Dark matter searches at future e+e- colliders

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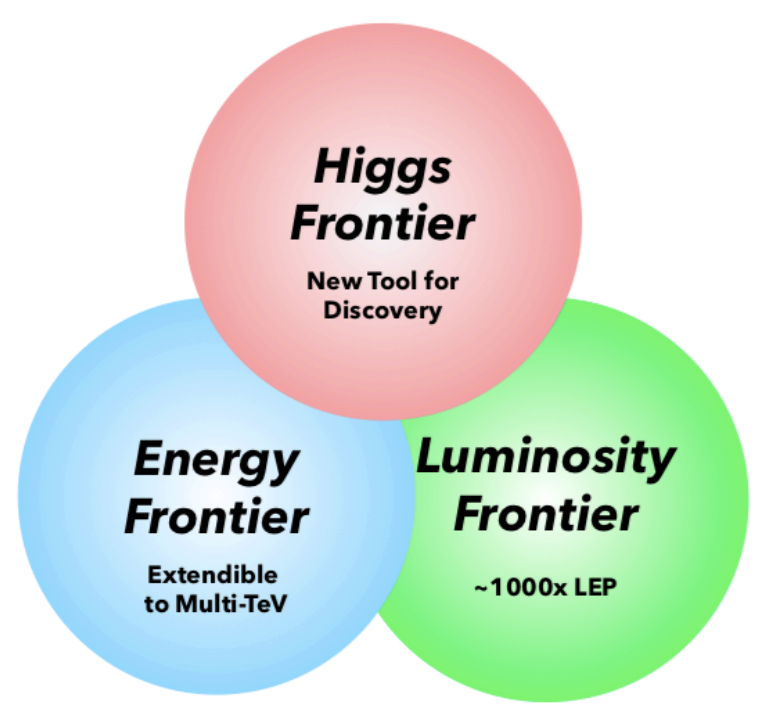
Dark matter searches at e+e- colliders

Many hints for Dark Matter (DM) but its nature is unknown

Many possible scenarios with wide range of masses and couplings

e+e- colliders are unique offering many options for DM searches



Higgs boson – a unique probe of fundamental questions in HEP today

New unchartered area to be explored at high energy colliders

Possible discovery in areas that at LEP were limited statistically

Tomohiko Tanabe @LCWS2021

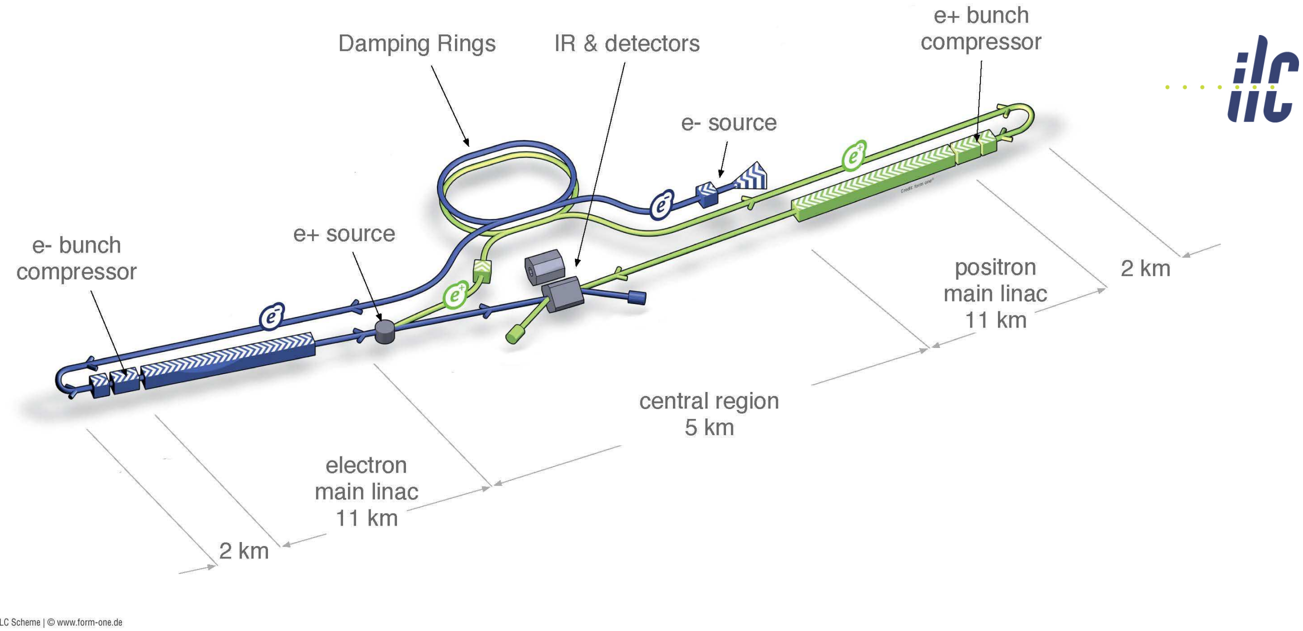
Outline

- Linear collides and experiments
- Collider measurements
  - Higgs frontier
  - Energy frontier
- Non-collider experiments
- Conclusions

Linear colliders and experiments

Colliders: ILC

International Linear Collider



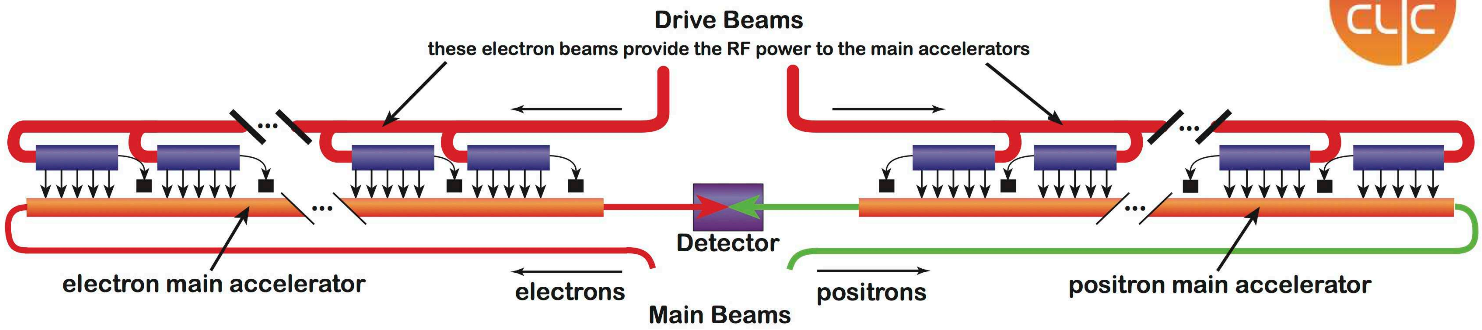
Technical Design (TDR) completed in 2013

arXiv:1306.6328

- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 31 km
- polarisation for both e^- and e^+ (80%/30%)

Colliders: CLIC

Compact LInear Collider



Conceptual Design (CDR) presented in 2012 CERN-2012-007

- high gradient, two-beam acceleration scheme
- staged implementation plan with energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- e^- polarisation (80%)

For details refer to arXiv:1812.07987

Colliders: detectors

Detector Requirement

"Particle Flow" concept:

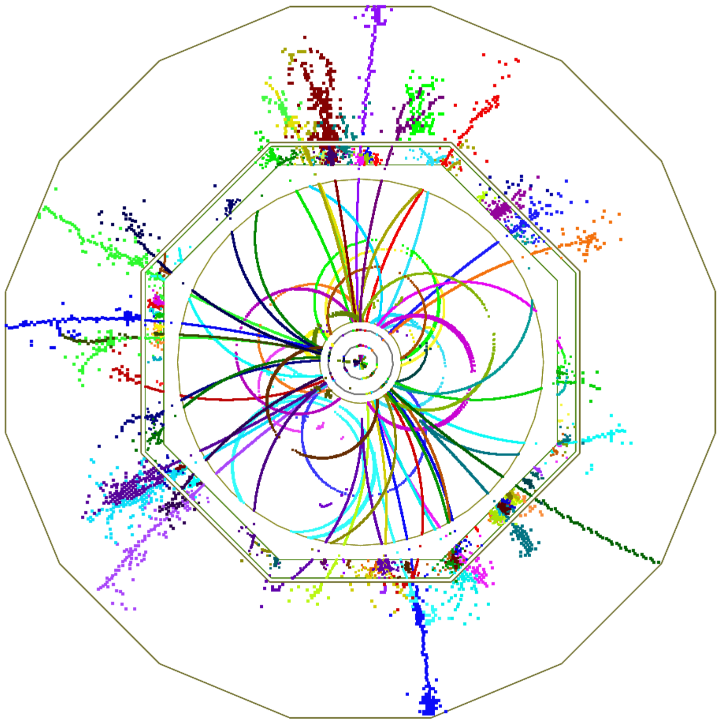
High calorimeter granularity
⇒ single particle reconstruction/ID

Precise momentum measurement
⇒ best energy for charged particles
⇒ dominates jet energy resolution

High precision vertex detector
⇒ very efficient flavour tagging

Instrumentation down to smallest angles
⇒ hermecity, missing energy tagging

Example event
$e^+e^- \to t\bar{t} \to 6j$



Colliders: experiments

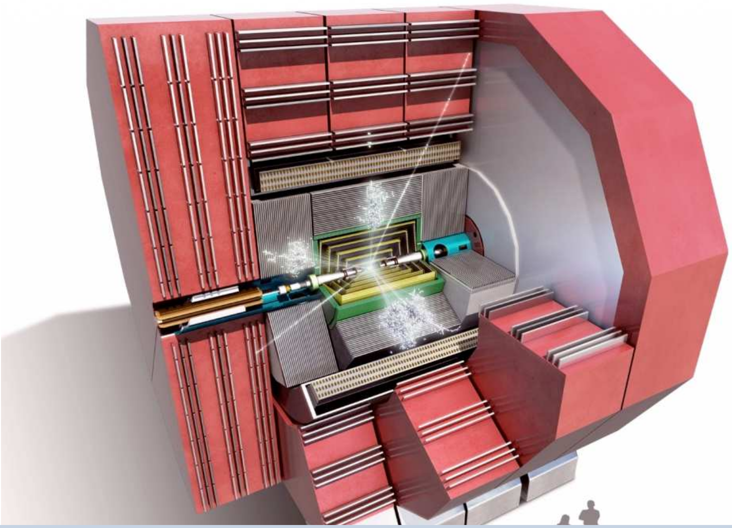
Detector Requirements same for ILC and CLIC

- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \text{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \frac{1\ \text{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (for highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Detailed detector concepts for ILC and CLIC:

ILD

CLICdet



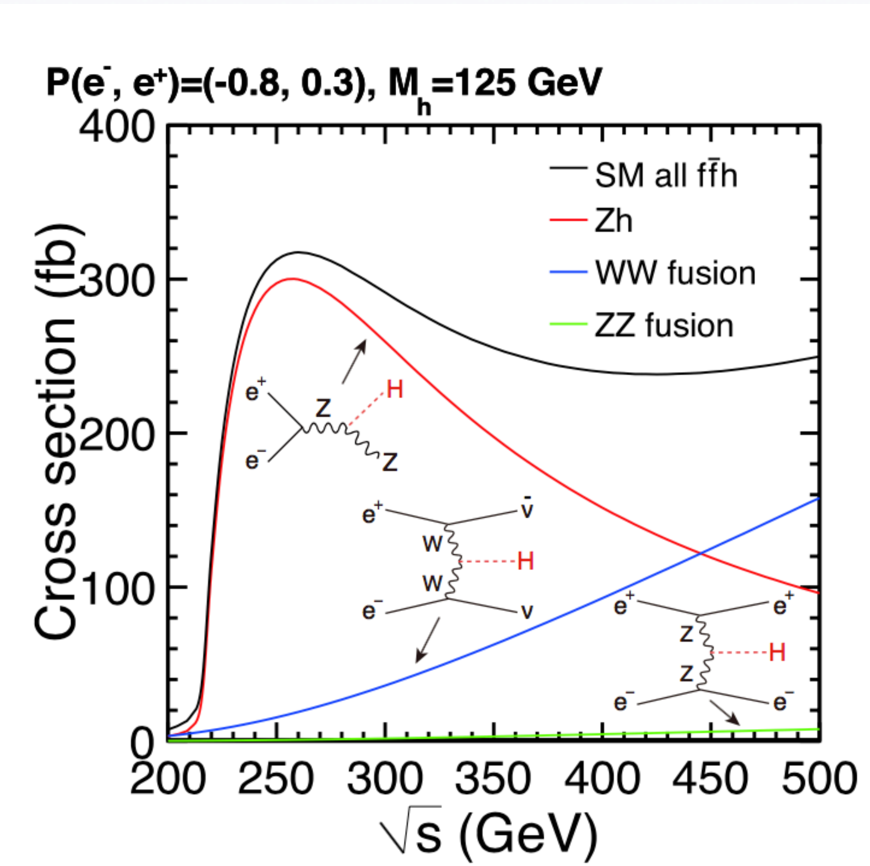
Colliders at the Higgs frontier

- Higgs precision measurements
- search for light scalars

Higgs precision measurements

First ILC running will be focused on Higgs measurements

Production cross sections



approx. 0.5 million Higgs with 2/ab at 250 GeV

beam polarisation crucial

For ILC both beams polarised

Integrated luminosity planned with different polarisation settings [fb^{-1}]

$\sqrt{s}$	$\mathrm{sgn}(P(e^-), P(e^+))$				Total
	$(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	
250 GeV	900	900	100	100	2000
350 GeV	135	45	10	10	200
500 GeV	1600	1600	400	400	4000

arXiv:1903.01629

four measurements instead of one to:

- increase accuracy of precision measurements
- more input to global fits and analyses
- remove ambiguity in many BSM studies
- reduce sensitivity to systematic effects

