Detector Design and R&D for the Next Generation of $e^+ e^-$ Colliders

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Physics Requirements and Experimental Conditions

Vertexing and Tracking

Calorimetry at a Future Electron-Positron Collider

Detector Design for a Future Electron Positron Collider

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Physics Requirements and Experimental Conditions

Detectors at a future e^+e^- collider will face different challenges compared to those at LEP and LHC. The distinctive feature of LC physics is precision for a large variety of measurements (spectroscopy, searches, rare decays, EW observables, …) to be performed over a broad energy range (~0.25 TeV – 3 TeV);

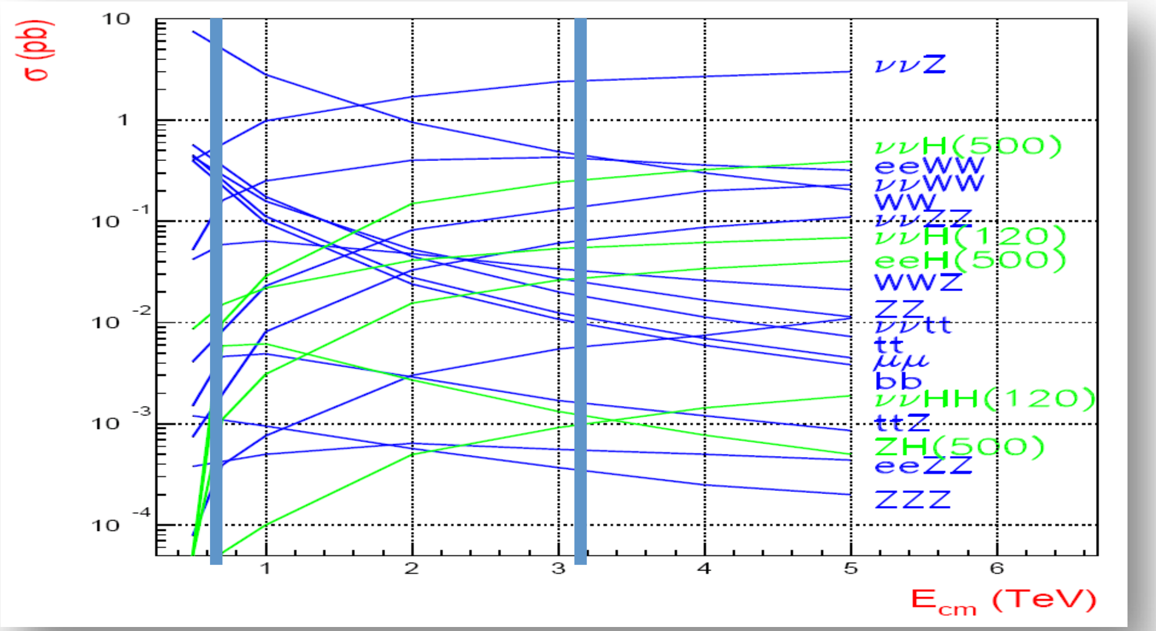
Background fluxes are lower compared to LHC and novel detector technologies and event reconstruction techniques can be exploited;

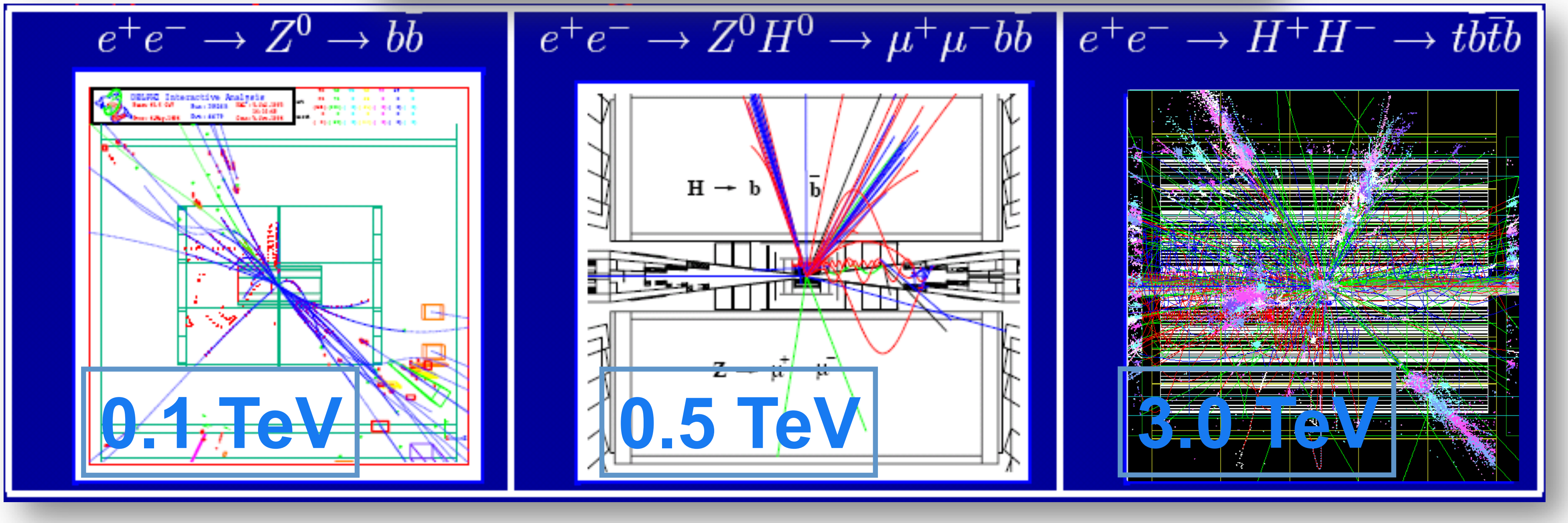
Main paths of LC-directed R&D towards detectors which have substantially lower material budget and higher (space or space-time) granularity compared to those developed for the LHC;

Sensor R&D motivated by ILC program has already found important applications in other HEP projects and fields of science outside accelerator particle physics;

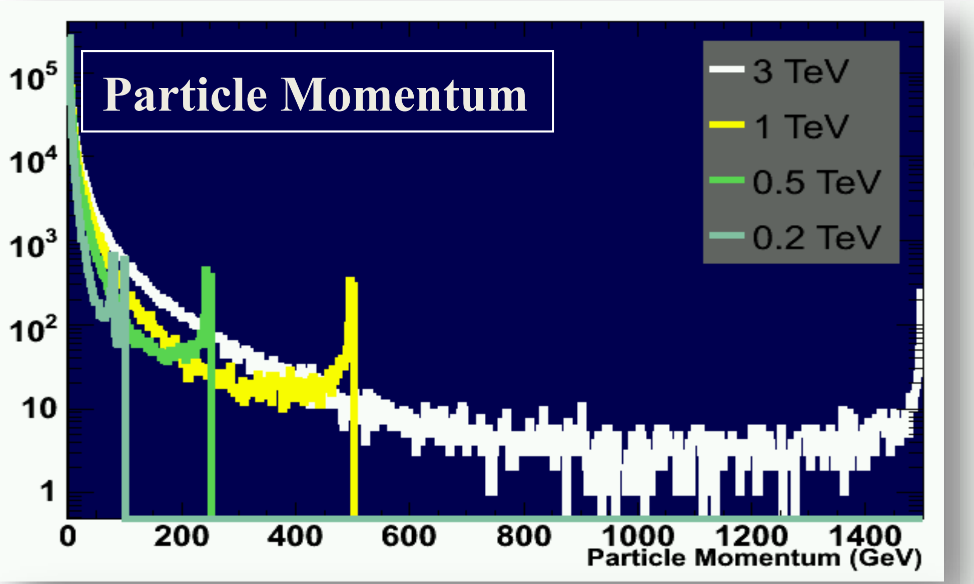
How is physics changing from 0.2 to 3.0 TeV ?

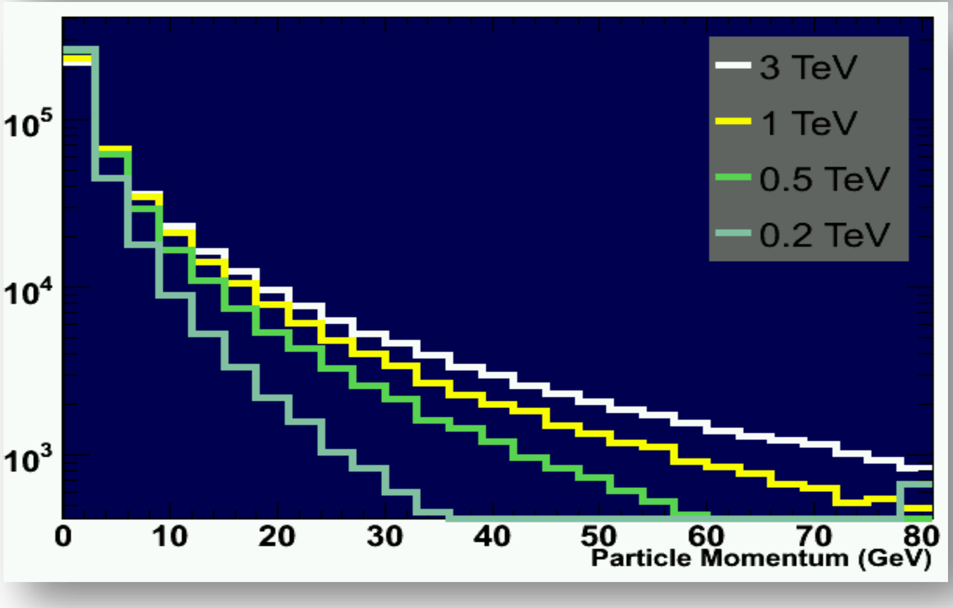
σ(pb) for
SM Processes
vs. E_{cm} (TeV)

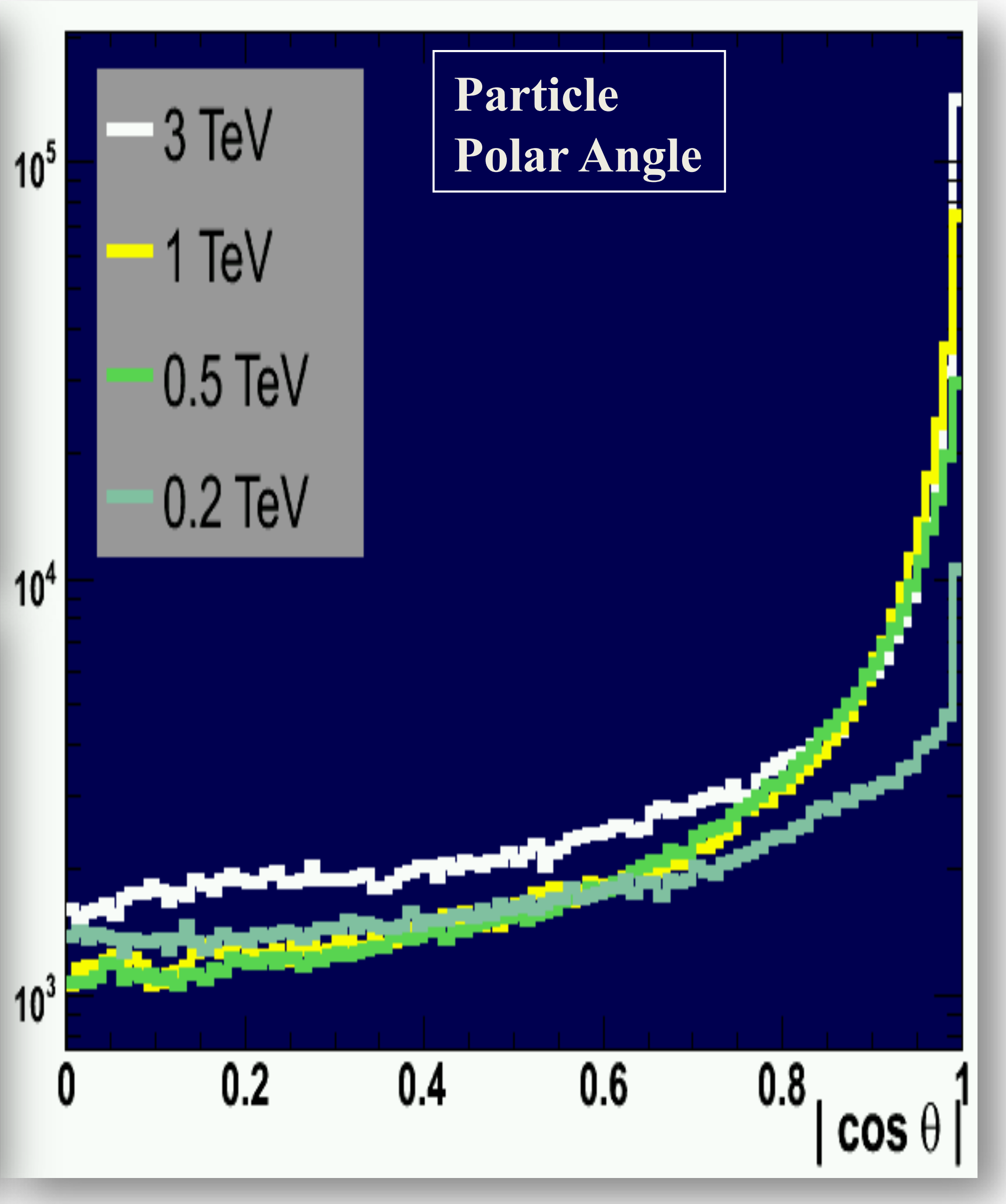




Observables from 0.2 TeV to 3 TeV (SM Evts)

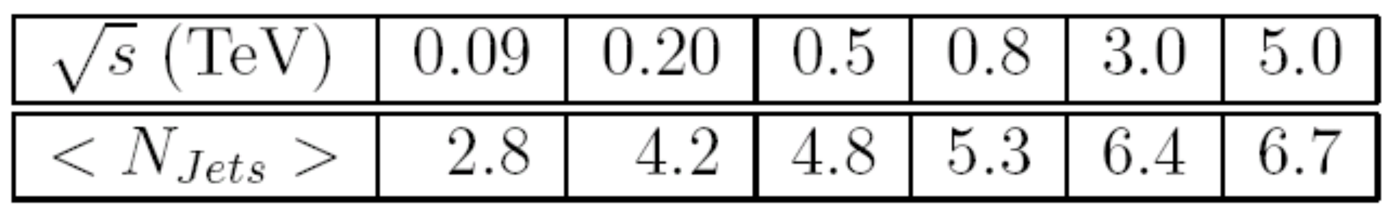






Observables from 0.2 TeV to 3 TeV (SM Evts)

Jet Multiplicity

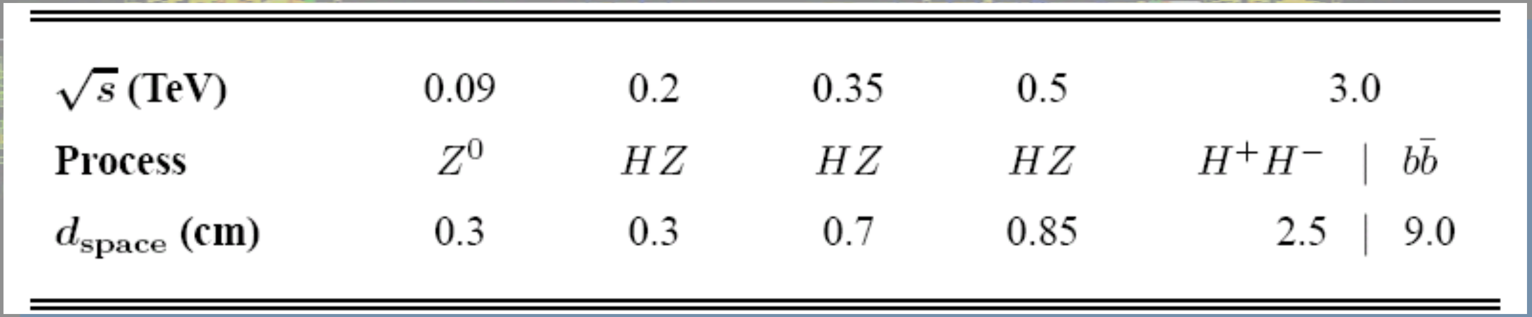


$\sqrt{s}$ (TeV)	0.09	0.20	0.5	0.8	3.0	5.0
$< N_{Jets} >$	2.8	4.2	4.8	5.3	6.4	6.7

Parton Energy

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

B Hadron Decay Distance

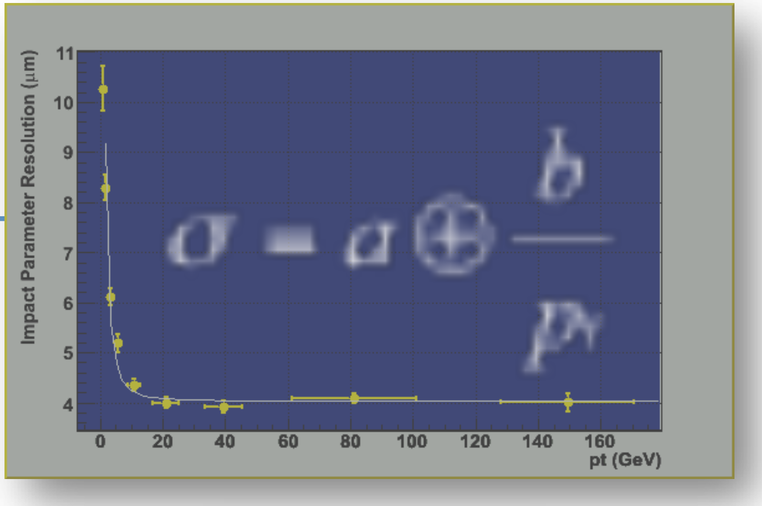


$\sqrt{s}$ (TeV)	0.09	0.2	0.35	0.5	3.0	
Process	Z^0	HZ	HZ	HZ	H^+H^-	$b\bar{b}$
d_{space} (cm)	0.3	0.3	0.7	0.85	2.5	9.0

MB, hep-ph/0103338

Requirements for a LC Vertex Tracker

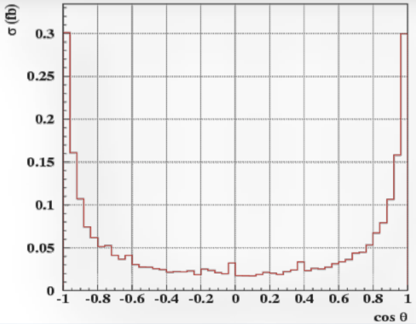
Asymptotic
I.P. Resolution [*a*]



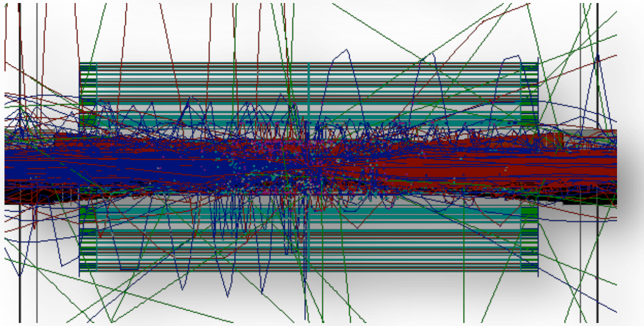
Multiple Scattering

I.P. Term [*b*]

Polar Angle Coverage



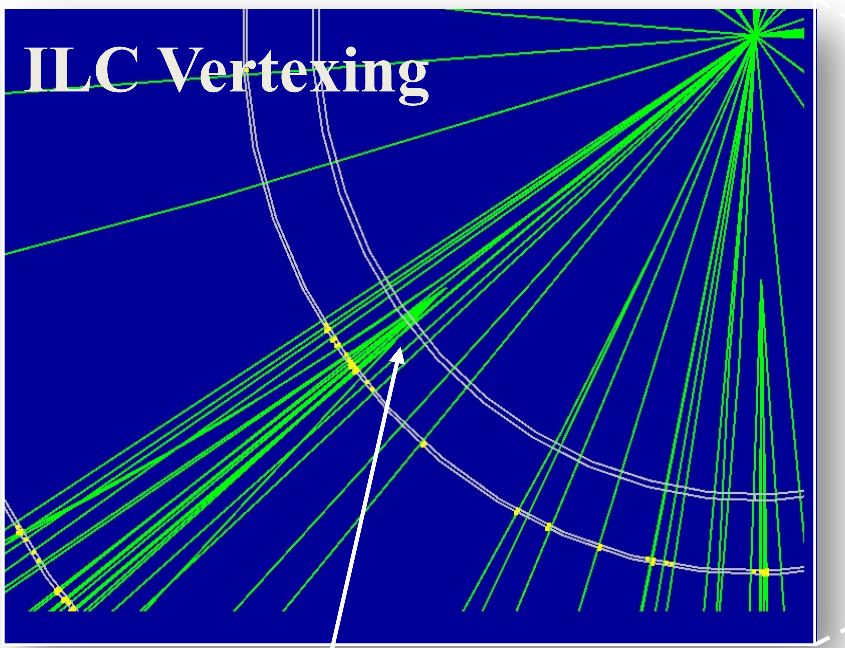
Space - Time
Granularity



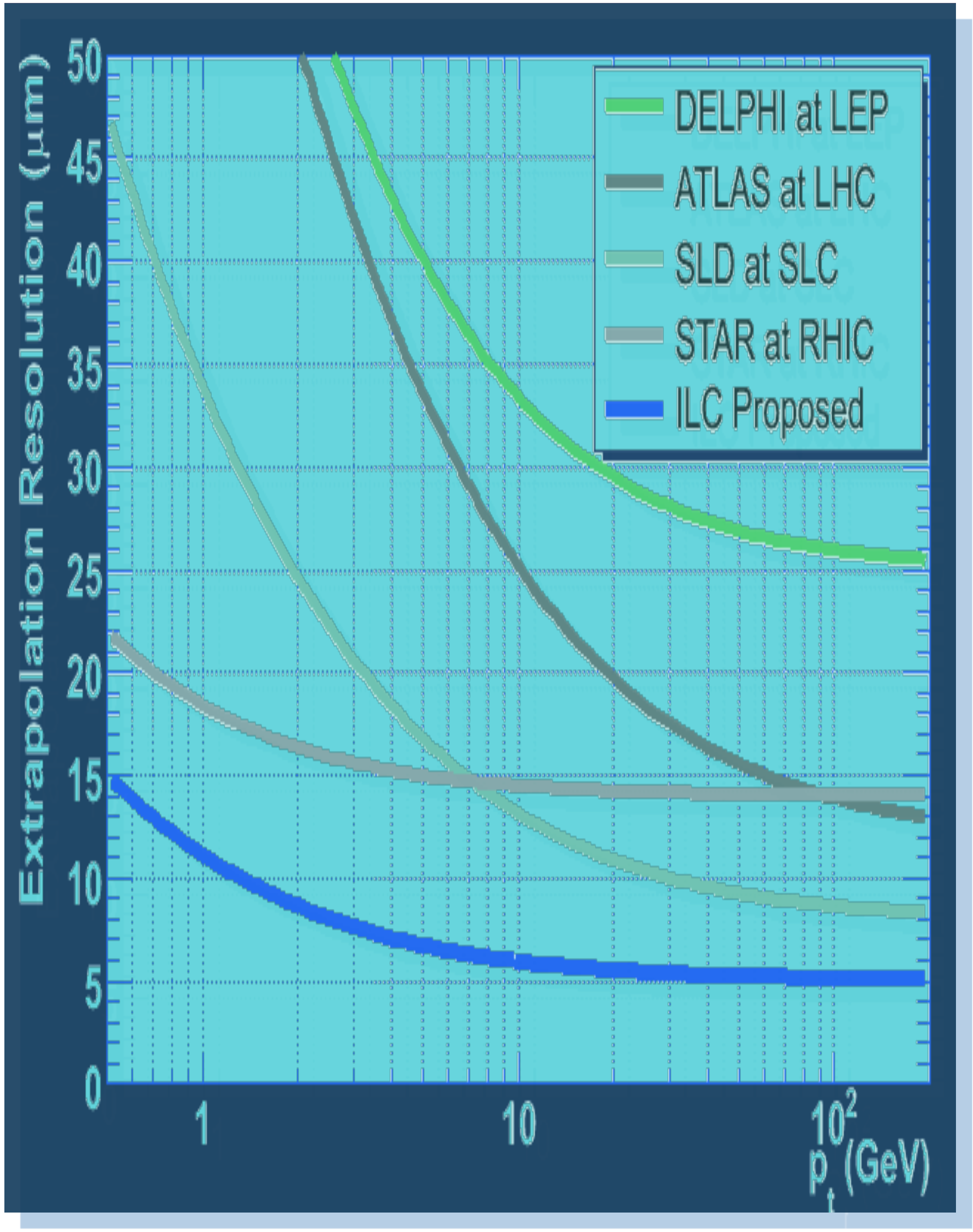
The Physics Matrix

	Testing the SM	**Understanding New Physics**	**Probing the TeraScale**
Asymptotic I.P. resolution (a)	$H_{SM} \rightarrow bb, \tau\tau, \mu\mu$ $e^+e^- \rightarrow HHZ$, $HH\nu\nu$	$HA \rightarrow bbbb$ $\tau_1\tau_1 \rightarrow \tau\tau\chi\chi$ $H^- \rightarrow \tau\nu$	
Multiple Scattering I.P. Term (b)	$H_{SM} \rightarrow cc, gg$ $e^+e^- \rightarrow HHZ$	CP violation H^- $\tau_1\tau_1 \rightarrow \tau\tau\chi\chi$	$\sigma(e^+e^- \rightarrow bb, cc)$
Polar Angle Coverage	A_{FB}		$e^+e^- \rightarrow HHZ$, $HH\nu\nu$

Track Extrapolation Resolution at 0.3-0.5 TeV



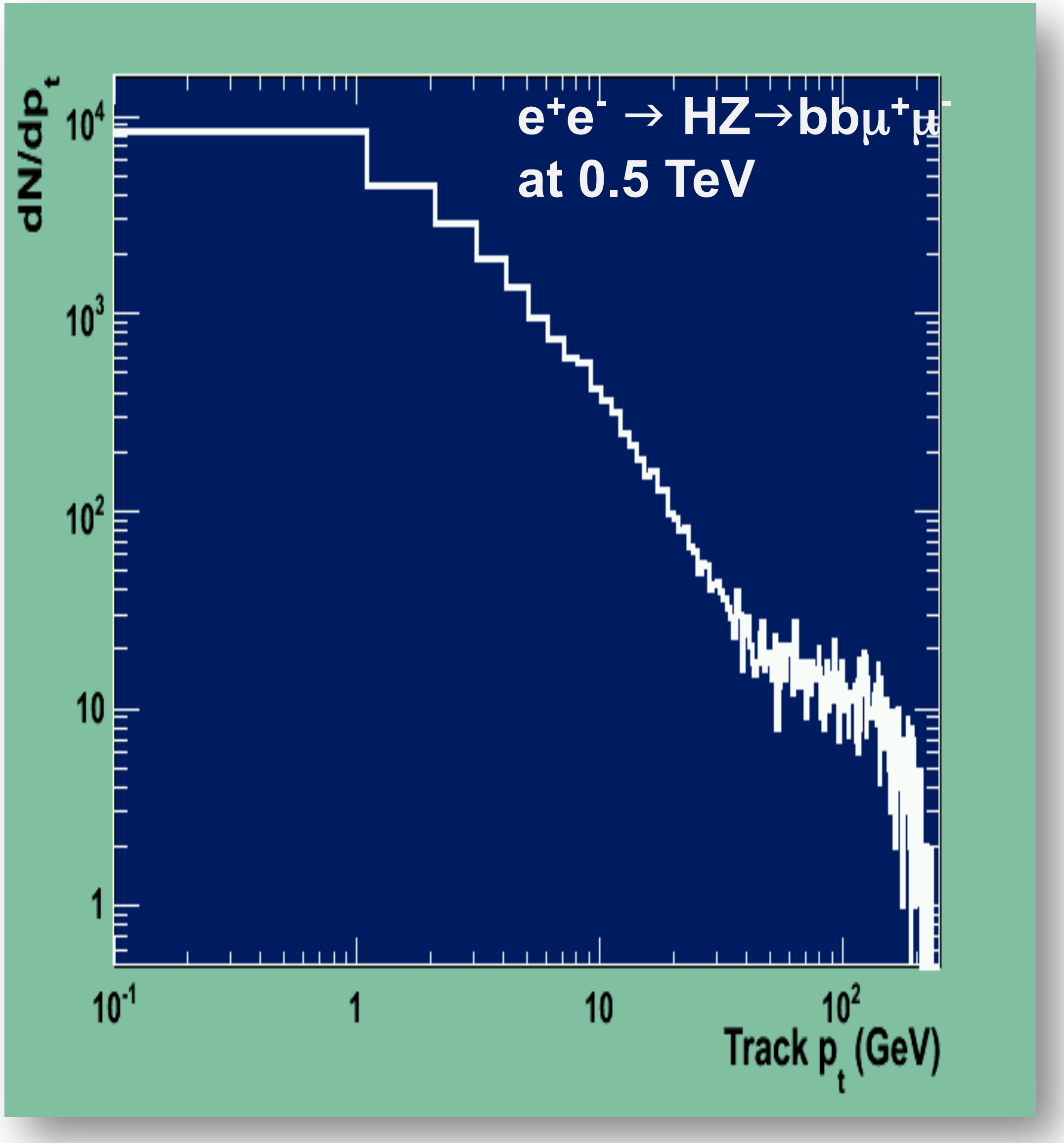
$\sigma_{ip} = a \oplus b / p_t$	a (μm)	b (μm/GeV)
LEP	25	70
SLD	8	33
LHC	12	70
RHIC II	14	12
ILC	5	10



Multiple Scattering Term

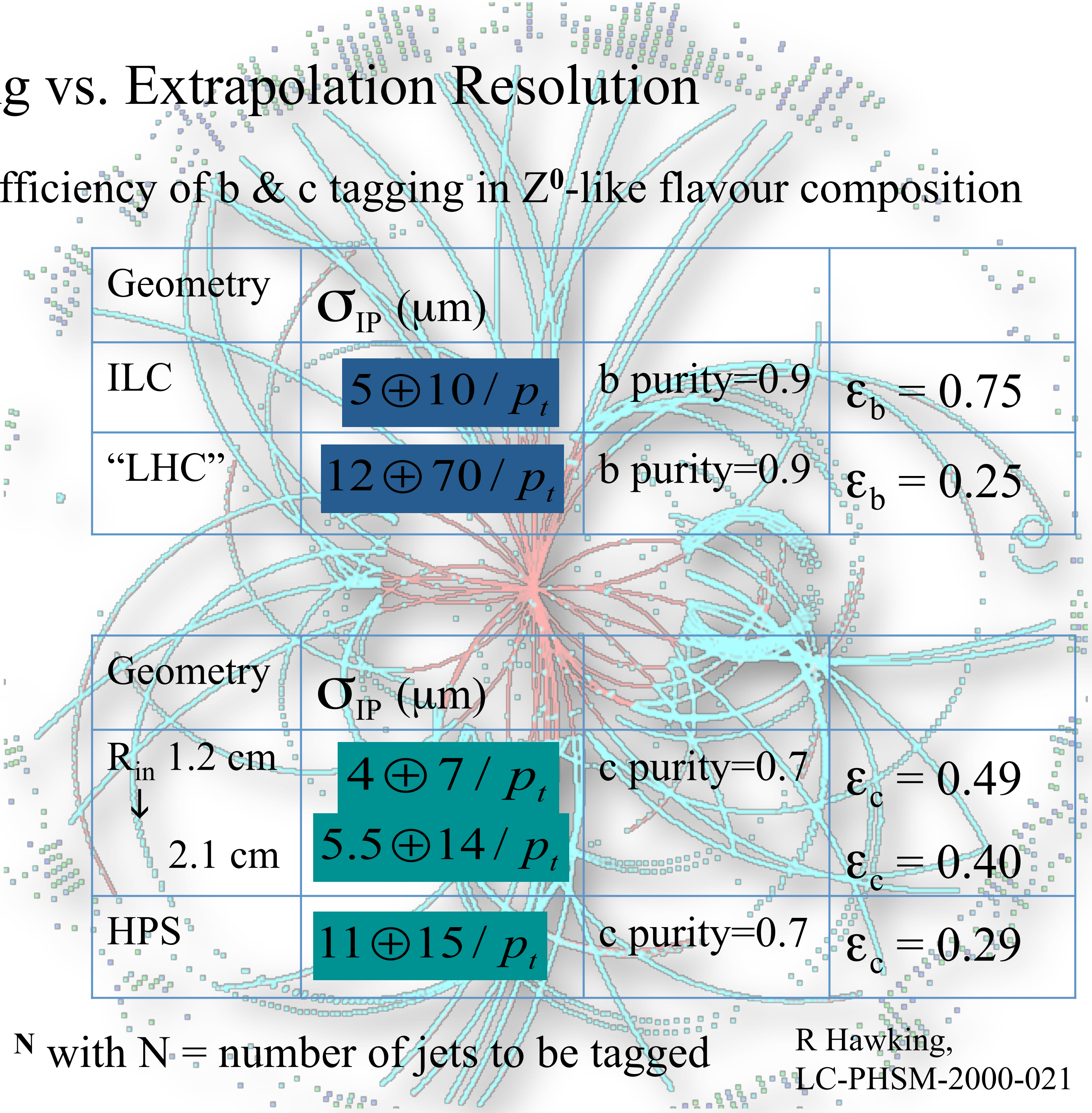
Despite large centre-of-mass energies, most charged particles are produced with rather moderate energies: interesting processes have large jet multiplicity (4 and 6 parton processes + hard gluon radiation) or large missing energies WW and ZZ fusion processes and SUSY with conserved R-parity;

Excellent track extrapolation at low momenta essential for sec. particle track counting, scenarios with very soft single prongs.



b and c Tagging vs. Extrapolation Resolution

Study change in efficiency of b & c tagging in Z^0-like flavour composition



Geometry	σ_{IP} (μm)		
ILC	$5 \oplus 10/p_t$	b purity=0.9	$\varepsilon_b = 0.75$
"LHC"	$12 \oplus 70/p_t$	b purity=0.9	$\varepsilon_b = 0.25$

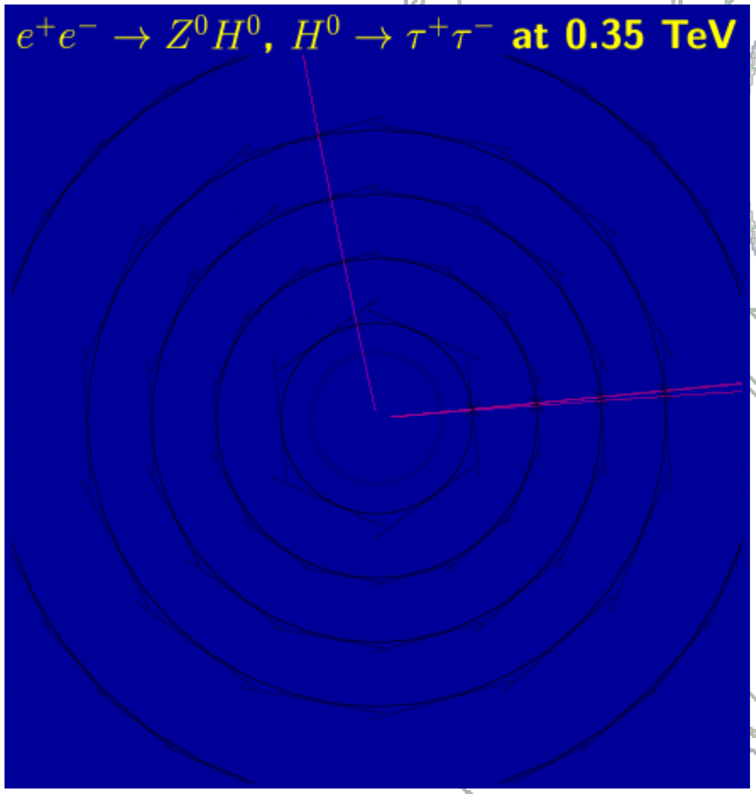
Geometry	σ_{IP} (μm)		
R_{in} 1.2 cm ↓ 2.1 cm	$4 \oplus 7/p_t$ $5.5 \oplus 14/p_t$	c purity=0.7	$\varepsilon_c = 0.49$ $\varepsilon_c = 0.40$
HPS	$11 \oplus 15/p_t$	c purity=0.7	$\varepsilon_c = 0.29$

Total efficiency = ε^N with N = number of jets to be tagged

R Hawking,
LC-PHSM-2000-021

$e^+e^- \rightarrow H^0Z^0$, $H^0\nu\nu$; $H^0 \rightarrow \tau^+\tau^-$, $\mu^+\mu^-$

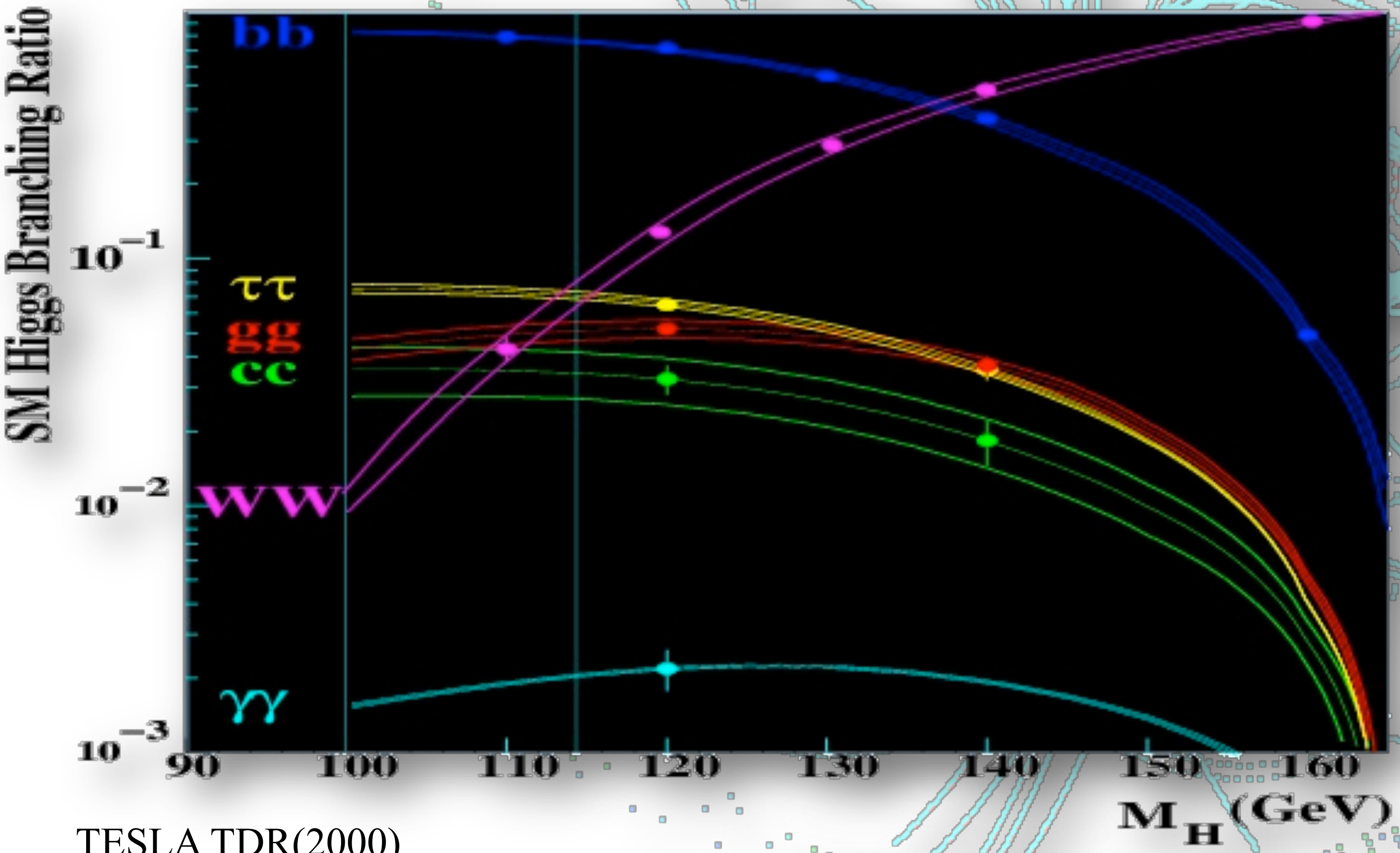
Fundamental test of Higgs mechanism requires verifying that its couplings to fermions scale as fermion masses, not only LC can do this to limiting δm_f accuracy for quarks but can also perform first test in leptonic sector;



Vertex Tracker plays major role to tag t leptons, improve δp/p for ms; essential excellent single point resolution for stiff, closely collimated (τ) or isolated (τ,μ) particle tracks;

$H^0 \rightarrow$ bb, cc, gg at 0.3 - 0.5 TeV

Determination of Higgs hadronic branching fractions, one of the most Crucial tests of the Higgs mechanism of mass generation and unique to the LC: experimental accuracy needs to match theory uncertainties and probe extended Higgs sector models;

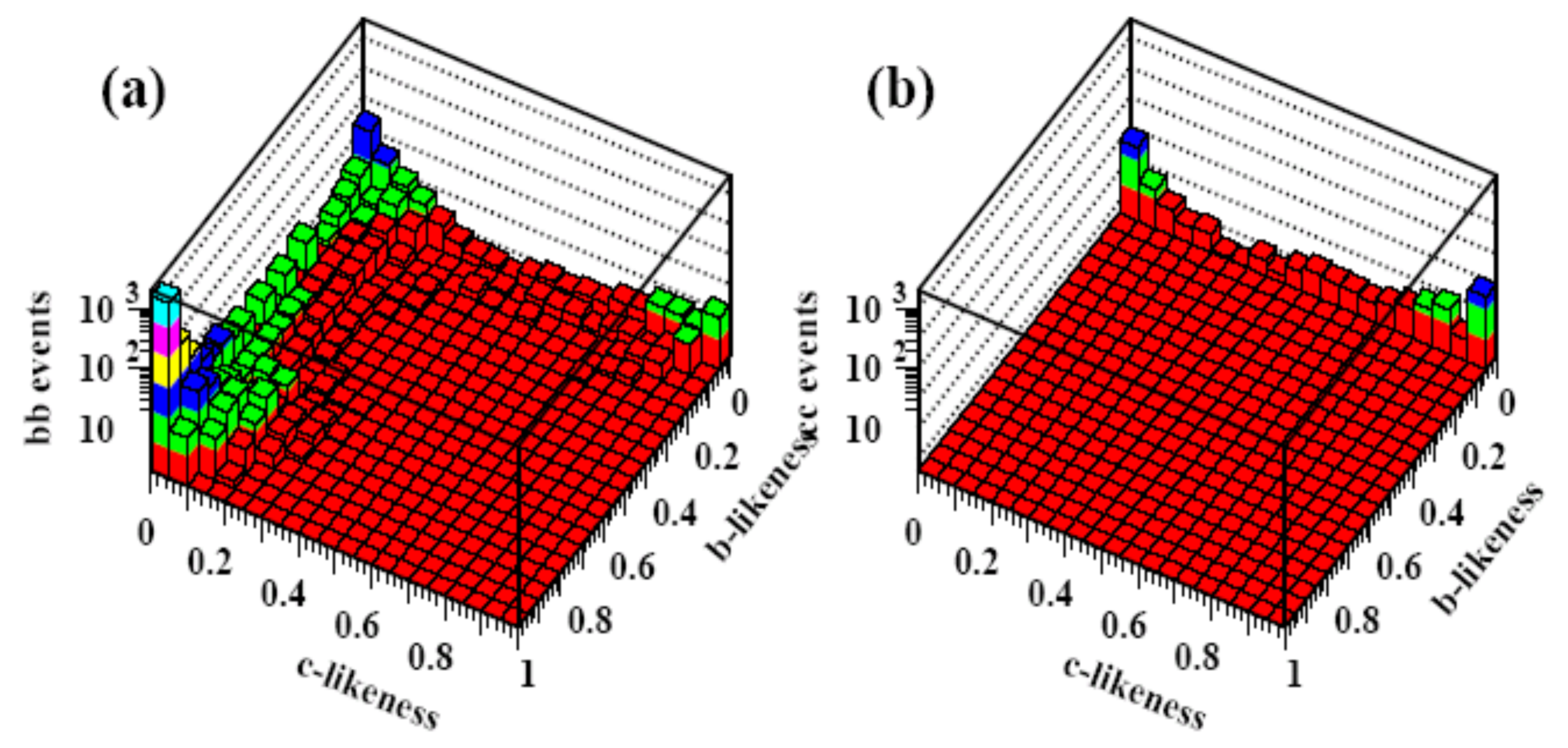


TESLA TDR(2000)

BR($H^0\to$bb, cc, gg) at 0.3 - 0.5 TeV

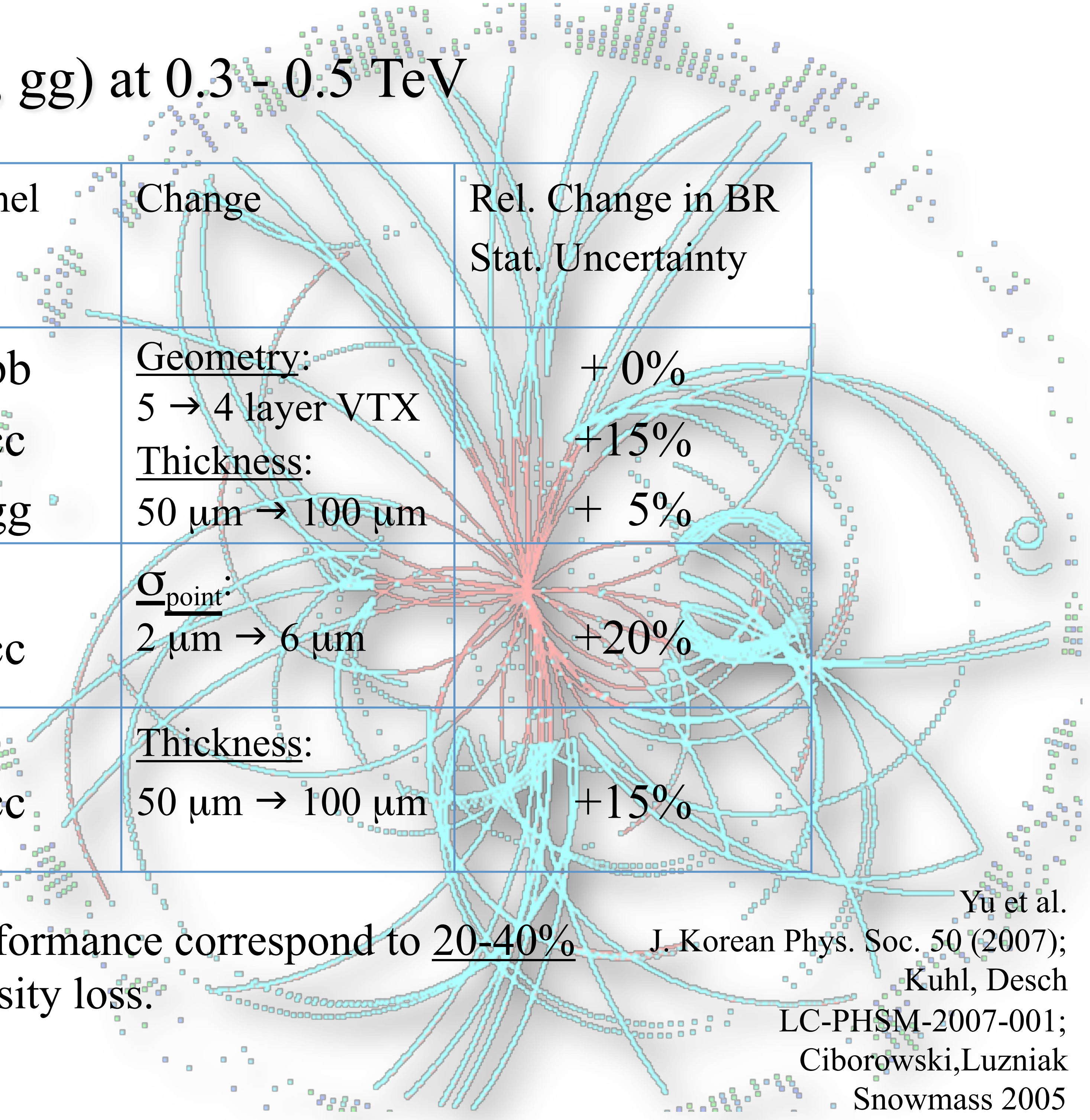
Light Higgs boson offers opportunity and challenge: couplings to b, c and t quark accessible, but need to tag b, c, **light** jets with **70** : **3** : **7** ratio in signal.

Fit response of jet flavour tagging based on tracking and vertexing variables:



Kuhl, Desch
LC-PHSM-2007-001

BR(H^0→bb, cc, gg) at 0.3 - 0.5 TeV



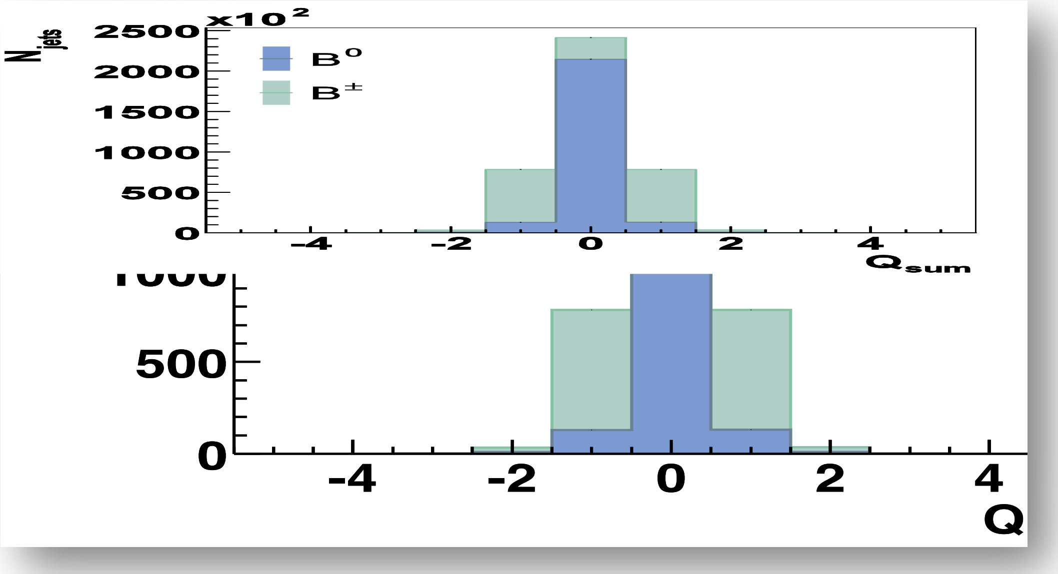
Channel	Change	Rel. Change in BR Stat. Uncertainty
H→bb H→cc H→gg	<u>Geometry</u>: 5 → 4 layer VTX <u>Thickness</u>: 50 μm → 100 μm	+ 0% +15% + 5%
H→cc	$\underline{\sigma_{point}}$: 2 μm → 6 μm	+20%
H→cc	<u>Thickness</u>: 50 μm → 100 μm	+15%

Degradation in performance correspond to <u>20-40%</u> equivalent Luminosity loss.

Yu et al.
J. Korean Phys. Soc. 50 (2007);
Kuhl, Desch
LC-PHSM-2007-001;
Ciborowski,Luzniak
Snowmass 2005

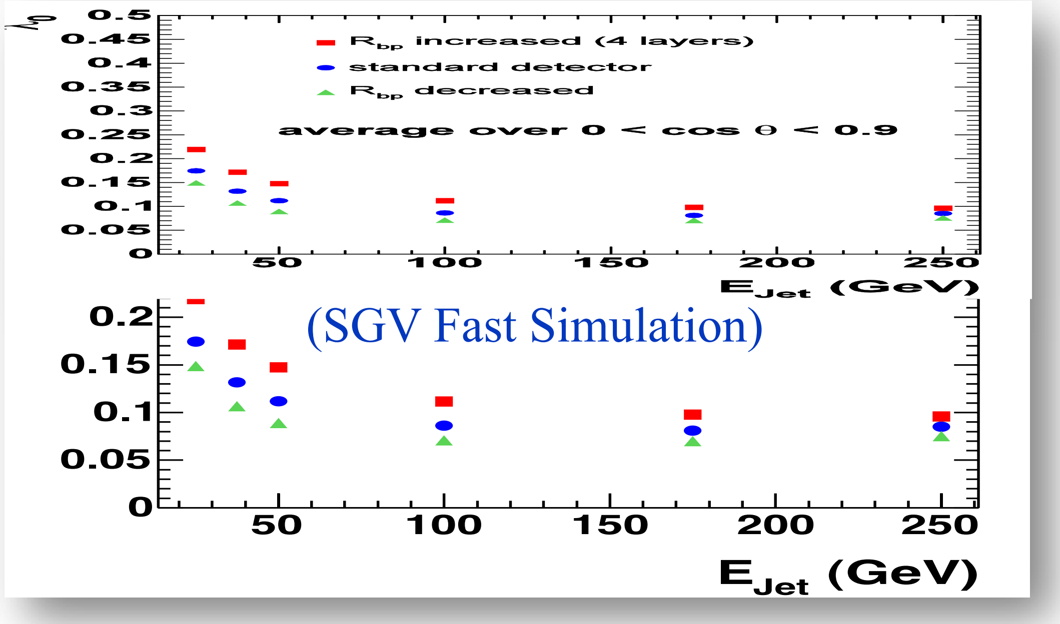
Vertex Charge

Vertex charge algorithms very promising for q-anti q discrimination of b and c jets (jet pairing, A_{FB}, …) based on charge of secondaries at reconstructed vertex;



Vertex charge extremely sensitive to correct secondary particle tags: any mistake changes result by ±1

Benchmark vertex charge performance using $P(B^0 \rightarrow B^\pm)$:



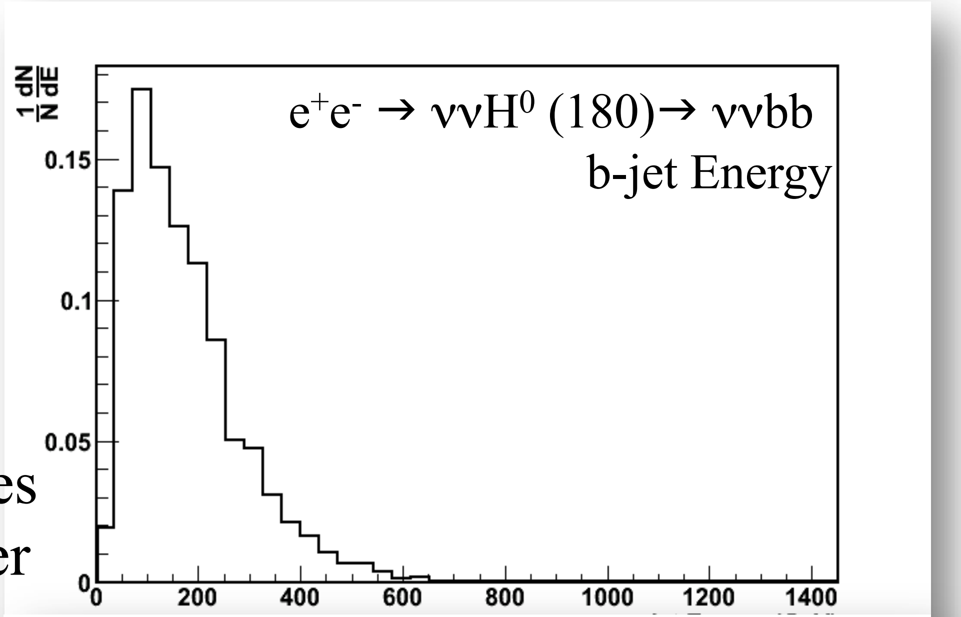
(SGV Fast Simulation)

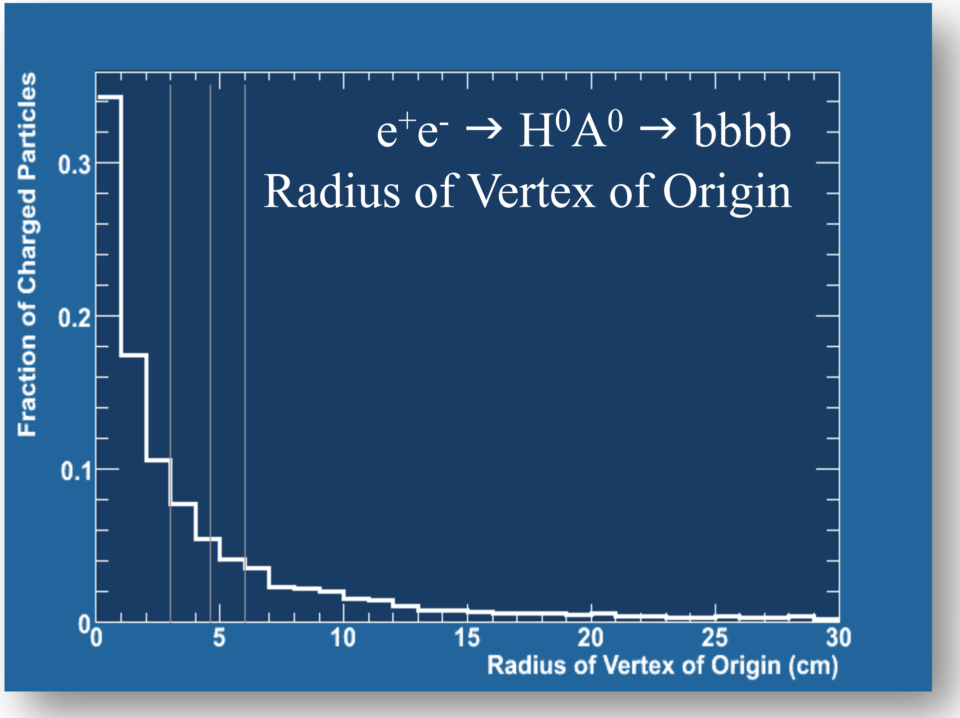
S Hillert & LCFI
Ringberg 2006

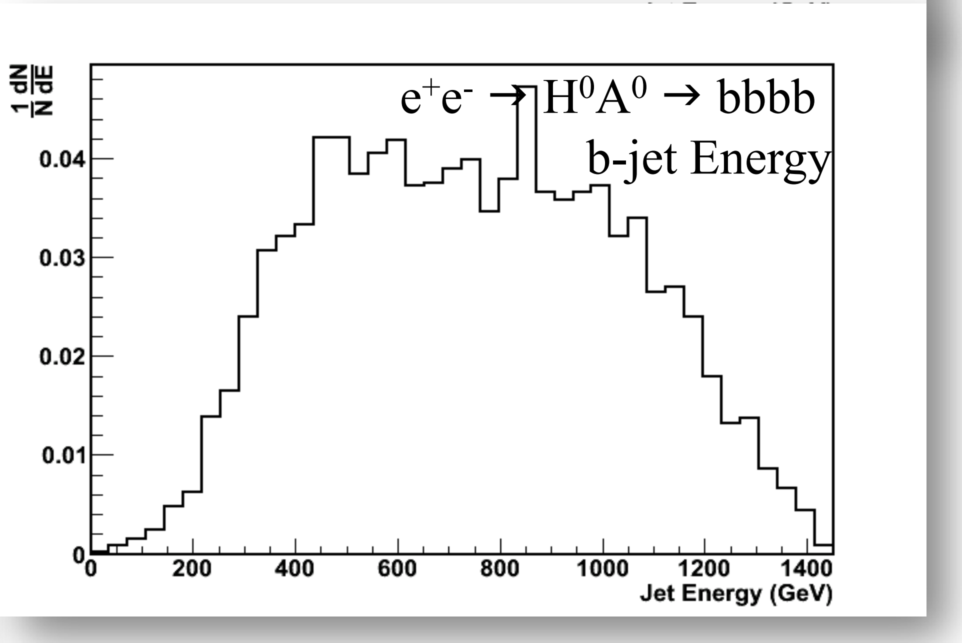
Track Extrapolation Resolution at 1.0-3.0 TeV

Broad range of b-jet energies of interest:
~0.1 → 1.5 TeV;

Long lived hadrons in b-jets acquire significant flight distance: in four jet 3 TeV events over 1/3 of charged particles with p>1 GeV decay after first VTX layer





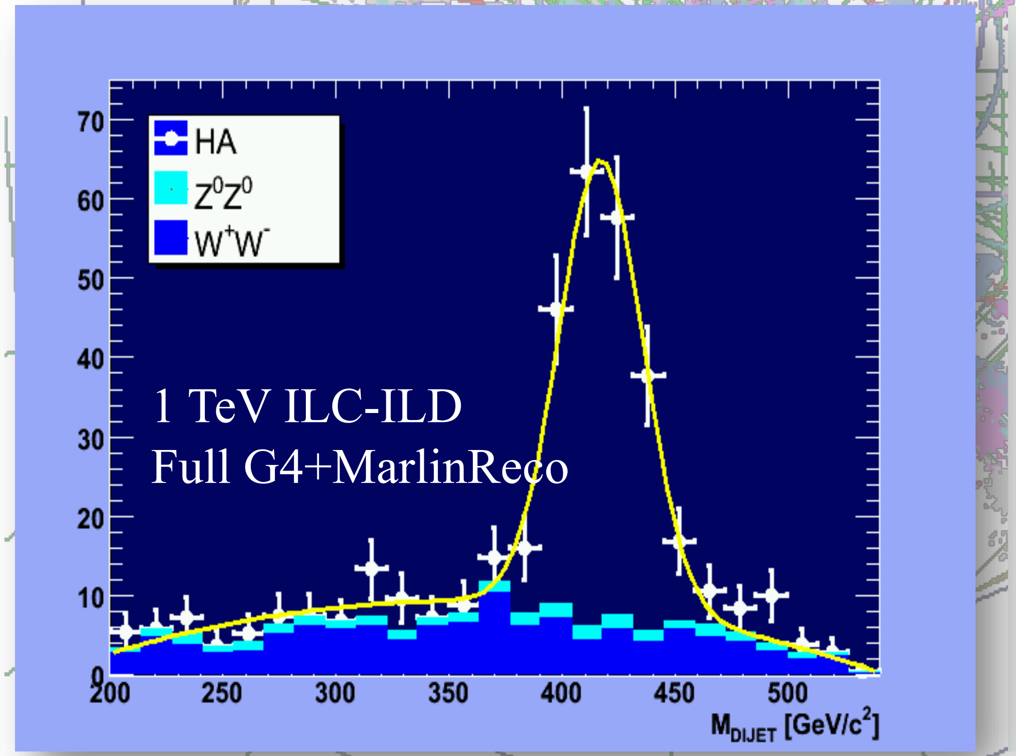


MB, CLIC09

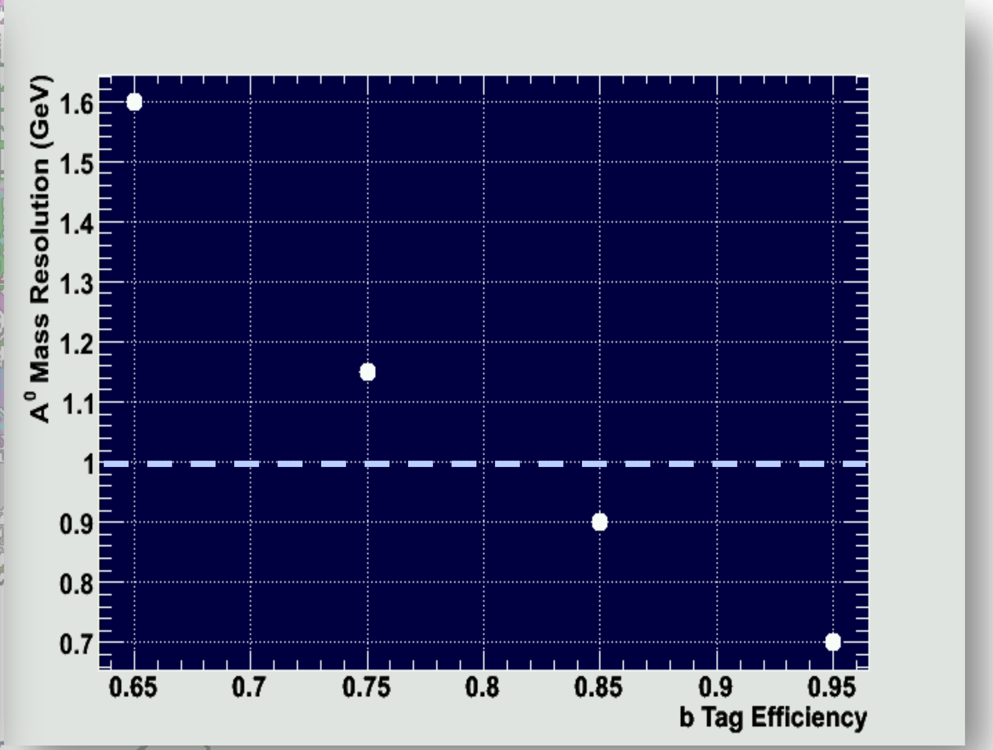
$e^+e^- \to H^0A^0 \to bbbb, \tau^+\tau^- bb$ at 1 TeV

LC unique to achieve the <1% accuracy on the A^0 mass needed to predict Ω_χ matching CMB WMAP precision;

Need to tag bbbb final state <u>high efficiency</u> ($\sigma_{\mathbf{HA}} \sim$ 1fb and 4b jets to tag) and <u>small misid</u> ($\sigma_{\mathbf{bkg}}/\sigma_{\mathbf{signal}} \sim 4 \times 10^3$), τ tagging important to fix additional SUSY parameters:



1 TeV ILC-ILD
Full G4+MarlinReco



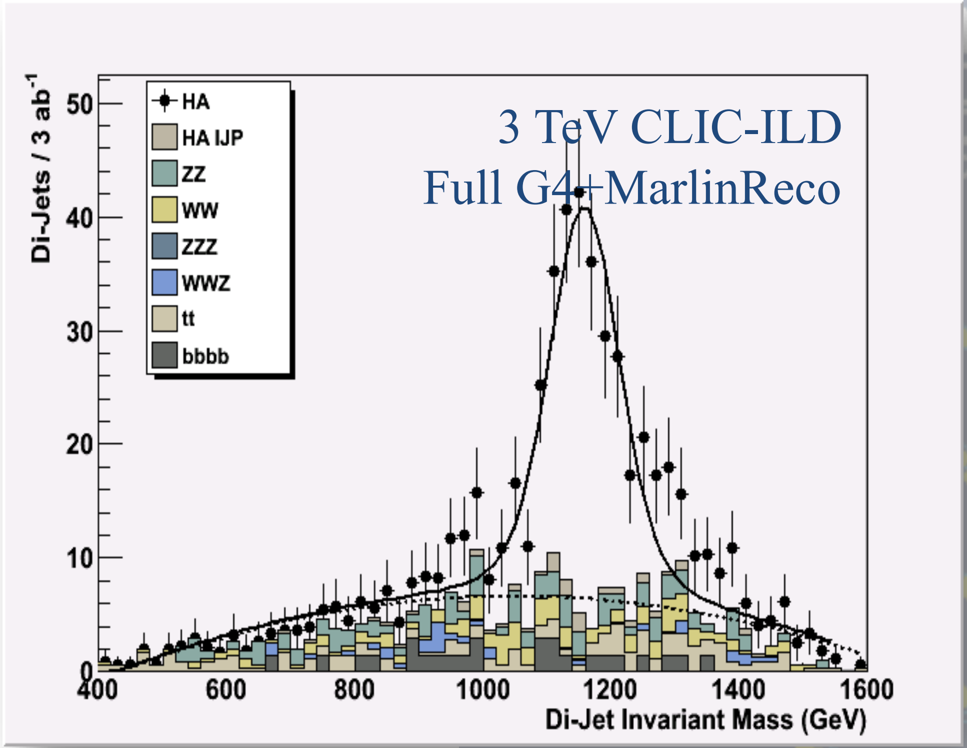
MB, Hooberman
PRD57 (2008)

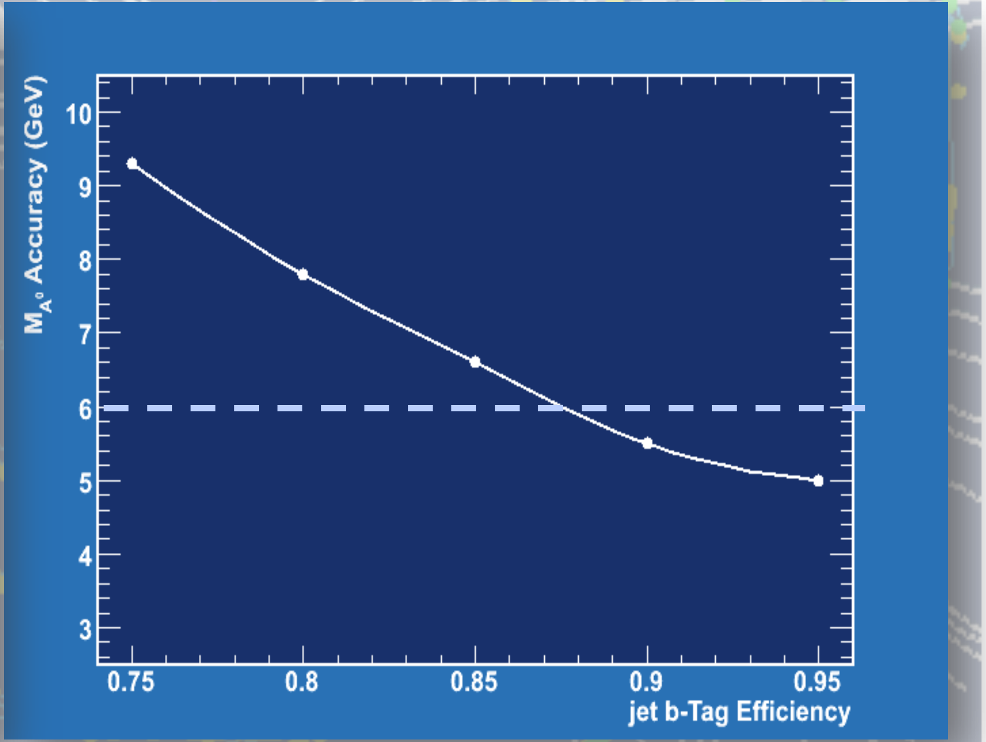
$e^+e^-\rightarrow H^0A^0\rightarrow bbbb,\tau^+\tau^-bb$ at 3 TeV

SUSY heavy Higgs boson expected to be a genuine feast for flavour tagging

- $e^+e^- \rightarrow H^0A^0 \rightarrow bbbb, \rightarrow bb\tau\tau, \rightarrow \tau\tau\tau\tau;$
- $e^+e^- \rightarrow H^+H^- \rightarrow tbtb, \rightarrow \tau\nu\tau\nu.$

Full MOKKA+Marlin w/ Full SM Bkg + 20 BX $\gamma\gamma$





MB, CLIC09

e+e-→H^0H^0 νν→bbbbνν at 3 TeV

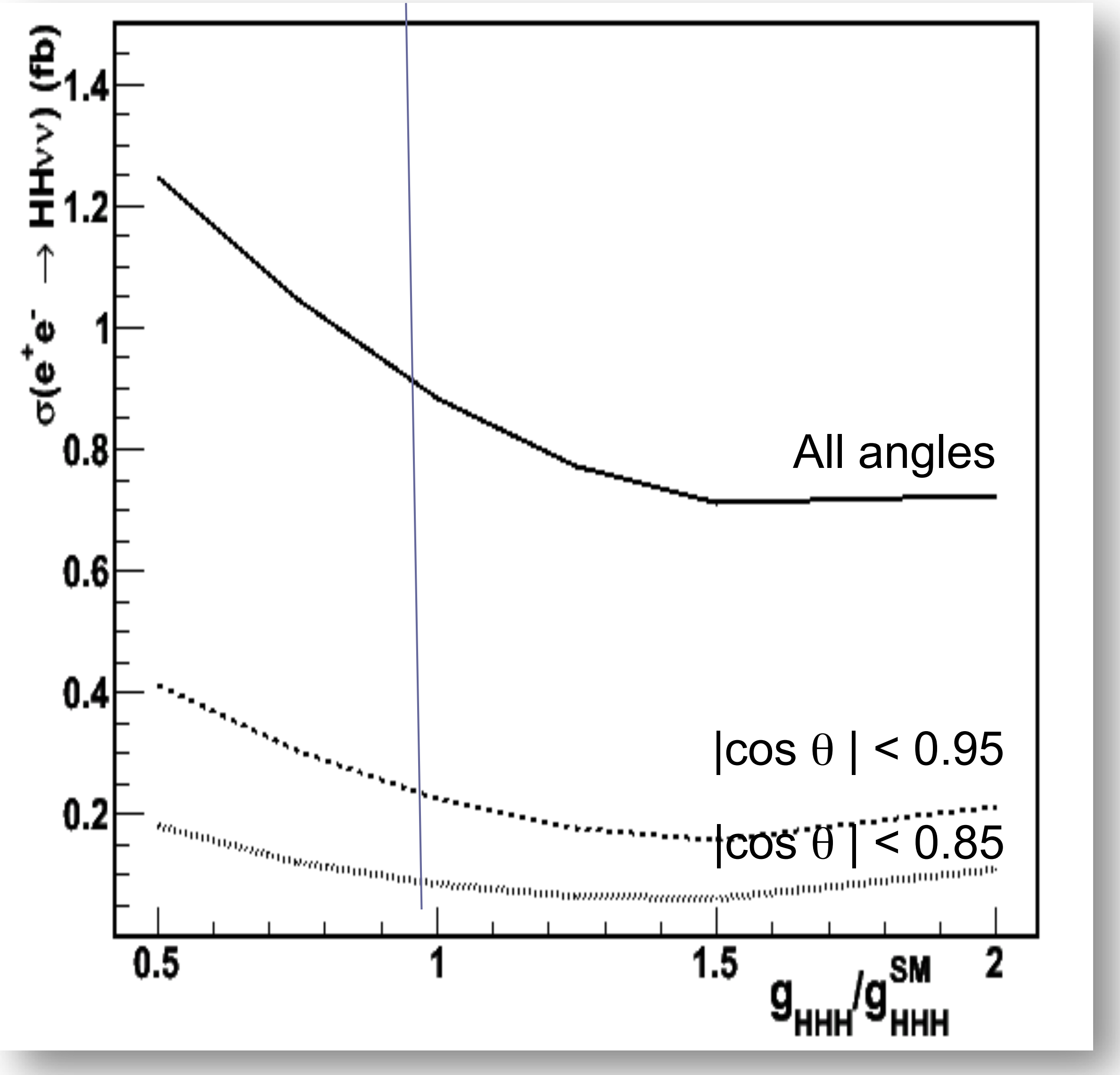
Non-trivial interference of double WW fusion with other diagrams yielding double Higgs production but not involving the triple Higgs vertex;

Imperative to accept & b-tag jets at low angles to retain sensitivity to g_{HHH};

$\varepsilon = \varepsilon_b^4$ with ~ 1.5-2.0k useful evts → need to achieve

$\varepsilon_b > 0.85$

Sensitivity of HHνν cross section to triple Higgs coupling for various polar angle coverages



MB, CLIC09

LC Tracking:
Momentum Resolution

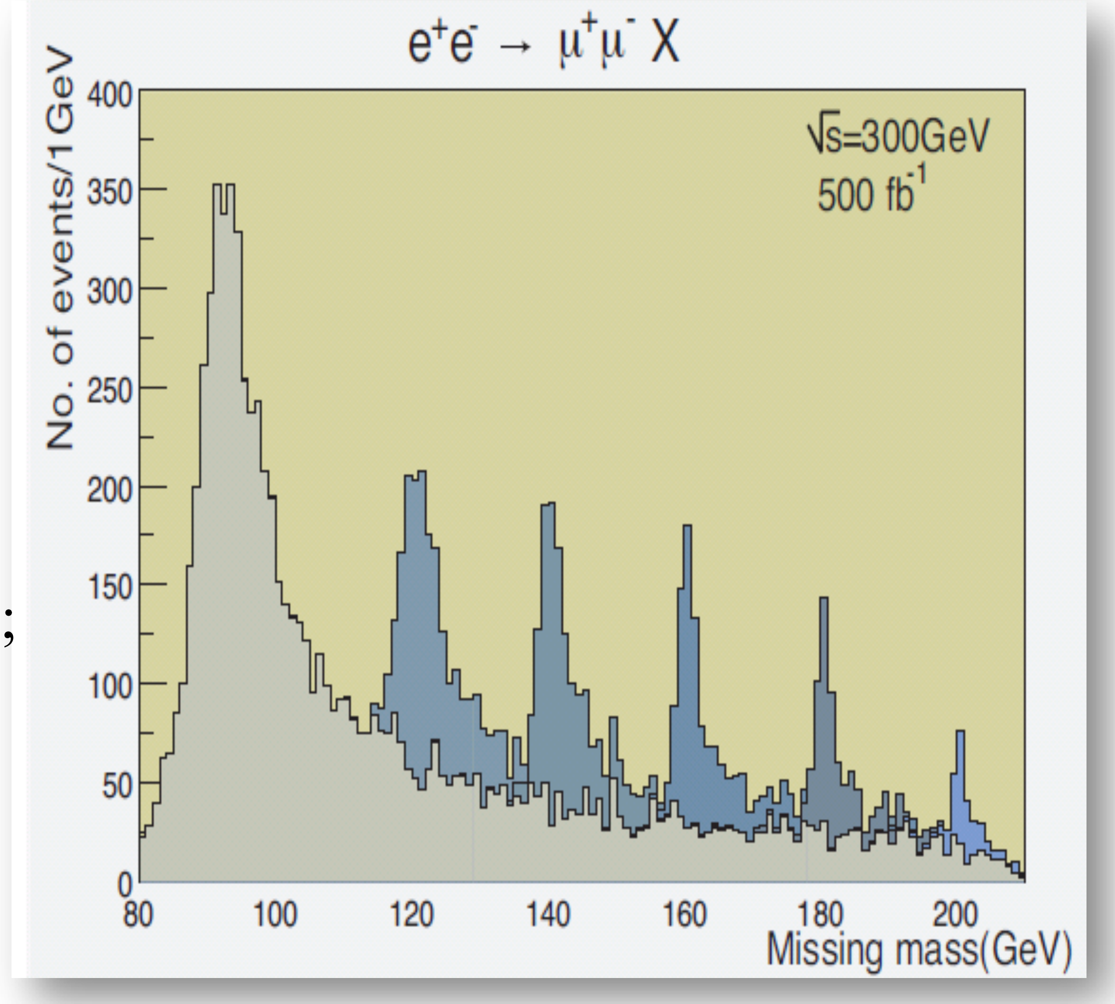
Track Momentum Resolution at 0.3-0.5 TeV

If Higgs boson light as predicted by EW data, associated HZ production $e^+e^- \rightarrow H^0Z^0 \rightarrow X\, l^+l^-$ will offer model-independent Higgs reconstruction.

$$M_H^2 = s - 2\sqrt{s}E_Z + M_Z^2$$

Resolution in e^+e^- and $\mu^+\mu^-$ recoil mass depends on accuracy in beam energy (peak and spread) and detector momentum resolution;

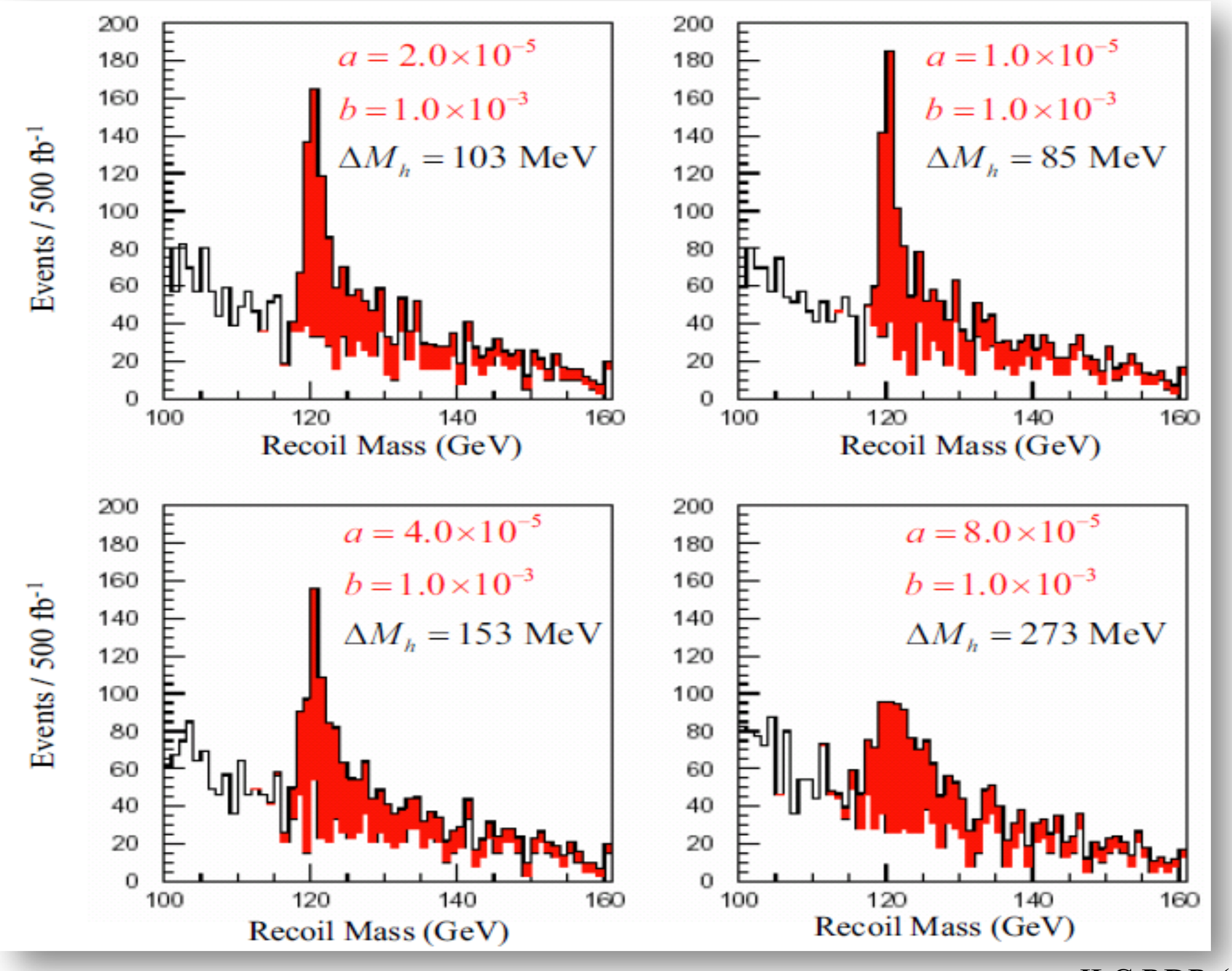
This process sets tightest constrain on track momentum resolution while HZ process is of interest.



K Abe et al, hep-ph/0109166

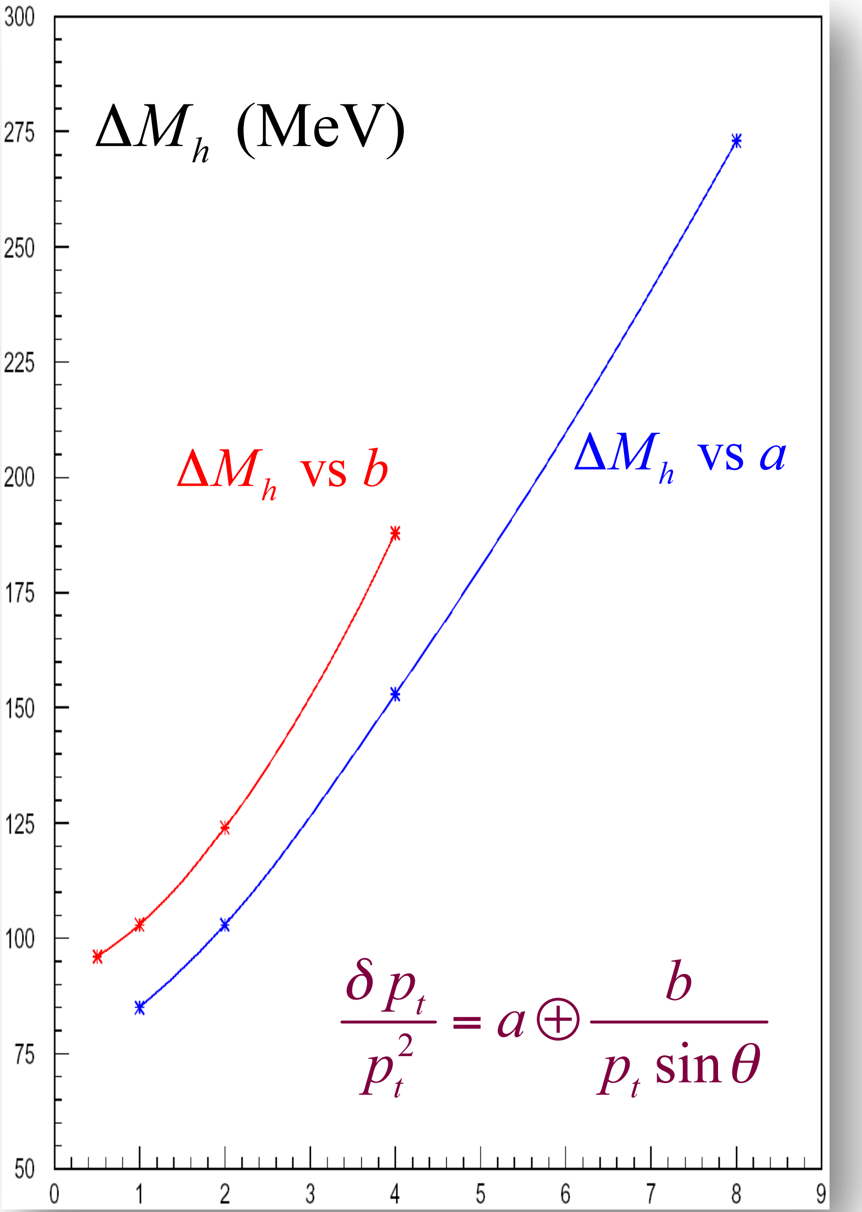
$e^+e^- \rightarrow Z^0H^0 \rightarrow \mu^+\mu^- X$ at 0.35 TeV

$$\frac{\delta p_t}{p_t^2} = a \oplus \frac{b}{p_t \sin\theta}$$

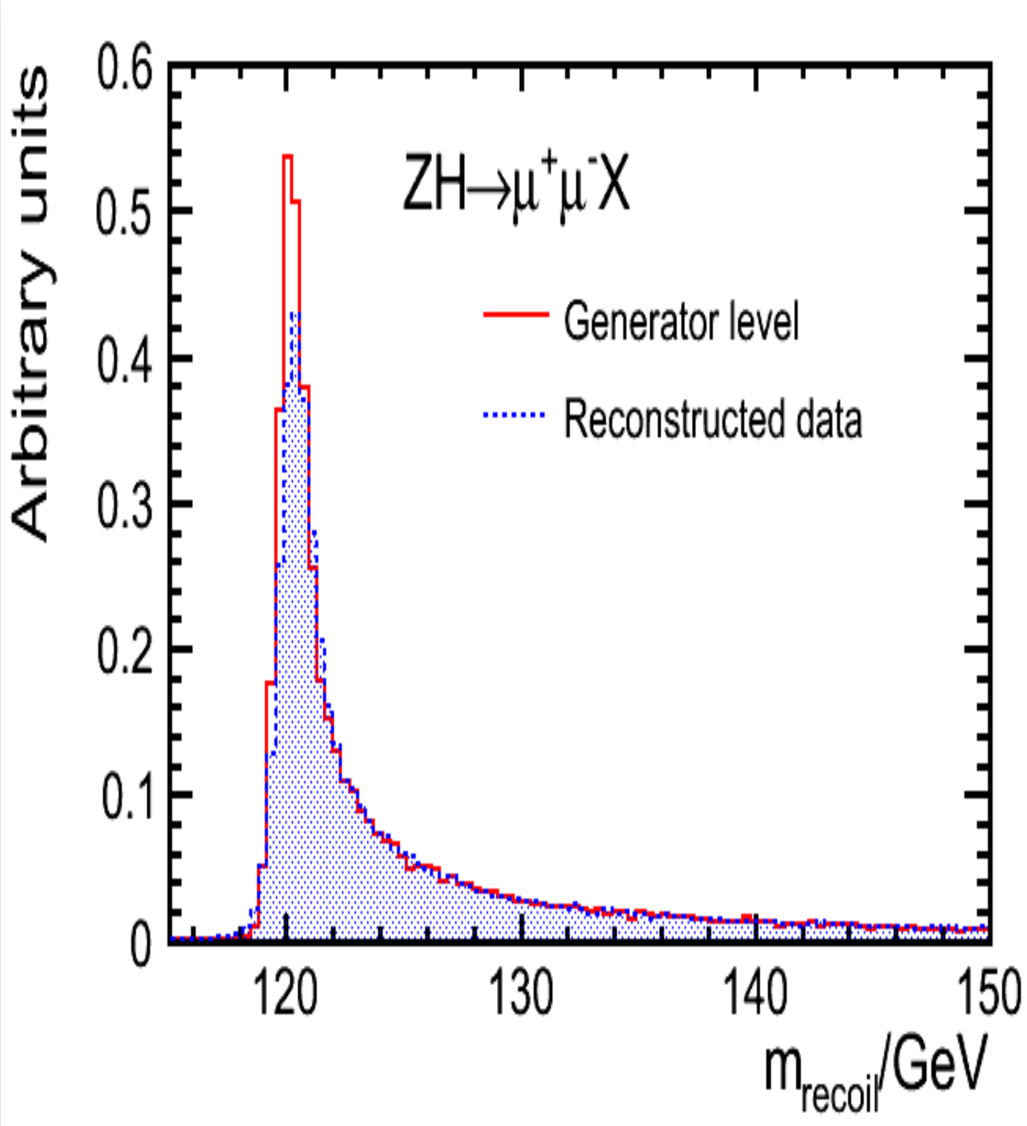


ILC RDR (2007)

$e^+e^- \rightarrow Z^0H^0 \rightarrow \mu^+\mu^- X$ at 0.35 TeV

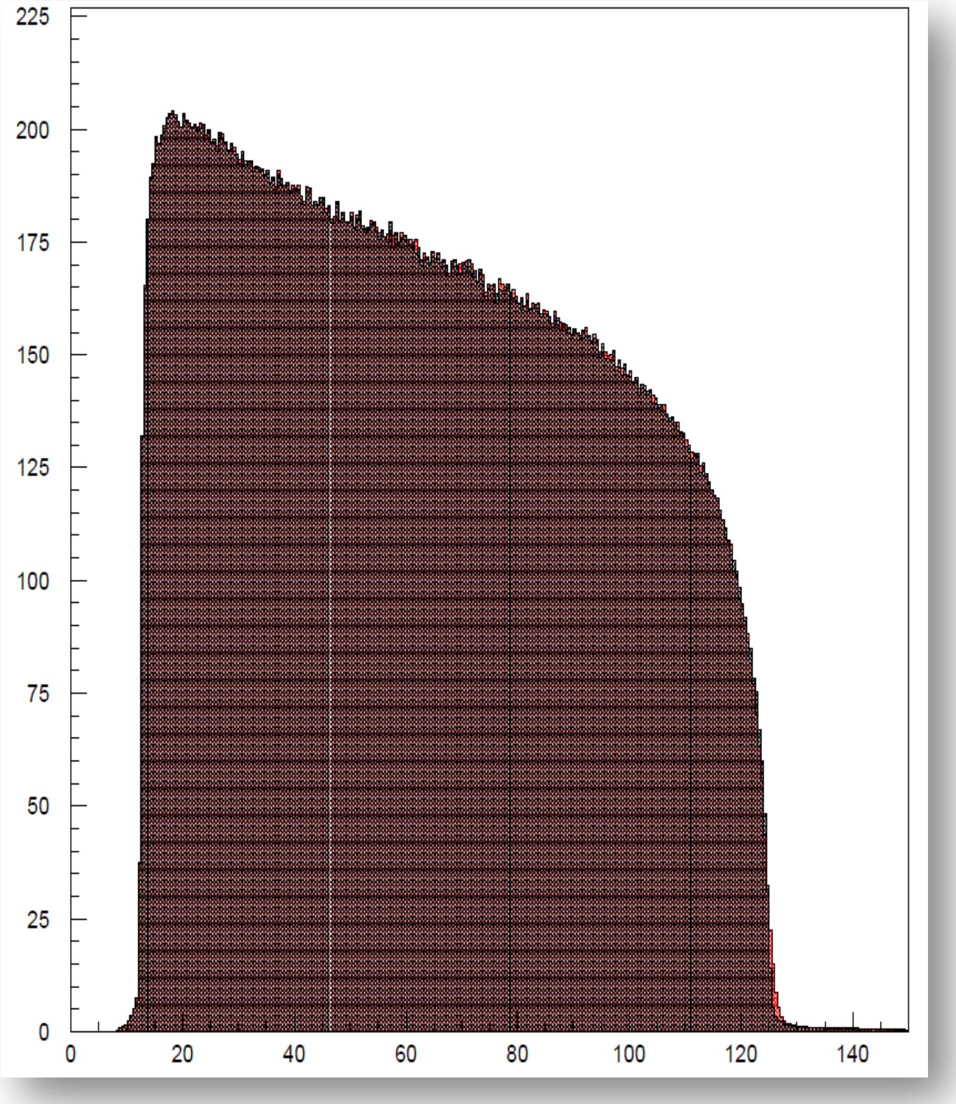


T Barklow, (2005)



ILD LoI (2009)

$e^+e^- \rightarrow \mu^+\mu^- \rightarrow \mu^+\mu^- \chi_1^0 \chi_1^0$ at 0.5 TeV



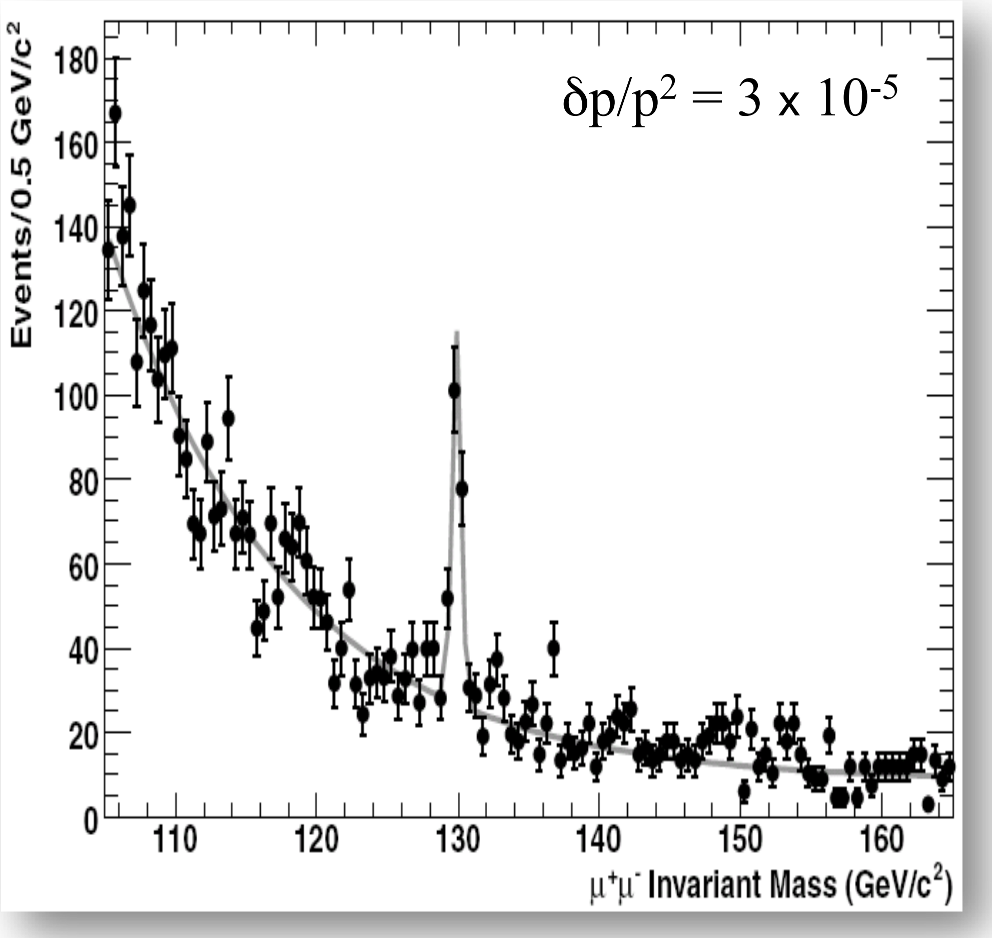
$\delta p/p^2$ (GeV^{-2})	$\delta M\mu$ (MeV)	$\delta M\ \chi$ (MeV)
0	98	86
2×10^{-5}	115	98
8×10^{-5}	139	113

T Barklow, ILC RDR (2007)

Track Momentum Resolution at 1 - 3 TeV

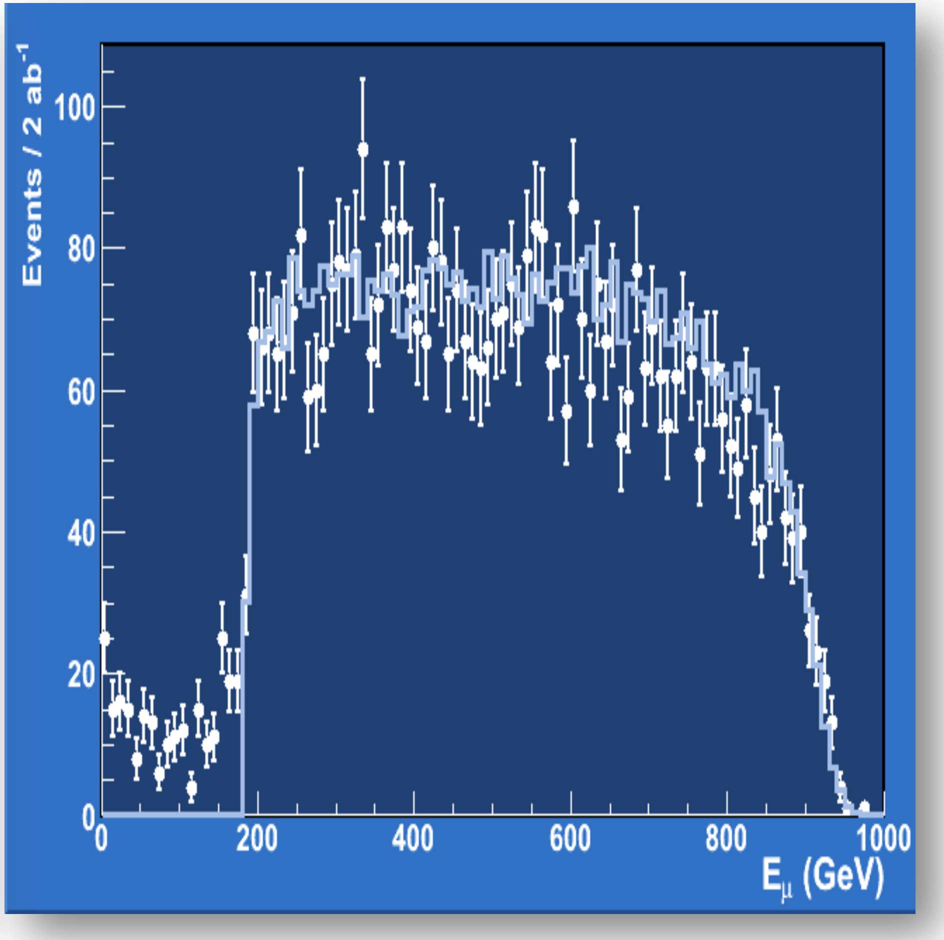
$e^+e^- \to \nu_e\nu_e H^0 \to \nu_e\nu_e\mu^+\mu^-$

Di-Muon Invariant Mass



$e^+e^- \to \mu^+_R\mu^-_R \to \mu+\chi^0_1\mu^-\chi^0_1$

Muon Energy

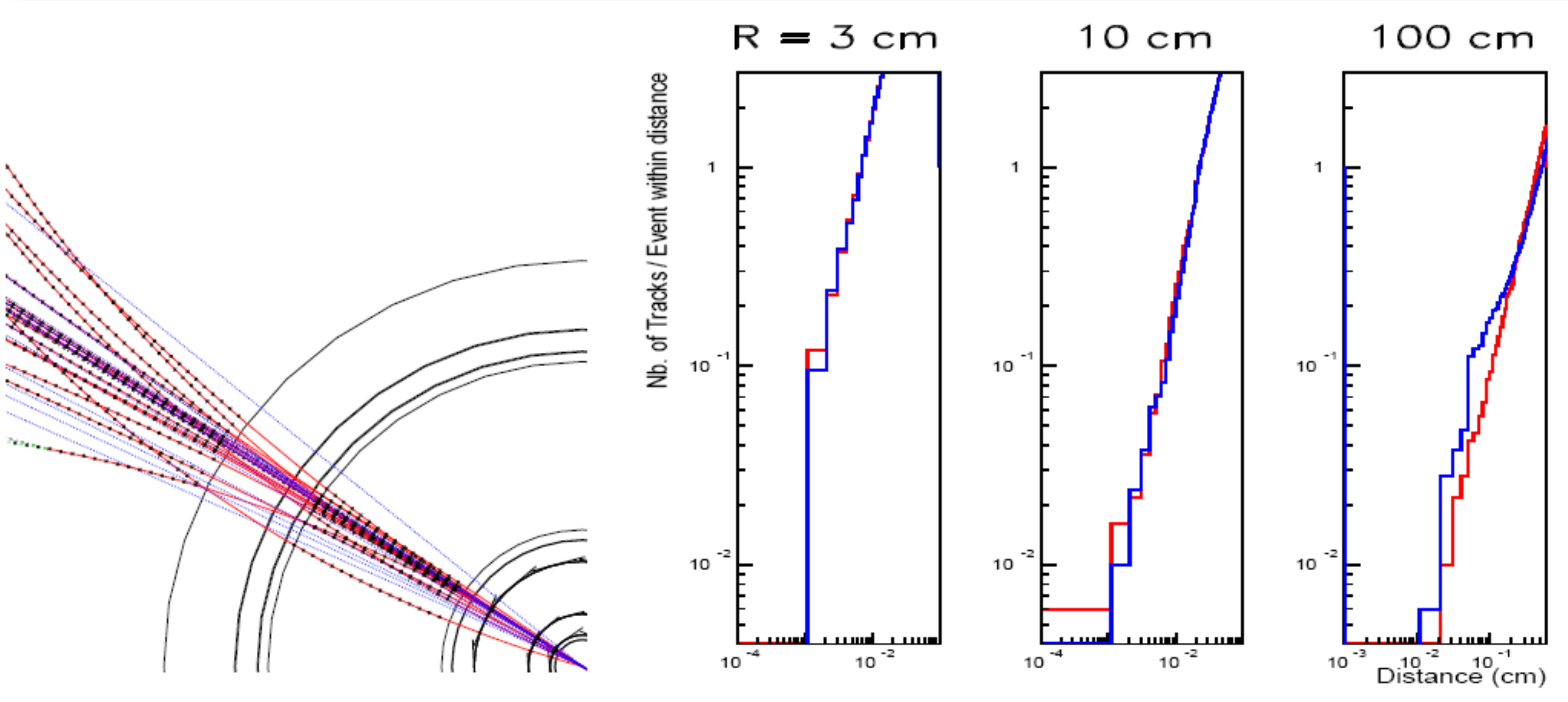


ILC Track momentum resolution adequate to analysis of multi-TeV events, resolution mostly dominated by beamstrahlung.

Tracking in multi-TeV Events

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

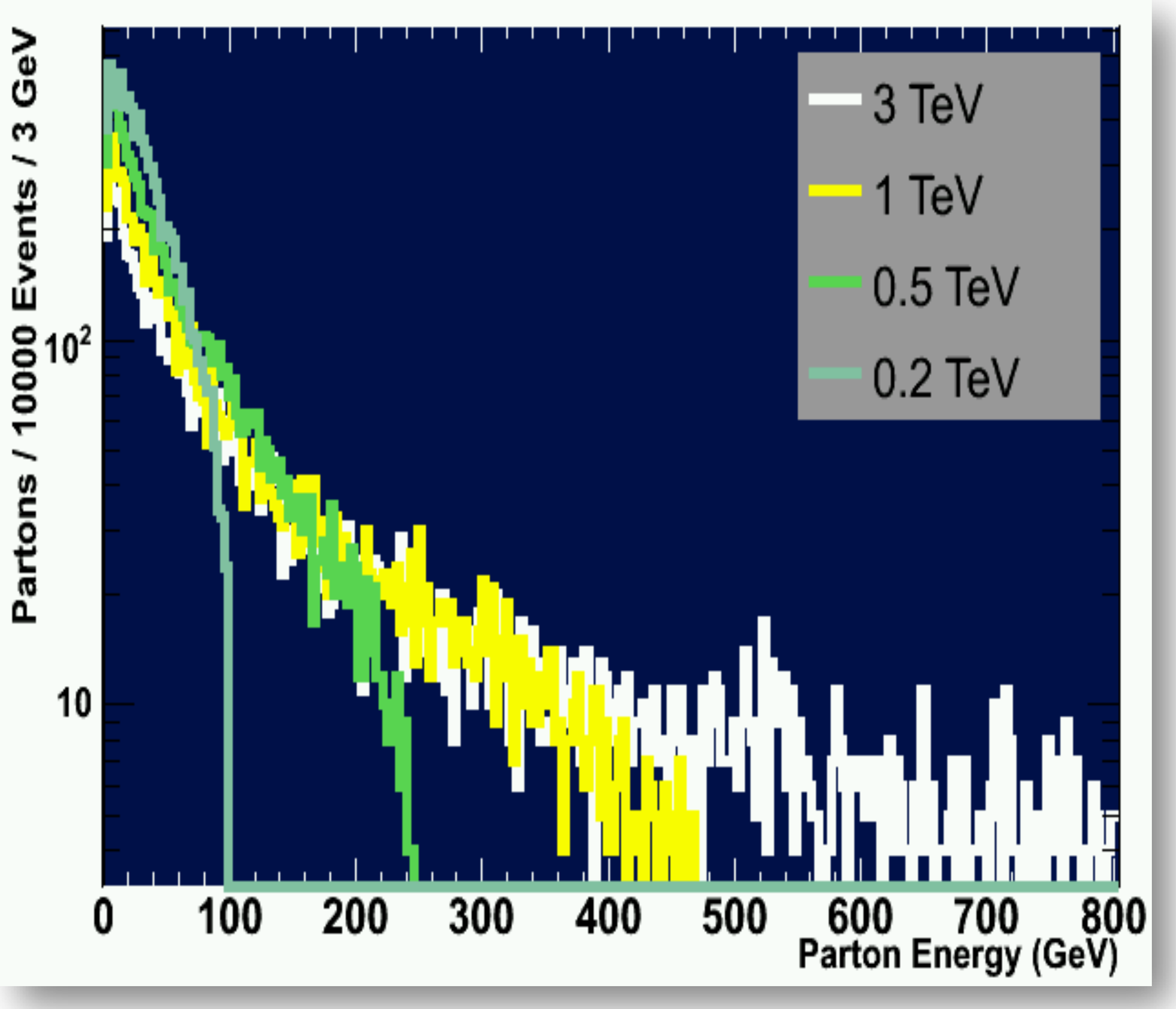
Minimum Distance between Tracks in Hadronic Events at 3 TeV



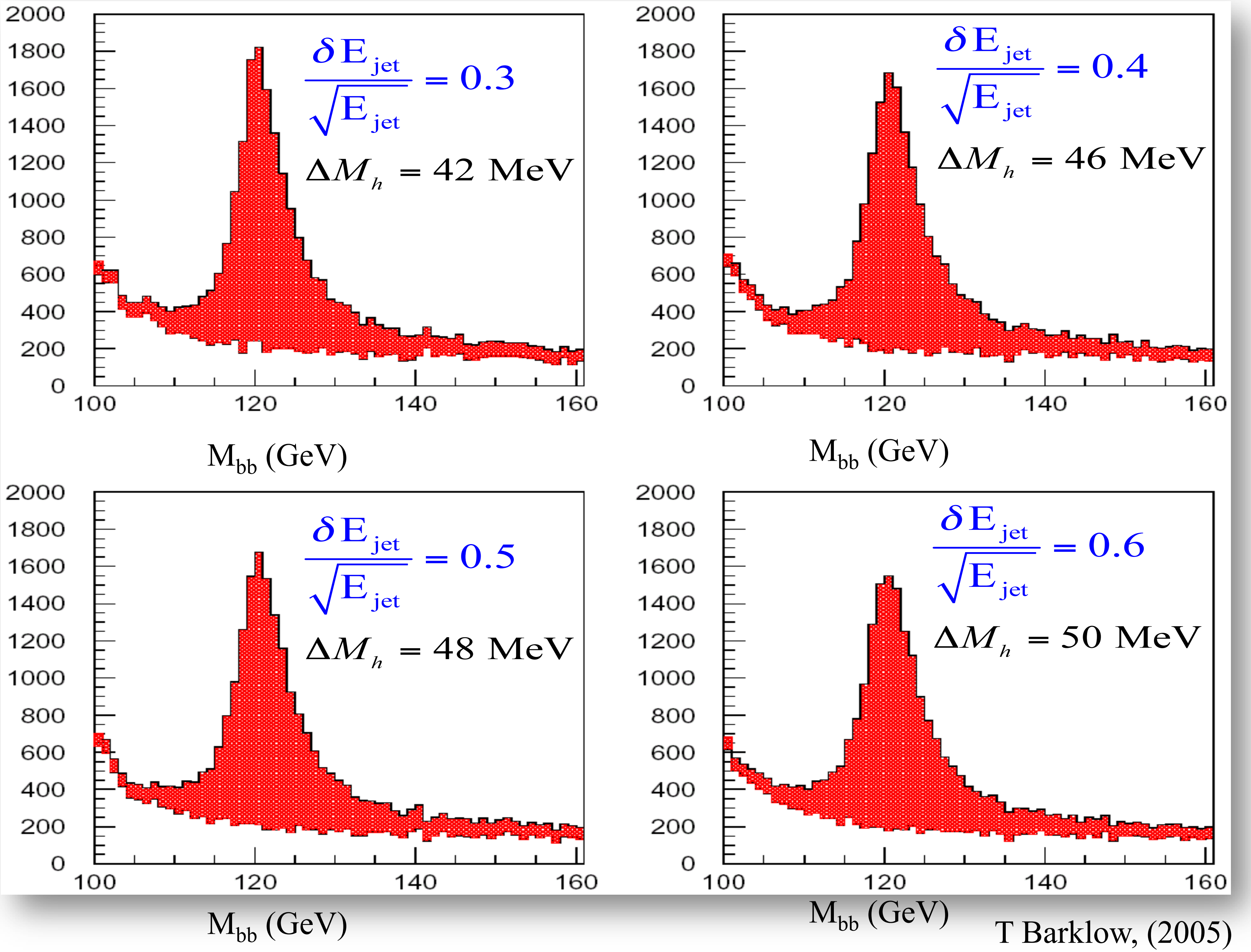
hep-ph/0103338

LC Parton Resonstruction:
Energy Resolution

Parton Energies

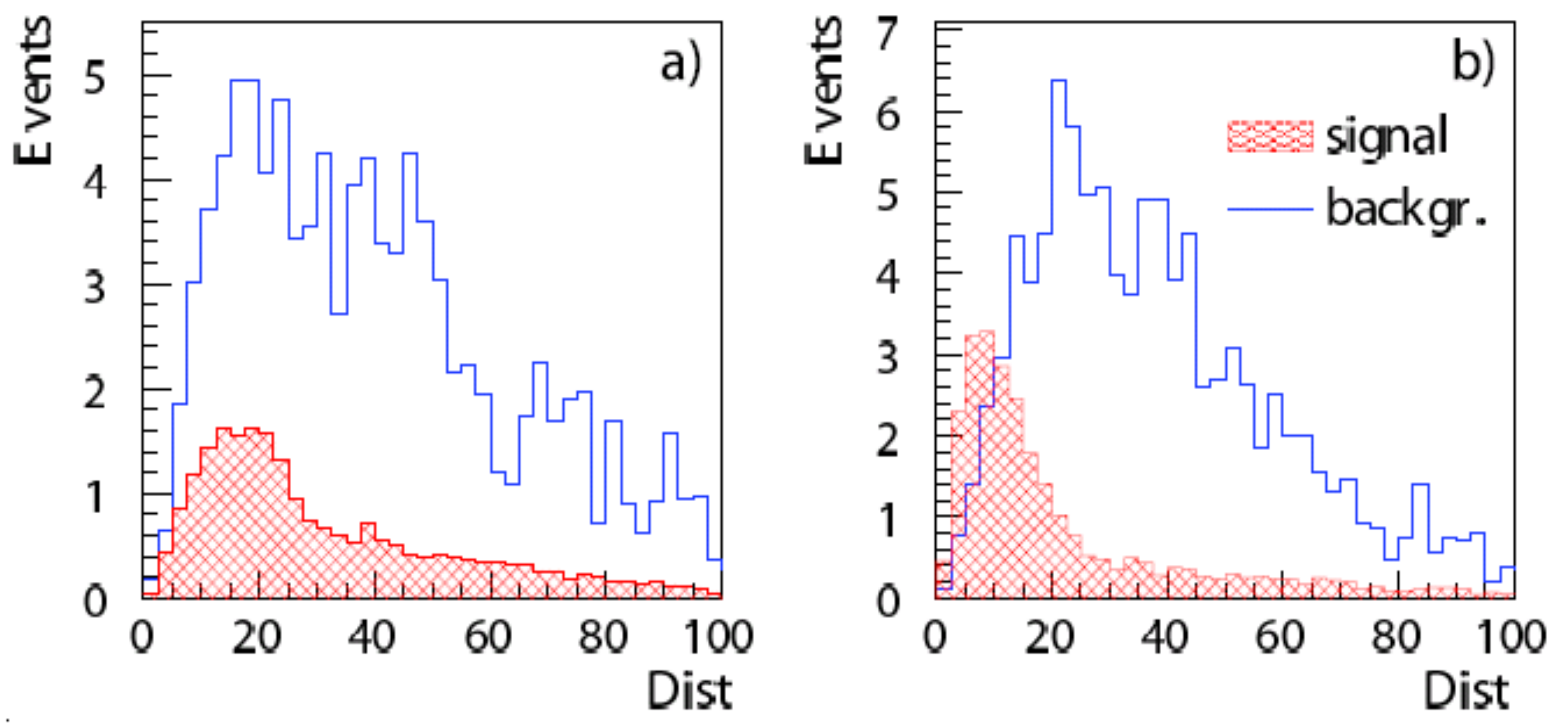


$e^+e^- \to Z^0H^0 \to$ qqbb at 0.35 TeV



T Barklow, (2005)

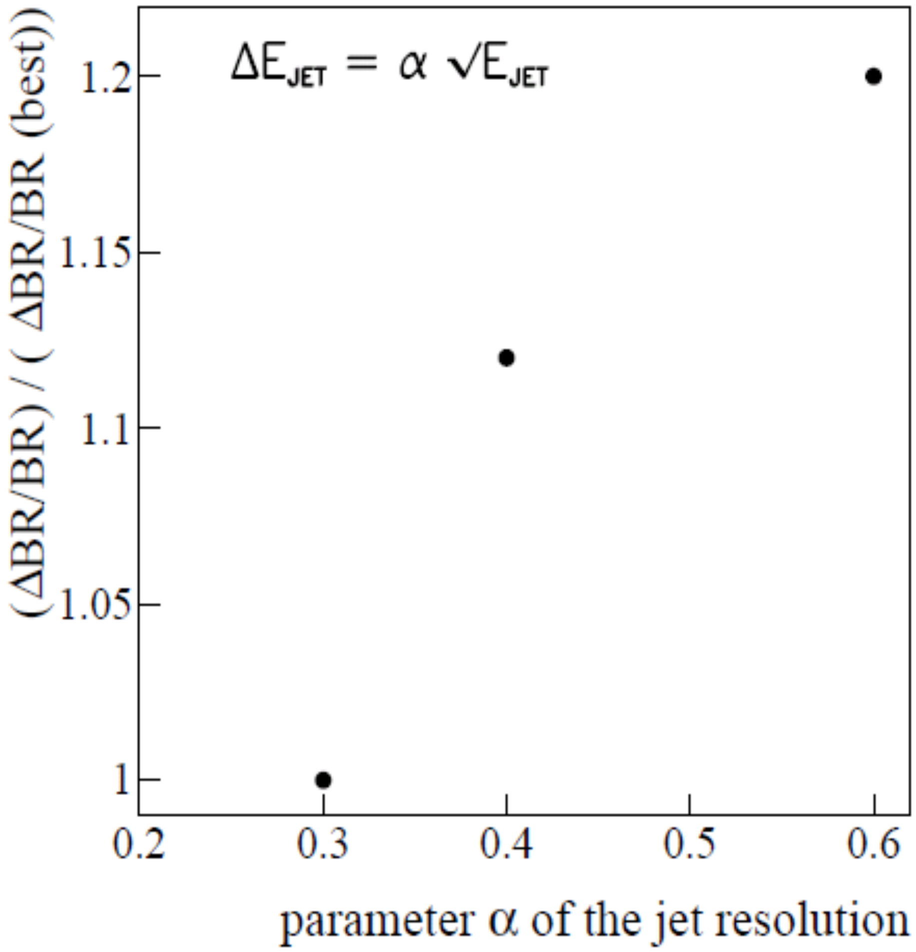
$e^+e^- \rightarrow Z^0H^0H^0 \rightarrow$ qqbbbb at 0.5 TeV

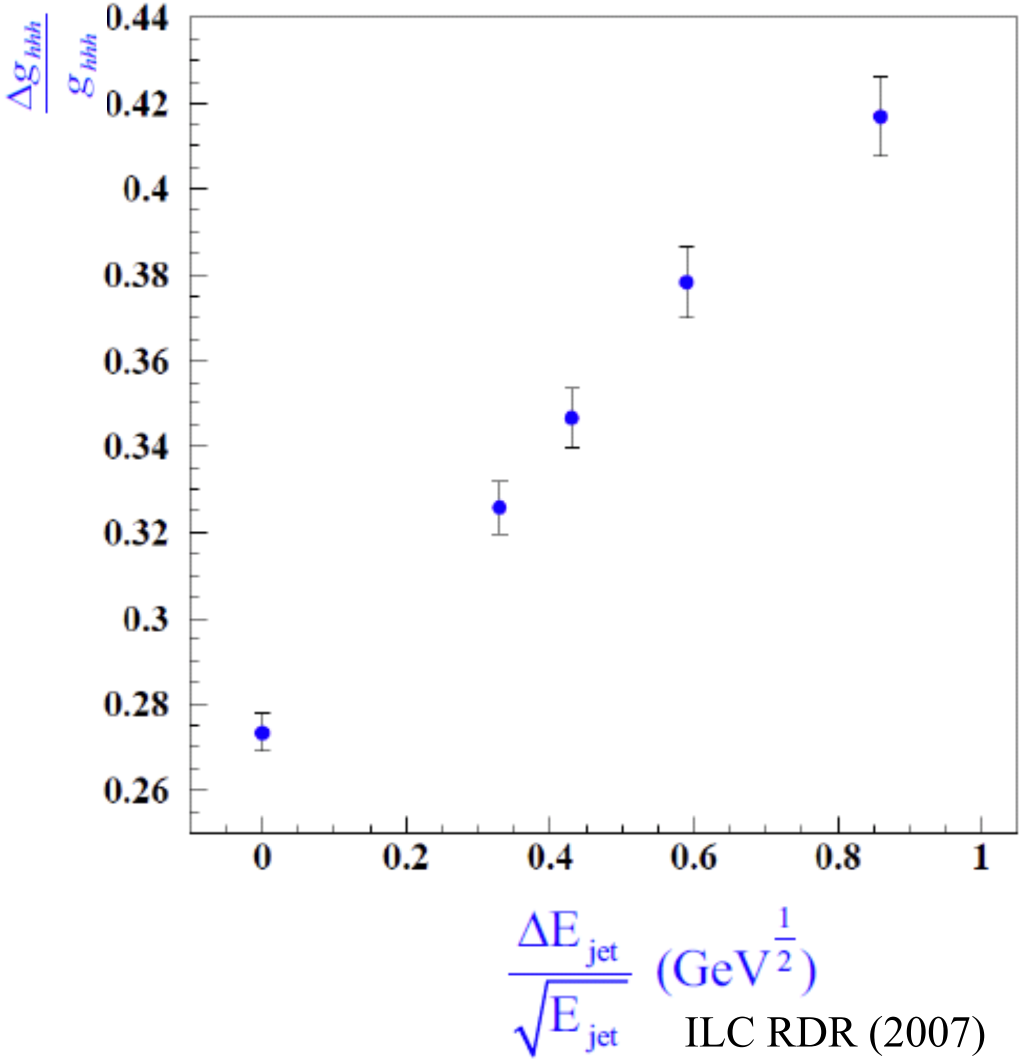


$$\sqrt{(m_{12}-m_H)^2+(m_{34}-m_H)^2+(m_{56}-m_H)^2}$$

ILC RDR (2007)

Invariant Mass Resolution



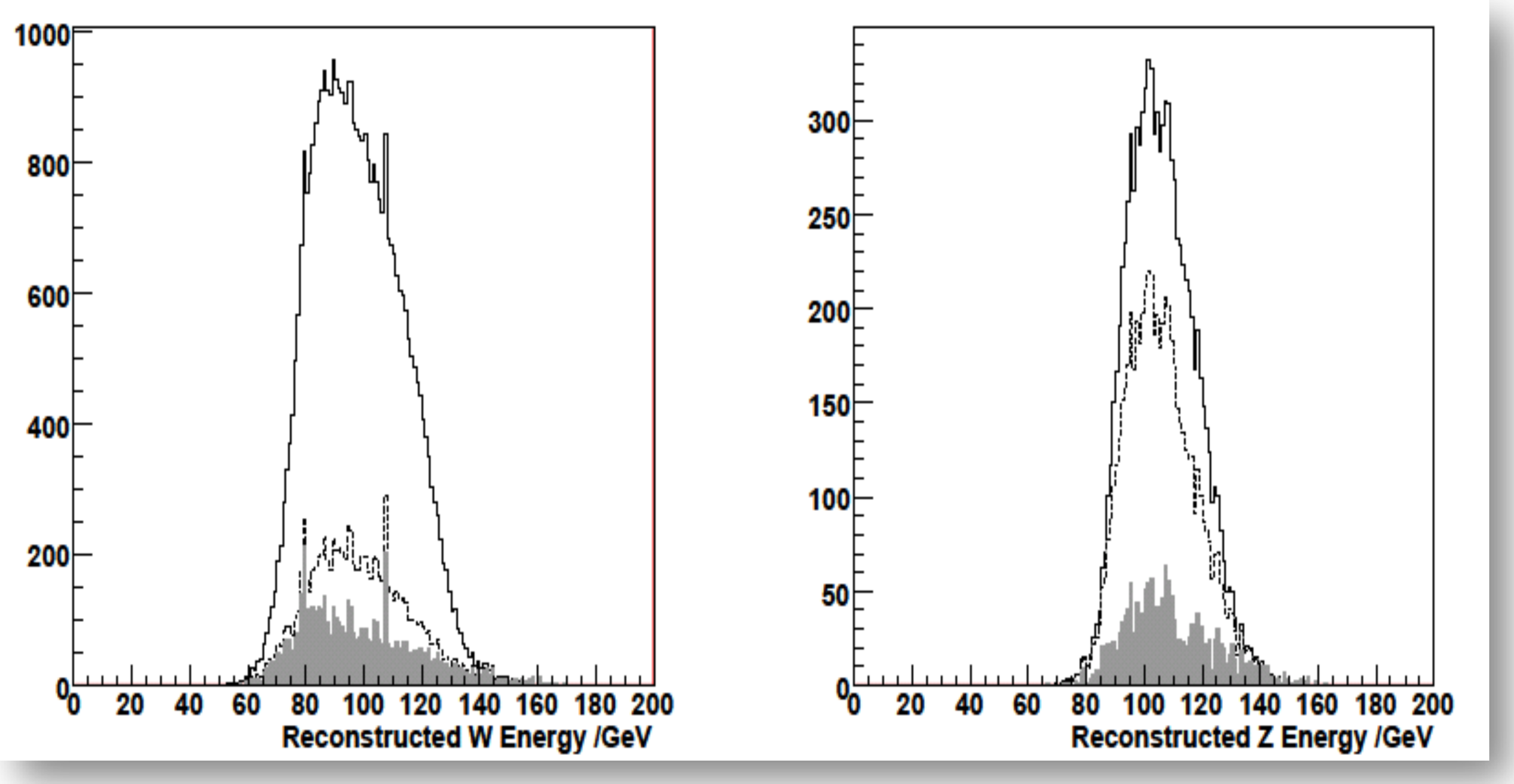


ILC RDR (2007)

Di-parton Energy Resolution at 0.5 TeV

W and Z energies for chargino and neutralino reconstruction in SiD

√s = 500 GeV

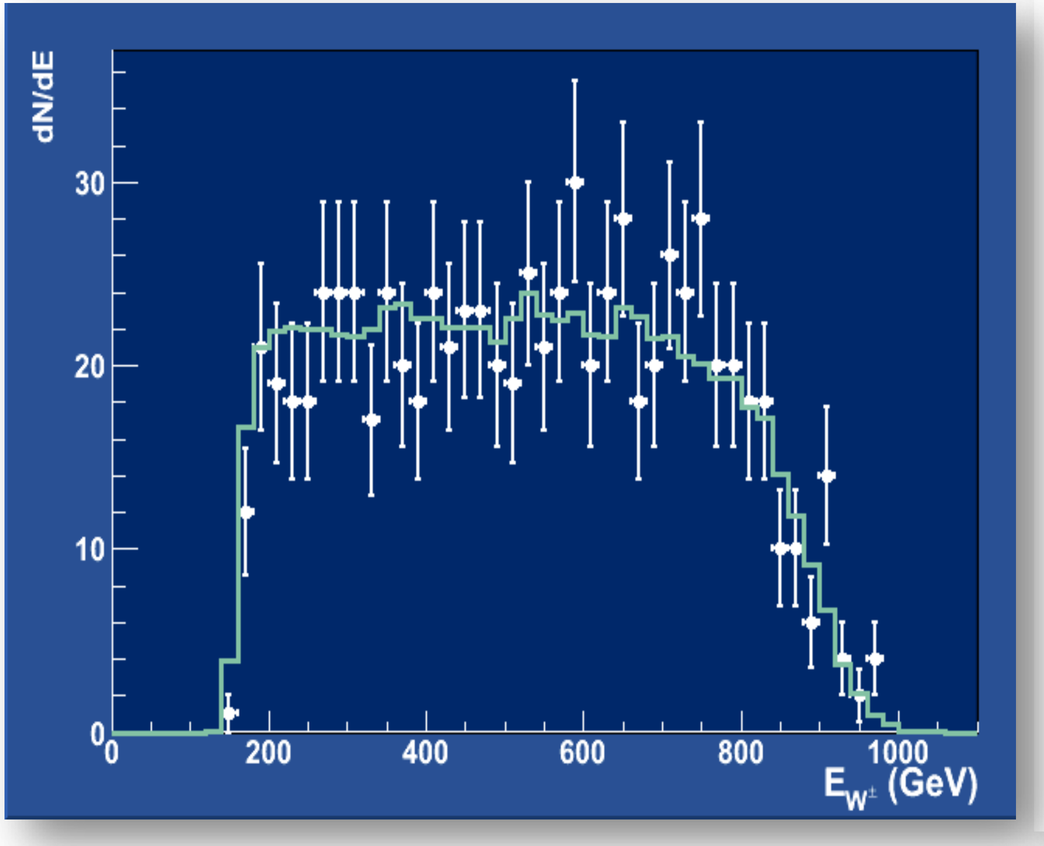


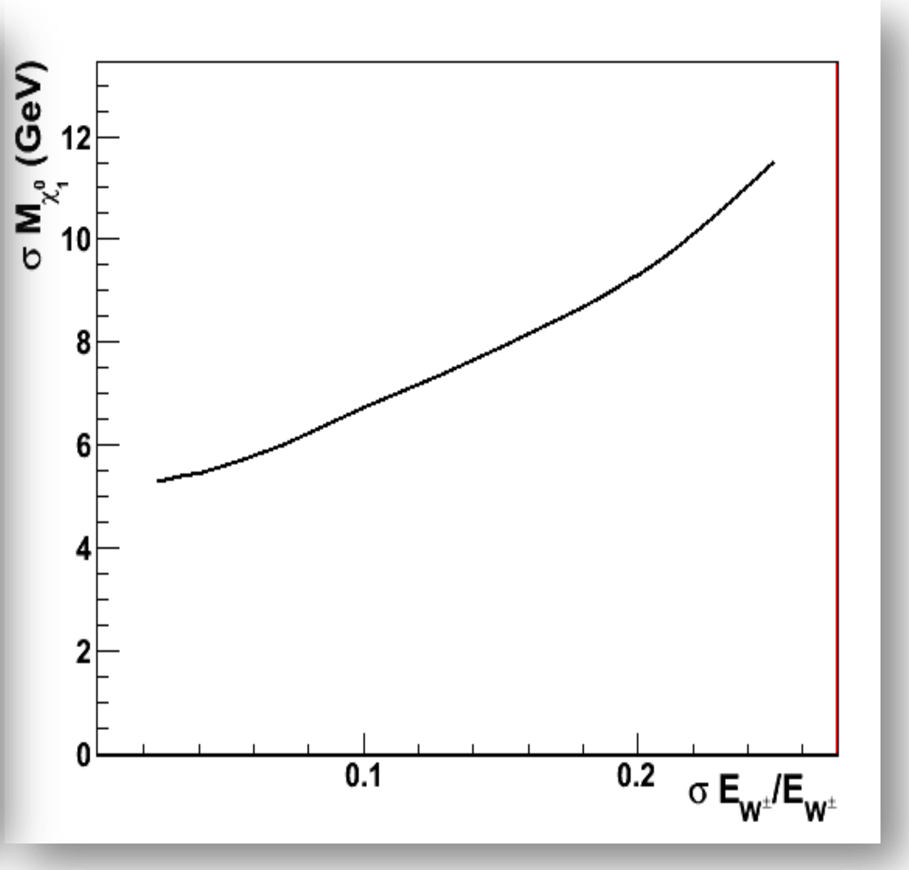
SiD LoI (2009)

Di-parton Energy Resolution at 1 - 3 TeV

$e^+e^- \rightarrow \chi^+_1\chi^-_1 \rightarrow W^\pm\chi^0_1X$

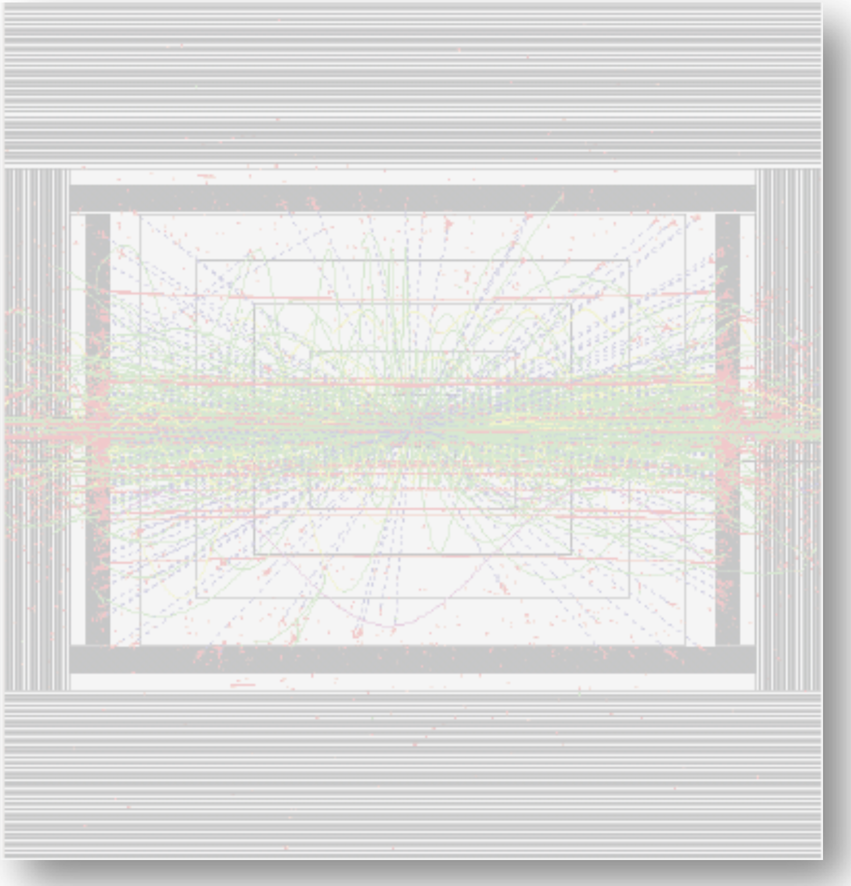
(Preliminary)





MB and JJ Blaising, CLIC09

Experimental Conditions
Machine-induced backgrounds



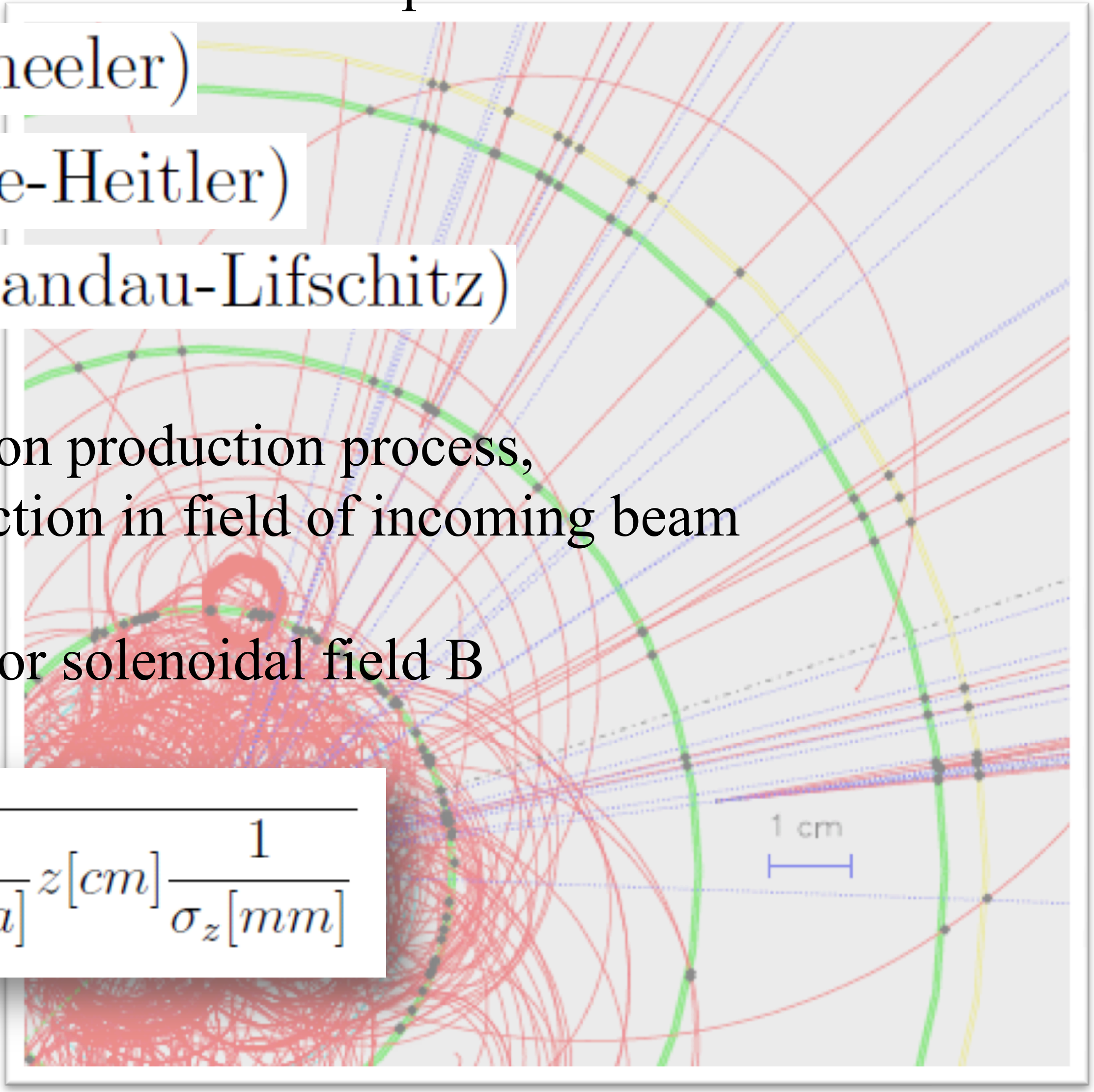
Main sources of background
in detector acceptance:

- incoherent pair production;
- γγ → hadrons, γγ → leptons;
- parallel muons;
- neutrons from dump of pairs and disrupted beam.

Incoherent pairs

Production of e+e- pairs through scattering of beam particles on (virtual) photons of incoming beam: three main processes:

- $\gamma\gamma \rightarrow e^+e^-$ (Breit-Wheeler)
- $e^\pm\gamma \rightarrow e^\pm e^+e^-$ (Bethe-Heitler)
- $e^+e^- \rightarrow e^+e^-e^+e^-$ (Landau-Lifschitz)



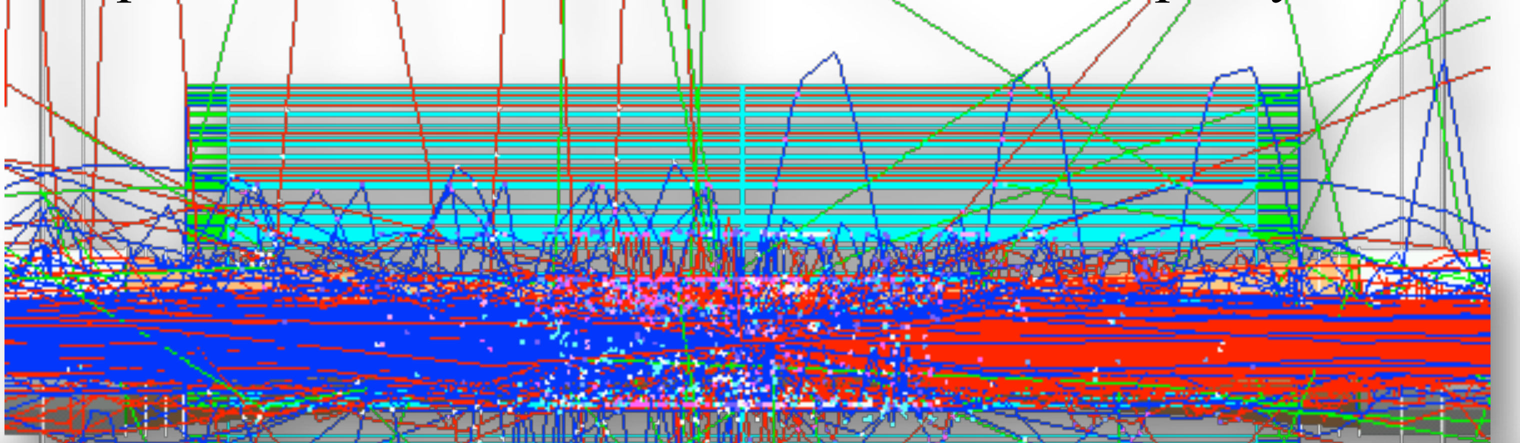
Production p_t of pairs depends on production process,
Final p_t depends on e.m. interaction in field of incoming beam

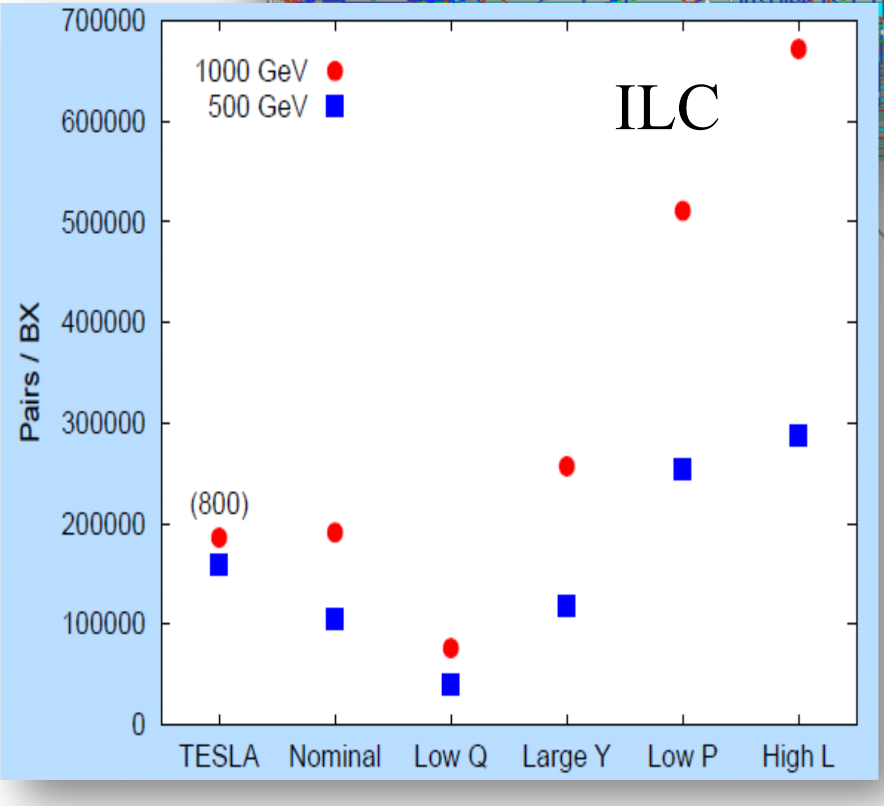
Radial reach depends on detector solenoidal field B

$$R_{max}[cm] = 0.35\sqrt{\frac{N}{10^{10}}\frac{1}{B[Tesla]}z[cm]\frac{1}{\sigma_z[mm]}}$$

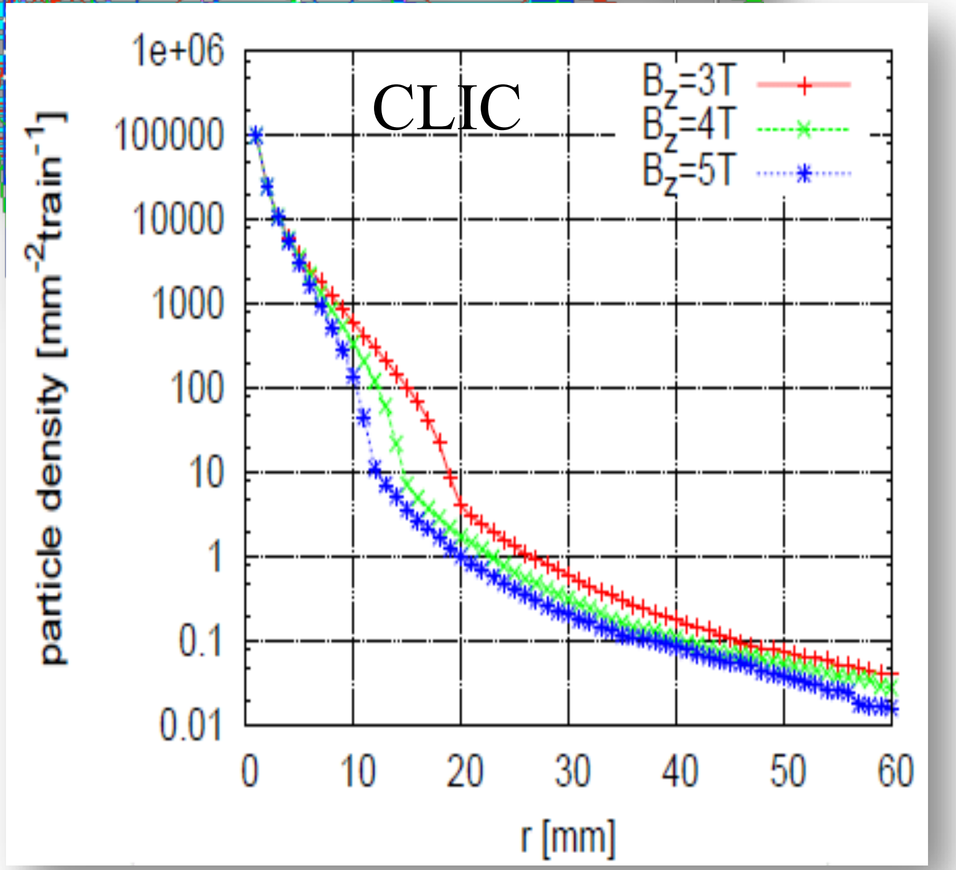
MB, V Telnov, 1997

Incoherent pairs contribute to both local detector occupancy and dose





S Gronenborn, EuroTeV 2005-003-1

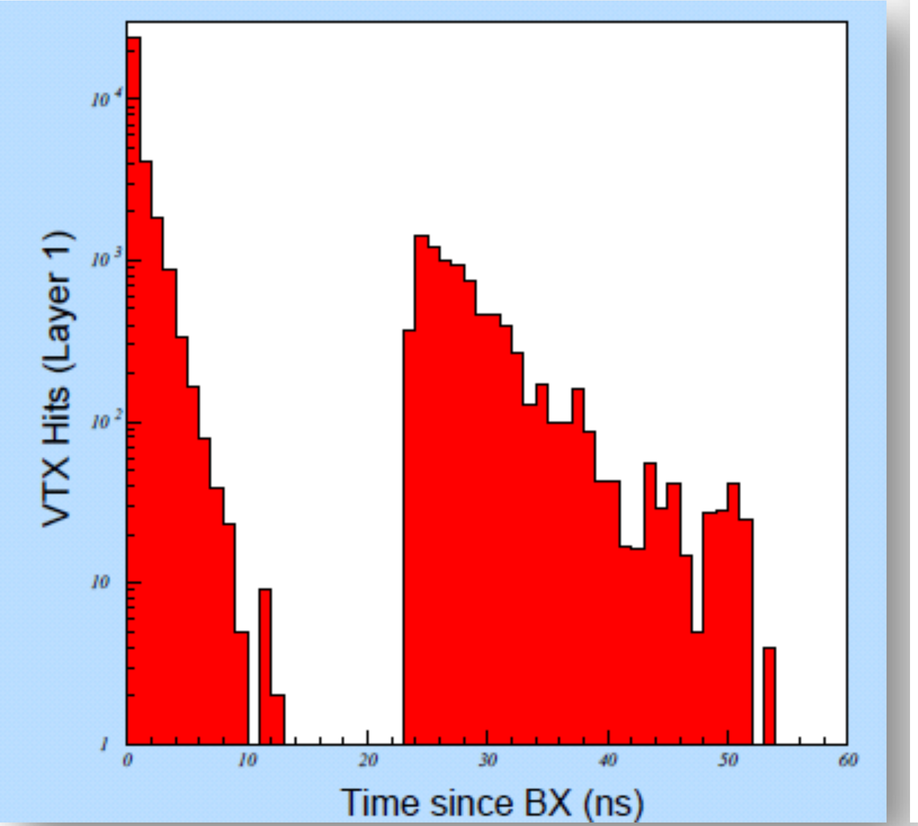


D Schulte, CLIC08

Hits from incoherent pairs at 0.5 and 3 TeV: direct and backscattering contribution

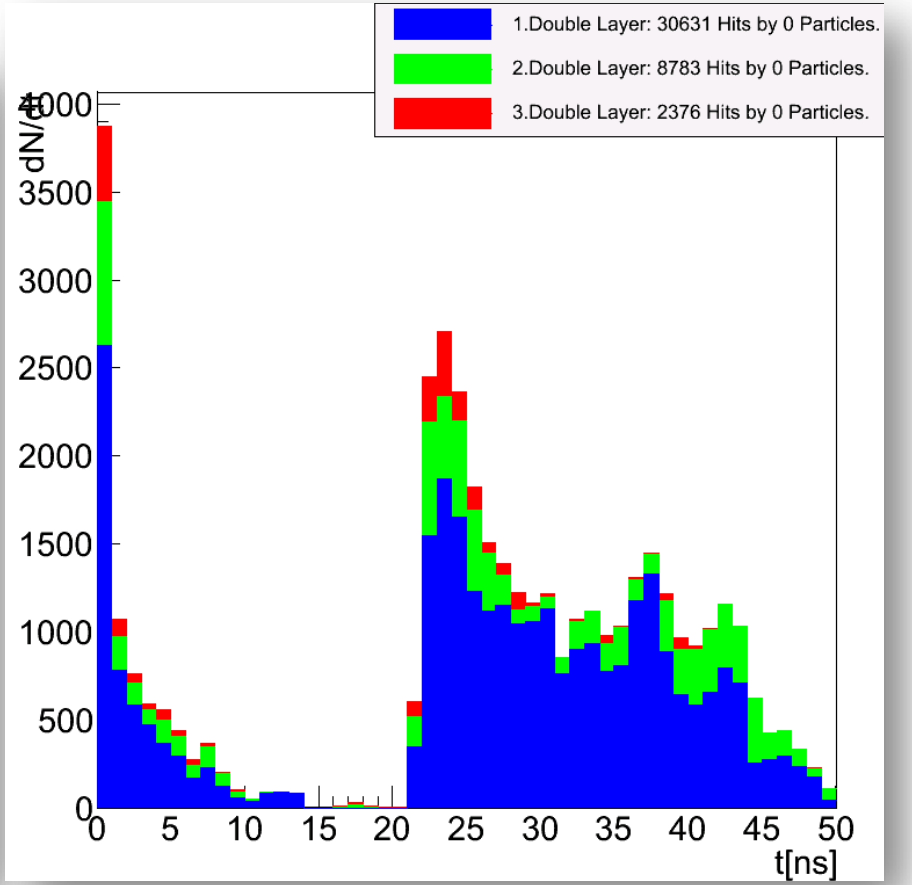
Number of hits on Vertex Tracker / BX vs time

ILC √s = 500 GeV, R = 16 mm



A Vogel(2007)

CLIC √s = 3 TeV, R = 32 mm



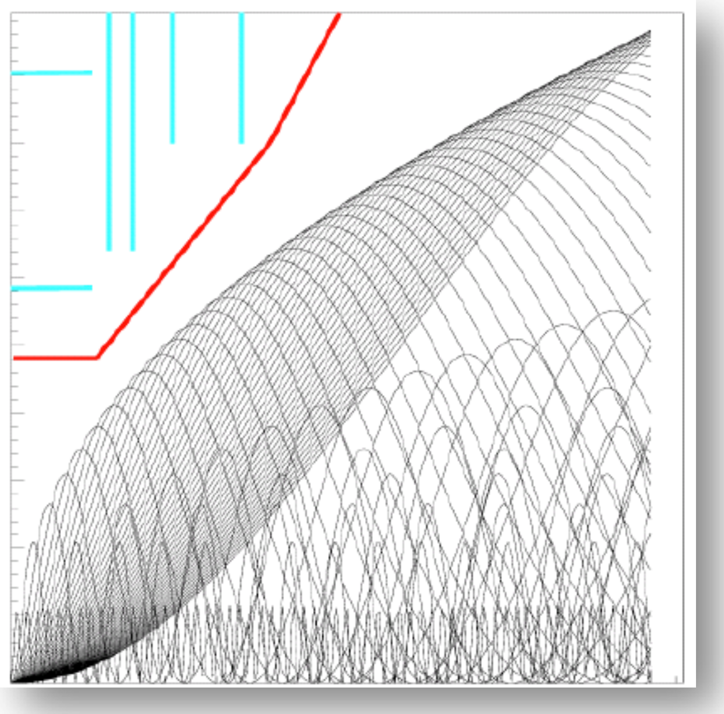
A Sailer(2009)

Intersection of deflected pair envelope with detector cylinder defines minimum radius and maximum length of innermost layer

Number of hits from pairs on innermost layer of Vertex Tracker

R_{inner} = 16 mm (ILC), 32 mm (CLIC)

	Hits cm^{-2} BX^{-1}
√s=0.5 TeV ILC Nominal	**4.4**
√s=0.5 TeV ILC low-P	**7.0**
√s=1.0 TeV ILC Nominal	**7.1**
√s=3.0 TeV CLIC	**2.0**



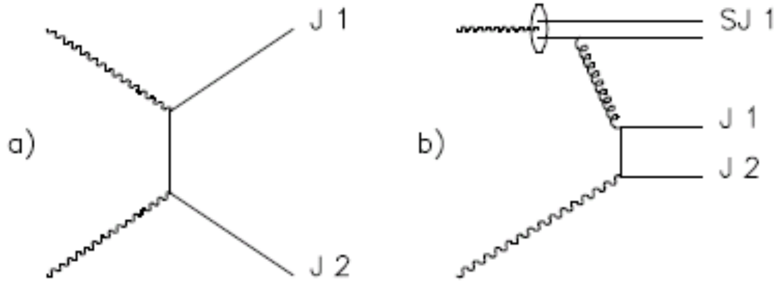
$\gamma\gamma \to$ hadrons

Hadron production from collision of beamstrahlung photons;
Rate depends on $\sqrt{s}$ and beam parameters;
Experimental data limited at LEP-2 energies, extrapolate using models

$\gamma\gamma \to$ hadrons contributes to local occupancy and energy deposition

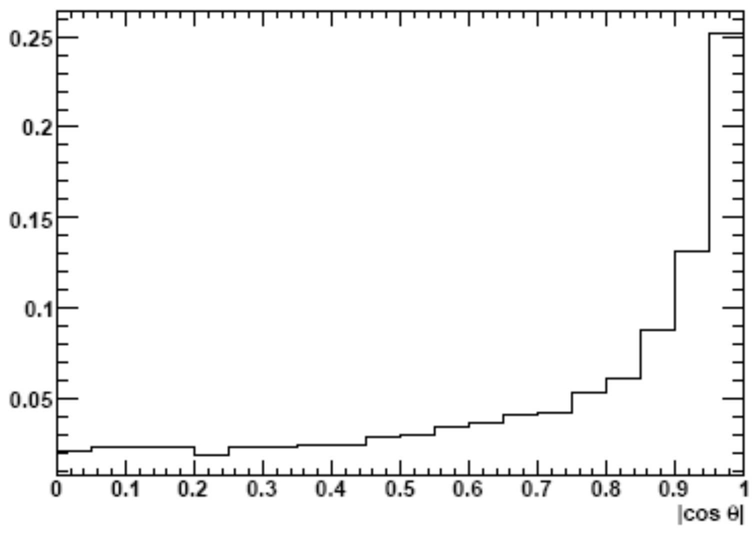
$e^+e^- \to WW\nu\nu \to H^0\nu\nu$ + hadrons at 0.35 TeV ILC

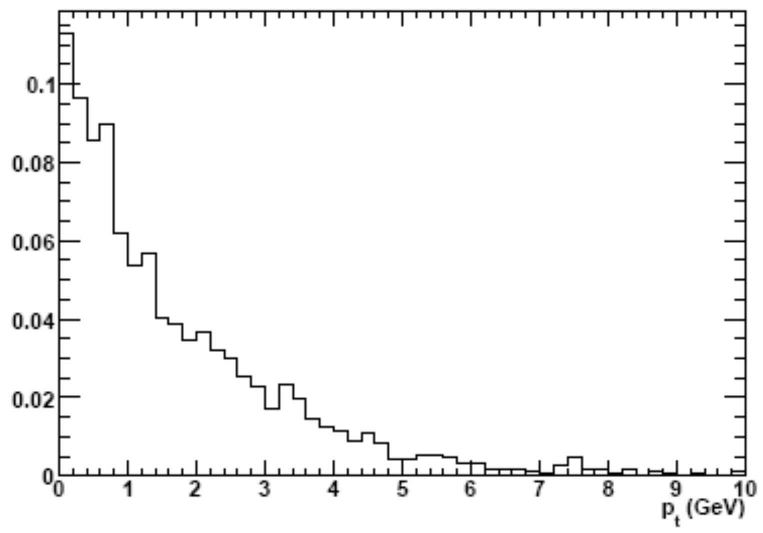
MB, Schulte, LC-PHSM-2000-052

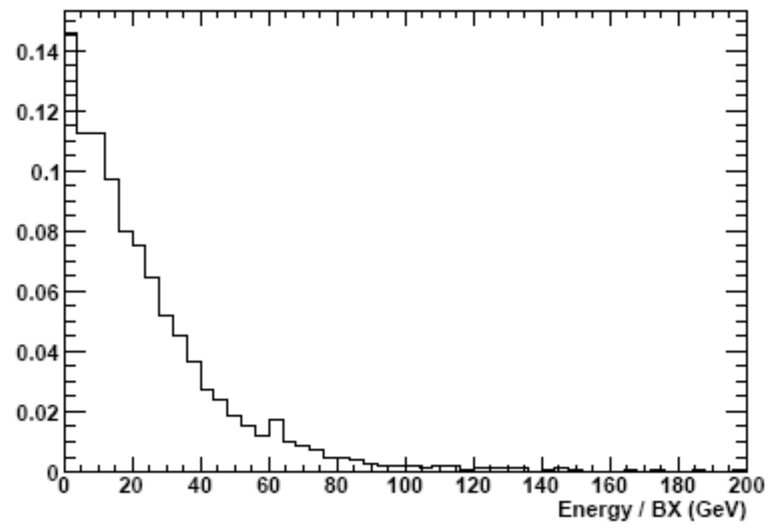


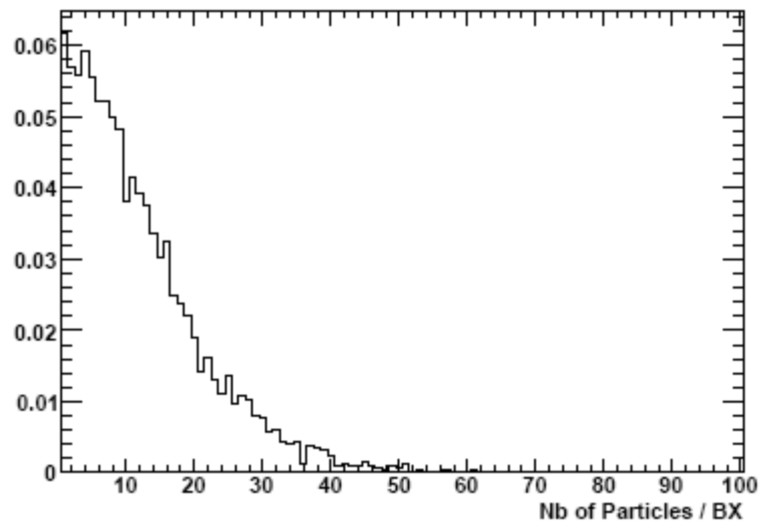
	$N_{\gamma\gamma}$ BX^{-1}
$\sqrt{s}$=0.5 TeV ILC	**0.12**
$\sqrt{s}$=3.0 TeV CLIC	**2.8**

γγ Background Characterisation at 3 TeV









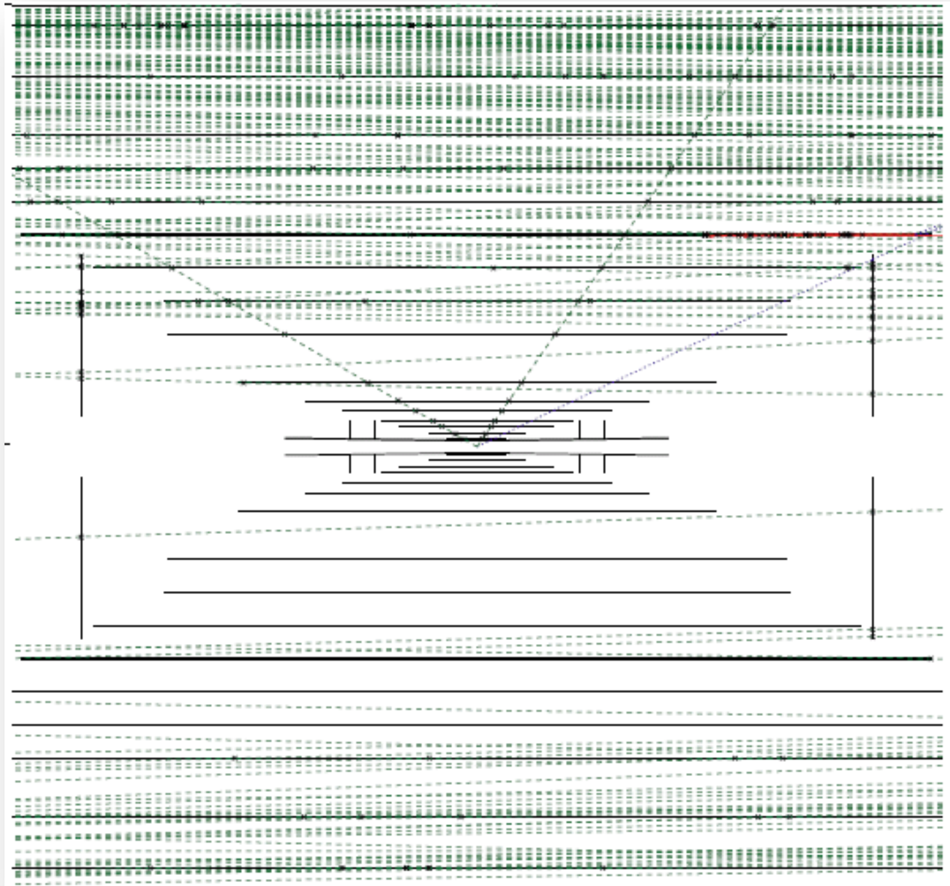
Parallel Muons

Parallel muons originate in Bethe-Heitler interactions of halo beam particles in collimators, fluxes depend on collimated fraction of bunch charge

Nb. of muons in detectors /BX assuming iron spoiler system in tunnel and 10^{-3} es in beam halo scraping collimators (but SLC experience has been up to 10^{-2})

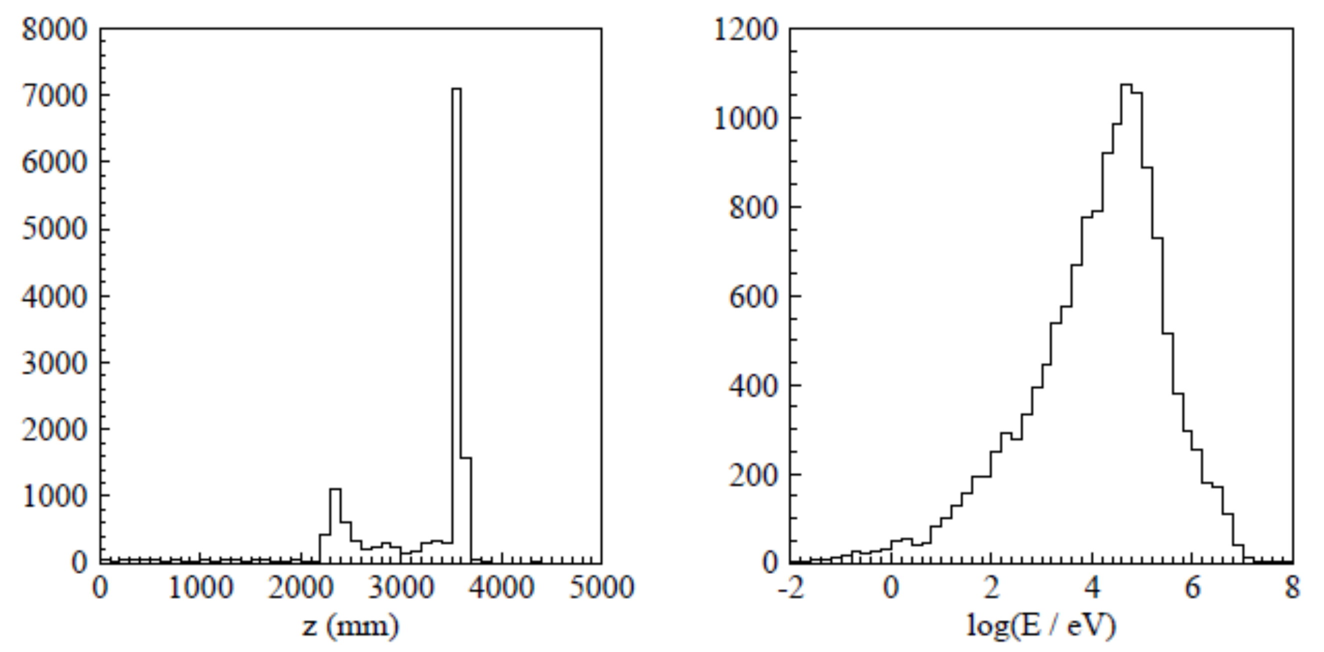
	Nb μ in Detector w/ spoilers BX^{-1}
√s = 0.5 TeV ILC	**1.7**
√s = 1.0 TeV ILC	**12.0**
√s = 3.0 TeV CLIC	**26.0**

ILC RDR (2007)
CERN-2004-005



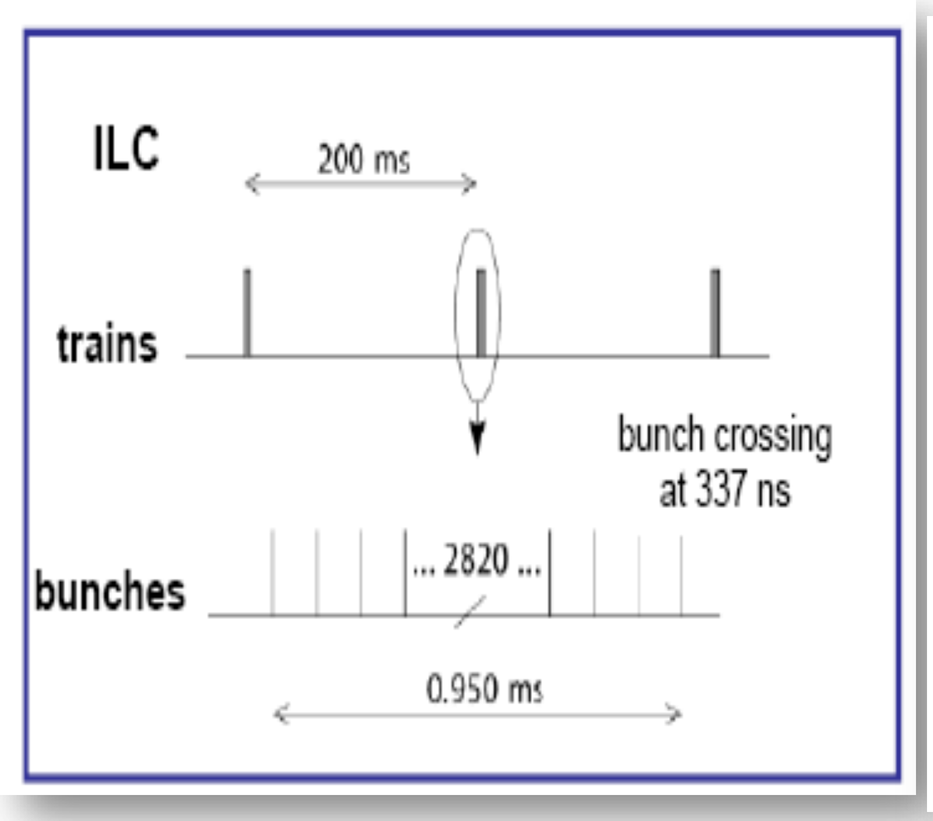
Neutrons

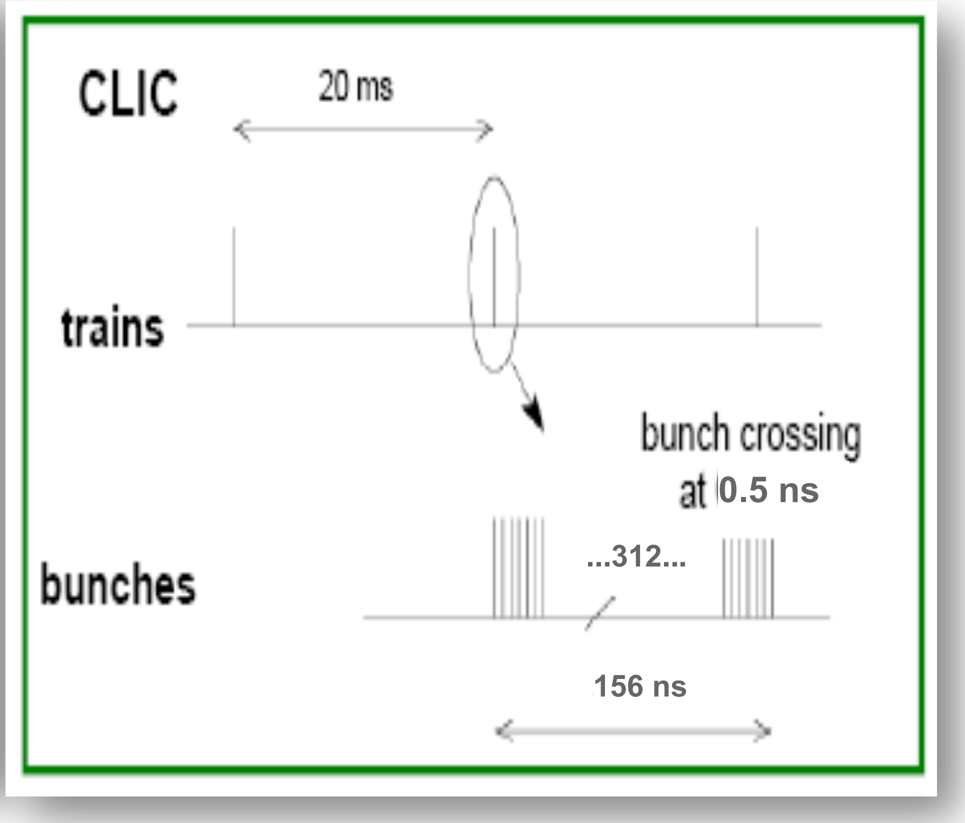
Neutrons are mostly generated through giant resonance production by dumped pairs and disrupted beam. Raw flux can be reduced by ~ 10^3 by masks, detailed simulation of actual MDI needed to get precise numbers



	n(1 MeV eq) cm^{-2} $year^{-1}$
$\sqrt{s}$ = 0.5 TeV ILC	**~ 10^{10}**
$\sqrt{s}$ = 3.0 TeV CLIC	**~5 x10^{10}**

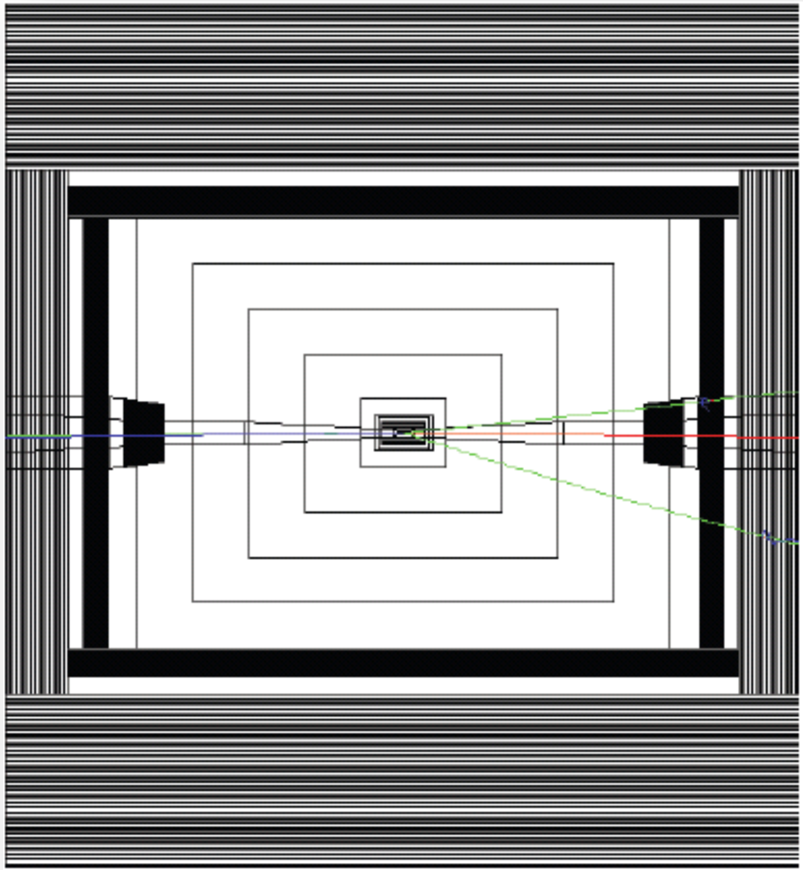
Experimental Conditions
Beam time-structure



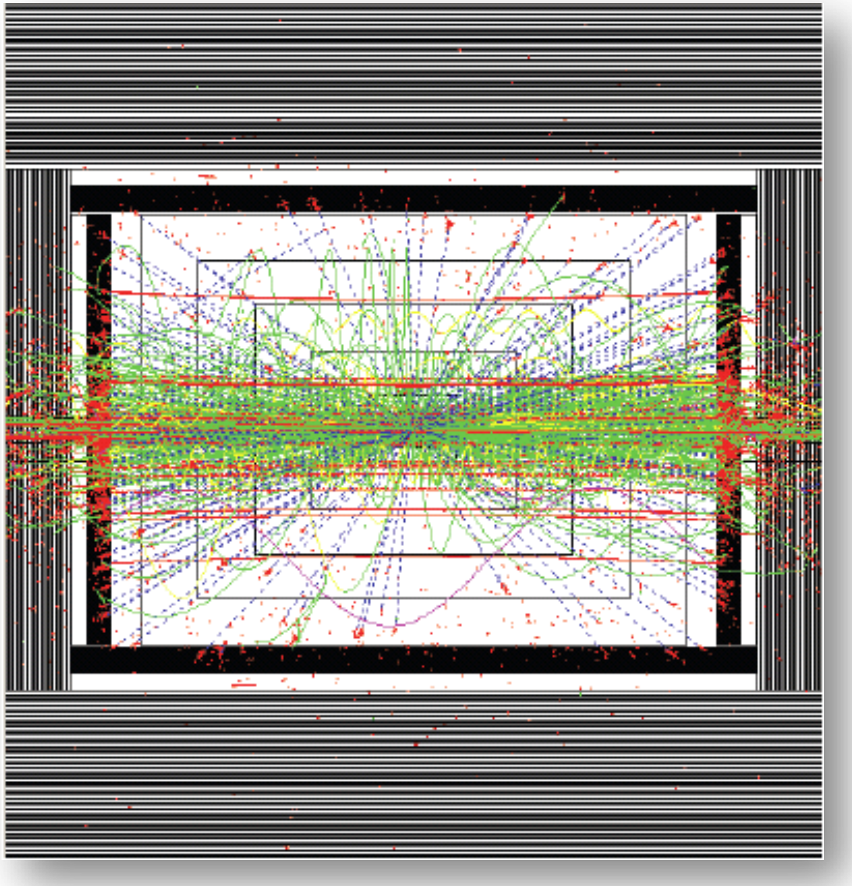


Simulated Backgrounds in Detector at ILC √s=500 GeV (SiD Simulation)

1 BX



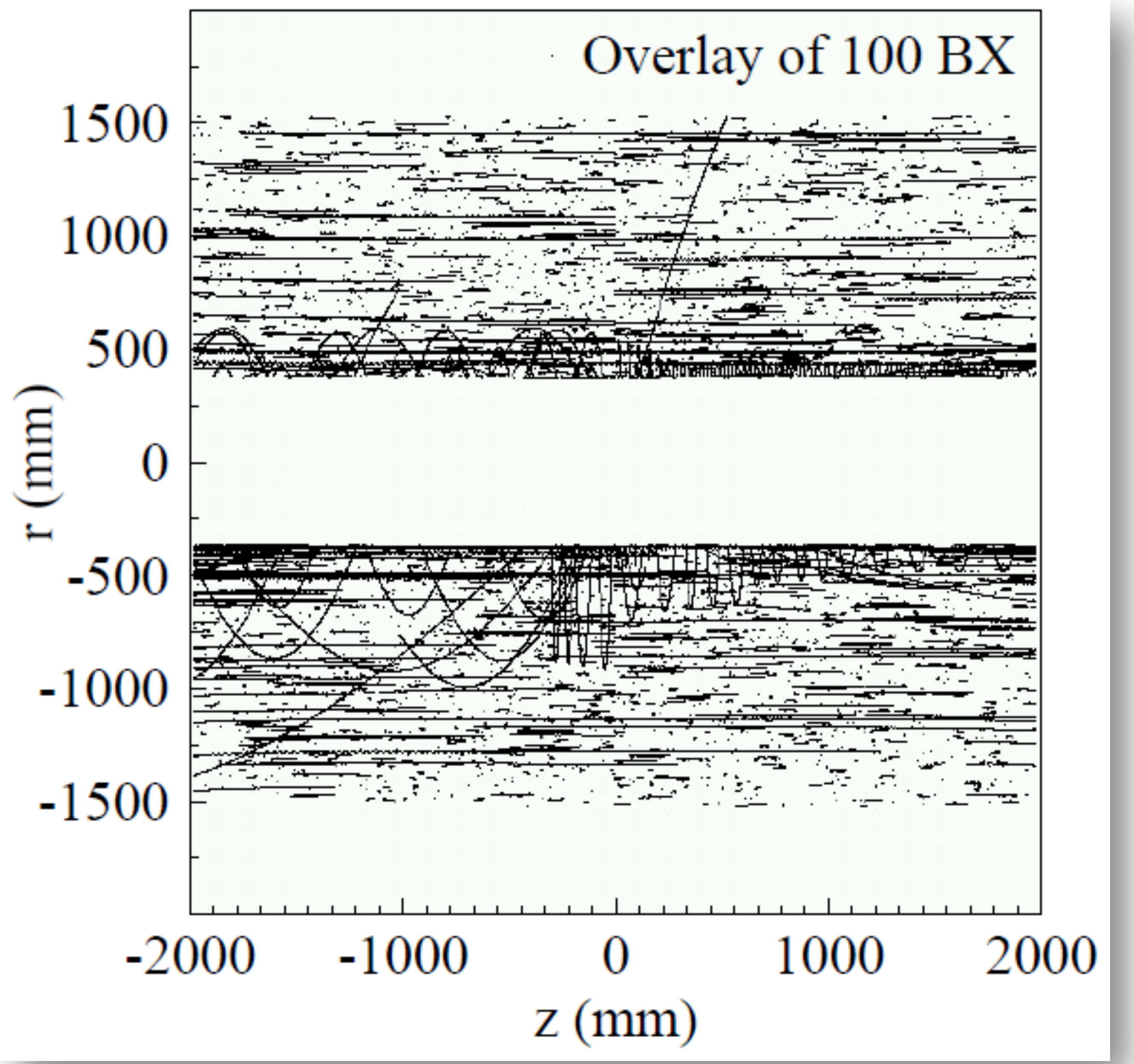
150 BX



125 tracks
920 GeV Energy

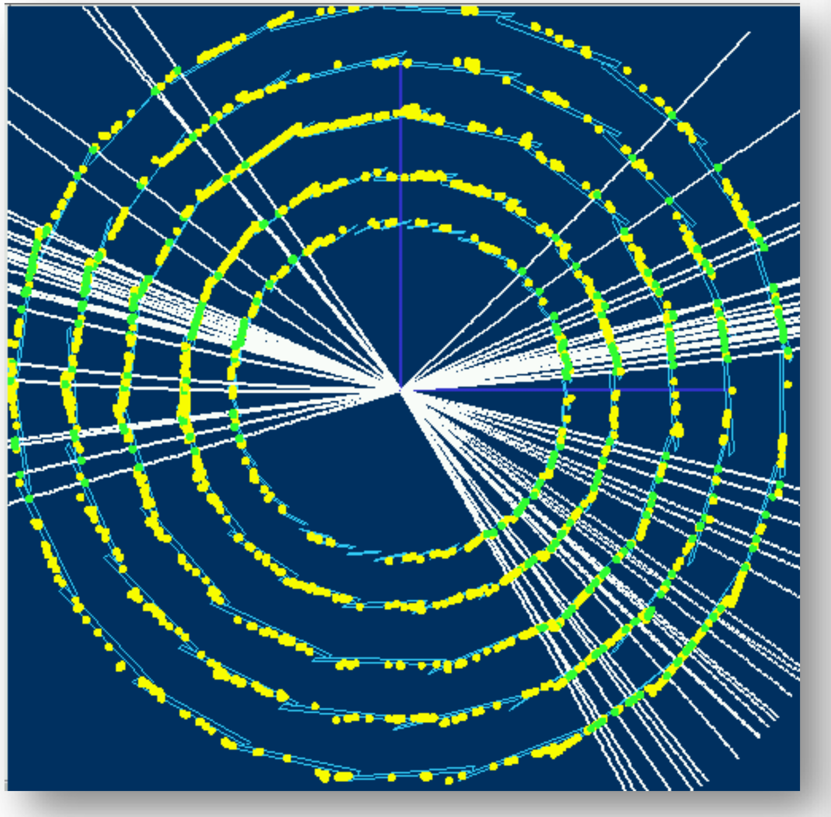
T Barklow
SiD LoI (2009)

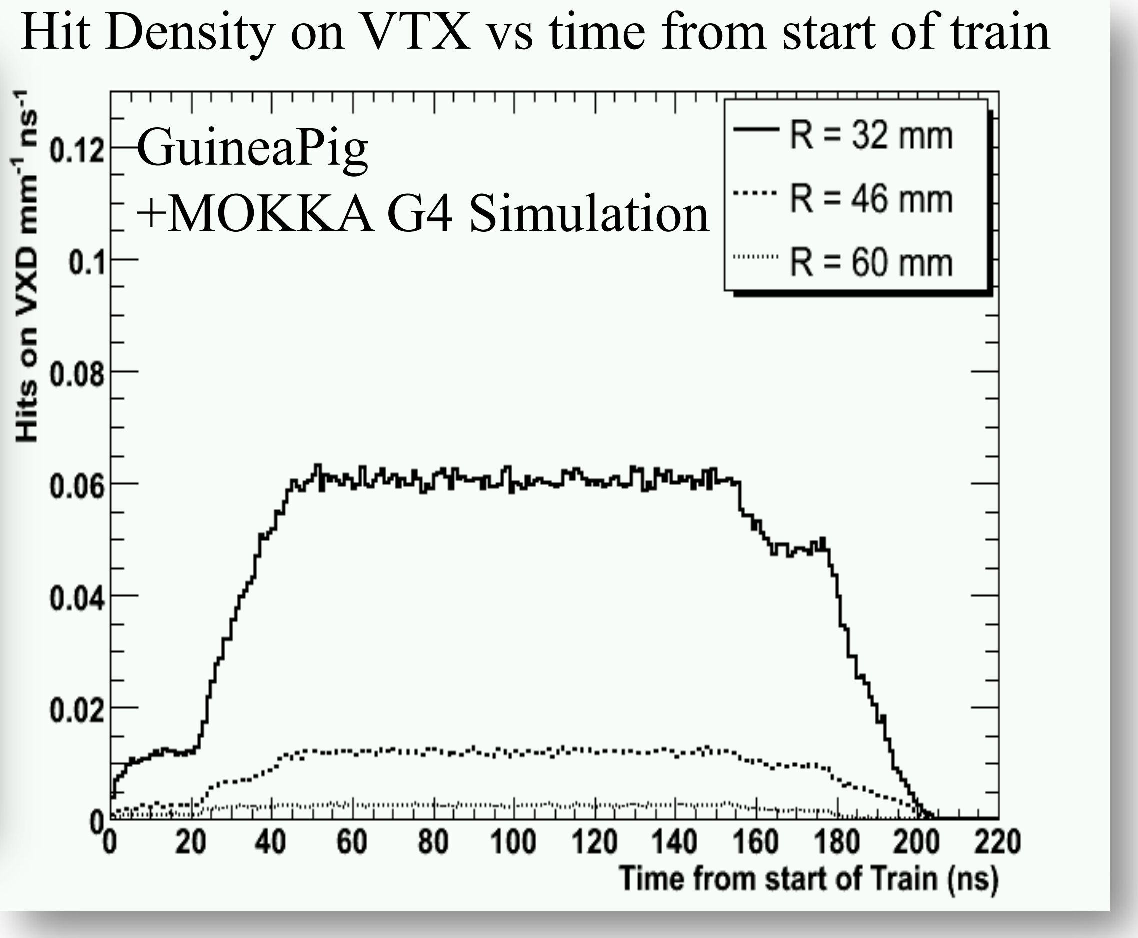
Overlay of Background in TPC at 0.5 TeV



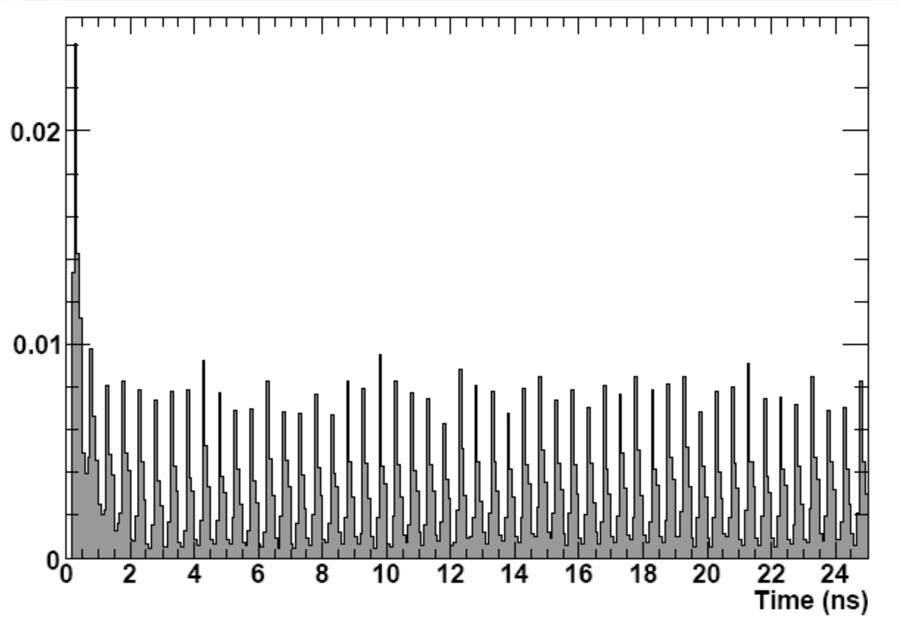
ILC RDR (2007)

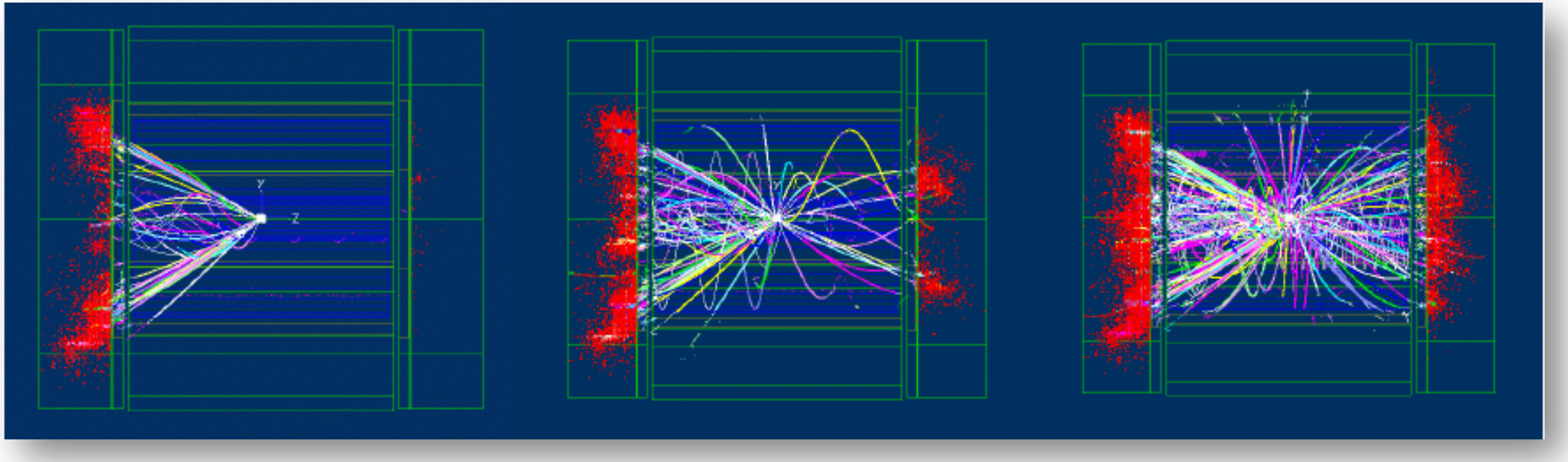
Overlay of Pair Background in Vertex Tracker at 3 TeV





Overlay of γγ Background in Detector at 3 TeV




0 BX

20 BX

60 BX