Detector Challenges for Lepton Colliders

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Detector Challenges for Lepton Colliders

- The prospective Colliders and Detectors

- Detector requirements and challenges

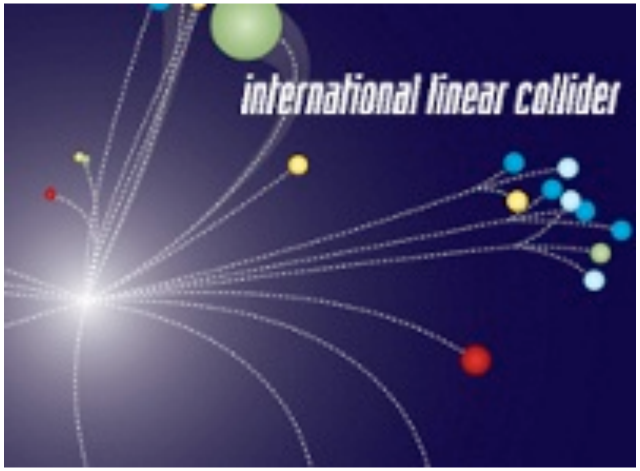
- Potential areas of connection with other frontiers/experiments (personal selection!)

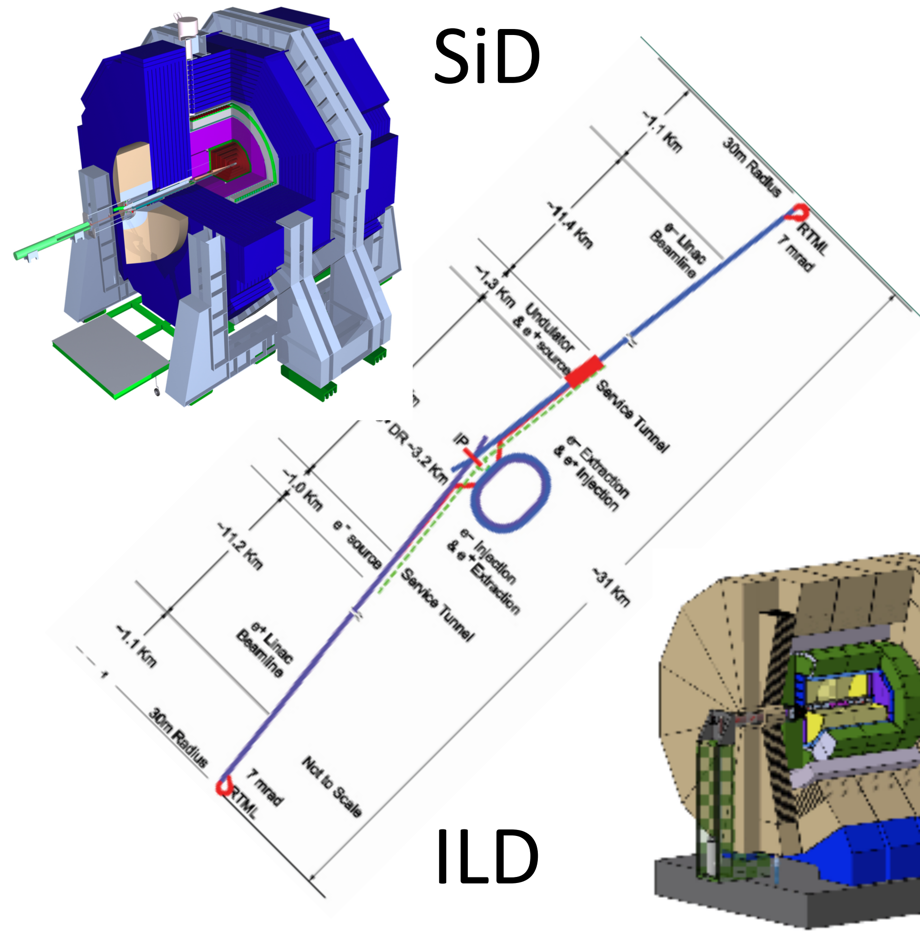
- Current R&D … Next steps…future possibilities

- Ideas for the future

With thanks for input from Jim Brau, Ron Lipton, and several unknowing donors

Colliders and Detectors - ILC





ILC

500 GeV – 1 TeV

$e^+ e^-$

35 MV/m

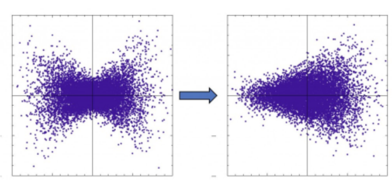
Detector Detailed Baseline Designs and Accelerator TDR -> Completion in Jan '13

Key concern with SB2009: Energy Scans – more luminosity needed at low E.
Now addressed by new parameter set:

ILC Parameters

Centre-of-mass energy	E_{cm}	GeV	200	230	250	350	500	upgrade 1,000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4
Electron linac rate	f_{linac}	Hz	10	10	10	5	5	4
Number of bunches	n_b		1,312	1,312	1,312	1,312	1,312	2,625
Electron bunch population	N_-	$x10^{10}$	2	2	2	2	2	2
Positron bunch population	N_+	$x10^{10}$	2	2	2	2	2	2
Main linac average gradient	G_{av}	MV/m	12.6	14.5	15.8	22.1	31.5	>31.5
RMS bunch length	σ_z	Mm	0.3	0.3	0.3	0.3	0.3	0.3
Electron RMS energy spread	$\Delta p/p$	%	0.22	0.22	0.22	0.22	0.21	0.11
Positron RMS energy spread	$\Delta p/p$	%	0.17	0.15	0.14	0.1	0.07	0.04
Electron polarisation	P_-	%	80	80	80	80	80	80
Positron polarisation	P_+	%	31	31	31	29	22	22
IP RMS horizontal beam size	σ_x^*	nm	904	843	700	662	474	554
IP RMS vertical beam size	σ_y^*	nm	9.3	8.6	8.3	7	5.9	3.3
Luminosity	**L**	$\times 10^{34}\ cm^{-2}s^{-2}$	**0.47**	**0.54**	**0.71**	**0.86**	**1.49**	**2.7**
Fraction of luminosity in top 1%	$L_{0.01}/L$		92.20%	89.80%	84.10%	79.30%	62.50%	63.50%
Average energy loss	δE_{BS}		0.61%	0.78%	1.23%	1.75%	4.30%	4.86%
Using Travelling Focus: IP RMS vertical beam size	σ_y^*	nm	6	5.6	5.3	4.5	3.8	2.7
Luminosity	**L**	$\times 10^{34}\ cm^{-2}s^{-2}$	**0.64**	**0.73**	**0.97**	**1.17**	**2.05**	**3.39**
Fraction of luminosity in top 1%	$L_{0.01}/L$		91.60%	89.00%	83.00%	77.90%	60.80%	62.30%
Average energy loss	δE_{BS}		0.61%	0.79%	1.26%	1.78%	4.33%	4.85%

Adjustment of the longitudinal position of the focal point (optical waist) of individual longitudinal segments of the bunch effectively compensates the luminosity diluting effects of the hourglass effect.



RDR Luminosity @ 500 GeV was $2 \times 10^{34}\ cm^{-2}s^{-1}$

Colliders and Detectors - ILC

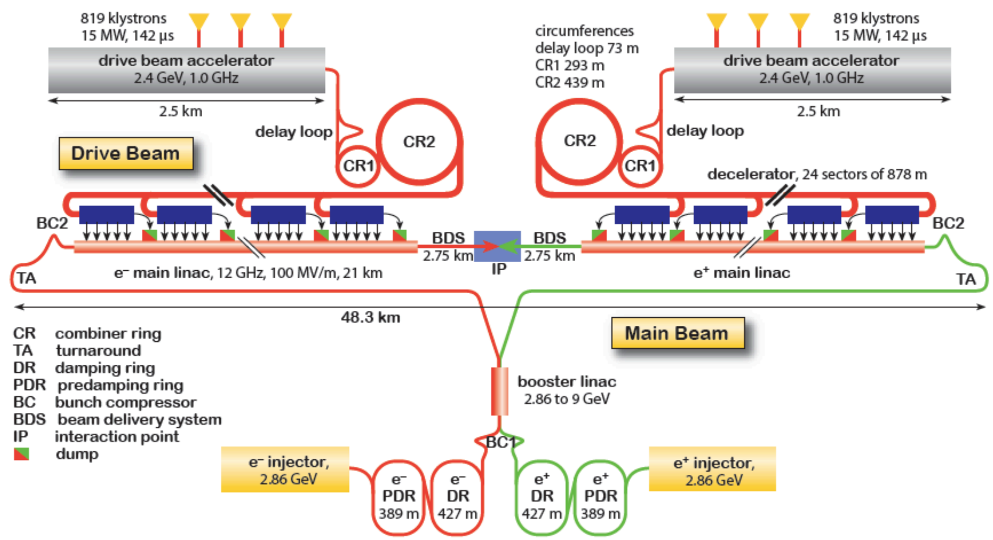
Collision rate 5 Hz
1312 bunches/bunch train (x2 for 1 TeV upgrade)
Bunch train length 1ms
199 ms intervals between trains

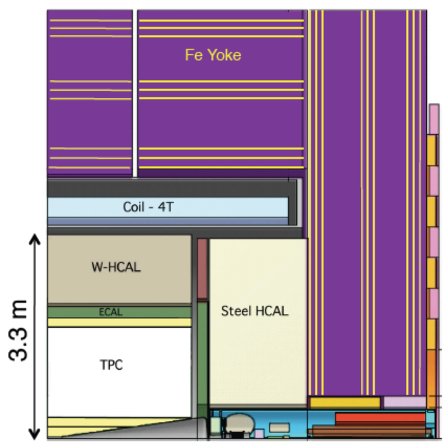
-> 762 ns between bunch crossings (/2 for 1 TeV upgrade)

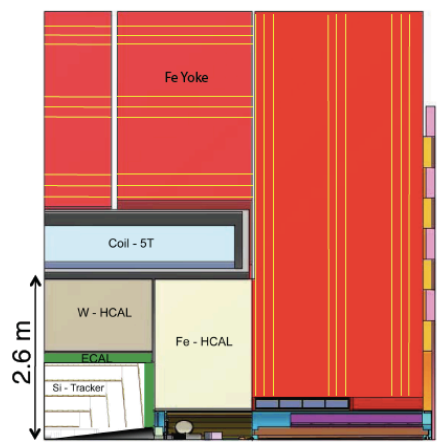
Colliders and Detectors - CLIC

≤ 3 TeV

$e^+ e^-$







ILD' and SiD'

100 MV/m

2 GHz bunch crossing rate !!

Detector and Accelerator CDR completed in 2011

Prepare full TDR 2017-2022

Colliders and Detectors - CLIC

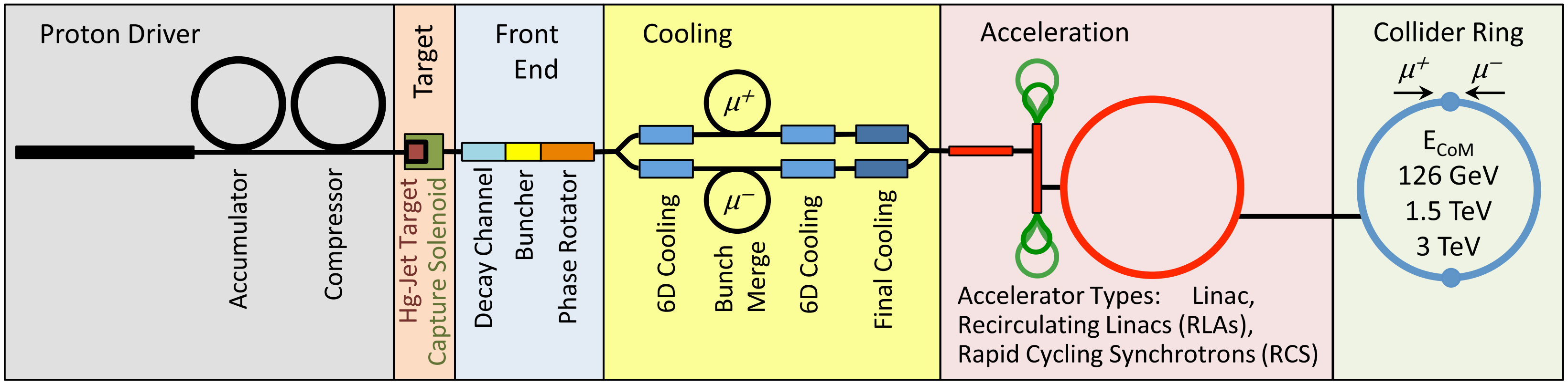
CLIC Machine environment

	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
σ_x / σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

Drives timing requirements for CLIC detector

very small beam size

Colliders and Detectors – Muon Collider



- Narrow beam energy spread
  - Precision scan
  - Kinematic constraints
- 2 Detectors
- ΔT_{bunch} ~ 10 μs
  - Lots of time for readout
  - Most backgrounds don't pile up

~300 meter circumference

ΔT_{bunch} ~ 500 ns

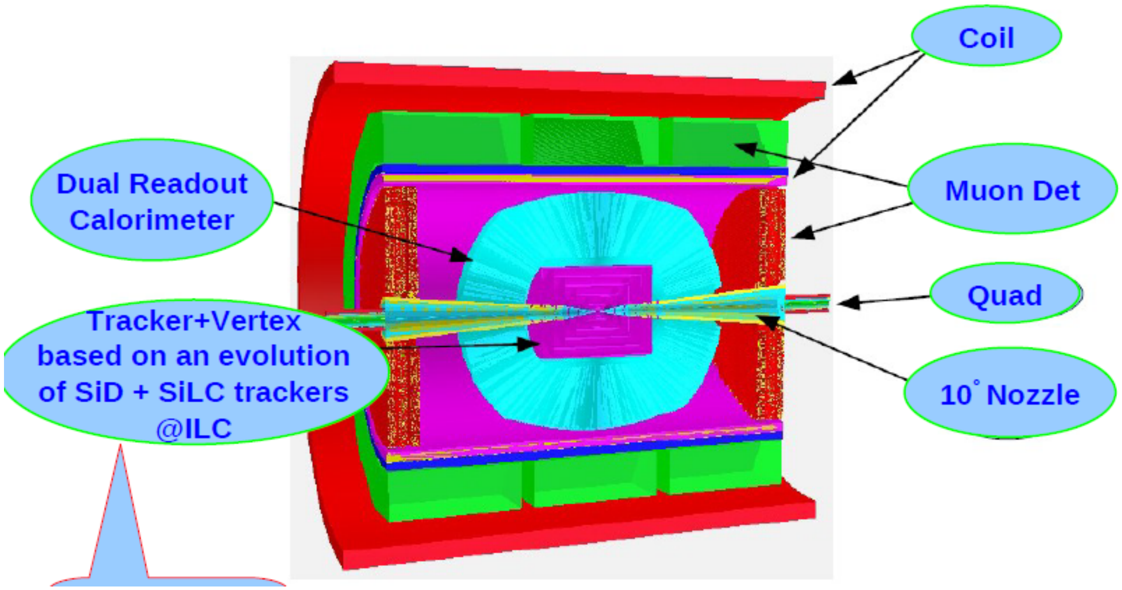
1000 turns (~0.8 ms)/store

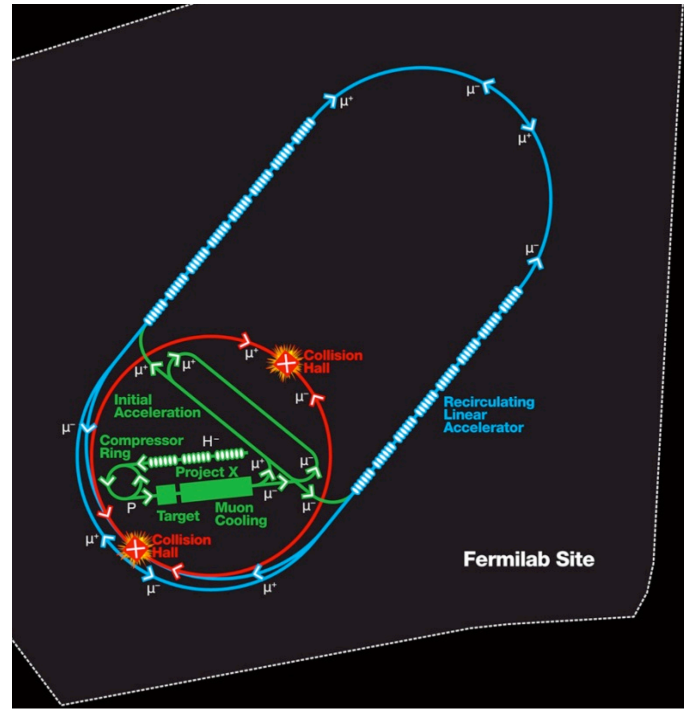
Luminosity estimates are in the 10^{31}-10^{32} range

The physics we can do depends strongly on machine parameters

Colliders and Detectors

Muon Collider





Muon Accelerator Proposal: studying design/feasibility

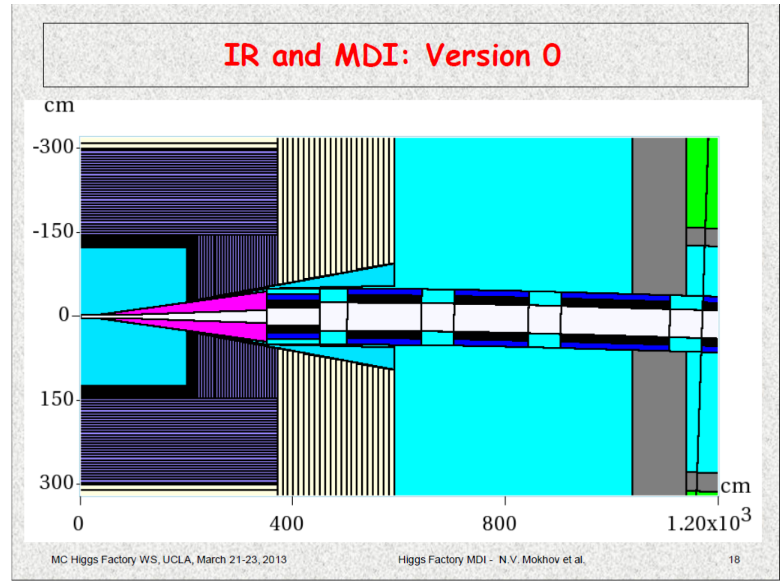
Colliders and Detectors – Muon Collider

The requirements are similar to CLIC, MuC has lower beamstrahlung – more precise fits.

•Precise, low mass tracking ($\mu\mu \rightarrow Zh$)

•Vertex Flavor tagging

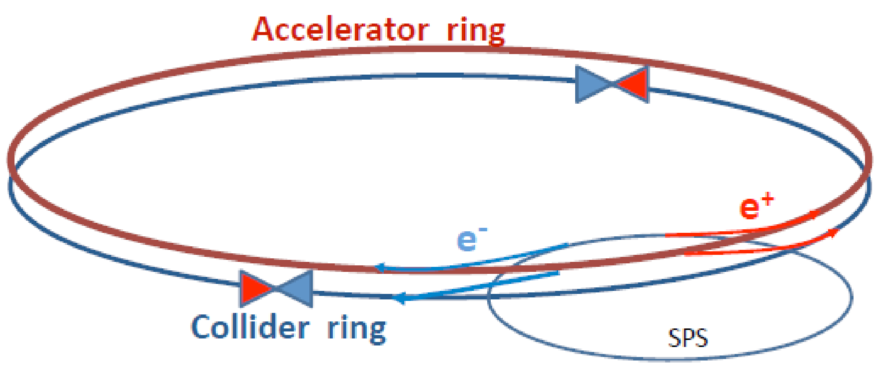
•Calorimetry capable of separating W/Z signals

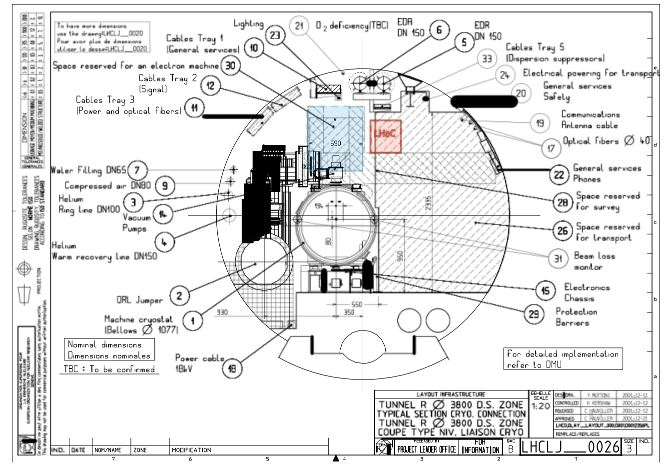


3. **Muon beam decays:** Unavoidable bilateral detector irradiation by particle fluxes from beamline components and accelerator tunnel - **major source** at MC: for 62.5-GeV muon beam of $2\text{x}10^{12}$ muon per bunch - $5.3\text{x}10^6$ dec/m

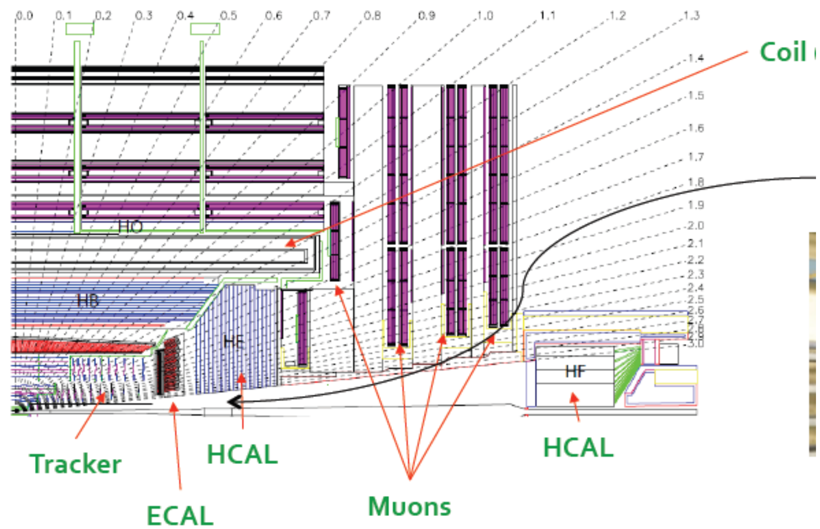
Colliders and Detectors

LEP3: A high Luminosity e^+e^- Collider in the LHC tunnel





A new proposal to use LEP3 with the CMS (+ATLAS?) detector as a Higgs factory



Detector(s) – CMS? ATLAS, SiD, ILD...?

ILC Physics and Detector Challenges

TABLE II: Benchmark reactions for the evaluation of ILC detectors

	Process and Final states	Energy (TeV)	Observables	Target Accuracy	Detector Challenge	Notes
Higgs	$ee \to Z^0h^0 \to \ell^+\ell^- X$	0.35	M_{recoil}, σ_{Zh}, BR_{bb}	$\delta\sigma_{Zh} = 2.5\%$, $\delta BR_{bb} = 1\%$	T	{1}
	$ee \to Z^0h^0,\ h^0 \to b\bar{b}/c\bar{c}/\tau\tau$	0.35	Jet flavour , jet $(E,\vec{p})$	δM_h=40 MeV, $\delta(\sigma_{Zh} \times BR)$=1%/7%/5%	V	{2}
	$ee \to Z^0h^0, h^0 \to WW^*$	0.35	M_Z, M_W, σ_{qqWW^*}	$\delta(\sigma_{Zh} \times BR_{WW^*})$=5%	C	{3}
	$ee \to Z^0h^0/h^0\nu\bar{\nu},\ h^0 \to \gamma\gamma$	1.0	$M_{\gamma\gamma}$	$\delta(\sigma_{Zh} \times BR_{\gamma\gamma})$=5%	C	{4}
	$ee \to Z^0h^0/h^0\nu\bar{\nu},\ h^0 \to \mu^+\mu^-$	1.0	$M_{\mu\mu}$	5σ Evidence for $M_h = 120$ GeV	T	{5}
	$ee \to Z^0h^0, h^0 \to$ *invisible*	0.35	σ_{qqE}	5σ Evidence for $BR_{invisible}$=2.5%	C	{6}
	$ee \to h^0\nu\bar{\nu}$	0.5	$\sigma_{bb\nu\nu}$, M_{bb}	$\delta(\sigma_{\nu\nu h} \times BR_{bb}) = 1\%$	C	{7}
	$ee \to t\bar{t}h^0$	1.0	σ_{tth}	δg_{tth}=5%	C	{8}
	$ee \to Z^0h^0h^0,\ h^0h^0\nu\bar{\nu}$	0.5/1.0	σ_{Zhh}, $\sigma_{\nu\nu hh}$, M_{hh}	δg_{hhh}=20/10%	C	{9}
SSB	$ee \to W^+W^-$	0.5		$\Delta\kappa_\gamma, \lambda_\gamma = 2 \cdot 10^{-4}$	V	{10}
	$ee \to W^+W^-\nu\bar{\nu}/Z^0Z^0\nu\bar{\nu}$	1.0	σ	$\Lambda_{*4}, \Lambda_{*5} = 3$ TeV	C	{11}
SUSY	$ee \to \tilde{e}^+_R\tilde{e}^-_R$ (Point 1)	0.5	E_e	$\delta M_{\tilde{\chi}^0_1}$=50 MeV	T	{12}
	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 1)	0.5	E_π, $E_{2\pi}$, $E_{3\pi}$	$\delta(M_{\tilde{\tau}_1} - M_{\tilde{\chi}^0_1})$=200 MeV	T	{13}
	$ee \to \tilde{t}_1\bar{\tilde{t}}_1$ (Point 1)	1.0		$\delta M_{\tilde{t}_1}$=2 GeV		{14}
-CDM	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 3)	0.5		$\delta M_{\tilde{\tau}_1}$=1 GeV, $\delta M_{\tilde{\chi}^0_1}$=500 MeV,	F	{15}
	$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3,\ \chi^+_1\chi^-_1$ (Point 2)	0.5	M_{jj} in $jj\not{E}$, $M_{\ell\ell}$ in $jj\ell\ell\not{E}$	$\delta\sigma_{\tilde{\chi}_2\tilde{\chi}_3} = 4\%$, $\delta(M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1})$= 500 MeV	C	{16}
	$ee \to \chi^+_1\chi^-_1/\tilde{\chi}^0_i\tilde{\chi}^0_j$ (Point 5)	0.5/1.0	$ZZ\not{E}$, $WW\not{E}$	$\delta\sigma_{\tilde{\chi}\tilde{\chi}}$=10%, $\delta(M_{\tilde{\chi}^0_3} - M_{\tilde{\chi}^0_1})$ =2 GeV	C	{17}
	$ee \to H^0A^0 \to b\bar{b}b\bar{b}$ (Point 4)	1.0	Mass constrained M_{bb}	δM_A=1 GeV	C	{18}
-alternative	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$ (Point 6)	0.5	Heavy stable particle	$\delta M_{\tilde{\tau}_1}$	T	{19}
SUSY	$\tilde{\chi}^0_1 \to \gamma + \not{E}$ (Point 7)	0.5	Non-pointing γ	$\delta c\tau$=10%	C	{20}
breaking	$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$ (Point 8)	0.5	Soft $\pi^\pm$ above $\gamma\gamma$ bkgd	5σ Evidence for $\Delta\tilde{m}$=0.2-2 GeV	F	{21}
Precision SM	$ee \to t\bar{t} \to 6$ *jets*	1.0		5σ Sensitivity for $(g-2)_t/2 \leq 10^{-3}$	V	{22}
	$ee \to f\bar{f}$ $(f = e,\mu,\tau; b,c)$	1.0	$\sigma_{f\bar{f}}$, A_{FB}, A_{LR}	5σ Sensitivity to $M_{Z_{LR}} = 7$ TeV	V	{23}
New Physics	$ee \to \gamma G$ (ADD)	1.0	$\sigma(\gamma + \not{E})$	5σ Sensitivity	C	{24}
	$ee \to KK \to f\bar{f}$ (RS)	1.0			T	{25}
Energy/Lumi	$ee \to ee_{fwd}$	0.3/1.0		δM_{top}=50 MeV	T	{26}
Meas.	$ee \to Z^0\gamma$	0.5/1.0			T	{27}

From M. Battaglia etc al. SLAC-PUB-11877

Detector Requirements -> Challenges

– Vertexing: heavy quark flavor identification, charge measurement

Hit resolution ~5 μm, < 0.3% X_0/layer

- Tracking: momentum resolution, track separation, efficiency

$\delta(1/p_T) \sim 2\text{-}5 \times 10^{-5}$ /GeV

- Calorimetry: jet energy measurement, jet-jet mass resolution

Jet energy resolution 3% or better for range of jet energies

- Overall: full angular coverage, minimize dead regions, dead materials, alignment, calibration,…

- General: Single bunch time resolution, robustness against backgrounds, survivability

Detector R&D perspective

- A large body of R&D exists for ILC detectors, developed over more than a decade and solutions exist that can deliver required physics performance – to be presented in Detailed Baseline Designs.

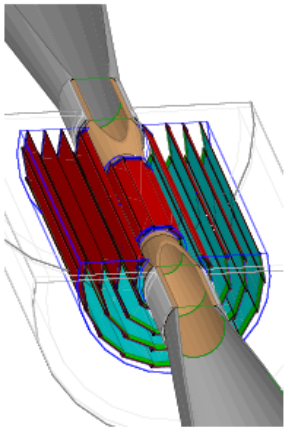
- Much of this R&D is applicable to the CLIC detectors, but higher backgrounds, more demanding timing, higher energies,…

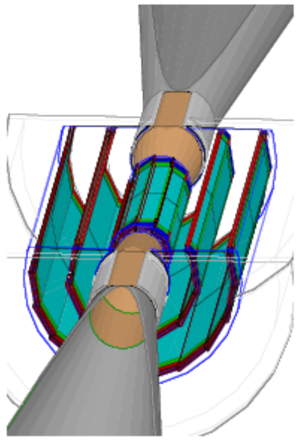
- For the Muon Collider, studies of backgrounds and their effects have been shown at recent meetings.

- For LEP3 initial studies have used the present CMS detector – special case and for Higgs factory only.

Vertexing – designs - ILC

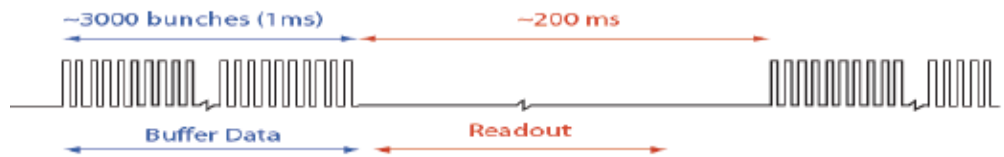
ILD

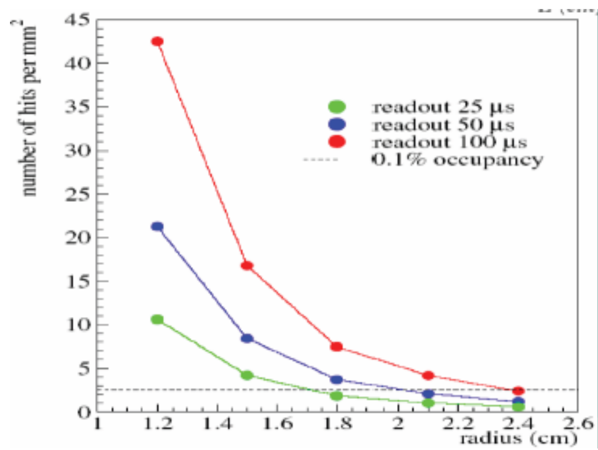


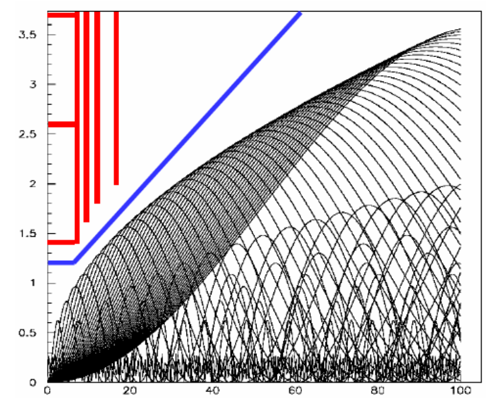


5 x single sided

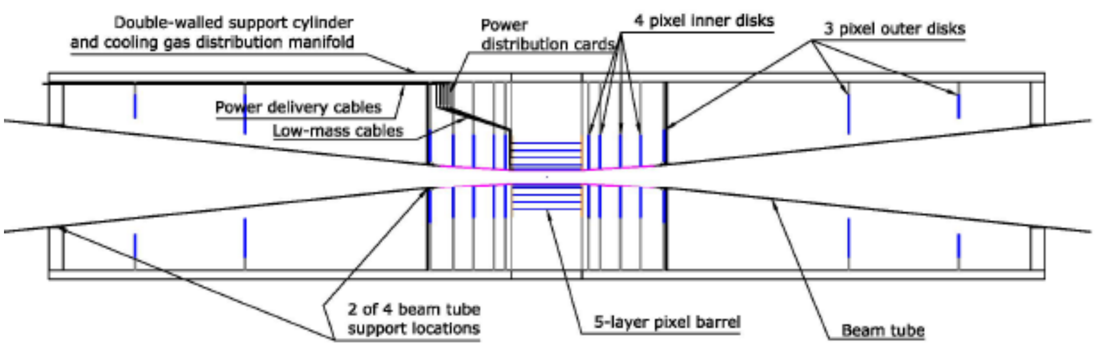
Double-sided

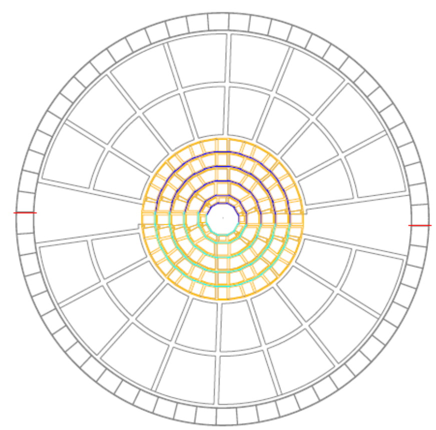






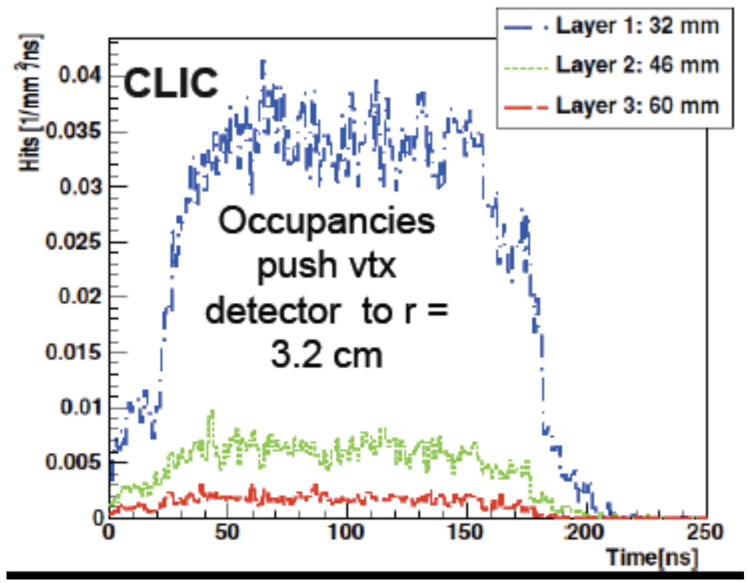
SiD



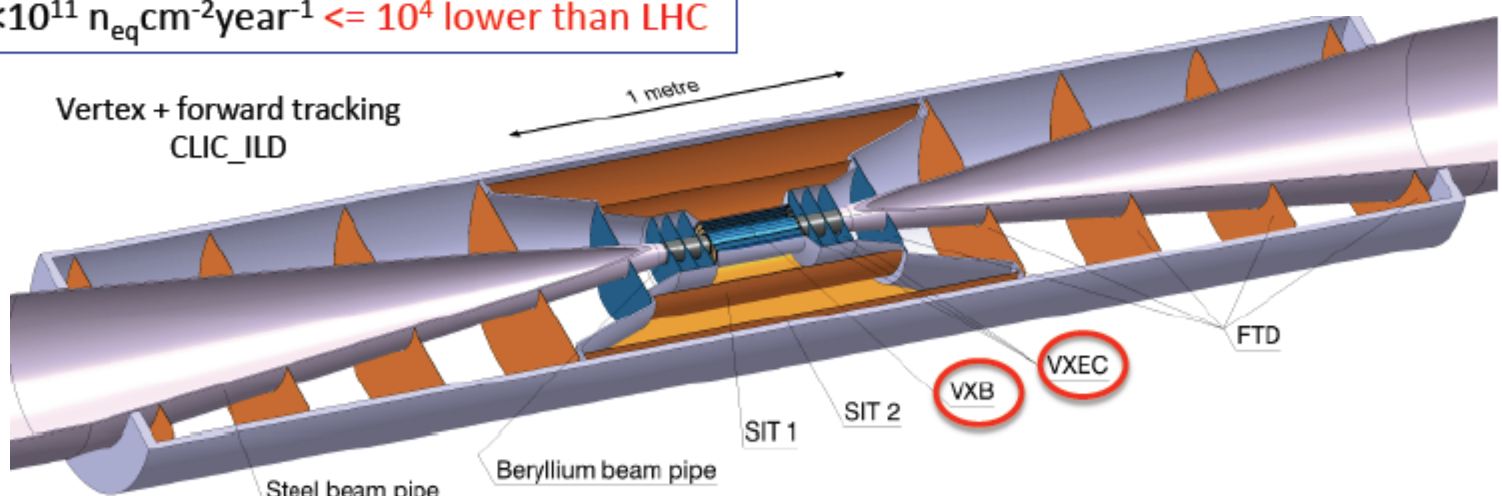


Vertexing – designs - CLIC

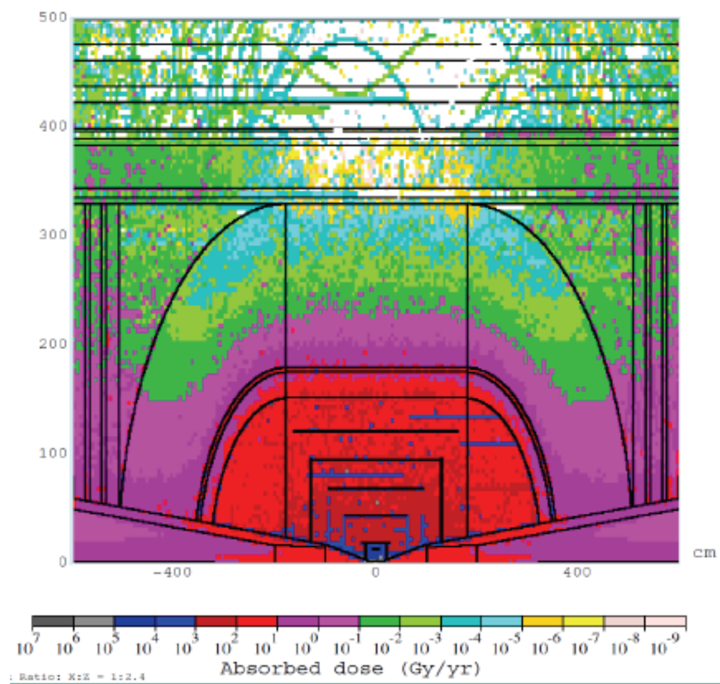
CLIC bunch separation 0.5ns !
CLIC beams are small in both x and y
-> higher level of beamstrahlung (vs. ILC)



- 20×20 μm pixel size
- 0.2% X_0 material par layer <= very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
- Time stamping 10 ns
- Triggerless readout for 156 ns bunch train
- Radiation level $<10^{11}$ $n_{eq}cm^{-2}year^{-1}$ <= 10^4 lower than LHC



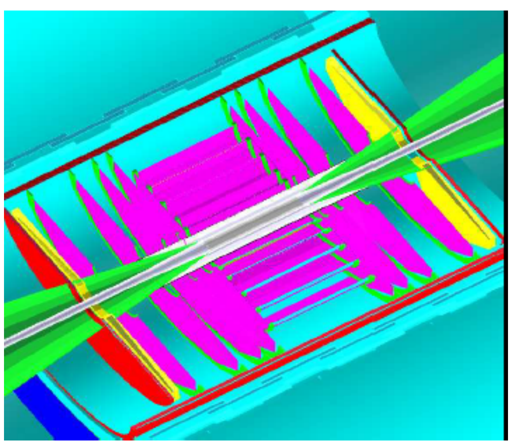
Vertexing – issues for Muon Collider



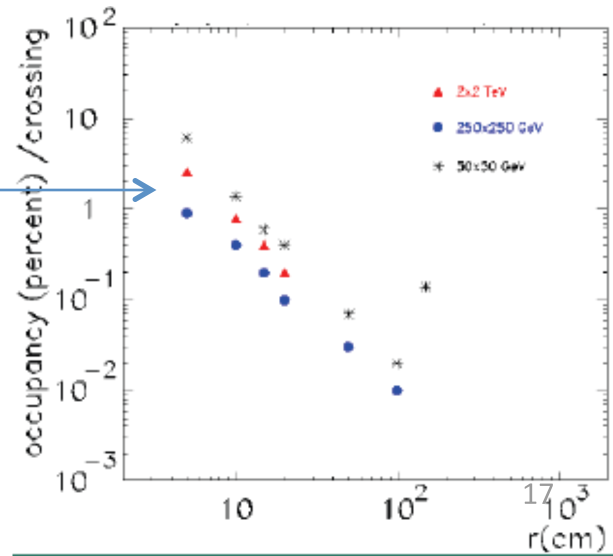
The muon collider detector environment is challenging:

3×10^4 pairs/bunch xing
Beam halo issues
Muon beam decays: 1.3×10^{10}/m/s for two beams of 0.75 TeV

-> high radiation dose – survivability?
-> high vertex detector occupancy

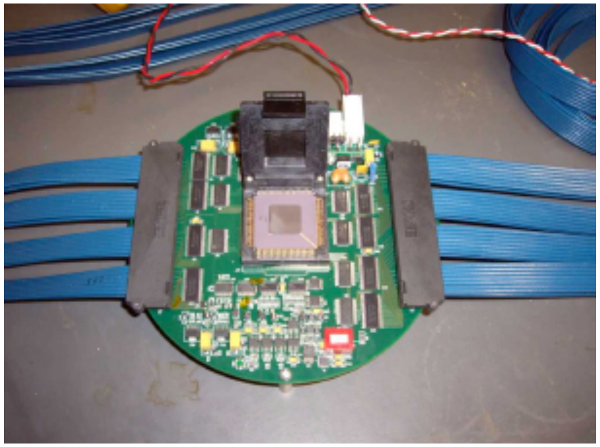


Occupancy drives vertex inner radius to ≥ 5 cm.



Modified SiD design

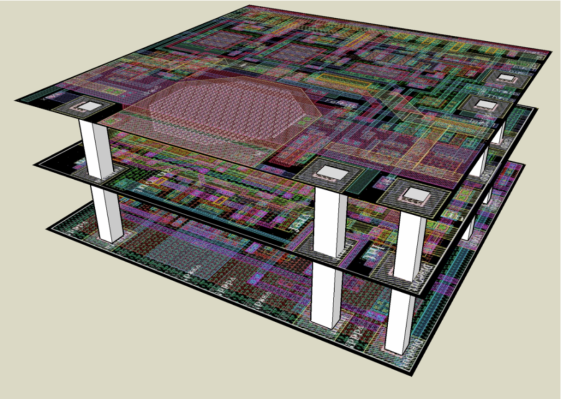
Vertexing - technologies



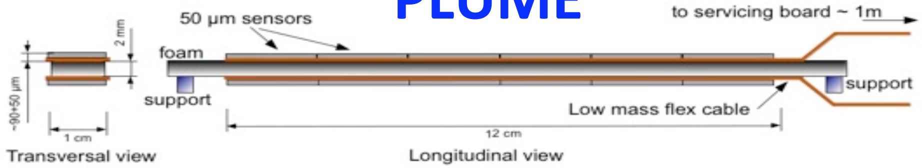
Examples

Chronopix
10 x 10 μm^2

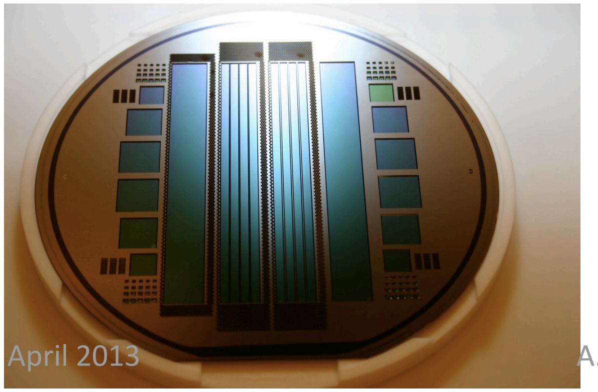
3-D



PLUME



Fully equipped ladder with 50 µm sensors
by 2012 ~ 0.3% X_0

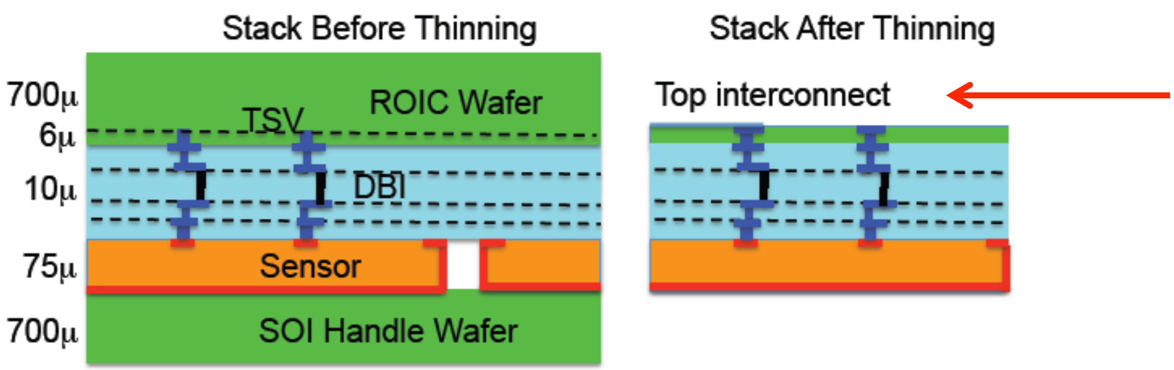


	ILC	*Belle 2*
occupancy	0.13 hits/μm^2/s	0.4 hits/μm^2/s
Frame time	25-100 µs	10 µs
Duty cycle	1/200	1
	Excellent spatial resolution (3- 5 µm) AND material budget (0.12 % X_0/layer)	Lowest possible material budget (0.15 % X_0/layer) Moderate pixel size (50 x 75 μm^2)

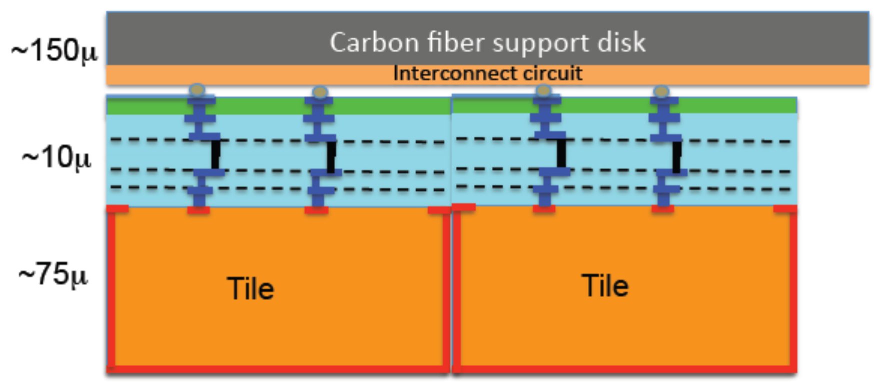
Vertex Detector

No preferred technology – many choices/still an evolving picture

Example 3-D/active edge design:



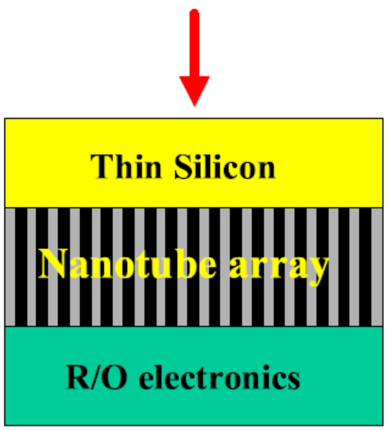
Barrel
Readout and power connections on top layer

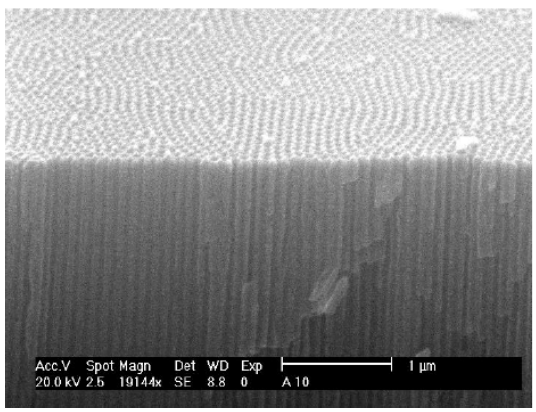


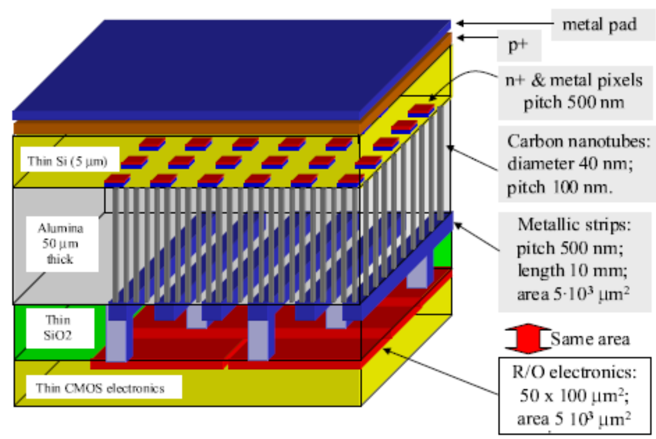
Disk tiling

Vertexing – challenges - ideas

- Too early to decide on any given technology
- Examples are what can be achieved in short term – assuming successful R&D
- Where will we stand when we come to build a lepton collider detector?
- => Follow electronics/sensor developments, try new ideas
- Can we learn from other areas e.g. nanotechnology:
  Ordered arrays of carbon nanotubes ?







R. Angelucci et al (2002)

Vertexing – challenges - ideas

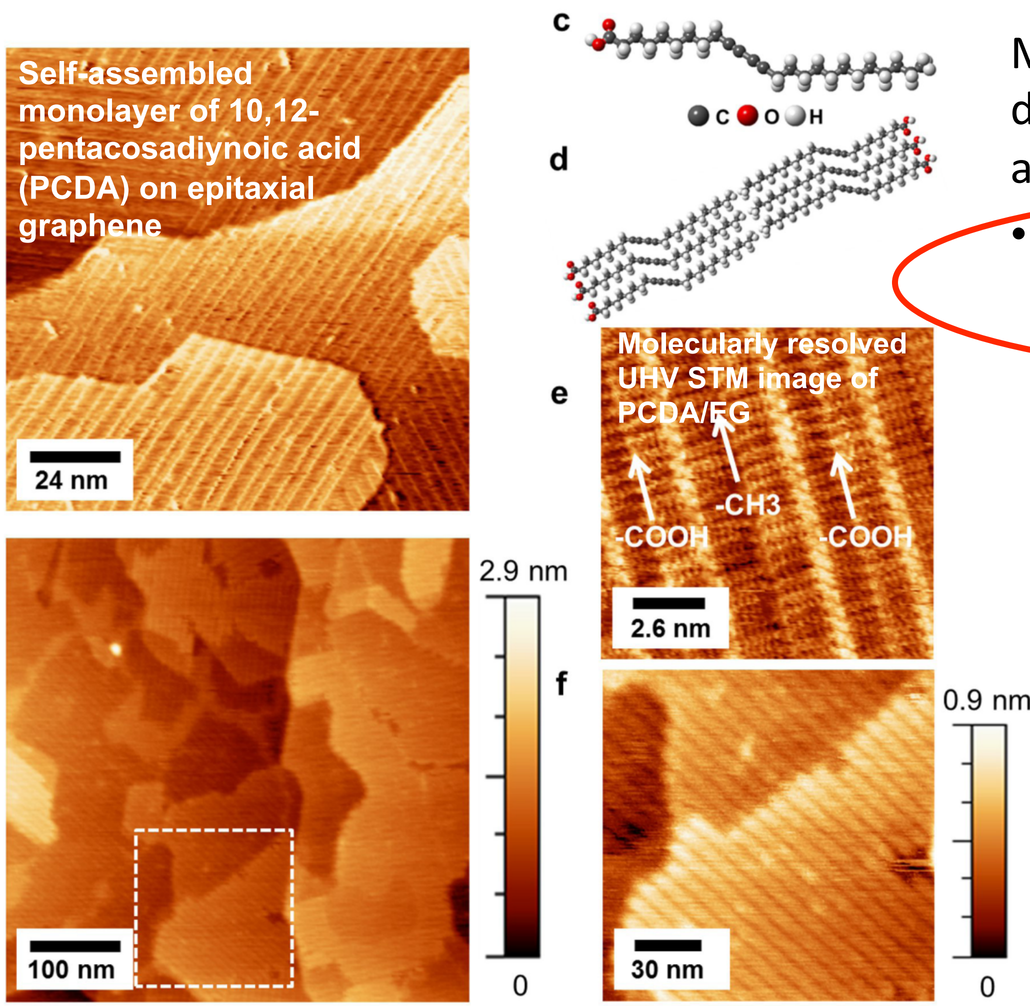
Material science is offering fantastic opportunities!

Our vertex detectors aim for the 1-few μm level of point resolution….

…what could we do with another factor 10-100 reduction in point resolution – do we need this?
…would this lead to other problems – power/cooling?

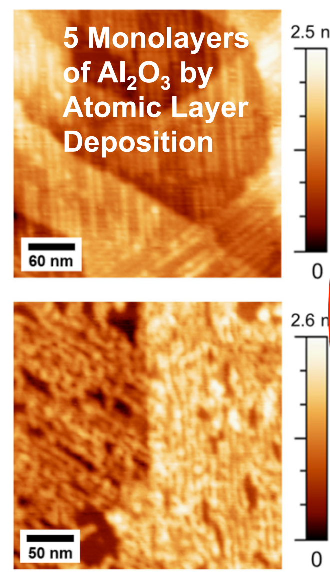
-> Extremely thin layers – graphene?
-> More layer for same material profile?
-> Creative shape layers – graphene?

Materials Development is aided by remarkable, new analytical tools



Much of the risk is mitigated by the use of detailed analytical tools that reveal meso and nanoscale order

- Graphene is a remarkable new conductor with wide applicability including as particle detector

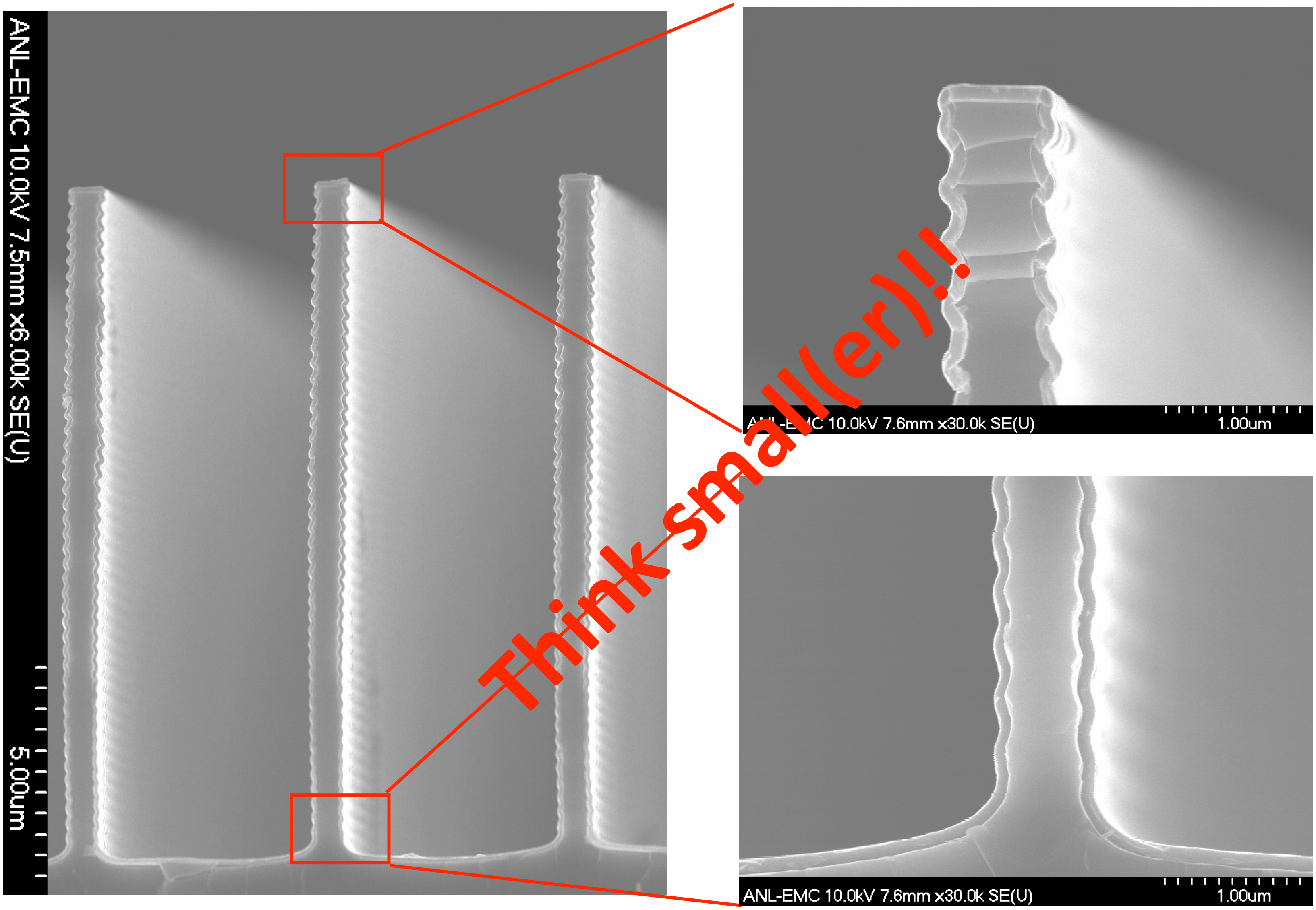


Assembly at the nanoscale!

- Thinnest capacitor
- High conductivity electrodes
- High Dielectric Constant Insulator

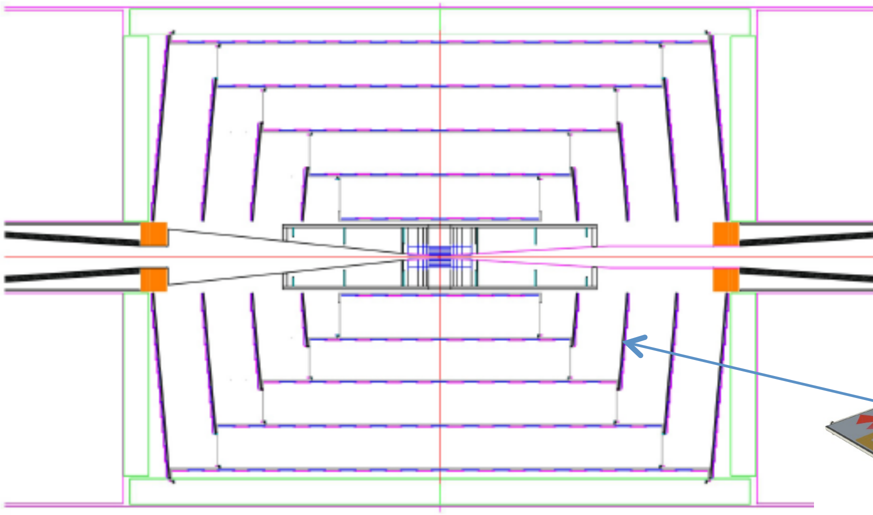
Alaboson, Sham, Kewalramani, Johns, Deshpande, Chien, Bedzyk, Elam, Pellin, Hersam Nano Letters 2013 in press.

NbSi in Silicon High Aspect Ratio Trench

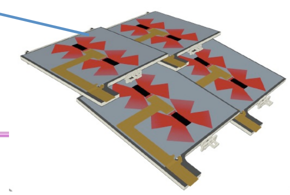


- ALD is *very* good at coating non-planar surfaces

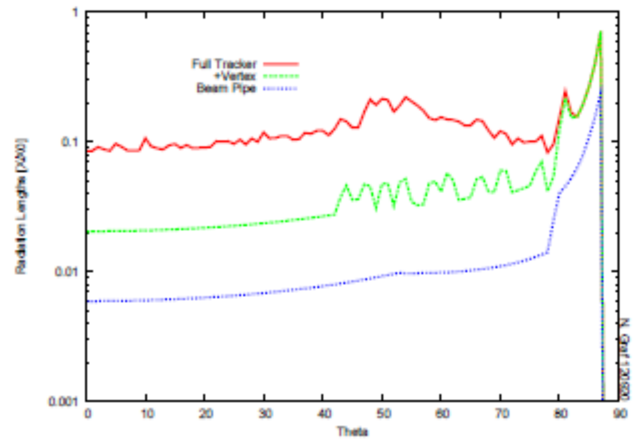
Tracking - designs



SiD



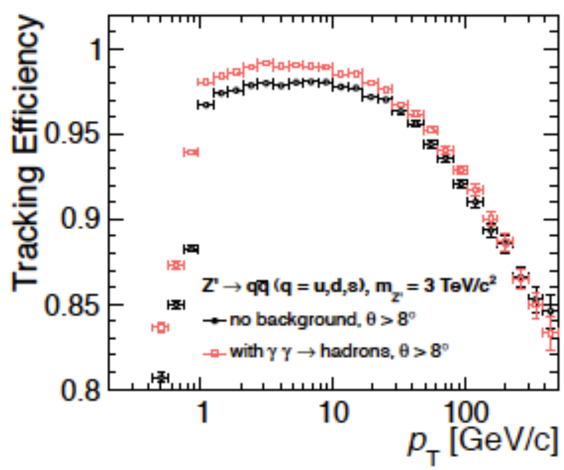
Low material budget

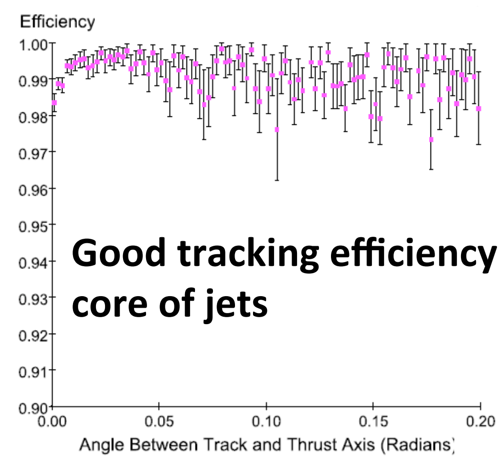


CLIC

SiD

- Optimized tracking algorithms for CLIC_SiD and studies at 3 TeV
  - Silicon tracking performs very well under severe conditions: Z' → qqbar @ 3 TeV



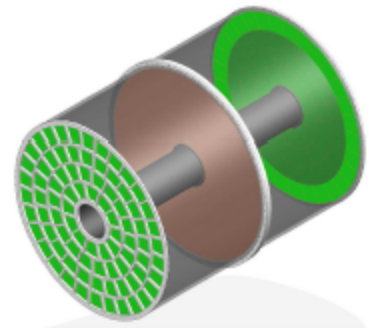


Good tracking efficiency in core of jets

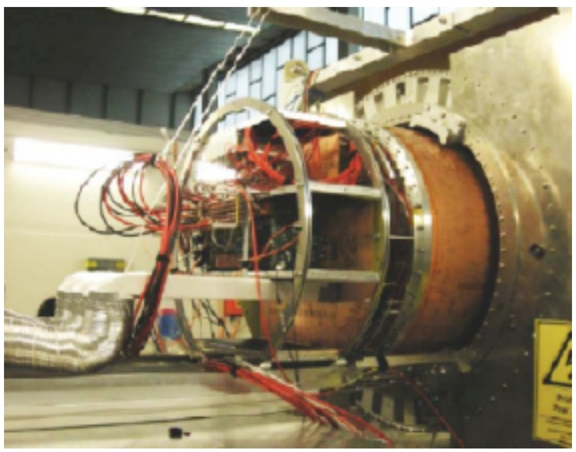
Tracking - designs

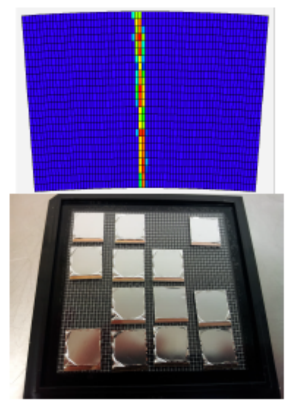
- $\sigma(r, \varphi) \leq 100\ \mu m$
- $\sigma(z) \approx 500\ \mu m$
- 2 hit resolution
  - $\approx$ 2mm in (r,φ)
  - $\approx$ 6 mm in z
- dE/dx ~ 5%

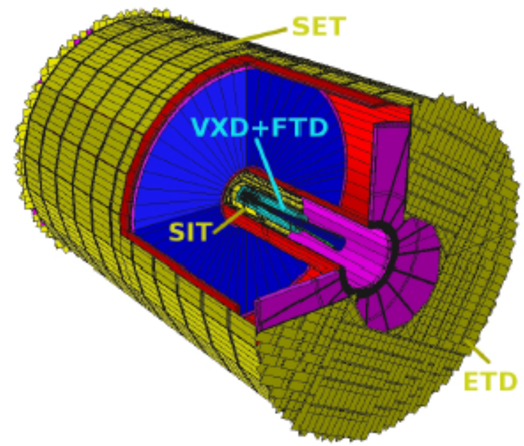
ILD

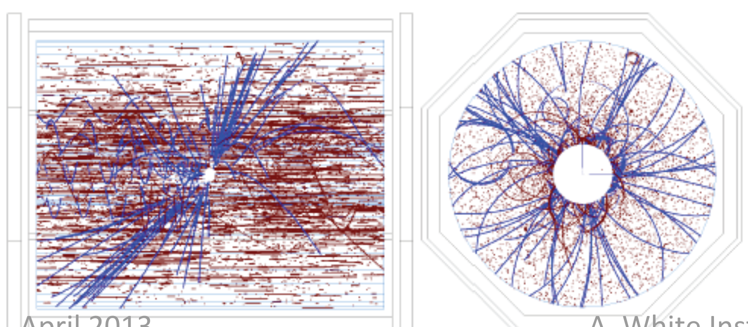


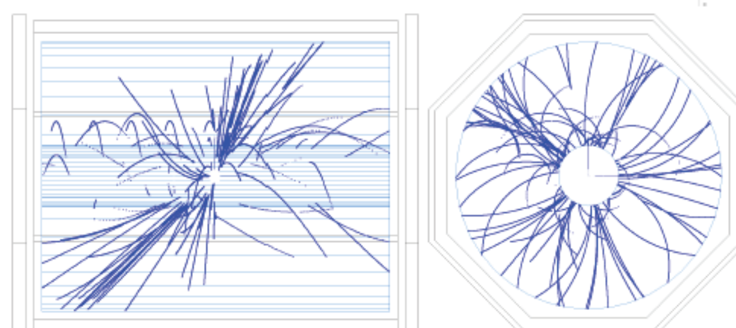
Silicon layers around a TPC





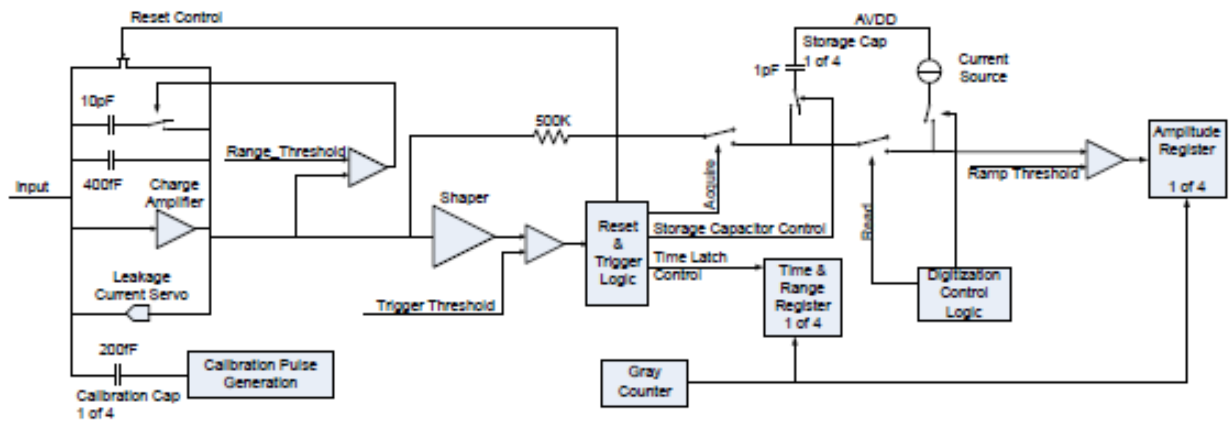




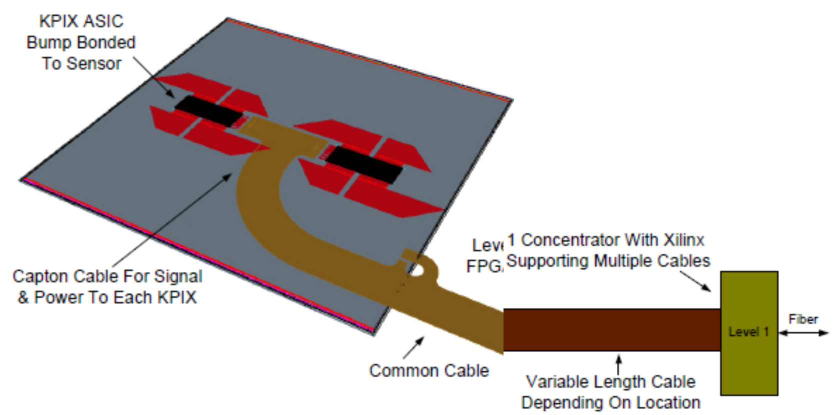


Electronics

SLAC KPiX
1024 channels

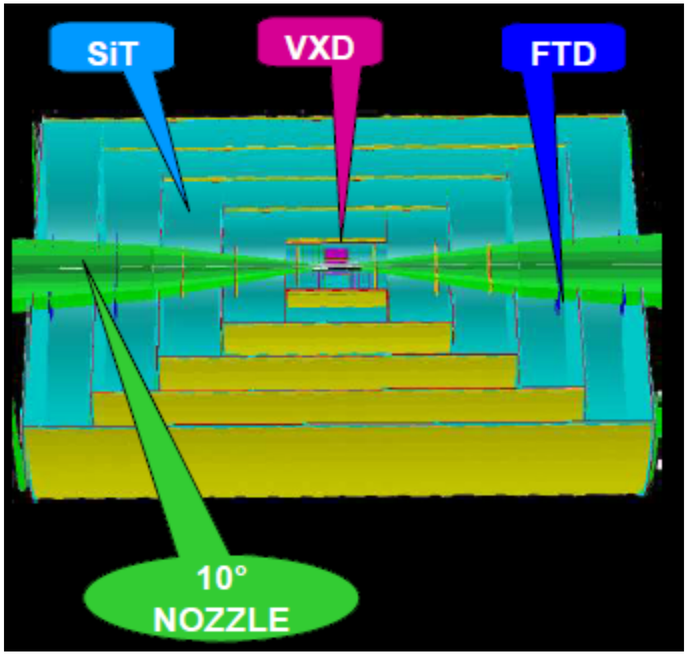


KPiX application to
SiD tracker



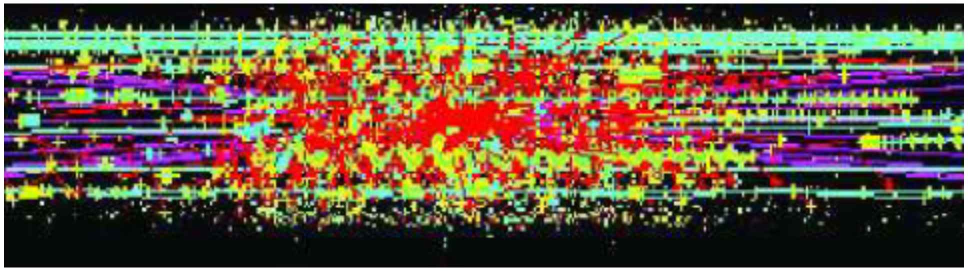
Tracking - challenges

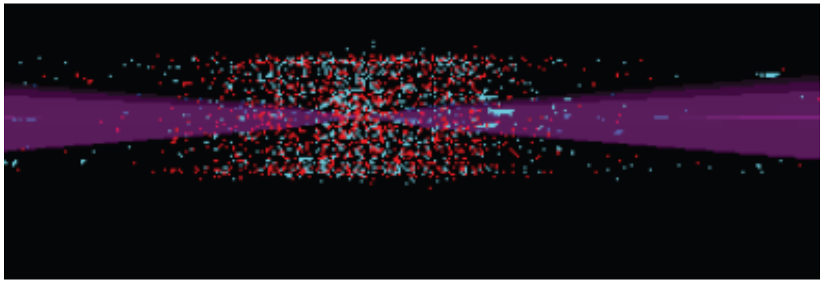
Muon Collider



Backgrounds very large!
-> need radiation hard devices

Use "traveling trigger" idea (as for calorimetry – see later)?





EM hits in time with traveling trigger

Potential applications to other Frontiers

What are limiting factors for CLFV?

- **Tracking**: requirement of precision tracking with very low (<<1% X_o) mass to reject backgrounds

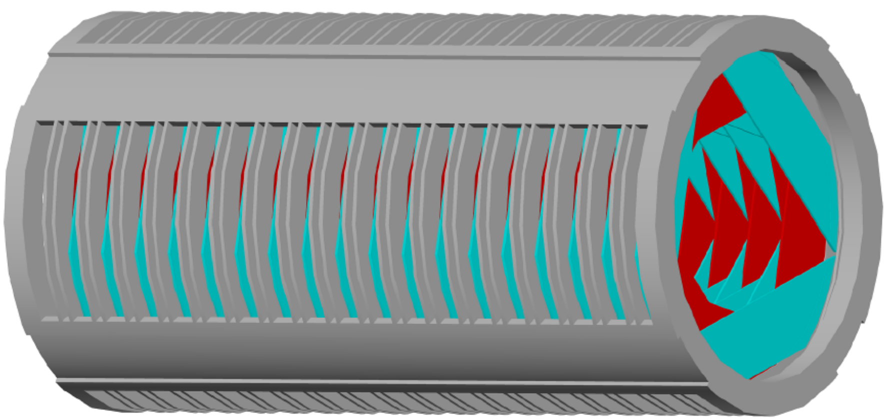
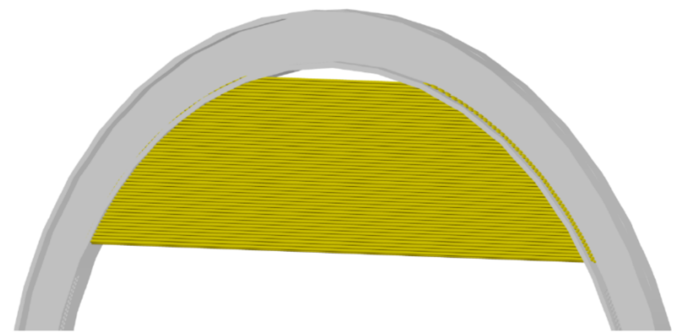


Figure 9.8. The assembled tracker.

Mu2e



Space-based experiments – low mass, radiation tolerant tracking systems?

ILC Physics and Detector Challenges

TABLE II: Benchmark reactions for the evaluation of ILC detectors

	Process and Final states	Energy (TeV)	Observables	Target Accuracy	Detector Challenge	Notes
Higgs	$ee \to Z^0h^0 \to \ell^+\ell^- X$	0.35	M_{recoil}, σ_{Zh}, BR_{bb}	$\delta\sigma_{Zh} = 2.5\%$, $\delta BR_{bb} = 1\%$	T	{1}
	$ee \to Z^0h^0$, $h^0 \to b\bar{b}/c\bar{c}/\tau\tau$	0.35	Jet flavour , jet $(E, \vec{p})$	δM_h=40 MeV, $\delta(\sigma_{Zh} \times BR)$=1%/7%/5%	V	{2}
	$ee \to Z^0h^0, h^0 \to WW^*$	0.35	M_Z, M_W, σ_{qqWW^*}	$\delta(\sigma_{Zh} \times BR_{WW^*})$=5%	C	{3}
	$ee \to Z^0h^0/h^0\nu\bar{\nu}$, $h^0 \to \gamma\gamma$	1.0	$M_{\gamma\gamma}$	$\delta(\sigma_{Zh} \times BR_{\gamma\gamma})$=5%	C	{4}
	$ee \to Z^0h^0/h^0\nu\bar{\nu}$, $h^0 \to \mu^+\mu^-$	1.0	$M_{\mu\mu}$	5σ Evidence for $M_h = 120$ GeV	T	{5}
	$ee \to Z^0h^0, h^0 \to invisible$	0.35	σ_{qqE}	5σ Evidence for $BR_{invisible}$=2.5%	C	{6}
	$ee \to h^0\nu\bar{\nu}$	0.5	$\sigma_{bb\nu\nu}$, M_{bb}	$\delta(\sigma_{\nu\nu h} \times BR_{bb}) = 1\%$	C	{7}
	$ee \to t\bar{t}h^0$	1.0	σ_{tth}	δg_{tth}=5%	C	{8}
	$ee \to Z^0h^0h^0$, $h^0h^0\nu\bar{\nu}$	0.5/1.0	σ_{Zhh}, $\sigma_{\nu\nu hh}$, M_{hh}	δg_{hhh}=20/10%	C	{9}
SSB	$ee \to W^+W^-$	0.5		$\Delta\kappa_\gamma, \lambda_\gamma = 2 \cdot 10^{-4}$	V	{10}
	$ee \to W^+W^-\nu\bar{\nu}/Z^0Z^0\nu\bar{\nu}$	1.0	σ	$\Lambda_{*4}, \Lambda_{*5} = 3$ TeV	C	{11}
SUSY	$ee \to \tilde{e}_R^+\tilde{e}_R^-$ (Point 1)	0.5	E_e	$\delta M_{\tilde{\chi}_1^0}$=50 MeV	T	{12}
	$ee \to \tilde{\tau}_1^+\tilde{\tau}_1^-, \tilde{\chi}_1^+\tilde{\chi}_1^-$ (Point 1)	0.5	E_π, $E_{2\pi}$, $E_{3\pi}$	$\delta(M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0})$=200 MeV	T	{13}
	$ee \to \tilde{t}_1\bar{\tilde{t}}_1$ (Point 1)	1.0		$\delta M_{\tilde{t}_1}$=2 GeV		{14}
-CDM	$ee \to \tilde{\tau}_1^+\tilde{\tau}_1^-, \tilde{\chi}_1^+\tilde{\chi}_1^-$ (Point 3)	0.5		$\delta M_{\tilde{\tau}_1}$=1 GeV, $\delta M_{\tilde{\chi}_1^0}$=500 MeV,	F	{15}
	$ee \to \tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_1^+\tilde{\chi}_1^-$ (Point 2)	0.5	M_{jj} in $jj\not{E}$, $M_{\ell\ell}$ in $jj\ell\ell\not{E}$	$\delta\sigma_{\tilde{\chi}_2\tilde{\chi}_3} = 4\%$, $\delta(M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0})$= 500 MeV	C	{16}
	$ee \to \tilde{\chi}_1^+\tilde{\chi}_1^-/\tilde{\chi}_i^0\tilde{\chi}_j^0$ (Point 5)	0.5/1.0	$ZZ\not{E}$, $WW\not{E}$	$\delta\sigma_{\tilde{\chi}\tilde{\chi}}$=10%, $\delta(M_{\tilde{\chi}_3^0} - M_{\tilde{\chi}_1^0})$ =2 GeV	C	{17}
	$ee \to H^0A^0 \to b\bar{b}b\bar{b}$ (Point 4)	1.0	Mass constrained M_{bb}	δM_A=1 GeV	C	{18}
-alternative	$ee \to \tilde{\tau}_1^+\tilde{\tau}_1^-$ (Point 6)	0.5	Heavy stable particle	$\delta M_{\tilde{\tau}_1}$	T	{19}
SUSY	$\tilde{\chi}_1^0 \to \gamma + \not{E}$ (Point 7)	0.5	Non-pointing γ	$\delta c\tau$=10%	C	{20}
breaking	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + \pi^\pm_{soft}$ (Point 8)	0.5	Soft $\pi^\pm$ above $\gamma\gamma$ bkgd	5σ Evidence for $\Delta\tilde{m}$=0.2-2 GeV	F	{21}
Precision SM	$ee \to t\bar{t} \to 6\ jets$	1.0		5σ Sensitivity for $(g-2)_t/2 \leq 10^{-3}$	V	{22}
	$ee \to f\bar{f}$ $(f = e, \mu, \tau; b, c)$	1.0	σ_{ff}, A_{FB}, A_{LR}	5σ Sensitivity to $M_{Z_{LR}} = 7$ TeV	V	{23}
New Physics	$ee \to \gamma G$ (ADD)	1.0	$\sigma(\gamma + \not{E})$	5σ Sensitivity	C	{24}
	$ee \to KK \to f\bar{f}$ (RS)	1.0			T	{25}
Energy/Lumi	$ee \to ee_{fwd}$	0.3/1.0		δM_{top}=50 MeV	T	{26}
Meas.	$ee \to Z^0\gamma$	0.5/1.0			T	{27}

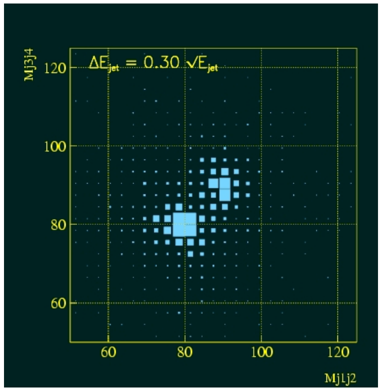
From M. Battaglia etc al. SLAC-PUB-11877

Calorimetry - goal

- Many physics processes for future linear colliders involve jets
- For precision studies, require excellent jet energy and jet-jet mass resolutions.

- The goal is 3% $\Delta E_{jet}/E_{jet}$ (set at $M_{W/Z}$ scale by requirement to separate W and Z bosons):

- Take 3% $\Delta E_{jet}/E_{jet}$ as a general goal for all jet energies



30%/√E

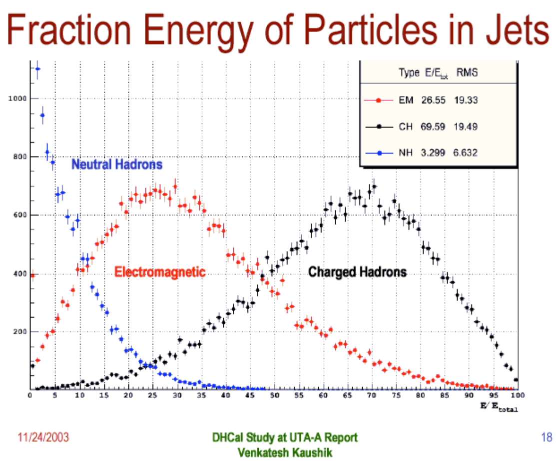
- The issue is then – how to achieve this goal

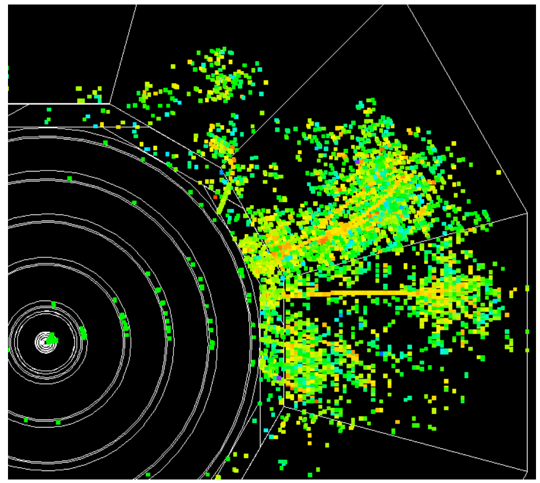
- Two basically different approaches:

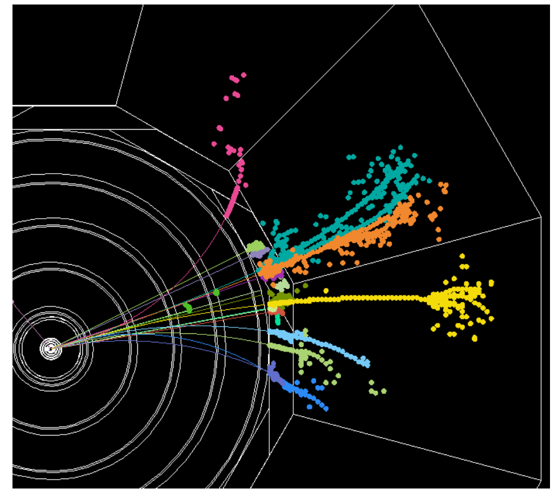
Calorimetry - designs

Achieving excellent jet energy resolution:

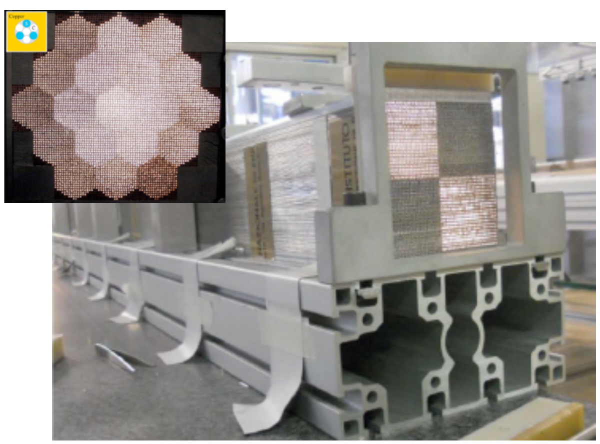
Particle flow



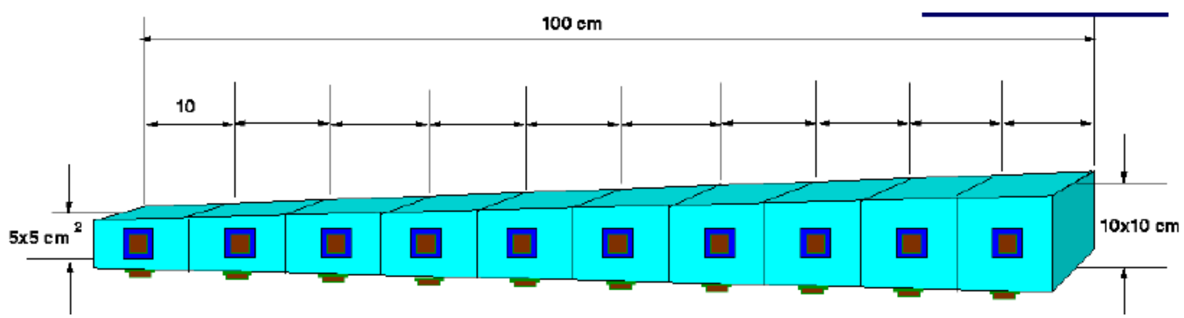




Dual readout



DREAM



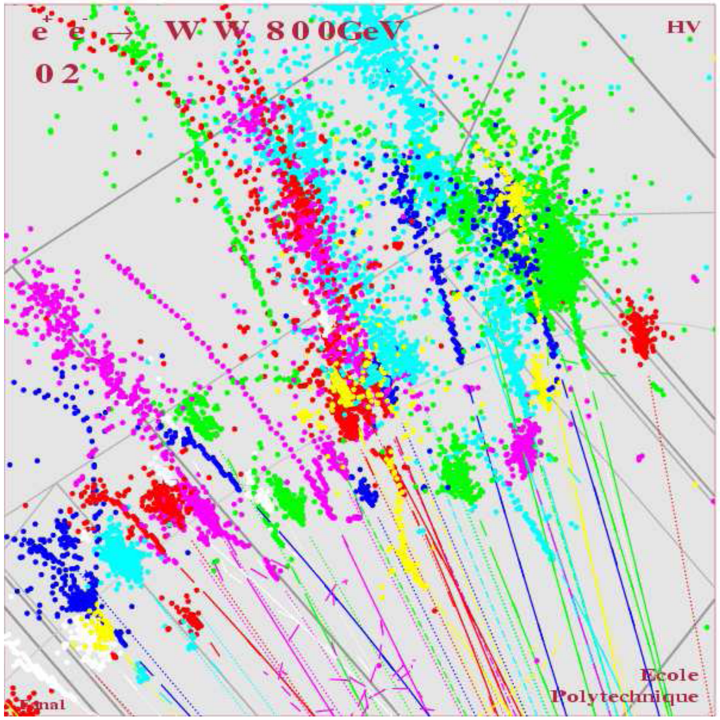
HOMOGENEOUS

Calorimetry - challenges

Implementing a successful PFA system is both a hardware and a software challenge

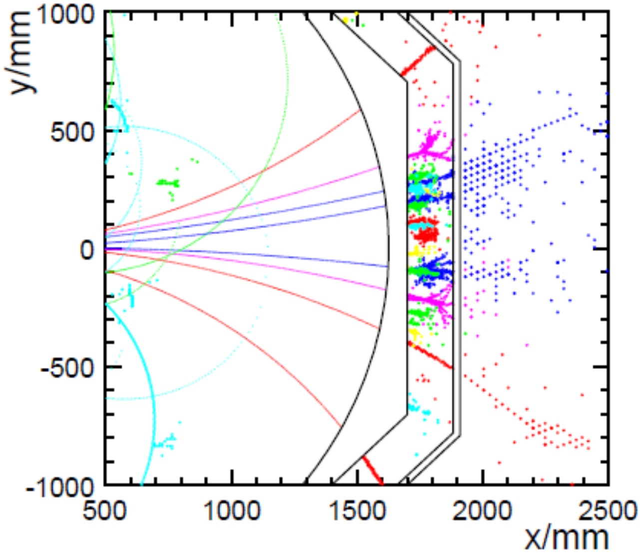
Requires an integrated approach to detector design: tracking ⊕ calorimetry

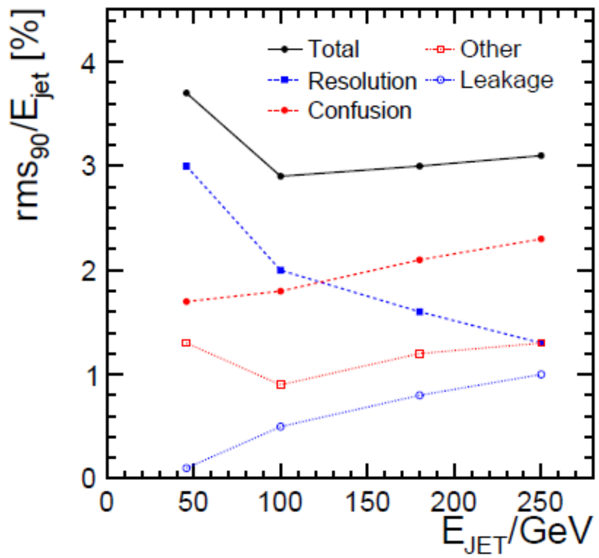
-> Requires "tracking calorimeters" – follow charged particles and associate with energy depositions
-> Requires high degrees of transverse and longitudinal segmentation – reduce "confusion" term especially for high energy jets
-> Requires thin active layers – contain ~40 layers inside magnet and contain cost
-> Requires sufficient depth to restrict losses due to leakage
+ timing for bunch resolution, stability, survivability, calibration, …



Calorimetry – challenge met

PANDORA/PFA M. Thompson



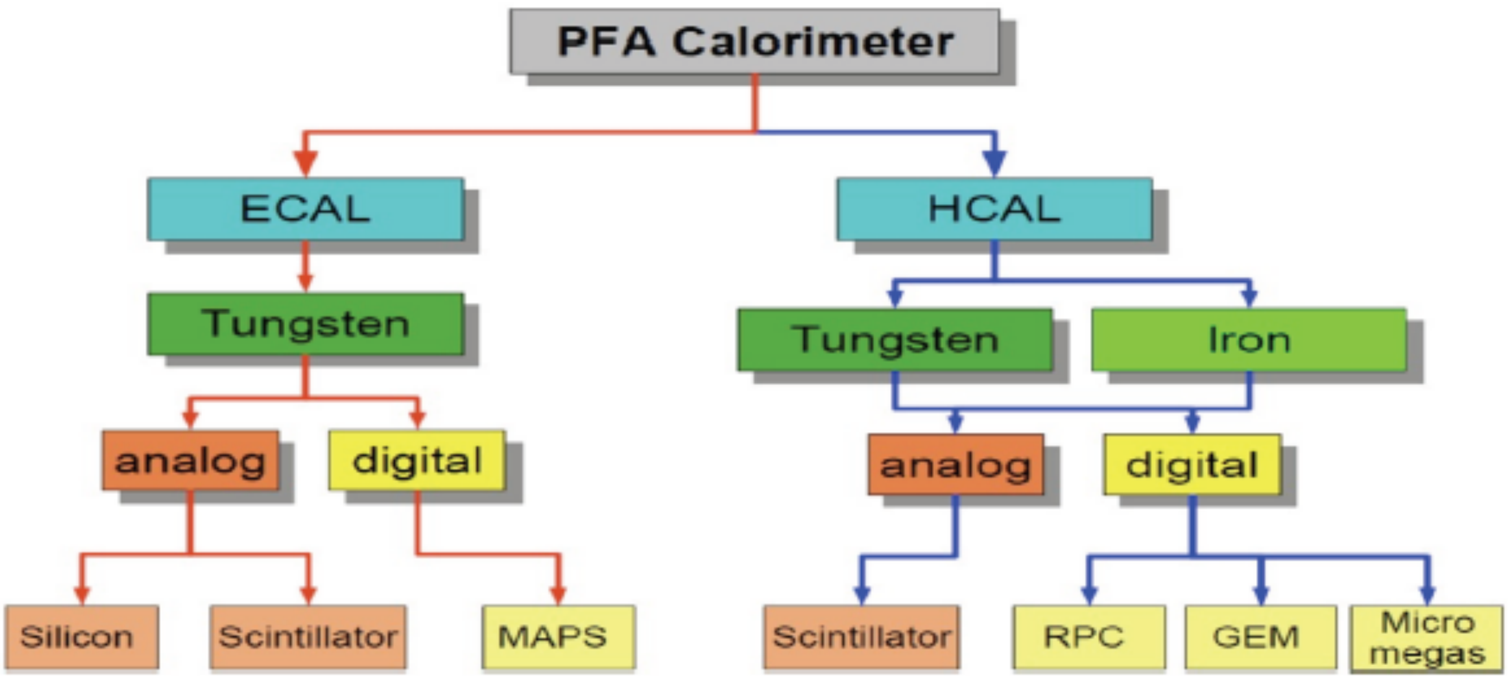


Alternative PFA developed by U. Iowa
- Being used in a SiD DBD process

Jet Energy	rms	$rms_{90}(E_{jj})$	$rms_{90}(E_{jj})/\sqrt{E_{jj}}$	$rms_{90}(E_j)/E_j$
45 GeV	3.4 GeV	2.4 GeV	25.2 %	(3.74 ± 0.05) %
100 GeV	5.8 GeV	4.1 GeV	29.2 %	(2.92 ± 0.04) %
180 GeV	11.6 GeV	7.6 GeV	40.3 %	(3.00 ± 0.04) %
250 GeV	16.4 GeV	11.0 GeV	49.3 %	(3.11 ± 0.05) %
375 GeV	29.1 GeV	19.2 GeV	81.4 %	(3.64 ± 0.05) %
500 GeV	43.3 GeV	28.6 GeV	91.6 %	(4.09 ± 0.07) %

Table 3: Jet energy resolution for $Z \rightarrow uds$ events with $|\cos\theta_{q\bar{q}}| < 0.7$, expressed as: i) the rms of the reconstructed di-jet energy distribution, E_{jj}; ii) rms_{90} for E_{jj}; iii) the effective constant α in $rms_{90}(E_{jj})/E_{jj} = \alpha(E_{jj})/\sqrt{E_{jj}(\mathrm{GeV})}$; and iv) the fractional jet energy resolution for a single jet where $rms_{90}(E_j) = rms_{90}(E_{jj})/\sqrt{2}$.

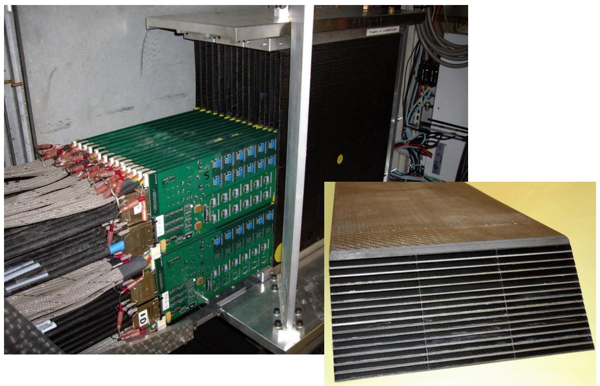
We have risen to the challenge
– no shortage of ways to implement PFA !



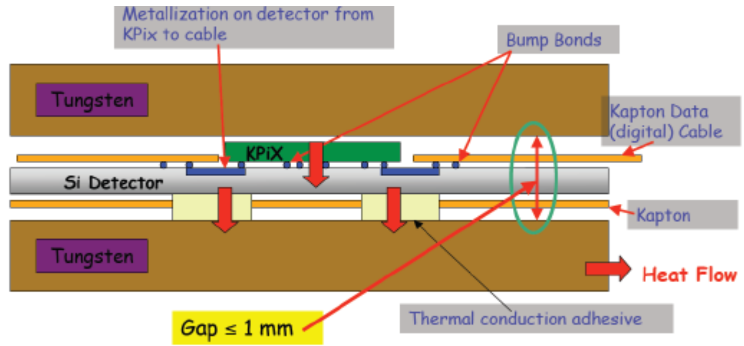
Calorimetry – challenges being met

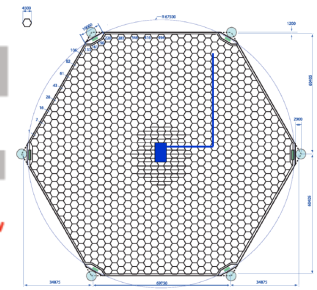
ECAL

Active layer 1.25mm !

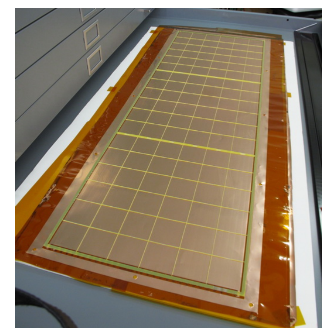


CALICE Si/W ECal



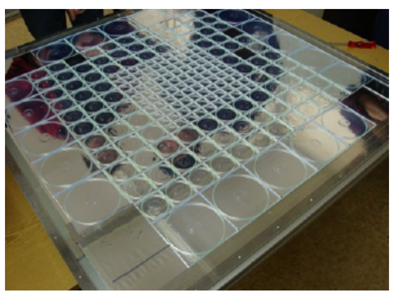


SiD Si/W ECal



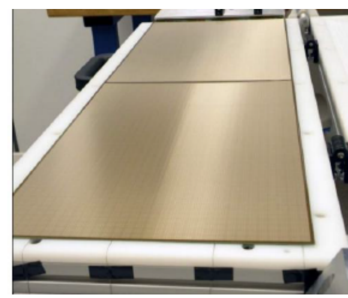
HCAL

Glass RPC

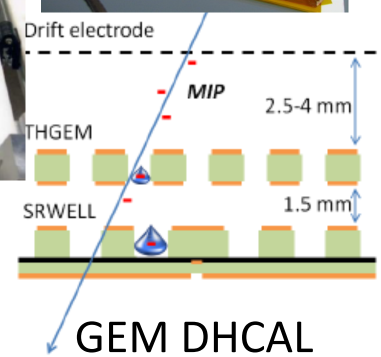


Scintillator AHCAL

SDHCAL



Micromegas DHCAL



GEM DHCAL

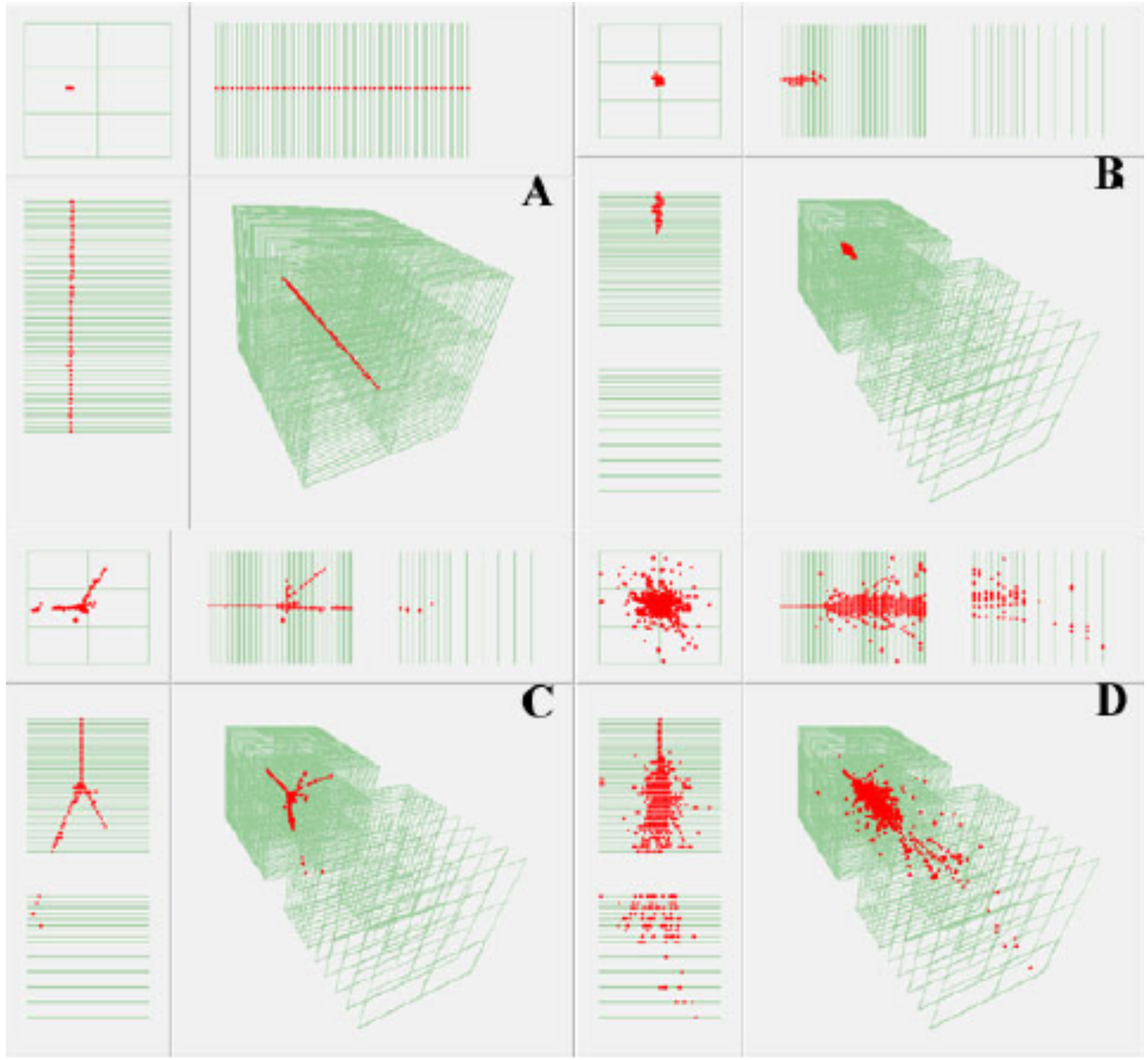
Calorimetry – challenges being met

ANL RPC Digital Hcal

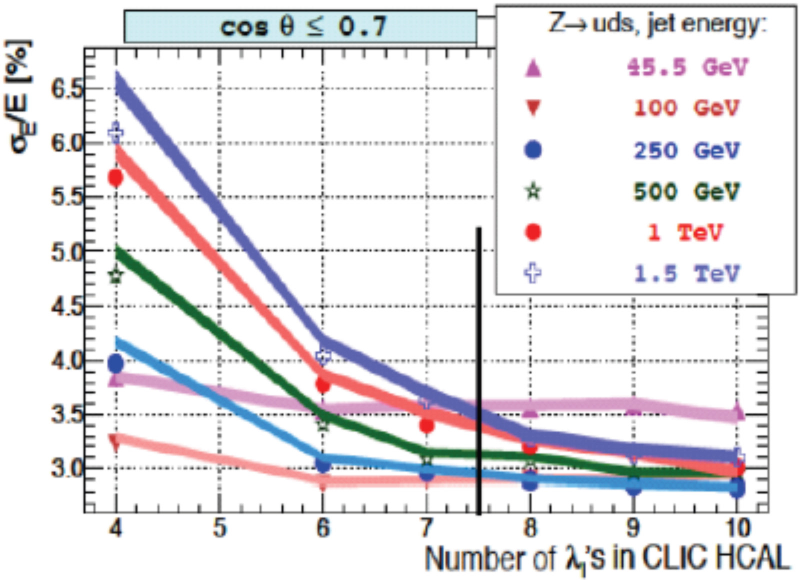
Major advance in study of hadronic showers

1 cm^2 cells

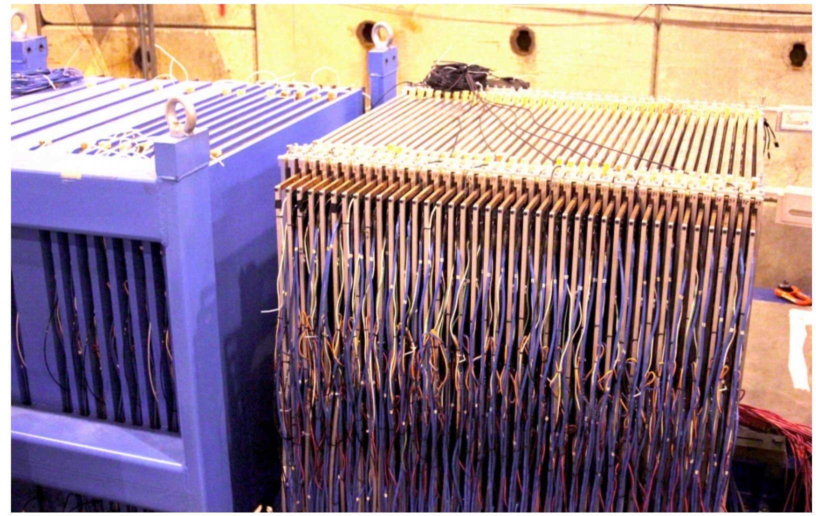
0.5M cells in $1m^3$!



Calorimetry – challenges being met



CLIC



CERN test beam – RPC/Tungsten plates

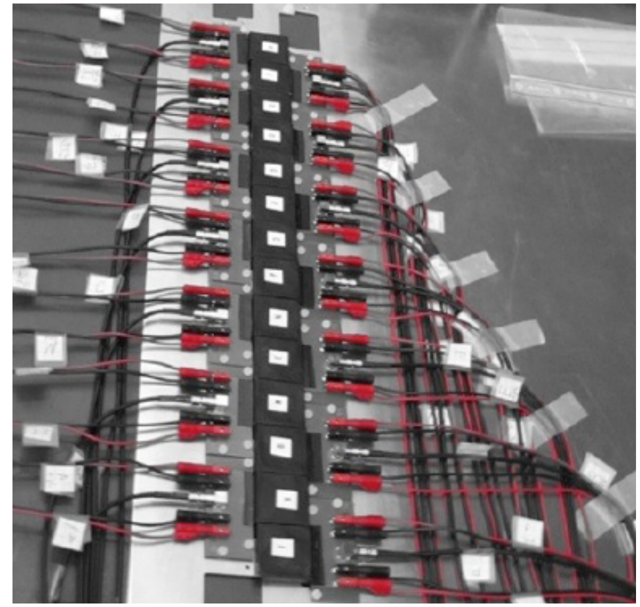
Jet Energy	$\mathrm{rms}_{90}(E_{jj})/\sqrt{E_{jj}}$		$\mathrm{rms}_{90}(E_j)/E_j$	
	3.5 T & 6 λ_I	4 T & 8 λ_I	3.5 T & 6 λ_I	4 T & 8 λ_I
45 GeV	25.2 %	25.2 %	(3.74 ± 0.05) %	(3.74 ± 0.05) %
100 GeV	29.2 %	28.7 %	(2.92 ± 0.04) %	(2.87 ± 0.04) %
180 GeV	40.3 %	37.5 %	(3.00 ± 0.04) %	(2.80 ± 0.04) %
250 GeV	49.3 %	44.7 %	(3.11 ± 0.05) %	(2.83 ± 0.05) %
375 GeV	81.4 %	71.7 %	(3.64 ± 0.05) %	(3.21 ± 0.05) %
500 GeV	91.6 %	78.0 %	(4.09 ± 0.07) %	(3.49 ± 0.07) %

Calorimetry – challenges being met

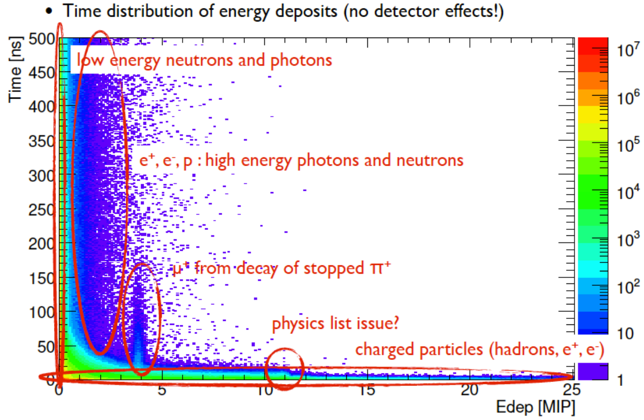
Frank Simon – TIPP2011

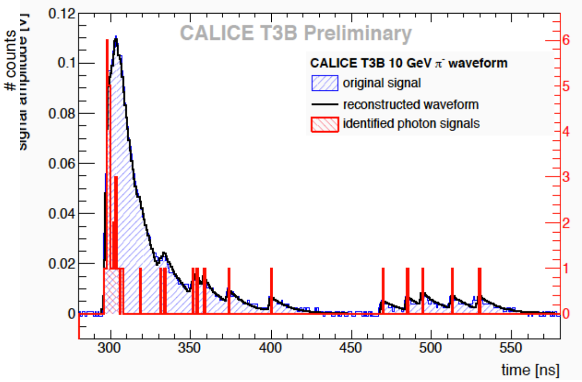
- $\gamma\gamma \rightarrow$ hadrons substantial:
  ~ 12 hadrons/bunch crossing in the barrel region
  (4 GeV / bunch crossing) [up to 50 hadrons /
  50 - 60 GeV barrel + endcap + plug calorimeters]
- extreme bunch crossing rate: every 0.5 ns

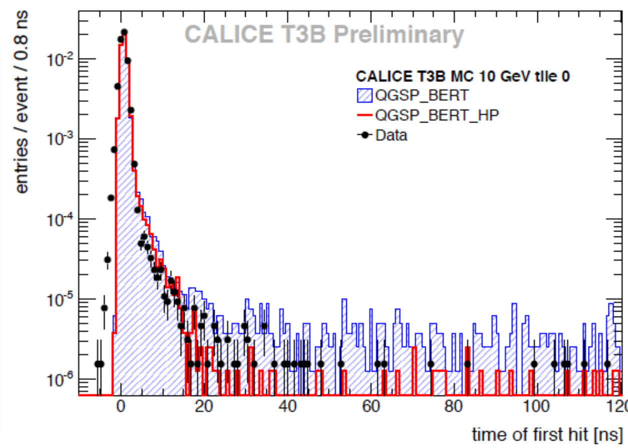
⇨ Very good time resolution in all detectors important to limit impact of background!



- Geant4 simulation of a 30 layer Scintillator-W calorimeter (QGSP_BERT)
  - Time distribution of energy deposits (no detector effects!)

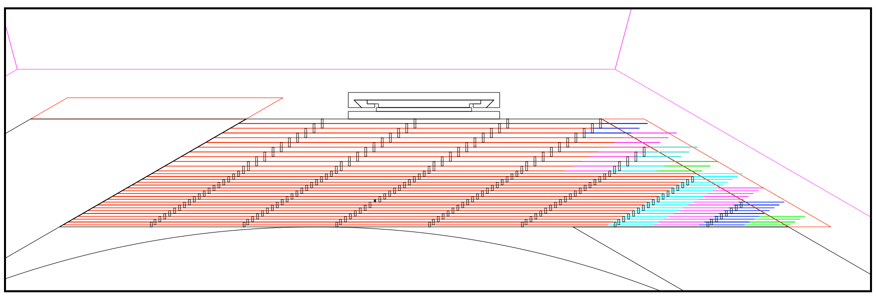




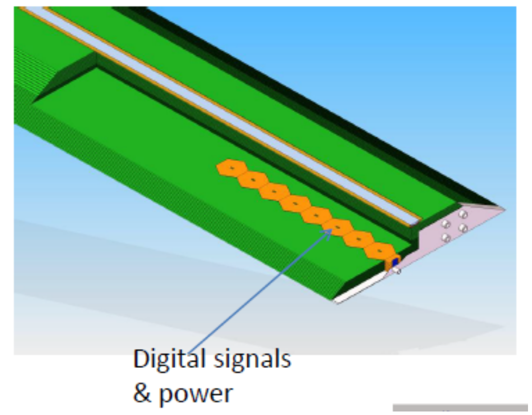


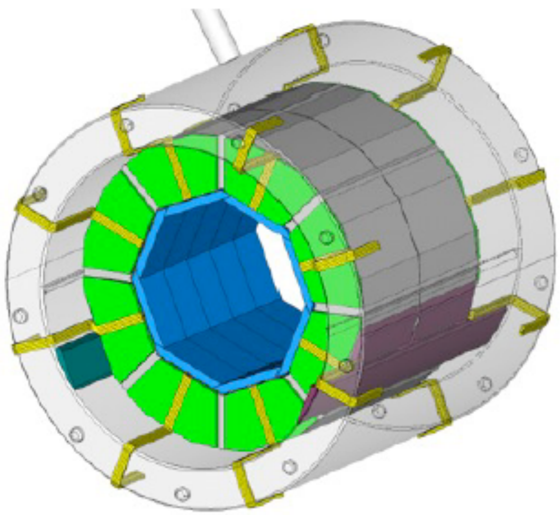
Calorimetry – current challenges

• Design of a fully realizable calorimeter module with full services as part of a complete calorimeter system design.

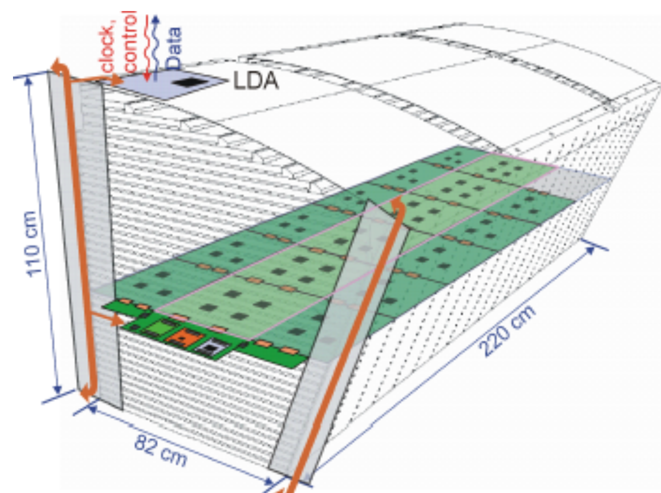


SiD ECAL





ILD AHCAL



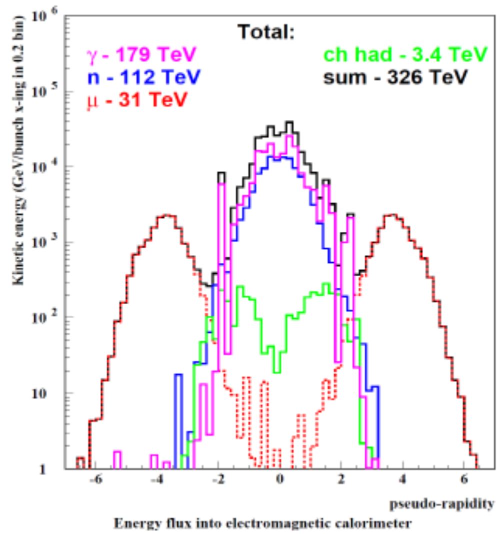
Calorimetry - challenges

Muon Collider

~100 TeV in HCAL for each bunch crossing !

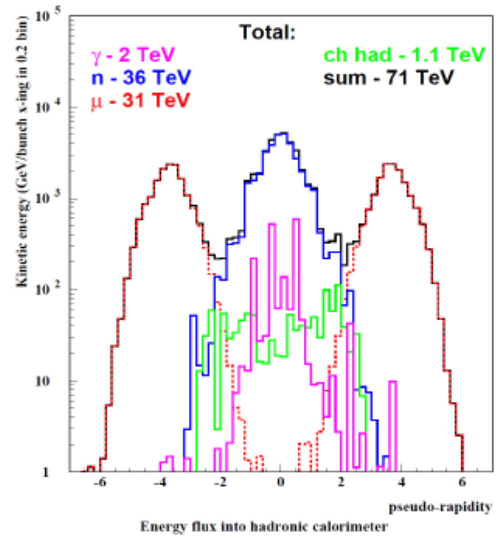
MARS Particles in Detector Volume		
Particle Type	Total Number	Total Kinetic Energy (TeV)
EM	1.785E8	169.9
MUONS	8021.	184.4
MESONS	17589.	6.8
BARYONS	0.409E8	177.4

Energy Flow into Ecal



Peak: ~1 GeV / 2x2 cm^2 cell with σ_E ~ 30 MeV

Energy Flow into Hcal



Peak: ~1.5 GeV / 5x5 cm^2 cell with σ_E ~ 80 MeV

"Traveling gate trigger" idea (R. Raja) with pixel (200μm) calorimeter
- Trigger for every crossing – timing "travels out" at v = c through calorimeter and gates each pixel
- Separate EM/Hadronic energy depositions via pattern recognition + use "compensation".

Particle Type	Total Number	$\delta_t < 2$ns	Surviving fraction
EM	1.79E+08	2.17E+06	1.21E-02
MUONS	8.02E+03	1.83E+03	2.28E-01
MESONS	1.76E+04	2.66E+03	1.51E-01
BARYONS	4.09E+07	3.93E+05	9.62E-03

Calorimetry – next challenges

Many other areas that are being addressed for ILC/CLIC and need to be addressed for other colliders:

e.g. Power pulsing, Cooling, Alignment,…

Also room for other ideas:

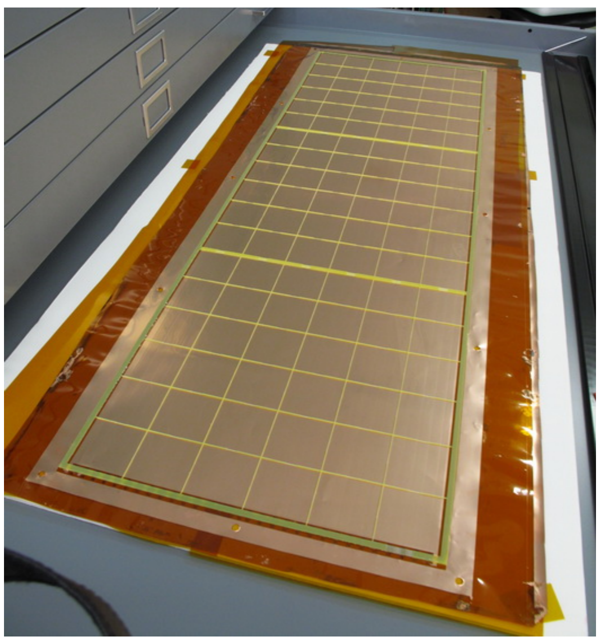
e.g. could be move some PFA functions into hardware? Local track/cluster associations, using double-layer vectors?

For Dual readout – fiber or homogeneous – need a specific design for a lepton collider detector – then show its physics performance.

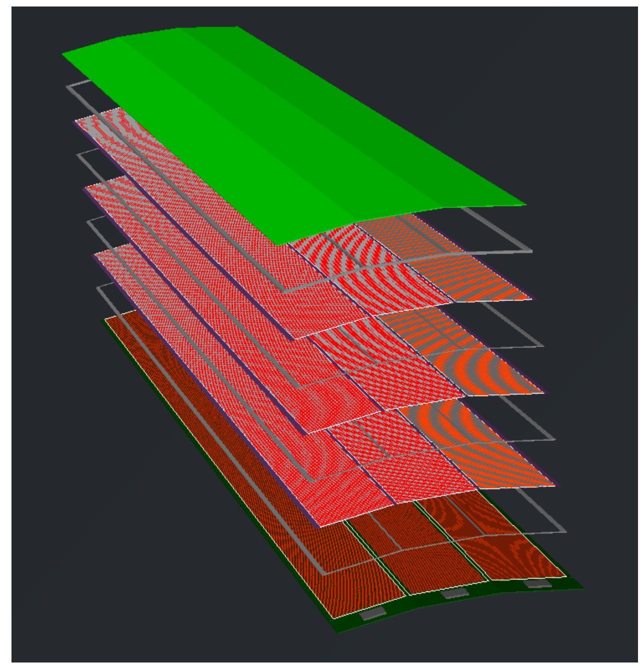
Potential applications to other Frontiers

Large (1m x 33cm) GEM foils/ chambers being developed for Linear Collider digital hadron calorimetry

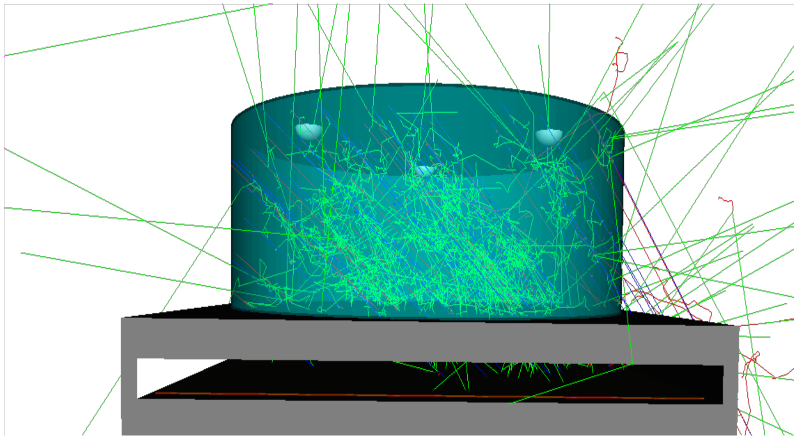
Proposed for ORKA experiment Range Stack



UTA

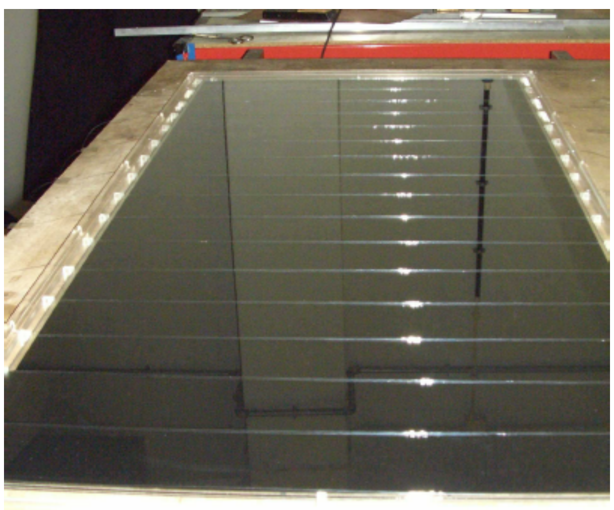


Potential applications to other Frontiers



Cosmic Frontier

Cosmic Ray – pointing?



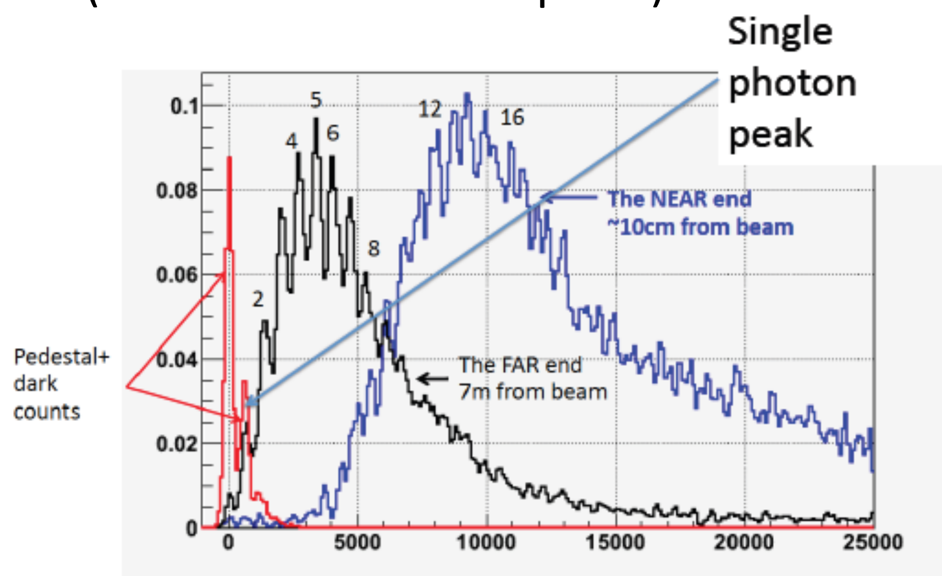
Large area RPC's

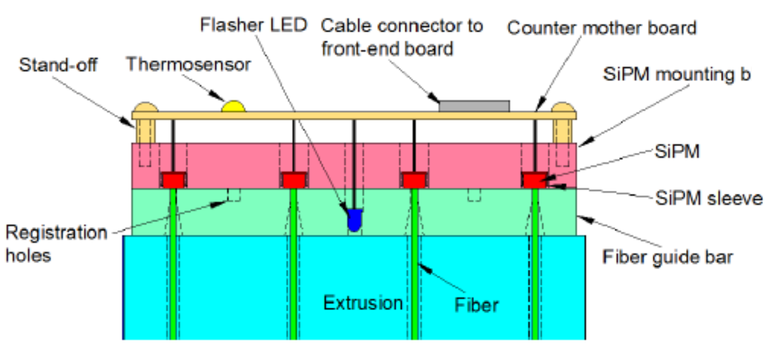
Muon System

Major change of baseline vs. LOI:

Scintillating strips/wavelength shifting fibers

(RPC remains as an option)

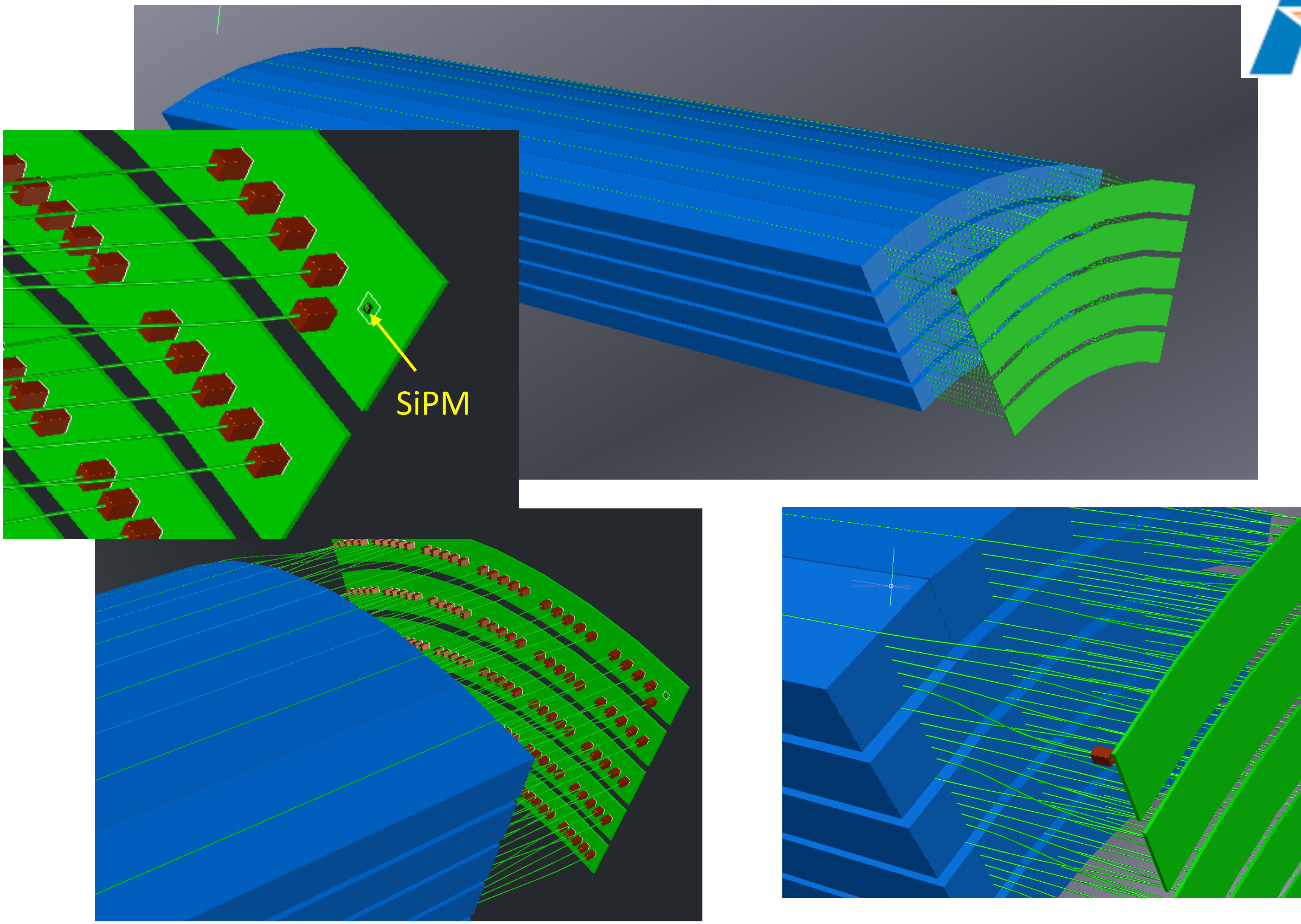




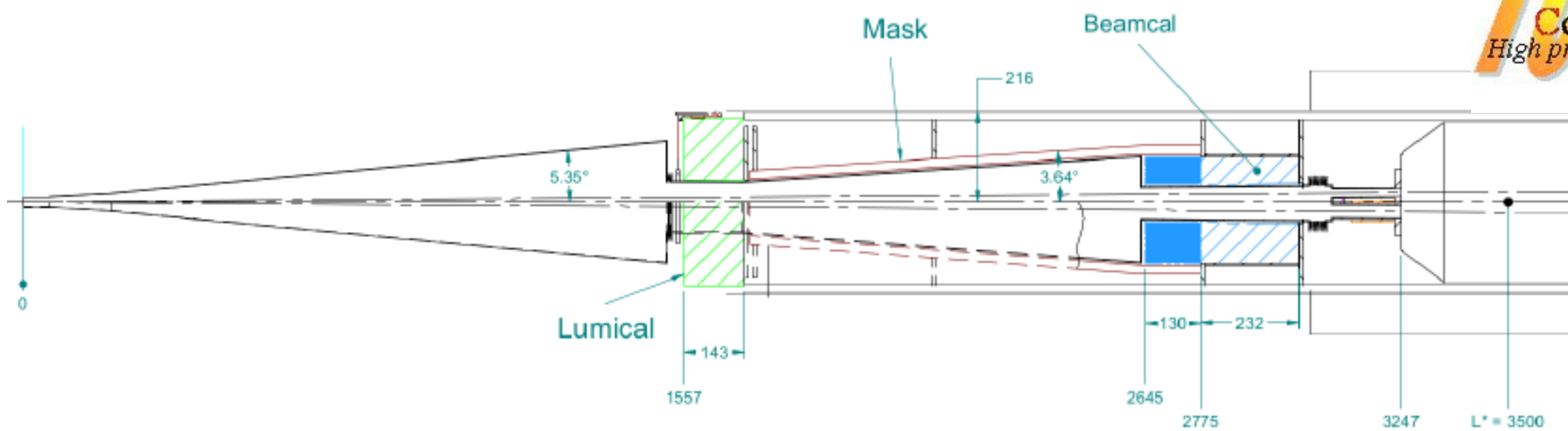
Development of system to position SiPM at the end of a fiber

ORKA Range Stack
Scintillator and SiPM board

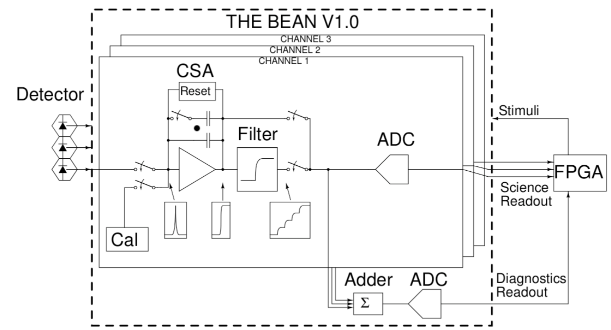
UTA



Forward Calorimetry

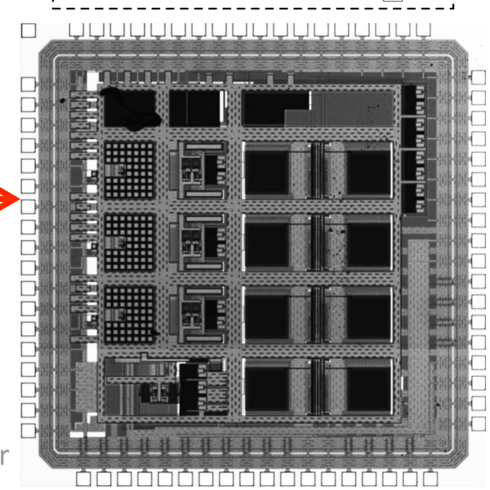


LumiCal - integrated luminosity and luminosity spectrum



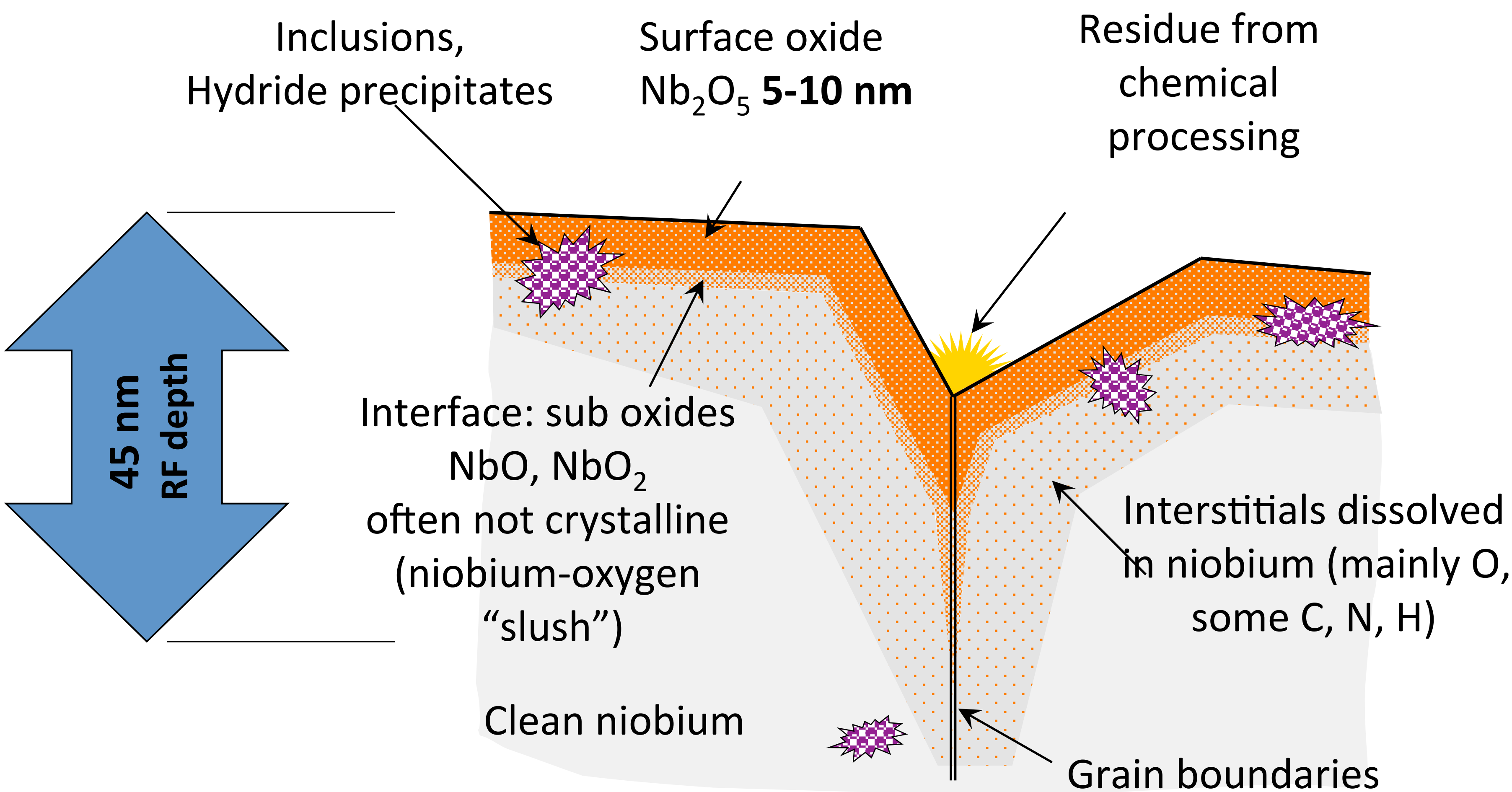
BeamCal – small angle coverage (with LumiCal), instantaneous luminosity

Dedicated ASIC (Bean chip) for high luminosity region



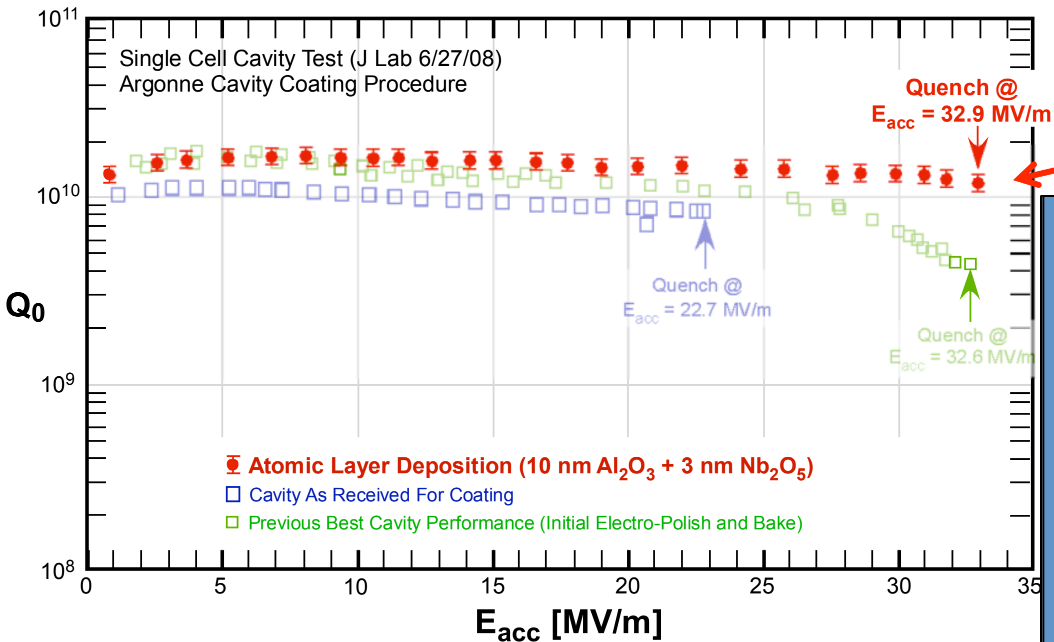
Accelerator/MDI Technology

Niobium surfaces are complex, important,
and currently poorly controlled at the nm level

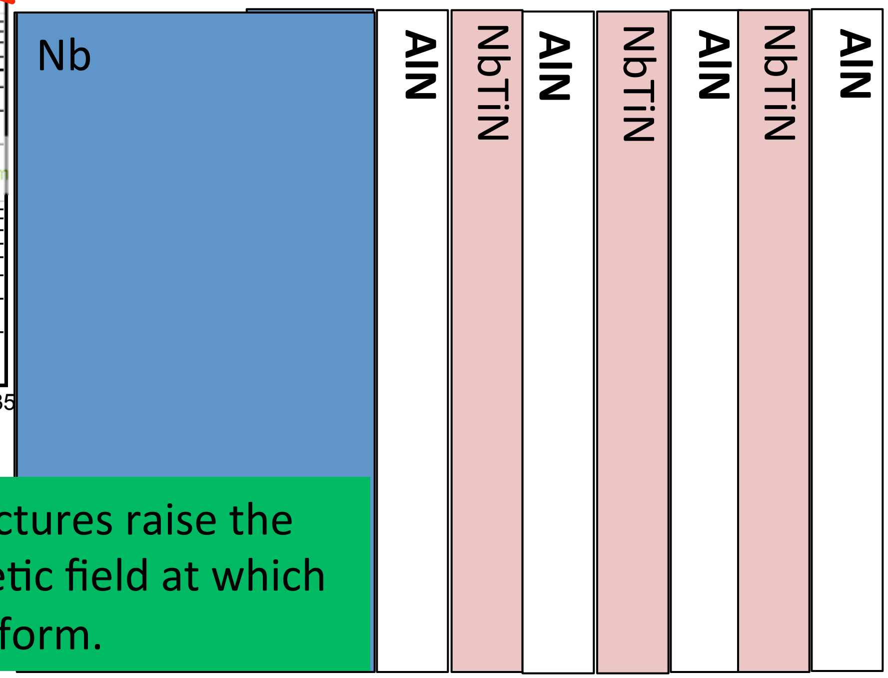


➡ **Probe the surface superconductivity**

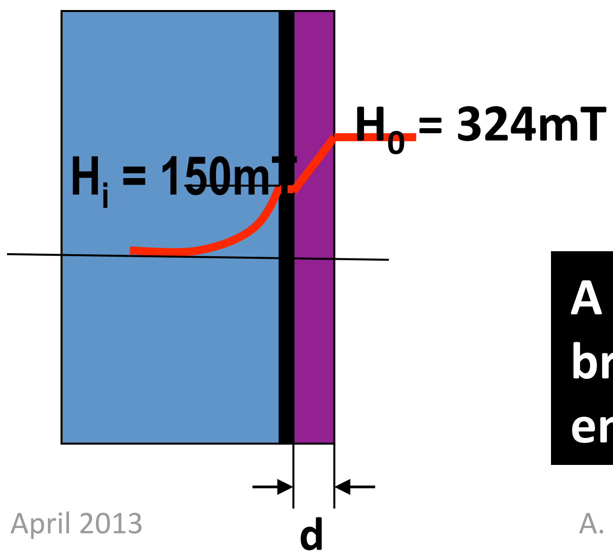
Accelerator/MDI Technology



ALD works !



•Layered structures raise the critical magnetic field at which vortex losses form.



A single layer coating more than doubles the breakdown field with no vortex penetration, enabling E_{acc}~ 100 MV/m

The story continues

New physics may well present new detector challenges!
Remain open to new technologies
Be prepared to adapt designs
Exploit synergies with other experiments/R&D
Follow new materials development
Use new techniques (3D printing?)

A large body of generic and concept specific R&D has been carried out
- essential to keep up the developments
- new CPAD in U.S. to promote instrumentation/exchange developments
- ECFA detector panel in Europe…

Detector R&D is the essential enabler of experiments!

e^+e^- Linear Colliders Detector Requirements and Limitations

Input to the Snowmass Instrumentation Frontier WG

Edited by Marcel Stanitzki and Andy White