For CLIC only electrons polarised

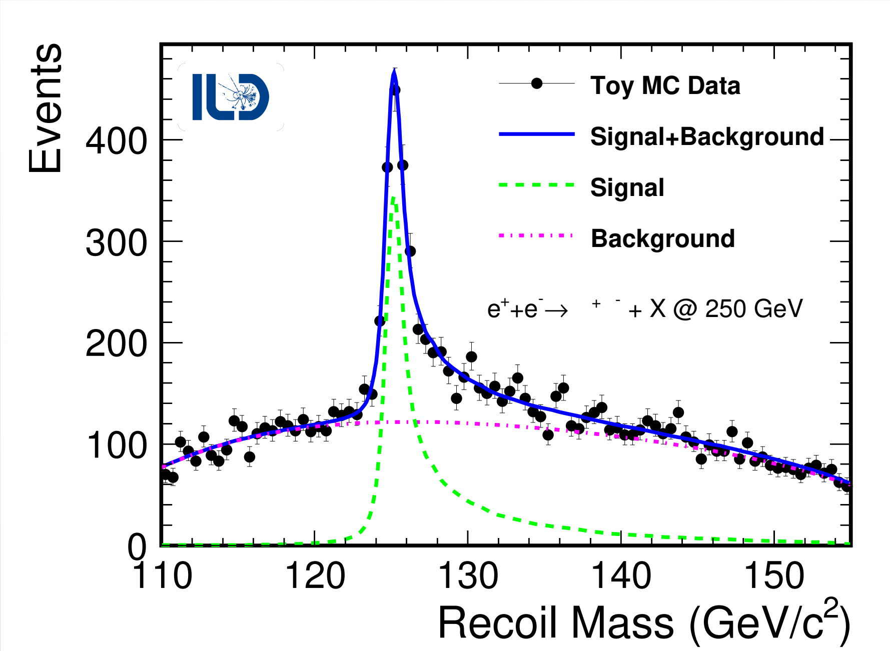
380 GeV	1.5 TeV	3 TeV
1/ab	2.5/ab	5/ab

Higgs precision measurements

At 250 GeV the Higgs production dominated by Higgs-strahlung (ZH production)

arXiv:2002.12048

- initial state known
- reconstruct Z decay
- compute recoil mass



Most important measurement:
model independent ZH production
cross section => access to Higgs width

Higgs precision measurements

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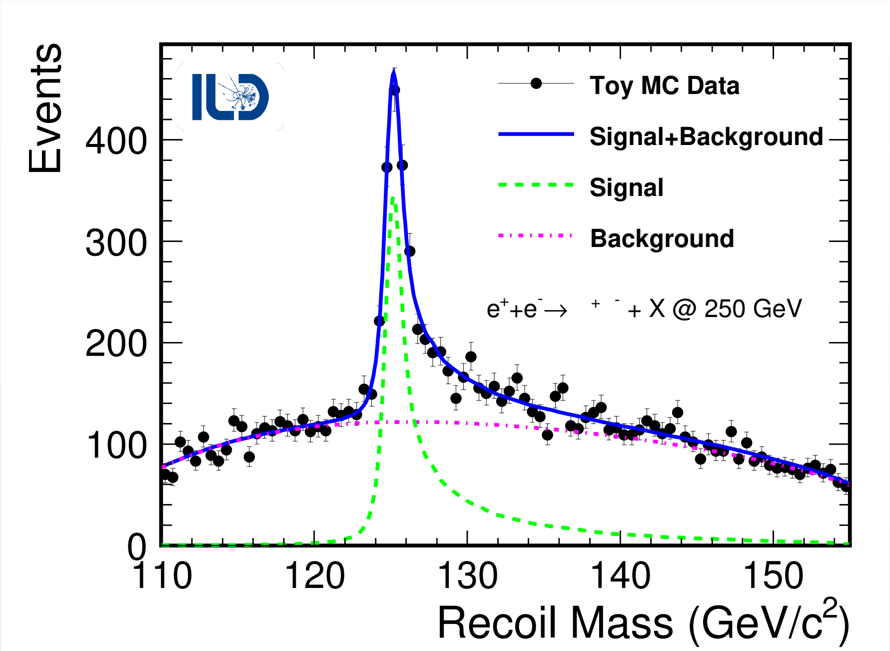
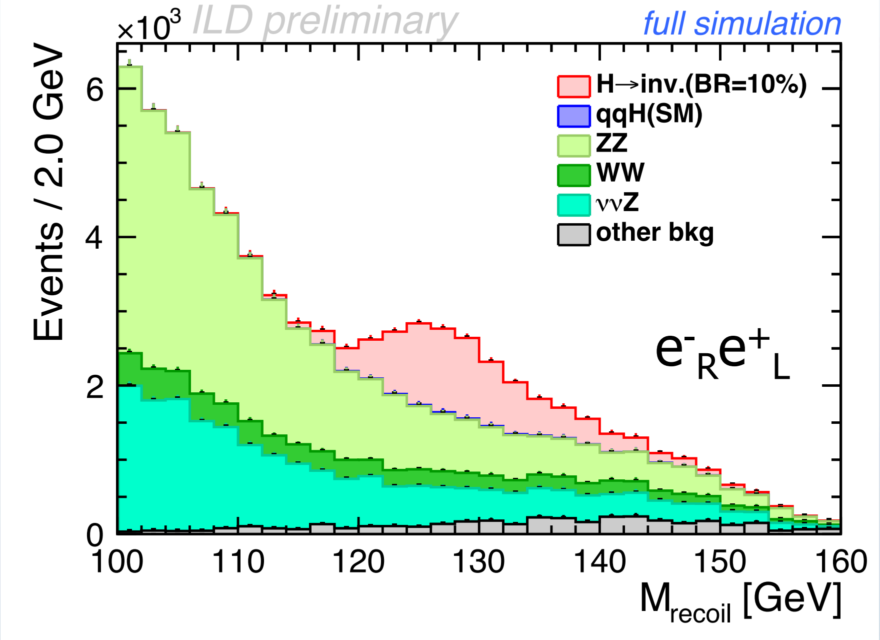
High sensitivity to invisible decay





Most important measurement:
model independent ZH production cross section => access to Higgs width

with 2/ab at 250 GeV expected 95% CL limit: BR_{INV} = 0.23%
a factor 10 better than HL-LHC

Search for light scalars

Higgs portal models: new scalars that couple to DM particles can mix with the SM one

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

- if mixing small, the h_1 state is the SM-like (125 GeV state)
  it can also decay invisibly to DM by the ϕ component with BR~ $\sin^2\alpha$

=> search for invisible Higgs decay

- if h_2 is also light, it can be searched in e+e- collisions in the same way as the SM-like Higgs

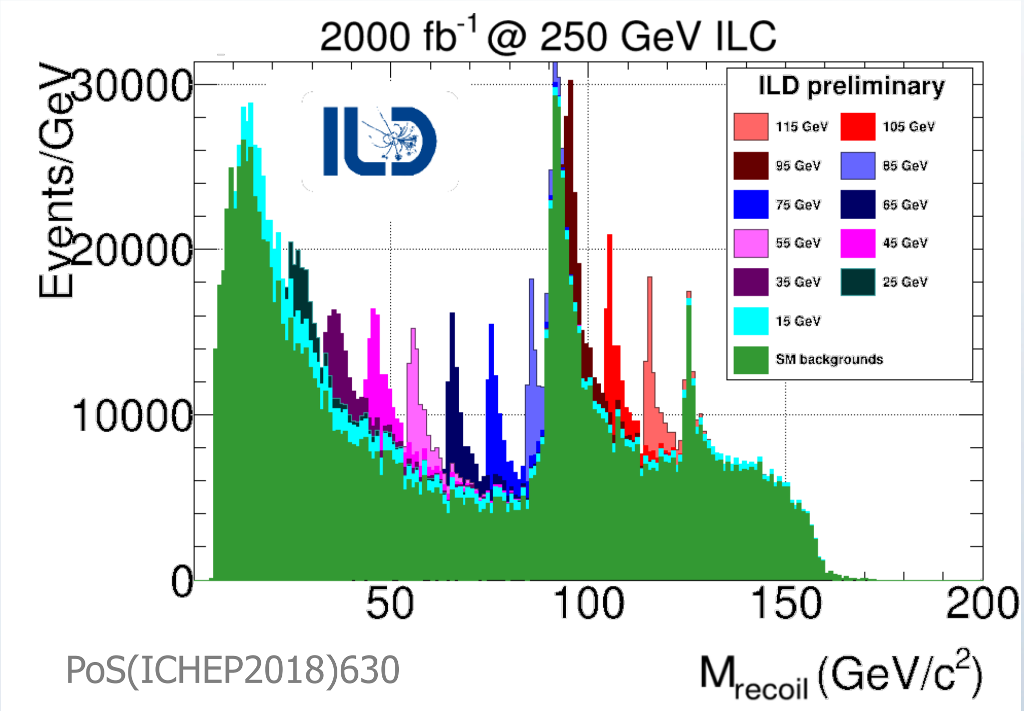
=> search for additional scalars either directly or via recoil mass

Search for light scalars

Many BSM predict new scalars that could be light if weakly coupled to SM particles

recoil mass distribution for various signals

$$e^+ e^- \to Z\, S^0 \to \mu^+ \mu^- + X$$



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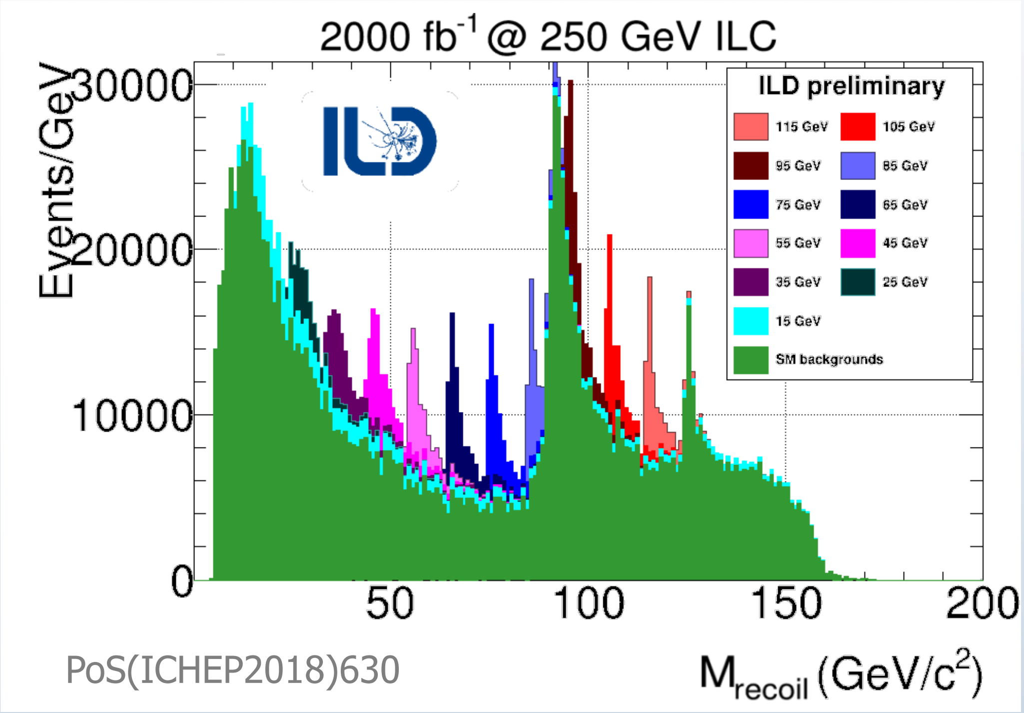

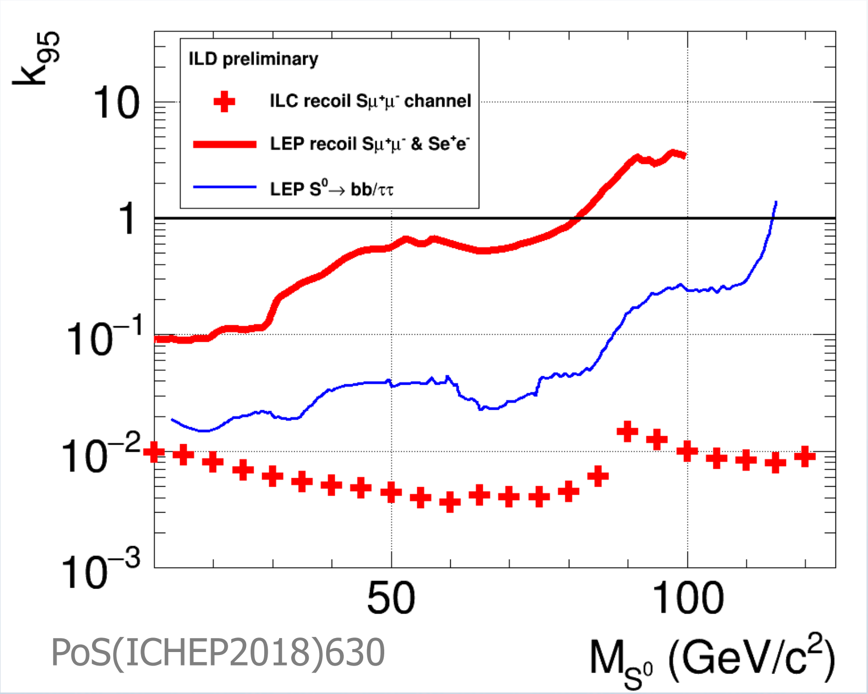

search independent of scalar decay modes

10-100 times better than at LEP

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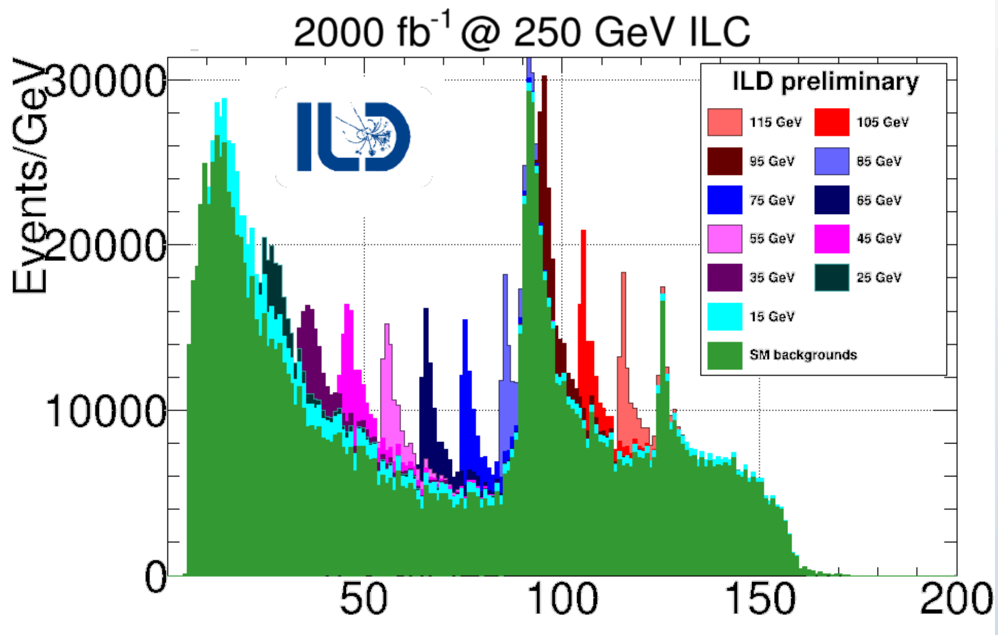
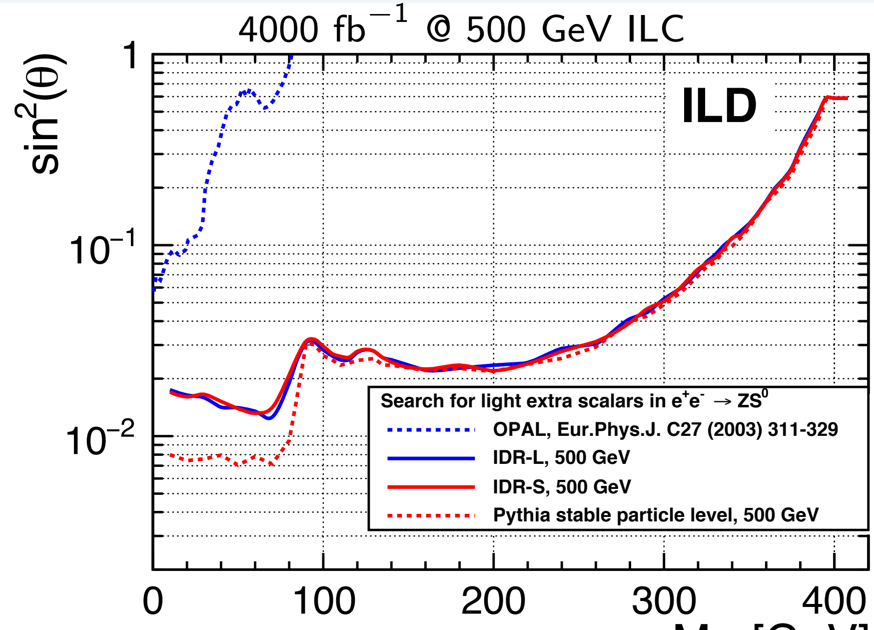


PoS(ICHEP2018)630



arXiv:2005.06265

search independent of scalar decay modes

10-100 times better than at LEP

Colliders at the energy froniter

- lepton signatures: e.g. Inert doublet model (IDM)
- mono-photon signature: a light mediator case

Inert doublet model

One of the simplest extensions of the Standard Model (SM).
The scalar sector consists of two doublets:

- Φ_S is the SM–like Higgs doublet,
- Φ_D (inert doublet) has four additional scalars H, A, $H^\pm$.

$$\Phi_S = \begin{pmatrix} G^\pm \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_D = \begin{pmatrix} H^\pm \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

We assume a discrete Z_2 symmetry under which

- SM Higgs doublet Φ_S is *even*: $\Phi_S \to \Phi_S$ (also other SM→SM)
- inert doublet Φ_D is *odd*: $\Phi_D \to -\Phi_D$.

⇒ Yukawa-type interactions only for Higgs doublet (Φ_S).
The inert doublet (Φ_D) does not interact with the SM fermions!

⇒ The lightest inert particle is stable: a natural candidate for dark matter!
We assume the neutral scalar H is the dark matter particle.

$$m_H < m_A,\ m_{H^\pm}$$

Inert doublet model

$$V = -\frac{1}{2}\left[m_{11}^2(\Phi_S^\dagger\Phi_S)+m_{22}^2(\Phi_D^\dagger\Phi_D)\right] + \frac{\lambda_1}{2}(\Phi_S^\dagger\Phi_S)^2+\frac{\lambda_2}{2}(\Phi_D^\dagger\Phi_D)^2$$
$$+\lambda_3(\Phi_S^\dagger\Phi_S)(\Phi_D^\dagger\Phi_D)+\lambda_4(\Phi_S^\dagger\Phi_D)(\Phi_D^\dagger\Phi_S) + \frac{\lambda_5}{2}\left[(\Phi_S^\dagger\Phi_D)^2+(\Phi_D^\dagger\Phi_S)^2\right]$$

After EWSB, the model contains a priori seven free parameters.

Two parameters can be fixed from the Standard Model (v, m_h).

We are left with five free parameters, which we take as:

$\Rightarrow$ three inert scalar masses: m_H, m_A, $m_{H^\pm}$

$\Rightarrow$ two couplings, eg. λ_2 and $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$

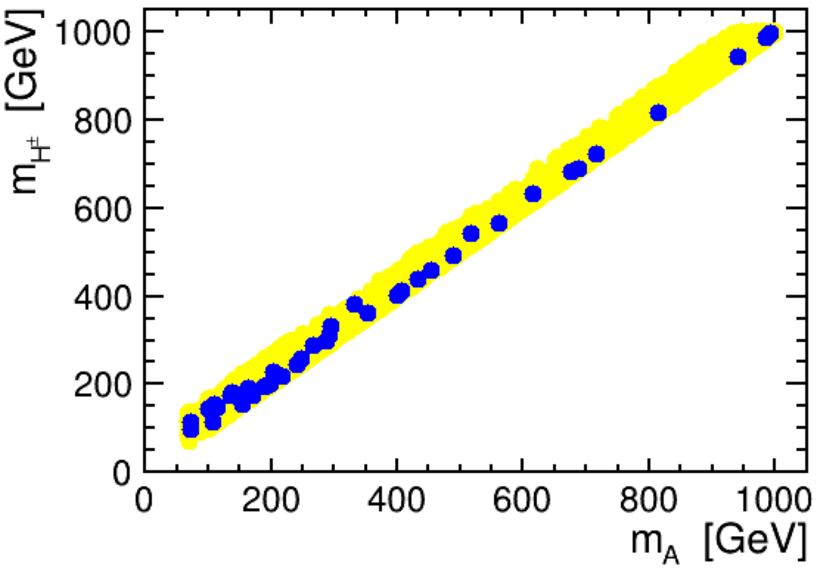
Inert scalars couplings to γ, $W^\pm$ and Z determined by SM parameters

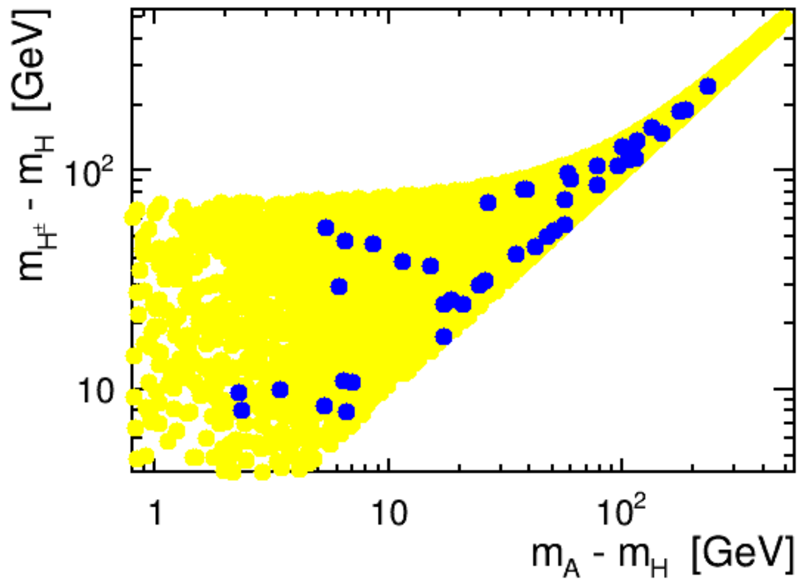
$\Rightarrow$ well established predictions for production and decay rates!

We scanned the IDM parameter space looking for scenarios consistent with current theoretical and experimental constraints, for masses up to 1 TeV.

Inert doublet model

Out of about 15'000 points consistent with all considered constraints, we chose 41 benchmark points (including 20 "high mass") for detailed studies:





The selection was arbitrary, but we tried to

- cover wide range of scalar masses and the mass splittings
- get significant contribution to the relic density

JK, W. Kotlarski, T. Robens, D. Sokolowska, A.F. Zarnecki, JHEP 12 (2018) 081

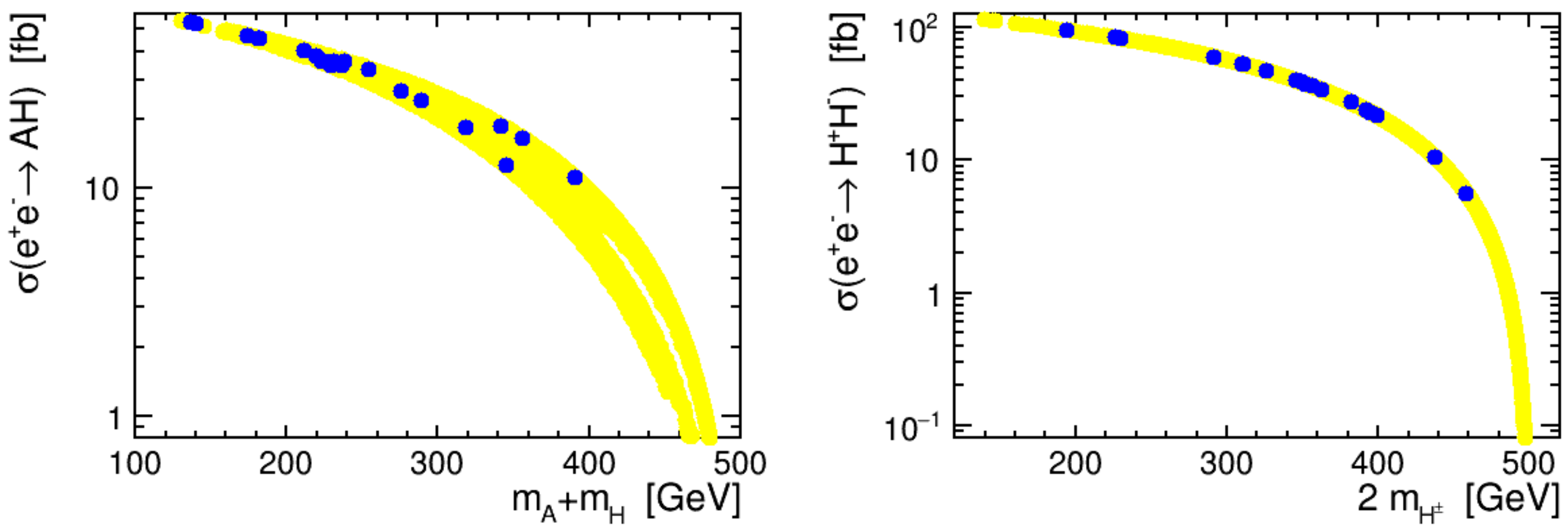
IDM: dominant DM production

Production of IDM scalars at e^+e^- colliders dominated by two processes:

$$e^+e^- \to A\ H \qquad\qquad e^+e^- \to H^+H^-$$

Leading-order cross sections for inert scalar production processes at 500 GeV:

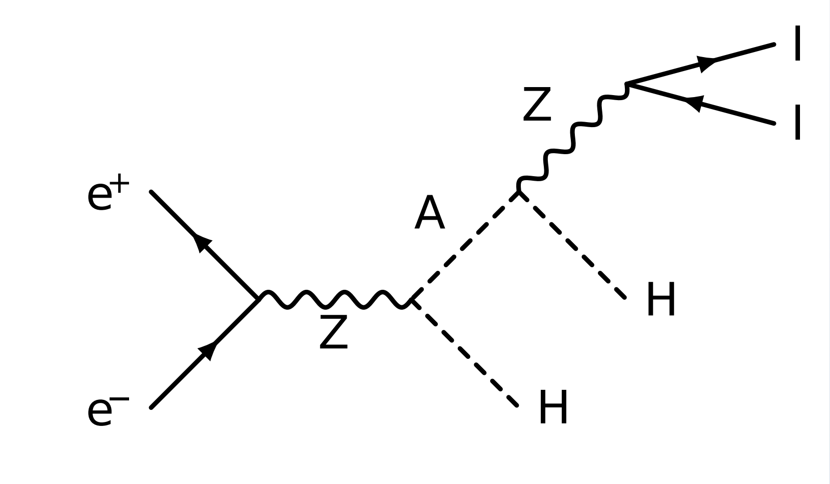
21 benchmarks   21 benchmarks



IDM: leptonic signatures

Same flavour lepton pair production can be considered a signature of the AH production process followed by the A decay:

$$e^+e^- \rightarrow HA \rightarrow HHZ^{(\star)} \rightarrow HH\mu^+\mu^-$$



signal

$$\begin{aligned} e^+e^- &\rightarrow \mu^+\mu^- \; HH, \\ &\rightarrow \mu^+\mu^-\nu_\mu\bar{\nu}_\mu \; HH, \\ &\rightarrow \tau^+\mu^-\nu_\tau\bar{\nu}_\mu \; HH, \;\; \mu^+\tau^-\nu_\mu\bar{\nu}_\tau \; HH, \\ &\rightarrow \tau^+\tau^- \; HH, \;\; \tau^+\tau^-\nu_\tau\bar{\nu}_\tau \; HH, \end{aligned}$$

