New CLIC physics studies for the European Strategy comparisons

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Introduction

- Several studies prepared before the Open Symposium in Granada and for the Briefing Book
- Based on previous results via recasting, Delphes studies or full simulation studies

Study	Level
Relaxions	Recast based on hidden valley studies
SUSY benchmarks	Fast simulation study incl. backgrounds
Stop pairs	Extend existing full sim study
Electroweak Z couplings	Generator level/extrapolations
Dark Matter	Recast mono-photon cross-section limits
Stau Pairs	Delphes fast simulation incl. background
Dark photons	Fast simulation study incl. backgrounds

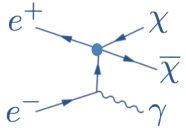
- Results appeared in comparison plots prepared by the BSM group presented in Granada and will appear in the Briefing Book
- See also talks by P. Roloff about BSM at future colliders and electroweak Z couplings measurements

Dark Matter

Dark Matter limits at CLIC in a simplified model

- Simplified Dark Matter model introduces dark matter candidate χ_d and mediator particle:
  - spin-1: vector or axial-vector
  - spin-0: scalar

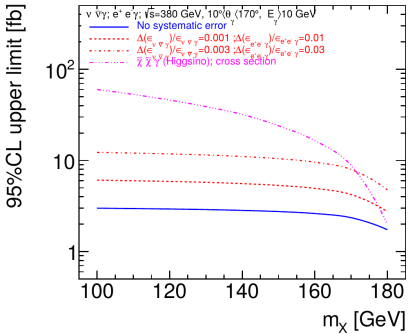
  Whizard model file prepared by Andrea Wulzer according to `http://feynrules.irmp.ucl.ac.be/wiki/DMsimp`
- Couplings in the model:
  - dark matter coupling to mediator
  - couplings of mediator to leptons and quarks
- Process: $\mathbf{e^+e^-} \rightarrow \boldsymbol{\chi_d\chi_d\gamma}$
  - Cross section depends on mass of mediator and dark matter particle
  - $\Rightarrow$ **mono-photon signature**



Existing study for monophoton sensitivity at 380 GeV

Study by J.-J. Blaising [CLIC Physics potential YR 1812.02093, ch. 5.1]

- Full simulation including beamspectrum and ISR
- Relevant backgrounds:
  $e^+e^- \to \nu\bar{\nu}\gamma$ and $e^+e^- \to e^+e^-\gamma$
- Based on $1\,ab^{-1}$ at 380 GeV
- Cuts on the final state photons:
  $E > 10\,GeV$, $10^\circ < \theta < 170^\circ$
- Systematic uncertainty: Bhabha scattering normalisation
  - dominated by forward electron tagging efficiency
  - here considered for the total background



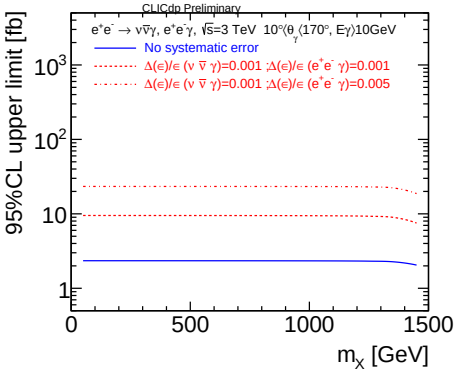
- Exclusion limits based on the cases with uncertainty of 0.3 % and without systematics

Higher energy: 3 TeV

- Use generator-level cross sections to extrapolate to 3 TeV (J.-J. Blaising)
- radiative Bhabha background $e^+e^- \to e^+e^-\gamma$ decreases by **a factor of 10** between 380 GeV and 3 TeV

