Tracking and Vertexing at the Future Linear Collider

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thanks to L Andricek, C Baltay, F Bogert, J Brau, R De Masi, A Potenza, W Snoeys, Y Sugimoto

Pixel 2010
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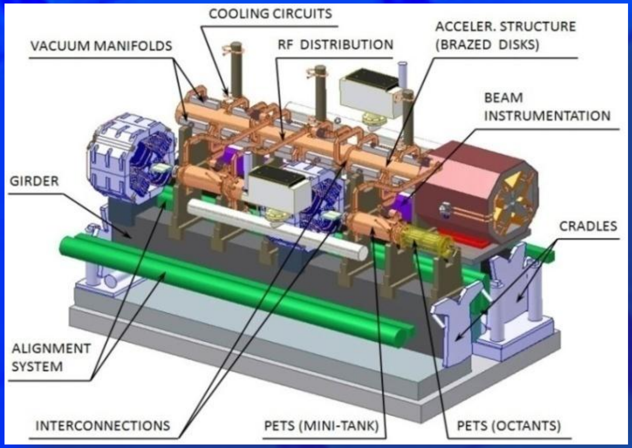
e^+e^- linear collider emerges as most practical and realistic way to achieve collisions at constituent energies matching those of the LHC with high luminosity: energy depends on available accelerating gradients, luminosity on power and beam emittance/size at IP:

Superconducting Linac
ILC - 0.25 – 1 TeV

E_{cm} = 0.35 TeV
L = 1.2 10^{34} cm^{-2} s^{-1}
E_{cm} = 0.5 TeV
L = 2.0 10^{34} cm^{-2} s^{-1}

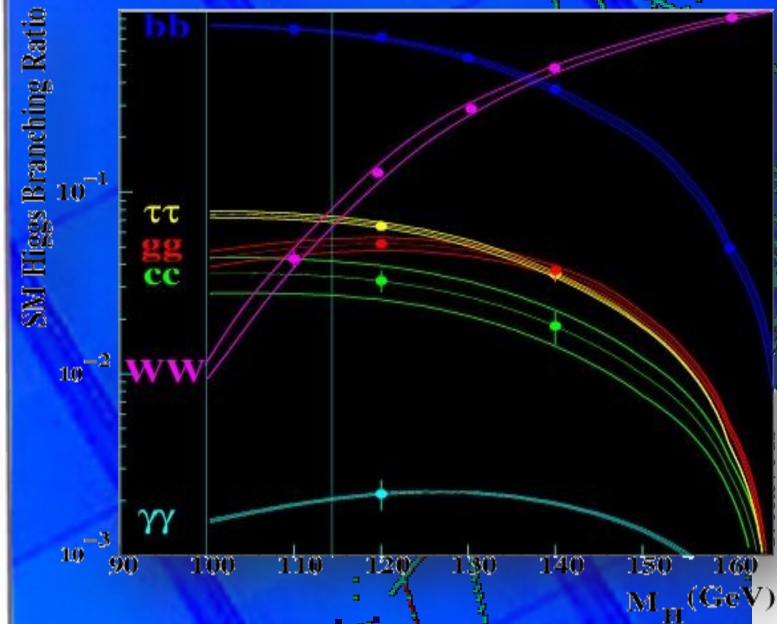
Two-beam Acceleration Scheme:
CLIC - 0.5 – 3 TeV

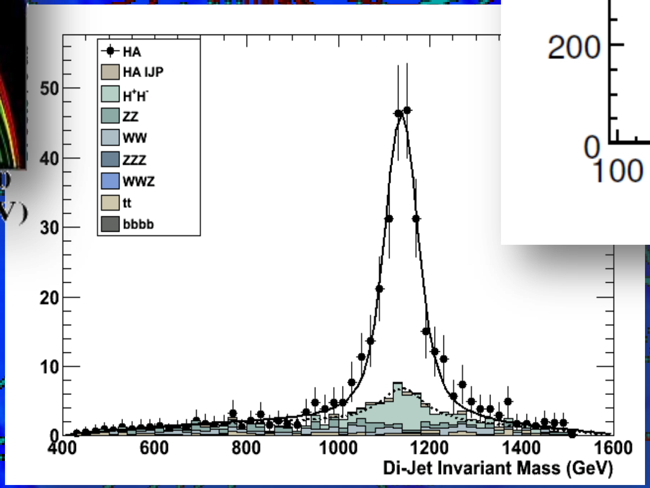


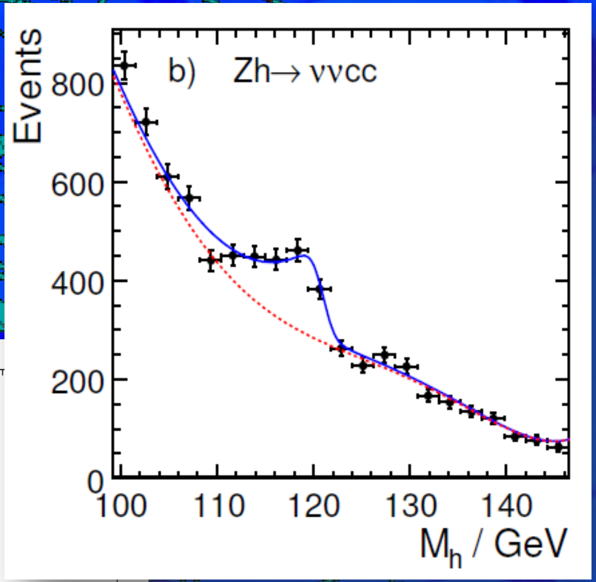
E_{cm} = 3 TeV
L = 6 10^{34} cm^{-2} s^{-1}

Role of heavy flavour tagging in LC physics

Heavy quarks represent an essential signature of anticipated physics of interest at future lepton colliders: Higgs sector, TeV-scale New Physics and search for very high mass phenomena through EW precision observables;



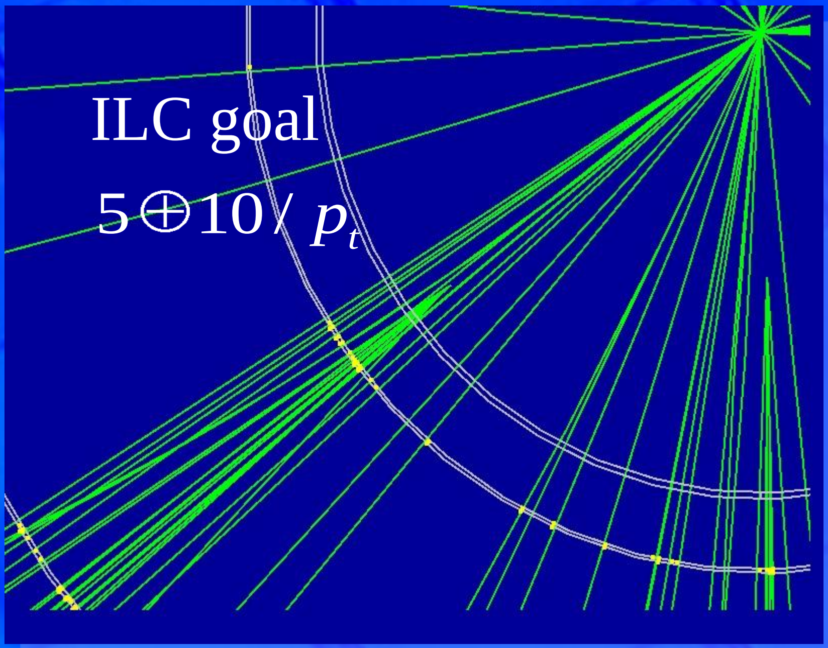


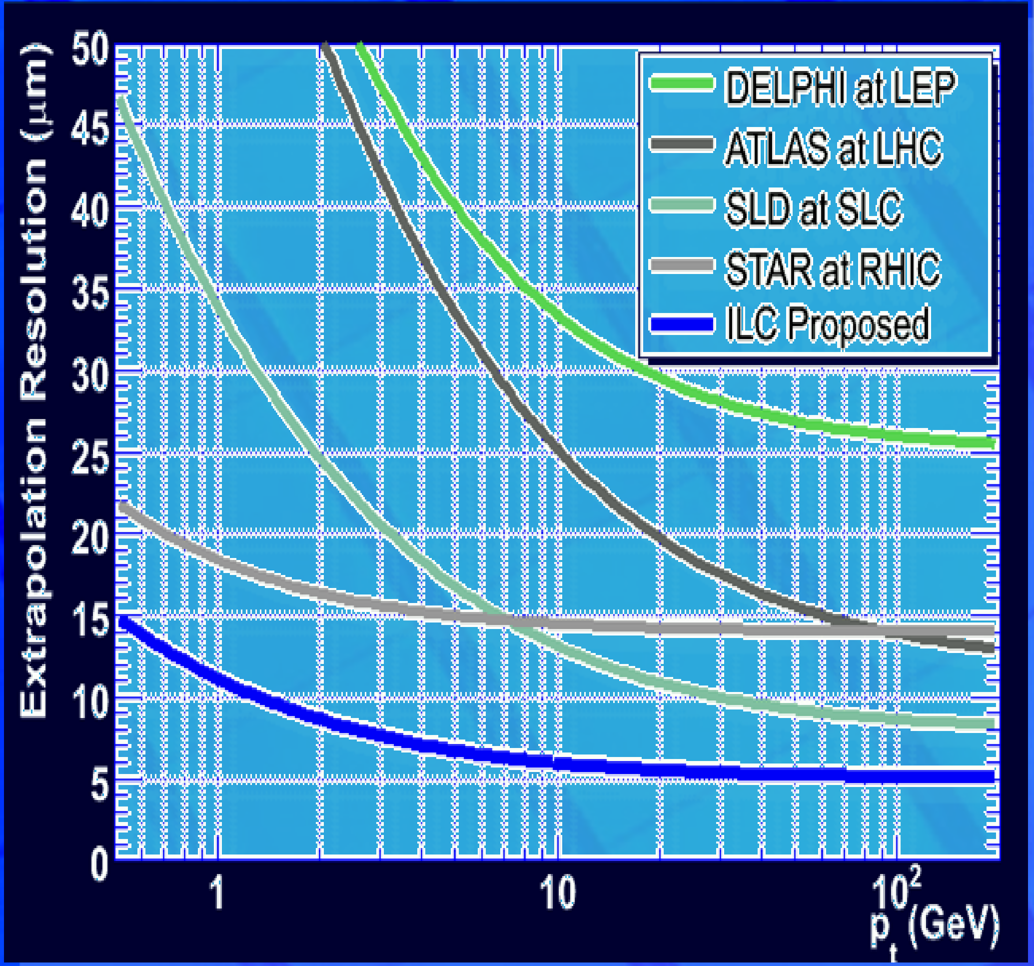


Jet flavour tagging and Track Extrapolation Resolution

Resolution on Extrapolation of Particle Tracks back to production point:

$$\sigma_{ip} = a \oplus b/p \cdot \sin^{3/2}\theta$$



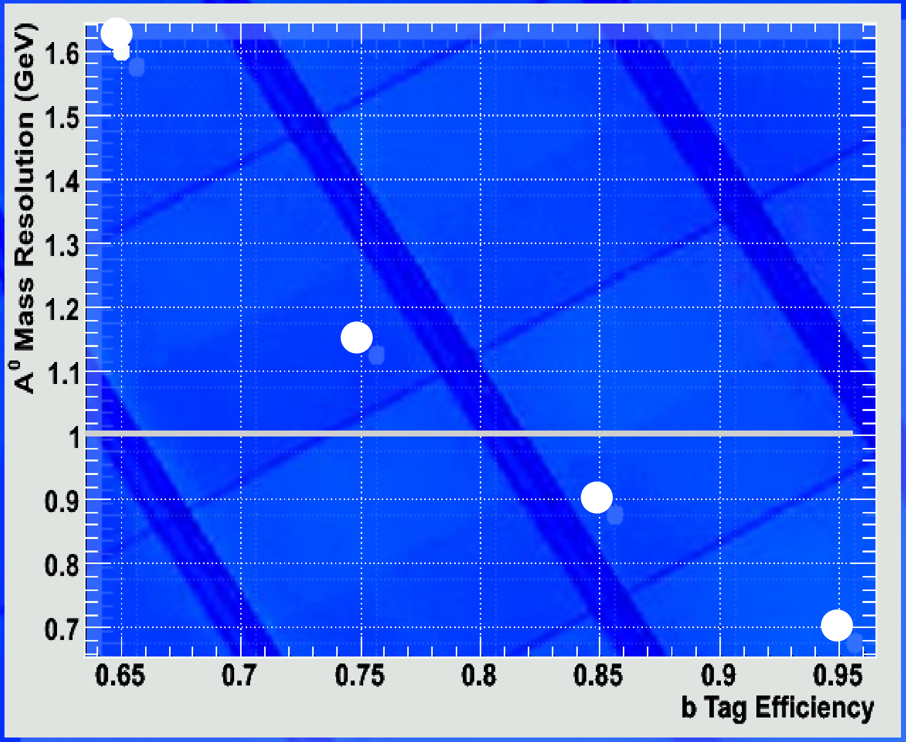


ILC Physics and Jet flavour tagging

Channel	Change	$\delta\sigma BR / \sigma BR$
$H \to cc$	σ_{point}: 2 μm → 6 μm	+20%
$H \to cc$	Thickness: 50μm→100μm	+15%

σ_{IP} (μm)	**c Purity**	ε_c
$5 \oplus 10/p_t$	**0.7**	**0.50**
$11 \oplus 15/p_t$	**0.7**	**0.29**

Degradation in performance corresponds to 20-30% luminosity loss



σ_{IP} (μm)	**b Purity**	ε_b
$5 \oplus 10/p_t$	**0.9**	**0.75**
$12 \oplus 70/p_t$	**0.9**	**0.25**

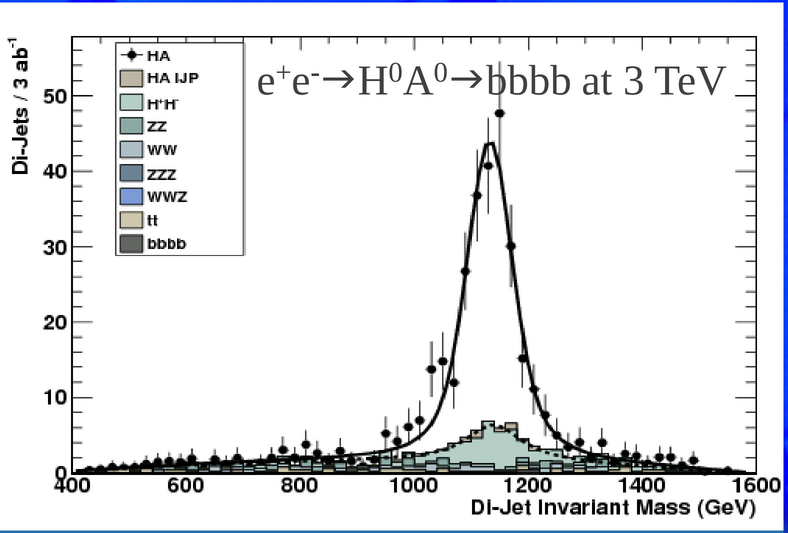
CLIC Physics and Jet flavour tagging

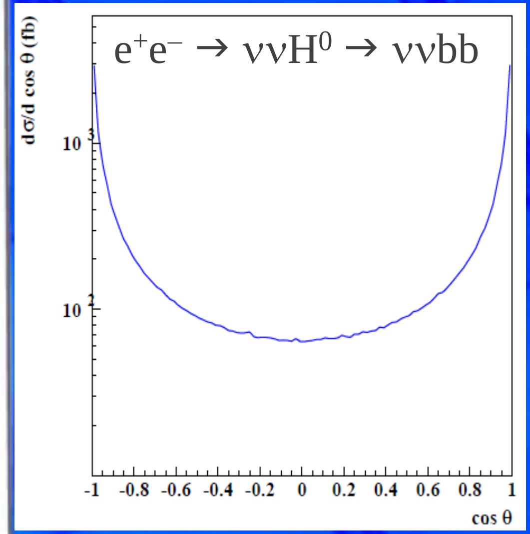
Multiple b and t quarks expected as main distinctive signature but signal cross sections often only O(1 fb) and S/B ~10^{-2} - 10^{-5}

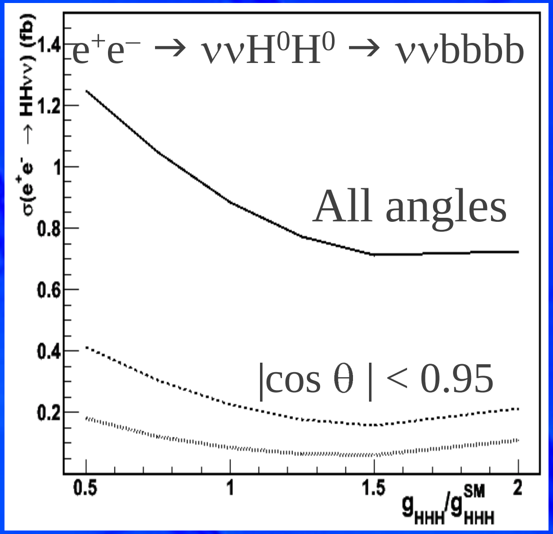
$\varepsilon_{Tag} = \varepsilon_b^N$ (with N=2,4,6)

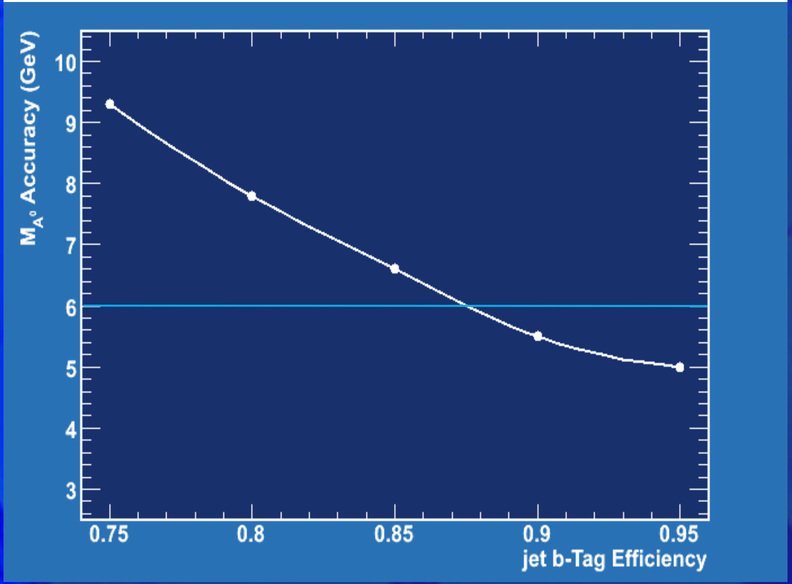
→Need efficient b tag with low misid;

Fwd Tagging crucial for rare SM processes to be studied at 3 TeV:



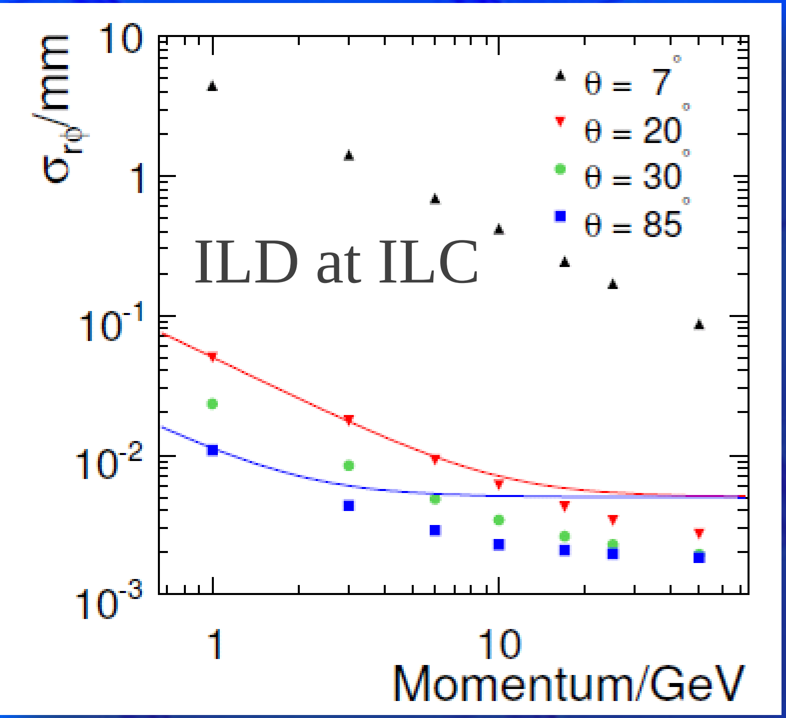


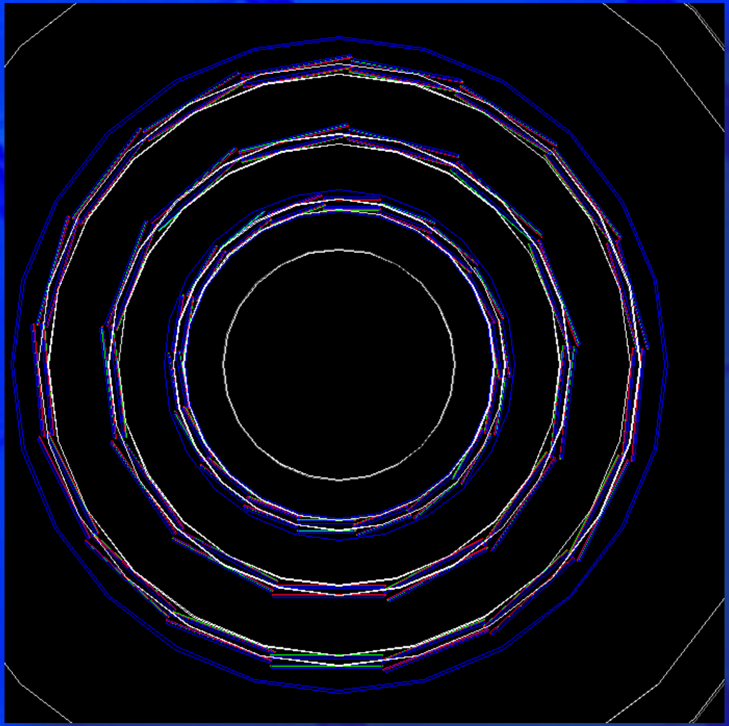




CERN-LCD-2010-006

Track Extrapolation resolution and Vertex Tracker

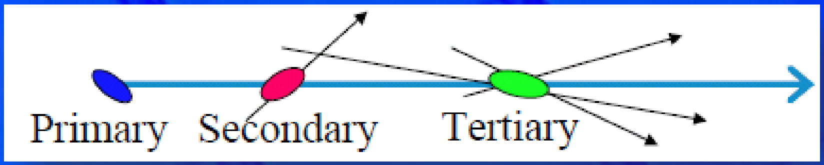


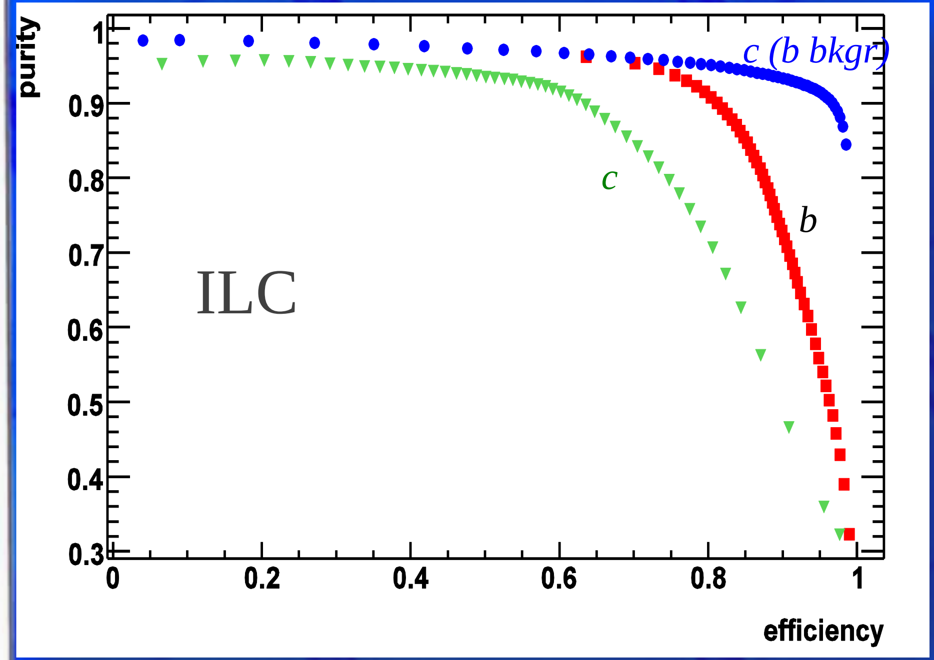


Track extrapolation resolution requires very thin layers (sensor thickness, power dissipation, ladder engineering) with first measurement as close as possible to IP (occupancy → space-time granularity)

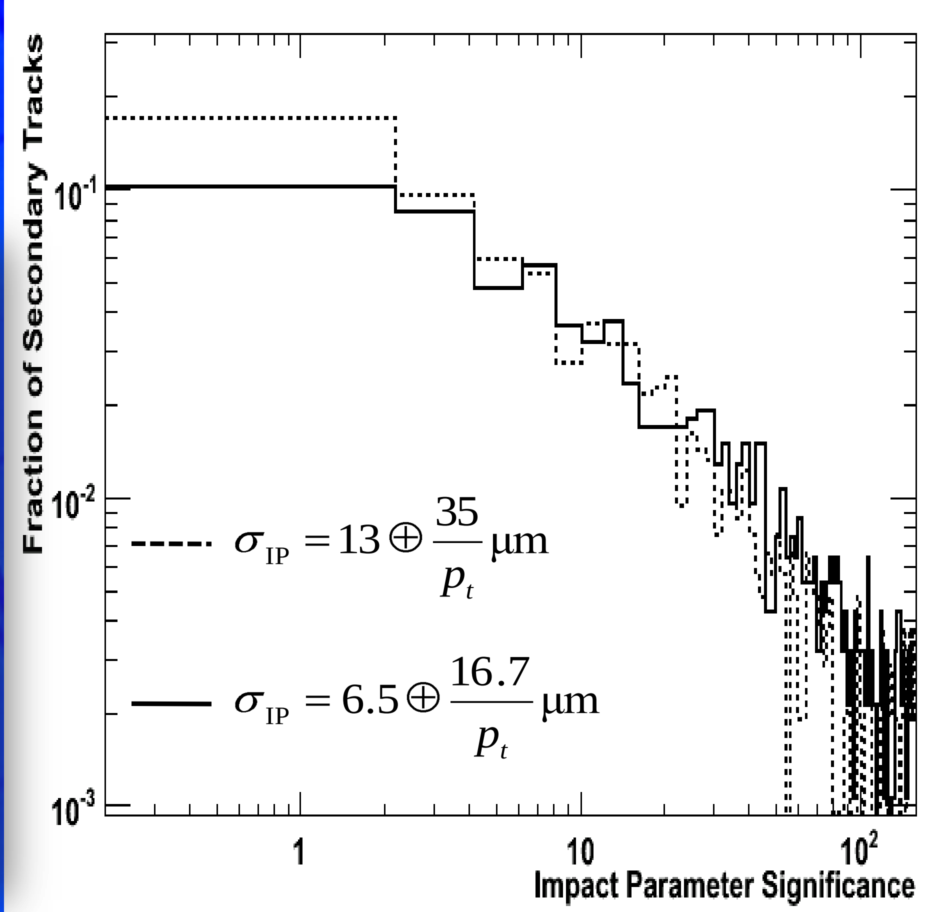
Jet flavour tagging and Track Extrapolation Resolution

Topological Vertex Reconstruction
ZVTOP





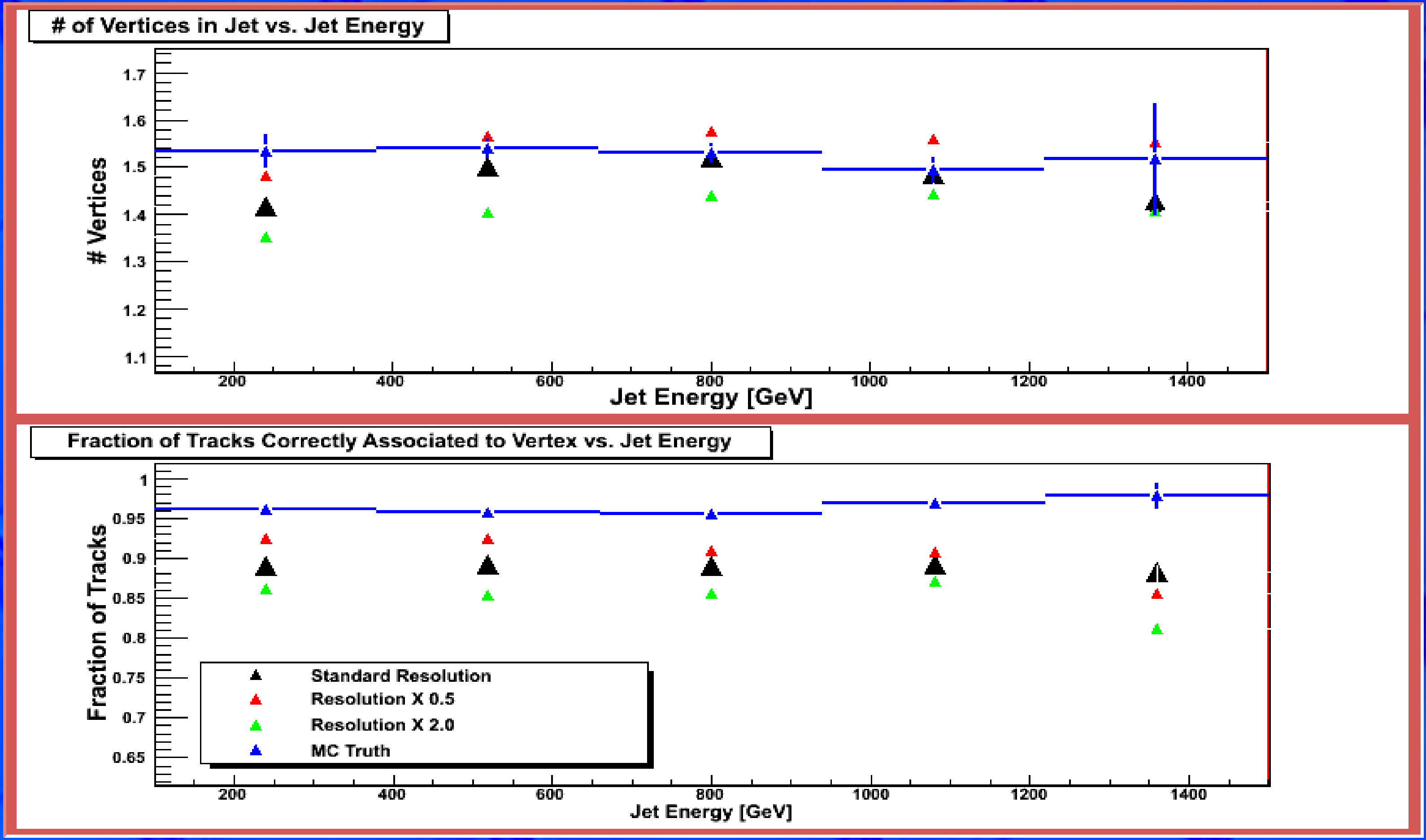
Imp. Par. Significance of Secondary Tracks



Bailey et al.,
NIM A610 (2009)

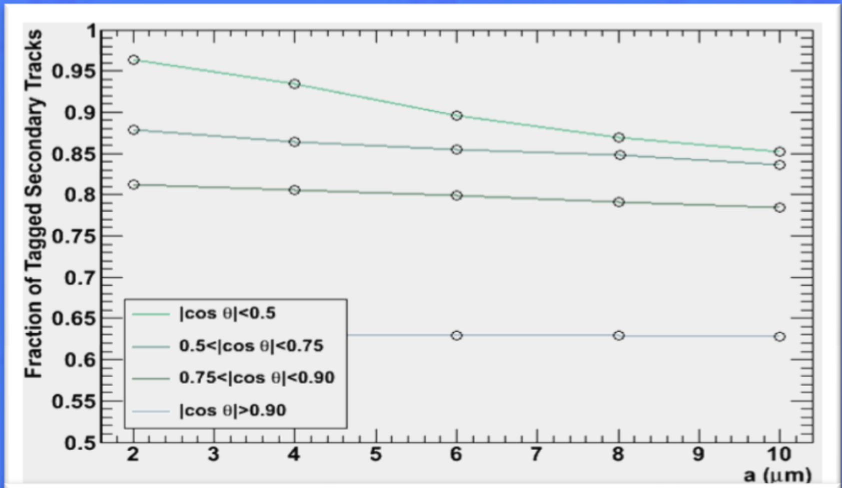
Jet flavour tagging and Track Extrapolation Resolution

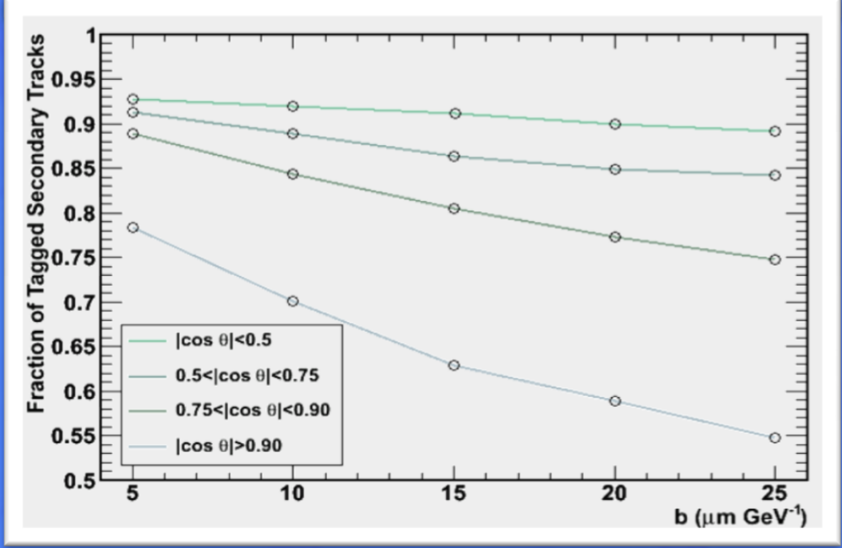
Performance of Jet Flavour Tagging at 3 TeV for std resolution $\sigma_{ip} = 3 \oplus 18/p_t$ $\sigma_{ip}/2$, σ_{ip} x 2 and unsmeared track parameters vs. E_{jet}

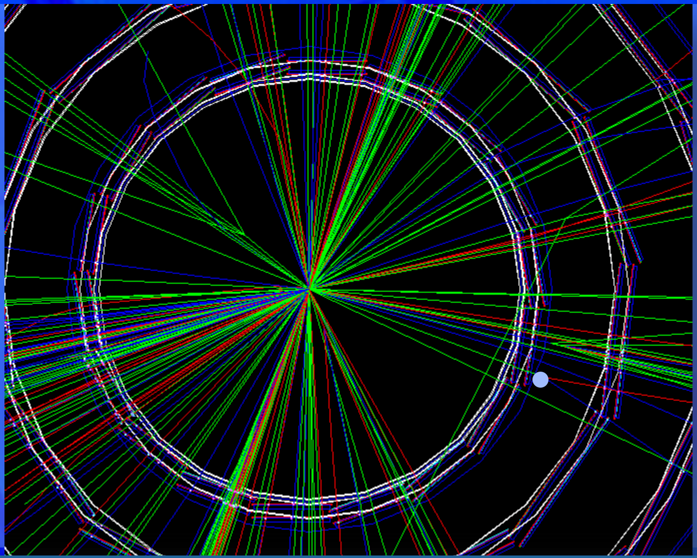


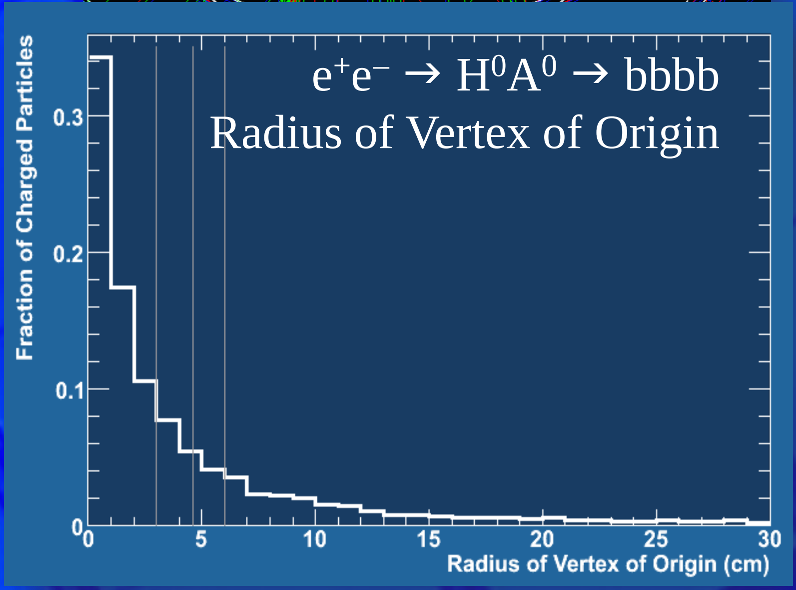
CLIC Jet flavour tagging and Track Extrapolation Resolution

Issues at multi-TeV energies







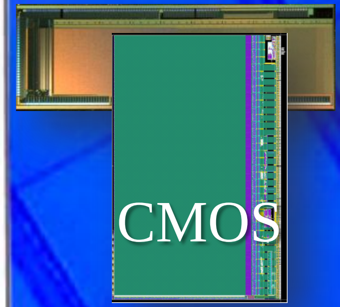


The Linear Collider Vertex Tracker R&D

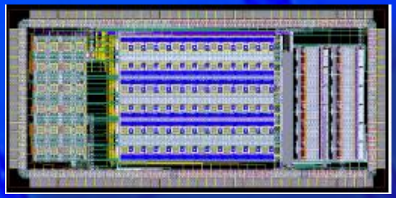
BERKELEY LAB

Requirements for the LC Vertex Tracker (~3 μm single point resolution, ~0.1%X_0 per active layer, power dissipation < 100 mW cm^{-2}, readout ~ 50 MHz [+ ~O(10ns) time stamping at CLIC], ~10-20 μm pixel pitch) require new generation of Si pixels:

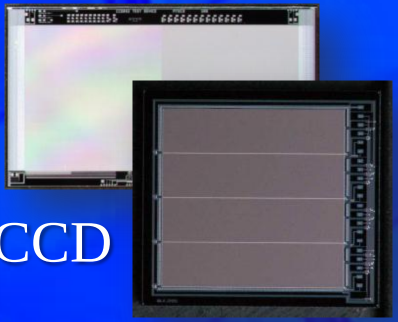
Monolithic Si Pixel Technologies



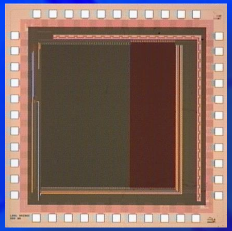
CMOS



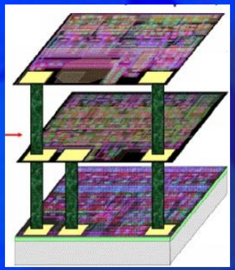
DEPFET



CCD



SOI

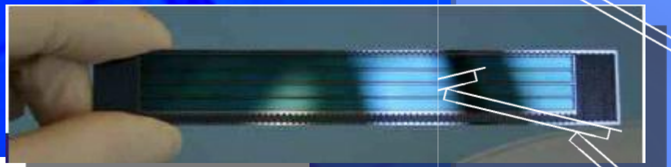


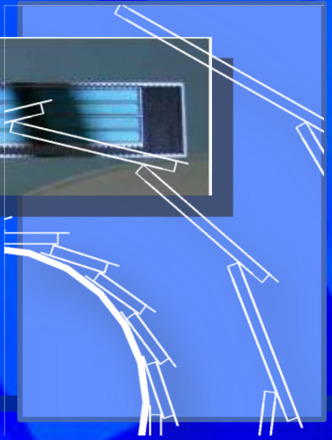
3D

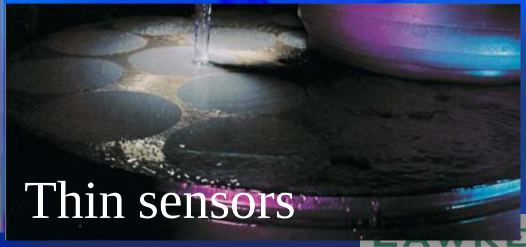
Vertical Integration

Architectures with advanced in-pixel and on-chip data processing

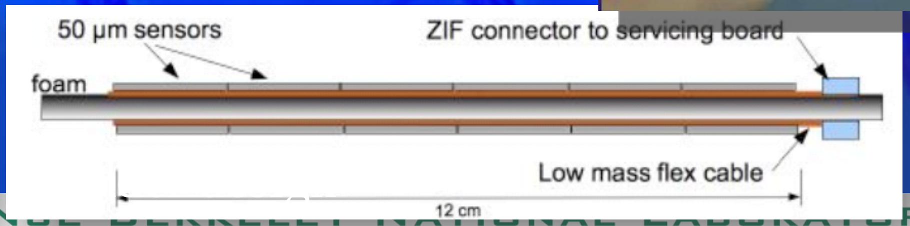
Innovative light-weight Ladders and Cooling





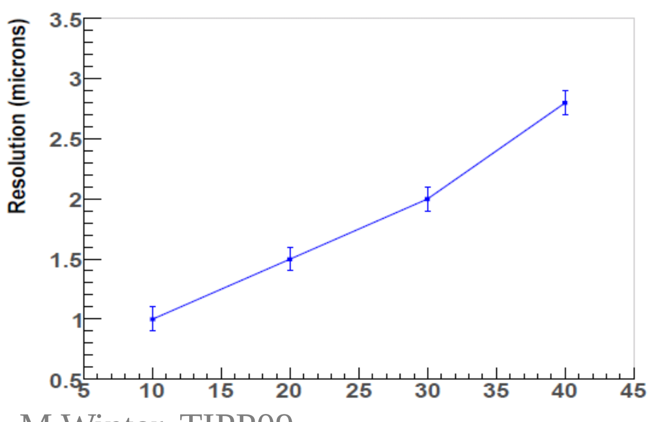


Thin sensors



Single Point resolution

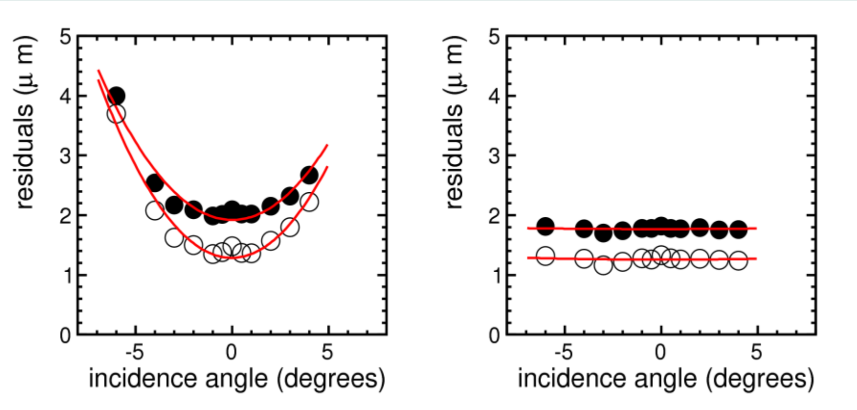
σ_{point} vs pitch



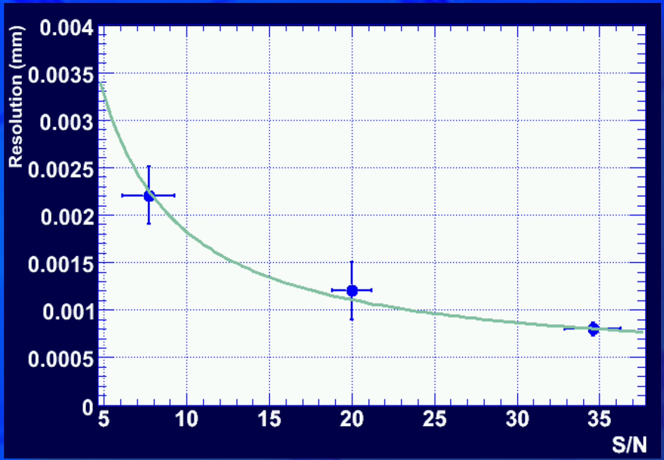
M Winter, TIPP09

σ_{point} vs incidence angle

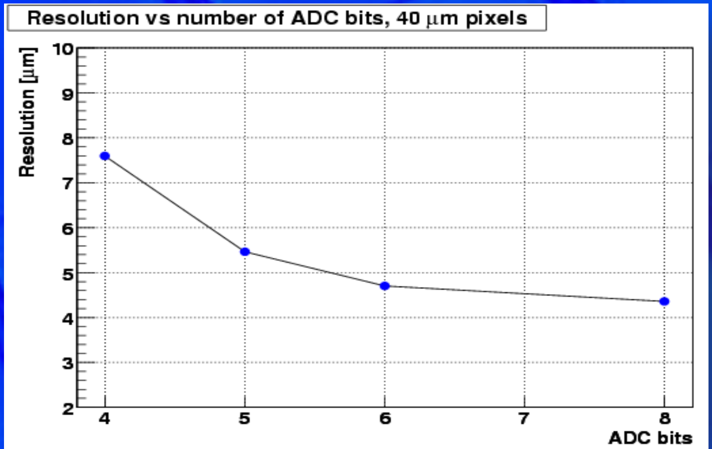
DEPFET TB2008, 120 GeV pions, 90˚±5˚ , 24 x 24 μm^2 pixel



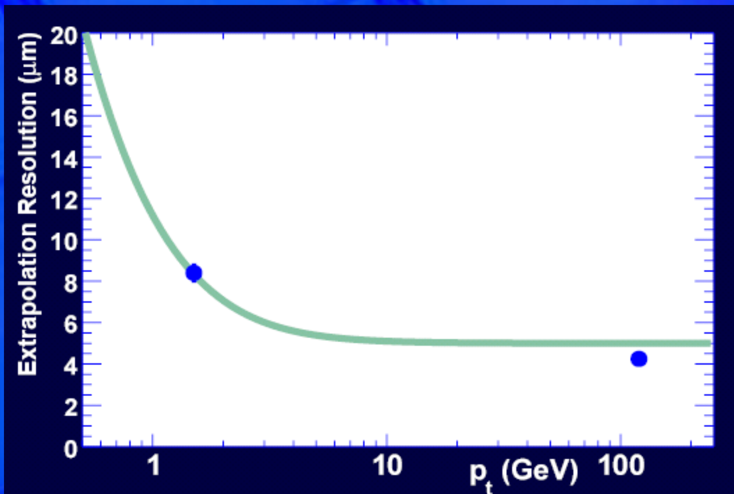
σ_{point} vs S/N



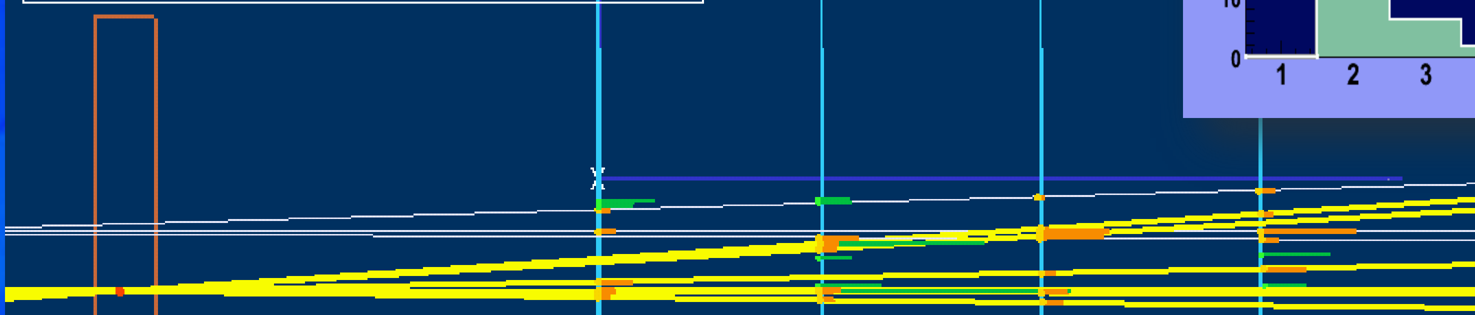
σ_{point} vs ADC accuracy

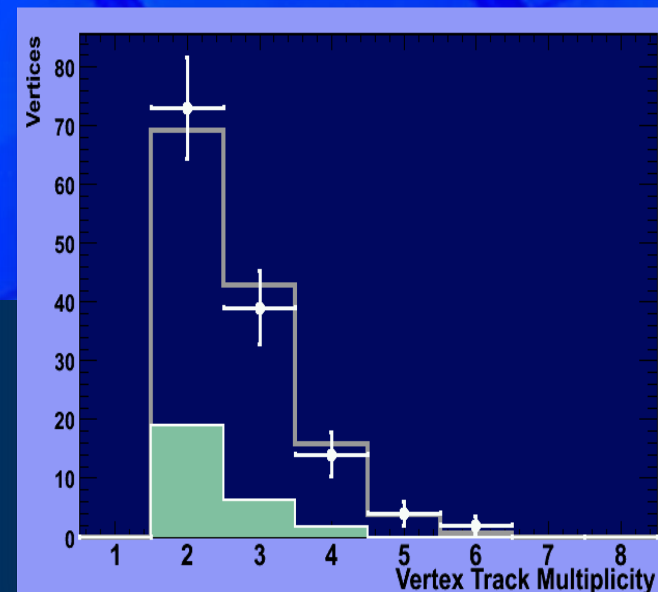


Track Extrapolation and Vertexing resolution



FNAL MBTF T966 Data
120 GeV p on Cu target
LBNL Thin CMOS Pixel Telescope





Extrapolate 3 cm upstream from first Si pixel layer:

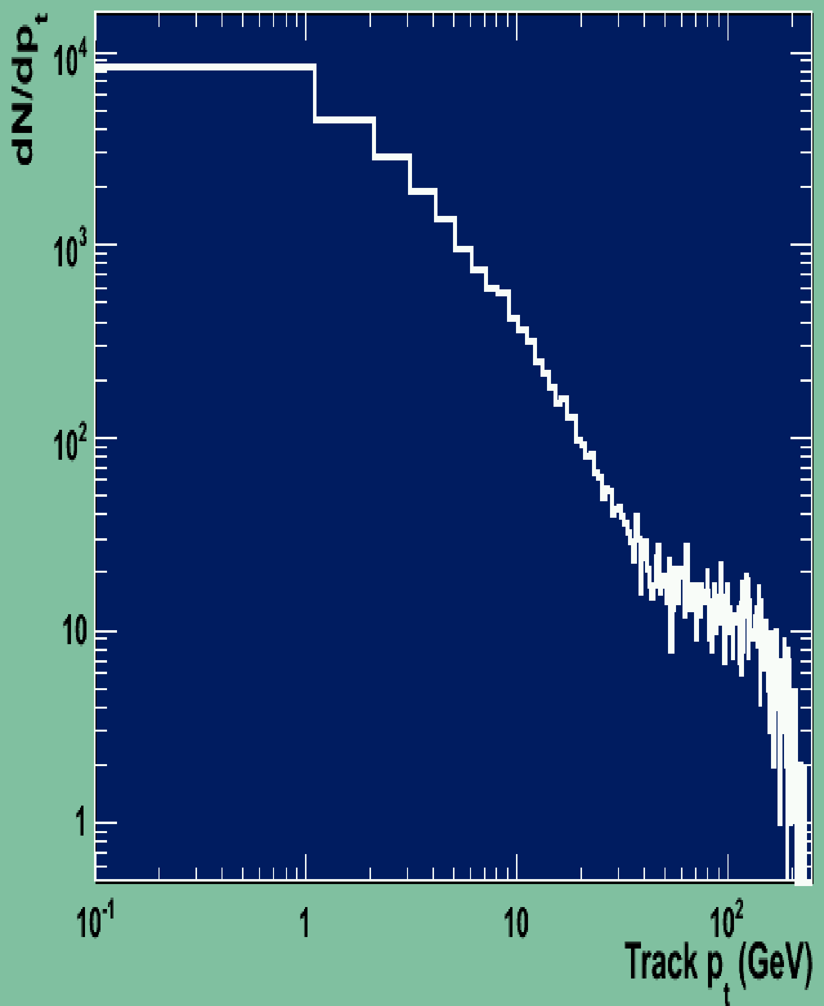
T966 σ_z vertex resolution = 230 μm
CLIC σ_z vertex resolution in B decays = 210 μm

MB et al., NIM A593 (2008)

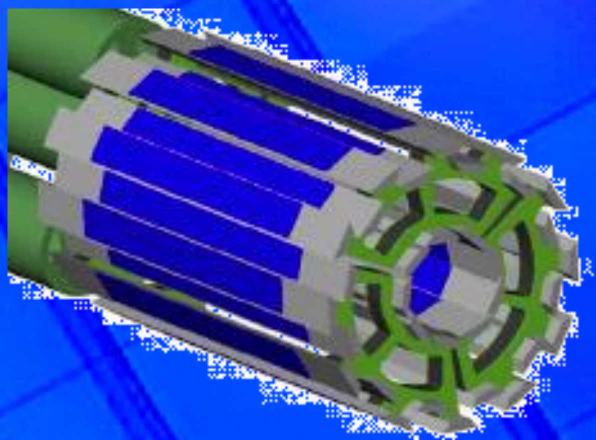
Despite large centre-of-mass energies, charged particles produced with moderate energies: interesting processes have large jet multiplicity (4 and 6 parton processes + hard gluon radiation) or large missing energies; Excellent track extrapolation at low momenta essential.

Impact Parameter resolution $a+b/p_t$ for ILC-like VTX with Si on 100 μm CFC

Si Thickness (μm)	a (μm)	b (μm)
25	3.5	8.9
50	3.7	9.6
125	3.8	11.7
300	4.0	17.5

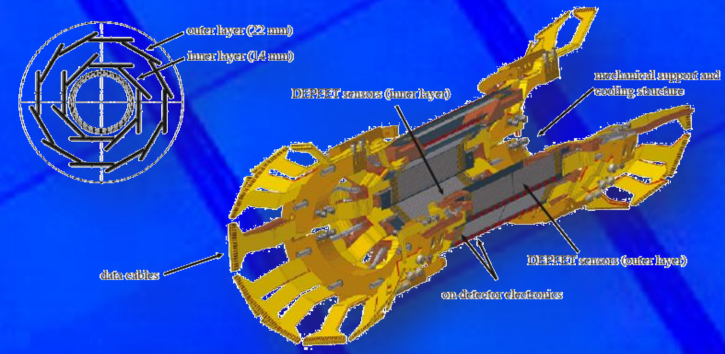


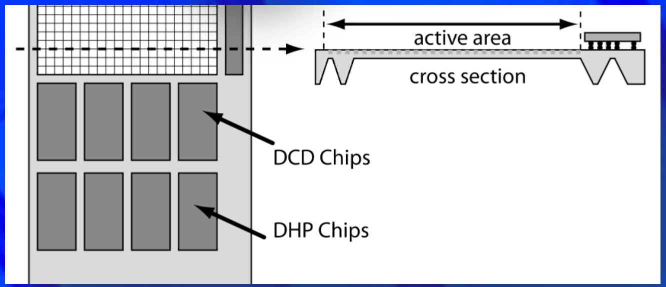
Ladder Thickness: Pioneer Experiments



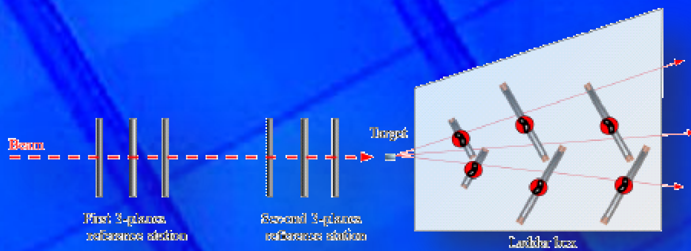
STAR 0.28% X_0

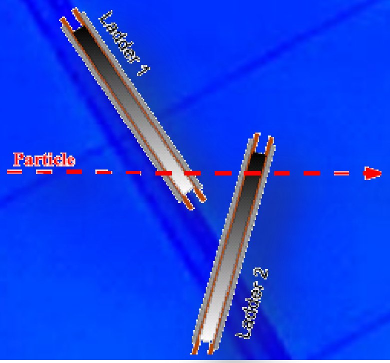
(see L Greiner talk)





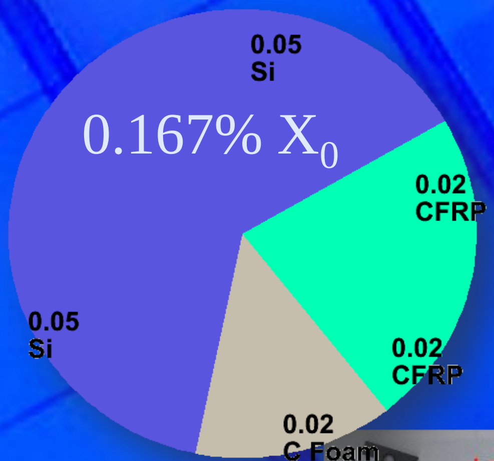
Belle-II 0.19% X_0



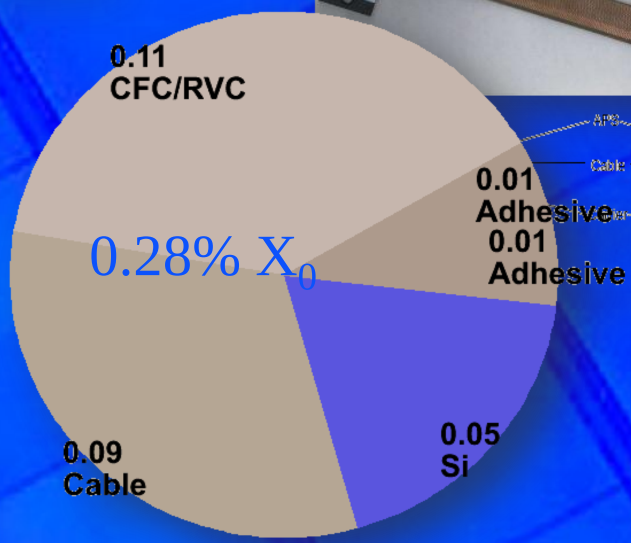


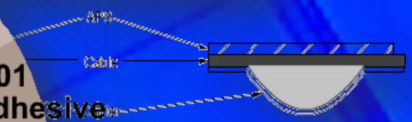
Ladder Thickness

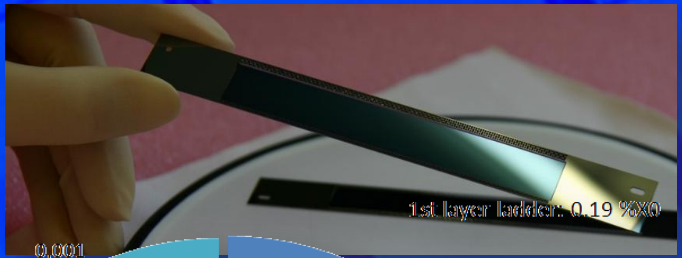
CCD

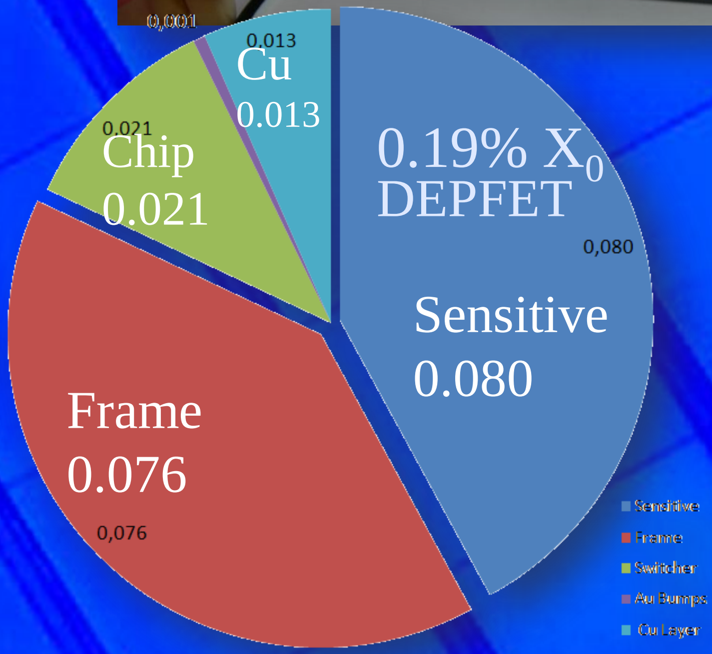


STAR HFT



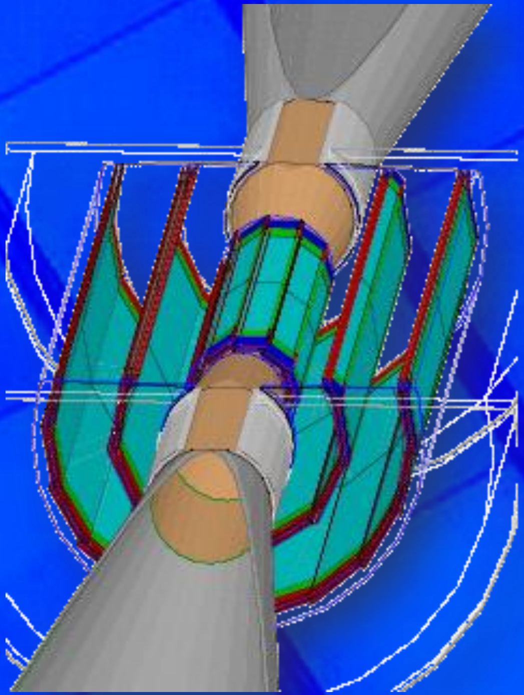




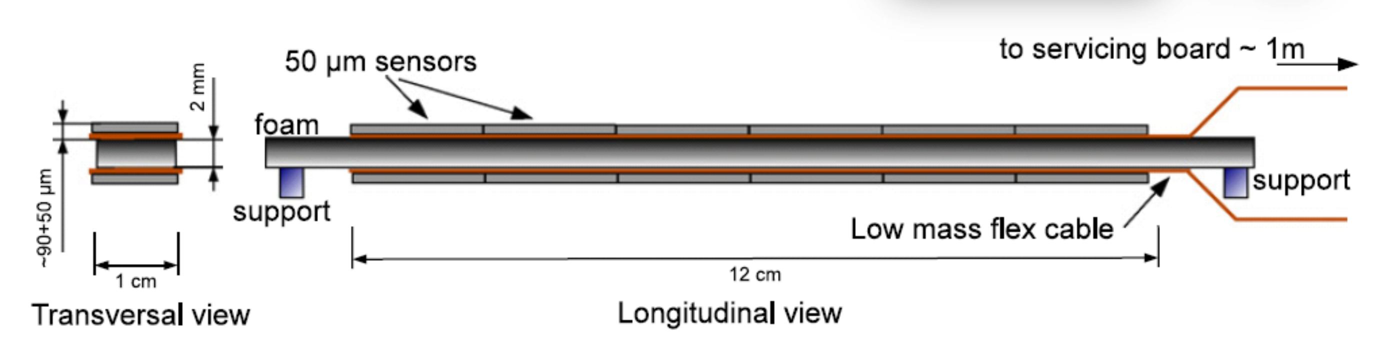


Ladder Thickness

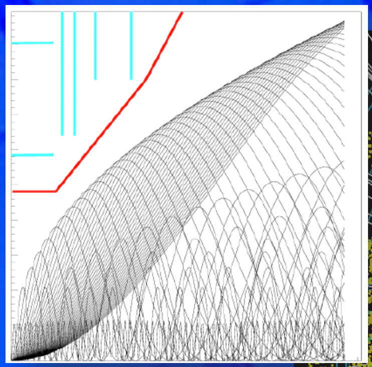
Double-layer ladder giving hit position correlation (low-E e^- rejection), advantageous in terms of material budget/point and support of thin sensors;

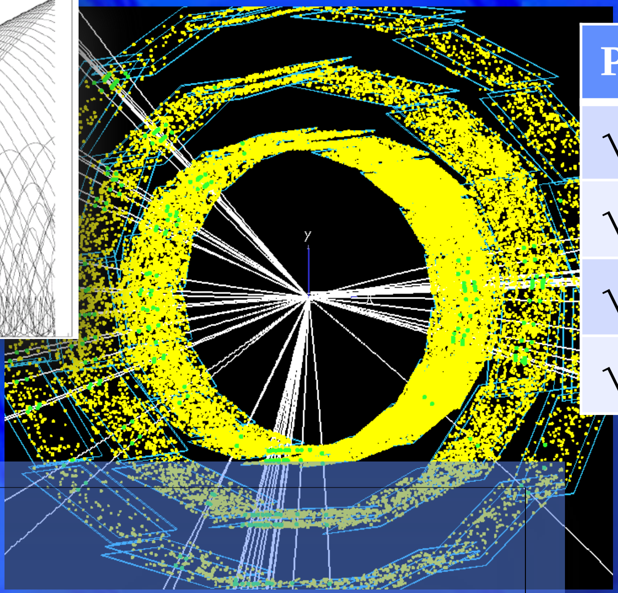


PLUME
R&D Program
(Bristol, DESY, Oxford, Strasbourg)
aim at 0.2-0.3%X_0

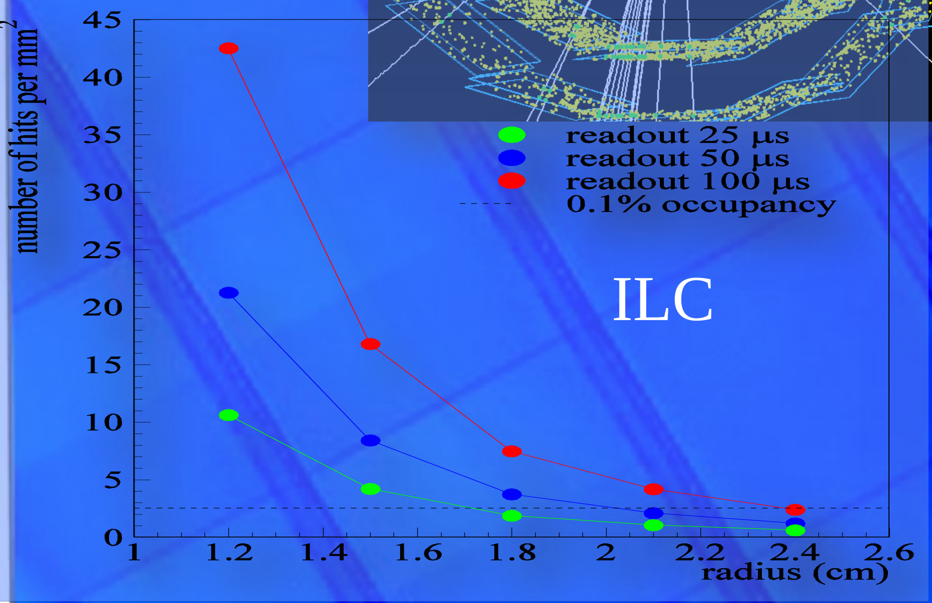


Vertex Tracker and Experimental Conditions





Pairs	Hits cm^{-2} BX^{-1}
√s=0.5 TeV ILC (Nominal)	4.4 (R=16mm)
√s=0.5 TeV ILC (low-P)	8.1 (R=16 mm)
√s=1.0 TeV ILC (Nominal)	7.1 (R=16mm)
√s=3.0 TeV CLIC	~5.0 (R=31mm)

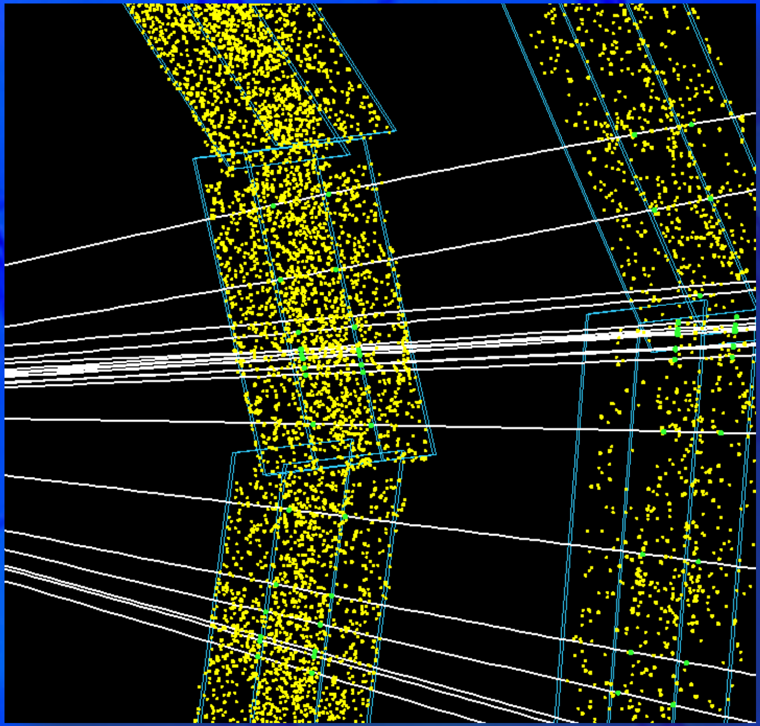


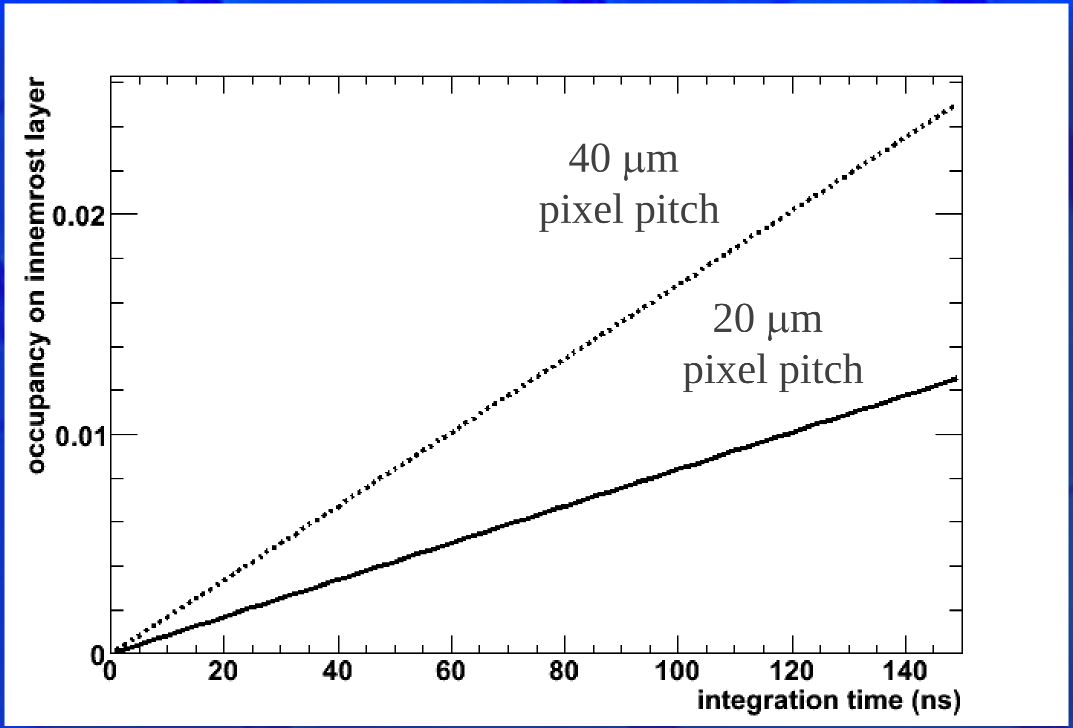
Two-photon	Nγγ BX^{-1}
√s=0.5 TeV ILC	**0.12**
√s=3.0 TeV CLIC	**3.3**

Neutrons	n(1 MeV eq) cm^{-2} yr^{-1}
√s = 0.5 TeV ILC	**~ 10^{10}**
√s = 3.0 TeV CLIC	**~5 x10^{10}**

Grandjean/IReS

CLIC Read-out Speed and Occupancy





Requirements in terms of space granularity from occupancy and single point resolution are comparable

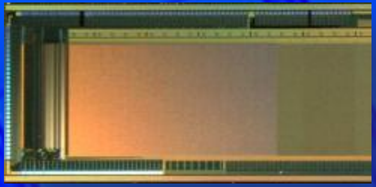
Read-out Speed and Occupancy

Most demanding requirement is mitigating occupancy:

ILC (2820 bunches w/ Δt_{bx}=337ns) r/o of first layers in 25-50 μs, time-stamping or 5μm pixels, at CLIC (312 bunches) Δt_{bx} = 0.5ns possibly 15-30 ns time-stamping

- Fast continuous readout architectures

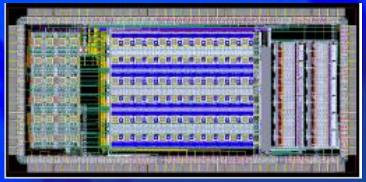
CMOS Pixels



Double-sided col // binary r/o + zero suppress, with 15 μm pixels

DEPFET Pixels

r/o 20 times during train data store on periphery

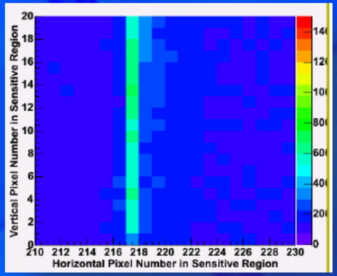


- In situ storage with high space-time granularity and r/o at end of train

Fine Pixel CCD

5μm pixels

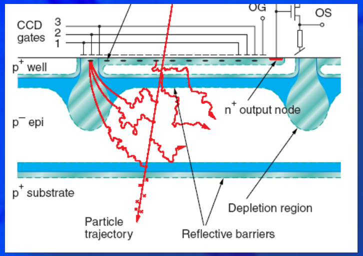
Reject bkg with cluster shape



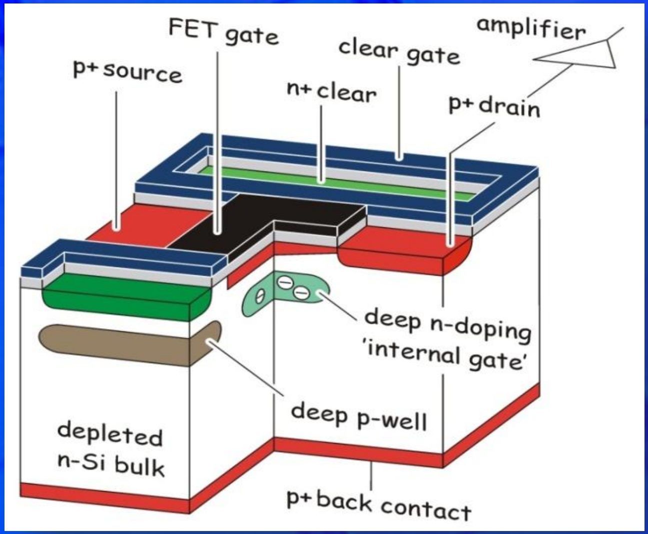
ChronoPixel

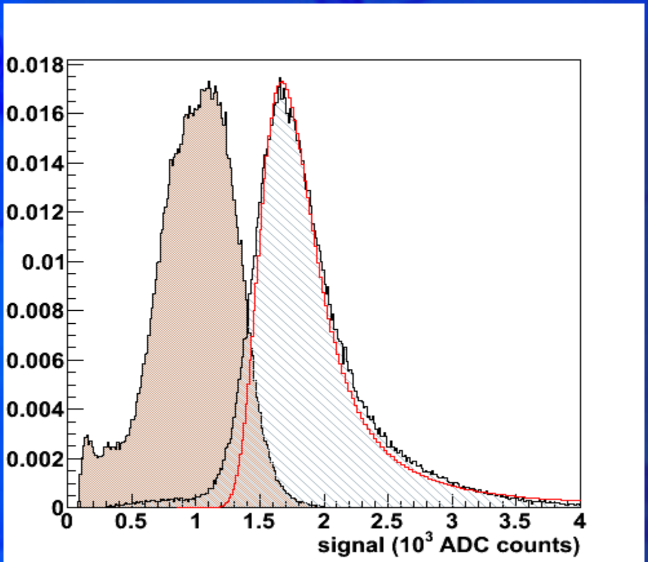
ISIS

In-situ 20-cell charge storage



Technologies for the Vertex Tracker : DEPFET





- fully depleted sensitive volume
  - fast signal rise time (~ns), small cluster size
- Fabrication at MPI HLL
  - Wafer scale devices possible
  - no stitching, 100% fill factor
- no charge transfer needed
  - faster read out
  - better radiation tolerance
- Charge collection in "off" state, read out on demand
  - potentially low power device
- internal amplification
  - charge-to-current conversion
  - large signal, even for thin devices
  - r/o cap. independent of sensor thickness

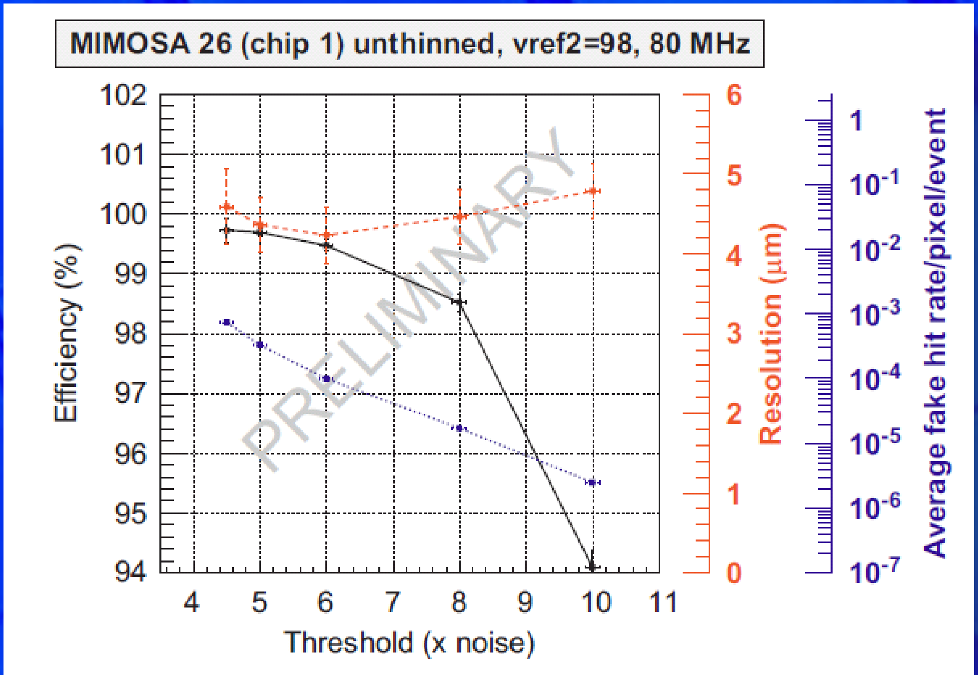
L Andricek

Technologies for the Vertex Tracker
CMOS Active Pixel Sensors

CMOS APS offer high granularity with thin sensitive layer, signal sensing and some processing in pixel, analog and/or digital processing in periphery, fast column parallel readout (rolling shutter);

R&D driven by ILC in the last decade, significant progress towards sensors ready for applications in real experiments (STAR, CBM)

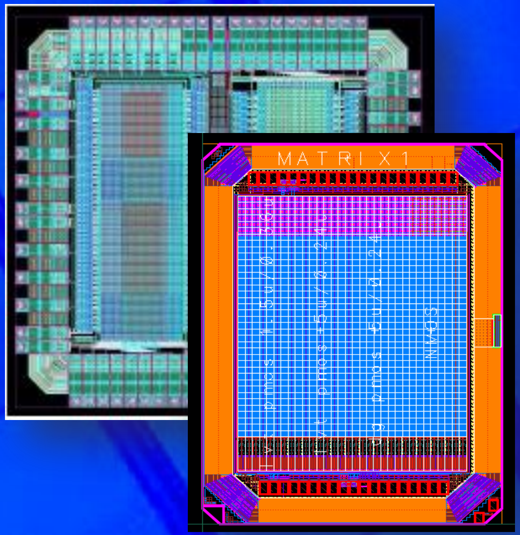
S/N, speed and radiation tolerance motivate transition towards CMOS technology integrated with high resistivity sensitive layer.



M Winter

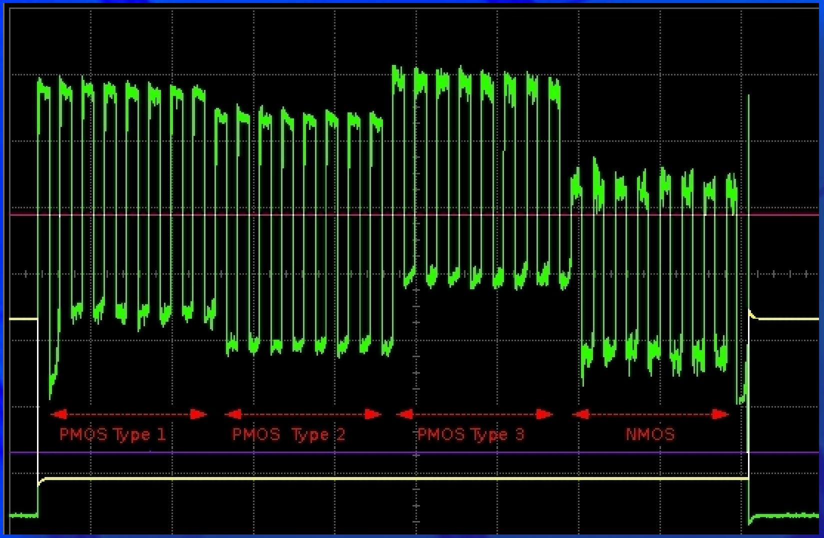
Technologies for the Vertex Tracker
CMOS with High Resistivity Substrate

Port of std CMOS process on wafers with high resisitivity substrate offer higher charge yield, faster charge collection dominated by drift, improved radiation tolerance and faster r/o:

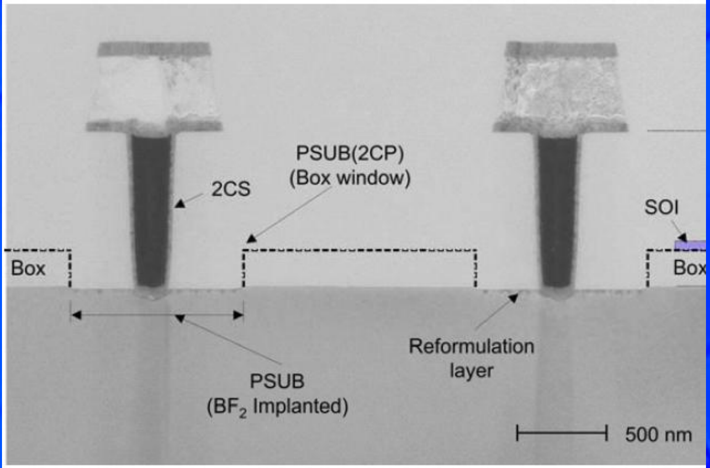


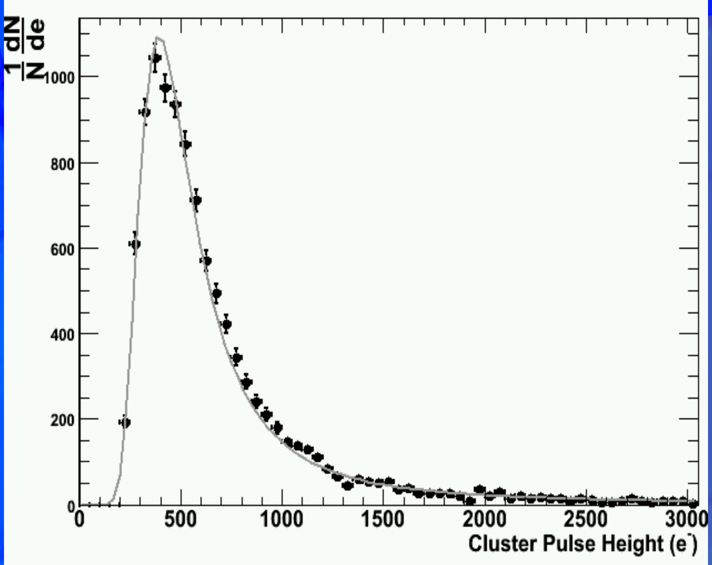
MIMOSA sensors with high-res epi-layer to be tested for application in STAR HFT (IReS, LBNL);

CMOS pixel sensors with high-res sensitive volume developed by the LEPIX collaboration led by CERN: first structures processed and being tested at CERN:



Technologies for the Vertex Tracker
Silicon-On-Insulator





SOI process offers appealing opportunity for monolithic pixel sensors, removing limitations of bulk CMOS processes;

- High resistivity sensitive volume → large signals;
- Deep submicron CMOS substrate for electronics;
- No interconnections;
- Low collection electrode capacitance;
- Potentially Rad-hard ;
- Main challenges: transistor back-gating & charge trapping in BOX

(Y Arai and P Giubilato talks)

Physics requirements at a future linear collider motivated significant R&D on monolithic pixel sensors to achieve small pixel cells with integrated charge sensing and some data processing, thin sensors with low power consumption and fast readout and/or high space-time granularity;

Contemplating energy increase from 0.5 TeV to multi-TeV implies new requirements on fwd vertexing capabilities and fast time stamping which need to be addressed by specific R&D;

Technologies developed in ILC-motivated R&D have significant impact on other particle physics experiments as well as imaging and spectroscopy in other fields of science from electron microscopy to biology and astronomy.