CLIC physics potential for DM searches at 3 TeV using mono-photons and polarised beams

On behalf of
J-J. Blaising, P. Roloff, U. Schnoor, A. Wulzer

Outline

- Introduction.
- Background cross-section calculation, event simulation and systematic errors.
- σ(95%) calculation for different polarisation conditions and exclusion limits for Simplified DM models.
- Simplified DM model discrimination and DM mass determination.
- Summary

Introduction

For the CLICdp Yellow report and for the contributions prepared for Granada, the DM exclusion limits were computed by Ulrike using simplified DM models provided by Andrea. The limits were derived using σ(95%) computed using backgrounds without polarisation.

(PeL,PeR) polarised e^- beams change significantly the main SM background rate, $\nu \bar{\nu} \gamma$.

This study shows that using the B cross-section ratio σ(L)/σ(R):

- improves significantly, σ(95%)
- allows DM model discrimination and DM mass determination.

Background cross-section calculation and event simulation

Background cross-sections calculated at 3 TeV without/with e^- beam polarisation for 10° < $\theta\gamma$ < 170° and $Pt\gamma/\sqrt{s} > 0.02$.

Cross-section calculation and event generation done using Whizard with beam spectrum, isr function and n(1...3) matrix element photons.

Events with Isr γ's overlapping ME γ's were rejected using the merging procedure (Note: CLICdp-2020-004, Filip, Pawel ...).

Fast simulation used to take into acount γ energy resolution and efficiency and $e^+ e^-$ γ veto efficiency.

The 3 TeV fast simulation based on extrapolation of full simulation.

Luminosity and Background Cross-sections 3TeV

	Polarisation		
	No	PeL= Pe$^-$:-80%	PeR= Pe$^-$:+80%
Integrated luminosity [ab^{-1}]	5	4	1
Process	σ[fb]	σ[fb]	σ[fb]
$e^+ e^- \rightarrow \nu \bar{\nu} \gamma + \nu \bar{\nu} \gamma \gamma + \nu \bar{\nu} \gamma \gamma \gamma \; (\gamma)$	1058	1880	235
$e^+ e^- \rightarrow e^+ e^- \gamma + e^+ e^- \gamma \gamma + e^+ e^- \gamma \gamma \gamma \; (\gamma)$	1925	1960	1890

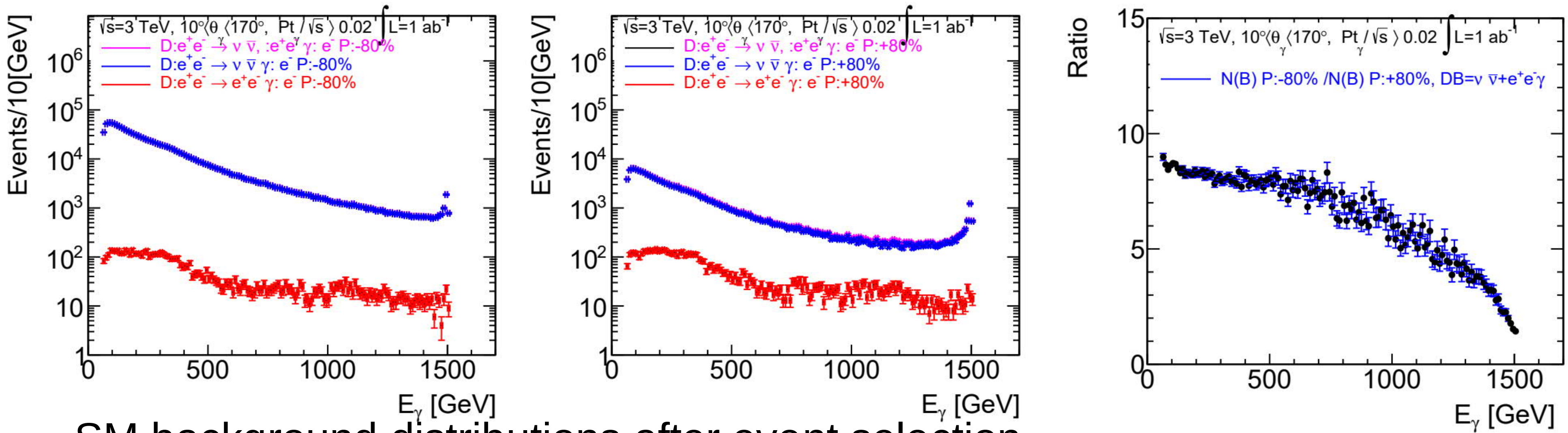
The luminosity sharing assumptions for different polarisation conditions.
Background σ values for $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$ and $e^+ e^- \rightarrow e^+ e^- \gamma$ processes.
For PeR, $\sigma(\nu, \bar{\nu}, \gamma)$ is a factor 4.5 lower w.r.t. no polarisation and by a factor 8 w.r.t. PeL. $\sigma(e^+ e^- \gamma)$ has very little dependence on the beam polarisation.

Experimental systematic errors

Systematic error	Value
Event selection $\nu \bar{\nu} \gamma$	0.002
Event selection $e^+ e^- \gamma$	0.01 *
Luminosity	0.002
Polarisation	0.0025

The values are those listed in the ILC paper arXiv:2001.03011v1.
* ILC does not assign a systematic error on the $e^+ e^- \gamma$ veto.
Assuming the sign of the polarisation can be reversed at each bunch train, experimental uncertainties will be strongly correlated and cancel out in cross section ratios.

SM backgrounds, $\int L=1ab^{-1}$



SM background distributions after event selection.

Left : dN/dEγ (PeL) for $\nu\bar{\nu}\gamma$, $e^+ e^- \gamma$ events and sum $N(e^+ e^- \gamma)/N(\nu\bar{\nu}\gamma)=0.005$

Midle: dN/dEγ (PeR) for $\nu\bar{\nu}\gamma$, $e^+ e^- \gamma$ events and sum: $N(e^+ e^- \gamma)/N(\nu\bar{\nu}\gamma)=0.04$

Right :dN/dEγ(B, PeL)/dN/dEγ(B, PeR), the shape of dR/dEγ is due to the $\nu\bar{\nu}\gamma$ s and t-channel contributions changing with Eγ.

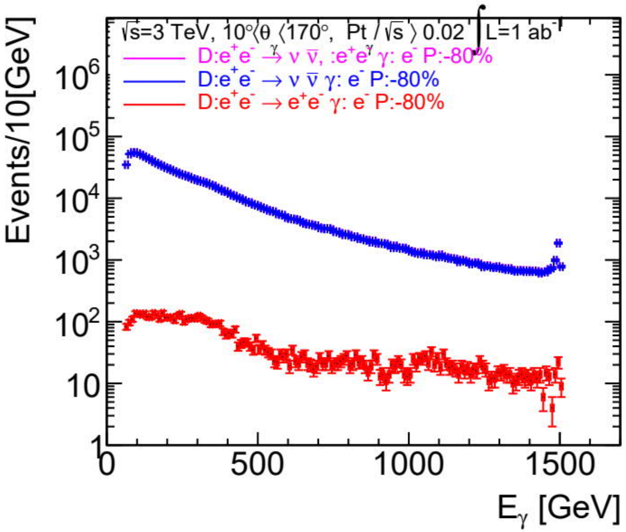
These 3 distributions are used to compute the 95%CL cross-section σ(95%).

σ(95%) and Z Calculation

To compute σ(95%) the likelihood ratio test statistic probability is computed using F1:
b= number of background events.
b+s = number of background + signal events.
Nobs=number of background events
Significance $Z=\sqrt{2}.Erf^{-1}(1-2P)$ (F2)
A 1 sided 95% CL upper limit corresponds to P >= 0.025 and Z <= 2.

$$P = \frac{\sum_{n=0}^{Nobs} (b+s)^n \frac{e^{-(b+s)}}{n!}}{\sum_{n=0}^{Nobs} (b)^n \frac{e^{-b}}{n!}} \quad \text{(F1)}$$

σ(95%) calculation for PeL=Pe⁻ :-80%



For a DM mass mXD, $E\gamma max = \sqrt{s}/2 - 2*mXD^2/\sqrt{s}$.
The number of background events b is computed for
50 GeV < Eγ < Eγmax using F1.
For each mXD the s excluded at 95%CL is computed using F2.
σ(95%) = s/Lumi.
σ(95%) is computed for mXD masses in the range:
200 GeV < mXD < 1400 GeV
with systematic errors.
Same procedure for PeR and PeL/PeR

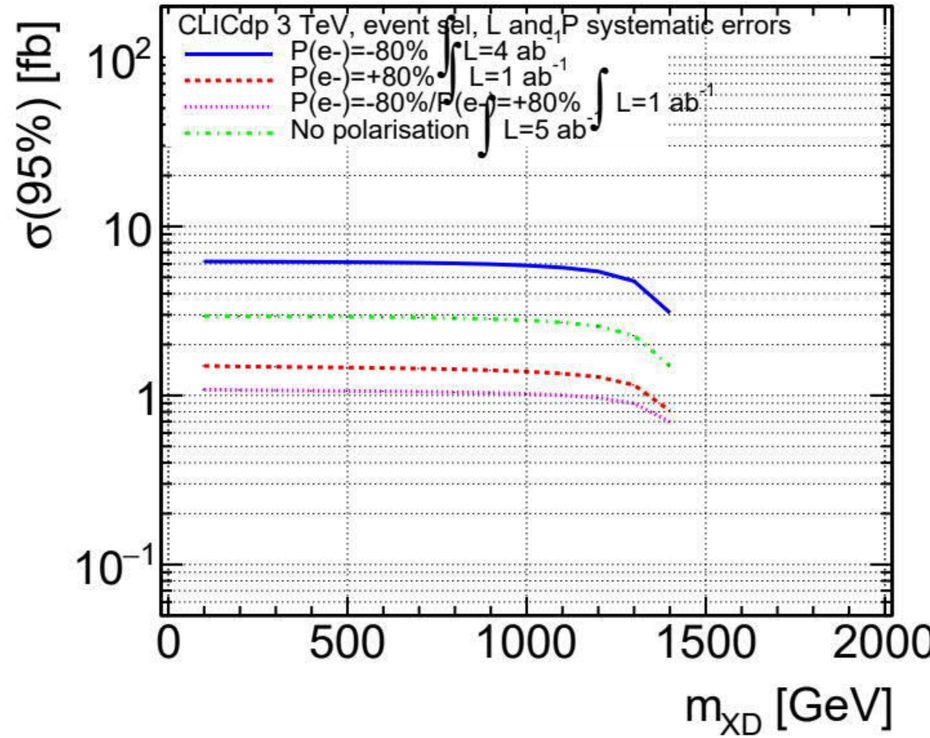
$$b = \int_{E_{\gamma_{min}}}^{E_{\gamma_{max}}} dN/dE_{\gamma} \quad \text{(F1)}$$

$$\frac{\sum_{n=0}^{Nobs} (b+s)^n \frac{e^{-(b+s)}}{n!}}{\sum_{n=0}^{Nobs} (b)^n \frac{e^{-b}}{n!}} \geq 0.025 \quad \text{(F2)}$$

dσ(95%)/dmXD results

dσ(95%)/dmXD for different polarisation and luminosity conditions with systematic errors (event selection+ luminosity+polarisation)

Polarisation	Luminosity ab^{-1}	σ(95%) fb
PeL	4	6
PeR	1	1.5
PeL/PeR	1	1
No	5	3



The lowest σ(95%) values are obained using the ratio dN/dEγ(PeL)/dN/dEγ(PeR) in which systematic errors cancel out.