$\to$ better reach is expected at 3 TeV

- Exclusion limits based on the cases without and with larger systematics



J.-J. Blaising

Exclusions in the plane of mediator vs. DM mass

- Obtain different cross sections for

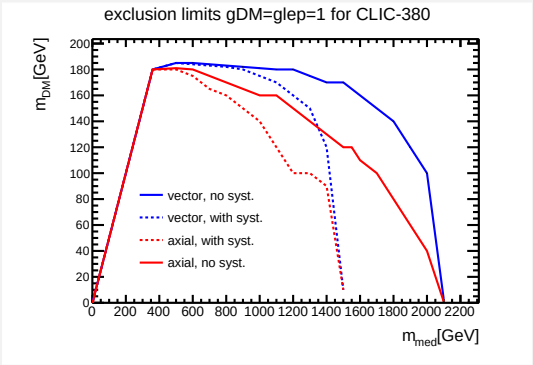
$$e^+e^- \to \chi_d \chi_d \gamma$$

  for different masses of the mediator and the dark matter candidate
- Recast the limits on cross sections obtained in the existing monophoton analyses at 380 GeV and 3 TeV to this model
- Cross sections determined with `Whizard 2.7` including ISR and CLIC beam spectrum
  - Using the same cuts, i.e. on the final state photons: $E > 10\,\text{GeV}$, $10^\circ < \theta < 170^\circ$
  - No beam polarisation
- Width of the mediator always fixed to the default value of WY1 $= 10\,\text{GeV}$
- Various cases of couplings considered:

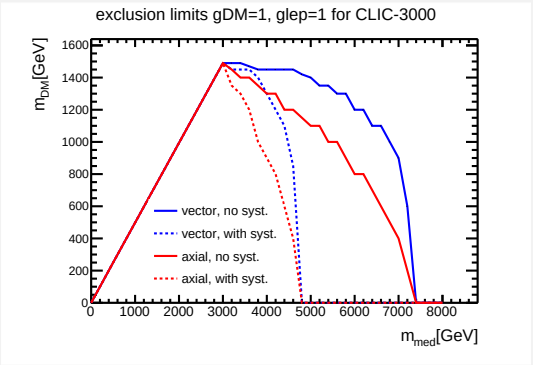
  Lepton to mediator $g_{\text{lep}} = 0.1, 0.25, 1$
  Mediator to dark matter $g_{\text{DM}} = 1$

Vector and axial-vector mediator

gDM=glep=1, spin 1 at 380 GeV



gDM=1, glep=1, spin 1 at 3 TeV

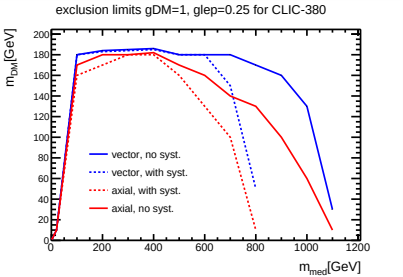


- Exclusion range increases from 1500 GeV to almost 5000 GeV from CLIC-380 to CLIC-3000
- Systematic uncertainties have a large effect in particular for light DM

LHC-like coupling points

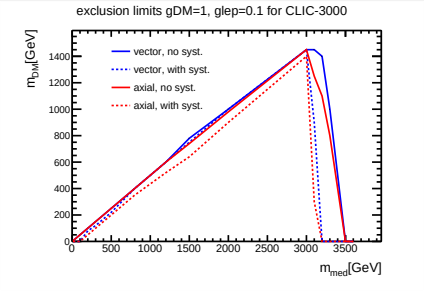
- LHC DM limits: $g_q = 0.25 \rightarrow$ transfered to lepton colliders: $g_{lep} = 0.25$ (for prospects comparison only; not the same point in the model)

gDM=1; glep=0.25, spin 1 at 380 GeV



For light DM incl. systematics:
$m_{DM} = 1$ GeV: $\boldsymbol{m_{\text{axial}} = 800\,\text{GeV}}$

gDM=1, glep=0.1, spin 1 at 3 TeV

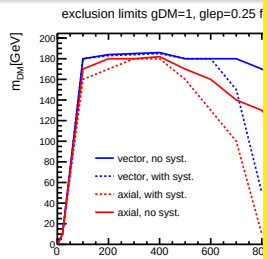


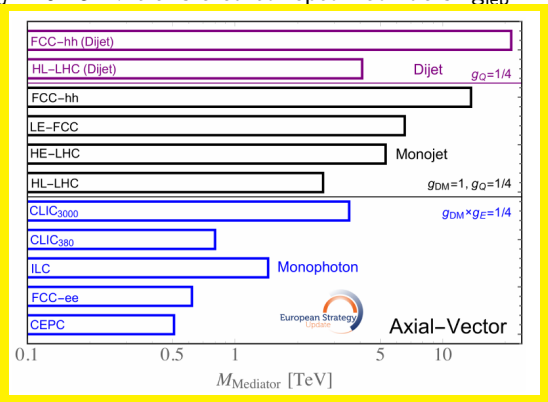
For light DM incl. systematics:
$m_{DM} = 1$ GeV: $m_{\text{med}} = 3200$ GeV
extrapolated to g_{lep}=0.25: $\boldsymbol{m_{\text{axial}} = 3800\,\text{GeV}}$

