Physics with polarised beams
- in the light of LHC results

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Outline

- Introduction.
  - Why polarisation?
- Examples
  - TGCs and polarisation
  - SUSY:
    - The LHC picture
    - $\tilde{\tau}$:s
    - Near degenerate $\tilde{\mathrm{e}}$
  - Model independent WIMPs
- Conclusions.

Introduction: Why polarisation ?

At the heart of the Standard Model (and it's extensions):

Particles with different chirality are different.

and

If $E >> m$, chirality = helicity = polarisation

Hence, being able to prepare the polarisation of the initial states is a very powerful tool.

Introduction: Uses of polarisation

For instance:

- Separates production diagrams:
  - s-channel = vector-exchange → *opposite* polarised beams.
  - t-channel: *opposite* or *same* polarisation beams. But final state particles have the same polarisation as the parent.
  - Couplings to L and R particles different → For $e^+e^- \to f\bar{f}$, $\sigma_{RL} \neq \sigma_{LR}$
  - Most strikingly: NO coupling the W to e^-_R nor to e^+_L.
- In SUSY: often huge differences: Channel selection.
- Increase Statistics if *both* beams polarised: For s-channel, half the collisions are “sterile” if one beam un-polarised - even if the other in 100 % polarised !
  - *Even* if the Signal and Background have the *same* polarisation dependence, precision is better with polarisation, as there is up to a factor two to gain in the useful luminosity.

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A few concrete examples:

- Top:
  - Top vector coupling: Need A_{LR}.
  - Need one polarised beam to measure, and
  - $\Delta(A_{LR})/A_{LR}$ gets smaller if the other one also is. (2 times @ 30 %, 3 times @ 60 %)
- Higgs
  - Separate Higgs-strahlung (s-channel) and WW fusion (t-channel, with ν:s)
  - Needed for total width of the Higgs.
  - Background suppression for ZHH and ttH.
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So, polarisation is

- Needed to analyse the chiral structure of interactions
  - Key observable A_{LR}.
  - Relative error goes as that of $P_{eff} = (P_{e^-} - P_{e^+})/(1 - P_{e^-}P_{e^+})$
- Useful to improve S/B:
  - Key-number $\mathcal{L}_{eff} = (1 - P_{e^-}P_{e^+})\mathcal{L}/2$
  - Useful even if S and B depends on P in the same way: error $\propto S/\sqrt{B}$!
- See:
  - Overview in hep-ph/0507011, Phys.Rept., 460 (2008).

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TGC:s and Polarisation

(I. Marchesini, PhD Thesis, DESY-THESIS-2011-044)

Polarisation measurement from data with the Blondel scheme:

$$\sigma = \sigma_u \left[1 - P_{e^+}P_{e^-} + A_{LR}(P_{e^+} - P_{e^-})\right], \quad (1)$$

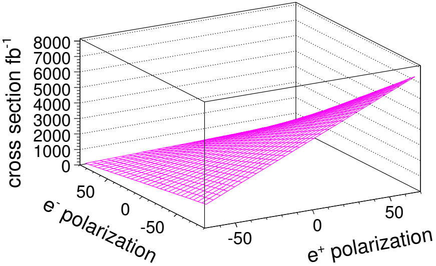
hence

$$P_{e^\pm} = \sqrt{\frac{(\sigma_{+-} + \sigma_{-+} - \sigma_{++} - \sigma_{--})(\mp\sigma_{-+} \pm \sigma_{+-} - \sigma_{++} + \sigma_{--})}{(\sigma_{-+} + \sigma_{+-} + \sigma_{++} + \sigma_{--})(\mp\sigma_{-+} \pm \sigma_{+-} + \sigma_{++} - \sigma_{--})}}$$

However: 100:s of fb^{-1} of all polarisation combinations needed to get to 0.2 %.

WW and Polarisation

Enter *WW* production : a high cross-section, highly polarisation dependent process



Ideally suited to make polarisation measurements, with less data than the Blondel scheme.

TGC:s in WW

There is a catch, however:

Triple Gauge Couplings, which modify the assumed W-couplings.

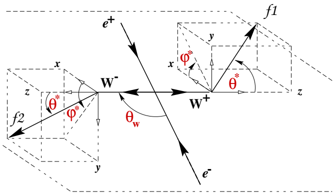
TGC:s :

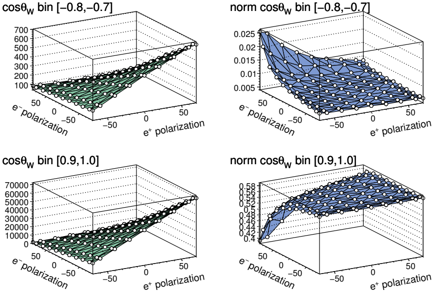
- 14 complex parameters, 8 CP conserving.
- In the SM: only 4 real parameters non-zero, all equal to unity.
- Deviations from SM loop-corrections and beyond SM physics

Deviations from the SM still allowed (by LEP), affecting the polarisation measurement up to the % level. LHC - using di-boson production - will eventually reach the few ‰ level

TGC:s+Polarisation in WW

TGC:s modifies angular diff. cross-sections $\rightarrow$ % level corrections to polarisation measurement $\rightarrow$ fit TGC:s and polarisation simultaneously.

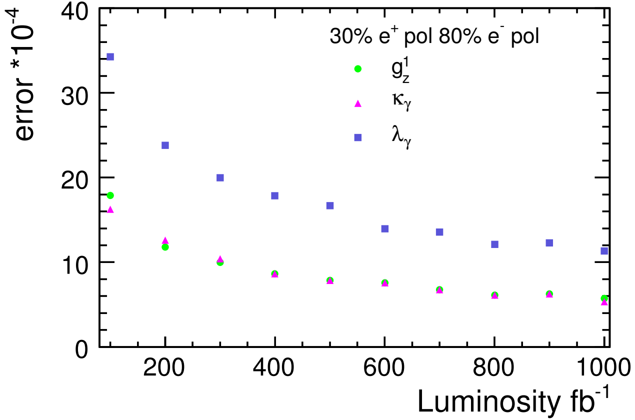




If individually C and P conserving and real: 6 TGC:s, but one fixed by EM-gauge invariance. Gauge conditions: some relations $\rightarrow$ 3 TGC parameters + 2 polarisations to fit.

Simultaneous fit : TGC:s

Result of simultaneous fit: TGCs



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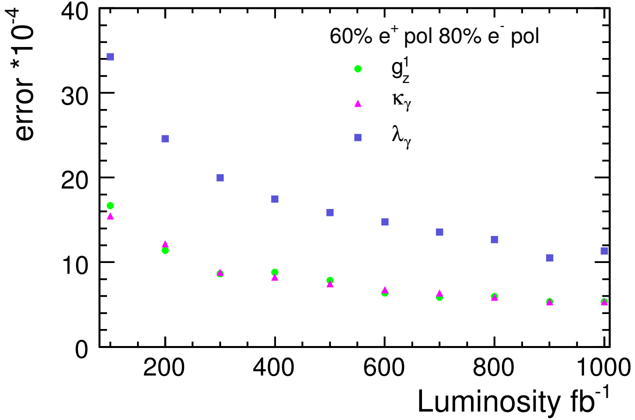

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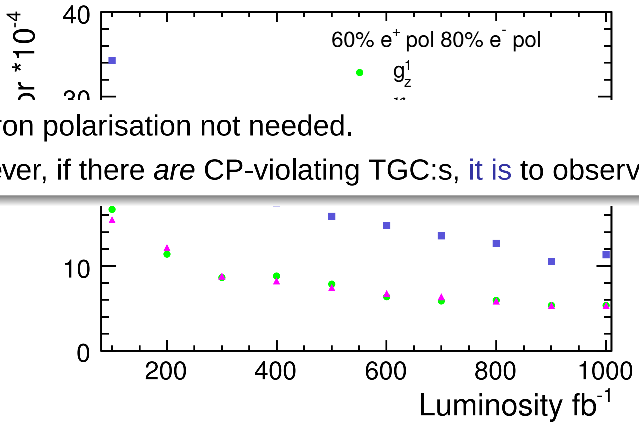
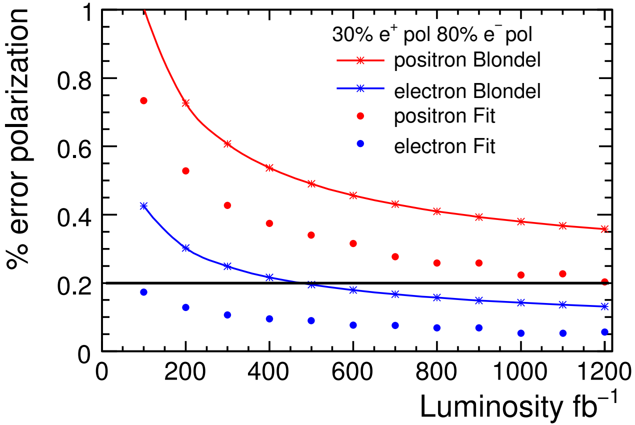


- Positron polarisation not needed.
- However, if there *are* CP-violating TGC:s, it is to observe them.

Simultaneous fit: Polarisation

Result of simultaneous fit: polarisation



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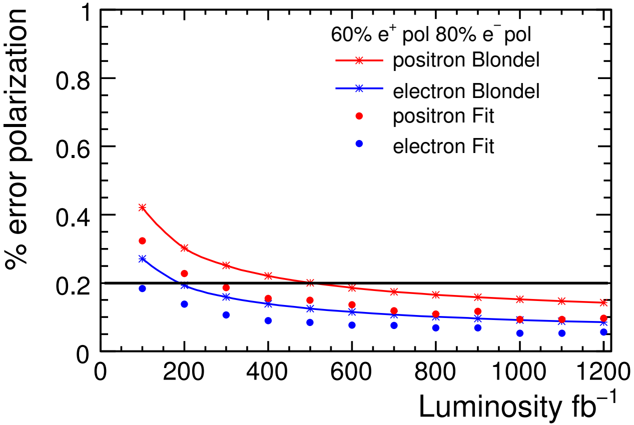

