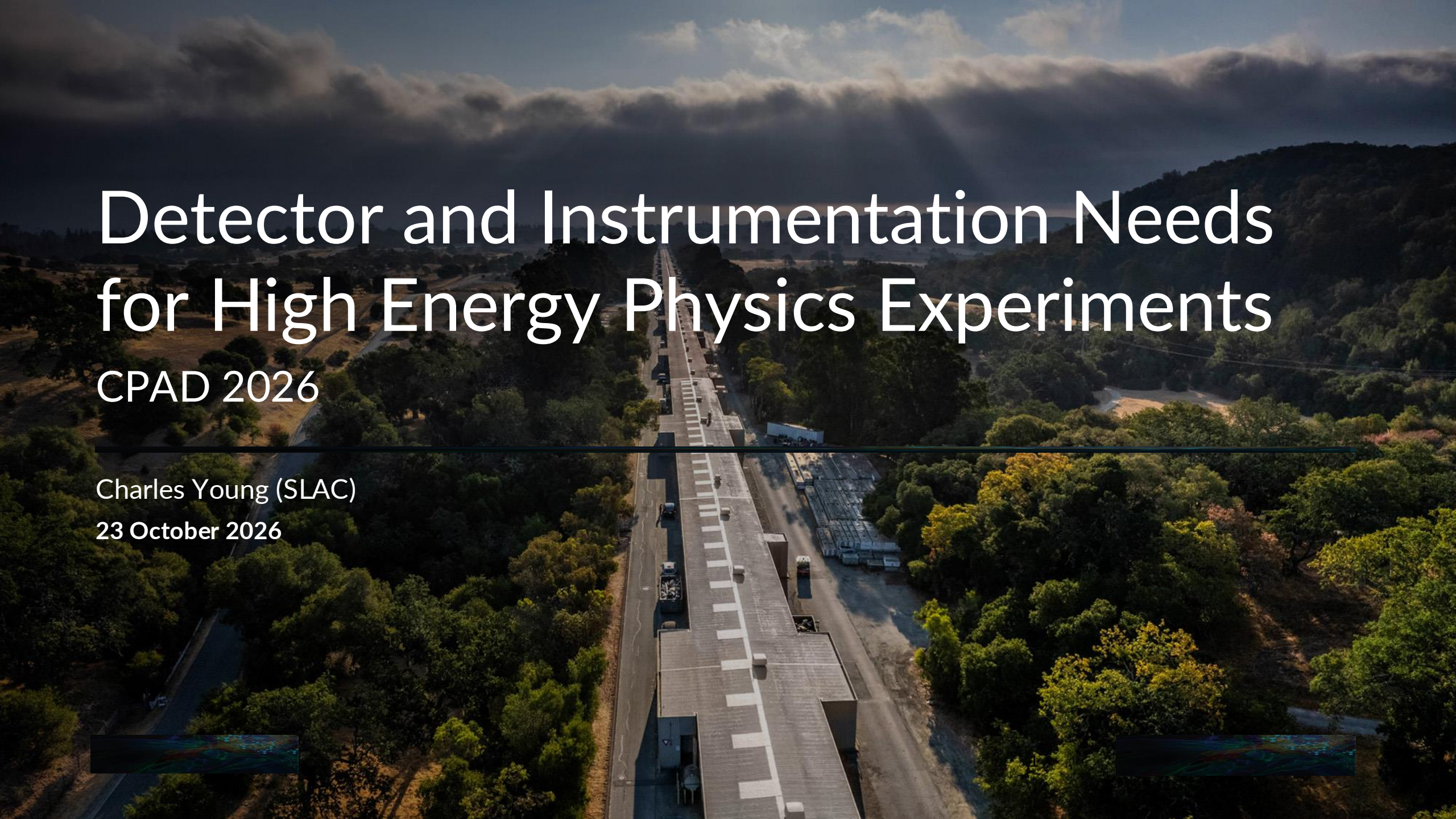


Detector and Instrumentation Needs for High Energy Physics Experiments

CPAD 2026

Charles Young (SLAC)

23 October 2026

Disclaimer

Not a tabulation of instrumentation and detector needs of all upcoming experiments / projects

- Note that programs with names often no longer reliant on “blue sky” R&D
- Pick a few topics to discuss, whether their needs are for generic detector R&D or focused development
- Choice of topics limited and biased by my experience
- Apologies that your area of passion is not represented

Lots of instrumentation overlap between HEP and NP, for example between FCC-*ee* and EIC

- All labeled FCC-*ee* here to stay on this side of the artificial HEP / NP divide



Who Am I and What Are My Biases?

I am an experimental particle physicist who has worked on various fixed target and collider experiments, and once dabbled in a satellite experiment. Some examples:

- Fixed target at Fermilab – “everything” in these small experiments
- DELCO at PEP – drift chamber, front-end electronics, DAQ
- SLD – drift chamber, readout electronics
- Polarized deep inelastic scattering – spectrometer design, Cherenkov detector, lead-glass calorimeter
- *BABAR* – limited streamer tube for muons
- Fermi Space Telescope – silicon tracker in Large Area Telescope
- ATLAS – pixel detector, ITk upgrade, muon spectrometer
- FCC-*ee* – everything(?) in this early stage



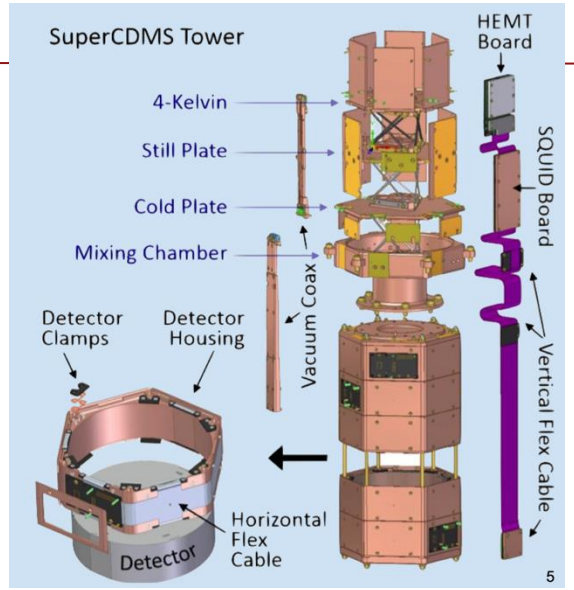
Experimental Conditions and Requirements

Extreme Conditions

Cryogenic Temperature

Dark Matter search and neutrino detectors

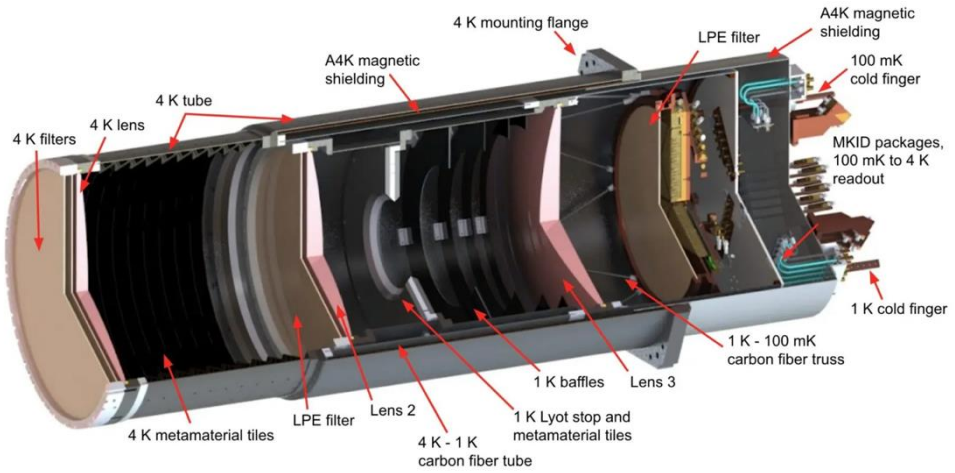
- sCDMS, CRESST etc, and next generation: $10 - 20\ mK$
- ADMX, BREAD, HAYSTACK: $\sim 100\ mK$
- Liquid argon TPC (DarkSide, ARGO, DUNE): $\sim 90\ K$
- Liquid xenon TPC (LZ, XENONnT, PandaX, XLZD) : $\sim 180\ K$



CMB

- SPT-3G, Simons Observatory etc: transition edge sensors (TES) at $\sim 100\ mK$
- CCAT-prime: kinetic inductance detectors (KIDs)

$0\nu\beta\beta$ experiments – nuclear physics!





Extreme Conditions

High Radiation

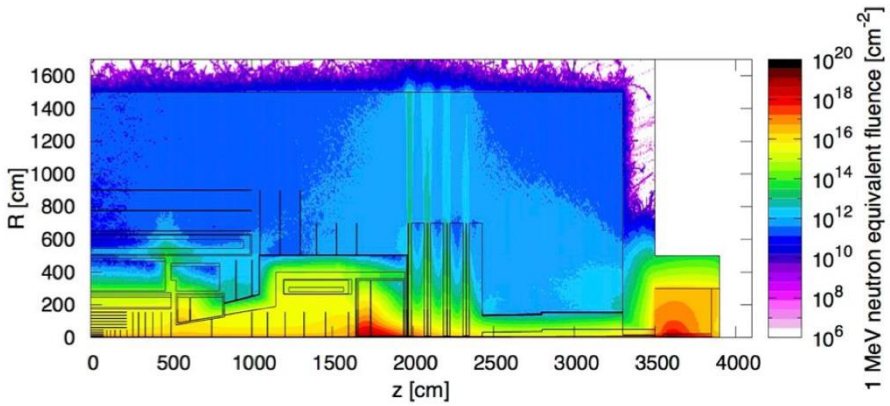
FCC-*hh* [integrated luminosity = $30\ ab^{-1}$]

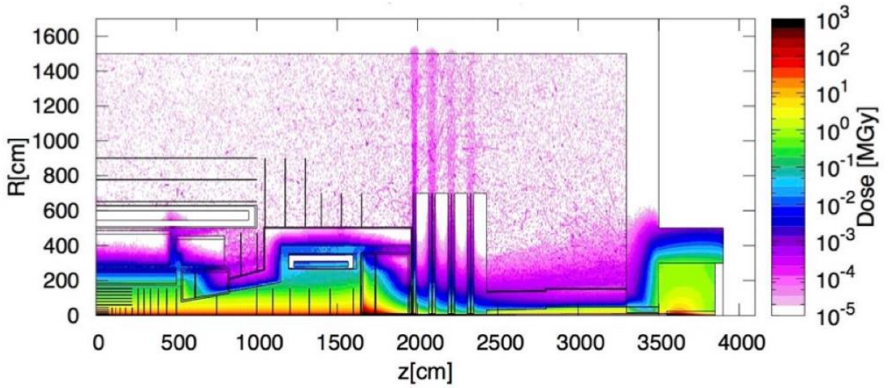
- Fluence in forward calorimeter:
  - $10^{18}/cm^2$ near beam pipe
  - $10^{15-16}/cm^2$ for $r > 40\ cm$
- Dose in tracker: $300\ MGy$ in first layer

Muon Collider [yearly]

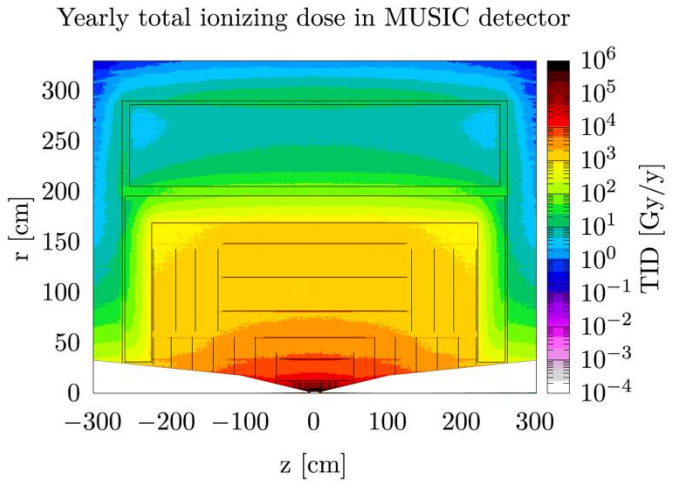
- Fluence $\sim 10^{15}/cm^2$ near shielding nozzle
- Dose $\sim 1\ MGy$ in vertex detector

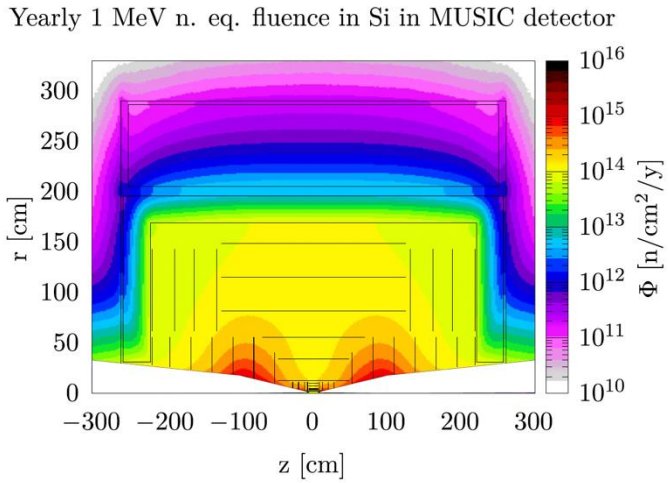
FCC-*hh*





Muon Collider







Extreme Detector Requirements

Low backgrounds – LZ, PandaX, sCDMS, Cuore, LEGEND etc

Spatial precision at FCC-*ee*

- $\sigma_x \approx few\ \mu m$ in vertex detector
- $\sigma_x \approx 10\ -100\ \mu m$ in main tracker (silicon or gaseous)

Timing precision

- $\sigma_t \approx 1\ nsec$ for beam crossing identification
- $\sigma_t \approx 25\ psec$ for pileup mitigation at FCC-*hh*

Energy resolution at FCC-*ee*

- $\sigma_E/E \sim 3\%/\sqrt{E}$ for ECAL
- $\sigma_E/E \sim 30\%/\sqrt{E}$ for jets

Momentum resolution at FCC-*ee*

- $\sigma(p_T)/p_T \sim 10^{-3} \oplus 2\ 10^{-5} \times p_T$

K/π identification up to ~ 30 GeV/c at FCC-*ee*



Examples of Detector Challenges

DUNE Time Projection Chamber Challenges

TPC high voltage

- 200 – 300 KV
- Discharge can lead to permanent electrode damage, carbon tracking and/or long-term contamination

Detectors in cryogenics

- Access for maintenance and repair is virtually impossible
- Reliability engineering is critical for decades of operations

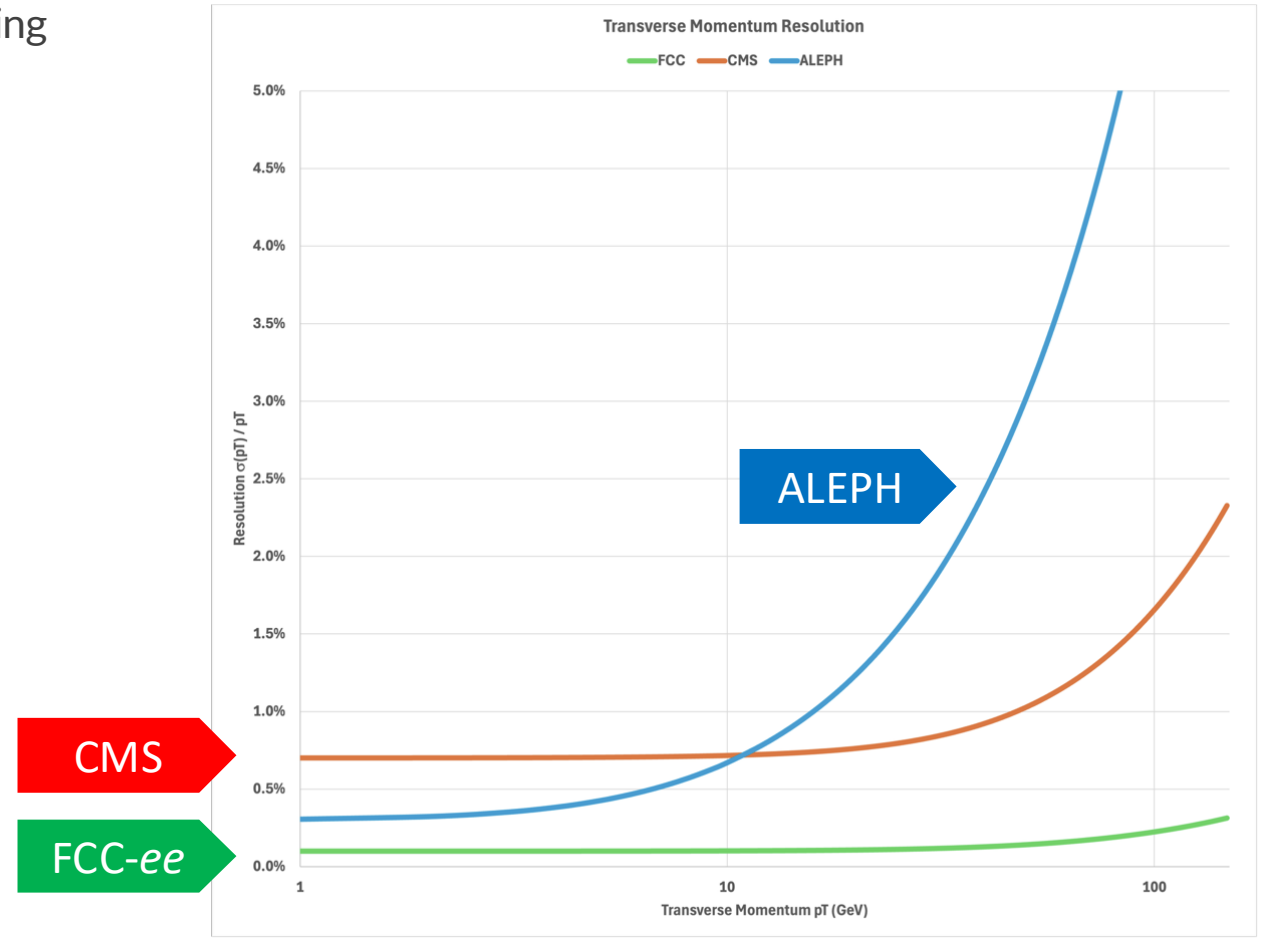


Charged Particle Tracker in FCC-*ee*

Momentum resolution goal: $\sigma\,(p_T)/p_T \approx 10^{-3} \oplus 2\,10^{-5}\,p_T$

More stringent than achieved in ALEPH or CMS

Dominated by multiple scattering





Charged Particle Tracker in FCC-*ee*

Multiple scattering contribution: $\sigma\,(p_T)/p_T \approx 0.054\,\sqrt{t}\,/\,(B \times L)$ (for uniform material distribution)

- t = material thickness in X_0
- B = magnetic field in *Tesla*
- L = path length in *meter* ~ tracker radius

Assuming 2-*T* field and 2-*m* path length, $\sigma(p_T)/p_T = 10^{-3}$ implies that $t \leq 0.55$ %.

Material	X_0	Thickness for 0.55% X_0
Silicon	9.37 cm	0.52 mm
Helium Isobutane 90/10	1.4 km	7.9 m
Carbon fiber reinforced composite	24 – 30 cm	1.3 – 1.7 mm
Copper	1.44 cm	0.08 mm
Air	300 m	1.67 m



Charged Particle Tracker in FCC-*ee*

Silicon Tracker (assuming $B = 2$ *Tesla* and $L = 2$ *m*)

10 layers x 100 μm silicon ~ 1% X_0 > 0.55% X_0

2 *m* air ~ 0.66% X_0 > 0.55% X_0

Support and services not accounted for yet and likely to exceed sensor

⇒ All non-critical features / functionalities need to be reduced or eliminated

⇒ Their additional power, cooling and services represent "digging a deeper hole"

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Silicon	9.37 cm	0.52 mm
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Support and services not accounted for yet and li

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⇒ Their additional p

There is interest in ultra thin sensors, which can be (partially) self-supporting in the vertex detector. But they must be supported in the main tracker.

However, there seems to be little effort in the development of low-mass supports to match.

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Hadronic Calorimeter in FCC-*ee*

Hadronic calorimeters have traditionally been sampling calorimeters, e.g.

- Scintillator steel sandwich
- Dual-readout fiber calorimeter

Energy resolution is limited by their low sampling fractions of few %.

Heavy scintillating glass has the potential to increase sampling fraction dramatically, and may even allow a homogeneous HCAL design. Unprecedented energy resolution possible given sufficient light yield.

- Proposed in the AGORA detector concept
- Many challenges remain to turn this research material into a viable hadron calorimeter.



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- Many challenges remain to turn this research material into a viable hadron calorimeter.

This is an opportunity for Detector R&D.



Single Particle Test Beam ≠ Physics Experiment Instrumentation

Detector R&D progression – rational approach that should be followed

- Table-top characterization to evaluate sensor fundamentals in controlled environment
- Single-particle test beam to validate performance with beam particles

Real-life physics experimental condition not reproduced

- Multi-particle performance, e.g. in a jet
- Experiment dependent => not a good match to Detector R&D



1) Hadron Calorimeter

Performance often discussed in terms of energy resolution in single-particle test beam, but

- Real-life experiments do not rely on hadronic calorimeter by itself
- Physics metric is based on jet performance rather than single-particle performance

Developments in particle-flow algorithm have demonstrated excellent jet performance with modest HCAL resolution

- Only neutral hadrons depend on HCAL performance
- Limited by “confusion term” – what is and is not neutral hadron energy deposit
- Performance expected to degrade for very highly collimated jets, for example in FCC-*hh*
- Algorithm must be tuned to attain performance



1) Hadron Calorimeter

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Developments in particle-flow algori dest HCAL resolution

- Only neutral h
- Limited by "c
- Performance e FCC-*hh*
- Algorithm must

Assessment of detector performance should be based on physics metric, and not just single-particle test beam results.

Co-development of hardware and software allows us to make meaningful comparisons.



2) Drift Chamber Cell Size and Geometry

Dimitris Ntounis

Likelihood of multiple tracks in one cell – not studied in single-particle test beam

Studied in simulation of 2-jet events:

$$e^+e^- \to ZH$$

$$Z \to \nu\nu$$

$$H \to b\bar{b}$$

Propagate tracks through detector magnetic field (using Delphes deck for IDEA detector).

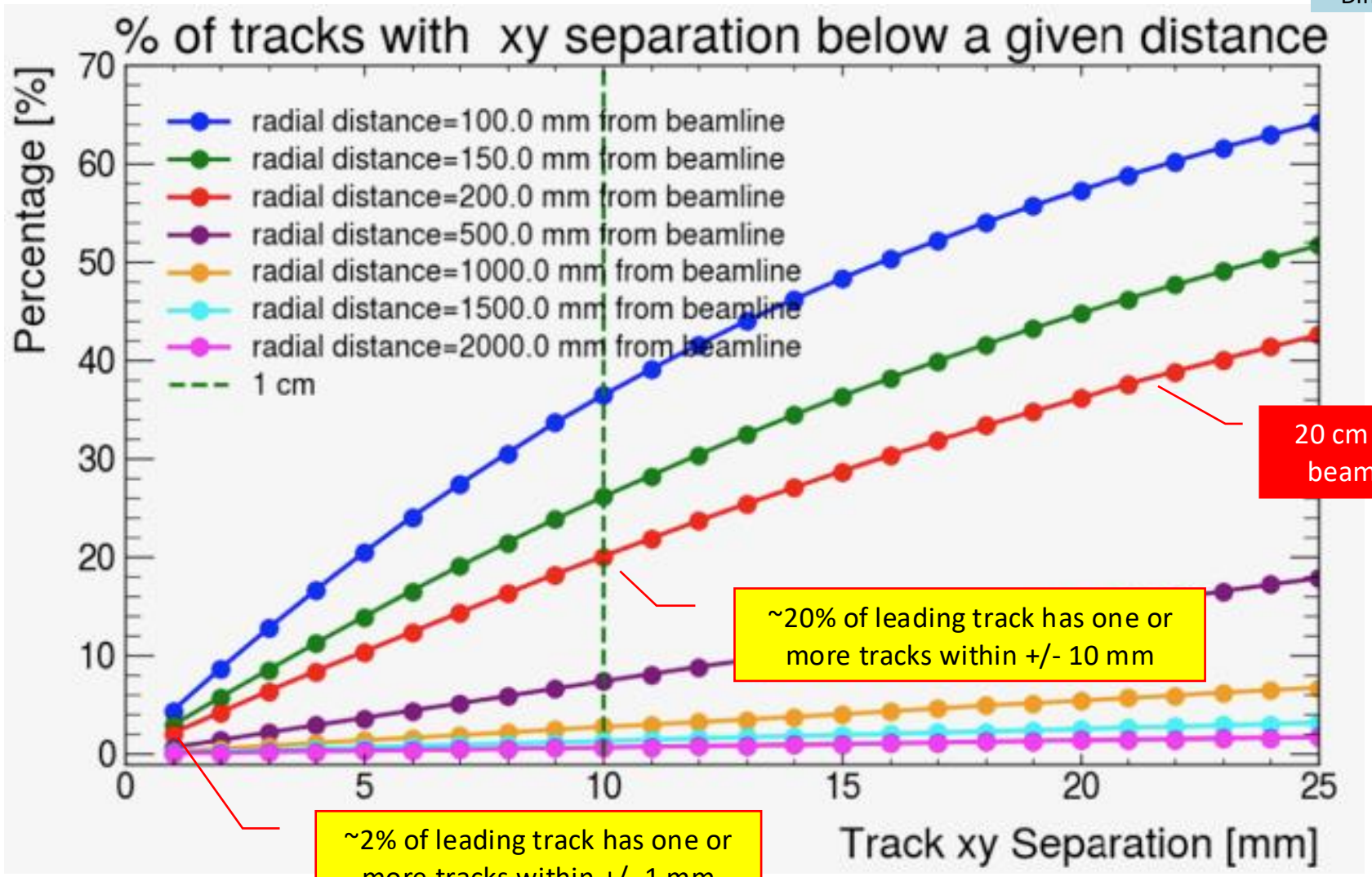
Take highest momentum track in a jet.

Count other tracks within window in x-y plane and within +/- 2 m in z (assumed length of drift chamber).



Drift Cell Multi-Hit Probability

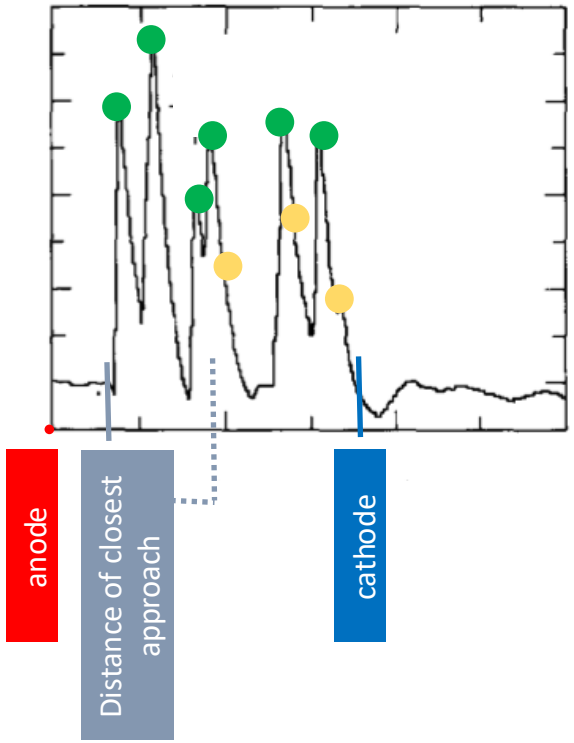
Dimitris Ntounis

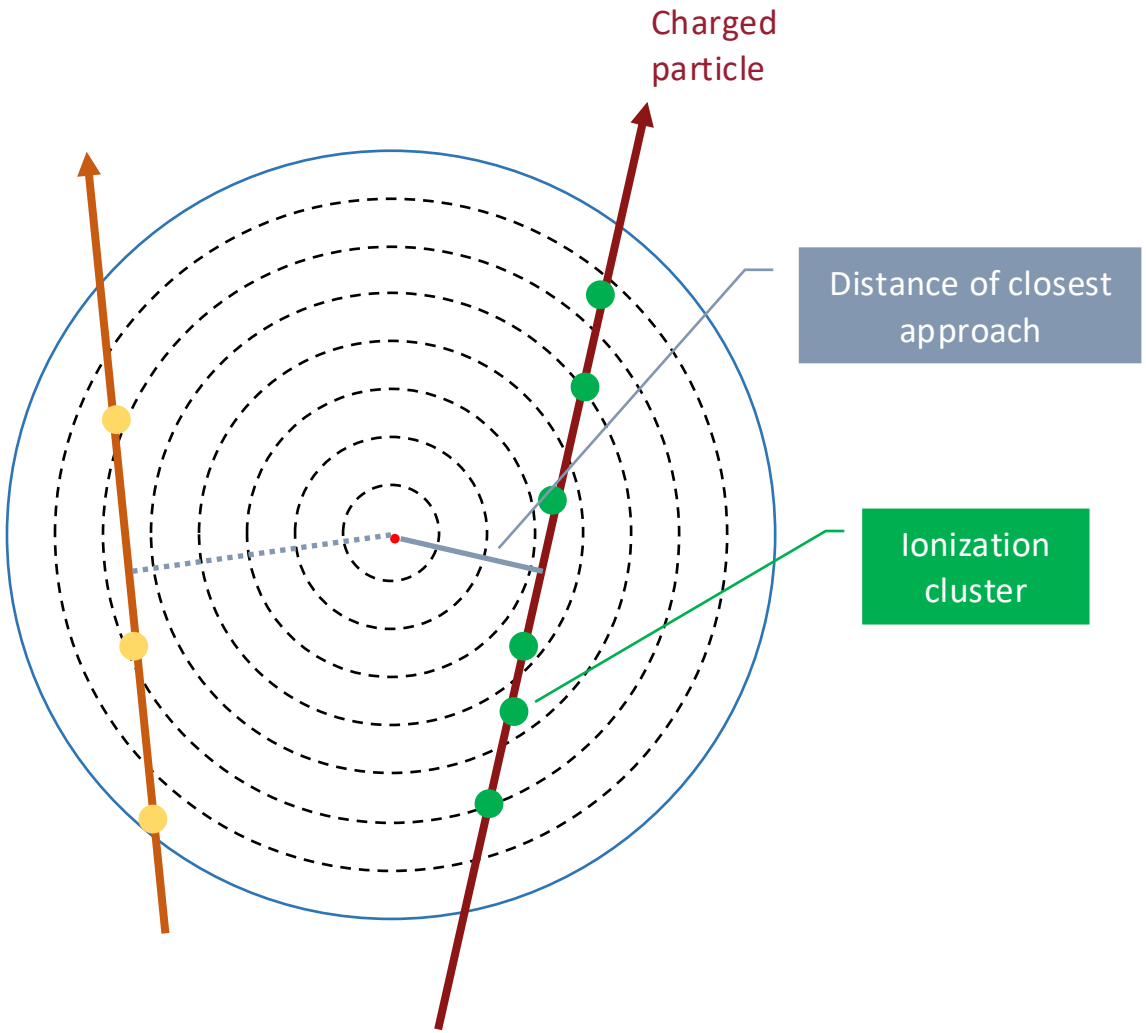




Drift Cell Geometry – Radial (to sense wire) Drift

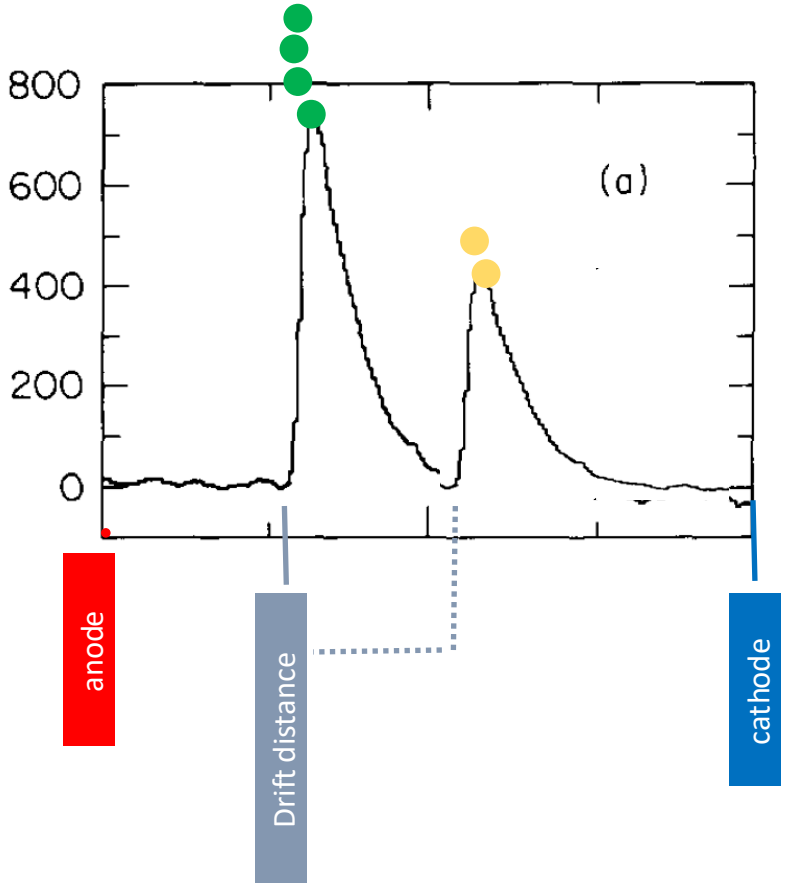
Confusion with multiple tracks

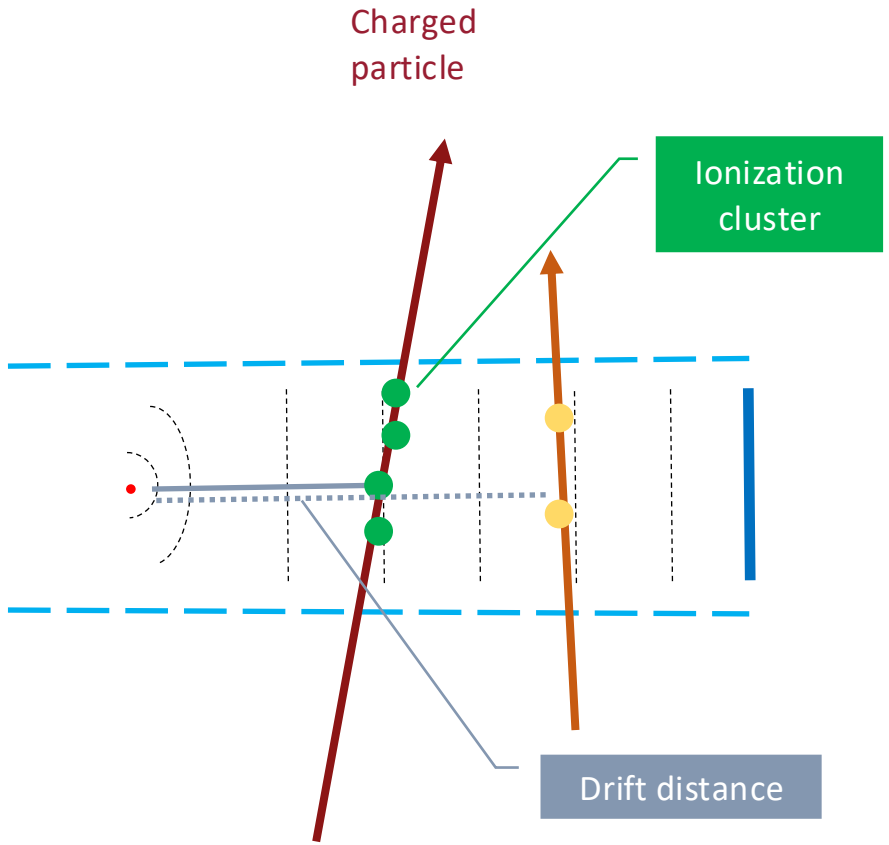






Drift Cell Geometry – Azimuthal (global coord) Drift







Radial vs Azimuthal Drift Geometry

Radial drift

- For one single track in a drift cell,
  - Distance of closest approach given by signal arrival time
  - Particle ID by cluster counting superior to dE/dx because ionizations are spread out in time and more readily counted
- In the case of multiple tracks in one drift cell,
  - No distance information for second and any subsequent tracks
  - Particle ID by cluster counting is compromised – which cluster belongs to which track?

Azimuthal drift

- Superior tracking performance in multi-track environment
- Cluster counting not possible and must rely on less performant dE/dx for particle identification



Radial vs Azimuthal Drift Geometry

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What are the reasons to prioritize single-particle ID over multi-particle tracking performance?

Azimuthal drift

- Superior tracking performance in multi-track environment
- Cluster counting not possible and must rely on less performant dE/dx for particle identification



Radial vs Azimuthal Drift Geometry

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Azimuthal drift

- Superior tracking performa[illegible]
- Cluster countin[illegible]less performant dE/dx for particle identification

What are the reasons to prioritize single-particle ID over multi-particle tracking performance?

And why is there so little R&D on Time Projection Chamber when it is an option?



Examples of Systematics at FCC-*ee*

FCC-*ee* Run Plan – Massive Statistics for *Z* and *WW*

Parameter	Unit	Z	WW	ZH	$t\bar{t}$
$\sqrt{s}$	GeV	91	~160	240	350-365
Luminosity (per IP)	$10^{34}\ cm^{-2}\ s^{-2}$	143	20	7.5	1.38
Bunch spacing	$nsec$	25	160	680	5000
Cross section	pb	35 x 10^3	10	0.2	0.5
Total cross section	pb	70 x 10^3	30	10	8
Total event Rate	Hz	100K	6	0.75	0.1
Run duration	Years	4	2	3	5
Integrated luminosity	ab^{-1}	~200	~10	~10	~3
# events		6 x 10^{12}	10^8	2 x 10^6	2 x 10^6

Collecting 6 x 10^{12} *Z* bosons and 10^8 *W*-pairs means statistical uncertainties are vanishingly small, shifting experimental design burden onto systematics.



FCC-*ee* Systematic Requirements from FSR

Observable	present value ± uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600 ± 2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500 ± 2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	231,480 ± 160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952 ± 14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times 10^3$)	20 767 ± 25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196 ± 30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2 ± 32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2 996.3 ± 7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216 290 ± 660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge



Fiducial Acceptance

Differential cross section:

$$\frac{d\sigma}{d(cos\theta)} \propto 1 + cos^2\theta + \frac{8}{3} A\, cos\theta \approx 1 + cos^2\theta + 0.275\, cos\theta$$

$$\delta cos\theta = \frac{\delta A_{FB}}{A_{FB}} \cdot \frac{cos\theta_{max}(3 + cos^2\theta_{max})}{3 - cos^2\theta_{max}}$$

Target Precision: Achieving $\frac{\delta A_{FB}}{A_{FB}} \leq 4\,10^{-5}$ dictates strict bounds on forward/backward tracking acceptance.

Acceptance: For nominal tracker geometry ($r = 2\,m, l = 4\,m$), acceptance edges must be known and stable to

Δz and $\Delta r \sim 20\ \mu m$

Operational Requirement: This precision must be continuously mapped across the azimuthal angle ϕ and dynamically monitored over years of data-taking.



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Acceptance: For nomina $= 4\ m$), acceptance edges must be known and stable to

What needs to be incorporated into detector design to facilitate this?

Δz and $\Delta r \sim 20\ \mu m$

Operational Requirement: This precision must be continuously mapped across the azimuthal angle ϕ and dynamically monitored over years of data-taking.



Residual Beam Longitudinal Polarization

The Asymmetry Perturbation: Asymmetry is sensitive to (stray) effective longitudinal beam polarization P_{beam}

$$A_{FB}^{b} \approx \frac{3}{4}\left(\frac{A_e - P_{beam}}{1 - A_e P_{beam}}\right) A_b$$

where A_e and A_b are the parity violating asymmetry parameters describing the vertex. For a given fermion f, the parameter A_f is defined by the vector and axial-vector neutral current couplings to the Z boson: $A_f = \frac{2 g_V^f g_A^f}{\left(g_V^f\right)^2 + \left(g_A^f\right)^2}$

Systematics Trap: While longitudinal polarization is not intentionally induced, spin rotations of natural transverse polarization can generate parasitic longitudinal polarization.

Requirement: Extracting clean physics results requires bounding P_{beam} continuously via precision polarimetry.



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$$A_{FB}^{b} \approx \frac{3}{4}\left(\frac{A_e - P_{beam}}{1}\right.$$

where A_e and A_b are the parity vi… fermion f, the parameter A_f is define… on: $A_f = \frac{2g_V^f g_A^f}{\left(g_V^f\right)^2 + \left(g_A^f\right)^2}$

Systematics Trap: While … …itionally induced, spin rotations of natural transverse polarization can generate … polarization.

What is the polarimeter design? Is it compatible with other detector subsystems?

What other instrumentation needs might we have overlooked?

Requirement: Extracting clean physics results requires bounding P_{beam} continuously via precision polarimetry.



Summary

Nearer term projects (such as DUNE and FCC-*ee*)

- Few fundamental detector challenges at individual subsystem level
  - However, current solutions may not be optimal or mutually compatible across subsystems
  - One potential game-changer seems to have little interest in the community
- Challenges for a complete detector design that is physics performant
  - Reliability engineering is a major consideration
  - Integrated design with all subsystems working together
  - Built-in control of systematics uncertainties
  - Cost! "The worst detector is the one that is too expensive to get built."

Longer term projects (such as FCC-*hh* and Muon Collider)

- Additional difficulties from intense radiation and particle density





Extras



Extreme Requirements

Particle Identification - π/K separation

Time of flight

- $\Delta t \approx \frac{L}{2c}\left(\frac{m_K^2 - m_\pi^2}{p^2}\right)$ feasible for low momentum $< 2 - 3\ GeV/c$

Specific ionization

- Blind spot around 1 – 2 GeV/c where π and K responses cross
- Cluster-counting (aka dN/dx) superior to dE/dx, potentially applicable for FCC-*ee* range of interest

Cherenkov radiation

- $\Delta\theta_C \approx \frac{m_K^2 - m_\pi^2}{2p^2\theta_C}$ where $\cos\theta_C = 1/(n\beta)$
- Provides separation up to $\sim 50\ GeV/c$ with multiple radiators
- Light yield and angular resolution challenges



Extreme Requirements

Material Impact on ECAL

Calorimeter energy resolution often parameterized as $\sigma(E)/E \sim a/\sqrt{E}$

This intrinsic resolution is degraded by material in front of calorimeter.

Empirical rule-of-thumb:

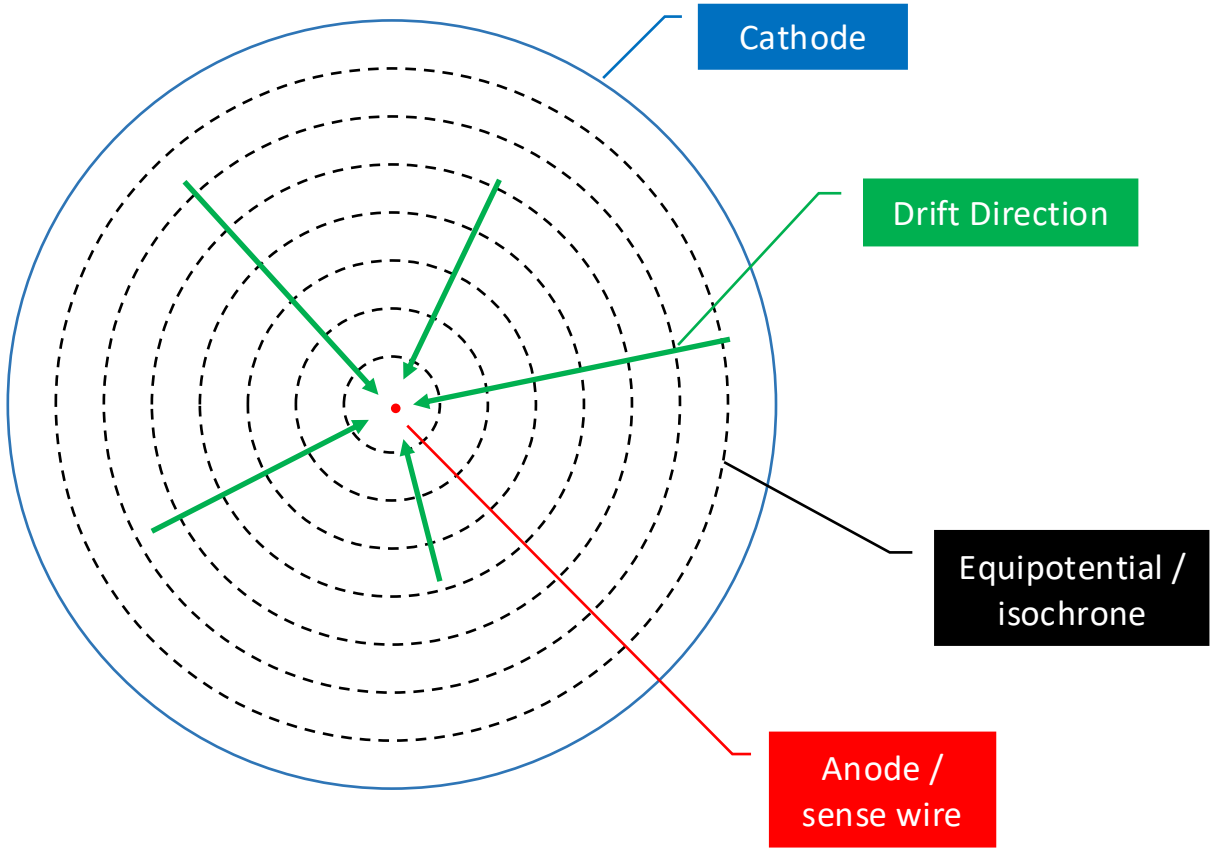
$$a \rightarrow a' = a \oplus (0.05 \ -0.08) \times \sqrt{t}$$

where t is material thickness in units of radiation length

a	a' (t=0.25)	a' (t=0.5)
3%	3.4%	4.4%
9%	9.1%	9.6%
15%	15.1%	15.3%



Drift Cell Geometry – Radial (to sense wire) Drift





Drift Cell Geometry – Radial (to sense wire) Drift

Examples

AMY and VENUS Central Drift Chamber

BABAR Central Drift Chamber

BES III Main Drift Chamber

CLEO Central Drift Chamber

High Resolution Spectrometer at PEP

BABAR: NIM A 419 (1998) 310 - 314

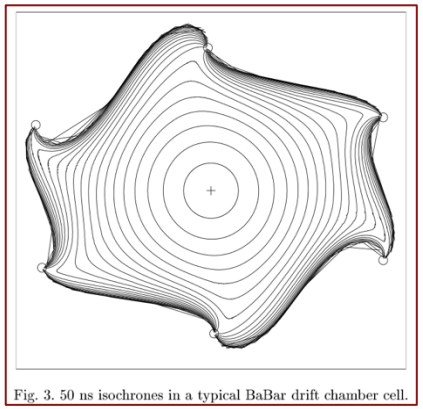


Fig. 3. 50 ns isochrones in a typical BaBar drift chamber cell.

AMY: NIM A 323 (1992) 601 – 610

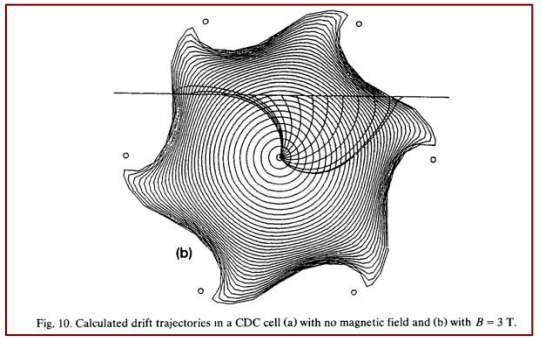


Fig. 10. Calculated drift trajectories in a CDC cell (a) with no magnetic field and (b) with $B = 3$ T.

HRS: NIM 203 (1982) 119 - 127

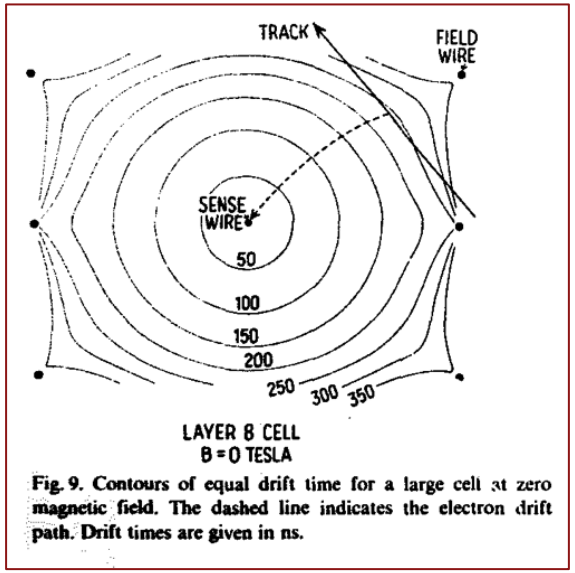
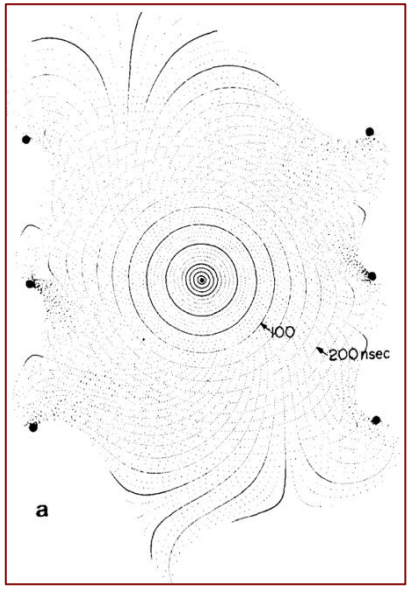


Fig. 9. Contours of equal drift time for a large cell at zero magnetic field. The dashed line indicates the electron drift path. Drift times are given in ns.

VENUS: NIM 217 (1983) 181 - 187





Drift Cell Geometry – Azimuthal (global coord) Drift

Examples

OPAL at LEP

SLD at SLAC

OPAL: NIM A 323 (1992) 169 - 177

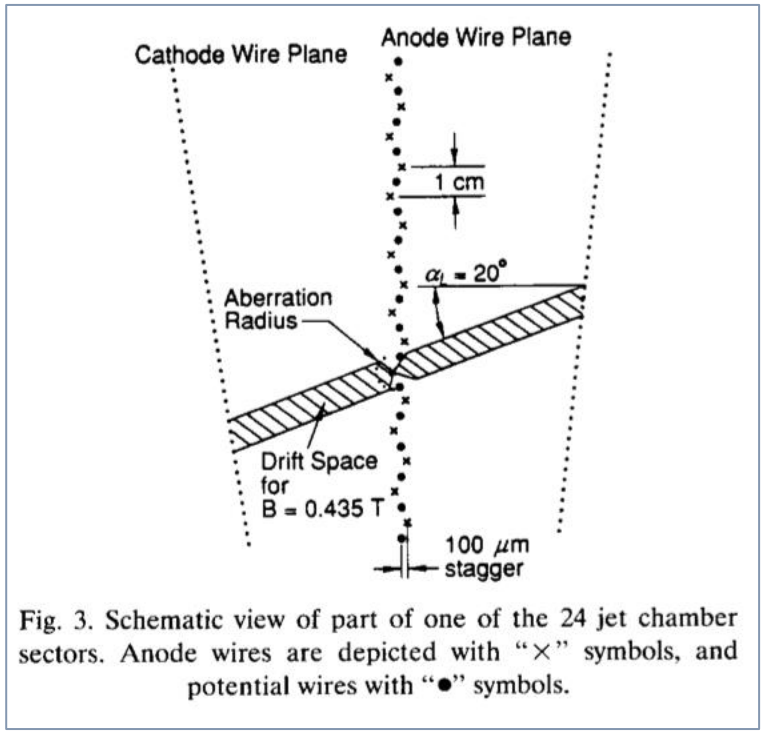


Fig. 3. Schematic view of part of one of the 24 jet chamber sectors. Anode wires are depicted with "×" symbols, and potential wires with "•" symbols.

SLD: IEEE Trans. Nuclear Science 33 (1986)

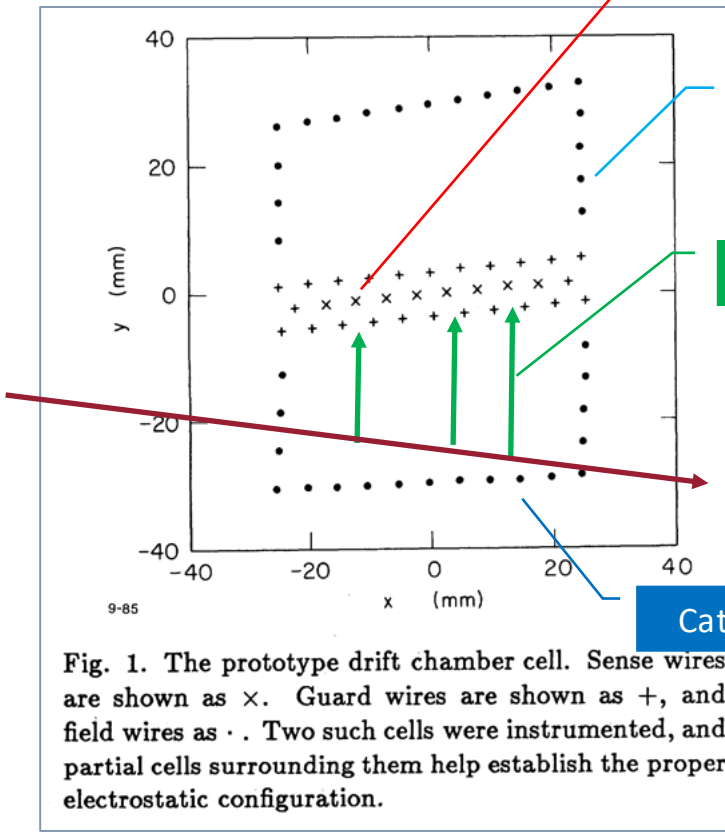


Fig. 1. The prototype drift chamber cell. Sense wires are shown as ×. Guard wires are shown as +, and field wires as · . Two such cells were instrumented, and partial cells surrounding them help establish the proper electrostatic configuration.





