Vertex Detection at the Muon Collider

Ronald Lipton, Fermilab
Muon Collider Workshop, Nov 11 2009

Vertex detector design concepts are fairly well advanced for the ILC (although we don't really know how to execute the designs).

Detailed studies by LCFI and others on B tagging

We can use these designs as a basis for Muon collider studies

Compare the machine environments – how must the designs change?

How do the changes affect the physics?

LC Vertex Physics Needs

Lepton Collider is designed to do precision physics

- Higgs couplings
  - Require excellent separation of b/c/light quark vertices
- Higgs self coupling:

$$\mu^+\mu^- \to Z^0 H^0 H^0 \to qqbbbb$$

$$backgrounds: tt \to bb\, csc\, s, ZZZ, ZZH$$

  - B quark ID within jets
- Forward-backward asymmetry ??
 - Flavor tagging
  - Vertex charge
  - Forward tracking

Typical precisions at ILC

Polarized beam, B, Bbar separation

$e^+e^- \to b\bar{b}$
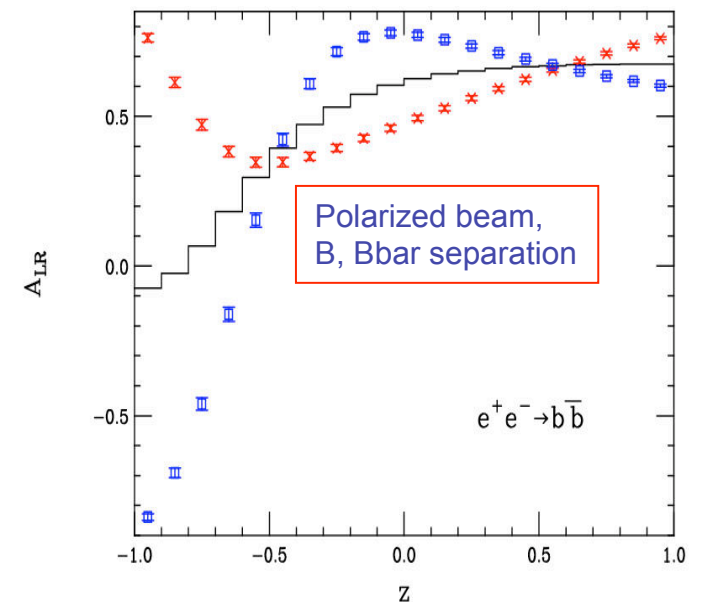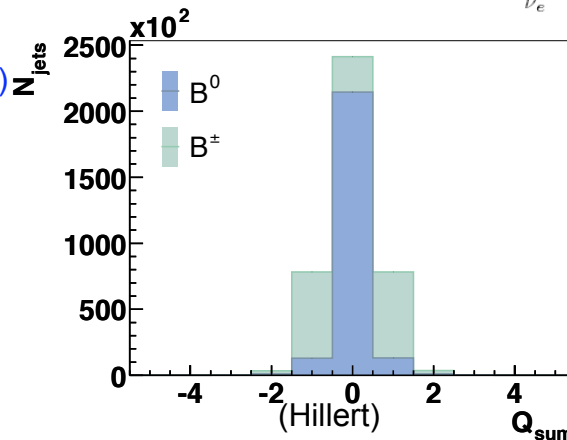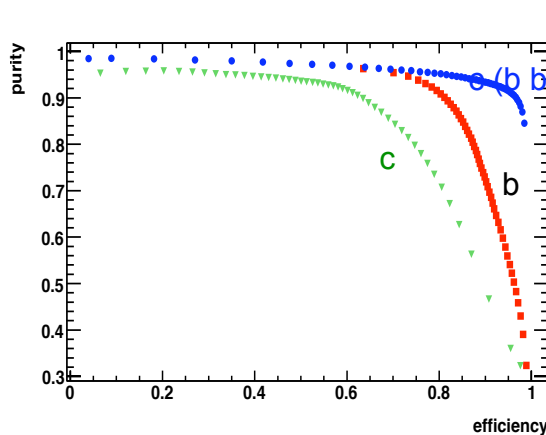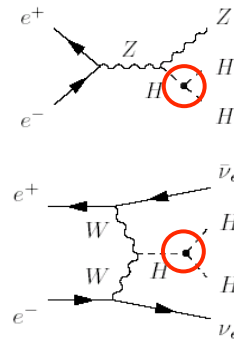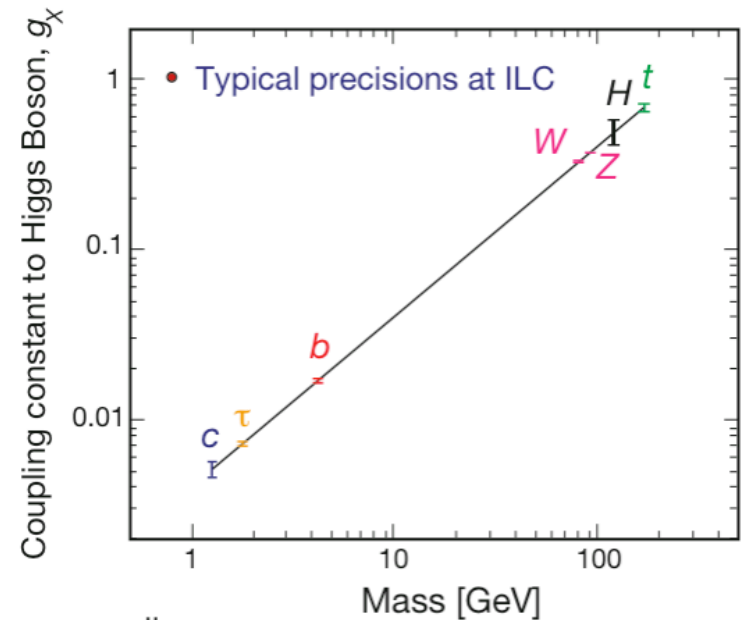
KK graviton exchange with jet-charge info
√s = 500 GeV, Λ = 1.5 TeV, 500 fb⁻¹
(Hewett)

(Hillert)

2

Physics Characteristics

- Machine design luminosity
  $L \sim 10^{34}$ cm^{-2}s^{-1} ($\sqrt{s}$ = 2 TeV)
  - Cross sections are small
  - Hadronic event rate low
  - Need to preserve signal
- Need excellent particle identification
  - Discriminate W and Z in hadronic decay mode
  - Distinguish quarks from antiquarks

(Demarteau)
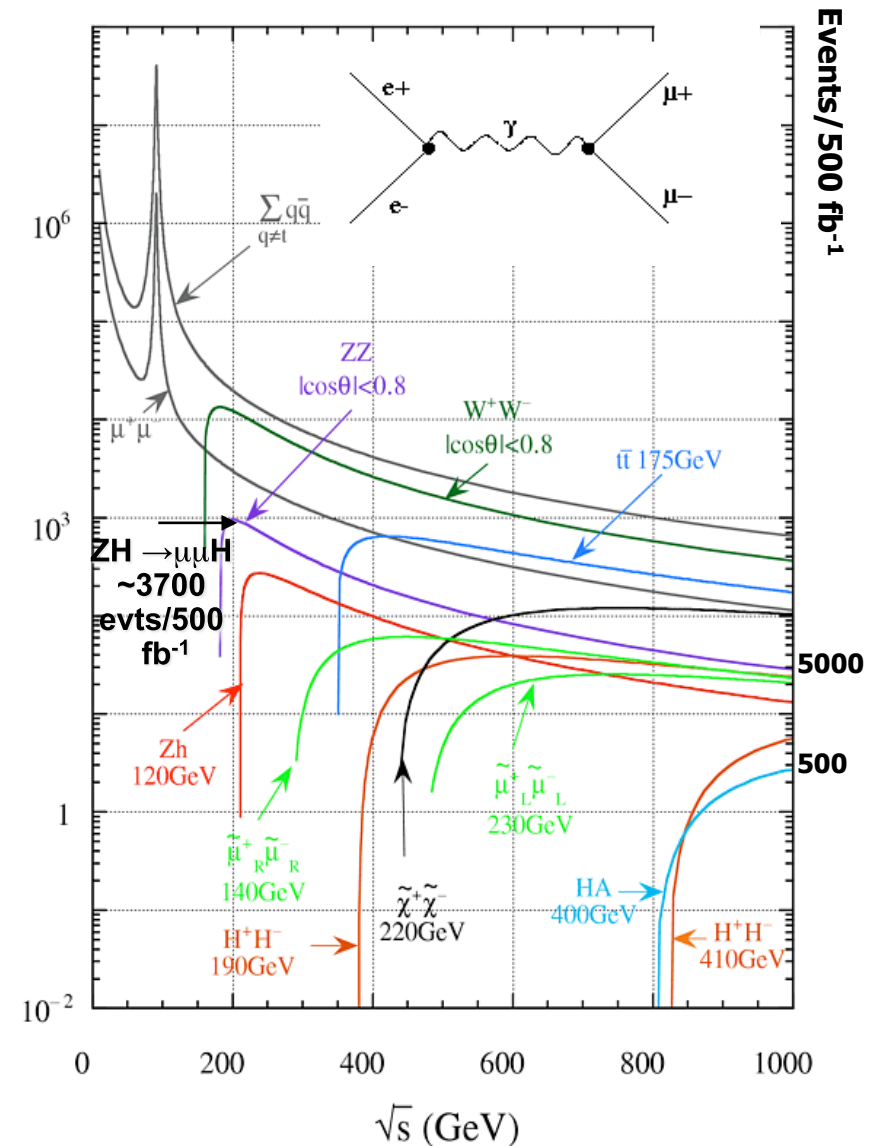
ILC Vertex Detector Goals
vs μ collider

Basic goals are extrapolated from the SLD CCD vertex detector.
   μ collider comments in red

- Excellent spacepoint precision (< 5 microns) ✓

- Superb impact parameter resolution ($5\mu m \oplus 10\mu m/(p\ sin^{3/2}\theta)$) ??

