Beam Parameters and Physics Reach

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Outline

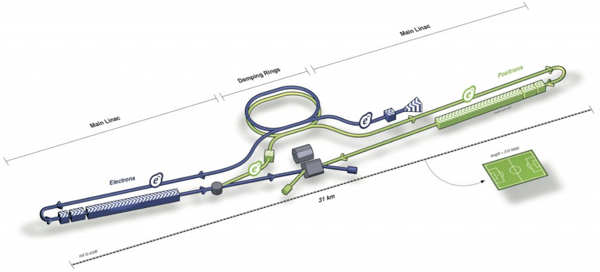
The ideal linear collider

- Exactly known initial e^+e^- state.
- Fully polarised beams.
- As many events that you need at any E_{CMS} .
- Pure electron/positron beams.
- No background from the machine.
- No $\gamma\gamma$ background ...

The real linear collider

- Beam energy has both initial and beam-beam induced spread.
- Low positron polarisation (~30 %), and $<$ 100 % electron polarisation.
- Limited luminosity.
- Mixed lepton and photon beams.
- Huge number of low energy background particles from the machine.
- $\gamma\gamma$ background exists ...
- There is ISR ...

Elements of the real collider



We need electrons and positrons:

- Electron source.
- Positron source.

We need well defined beams:

- Damping system.

We need high energy:

- Main linac.

We need to get the beams to the detectors:

- Beam delivery system.
- Final focus.

Elements of the real collider: Sources

- Electron source.
  - Polarised laser shining on photo-cathodes, specially designed to yield polarised electrons. Collect and pre-accelerate, then send to damping system.
- Positron source
  - High ($>$ 150 GeV) energy electron beam passes an helical undulator acting as a FEL, to produce high intensity, polarisation and energy ($\sim$ 10MeV) photons. These hit a rotating target to produce e^+e^-e-pairs. Positrons are collected, pre-accelerated and sent to damping.
  - Electrons are from the main beam $\rightarrow$ an additional energy dispersion, due to to the synchrotron radiation losses in the undulator.

Elements of the real collider: Damping system

- From the sources, the dispersion both in angle and energy are way to big.
- Send beams (now at $\sim$ 5 GeV) to rings where they pass ”wigglers” making them cool off by synchrotron radiation.
- Kick out bunches, one-by-one, every $\sim$ 100 ns to make the bunch train. Bunches are separated by a few ns, given by (circumference of damping ring)/(number of bunches).
- All this must be done in the 200 ms between bunch trains.
- The damping rings are at the centre of the complex: need to transport the bunches $\sim$ 15 km to the start of the main linac after damping.

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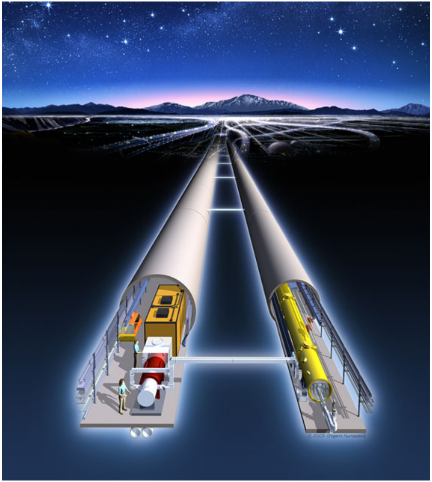
Elements of the real collider: Main linac

- Super-conducting RF cavities, 31.5 MV/m gradient, 9 cells.
- One RF unit = 3 cryo-units, 2 with 9 cavities, one with 8 + a focusing quadropole.
- 278 of these in the positron linac, 282 in the electron one (more, since energy is lost in the undulator !) ⇒ 132 912 cells...
- The linac needs power: Klystrons all along. How many particles one can get/time depends on how many of these one installs.



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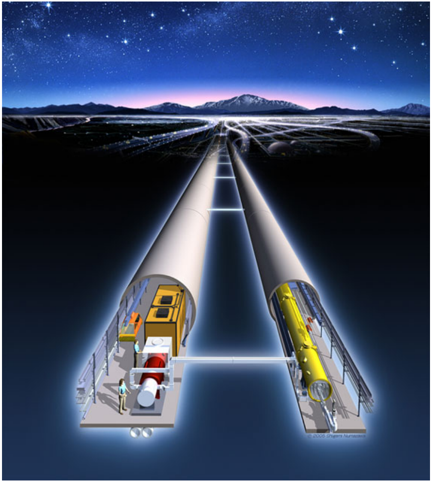

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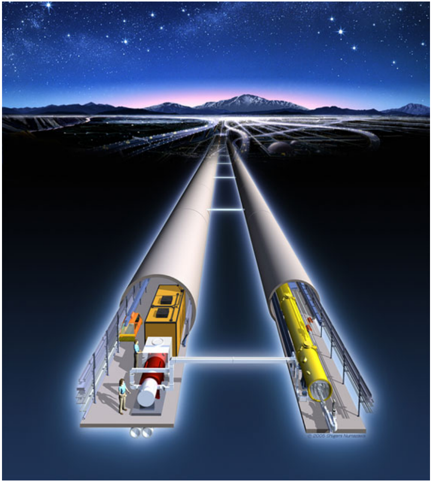

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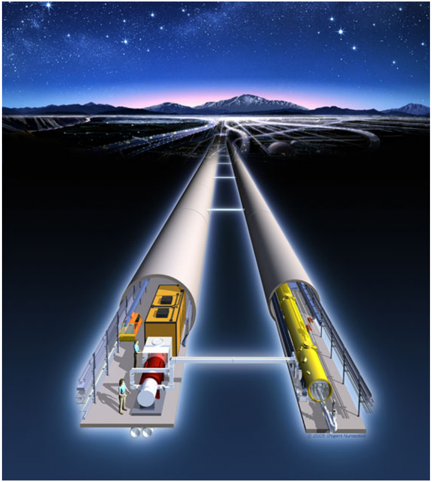


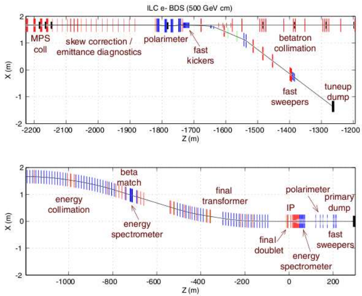
Elements of the real collider: BDS and final focus

BDS:

- Last 2 km.
- Monitor and measure beam.
- Clean up beam-halo etc.
- Protect detectors.
- Anything the beam hits here will give secondaries (E_{beam} is up to 500 GeV!), that might hit the detectors.

Final focus:

- Last 20 m.
- Focuses beams to few 100 nm horizontally, and few nm vertically.



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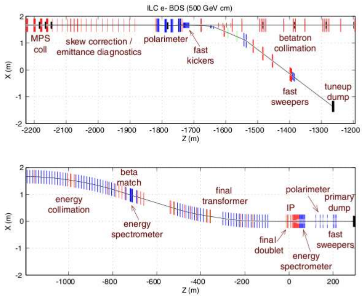

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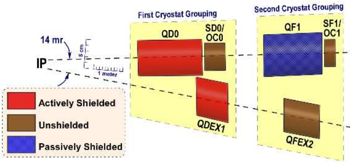

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Elements of the real collider: Beam-strahlung

Due to the very strongly focused beams, the fields (both E and B) has a large bending power on the other beam. Consequences:

- Primary beam is focused by the other beam.
- Strong bending $\rightarrow$ much synchrotron radiation. Widens the distribution of the primary $e^{\pm}$ energy.
- Photons
  - .. get Compton-backscattered $\rightarrow$ photon component of beam, long tail to lower energies for the $e^{\pm}$.
  - ... interact with photons (synchrotron ones, or virtual ones) in the other beam $\rightarrow$ $e^{\pm}$-pairs.
- So, there will be a component of $e^{\pm}$ with the opposite charge to that of its parent beam.
- These gets de-focused: The pairs background.

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The wrong-sign $e^{\pm}$:s gets a maximum kick if they are at the outer edge of the beam. The kick is independent of the (longitudinal) momentum of the particle.

p_T and θ anti-correlates, and accumulate at the edge.

To study the effect, also draw the detector in these coordinates:

Place it at the p_T-θ corresponding to the p_T and θ a particle should have to turn back at the radius and z of the detector.

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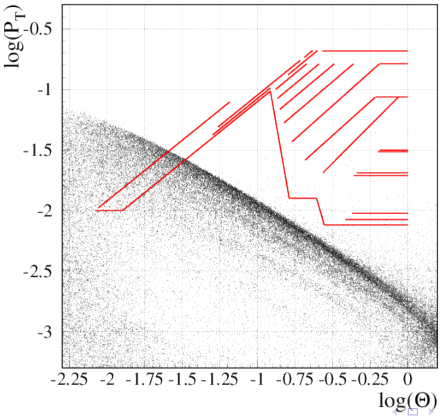
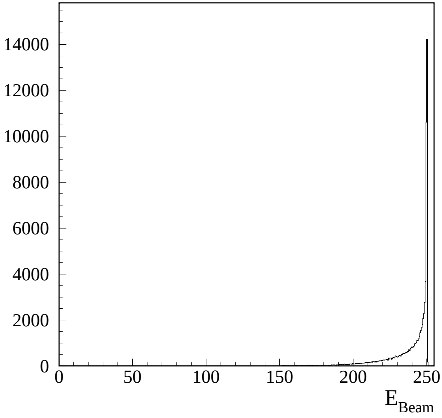
Example: Pairs in ILD, RDR nominal parameters. Generated with GuineaPig. 124000 particles/BX.



Elements of the real collider: Beam-spectrum

- On the large scale:
  - Beam-strahlung gives a long tail to lower energies
- Zoom to the peak
  - Noticeable spread in energy.
  - Can be comparable to detector resolution.
  - Note that E_{e^-} is wider: the ondulator.



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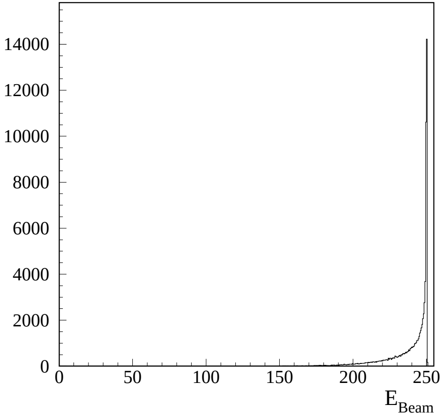

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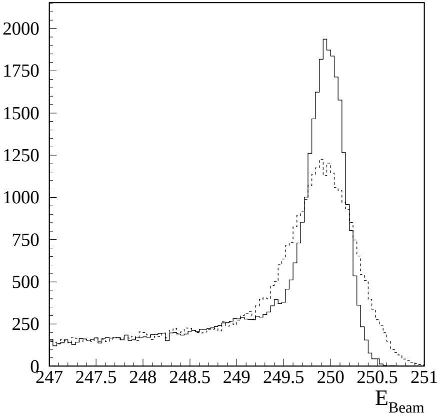

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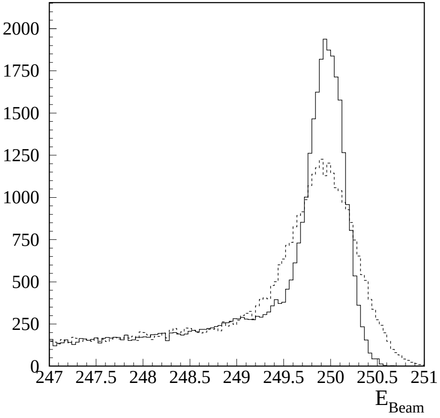

Elements of the real collider: Luminosity

Luminosity(L) = Density of particles that pass each other per time-unit.
Number of interactions/time=L×cross-section.

- $L = N^2/(t \times A)$
- $N^2/t =$ (particles in bunch)$^2\times$ (number of bunches in train)$\times$ (number of trains per second (=”rep rate”)) $=n^2 N_{bunch} f_{rep}$
- RF-power (P_{RF})$=E_{cm}(nN_{bunch}f_{rep}) \times \eta$ (η= efficiency of the transfer from the RF-system $\rightarrow$ beam)

So: $L \propto P_{RF}n/AE_{cm}$

- $A =$ cross-section of beams at IP $\propto \sigma_x \times \sigma_y$
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- Relative energy-loss due to beam-strahlung: $\delta_{BS} \propto (E_{cm}/\sigma_z) \times (n^2/(\sigma_x + \sigma_y)^2)$
- To reduce beam-strahlung: keep $\sigma_x + \sigma_y$ big.
- To get high L :$\sigma_x \times \sigma_y$ small.

Need a flat beam!

$$\sigma_y << \sigma_x \rightarrow \delta_{BS} \propto (E_{cm}/\sigma_z) \times (n^2/\sigma_x^2)$$

$$n/\sigma_x \propto \sqrt{\delta_{BS}\sigma_z/E_{cm}}.$$

So:

$L \propto P_{RF} \times \sqrt{\delta_{BS}\sigma_z}/(\sigma_y E_{cm}^{3/2})$

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$$\sigma_y << \sigma_x \rightarrow \delta_{BS} \propto (E_{cm}/\sigma_z) \times (n^2/\sigma_x^2)$$

$$n/\sigma_x \propto \sqrt{\delta_{BS}\sigma_z/E_{cm}}.$$

So:

$L \propto P_{RF} \times \sqrt{\delta_{BS}\sigma_z}/(\sigma_y E_{cm}^{3/2})$

or

$L \propto (nN_{bunch}f_{rep}) \times \sqrt{\delta_{BS}\sigma_z}/(\sigma_y E_{cm}^{1/2})$

or

$L \propto (n^2 N_{bunch}f_{rep})/(\sigma_x\sigma_y) \propto (n^2 N_{bunch}f_{rep}E_{cm})/(\epsilon_{norm}\beta)$

Beam conditions and the Detector

RDR, SB2009 and TDR

During the SB2009 exercise, a number of studies were done comparing physics and detector implications of two different beam-parameter sets.

- The RDR parameters.
- The SB2009 parameters:
  - Half the number of bunches.
  - Recuperate the luminosity by more aggressive focusing.
  - In addition: modified positron-source, giving low luminosity below $E_{cms} = 300$ GeV

The TDR largely follows the SB2009, except that the loss of luminosity at low E_{cms} has been mitigated.
Here I will present some of the observations from the SB2009 exercise.

RDR and SB2009

- Twice as much beam-strahlung:
  - more overlaid tracks (real or fake)
  - Twice as much energy in BeamCal

At 500 GeV

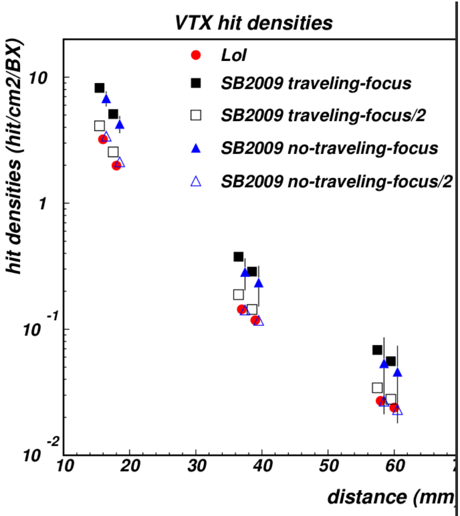
- Total luminosity unchanged RDR $\rightarrow$ SB2009 w TF, but reduced by %25 for SB2009 w/o TF.
- P(e^{+}) goes from 33 % to 22 %.
- Incoming energy-spread grows from 0.16 to 0.21
- Luminosity within 1 % of nominal reduced from 0.83 to 0.72.

At 250 GeV

- Lumi reduced by a factor three.

Beam-strahlung: Hits in Vertex detector

- Full simulation (Mokka), with crossing-angle and anti-DID field.
- The ILD VTX integrates of a certain time-window → Half as many BX:es overlaid in SB2009 wrt. RDR.
- ⇒ The net effect is small.
- The SiD VTX time-stamps every BX → Twice as many background hits with SB2009.



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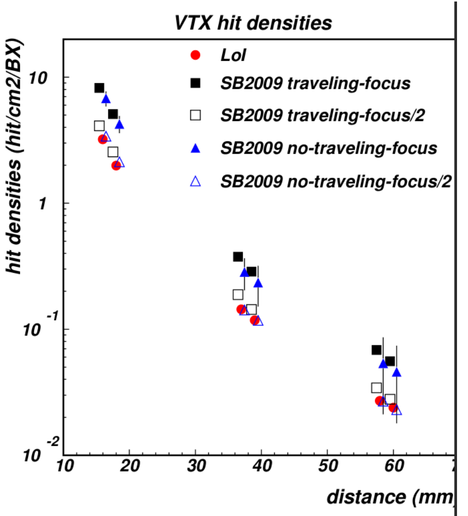

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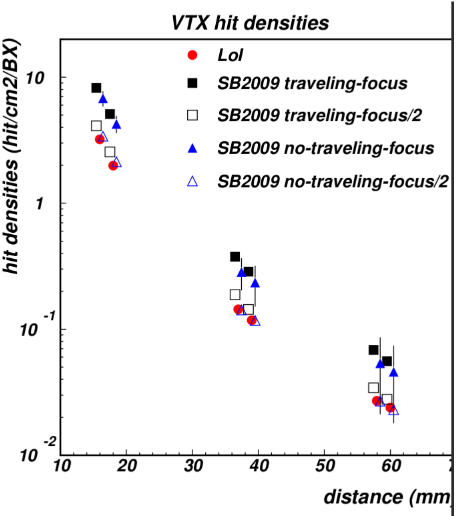
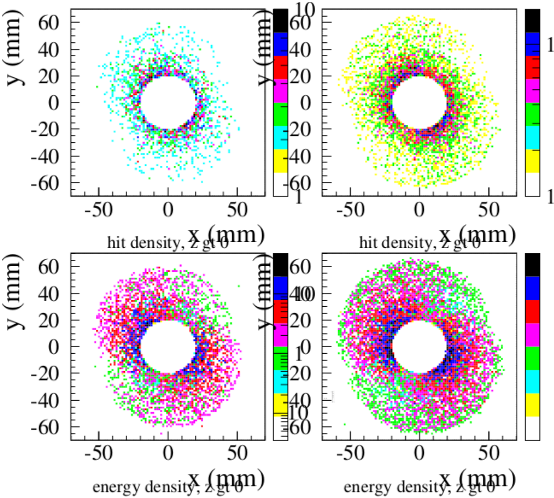


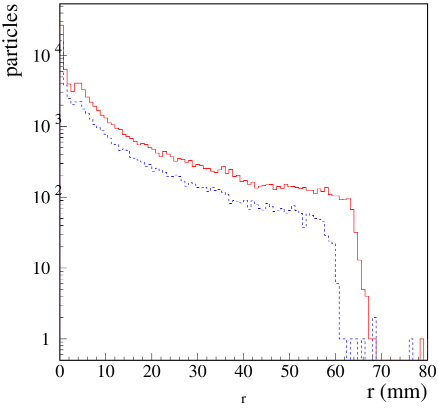
Beam-strahlung: BeamCal

- Only GP, but with crossing-angle and anti-DID.
- Both hit-densities (top) and energy-density (bottom) matters.
- The issue: can one still see a $\approx$ 250 GeV electron from a $\gamma\gamma$ process over the pairs-background?



Beam-strahlung: BeamCal

- Distribution of particle energy for r $>$ 20 mm.
- Total energy in BeamCal per BX: 24 TeV for SB2009TF, 10 TeV for RDR nom.
- Number of particles per BX 11500 for SB2009TF,5400 for RDR nom.
- Energy density vs Radius. SB2009TF has about twice at any given radius, and extends 5 mm further.
- All the relevant numbers double



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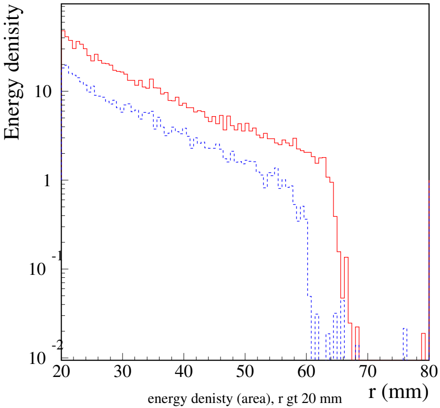

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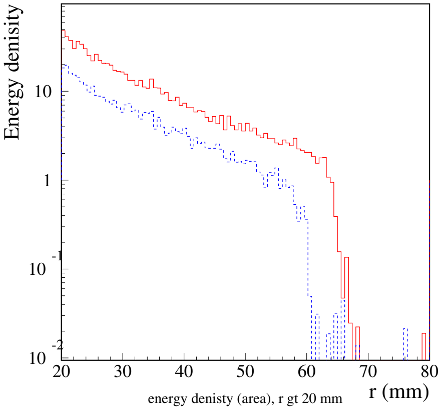


SB2009 and physics: $\tilde{\tau}$ in SPS1' or STCx

Small mass difference $\tilde{\tau}$-LSP ($\sim$ 10 GeV) $\Rightarrow$ soft τ:s.
Potential effects:

- Decrease of P(e^+): More background, less-signal for $\tilde{\tau}_1$
- Incoming energy-spread grows: end-point blurred.
- Luminosity within 1 % of nominal reduced: lower signal.
- Twice as much beam-strahlung:
  - more overlaid tracks (real or fake): Destroys τ topology.
  - Twice as much energy in BeamCal: More $\gamma\gamma$
- Higher probability for a $\gamma\gamma$ event in the same BX as the physics event.
- (Total luminosity decrease for SB2009 w/o TF.)

SB2009 and physics: $\tilde{\tau}$ - finally selected events

	Events for end-point analysis					
case	$\tilde{\tau}_1$			$\tilde{\tau}_2$		
	SM	SUSY	signal	SM	SUSY	signal
RDR	317	998	10466	1518	241	1983
SB09(TF)	814	956	8410	1346	223	1555
SB09(noTF)	611	717	6308	1009	167	1166
	Events for cross-section analysis					
	$\tilde{\tau}_1$			$\tilde{\tau}_2$		
	SM	SUSY	signal	SM	SUSY	signal
RDR	17.6	47.7	2377	1362	33.7	1775
SB09(TF)	17.6	45.7	1784	1194	32.4	1366
SB09(noTF)	13.2	34.3	1337	895	24.3	1025

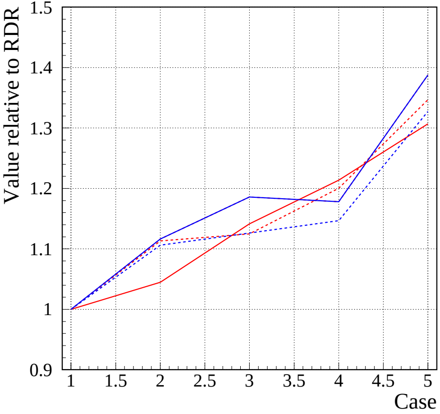
SB2009 and physics: $\tilde{\tau}$ - SUSY model parameters

Errors on end-point (GeV)

case	#	$\tilde{\tau}_1$	$\tilde{\tau}_2$
RDR	1	0.129	1.83
+SB bck	2	0.144	2.02
+SB ppol	3	0.153	2.06
+SB spect	4	0.152	2.10
+SB noTF	5	0.179	2.42

Errors on cross-section (%)

case	#	$\tilde{\tau}_1$	$\tilde{\tau}_2$
RDR	1	2.90	4.24
+SB bck	2	3.03	4.72
+SB ppol	3	3.31	4.77
+SB spect	4	3.52	5.09
+SB noTF	5	3.79	5.71



Red: cross-section, Blue: end-point, Solid : $\tilde{\tau}_1$, Dashed: $\tilde{\tau}_2$.

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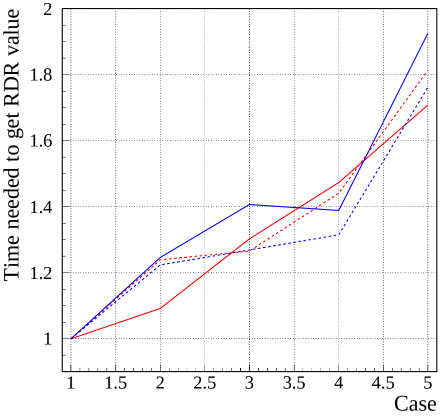

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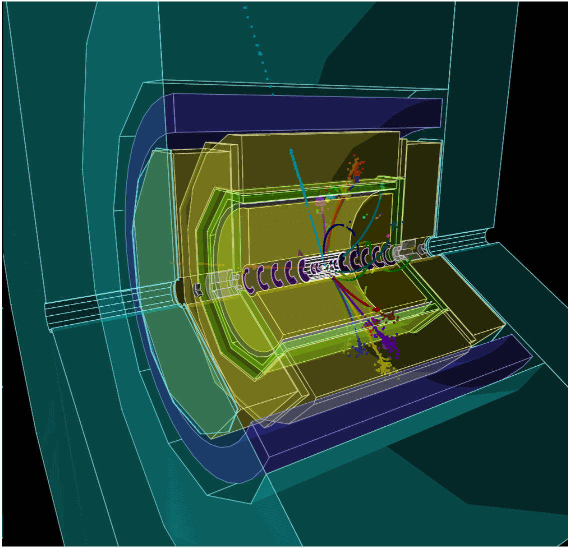
SB2009 and physics: SM Higgs at 120 GeV



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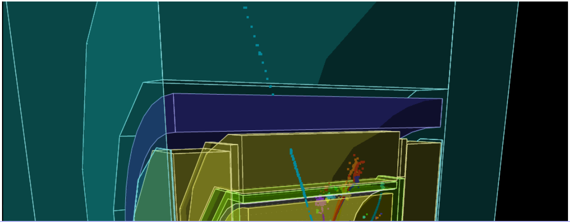
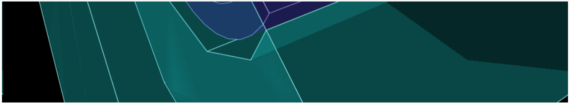


Topic: Model independent Higgs mass

Recoil mass measurement:

- Only reconstruct the $Z \rightarrow \mu\mu$
- Using E & p conservation the Higgs mass can be measured from the recoil independent of the decay mode



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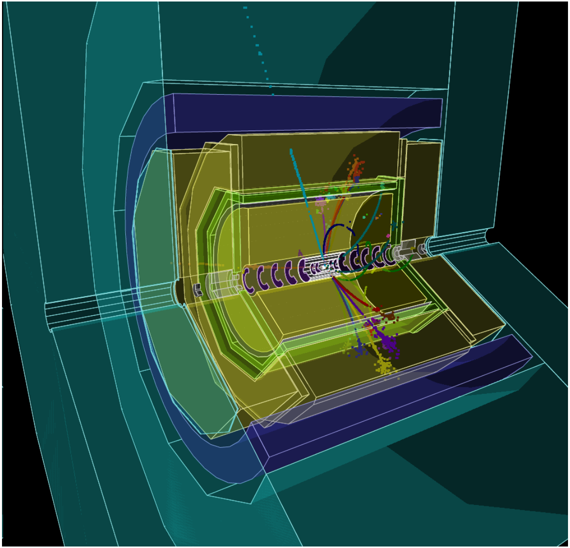
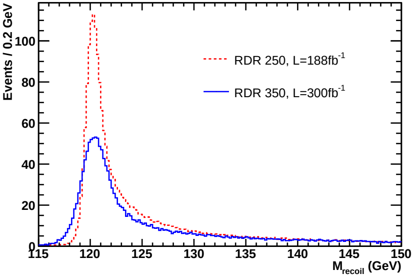


SB2009 and physics: SM Higgs at 120 GeV

Compare recoil-mass peak obtainable with the same running-time at 250 or 350 GeV, for...

- RDR
- Peak is broader at 350 GeV due to detector-resolution. Higher momentum gives higher error !



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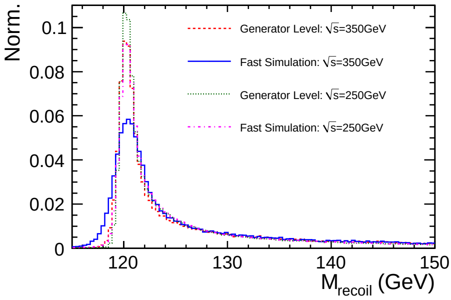
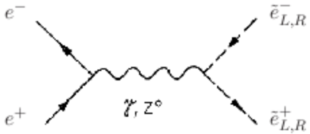
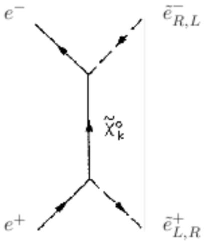


SB2009 and physics: Polarisation and Near Degenerate ẽ

Super-symmetry associates scalars to chiral (anti)fermions

$$e^-_{\mathrm{L,R}} \leftrightarrow \tilde{e}^-_{\mathrm{L,R}} \quad \text{and} \quad e^+_{\mathrm{L,R}} \leftrightarrow \tilde{e}^+_{\mathrm{R,L}}. \tag{1}$$





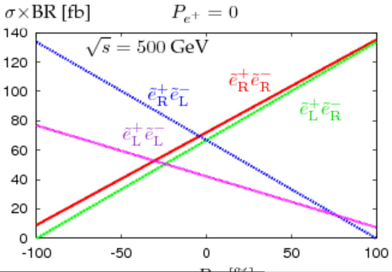
What if $M_{\tilde{e}_L} \approx M_{\tilde{e}_R}$, so that thresholds can't separate $e^+e^- \rightarrow \tilde{e}_L\tilde{e}_L, \tilde{e}_R\tilde{e}_R$ and $\tilde{e}_R\tilde{e}_L$?

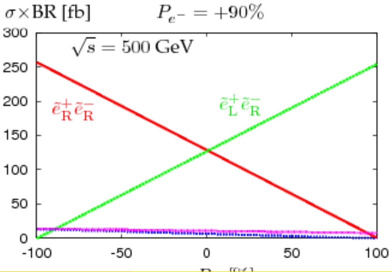
SB2009 and physics: Polarisation and Near Degenerate $\tilde{e}$

Model: SPS1a' like, but:

$M_{\tilde{e}_L}$ = 200 GeVand $M_{\tilde{e}_R}$ = 195 GeV. Both decay 100 % to $\tilde{\chi}_1^0$ e.

Even with $P_{e^-} \geq +90\%$, one can't disentangle the pairs $\tilde{e}_L^+\tilde{e}_R^-$ and $\tilde{e}_R^+\tilde{e}_R^-$': Ratio of the cross sections ≈ constant.





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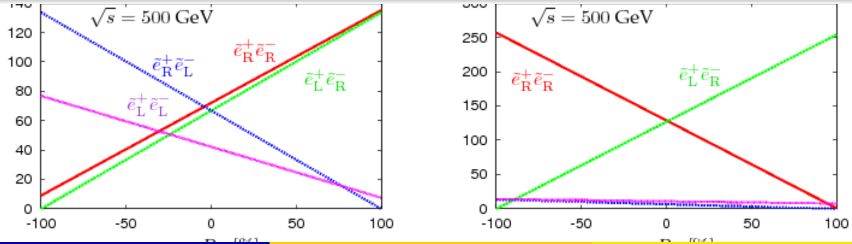
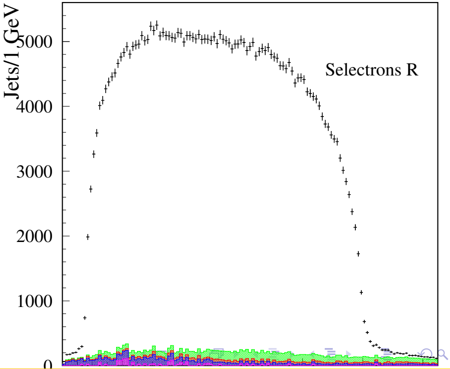
Polarised positrons a must !



SB2009 and physics: Polarisation and Near Degenerate $\tilde{e}$

Background and efficiency from Full-sim SPS1a' sample, kinematics from Whizard simulation of the model.

- The $\tilde{e}$ signal was extracted from the same sample as was used for the $\tilde{\tau}$ study, using the same cuts except
  - Demand exactly two well identified electrons.
  - Reverse the $\tilde{\tau}$ anti-SUSY background cut
  - Some cuts could be loosened
- Almost background-free !



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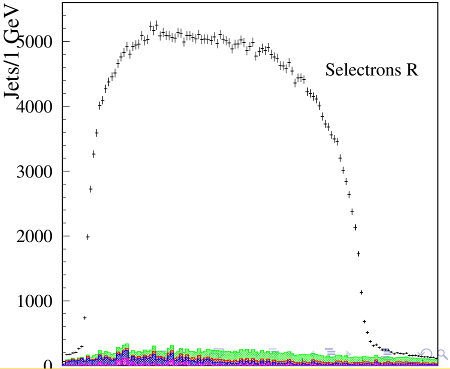

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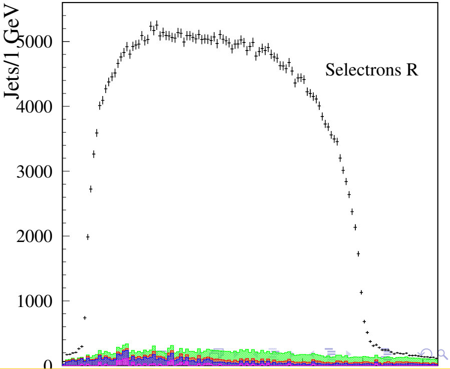

SB2009 and physics: Polarisation and Near Degenerate $\tilde{e}$

The handle:
Opposite polarisation beams produces $\tilde{e}$:s in both s- and t-channel.
Same polarisation produces $\tilde{e}$:s in t-channel only $\Rightarrow$

Modification of Θ distribution with changed positron polarisation

However, the effect is small since t-channel always dominates ! $\tilde{e}$:s are heavy (and are scalars) $\Rightarrow$ t- and s- channel kinematic distributions of the electrons are not very different.
Need to reconstruct the $\tilde{e}$ direction:

- 8 Unknown $\tilde{\chi}_1^0$ momentum components
- Assume $M_{\tilde{e}}$ and $M_{\tilde{\chi}_1^0}$ known $\rightarrow$
- 8 constraints (E and p conservation, 4 mass-relations)

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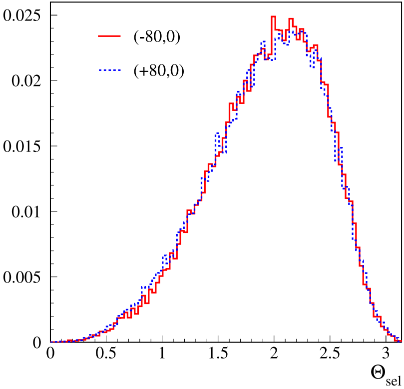
SB2009 and physics: Polarisation and Near Degenerate $\tilde{e}$

Analyse assuming 100 fb^{-1} for each of the polarisations configurations.

- For P(e^-)= ± 80 % P(e^+) = 0 and then ..
- ... for P(e^-)= +80 % and P(e^+) = ± 22 % or ...
- P(e^+) = ± 30 % or ...
- P(e^+) = ± 60 % .



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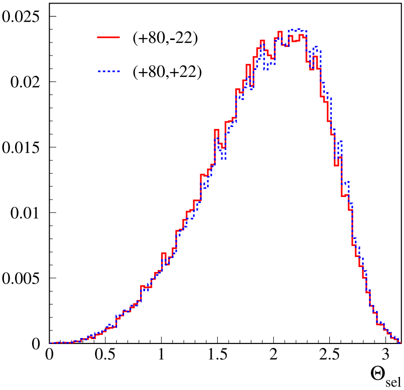

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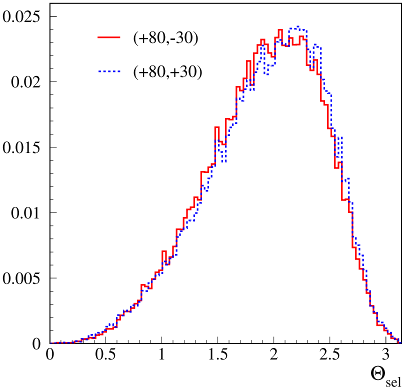

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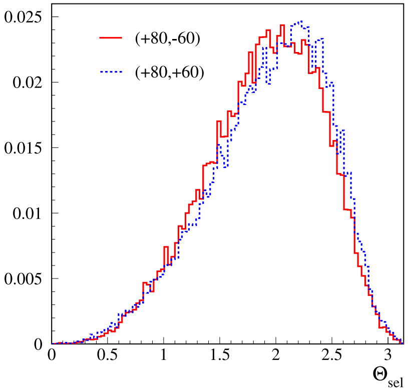

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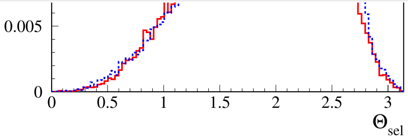
$\lvert P(e^+)\rvert$ (%)	significance of shift(σ)	Title of paper
22	2.4	"Limit on ..."
30	3.5	"Evidence for ..."
60	6.6	"Observation of ..."



Conclusions...

Machine-parameters:

- Depending on what is built in to the machine (P_{RF} , f_{rep} , N_{bunch} , δ_{BS}...), luminosity scales differently with E_{cm} , but it's never constant.
- Different machine setups give different gives different luminosity scaling, different polarisation scaling, different energy within 1 % to nominal, different spread in E_{beam} .

Lessons from $\tilde{\tau}$:s:

- For "fragile" signals, beam-background influences signal directly.
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- RDR $\rightarrow$ SB2009: 15-20 % degradation (end-point and cross-section, $\tilde{\tau}_1$ and $\tilde{\tau}_2$).
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