PROCEEDINGS OF SCIENCE

LHC/ILC/CLIC

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LHC-LC -… ?

Gudrid Moortgat-Pick, IPPP Durham, UK
22.8.2009

- ‘Big’ HEP questions
- Overview LHC2FC and synergy effects
- LC technical requirements
- More detail on LHC and LC synergy
- Staged approach
- Summary

Sceptical thoughts

- Many options and ideas for experiments
  - Most are expensive, some ‘rather’ cheap
  - Should cost be a criteria? Or diversity?
- Priority list needed
  - Many lists exist (CERN strategy group, P5, UK roadmaps,…) *any bias ?*
- Big experiments require long term planning
  - To which extent physics needs in advance predictable?
    Particle scales? Physics Models? …
- Can we really weight today all options?
  - ILC, SLHC, LHeC, CLIC, ν-fact, DLHV, μ-collider,….

(My) Pragmatic approach

- **Physics: what are the 'big' questions?**
  - Define steps ... 'physics milestones'
  - Identify which models tic which question
  - Common features: masses, couplings, spin, quantum numbers … 'verify at quantum level'

- **Machine: next physics milestone achievable?**
  - Technical requirements can be defined
  - Synergy with other experiments
  - Flexibility required: the 'unexpected'

'Big' questions …and possible answers

- **Shortcomings of the Standard Model**

•Establish electroweak symmetry breaking	LC
•Hierarchy problem?	LHC, LC
•Unification of all interactions?	LC
•Embedding of gravity	cosmo,LHC, LC
•Baryon asymmetry in Universe?	ν-, cosmo, LHC, LC
•Dark matter	ν-, cosmo, LHC, LC
•Neutrino mixing and masses	ν-, cosmo-exp.

- **Why TeV scale?**
  - Protect hierarchy between m_{weak} and m_{planck}
  - Dark matter consistent with sub-TeV scale WIMPs

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  - **Dark matter**
  - **Neutrino mixing and masses**

Higgs mass with respect to large quantum corrections:

$$\delta M_H^2 \sim \Lambda^2$$

- **Why TeV scale?**
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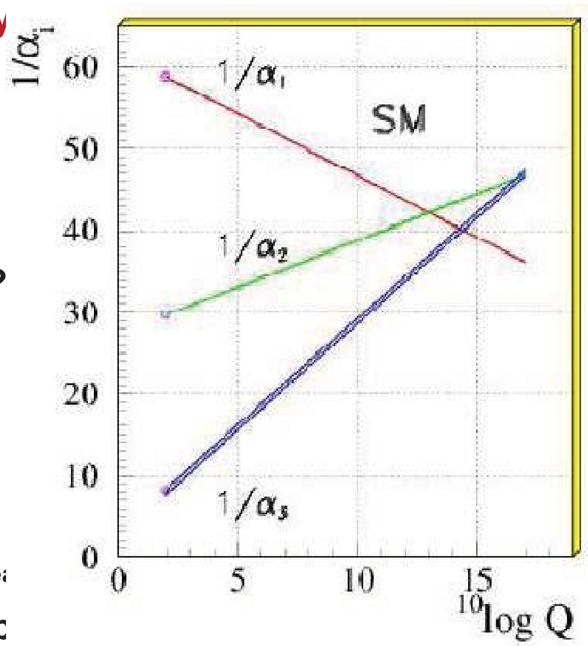
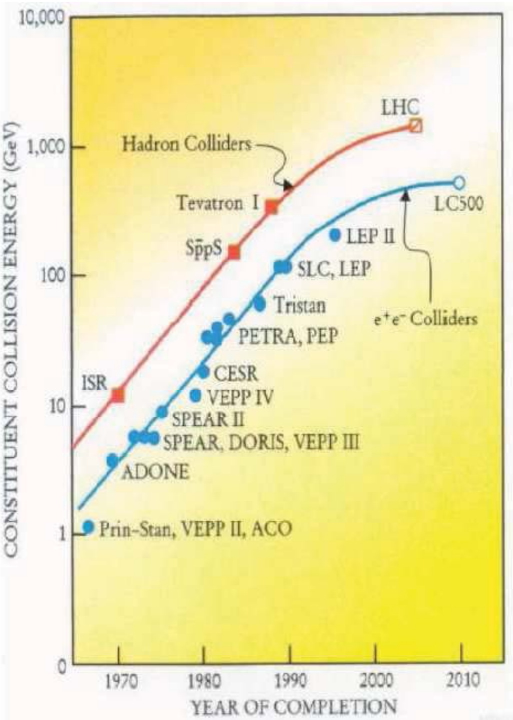


- **Why TeV scale?**
  - **Protect hierarchy between m_{wea}**
  - **Dark matter consistent with sub**

Synergy: hadron and e+e- colliders



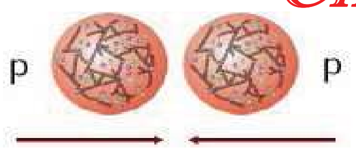
- long and fruitful tradition

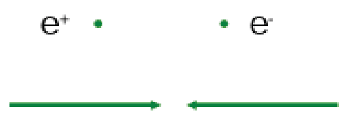
> - J/ψ at SPEAR (e+e−) and AGS (proton fixed target)
> - ´Υdiscovery at E288 (p fixed target), precision B studies at the e+e− B factories
> - top quark at LEP and Tevatron

- To be continued in the form of

LHC and LC

Characteristics of





pp collider
composite particles collide
E(CM) < 2 E(beam)
strong interaction in initial state
superposition with spectator jets
LHC: $\sqrt{s}$ = 10-14TeV,
used $\hat{s} = x_1 x_2 s$ few TeV
small fraction of events analyzed
multiple triggers
`no' polarization applicable

and of e +e-(γe, γ γ) collider
pointlike particles collide
E(CM) = 2 E(beam)
well defined initial state
clean final state
ILC: $\sqrt{s}$ = 90 GeV -- 1 TeV
CLIC: $\sqrt{s}$ up to 3 TeV
most events in detector analyzed
no triggers required
polarized initial beams

> **Main potential: direct discovery**

> **Main potential: precision discovery**

At the precision frontier: the LC

ICFA Parameter Group (chaired by R. Heuer)

- 'Scope Document no.1' (2003) and 'no.2' (2006): baseline
  - 'full luminosity of 2 x $10^{34} cm^{-2} s^{-1}$'
  - 'beam energy stability and precision below tenth of percent level.'
  - 'Machine interface must allow measurements of beam energy and diff. lumi spectrum with similar accuracy.'
  - 'electron beams with polarisation of at least 80% within whole energy range.'
- Options:
  - 'e^+ polarisation ~50% in whole energy range wo sign. loss of lumi...., Reversal of helicity ... between bunch crossings.'
  - GigaZ: e^+ polarisation+frequent flips essential; energy stability+calibration accuracy below tenth of percent level.'