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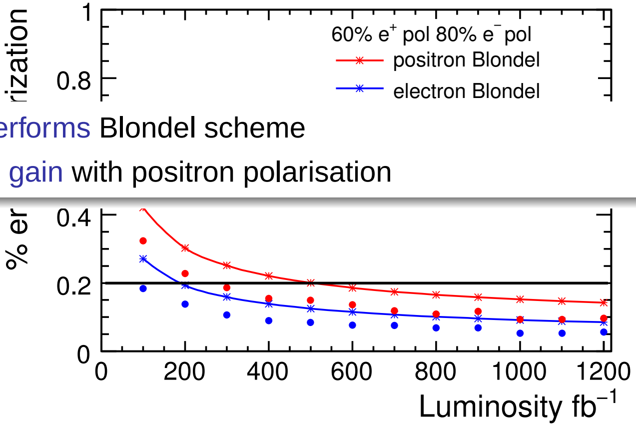
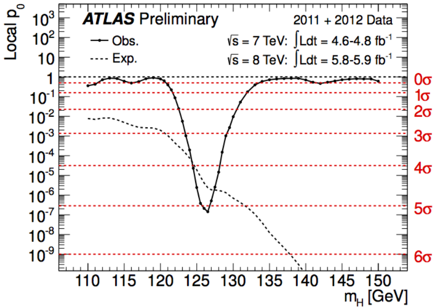


- Outperforms Blondel scheme
- Much gain with positron polarisation

LHC results and SUSY

- The Higgs as seen by ATLAS and CMS:
- ... and it's implication for SUSY models (from A. Djouadi).
- Limits in the Constrained Minimal Susy Model (CMSSM) from ATLAS
- Limits in the "simplified SUSY model"



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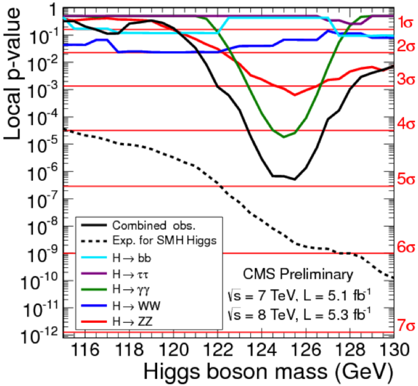

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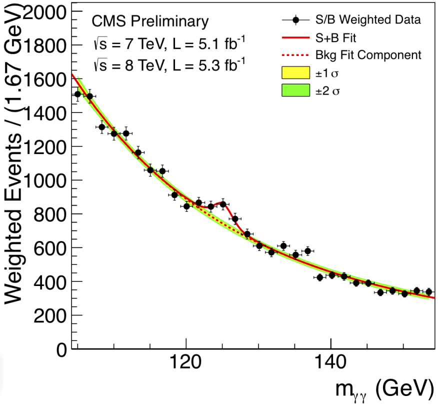

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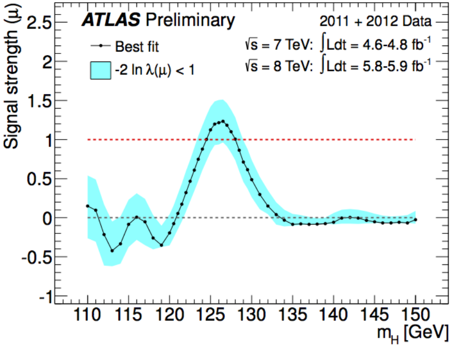

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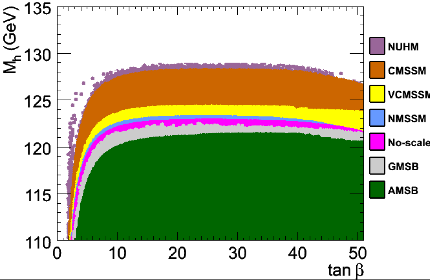

model	amsb	gmsb	sugra	noscale	cnmssm	vcmssm
M_h^{max}	120	121	128	123	123	126

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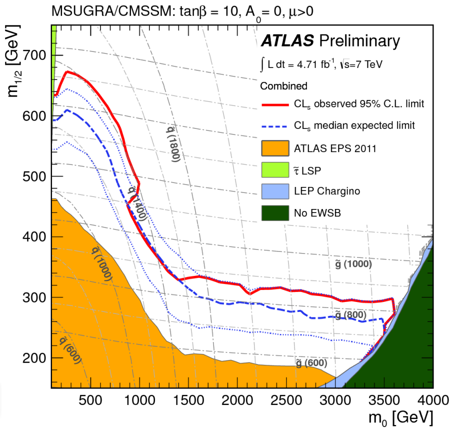

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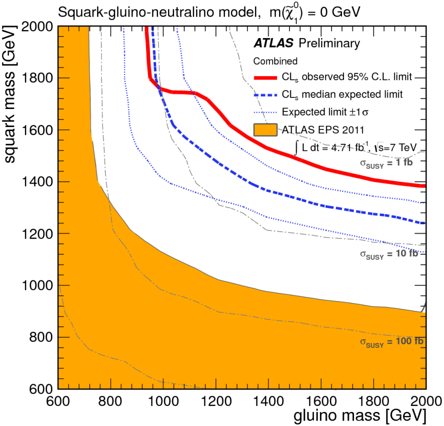

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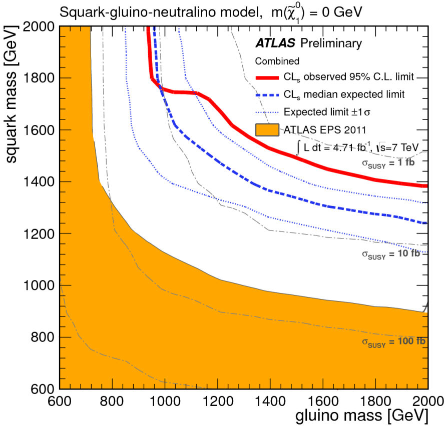
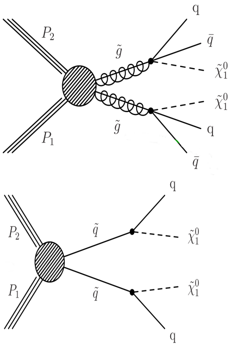


LHC: the fine-print

- Simplified models are (very) special cases: the produced SUSY particle goes directly to it's SM partner+MET.
- CMSSM is also a (very) special case: coloured sector ↔ non-coloured sector.
- Production needs a gluino in reach.
- Only gen. 1&2 squarks (≈ no t, b in protons!)
- But what matters for naturalness is the third generation:
  - M_H is destabilised by fermion-loops
  - but boson-loops have the same size but opposite sign
  - ⇒ Divergences cancel !
  - For this to work: $M_{particle} \approx M_{sparticle}$
  - Higgs coupling ∝ Mass ⇒ what matters is the top !



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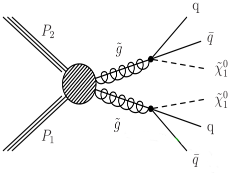

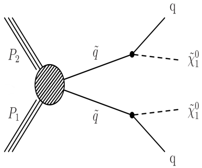

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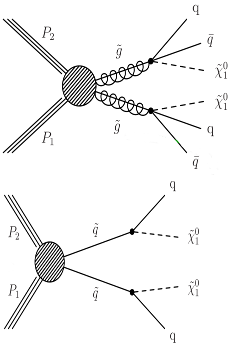

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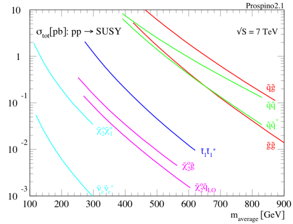

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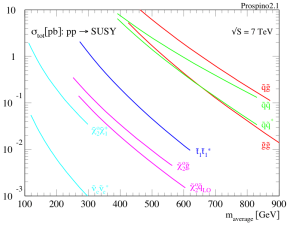

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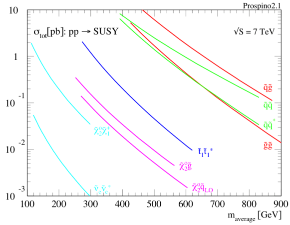

LHC: the fine-print

- Simplified models are (very) special cases: the produced SUSY particle goes directly to it's SM partner+MET.
- CMSSM is also a (very) special case: coloured sector $\leftrightarrow$ non-coloured sector.
- Production needs a gluino in reach.
- Only gen. 1&2 squarks ($\approx$ no t, b in protons!)
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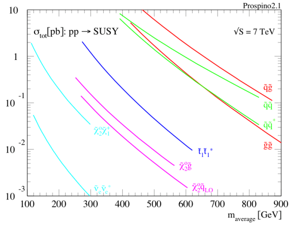

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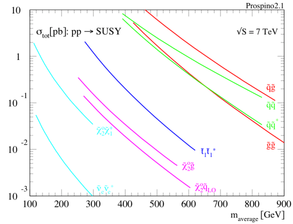

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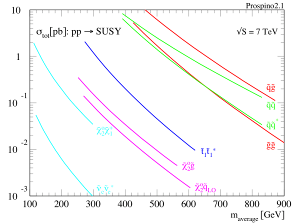

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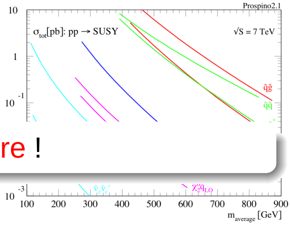

SUSY under pressure ?? No, but simple models are !

- But what matters for naturalness is the third generation:
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  - ⇒ Divergences cancel !
  - For this to work: $M_{particle} \approx M_{sparticle}$
  - Higgs coupling ∝ Mass ⇒ what matters is the top !

A New bench-mark point

Remember, apart from naturalness:

- Anomaly in $g-2$ of the μ: Would prefer a not-too-heavy smuon.
- Dark matter : A WIMP of ~ 100 GeV would be required.
- EW symmetry breaking, coupling constant unification: points to NP at or below 1 TeV
- Suppress the SUSY flavour problem (FCNC:s etc): Heavy 1:st & 2:nd generation squarks would be nice ...
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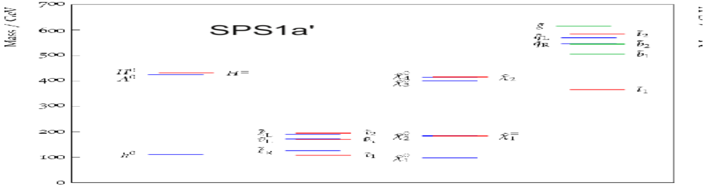

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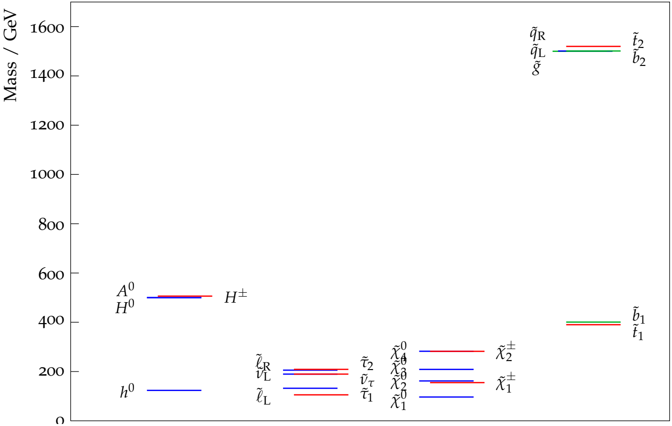

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How ?

SPS1a: mSUGRA

- 5 parameters.
- One gaugino parameter
- One scalar parameter

TDR1: natural SUSY

- 11 parameters.
- Separate gluino
- Higgs, un-coloured, and coloured scalar parameters separate

Parameters chosen to deliver all constraints,≈ same ILC accessible spectrum ⇒ old analyses still valid !

$\tilde{\tau}$ in SPS1a'/ TDR 1-4

(Work by J. List, P. Bechtle, P. Schade, M.B., PRD 82,no5 (2010), arXiv:0908.0876)

SPS1a'/TDR 1-4 are similar SUSY models, just outside what is excluded by LEP and low-energy observations.
Compatible with WMAP, with $\tilde{\chi}_1^0$ Dark Matter.
At E_{CMS} = 500 GeV:

- All sleptons available.
- No squarks.
- Lighter bosinos, up to $\tilde{\chi}_3^0$ (in $\mathrm{e^+e^-} \rightarrow \tilde{\chi}_1^0\tilde{\chi}_3^0$)

Features of $\tilde{\tau}$:s in SPS1a'/ TDR 1-4

- The $\tilde{\tau}_1$ is the Next to Lightest Susy Particle (NLSP).
- For $\tilde{\tau}_1$: $E_{\tau,min} = 2.6\ \mathrm{GeV}, E_{\tau,max} = 42.5\ \mathrm{GeV}$:
  $\gamma\gamma - background \Leftrightarrow pairs - background$.
- For $\tilde{\tau}_2$: :$E_{\tau,min} = 35.0\ \mathrm{GeV}, E_{\tau,max} = 152.2\ \mathrm{GeV}$:
  $WW \rightarrow l\nu l\nu - background \Leftrightarrow Polarisation$.
- $\tilde{\tau}$ NLSP $\rightarrow$ τ:s in most SUSY decays $\rightarrow$ SUSY is background to SUSY.
- For pol=(-1,1): $\sigma(\tilde{\chi}^0_2\tilde{\chi}^0_2)$ and $\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1)$ = several hundred fb and BR(X$\rightarrow \tilde{\tau}$) $>$ 50 %. For pol=(1,-1): $\sigma(\tilde{\chi}^0_2\tilde{\chi}^0_2)$ and $\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1) \approx 0$.

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Extracting the $\tilde{\tau}$ properties

From decay kinematics:

- $M_{\tilde{\tau}}$ from $M_{\tilde{\chi}_1^0}$ and end-point of spectrum = $E_{\tau,max}$.
- Need to measure end-point of spectrum.
- Other end-point hidden in $\gamma\gamma$ background: Must get $M_{\tilde{\chi}_1^0}$ from other sources. ($\tilde{\mu}$, $\tilde{e}$, ...)

From cross-section:

- $\sigma_{\tilde{\tau}} = A(\theta_{\tilde{\tau}}, \mathcal{P}_{beam}) \times \beta^3/s$, so
- $M_{\tilde{\tau}} = E_{beam}\sqrt{1-(\sigma s/A)^{2/3}}$: no $M_{\tilde{\chi}_1^0}$!

Fitting the $\tilde{\tau}$ mass

- Only the upper end-point is relevant.
- Background subtraction:
  - $\tilde{\tau}_1$: Important SUSY background,but region above 45 GeV is signal free. Fit exponential and extrapolate.
  - $\tilde{\tau}_2$: $\sim$ no SUSY background above 45 GeV. Take background from SM-only simulation and fit exponential.
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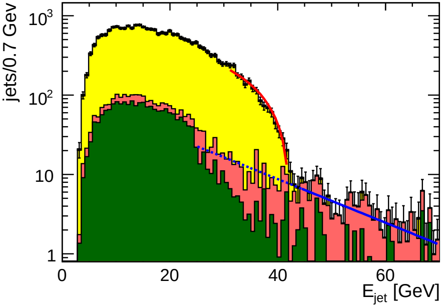

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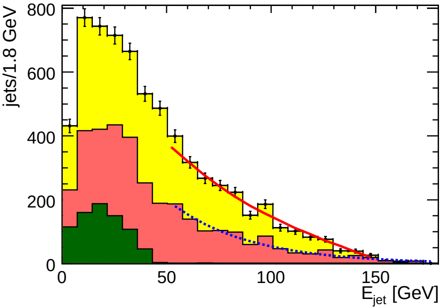

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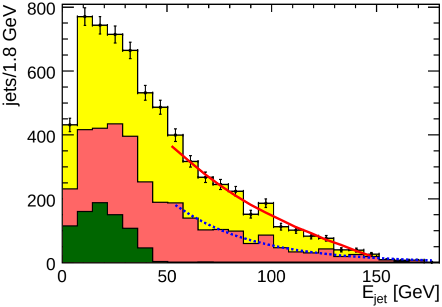

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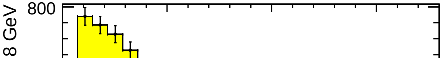


Results from end-point for $\tilde{\tau}_1$

$M_{\tilde{\tau}_1} = 107.73^{+0.03}_{-0.05}\mathrm{GeV}/c^2 \oplus 1.3\Delta(M_{\tilde{\chi}_1^0})$. The error from $M_{\tilde{\chi}_1^0}$ largely dominates

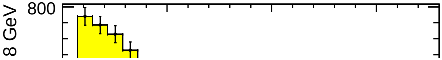
Results from end-point for $\tilde{\tau}_2$

$M_{\tilde{\tau}_2} = 183^{+11}_{-5}\mathrm{GeV}/c^2 \oplus 18\Delta(M_{\tilde{\chi}_1^0})$. The error from the endpoint largely dominates

- Fit line to (data-background fit).

Fitting the $\tilde{\tau}$ mass

- Only the upper end-point is relevant.
- Background subtraction:
  - $\tilde{\tau}_1$: Important SUSY



Results from cross-section for $\tilde{\tau}_1$

$$\Delta(N_{signal})/N_{signal} = 3.1\% \rightarrow \Delta(M_{\tilde{\tau}_1}) = 3.2\mathrm{GeV}/c^2$$

  - $\tilde{\tau}_2$: no SUSY background

Results from cross-section for $\tilde{\tau}_2$

$$\Delta(N_{signal})/N_{signal} = 4.2\% \rightarrow \Delta(M_{\tilde{\tau}_2}) = 3.6\mathrm{GeV}/c^2$$

End-point + Cross-section $\rightarrow \Delta(M_{\tilde{\chi}^0_1}) = 1.7\mathrm{GeV}/c^2$

- Fit line to (data-background fit).

Polarisation and $\tilde{\tau}$:s

Potential effects on the $\tilde{\tau}$-channels:

- Decrease of $P(e^+)$: Less signal, more background for $\tilde{\tau}_1$, and more signal, but still more background for $\tilde{\tau}_2$
- Studied in BAW II: $P(e^+)$ would be 22 % for SB2009, compared to 30 % for the RDR:
- $\tilde{\tau}_1$
  - Error on :
    - End-point: 153 MeV instead of 144 MeV.
    - Cross-section: 3.31 % instead of 3.03 %.
  - $\approx$ 10 % worse. More background, less signal.
- $\tilde{\tau}_2$:
  - Error on :
    - End-point: 2.06 GeV instead of 2.02 GeV.
    - Cross-section: 4.77 % instead of 4.72 %.
  - $\approx$ 2 % worse.Pure $\mathcal{L}_{eff}$ effect.

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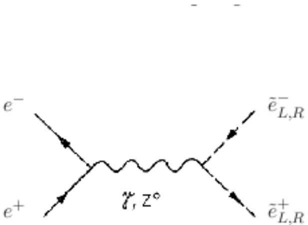
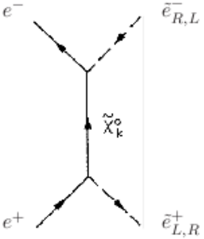
Polarisation and Near Degenerate ẽ

Super-symmetry associates scalars to chiral (anti)fermions

$$e^-_{L,R} \leftrightarrow \tilde{e}^-_{L,R} \quad \text{and} \quad e^+_{L,R} \leftrightarrow \tilde{e}^+_{R,L}. \tag{2}$$





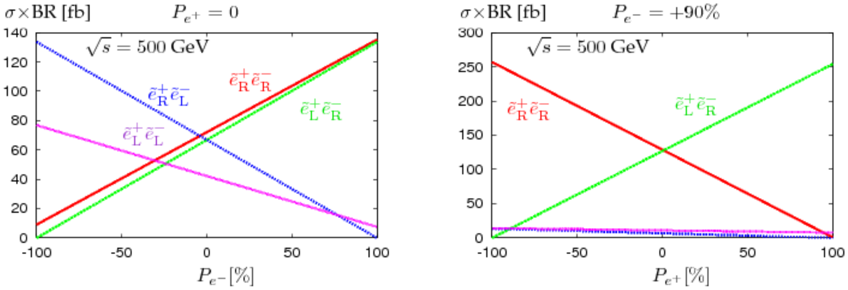
What if $M_{\tilde{e}_L} \approx M_{\tilde{e}_R}$, so that thresholds can't separate $e^+e^- \to \tilde{e}_L\tilde{e}_L, \tilde{e}_R\tilde{e}_R$ and $\tilde{e}_R\tilde{e}_L$?

Polarisation and Near Degenerate ẽ

Model: SPS1a' like, but:

$M_{\tilde{e}_L}$ = 200 GeV and $M_{\tilde{e}_R}$ = 195 GeV. Both decay 100 % to $\tilde{\chi}^0_1$ 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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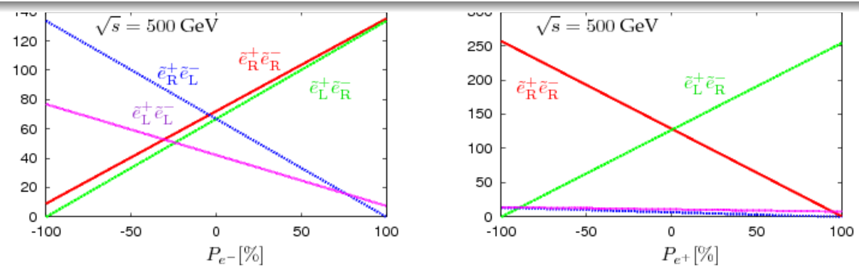
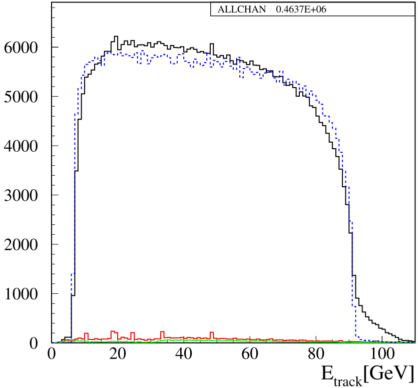
Polarised positrons a must !



Polarisation and Near Degenerate ẽ

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

- The ẽ 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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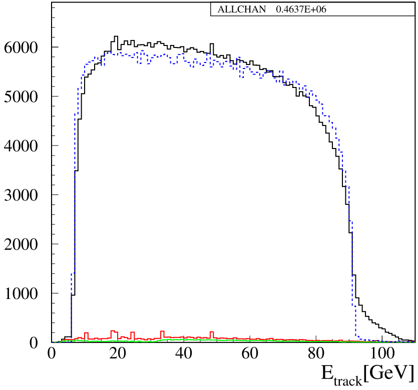

Polarisation and Near Degenerate $\tilde{e}$

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

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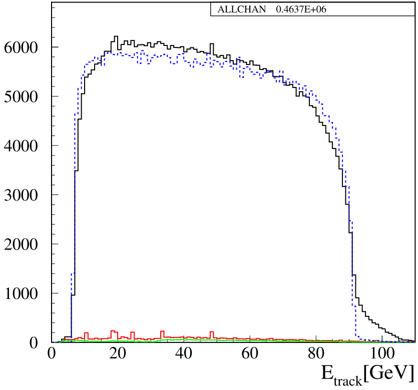

Polarisation and Near Degenerate $\tilde{e}$

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)

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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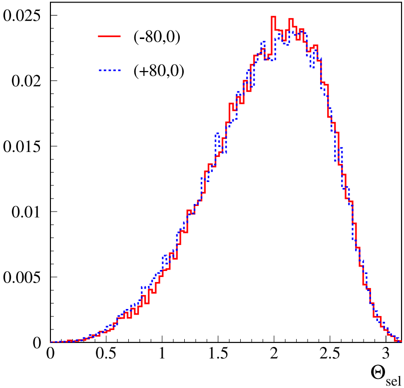
Polarisation and Near Degenerate $\tilde{e}$

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

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



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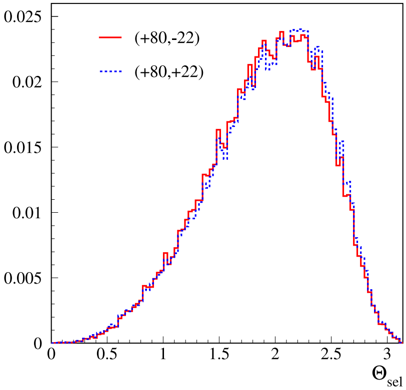

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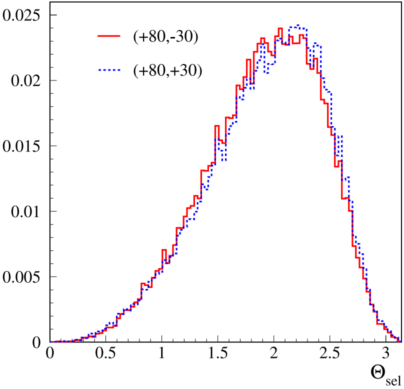

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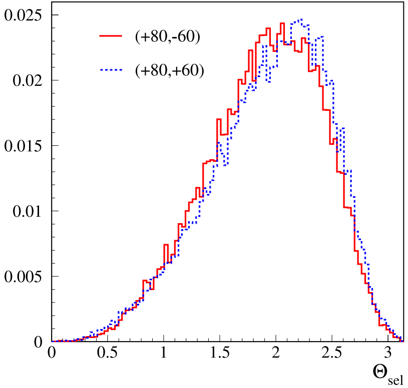

Polarisation and Near Degenerate ẽ

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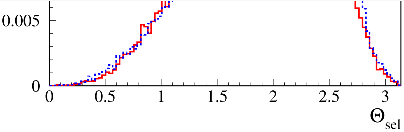
- For P(e^-)= $\pm$ 80 % P(e^+) = 0

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



Search for WIMPS and polarisation

(See arXiv:1206.6639)

WIMP Dark Matter

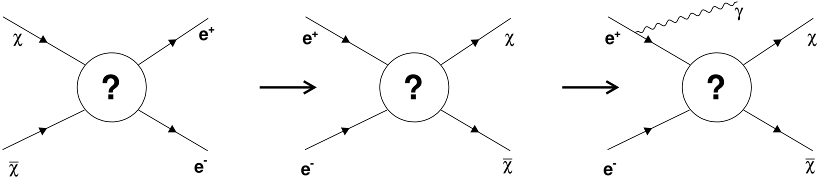
- Masses of 0.1–1 TeV.
- In thermal equilibrium with SM soup after inflation.
- Weak interactions naturally give observed relic density.
- In SUSY with conserved R-Parity: LSP: $\tilde{\chi}_1^0$ or $\tilde{G}$.
- Here: no model assumptions.

RDR , SB2009 and WIMPS

Birkedal *et al.* [hep-ph/0403004]

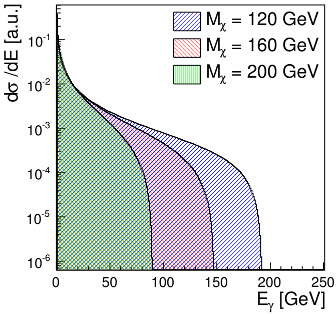
Model independence

- Assume only one DM candidate, no co-annihilation.
- Constrain WIMP pair annihilation XSec from observation.
- Crossing Symmetry (annihilation $\Rightarrow$ production).
- ISR.



Model Independent Production Cross Section

Mass dependent signal cut-off.

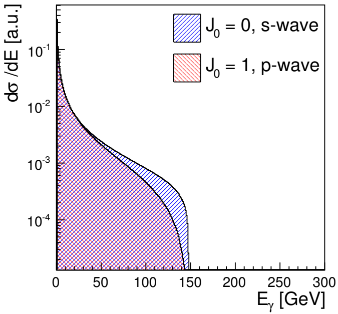


Parameters:

- $\kappa_e(P_e, P_p)$: Helicity dependent annihilation fraction to e^+e^-.
- S_χ: Spin, scale factor.
- M_χ, J_0 $\rightarrow$ shape, J_0 dominant partial wave.

Model Independent Production Cross Section

Signal shape at threshold provides information on partial wave (s- or p-wave).



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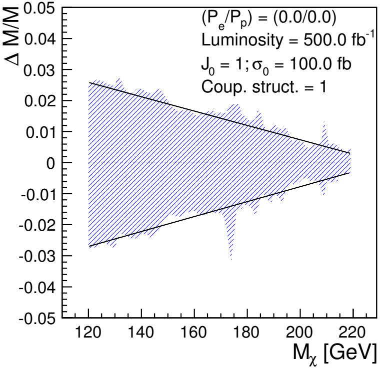
Mass Determination, $P_{e^-} = 0\% \; P_{e^+} = 0\%$

$\sigma_{LR} = \sigma_{RL}; \sigma_{RR} = \sigma_{LL} = 0$

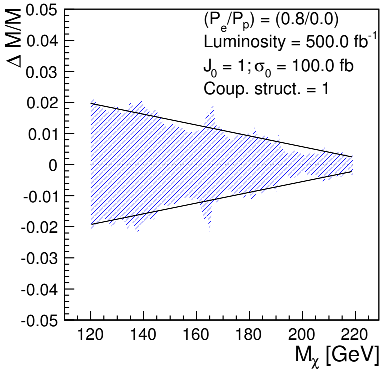
- $\Delta M/M$ from $\sim 2.5\%$ at $M = 120$ to 0.5% at $M = 220$.



Mass Determination, $P_{e^-} = 80\%$ $P_{e^+} = 0\%$

$\sigma_{LR} = \sigma_{RL}; \sigma_{RR} = \sigma_{LL} = 0$

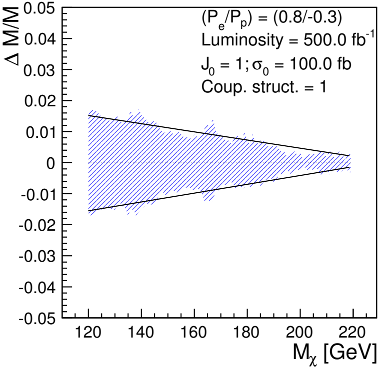
- Increased resolution
  Factor $\sim 2/3$



Mass Determination, $P_{e^-} = 80\% \; P_{e^+} = -30\%$

$\sigma_{LR} = \sigma_{RL}; \sigma_{RR} = \sigma_{LL} = 0$

- Additional resolution increase by 3/4.



Conclusions

Also when full simulation of both detector and beams:

- The $\mathcal{L}_{eff}$ effect is seen in $\tilde{\tau}$ and WIMP:s
  - Strongly in in $\tilde{\tau}_1$and WIMPS : signal and background have opposite P dependence.
  - But also in $\tilde{\tau}_2$, even though they have the same.
- The polarisation measurement using WW was shown to
  - More powerful than the Blondel scheme.
  - Profit strongly from positron polarisation.
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Higher positron polarisation enhances the physics potential of the ILC

  - Profits largely even from a modest increase (22 % to 30 % doubling the luminosity)