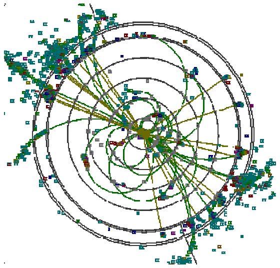
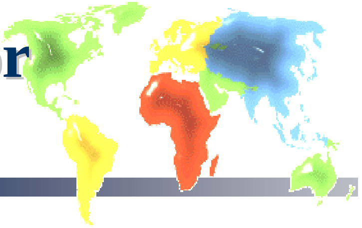


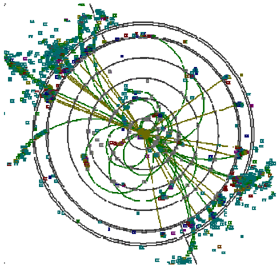
The Science and Challenges for Future Detector Development in High Energy Physics



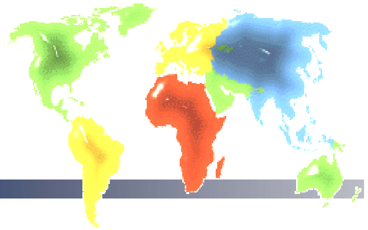
Future Detectors will include:

- Super Large Hadron Collider upgrades
  - High radiation, pileup, and backgrounds
- International Linear Collider Detectors
  - Precision measurements press detectors
- Super B Factory
  - 10^{36} luminosity presents many challenges
- Neutrino detectors
  - Massive, high efficiency
- Rare Kaon Decay, τ/Charm Detectors
  - High bandwidth, high precision

Other experiments critical to advances in HEP
(eg. dark matter detectors, or space-based experiments,
left for the Particle Astrophysics Introduction)



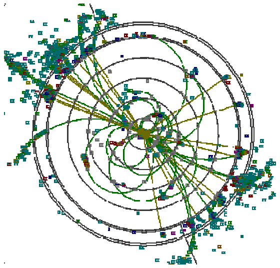
Challenges for Future Detector Development in High Energy Physics



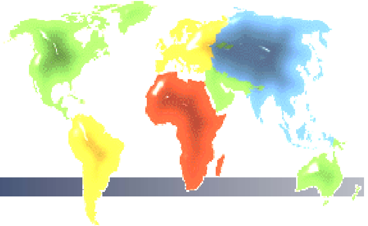
OUTLINE

- Physics Goals for the coming experiments
  - EWSB, SUSY, CKM and rare decays, neutrinos, …
- Experimental Opportunities
  - Super LHC, ILC, Super B Factory, Neutrinos
- Detector Challenges of Future Experiments
  - Precision, Rate, Radiation, Occupancies
- Some Important Trends in Detector Advances
  - Advances empower our exploration
- Examples of Proposed/Planned Future Detectors
  - Calorimetry
  - Silicon Detectors for Vertex Detectors and tracking
  - Gaseous Tracking
  - Cherenkov
  - Neutrinos

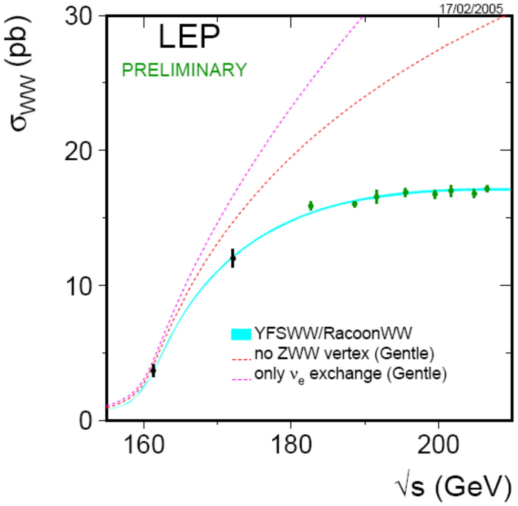
Note – necessarily biased by speaker’s familiarity
– apologies for omissions

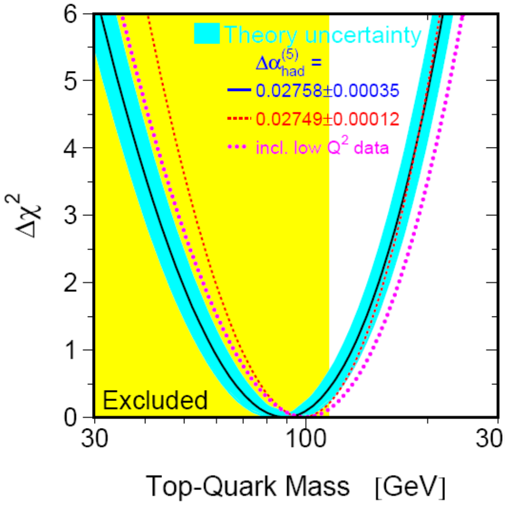


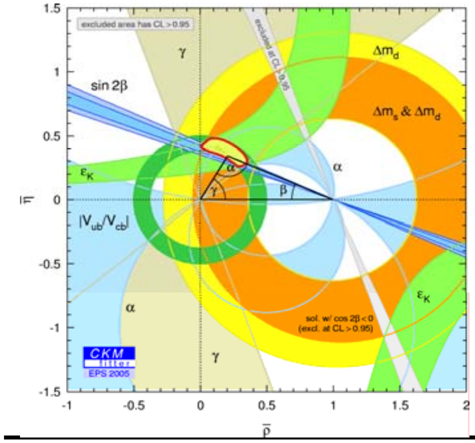
The State of Physics in 2006

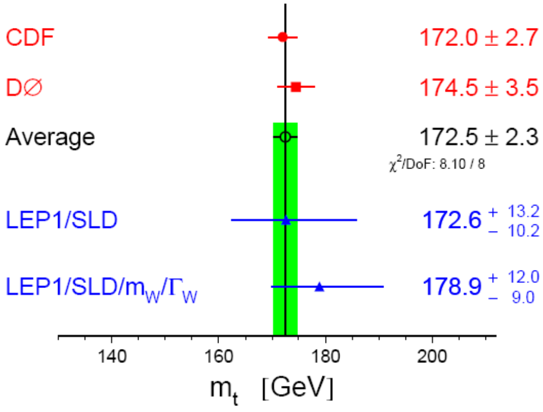


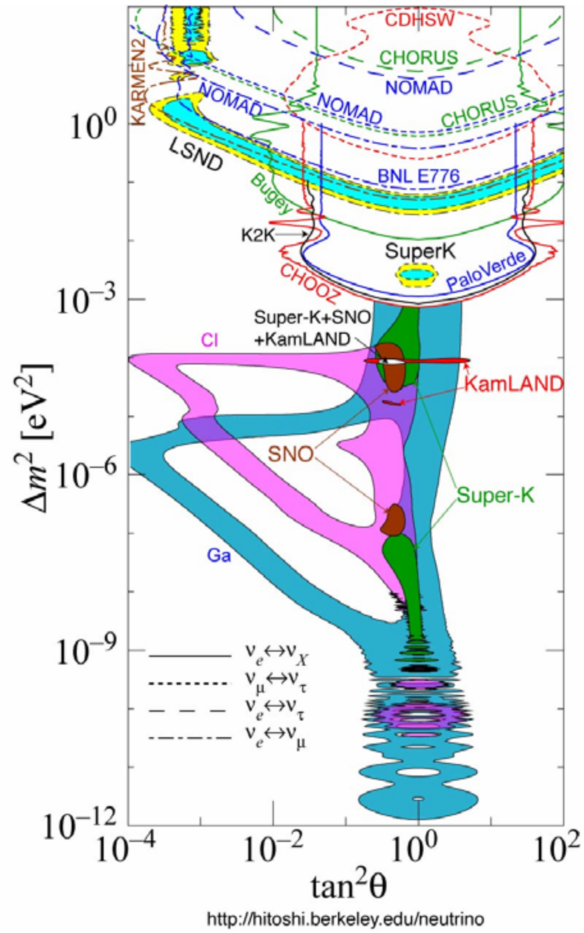
Standard Model is a well tested, precise description of what we have measured. But we are certain it is not a complete theory.

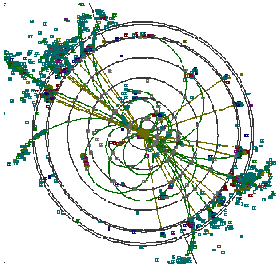




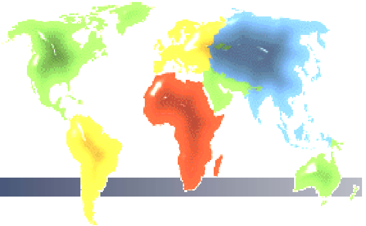








The State of Physics in 2006



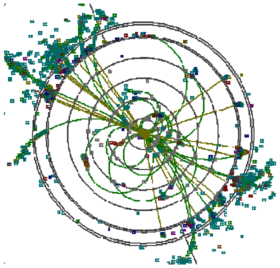
Some current fundamental priorities

- electroweak symmetry breaking and origin of mass
- hierarchy problem
- dark matter (dark energy)
- neutrino mass
- matter/anti-matter asymmetry
- unification of gravity (connection to extra dimensions?)

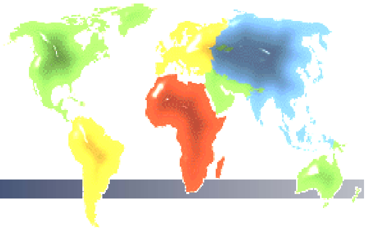
Experiment must lead the way to understanding of these issues

Detector R&D of is critical to advance our capabilities

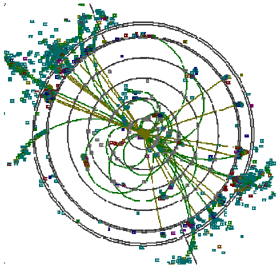
accelerator technology is advancing significantly
providing opportunities and increasing demands on detectors
physics questions demand ever improved detector capabilities



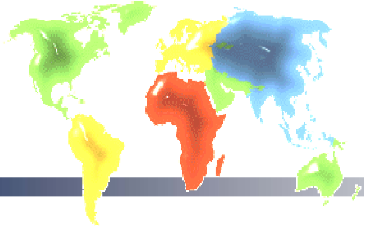
Experimental Opportunities



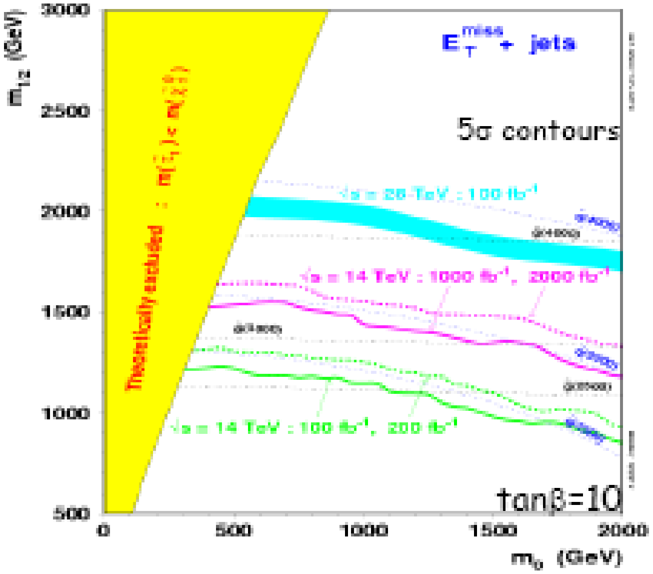
- Electroweak Symmetry Breaking
  - Discovery of Higgs – expected with LHC (Tevatron?)
  - Study of Higgs – precision measurements
  - or Investigation of other mechanisms
    - Strong interactions, Extra dimensions, or something else?
- Supersymmetry
  - Discovery of new form of matter
  - Precision measurements follow
- Rare decays
  - B, D, K, tau, mu
- Neutrinos
  - Oscillation measurements
  - Neutrinoless double beta decay
- Other important opportunities, notably those connected to Particle Astrophysics

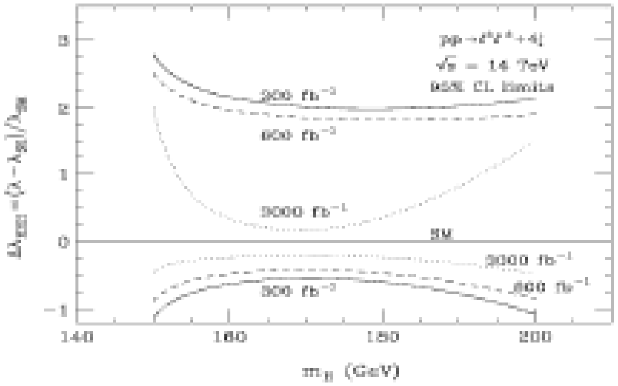


Super LHC Physics Motivation



- **Expand ATLAS/CMS physics potential with luminosity upgrade to 10^{35} cm^{-2} s^{-1} for**
  - Discoveries
    - increase mass reach by 20-30 %
    - access to rare decays (Higgs, FCNC top, …)
  - Precision measurements
    - Higgs-to-fermion/boson couplings
    - Higgs self-coupling (?)
    - TGCs, QGCs, strong VL-VL scattering
    - SUSY mass measurements (where rate limited)
- **Aim to exploit fully the increased potential of SLHC, with a performance similar to LHC**
  - Special need for improved tracking
  - Trigger and DAQ will demand significant mods
  - Other needs – eg. forward CMS crystals





Tapprogge, ATLAS

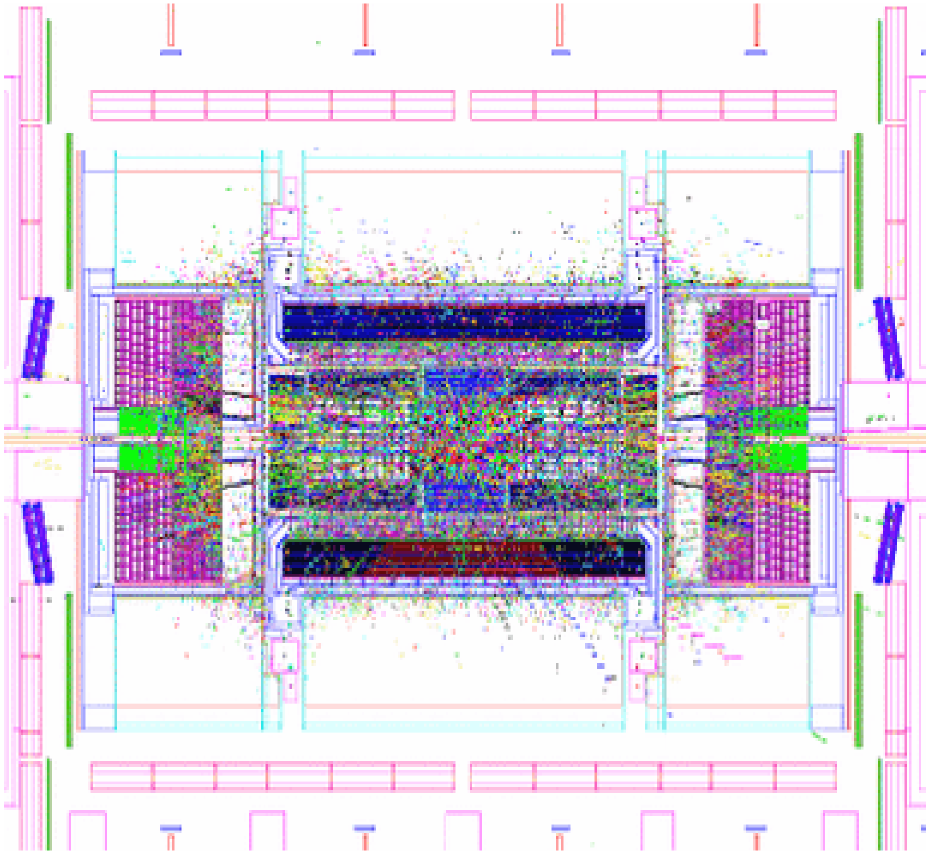
Super LHC Challenges

- **Central Radiation**
  - **fluence**
    - 10^{16} /cm^2 @ 5 cm (~400 MRad)
    - 10^{15} /cm^2 @ 20 cm (~40 MRad)
    - 2×10^{14} /cm^2 @ 50 cm (~10 MR)
  - **(dictates technology for tracker)**

- **Pileup**
  - 200* interactions/crossing
  - $dN_{ch}/d\eta(\eta=0) = 1500^*$
  - **(dictates geometry for tracker)**

- **Forward Radiation**

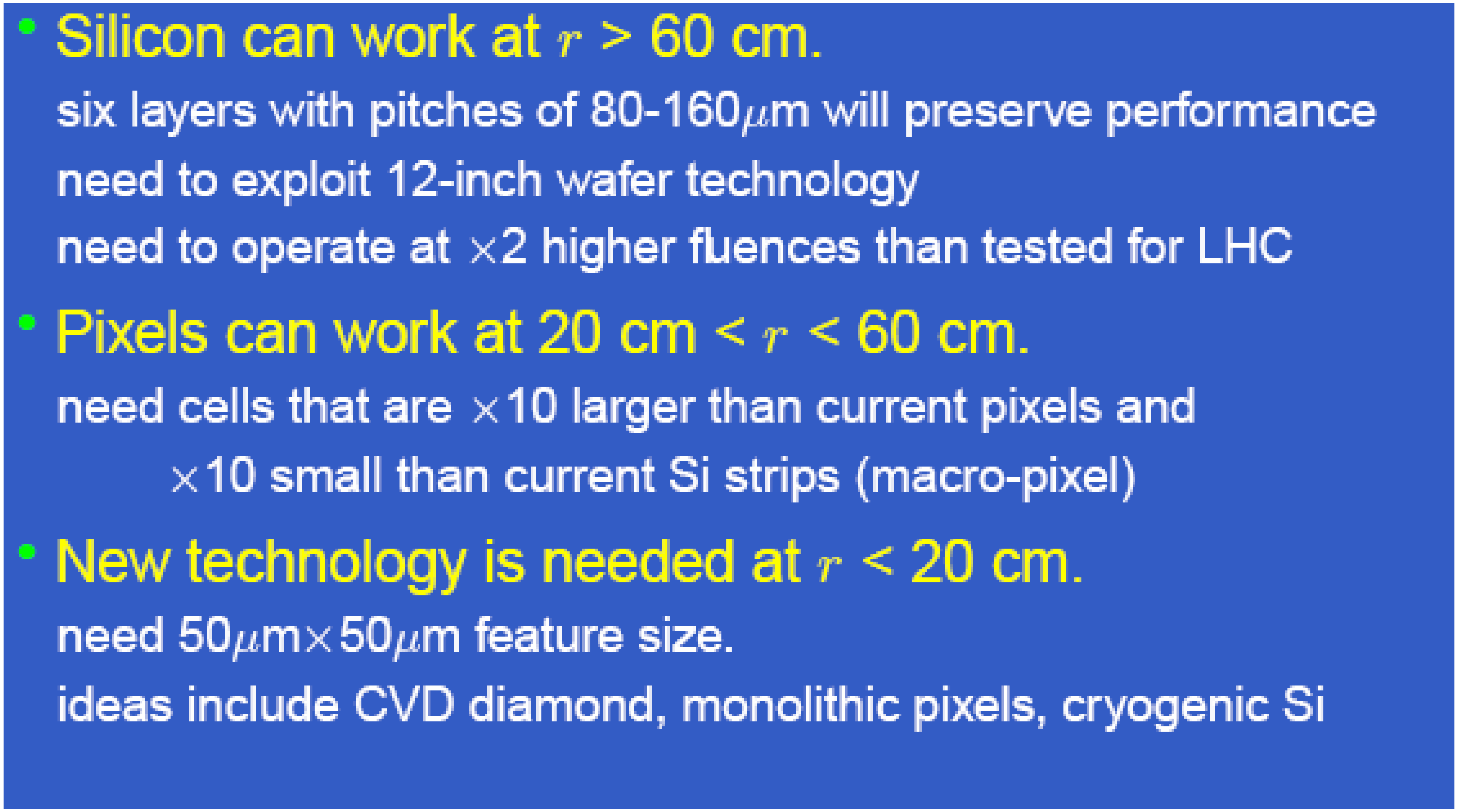
ATLAS



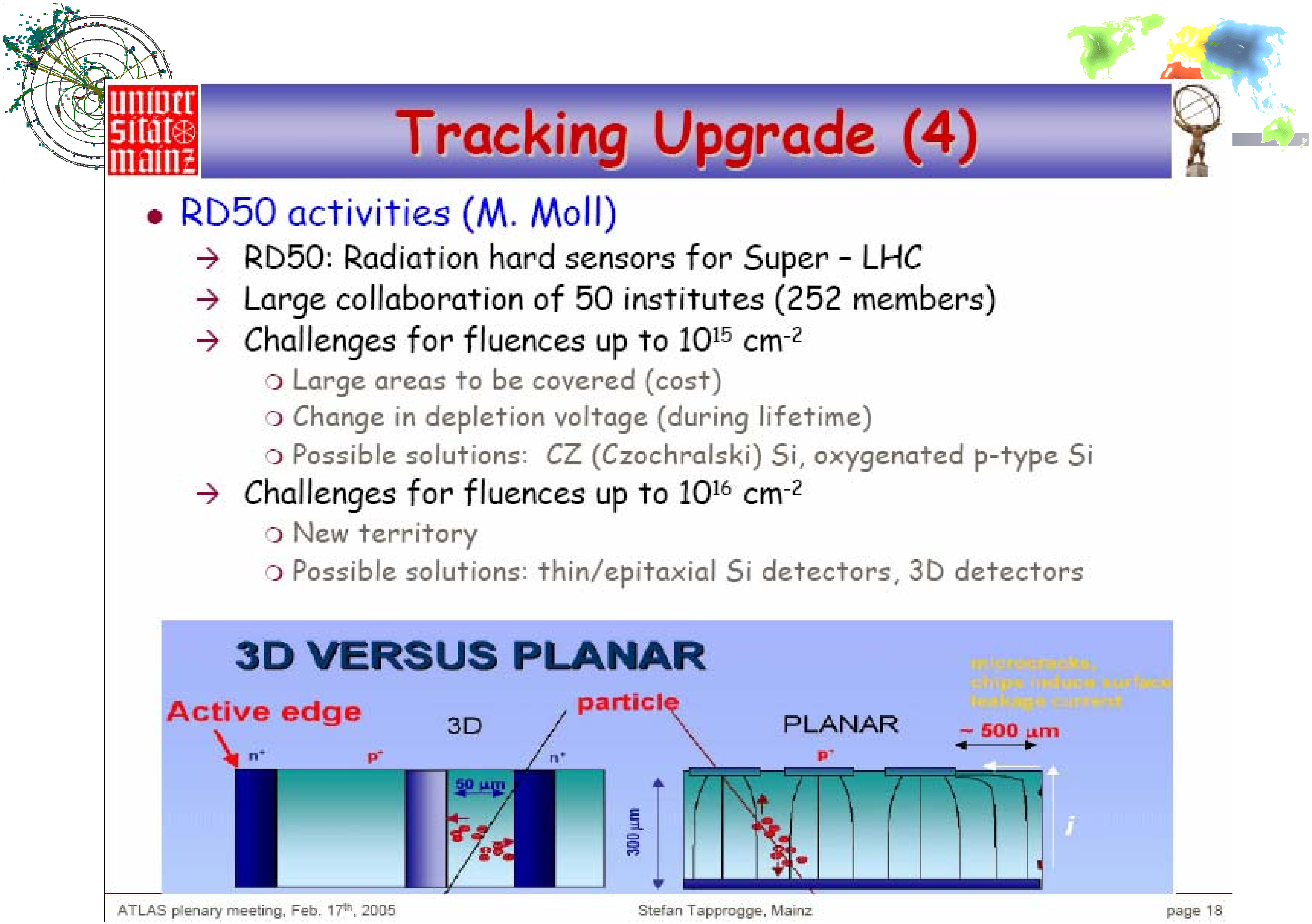
- ~ 10000 particles in $|\eta| \leq 3.2$
- mostly low p_T tracks

P. Nevski

SLHC Tracking



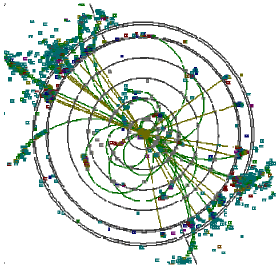
- Silicon can work at $r > 60$ cm.
  - six layers with pitches of 80-160μm will preserve performance
  - need to exploit 12-inch wafer technology
  - need to operate at ×2 higher fluences than tested for LHC
- Pixels can work at 20 cm $< r <$ 60 cm.
  - need cells that are ×10 larger than current pixels and ×10 small than current Si strips (macro-pixel)
- New technology is needed at $r <$ 20 cm.
  - need 50μm×50μm feature size.
  - ideas include CVD diamond, monolithic pixels, cryogenic Si



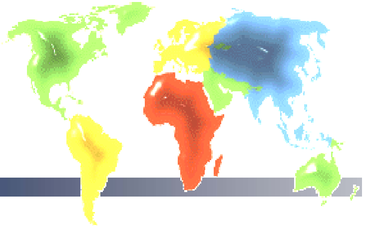
Tracking Upgrade (4)

- RD50 activities (M. Moll)
  - → RD50: Radiation hard sensors for Super - LHC
  - → Large collaboration of 50 institutes (252 members)
  - → Challenges for fluences up to 10^{15} cm^{-2}
    - ○ Large areas to be covered (cost)
    - ○ Change in depletion voltage (during lifetime)
    - ○ Possible solutions: CZ (Czochralski) Si, oxygenated p-type Si
  - → Challenges for fluences up to 10^{16} cm^{-2}
    - ○ New territory
    - ○ Possible solutions: thin/epitaxial Si detectors, 3D detectors

ATLAS plenary meeting, Feb. 17th, 2005 Stefan Tapprogge, Mainz page 18



ILC Detector Challenges



- ILC physics places premium on jet measurements and tagging, in an environment where event reconstruction is possible
  - tth $\Rightarrow$ 8 jets
  - hZ $\Rightarrow$ 2l + 2 jets, 4 jets
  - hhZ $\Rightarrow$ 2l + 4 jets, 8jets

  Aim to fully reconstruct final state
- + SUSY, quark, τ tagging, lepton/hadron id
- Vertex precision complements calorimetry

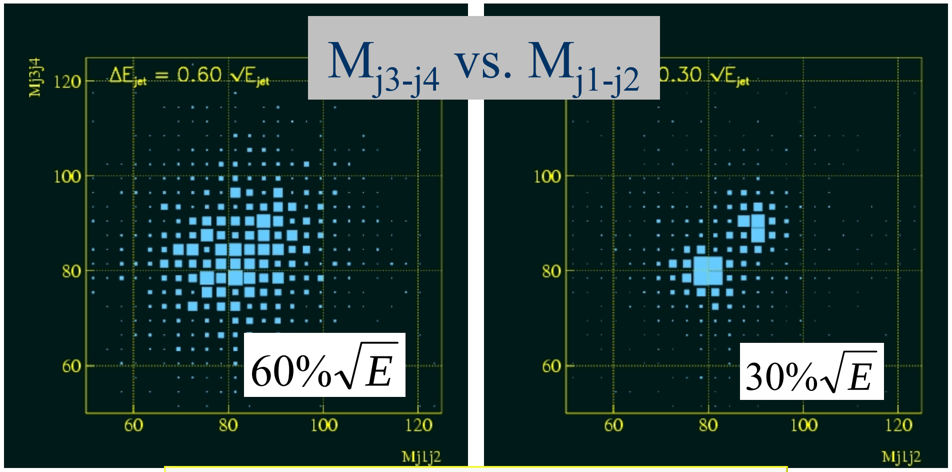
$$\boxed{\sigma_{ip} = 5\mu m \oplus 10\mu m / p \sin^{3/2}\theta}$$

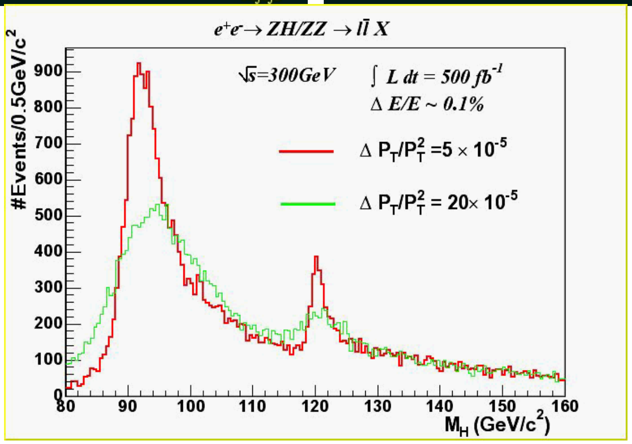
- Precision tracking needed for decay-mode independent Higgs detection

e e → Z H
Z → l⁺l⁻
H → anything

$$\boxed{\sigma(1/p) = 5\times10^{-5}\,/\mathrm{GeV}}$$

$e^+e^- \rightarrow WW\nu\bar{\nu}$, $e^+e^- \rightarrow ZZ\nu\bar{\nu}$

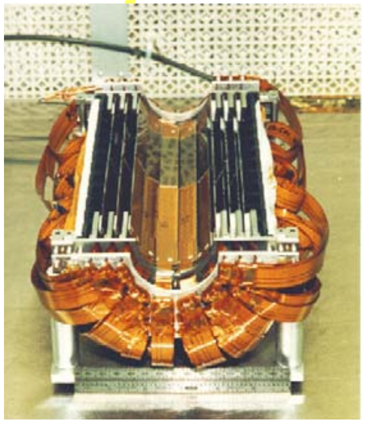


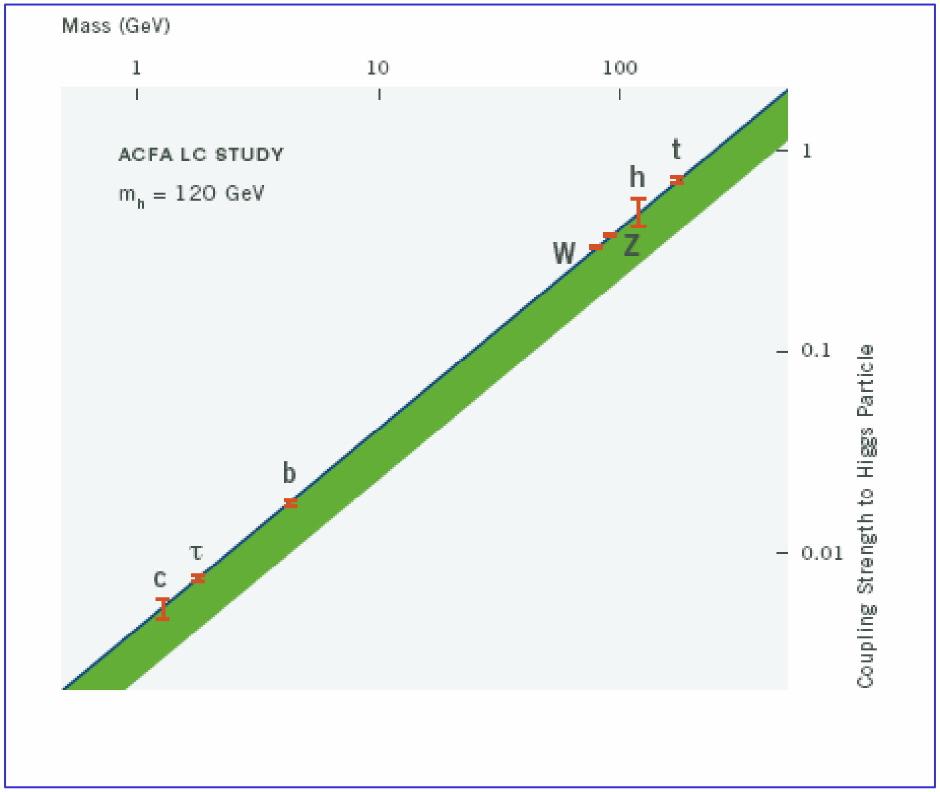


ILC Flavor Tagging Challenge

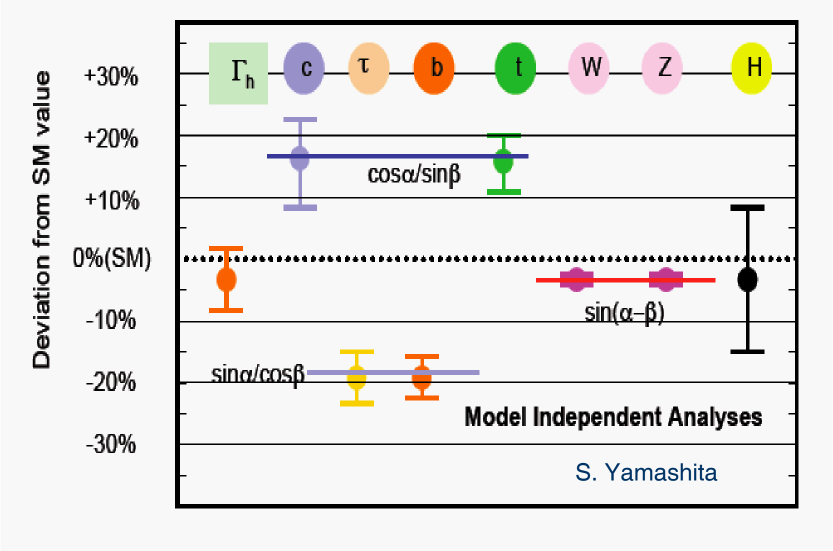
- **~<u>billion pixel</u> vertex detectors with ~3 µm pt. res., and 0.1 % X_0 ladders, being developed**

- SLD comprised 307 Mpixels with < 4 µm point resolution over entire system

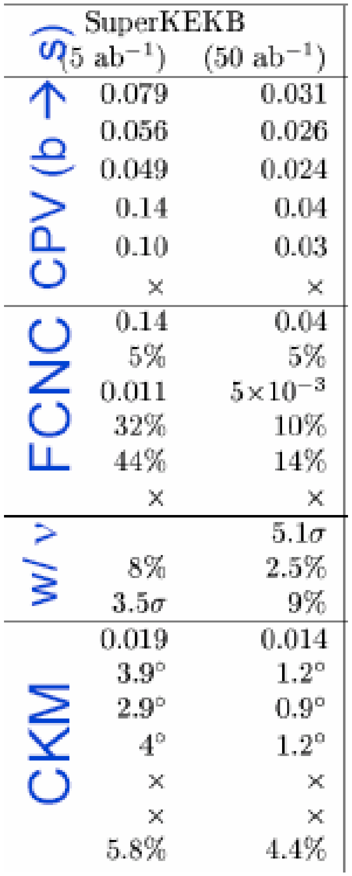




SUSY (2 Higgs Doublet Model)

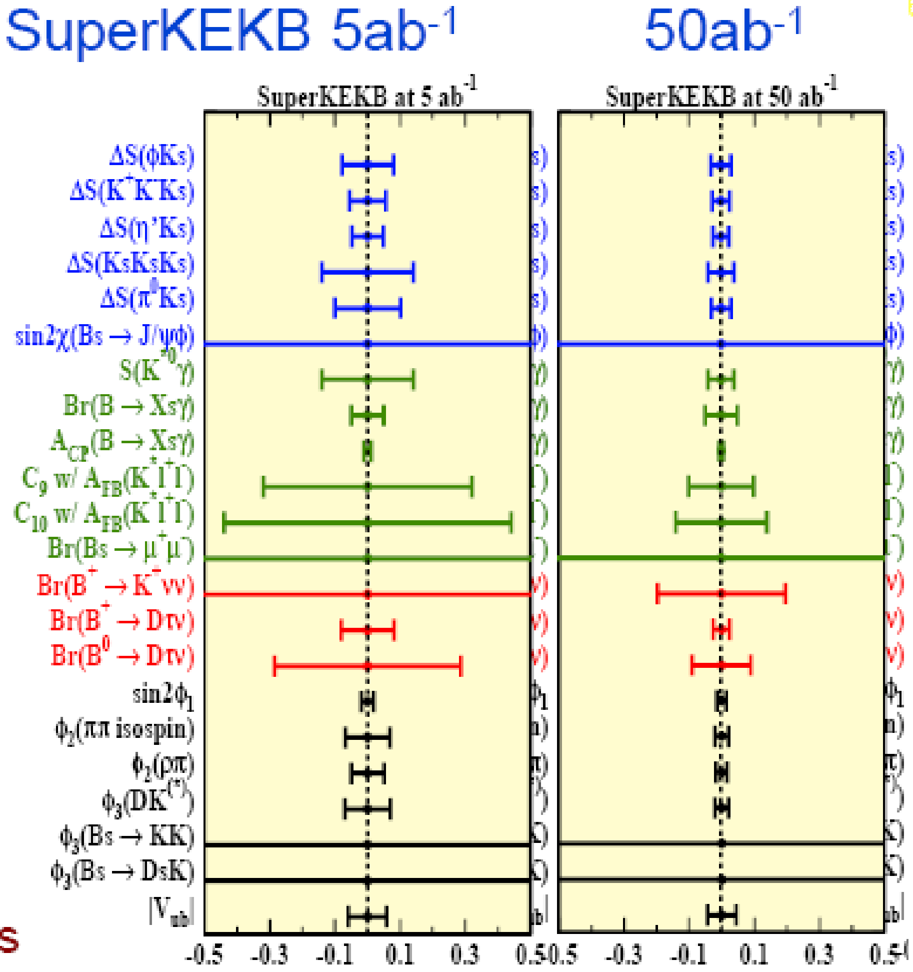


Precision measurements at a Super B Factory



	SuperKEKB (5 ab^{-1})	(50 ab^{-1})
CPV (b → s)	0.079	0.031
	0.056	0.026
	0.049	0.024
	0.14	0.04
	0.10	0.03
	×	×
FCNC	0.14	0.04
	5%	5%
	0.011	5×10^{-3}
	32%	10%
	44%	14%
	×	×
w/ ν		5.1σ
	8%	2.5%
	3.5σ	9%
CKM	0.019	0.014
	3.9°	1.2°
	2.9°	0.9°
	4°	1.2°
	×	×
	×	×
	5.8%	4.4%

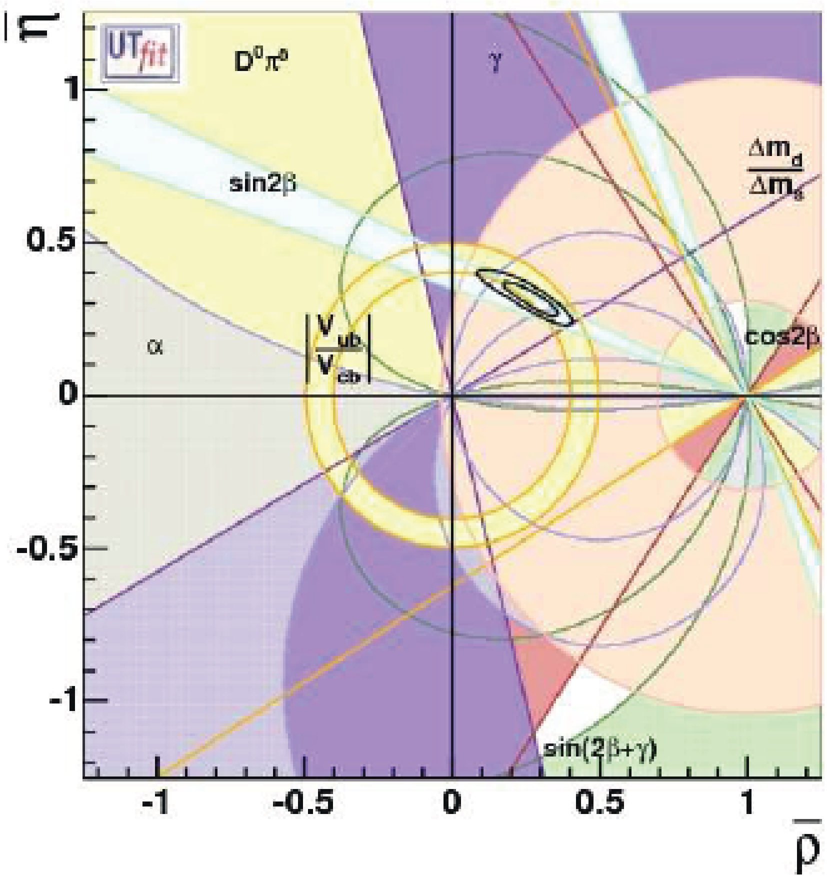
and rich τ physics

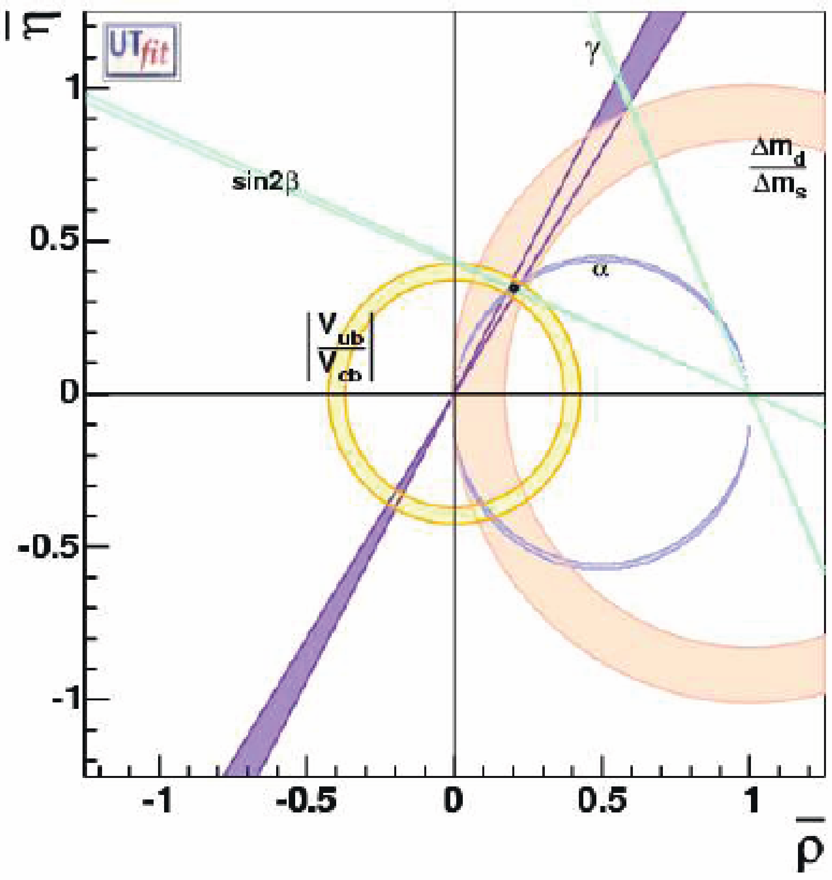


Physics at Super B Factory (hep-ex/0406071)

Many sensitivities superior to LHC-b

Universal Unitarity Triangle today and "tomorrow"



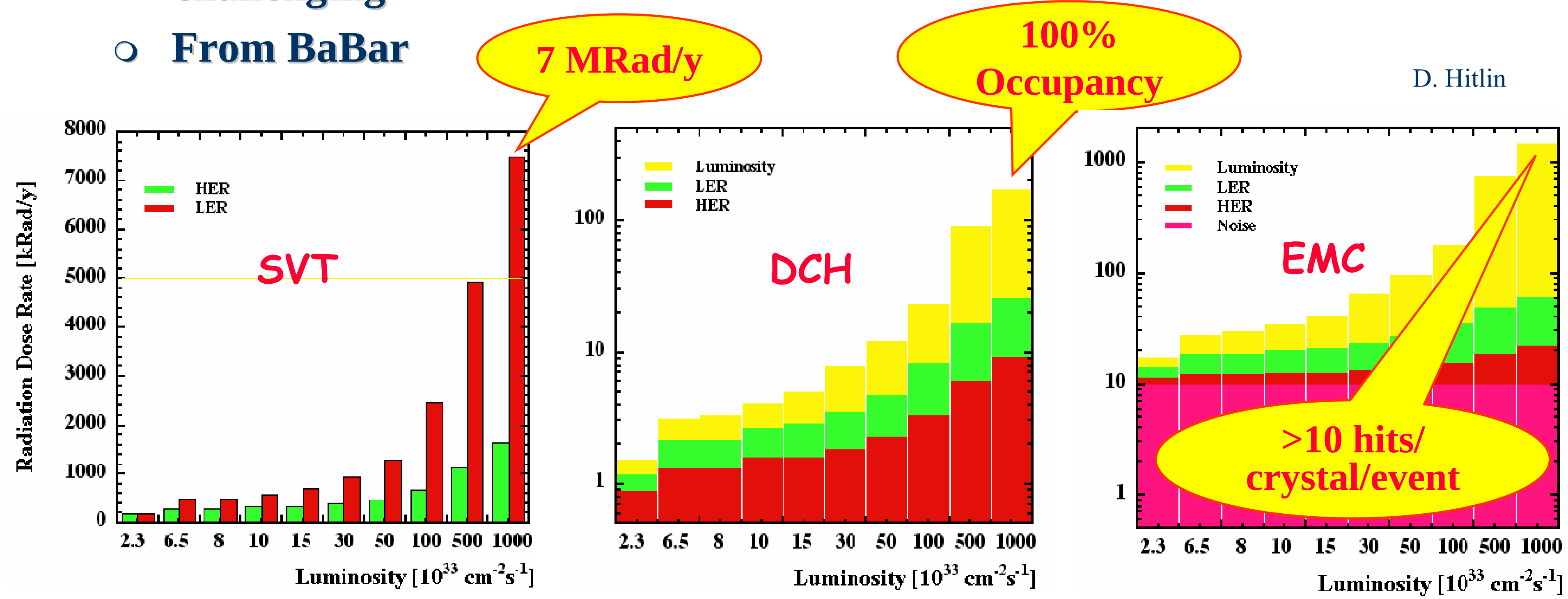


Ciuchini, Super B Factory Meeting Frascati, 11/2005

Super B Factory Issues

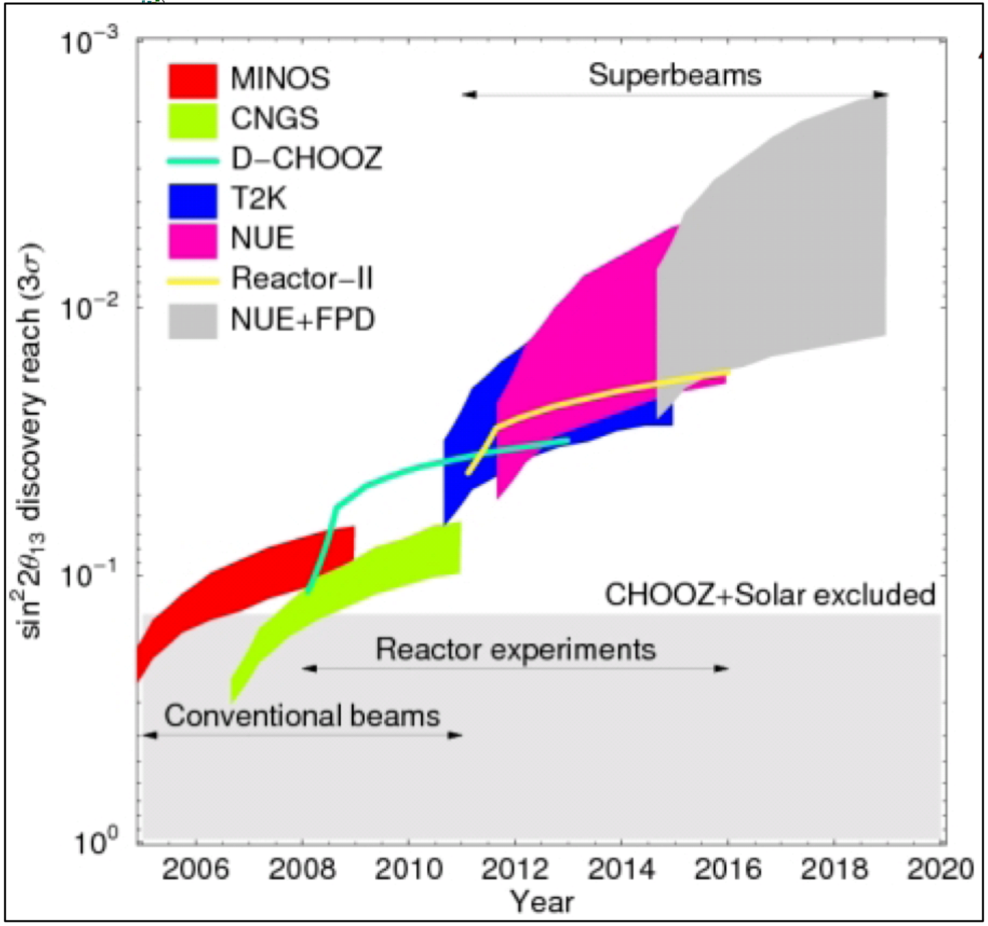
- Rates, backgrounds, occupancies, and radiation doses are challenging
- From BaBar

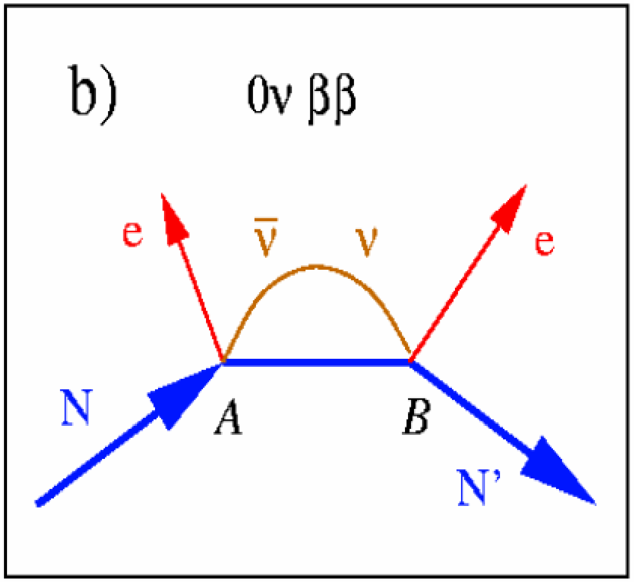
D. Hitlin



- Issues relaxed with Linear Super B Factory
  - Thousand-fold reduction in beam current seen by detector

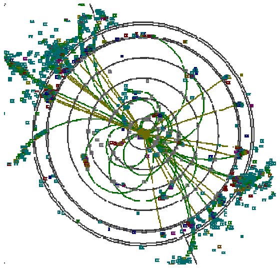
Neutrinos



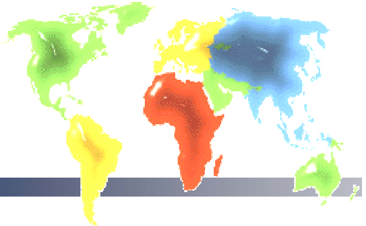


- **Neutrino-less double beta decay**
  Majorana ν mass sens. ~ tens meV

- **Progress in neutrino oscillations motivates more massive, more sensitive detectors**



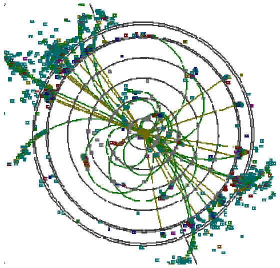
Enabling Developments



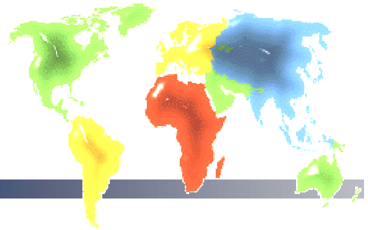
Trends in technology *enable* advances in detectors

(some trends. not independent)

- **Segmentation**
  - Vertex elements with 20 μm and smaller features
  - Calorimetry employing silicon elements
  - Micro Pattern Gas Detectors (MPGD) applications
- **Speed**
  - Faster electronics, low noise and low power
- **Integration**
  - Microelectronics
  - Mechanical sophistication
- **Materials**
  - Rad-hard, robust, thin, etc.
- **Radiation immunity**
  - Understanding damage mechanisms and annealing
  - design optimization



Segmentation



Advancing technology enables finer granularity

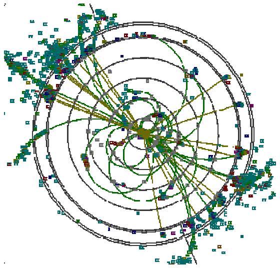
- Microelectronics – eg. Silicon pixels
- Bump bonding technology – low capacitance connections
- Modern etching technology – eg. Micro pattern Gaseous Detectors

Trade-offs between read-out, S/N, power, and segmentation

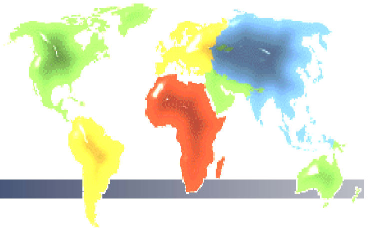
- Limits granularity
- Often defined by state-of-the-art in microelectronics or etching technology

ILC examples of proposed increased granularity

Silicon-tungsten calorimetry	90×10^6 cells ($12\ \mathrm{mm}^2$)
Digital hadron calorimetry	40×10^6 cells ($1\ \mathrm{cm}^2$)
TPC readout – MPGD, also w/ Medipix2	
Vertex detectors	$\sim 10^9$ pixels ($\leq 20 \times 20\ \mu\mathrm{m}^2$)



Speed



- **Speed is often a critical parameter**
  - **Super LHC**
    - Pile up of events – a limiting issue
  - **ILC**
    - Accumulation of background hits in inner layer of Vertex detector
  - **Super B Factory**
    - Similar issues

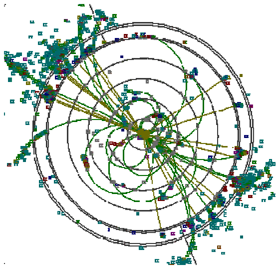
- **A notable advance from Micromegas and GEMs**

  Produced good detection efficiency, with accuracy (< 100 μm), at high rates (nearly MHz mm^{-2})

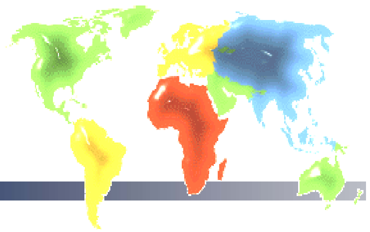
  - **Ioanis Giomataris (Saclay)**

    High Rate Capability of Micromegas
  - **Fabio Sauli**

    Recent developments in Micro-Pattern Gas Detectors

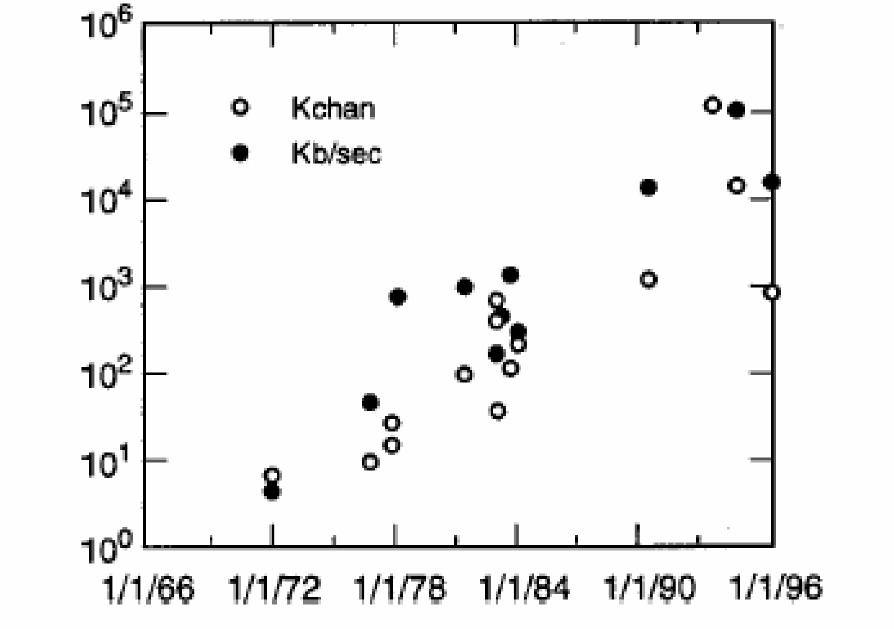


Growth and Integration



Panofsky and Breidenbach, "Accelerators and detectors," Rev. Modern Physics 71, S121 (1999).