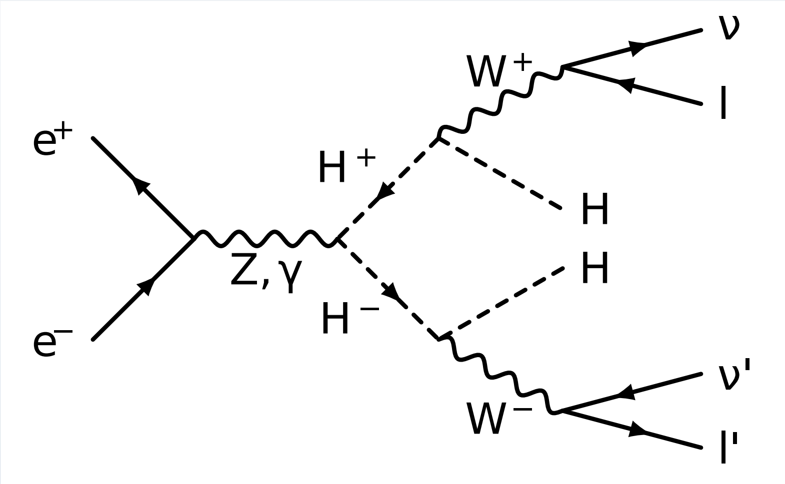
background

$$\begin{aligned} e^+e^- &\rightarrow \mu^+\mu^-, \\ &\rightarrow \mu^+\mu^- \; \nu_i\bar{\nu}_i, \\ &\rightarrow \tau^+\mu^- \; \nu_\tau\bar{\nu}_\mu, \;\; \mu^+\tau^- \; \nu_\mu\bar{\nu}_\tau, \\ &\rightarrow \tau^+\tau^-, \;\; \tau^+\tau^- \; \nu_i\bar{\nu}_i, \end{aligned}$$

IDM: leptonic signatures

signature for H^+H^- production: different flavour lepton pair

$$e^+e^- \rightarrow H^+H^- \rightarrow HHW^{+(*)}W^{-(*)} \rightarrow HH\ell^+\ell'^-\nu\bar{\nu}'$$



signal

$$\begin{aligned} e^+e^- &\rightarrow \mu^+\nu_\mu\, e^-\bar{\nu}_e\, HH,\;\; e^+\nu_e\, \mu^-\bar{\nu}_\mu\, HH, \\ &\rightarrow \mu^+\nu_\mu\, \tau^-\bar{\nu}_\tau\, HH,\;\; \tau^+\nu_\tau\, \mu^-\bar{\nu}_\mu\, HH, \\ &\rightarrow e^+\nu_e\, \tau^-\bar{\nu}_\tau\, HH,\;\; \tau^+\nu_\tau\, e^-\bar{\nu}_e\, HH, \\ &\rightarrow \tau^+\,\tau^-\, HH,\;\; \tau^+\nu_\tau\, \tau^-\bar{\nu}_\tau\, HH, \end{aligned}$$

background

$$\begin{aligned} e^+e^- &\rightarrow \mu^+\nu_\mu\, e^-\bar{\nu}_e\,,\;\; e^+\nu_e\, \mu^-\bar{\nu}_\mu\,, \\ &\rightarrow \mu^+\nu_\mu\, \tau^-\bar{\nu}_\tau\,,\;\; \tau^+\nu_\tau\, \mu^-\bar{\nu}_\mu, \\ &\rightarrow e^+\nu_e\, \tau^-\bar{\nu}_\tau\,,\;\; \tau^+\nu_\tau\, e^-\bar{\nu}_e\,, \\ &\rightarrow \tau^+\tau^-,\;\; \tau^+\nu_\tau\, \tau^-\bar{\nu}_\tau\,. \end{aligned}$$

IDM: leptonic signatures

- muon pair production, $\mu^+\mu^-$, for AH production
- electron-muon pair production, μ^+e^- or $e^+\mu^-$, for H^+H^- production

Both channels include contributions from AH and H^+H^- production!
In particular due to leptonic tau decays.

Signal and background samples were generator with WHizard 2.2.8
based on the dedicated IDM model implementation in SARAH,
parameter files for benchmark scenarios were prepared using SPheno 4.0.3

Generator level cuts reflecting detector acceptance:

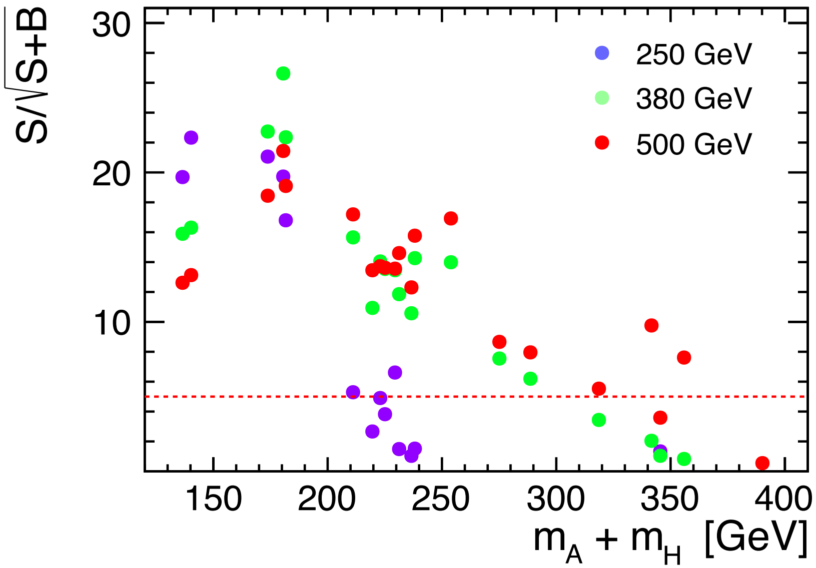
- require lepton energy $E_l > 5\,\text{GeV}$ and lepton angle $\Theta_l > 100\,\text{mrad}$
- no ISR photon with $E_\gamma > 10\,\text{GeV}$ and $\Theta_\gamma > 100\,\text{mrad}$

No detector resolution/efficiency taken into account
(but only electrons and muons in the final state)

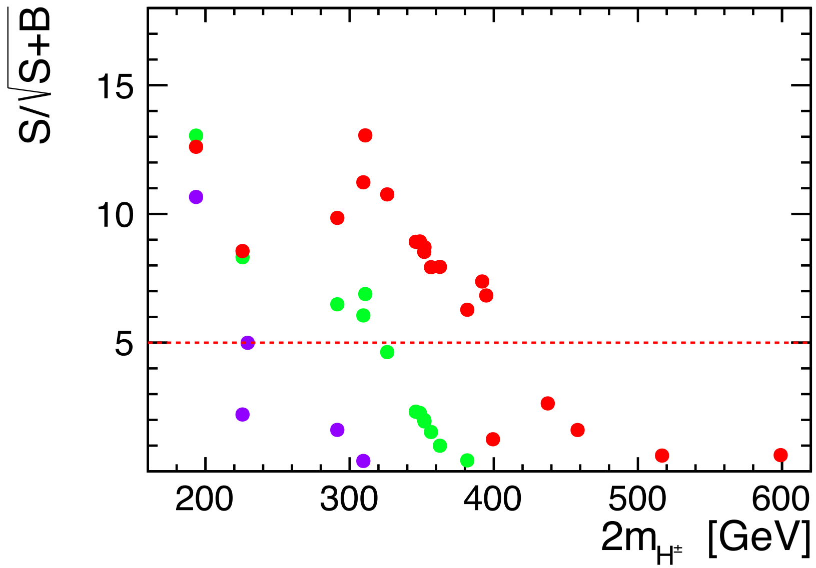
IDM: expected significances

Search for pair-production of IDM scalars, for different $\sqrt{s}$

AH signature ($\mu^+\mu^-$)



H^+H^- signature ($\mu^\pm e^\mp$)



Discovery reach mainly depends on the scalar masses!

- $m_A + m_H < 220,\ 300,\ 330$ GeV
- $m_{H^\pm} < 110,\ 160,\ 200$ GeV

for 1000 fb^{-1} at $\sqrt{s} = 250,\ 380,\ 500$ GeV

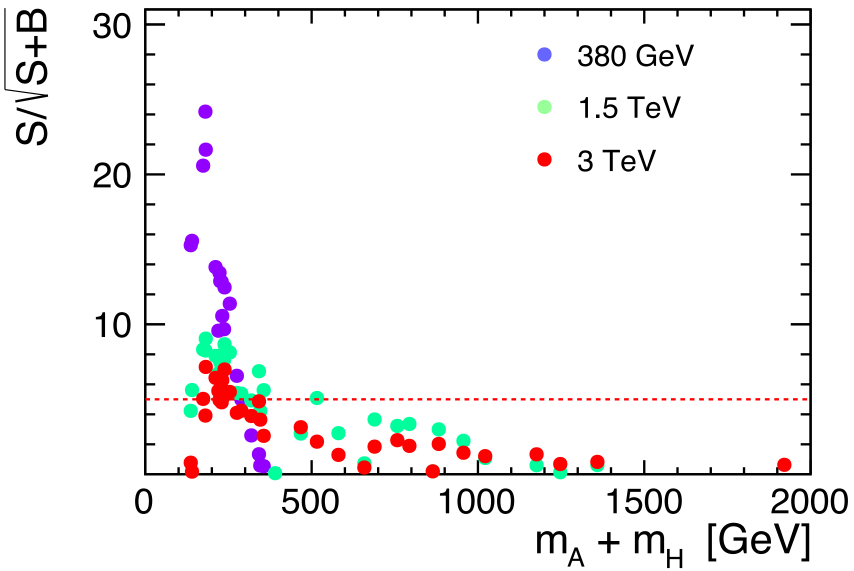
IDM: expected significances

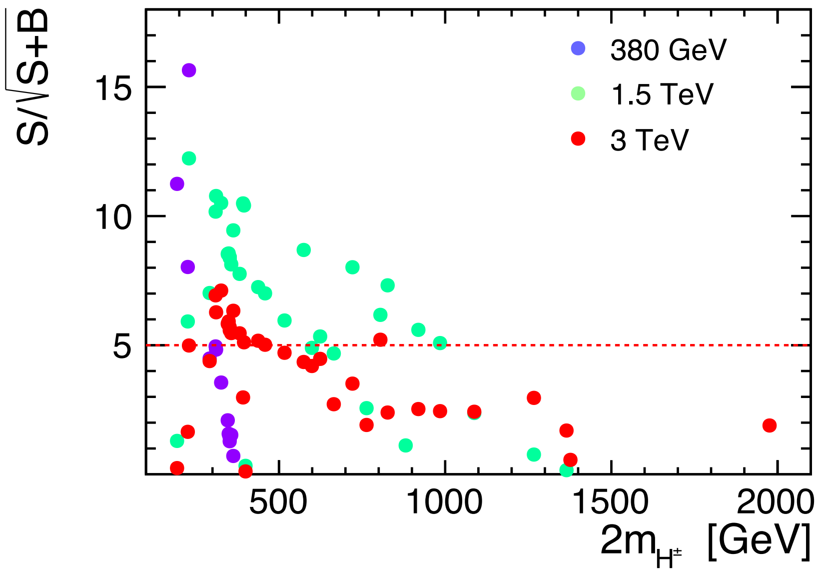
including luminosity spectra

Comparing CLIC running scenarios:

$1000\,\mathrm{fb}^{-1}$ at 380 GeV $2500\,\mathrm{fb}^{-1}$ at 1.5 TeV $5000\,\mathrm{fb}^{-1}$ at 3 TeV

AH signature ($\mu^+\mu^-$) H^+H^- signature ($\mu^\pm e^\mp$)





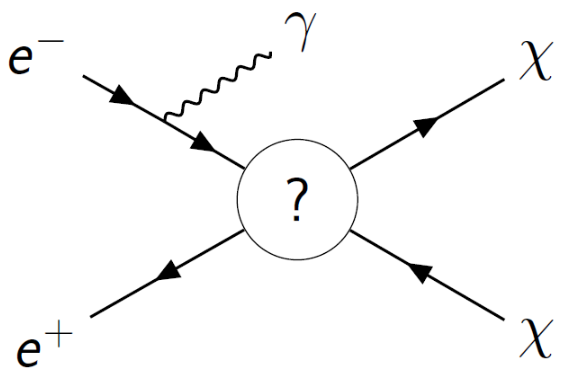
Only moderate increase in discovery reach for 1.5 TeV:

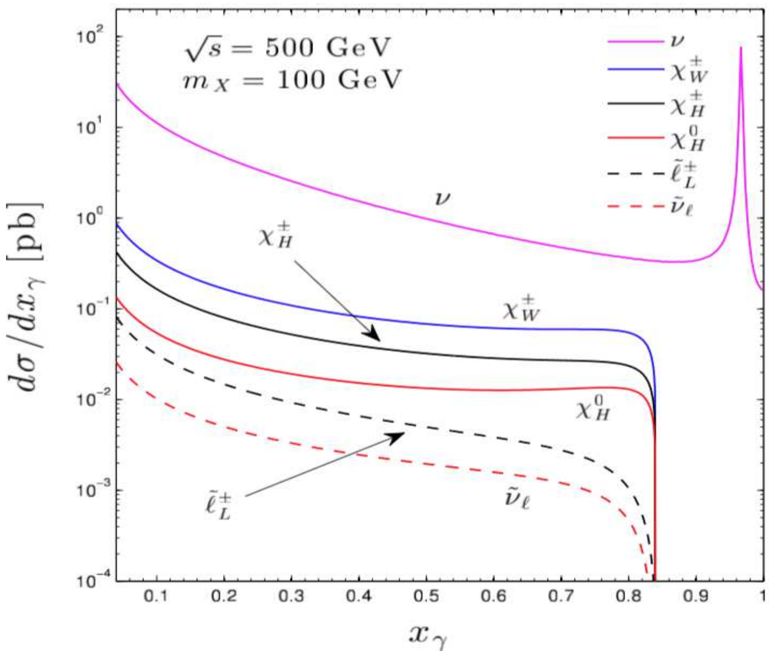
- neutral scalar production: $m_A + m_H < 450$ GeV (290 GeV @ 380 GeV)
- charged scalar production: $m_{H^\pm} < 500$ GeV (150 GeV @ 380 GeV)

might be worthwhile to invesitgate semi-leptonic signature for H+H- channel

Mono-photon signature

The mono-photon signature is considered to be the most general way to look for DM particle production in future e^+e^- colliders.