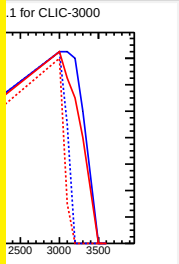
LHC-like coupling points

- LHC DM limits: $g_q = 0.25 \rightarrow$ transfered to lepton colliders: $g_{lep} = 0.25$ (for prospects comparison only; [illegible]

gDM=1; glep=0.25, sp … **pin 1 at 3 TeV**







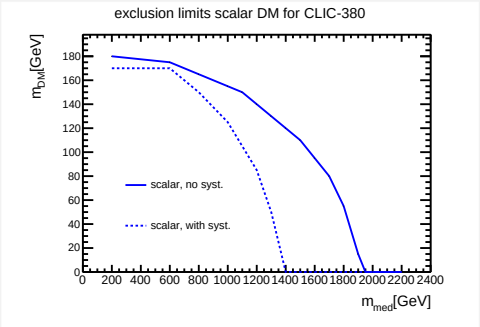
→ talk by P. Roloff (BSM at future colliders)

For light DM incl. systematics:
$m_{DM} = 1$ GeV: $\boldsymbol{m_{axial} = 800\ GeV}$

…stematics:
$m_{DM} = 1$ GeV: $m_{med} = 3200$ GeV
extrapolated to g_{lep}=0.25: $\boldsymbol{m_{axial} = 3800\ GeV}$

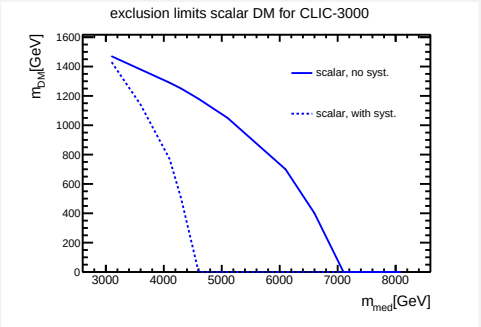
Scalar Dark Matter candidate

gDM=glep=1, spin 0 at 380 GeV



For light DM incl. systematics:
$m_{DM} = 1$ GeV: $\boldsymbol{m_{\text{med}} = 1400\,\text{GeV}}$

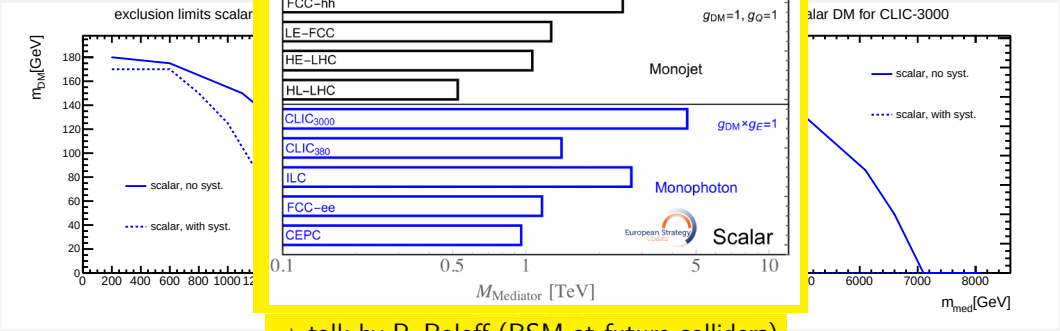
gDM=glep=1, spin 0 at 3 TeV



For light DM incl. systematics:
$m_{DM} = 1$ GeV: $\boldsymbol{m_{\text{med}} = 4600\,\text{GeV}}$

Scalar Dark Matter candidate

gDM=glep=1, spin 0 a … **0 at 3 TeV**



→ talk by P. Roloff (BSM at future colliders)

For light DM incl. systematics:
$m_{DM} = 1$ GeV: $\boldsymbol{m_{\text{med}} = 1400}$ **GeV**

… incl. systematics:
$m_{DM} = 1$ GeV: $\boldsymbol{m_{\text{med}} = 4600}$ **GeV**