Instrumented signal channels and data rate

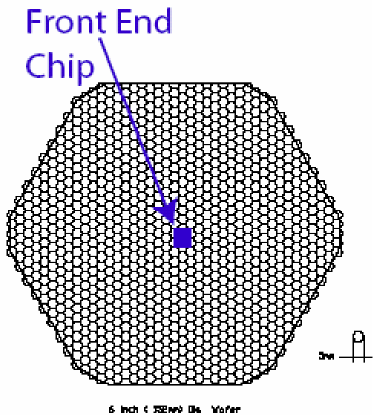


"growth with only moderate cost increase rests largely on continuing developments in circuit integration and computing technologies" – WKHP+MB 1999

This growth trend impact continues, with big impact

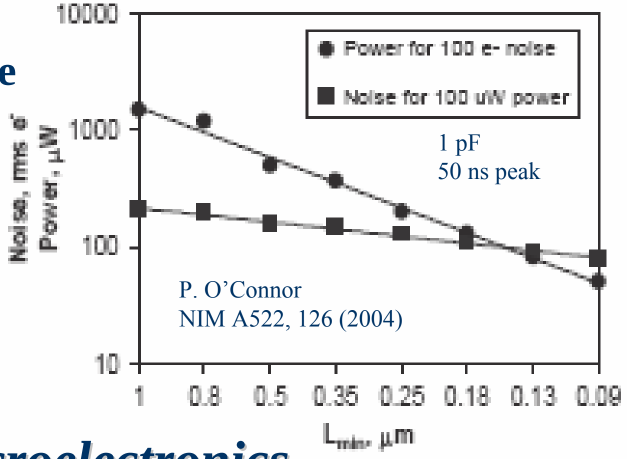
High degrees of multiplexing examples:

1.) SLD vertex detector
   307 Mpixels -> 96 channels
2.) ILC Si/W EM cal design
   1024 pixels/channel
   90 Mcells ⇒ 90 kchan



Power constrained, low-noise electronics

- Principles applied to “highly segmented detectors” can be generalized
  - Finer segmentation often does not reduce signal
  - Noise is reduced due to
    - **Lower capacitances**
    - **Lower leakage currents**
    - **Lower rate/pixel**
  - Cost is weakly dependent on number of pixels, dominated by total area
  - Noise control demands electronics close to detector (minimize capacitances)
  - Temperature control required to control leakage currents, and gain inhomogeneity
    - **Practical power dissipation a critical design issue**
  - Front-end design choices for noise, shaping time, and power budgets need care
  - Interconnect issues increasing in importance

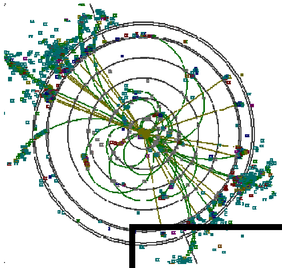


1 pF
50 ns peak

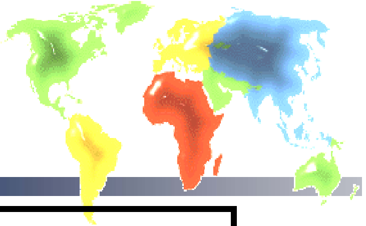
P. O’Connor
NIM A522, 126 (2004)

Paul O’Connor

Future Developments of IC Processing and Microelectronics



ITRS Roadmap



	2004	2007	2010	2013	2016
Technology Node [nm]	90	65	45	32	22
Transistor count [Mtr]			1500	3092	6184
Transistor Density [Mtr/cm2]	77	154	309	617	1235
Chip Size	140				280
Clock freq [GHz]	3		15		53
Vdd	1.2	1.1	1.0	0.9	0.7
DRAM half pitch	90	65	54	32	22
Signal IO Pads	512	1024	1024	1024	1024
Power Pads	1024				2048

International Technology Roadmap for Semiconductors

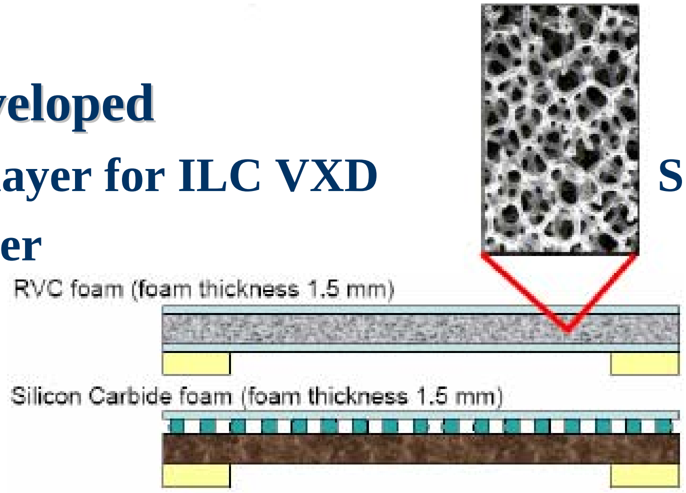
A. Marchioro, CERN-PH, 2005

Mechanical complexity

- Careful and skilled mechanical design and construction can optimize detector performance
  - compactness, integration, thinness, and ultimate operation

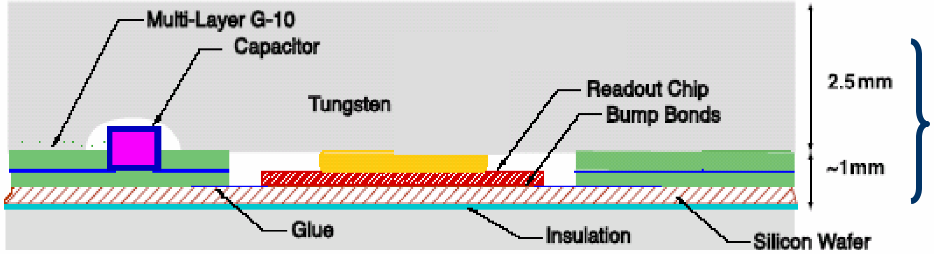
- Examples being developed
  - Very thin silicon layer for ILC VXD S. Worm/C. Damerell

    ~ 0.1% X_0 per layer



  - Very dense silicon/tungsten EM cal R. Frey/M. Breidenbach

Critical parameter: minimum space between tungsten layers.



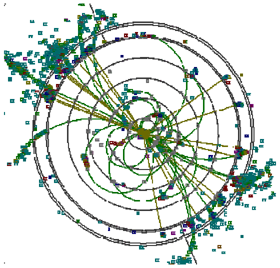
Intrinsic Moliere radius preserved

Radiation Immunity

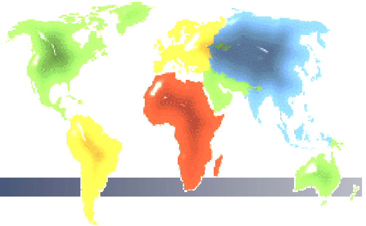
- Accelerator advances producing higher luminosities require experiments to confront higher radiation exposures (even moderate levels limit options)

- Super LHC
  - 10^{16} n_{eq}/cm^2 @ 5 cm
  - 10^{15} n_{eq}/cm^2 @ 20 cm
  - 2×10^{14} n_{eq}/cm^2 @ 50 cm **H. Sadrozinski**
- ILC
  - 1 GigaRad/yr in BeamCal **W. Lohmann**
- Super B Factory
  - Several MRad per year in vertex detector **T. Iijima**
- Ongoing advances

Silicon	M, Bruzzi, M. Swarz
Crystals	R-Y. Zhu
Gaseous Detectors	V. Lepeltier
Issues for moderate exposures	J. Schwiening
… and others	



Advancing Concepts in CALORIMETRY

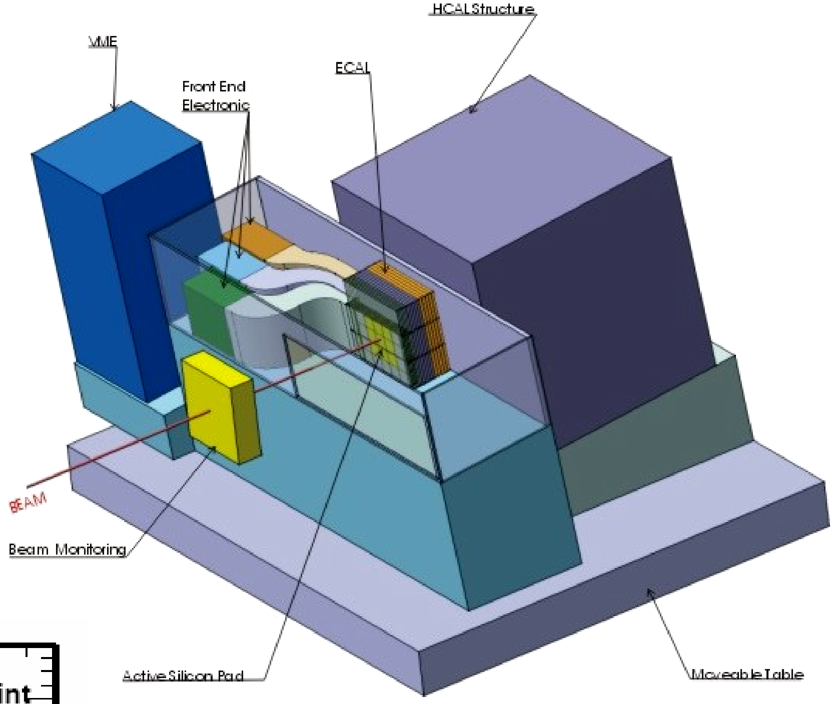


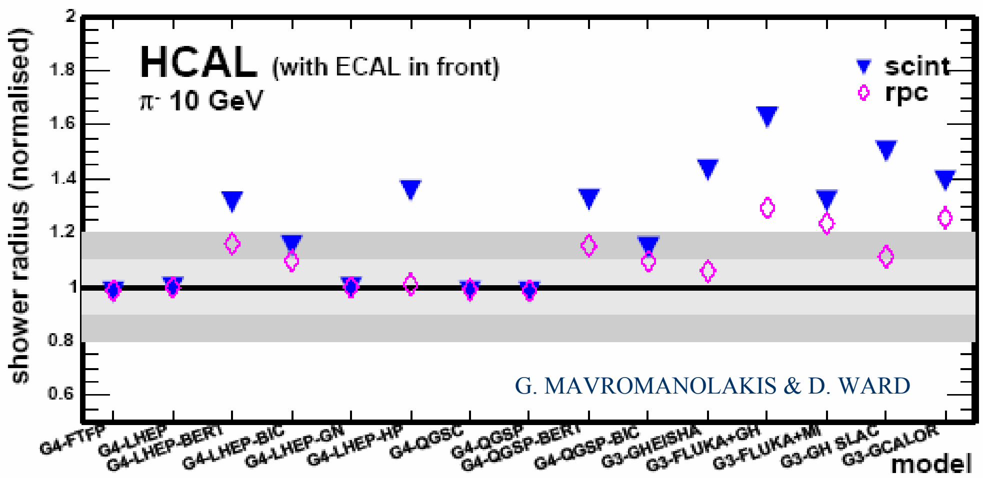
Some Advancing Techniques

- Digital Hadron Calorimetry
- Silicon/Tungsten Electromagnetic Calorimetry
- Particle Flow Calorimetry
- Dual Readout Calorimetry
- Rad-hard Crystals

Digital Hadron Calorimetry for ILC

- **Effort based on RPCs or GEMs (w/CALICE)**
  - Few layer test of RPCs has started at Fermilab
- **1 m^3 prototype planned to test concept**
  - Lateral readout segmentation: 1 cm^2
  - Longitudinal readout segmentation: layer-by-layer
- **Objectives**
  - Validate RPC approach (technique and physics)
  - Validate concept of the electronic readout
  - Measure hadronic showers with unprecedented resolution
  - Validate MC simulation of hadronic showers

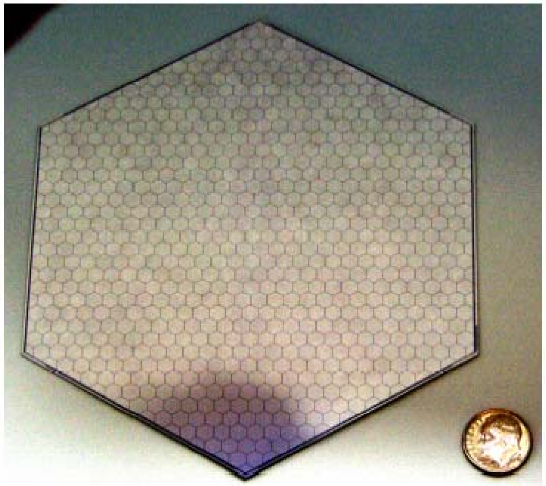


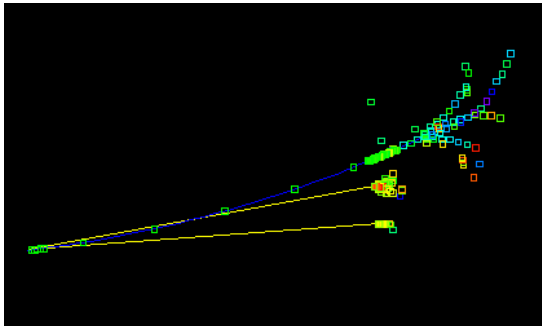


G. MAVROMANOLAKIS & D. WARD

Argonne National Laboratory
Boston University
University of Chicago
Fermilab
Iowa
University of Texas at Arlington

Silicon/Tungsten EM Calorimetry for ILC

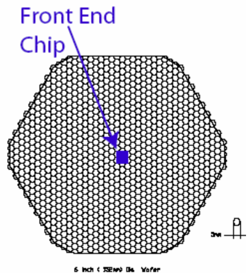




SLAC/Oregon/BNL/Davis/Annecy

Dense, fine grained silicon tungsten calorimeter (builds on SLC/LEP experience)

- Pads: 12 mm^2 to match Moliere radius (~ $R_m/4$)
- Each six inch wafer read out by one chip
- < 1% crosstalk

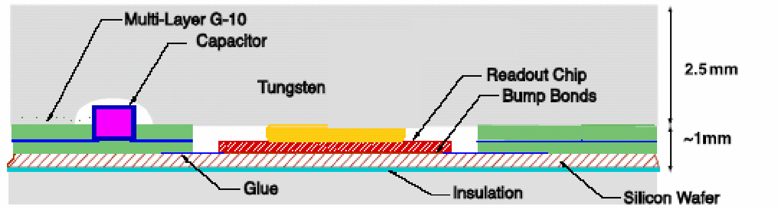


Electronics design

- Noise < 2000 electrons
- Single MIP tagging (S/N ~ 7)
- Dynamically switchable feedback capacitor scheme achieves required dynamic range: 0.1-2500 MIPs

Passive cooling – conduction in W to edge

Critical parameter: minimum space between tungsten layers.



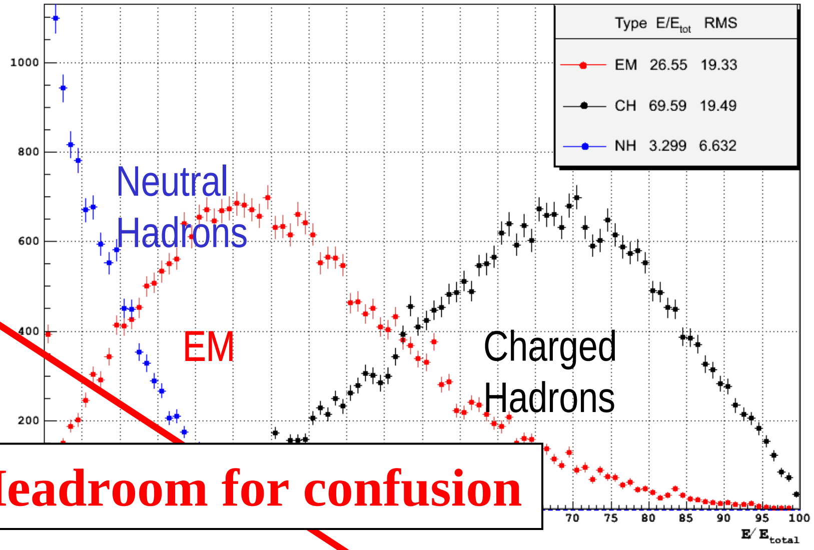
Si/W also being prototyped by CALICE

Particle Flow Calorimetry

ILC event properties make

<u>Particle Flow Calorimetry</u> attractive
(optimal performance unproven)

- Jet resolution goal is 30%/√E
- In jet measurements, use the excellent resolution of tracker, which measures bulk of the energy in a jet



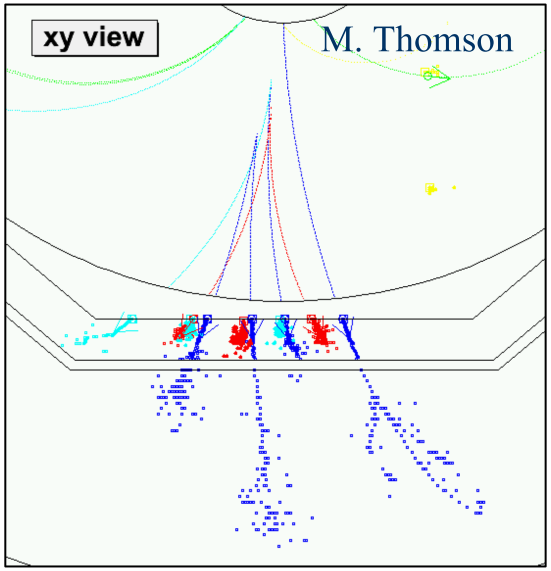
Headroom for confusion

Particles in Jet	**Fraction of Visible Energy**	**Detector**	**Resolution**
Charged	~65%	Tracker	< 0.005% p_T negligible
Photons	~25%	ECAL	~ 15% / √E
Neutral Hadrons	~10%	ECAL + HCAL	~ 60% / √E

~ 20% / √E

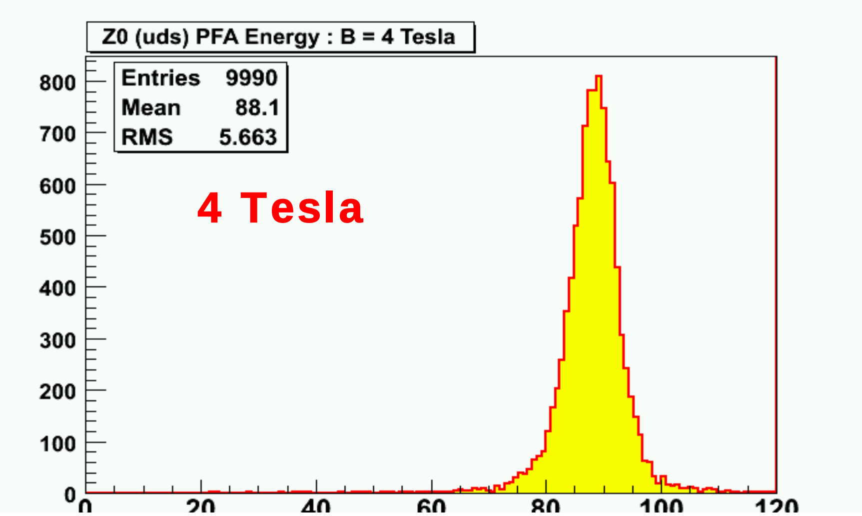
REQUIRES UNPRECEDENTED GRANULARITY

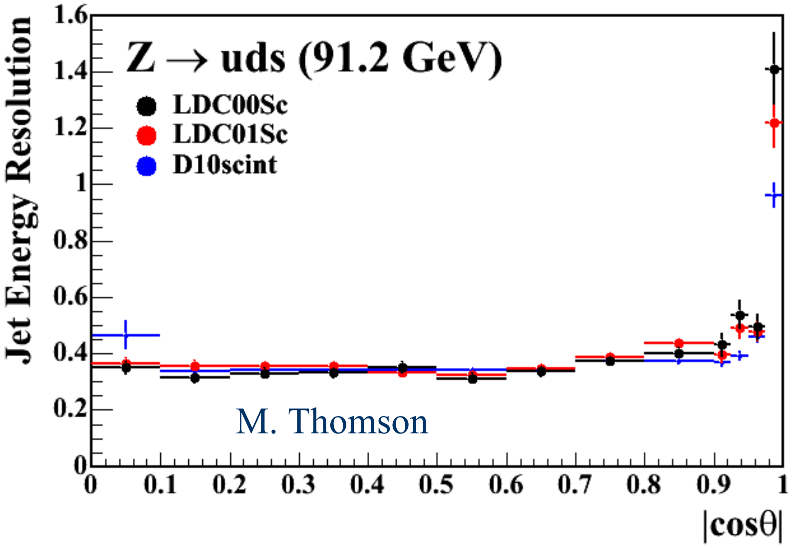
Particle Flow Simulation



GRANULARITY CRITICAL
(eg. SiD)
EMCal 90 Mcells
($12\ mm^2$)
HADCal 40 Mcells
($1\ cm^2$)

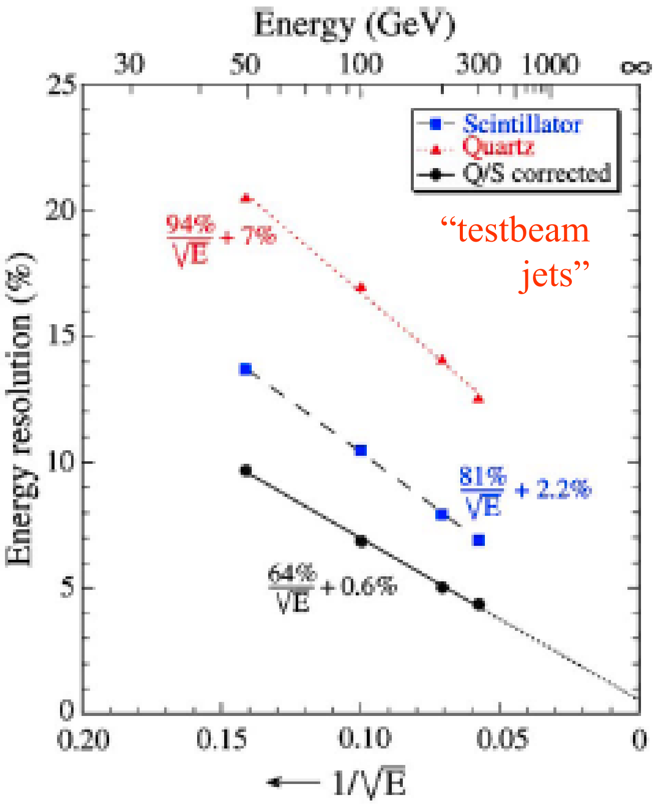
A. White





Dual Readout Calorimetry

- **Dual readout concept to establish compensation between electromagnetic and hadronic components of hadronic showers**
  - D. R. Winn and W. Worstell, "Compensating Hadron Calorimeters with Cerenkov Light", IEEE Trans. Nuclear Science Vol. NS-36 , No. 1, 334 (1989)
  - Scintillation and Cherenkov signals have different sensitivities to electromagnetic and hadronic components of a hadronic shower
- **Idea realized by Dream detector**
  - Scintillator and quarz fibers
  - N. Akchurin et al., “Hadron and Jet Detection with a Dual-Readout Calorimeter,” Nucl. Instr. and Meth. **A537** (2005) 537–561.
- **Challenge for application to an experiment:**
  - **Transverse and longitudinal segmentation**



“testbeam jets”

Rad-hard Crystals

- **Endcap radiation damage for CMS crystals at SLHC**
- **Attractive prospect: LSO/LYSO** (Ce:Lu_2SiO_5 Cerium doped Lutetium Orthosilicate
  $Lu_{2(1-x)}Y_{2x}SiO_5$: Ce - Cerium doped Lutetium Yttrium Orthosilicate)
- **Also at Super B Factory and/or ILC?**

- A better energy resolution, $\sigma(E)/E$, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

$$2.0\% / \sqrt{E} \oplus 0.5\% \oplus .002/E$$

- Less demanding to the environment because of small temperature coefficient.
- Radiation damage is less an issue as compared to the CMS PWO ECAL.

R-Y Zhu

Advancing Concepts in SILICON TRACKING

Vertex Detectors/Inner Trackers

- Advanced pixels for LHC
- Column Parallel Readout CCDs
- DEPFETs
- Monolithic CMOS
- Several other approaches

Future Tracking Application

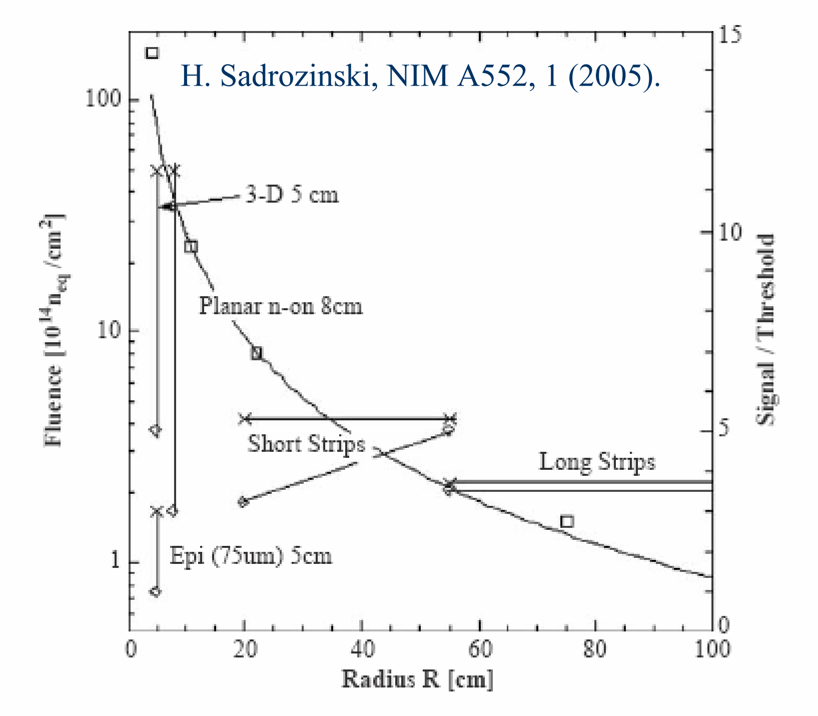
- ILC Tracker

SLHC Pixels

- **New technology is needed for r < 20 cm**

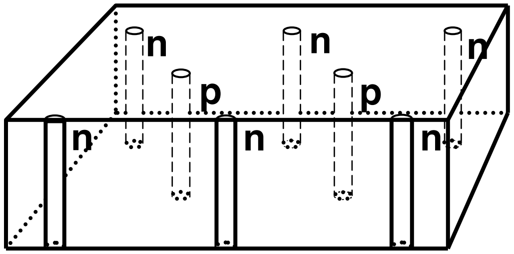
  > 10^{15} /cm^2 (> 40 MRad)

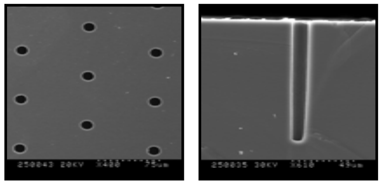
  Need 50 μm × 50 μm feature size

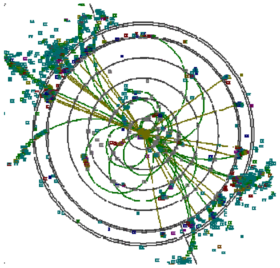

H. Sadrozinski, NIM A552, 1 (2005).

<u>Possible solutions</u>

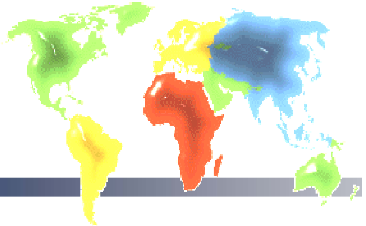
CVC diamond	**W. Trischuk** **J. Zhang**
Monolithic pixels	
Cryogenic silicon	
3D detectors	**C. Kenney**







ILC Inner Tracking/Vertex Detection



ILC Detector Requirements

- Superb flavor tagging
  ⇒ impact parameter resolution (**$5\mu m \oplus 10\mu m/(p \sin^{3/2}\theta)$**)
- Excellent spacepoint precision (**< 4 microns**)
- Transparency **(~0.1% X_0 per layer**)
- Track reconstruction (**find tracks in VXD alone**)

Concepts under Development for ILC

- Charge-Coupled Devices (CCDs)
  - CCDs demonstrated in large (307 Mpix) system at SLD ⇒ CPCCD
- Monolithic Active Pixels – CMOS (MAPs, FAPS, Macro/Micro, etc.)
  R. Turchetta, C. Baltay, L. Ratti
- DEpleted P-channel Field Effect Transistor (DEPFET) L. Andricek
- Silicon on Insulator (SoI) Y. Arai
- Image Sensor with In-Situ Storage (ISIS)
- HAPS (Hybrid Pixel Sensors)

Column Parallel CCD for ILC

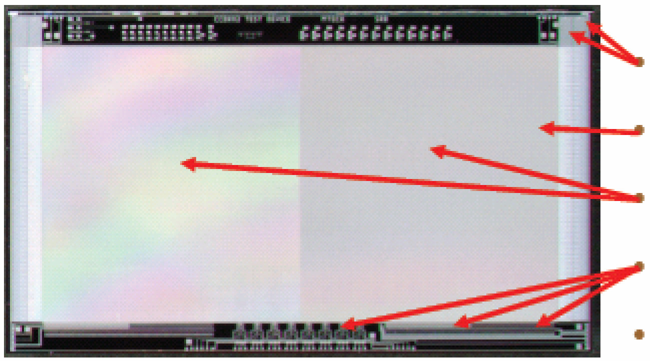
SLD Vertex Detector designed to read out
800 kpixels/channel at 10 MHz, operated at
5 MHz => readout time = 200 msec/ch

ILC requires faster readout for 300 nsec bunch spacing

Possible Solution: Column Parallel Readout

LCFI (Bristol,Glasgow,Lancaster,Liverpool,Nijmegen,Oxford,RAL)

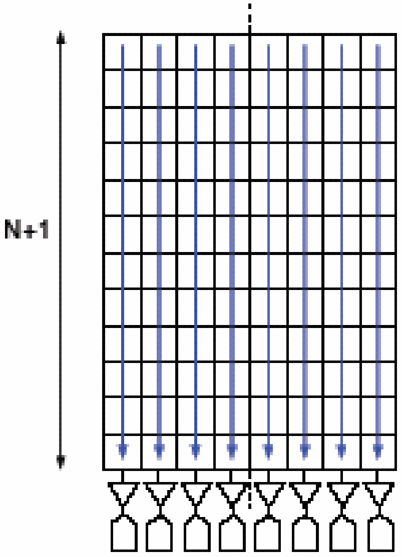
CPC1 produced by E2V



- **Two phase operation**
- **Metal strapping for clock**
- **2 different gate shapes**
- **3 different types of output**
- **2 different implant levels**

➢*Clock with highest frequency at lowest voltage*

- **Separate amplifier and readout for each column**

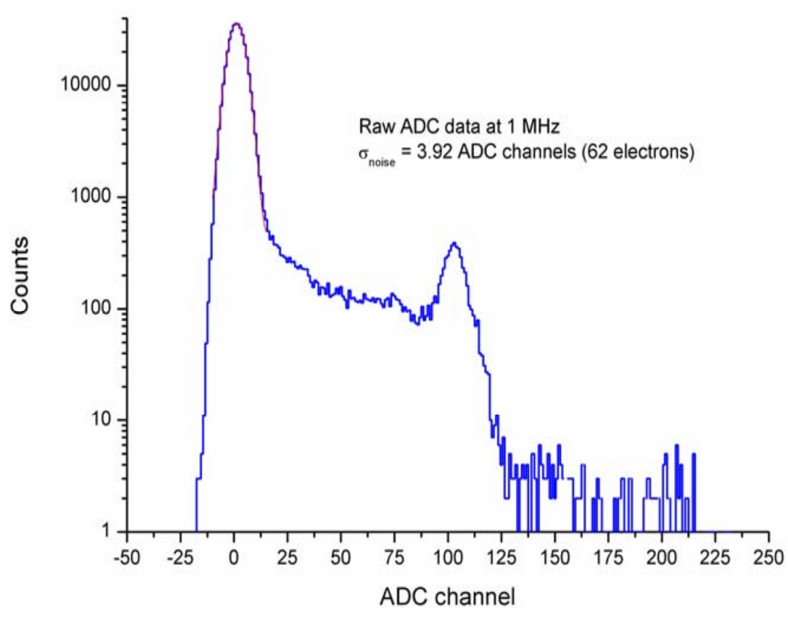


Column Parallel CCD
Readout time = (N+1)/F_{out}

(Whereas SLD used one readout channel for each 400 columns)

CPC2/ISIS1 Wafer

- **First-generation tests (CPC1):**
  - **Noise ~100 e⁻ (60 e⁻ after filter).**
  - **Minimum clock potential ~1.9 V.**
  - **Max clock frequency above 25 MHz (design 1 MHz).**
  - **Limitation caused by clock skew**



- **CPC2 - 3 CPCCD sizes:**
  - **CPC2-70: 92 mm x 15 mm image area**
  - **CPC2-40: 53 mm long**
  - **CPC2-10: 13 mm long**

Currently under test…

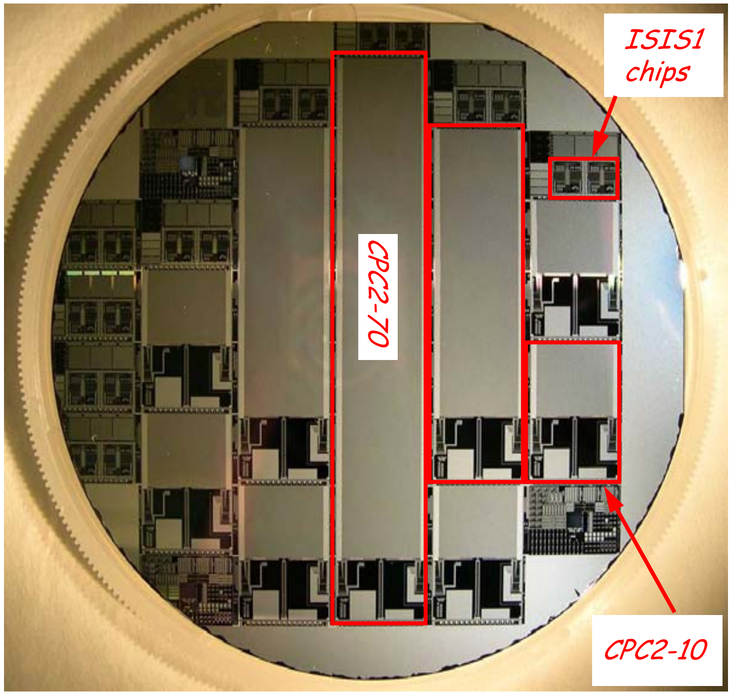
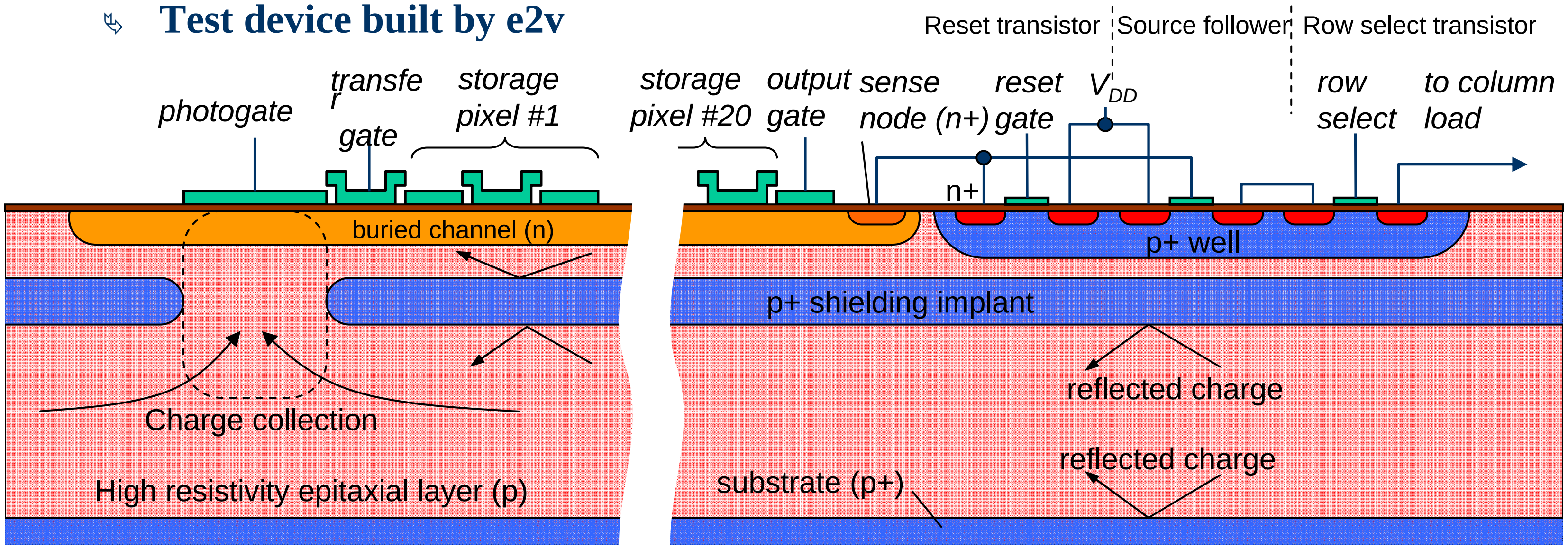


Image Sensor with In-situ Storage (ISIS)

- EMI concern (SLC experience) motivates delayed operation during beam
- Robust storage of charge in buried channel during beam passage
  - Pioneered by W F Kosonocky et al IEEE SSCC 1996, Digest of Technical Papers, 182
  - T Goji Etoh et al, IEEE ED 50 (2003) 144; runs up to 1 Mfps.
- ISIS Sensor details:
  - CCD-like charge storage cells in CMOS or CCD technology
  - Processed on sensitive epi layer
  - p+ shielding implant forms reflective barrier (deep implant)
  - Overlapping poly gates not likely to be available, may not be needed
  - Test device built by e2v



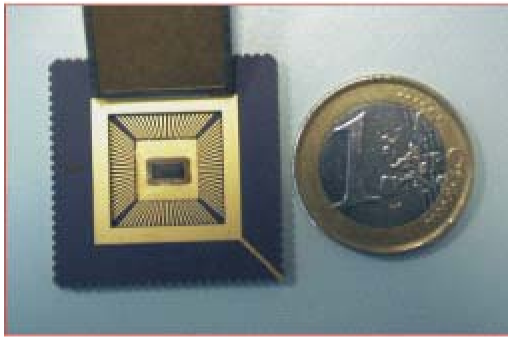
Monolithic CMOS for Pixel Detector

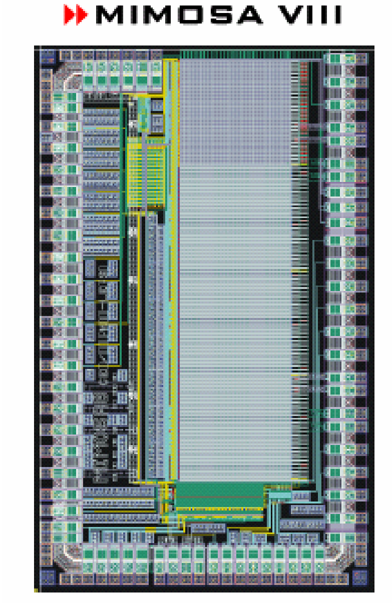
Concept

- Standard VLSI chip, with thin, un-doped silicon sensitive layer, operated undepleted

Advantages

- decoupled charge sensing and signal transfer (improved radiation tolerance, random access, etc.)
- small pitch (high tracking precision)
- Thin, fast readout, moderate price





R&D

- Strasbourg IReS has been working on development of monolithic active pixels since 1989; others (RAL, Yale/Or., etc.)
- IReS prototype arrays of few thousands pixels demonstrated viability.
- Large prototypes now fabricated/tested.
- Attention on readout strategies adapted to specific experimental conditions, and transfer to AMS 0.35 OPTO from TSMC 0.25
    - ~< 12 um epi vs. < 7 um
- Application to STAR

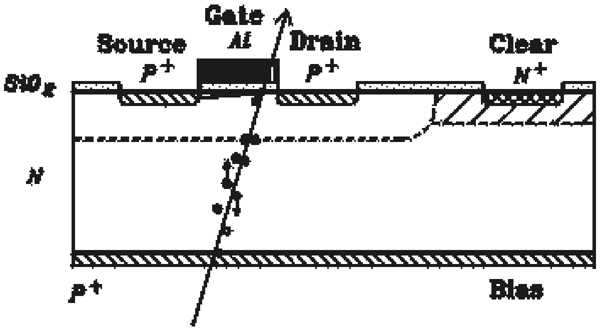
Parallel R&D:

- FAPS (RAL): 10-20 storage caps/pixel R. Turchetta
- New concepts (Macro/Micro) C. Baltay
  (STMicro) L. Ratti

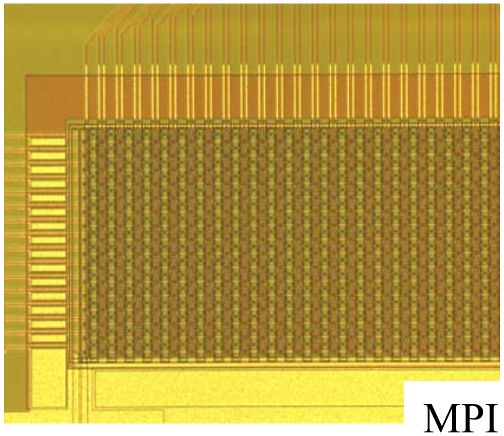
Inner Tracking/Vertex Detection (DEPFET)

Concept

- Field effect transistor on top of fully depleted bulk
- All charge generated in fully depleted bulk; assembles underneath the transistor channel; steers the transistor current
- Clearing by positive pulse on clear electrode
- Combined function of sensor and amplifier



16x128 DEPFET-Matrix



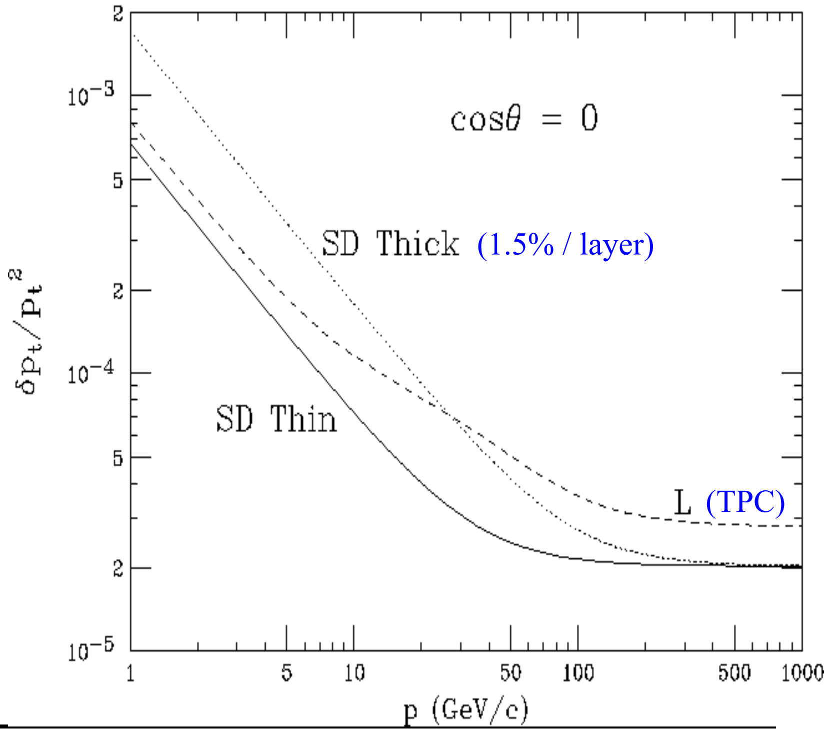
Properties

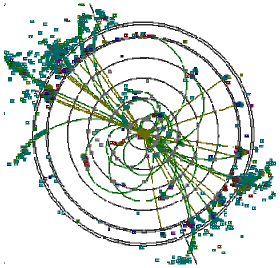
- low capacitance ▸ low noise
- Signal charge remains undisturbed by readout ▸ repeated readout
- Complete clearing of signal charge ▸ no reset noise
- Full sensitivity over whole bulk ▸ large signal for m.i.p.; X-ray sens.
- Thin radiation entrance window on backside ▸ X-ray sensitivity
- Charge collection also in turned off mode ▸ low power consumption
- Measurement at place of generation ▸ no charge transfer (loss)
- Operation over very large temperature range ▸ no cooling needed

MPI Munich, MPI Halle, U. Bonn, U. Mannheim

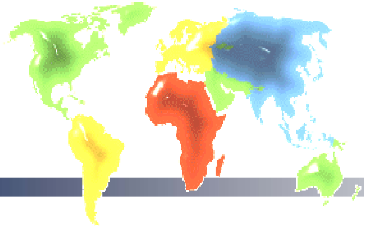
Silicon Tracking for ILC

- Silicon strip and pixel detectors (SiD approach)
  - Manage increased radiation and pile-up
  - Superb spacepoint precision allows tracking measurement goals to be achieved in a compact tracking volume
  - Robust to spurious, intermittent backgrounds, eg. at ILC
- Compact tracker
  - achieves superb performance
  - allows more aggressive technical choices for outer systems (assuming an overall cost constraint)
- Robust against ILC backgrounds
  (esp. beam loss, a la SLC)
- 3^{rd} dimension "measured" and
  backgrounds suppressed
  with segmented silicon strips





Advancing TPC for ILC



- **Time Projection Chamber technology**
  - **Builds on successful experience of PEP-4, ALEPH, ALICE, DELPHI, STAR, …..**
  - **Large number of space points, making reconstruction straight-forward**
  - **dE/dx ⇒ particle ID, bonus**
  - **Minimal material in tracking volume, valuable for barrel calorimetry**
  - **Tracking up to large radii**
  - **New readouts promise to improve robustness**

Issues for ILC TPC

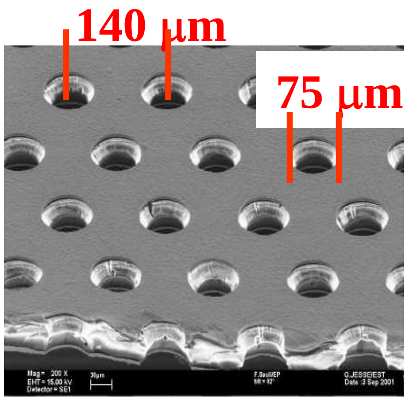
- **Optimize novel gas amplification systems**
  - **Conventional TPC readout based on MWPC and pads**
    - limited by positive ion feedback and MWPC response
  - **Improvement by replacing MWPC readout with micropattern gas chambers (eg. GEMs, Micromegas)**
    - Small structures (no E×B effects)
    - 2-D structures
    - Only fast electron signal
    - Intrinsic ion feedback suppression
- **Neutron backgrounds**
- **Optimize single point and double track resolution**
- **Performance in high magnetic fields**
- **Demonstrate large system performance with control of systematics**
- **Endplate design for minimal material**

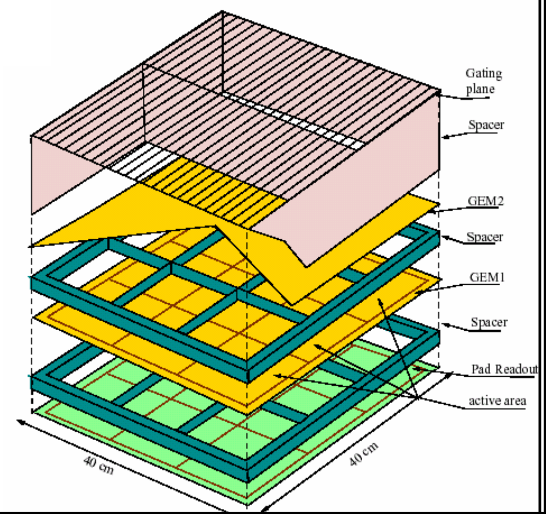
TPC Advances for ILC

Micro-Pattern Gas Chambers for gas amplification at end plate

GEM towers for safe operation (COMPASS)

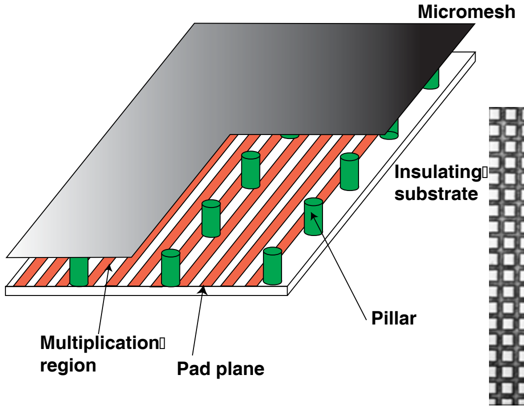
- 50 μm kapton foil, double sided copper coated
- 75 μm holes, 140 μm pitch
- GEM voltages up to 500 V yield 10^4 gas amplification

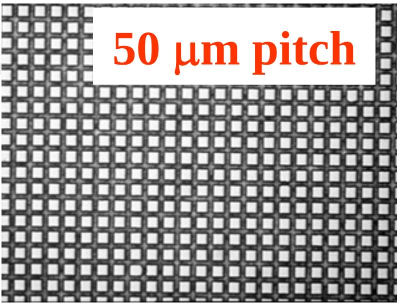




Micromegas for TPC Readout

- asymmetric parallel plate chamber with micromesh
- saturation of Townsend coefficient mild dependence of amplification on gap variations
- ion feedback suppression





Also investigating Silicon – Medipix2 w/ GEMs

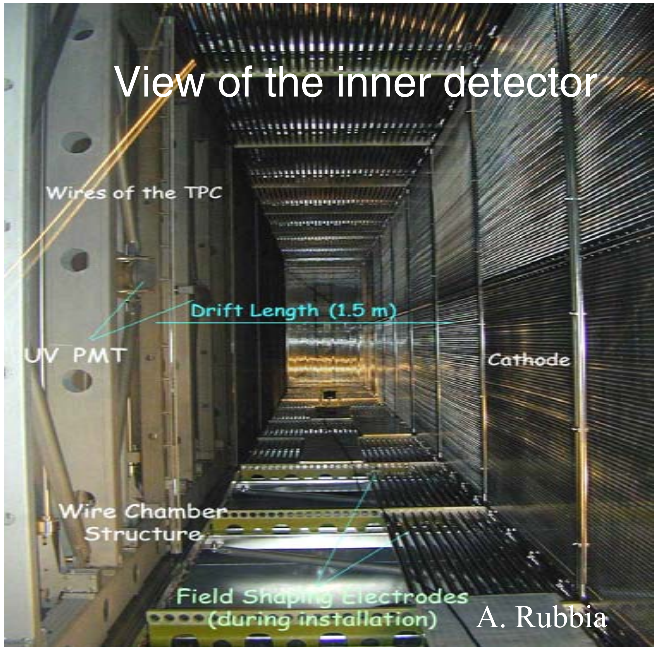
Cherenkov Detection

- **Powerful ring imaging detectors for past and present experiments**
  - **CRID @ SLD**
  - **RICH @ DELPHI**
  - **DIRC @ BaBar**

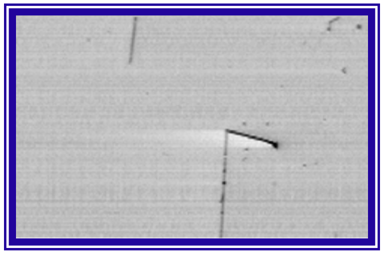
- **Future**
  - **Dual readout Calorimetry**
  - **HE Energy Neutrino Interactions** **G. Varner**
  - **Advances in the development of the Ring Imaging technology**
    - **thick GEMs** **R. Chechik**
    - **aerogel radiator** **E. Kravchenko**

Neutrinos

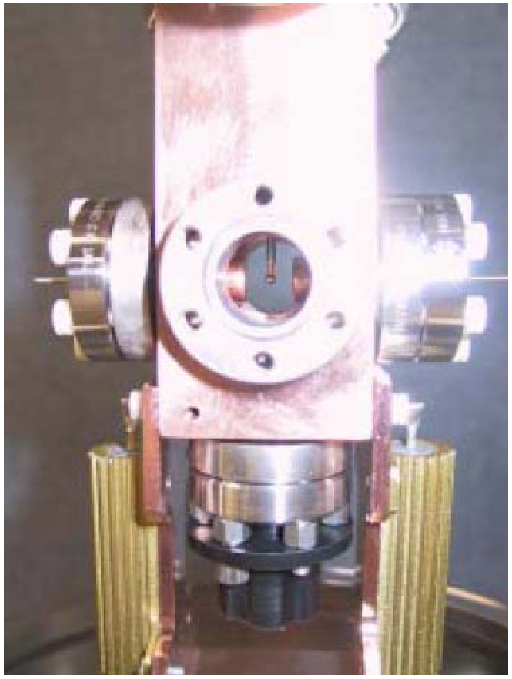
- **Liquid Argon TPC (Icarus)**



A. Rubbia



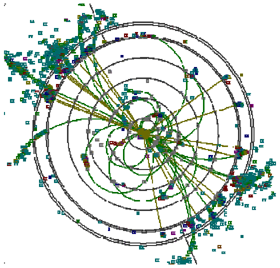
- **Neutrinoless Double beta Decay**



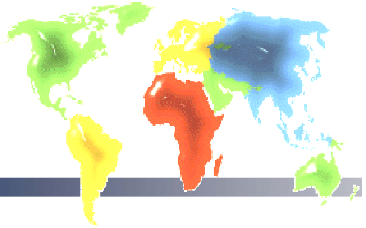
eg. EXO (liq. Xe)   D. Leonard

- related:

Liquid Noble Gas Calorimeters with High Space Resolution - S. Peleganchuk



Challenges for Future Detector Development in High Energy Physics



- Physics opportunities for the next decade are fundamental to our understanding of the Nature of the Universe (“the Quantum Universe”)
- Experimental opportunities beyond LHC and the current experiments should be excellent
- These opportunities bring new and difficult challenges to the experimenter
- Trends in the advances of detector technology promise to provide continued progress in addressing the challenges
- At this conference we will hear the latest progress on many important developments, and their connections to other fields