  – Increased mass and larger inner radius will degrade resolution

- Transparency (~0.1% X_0 per layer)

  – Mass associated with liquid cooling

  – Power density

  – Guess ~ 0.4%

- Integration over <150 bunch crossings (45 μsec) ✓

  – Closer to 10 μs for μ collider

- Moderately radiation hard

  – Significant radiation hardness

- Stand-alone pattern recognition (SiD)

4

Backgrounds

- Background considerations will likely dominate the design at the muon collider

  - Instantaneous backgrounds associated with beam crossing that increase occupancy

  - Radiation levels near the vertex detector that will generate radiation damage and dictate operating temperature and mechanical design

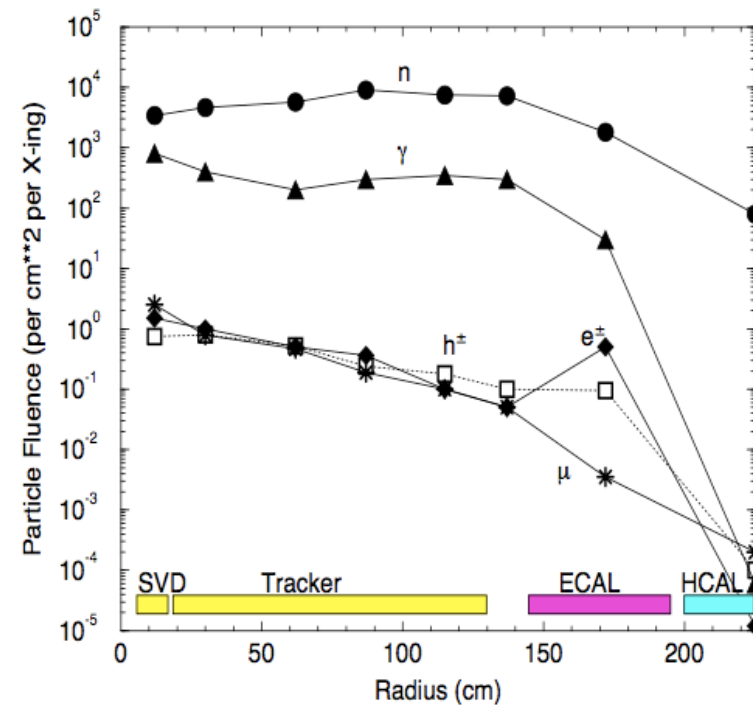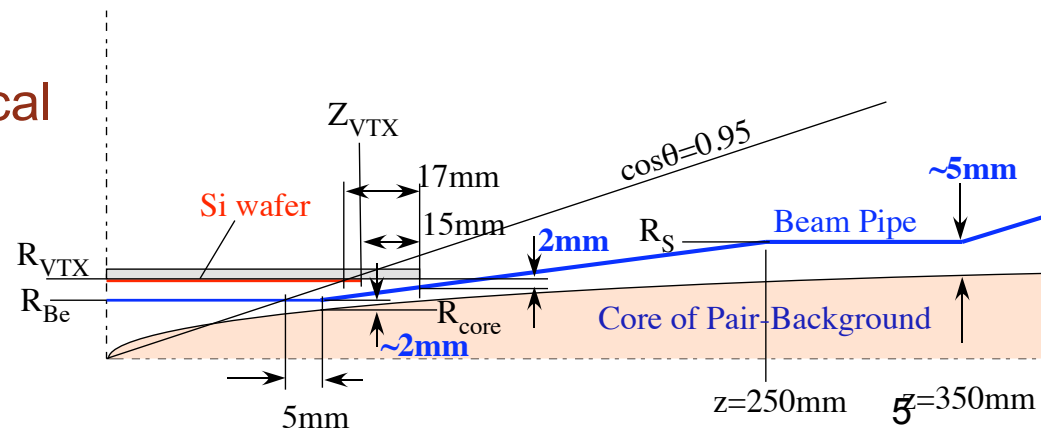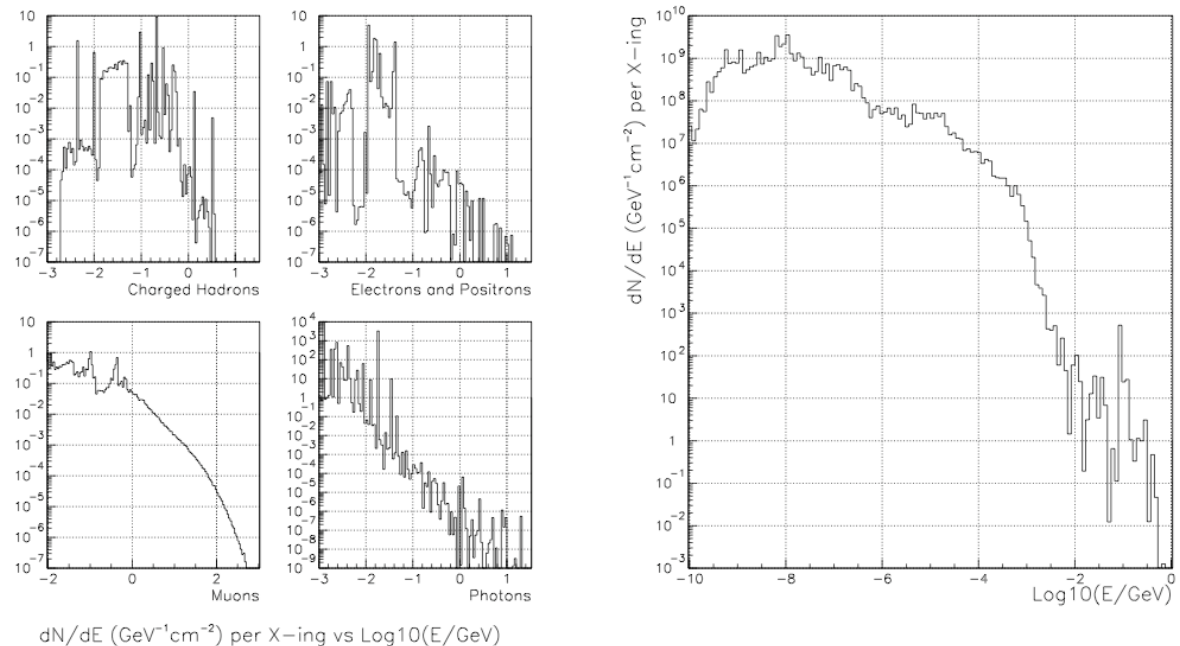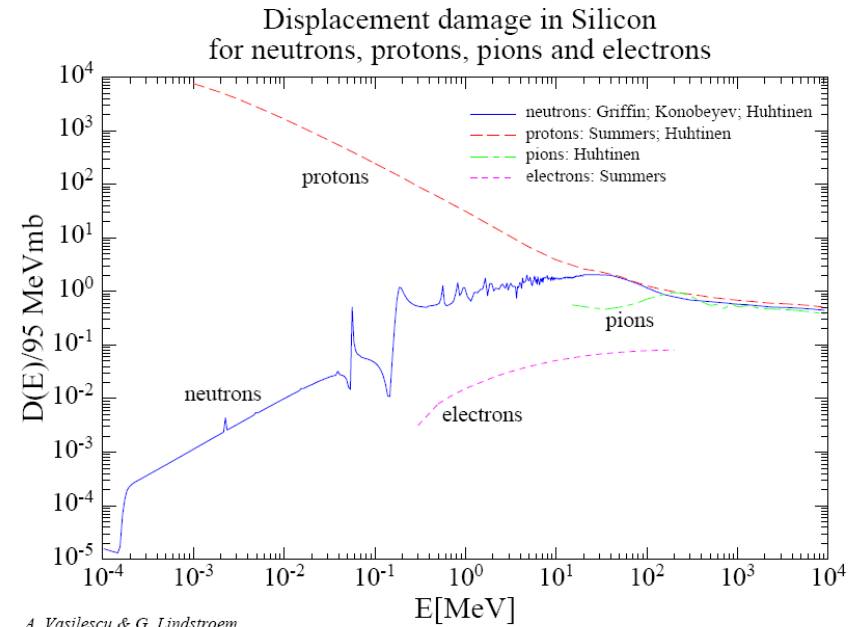- Will force compromises with respect to ILC designs and eliminate some technologies

Figure 10. Particle flux radial distributions in a $\pm 1.2\,\mathrm{m}$ detector region around the IP per $2 \times 2\,\mathrm{TeV}$ $\mu^+\mu^-$ bunch crossing.

Backgrounds II

- Muon collider has a different radial distribution than a electron collider
  - More neutrons
  - Less disrupted beam
  - Upstream backgrounds
  - More complex shielding
- Particle composition is different: need to calculate effective radiation damage factor vs radius for detailed folding of spectra
- Scale to non-ionizing energy loss
- Electrons cause much less displacement damage

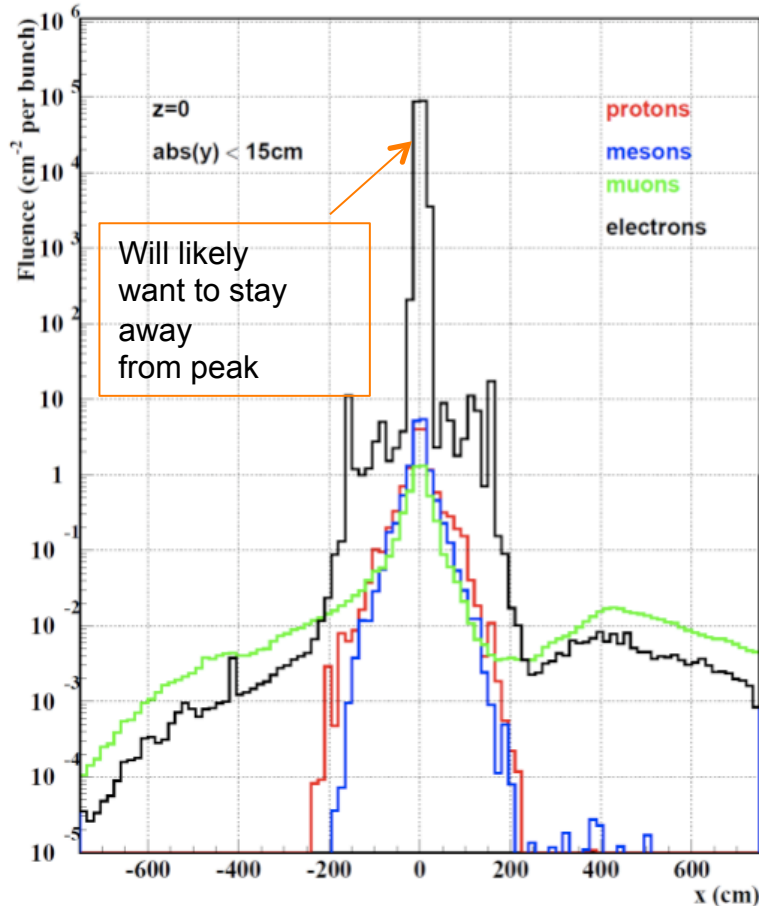Displacement damage in Silicon for neutrons, protons, pions and electrons

neutrons: Griffin; Konobeyev; Huhtinen
protons: Summers; Huhtinen
pions: Huhtinen
electrons: Summers

A. Vasilescu & G. Lindstroem

dN/dE (GeV⁻¹cm⁻²) per X−ing vs Log10(E/GeV)

Radiation Damage

- Dominated by neutrons
- 1200/cm^2/xing at 5 cm at 2x2 TeV
- 1200 x 10^5/sec x 3600sec/hr x 500 hr/yr ~ 2.6x10^{14}/year
  - Significant, still less than SLHC
  - Assume 200 micron thick, V_{dep}~ 200 V
  - Vertex (and tracker) need to be cooled to around 0 deg C
- This is a simple calculation that assumes 1 MeV neutrons and does not include other species
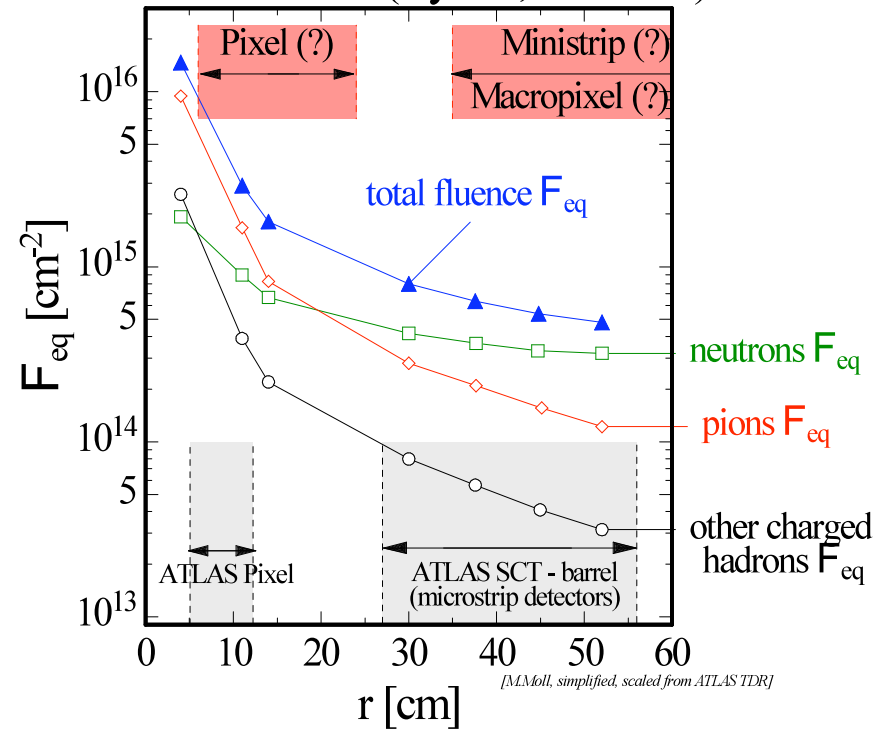- Nikoli's latest – small nose calculation has higher fluences
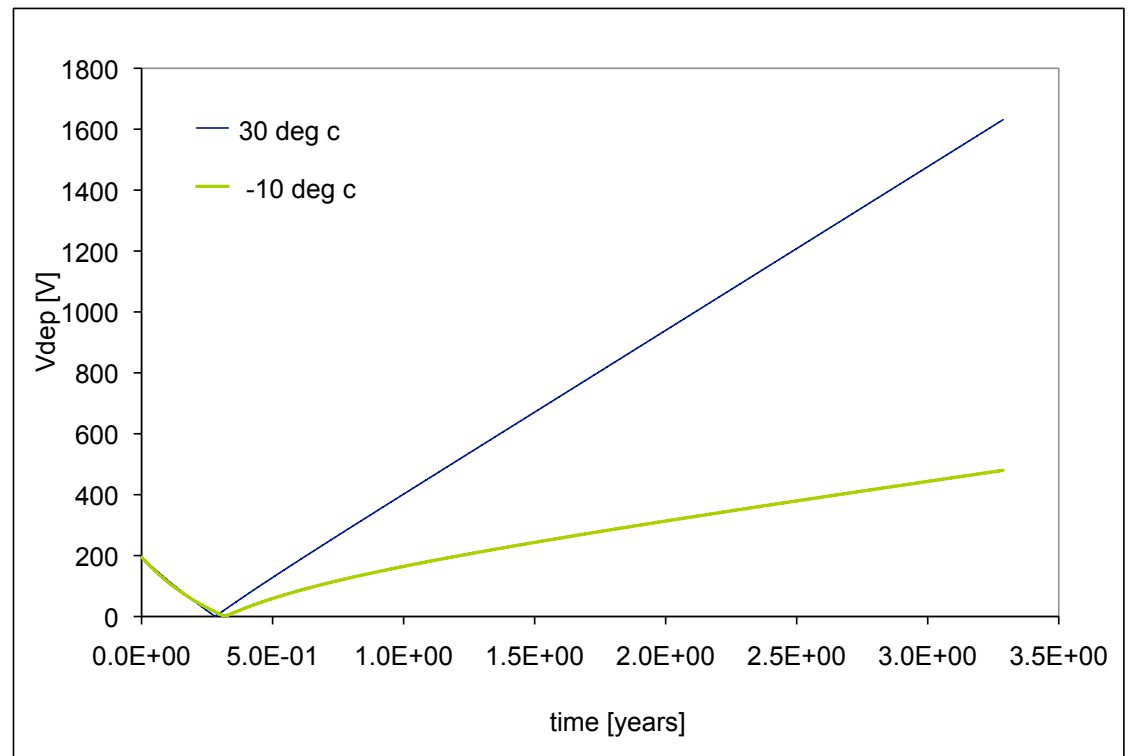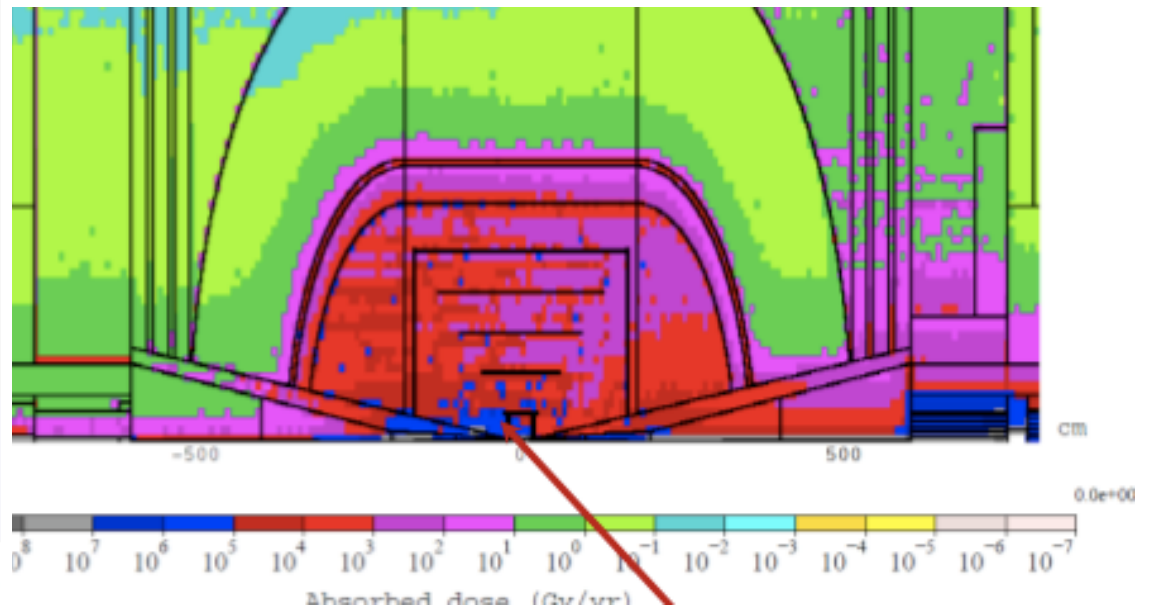
LHC and μColl

1 Mgy = 100 Mrad
Need to scale all particle fluxes
to NIEL damage, then compare
to LHC

Will likely
want to stay
away
from peak

SUPER - LHC (5 years, 2500 fb⁻¹)

total fluence F_{eq}

neutrons F_{eq}

pions F_{eq}

other charged hadrons F_{eq}

Pixel (?)   Ministrip (?)
             Macropixel (?)

ATLAS Pixel   ATLAS SCT - barrel
               (microstrip detectors)

[M.Moll, simplified, scaled from ATLAS TDR]

(Mokhov)

Vertex detector Geometry

Why do we worry so much about geometry

- Efficiency is important – the event rates are low
- Resolution really depends on inner radius and vertex detector mass
  - B-id efficiency and vertex charge ID depends strongly on resolution
  - Charm, B, and light quark separation for Higgs decay measurements
- Radiation levels determine cooling requirements
  - ILC detectors assume air cooling near RT
  - Heavily irradiated detectors will need to operate near -10 deg and may require liquid cooling – probably CO_2, which is more massive.

$$\sigma_z = \sigma_{hit} \frac{\sqrt{1 + \frac{r_i}{r_o}}}{1 - \frac{r_i}{r_o}}$$
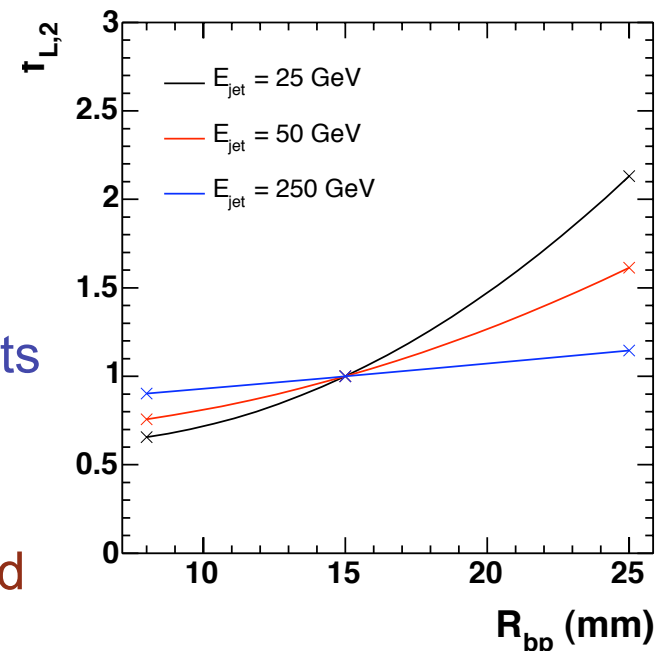
Luminosity factor as a function of radius for processes requiring vertex charge for 2 jets

(Hillert)   9

Performance Measures

- LCFI vertex charge ID performance measure for B decays in jet

$$\lambda_0 = 1 - \frac{\textit{Neutral vertices reconstructed as neutral}}{\textit{All generated neutral vertices}}$$

- Stringent – a single missed track can ruin the measurement
- Inner layer radius increase not accompanied by outer radius increase
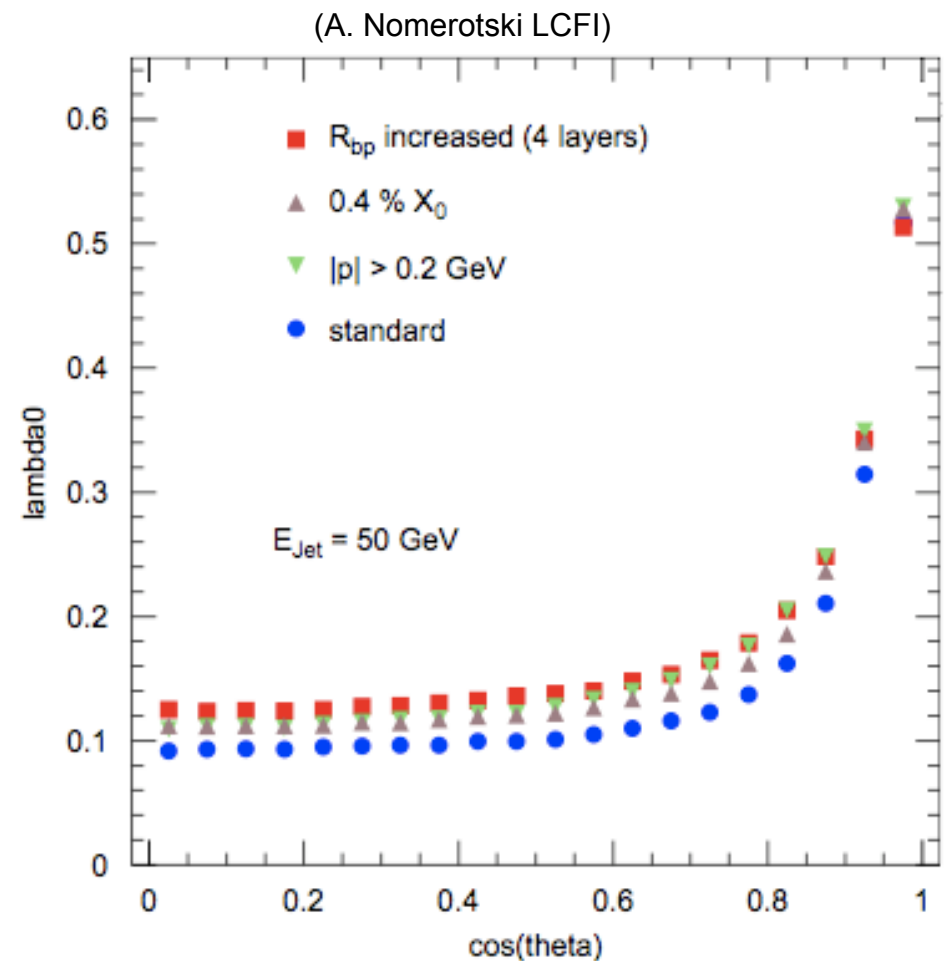- Should "scale" with IP resolution

(A. Nomerotski LCFI)

Fig. 4. Degradation in performance for minimal radius 25 mm, P_T cutoff in tracking 0.2 GeV and thickness per layer 0.4% X_0.
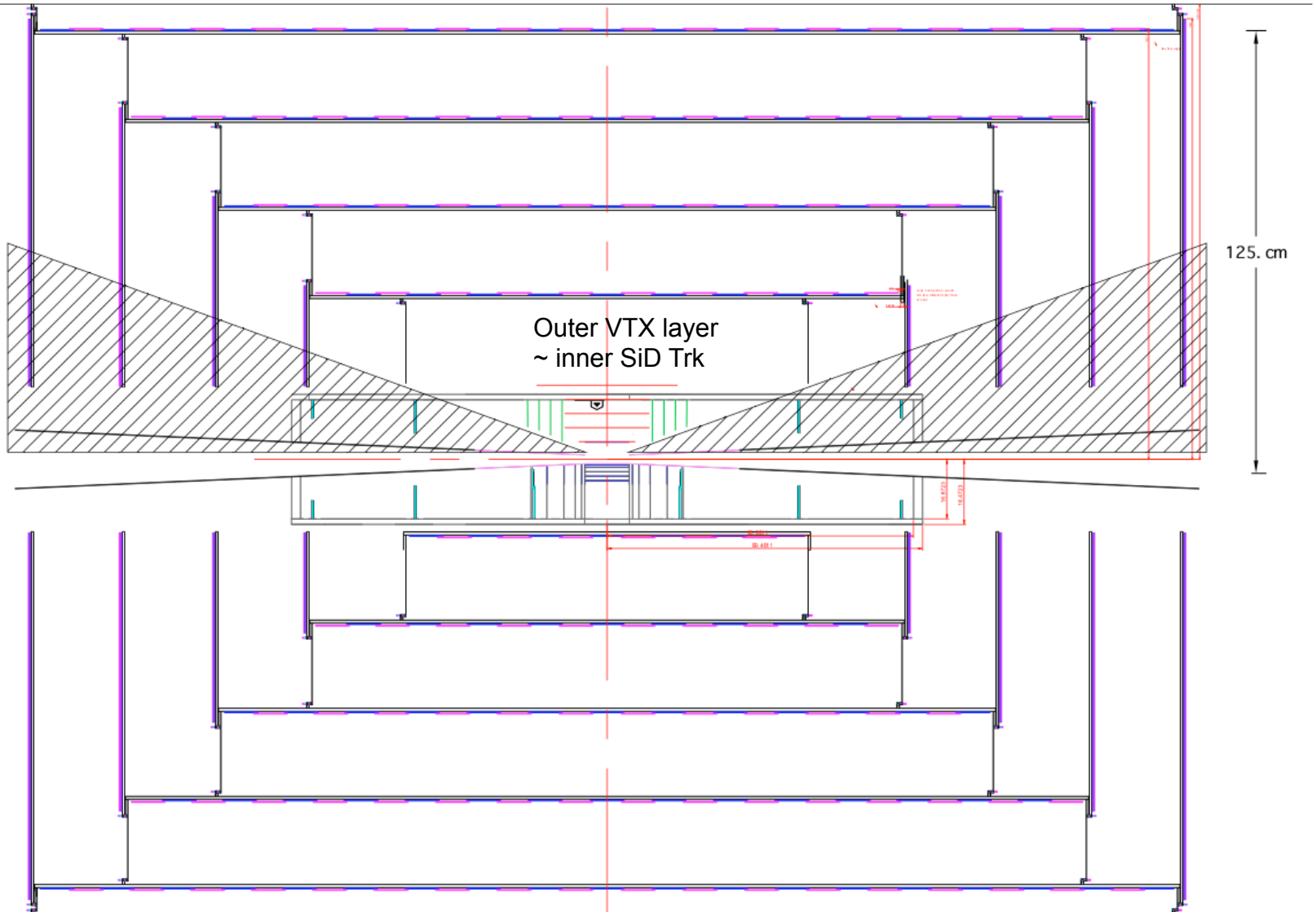
10

SID MuColl Frankenstein

20 deg
cones

Outer VTX layer
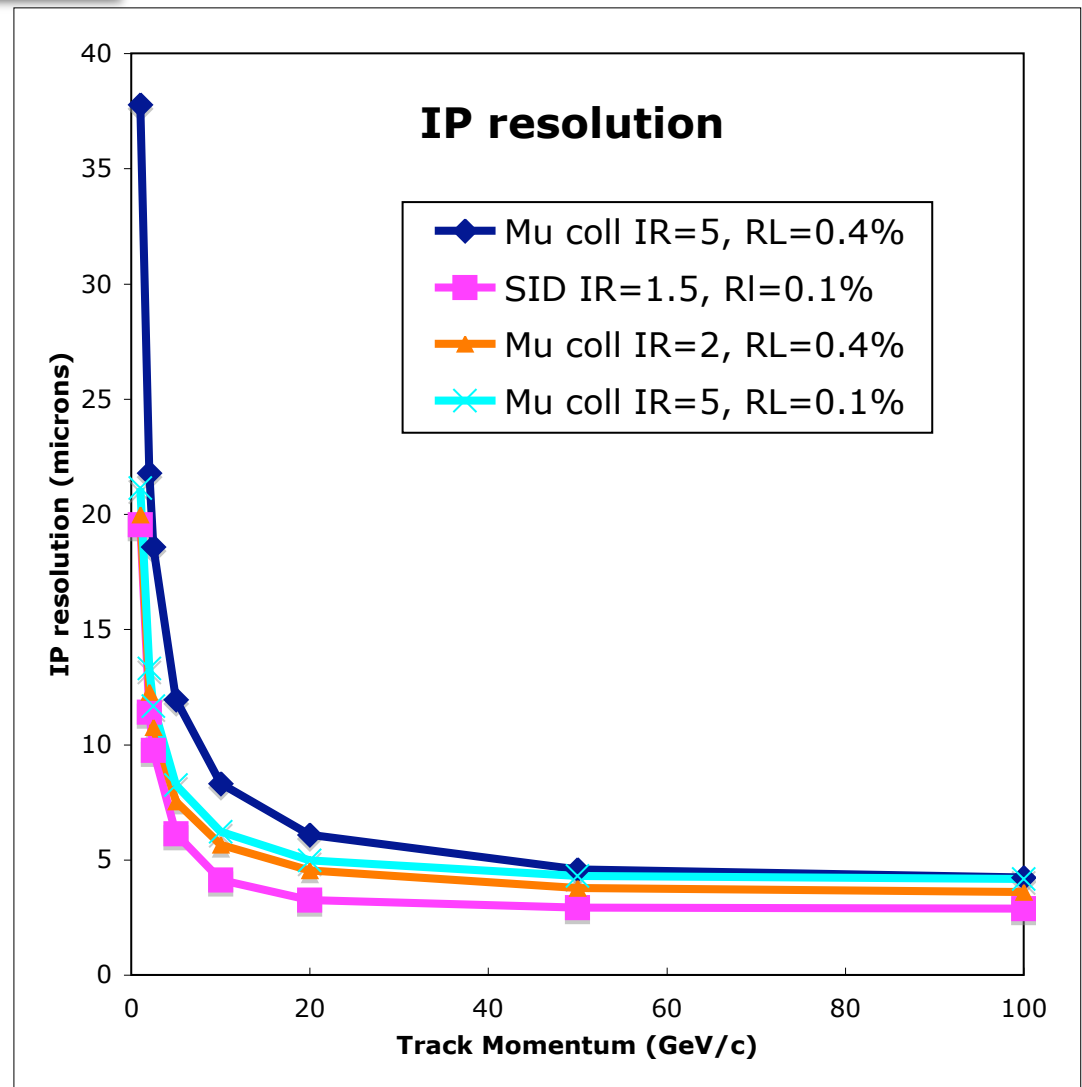~ inner SiD Trk

125. cm

Ronal

Design Features

- ILC
  - Outer radius ~ 6 cm
  - Barrel length ~ 14 cm
  - Ladder widths 1-2 cm
  - Disks to cover forward reg
- Muon Collider
  - Inner radius ~ 5 cm
  - Outer radius ~ 15- 20 cm
- Caveat – this is *NOT* a real design – just a sketch of how designs might evolve
- The nose does provide a convenient support and service routing region
- Could also serve as heat sink?