Stau pair production

Stau pair production in the MSSM

Signal processes: $e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$ **and** $e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^- \to \tau^+\tau^-\tilde{\chi}_2^0\tilde{\chi}_2^0$

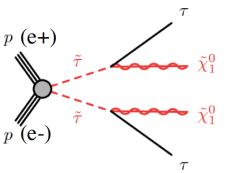
- stau-1 $\tilde{\tau}_1$ is the lightest of two states, decays to τ and neutralino
- diagonal mixing matrix: $\tilde{\tau}_1 = \tilde{\tau}_L$ and $\tilde{\tau}_2 = \tilde{\tau}_R$

production: the cross section depends on the beam polarisation

- CLIC baseline: less luminosity at P(e^-)=+80 %, which disfavors $\tilde{\tau}_R$

decay: mixing of LH and RH $\tau \Rightarrow$ cross sections for $\tilde{\tau}_R$ are generally lower

$\Rightarrow$ right-handed $\tilde{\tau}_R$ challenging



Main background: $e^+e^- \to \tau^+\nu_\tau\tau^-\bar{\nu}_\tau$

- Run Delphes CLICdet card on Signals and Background
- Use baseline polarisation scenario and compare to unpolarised scenario

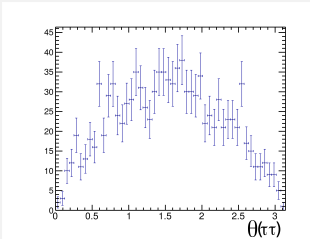
Analysis for stau pair production

Selection adapted from LCD-Note-2012-004, optimised separately for right-handed staus:

- VLC jets with $R = 0.7$, $N = 2$
- Tau tagging: TauTagger efficiencies from LCD-2010-009 implemented in Delphes CLIC card
- $15^\circ < \theta_\tau < 165^\circ$
  (detector acceptance)
- $p_T(\tau) > 30\,\text{GeV}$
- $\tilde{\tau}_L : 1 < \Delta\phi(\tau\tau) < 3.1$
  $\tilde{\tau}_R : 2 < \Delta\phi(\tau\tau) < 3.1$
  (suppress $e^+e^- \to \tau\tau$ backgr.)
- $m_{\tau\tau} > 200\,\text{GeV}$
- angle of the di-tau system:
  $\tilde{\tau}_L : 0.8 < \theta(\tau\tau) < \pi - 0.8$
  $\tilde{\tau}_R : 0.5 < \theta(\tau\tau) < \pi - 0.5$
  (suppress $e^+e^- \to \tau\nu\tau\nu$ backgr.)

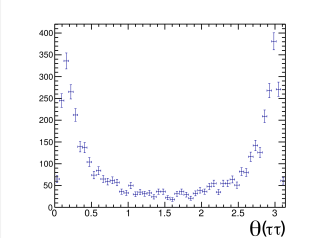
Signal

$m_{\tilde{\tau}_1}$=400 GeV, $m_{\tilde{\chi}^0}$=298 GeV



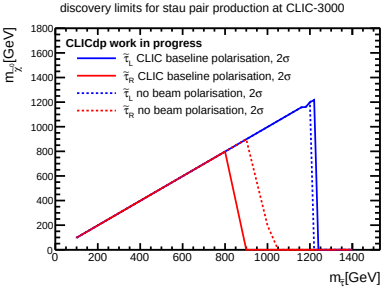
Background

$e^+e^- \to \tau^+\nu_\tau\tau^-\bar{\nu}_\tau$

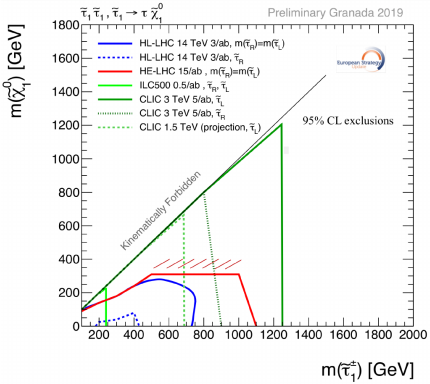


Results for stau production at 3 TeV

- Counting all signal and background events after selection cuts
- $2\,\sigma$ discovery significances in the neutralino mass $m_{\tilde{\chi}^0}$ vs. stau mass $m_{\tilde{\tau}}$ plane



Contours used as 95 % C.L. exclusions:



- increasing the contribution from $P(e^-) = +80\,\%$ favorable for $\tilde{\tau}_R$ discovery
- reminder: $\tilde{\tau}_1 = \tilde{\tau}_L$ is the lightest state

Dark photons

Dark photon production

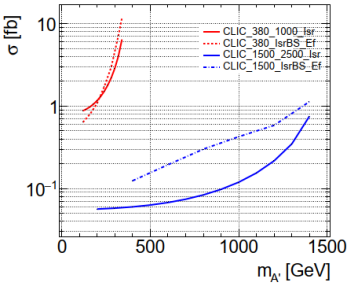
Dark photons studied by J.-J. Blaising and presented in 19 August analysis group meeting

Dark photon A': dark matter candidate

- particle coupling very weakly to electrically charged particles and mixing with the photon
- cross section of $e^+e^- \to A' \to f\bar{f}$ is a function of the mass $m_{A'}$ and the kinetic mixing ϵ
- A' appears as a very narrow resonance with photon-like coupling

Signal process at CLIC: $e^+e^- \to A' \to \mu\mu$

- full lines: ISR, no selection cuts
- dashed lines: ISR+Beamspectrum, selection cuts
- beamspectrum increases the A' cross section
- mixing parameter $\epsilon = 0.01$



Dark photon analysis

J.-J. Blaising

Backgrounds

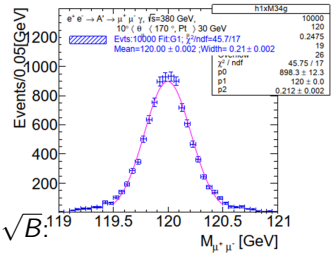
Process	σ[fb] 380 GeV	σ[fb] 1500 GeV
$e^+e^- \to \mu\mu$	1650	177
$\gamma\gamma \to \mu\mu$	229	457
$e^-\gamma \to e^-\mu^+\mu^+$	336	244

additional processes
- $e^+e^- \to WW \to \mu^+\mu^-\nu\bar{\nu}$
- $e^+e^- \to \tau^-\tau^+ \to \mu^+\mu^-$

are small and can be reduced with missing ET cut

Selection:

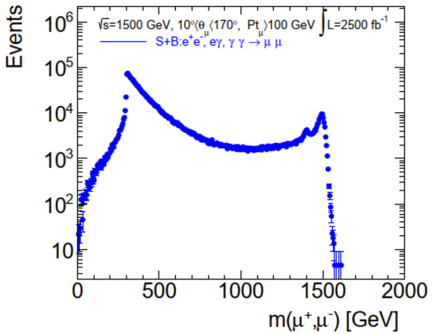
- at 380 GeV:
  - $10 < \theta(\mu) < 170^\circ$
  - $p_T > 30$ GeV
  - $M(\mu\mu) > 100$ GeV
- at 1500 GeV:
  - $10 < \theta(\mu) < 170^\circ$
  - $p_T > 100$ GeV
  - $M(\mu\mu) > 300$ GeV



- For each mass point, the $M(\mu\mu)$ window is chosen to maximise $S/\sqrt{B}$:

Resulting limits on dark photons

Counting experiment in the signal region with $M(\mu\mu)$ window

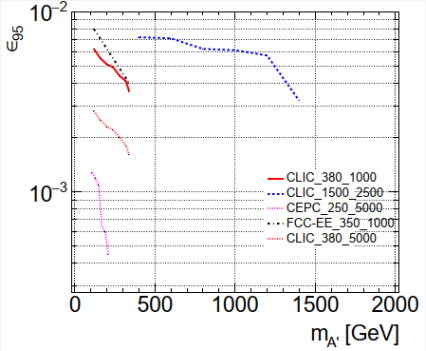


Signal with $m_{A'} = 1400\,\text{GeV}$ and $\epsilon = 0.01$: visible over SM backgrounds with $S/\sqrt{B} = 18$

J.-J. Blaising

Limits

95 % C.L. limits on the mixing parameter ϵ as a function of $m_{A'}$



→ see talk by P. Roloff (BSM)

Conclusion

- Various analyses performed in the context of the European Strategy update comparisons
- Results have appeared in talks in Granada and will be a part of the Briefing Book

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Studies by J.-J. Blaising, R. Franceschini, P. Roloff, U.S., R. Ström, A. Wulzer

Additional Material

Stau production discovery

$5\,\sigma$ limits: