Physics Requirements for the ILC Vertex Tracker

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WWS ILC Vertex Tracker Review
October 22, 2007

Physics Scenarios for the ILC Vertex Tracker

Test the SM through precision study of the Higgs boson profile;

Investigate nature of new physics beyond the SM
and its relation with Cosmology;

Search for new phenomena through precision EW data;

Ecm (TeV)	σ_{bbbb}	$\sigma_{\tau\tau\nu\nu}$	σ_{qqqq}
0.5	15 fb	23 fb	500 fb
1.0	3.0 fb	45 fb	140 fb

Benchmarking the ILC Vertex Tracker

arXiv:hep-ex/0603010 v1 6 Mar 2006

Report to the ILC World-wide Study

Physics Benchmarks for the ILC Detectors

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This note presents a list of physics processes for benchmarking the performance of proposed ILC detectors. This list gives broad coverage of the required physics capabilities of the ILC experiments and suggests target accuracies to be achieved. A reduced list of reactions, which capture within a very economical set the main challenges put by the ILC physics program, is suggested for the early stage of benchmarking of the detector concepts.

Develop list of benchmark processes where i) ILC physics scenarios broadly covered, ii) benchmarks robust and retain wider scope, iii) detector performance manifest in direct way, iv) target performance motivated by quantitatively well-defined requirements.

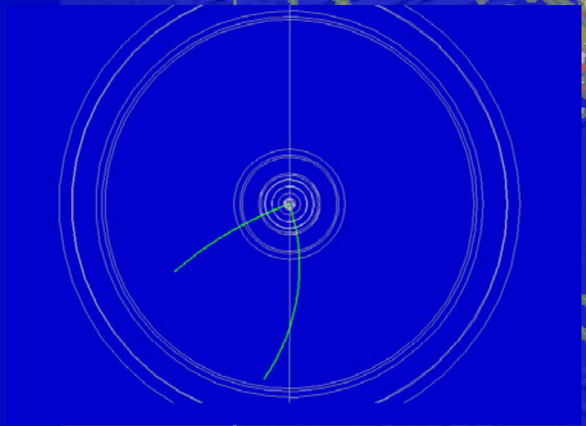
Benchmarks for the ILC Vertex Tracker

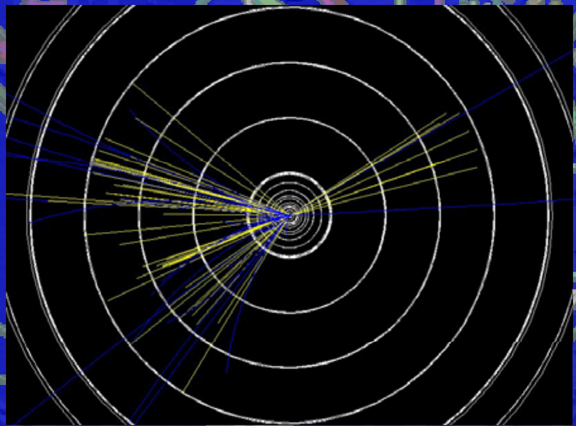
Process	Vertex	Tracking		Calorimetry		Fwd		Very Fwd	Integration					Pol.
	σ_{IP}	$\delta p/p^2$	ϵ	δE	$\delta\theta,\ \delta\phi$	Trk	Cal	θ^e_{min}	δE_{jet}	M_{jj}	ℓ-Id	V^0-Id	$Q_{jet/vtx}$	
$ee \to Zh \to \ell\ell X$		x									x			
$ee \to Zh \to jjbb$	x	x	x			x				x	x			
$ee \to Zh, h \to bb/cc/\tau\tau$	x		x							x	x			
$ee \to Zh, h \to WW$	x		x		x				x	x	x			
$ee \to Zh,\ h \to \mu\mu$	x	x									x			
$ee \to Zh,\ h \to \gamma\gamma$				x	x		x							
$ee \to Zh, h \to invisible$			x			x	x							
$ee \to \nu\nu h$	x	x	x	x			x			x	x			
$ee \to tth$	x	x	x	x	x		x	x	x		x			
$ee \to Zhh,\ \nu\nu hh$	x	x	x	x	x	x	x		x	x	x	x	x	x
$ee \to WW$										x			x	
$ee \to \nu\nu WW/ZZ$						x	x		x	x	x			
$ee \to \tilde{e}_R\tilde{e}_R$ (Point 1)		x						x			x			x
$ee \to \tilde{\tau}_1\tilde{\tau}_1$	x	x						x						
$ee \to \tilde{t}_1\tilde{t}_1$	x	x							x	x		x		
$ee \to \tilde{\tau}_1\tilde{\tau}_1$ (Point 3)	x	x			x	x	x	x	x					
$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3$ (Point 5)									x	x				
$ee \to HA \to bbbb$	x	x								x	x			
$ee \to \tilde{\tau}_1\tilde{\tau}_1$			x											
$\chi^0_1 \to \gamma + \not{E}$					x									
$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$			x					x						
$ee \to tt \to 6\ jets$	x		x						x	x	x			
$ee \to ff\ [e, \mu, \tau; b, c]$	x		x				x		x		x		x	x
$ee \to \gamma G$ (ADD)				x	x			x						x
$ee \to KK \to f\bar{f}$		x									x			
$ee \to ee_{fwd}$						x	x	x						
$ee \to Z\gamma$		x		x	x	x	x							

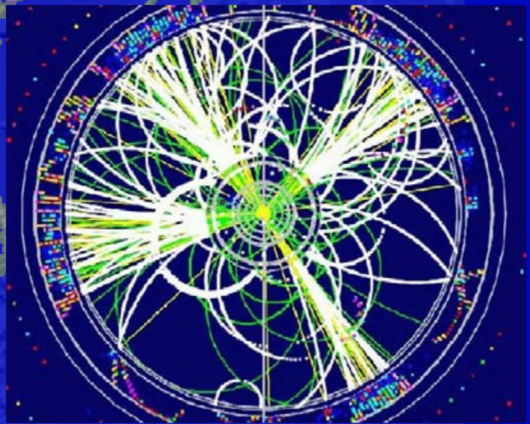
ILC Physics Signatures

ILC Physics program has possibly the broadest range of particle kinematics and event topologies;

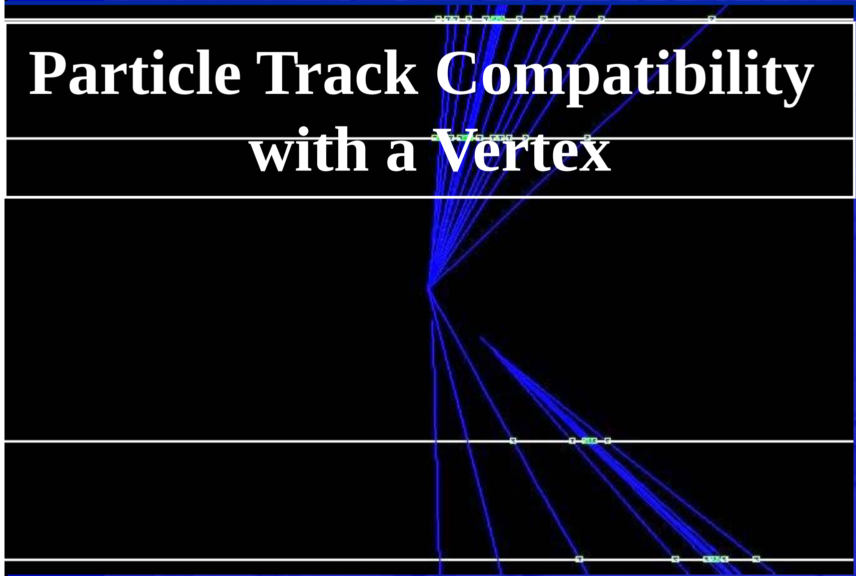
Within a single physics scenario, DM-motivated Supersymmetry, below are some of the signal signatures which need to be measured with O(0.1 - 1%) accuracy:





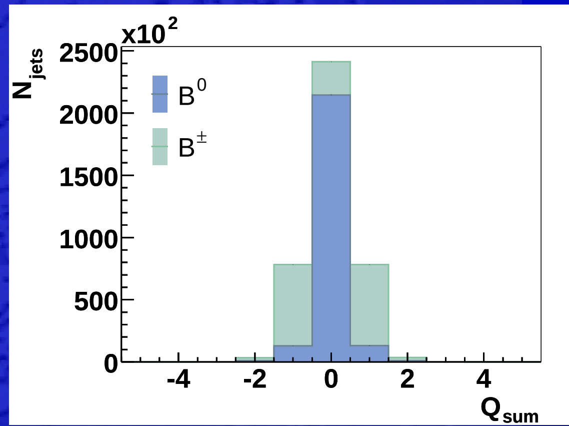


Physics Objects from the ILC Vertex Tracker

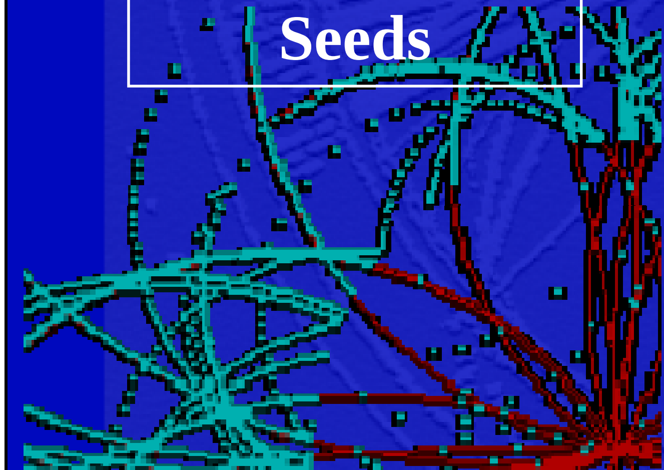


Particle Track Compatibility with a Vertex

Vertex Charge

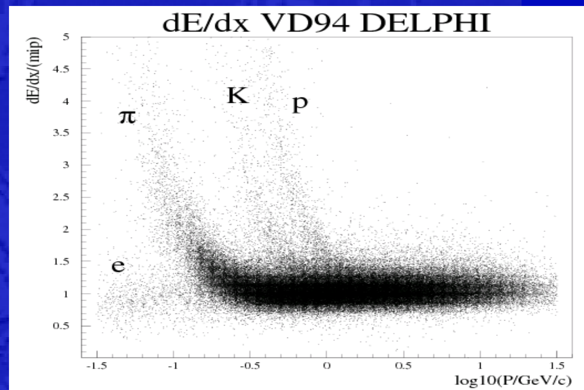


Particle Track Seeds



Charged Particle Momentum

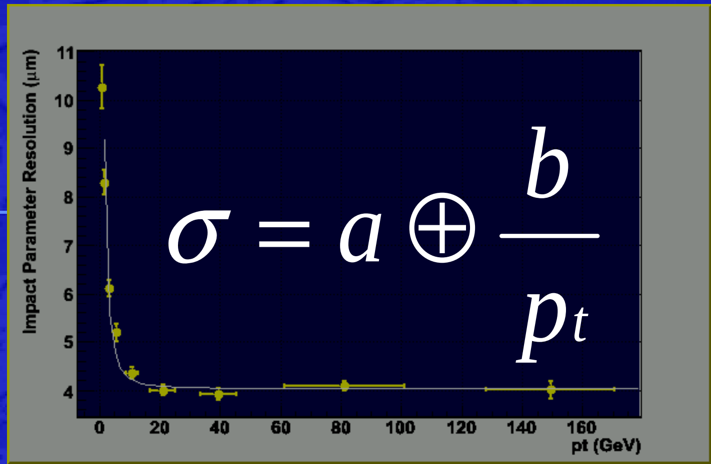
Charged Particle Mass



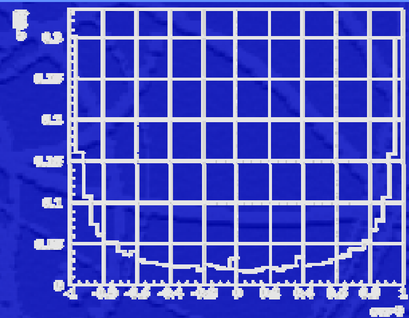
Requirements for ILC Vertex Tracker

Asymptotic
I.P. Resolution [*a*]

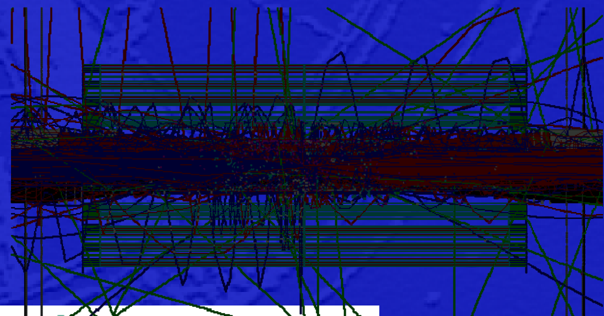
Multiple Scattering
I.P. Term [*b*]



Polar Angle Coverage



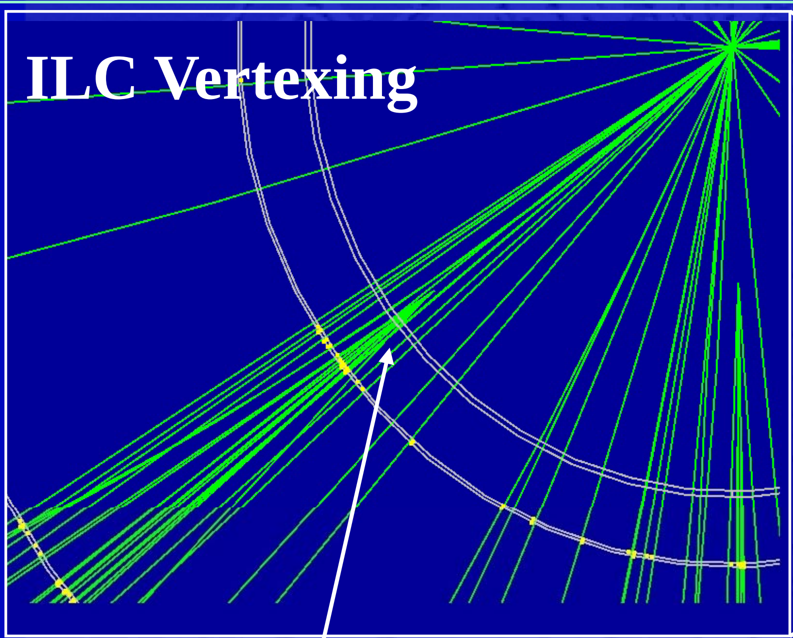
Space / Time
Granularity

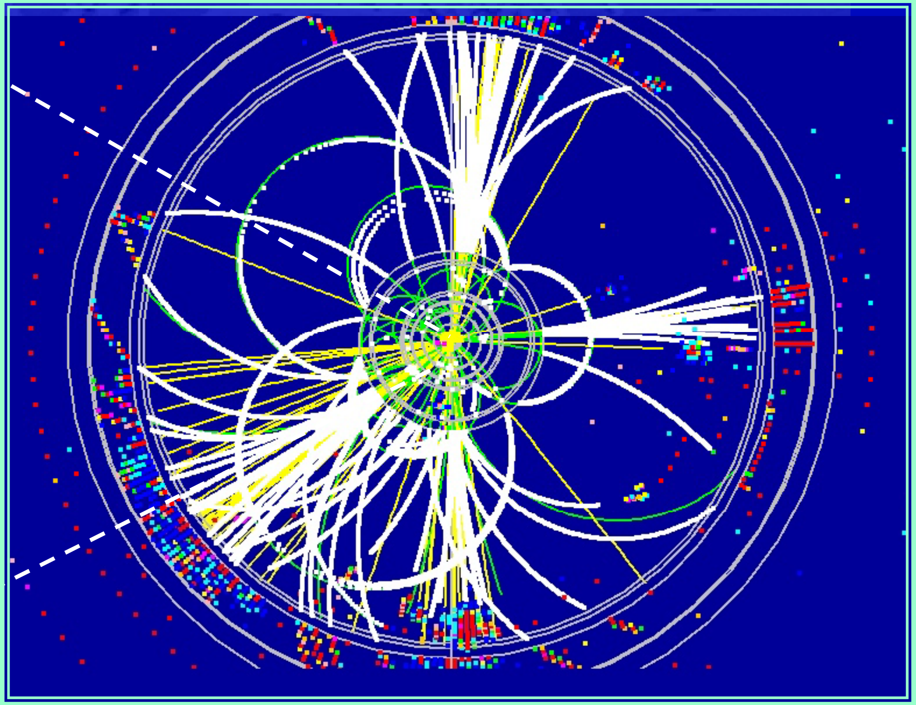


The Physics Matrix

	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}		$e^+e^- \rightarrow HHZ, HH\nu\nu$
Space/Time Granularity	**Bkg**	**Bkg**	$\sigma(e^+e^- \rightarrow bb, cc)$ **Bkg**

Requirements for ILC Vertexing





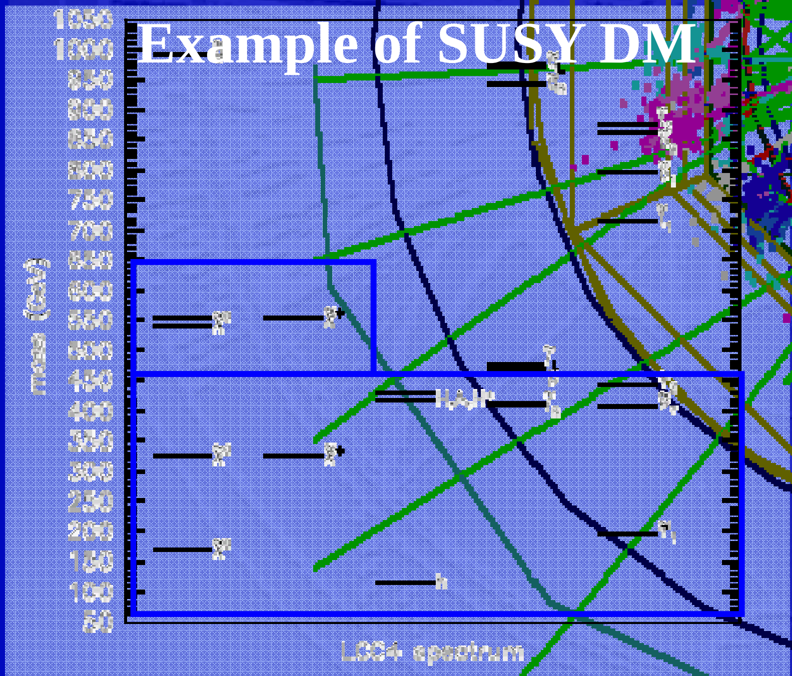
$\sigma_{ip} = a \oplus b / p_t$	a (µm)	b (µm GeV)
LEP	25	70
SLD	8	33
LHC	12	70
RHIC II	14	12
ILC	5	10

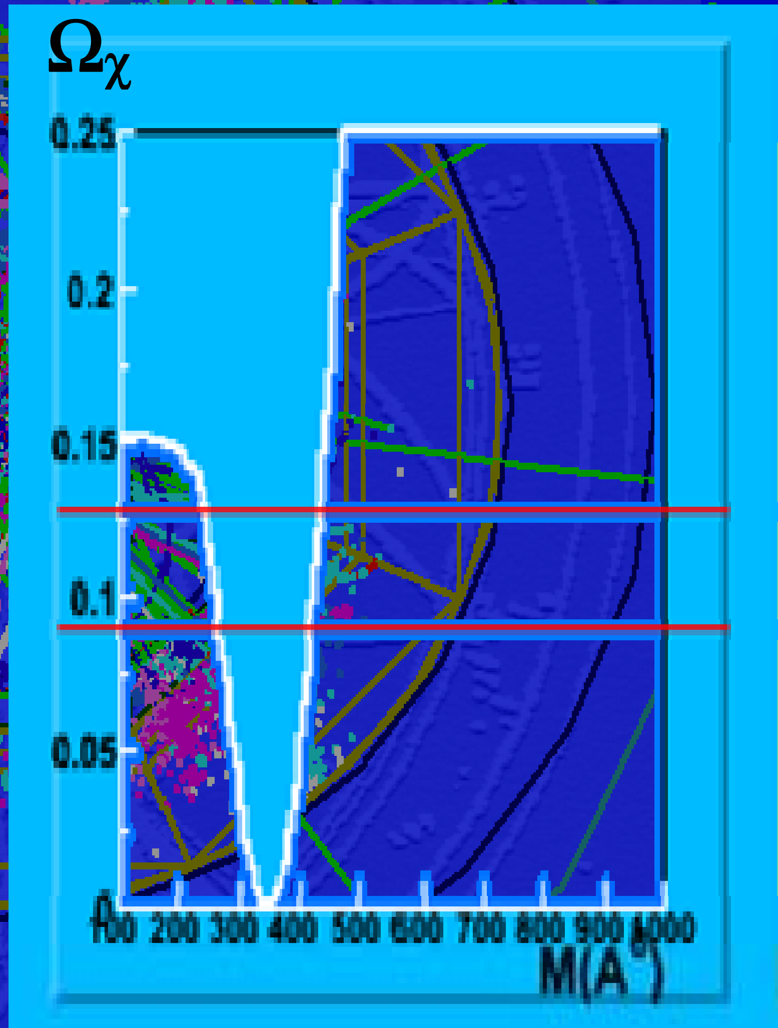
Asymptotic I.P. Resolution

Vertex Tracker, $e^+e^- \rightarrow H^0A^0$ and Dark Matter

Understanding the nature of **Dark Matter** in the Universe and match the accuracy on its relic density from satellite expts with collider data requires highly accurate determinations of masses and couplings of new particles responsible for DM and its annihilation in early Universe:

Example of SUSY DM

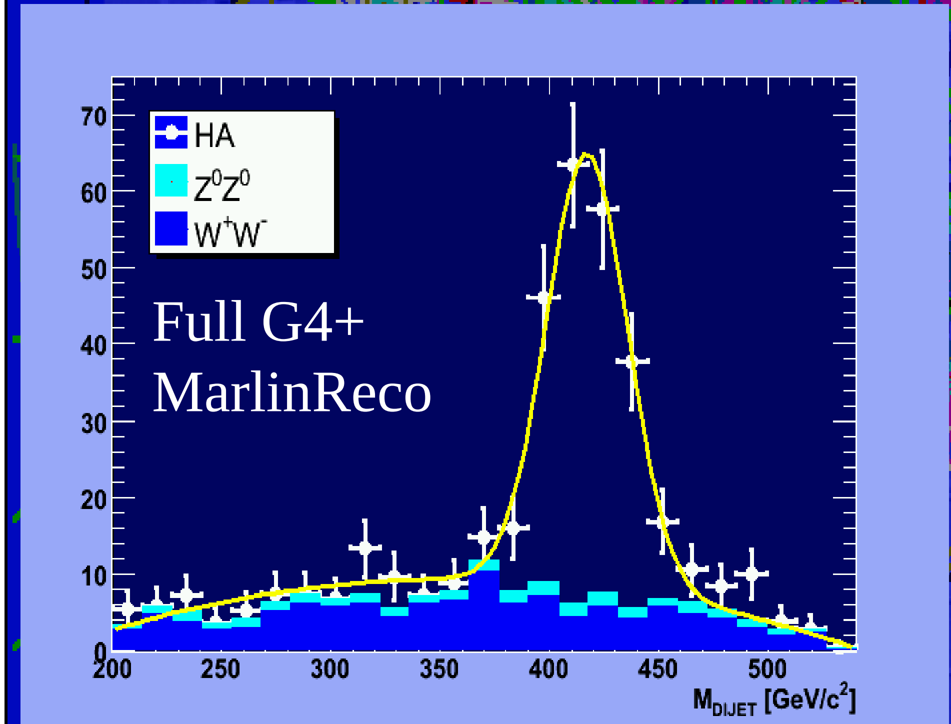


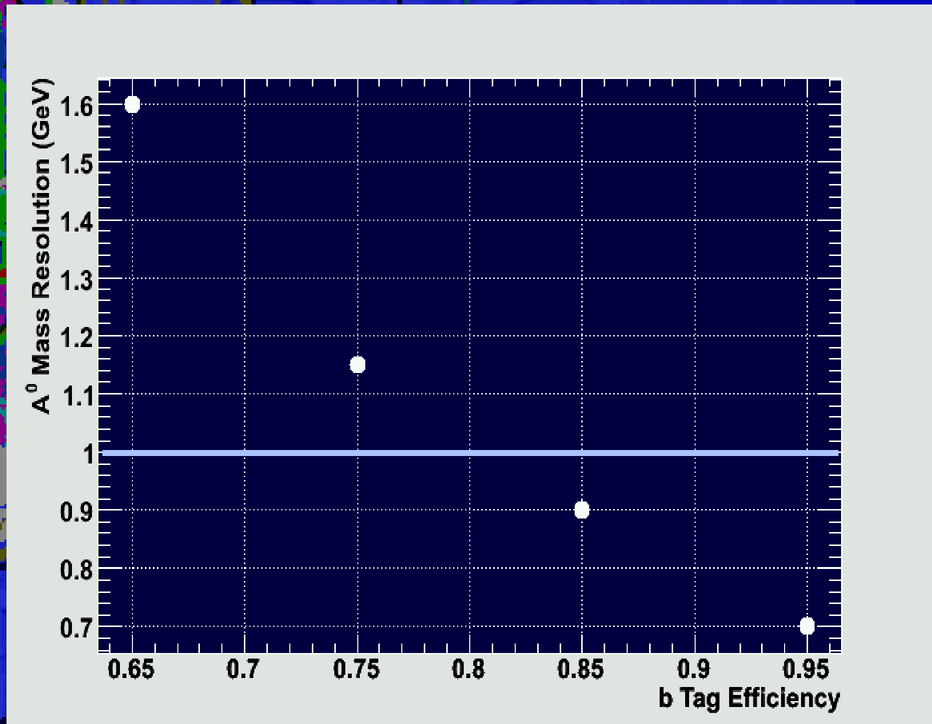


$e^+e^- \rightarrow H^0A^0 \rightarrow bbbb, \tau^+\tau^- bb$ at 1.0 TeV

ILC unique to achieve the ~0.25% accuracy on the A^0 mass needed to predict Ω_χ matching CMB WMAP precision;

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



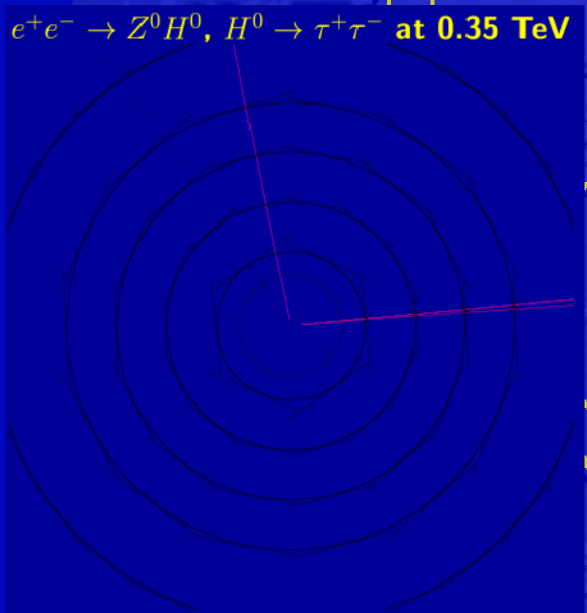


Battaglia, Hooberman

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

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

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



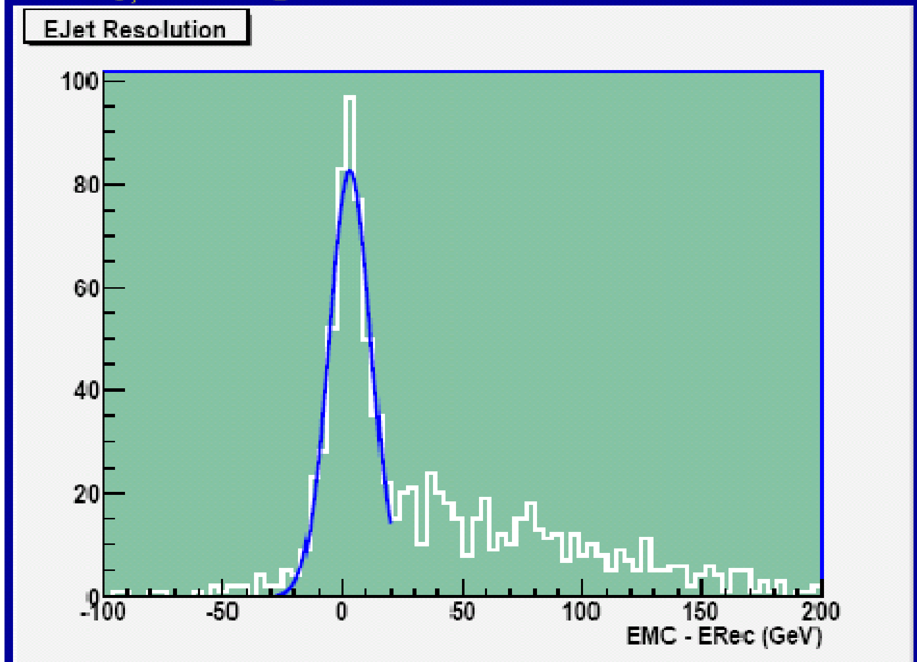
	E_{cm} TeV	M_H 120	140
$\delta g_{H\tau\tau}/g_{H\tau\tau}$	**0.5**	0.027	0.050
$\delta g_{H\mu\mu}/g_{H\mu\mu}$	**0.8**	0.150	

b-Jet Energy at 0.35 – 1.0 TeV

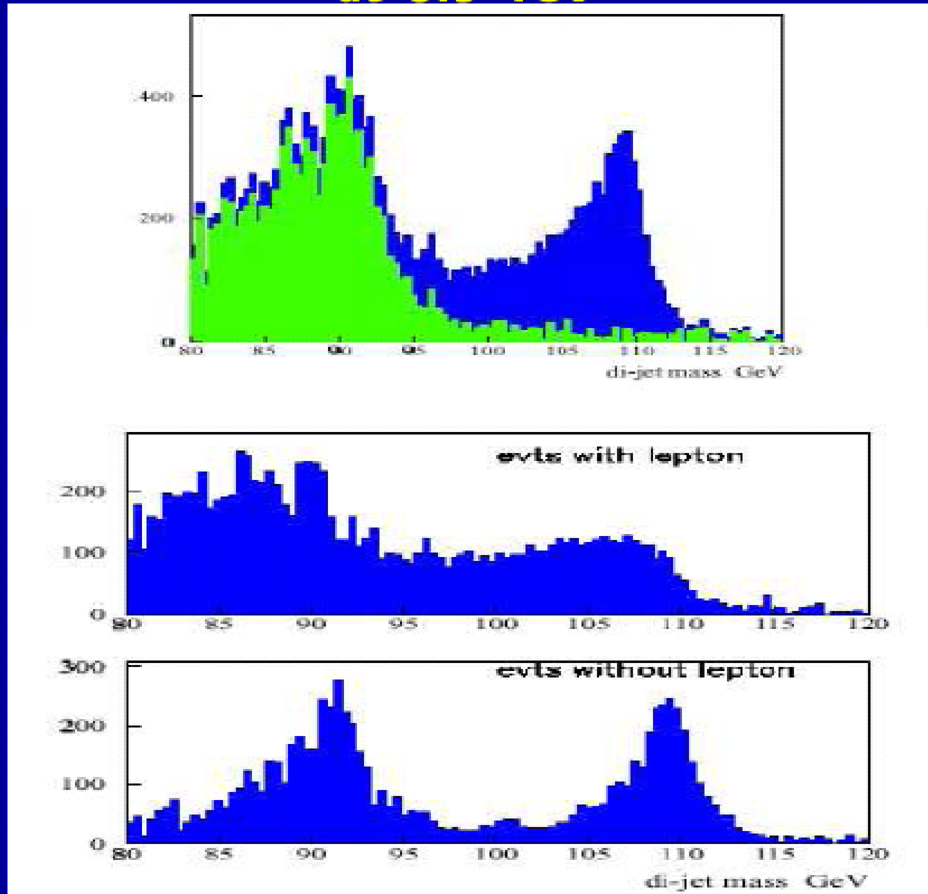
Semileptonic b decays [BR(b→clν) = 0.22] introduce loss of jet energy due to escaping ν, which causes smearing to mass and energy reconstruction;

Can identify through tag of lepton with significant ip and correct using combination of jet p vector and pri.-sec. vtx vector.

$\chi^0_{3,4} \rightarrow \chi^0_1 Z^0$, $Z^0 \rightarrow q\bar{q}$ **at 1.0 TeV**



$e^+e^- \rightarrow H\nu\bar{\nu}$ **and** $e^+e^- \rightarrow ZZ\nu\bar{\nu}$ **at 0.5 TeV**

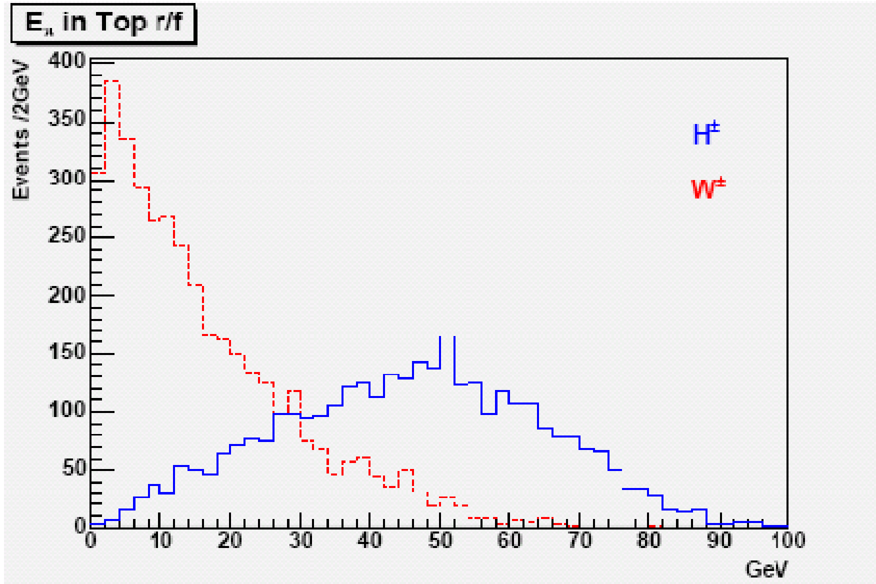


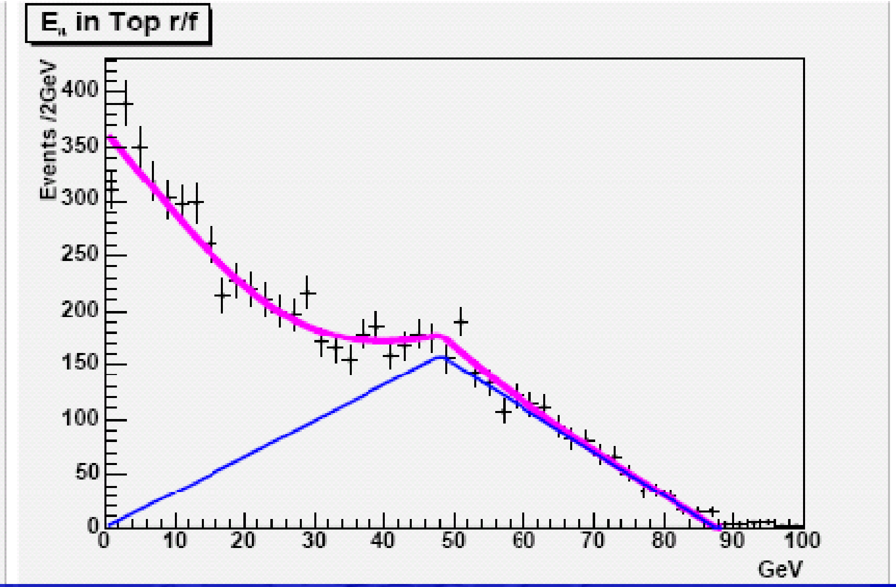
Identify Light H^- in large tan β SUSY

SUSY scenarios with light charged Higgs bosons and large tan β bring $H^- \rightarrow \tau\nu$ signature which can be distinguished from $W^- \rightarrow \tau\nu$ using τ polarization (RH vs. LH τs);

If $m_{H^-} < m_{top}$, study can be performed in recoil of hadronic top and experimental challeng is to tell $\tau \rightarrow \pi$ decay over broad momentum range;

Vertex Tracker must identify single-prong τ at moderate to large momenta;





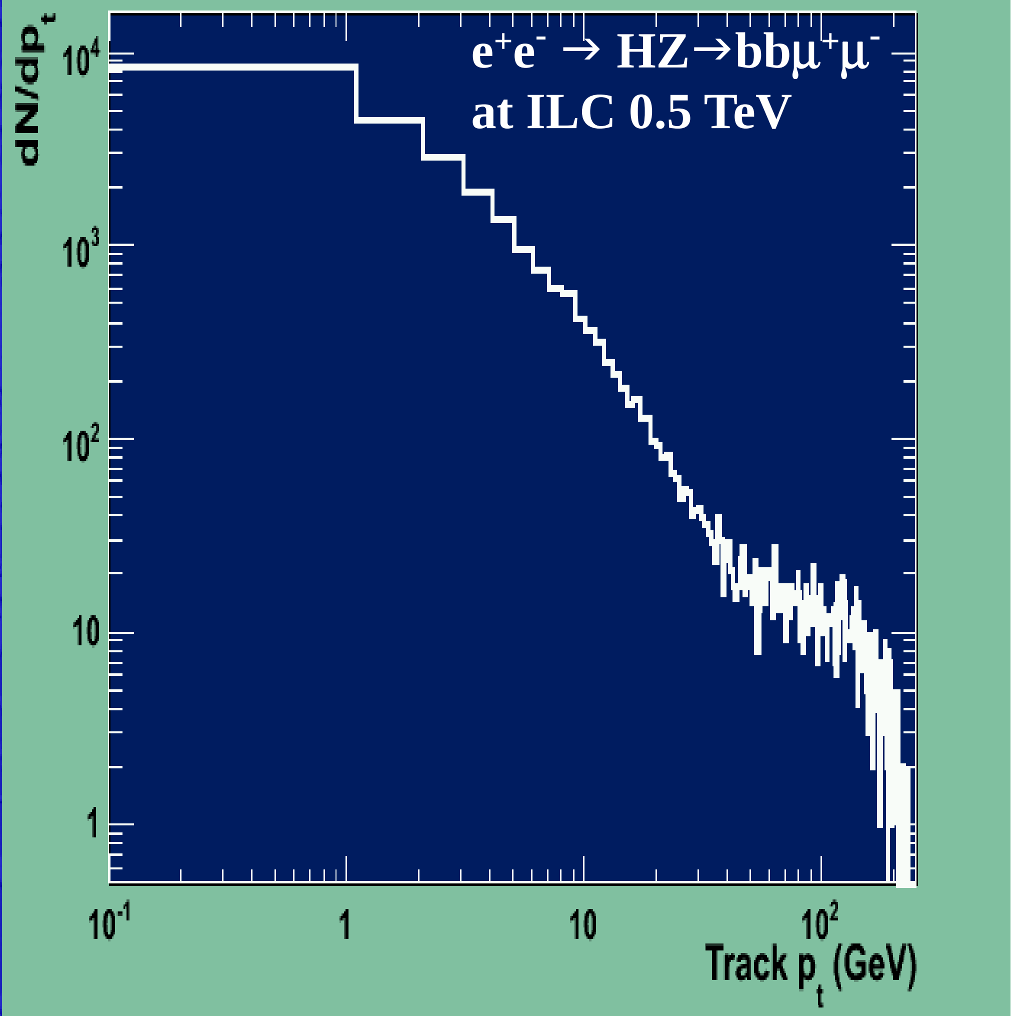
Boos, Carena, Wagner, hep-ph/0507100

Multiple Scattering I.P. Term

Multiple Scattering

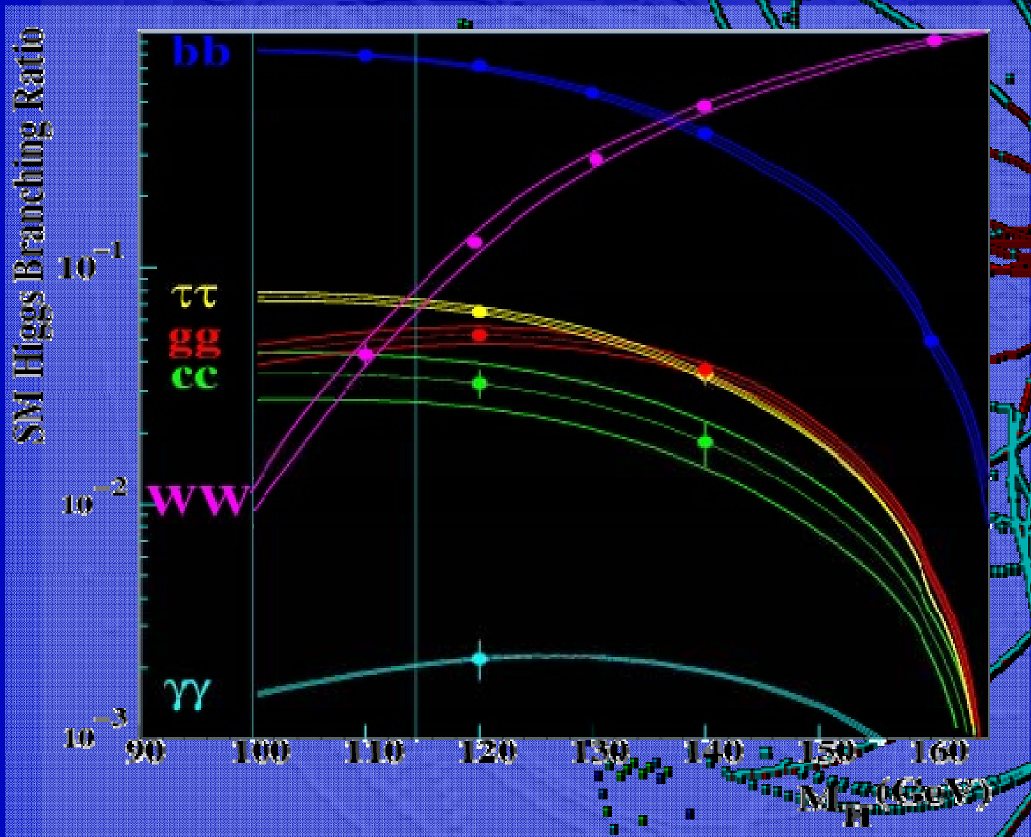
Despite large centre-of-mass energies, most charged particles are produced with rather moderate energies: interesting processes have large jet multiplicity (4 and 6 parton processes + hard gluon radiation) or large missing energies WW and ZZ fusion processes and SUSY with conserved R-parity;

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



$H^0 \rightarrow bb$, cc, gg at 0.35 - 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 ILC for the experimental accuracy needed to match theory uncertainties and probe extended Higgs sector models;

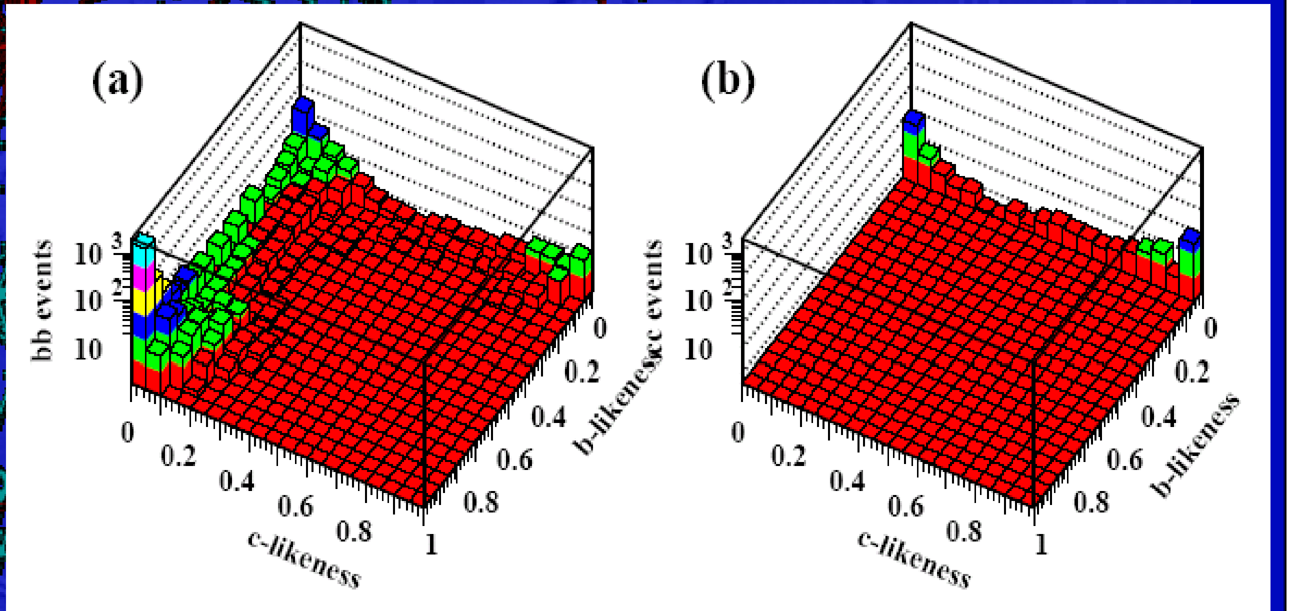


$H^0 \rightarrow bb, cc, gg$ at 0.35 - 0.5 TeV

Determination of Higgs hadronic branching fractions, one of the most crucial tests of the Higgs mechanism of mass generation and unique to the ILC;

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.

120GeV	δBR(H→X)/BR
H→bb	±1.0%
H→cc	±12.3%
H→gg	±8.3%



Kuhl, Desch
LC-PHSM-2007-001

$H^0 \rightarrow bb$, cc, gg at 0.35 - 0.5 TeV

Channel	Change	Rel. Change in Stat. Uncertainty
$H \rightarrow bb$ $H \rightarrow cc$ $H \rightarrow gg$	Geometry: 5 → 4 layer VTX Thickness: 50 μm → 100 μm	+ 0% +15% + 5%
$H \rightarrow cc$	σ_{point}: 4 μm → 6 μm 4 μm → 2 μm	+10% -10%
$H \rightarrow cc$	Thickness: 50 μm → 100 μm	+10%

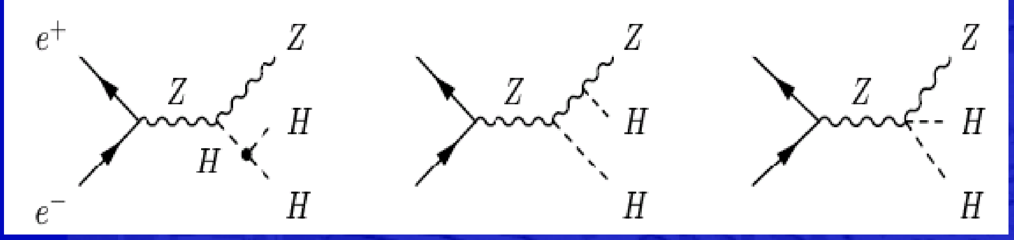
Degradation in performance correspond to 20-30% equivalent Luminosity loss.

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

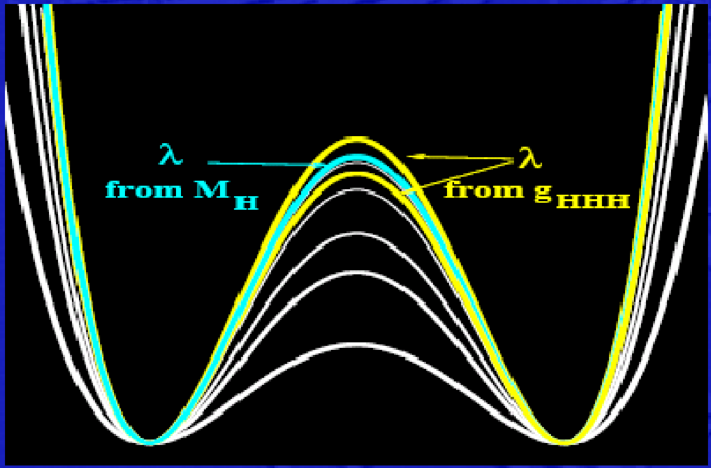
Higgs Potential

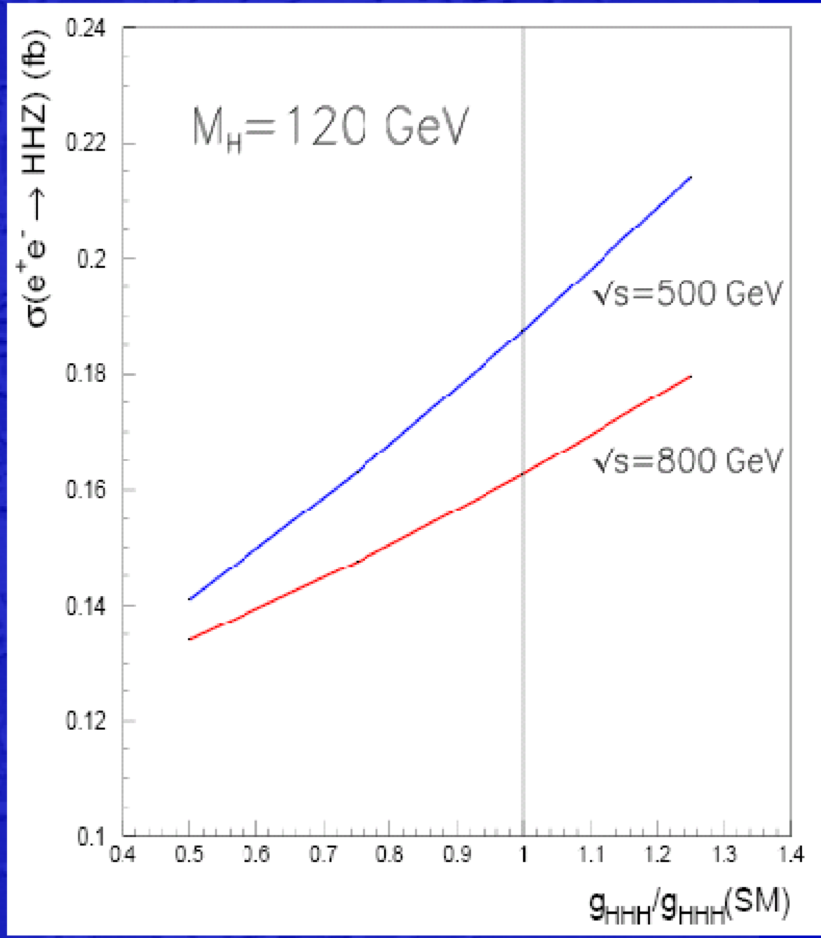
ILC offers unique opportunity to study the shape of the Higgs potential through measurement of Higgs self-coupling in HHZ and HHνν at 0.5 and 1TeV

Double Higgstrahlung: $e^+e^- \to H^0H^0Z^0$



$$g_{HHH} = \frac{3}{2}\frac{M_H^2}{v}$$





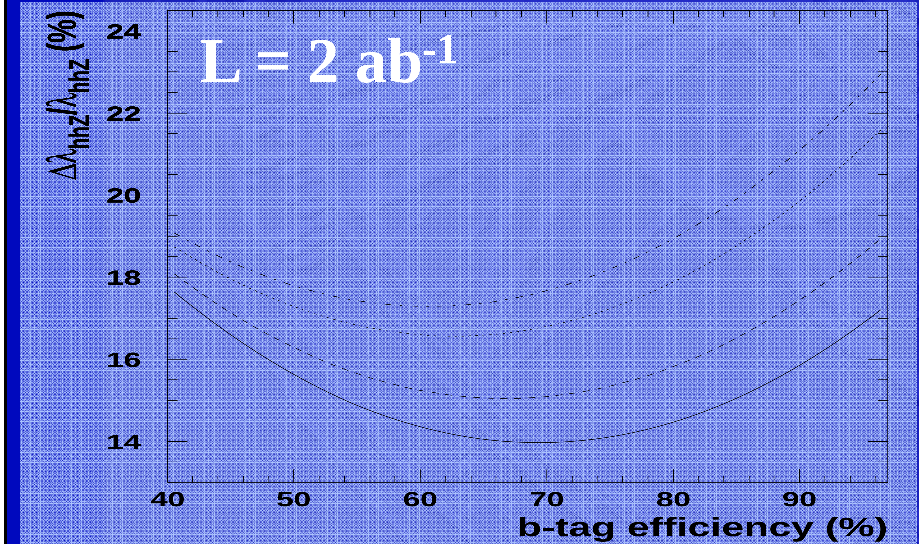
Battaglia, Boos, Yao,
Snowmass 2001

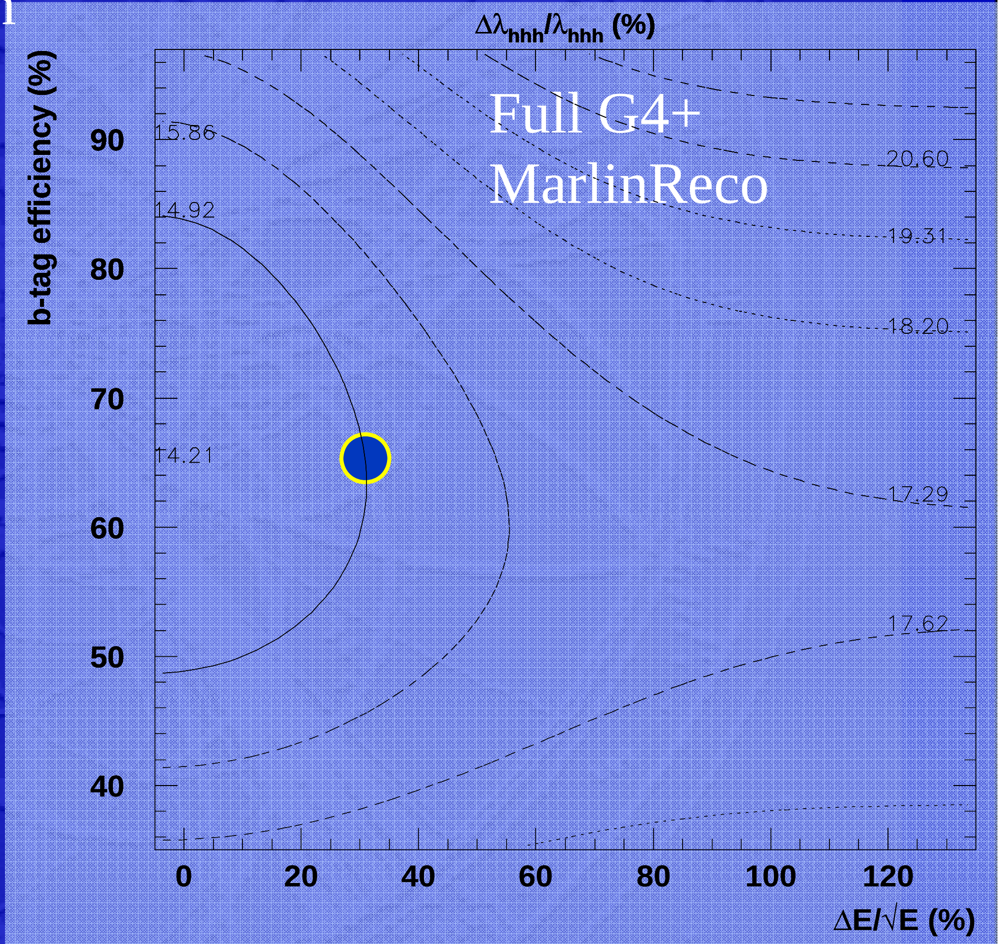
$e^+e^- \rightarrow H^0H^0Z^0$ at 0.5 TeV

ILC offers unique opportunity to study the shape of the Higgs potential through measurement of Higgs self-coupling in HHZ and HHνν at 0.5 and 1TeV

Isolating HHZ signal (σ=0.18pb) from tt (s=530pb), ZZZ (σ=1.1pb), tbtb (s=0.7pb) and ttZ (s=0.7pb) is an experimental ***tour-de-force***;

b-tagging and jet energy resolution essential to suppress backgrounds;

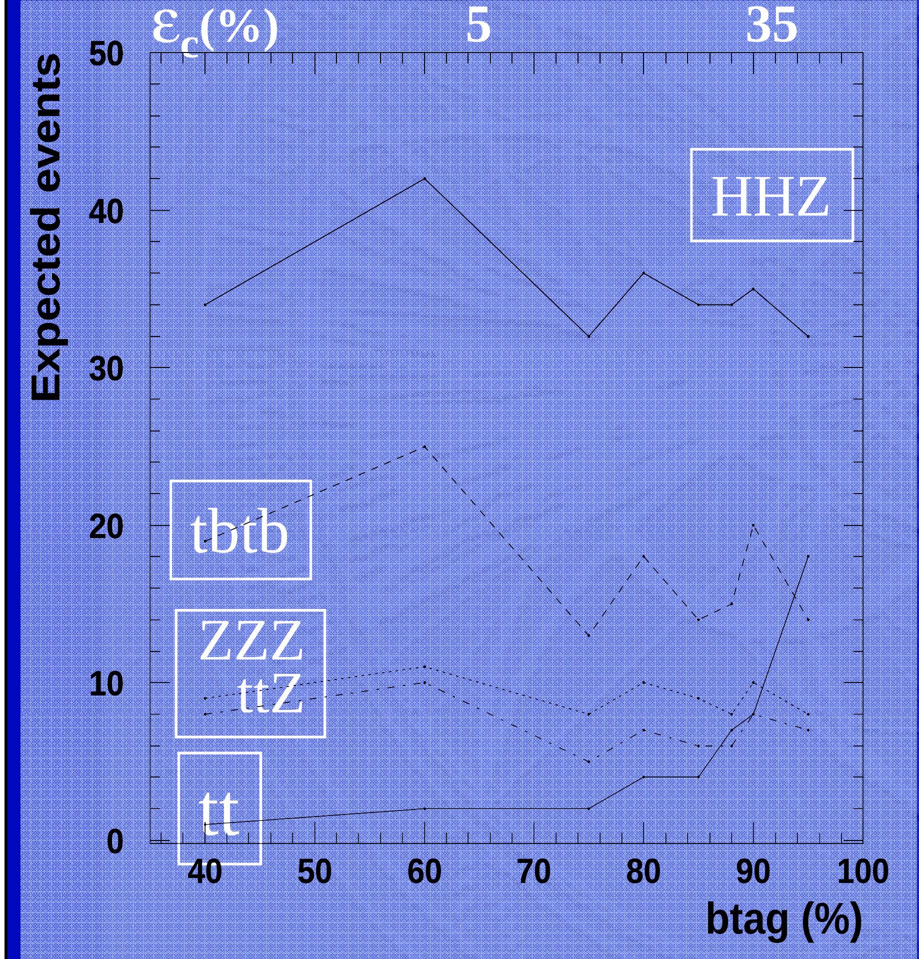


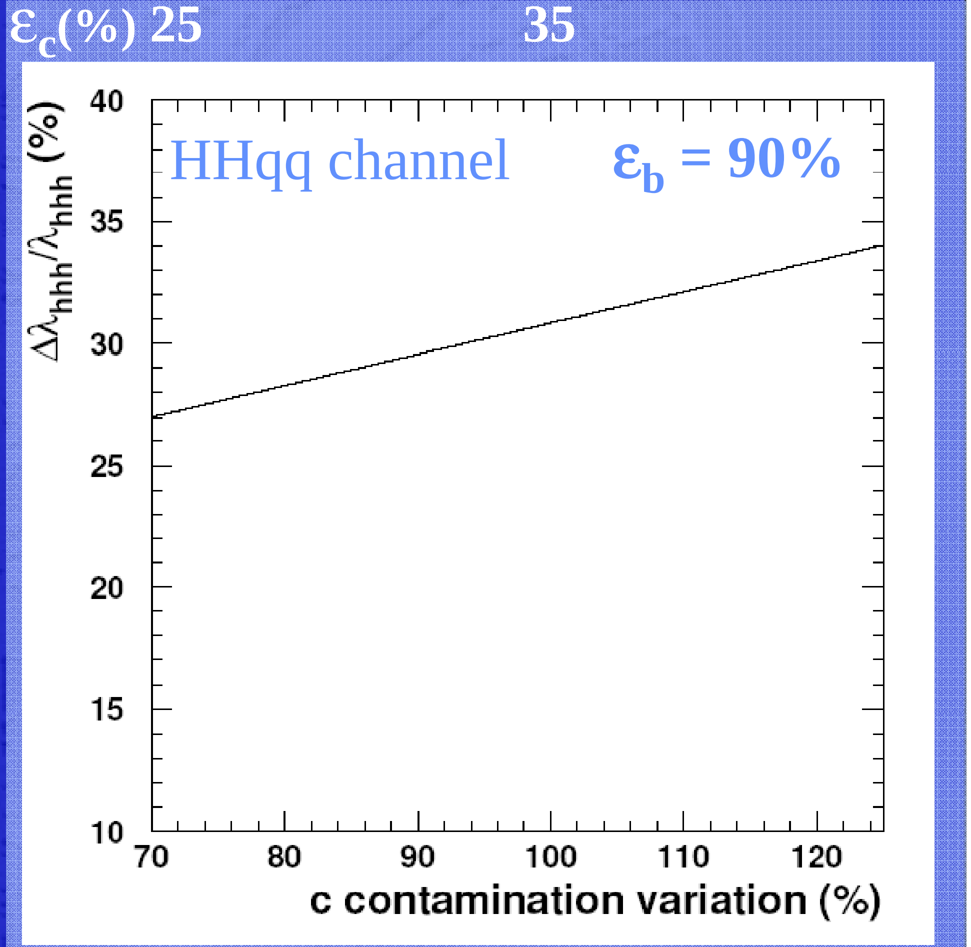


Boumediene, Gay, LCWS07

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

tt→WbWb→bbcscs with mis-tagged charm jets resembles bbbbqq signal;





Boumediene, Gay, LCWS07

CP-violation in H^- Decays

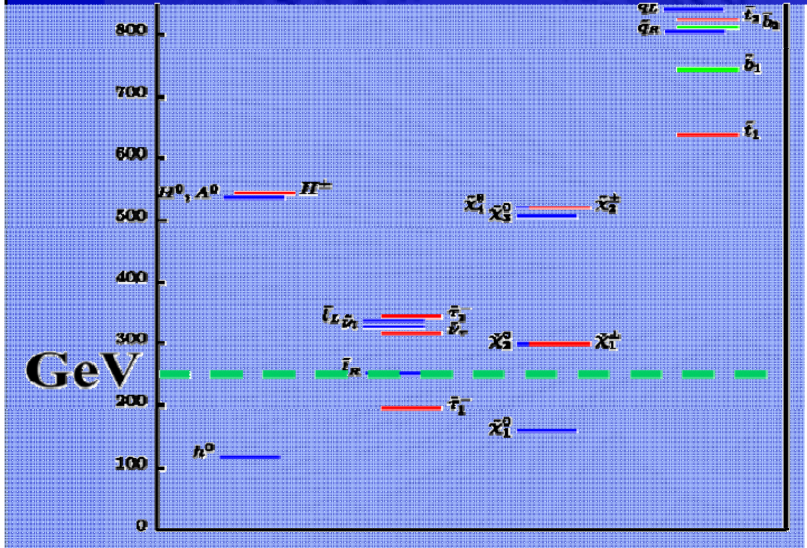
SUSY loop contributions $(\tilde{t},\, \tilde{b},\, \tilde{g})$ may induce sizeable CP asymmetries in heavy Higgs boson decays:

$$\delta CP = \frac{\Gamma(H^- \to b\bar{t}) - \Gamma(H^+ \to t\bar{b})}{\Gamma(H^- \to b\bar{t}) + \Gamma(H^+ \to t\bar{b})}$$

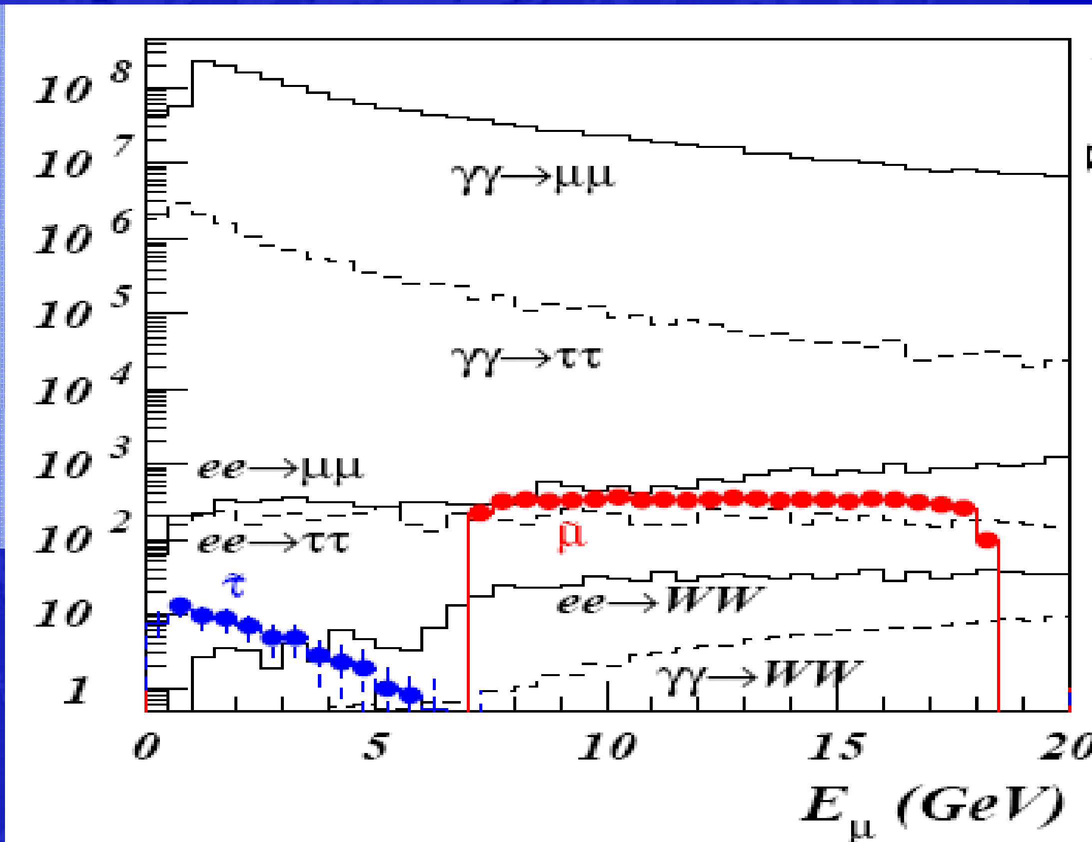
Asymmetry can be measured with quark-antiquark tagging, need to use hadronic top decays and adopt vertex charge algorithm for b and c jets.

Vertex Tracker, $e^+e^- \to \tau_1\tau_1 \to \tau^+\tau^-\chi^0\chi^0$, DM

In co-Annihilation SUSY scenarios DM density controlled by stau-LSP mass splitting: sensitivity to small ΔM depends on $\gamma\gamma$ background rejection:



Essential to reject $\gamma\gamma$ bkg ee $\to$ ee$\tau\tau$ by low angle electron tagging and ee$\tau\tau$, ee$\mu\mu$ also by i.p. tag:

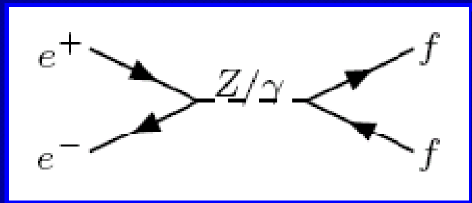


Bambade et al. LCWS04

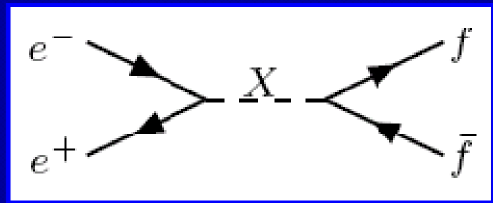
$e^+e^-\to q\bar{q}$ at High Energy Frontier

Indirect effect of exchange of new particles in Standard Model processes offers unique window to search for new phenomena at scales >> centre-of-mass energies:

$\mathcal{O} =$



$+$



$$M_{NP} \propto \sqrt{s\frac{\mathcal{O}}{\delta\mathcal{O}}} \propto \sqrt{s\sqrt{\frac{\mathcal{L}}{s}}} = (s \times \mathcal{L})^{1/4}$$

Cross sections

$$\sigma = \frac{N_{\rm sel} - N_{\rm bg}}{\epsilon_{\rm sel}\mathcal{L}} .$$

Fermion Tag,
Efficiency, Purity

Asymmetries

$$A_{\rm FB} = \frac{\sigma_{\rm F} - \sigma_{\rm B}}{\sigma_{\rm F} + \sigma_{\rm B}}$$

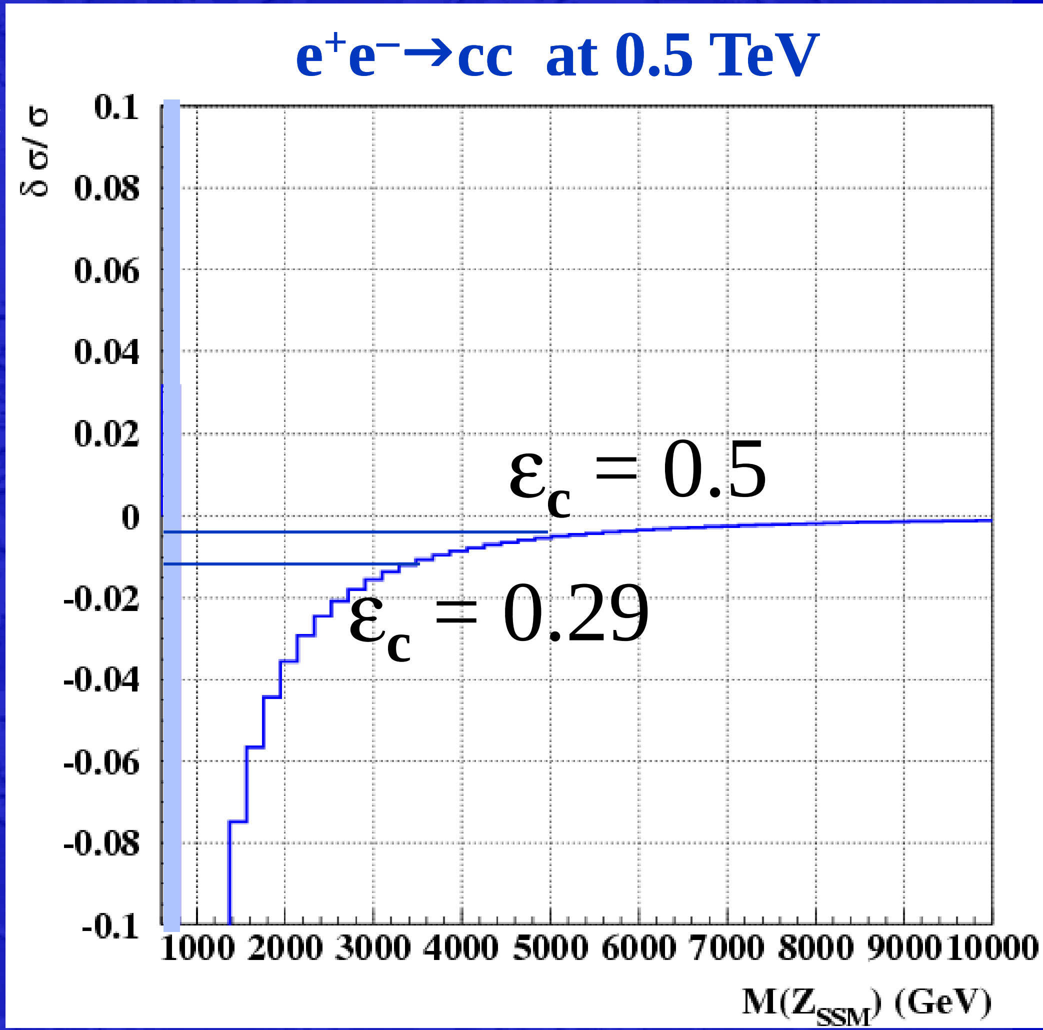
$$A_{\rm LR} = \frac{\sigma_{\rm L} - \sigma_{\rm R}}{\sigma_{\rm L} + \sigma_{\rm R}} \frac{1}{\langle|\mathcal{P}_{\rm e}|\rangle}$$

Fermion Tag,
Charge ID,
Beam Polarization

$e^+e^- \rightarrow cc$ at 0.5 – 1.0 TeV

Measurement of cc cross section: moderate cross section, requires 2 tags and low background;

	σ_{ff} (pb)
cc	0.74
bb	0.40
μμ	0.45

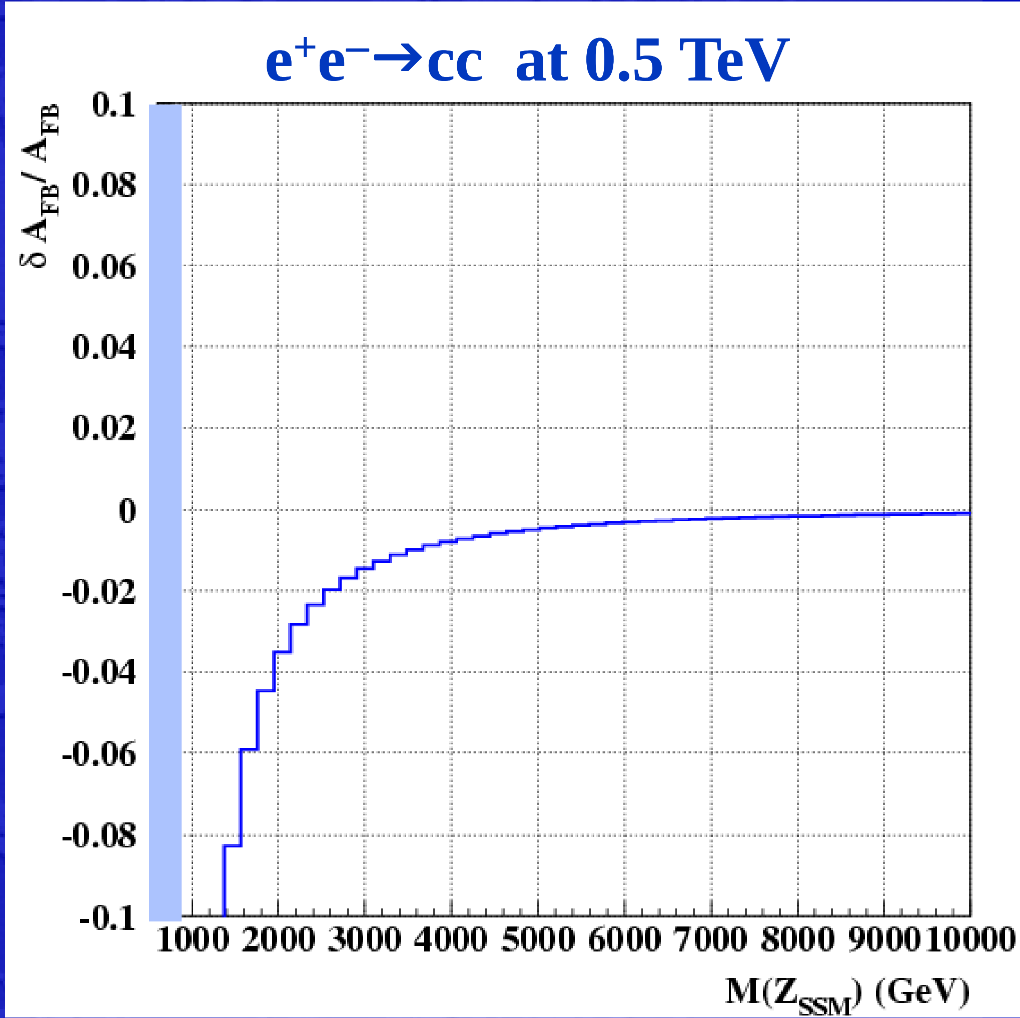


A_{FB} in $e^+e^- \rightarrow cc$ at 0.5 – 1.0 TeV

Further sensitivity on NP scale and nature can be obtained with A^{cc}_{FB} determination;

Experience at LEP with Jet charge algorithms;

Improved sensitivity expected using vertex charge, requires fwd coverage;



Charm Tagging vs. I.P. Resolution

Study change in efficiency of charm tagging in Z^0-like flavour composition

Geometry	σ_{IP} (μm)		
R1 1.2 cm ↓ 1.7 cm	$4 \oplus 7/p_t$ $4 \oplus 10/p_t$	c purity=0.7	ε_c = **0.49** ε_c = **0.46**
R1 1.2 cm ↓ 2.1 cm	$4 \oplus 7/p_t$ $5.5 \oplus 14/p_t$	c purity=0.7	ε_c = **0.49** ε_c = **0.40**
HPS	$11 \oplus 15/p_t$	c purity=0.7	ε_c = **0.29**

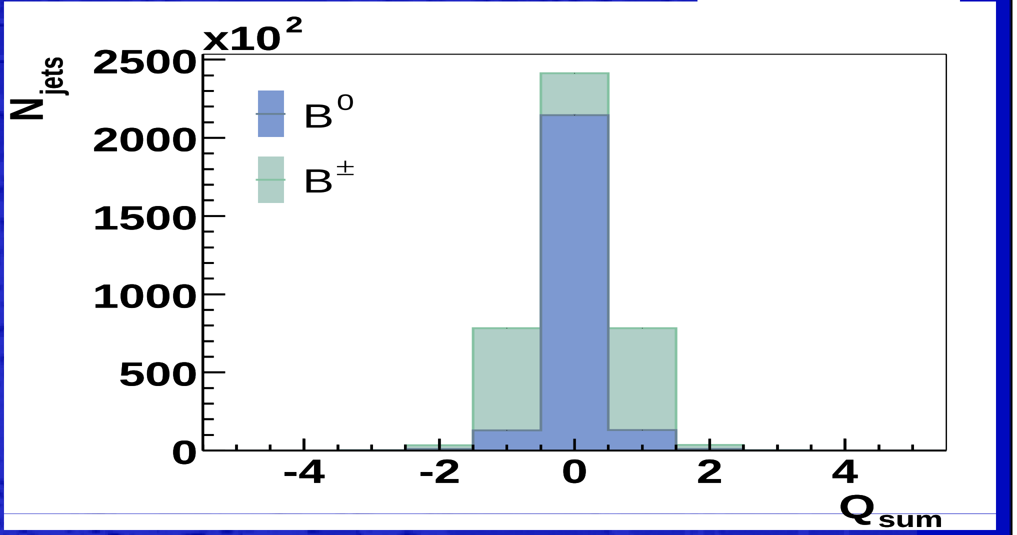
Total efficiency = ε^N with N = number of jets to be tagged

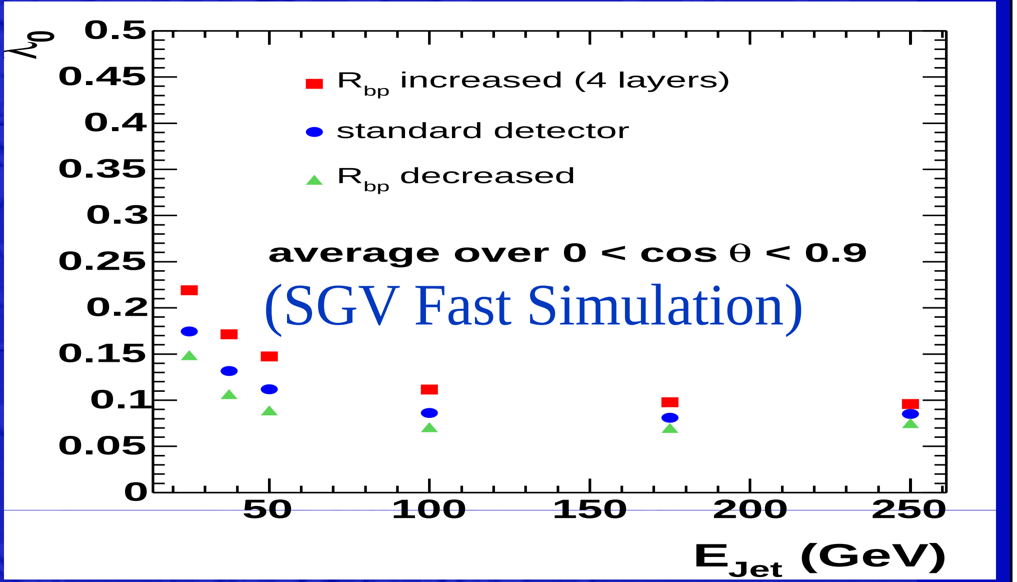
Vertex Charge

Vertex charge algorithms very promising for q-anti q discrimination in b and c jets

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

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



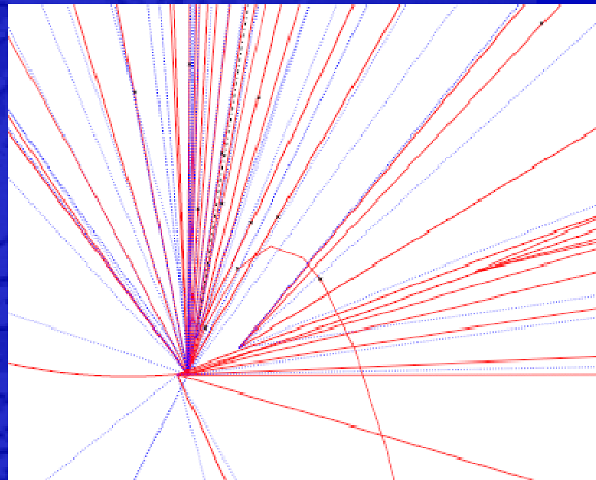


$\gamma\gamma \to$ hadrons at 0.35 – 1.0 TeV

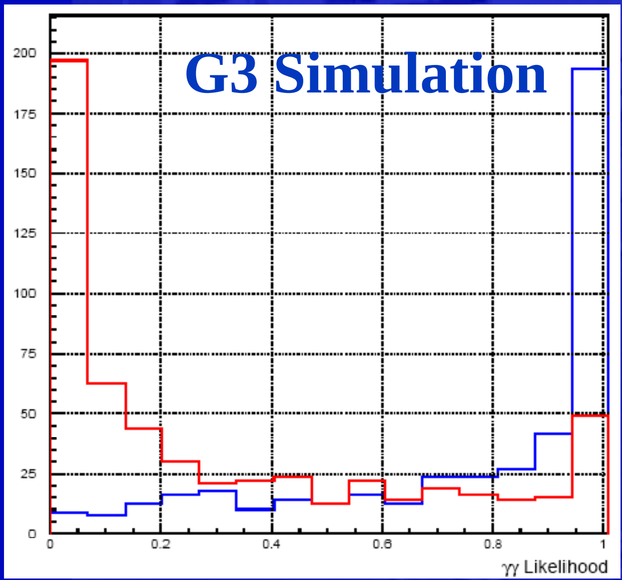
Underlying bkg from $\gamma\gamma \to$ hadrons create source of confusion in event reco and selection;

Expect 0.10-0.15 $\gamma\gamma \to$ hadrons events /BX mostly fwd peaked;

$e^+e^- \to WW\nu\nu \to H^0\nu\nu$ crucial process to determine g_{HWW} and Γ_H whose selection relies on missing energy and recoil mass: both are distorted by additional hadronic activity;



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



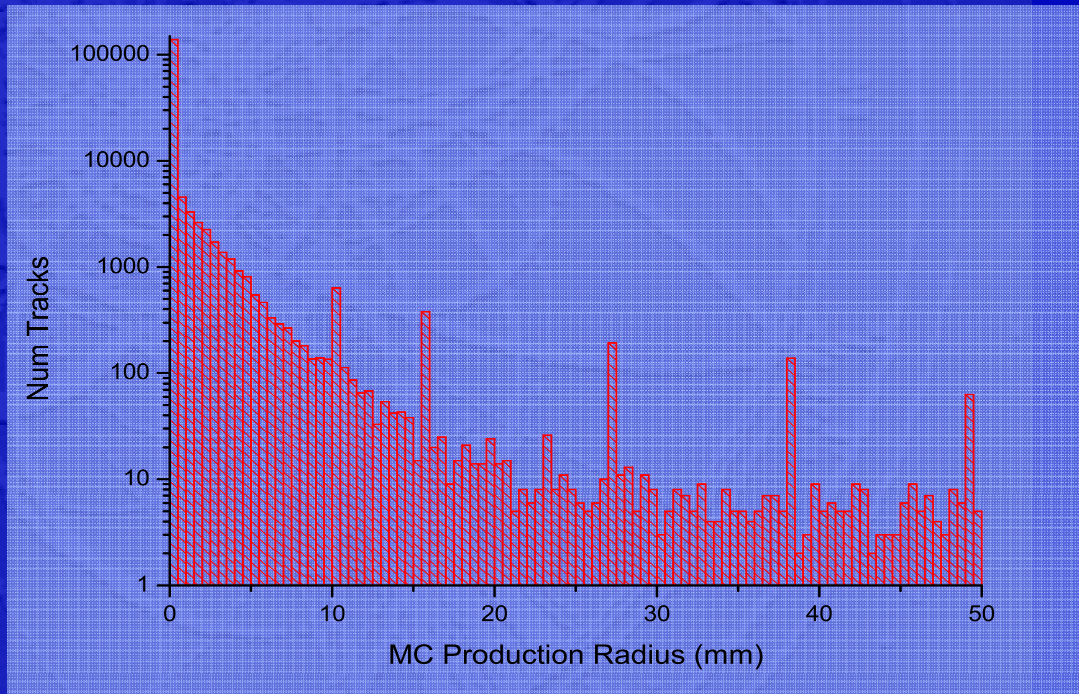
Tracks from $\gamma\gamma \to$ hadrons events, occuring randomly within bunch envelope, characterised by i.p. w.r.t. physics event large along z and small in $R\phi$

Likelihood based on precise i.p. measurements in both projection provides rejection of spurious particle tracks with only 20% efficiency loss.

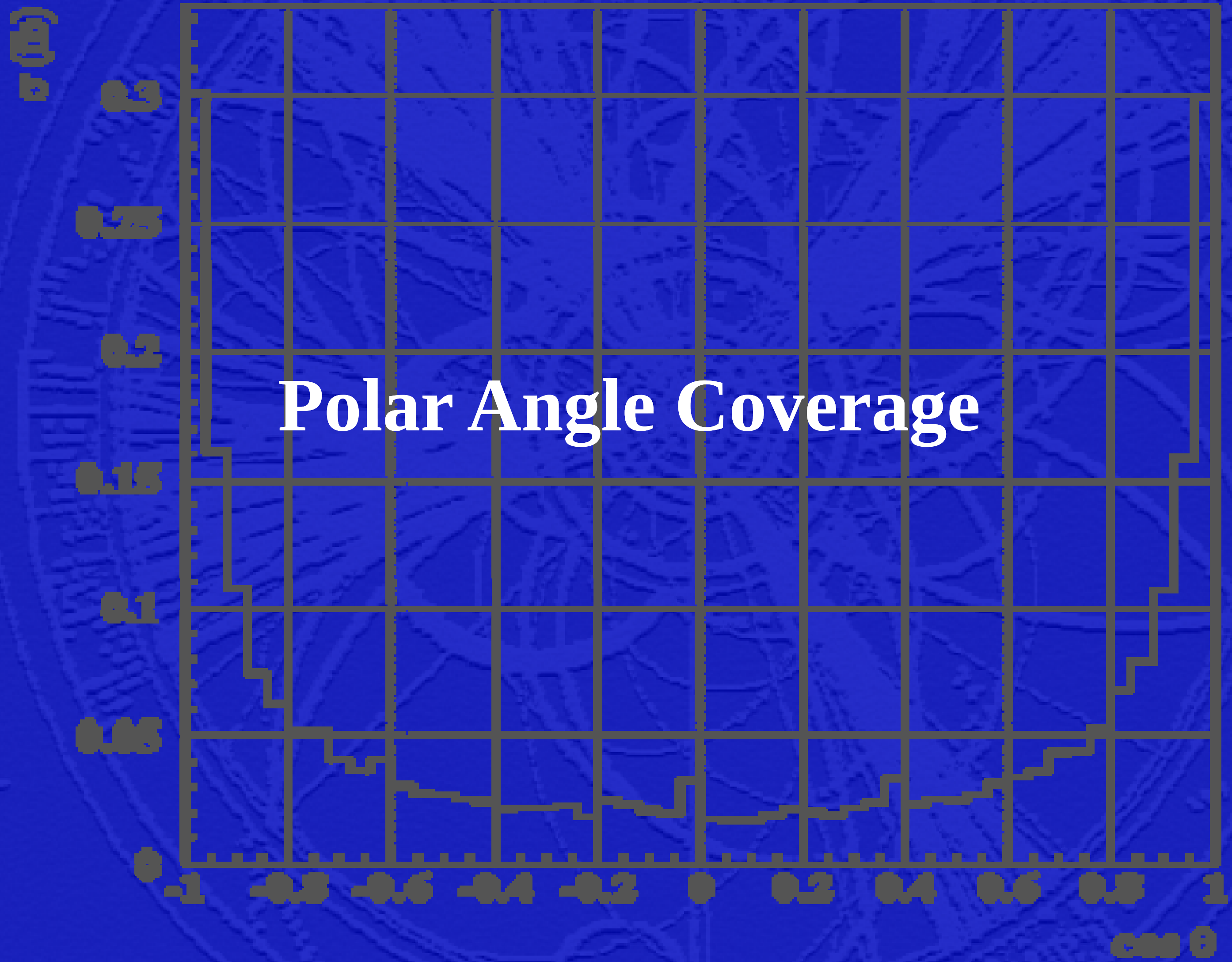
Battaglia, Schulte, LC-PHSM-2000-052

Hadronic Interactions

Ladder thickness is not only causing distortions in track extrapolation but also hadronic interaction which adversely affect rejection of light quarks;



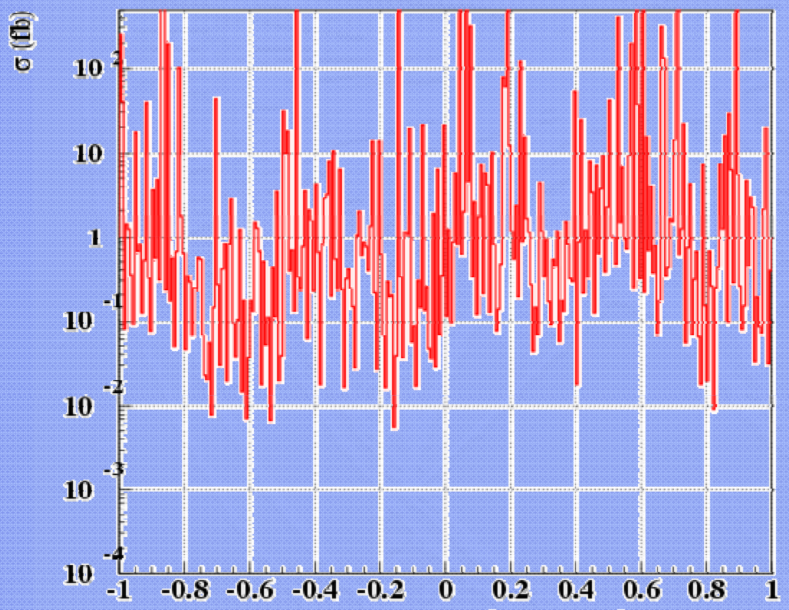
Polar Angle Coverage



The Importance of Being Forward

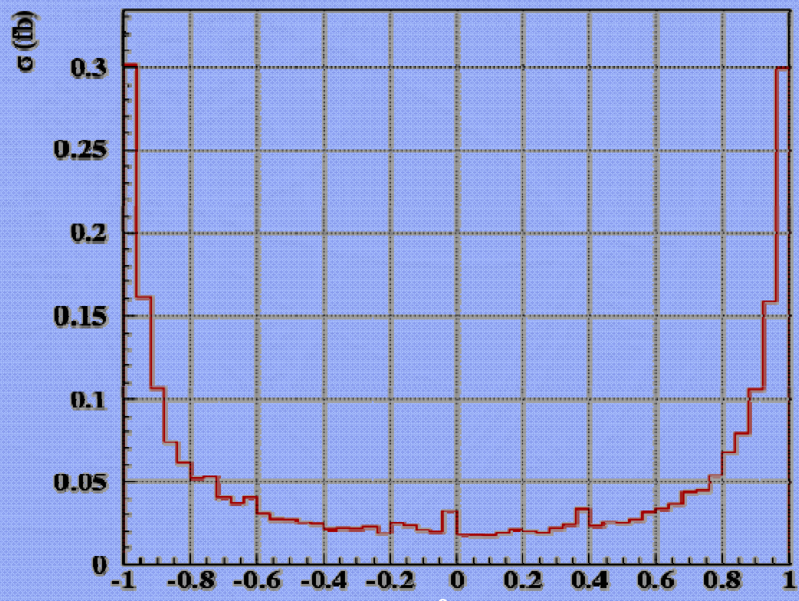
Weak Boson Fusion, t-channel and processes with large multiplicity final states require coverage for tracking/tagging close to beam axis;

$e^+e^- \rightarrow \tau_1\tau_1 \rightarrow \tau\chi^0\tau\chi^0$ **at 0.5 TeV**



τ polar angle

$e^+e^- \rightarrow H^0H^0\nu\nu \rightarrow bbbb\nu\nu$ **at 1 TeV**

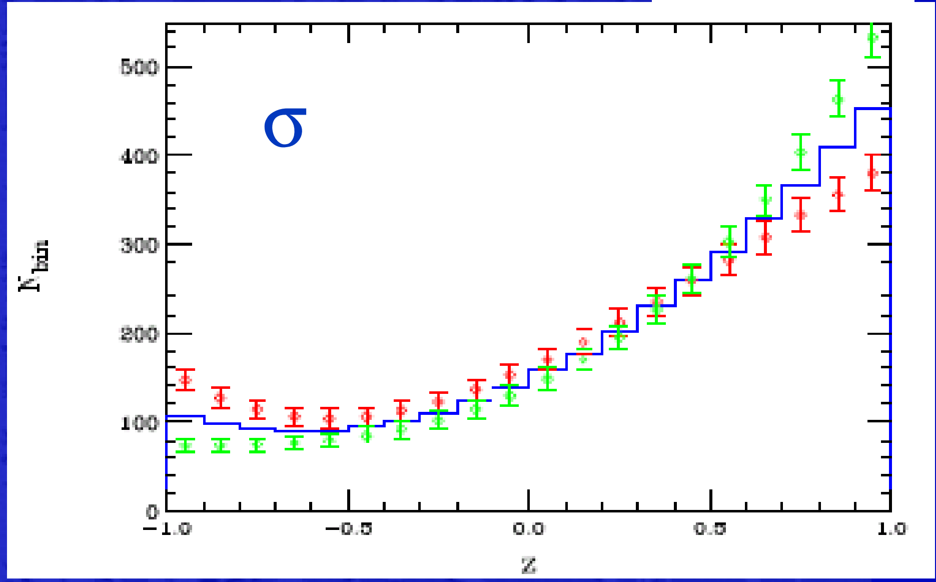


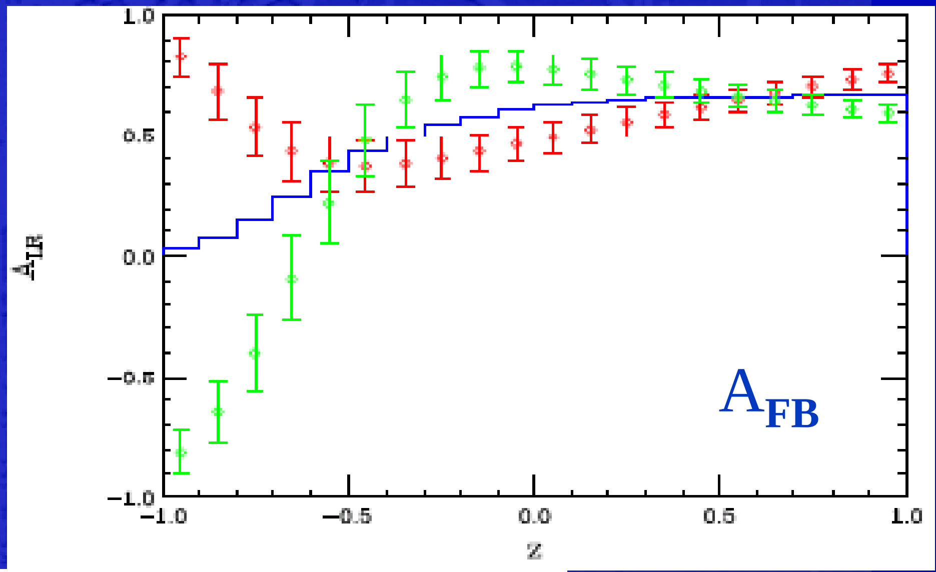
H^0 polar angle

Polar Angle Analysis of EW Observables

Beyond observation of deviation from SM, analysis of polar angle dependence of EW observables provides discrimination between New Physics models:

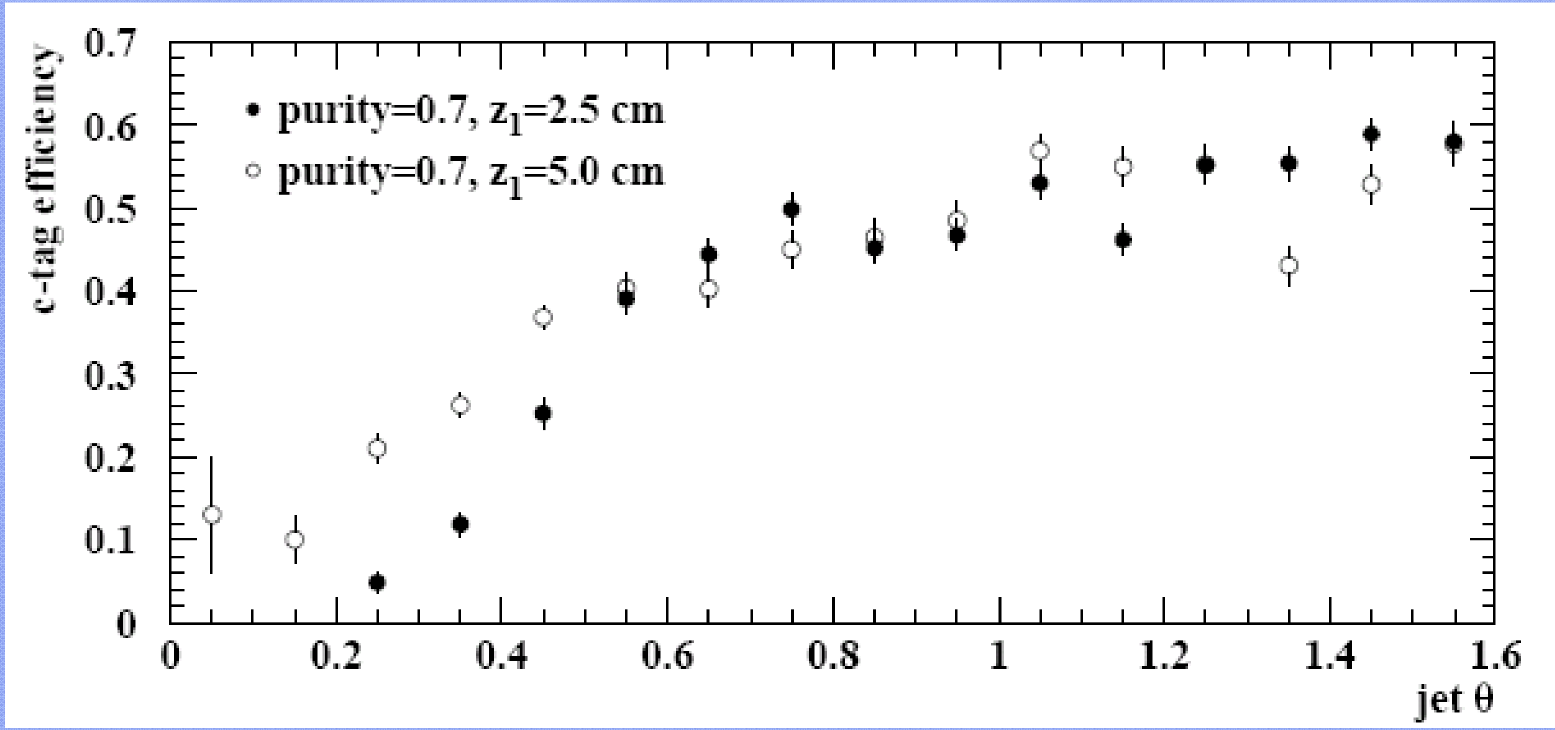
Extra Dimensions,
Extra Gauge Bosons,
Radions, ...



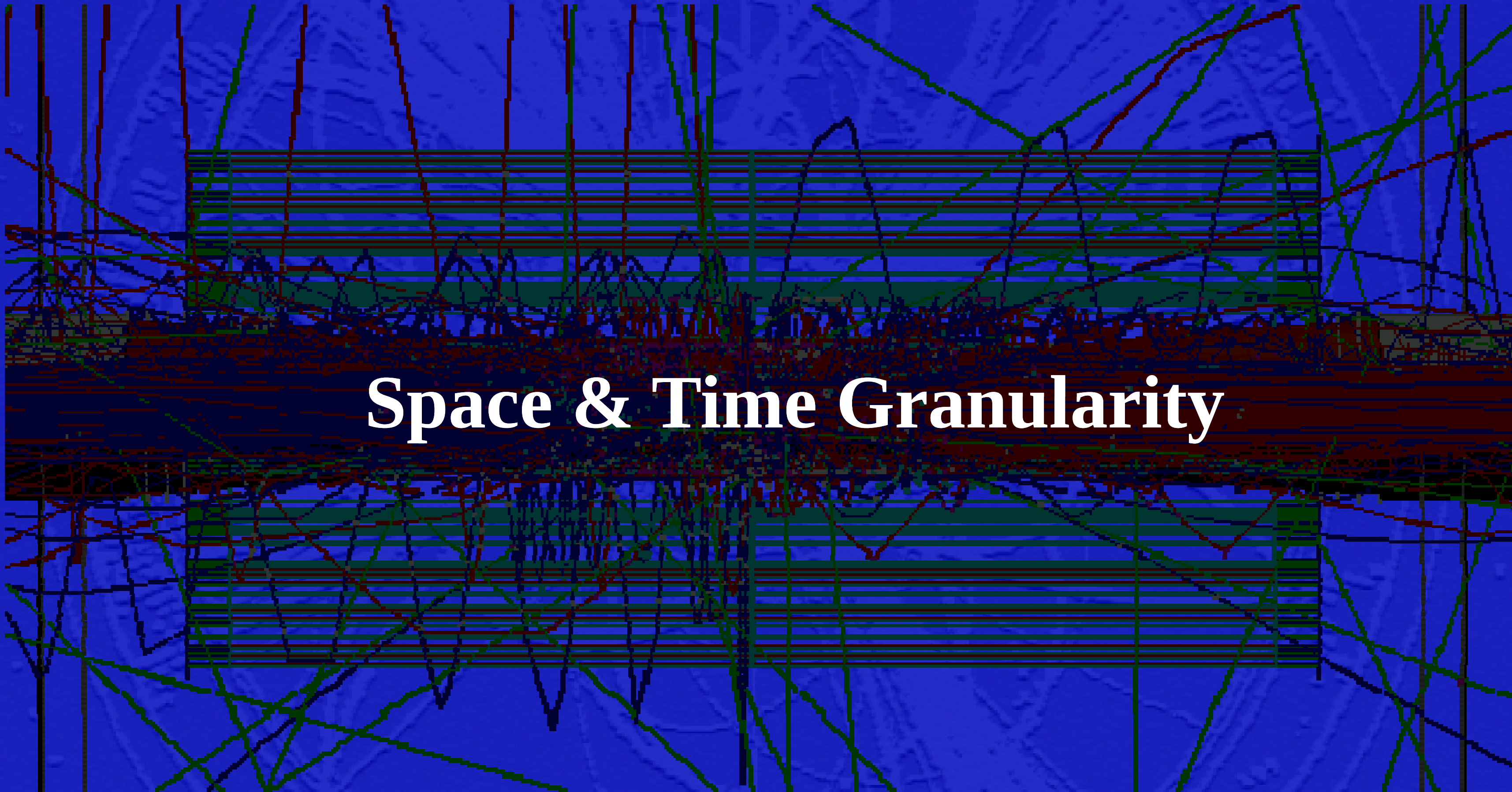


Hewett, Riemann

Long vs. Short Barrel Section

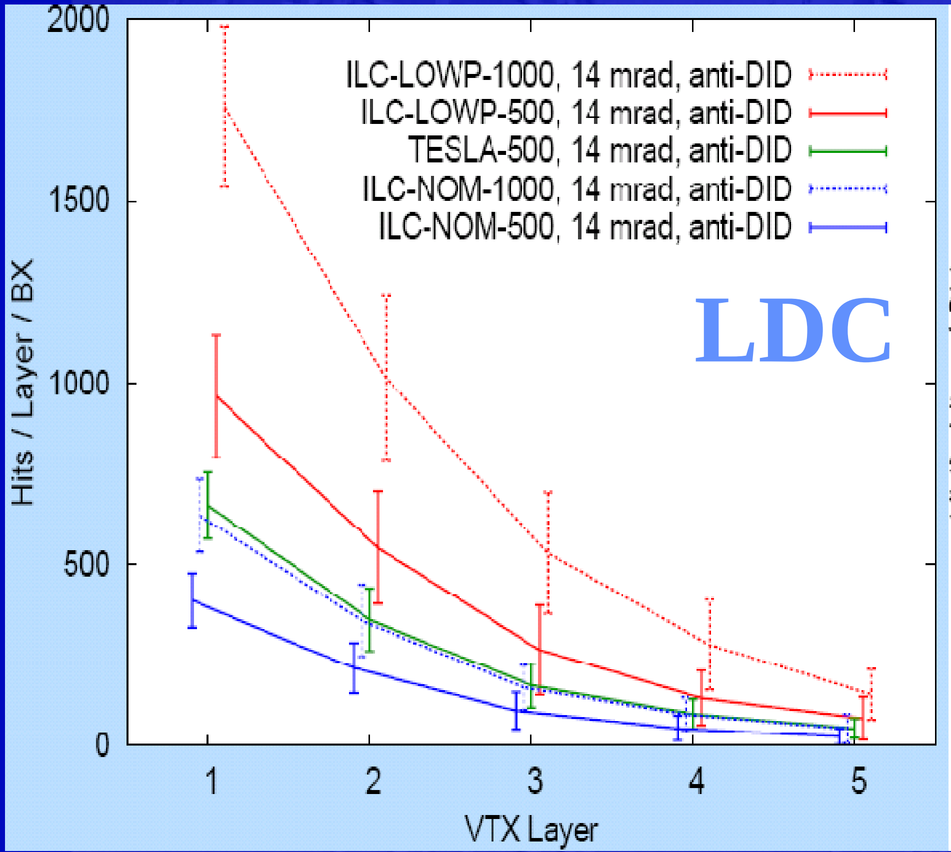


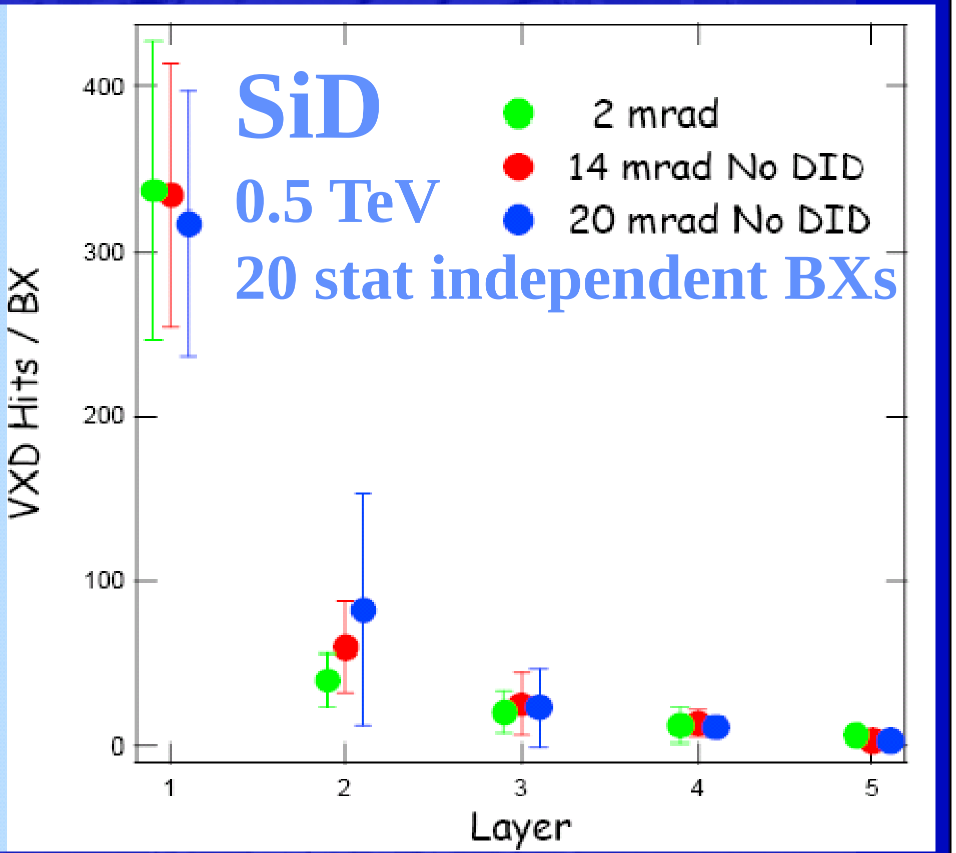
Hawking,
LC-PHSM-2000-021



Space & Time Granularity

Incoherent Pair Background





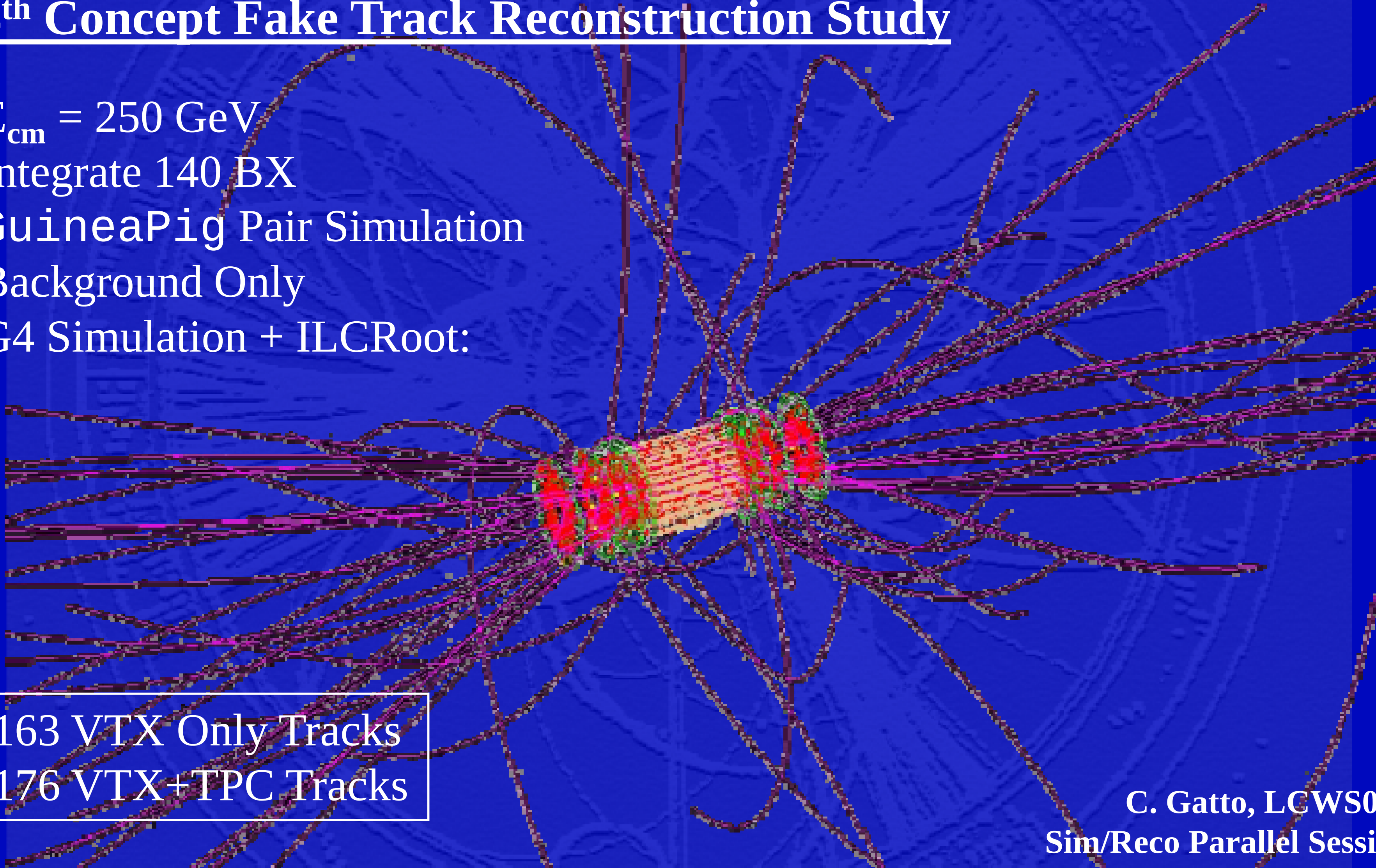
Vogel, LCWS07

Maruyama, LCWS07

Occupancy Limitations

4th Concept Fake Track Reconstruction Study

E_{cm} = 250 GeV
Integrate 140 BX
`GuineaPig` Pair Simulation
Background Only
G4 Simulation + ILCRoot:

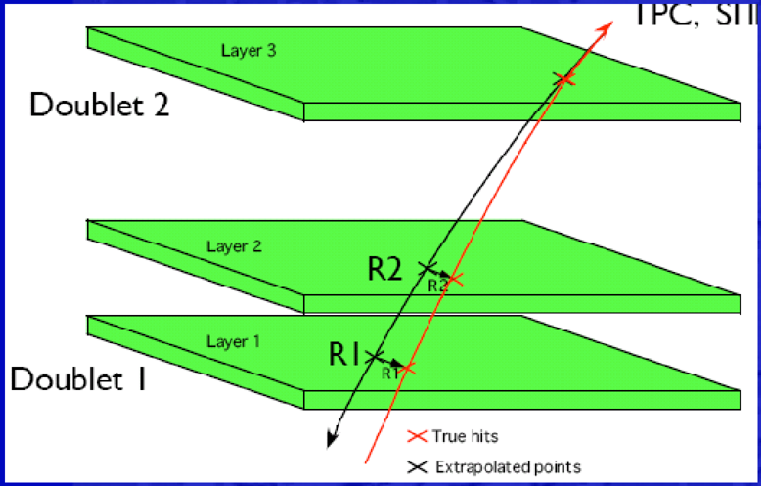


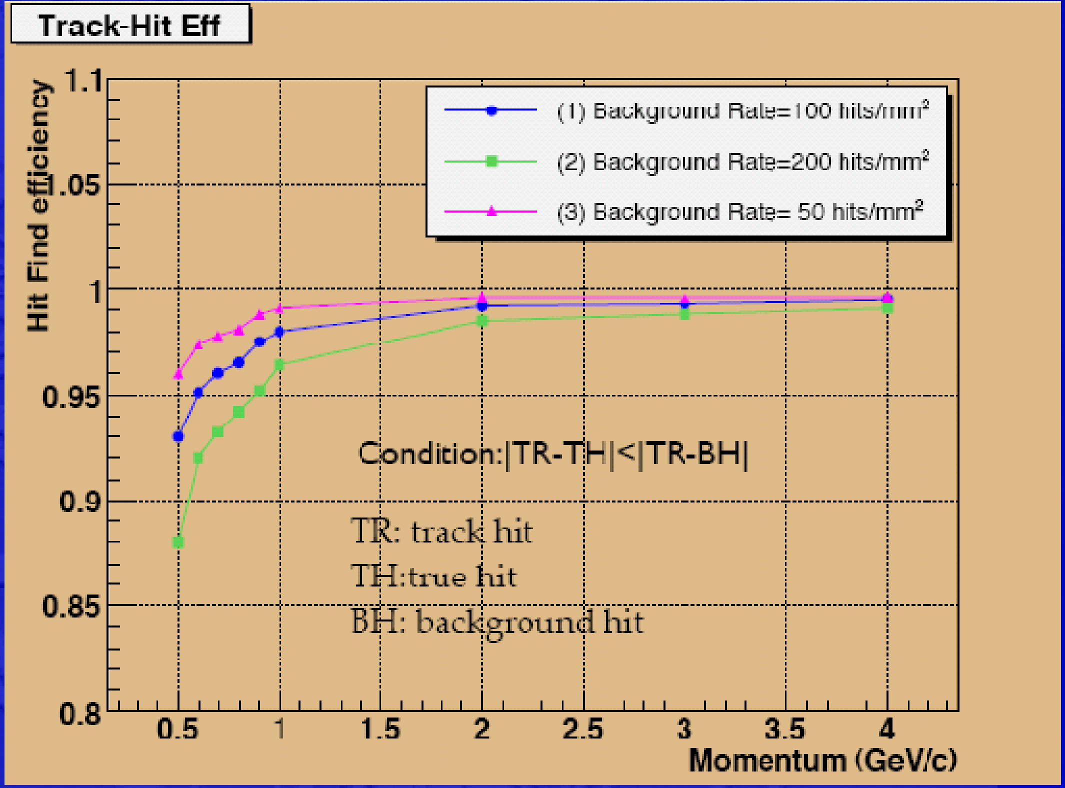
163 VTX Only Tracks
176 VTX+TPC Tracks

C. Gatto, LCWS07, Sim/Reco Parallel Session

Occupancy Limitations

Track Finding Efficiency in Vertex Tracker using layer doublets

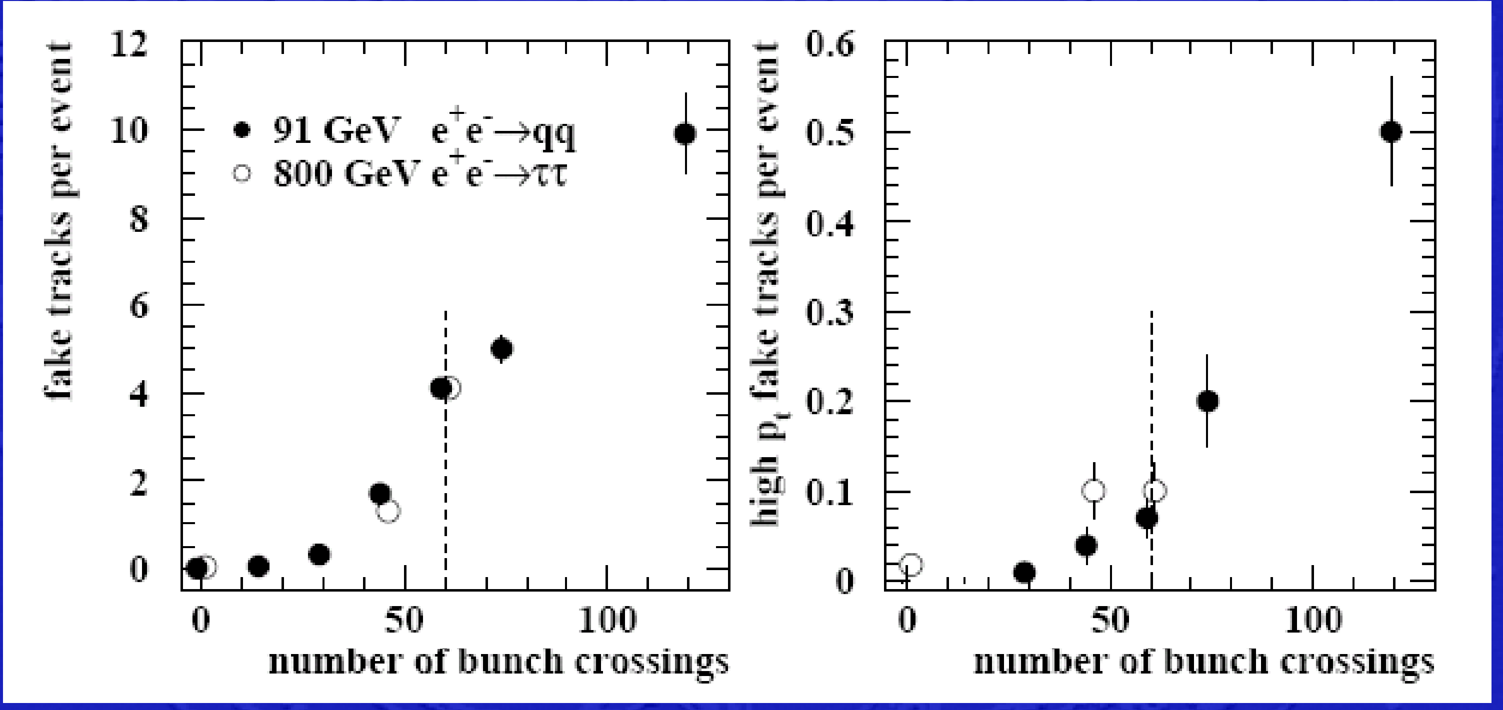




Occupancy Limitations

Standalone PatRec in VTX in presence of Pair Background

(Full G3 Simulation)

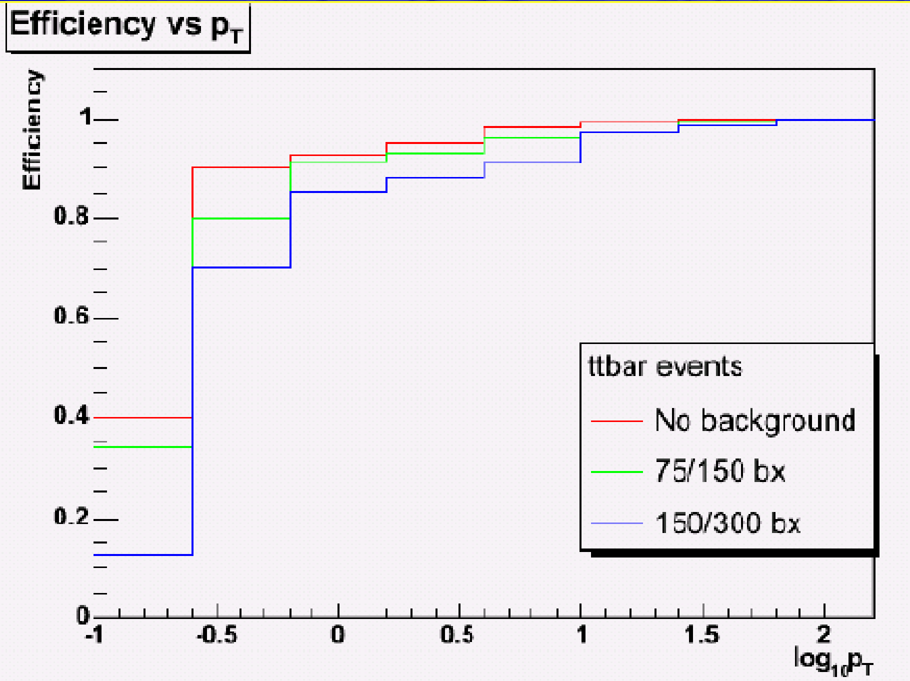


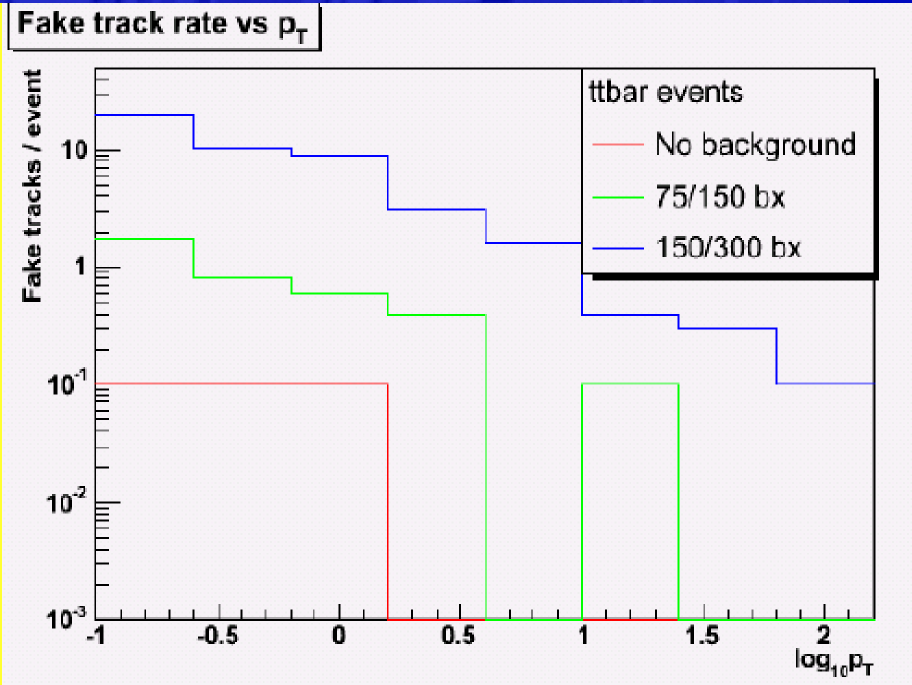
Hawking, LC-PHSM-2000-021

Occupancy Limitations

Standalone PatRec in VTX in presence of Pair Background

(Full G4 Simulation + MarlinReco)

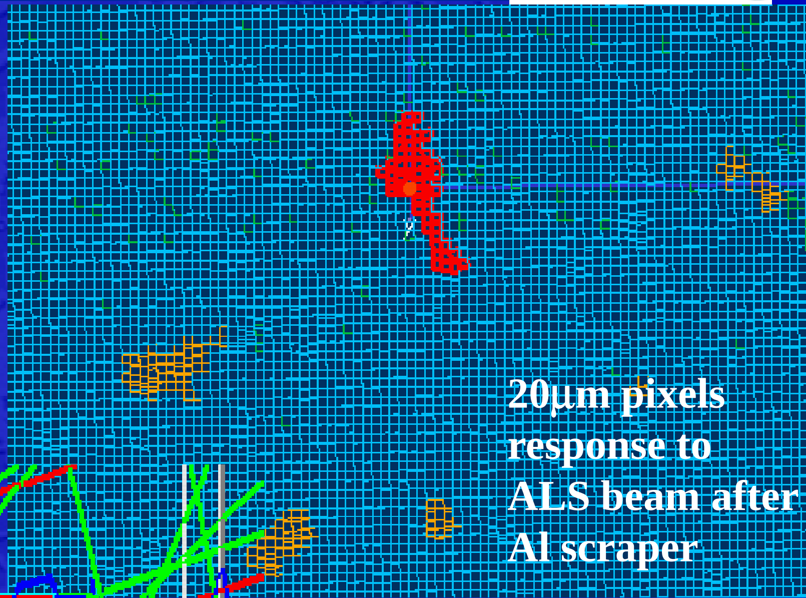


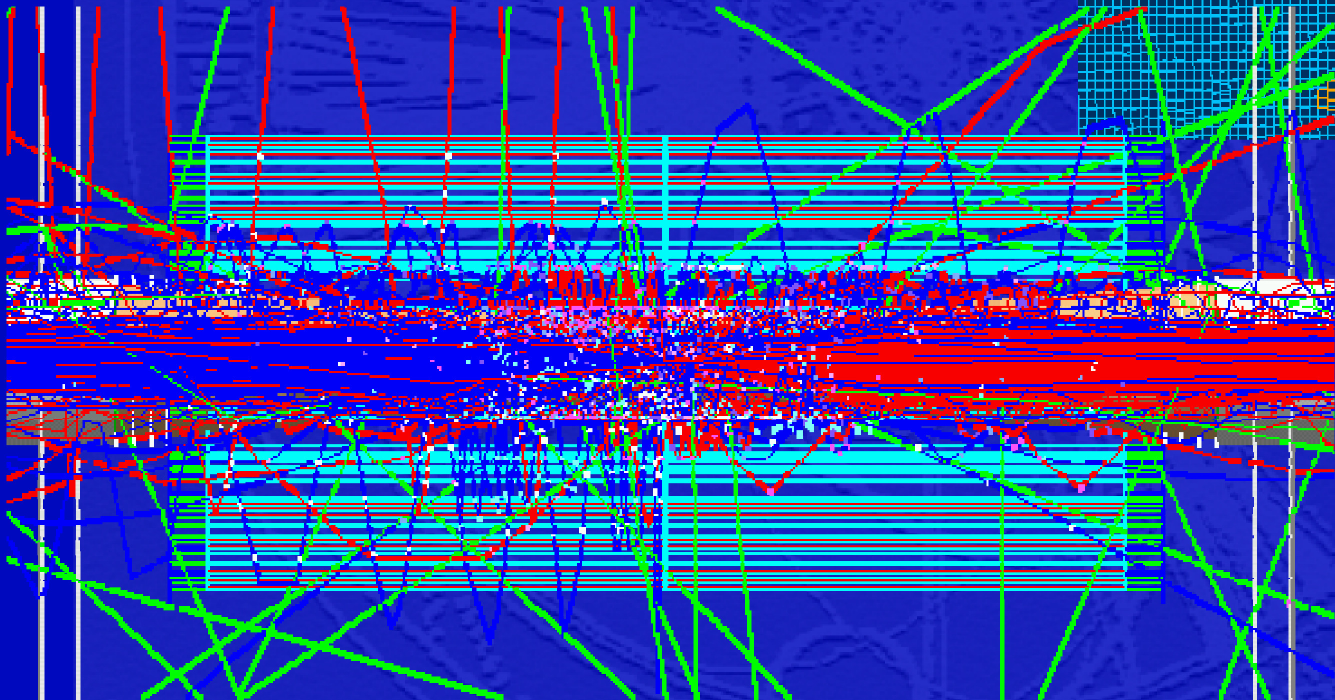


Raspereza, LCWS07

Occupancy Limitations

Understand cluster shape/occupancy of low momentum pairs striking detectors at small angle and use shape to possibly discriminate them;





Very fascinating and compelling anticipated physics program with crucial contributions from Vertex Tracker;

Significant simulation and reconstruction efforts by many of the groups involved in sensor R&D and detector design;

Essential to promote vigorous program of physics benchmark studies using full simulation and reconstruction and realistic background conditions to guide R&D and design.