μ Collider

20 deg nose

Vertex Disks

Vertex Barrel

SiD
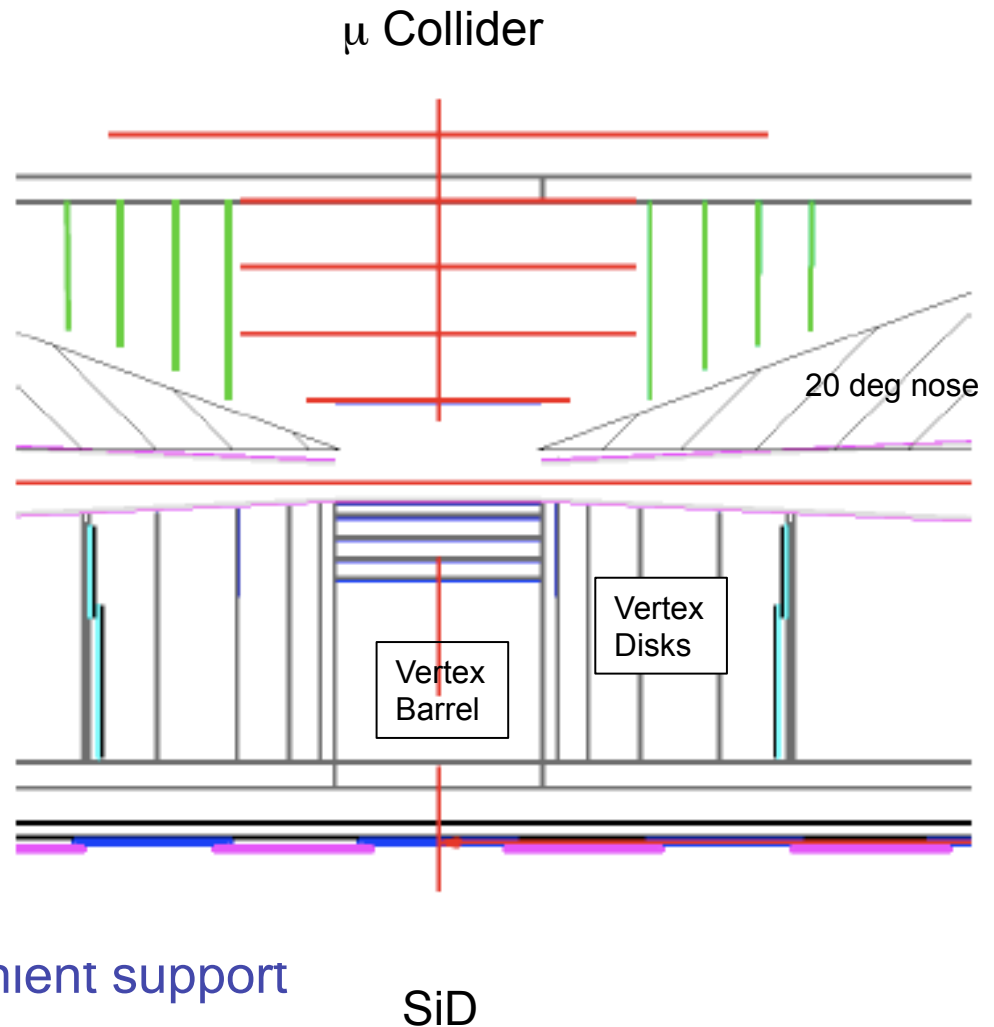
IP Resolution

- Use track fit spreadsheet to estimate degradation of resolution
  - Based on SiD design
  - 5 micron vertex and 12 micron track hit resolution
  - Radii of (1.5→6 cm) go to (5→20 cm) or (2→20 cm)
  - 0.1% RL/layer → 0.4%
- At most x 2 worse
- Keeping constant r_{in}/r_{out} important
- Can trade radius for RL

IP resolution

Legend:
- Mu coll IR=5, RL=0.4%
- SID IR=1.5, Rl=0.1%
- Mu coll IR=2, RL=0.4%
- Mu coll IR=5, RL=0.1%

Y-axis: IP resolution (microns)
X-axis: Track Momentum (GeV/c)

Beam structure and Time Resolution

- ILC – 1 ms train every 0.2 sec
- ILC - No trigger - read all hits

- Muon collider short bunches every 10-20 μs
  - 1 event every 90 seconds at 10^{34} at 1.5 TeV
  - This will probably be a triggered system
    - 10^6 less data flow
    - Can an efficient trigger be formed
  - Long FE integration time → lower FE power
  - Low digital and data transmission power
  - Latency is probably modest (triggers would not be complex)

- Time is power (FE current, more clock cycles, power = f x ΔV x C …)
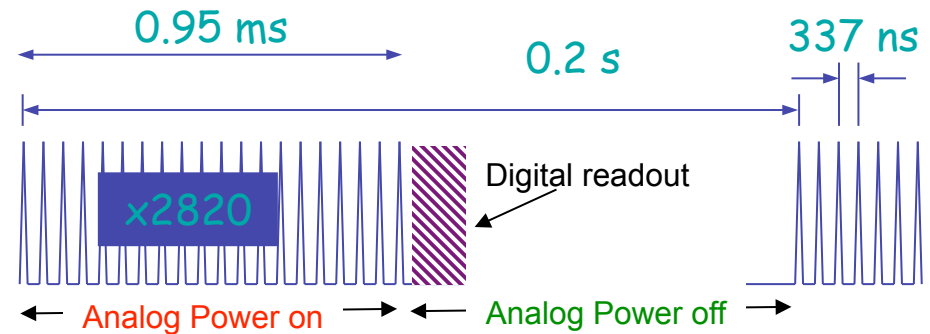
Material

- To achieve ILC goals we must improve RL/layer over LHC by ~20 x
- For muon collider we need to deal with
  - Liquid cooling   - Increased power
  - Increased data load?   -
- Detector will be thinned to 50-100 microns
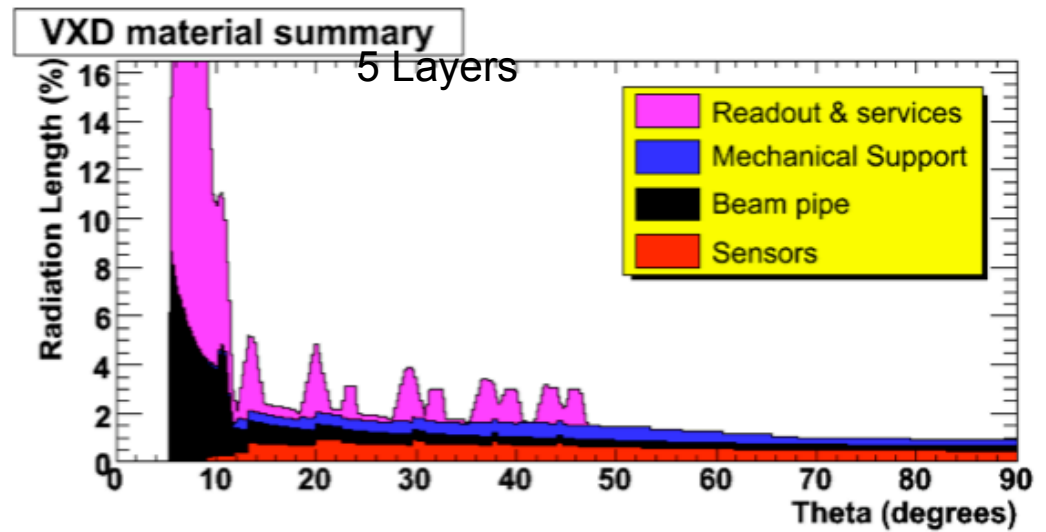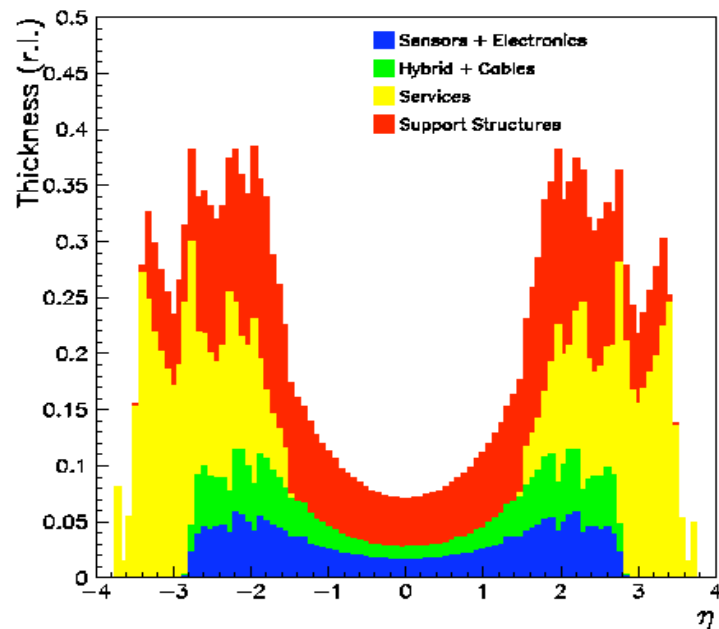 - Less mass and more rad hard

Figure 33 VXD hit pattern and material summary as a function of polar angle.

Noise and Power

For pixel amplifier-based devices the FE amplifier usually dominates power consumption:

- Series white noise:

$$ENC^2 = (C_{det} + C_{gate})^2 \frac{a_1 \gamma 2kT}{g_m t_s}$$

- Noise scales as C and 1/sqrt[transductance (g_m)]
- Pixel front end transistors will operate in weak inversion - where g_m is independent of device geometry and $\sim (I_d/nV_T)$.
- Need < 200 μW/mm^2
- Acceptable low current operation (<1 μA) requires long shaping and/or low node capacitance
  - For t_s = 1000ns, I_d=0.1 μA C_d ~ 100 ff noise ~ 35-50 e
  - ~10 ff should be achievable in SOI devices, 20-40 in MAPS
  - FE power ~ 200 μW/mm^2 with 20 micron pixels – but this does not count any other parts of the circuit – pretty hard to achieve air cooling.

Air Cooling

Air In   Air Out


(Cooper, SID)
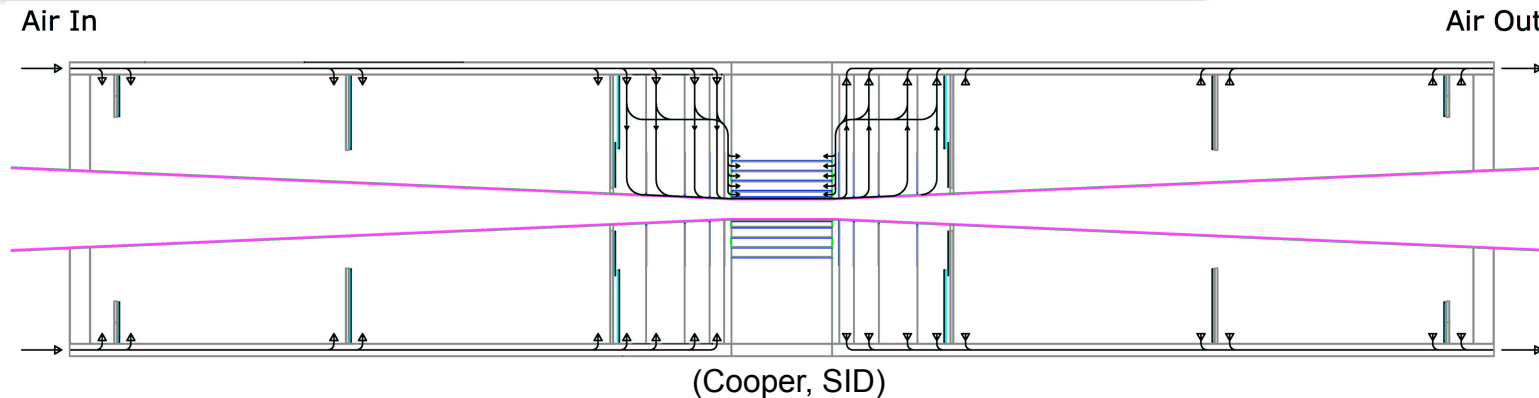
- Air cooling in ILC is needed to keep mass to a minimum (remember 0.1%)
  - implies a limit on power dissipation
- Estimate by requiring laminar flow through available apertures
  - This sets total mass flow – other quantities follow
- For SiD design
  - Use the outer support CF cylinder as manifold (15mm Δr)
  - Maintain laminar flow (Re_{max} = 1800).
  - Total disk (30W) + barrel (20W) power = 50W *average*
    - For SiD ~ 131 $\mu W/mm^2$.
   - Max ΔT ~ 8 deg

17

Power Distribution

- Power goals in ILC are "met" using power pulsing
  - Duty factor ~1/200 assume 1/100 power savings
  - Peak and average power are both crucial issues for the vertex detector
  - Power pulsing for FE chips - just turn power on during 0.95/200 ms
    - Maximum duty factor ~200, assume ~100 may be practical 2000 W=> 20 W (average)
    - But I_{peak} is still the same - 2000A if we saturate the 20W limit
  - High peak currents => more conductor to limit IR drop => Mass
  - Serial powering, DC-DC conversion can lower instantaneous current
- The μ collider beam structure does not allow for power pulsing
  - Probably need liquid cooling
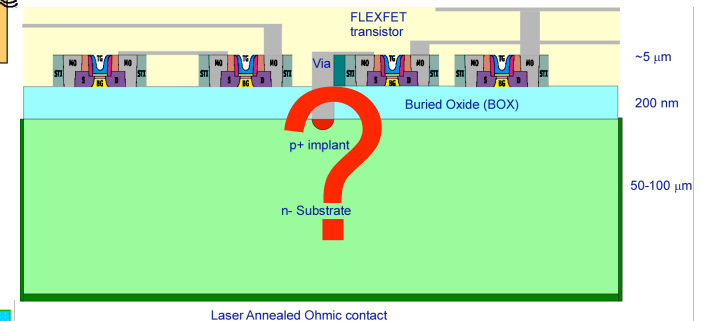 - More than 0.1% RL mass

Sensor Design

- CCDs
  - Readout too slow
- CMOS Active Pixels
  - Possible, radiation hardness?
- SOI
  - Possible, radiation hardness?
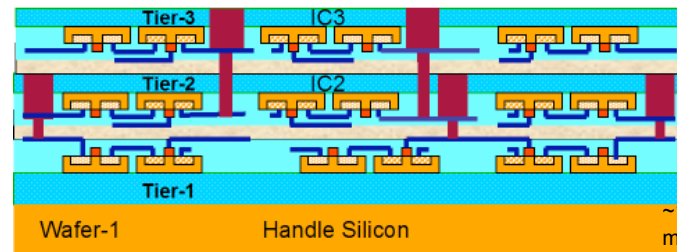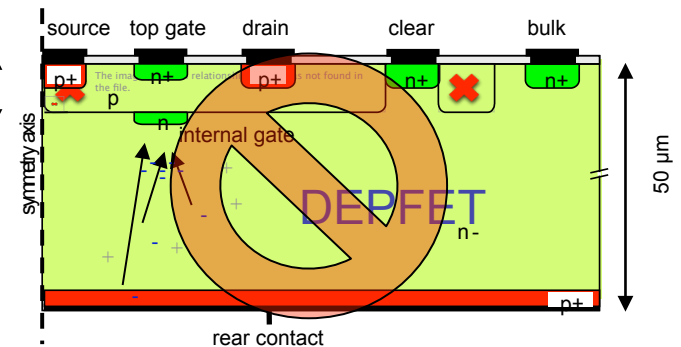- 3D
  - Yes
- DEPFET
 - Probably too slow
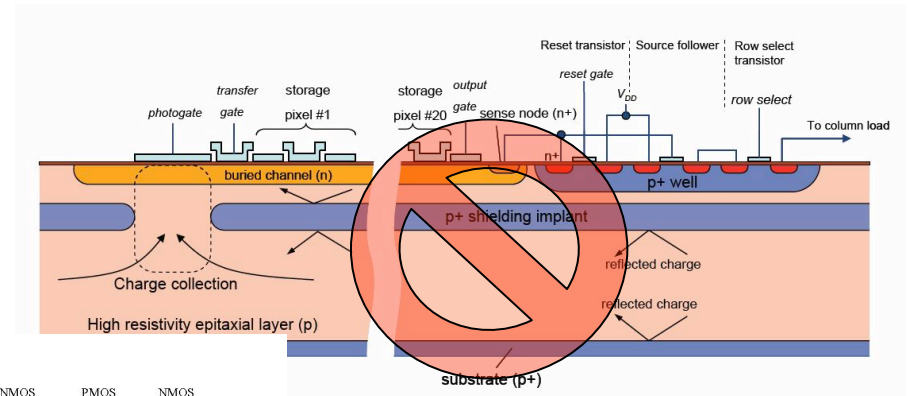
CCD
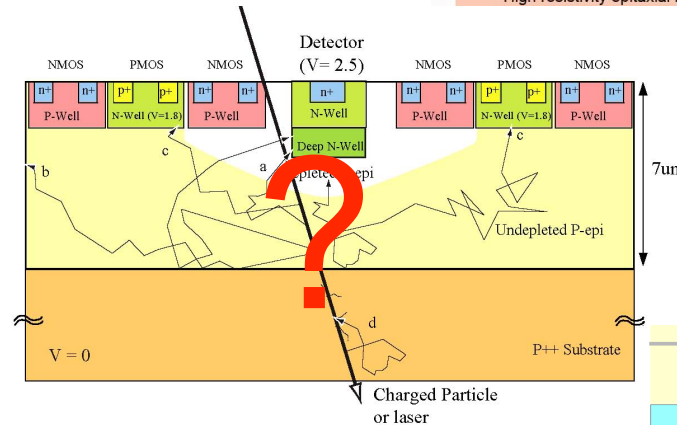
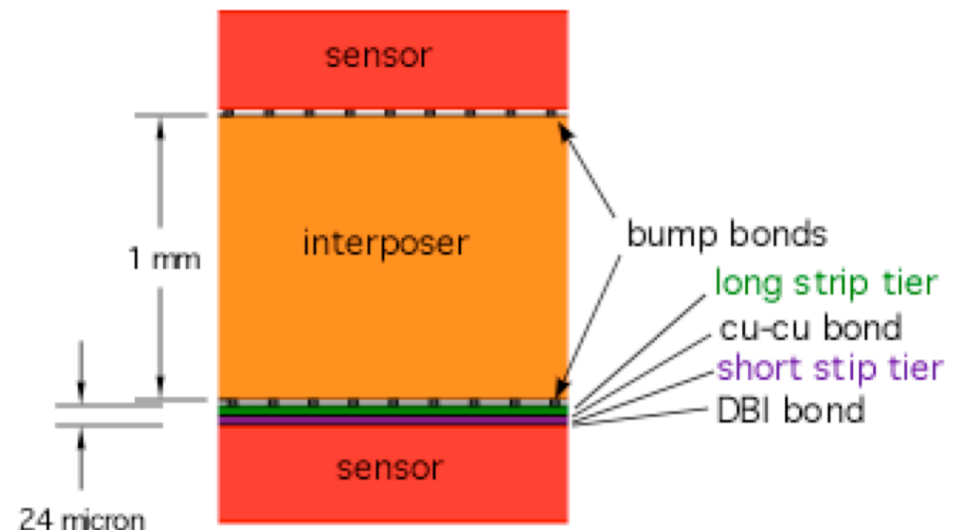

CMOS Active Pixels

SOI

3D

DEPFET

Sensors

- 20th Century studies assumed 300 μm square pixels
- ILC studies assume ~ 20 μm square pixels x 225 less occupancy/pixel
- It is likely that these smaller pixelated devices will provide sufficient resolution for good pattern recognition.
- But other techniques can be used to reduce occupancy based on inter-layer correlations
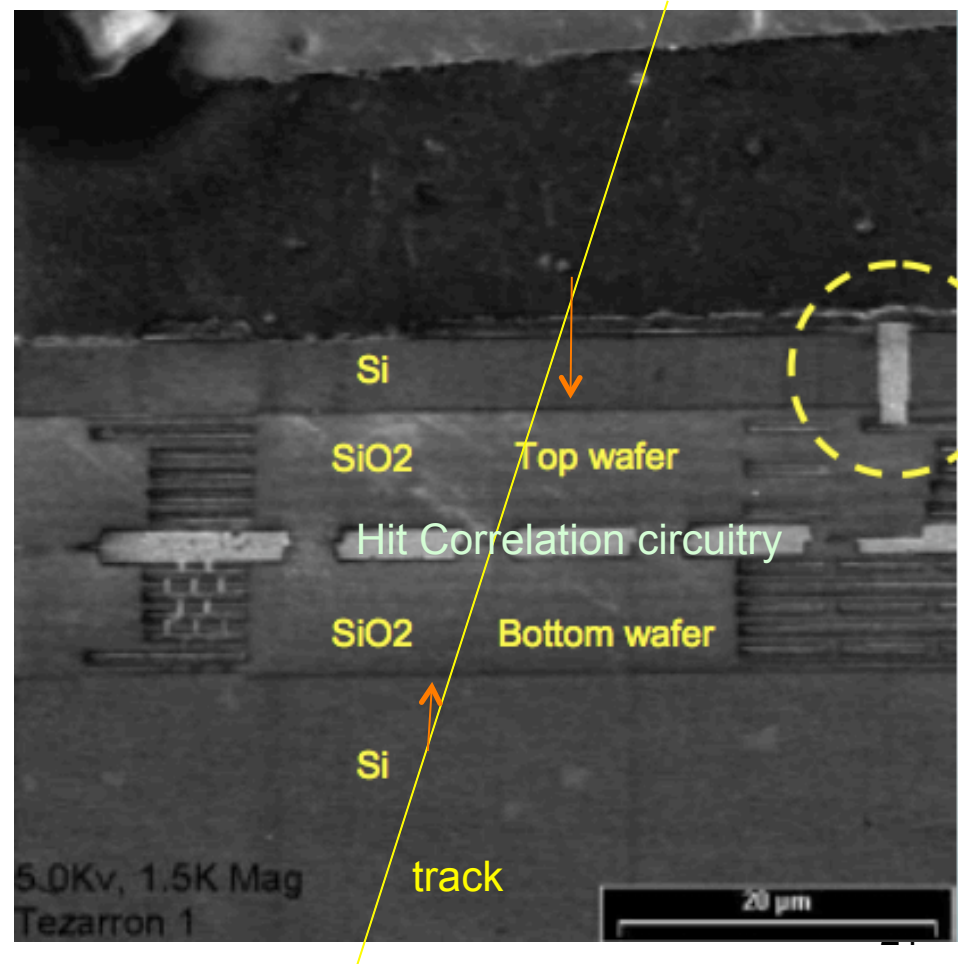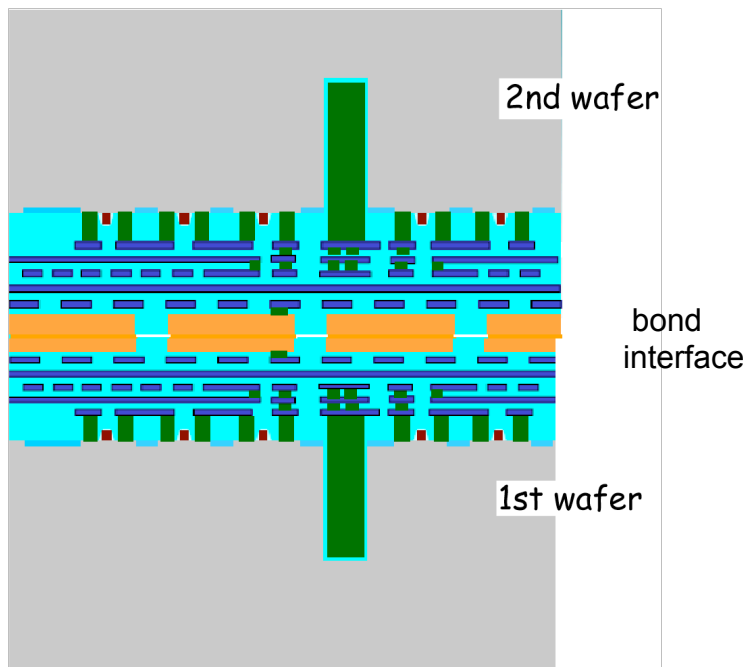- This technology is being developed for CMS upgrade

Ronald Lipton MCWS 2009
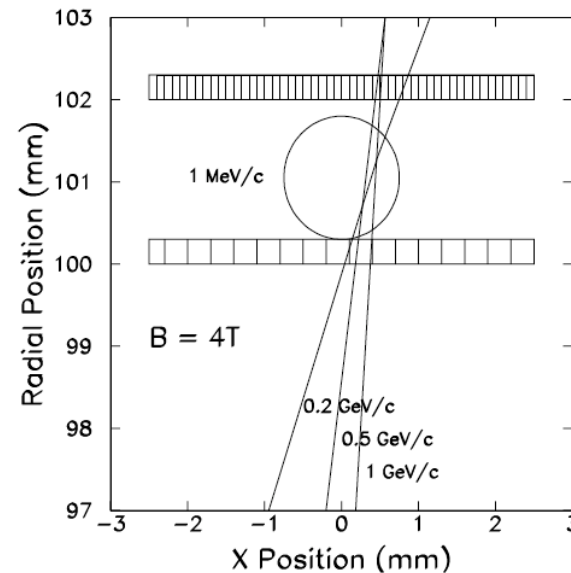
1999 μCol Track correlation module

2009 Track trigger module for CMS Phase II Based on 3D electronics

False hit rejection

- Random false hits can be rejected with minimal material and modest power penalty using 3D bonded monolithic active pixel ICs
- We could almost do this now

2nd wafer

bond interface

1st wafer

Si

SiO2   Top wafer

Hit Correlation circuitry

SiO2   Bottom wafer

Si

5.0Kv, 1.5K Mag
Tezarron 1

track

20 μm

Ronald Lipton MCWS 2009

Conclusions

- A few initial comments:
  - Both vertex and tracker will need to be cooled below 0 deg C
  - Vertex detector inner and outer radii will increase over ILC
  - Increased mass/layer due to water cooling
- Loss of forward region due to collimation "nose"
  - Can A_{fb} measurements be retained?
  - Can the nose be modified?
  - Can it be used for cooling and services?
- Too early for real conclusions but it appears that excellent tracking and vertexing can be retained with moderate effective luminosity loss.