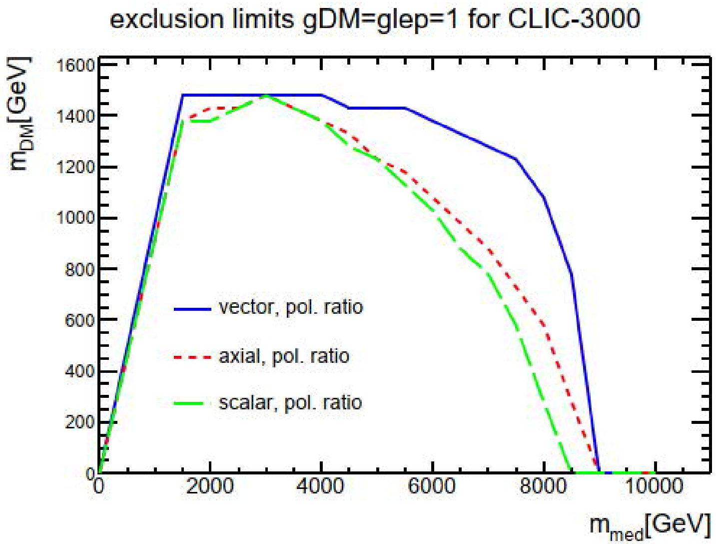
Simplified DM models and exclusion limits calculation

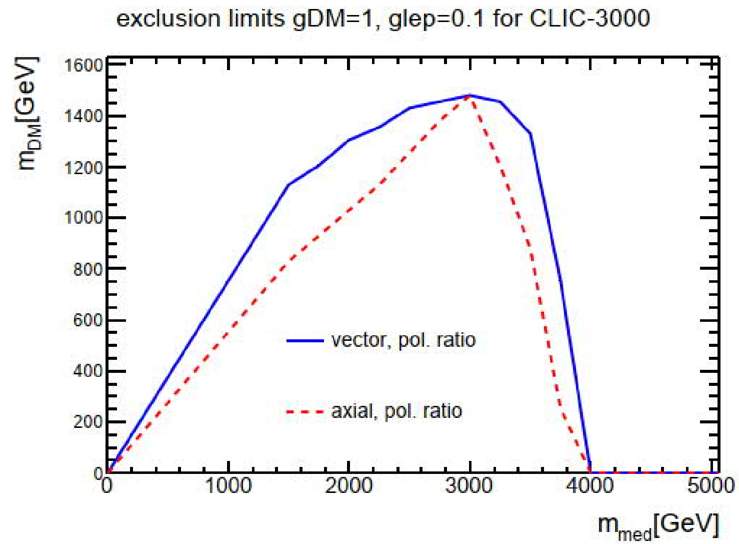
Simplified DM models with interface to Whizard provided by Andrea Wulzer or made available by the Dmsimp authors at :
http://feynrules.irmp.ucl.ac.be/wiki/DMsimp
The parameter are

- DM mediator type YD, vector (v) or axial-vector(a-v) or scalor(s)
- Mediator mass mYD and electron-YD coupling ge-Y
- DM mass mXD, mediator-XD coupling gY-X

  Limits were derived in the mXD-mYD plane by Ulrike using σ(95%) computed with the cross-section ratio σ(PeL)/σ(PeR).
  In the plane mXD-mYD, in many points, a scan over the cross-sections is performed. For each mediator mass mYD, the limit in mXD is the point where the cross-section σ(mXD,mYD) >= σ(95%).

Simplified DM model limits





compared to ESU limits from last year at m(DM)=1 GeV for 3 TeV with systematics:

- vector & axial-vector: 4800 GeV
- scalar: 4600 GeV

compared to ESU limits from last year at m(DM)=1 GeV for 3 TeV with systematics:

- vector & axial-vector: 3200 GeV

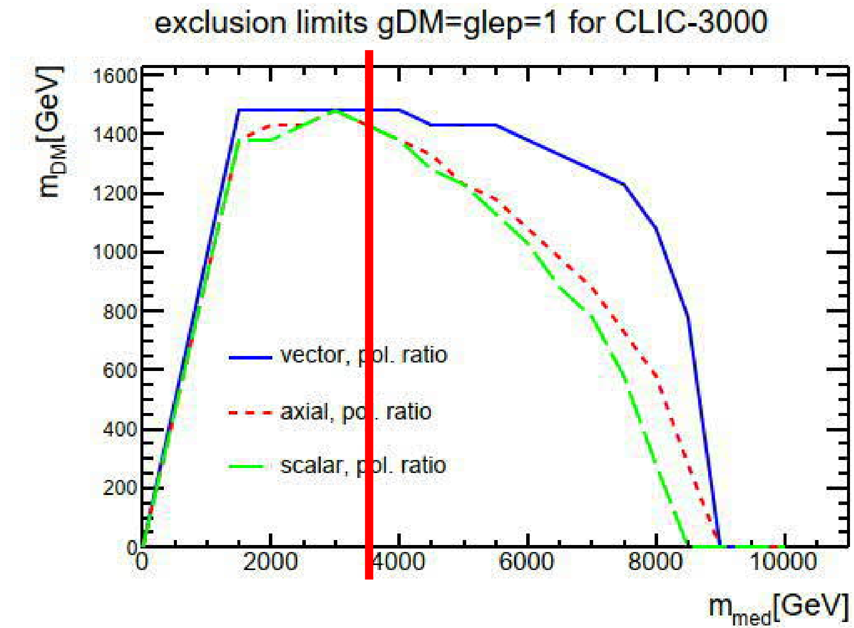
scalar case only available for glep=1

ge-Y=1, large σ, w.r.t.2019, gain: 1.9 ge-Y=0.1, small σ, gain 1.25
2019 limits determined with σ(95) computed without polarized beams.

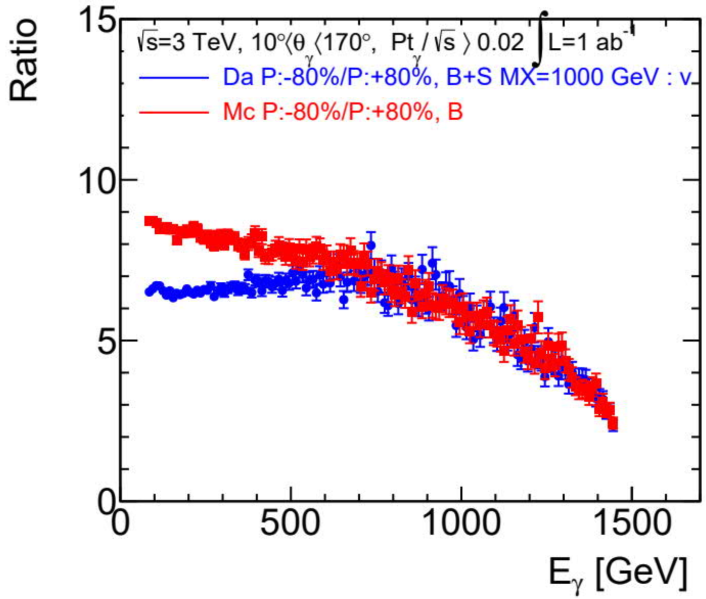
Model discrimination and mass determination

The Study done using the simplified DM models with the following conditions:

- DM mediator, v or a-v, mYD=3.5 TeV
- Coupling ge-Y=1 or 0.5
- DM mass mXD from 200 GeV to 1.4 TeV (along the red line in the exclusion plot)
- Coupling gY-X=1



Expected Signal and Z calculation



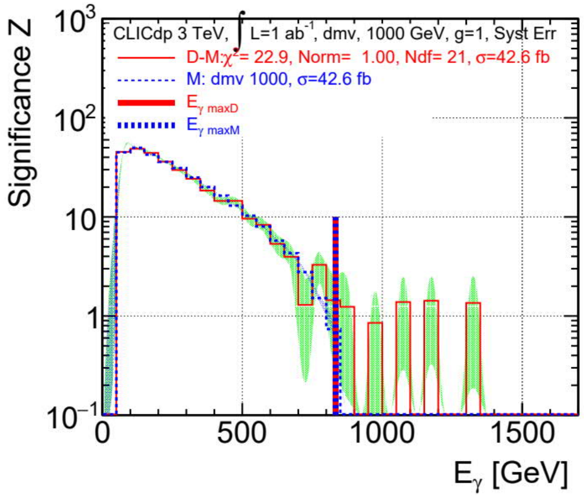
RBM(Eγ)= [dNB/dEγ(PeL)]/[dNB/dEγ(PeR)] (B only, red) computed for 50 GeV < Eγ < 1400 GeV

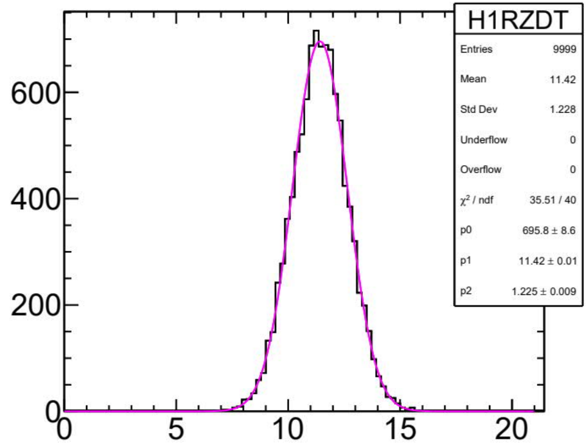
In presence of signal: e.g Data:YD-v, mXD=1000 GeV
RBPS(Eγ)=[dNBPS/dEγ(PeL)] /[dNBPS/dEγ(PeR)] (B+S, blue)
=> NSD(Eγ)=NBM(PeR)*(RBM-RBPSD)/(RBPSD-1)

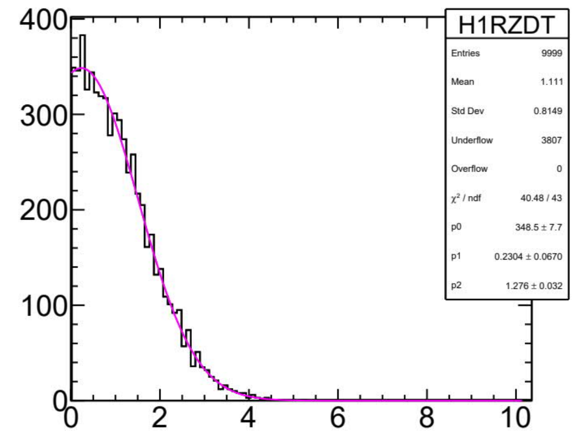
For the templates (T), for v, a-v models the ratio:
RBPST(Eγ)=[dNBPS/dEγ(PeL)]/[dNBPS/dEγ(PeR)]
=> NST(Eγ)=NBM(PeR)*(RBM-RBPST)/(RBPST-1)

NSD(Eγ) and NST(Eγ) are used to compute the significance Z(Eγ) of data and templates using the Roostat implementation of F2 slide 8.

dZ/dEγ, δZ calculation data-template χ^2 fit

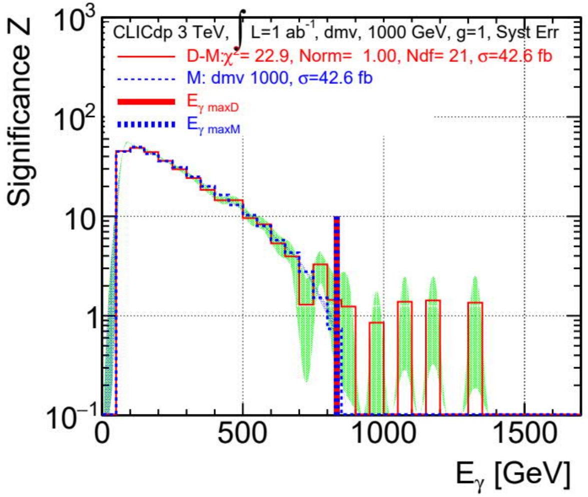


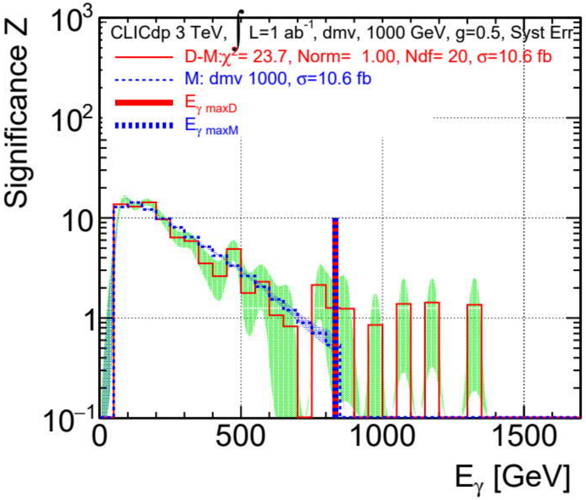




dZ/dEγ Data**:** mXD=1000 GeV (red), dZ/dEγ Tmp **:** mXD=1000 GeV (blue).
in each Eγ bin, δZ obtained using Toy MC events and a fit of dN/dZ
(plots for bin2 and bin14), green band is ZData ± 1 σ.
For Tmp, B statistics 10x larger, to reduce B fluctuations, dN/dEγ histos are weighted.
Data-Tmp fit using: $\chi^2 = \Sigma\, [(ZData(E\gamma)-ZTmp(E\gamma))^2/\delta Z(Data(E\gamma))^2]$, normalisation free.

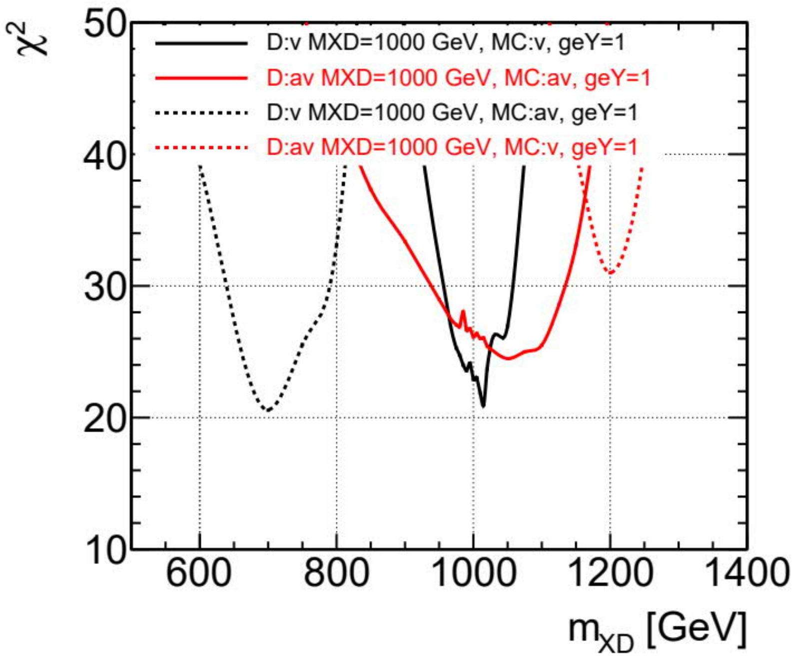
data-template χ^2 fit check





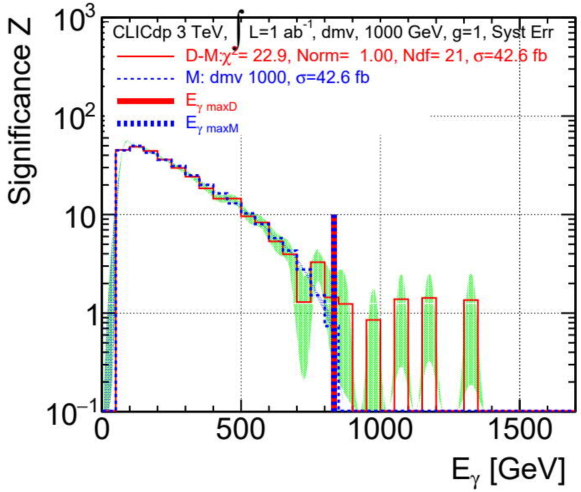
Left:dZ/dEγ Data:Yv**,** ge-Y=1.0, mXD=1000 GeV, Tmp:Yv, ge-y=1.0, mXD= 1000, GeV
The plots shows also χ^2, normalisation, Ndf and σ values and expected end-points.
The data bins beyond end-point are due to data background fluctuations.
Right:dZ/dEγ Data:Yv**,** ge-Y=0.5, mXD=1000 GeV, Tmp:Yv, ge-Y=0.5 mXD= 1000 GeV
Ge-Y=0.5 => σ four times lower, significance is lower, nevertheless X^2 / Ndf ~ 1

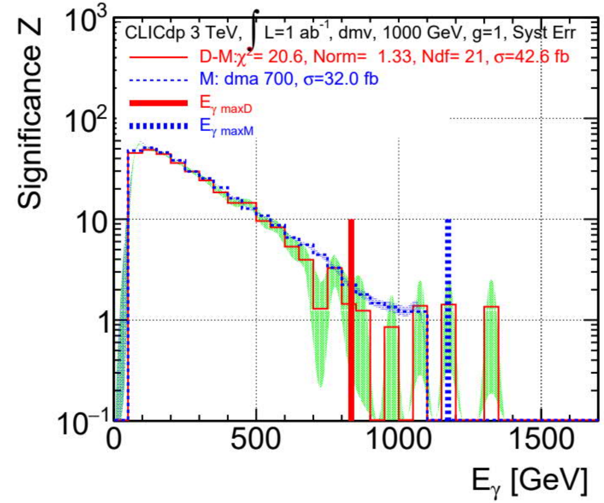
χ^2 fit for different data-tmp assumptions



X^2 distributions as a function of mXD for Data-Tmp fits (normalisation free) for ge-Y=1.
For (Data-v,Tmp-v) fit (black) the min of χ2 is 1015 GeV, the true mass is 1 TeV.
For (Data-a-v, Tmp-a-v) fit (red) the min of χ^2 is 1050 GeV, the true mass is 1 TeV.
For (Data-v,Tmp-a-v) fit (black dotted) the min of χ^2 is ~700 GeV, the true mass is 1 TeV.
For (Data-a-v,Tmp-v) fit (red dotted) the min of χ^2 is ~1.2 TeV, the true mass is 1 TeV.
How discriminate (v,v) from (v,a-v) and (a-v,a-v) from (a-v,v) ?

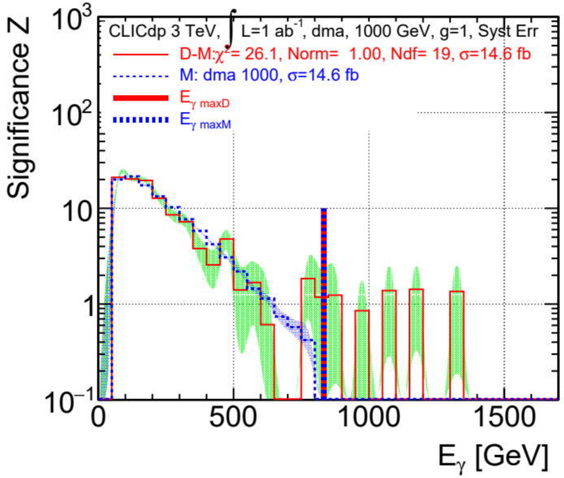
dZ/dEγ:data-template χ^2 fit
v, a-v model discrimination

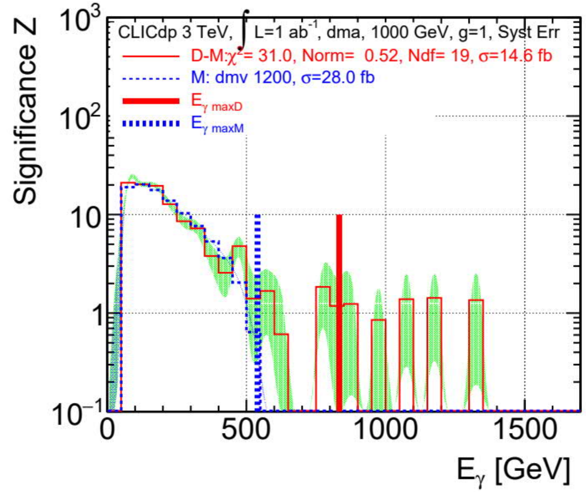




dZ/dEγ Data:Y-v, ge-y=1.0, mXD=1000 GeV, Tmp:Y-v , ge-y=1.0, mXD=1000 GeV
dZ/dEγ Data:Y-v, ge-y=1.0, mXD=1000 GeV, Tmp:Ya-v, ge-y=1.0, mXD= 700 GeV
X^2 (v,v)=22.9 > X^2 (v,a-v)=20.6, *cannot discriminate using shape only.*
Norm (v,v)=1.0 and Norm (v,a-v)=1.33
Use normalisation to discriminate models.

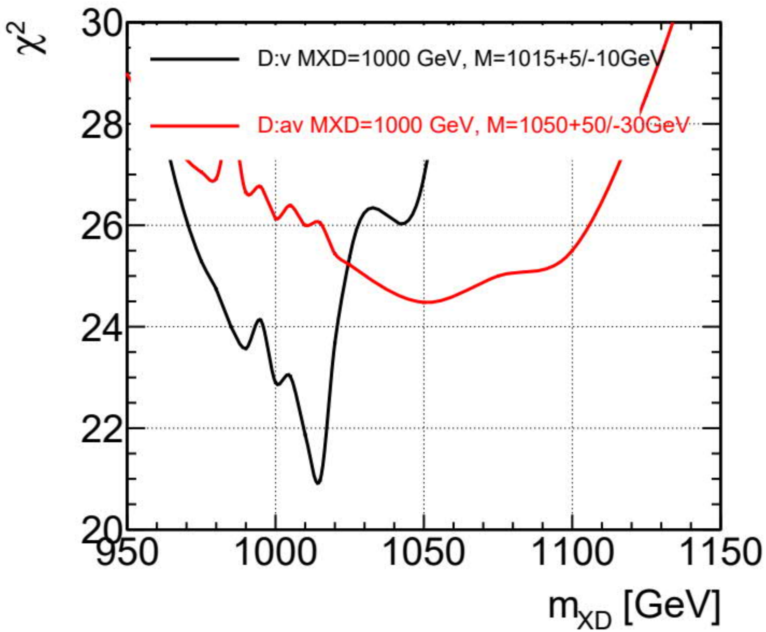
dZ/dEγ, data-template χ^2 fit
a-v, v model discrimination





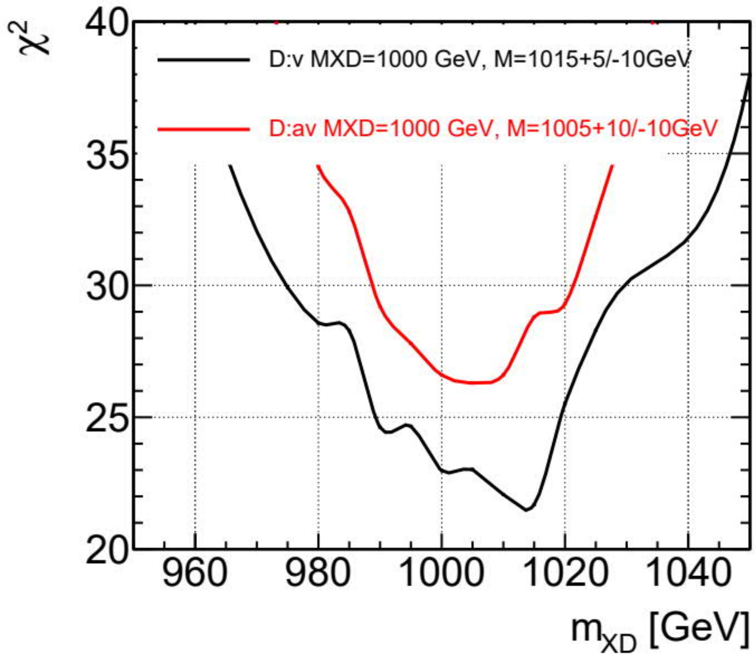
dZ/dEγ Data:Y-a-v, ge-y=1.0, mXD=1000 GeV, Tmp:Y-a-v, ge-y=1.0, mXD=1000 GeV
dZ/dEγ Data:Y-a-v, ge-y=1.0, mXD=1000 GeV, Tmp:Y-v , ge-y=1.0, mXD=1200 GeV
X^2 (a-v, a-v)=26.1 < X^2 (a-v,v)=31*, can use shape to discriminate, but not alone, $\delta\chi^2$ =4.9.*
Norm (a-v,a-v)=1.0 and Norm (a-v,v)=0.52
Use shape and normalisation to discriminate models.

χ^2 fit, mXD and δM determination



X^2 distributions as a function of MXD for Data-Tmp fits (normalisation free) for ge-Y=1.
Zoom into the region of the minimum.
mXD is the value where χ^2 is minimum, δM corresponds to χ^2 variation of 1.
For (v,v) fit (black) mXD=1015 +5/-10 GeV
For (a-v,a-v) fit (red) mXD=1050+50/-30 GeV (lower σ => larger δM)

χ^2 fit with normalisation =1



X^2 distributions as a function of mXD for Data-Tmp fits (normalisation=1) for ge-Y=1.
For (v,v) fit (black) mXD=1015 +5/-10 GeV
For (a-v,a-v) fit (red) mXD=1005+10/-10 GeV
For mXD=1 TeV, and normalisation fixed to 1, δmXD=1%.

Summary

Using [dσ/dEγ(PeL)] /[dσ/dEγ(PeR)] allows computing dσ(95%)/dmXD with reduced systematic errors, it improves significantly the exclusion limits.

Data-Temp χ^2 fits of dZ/dEγ with normalisation free allow discriminating between v and a-v models, it requires taking into account the normalisation values.

It allows also the determination of the DM mass and error, the error δmXD, depends on the cross section value.

For mXD=1 TeV, and normalisation=1, δmXD=1%.

Thank You

Additional slides

Radiative Neutrinos Diagrams

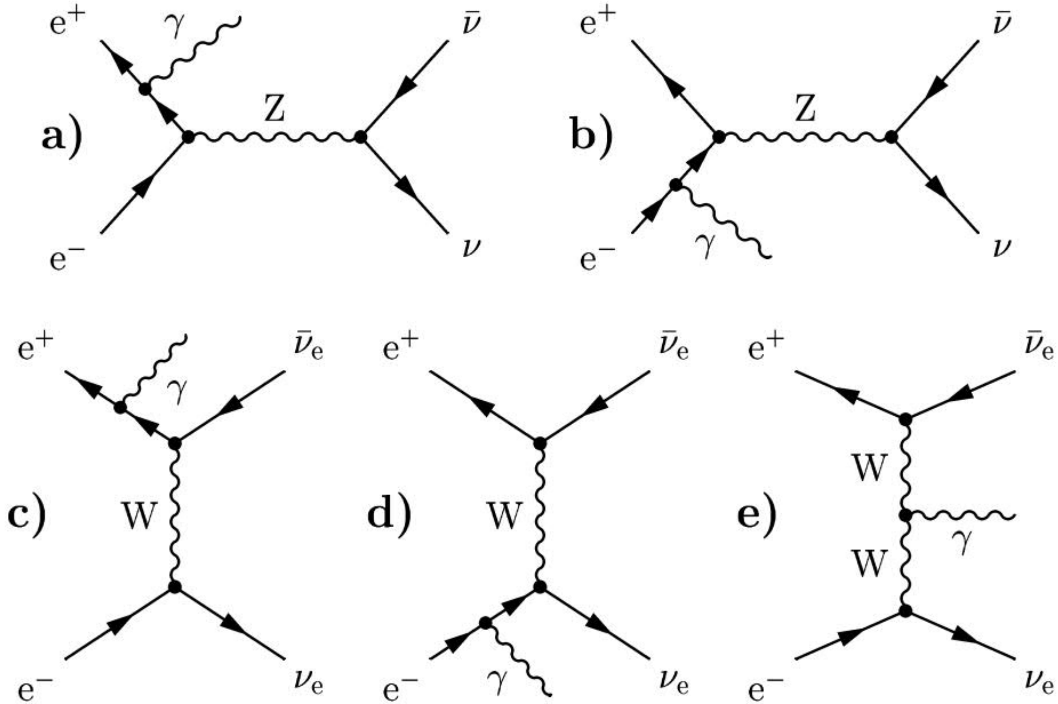
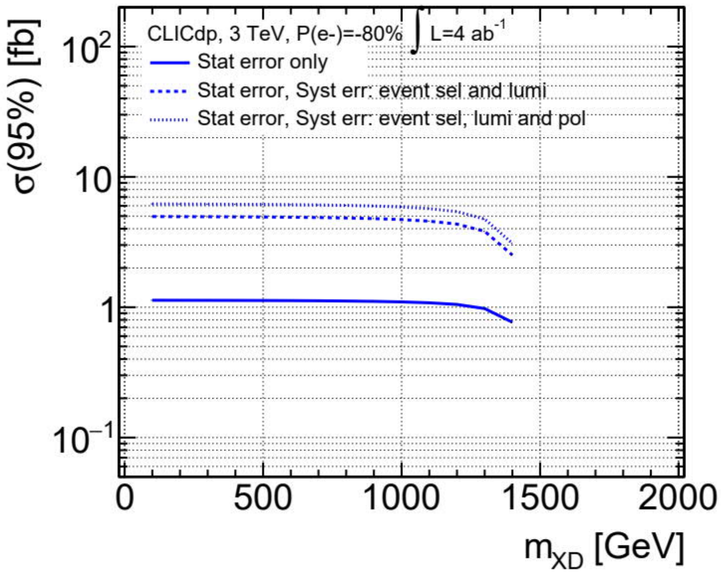
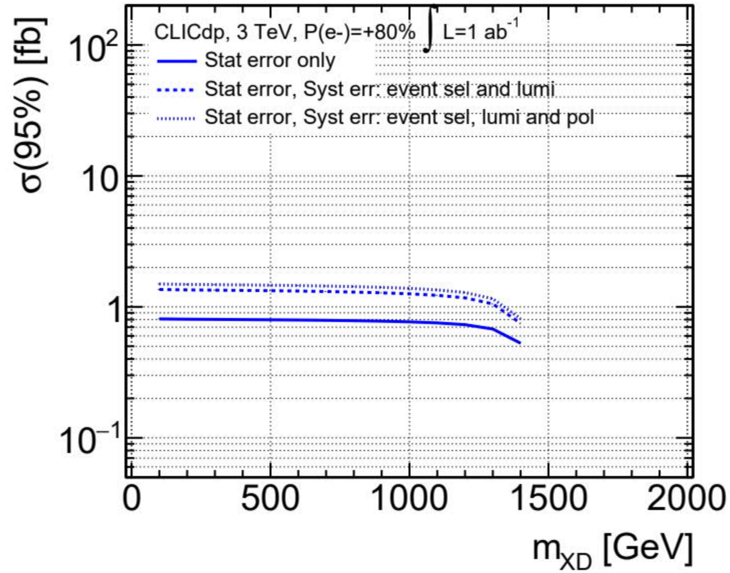


Figure 2.6: Lowest-order Feynman diagrams for the reaction $e^+e^- \to \nu\bar{\nu}\gamma$.

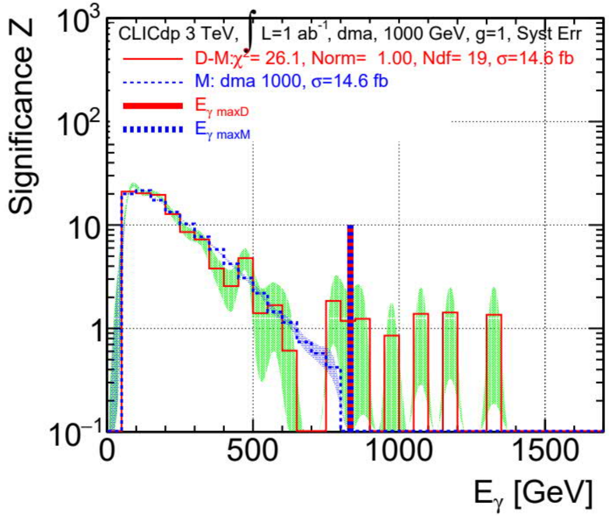
dσ(95%)/dmXD for PeL and PeR

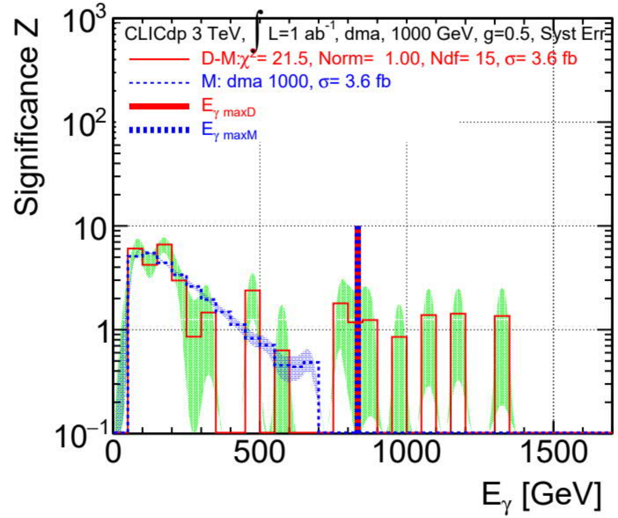




Polarisation	∫L ab^{-1}	σ(95%) [fb] No syst err	σ(95%) [fb] with syst err
PeL	4	1.1	6
PeR	1	0.8	1.5

dZ/dEγ:Ya-v, data-template χ^2 fit





dZ/dEγ Data:Ya-v**,** ge-Y=1.0, mXD=1000 GeV, Tmp:Ya-v, ge-Y=1.0, mXD= 1000, GeV
The plots shows χ^2 , normalisation, Ndf and σ values, σ(a-v)/σ(v)=0.34 => lower Z.
dZ/dEγ Data:Ya-v**,** ge-Y=0.5, mXD=1000 GeV, Tmp:Ya,-v ge-Y=0.5 mXD= 1000, GeV
Ge-Y=0.5 => σ four times lower, Z much lower.