System Aspects for Vertex Performance

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Some general considerations on detectors for FCCee

- Consider this talk as a follow on to the talk by P.Azzi on July 1, concerning requirements.
- FCCee envisions up to 4 detectors, covering (at least) 4 broad physics goals
  - Precision EW (Tera Z and WW)
  - Heavy Flavor
  - Higgs
  - Top and BSM
- While all of these require vertex detectors, might the requirements differ?
- In particular how do we balance the needs for unprecedented control of systematic errors with the other characteristics of the vertex tracker (or any other component as well)?
- **Is there a concept for a “low-systematics” detector?**
- Could thinking in these terms lead to new ideas and insights?

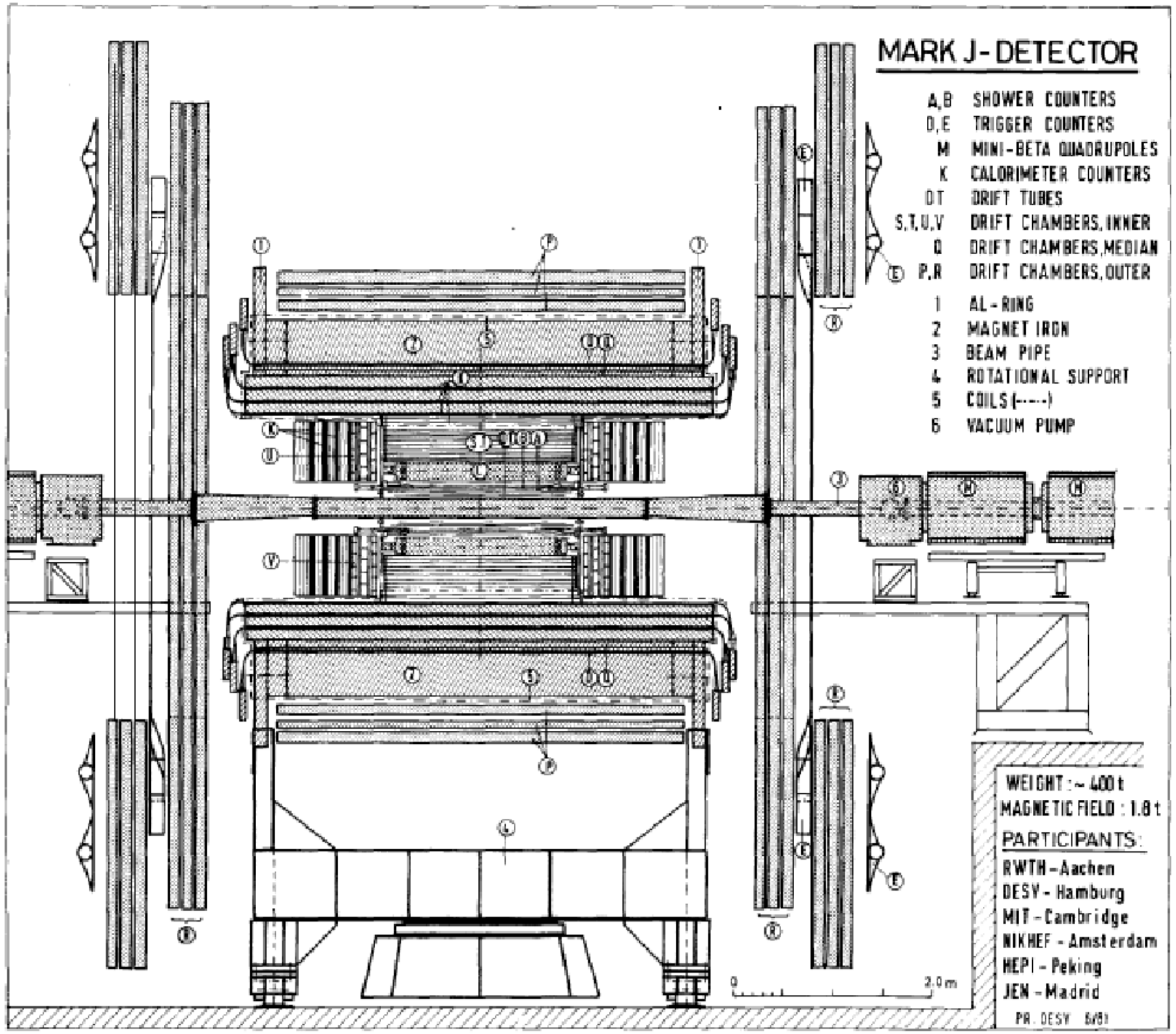
Systematic Errors at Tera Z

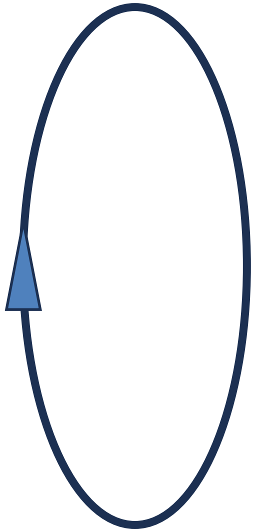
- With 10^{12} Z's produced at Tera-Z, statistical errors will be so small that measurements will become systematics dominated
- Ignore here the major systematics from energy and luminosity. These will be addressed by other "specialists"
- Orthodoxy – some systematic errors also improve by sqrt(N)? So 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
- Many of these particularly impact the tracking
- 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?

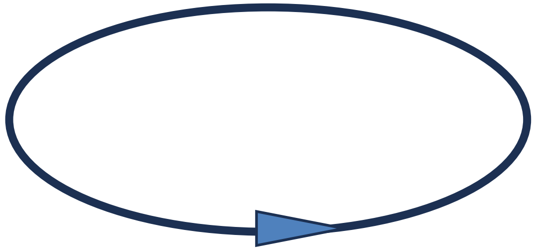
MARK J DESY/PETRA ~1979

Example of a detector design with built in control of systematics >measure muon charge asymmetry to 1%

“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 ±90º and 180 ° about a vertical axis.”*







*not clear they actually used this feature

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 dσ/dθ / 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….

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 bb 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^Z_ℓ (x 10^3)	20725 +/-33 +/-20 +/-5	ALEPH	0.06	0.2-1	Acceptance for leptons	
R_b (x 10^6)	216340 +/-670 +/-600	DELPHI	0.3	<60	B tag efficiency?	
A^b_{FB} (x 10^4)	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 +/- $0.12^{+0.1}_{-0.13}$	BES	0.004	0.04	Momentum scale	
τ leptonic BR%	17.319 +/- 0.070 +/-0.032	ALEPH	0.0001	0.003	e/μ/h separation**	Bkg, τ-selection**

*From Blondel and Janot, arXiv:2106:13885v2 Dec 2021

- 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

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

#	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	Guess	1-3															
	FCCee	Statistical	0.02															

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

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 ip resolution and ML techniques
- Does the **uncertainty** on the efficiency improve correspondingly?
- Impact parameter (ie: single track) vs
- 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 - overlap of precision EWK with heavy flavor program
    - dE/dX, dN/dX
    - TOF
    - Threshold Cherenkov

τ Lifetime: FCCee stat =+/- 0.001 fs

- 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
- Belous PRL 112 031801 (2014)
- Largest source of systematic error is due to vertex detector alignment
- Note the “aspirational goal” is 0.04 fs which is an improvement of X8, meaning 0.01 microns (10 nanometers)
- 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
- Abdallah EPJ C36 283 (2004)
- Again, alignment dominates

- Why does BELLE achieve a much smaller systematic error? What can we learn from this?

Alignment Uncertainty

- BELLE: perform a nominal alignment of the vertex tracker (how? quoted reference has no information) Using a MC, shift positions of sensors by 10 um and/or 1 mRad (based upon the known accuracy of the nominal alignment), to gauge the effect on the τ lifetime.
- Result $c\tau_\tau$=[86.99 +/- 0.16 (stat) +/- 0.10 (syst)] microns of which 0.03 is due to alignment

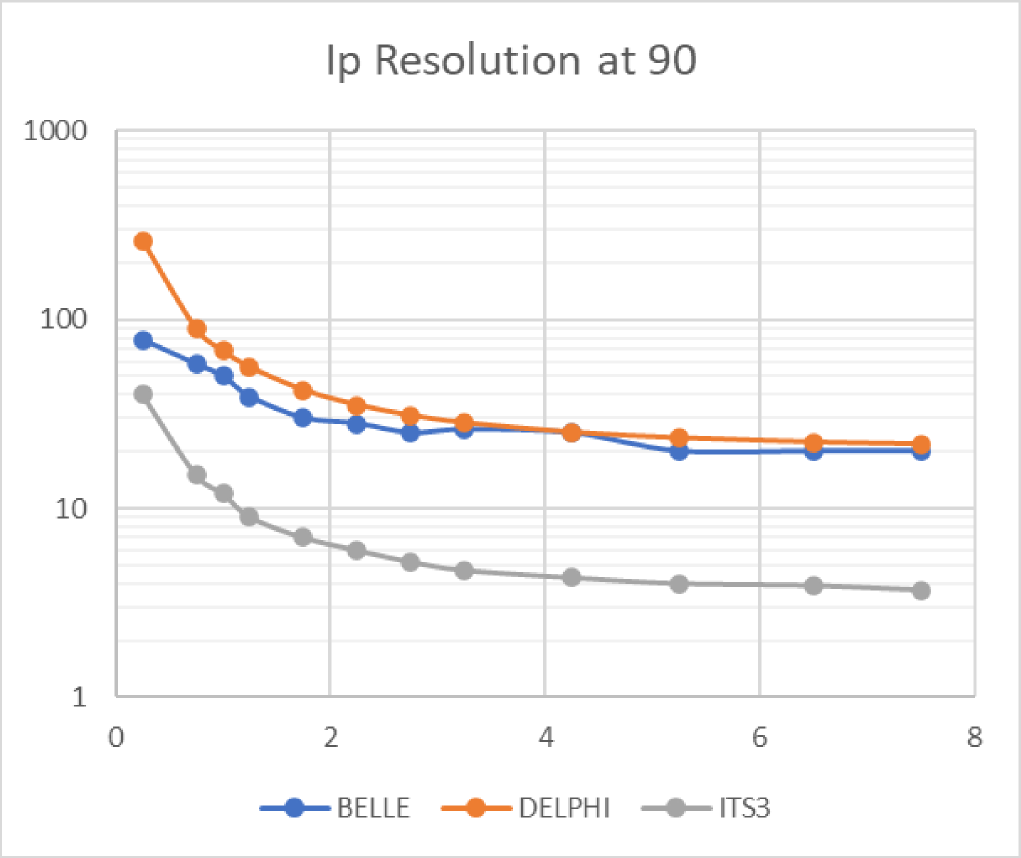
- DELPHI: Used 3 methods, consider here just the **"3-prong"** method, they used (τ-like) Z to hadron events (at least 3, >=3 charged particles in the two hemispheres), annual alignment shifts were determined, applied to decay distances, and lifetime re-calculated.
- Shifts were many 10's of microns per year
- Result $c\tau_\tau$=[85.9 +/- 0.8 (stat) +/- 0.4 (syst)] microns of which 0.3 is due to alignment
- So BELLE is ~10x better than the next best result, why?
- And FCCee statistical error is projected to be 0.001 fs (0.0003 um)
- Aspirational systematic (Blondel and Janot) was 0.04 fs (0.014 um)

- **Origin of sys errors (microns)**
- 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

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 is to be expected, but also on systematic error?

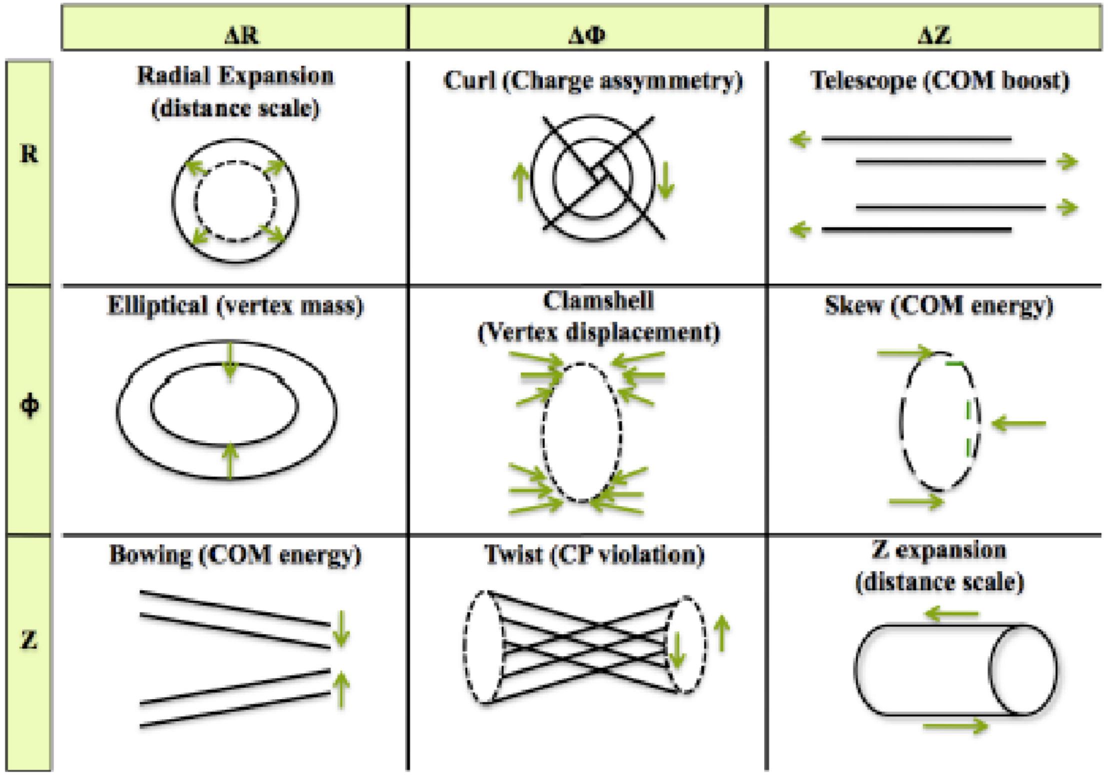


Comments

- Both experiments use techniques which apply ~10(s) of microns of shifts to sensors
- These result in systematic errors which are ~10's of nanometers
- Not sure why, but…
- The both have similar ip resolution
- They both use "thick" old fashioned sensors (not thinned MAPS)
- As we shift from (many) "ladder" designs, to bent wafers, does the alignment problem relax?
- Offers some hope that improved alignment, monitoring, instrumentation could allow future FCCee experiments to reach the ultimate statistical errors set by the statistics

How do weak modes scale with bent wafers?

- Long standing methodology, but how does it scale when we seek this new level of precision?
- 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?



Interesting Questions

- New specifications, design features?
- Shall we build precision metrology, or other tools, into the detector design ab initio? (like Mark J)
- 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? Do we need to separately “calibrate” the entire system?
- 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. Built into the run/operations plan.

Questions (cont.)

- Would the “low systematics” program benefit (or require) a dedicated, special purpose detector (devote an interaction region to this, or test beam facility?) specifically to carry out various 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? Another example of a dedicated instrument?
- What else can we learn from present and past programs?

Back Up

Basic Specs from the ECFA R&D Roadmap

	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.

Mark J Experiment, DESY/PETRA ~1979

The MARK J 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° and 180 ° about a vertical axis. *

The rotation about the vertical axis maps 0° into 180°, 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

This is a generic FCCee detector performance slide shown widely

4

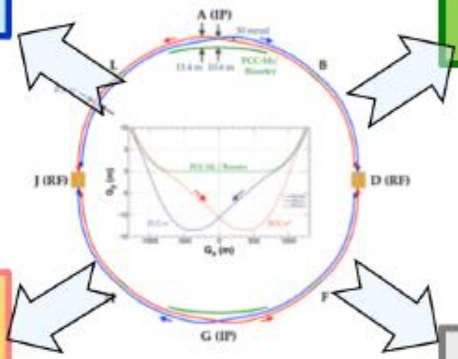
General detector requirements

"Higgs Factory" Programme

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{pT}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity