Technologies for Tracking and Timing Detectors for the FCC_{ee}

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Local discussion group:
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Disclaimer and Focus

- Already there are extensive design studies for concrete detector concepts (CLD, IDEA, Allegro) to meet basic FCCee specifications
  - Many published reports, CDR's, and see the recent Annecy workshop, for example, and the excellent talks of Monday, here.
- In parallel the RD, now DRD (and RDC) structures are addressing specific sensor, electronic, and other technologies, and the ECFA R&D Roadmap, the Snowmass reports, and the DOE BRN Study for Future Instrumentation.
- In 15 minutes I cannot review all the technologies under development, particularly in the area of MAPS and LGAD's
  - See also the excellent summary slides shown in the synergy session by C. Vernieri
- Focus instead on specific technical challenges to realize tracking and timing
- Rather than specifications (already widely addressed) I will also consider the requirements of low systematic errors, particularly for the Tera-Z phase of FCCee, in areas best addressed by detector builders.

Basic Specs from the ECFA R&D Roadmap for FCCee

	Vertex	Tracker	Timing Layer
position um	3	6	
X/Xo layer	0.05	1	
Power mW/cm^2	20	100	
Rates	0.05		
Wafer size	12	12	
Timing ns	25	0.1	0.01
Rad Neil 10^16			
Rad TID Grad			

There is already, considerable technology, both in R&D, and for specific near term experiments, which can approach or meet these specifications.

Key Technologies

- Tracking with MAPS (see for example: M.Winter, FCCee MDI meeting 11 March 2024 (CERN), DRD3 meetings etc, ALICE ITS3 project)
- System implementation of MAPS devices – pioneered by the RHI collaborations, see the ALICE ITS3 TDR, now posted https://cds.cern.ch/record/2890181?ln=en
- Low mass support structures (see for example: Corado Gargiulo 2024 7th FCC Workshop (Annecy))
- Fast Timing – mainly for PID
    - Current CMS and ATLAS timing layer upgrades
    - DRD3 and RDC7
    - PICOSEC project (gas), this session
    - Much development in AC LGADs, resistive LGADs, and other variants, which promise both pixel-like segmentation and fast timing – work of UCSC/SCIPP, BNL, FNAL, Torino groups – we have requested specific talks for the June FCC week in San Francisco
    - High granularity/Power density/Fast readout issue
    - Wide band gap LGADs – could be faster than silicon, high temperature operation, reduced cooling mass, growing internation efforts in this area, also to be presented at the June FCC week in SF

CMOS Pixel Sensors for Tracking Devices at Future Higgs-Top-EW Factories: Where Do We Stand? What Can We Anticipate? Which Relevance for FCCee?

Marc Winter, IJCLab-Orsay

FCCee MDI meeting 11 March 2024 CERN

https://indico.cern.ch/event/1389303/

- What are the perspectives anticipated by the evolution of CMOS (imaging) technologies ?
- Is there a chance that they will provide all prominent ambitioned performances in a single sensor ? < 3 µm, O(100) ns, O(10^2) MHz/cm^2, > 10 MRad, 0(0.1)% X_0/layer
- If not, which trade-offs/compromises could be envisaged ? relaxed time stamping, relaxed spatial resolution, alternative concepts or technologies, etc.
- Discussion on single point resolution: pixel dimension, EPI thickness/alternatives, drift vs diffusion, in-pixel µcircuitry, CMOS process, …
- Discussion on material budget: sensor thickness, power consumption & I(leak), stitching, layer thermo-mechanics, detector geometry, …
- Discussion on the perspectives offered by the ALICE-ITS3 concept: TDR close to printing - added value, limits, drawbacks of large curved sensors based on stitching - added value, limits, drawbacks of deep-submicron CMOS imaging technologies (e.g. 65 nm vs 180 nm)

Support Structures for Si Detectors

Corado Gargiulo

2024 7th FCC Workshop (Annecy)

https://indico.cern.ch/event/1307378/contributions/5727847/attachments/2790021/4866185/20240130-Gargiulo_c2.pdf

- Past experience and examples
- Materials calculations
- Materials
- Fabrication/Assembly/Bonding
- Thermal-Mechanical Performance
- Electrical services
- Cooling

Relevant contributions to this session

Fabrizio Palla
Design, performance and future prospects for a vertex detector for FCC

Artur Apresyan
Development of precision tracking and quantum detectors at Fermilab

Gian Michele Innocenti
MIT PixElPhi: A Pixel Lab for Elementary Physics at MIT

Sebastian White
Towards robust PICOSEC Micromegas precise timing detectors

Lessons from Past, Present and Near(er) Term

- LHC program
- LHC HI, RHIC, and EIC programs
- Ancient history
- Precision EWK from LEP, and B factories

Lessons: HL-LHC Upgrades

- Tension between integrating electronics/mechanical/thermal functions into large pre-loaded structures (staves etc, being optimized for low mass) and maintaining precision and accuracy
  - More material can imply greater stability- both mechanical/thermal and electrical
  - Sometimes adding material can benefit stress relief
- Build and operate at the same temperature
- Avoid CTE mismatch
- Real DC power is better than switching: both high and low frequency

Lessons Learned, and to be learned from the Relativistic HI program and the EIC

- The HI programs at RHIC and the LHC (ALICE) have done the key pioneering work on MAPS based trackers and extremely low mass
  - Heavy Flavor Tracker at STAR: thinned MAPS on air cooled CF supports
  - ALICE ITS3: thinned MAPS bent around the beam pipe
- According to the EFCA R&D Roadmap the tracking and timing specifications for next generation lepton colliders, and the EIC are identical
  - While the physics interests of these communities are quite different is there some way to work together to mutual benefit?

Wither systematic errors at Tera-Z?

- With 10^{12} Z's produced at Tera-Z, statistical errors will be so small that measurements can become systematics dominated
- Ignore here the major systematics from energy and luminosity. These will be addressed by other "specialists"
- Orthodoxy – systematic errors also improve by sqrt(N)? So no problem???
- Actually, the need to reduce systematic errors may create new technical challenges to detector builders
- We will need to understand alignment, positioning, stability, tagging, efficiencies and acceptances with unprecedented accuracy
- These may be more challenging than meeting the regular physics performance specs like X_o, P_t resolution, ip_res, timing, etc.
- What does this mean in practice? Does it lead to new types of specifications and/or detector features, systems?

Mark J Experiment at DESY ~1979

The MARK I collaboration, “Physics with high energy electron-positron colliding beams” Physics Reports (63) 1980

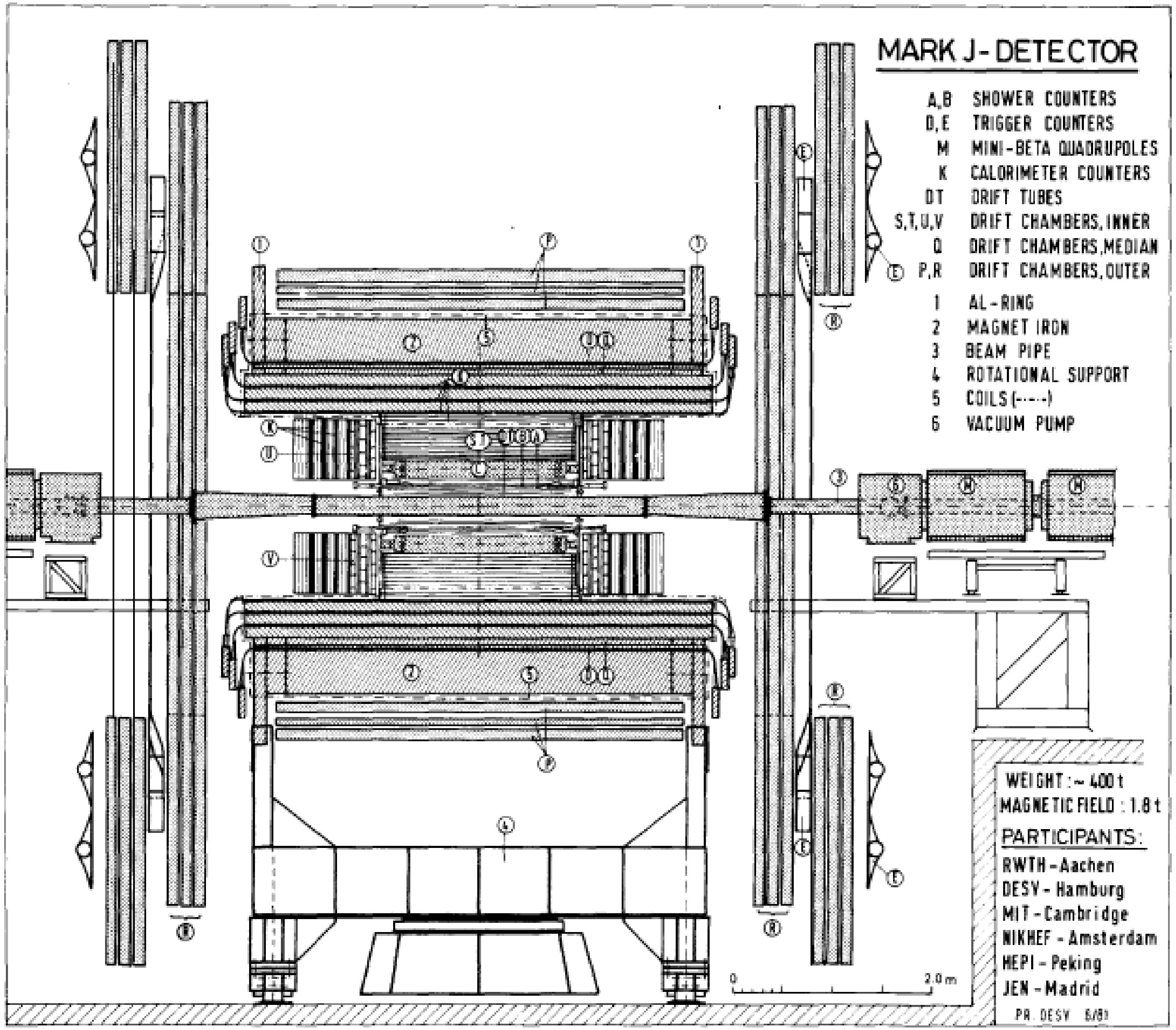
“One of the prime goals of the MARK J experimental program (see section 3.1) is to measure the charge asymmetry in the angular distribution of muon pairs produced in e+e - annihilation to an accuracy of --1%.

This goal can only be achieved if small systematic effects due to variations in chamber efficiency and counter gains, and slight asymmetries in the construction of the magnet and the positions of particle detectors in space, do not influence the overall charge asymmetry measurement.

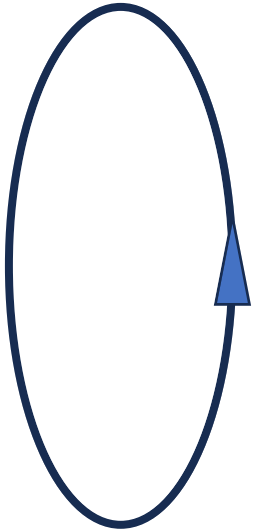
In order to isolate and subsequently eliminate the effects of these systematic errors in the measurement, the supporting structure is designed so that the entire detector can be rotated azimuthally about the beam line by ±90^{o} and 180 ° about a vertical axis. *

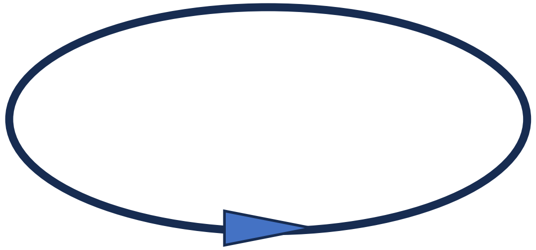
The rotation about the vertical axis maps 0^{o} into 180^{o}, and is therefore most useful in checking the measurement of the front-back charge asymmetry. The azimuthal rotation, which is used to check for beam polarization, can also be used to aid in the charge asymmetry measurement in the presence of polarized beams.”

*****Not clear they actually used this capability as I could not find a mention of it in a later review article on physics results: The Mark J collaboration, “A summary of experimental results from MARK J”, Physics Reports (109) 1984



Example of a detector design with built in control of systematics





The Z lineshape challenge: ppm and keV measurements

Juan Alcaraz Maestre, Alain Blondel, Mogens Dam, and Patrick Janot

https://arxiv.org/abs/2107.00616

Focusing on experimental aspects, a typical limiting factor for cross-section measurements is the systematic uncertainty on the acceptance determination. **A 10^{-5} uncertainty, even in processes presenting a relatively smooth behavior of the angular distributions, implies a knowledge of the positions of the edges of sub-detectors at the 10 µm level over distances of the order of a meter.** A first consequence is that detectors should be as homogeneous as possible. Such a precision is a realistic target given current tracking accuracy, but it demands **dedicated efforts in terms of metrology, alignment, monitoring and designs able to ensure the stability of large detector volumes as a function of time**. The challenge is even bigger for detectors located at very low polar angles and measuring differential cross sections with a $d\sigma/d\theta$ / 1/ sin θ behavior. For instance, **a luminosity monitor located at 1m of the interaction point with an inner radius of 65mm demands a 1 µm (1 µrad) precision in positioning**, in order to reach 10^{-4} uncertainties [1]. Other requirements imposed by acceptance systematics are the uniformity in the detector response, **redundant particle identification capabilities**, beam stability and a detailed monitoring of the beam geometry conditions at the interaction point.

Table 3. Measurement of selected precision measurements at FCC-ee, compared with present precision. The systematic uncertainties are initial estimates, aim is to improve down to statistical errors. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in specific new physics (non-decoupling) models.

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff} (\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2) (\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu (\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation

= where systematics are not dominated by beam energy or luminosity

Blondel and Janot
arXiv:2106:13885v2 Dec 2021

Observable	Best Present value	Source	FCC-ee Stat	FCC-ee Syst*	Leading error*	NLE
R_ℓ^Z (x 10³)	20725 +/-33 +/-20 +/-5	ALEPH	0.06	0.2-1	Acceptance for leptons	
R_b (x 10⁶)	216340 +/-670 +/-600	DELPHI	0.3	<60	B tag efficiency?	
A_{FB}^b (x 10⁴)	1000 +/-27 +/- 11	ALEPH	0.02	1-3	Jet charge	
τ Lifetime (fs)	290.17 +/-0.53 +/-0.33	Belle	0.001	0.04	Radial alignment	Asymmetry
τ mass (MeV)	1776.91 +/- 0.12 $^{+0.10}_{-0.13}$	BES	0.004	0.04	Momentum scale	
τ leptonic ($\mu\nu_\mu\nu_\tau$) B.R. (%)	17.319 +/- 0.070 +/-0.032	ALEPH	0.0001	0.003	e/μ/h separation**	Bkg, τ-selection**

*From Blondel and Janot

- Standard statistical error improves by a factor of ~500
- They assume less than scaling by statistics

➢ Changed present values from PDG averages to best single value to see also statistical and systematic errors

➢ Also, to understand how to improve systematics, it seems best to focus on the best single experiment, and try to understand what systematics they faced

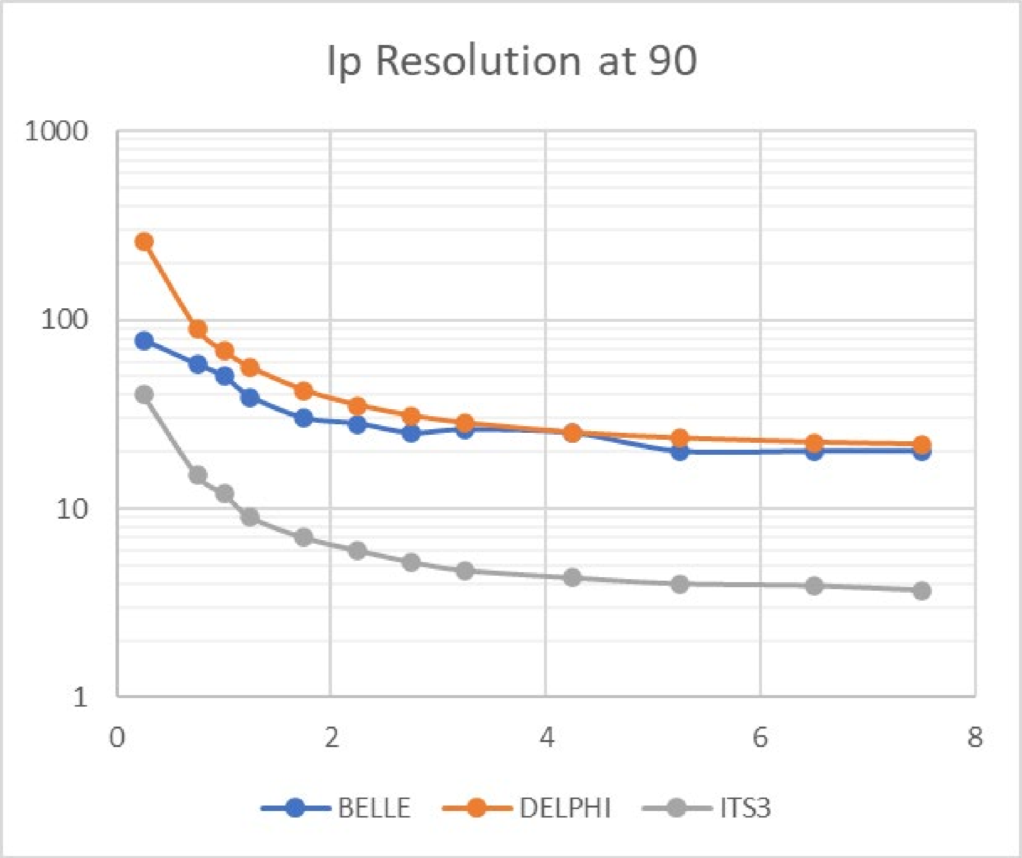
➢ ** all ID’s are equal at ~0.02 contribution to sys error

τ Lifetime

- τ_τ=(290.17 +/- 0.53 (stat) +/- 0.33 (syst))x 10^{-15} seconds (Belle)
- $c\tau_\tau$=[86.99 +/- 0.16 (stat) +/- 0.10 (syst)] microns
- Largest source of systematic error is due to vertex detector alignment
  - By a MC method (moving elements around) they determine it to be 0.09 microns
  - If this error was zero, the remaining systematics would add up to 0.045 microns, having the total systematic error
- Note the "goal" is 0.04 fs which is an improvement of X8, meaning 0.01 microns (10 nanometers)
- How can this be achieved?
  - If the vertex detector is constructed of bent wafers, 50 microns thick, is it intrinsically better aligned?
  - If not, or partially, we are in the domain of optical instrumentation, feedback/control
- The next largest contribution is due to an "asymmetry" factor in the resolution function
- Next best measurement
- τ_τ=(290.9 +/- 1.4 (stat) +/- 1.0 (syst))x 10^{-15} seconds (DELPHI)
- $c\tau_\tau$=[87.2 +/- 0.4 (stat) +/- 0.3 (syst)] microns
- Why does BELLE achieve a much smaller systematic error? What can we learn from this?
- Other lifetimes
- B+/- 1637 +/-4 (stat) +/- 3 (syst) x 10-15 seconds (LHCb)
- B0   1515 +/-5 (stat) +/- 6 (syst) x 10-15 seconds (CMS)

Comparison of Impact Parameter Resolution

- BELLE and DELPHI have similar point resolution but BELLE is apparently lower mass
- ITS3 (and FCCee) will be dramatically better due to
- ~3 um point resolution
- ~50 um sensor thickness
- Concurrent improvement on tagging efficiencies and resolution function

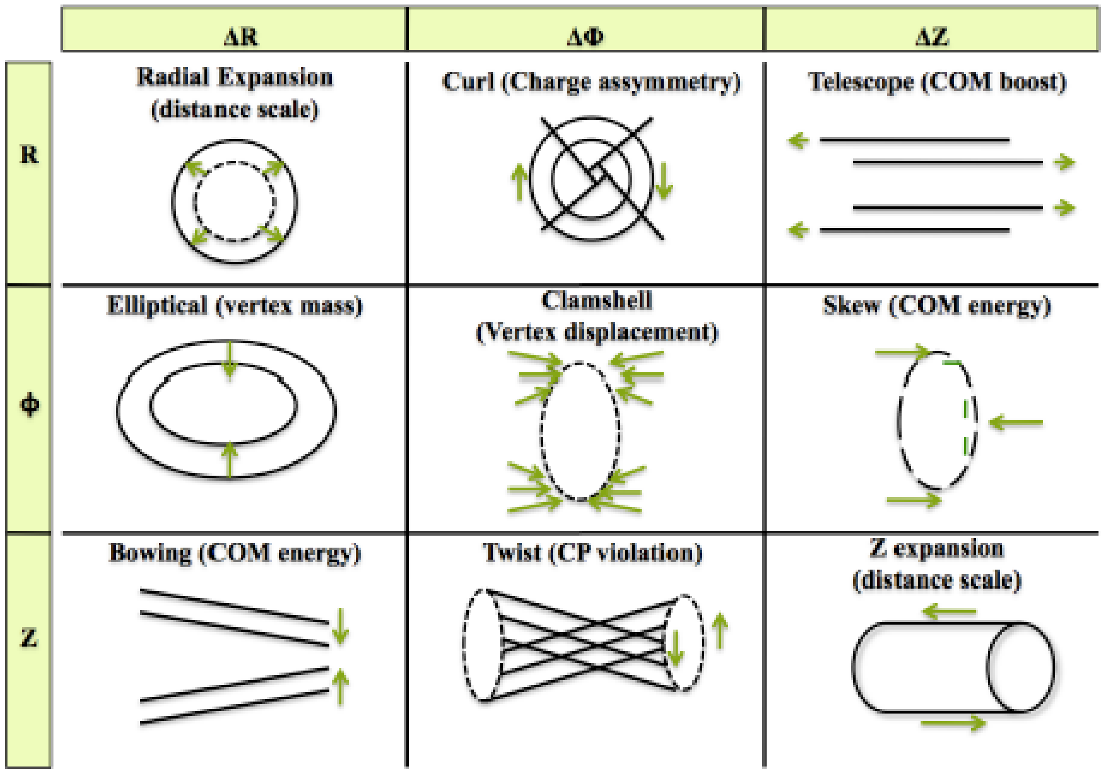


- **Origin of sys errors (microns)**
- Note: FCCee goal is 0.04 (0.001) fs (!)
- Certain errors are based upon MC studies and models
- Appears that these are studied up to the point that they do not exceed the statistical error
- Hard to know how these would all evolve when statistical errors are much smaller
- A key "hardware" error is due to alignment. For BELLE it is the dominant error but still smaller than that of DELPHI
  - But BELLE actually uses a MC method to evaluate it…
- Based upon ITS3, the ip resolution at FCCee will dramatically improve. Should have an important effect on efficiency but **how does it affect alignment?**

	BELLE	**stat**	**sys**	**DELPHI**	**stat**	**sys**
fs	290.17	0.53	0.33	290.9	1.4	1
um	86.99	0.16	**0.1**	87.2	0.4	**0.3**
BELLE systematics						
SVD alignment			0.09			
Asymmetry fixing			0.03			
Beam energy, ISR/FSR desc			0.024			
Fit range			0.02			
Background			0.01			
t-lepton mass			0.009			
DELPHI						
3-prong full syserr						**0.39**
Background						0.06
Radiative energy loss						0.03
Recon bias						0.24
Alignment						0.30
1-prong full syserr						**0.45**
Method bias						1.05
Trim						1.68
Trim/MC agree						0.36
Background						0.45
Alignment						0.12
Resolution						0.15
Miss Distance full syserr						**0.63**
Method bias						0.06
Event Selection						0.33
Physics Function						0.24
Resolution Function						0.39
Particle MisID						0.06
Background						0.18
Alignment						0.15
Polarization						0.12
Fit Range						0.21

Alignment

- Weak modes are the most difficult aspect
- Note: past vertex detectors have been polygonal and thick
- Are these better or worse in an “idealized” cylindrical geometry
- How to design a detector appropriately?



A^b_{FB}: Many approaches to tagging b and charge

- 1 DELPHI: ABDALLAH 05 obtain an enriched samples of b b events using lifetime information. The quark (or antiquark) charge is determined with a neural network using the secondary vertex charge, the jet charge and particle identification. 14
- 2 DELPHI: ABDALLAH 04F tag b– and c–quarks using semileptonic decays combined with charge flow information from the hemisphere opposite to the lepton. Enriched samples of c c and b b events are obtained using lifetime information. 25
- 3 OPAL: ABBIENDI 03P tag heavy flavors using events with one or two identified leptons. This allows the simultaneous fitting of the b and c quark forward-backward asymmetries as well as the average B 0-B 0 mixing. 15
- 4 OPAL: ABBIENDI 02I tag Z 0 → b b decays using a combination of secondary vertex and lepton tags. The sign of the b-quark charge is determined using an inclusive tag based on jet, vertex, and kaon charges. 18
- 5 ALEPH: HEISTER 02H measure simultaneously b and c quark forward-backward asymmetries using their semileptonic decays to tag the quark charge. The flavor separation is obtained with a discriminating multivariate analysis. 17
- 6 ALEPH: HEISTER 01D tag Z → b b events using the impact parameters of charged tracks complemented with information from displaced vertices, event shape variables, and lepton identification. The b-quark direction and charge is determined using the hemisphere charge method along with information from fast kaon tagging and charge estimators of primary and secondary vertices. The change in the quoted value due to variation of Ac FB and Rb is given as +0.103 (Ac FB – 0.0651) −0.440 (Rb – 0.21585). 11
- 7 DELPHI: ABREU 99Y tag Z → b b and Z → c c events by an exclusive reconstruction of several D meson decay modes (D∗+, D0, and D+ with their charge-conjugate states). 85
- 8 L3: ACCIARRI 99D tag Z → b b events using high p and pT leptons. The analysis determines simultaneously a mixing parameter χb = 0.1192 ± 0.0068 ± 0.0051 which is used to correct the observed asymmetry. 35
- 9 L3: ACCIARRI 98U tag Z → b b events using lifetime and measure the jet charge using the hemisphere charge. 55
- 10 OPAL: ALEXANDER 97C identify the b and c events using a D/D∗ tag. 220

A^b_{FB}:(x10^4)=992, many approaches to tagging b and charge

#	Exp	Author, #	Sys Err	τ	Svq NN	Jq	pid	Semi-l	had	qflow	svtag	ltag	Kq	mva	ip_q	shape	D	lept
1	DELPHI	Abdallah05	14	x	x	x	x											
2	DELPHI	Abdallah04F	25					x		x								
3	OPAL	Abiendi03P	15															x
4	OPAL	Abiendi02I	18		x	x					x	x	x					
5	ALEPH	Heister02H	17					x						x				
6	ALEPH	Heister01D	11						x						x	x		x
7	DELPHI	Abreu99Y	85														x	
8	L3	Acciarri99D	35															x
9	L3	Acciarri98U	55	x		x												
10	OPAL	Alexndr97C	220														x	
	FCCee	GOAL	1-3															

Sys error “goal” = 1-3, statistical limit = 0.02

What would it take to understand the error on the efficiency of any of these tools 5-10x better?

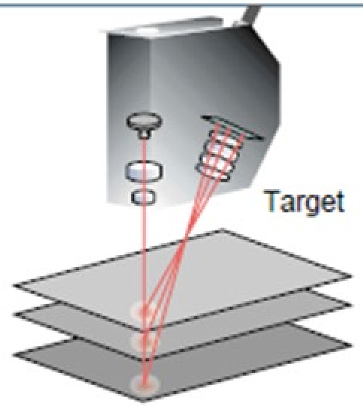
- Expect efficiencies will overall improve due to ML techniques
- Does the uncertainty on the efficiency improve correspondingly?
- Impact parameter (ie: single track)
- Secondary vertex (ie: multiple tracks)
- Bias on curvature – single vs multi-track vertices
- Jet charge
- Secondary vertex charge
- Kaon charge – first identify
- Mis-identification
- PID
  - dE/dX, dN/dX
  - TOF
  - Threshold Cherenkov

Interesting Questions

- New specifications, design features?
- How shall we build precision metrology into the detector design ab initio?
- Does “scaling” still make sense?
  - Solid state sensors have benefited from scaling for ~30 years. ie: performance of modules on a “bench” mapped well to the “system test” and beyond. But does this continue to make sense when we have to meet precision/accuracy requirements set by the low systematics of the FCCee detectors?
- To what extent does the detector need to perform **precision** “engineering” functions concurrent with physics data taking?
  - “Engineering” refers to measurements which provide information on alignment, stability, calibration, particle response, etc.
- Would the the “low systematics” program benefit (or require) a dedicated, special purpose detector (devote an interaction region to this, or test beam facility?) to carry out broad studies needed to control systematics?
- Does it make sense to trade off acceptance (or other aspects) for control of systematics? For example a restricted solid angle but with elements otherwise optimized?
- What else can we learn from present and past programs?

End

Modern laser displacement sensor technology



The measurement principle uses triangulation. The position of the reflected light on the Li-CCD moves as the position of the target changes. The displacement amount of the target is measured by detecting this change.

High Accuracy	Small spot	LK-G32	25 mm – 35 mm; Measuring range 30±5 mm	0.05 µm	ø30 µm
	Wide beam	LK-G37			30 x 850 µm
Multi-Purpose	Small spot	LK-G82	80 mm; 65 mm – 95 mm; Measuring range 80±15 mm	0.2 µm	ø70 µm
	Wide beam	LK-G87			70 x 1100 µm
Long Distance	Small spot	LK-G152	150 mm; 110 mm – 190 mm; Measuring range 150±40 mm	0.5 µm	ø120 µm
	Wide beam	LK-G157			120 x 1700 µm
High-speed Long Distance	Small spot	LK-G402	300 mm, 400 mm, 500 mm; Measuring range 400±100 mm	2 µm	ø290 µm
	Wide beam	LK-G407			290 x 8300 µm
Ultra Long Distance	Small spot	LK-G502	250 mm, 500 mm, 1000 mm; Measuring range 500-250/+500 mm	2 µm	ø300 µm
	Wide beam	LK-G507			300 x 9500 µm

2 um res on distance @1m
300 um spot

Challenge

- While meeting the aggressive performance specs of the FCCee (as defined in, for example, the ECFA Roadmap) is of great importance…
- What about a different set of specifications, as well, derived from the requirements, or ambition, to reduce systematics to even the levels advocated by Blondel and Janot, or beyond?
- Would this lead to different detector designs, or new features, and certainly to interesting technical challenges.
- Important to coordinate with the physics motivation to reach a particular precision

Coupled Scenarios – ?

- Simple cylindrical shapes will expand with temperature rise
- Air cooling will lower the temperature leading to a contraction
- But reduced volume for the air flow, without temperature monitoring and feedback could lead to expansion…
- Weak mode oscillations?

R_b

- From Rev of Particle Properties
- SLD (ABE 05F) use hadronic Z decays collected during 1996–98 to obtain an enriched sample of b b events using a double tag method. **The single b–tag is obtained with a neural network trained to perform flavor discrimination using as input several signatures (corrected secondary vertex mass, vertex decay length, multiplicity and total momentum of the hemisphere; the key tag is obtained requiring the secondary vertex corrected mass to be above the D–meson mass)**. ABE 05F obtain Rb =0.21604 ± 0.00098 ± 0.00074 where the systematic error includes an uncertainty of ±0.00012 due to the uncertainty on Rc . The value reported here is obtained properly combining with ABE 98D. The quoted systematic error includes an uncertainty of ±0.00012 due to the uncertainty on Rc
- DELPHI (ABREU 99B) obtain this result combining in **a multivariate analysis several tagging methods (impact parameter and secondary vertex reconstruction, complemented by event shape variables**). For Rc different from its Standard Model value of 0.172, Rb varies as −0.024×(Rc –0.172).

Role of Wide Band Gap Sensors (and circuits)

- Rapidly increasing interest in these materials for fast timing application in the HEP detector R&D community and industry (SBIR)
- Prominent materials are Silicon Carbide (SiC) and Gallium Nitride (GaN)
- Fast response (ie SiC LGAD should be 2X faster than Silicon LGAD)
- "Solar Blind" ie: not sensitive in the visible wavelengths – no light leaks
- Dramatically relaxed cooling requirements
- Increasingly large industrial base and availability of materials
- Talk planned for the detector session at the FCC week in SF 6/24

Additional aspects to consider

- PID appropriate for Kaon ID, Kaon momentum spectrum
- Bias on curvature
  - Charge
  - Impact parameter – less important
  - Secondary vertex – more important
- False curvature
- Selection/identification
  - Pi/K background to muons
  - Dalitz, conversions for electrons
- Expect new taggers will be more efficient – ie: ML etc but will we understand them better? How will systematic error evolve?