Synergy effects: LHC2FC@CERN 2/09

Questions from early LHC data (~10 fb^{-1})

- 'Famous' 3 cases (cf. CERN strategy documents) :
  - LHC not detected anything (-> cf. also WG2@LHC2FC)
  - LHC only detected SM-like Higgs (-> cf. also WG1)
  - LHC detected some new physics (-> WG3+4)
- What could the LC do
  - in first ILC stage of 90 up to 500 GeV?
  - in LC upgrades?
  - in multi-TeV CLIC option?

Nothing found at (early) LHC

- **Interpretation for ILC?**
  - **'Top' physics**
  - **indirect searches in $b\bar{b}$, $c\bar{c}$, $l\,\bar{l}$ (large ED, CI)**
  - **ew precision runs from Z-pole data**
- **But is then really 500 GeV as first ILC stage needed?**
  - **or better 350 GeV? High-lumi Z-factory?**

Why 'top' physics?

- **Current average:** m_{top}= 172.4 +- 1.2 GeV
- **Expectations at the LHC:**
  - Δm_{top} ~ 1 GeV
  - Yukawa couplings ~ 20 % (with slight model assumptions)
- **Expectations at the ILC:**
  - Mass via threshold scans: m_{top}~ 100 MeV (theory dominant)
  - Yukawa couplings via $t\,\bar{t}\,H$: difficult due to small rates, but < 20%
  - Unique access to electroweak couplings
- **Why are top properties so important?**
  - m_{top} is dominant uncertainty for elw. precision observables
  - ILC precision mandatory already now to exploit theory at quantum level!

Importance of 'top' mass

- Top mass is important input parameter for electroweak precision tests
  - SM prediction for m_W and $\sin^2\theta_{eff}$: consistency checks, sensitivity to m_{Higgs}
  - compare m_W and $\sin^2\theta_{eff}$: experimental accuracy with theoretical prediction

- Theoretical uncertainties

  1. unknown higher orders: $\Delta \sin^2\theta_{eff}^{ho} \sim 5 \times 10^{-5}$, $\Delta m_W^{ho} \sim 4$ MeV

- High precision of top mass mandatory to exploit theory at quantum level!

If $\Delta m_{top} \sim 1$ GeV (LHC):	$\Delta \sin^2{}_{eff}^{input} \sim 3 \times 10^{-5}$, $\Delta m_W^{input} \sim 6$ MeV	
If $\Delta m_{top} \sim 0.1$ GeV (ILC):	$\Delta \sin^2{}_{eff}^{input} \sim 0.3 \times 10^{-5}$, $\Delta m_W^{input} \sim 1$ MeV	

Only SM-like Higgs at early LHC

- Interpretation for ILC
  - best-suited for studying Higgs properties
  - precise determination of couplings:

    determination of $Hb\bar{b}$ is crucial!
  - distinction: SM- versus SUSY Higgs
  - $t\bar{t}H$ and trilinear Higgs coup. challenging

- But is then really 500 GeV as 1st step needed?
  - Optimize running scenarios (tunable energy, polarization, use of calibration Z-pole data)

Determination of Higgs properties

- **Expectations at the LHC:**
  - Higgs mass: up to Δm_H =100-200 MeV
  - Higgs couplings: 15%-40% (with some model assumptions)
- **Expectations at the ILC:**
  - absolute couplings: 1-5 %
  - Establishing of ew sym. breaking: triple Higgs couplings at 500 GeV up to 22%
  - estimate: further gain of 30%-50% precision if both beams polarized
  - process t t H: difficult due to small rates (but threshold effects!)
  - accuracy about 24% for mH=120 GeV (unpolarized beams)
  - improvement factor 2.5 when (80%, 0%) -> (80%,60%)

LHC input for optimal choices of running scenarios !

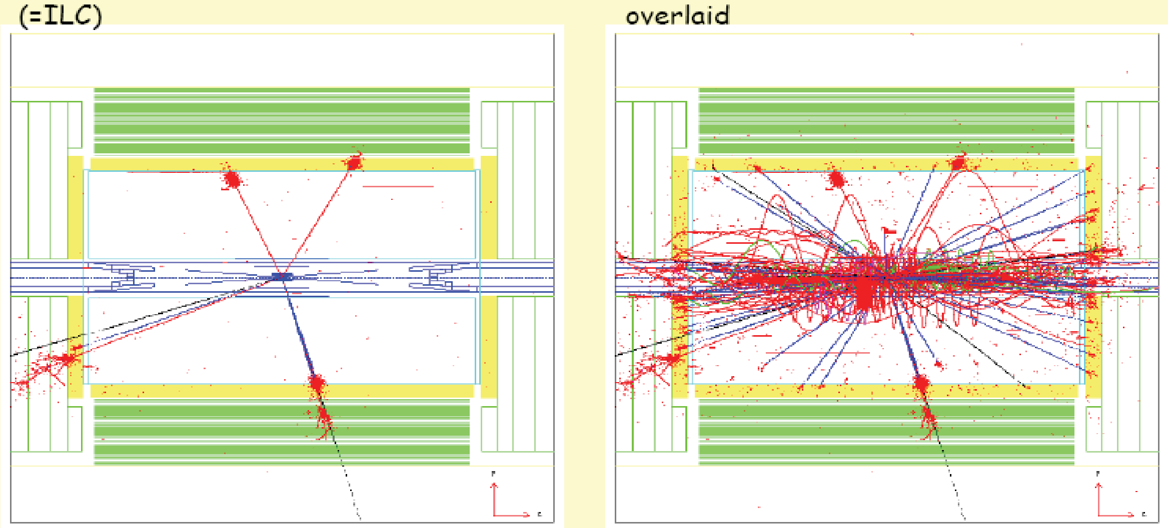
Klaus Desch@LHC2FC

Does LC Technology matter?

HZ → $\tau\tau$ee event

Without soft hadronic events overlaid (=ILC)

With 32 BX (=16 ns) „CLIC nominal 500" overlaid

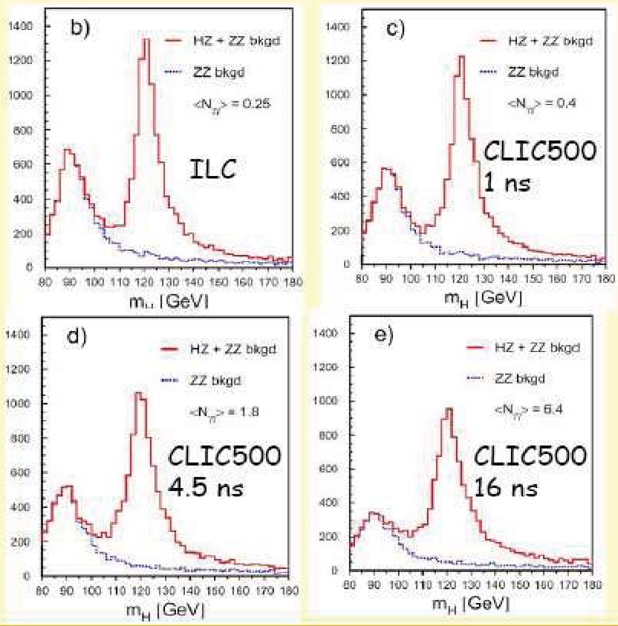


note: CLIC 3000 nominal has 14 times CLIC500 overlaid

Klaus Desch@LHC2FC

Does LC Technology matter?

Higgs recoil mass



many LC precision measurements depend on machine presicions more than on detector precision

- threshold scans
- polarized cross sections

Needs careful consideration!

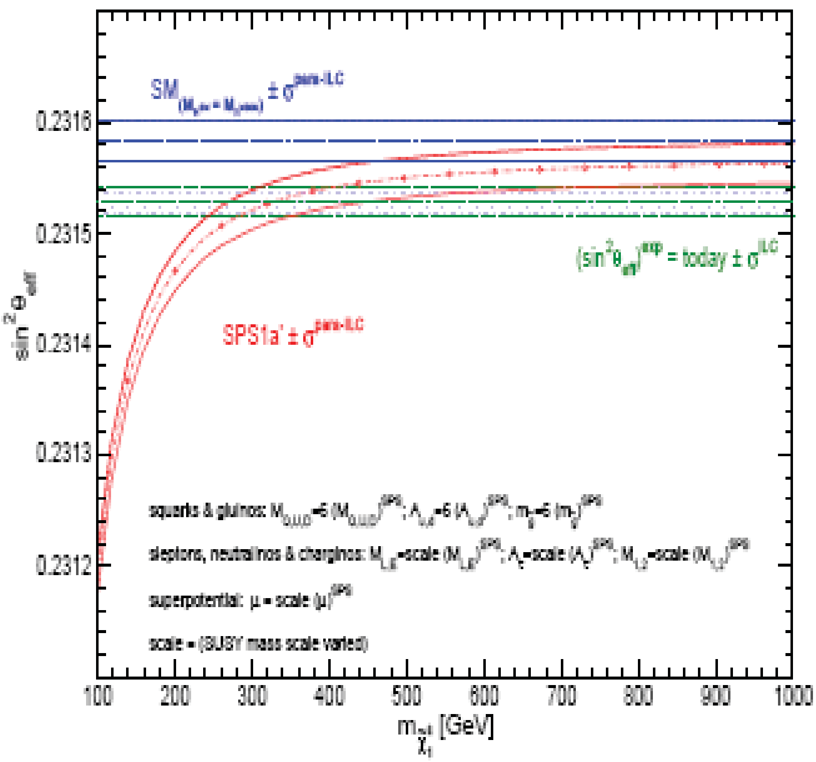
Average energy loss (beamstrahlung)

2.4% / 7% / 29%
ILC500/CLIC500/CLIC300

Hints for SM versus SUSY?

Only Higgs @LHC
No hints for SUSY

- **Deviations in $\sin^2\theta_{eff}$**
  - **hints for SUSY**
- **Powerful test!**
  - **Do not miss it**



Something 'new' detected at early LHC

- **SUSY-like signals** *(many tics at big questions!)*
  - **At least partial spectrum accessible at ILC**
  - **Ideal playground for synergy effects**
  - **Hints for CP-violation in new physics**
- **Extra gauge bosons and/or large extra dimensions** *(some tics at big questions!)*
  - **High precision in indirect searches allow model distinction and couplings determination**
- **Which running scenarios and design issues?**

SUSY challenges

- Whats needed for establishing SUSY?
  - Spin verification: via analysis of angular distributions
  - Couplings measurement: Yukawa couplings = gauge couplings
  - Precise mass measurements
  - Unraveling the SUSY breaking mechanism and test unification
  - 'model- independent' determination of the parameters (105 already in the MSSM!)
- **At LHC**
  - Parameter determinations: in specific SUSY breaking models

Free parameters in the MSSM

- mass matrices are 3 x 3 hermitian

  → m_Q^2, m_u^2, m_d^2, m_L^2, m_e^2 : 45 parameters

- gaugino masses M_1, M_2, M_3 are complex numbers: 6
- trilinear couplings a_u, a_d, a_e are 3 x 3 complex matrices: 54
- bilinear coupling b is 2 x 2 matrix: 4
- Higgs masses m^2_{Hu}, m^2_{Hd} : 2

  → altogether 111 parameter ???

Symmetries (lepton + baryon number, Peccei-Quinn, R symmetry) lead to'rotations':

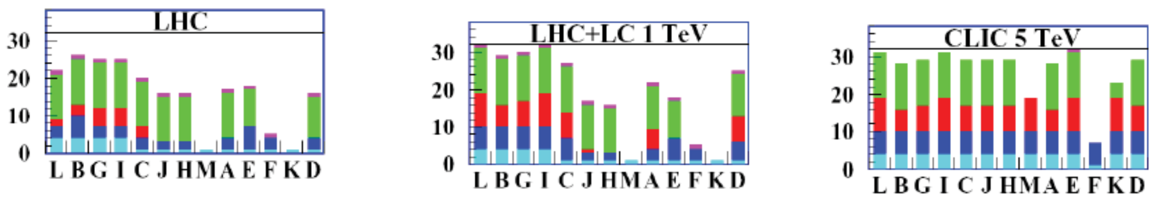
-4 non-trivial field redifinitions

-2 in the Higgs sector (since minimal model only 2 parameters in the Higgs sector)

→ remain 105 free new parameters in the MSSM!

DisneyWorld of SUSY scenarios

- **Often (ab)used: Manhattan plots**



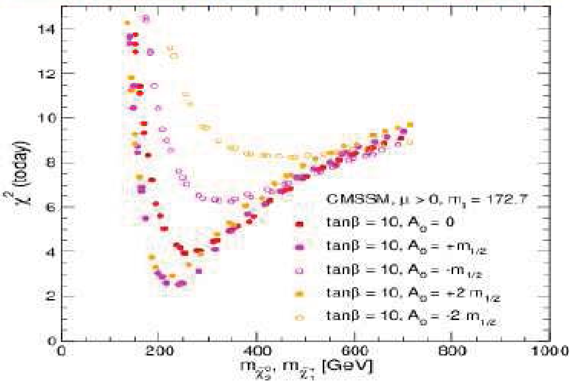
- **13 SUSY 'benchmarks' scenarios out of millions …**
  really a true representative choice ?
- **heavy masses often mass degenerated: no resolution (beamstrahlung!) has been taken into account…**
  really a reliable 'counting' ?
- **experimental verification of properties not studied …**
  really a useful basis for future decisions?

Physics or just propaganda, that's the question….

Where do we expect SUSY?

- In which range do we expect SUSY?
  - at least some light particles should be accessible at 500 GeV
  - best possible tools needed to get maximal information out of only the part of the spectrum

Ellis, Heinemeyer, Olive, Weber, Weiglein '07



- To reveal the structure of the underlying physics, it is important to determine the parameters in a model-independent way and test all model assumptions experimentally
- Soon we will have LHC data, but LHC/ILC interplay will be essential and both machines cover a large range of the parameter space !

Now more details: searches for NP

- ***High statistics*** **needed**
  - **L = 2 x 10^{34} cm^{-2} s^{-1}**
- **Clean experimental environment**
  - ***low beamstrahlung*** **(Υ_{ave}=0.048)**
  - **precise *luminosity* (ΔL<10^{-3}) and *energy* (Δsqrt(s)<200 ppm) *measurement***
- **Excellent detector resolution**
  - ***b-, c-tagging*** **(even the charge if needed)**
  - ***τ-polarization***
  - **4π – ε angle coverage**
  - **exloitation of angular distributions, BR's, T's**

Needed features, cont.

- ***Threshold scans***
  - *Tuneable energy* allows to vary energy around the mass threshold of new particles
  - Cost luminosity
  - Optimization of required energy steps a priori possible via rather accurate continuums measurements
- ***Beam polarization***
  - Polarized e- with P(e-)~90% expected
  - Polarized e+ with P(e+)~60% (even in baseline ~30% expected !)
  - Enable to reveal underlying structure of new physics
  - Enhance statistics

Why polarized e^- and e^+ beams?

- Comprehensive overview in *hep-ph/0507011, Phys.Rept.460 (2008), GMP et al.*
  - executive summary: http://www.ippp.dur.ac.uk/LCsources/
- Goals: Polarized beams required to
  - analyze the structure of all kinds of physics
  - improve statistics: enhance rates, suppress backgrounds
  - get systematic uncertainties under control
- Discoveries via deviations from SM predictions in precision measurements !
  - important in particular at sqrt{s}≤500 GeV!

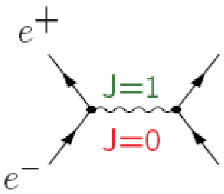
Remarks about couplings structure

- Definition: Helicity $\lambda = s * p/|p|$ 'projection of spin'
- Chirality = handedness is equal to helicity only of m=0!

Def.: left-handed $\equiv P(e^{\pm}) < 0$ right-handed $\equiv P(e^{\pm}) > 0$

Which configurations are possible in principle?

s–channel:



← only from RL,LR: SM (γ, Z)

← only from LL,RR: NP!

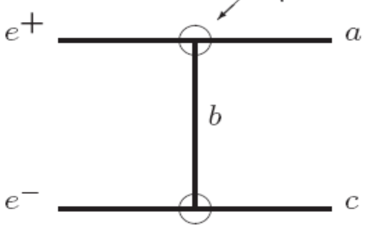
$\Rightarrow$ In principle: $P(e^-)$ fixes also helicity of e^+!

General remarks, cont.

Which configurations are possible in the crossed channels?

t–channel:

depends on $P(e^+)$!



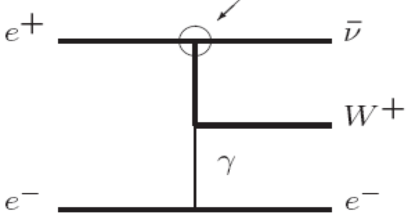
depends on $P(e^-)$!

$\Rightarrow$ helicity of e^- not coupled with helicity of e^+!

Two examples:

a) Single W production

only influenced by $P(e^+)$!



b) Bhabha scattering

$\Rightarrow$ γ, Z exchange in s–channel: selects LR, RL

$\Rightarrow$ γ, Z exchange in t–channel: LL,RR possible!

unpolarised	4.50 pb
$P_{e^-} = -80\%$	4.63 pb
$P_{e^-} = -80\%$, $P_{e^+} = -60\%$	4.69 pb
$P_{e^-} = -80\%$, $P_{e^+} = +60\%$	4.58 pb

Statistical arguments for P(e+)

- Polarized cross sections can be subdivided in:

$$\sigma_{P_{e^-}P_{e^+}} = \frac{1}{4}\{(1+P_{e^-})(1+P_{e^+})\sigma_{RR} + (1-P_{e^-})(1-P_{e^+})\sigma_{LL} + (1+P_{e^-})(1-P_{e^+})\sigma_{RL} + (1-P_{e^-})(1+P_{e^+})\sigma_{LR}\},$$

σ_{RR}, σ_{LL}, σ_{RL}, σ_{LR} are contributions with fully polarized L, R beams.

In case of a vector particle only (LR) and (RL) configurations contribute:

$$\begin{aligned}\sigma_{P_{e^-}P_{e^+}} &= \frac{1+P_{e^-}}{2}\frac{1-P_{e^+}}{2}\sigma_{RL} + \frac{1-P_{e^-}}{2}\frac{1+P_{e^+}}{2}\sigma_{LR} \\ &= (1-P_{e^-}P_{e^+})\frac{\sigma_{RL}+\sigma_{LR}}{4}\left[1 - \frac{P_{e^-}-P_{e^+}}{1-P_{e^+}P_{e^-}}\frac{\sigma_{LR}-\sigma_{RL}}{\sigma_{LR}+\sigma_{RL}}\right] \\ &= (1-P_{e^+}P_{e^-})\,\sigma_0\,[1 - P_{\rm eff}\,A_{LR}],\end{aligned}$$

Statistics, II

- Effective polarization

$$P_{eff} := (P_{e^-} - P_{e^+})/(1 - P_{e^-}P_{e^+}) = (\#LR - \#RL)/(\#LR + \#RL)$$

- Fraction of colliding particles

$$\mathcal{L}_{eff}/\mathcal{L} := \tfrac{1}{2}(1 - P_{e^-}P_{e^+}) = (\#LR + \#RL)/(\#all)$$

Colliding particles:

	RL	LR	RR	LL	P_{eff}	$\mathcal{L}_{eff}/\mathcal{L}$
$P(e^-)=0$, $P(e^+)=0$	0.25	0.25	0.25	0.25	0.	0.5
$P(e^-)=-1$, $P(e^+)=0$	0	0.5	0	0.5	-1	0.5
$P(e^-)=-0.8$, $P(e^+)=0$	0.05	0.45	0.05	0.45	-0.8	0.5
$P(e^-)=-0.8$, $P(e^+)=+0.6$	0.02	0.72	0.08	0.18	-0.95	0.74

$\Rightarrow$ Enhancing of $\mathcal{L}_{eff}$ with $P(e^-)$ and $P(e^+)$!

Statistics, III

- **How are P_{eff} and A_{LR} *related*?**

$$A_{LR} = \frac{1}{P_{eff}} A^{obs}_{LR} = \frac{1}{P_{eff}} \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}},$$

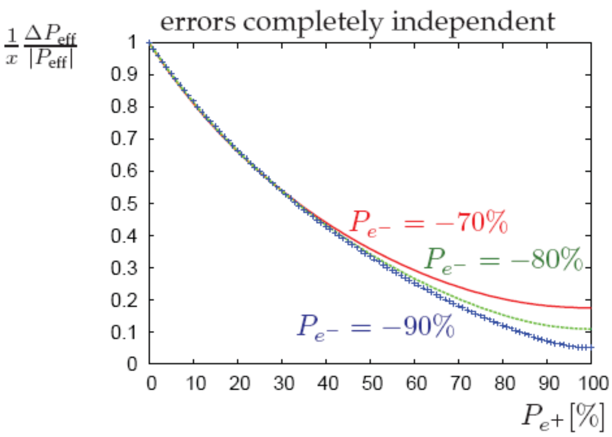
- **That means:** $\left|\frac{\Delta A_{LR}}{A_{LR}}\right| = \left|\frac{\Delta P_{eff}}{P_{eff}}\right|$

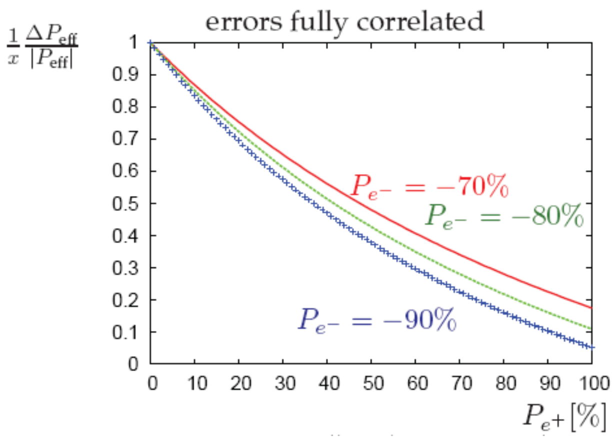
- **With pure error propagation (and errors uncorrelated), one obtains:**

$$\frac{\Delta P_{eff}}{P_{eff}} = \frac{x}{(|P_{e^+}| + |P_{e^-}|)\,(1 + |P_{e^+}||P_{e^-}|)} \sqrt{(1 - |P_{e^-}|^2)^2\, P^2_{e^+} + (1 - |P_{e^+}|^2)^2\, P^2_{e^-}}$$

$$x \equiv \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$$

Statistics, IV





$\Delta A_{LR}/A_{LR} = 0.3$ **$\Delta A_{LR}/A_{LR} = 0.27$** **$\Delta A_{LR}/A_{LR} = 0.5$**

gain: factor~3 factor>3 factor~2

→ NO gain with only polarized e^- !

Background suppression

WW, ZZ production = large background for NP searches!

W^- couples only left–handed:

$\rightarrow$ WW background strongly suppressed with right polarized beams!

Scaling factor= $\sigma^{pol}/\sigma^{unpol}$ for WW and ZZ:

$P_{e^-} = \mp 80\%$, $P_{e^+} = \pm 60\%$	$e^+e^- \rightarrow W^+W^-$	$e^+e^- \rightarrow ZZ$
(+0)	0.2	0.76
(−0)	1.8	1.25
(+−)	0.1	1.05
(−+)	2.85	1.91

One more SUSY Test at the ILC

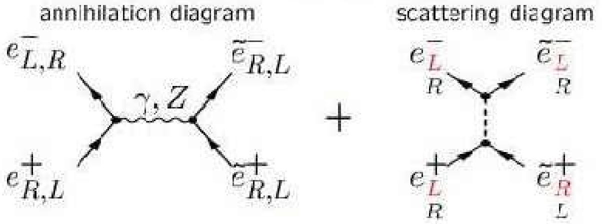
Test of SUSY assumption: SM $\leftrightarrow$ SUSY have same quantum numbers!

$\Rightarrow$ $e^-_{L,R} \leftrightarrow \tilde{e}^-_{L,R}$ and $e^+_{L,R} \leftrightarrow \tilde{e}^+_{R,L}$

Scalar partners $\leftrightarrow$ chiral quantum numbers!

How to test this association?

Strategy: $\sigma(e^+e^- \rightarrow \tilde{e}^+_{L,R}\tilde{e}^-_{L,R})$ with polarised beams



$\Rightarrow$ 2nd diagram: unique relation between chiral fermion $\longleftrightarrow$ scalar partner

Use e.g. $e^+_L e^-_L$

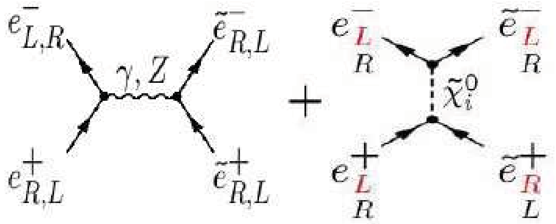
$\rightarrow$ scattering diagram: $\tilde{e}^+_R \tilde{e}^-_L$ $\longrightarrow$ $\tilde{e}^+_R$ $\leftrightarrow$ $\tilde{e}^-_L$

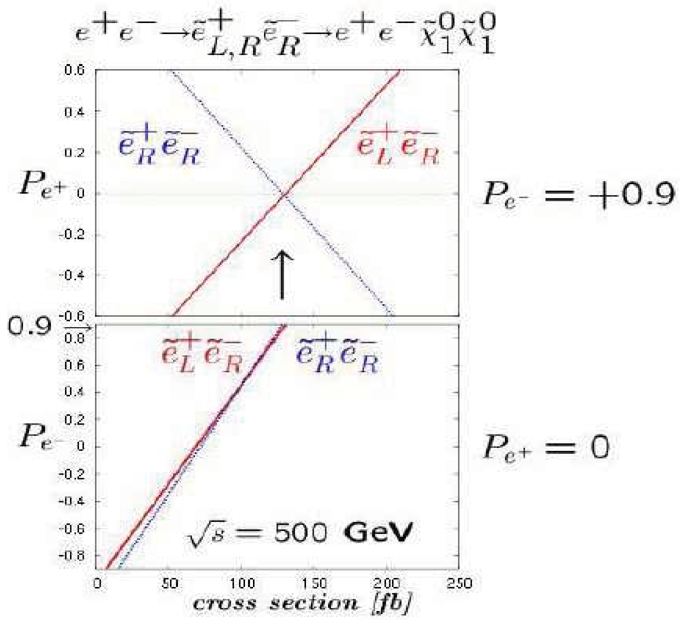
$\rightarrow$ no annihilation diagram

Chiral quantum numbers

- Association of chiral electrons to scalar partners $e^-_{L,R} \leftrightarrow \tilde{e}^-_{L,R}$ and $e^+_{L,R} \leftrightarrow \tilde{e}^+_{R,L}$:

s-channel t-channel





1. separation of scattering versus annihilation channel
2. test of 'chirality': only $\tilde{e}^+_L\tilde{e}^-_R$ may survive at P(e-) > 0 and P(e+) > 0 !

- *Even high P(e-) not sufficient, P(e+) is substantial!*

Back to the ILC physics case…

- ***But since the ILC can not start before 2015+, all physics issues have to be seen in view of expected LHC results***
- ***In the following we discuss several physics topics, starting at 500 GeV, 1TeV, multi-TeV***
- ***Applying the mentioned tools, threshold scans, beam polarization, precision measurements***
- ***But only a personal selection of examples ……***

SUSY mass measurement im continuum

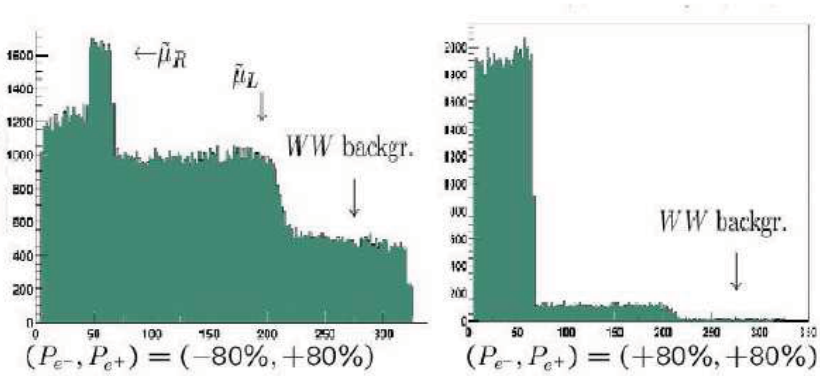
- To optimize threshold scans: precise continuum measurements important!
- Worst SM background is WW-pair production
  - e.g. $e^+e^- \to \tilde{\mu}^+_{L,R}\tilde{\mu}^-_{L,R}$

Muon energy spectrum: $\mu^+\mu^-$ events (incl. W^+W^-) at $\sqrt{s} = 750$ GeV

- Strong WW-backgr.:
  - all edges observable only with P(e-) and P(e+)
  - at 65 GeV and 220 GeV

S / B = 0.07 (+80%,0)

S / B= 0.46 (+80%,-80%)

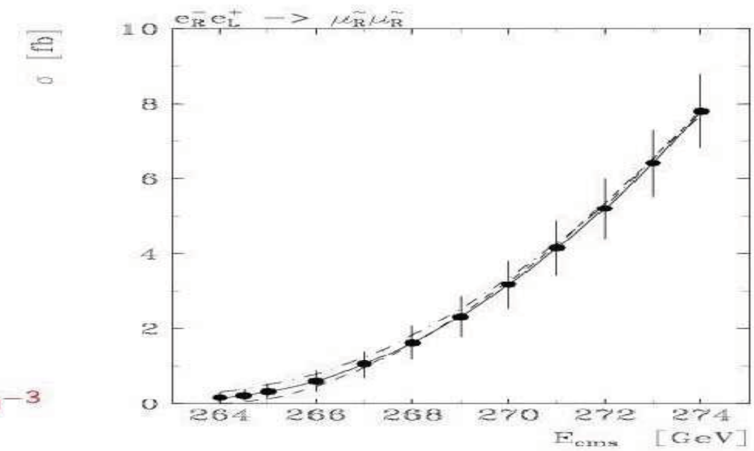


- $\Delta(m_{\tilde{\mu}_{L,R}}) \sim$ few GeV if both beams are polarized !

SUSY 'spin verification'

- **Assume LHC provides mass of a SUSY particle:**
  - **Important input for threshold scans:**

Determination of mass and spin of $\tilde{\mu}_R$ from production at threshold:
[TESLA TDR '01]



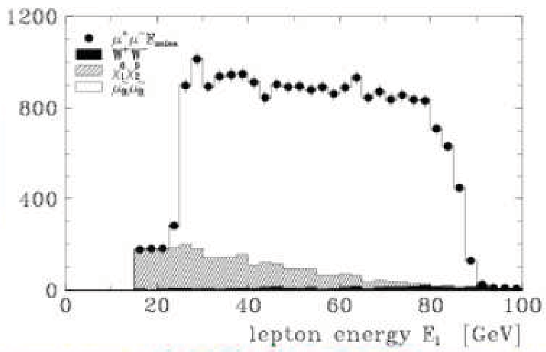
$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$

$\Rightarrow$ test of $J = 0$ hypothesis

Mass measurement of the LSP mass

- A promising cold dark matter candidate = lightest SUSY particle (LSP)
  - in many scenarios: $\tilde{\chi}^0_1$
  - excellent mass resolution e.g. in slepton decays $\tilde{\mu}_R\tilde{\mu}_R \rightarrow \mu\mu\tilde{\chi}^0_1\tilde{\chi}^0_1$

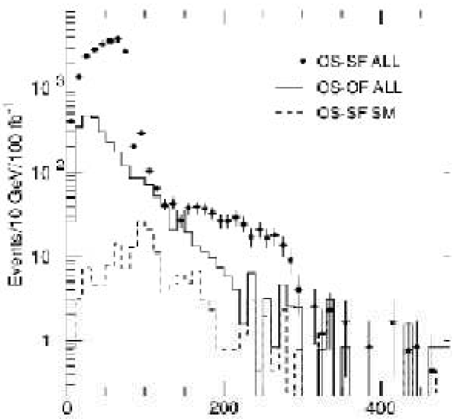
→ $\Delta m\tilde{\chi}^0_1$ up to 0.3%, here 100 MeV!



- Further improvement in mass measurements via threshold scans possible !
  - costs luminosity, therefore should be optimized via excellent measurements in the continuum
- **Reliable dark matter prediction possible**

MSSM parameter s from $\chi^0_1, \chi^0_2, \chi^\pm_1$

- If fundamental parameters determined: allows mass predictions for heavier particles
  - significant increase of sensitivity for searches at the LHC and unique identification of particles in decay chain
  - *Powerful test of the model*



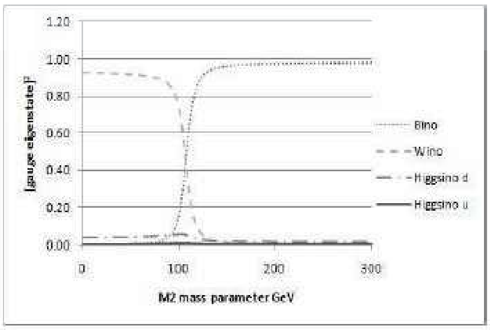
	M_1	M_2	μ	$\tan\beta$
input	99.1	192.7	352.4	10
LC_{500}	99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5
$LHC+LC_{500}$	99.1 ± 0.1	192.7 ± 0.3	352.4 ± 2.1	10.2 ± 0.6

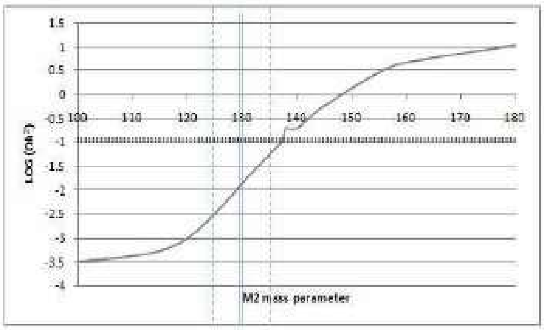
- strong improvement in parameter determination via interplay!

Dark matter analysis at LC

- ***High precision in parameter determination required for reliable DM prediction***
  - **Parameter ranges where abrupt changes of neutralino character happen**

V. Morton-Thurtle





  - **Precise determination of M_1,M_2….required**

SUSY model distinction

- **SUSY scenario in the NMSSM: Higgs and light particle sector (neutralino / chargino) show no hints for model distinction**
- **measured at ILC (500 GeV):** $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_{1,2}^0}, \sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_2^0)$
  - **Consistent within MSSM-analysis**
  - **Predictions:**

    $m_{\tilde{\chi}_3^0} = [352, 555]$ GeV $\longrightarrow$ pure higgsino

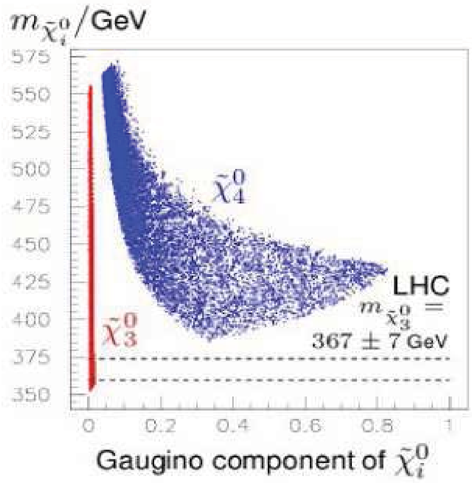
    $m_{\tilde{\chi}_4^0} = [386, 573]$ GeV $\longrightarrow$ larger gaugino comp.

    $m_{\tilde{\chi}_2^\pm} = [450, 600]$ GeV

  $\Rightarrow$ $\tilde{\chi}_3^0$ not accessible at LHC

  However: $\tilde{\chi}_3^0$ in underlying NMSSM scenario has large gaugino component

  $\longrightarrow$ visible at LHC $\longrightarrow$ inconsistency



- **Model inconsistency determined via LHC/ILC**

Heavy sfermions -- FP inspired

- Feature of, for instance, focuspoint - inspired scenarios
  - features: very heavy squarks, sleptons, heavy H, A but light SM-like h and light gluino and light charginos / neutralinos
  - challenging for the LHC......but is the ILC then the right machine ?
  - some analysis done at LHC, but within mSUGRA and still difficult
- take a focuspoint-inspired scenario, but do not impose any assumption on the SUSY breaking mechanism and apply LHC / ILC analysis
- How well is it possible to
  - determine the underlying fundamental parameters?
  - predict masses of heavier states?

Case study

- Squarks, sleptons ~ 2 TeV, but light gluino
- Light chargino+neutralinos accessible at ILC500
- Using mass information (LHC) + angular distribution (ILC)
- Results (without using SU(2) relation) :

$$59.45 \le M_1 \le 60.80 \text{ GeV}, \quad 118.6 \le M_2 \le 124.2 \text{ GeV}, \quad 420 \le \mu \le 770 \text{ GeV}$$

$$1900 \le m_{\tilde{\nu}_e} \le 2120 \text{ GeV}, \quad m_{\tilde{e}_L} \ge 1500 \text{ GeV}, \quad 11 \le \tan\beta \le 60.$$

- precise parameter determination allows also accurate prediction of heavy gaugino states

CP-violation in SUSY

- **SUSY provides many new sources for CP-violation**
  - constraints on parameters from e, n, Hg dipole moments, LEP, Tevatron, b -> sγ, g_μ-2, dark matter searches, etc....
- **Determination of phases in two steps**
  - observation of unique effects of CP-violation at LHC
  - disentangling and determination of corresponding phase parameter at ILC

Use CP-odd observable:

- Triple product correlations show different dependence on phases
- At LHC: qq,gg -> squarks -> gauginos -> leptons

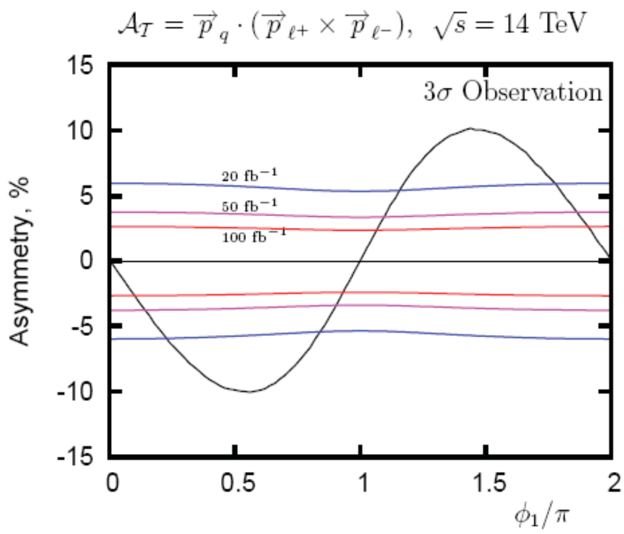
Hints for CP violation at LHC/ILC

- **Study today:**

$$q\,g \Longrightarrow \tilde{q}_L\,\tilde{g},$$
$$\tilde{q}_L \Longrightarrow \tilde{\chi}^0_2\,q,$$
$$\tilde{\chi}^0_2 \Longrightarrow \tilde{\chi}^0_1\,l^+\,l^-$$

- **CP-asymmetry**

  based on $\mathcal{T} = \vec{p}_q \cdot (\vec{p}_{\ell+} \times \vec{p}_{\ell-})$

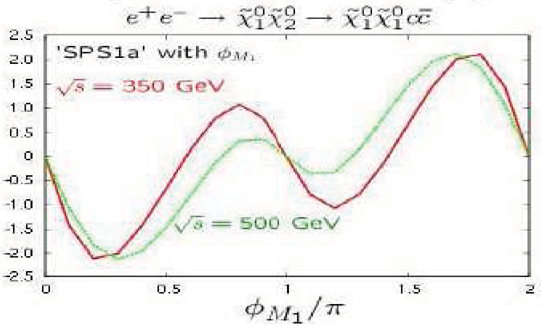


Tattersall et al.

- **Hints for CP-violation at LHC**

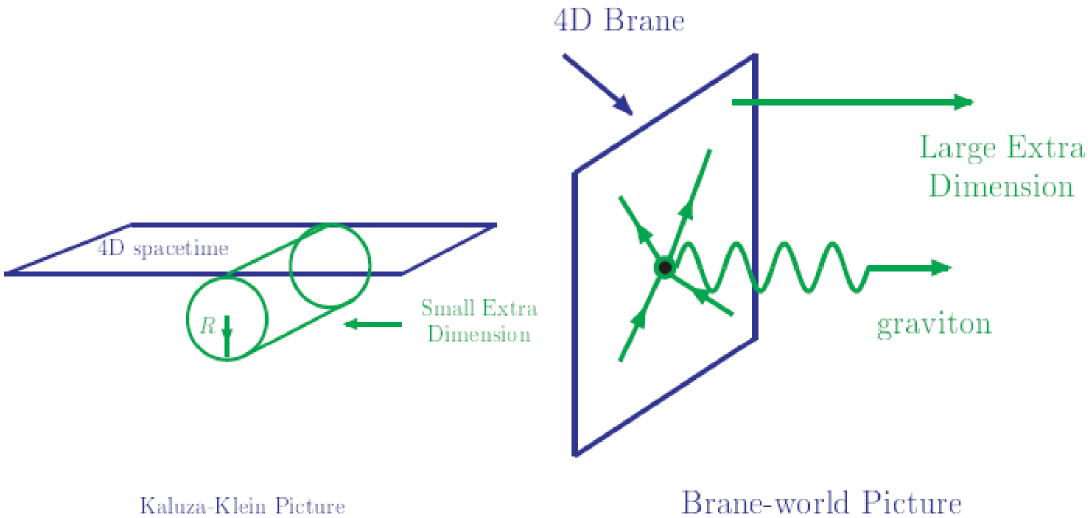
Determination of phases at LC

- SUSY provides new sources for CP-violation (→ explain baryon asymmetry....)
  - many phases available in SUSY, but strong experimental constraints from measurements of the e, n, Hg, Tl dipole moments
  - sensitive observables needed to detect even small phases: very sensitive are asymmetries constructed via three momenta 'triple products'
  - use transversely polarized beams: effects ~ $P^T(e^-)\, P^T(e^+)$
  - use SUSY decays into τ's and exploit τ polarization
  - use SUSY leptonic or hadronic decays, often b- and c-tagging needed:



→ c and $\bar{c}$ distinction needed!

Indirect searches: extra dimensions

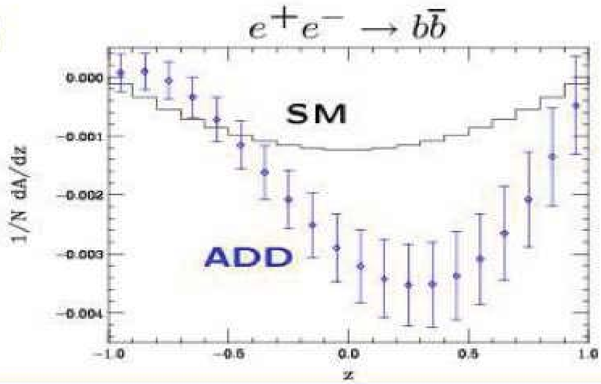


Hierarchy between $M_{\rm Planck}$ and $M_{\rm weak}$ is related to the volume or the geometrical structure of additional dimensions of space

⇒ observable effects at the TeV scale

Extra dimensions

- **LHC input: observed monojets**
- Transversely polarized beams (only effects detectable with P(e$^-$) x P(e$^+$) !)
  - enables to exploit azimuthal asymmetries in fermion production !
- Distinction between SM and diff
  models of extra dimension:
  - asymmetry signals contribution from spin-2 graviton



→ Detect new kind of physics even if new scale is in the multi-TeV range, but transversely polarized beams need polarized e$^-$ and e$^+$!

Input from (early) LHC possible?

On possible design features:

- **energy scale(s)** of a LC
- **running scenarios** (when GigaZ? # of steps in scans?)
- **e$^+$ polarization degree** (45% ,60%,?)
- **detector concepts ?**
  - impact on physics? On # of lumi data? $b\bar{b}$,$c\bar{c}$?..
- **options** (e$^-$g, gg, e$^-$e$^-$,high lumi GigaZ)
- **# of interaction regions (push-pull, two or one IR's) ?**

Status ILC

- reasonable to plan LC in several stages
  - ILC at 500 GeV design 'ready to go'
  - upgrade to 1 TeV foreseen
  - maybe even multi-TeV 'upgrade'
- already baseline design provides polarized e^- (90%) and e^+ (30%~45%, option of 60%) beams
- tuneable energy from $\sqrt{s}$=90 to 500 GeV
  - 2 x $10^{34}cm^{-2}s^{-1}$ and beam energy stability
  - beam energy+precision below tenth of percent level

Cf. Scope documents ' 03+'06 !!!

- ILC technology ready for industrialisation phase …

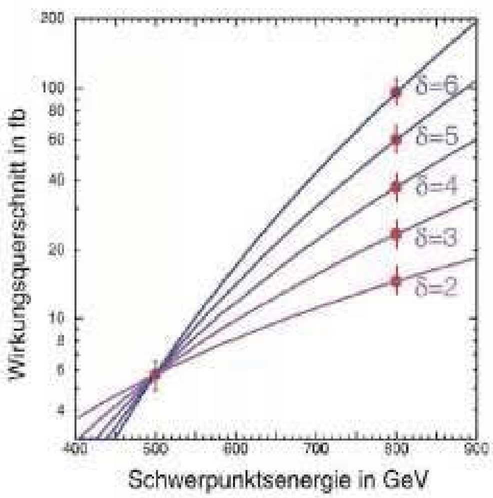
Physics up to 1 TeV

- Top couplings
  - improvement of top Yukawa couplings
  - higher cross cross sections (depends on Higgs mass)
  - couplings up to 5% !
- Direct search for SUSY particles
  - high probability for access to almost the full gaugino/higgsino SUSY spectrum
  - powerful consistency tests and model determination
- Extrapolation of masses and gauge couplings to high scales
  - consistency tests for the underlying SUSY breaking scheme
  - consistency check for gauge unification

•Direct search for extra dimensions

Direct search for extra dimensions

- Direct search for gravitons in the process e+e- →
  - measuring the cross sections at two different cms energies, allows to determine the number of extra dim !
  - ILC with polarized beams exceeds / complements discovery region of LHC



- serious background from $\gamma\nu\nu$, similar behaviour
  - polarized e- and e+ essential for background suppression
  - (Pe-,Pe+)=(+80%,+60%) / (+80%,0) : suppresses B by factor 2, enhances S by 1.5

Multi-TeV option at CLIC - Higgs

- Needed scale and physics case for the multi-TeV option depends on results at LHC and ILC
- Improvement in all sectors (direct and indirect searches) if
  - same precision available as at ILC
  - beamstrahlung fully under control
- Triple Higgs couplings: improvement by about a factor 2
  - enhancement of cross sections of WW-fusion process
  - uncertainty of triple Higgs couplings up to 13%
  - important for further understanding of the electroweak symmetry mechanism !

Klaus Desch@LHC2FC

On staging

Various „natural" stages (ordered in √s) for an e^+e^- collider:

91.2 GeV -- Giga-Z

~ 250 GeV -- maximum of HZ cross section

344 GeV -- ttbar threshold

2 m(LSP,LKP,...) + X -- model independent WIMP measurements

2 m(NLSP) + X -- SUSY spectroscopy (part I)

~ 800 GeV -- maximum of ttH cross section, HH coupling

m (Z´)

2 m (squarks) + X

3 TeV

Different stages (and when to reach them) will (hopefully) be known from LHC data

Hard to imagine any LHC discovery which would not trigger the start of an e^+e^- programme ...

and do not forget the top!

- **LHC input important for ILC-2-CLIC physics**
  - motivate running scenarios (threshold scans, polarization, low energy runs)
  - detector capabilities (flavour charge tagging)
  - motivate upgrade options
- **LC = discoveries at the precision frontier asap**
  - 'understanding' of underlying structure at quantum level
  - fulfill requirements of scope documents
- **Staged LC approach most reasonable** *start now*
  - ***Goal:* *ILC∞ CLIC = combined design ….***