Experimental Issues at CLIC

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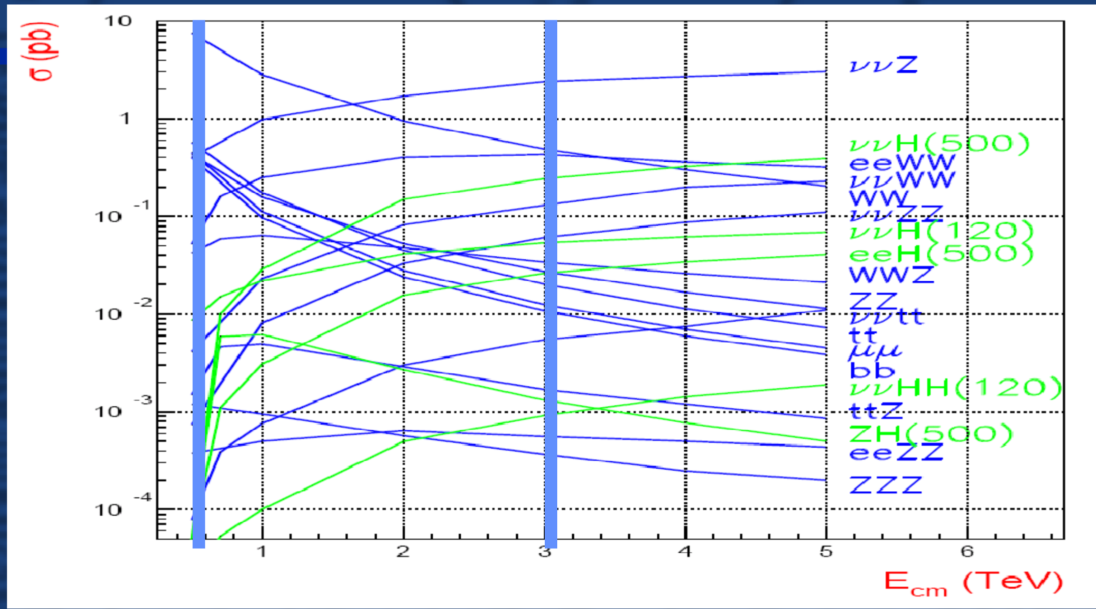
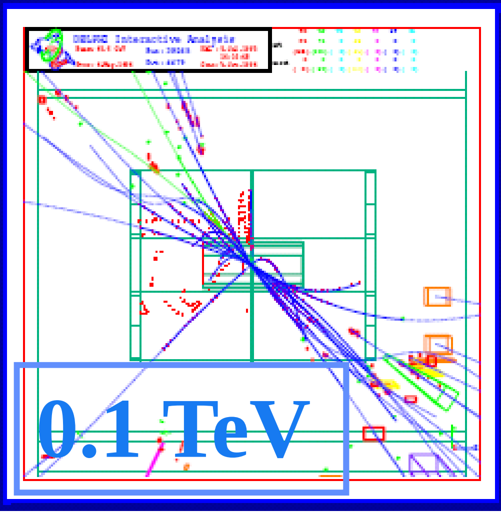
UC Berkeley - LBNL
and IPN Lyon

CLIC 08 Workshop
CERN, October 14, 2008

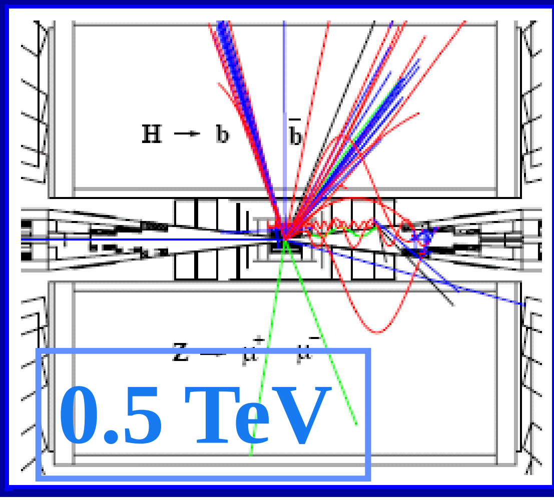
How is physics changing from LEP to CLIC ?



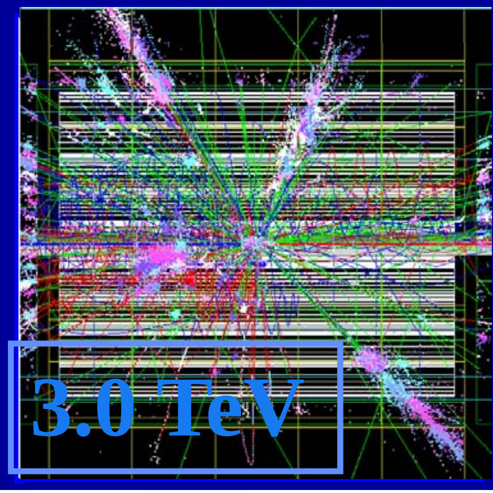
$e^+e^- \to Z^0 \to b\bar{b}$



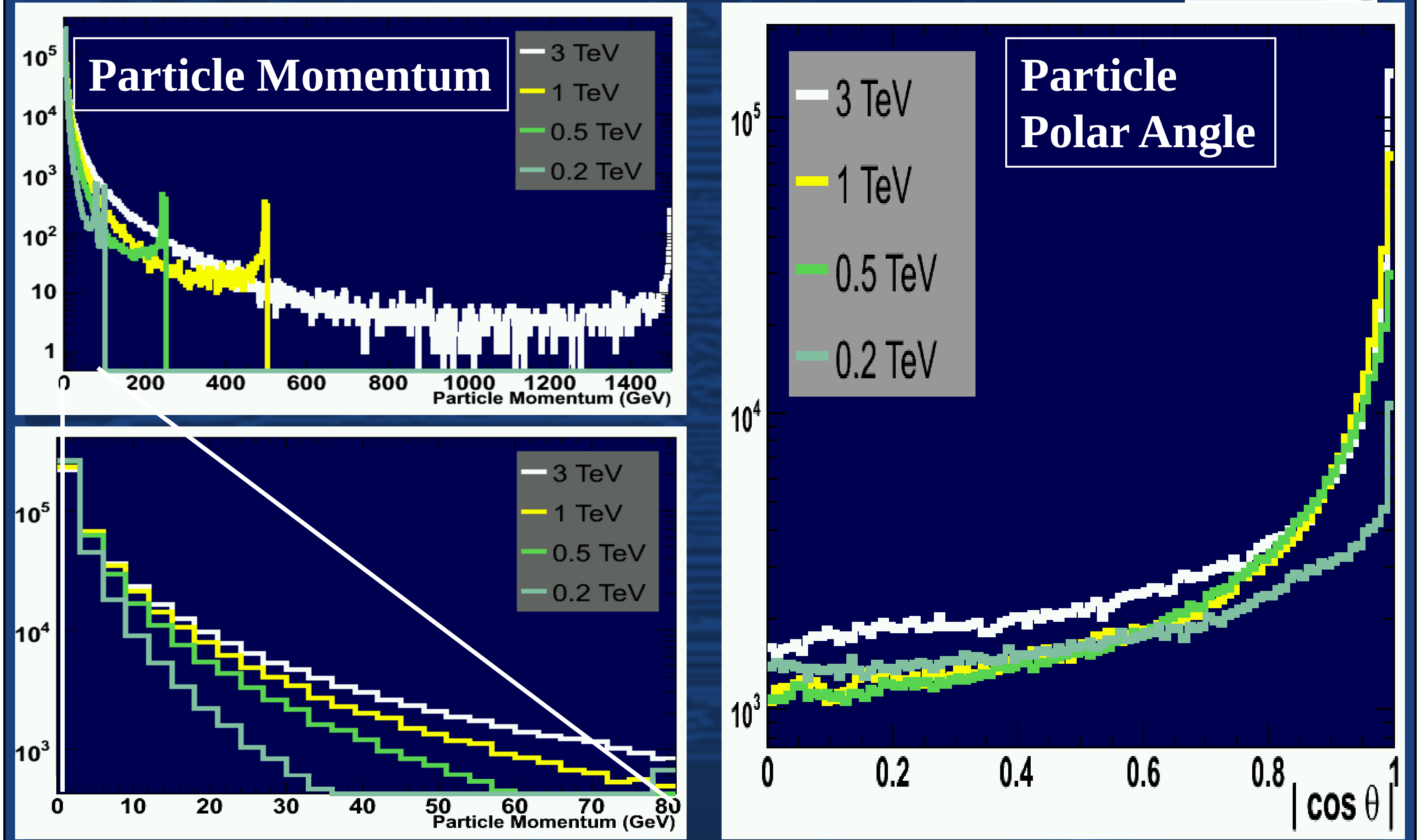
$e^+e^- \to Z^0 H^0 \to \mu^+\mu^- b\bar{b}$



$e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b$



Observables from 0.2 TeV to 3 TeV (SM Evts)



Observables from 0.2 TeV to 3 TeV (SM Evts)

Jet Multiplicity

$\sqrt{s}$ (TeV)	0.09	0.20	0.5	0.8	3.0	5.0
$< N_{Jets} >$	2.8	4.2	4.8	5.3	6.4	6.7

Parton Energy

$\sqrt{s}$ (TeV)	**0.2**	**0.5**	**1.0**	**3.0**
$\langle E_{\text{Parton}} \rangle$ (GeV)	**32**	**64**	**110**	**240**

B Hadron Decay Distance

$\sqrt{s}$ (TeV)	0.09	0.2	0.35	0.5	3.0	
Process	Z^0	HZ	HZ	HZ	H^+H^-	$b\bar{b}$
d_{space} (cm)	0.3	0.3	0.7	0.85	2.5	9.0

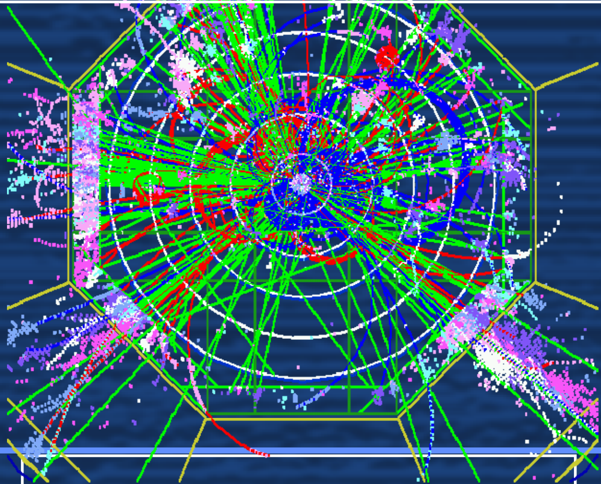
Event Reconstruction: New Challenges at CLIC

Worldwide LC studies have gained a lot of insight on experimentation at a linear collider at ~ 2.5 x LEP energy, new role for the CLIC study:

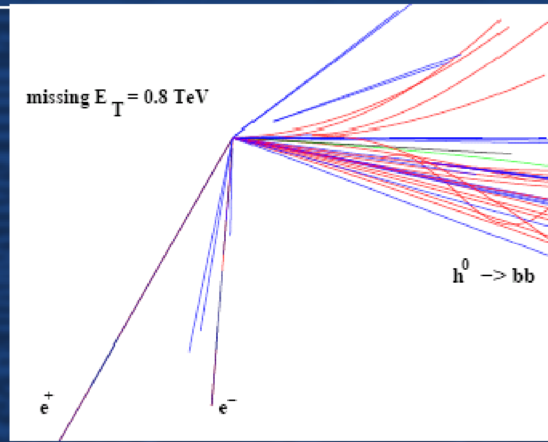
- Define parameter scaling from 0.2-0.5 TeV to multi-TeV and optimisation within technological/engineering constraints;
- Identify issues requiring new/alternative approach;
- Evaluate CLIC potential / limitations at 0.5 – 1.0 TeV.

Physics Signatures at CLIC

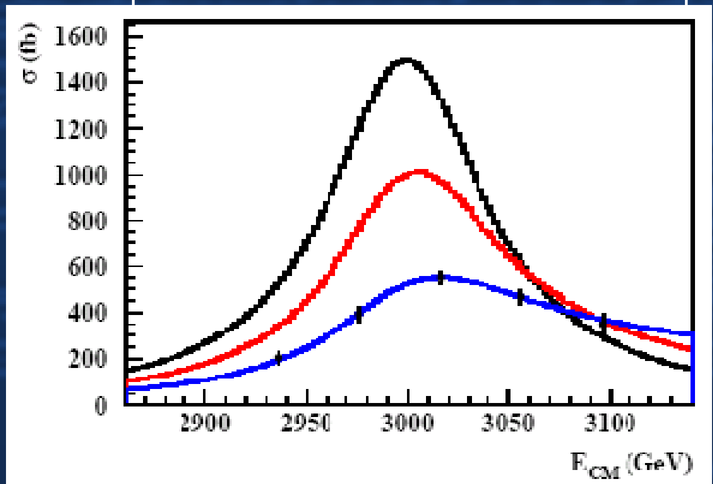
Multi-Jet Final States



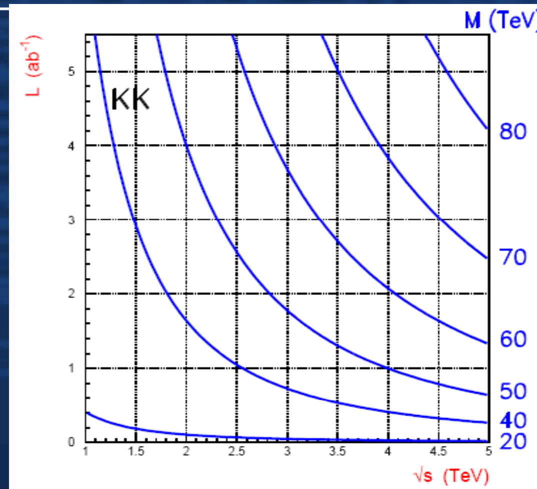
Missing Energy Final States



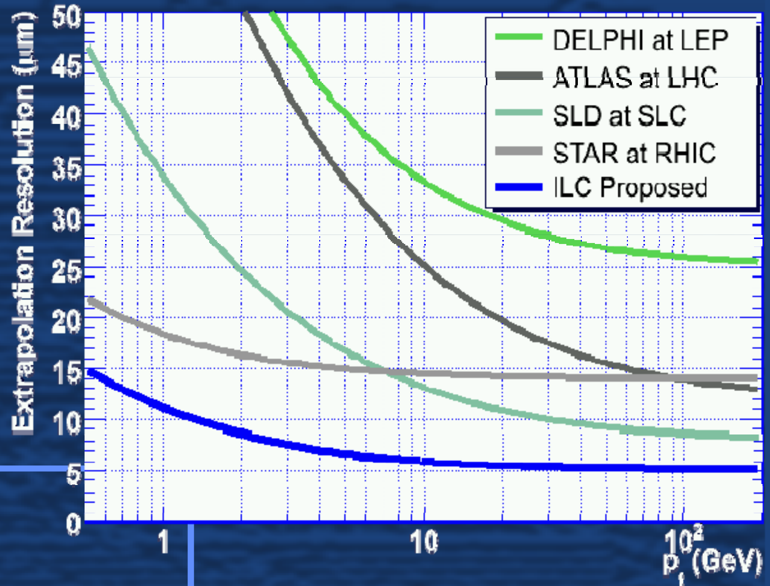
Resonance Scan



Electro-Weak Fits



Event Reconstruction: The LEP&ILC Paradigm

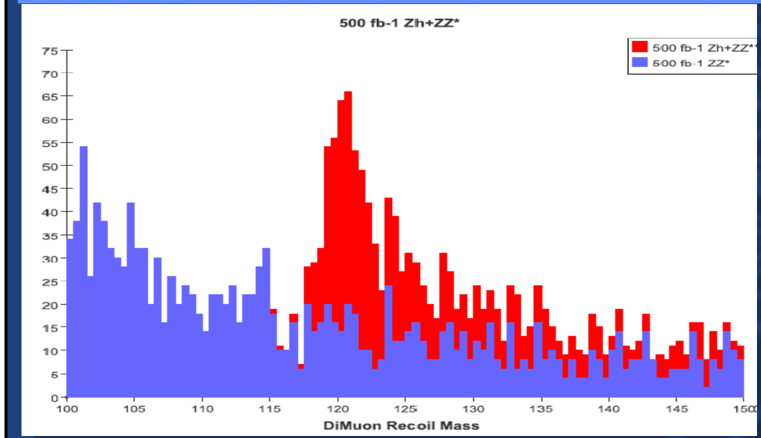


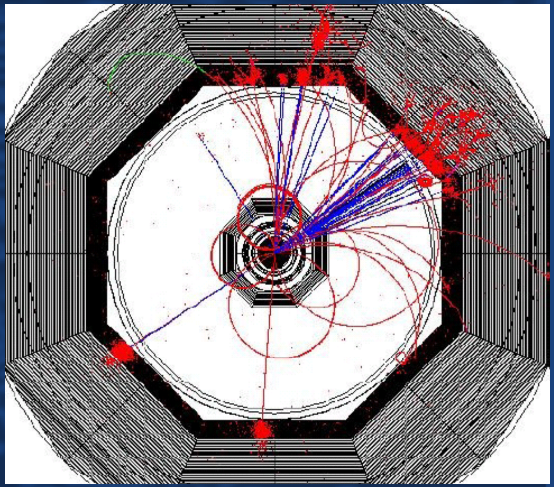
σ(IP)

Vertex of origin determined by accurate extrapolation inside beam pipe;

$\delta p/p^2$

Momentum resolution of paramount importance;

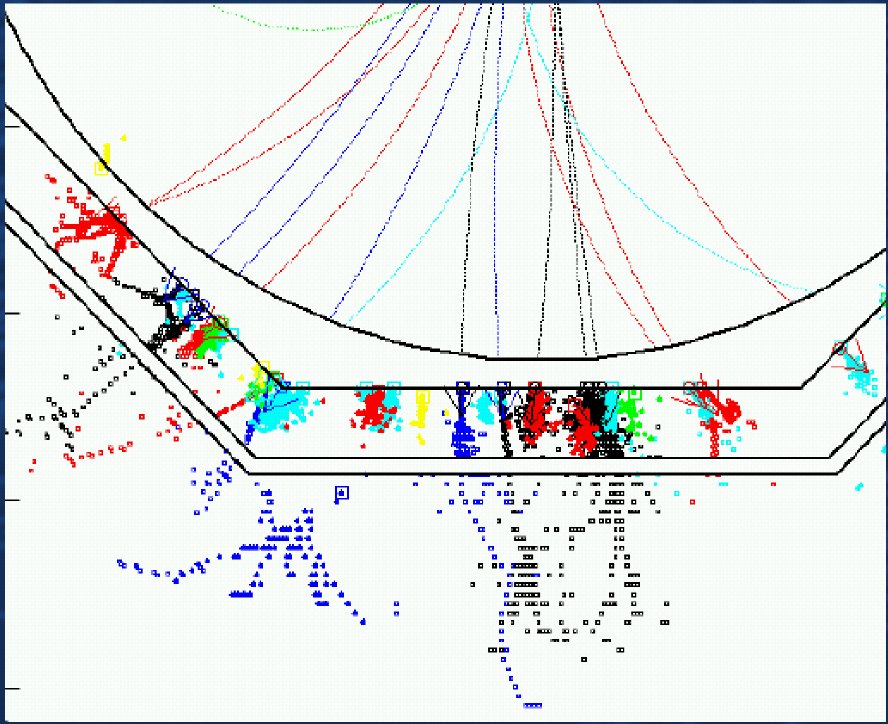


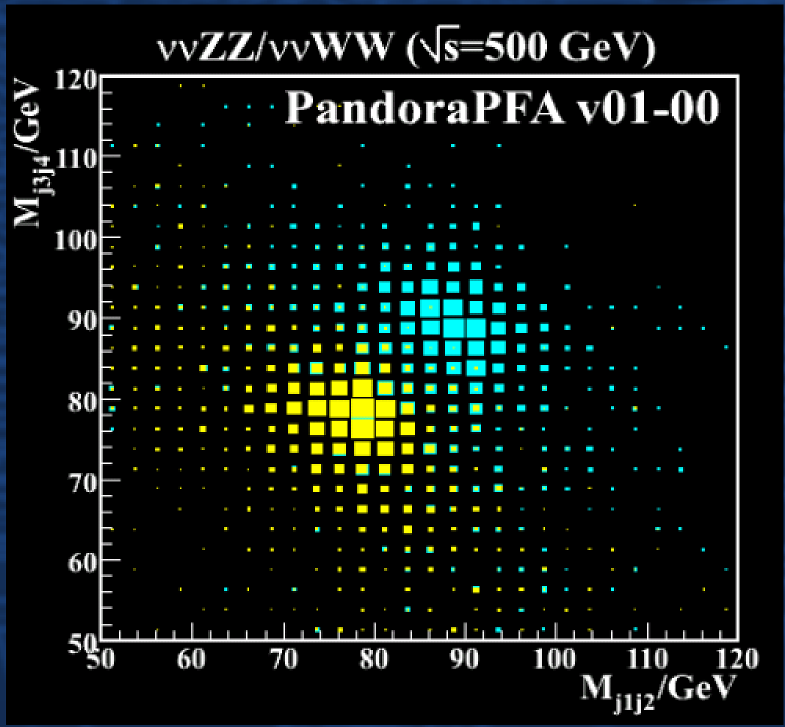


$\sigma(E_{jet})/E_{jet}$

Parton energy determined through particle flow reconstruction;

$$\frac{BR^2}{R_M^2 R_{pixel}^2}$$





M Thompson

Benchmarks at ILC

Report to the ILC World-wide Study

Physics Benchmarks for the ILC Detectors

arXiv:hep-ex/0603010 v1 6 Mar 2006

0. Single $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, π^0, $K^{\pm}$, K_s^0, γ, u, s, c, b; $0 < |\cos\theta| < 1$, $0 < p < 500$ GeV

1. $e^+e^- \to f\bar{f}$, $f = e, c, b$ at $\sqrt{s}$=1.0 TeV;

2. $e^+e^- \to Zh, \to \ell^+\ell^- X$, $m_h = 120$ GeV at $\sqrt{s}$=0.35 TeV;

3. $e^+e^- \to Zh$, $h \to c\bar{c}, \tau^+\tau^-, WW^*$, $m_h = 120$ GeV at $\sqrt{s}$=0.35 TeV;

4. $e^+e^- \to Zhh$, $m_h = 120$ GeV at $\sqrt{s}$=0.5 TeV;

5. $e^+e^- \to \tilde{e}_R\tilde{e}_R$ at Point 1 at $\sqrt{s}$=0.5 TeV;

6. $e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$, at Point 3 at $\sqrt{s}$=0.5 TeV;

7. $e^+e^- \to \chi_1^+\chi_1^- / \chi_2^0\chi_2^0$ at Point 5 at $\sqrt{s}$=0.5 TeV;

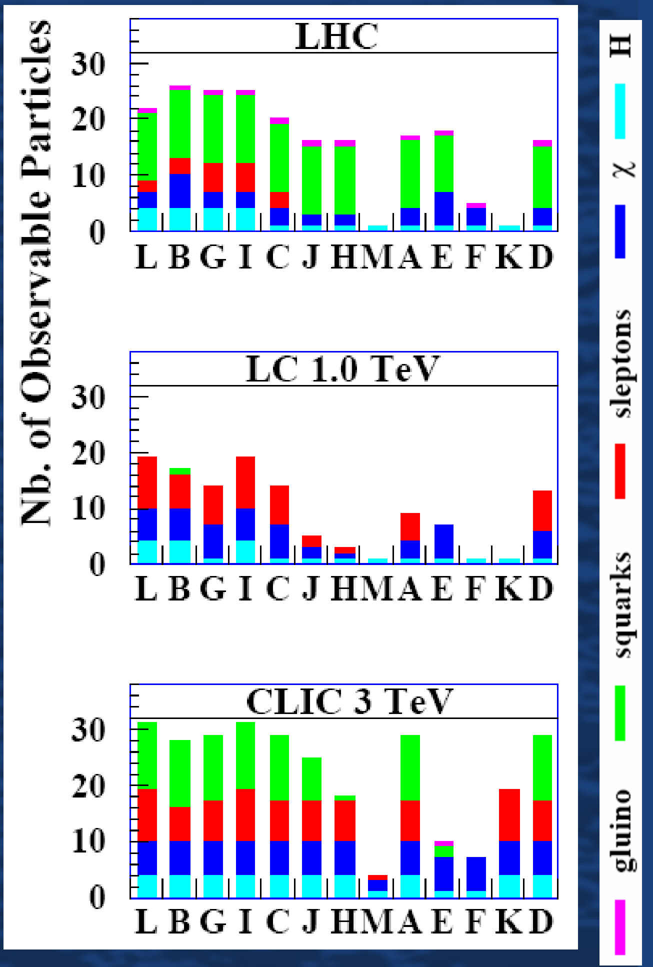
	Process and Final states	Energy (TeV)	Observables	Target Accuracy	Detector Challenge
Higgs	$ee \to Z^0h^0 \to \ell^+\ell^- X$	0.35	M_{recoil}, σ_{Zh}, BR_{bb}	$\delta\sigma_{Zh} = 2.5\%$, $\delta BR_{bb} = 1\%$	T
	$ee \to Z^0h^0, h^0 \to b\bar{b}/c\bar{c}/\tau\tau$	0.35	Jet flavour , jet $(E, \vec{p})$	δM_h=40 MeV, $\delta(\sigma_{Zh} \times BR)$=1%/7%/5%	V
	$ee \to Z^0h^0, h^0 \to WW^*$	0.35	M_Z, M_W, σ_{qqWW^*}	$\delta(\sigma_{Zh} \times BR_{WW^*})$=5%	C
	$ee \to Z^0h^0/h^0\nu\bar{\nu}, h^0 \to \gamma\gamma$	1.0	$M_{\gamma\gamma}$	$\delta(\sigma_{Zh} \times BR_{\gamma\gamma})$=5%	C
	$ee \to Z^0h^0, h^0\nu\bar{\nu}, h \to \mu^+\mu^-$	1.0	$M_{\mu\mu}$	5σ Evidence for $m_h = 120$ GeV	T
	$ee \to Z^0h^0, h^0 \to invisible$	0.35	σ_{qqE}	5σ Evidence for $BR_{invisible}$=2.5%	C
	$ee \to h^0\nu\bar{\nu}$	0.5	$\sigma_{bb\nu\nu}$, M_{bb}	$\delta(\sigma_{\nu\nu h} \times BR_{bb}) = 1\%$	C
	$ee \to t\bar{t}h^0$	1.0	σ_{tth}	δg_{tth}=5%	C
	$ee \to Z^0h^0h^0$, $h^0h^0\nu\bar{\nu}$	0.5/1.0	σ_{Zhh}, $\sigma_{\nu\nu hh}$, M_{hh}	δg_{hhh}=20/10%	C
SSB	$ee \to W^+W^-$	0.5		$\Delta\kappa_\gamma, \lambda_\gamma = 2 \cdot 10^{-4}$	V
	$ee \to W^+W^-\nu\bar{\nu}/Z^0Z^0\nu\bar{\nu}$	1.0	σ	$\Lambda_{*4}, \Lambda_{*5} = 3$ TeV	C
SUSY	$ee \to \tilde{e}^+_R\tilde{e}^-_R$ (Point 1)	0.5	E_e	$\delta m_{\tilde{\chi}^0_1}$=50 MeV	T
	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$, $\tilde{\chi}^+_1\tilde{\chi}^-_1$ (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
	$ee \to \tilde{t}_1\tilde{t}_1$ (Point 1)	1.0		$\delta m_{\tilde{t}_1}$=2 GeV	
-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
	$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 2)	0.5	M_{jj} in $jj\not{E}$, $M_{\ell\ell}$ in $jj\ell\ell\not{E}$	$\delta\sigma_{\chi_2\chi_3} = 4\%$, $\delta(m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1})$= 500 MeV	C
	$ee \to \tilde{\chi}^+_1\tilde{\chi}^-_1/\tilde{\chi}^0_i\tilde{\chi}^0_j$ (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
	$ee \to H^0A^0 \to b\bar{b}b\bar{b}$ (Point 4)	1.0	Mass constrained M_{bb}	δm_A=1 GeV	C
-alternative	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$ (Point 6)	0.5	Heavy stable particle	$\delta m_{\tilde{\tau}_1}$	T
SUSY	$\chi^0_1 \to \gamma + \not{E}$ (Point 7)	0.5	Non-pointing γ	$\delta c\tau$=10%	C
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
Precision SM	$ee \to t\bar{t} \to 6$ *jets*	1.0		5σ Sensitivity for $(g-2)_t/2 \leq 10^{-3}$	V
	$ee \to f\bar{f}$ $(f = e, \mu, \tau; b, c)$	1.0	$\sigma_{f\bar{f}}$, A_{FB}, A_{LR}	5σ Sensitivity to $M(Z_{LR}) = 7$ TeV	V
New Physics	$ee \to \gamma G$ (ADD)	1.0	$\sigma(\gamma + \not{E})$	5σ Sensitivity	C
	$ee \to KK \to f\bar{f}$ (RS)	1.0			T
Energy/Lumi	$ee \to ee_{fwd}$	0.3/1.0		δm_{top}=50 MeV	T
Meas.	$ee \to Z^0\gamma$	0.5/1.0			T

Physics Program at CLIC

Complete definition of Higgs Profile (lepton coupling, H self-coupling, heavy H sector of extended models, ...);

Probe precisely physics beyond SM, directly up to LHC reach, indirectly well beyond hadron collider reach;

Probe details of DM-motivated SUSY complementing LHC and lower energy LC;



need to identify set of benchmarks for a multi-TeV e+e- linear collider.

A Detector Concept for CLIC

First CLIC Physics Study (2002-2004) proposed a detector with performances rescaled from those proposed for TESLA TDR (2001);

CERN-2004-005
10 June 2004
Physics Department
hep-ph/0412251

arXiv:hep-ph/0412251 v1 17 Dec 2004

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AT THE CLIC MULTI-TeV LINEAR COLLIDER

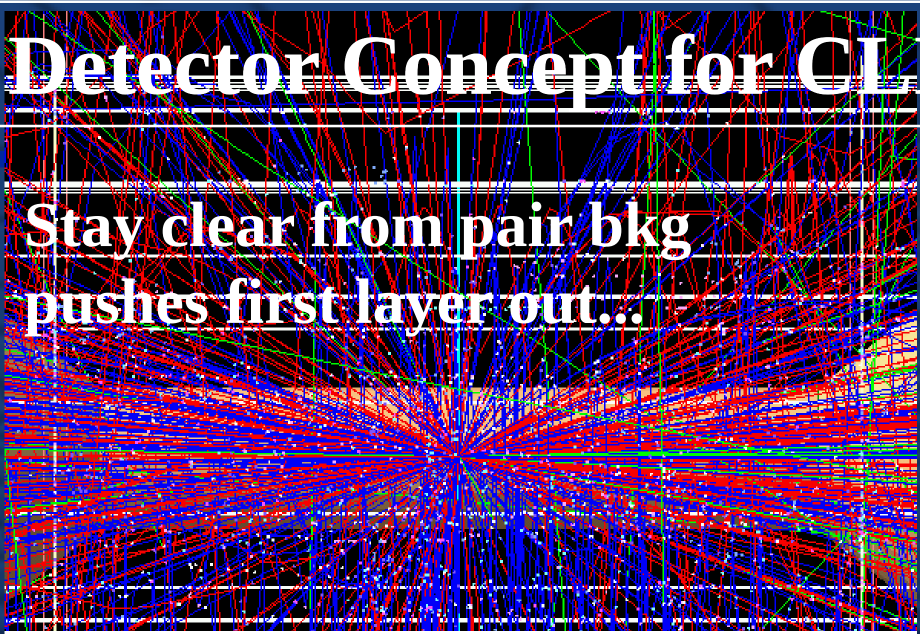
Report of the CLIC Physics Working Group

Editors: M. Battaglia, A. De Roeck, J. Ellis, D. Schulte

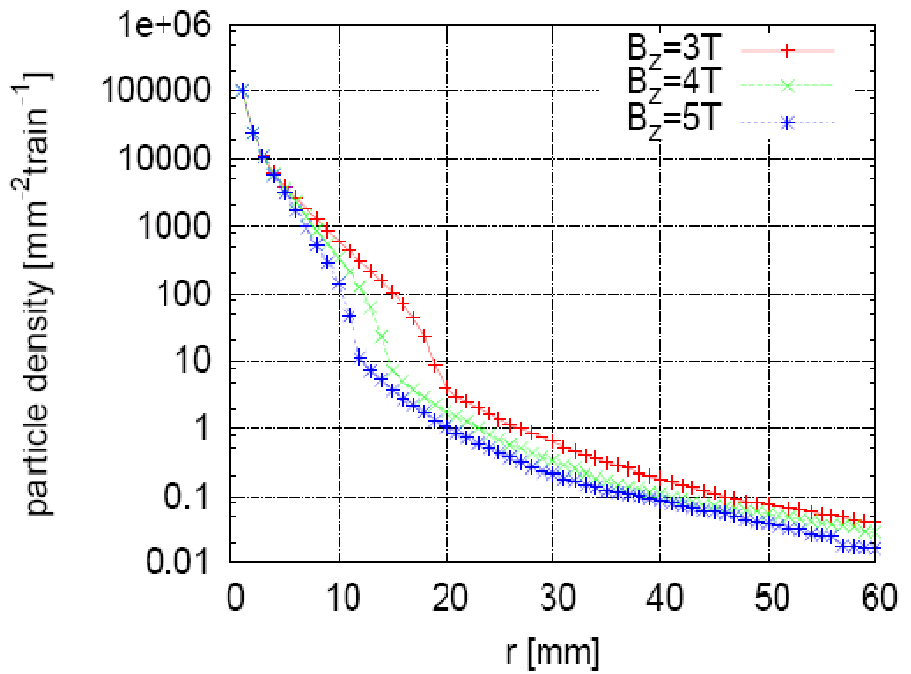
Detector	CLIC studies
Vertexing	$\delta(IP_{r\phi}) = 15\ \mu\mathrm{m} \oplus \frac{35\ \mu\mathrm{m\ GeV}/c}{p\sin^{3/2}\theta}$ $\delta(IP_z) = 15\ \mu\mathrm{m} \oplus \frac{35\ \mu\mathrm{mGeV}/c}{p\sin^{5/2}\theta}$
Solenoidal field	B = 4.0 T
Tracking	$\frac{\delta p_t}{p_t^2} = 5.0 \times 10^{-5} \left(\frac{\mathrm{GeV}}{c}\right)^{-1}$
E.m. calorimeter	$\frac{\delta E}{E\ (\mathrm{GeV})} = 0.10 \frac{1}{\sqrt{E}} \oplus 0.01$
Hadron calorimeter	$\frac{\delta E}{E\ (\mathrm{GeV})} = 0.50 \frac{1}{\sqrt{E}} \oplus 0.04$
μ detector	Instrumented Fe yoke $\frac{\delta p}{p} \simeq 30\%$ at 100 GeV/c
Energy flow	$\frac{\delta E}{E\ (\mathrm{GeV})} \simeq 0.3 \frac{1}{\sqrt{E}}$
Coverage	$\lvert\cos\theta\rvert < 0.98$

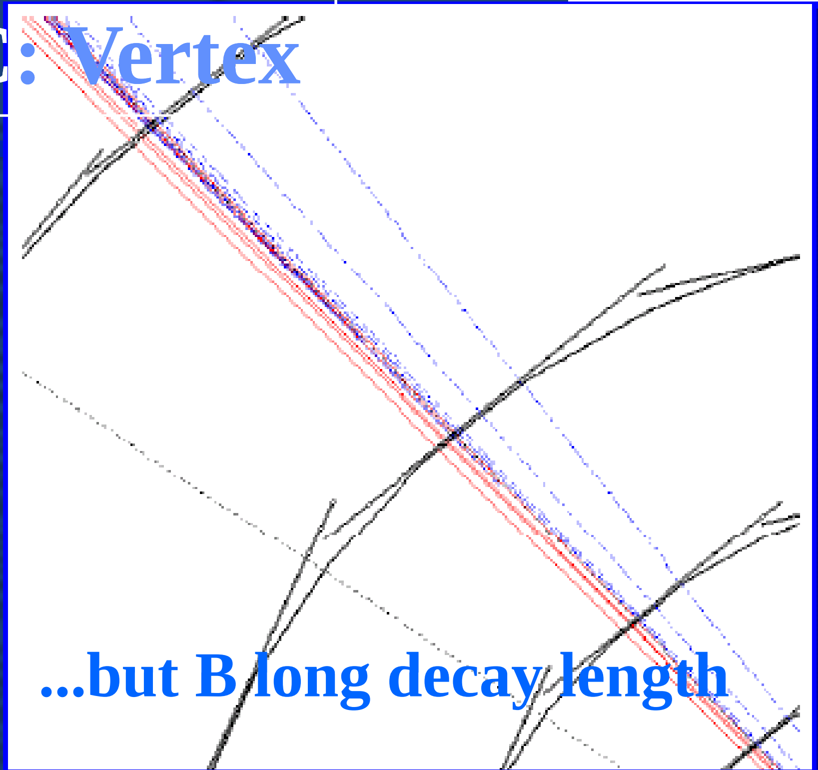
Physics validation and detector implementation of such performances aim of current study.

Detector Concept for CLIC: Vertex

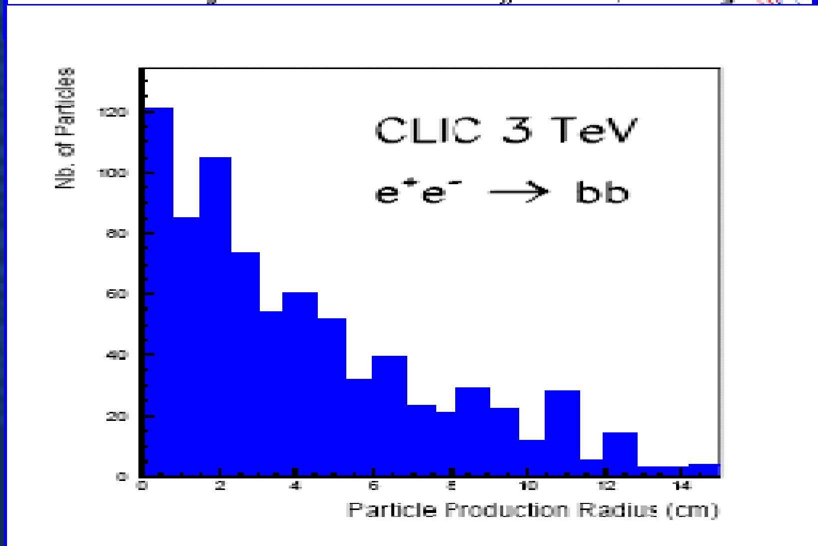


Stay clear from pair bkg pushes first layer out...



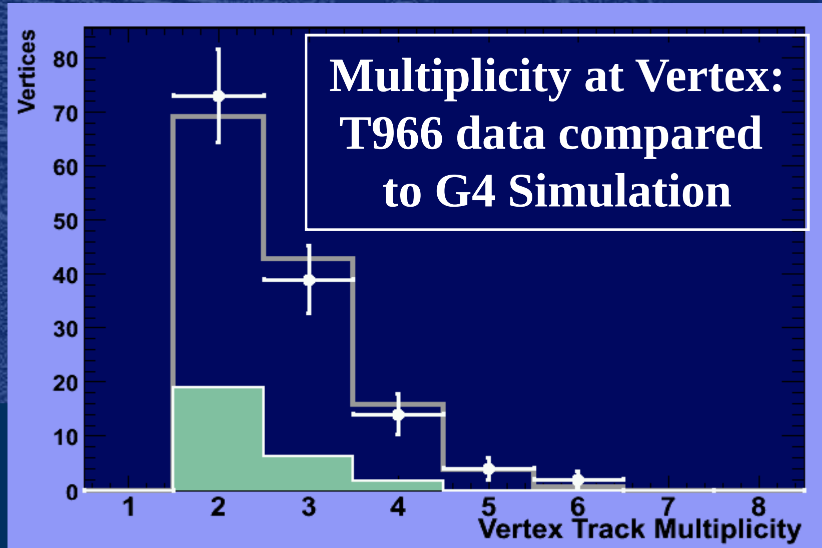


...but B long decay length



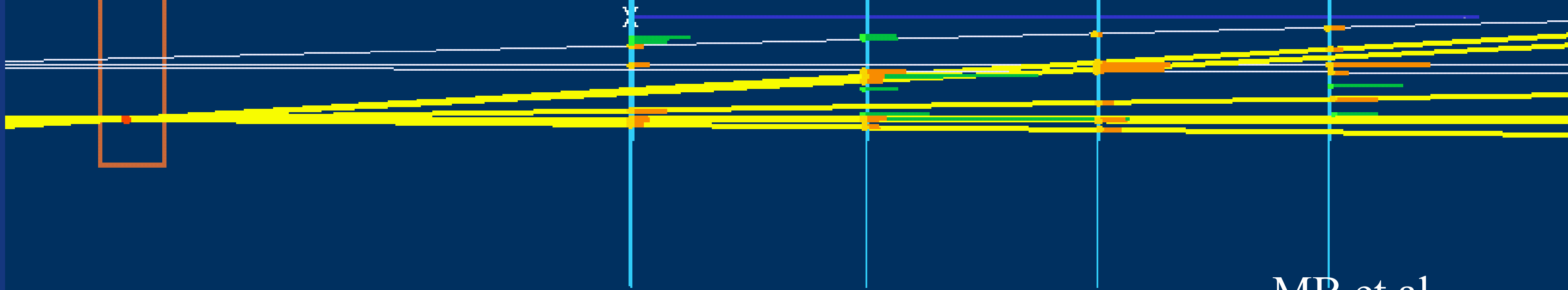
Tracking & Vertexing: Beam Test Validation

Experience with beam telescopes based on pixel sensors (EUDET, IReS, MPI, LBNL,...)
T966: Study trk extrapolation and vertex reconstruction using a four-layered thin monolithic CMOS pixel telescope on high energy beam with realistic occupancy



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

Extrapolate 3.3 cm upstream from first Si pixel layer: $\sigma_{z\ Vtx} = 230\ \mu m$



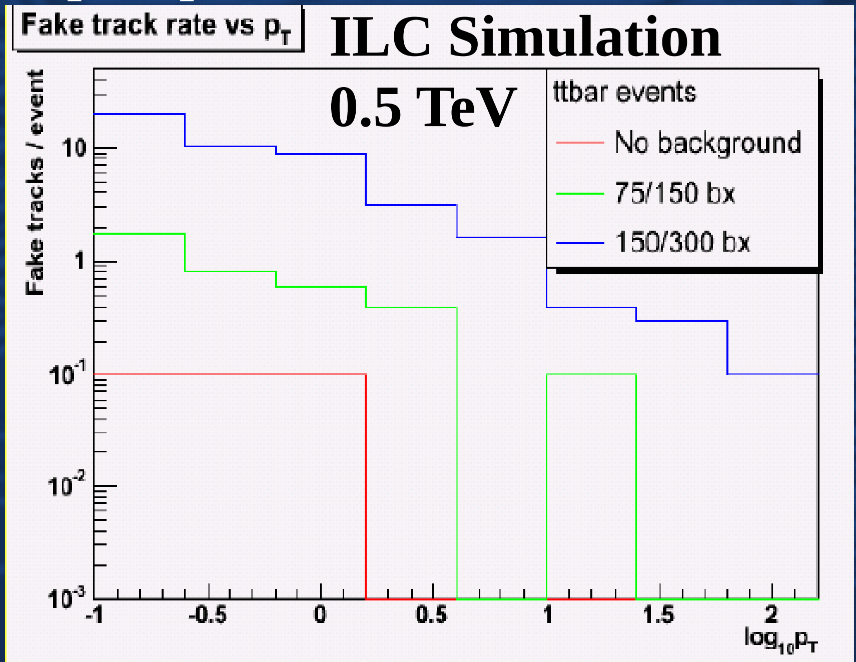
MB et al,
NIM A593 (2008)

Vertexing: Bunch Tagging

Efficient patrec requires blg occupancy << 1 hits mm^{-2}

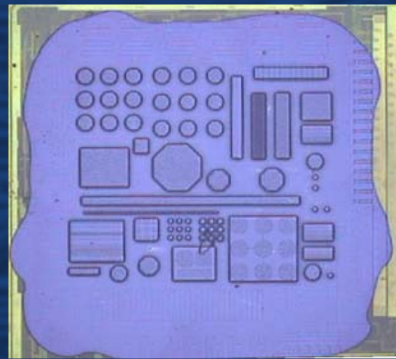
May reduce bkg hit density by moving away in radius or identifying BX;

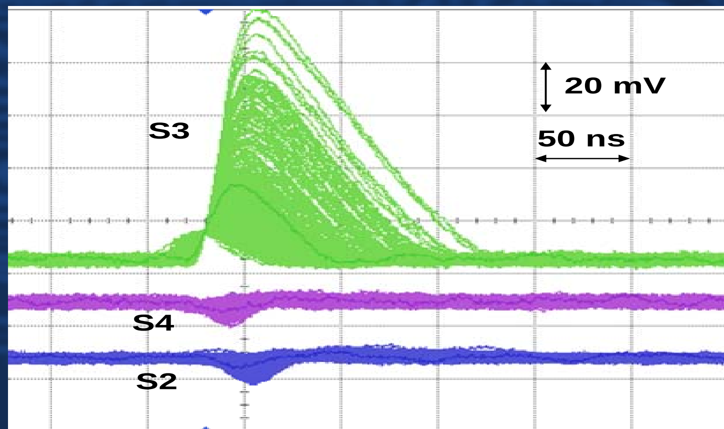
- loss in vertex tracking efficiency;
- increase in fake tracks;
- build-up of non-Gaussian tails in impact parameter distribution.



A Raspereza, LCWS07

Thin Film on ASIC



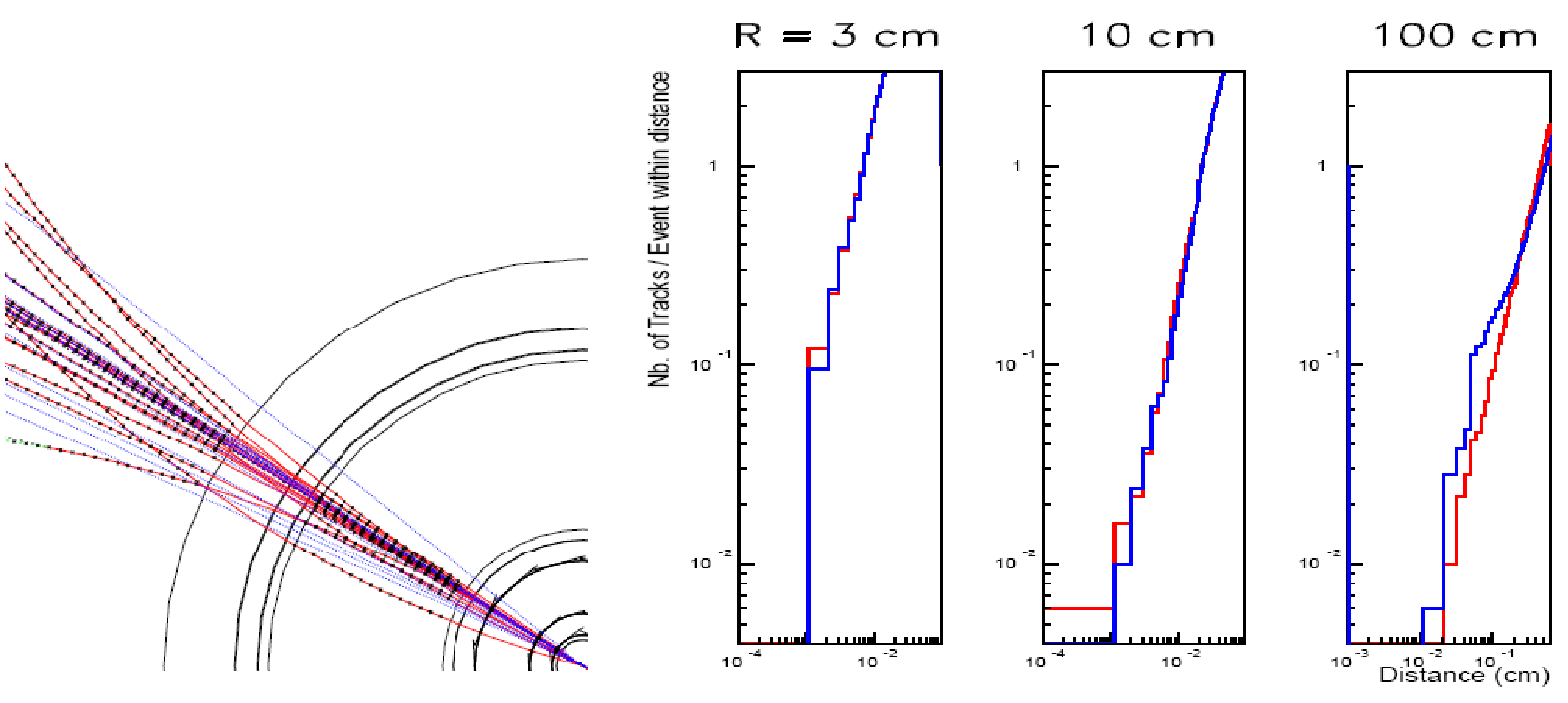


P Jarron

Detector Concept for CLIC: Tracker

At CLIC significant track density in collimated hadronic jets + parallel muon bkg, γγ → hadrons and low momentum spiralling tracks:

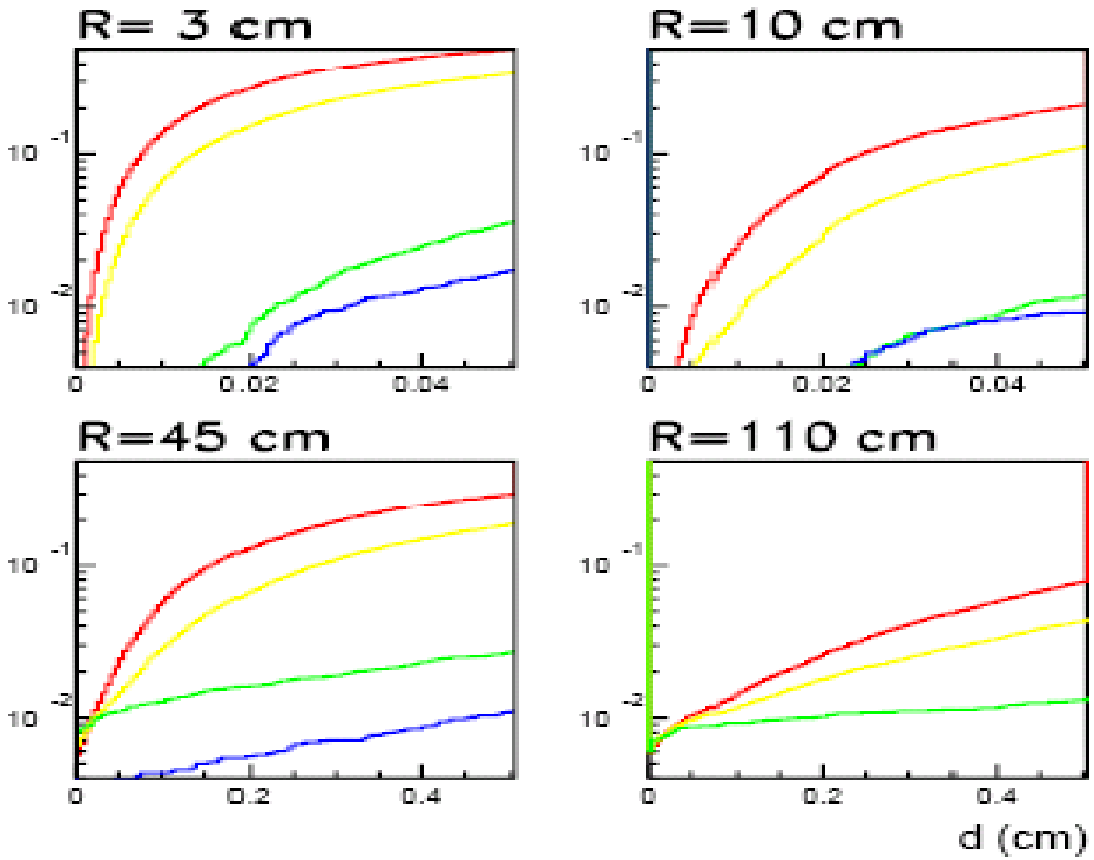
Minimum Distance between Tracks in Hadronic Events at 3 TeV



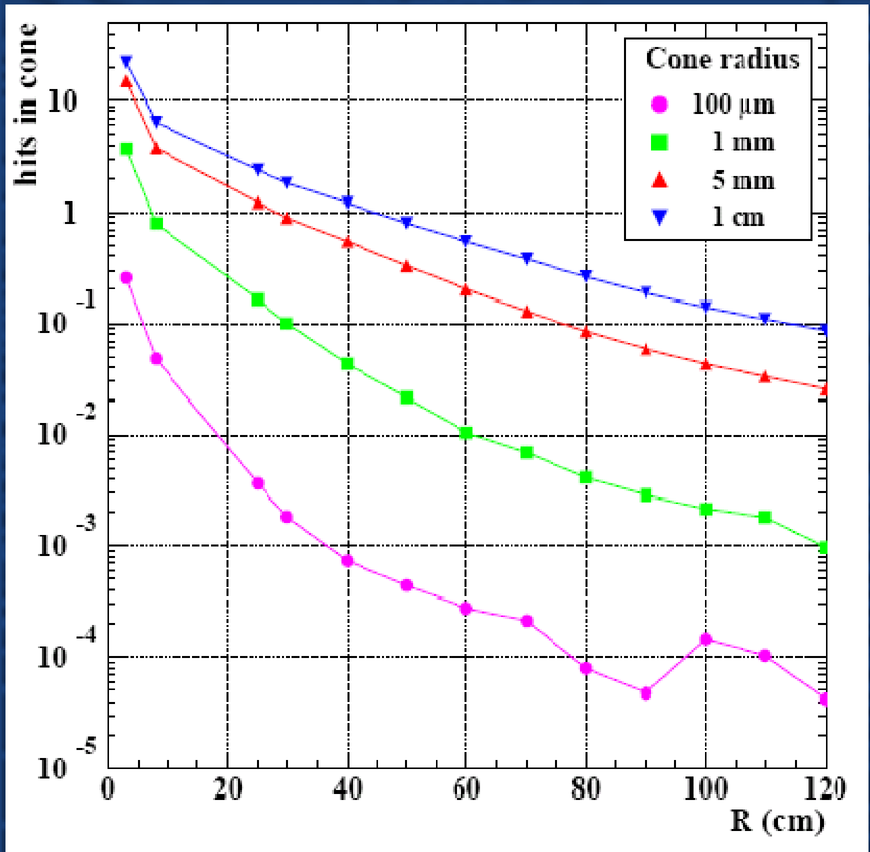
hep-ph/0103338

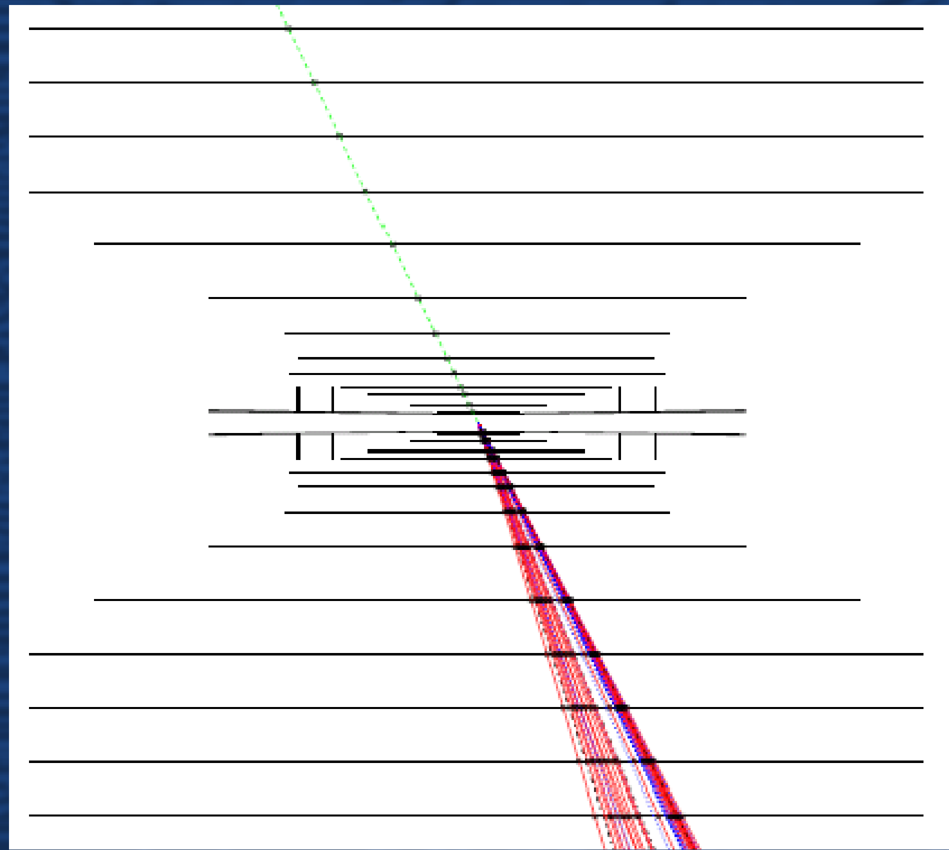
$\sqrt{s} = 200, 500, 3000, 5000$ GeV

$e^+e^- \longrightarrow W^+W^-$



CLIC 2004 Report suggested multi-layered high-resolution Si detectors Main Tracker, inspired by CMS and adopted by the SiD concept at ILC;





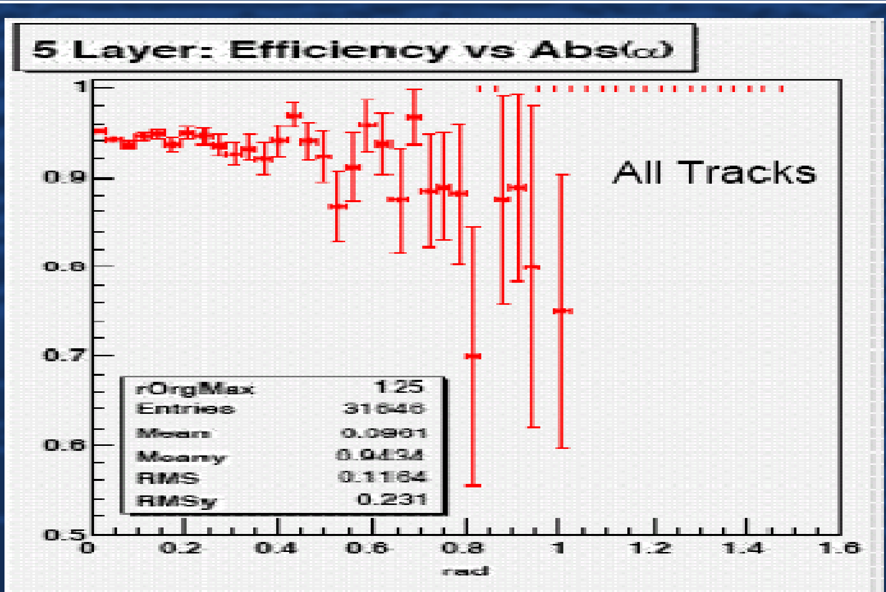
Discrete Si tracker adopted as baseline but detailed study is now needed.

MB, A Frey

Need to assess tracking capability of SiD-like detector at CLIC:

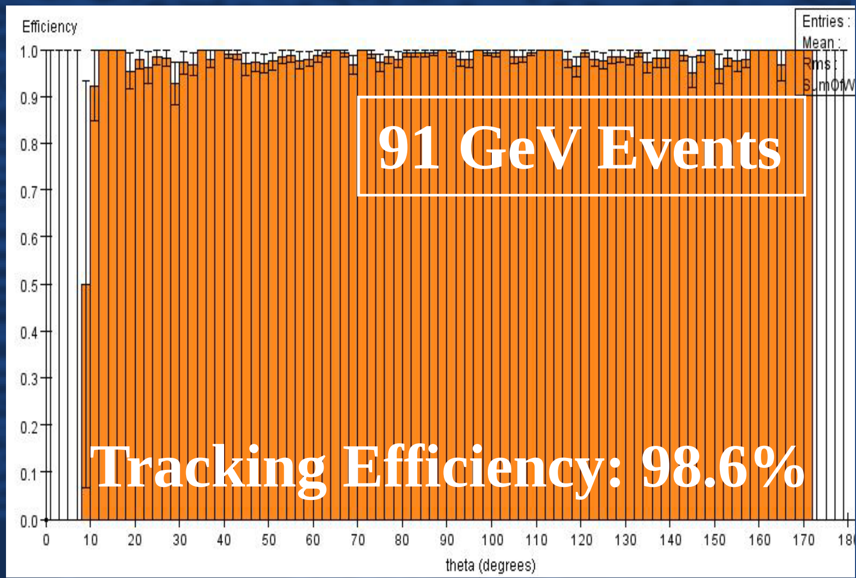
Some encouraging results on tracking performance of 5-layered tracker (assisted by Vertex and ECAL) from "realistic" simulation, but for low energy jets (Z pole and tt at 0.5 TeV) and w/o machine induced bkg

Tracking Efficiency vs Angle from Jet



Partridge, BILCW07

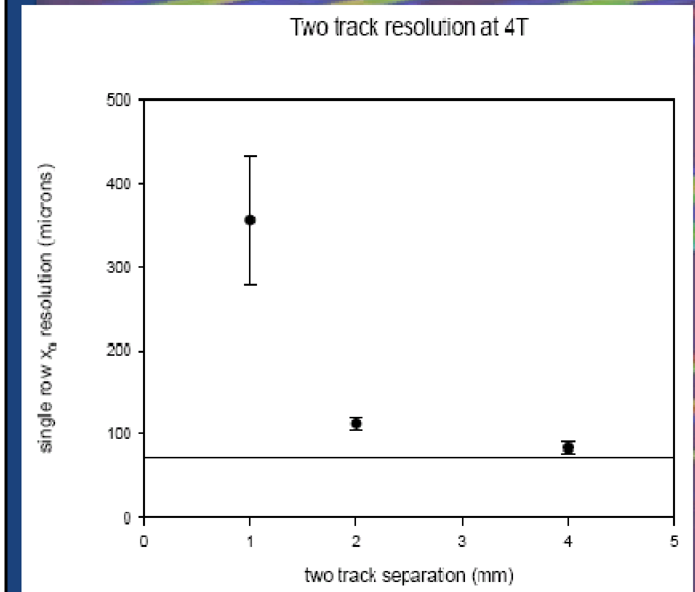
Tracking Efficiency vs Polar Angle

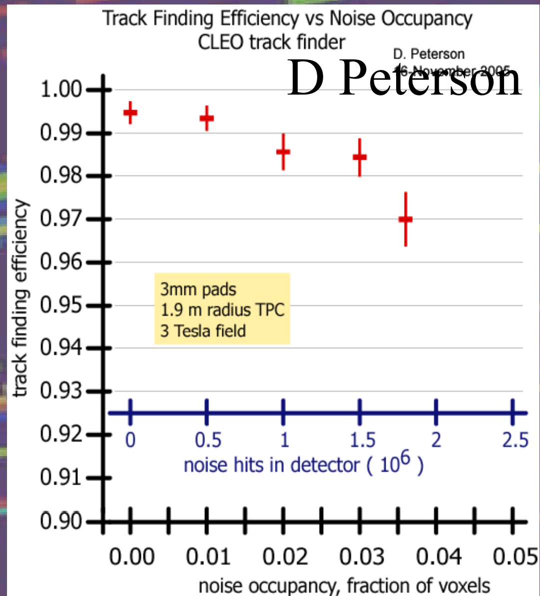


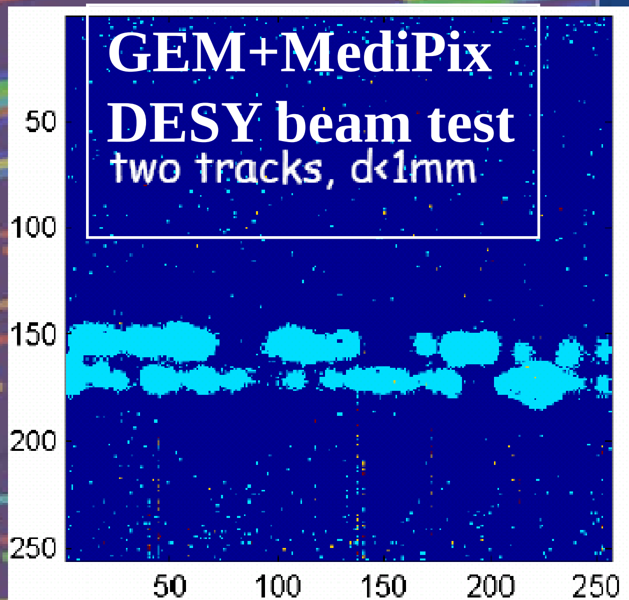
Partridge, SiD08

Essential to evaluate performance of 3D continuous tracker (TPC) offering redundancy in patrec and dE/dx info;

TPC prototype tests and simulation shows that
• two track separation ~1mm (or better ?) may be feasible;
• track finding efficiency stable up to 3-4% occupancy:



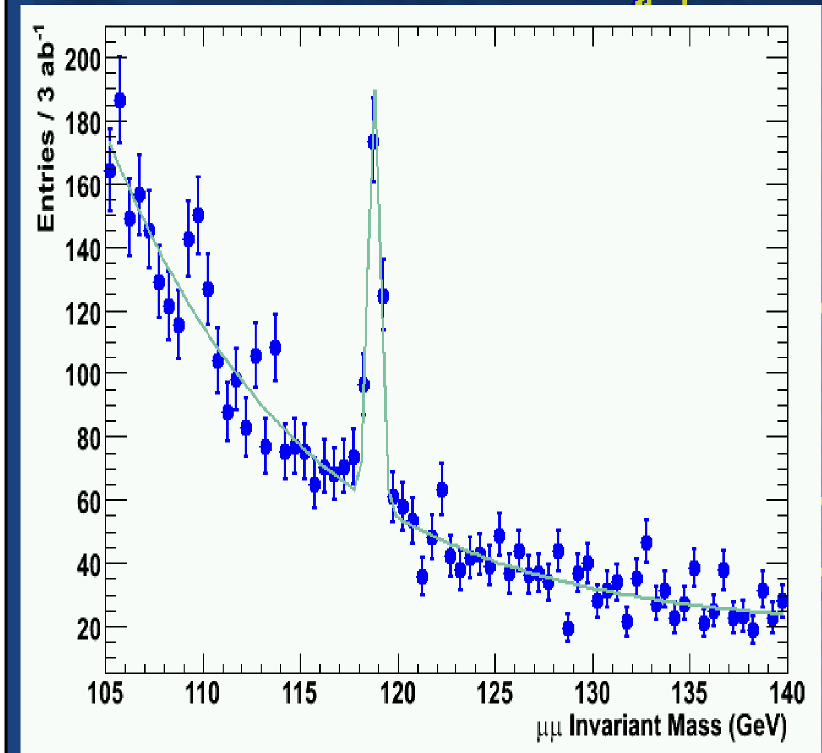




Momentum Resolution

Use SiD model at 3 TeV to study $e^+e^- \rightarrow H\nu\nu$; $H \rightarrow \mu^+\mu^-$

Process is possibly one of most demanding for $\delta p/p^2$ at E_{cm} > 1 TeV
ILC-like $\delta p/p^2$ resolution appears adequate at CLIC energies.



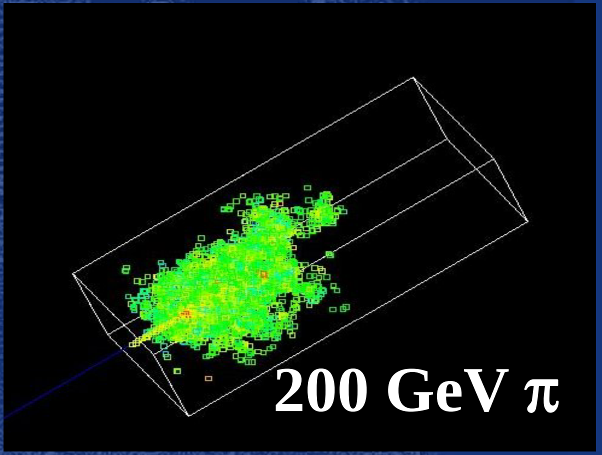
M_H (GeV)	Nb. Signal Evts.	Nb. Bkg. Evts.	$S/\sqrt{B}$	$\delta BR/BR$
120	229.6	161.1	18.1	0.086
130	153.1	88.1	16.3	0.101
140	103.2	64.3	12.9	0.125
150	68.1	58.1	9.5	0.160
155	68.1	58.0	5.2	0.253
160	12.1	33.0	2.1	

MB, J. Phys. G35 (2008) 095005

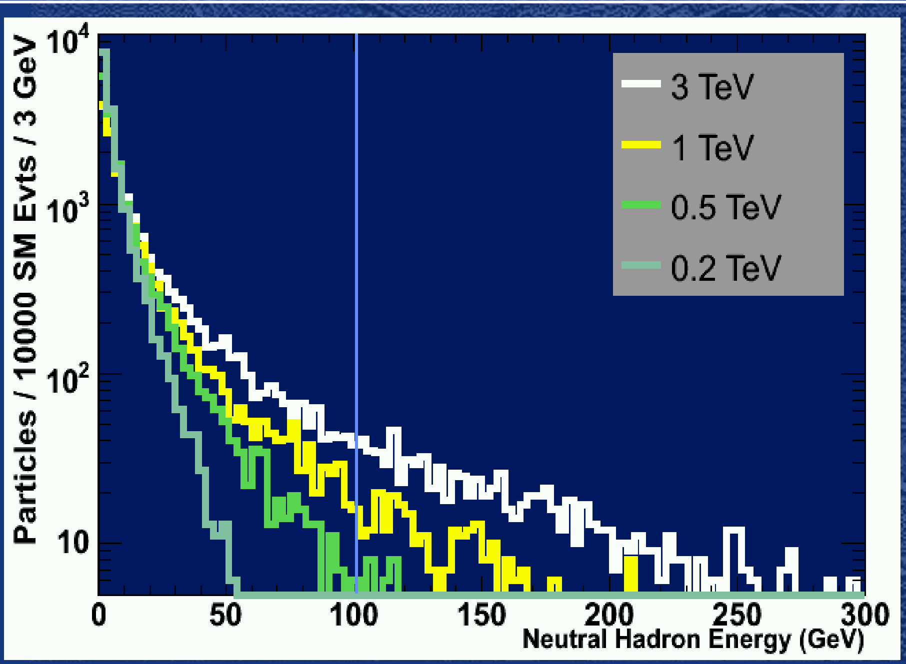
Detector Concept for CLIC: Calorimetry

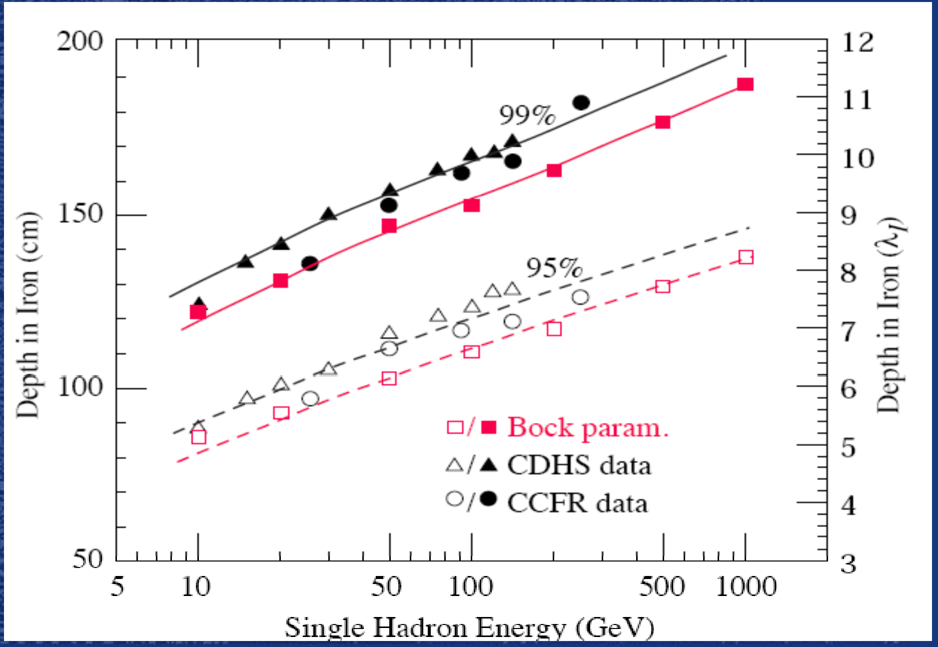
Scale depth of HCAL

1.6 m Fe $\lambda_{int} \leq 10$ to get
99% containment for E > 100 GeV



Neutral Hadron Energy at 3 TeV

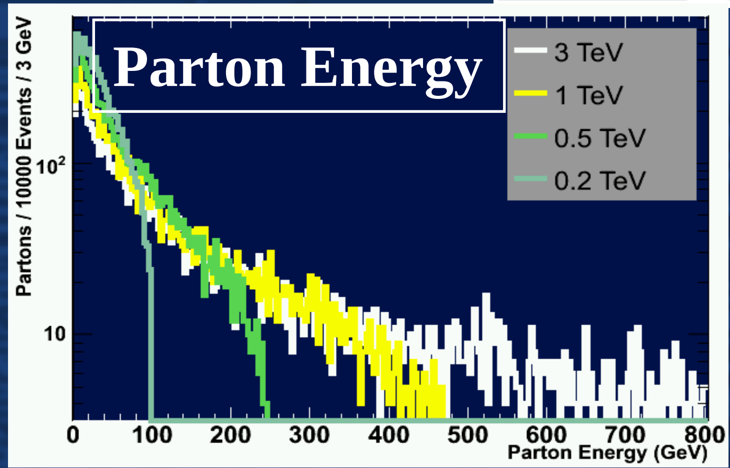




Particle Flow

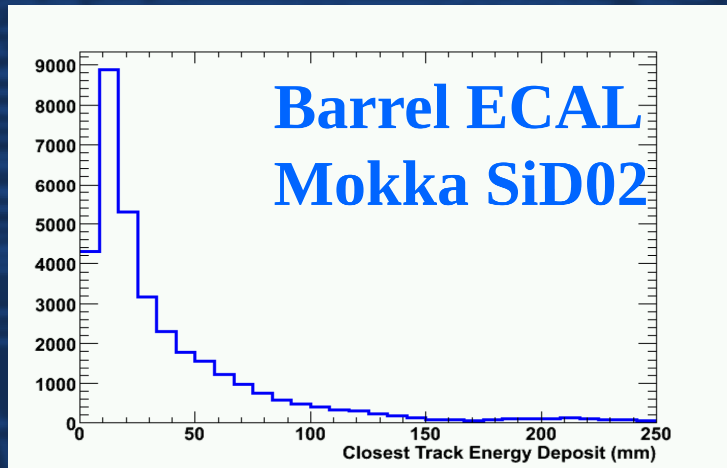
Is Particle Flow applicable to multi-TeV collisions ?

PFA gives unprecedented performance for $E_{jet} \sim 100$ GeV, at CLIC N_{jet} also grows
→ E_{jet} does not scale proportional to E_{cm}



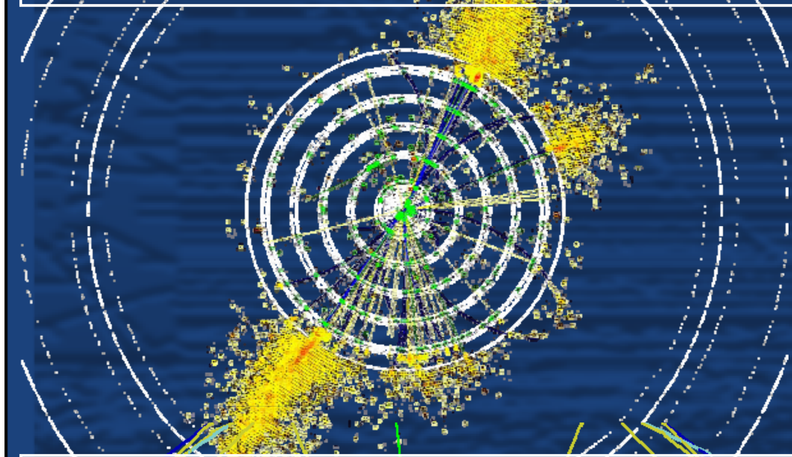
Large boost and high jet multiplicity gives particle overlaps in calorimeters.
Simple benchmark: study distance (charged particle E > 5 GeV to closest cluster from neutral with E > 10 GeV) in ECAL and HCAL (full G4 simulation)

$e^+e^- \rightarrow H^+H^- \rightarrow tbtb$ at 3 TeV

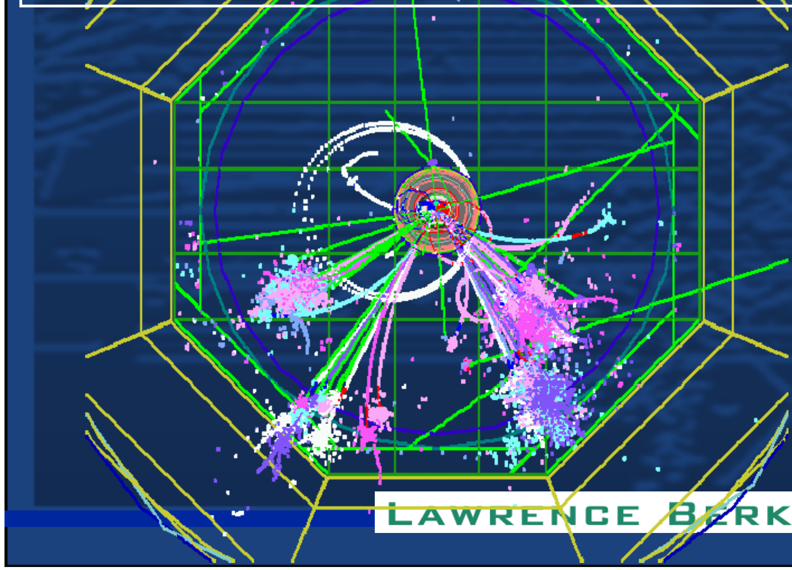


Charged-Neutral Particle Distance in Calorimeters

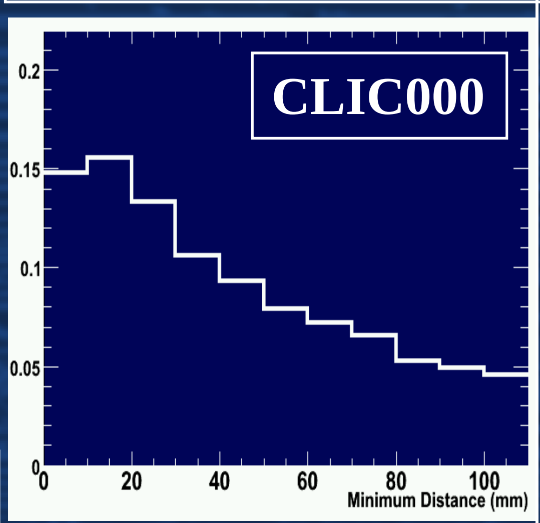
$e^+e^- \rightarrow WW/ZZ$ at 3 TeV

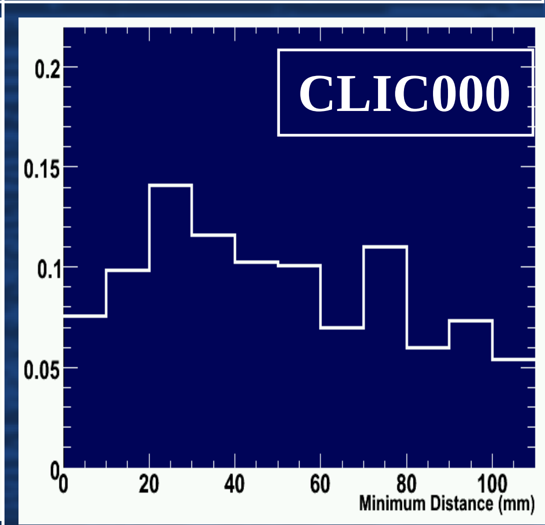


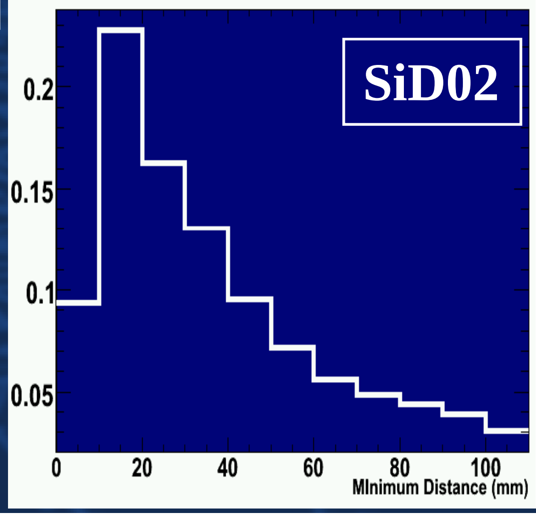
$e^+e^- \rightarrow ZZ\nu\nu$ at 3 TeV

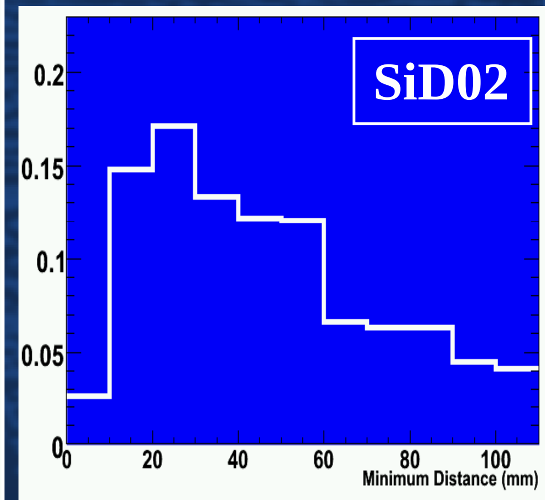


ECal	HCal

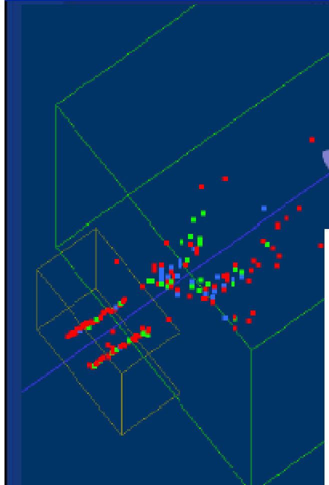


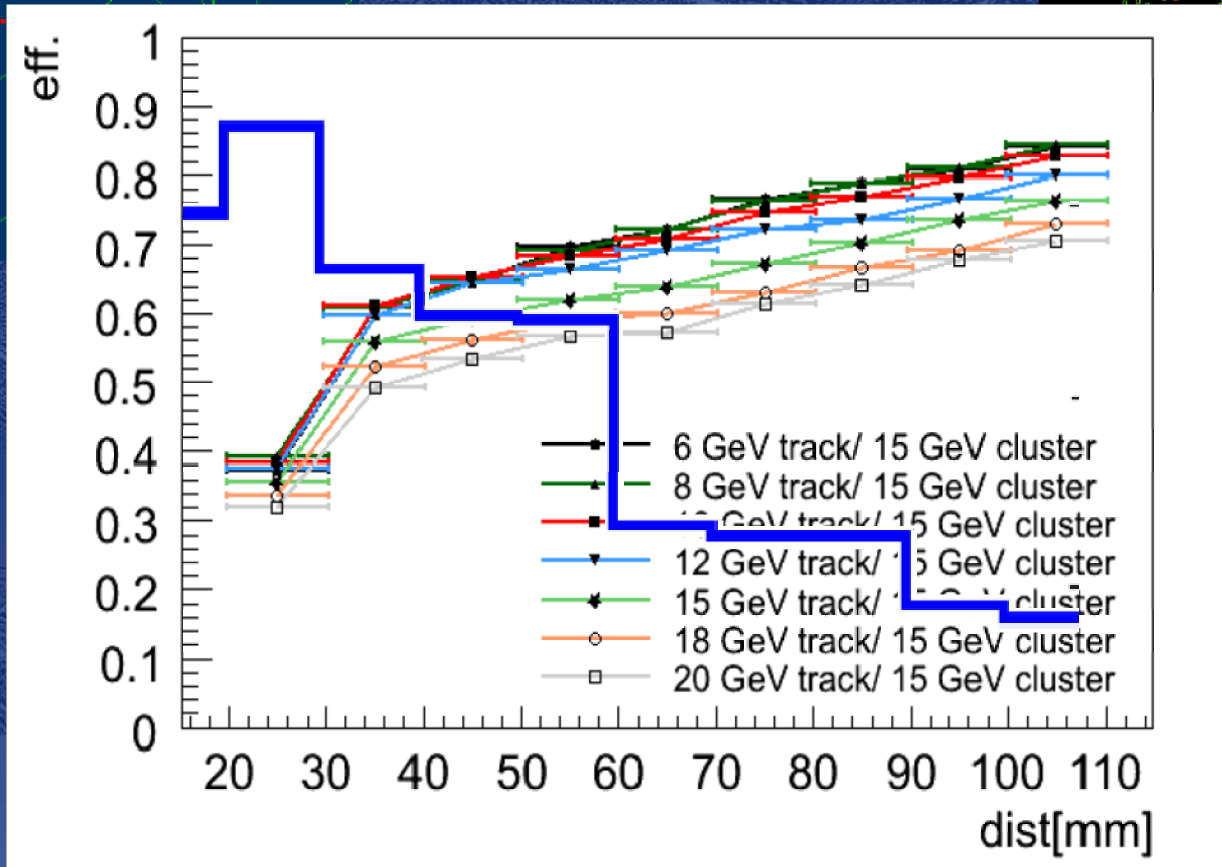


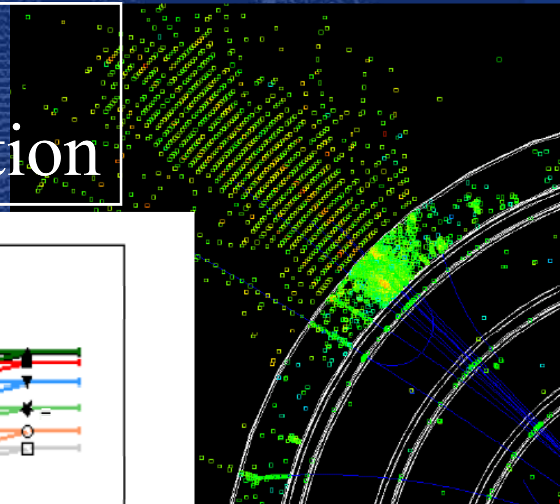




Track - Shower separation: CALICE data – CLIC Simulation



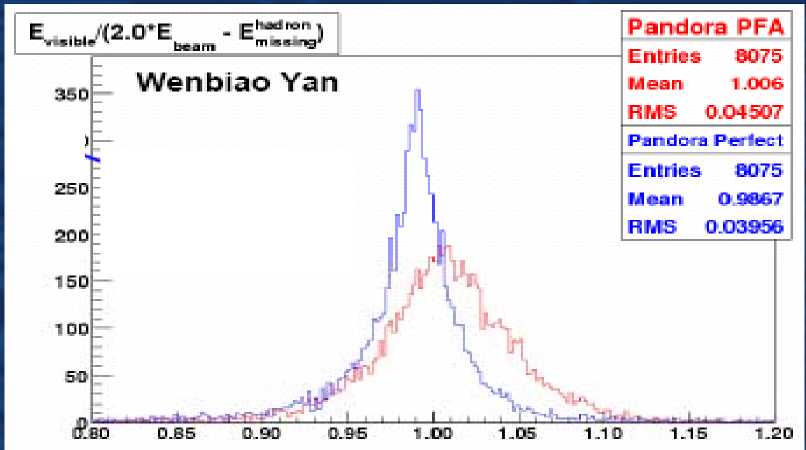


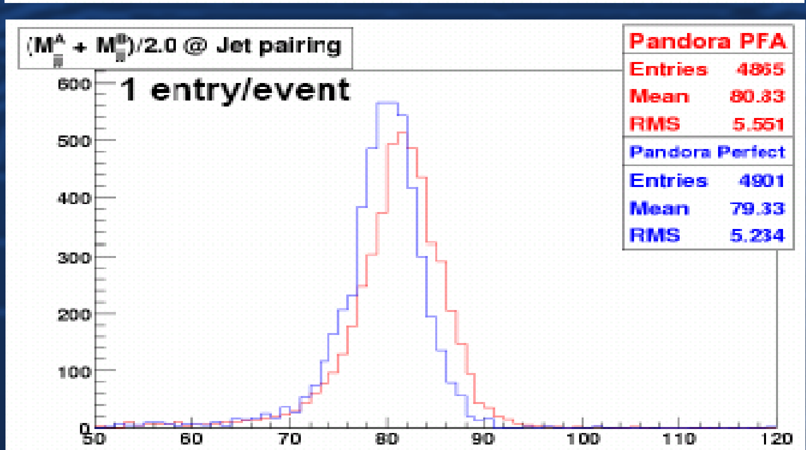


CALICE Data
D Ward
CLIC G4 ZZνν
MB

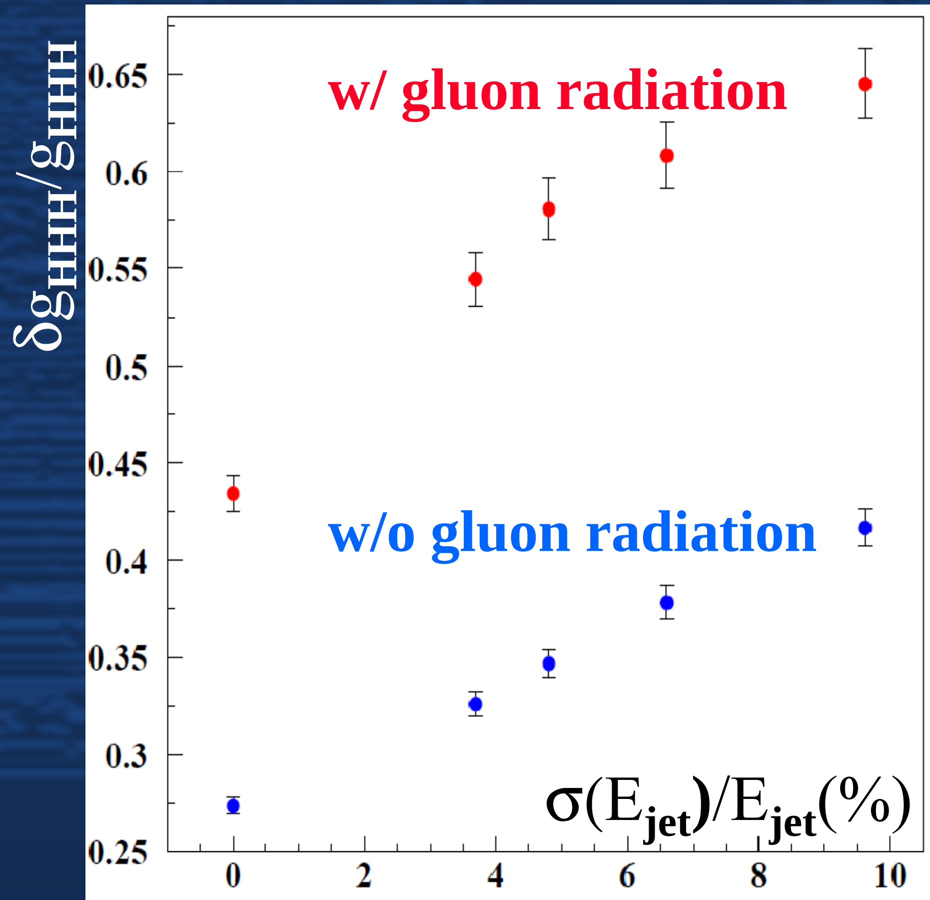
Event reco, Jet clustering and gluon radiation affect physics reconstruction performances beyond particle flow response:

$e^+e^- \rightarrow WW\nu\nu$ at 0.8 TeV





$e^+e^- \rightarrow HHZ$ at 0.5 TeV



M Thompson LAWRENCE BERKELEY NATIONAL LABORATORY T Barklow

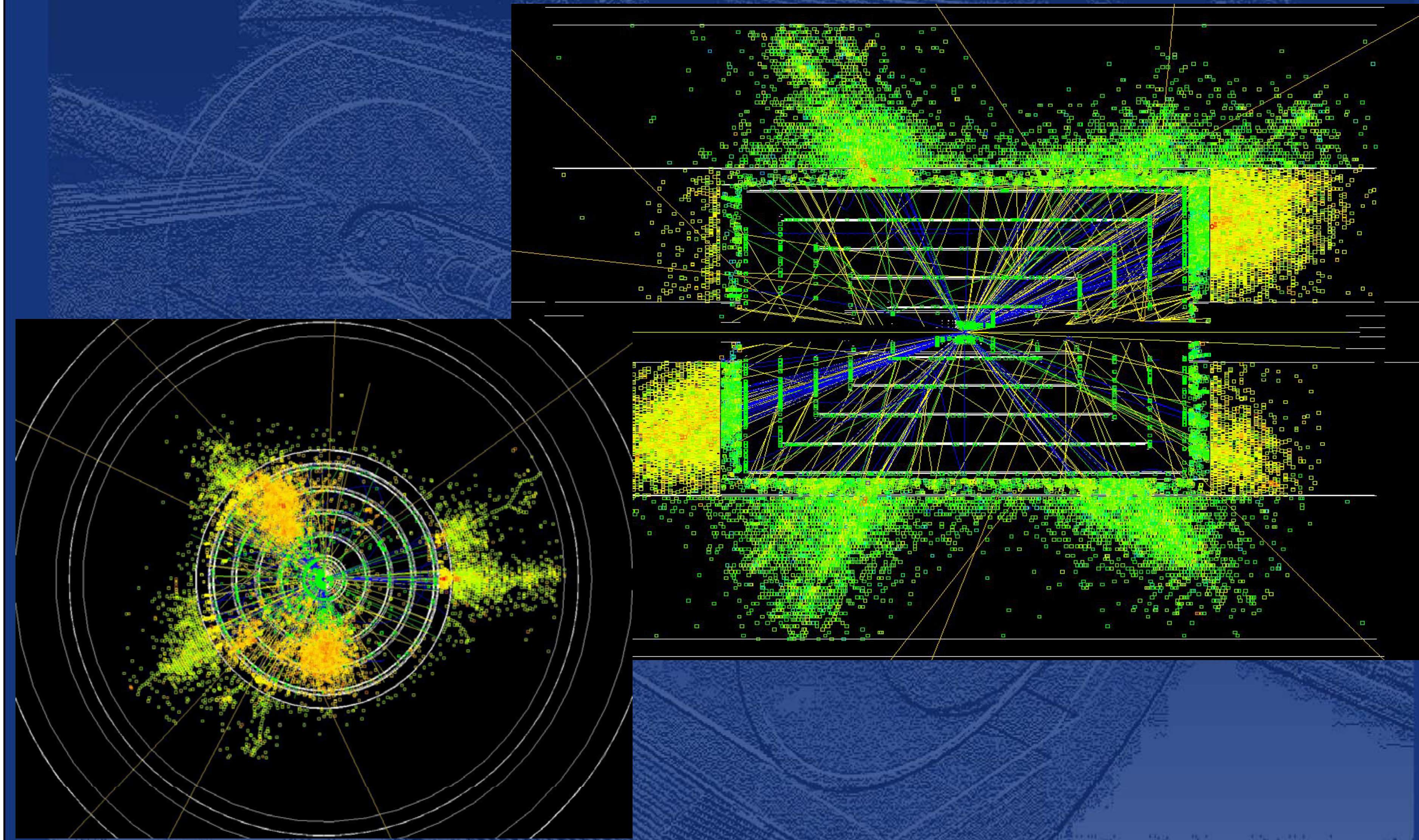
Scaling the SiD Concept: CLIC000 Model

Start from SiD01 model:

- HCAL from 4.6 to 9 λ_{int}
- R_{vtx} from 1.4 to 4 cm

M Stanitzki
C Grefe

WW/ZZ Events at 3 TeV in SID-CLIC000

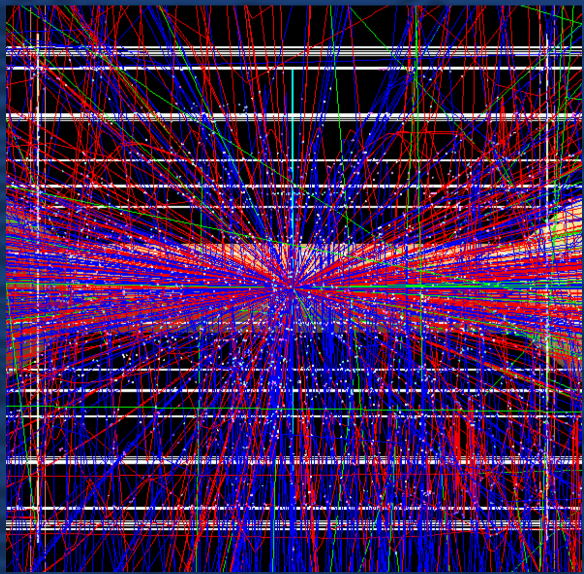


C Grefe

(Some) Questions for the Study

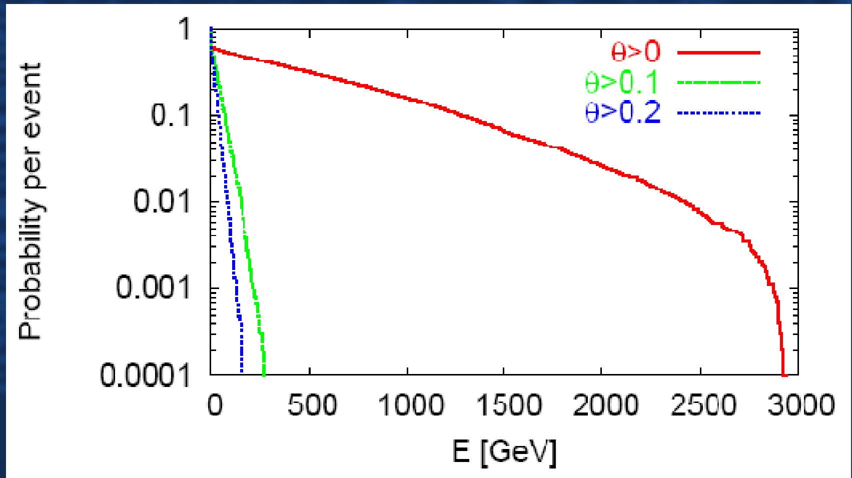
B Field strength

B=5 T adequate for dp/p, main constrain to come from confinement of soft particles from bkgs and engineering; (A. Herve)



Tracker Technology & Optimisation

Background and collimated hadronic jets require to assess/review SiD strategy for track reconstruction and detailed evaluation of competing tracking technologies for CLIC, taking into account ILC R&D and simulation studies;



Applicability of Particle Flow

Success of PFA at ~ 100 GeV jets needs to be reassessed at CLIC for well-defined physics benchmarks; alternative approaches to calorimetry may be worth pursuing;

Forward Regions

Fusion, t-channel processes and large jet multiplicity push much of the interesting part of the cross section in the forward region, where machine induced backgrounds are larger: need to assess requirements for vertexing, tracking, lepton tagging and calorimetry vs polar angle.

Bunch Tagging

Timing layers with ~ 1 BX time resolution are proposed: essential to support dedicated R&D and assess how to integrate timing information in vertex tracking and calorimetry.

The work in front of us

Experiments at CLIC not a simple scaling of LEP + ILC, machine parameters & multi-TeV energy are a new regime for experiments, which requires an open-minded approach;

Progress in defining physics potential, machine parameters and detector optimisation for the CLIC program to come from effective collaboration and strong synergies with world-wide linear collider efforts on R&D, physics and software;

CLIC study working towards CDR to outline physics potential of multi-TeV collisions and feasibility of accelerator and detector techniques.