



e⁺e⁻ Collisions at 1 TeV and Beyond Physics Motivations and Experimental Issues

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The logo for the Compact Linear Collider (CLIC) is positioned in the bottom right corner. It consists of the letters "CLIC" in a stylized, italicized font, with the "C" and "L" being red and the "I" and "C" being blue.

LCWS08 Conference

U Illinois, Chicago, November 16, 2008

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Physics Motivations for 1 TeV and beyond



Precision study of rare SM processes:
 $g_{H\mu\mu}$, g_{Hbb} for intermediate M_H , g_{HHH} , g_{tth}

Access new thresholds

DM motivated SUSY, access thresholds in A funnell and co-annihilation
Solve LHC inverse problem, KK, SSB

Indirect NP sensitivity through EW observables

Precision on Higgs Profile vs. E_{cm}

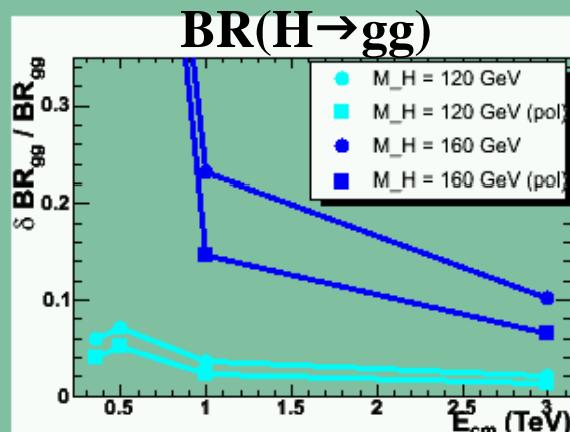
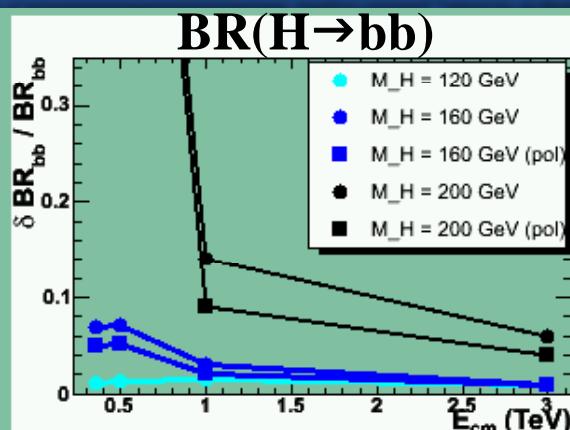
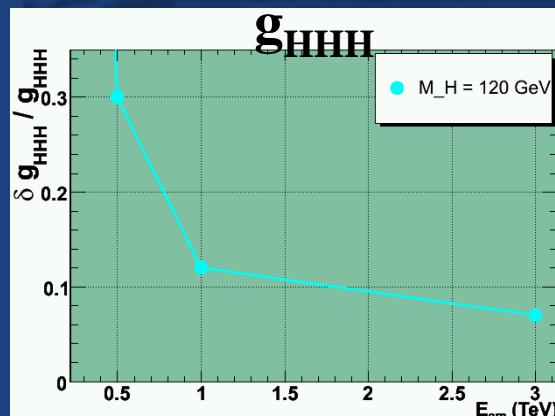


Barklow, hep-ph/0312268

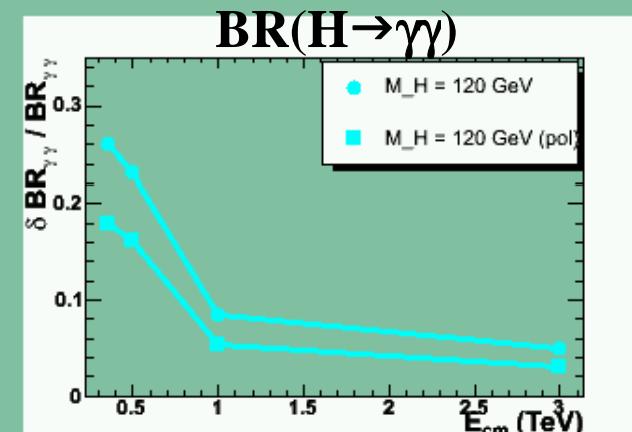
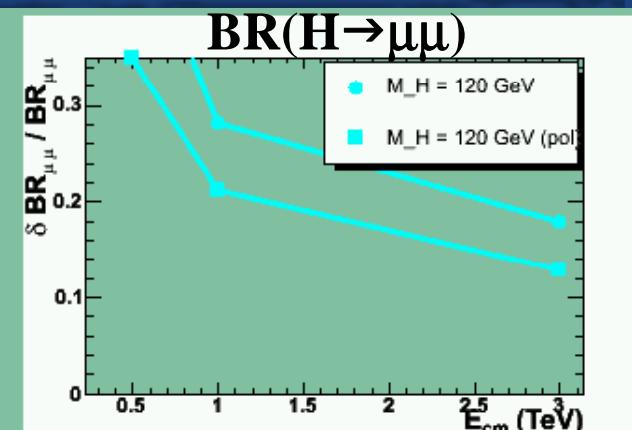
E_{cm}	L
0.35 TeV	0.5 ab^{-1}
0.50 TeV	0.5 ab^{-1}
1.0 TeV	1.0 ab^{-1}
3.0 TeV	2.0 ab^{-1}
Pol: e^-	80%
e^+	50%

TESLA-TDR 2001

Kuhl, Desch, LC-PHSM-2007-001
 Barklow, hep-ph/0312268
 MB, DeRoeck, hep-ph/0211207
 MB, J Phys G35 (2008) 095005



\sqrt{s} (GeV)	e_{pol}^+ (%)	Higgs Mass (GeV)			
		120	140	160	200
350	0	110280	89150	69975	37385
350	+50	159115	128520	100800	53775
1000	0	386550	350690	317530	259190
1000	+50	569750	516830	467900	382070



Solving the SUSY Inverse Problem



Reconstruct fundamental SUSY parameters from data, significant degeneracy at LHC:
242 MSSM points, 162 pairs indistinguishable at LHC:

only 85 have charged SUSY particles kinematically accessible at 0.5 TeV, 82 visible;

57/73 pairs which are visible can be distinguished at 5σ level with ILC data at 0.5 TeV;

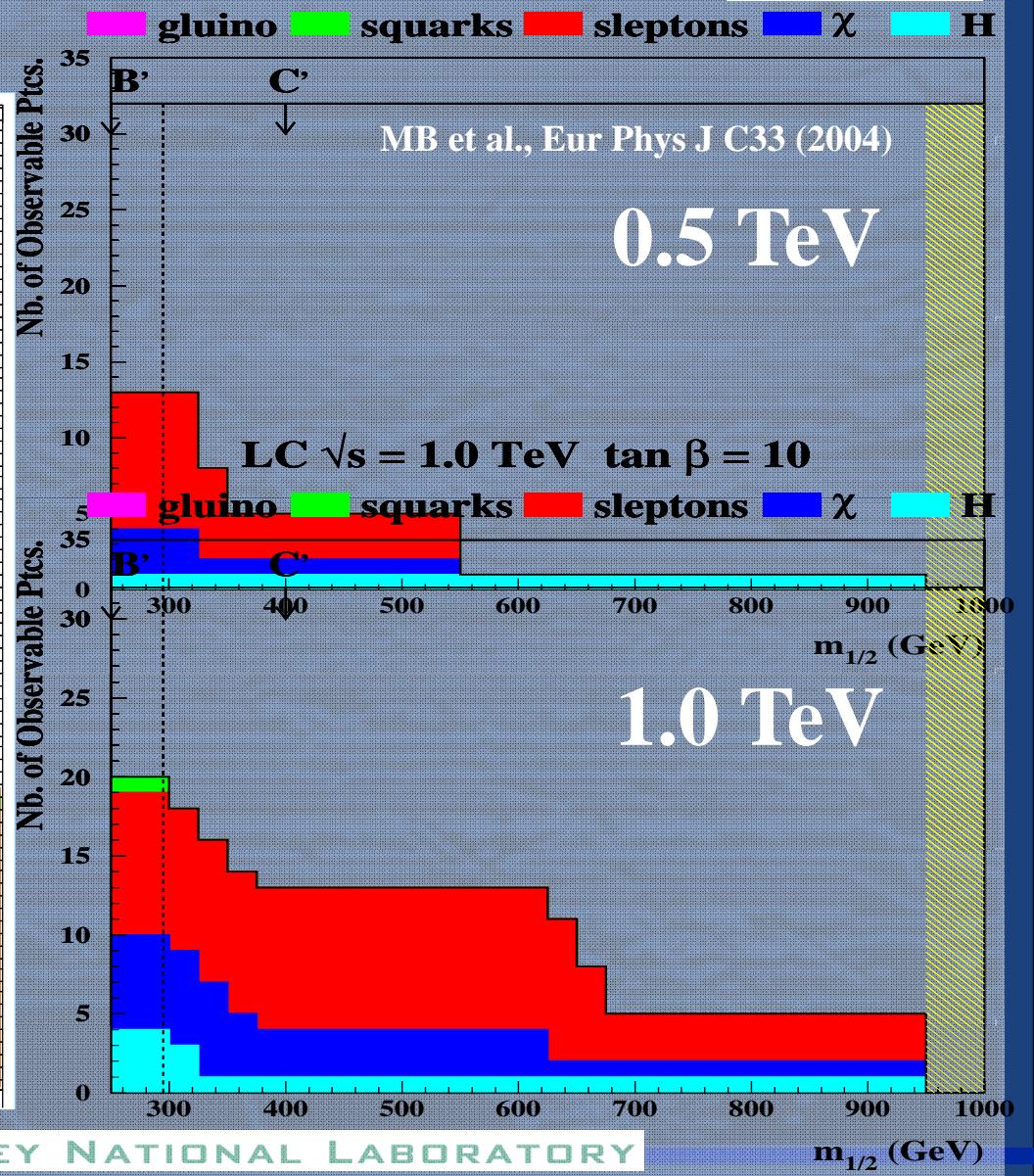
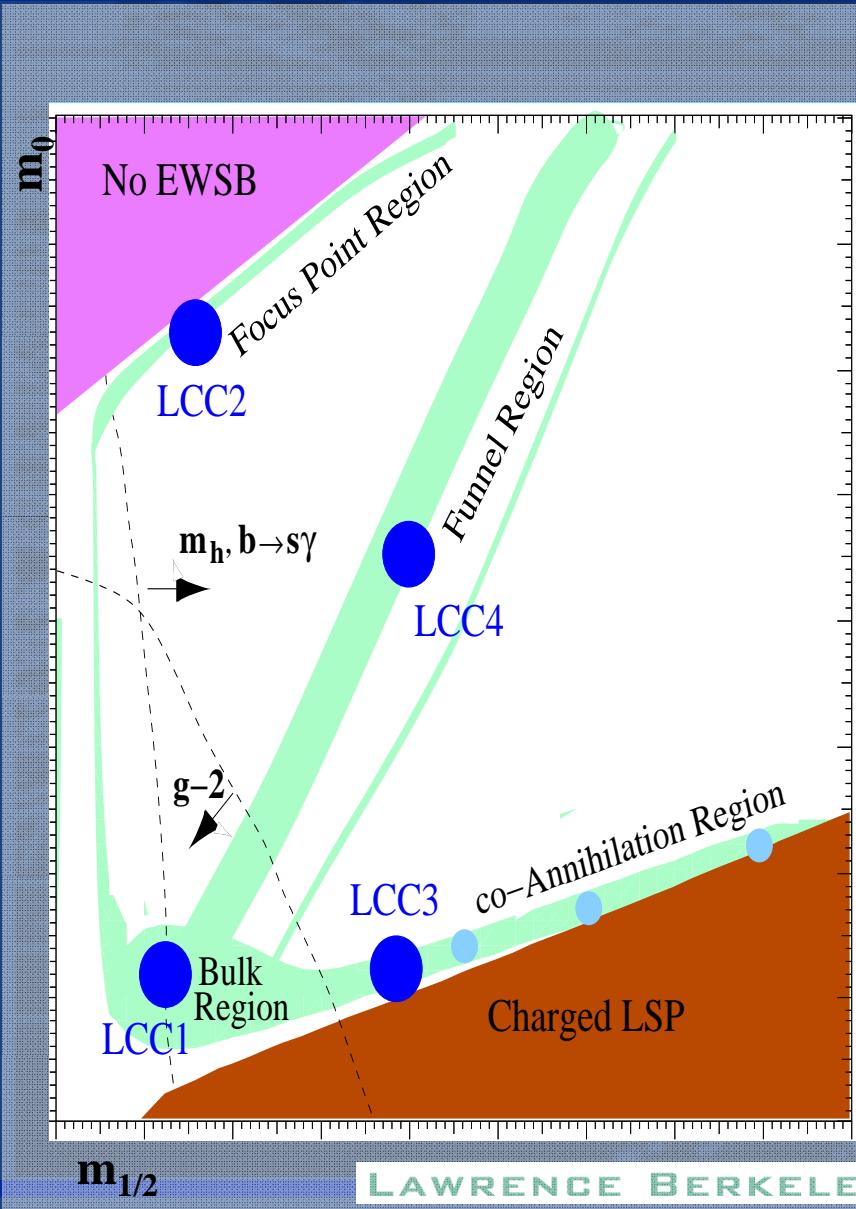
But 1 TeV data highly desirable for extending sensitivity;

Final State	500 GeV	1 TeV
$\tilde{e}_L^+ \tilde{e}_L^-$	9	82
$\tilde{e}_R^+ \tilde{e}_R^-$	15	86
$\tilde{e}_L^\pm \tilde{e}_R^\mp$	2	61
$\tilde{\mu}_L^+ \tilde{\mu}_L^-$	9	82
$\tilde{\mu}_R^+ \tilde{\mu}_R^-$	15	86
Any selectron or smuon	22	137
$\tilde{\tau}_1^+ \tilde{\tau}_1^-$	28	145
$\tilde{\tau}_2^+ \tilde{\tau}_2^-$	1	23
$\tilde{\tau}_1^\pm \tilde{\tau}_2^\mp$	4	61
$\tilde{\nu}_{e\mu} \tilde{\nu}_{e\mu}^*$	11	83
$\tilde{\nu}_\tau \tilde{\nu}_\tau^*$	18	83
$\tilde{\chi}_1^+ \tilde{\chi}_1^-$	53	92
Any charged sparticle	85	224
$\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$	7	33
$\tilde{\chi}_1^0 \tilde{\chi}_1^0$	180	236
$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ only	91	0
$\tilde{\chi}_1^0 + \tilde{\nu}$ only	5	0
$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	46	178
$\tilde{\chi}_1^0 \tilde{\chi}_3^0$	10	83
$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	38	91
$\tilde{\chi}_2^0 \tilde{\chi}_3^0$	4	41
$\tilde{\chi}_3^0 \tilde{\chi}_3^0$	2	23
Nothing	61	3

Probe DM-motivated SUSY



LC $\sqrt{s} = 0.5 \text{ TeV}$ $\tan \beta = 10$



$m_{1/2}$

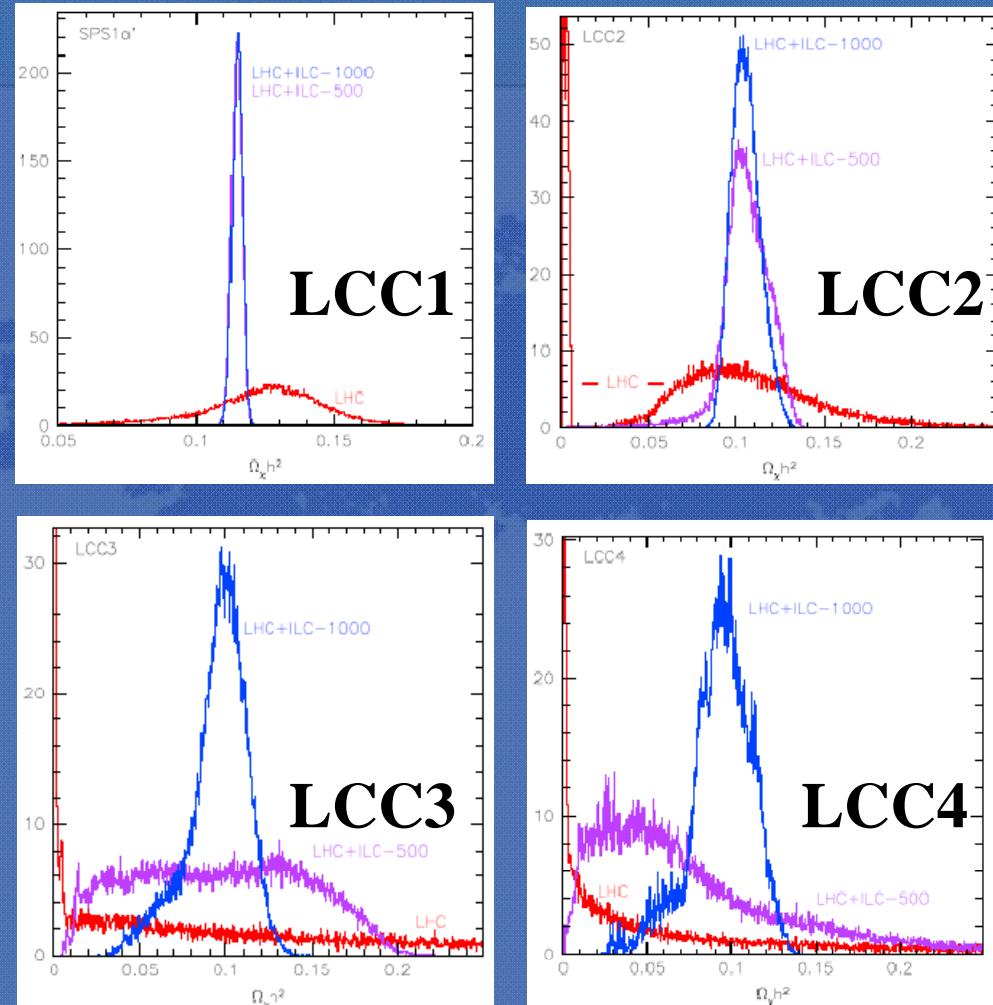
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$m_{1/2}$ (GeV)

Test DM-motivated SUSY



Dark Matter Density



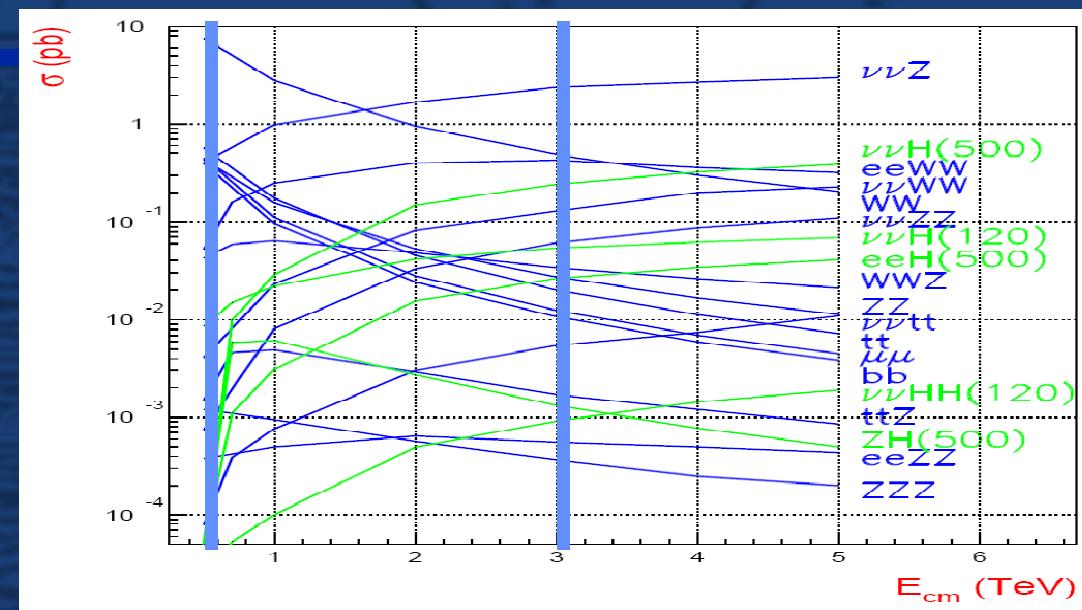
	Ωh^2	LHC	ILC-500	ILC-1000
LCC1	0.192	7.2%	1.8%	0.24%
LCC2	0.109	82.0%	14.0%	7.6%
LCC3	0.101	167%	50.0%	18.0%
LCC4	0.114	405%	85.0%	19.0%
	σv	LHC	ILC-500	ILC-1000
LCC1	0.0121	165.0%	54.0%	11.0%
LCC2	0.547	143.0%	32.0%	8.7%
LCC3	0.109	154.0%	178.0%	10.0%
LCC4	0.475	557.0%	228.0%	20.0%
	$\sigma(\chi p)$	LHC	ILC-500	ILC-1000
LCC1	0.418	44.0%	45.0%	5.7%
LCC2	1.866	62.0%	63.0%	22.0%
LCC3	0.925	184.0%	146.0%	8.6%
LCC4	1.046	150.0%	190.0%	7.5%

Baltz, MB, Peskin, Wiszanski, Phys Rev D74 (2006)

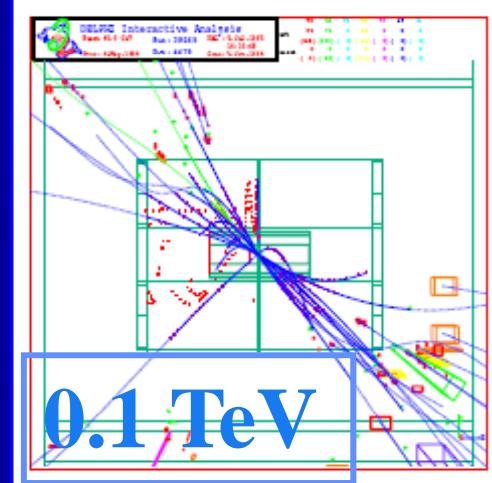
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How is physics changing from 0.2 to 3 TeV ?

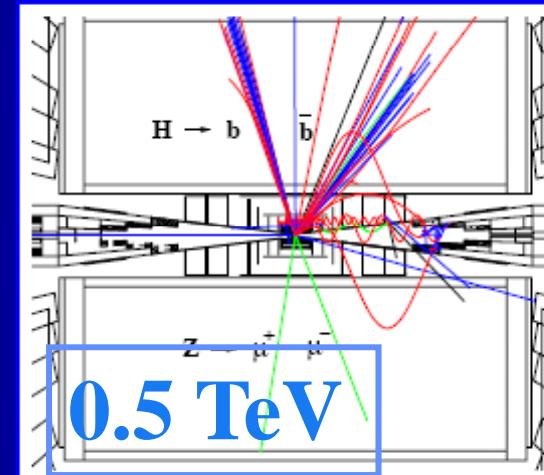
$\sigma(\text{pb})$ for
SM Processes
vs. E_{cm} (TeV)



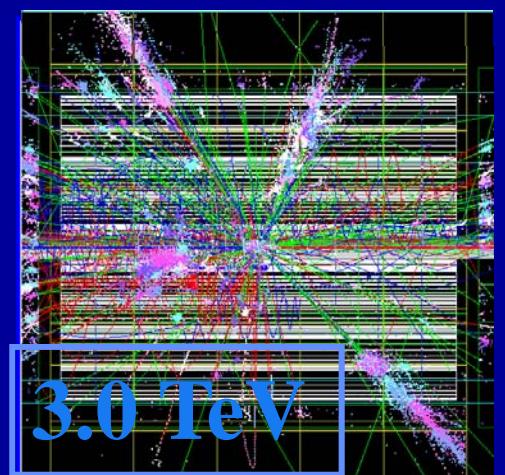
$e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$



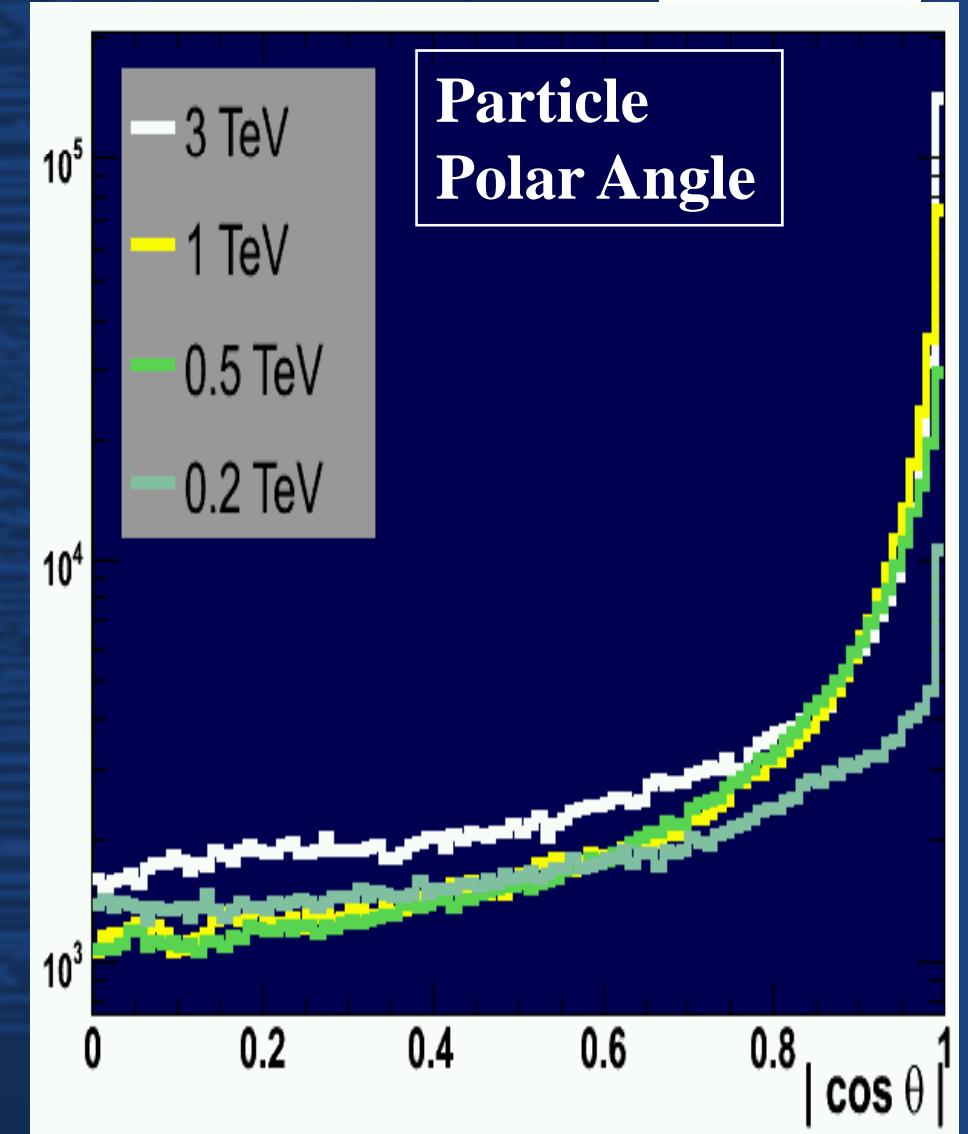
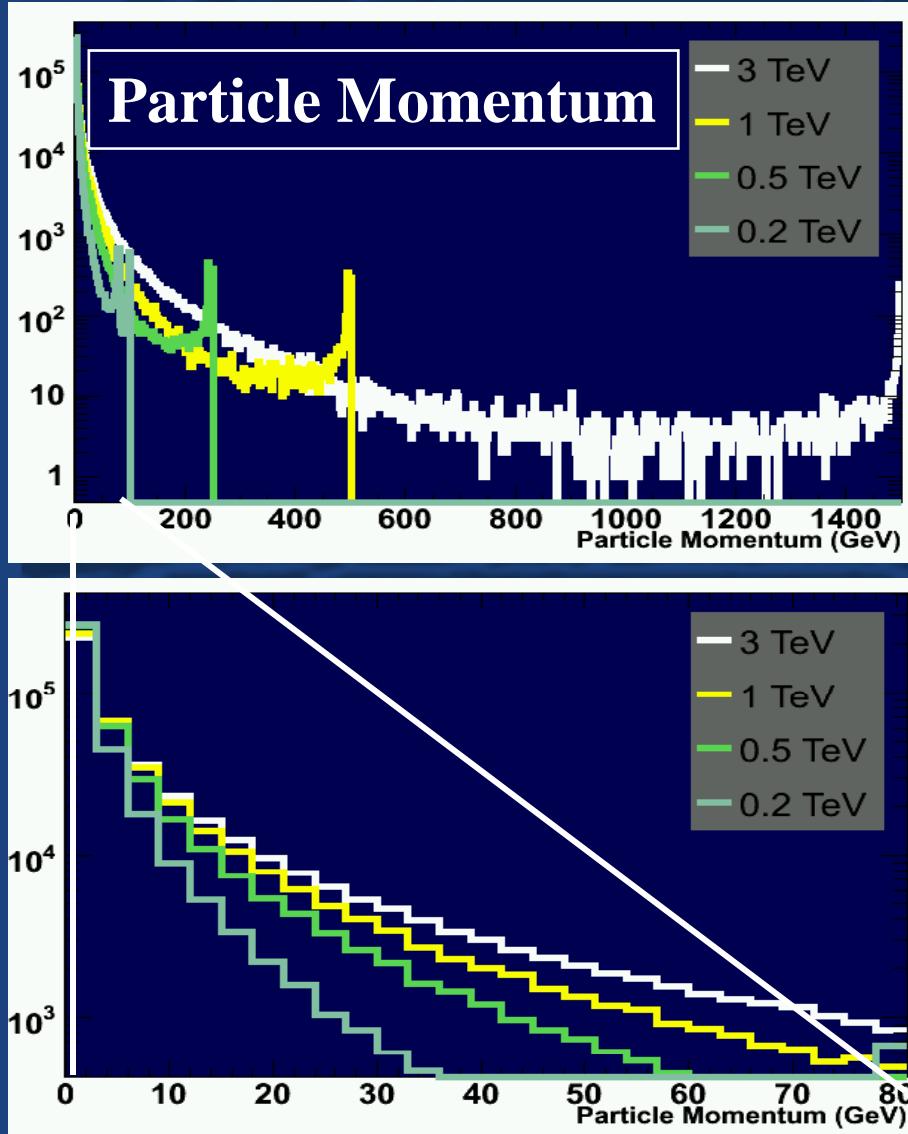
$e^+e^- \rightarrow Z^0 H^0 \rightarrow \mu^+\mu^- b\bar{b}$



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



Observables from 0.2 TeV to 3 TeV (SM Evt)



Observables from 0.2 TeV to 3 TeV (SM Evt)



Jet Multiplicity

\sqrt{s} (TeV)	0.09	0.20	0.5	0.8	3.0	5.0
$\langle N_{Jets} \rangle$	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

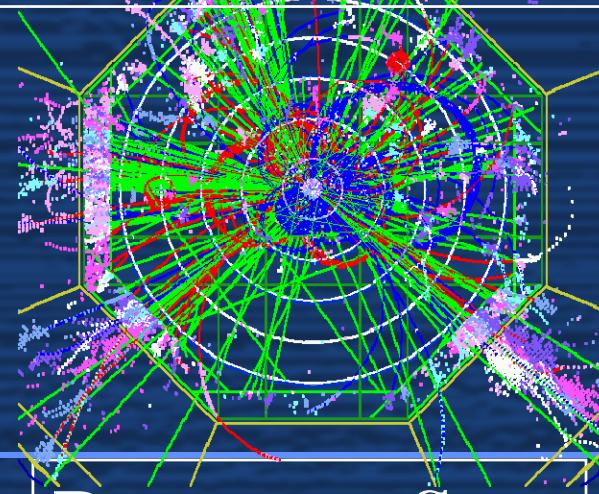
B Hadron Decay Distance

\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

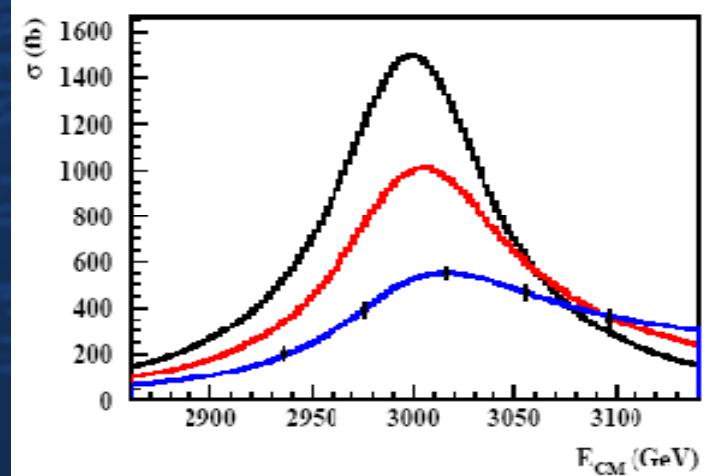
Physics Signatures at multi-TeV



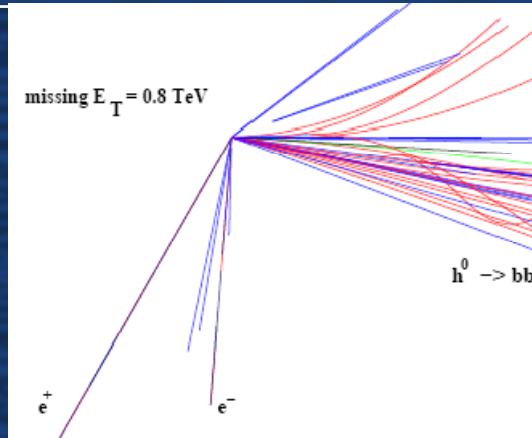
Multi-Jet Final States



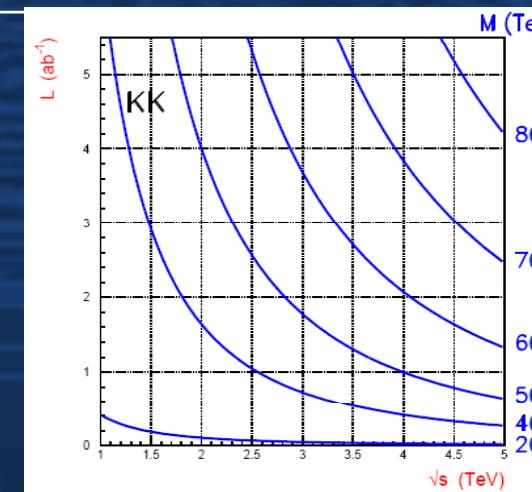
Resonance Scan



Missing Energy Final States



Electro-Weak Fits

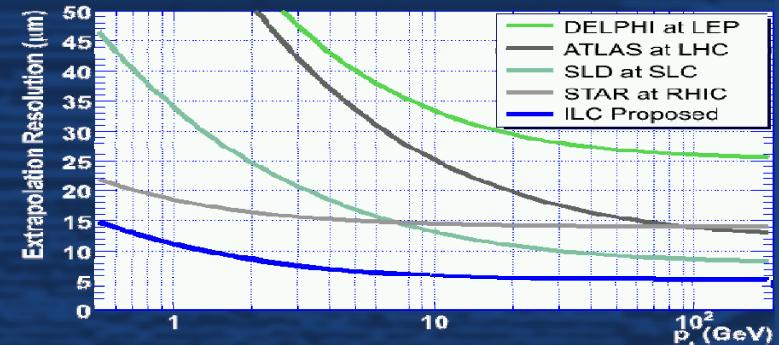


Event Reconstruction: The LEP&ILC Paradigm



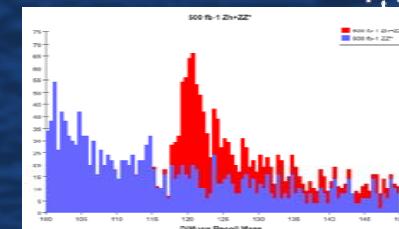
$\sigma(\text{IP})$

Vertex of origin determined by
accurate extrapolation inside beam pipe;



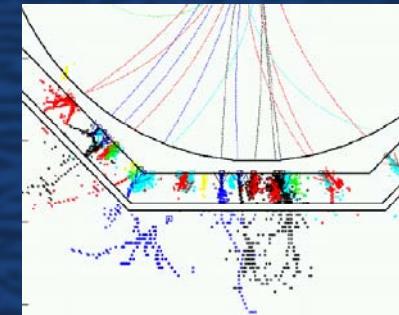
$\delta p/p^2$

Momentum resolution of paramount importance;



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

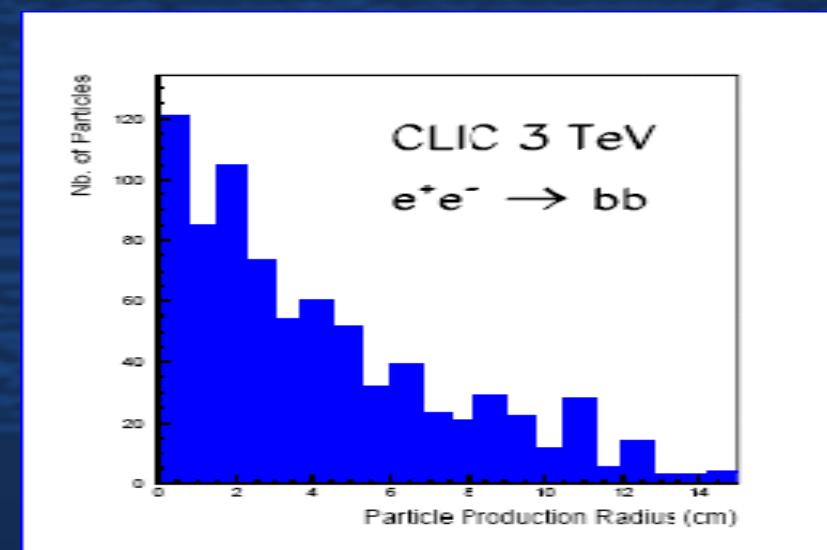
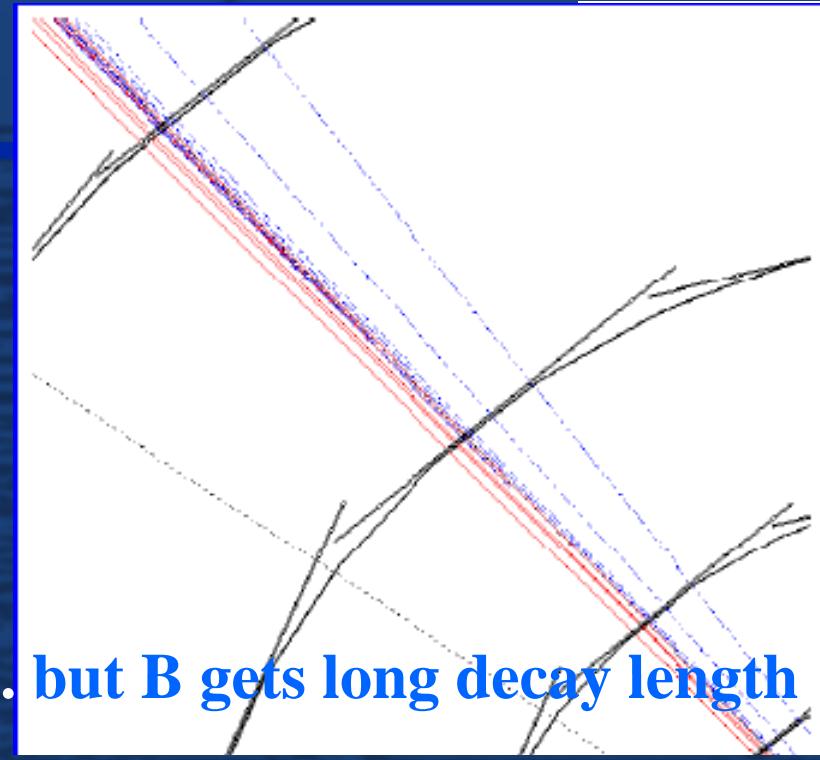
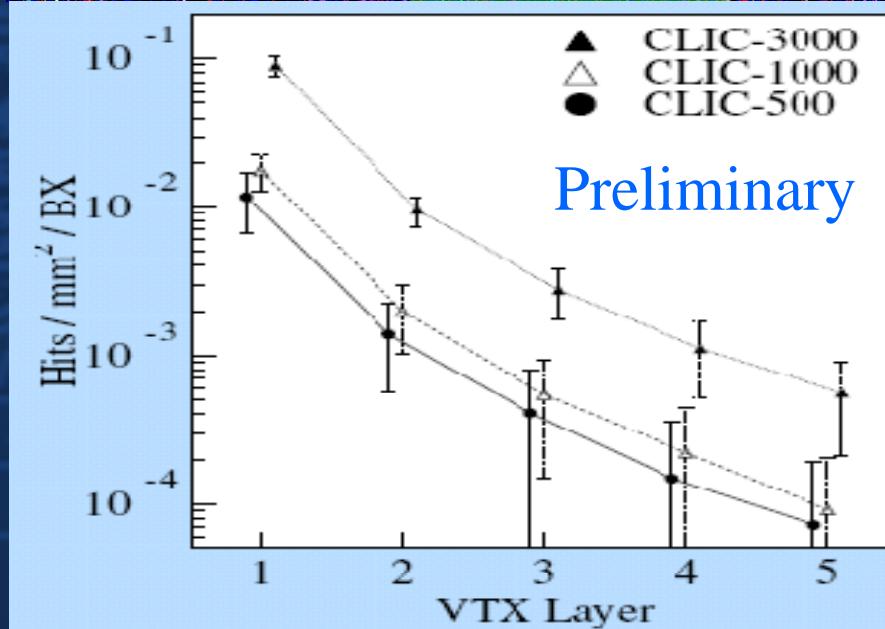
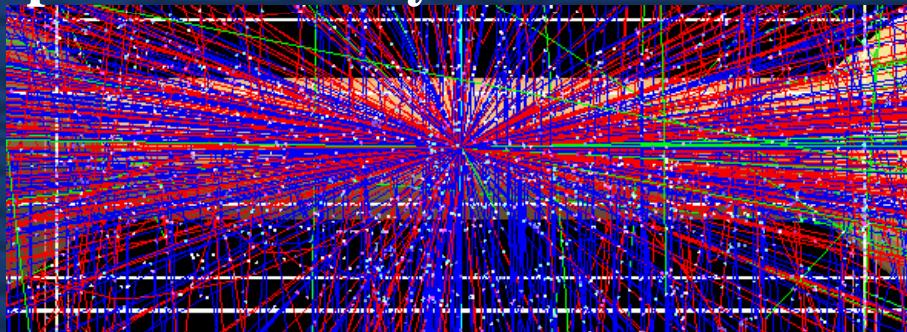
Parton energy determined through particle flow
reconstruction;



Now study scaling and applicability at 1 TeV and beyond and exploit results of ILD R&D to guide design of possible detector for multi-TeV collisions.

Vertex ID at multi-TeV

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



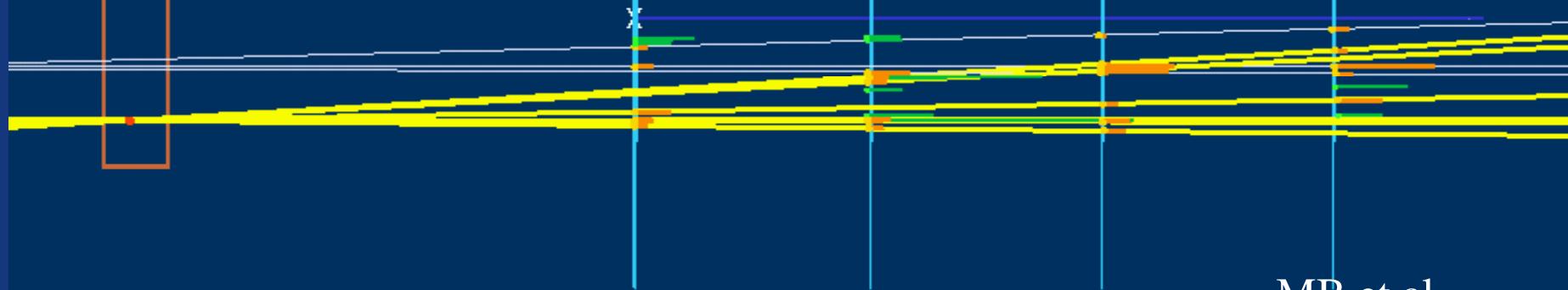
Tracking & Vertexing: Beam Test Validation



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: $\sigma_z \text{ v}_{tx} = 230 \mu\text{m}$



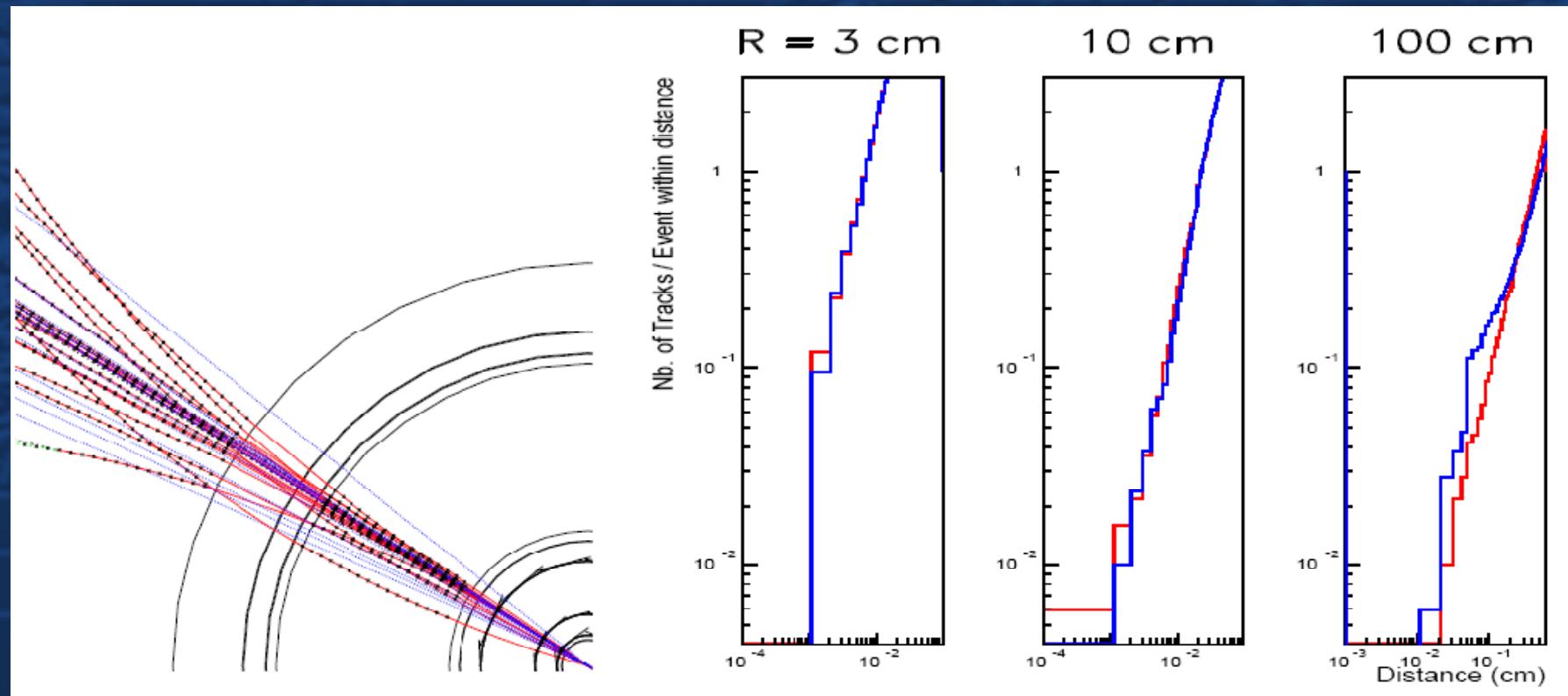
MB et al,
LAWRENCE BERKELEY NATIONAL LABORATORY NIM A593 (2008)

Tracker at multi-TeV



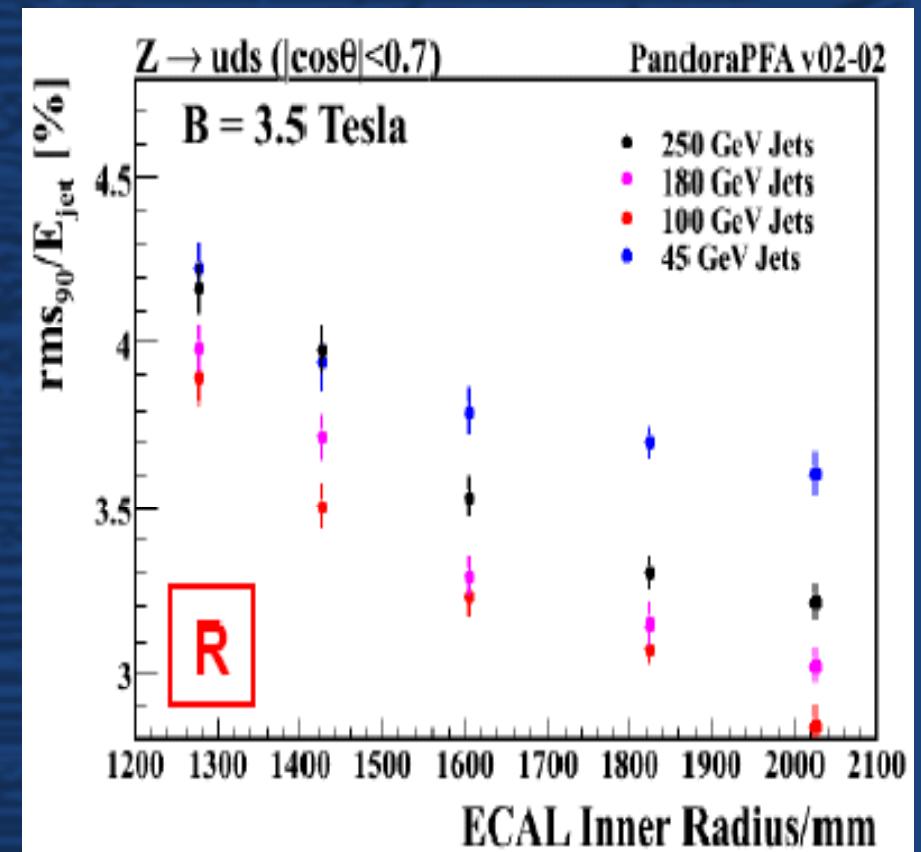
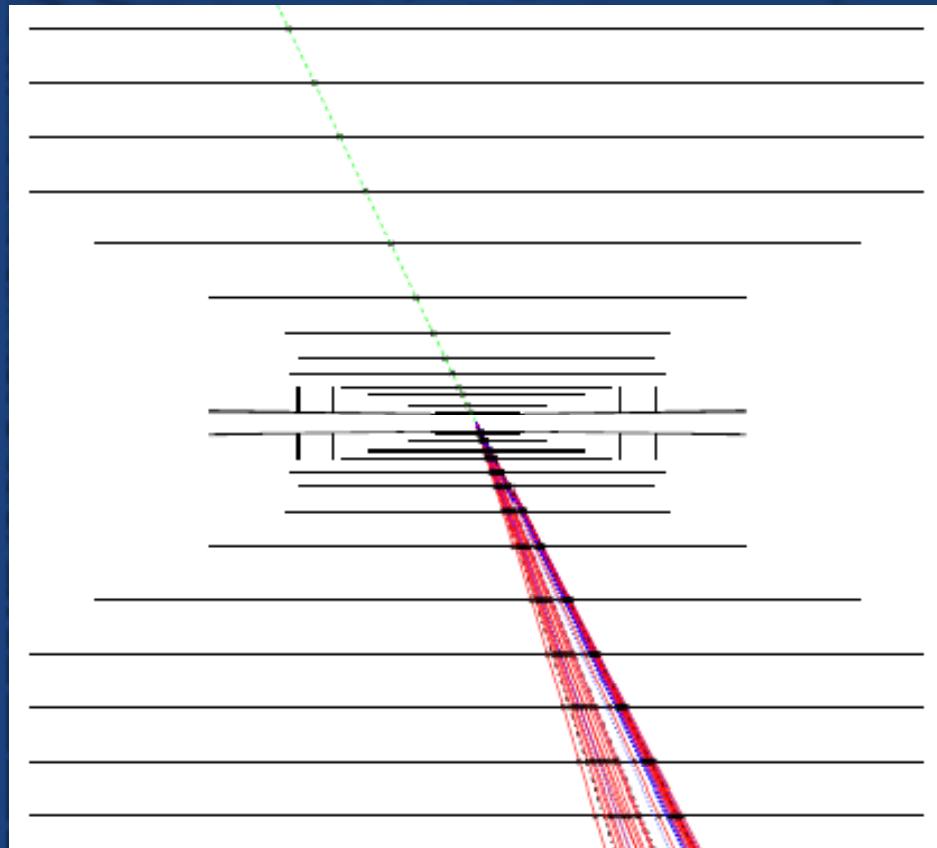
Significant track density in collimated hadronic jets + parallel muon bkg, $\gamma\gamma \rightarrow$ hadrons and low momentum spiralling tracks:

Minimum Distance between Tracks in Hadronic Events at 3 TeV





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



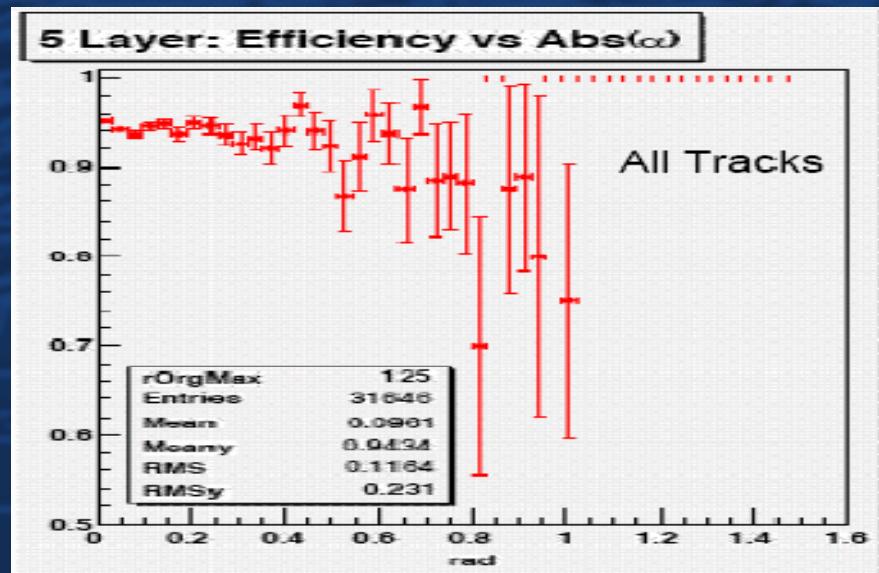
Discrete Si tracker adopted as baseline but detailed study is now needed.
MB, A Frey LAWRENCE BERKELEY NATIONAL LABORATORY M Thomson



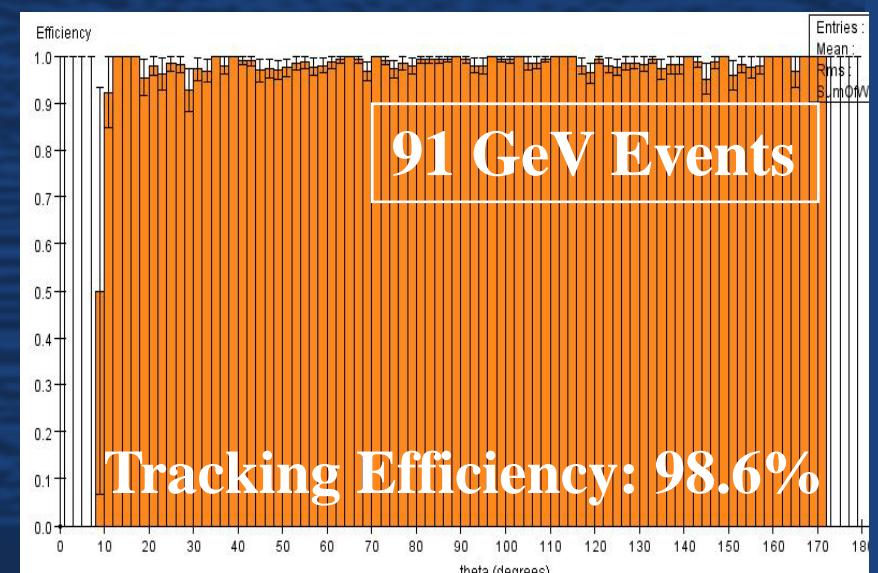
Need to assess tracking capability of SiD-like detector at CLIC:

Encouraging results on tracking performance of five-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



Tracking Efficiency vs Polar Angle



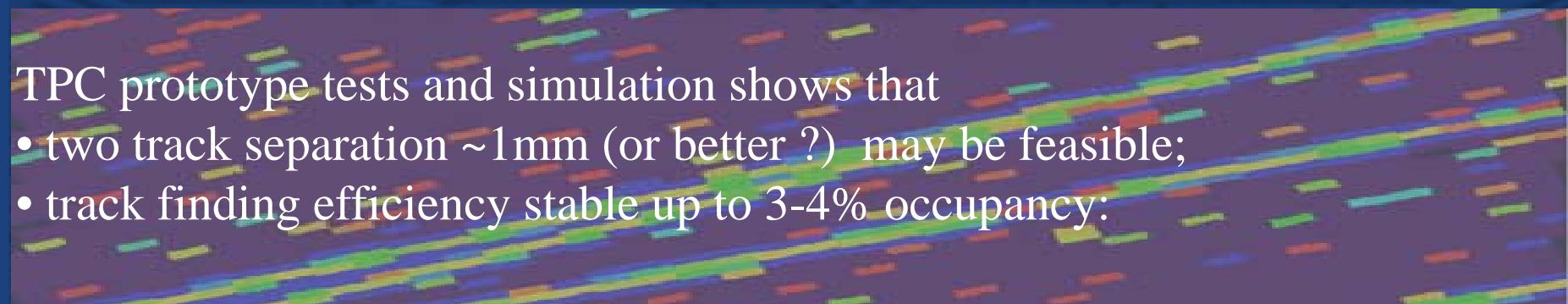
Partridge,
BILCW07

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Partridge,
SiD08

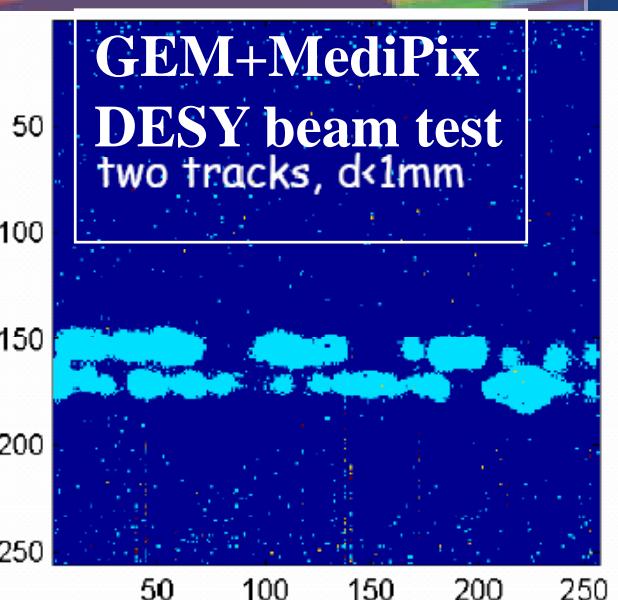
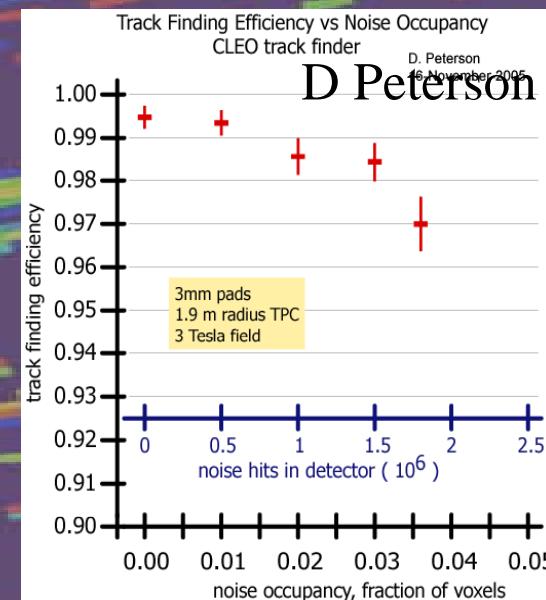
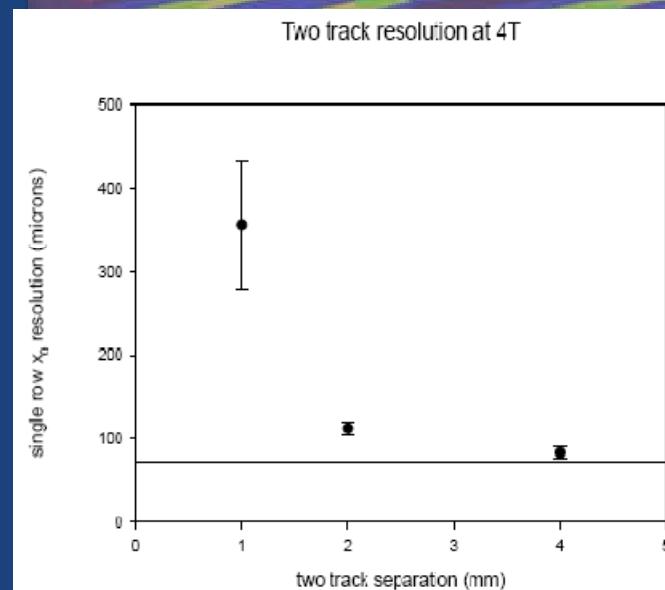


Essential to evaluate performance of 3D continuous tracker (TPC)
offering redundancy in patrec and dE/dx info;

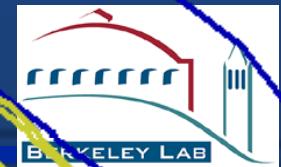


TPC prototype tests and simulation shows that

- two track separation $\sim 1\text{mm}$ (or better ?) may be feasible;
- track finding efficiency stable up to 3-4% occupancy:

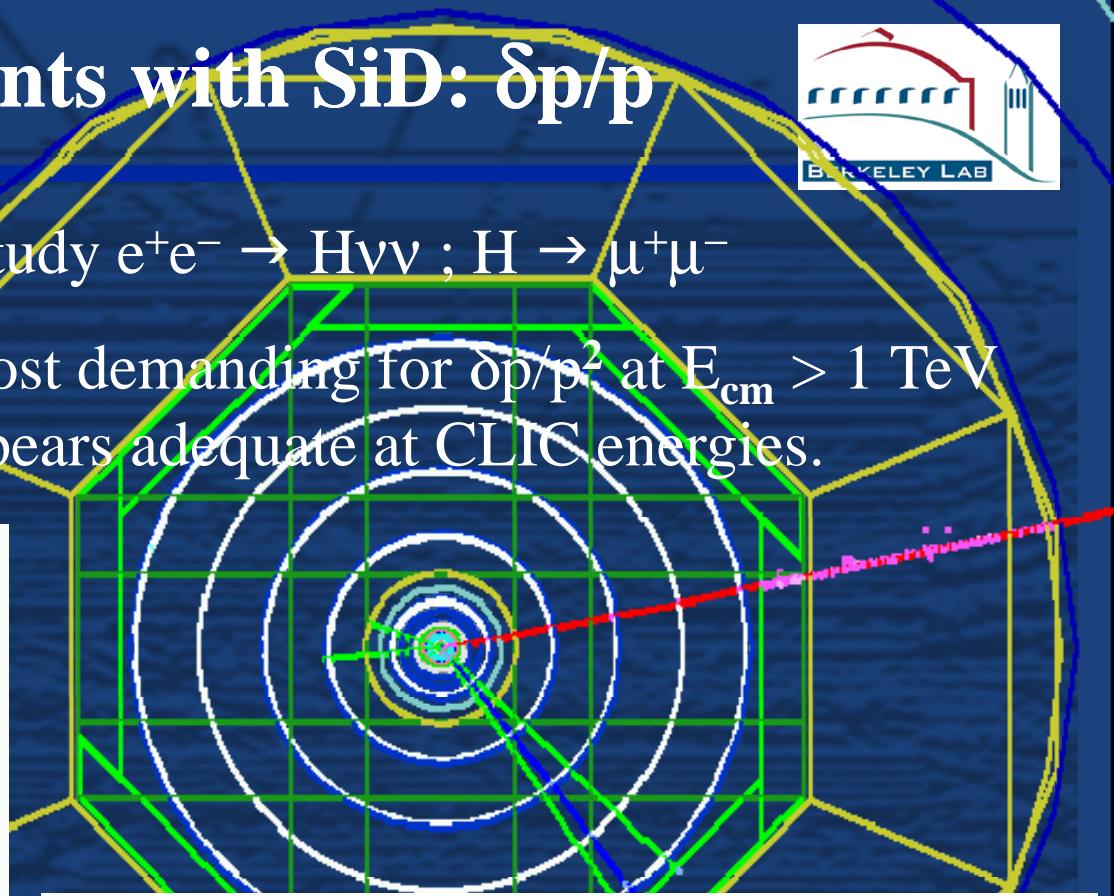
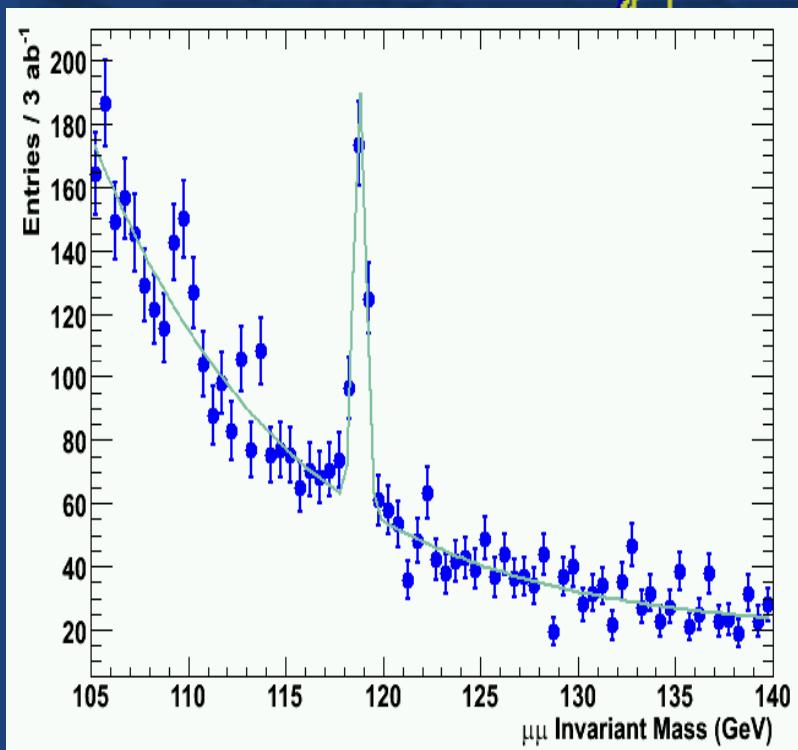


Analysing 3 TeV Events with SiD: $\delta p/p$



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

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	

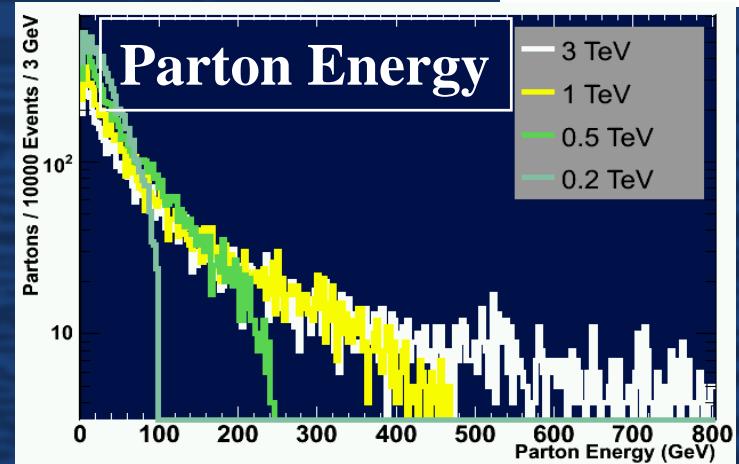
MB, J. Phys.G 35

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Particle Flow

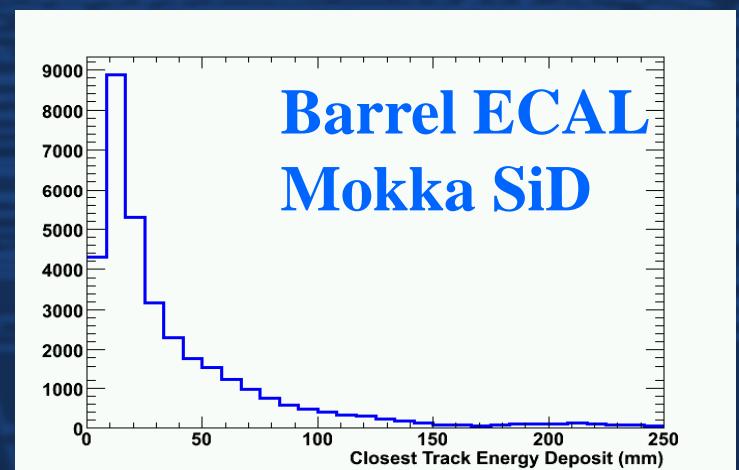
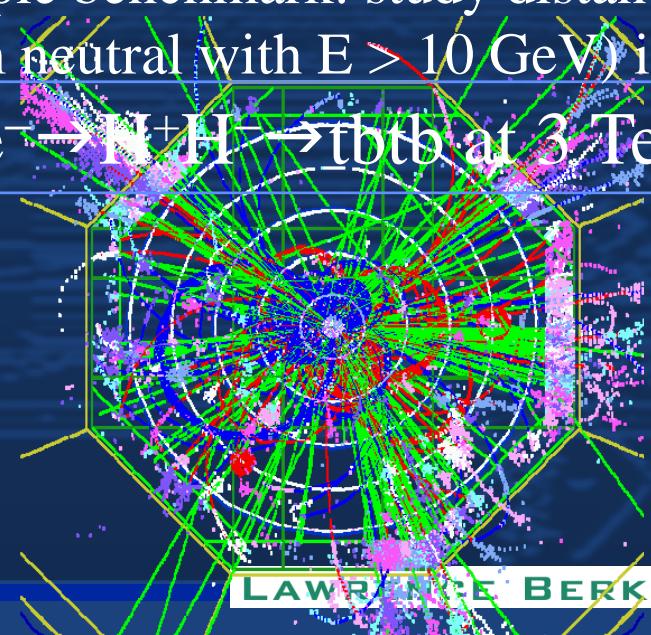
Is Particle Flow applicable
to multi-TeV collisions ?

PFA gives unprecedented performance for
 $E_{\text{jet}} \sim 100 \text{ GeV}$, at multi-TeV N_{jet} also grows
 $\rightarrow E_{\text{jet}}$ does not scale proportional to E_{cm}



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

$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{t}b\bar{b}$ at 3 TeV

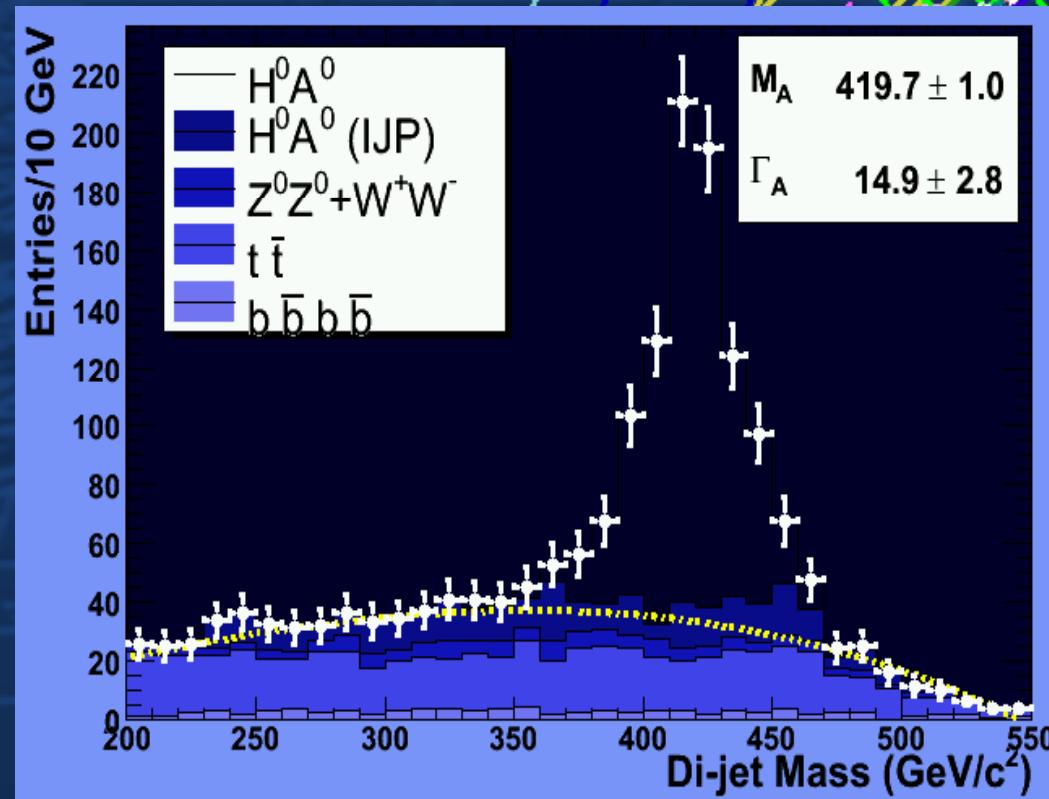


Analysing 1 TeV Events with LDC



Use LDC model at 1 TeV to study $e^+e^- \rightarrow HA \rightarrow bbbb$

Establish SUSY DM in A funnel region through precision measurement of M_A , Γ_A and $A_{\tau\tau}$



MB et al

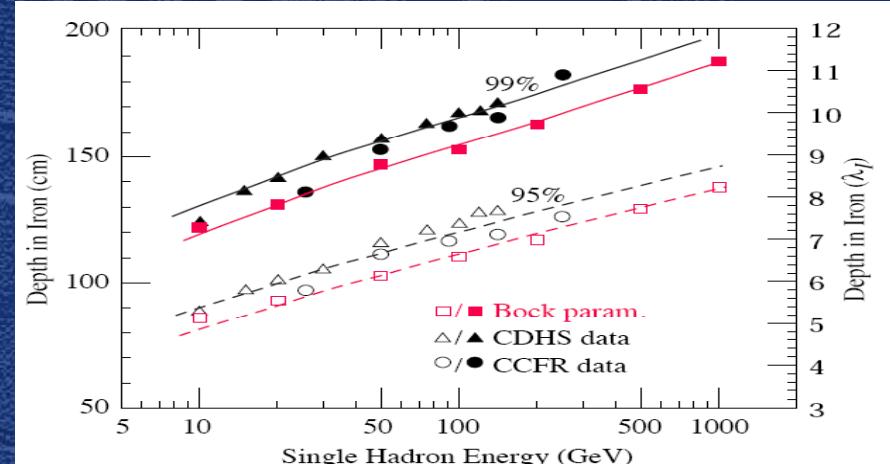
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Calorimetry at multi-TeV

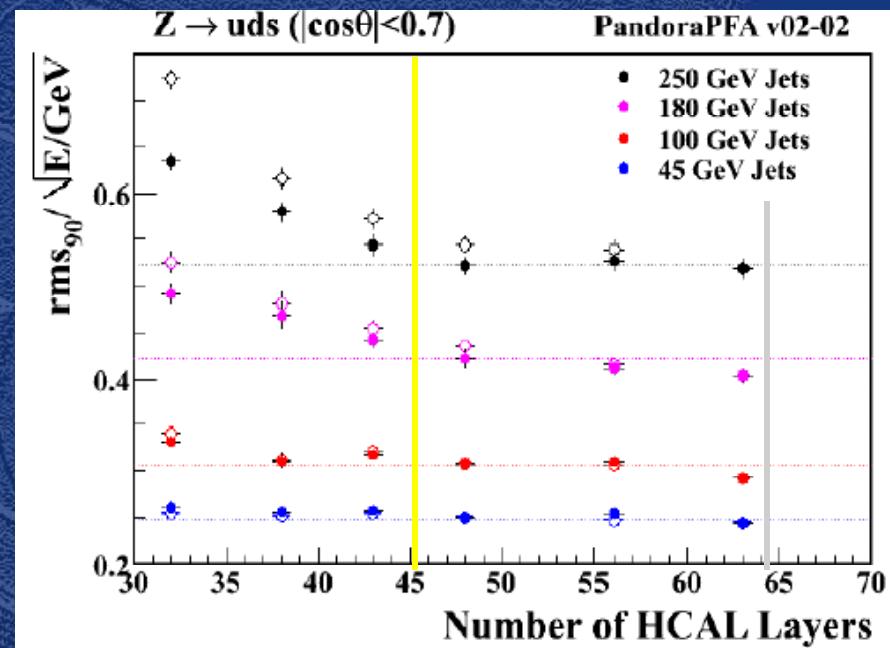
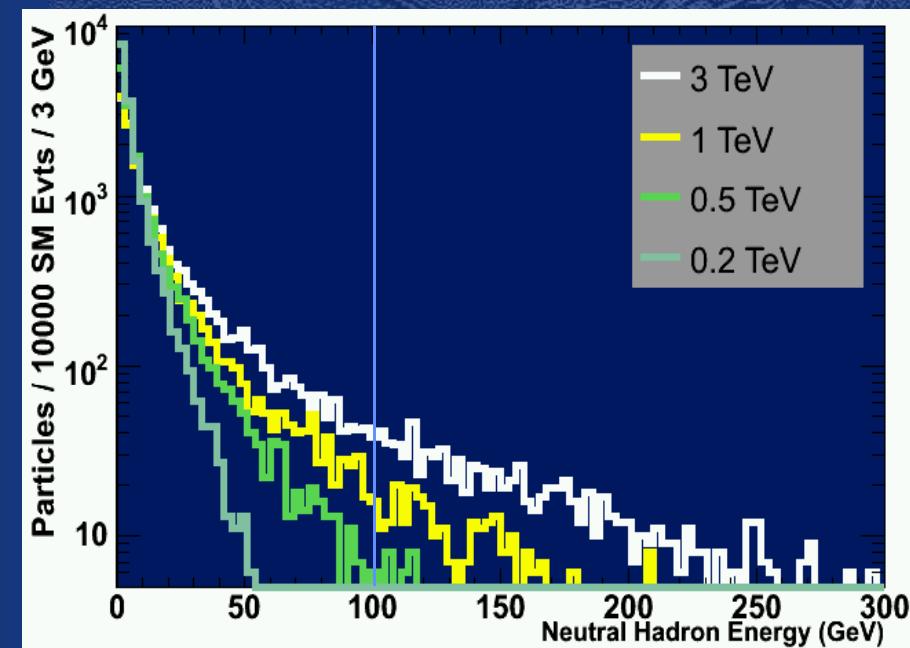


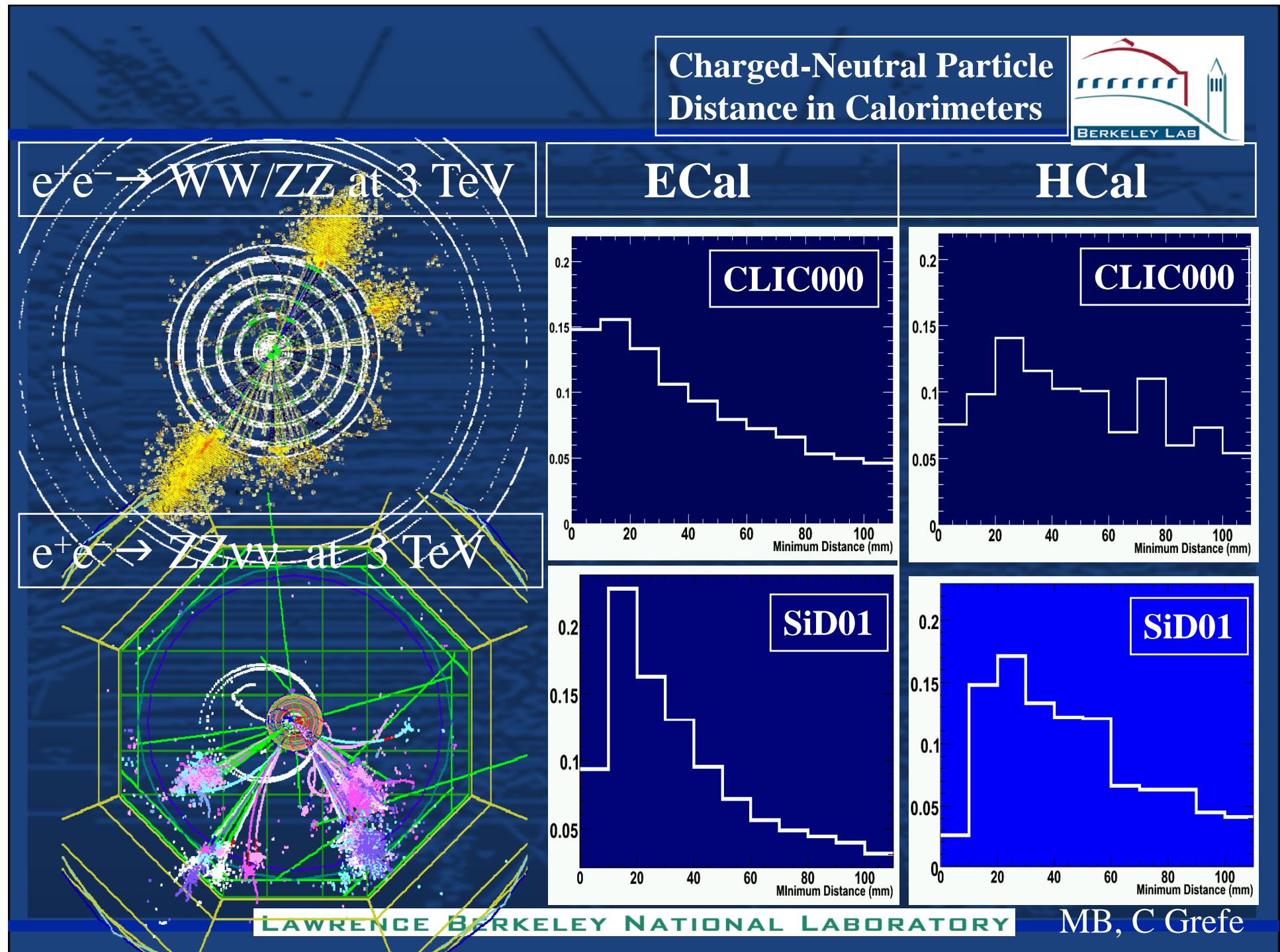
Scale depth of HCAL

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



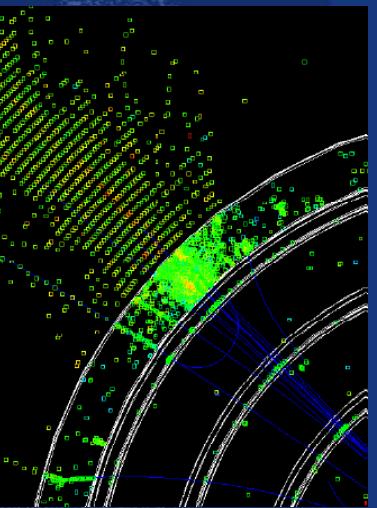
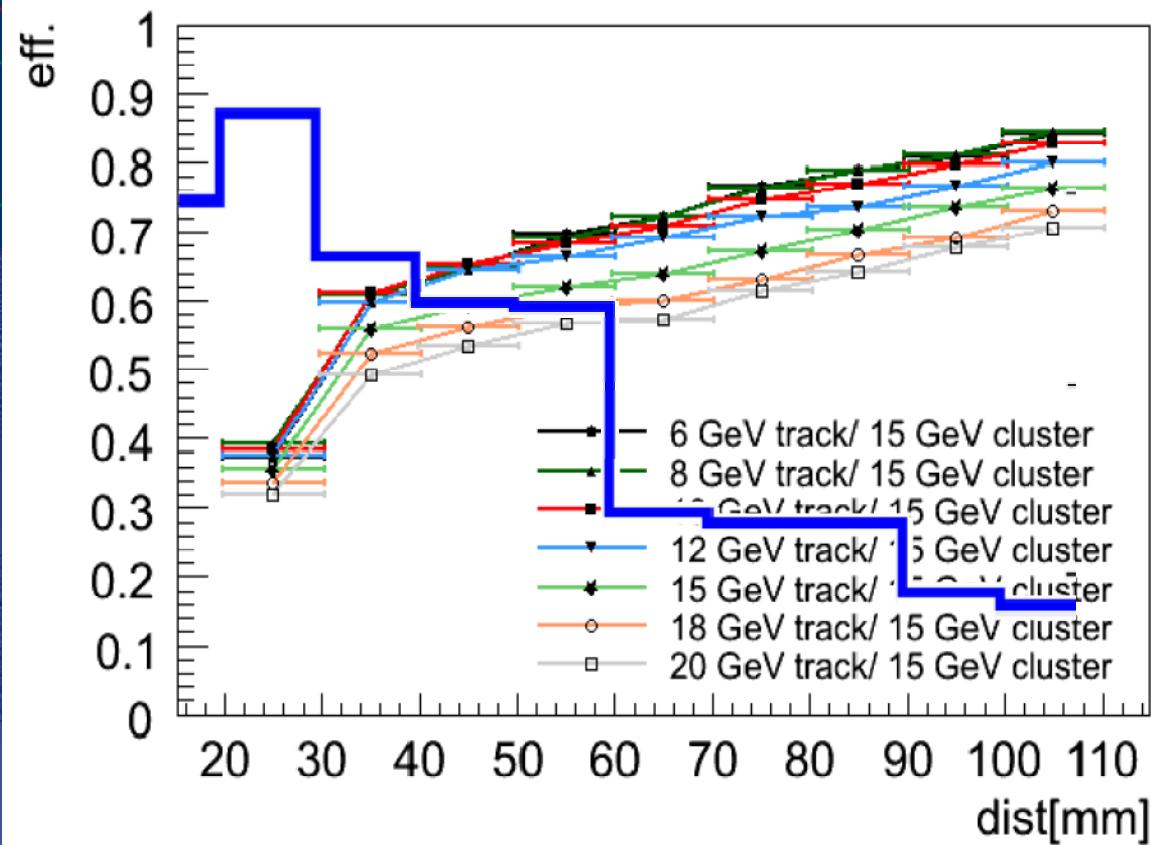
Neutral Hadron Energy at 3 TeV







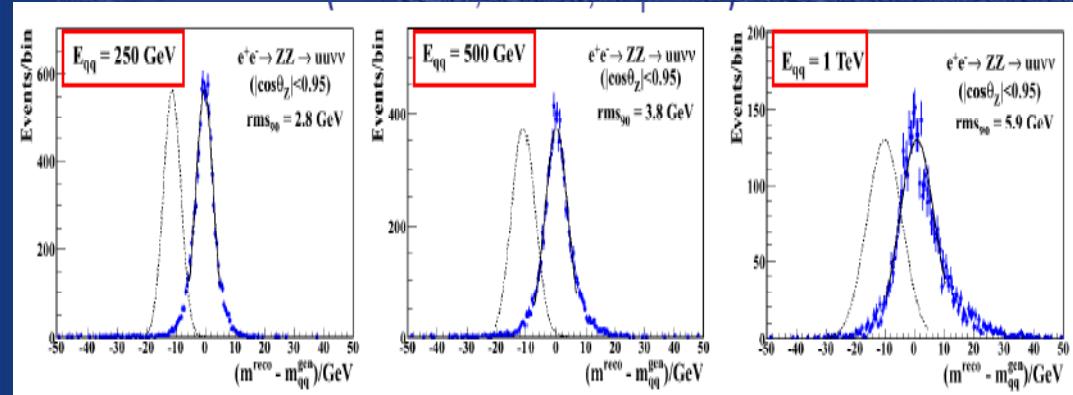
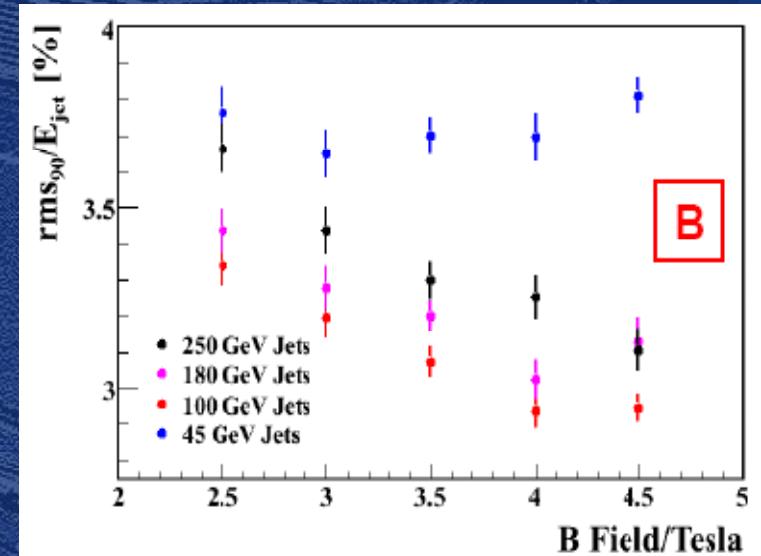
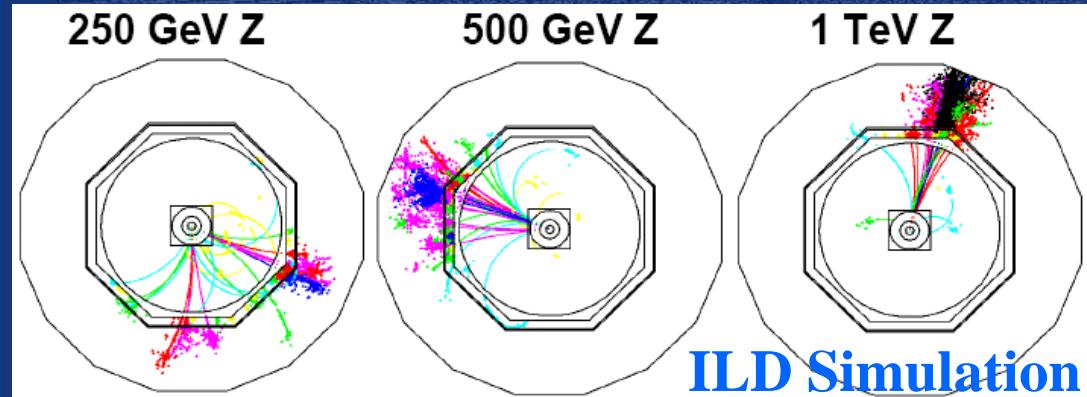
Track - Shower separation: CALICE data – CLIC Simulation



CALICE Data
D Ward
CLIC G4 ZZvv
MB



Multi-TeV collisions push limits of Particle Flow calorimetry;
much depends of physics programs;

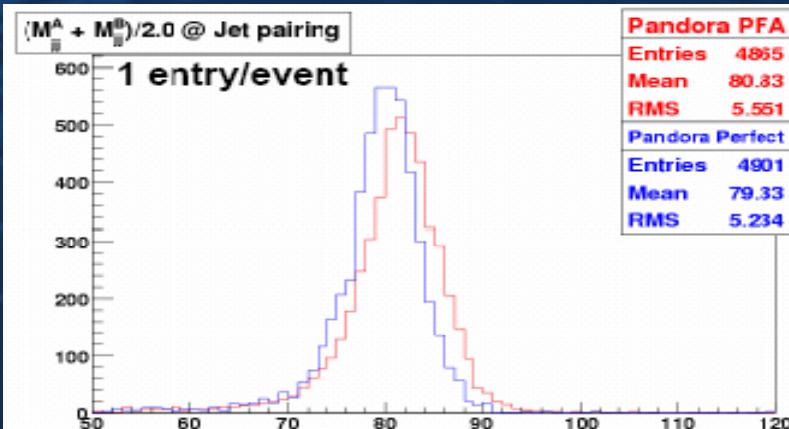
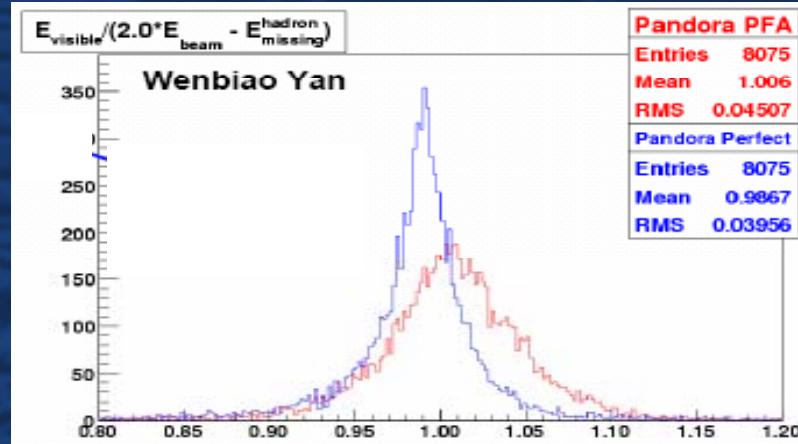


Particle Flow calorimetry not *a priori* obvious for multi-TeV events but possible to get good performance tuning HCAL depth, Tracker Outer radius, B field and by optimising PFA

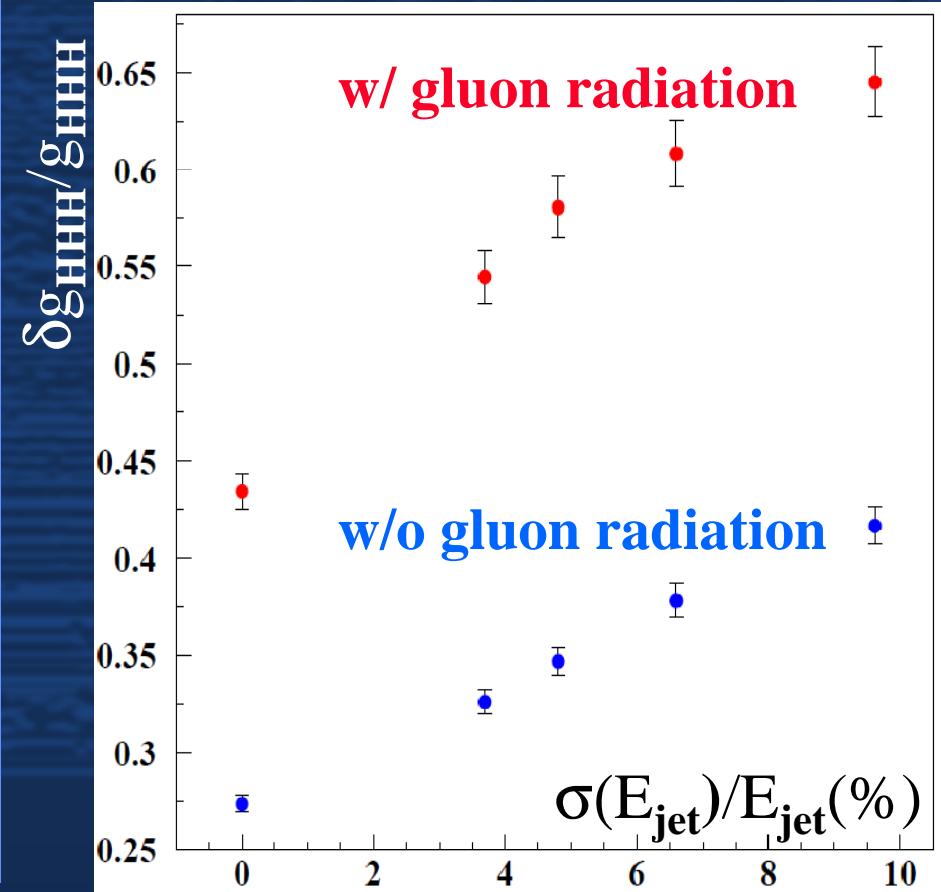


Event reco, Jet clustering and gluon radiation affect physics reconstruction performances beyond particle flow response:

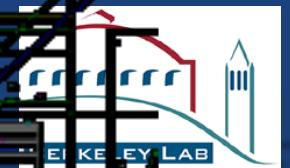
$e^+e^- \rightarrow WWvv$ at 0.8 TeV



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



Towards 1 TeV and beyond



TeV, and possibly multi-TeV, e+e- collisions promise to extend the Linear Collider analytical power to, and beyond, the LHC mass range

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

After LoI's opportunity to fully benchmark ILD detector concepts at 1 TeV and contribute to CLIC study to outline physics potential of multi-TeV collisions and feasibility of accelerator and detector techniques.