, at flavor factories (e.g. BESIII and future STCF) is a non-trivial task
    - Precision can be much compromised without refined algorithms



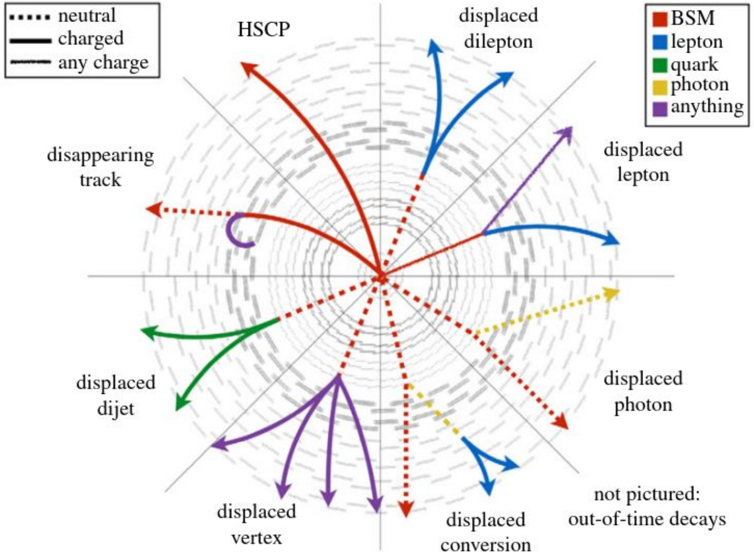




Plots from Y.P. Pei

More complex tracking signatures

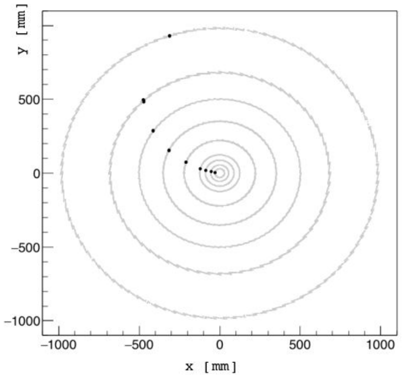
- Tracking of long-lived particle signatures is import for New Physics search at LHC and future Higgs factory:
  - Displaced tracks
  - Disappearing tracks
  - Anomalous Ionization
  - Magnetic monopole
  - Fractional/multiple Electric Charge

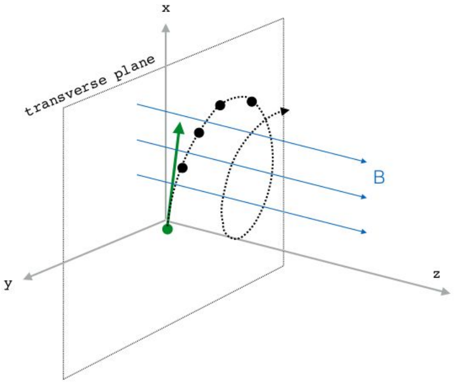


Phil. Trans. R. Soc. A 377, 20190047

Tracking strategies

A helix trajectory in homogeneous magnetic field

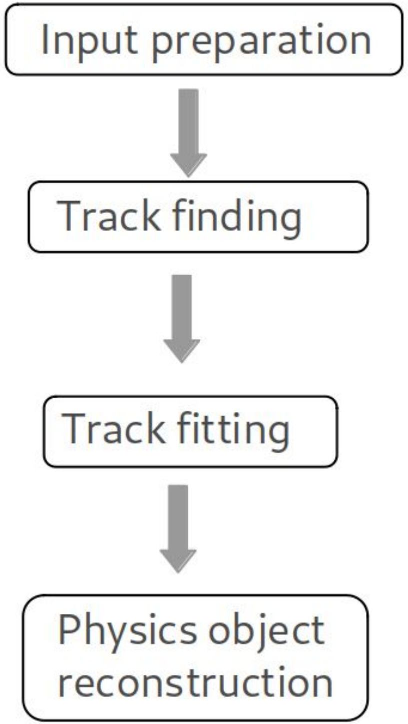




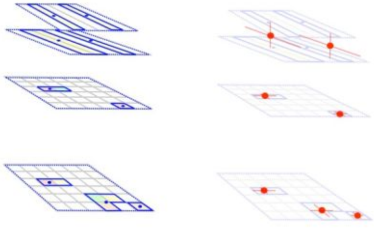
$$\frac{d^2\mathbf{r}}{ds^2} = \frac{q}{p}\left[\frac{d\mathbf{r}}{ds} \times \mathbf{B}(\mathbf{r})\right]$$

Track propagation is solved numerically using fourth-order Runge-Kutta-Nyström method

How to find & fit tracks ?

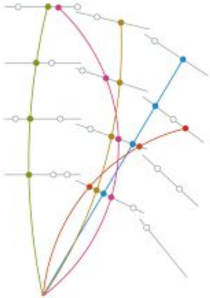


- Raw data converted to cluster/drift circle
- Formation of 3D space point



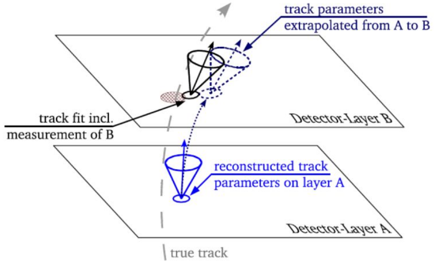
Identify measurements to individual tracks

- Global approach: Hough transform, Graph Neural Networks
- Local approach: Cellular automaton, Combinatorial Kalman Filter (CKF)

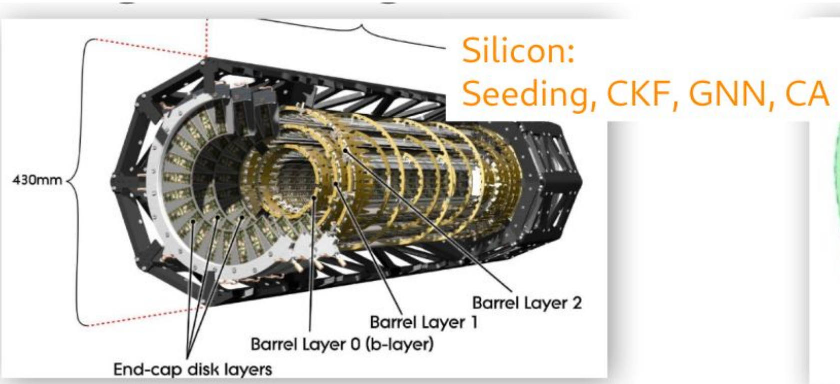


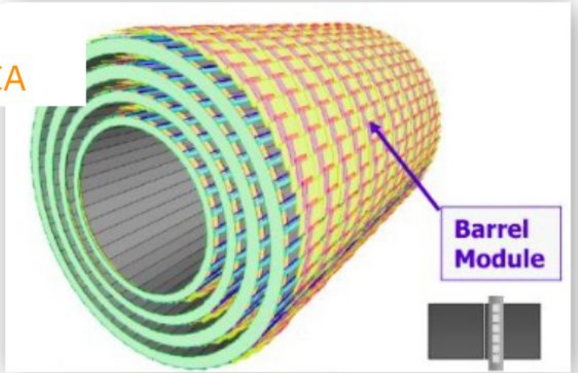
Estimate the track parameters

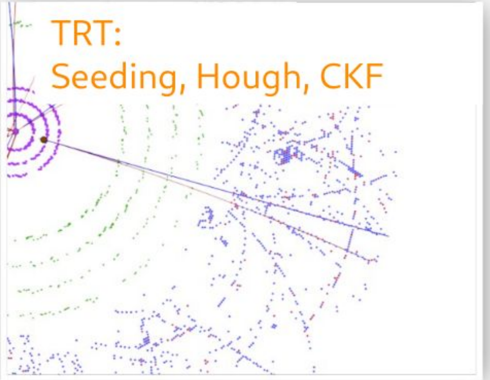
- Least-square fitter (superceded by Kalman filter, can resolve left/right ambiguity)
- Kalman-filter

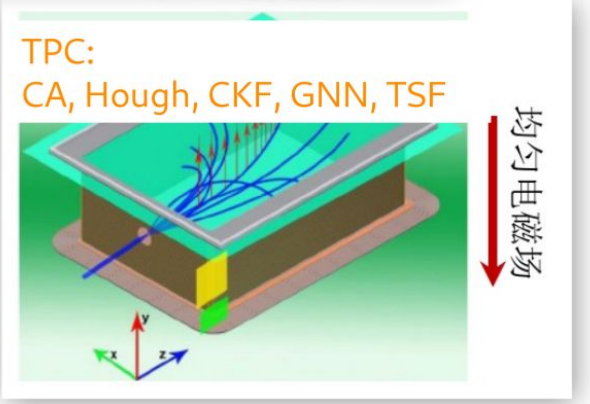


Tracking strategies are about detectors



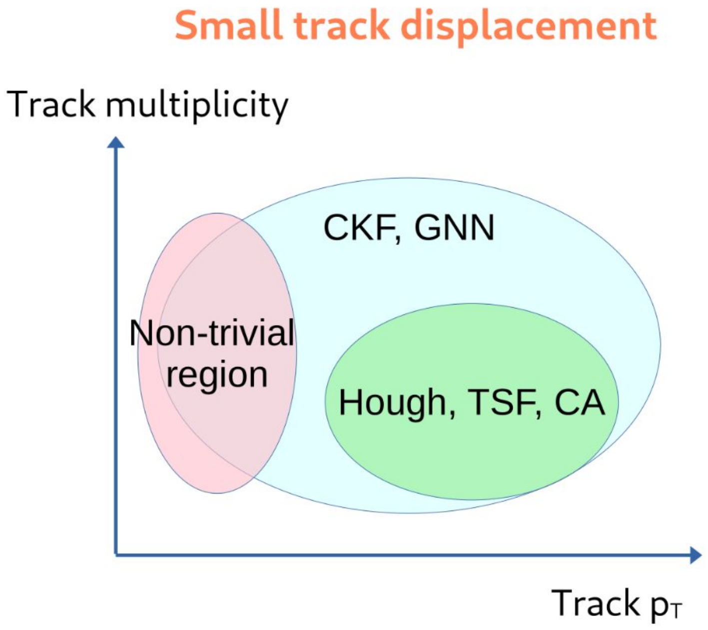


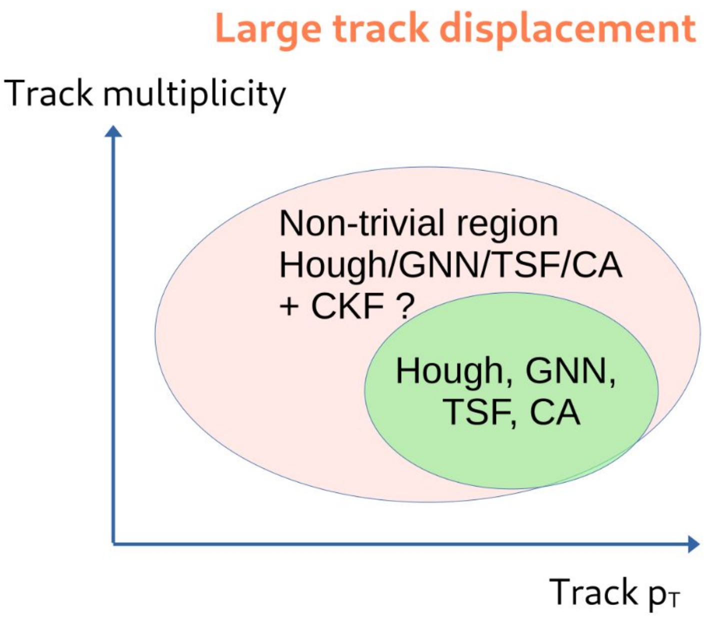




Tracking strategies are about tracks

- In addition to detector type/resolution, tracking strategies are mainly driven by track p_T , track multiplicity and track displacement





Towards a modern, efficient, accurate and fast common tracking software

What is A Common Tracking Software (ACTS)

- A modern **open-source detector-independent** tracking toolkit for current&future HEP experiments based on LHC (and beyond) tracking experience
  - Deployed for data production by **ATLAS, FASER, sPHENIX**
  - Used for detector R&D by **CEPC, STCF, EIC, ePIC, LDMX, LUXE, NA60+** …
- A R&D platform for innovative tracking techniques (ML) & computing architectures (GPU)

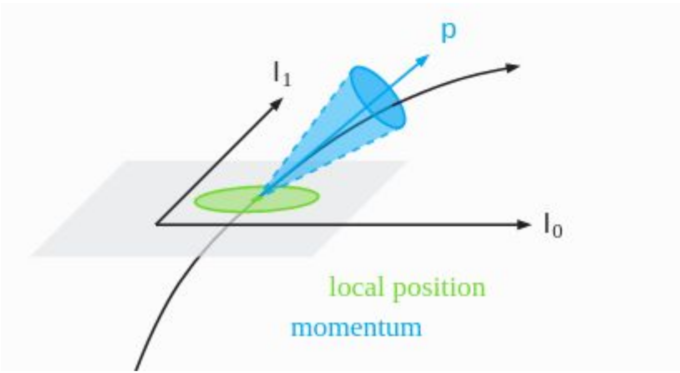
ZZU is making core contribution to ACTS and leading the efforts for developing ACTS-based tracking algorithms for ATLAS, FASER, STCF and CEPC !

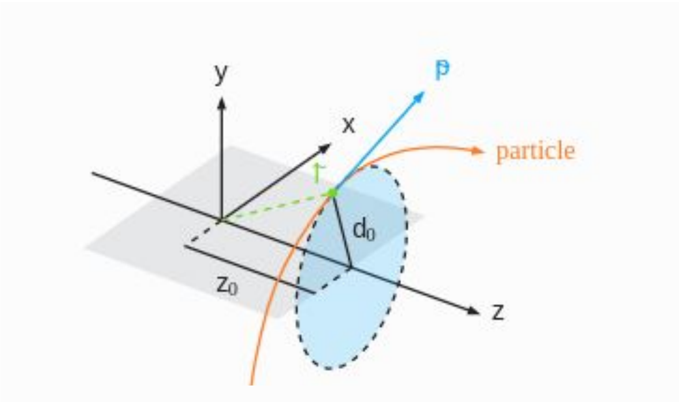
X. C. Ai. et al, CSBS (2022) ***6;***
https://github.com/acts-project/acts

Figure from A. Salzburger

ACTS design and features

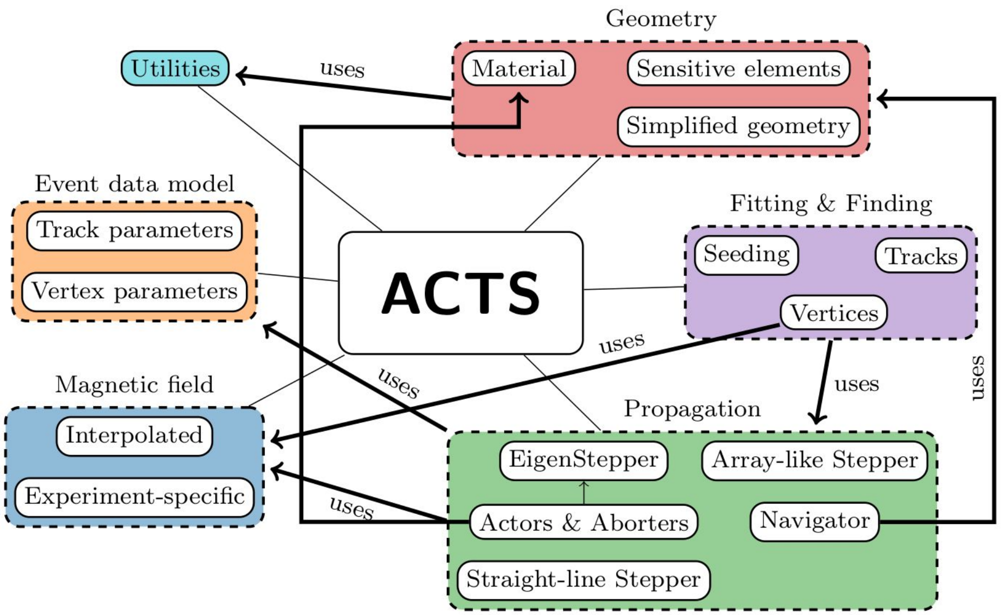
- Modern C++ 17 (→ 20) concepts
- Detector and magnetic field **agnostic**
- Strict **thread-safety** to facilitate concurrency
- Flight time in track parameterization (facilitate **4D tracking**)
- Supports **contextual condition**
- Minimal dependency (only Eigen as algebra library)
- Highly configurable for usability
- Well documented and maintained





$$\vec{x} = (l_0, l_1, \phi, \theta, q/p, t)^T$$

ACTS tracking/vertexing/alignment modules



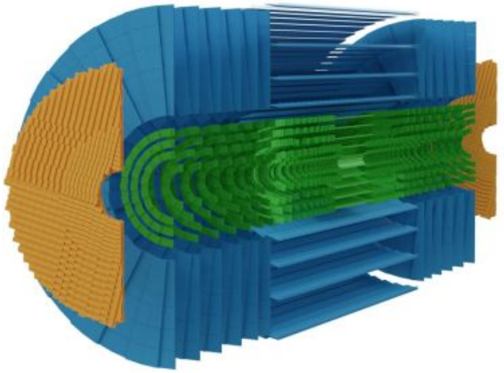
Figures from CSBS (2022) ***6,*** *8*

- Track fitting:
  - (Extended) KF, Gaussian Sum Filter, Non-linear KF
  - Global chisq fitter
- Track finding
  - Seeding, Combinatorial Kalman Filter (CKF), Graph Neural Networks
  - Hough Transform
- Vertex finding&fitting
  - Primary vertex: AMVF, IVF
- KF-based Alignment prototype

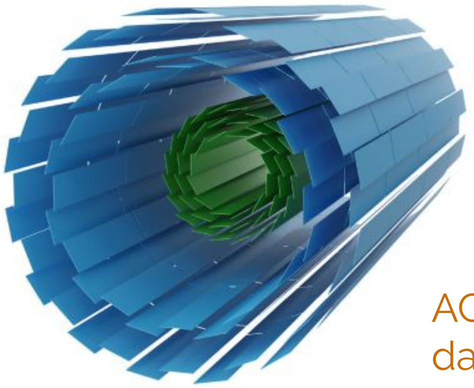
ACTS works well for silicon tracker

- ACTS works well for solid state silicon trackers. Lots of clients in the past three years:
  - ATLAS silicon and ITk, sPHENIX silicon, ALICE silicon, FASER, LDMX, ePIC …
    - These are mostly about track parameters/measurements represented on a planar surface

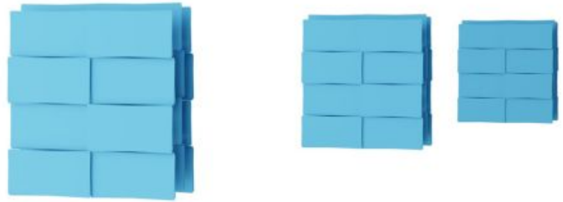
ATLAS ITk



sPHENIX silicon



FASER tracker

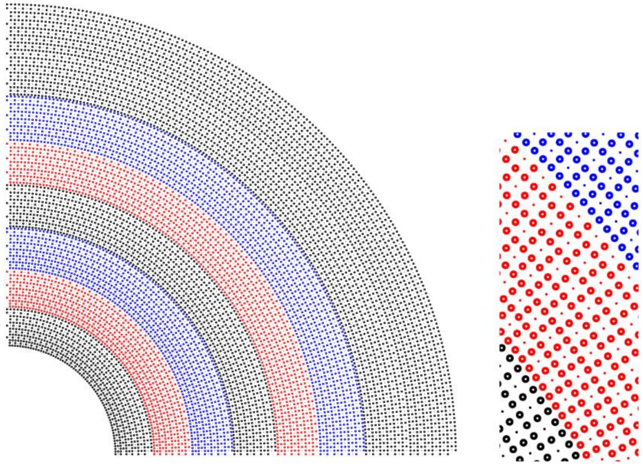


ACTS modules are already used for real data processing for ATLAS, sPHENIX, FASER

*Figures from CSBS (2022) **6**, 8*

ACTS also works for gaseous tracker

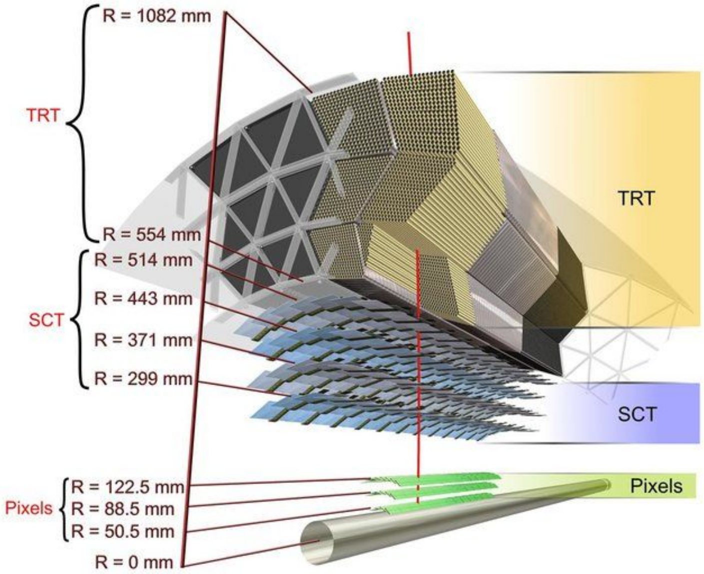
- ACTS is designed with the capability of working for **gaseous trackers**
    - **Drift chamber and Transition Radiation Tracker** are represented with N-layer drift wire/tubes, e.g.
        - CEPC
        - STCF
        - ATLAS TRT
        - BESIII
    - **Time Projection Chamber (TPC)** is represented with fake Planar detectors, e.g. sPHENIX TPC



STCF Drfit chamber
from STCF CDR arXiv:2303.15790

ACTS for ATLAS

ATLAS current Inner Detector (ID)



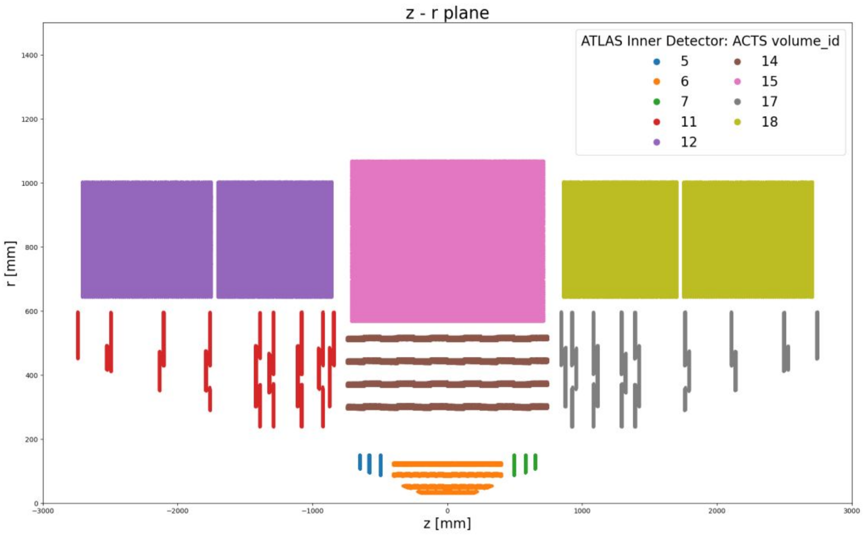
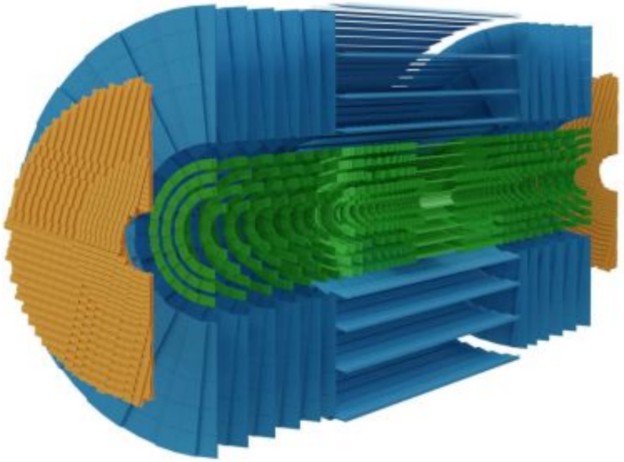
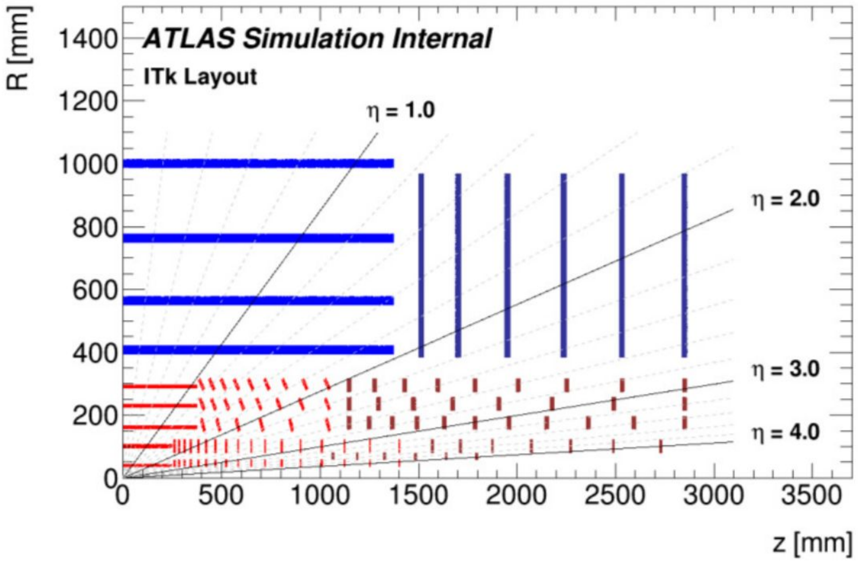


Figure 18: Visualization of simulation hits for z-r plane

ID (Pixel + SCT + TRT) geometry implemented in ACTS

ATLAS future ITk in HL-LHC era (Run4)



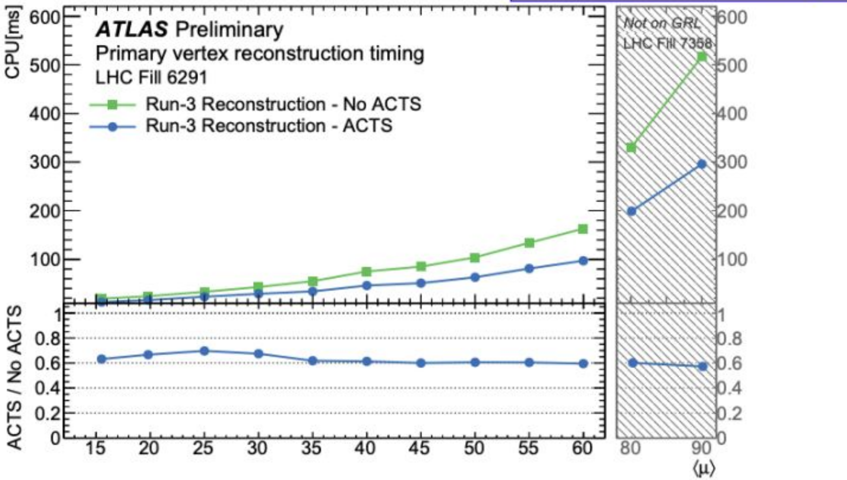


ITk (pixel + strip) geometry implemented in ACTS

ACTS for current ATLAS Run3

- ACTS-based vertex reconstruction already **default in Run 3 data-taking and Run2 reprocessing**
  - ACTS AMVF about 40% faster than Athena counterpart, with identical physics performance
- ACTS Kalman Filter (KF) track fitting implemented in standalone ACTS
  - Implementing Tracking Geometry of ATLAS TRT in Standalone ACTS
- Ongoing work to implement full ACTS track finding + fitting for ATLAS Run3

ATL-PHYS-PUB-2021-012.pdf

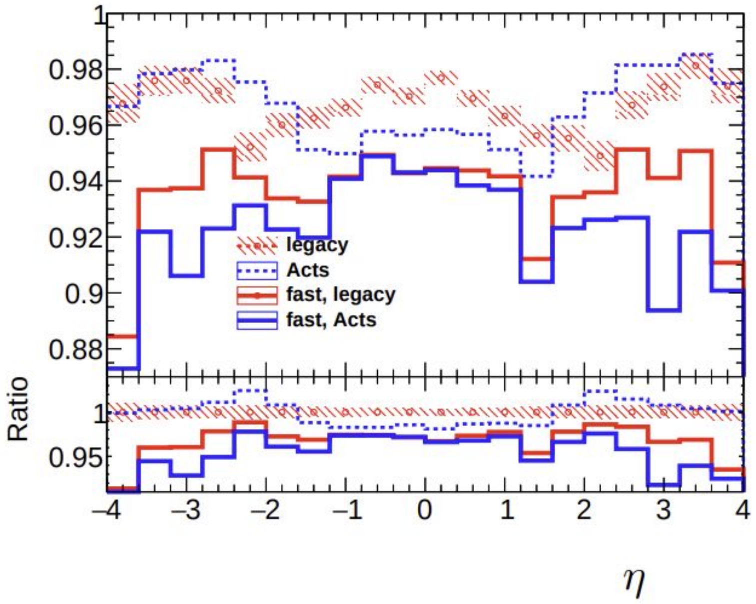


ACTS for ATLAS Run4

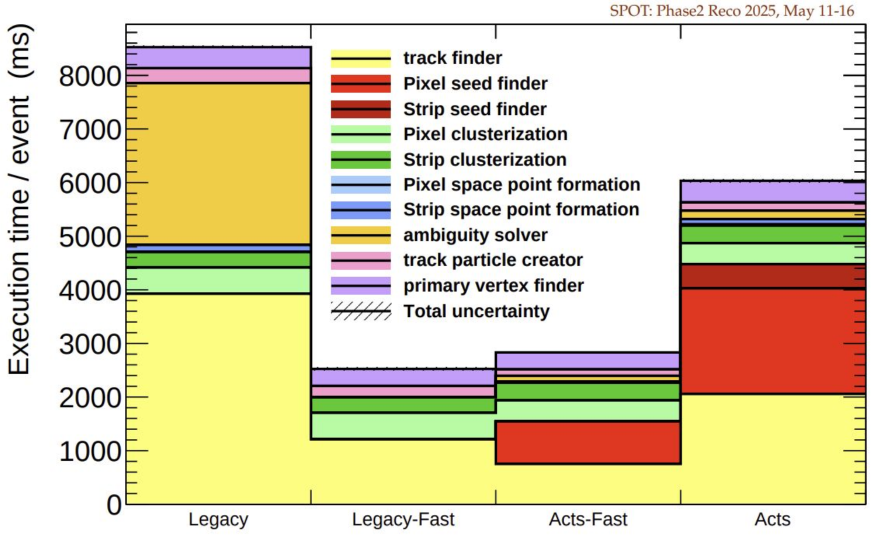
- Acts chain consolidates, but a bit lower efficiency in central region and faster speed

From G. Gaycken' slides at recent ATLAS tracking workshop

Technical efficiency



Execution time



ACTS for Circular Electron Positron Collider (CEPC)

Circular Electron Positron Collider (CEPC)

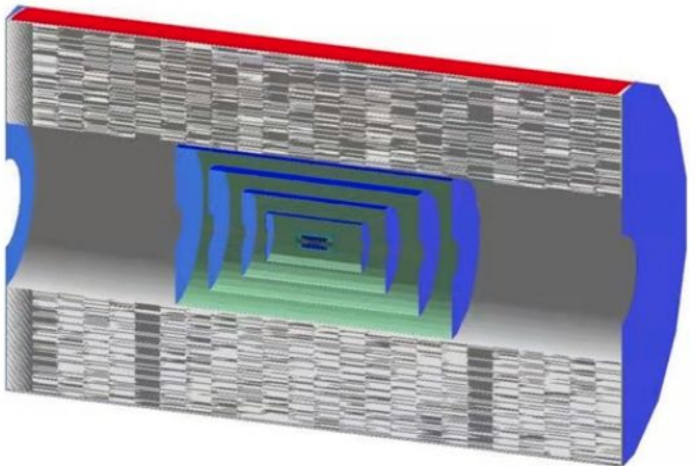
Operation mode			ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]			240	91	160	360
Run time [years]			7	2	1	-
CDR (30 MW)		L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**3**	**32**	**10**	-
		$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	-
		Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	-
Run Time [years]			10	2	1	5
TDR (Latest)	30 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	0.5
		$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
		Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
	50 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
		$\int L\,dt$ [ab^{-1}, 2 IPs]	21.6	100	6.9	1.0
		Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

- Precision measurements of Higgs boson properties
- SM measurements: electroweak physics, QCD, flavor physics…
- Search for exotic decays of H, Z, B and τ, and BSM

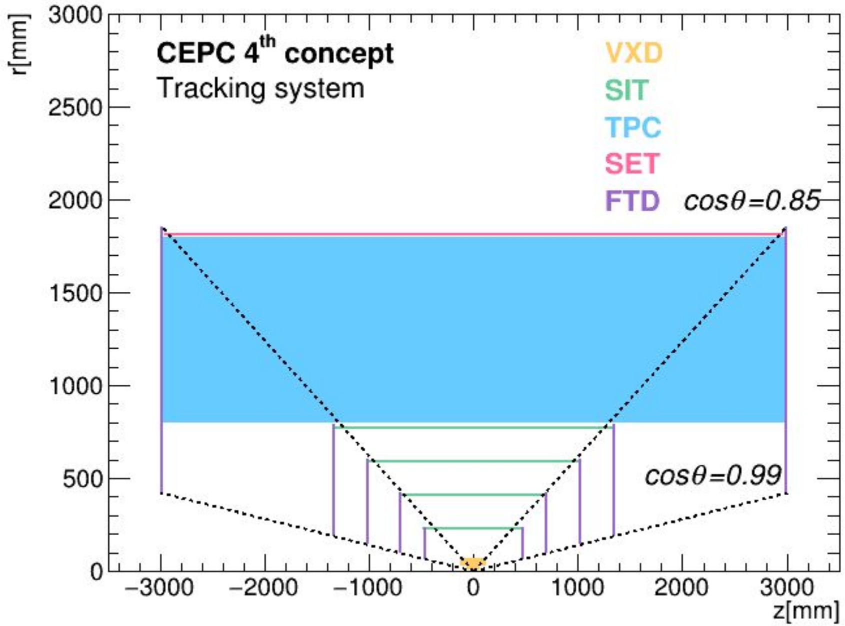
Far more than a Higgs factory !

From J. B. Liu's slides at CEPC workshop 2023, Oxford

Tracking system of CEPC 4th concept



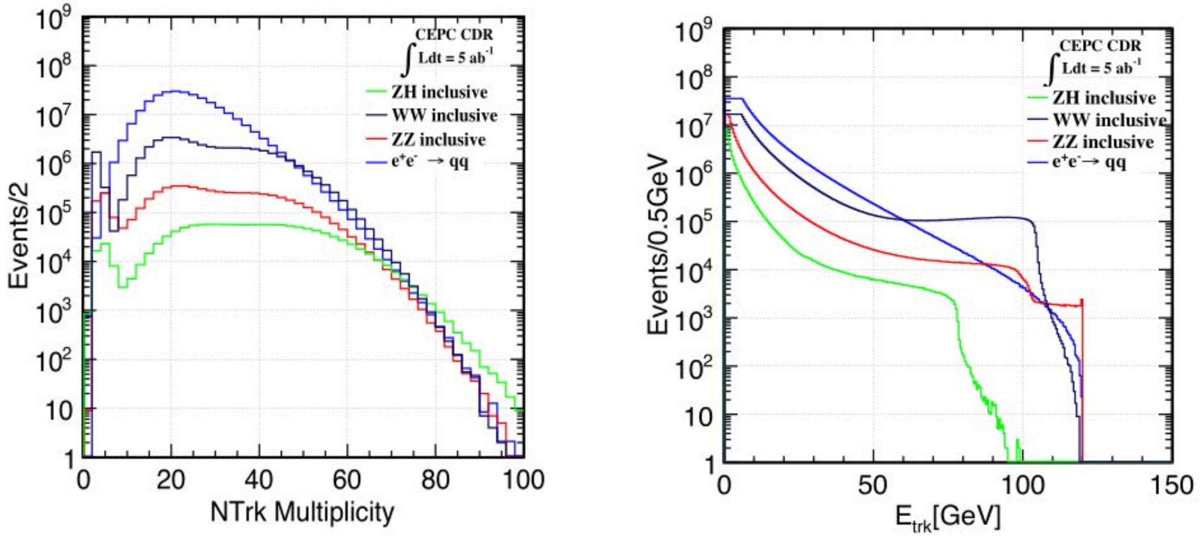
Silicon (VXD, SIT, SET, FTD) + Drift chamber



Tracker	Number of layers	Radius/ |z| (mm)	σ_x (μm)	σ_y (μm)	Technology
VXD	3 double layers	16-58	2.8/6/4/4/4/4	2.8/6/4/4/4/4	Silicon (pixel/strip)
SIT	4 layers	230-770	7.2	86	
SET	1 layer	1815	7.2	86	
FTD	5/7 layers at each endcap	467-2991	(2.8)/(2.8)/7.2/ 7.2/7.2/7.2/7.2	(7.2)/(7.2)/7.2/7. 2/7.2/7.2/7.2	
DC	100 layers	805-1795	110		Drift Chamber

CEPC tracking requirements

- Mostly >20 tracks per event (up to 100 tracks per event)
  - >99% tracking efficiency for p_T > 1 GeV
  - Impact track parameter resolution at ~ 5 um
  - Momentum resolution reaches per mille level in the range [10, 100] GeV

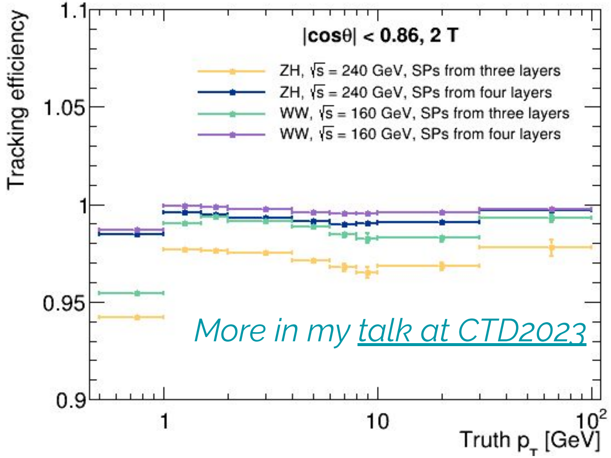


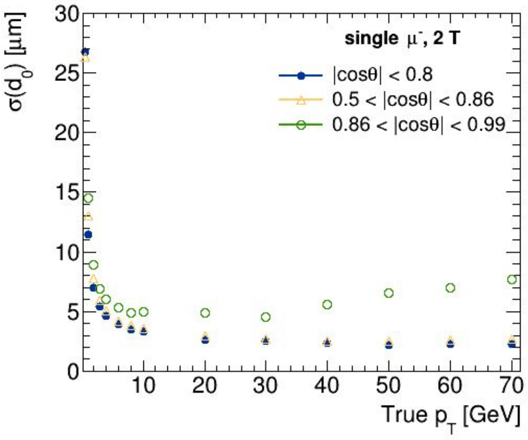
From CEPC CDR (arXiv: 1811.10545)

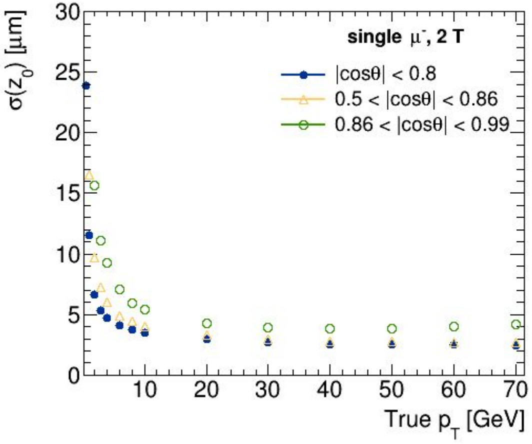
CEPC tracking performance

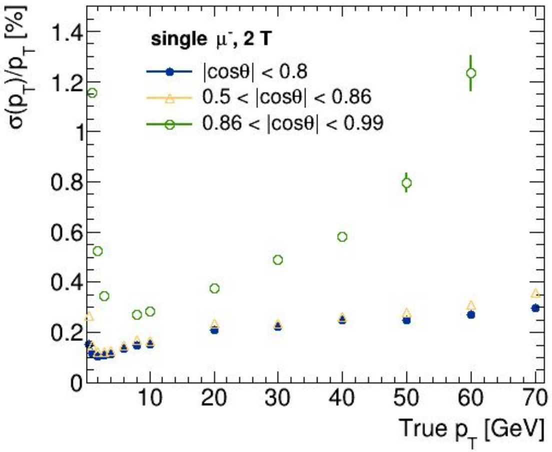
Using ACTS FATRAS simulation (full tracking system)

- >=95% tracking efficiency for p_T > 1 GeV in benchmark physics processes
  - 1-2% fake tracks and 10% duplicate tracks
- At p_T = 10 GeV, central region (|cosθ|<0.8) :
  - σ(d0) = 3 μm, σ(z0) = 3.5 μm, $\sigma(p_T)/p_T$ = 0.16%







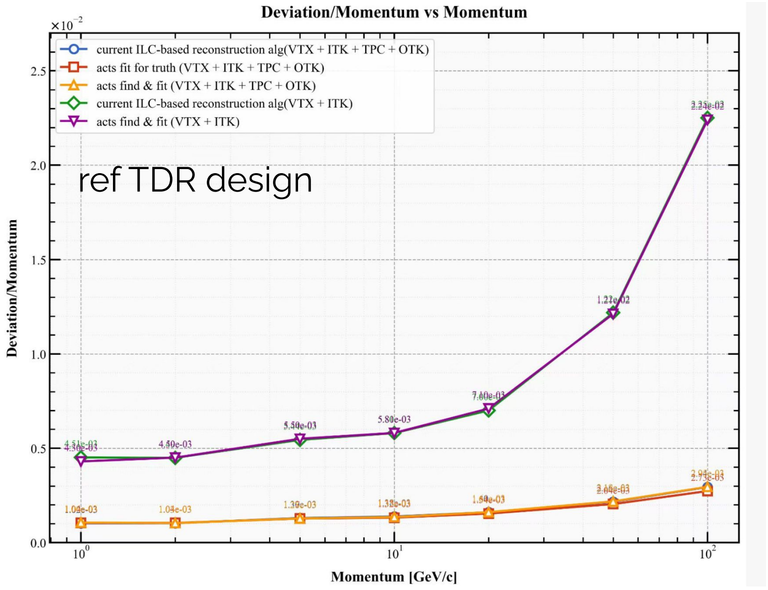


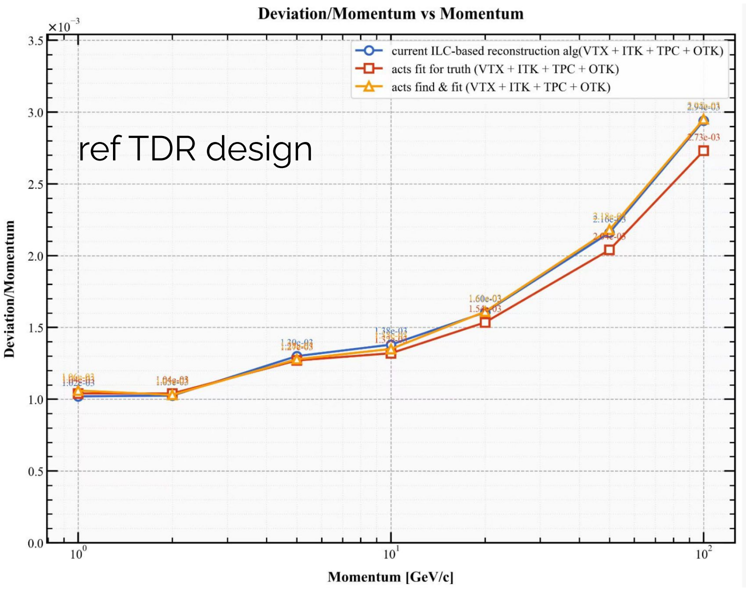
CEPC tracking performance

Using CEPCSW full simulation

Y. Z. Zhang, X. C. Ai, W. D. Li, T. Lin

- ACTS has been successfully integrated to CEPCSW
- Performance is comparable with current baseline (can be slightly better than) CEPC tracking

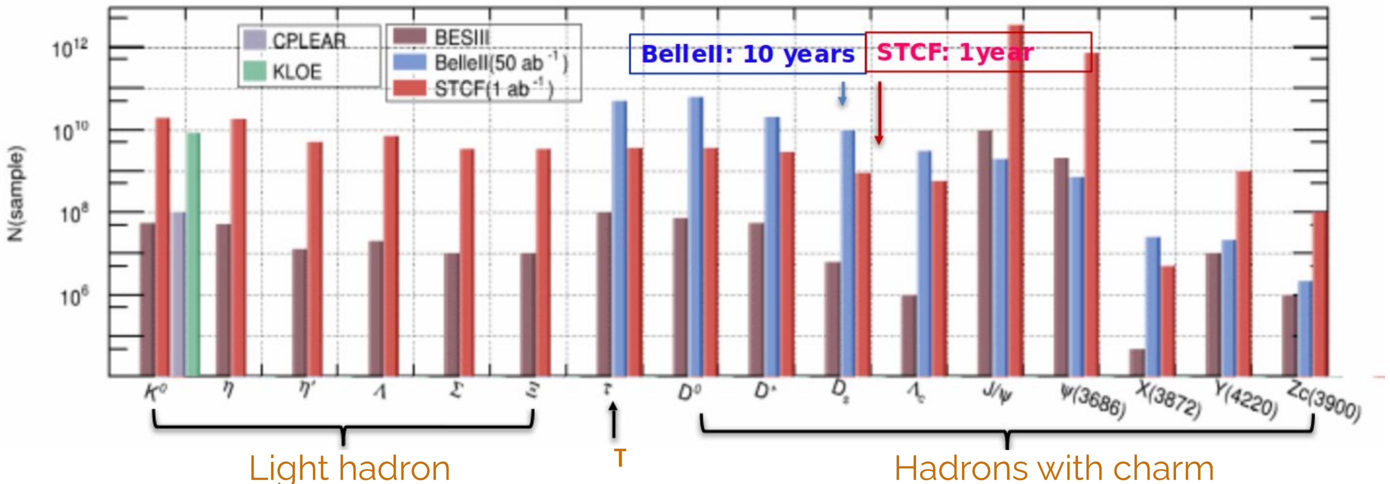




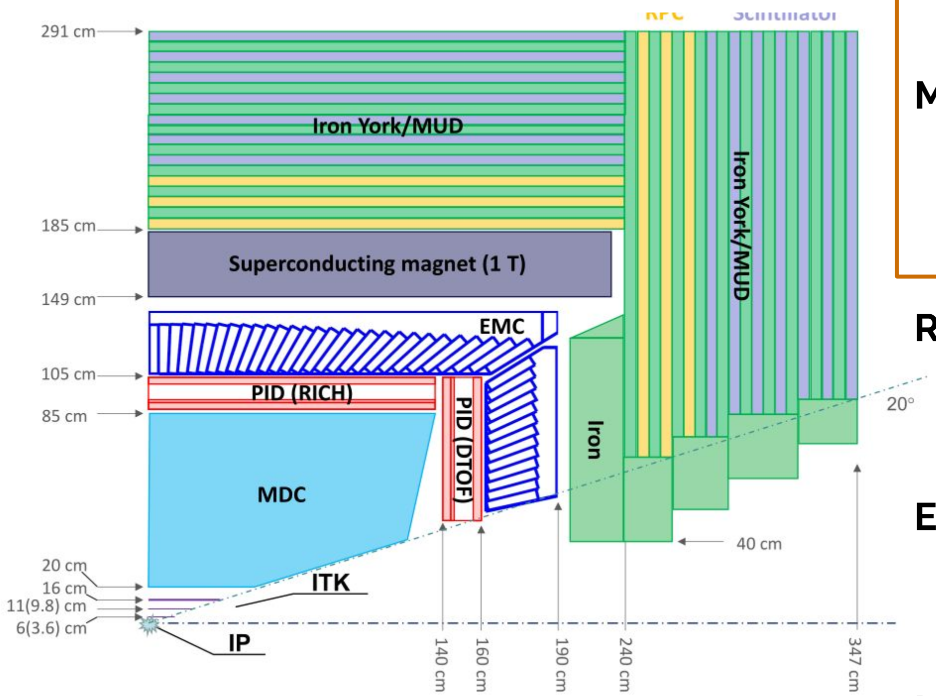
ACTS for Super Tau-Charm Facility (STCF)

Super Tau-Charm Facility (STCF)

- A future e+e- collider in China operating at tau-charm region ($\sqrt{s}$ = 2~7 GeV) with peak lumi of 0.5×10^{35} cm^{-2} s^{-1} (>x50 of current BEPCII collider)
  - A factory of charmonium (J/ψ, $\psi(3686)$, …), open charm meson, τ …
- Physics topics:
  - QCD and Hadron spectroscopy (new hadrons, e.g. glueballs, hybrid hadrons…)
  - Flavor physics and CP violation
  - Exotic decays and new physics



The detector and performance requirements



ITK (cylindrical MPGD/ CMOS MAPS)
- Material < 0.01 X0, σ_{xy} < 100 um

MDC (drift chamber)
- Material < 0.05 X0
- σ_{xy} < 130 um, σ_p/p < 0.5% at 1 GeV/c
- dE/dx resolution < 6%

RICH (CsI-MPGD) & **DTOF** (DIRC-like TOF)
- PID π/K PID efficiency > 97% up to 2 GeV/c @mis-ID rate 2%

EMC (pure CsI + APD)
- σ_E < 2.5%, σ_{pos} < 5 mm, σ_t < 300 ps @ 1 GeV

MUD (RPC + scintillator strips)
- μ PID efficiency > 95% with π→ μ mis-ID rate < 3.3% @ p = 1 GeV/c

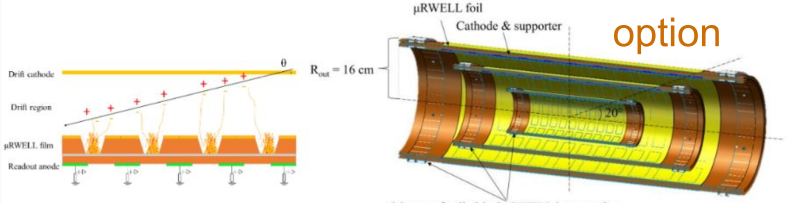
STCF tracking system

ITK (MPGD): $\sigma_{r\text{-}\phi} \times \sigma_z \approx$ 100 um x 400 um
MDC: $\sigma_{\text{drift dist}} \approx$ 120~130 um

- Two options inner tracker(ITK)

ITK Gaseous option : MPGD

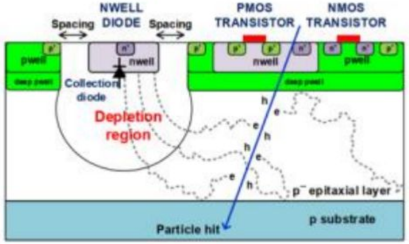
Current baseline option



3 layers of cylindrical μRWELL inner tracker
(with sensitive length of 33, 61, 88 cm respectively)

3 layers(R = 6, 11, 16cm)

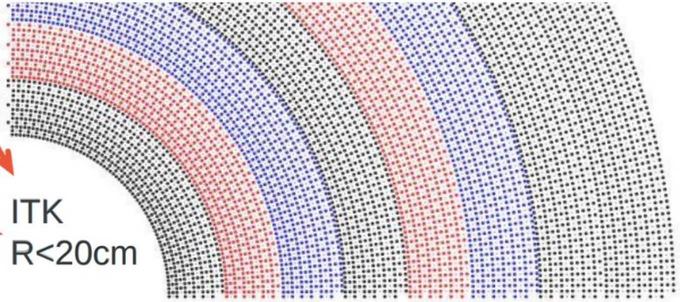
ITK Silicon option: CMOS MAPS



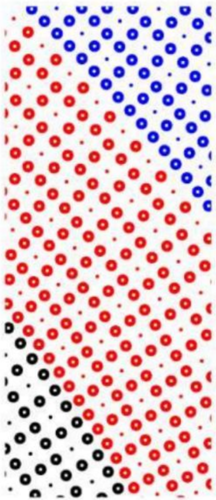
- Main tracker

MDC(Main Drift Chamber)
R 20cm-840cm, 48layers

Superlayer	Radius (mm)	Num. of Layers	Stereo angle (mrad)	Num. of Cells	Cell size (mm)
A	200.0	6	0	128	9.8 to 12.5
U	271.6	6	39.3 to 47.6	160	10.7 to 12.9
V	342.2	6	-41.2 to -48.4	192	11.2 to 13.2
A	419.2	6	0	224	11.7 to 13.5
U	499.8	6	50.0 to 56.4	256	12.3 to 13.8
V	578.1	6	-51.3 to -57.2	288	12.6 to 14.0
A	662.0	6	0	320	13.0 to 14.3
A	744.0	6	0	352	13.3 to 14.5
total	200 to 827.3	48		11520	



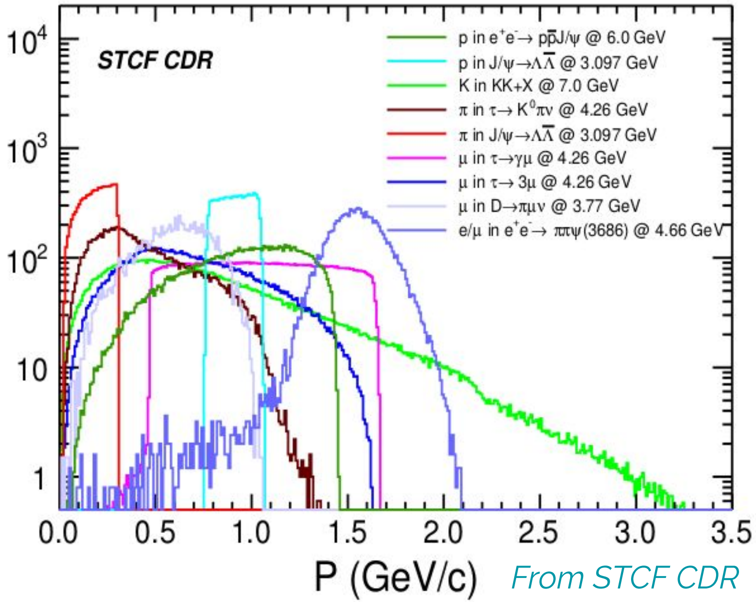
ITK
R<20cm



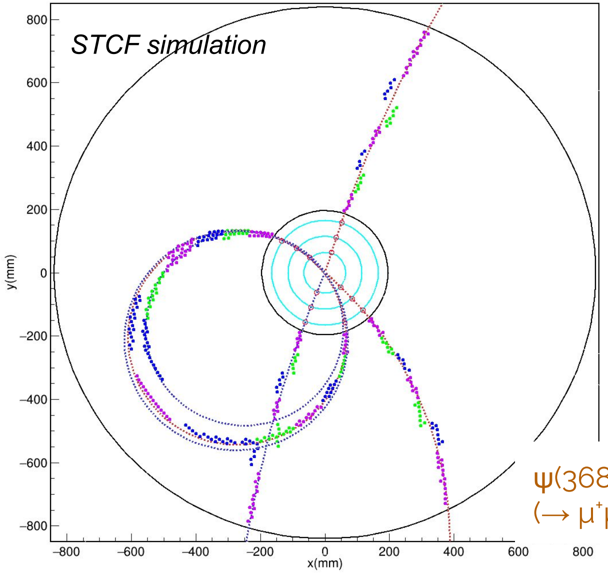
From [H. Zhou's CHEP2024 talk]

STCF tracking challenges

- Most physics processes have charged particles with $p_T < 500$ MeV/c
  - More material effects → worse resolution
  - Looping tracks with $p_T < 130$ MeV/c → fake/duplicate tracks
- Long-lived particles (Λ, K_s, ...) can decay outside ITK



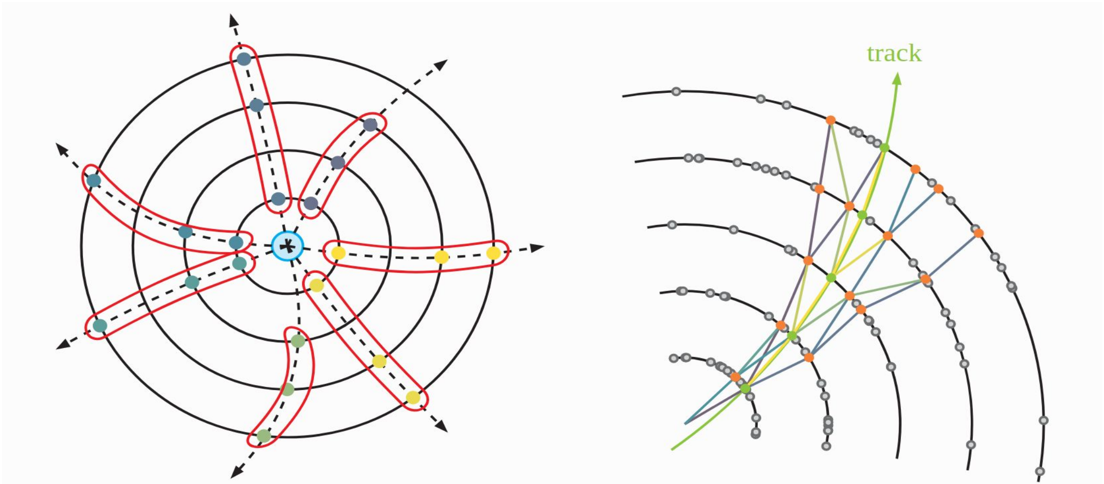
From STCF CDR

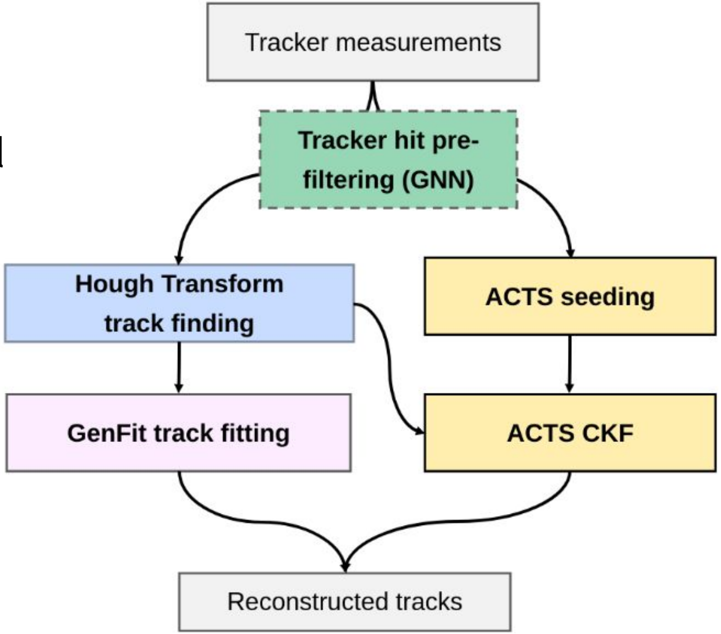


$\psi(3686) \to \pi^+\pi^- J/\psi$ $(\to \mu^+\mu^-)$

ACTS tracking strategy

- ACTS has been integrated into STCF offline software
  - Hough + GenFit has been well optimized
  - ACTS seeding + ACTS CKF is used as second tracking option at STCF
  - Hough (as seeding) + ACTS CKF is also being studied for long-lived particle tracking

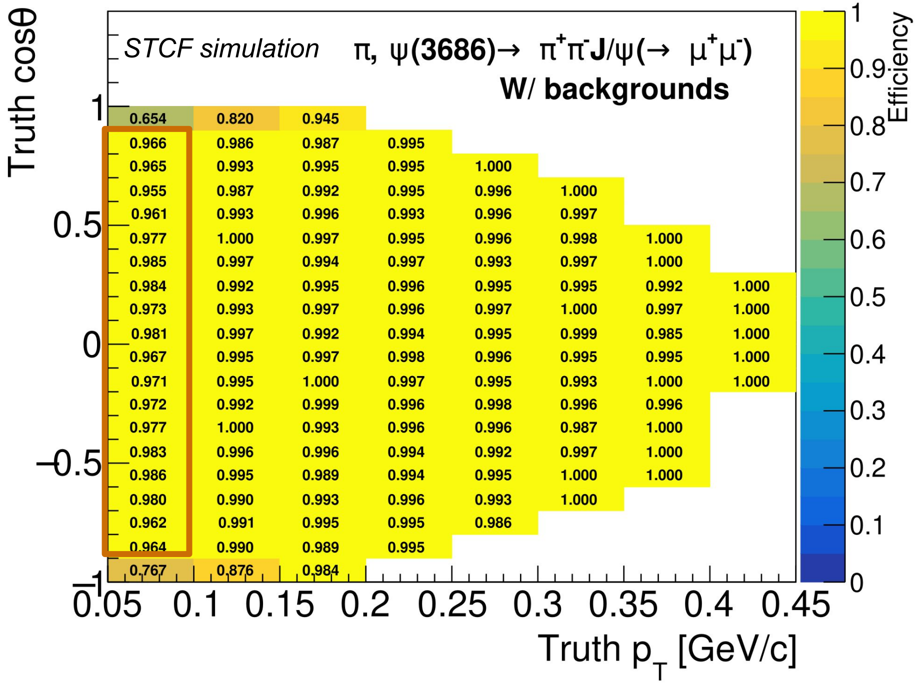


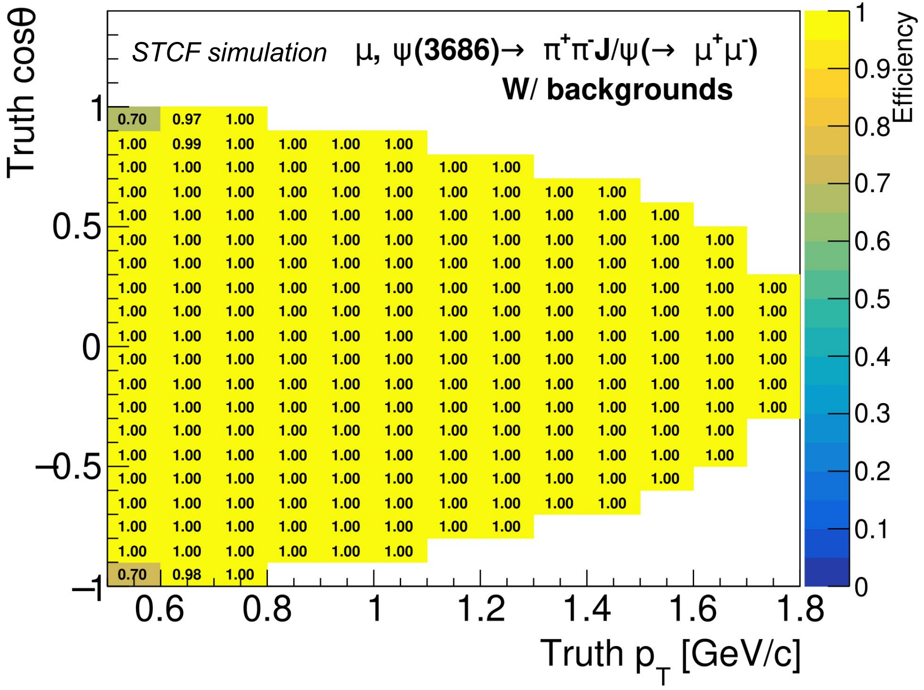


Details about Hough + GenFit in [H. Zhou's CHEP2024 talk]

ACTS tracking (seeding + CKF) efficiency

- >96% tracking efficiency for particles in the region |cosθ|<0.9, 50 MeV < p_T<100 MeV for prompt tracks!

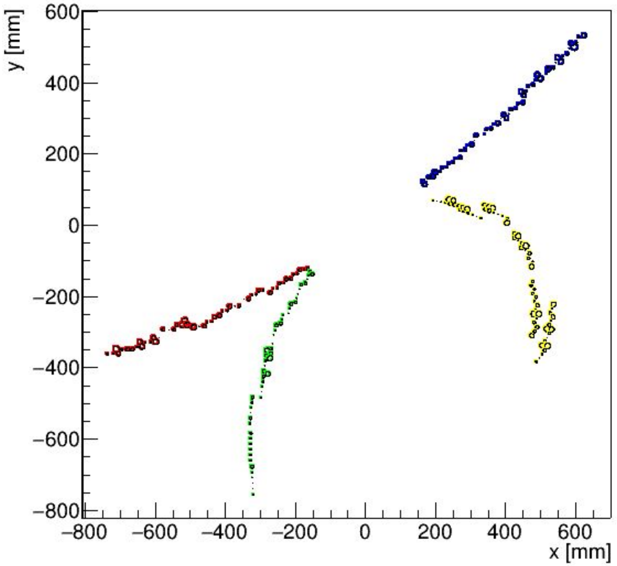


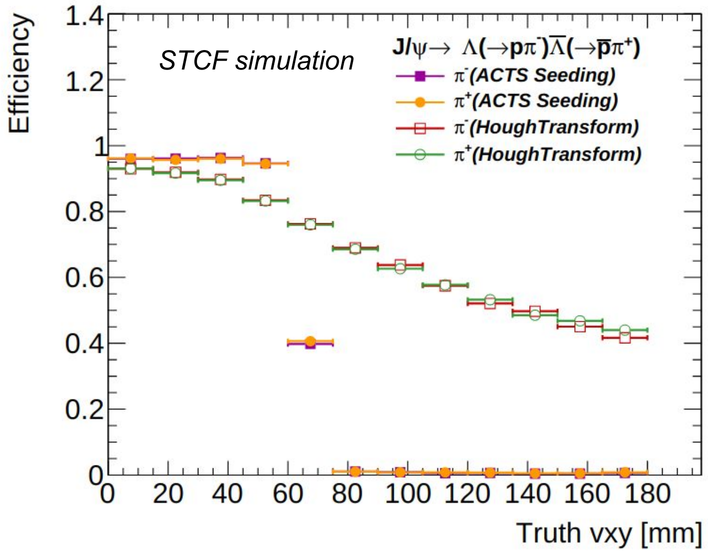


Particle requirements: nHits>=5, |cosθ|<0.94
Track requirements: nHits>=5, matchingProb > 0.5

Hough Transform + ACTS tracking performance

- Hough transform is more robust against local hit loss/inefficiency
- ACTS has slightly better seeding efficiency if there are enough hits
- Efficiency loss can be recovered by using Hough as seeding





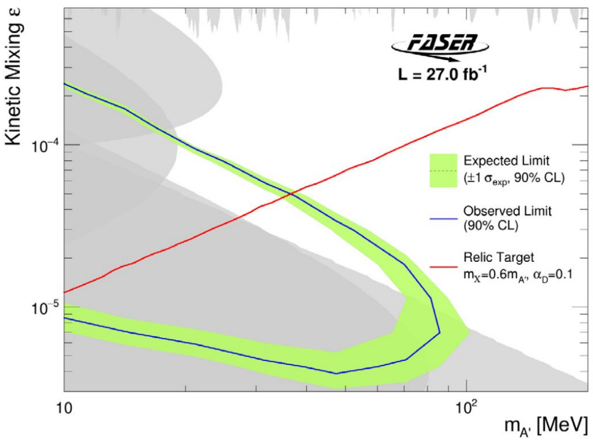
Particle requirements: nHits>=5, |cosθ|<0.94
Track requirements: nHits>=5, matchingProb > 0.5

ACTS for FASER

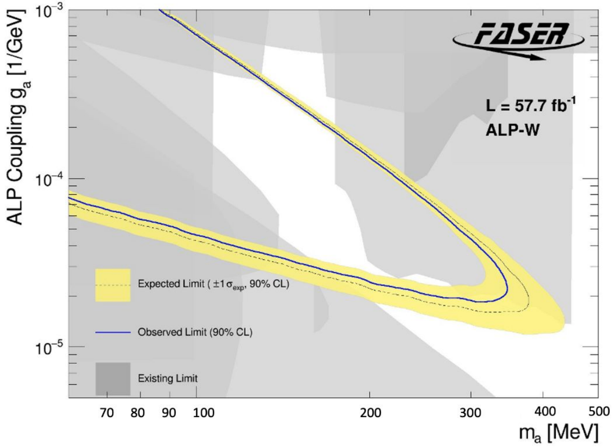
Detecting tracks from ‘invisible’ particles

FASER physics goals

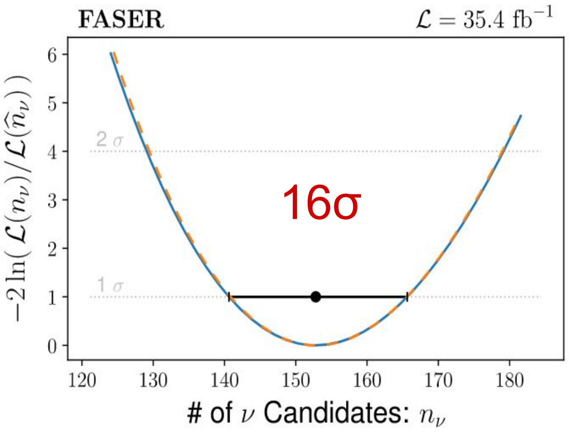
- **LLPs search:** dark photon (mainly from ~TeV forward π^0, $\pi^0 \rightarrow A'\gamma$) , Axion-like particles (ALPs) from e.g. high energy photons colliding with the TA(X)N…
- **Direct collider neutrinos search**: ν_e, ν_μ, ν_τ from hadron decays
  - **Tracking plays a significant role in planned ν_τ search**!



Search for dark photons at FASER, PLB 848 (2024) 138378



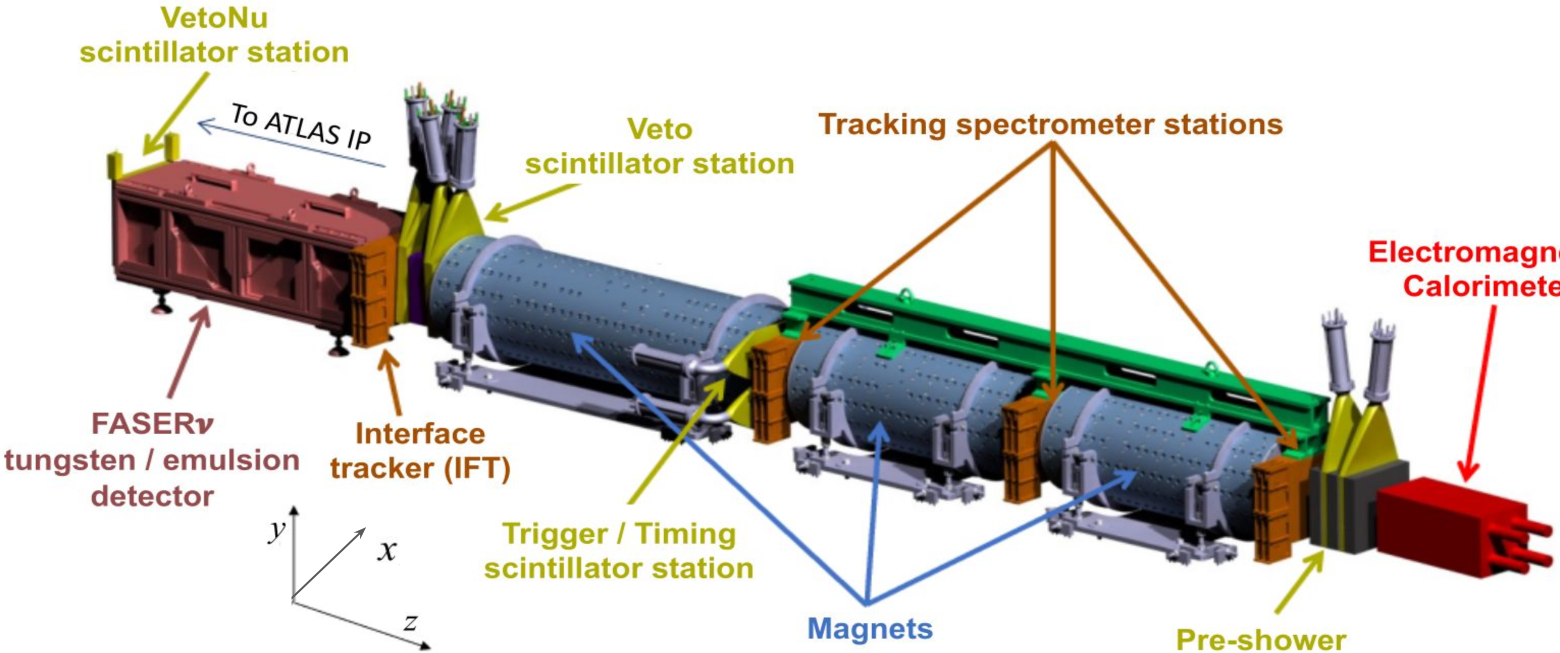
Search for ALP at FASER arXiv: 2410.10363



First direct observation of collider ν_μ neutrino PRL 131, 031801 (2023)

FASER detector

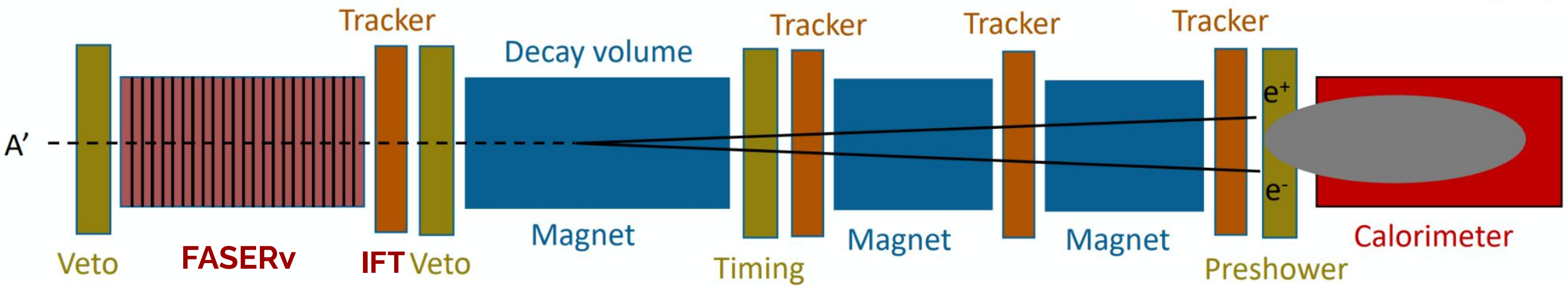
- For detection of charged tracks, photons and neutrinos



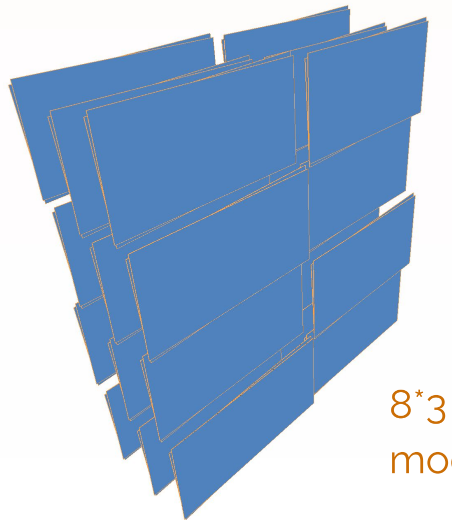
Homogeneous B field of 0.57 T **along x direction** using dipole magnets

FASER tracking system

Sketch from Brian Petersen



- Including 4 tracker stations
- Each tracking station is made of 3 layers of double-sided silicon micro-strip detectors
    - coverage 24cm x 24cm
- Each layer has 8 SCT modules (same as ATLAS SCT modules)
    - 80 μm strip pitch, 40 mrad stereo angle

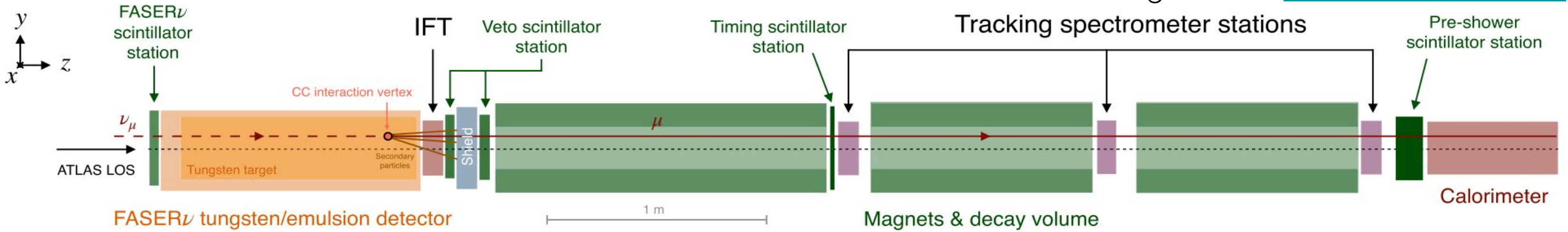


8*3 = 24 modules/station

The charged tracks from invisible particles to detect

- Single high-momentum (e.g. >30 GeV) lepton resulting from neutrino interaction with tungsten (e.g. ν_μ + N $\rightarrow \mu$ + X)
- Two highly collimated (e.g. r<95mm) charged tracks (e.g. >20 GeV) from dark photon (e.g. A' $\rightarrow e^+e^-$)
- Also three tracks in final state (e.g. μ with dark scalar to dimu)

Figure from PRL 131, 031801 (2023)



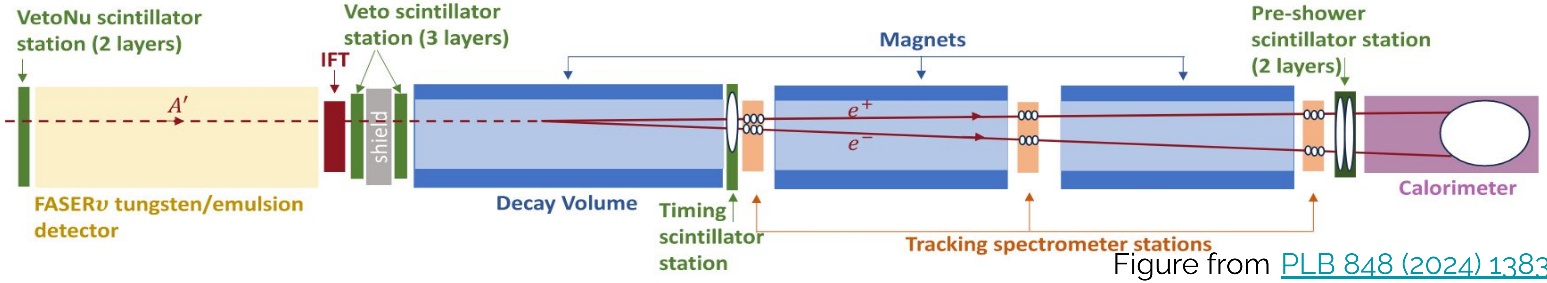
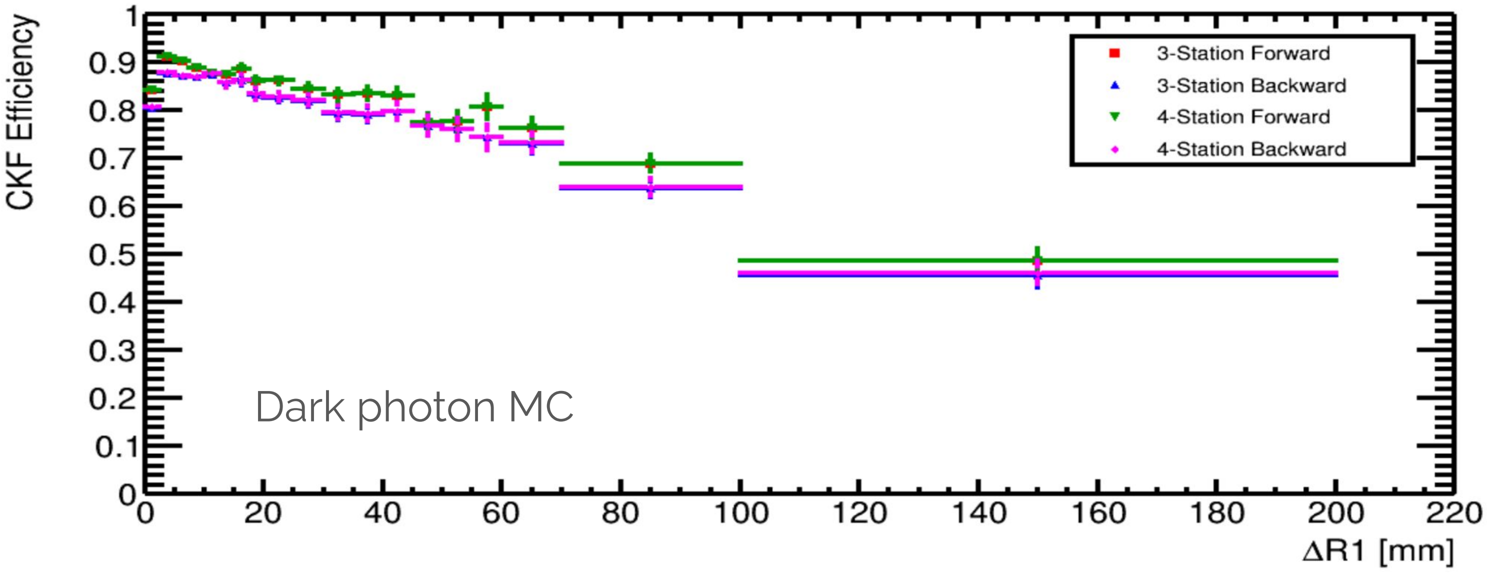


Figure from PLB 848 (2024) 138378

FASER tracking performance

S. Zhang, X. Ai

- Still room for improvement (current placement of detector is not ideal due to the theta =0 singularity issue using ACTS track parameterization)



Summary

Summary

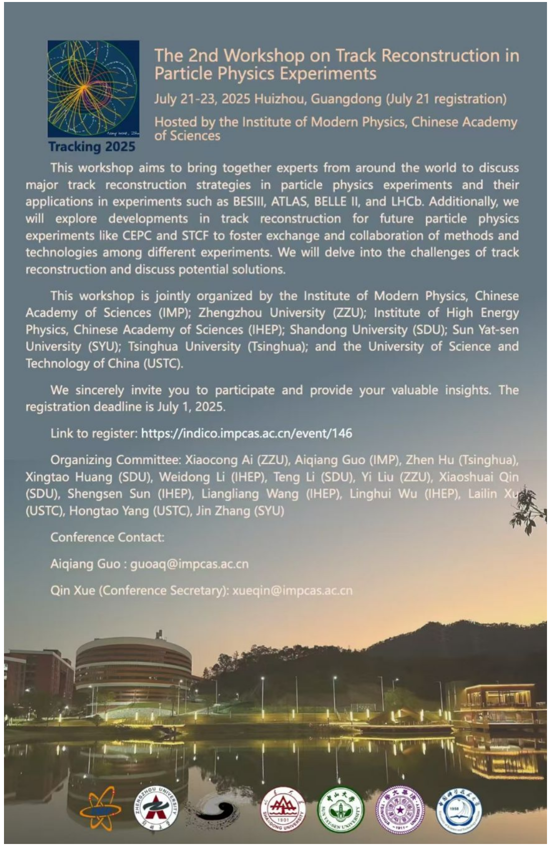
- Tracking is a challenging task and pivotal to HEP event reconstruction
- ACTS is targeting at ATLAS at Run4, but has been growing fast with worldwide clients, including collider/non-collider, HEP and nuclear physics experiment, with both promising physics and CPU performance
    - ATLAS, FASER, CEPC, STCF …
    - Also interest from Belle-II/EIC/FCC-ee
- First implementation of ACTS for drift chambers in the past two years
- Full swing of ACTS optimization for ATLAS Run4
- Developing KF-based alignment for ATLAS Run4 alignment and beyond …

Please get in contact if you are interested in tracking with ACTS!

Future “tracking” events

- **The 2nd Workshop on Track Reconstruction in Particle Physics Experiments**, July 21-23, 2025, Huizhou, https://indico.impcas.ac.cn/event/146

- **Connecting The Dots 2025**, Nov. 10 - 14, 2025, Tokyo, Japan, https://indico.cern.ch/event/1499357/

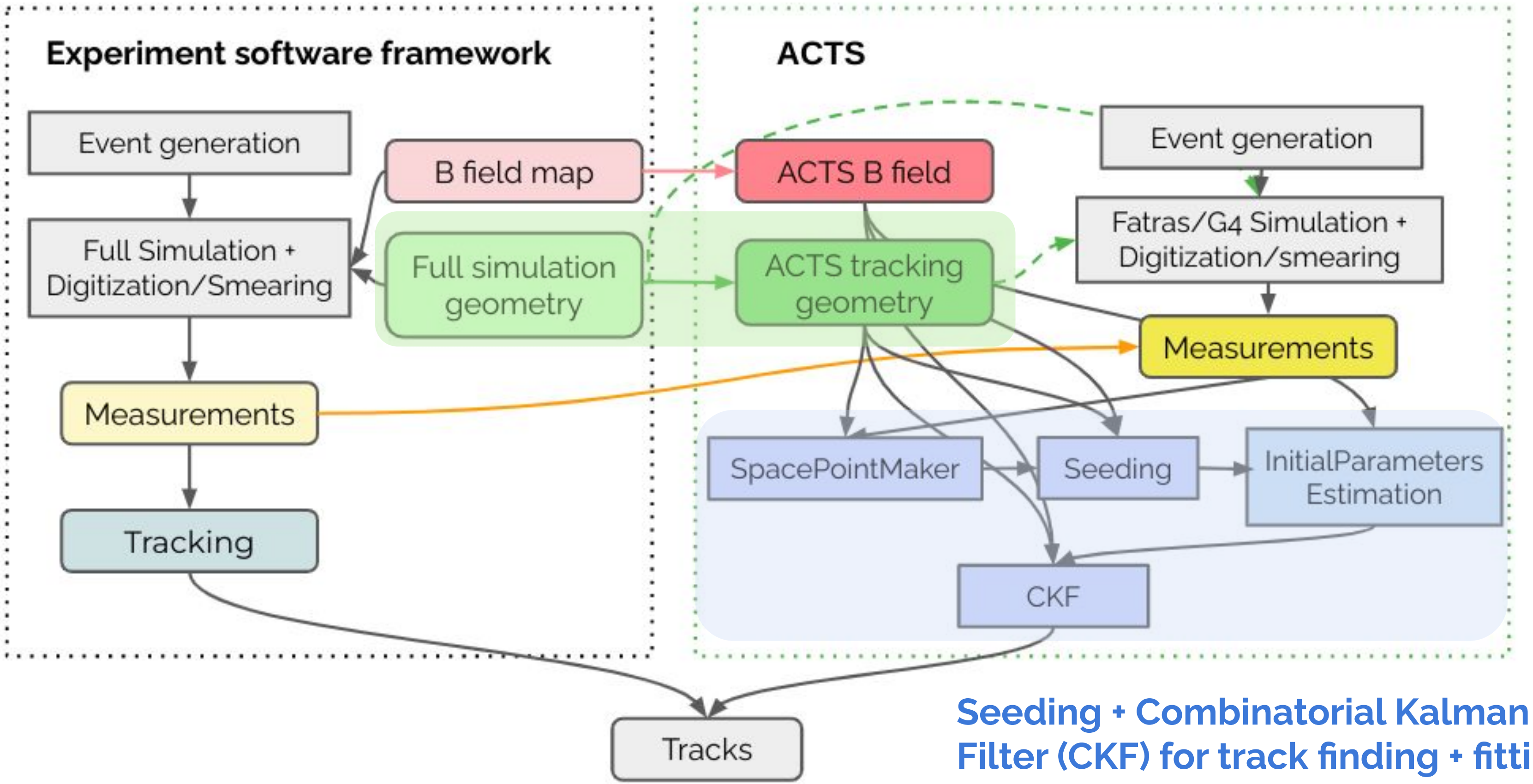


Q&A

Backup

ACTS application strategies

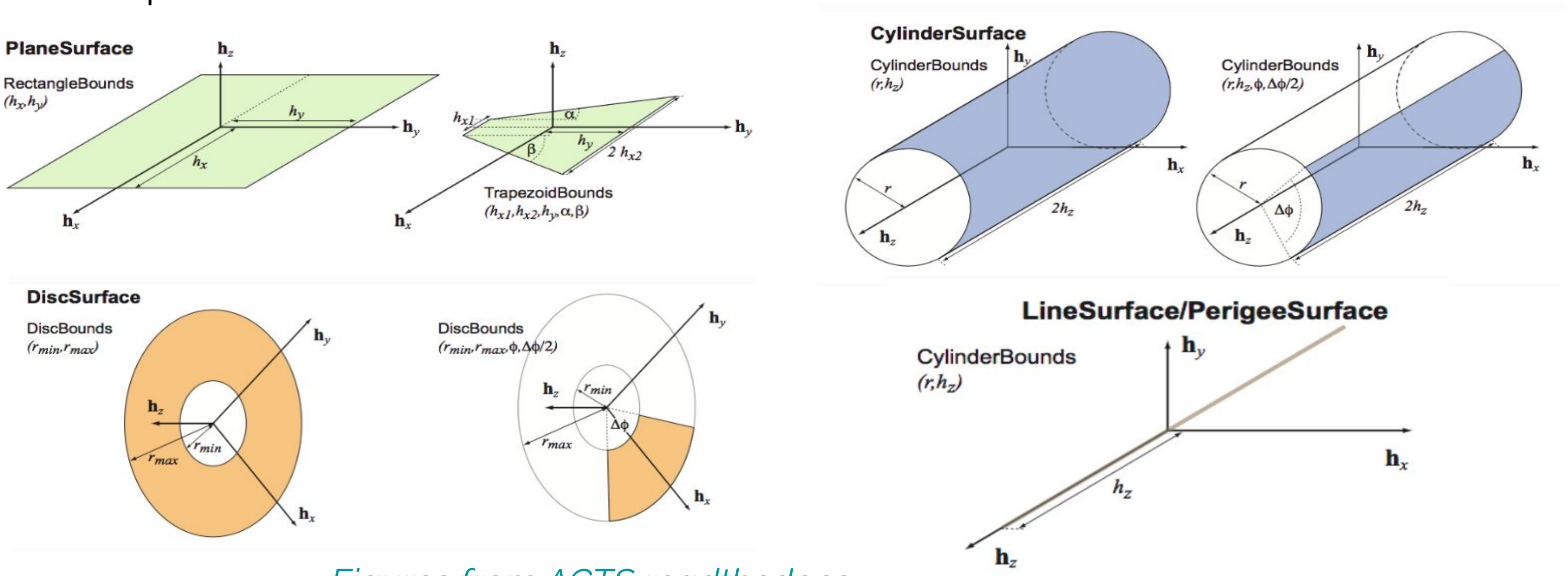
Geometry transformation is the first step



Seeding + Combinatorial Kalman Filter (CKF) for track finding + fitting

ACTS tracking geometry

- ACTS tracking geometry is simplified from full simulation geometry for fast track propagation
- Different concrete surfaces types for various tracking detectors
    - A surface has shape, bounds, rotation+translation, local coordinates and its unique identifier…



Figures from ACTS [readthedocs]

Tracking geometry for drift chamber

- Currently, layer-based geometry model is used, i.e. drift wires are associated to concentric Acts::Layer (suboptimal for navigation. More intelligent model will be tried)

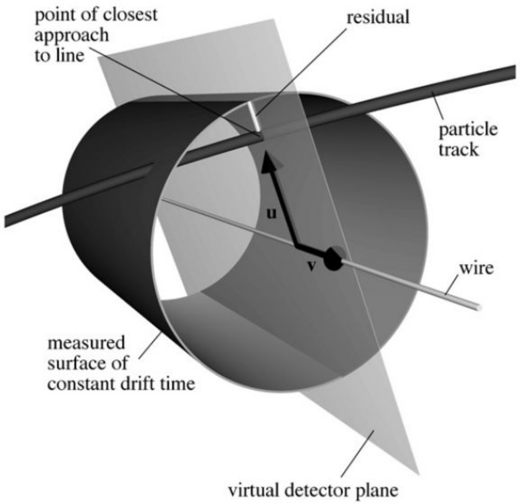
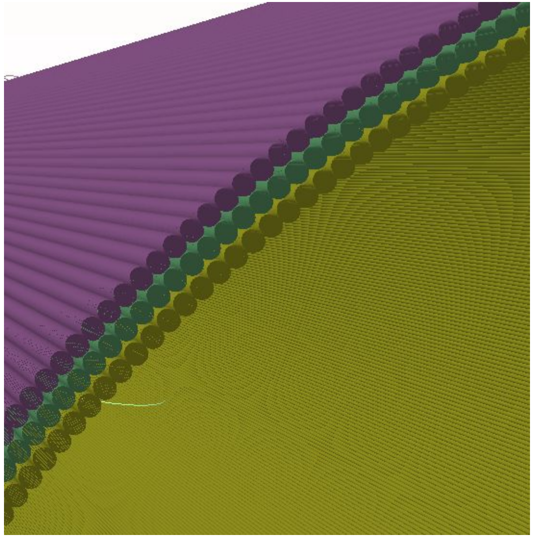


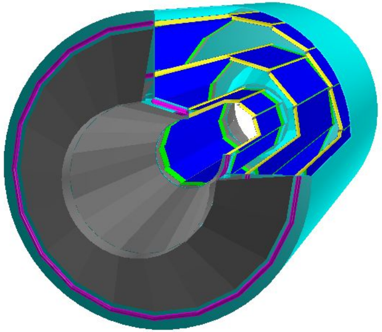
Figure from NIMA 620 (2010) 518



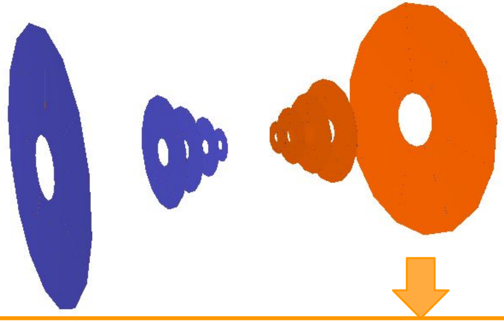
Example of three layers of drift wires

CEPC tracker geometry in ACTS format

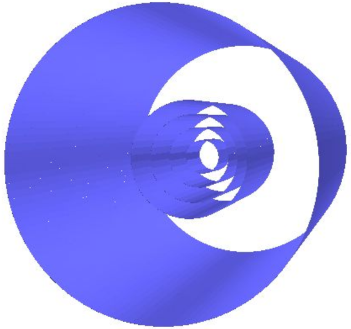
VXD



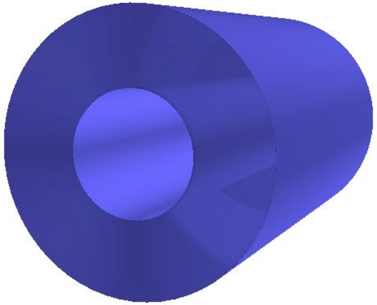
FTD



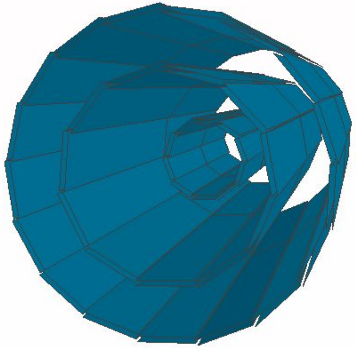
SIT + SET



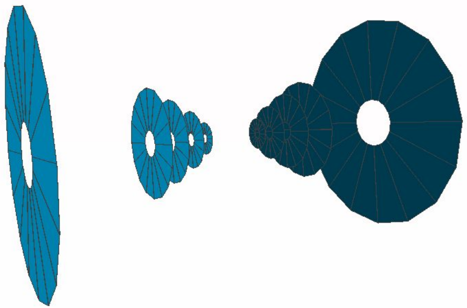
Drift Chamber



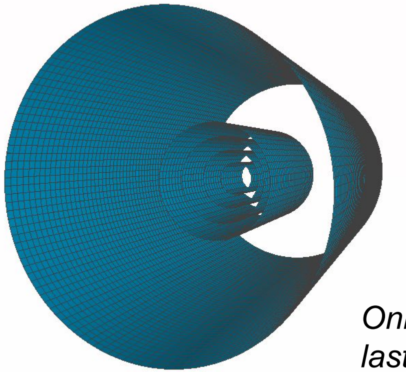
Acts::PlaneSurface



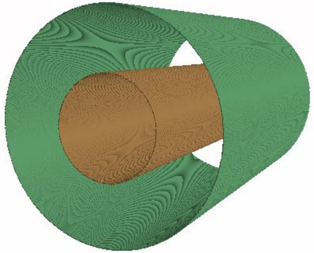
Acts::DiscSurface



Acts::PlaneSurface



Acts::LineSurface

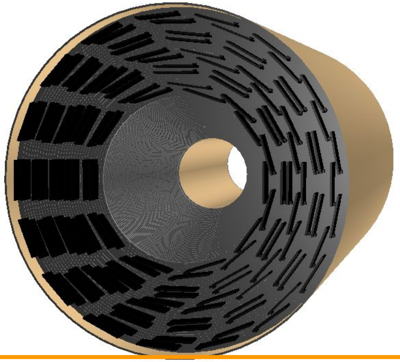


Only showing the first and last layer of line surfaces

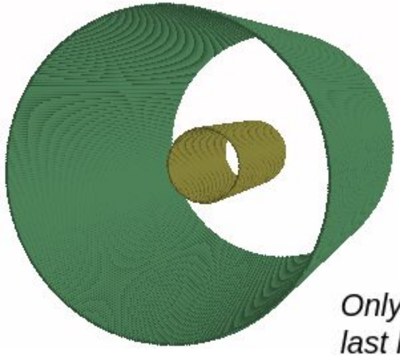
STCF tracker geometry in ACTS format

ITK

MDC



Acts::CylinderSurface



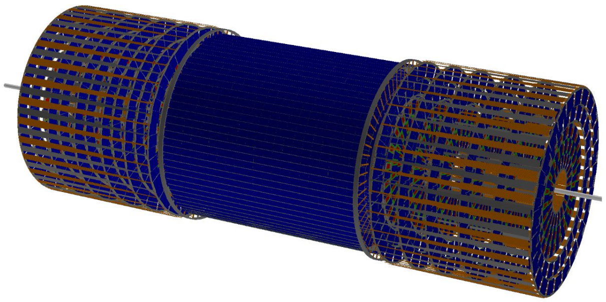
Acts::LineSurface

Only showing the first and last layer of line surfaces

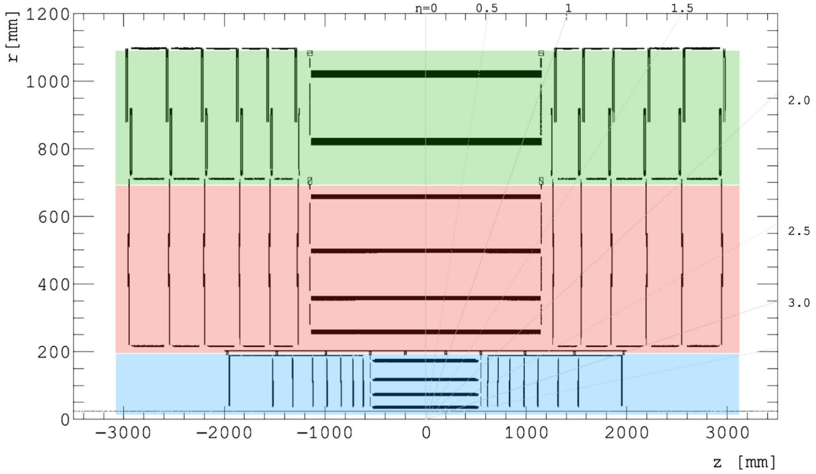
Open Data Detector in ACTS

- Open Data Detector (ODD) in ACTS is a full silicon tracker with realistic material description
- An Open Drift Chamber prototype has been implemented

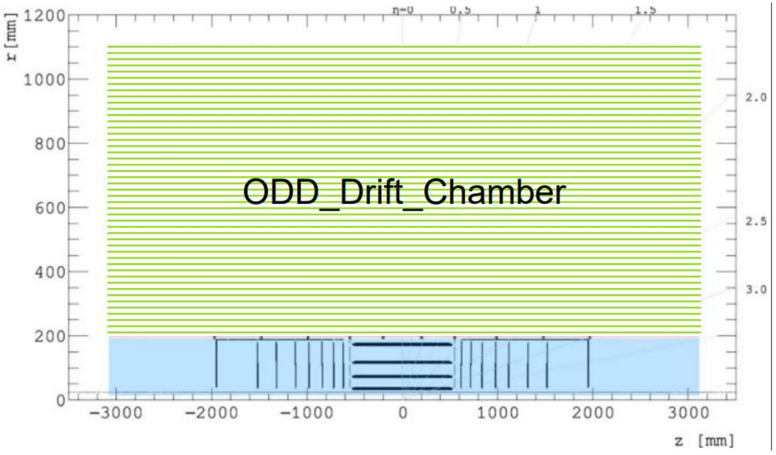
https://gitlab.cern.ch/acts/OpenDataDetector
More details here



ODD: Pixel + Short Strip + Long Strip

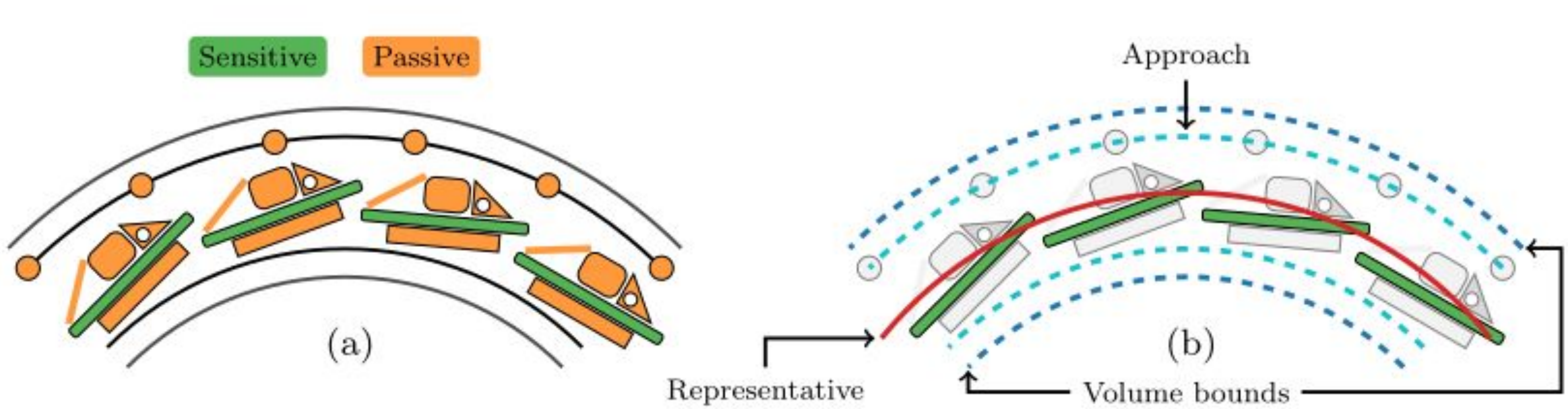


ODD: Pixel + Drift Chamber ?



The ACTS tracking geometry

*Figures from CSBS (2022) **6** 8*

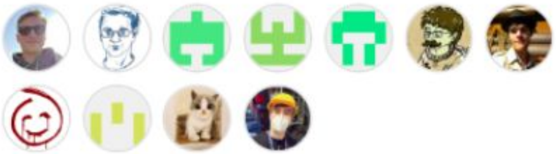


- Tracking geometry is simplified from detailed full simulation geometry for fast navigation, but with material effects well taken into account
- Navigation via hierarchical arrangement of the detector elements:
  - Legacy model: surfaces -> layers -> volumes
  - Layerless model: surfaces -> volumes (with grid indexed search)

ACTS community

- 10~15 active developers on Core project

Contributors 54



+ 43 contributors

supported by

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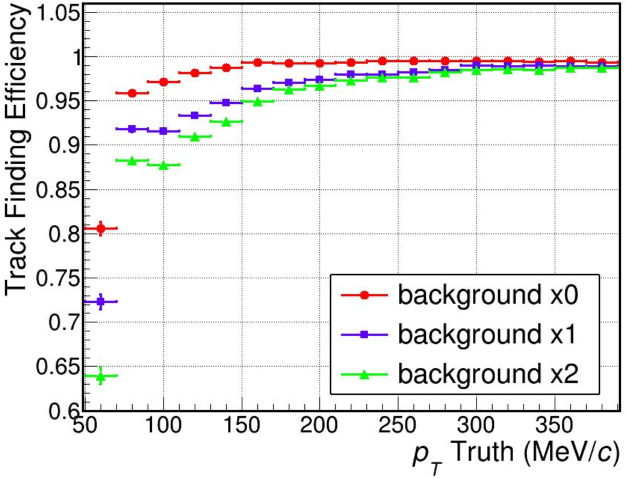
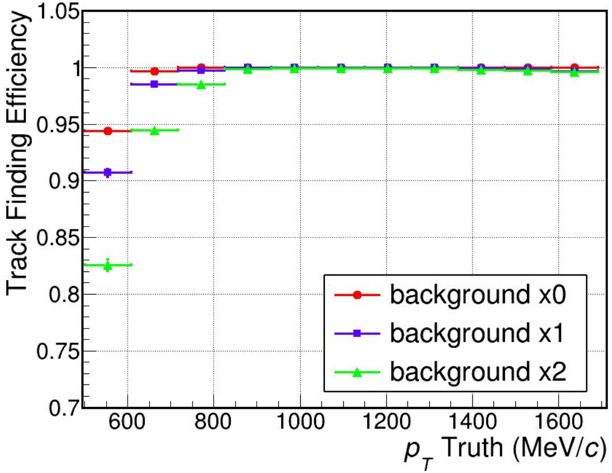
ACTS is one of the four projects in IRIS-HEP **(Institute for Research and Innovation in Software for High Energy Physics)**

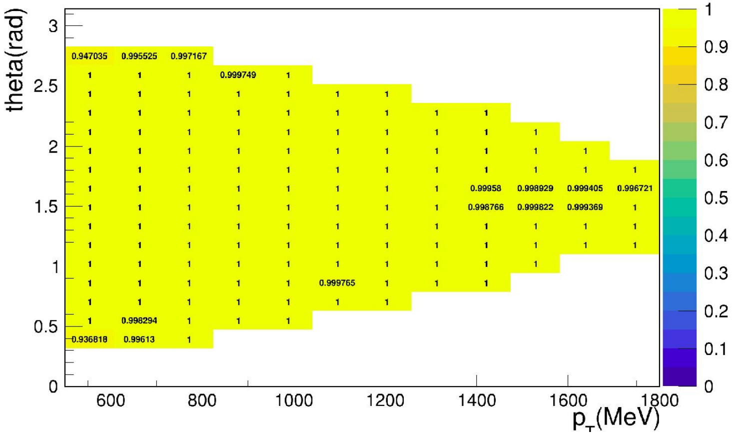
→ $25M, i.e. **~0.17 B CNY**, funded by National Science Foundation

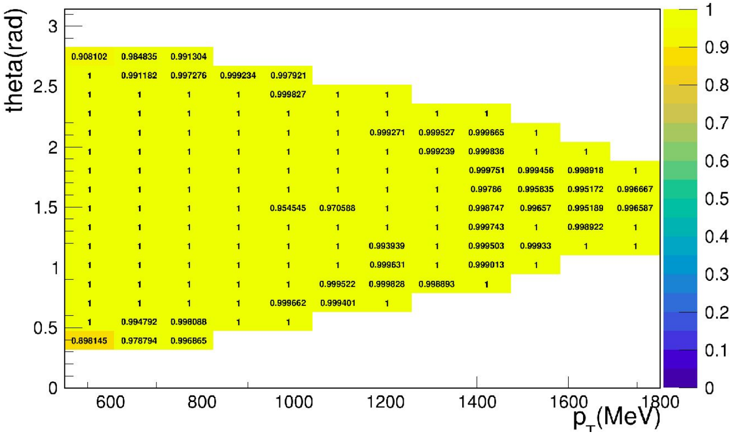
https://iris-hep.org

STCF performance with Hough Transform









CEPC Detector Conceptual Designs

CEPC CDR Baseline Design (Particle Flow Approach)