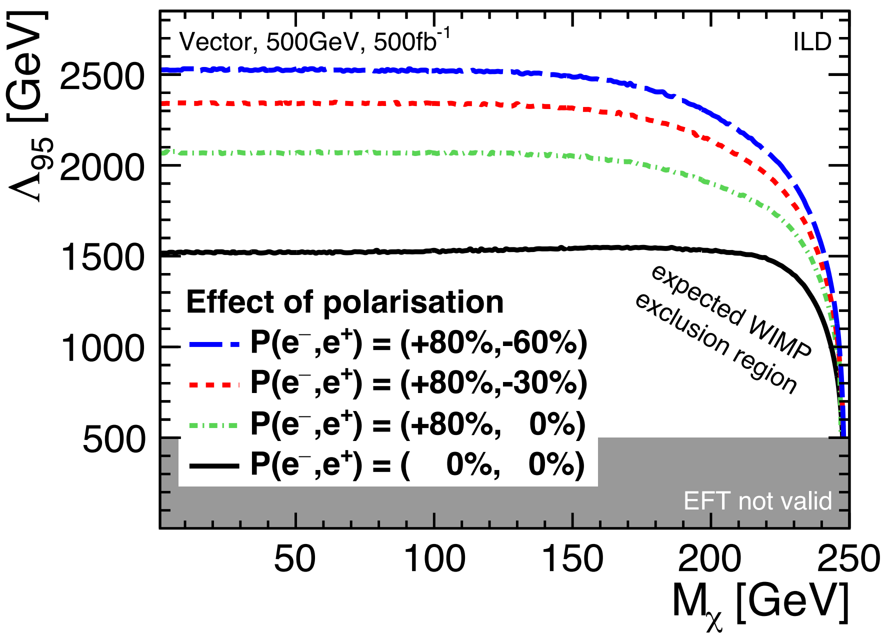
DM can be pair produced in the e^+e^- collisions via exchange of a new mediator particle, which couples to both electrons (SM) and DM states

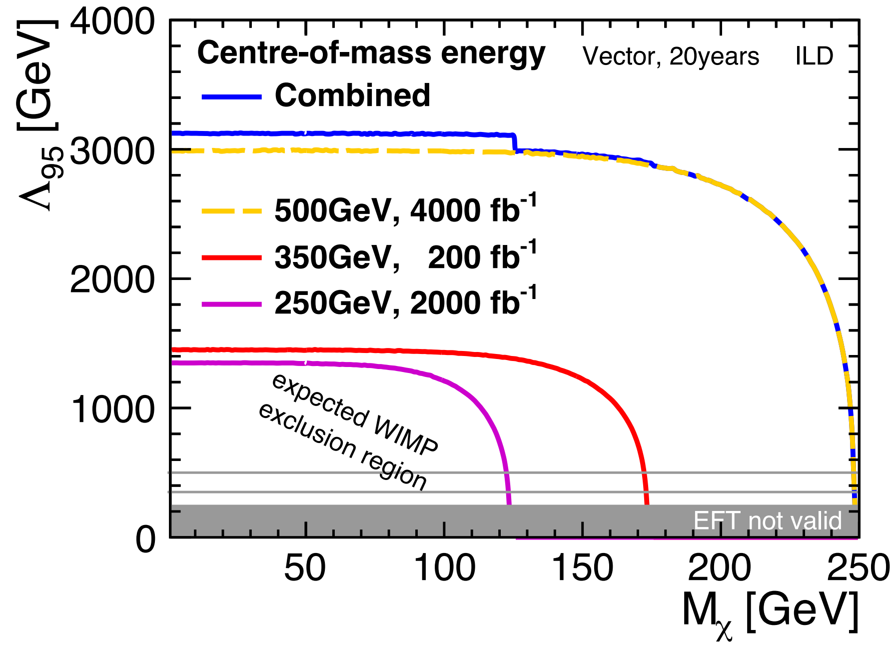
This process can be detected, if additional hard photon radiation from the initial state is observed in the detector...

Heavy mediator studies

Scenarios with heavy mediator and coupling values $\mathcal{O}(1)$ (EFT limit)

Different polarisation combinations help to reduce the systematics
$\Rightarrow$ significant improvement of mass scale limits





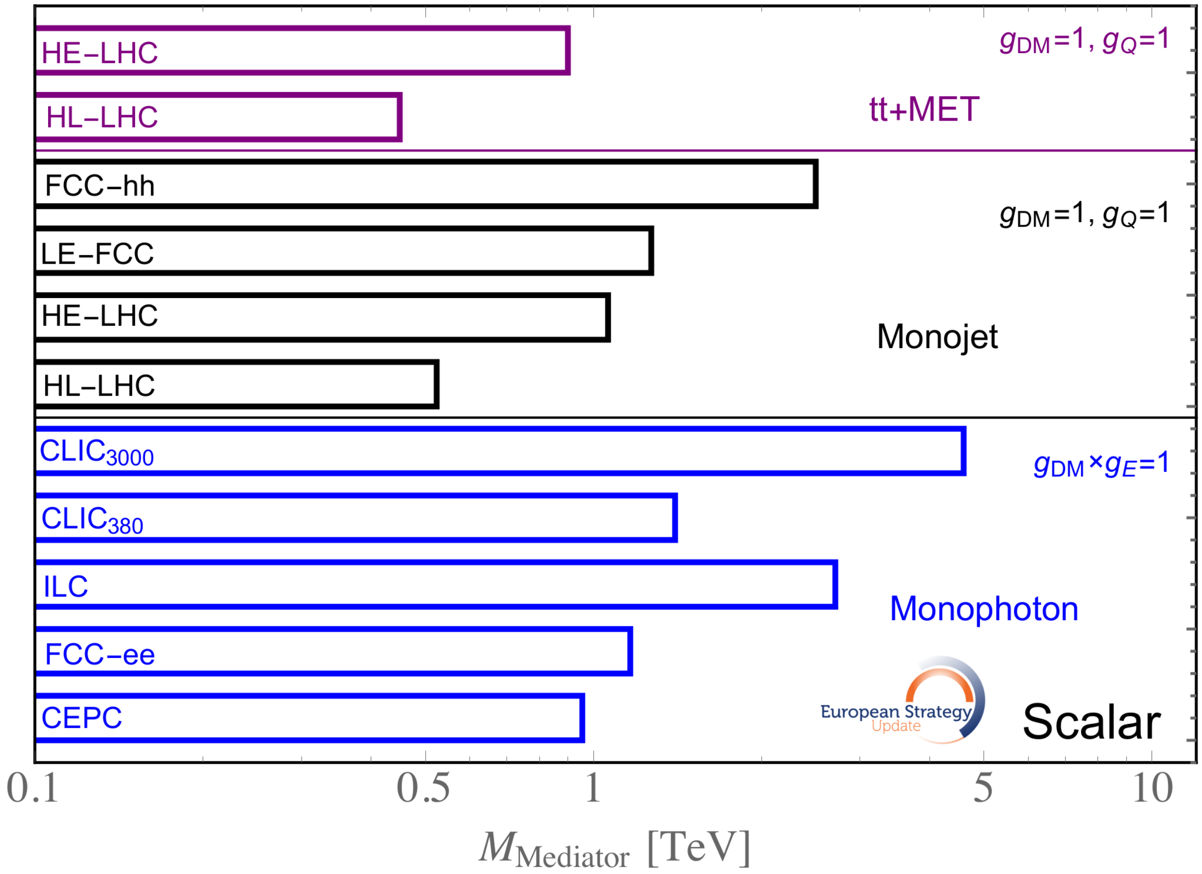
Sensitivity to the BSM mass scales up to $\Lambda \sim 3$ TeV

$$\Lambda^2 = \frac{M_Y^2}{|g_{eeY} g_{\chi\chi Y}|}$$

with full simulation: see arXiv:2001.03011

Heavy mediator studies

Comparison of extracted mediator mass limits



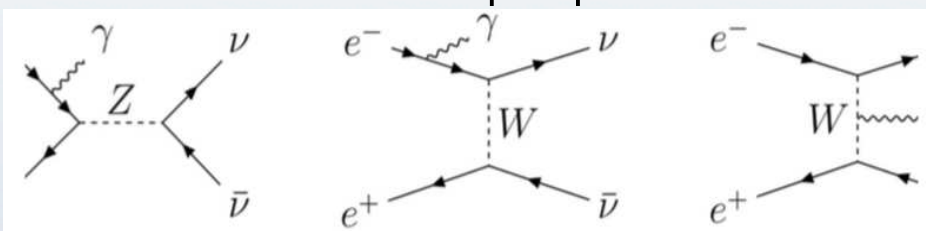
ILC mass reach comparable with that of FCC-hh !!!

Light mediator study

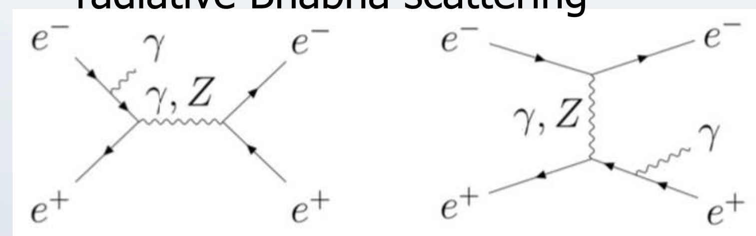
DM production via a light mediator exchange still not excluded
for scenarios with very small mediator couplings to SM, $\Gamma_{SM} << \Gamma_{tot}$

- Before assessing the discovery potential of the mono-photon processes the SM background must be carefully studied

radiative neutrino pair-production



radiative Bhabha scattering



- For simulation we used WHIZARD
  the WHIZARD ISR photons are not ordinary final state photons
  hard photons from the matrix element must be added
- Dedicated simulation procedure to merge soft ISR and hard photons and avoids double counting

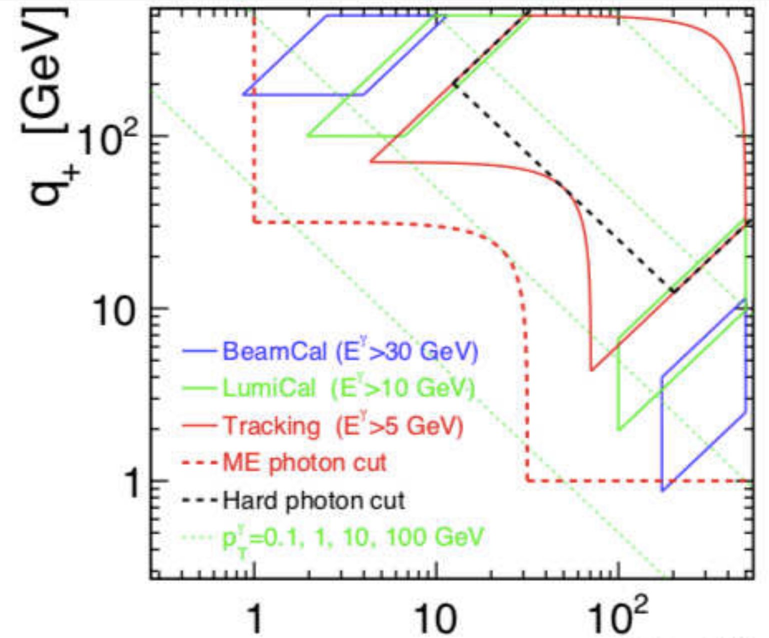
JK, W. Kotlarski, P. Sopicki, A.F. Zarnecki, Eur.Phys.J.C 80 (2020) 634

Merging ISR and ME photons

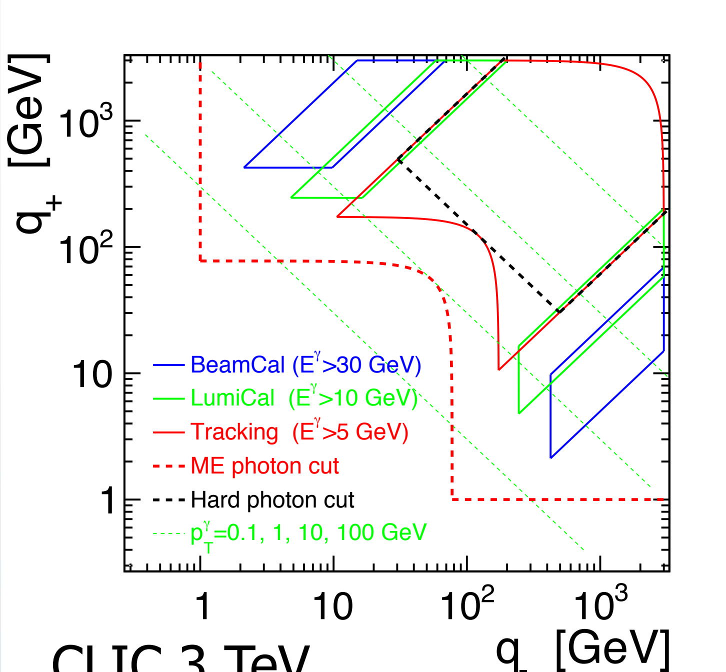
Define for each photon $q_- = \sqrt{4E_0E_\gamma}\ \sin\frac{\theta_\gamma}{2}, \quad q_+ = \sqrt{4E_0E_\gamma}\ \cos\frac{\theta_\gamma}{2}$

for events with only one photon these variables would correspond to virtualities of electron and/or positron after photon emission

detector coverage in $q_-,\ q_+$ plane



ILC 500 GeV



CLIC 3 TeV

$$E_{min} = 1\ \text{GeV}, \quad q_{min} = 1\ \text{GeV}$$

Light mediator study

Simplified model covering most popular scenarios of dark matter pair-production

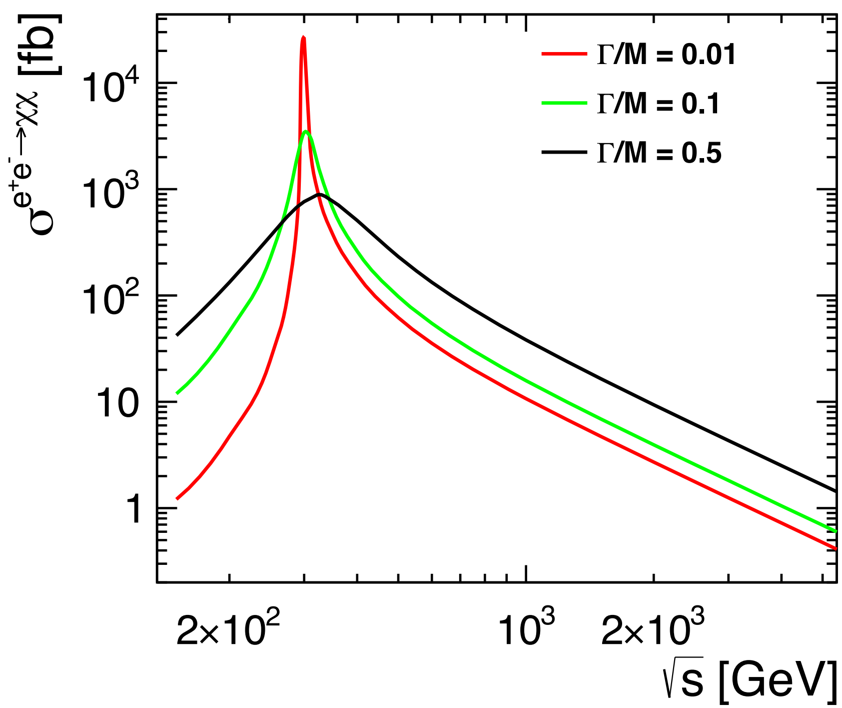
Possible mediators: Y

- scalar
- pseudo-scalar
- vector
- pseudo-vector
- V−A coupling
- V+A coupling

Possible DM candidates: χ

- real or complex scalar
- Majorana or Dirac fermion
- real vector

Cross section for $e^+e^- \to \chi\chi$ for $M_\chi = 50\ GeV$ and $M_Y = 300\ GeV$



model encoded to FeynRules and exported in UFO for Whizard simulations

JK, W. Kotlarski, K. Mekala, P. Sopicki, A.F. Zarnecki, Eur.Phys.J.C 81 (2021) 955

Light mediator study: setting limits

Experimental-like approach

Cross section for DM pair-production via mediator exchange depends on

- mediator mass, M_Y, and DM mass m_χ
- SM-mediator coupling value, g_{eeY} and coupling structure $\mathcal{O}_{eeY}$
- DM-mediator coupling value, $g_{\chi\chi Y}$ and coupling structure $\mathcal{O}_{\chi\chi Y}$

The cross section can also be expressed in terms of the widths

$$\sigma(e^+e^- \to Y \to \chi\chi) = \frac{12\pi}{M_Y^2} \frac{s\,\Gamma_{ee}\,\Gamma_{\chi\chi}}{(s - M_Y^2)^2 + M_Y^2\Gamma_Y^2}$$

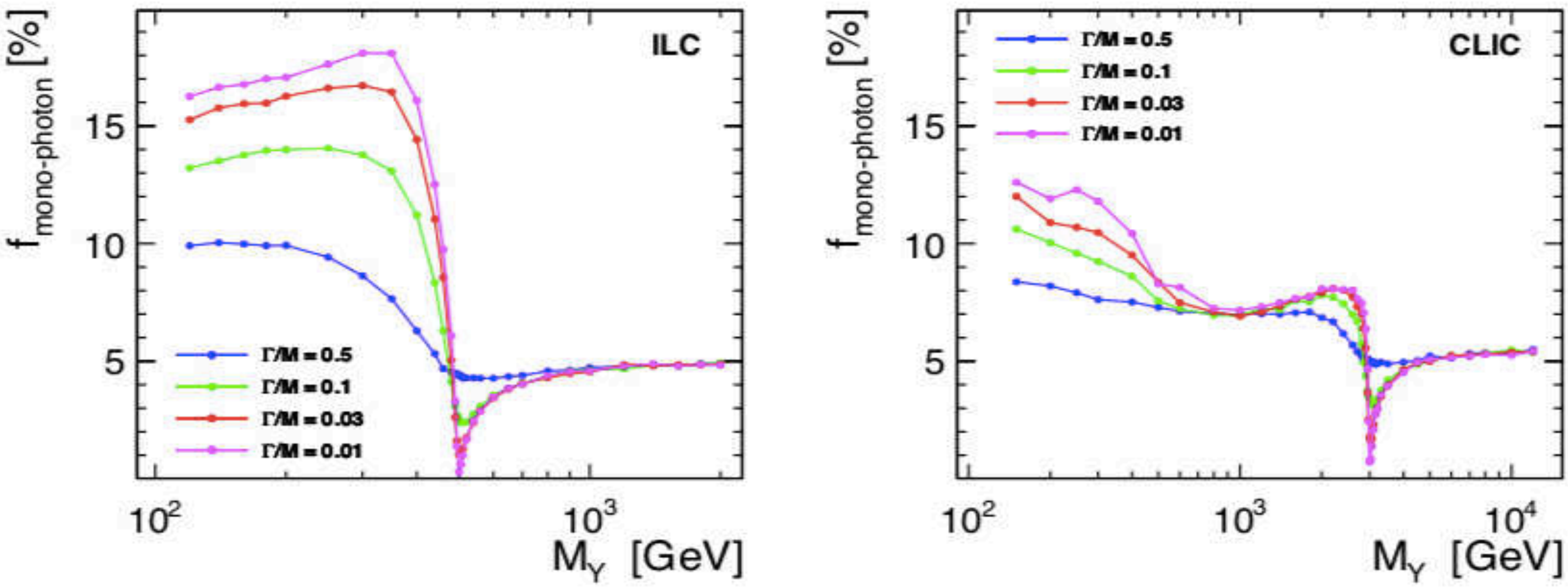
In the limit $\Gamma_{ee} \ll \Gamma_{\chi\chi} \approx \Gamma_Y$ the cross section depends only on M_Y, Γ_Y, g_{eeY} and $\mathcal{O}_{eeY}$ (dependence on m_χ, $g_{\chi\chi Y}$ and $\mathcal{O}_{\chi\chi Y}$ "absorbed" in Γ_Y)

$\Rightarrow$ study limits on the DM pair-production cross section (or g_{eeY}) as a function of the mediator mass and width (for given $\mathcal{O}_{eeY}$)

Simulating mono-photon events

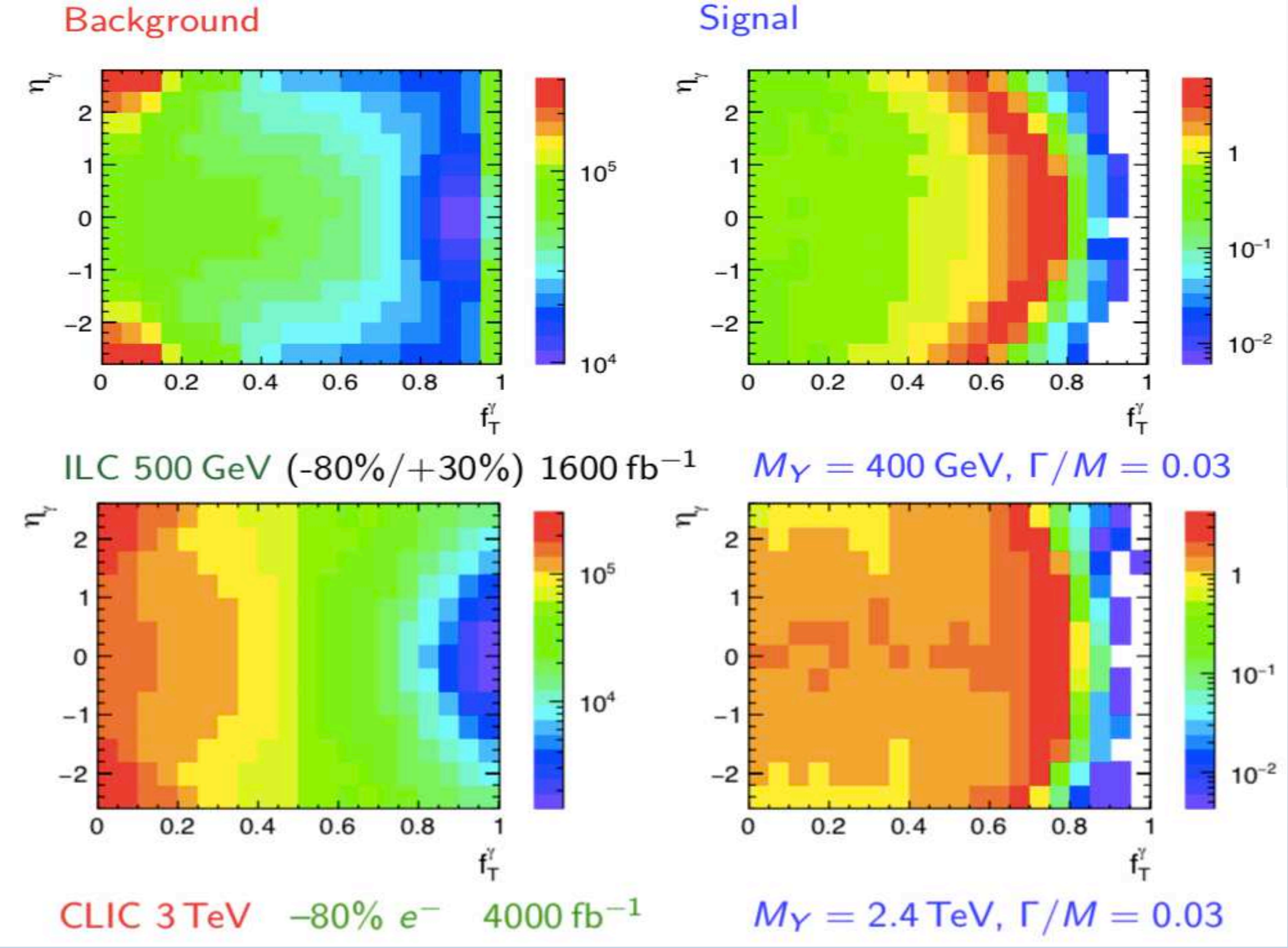
Detectable hard photon emitted only in a fraction of signal events

$$\sigma\left(e^+e^- \to \chi\,\chi\,\gamma_{tag}\right) = f_{\text{mono-photon}} \cdot \sigma\left(e^+e^- \to \chi\,\chi\,(\gamma)\right)$$



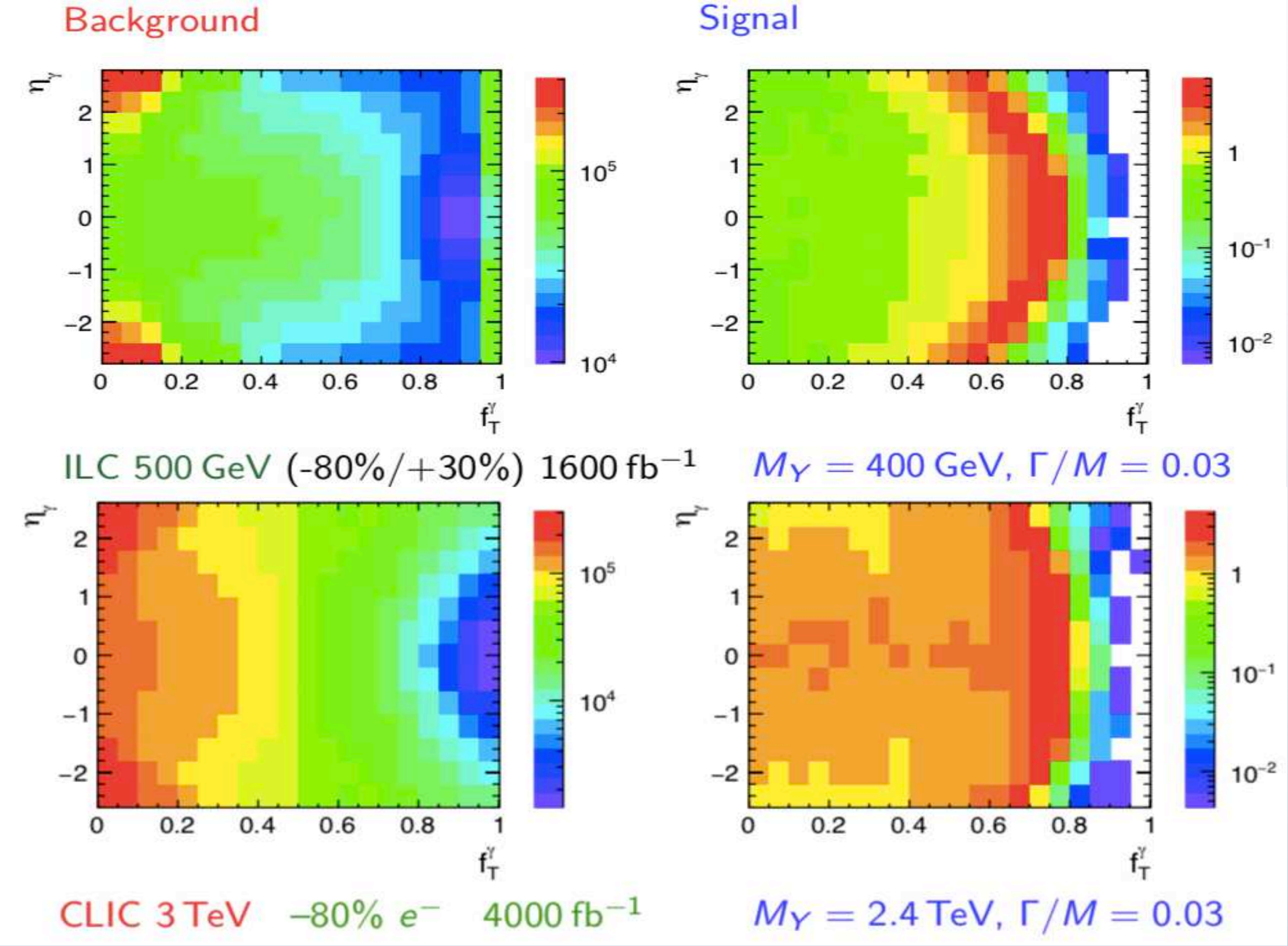
efficiency: for light mediators ~ 10-15%
for heavy ones only ~ 5% events can be tagged

Simulating mono-photon events



$$f_T^\gamma = \frac{\log\left(\frac{p_T^\gamma}{p_T^{min}}\right)}{\log\left(\frac{p_T^{max}}{p_T^{min}}\right)}$$

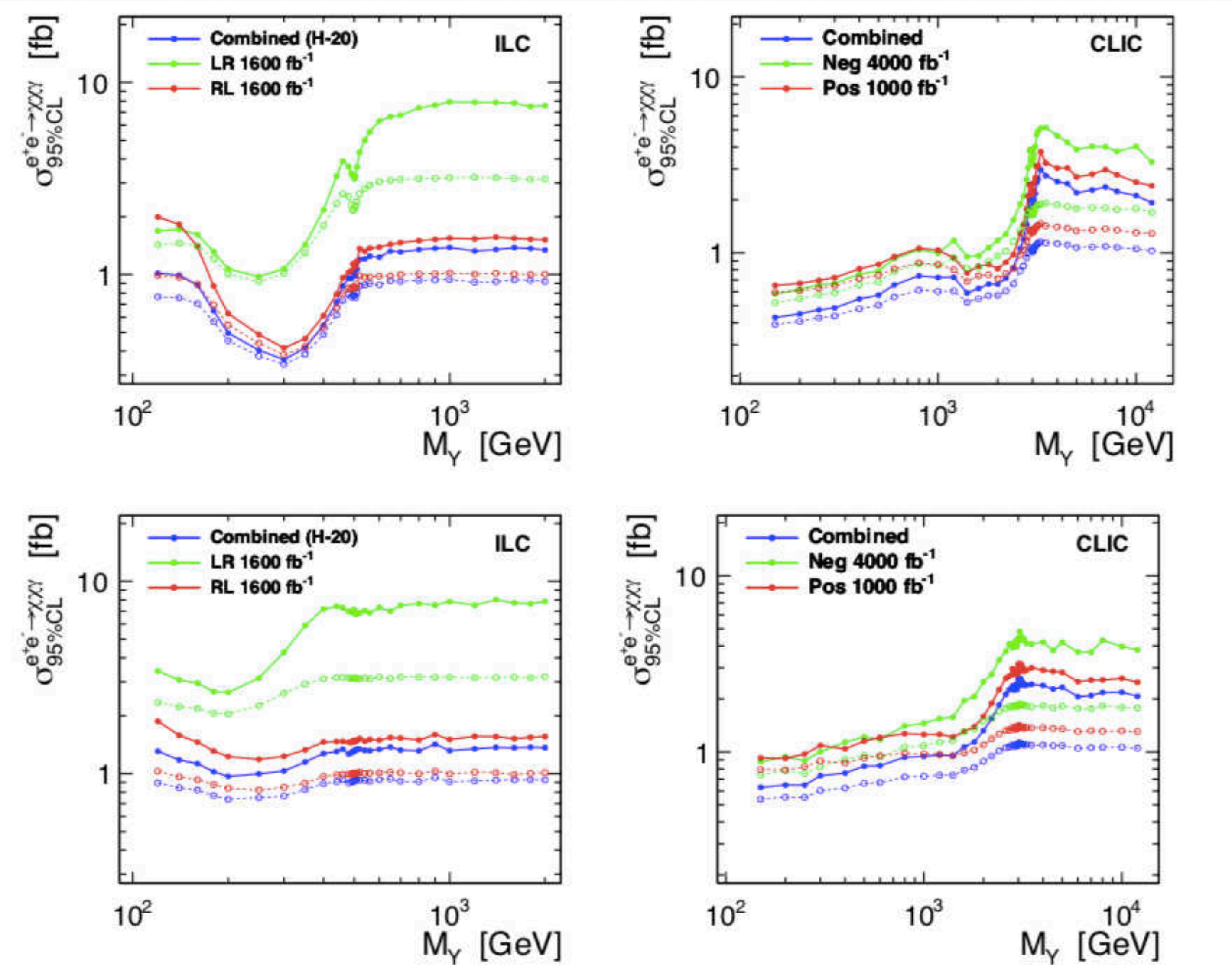
Simulating mono-photon events



$$f_T^\gamma = \frac{\log\left(\frac{p_T^\gamma}{p_T^{min}}\right)}{\log\left(\frac{p_T^{max}}{p_T^{min}}\right)}$$

use 2-D distributions as input to RooFit and calculate 95% C.L. for cross section limits using CL_s

Simulating mono-photon events



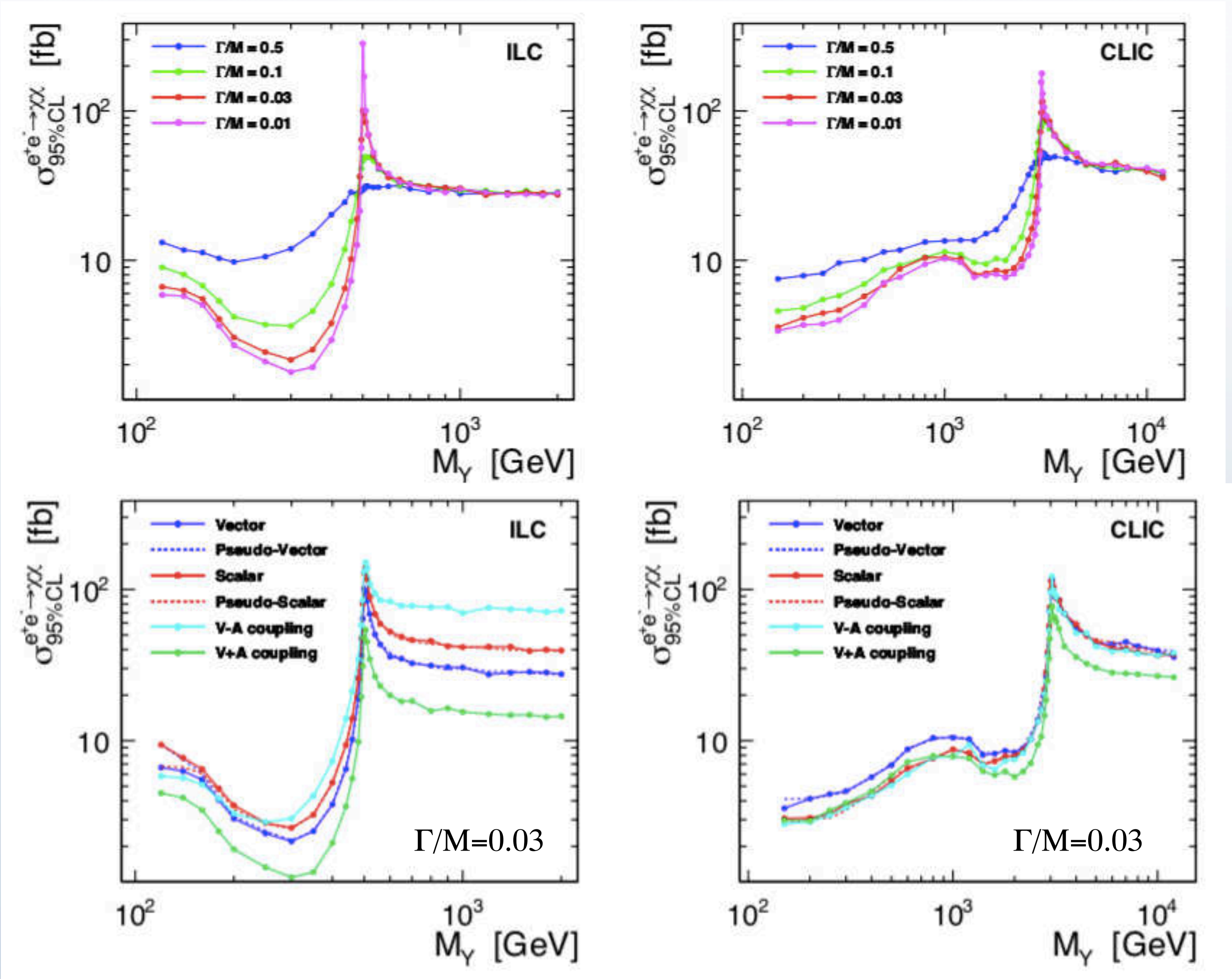
Cross section limits on radiative light DM pair-production with vector mediator

solid lines – with systematic uncert.
dashes - without

systematic effects reduced for on-shell mediator production

top row $\Gamma/M=0.03$
bottom row $\Gamma/M=0.5$

Simulating mono-photon events

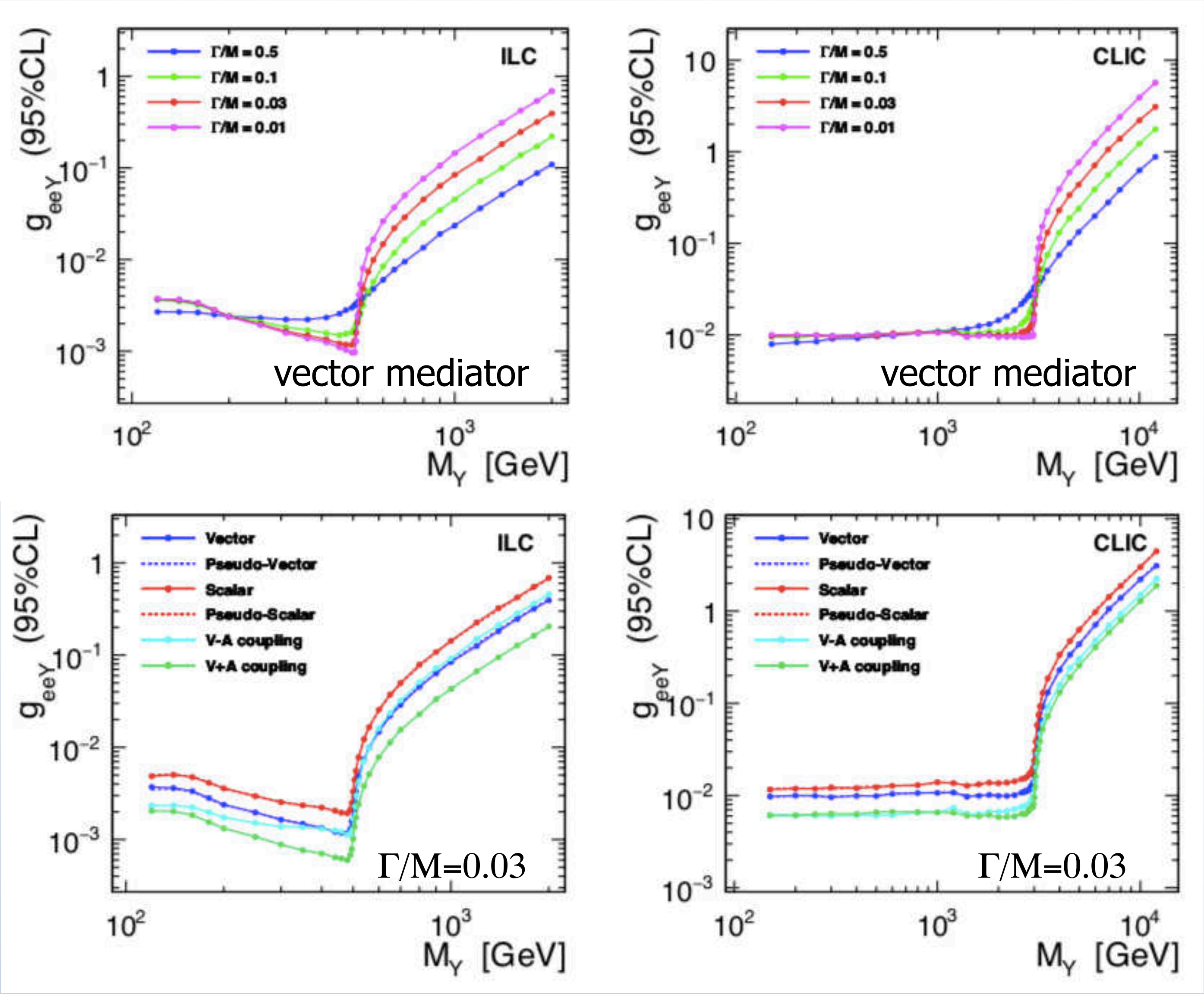


limits on cross sections including photon tagging efficiency

for light Y the difference between ILC and CLIC due wider CLIC luminosity spectra

for heavy Y limits hardly depend on its mass but more sensitive to its nature

Simulating mono-photon events

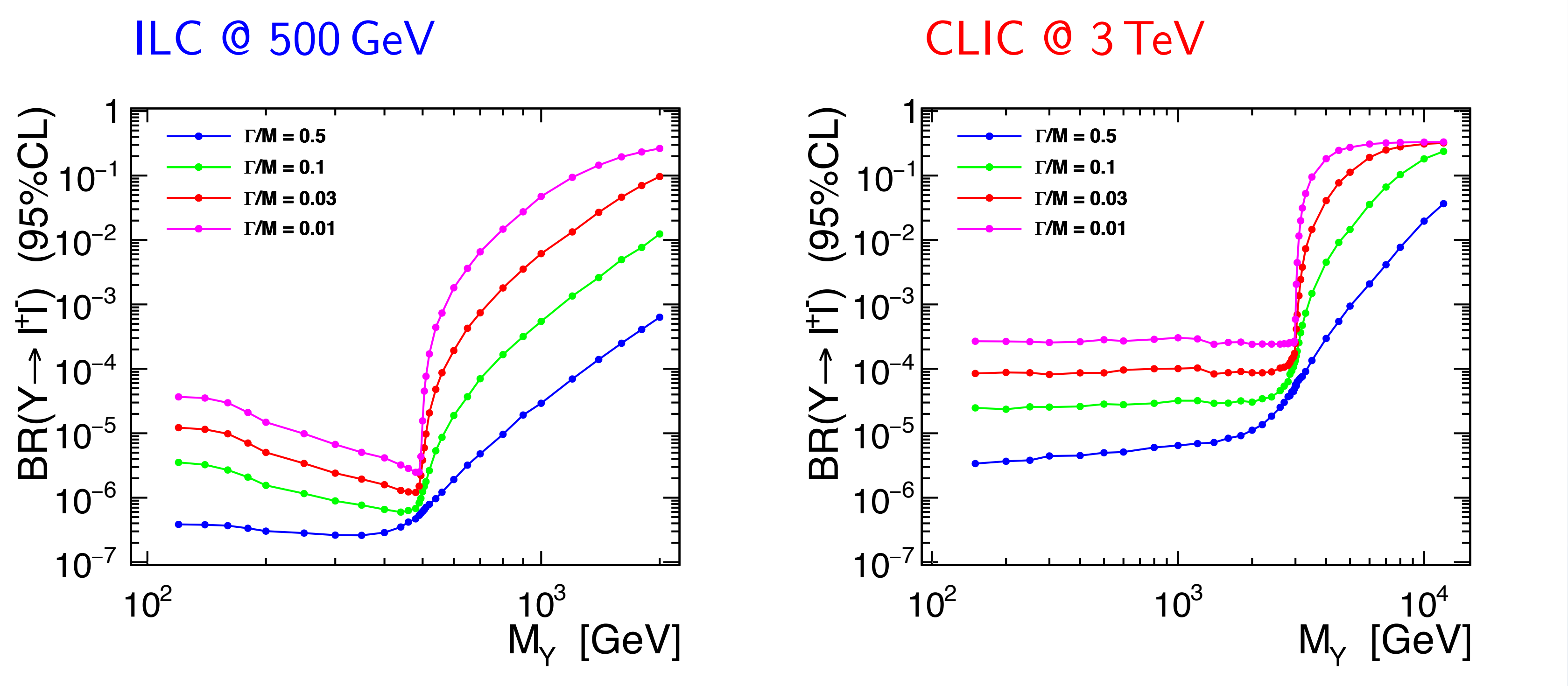


limits on electron-mediator couplings

best limits for V+A scenario

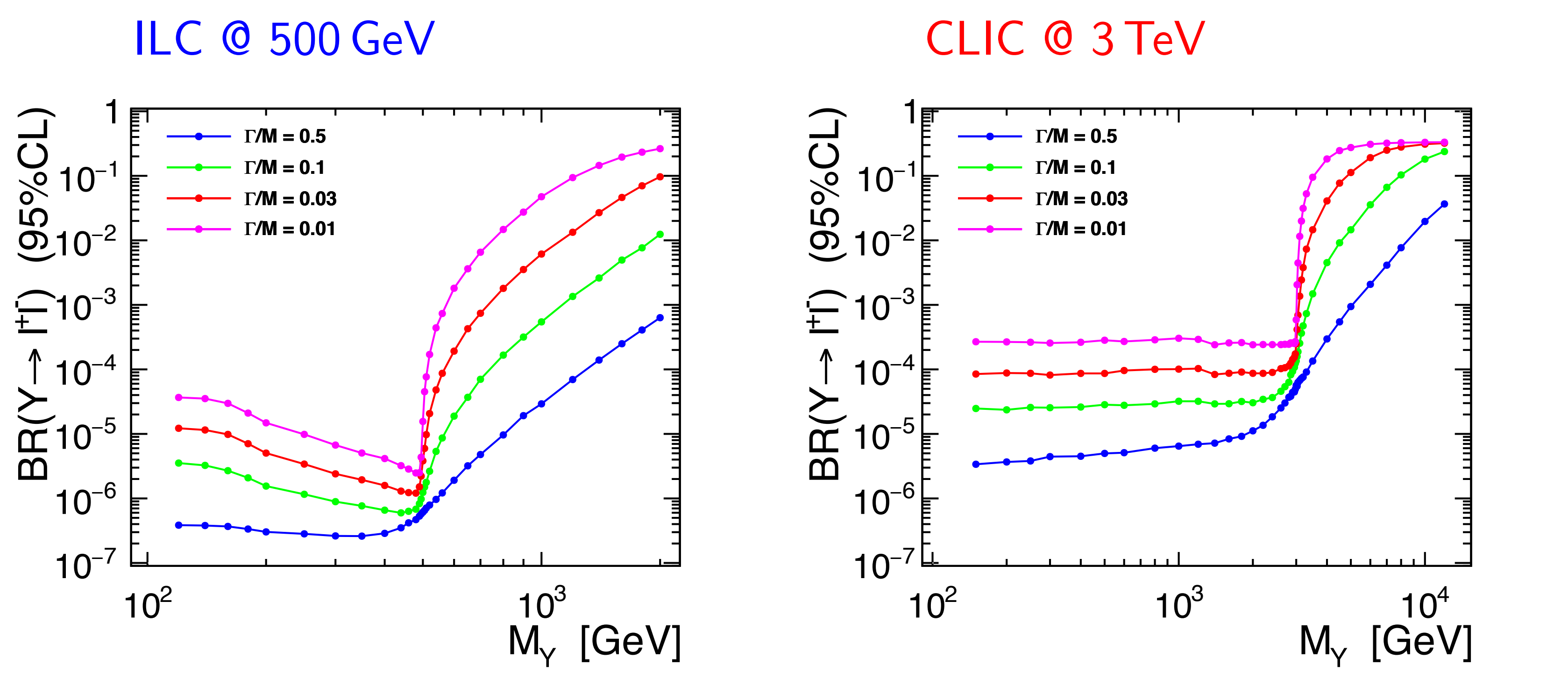
Simulating mono-photon events

Limits on electron-mediator couplings can be translated into limits on the mediator branching ratio to charged leptons



Simulating mono-photon events

Limits on electron-mediator couplings can be translated into limits on the mediator branching ratio to charged leptons



$\mathcal{O}(1)\ e^+e^- \to Y \to e^+e^-$ events expected at ILC or CLIC

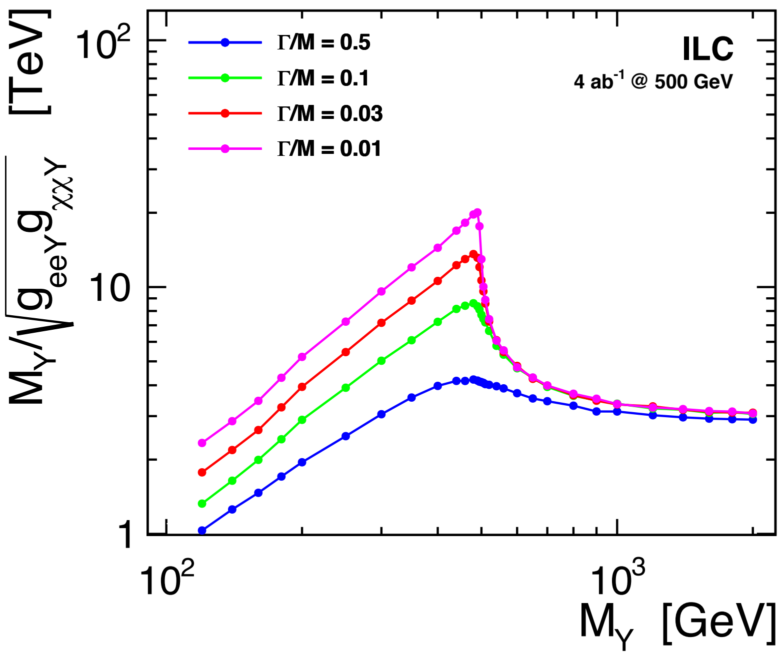
⇒ for light mediators the limits from mono-photon search are more stringent than from the direct resonance search

Simulating mono-photon events

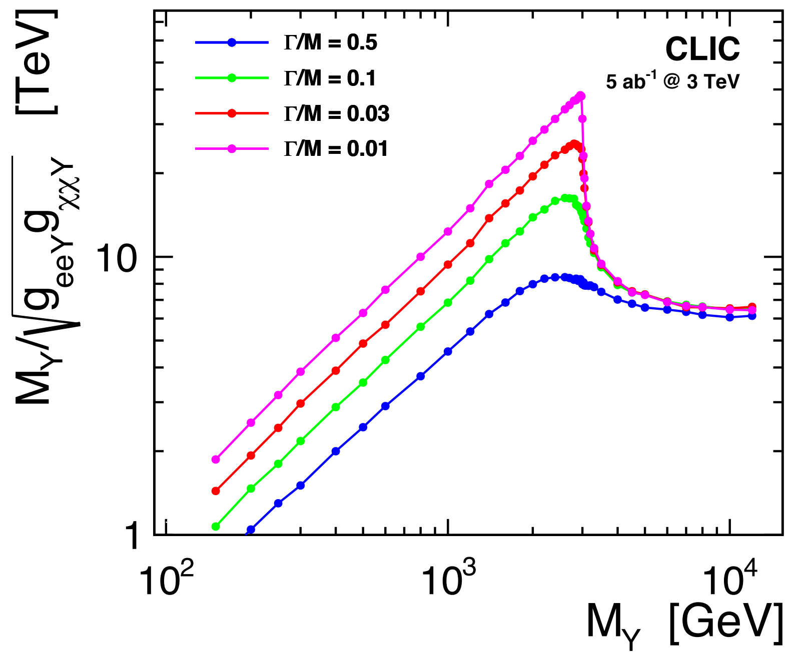
Effective mass scale limits $\Lambda^2 = \frac{M_Y^2}{|g_{eeY} g_{\chi\chi Y}|}$

Combined limits for Vector mediator

ILC @ 500 GeV



CLIC @ 3 TeV



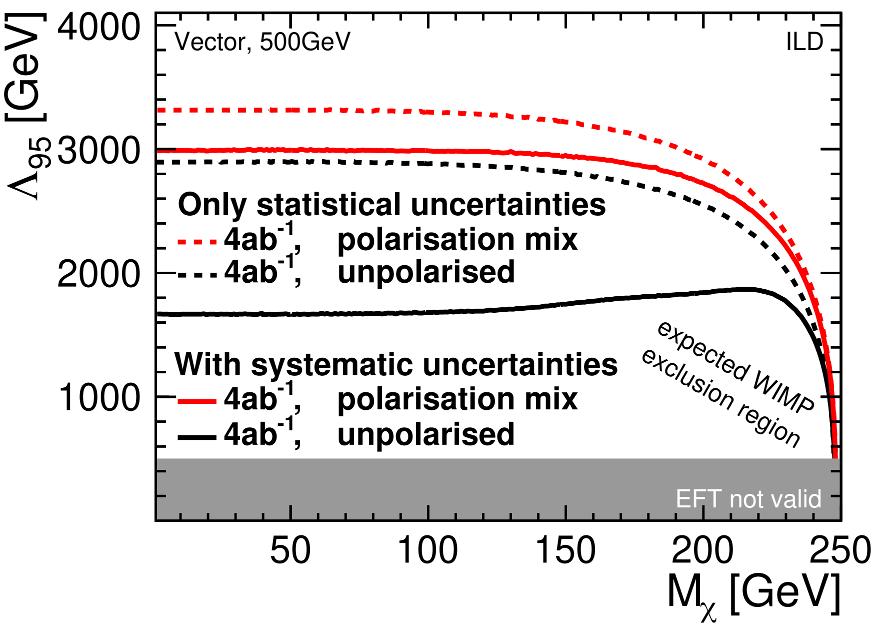
EFT approach valid only for $M_Y \gtrsim 3\sqrt{s}$!...

Simulating mono-photon events

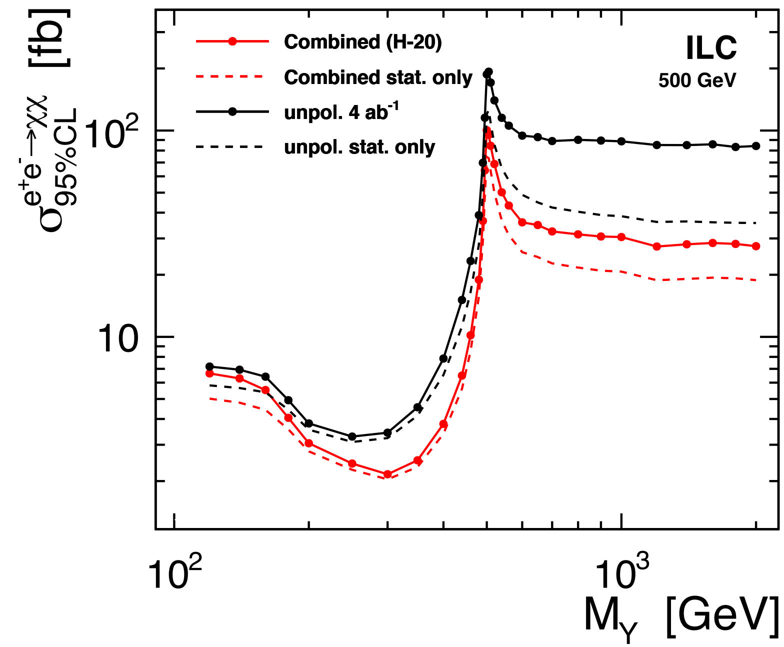
Impact of beam polarisation

Combination results in best sensitivity to all scenarios
but also significantly reduces the impact of systematic uncertainties

Heavy mediator exchange



Light mediator exchange



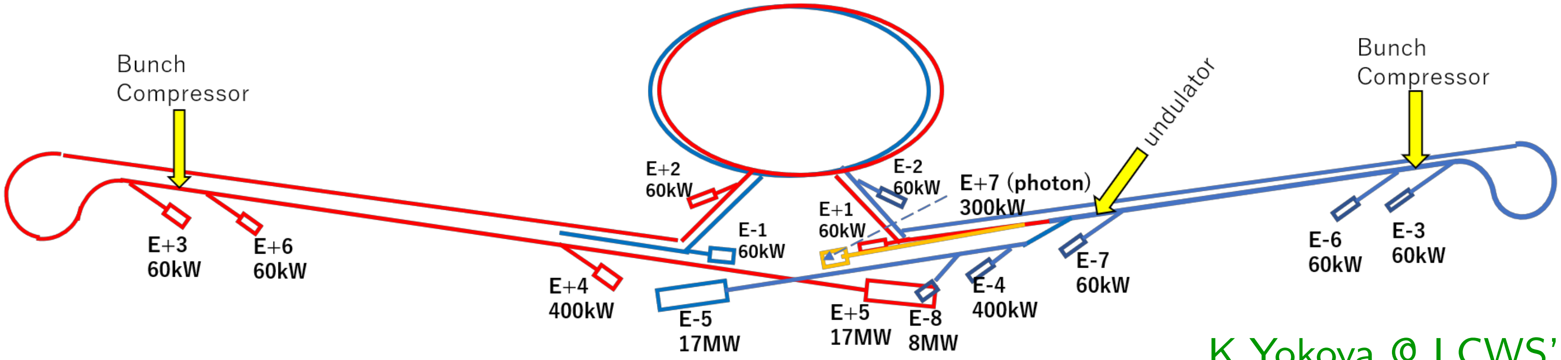
Non-collider experiments

- beam-dump experiments
- experiments with extracted beams

ILC beam-dump experiments

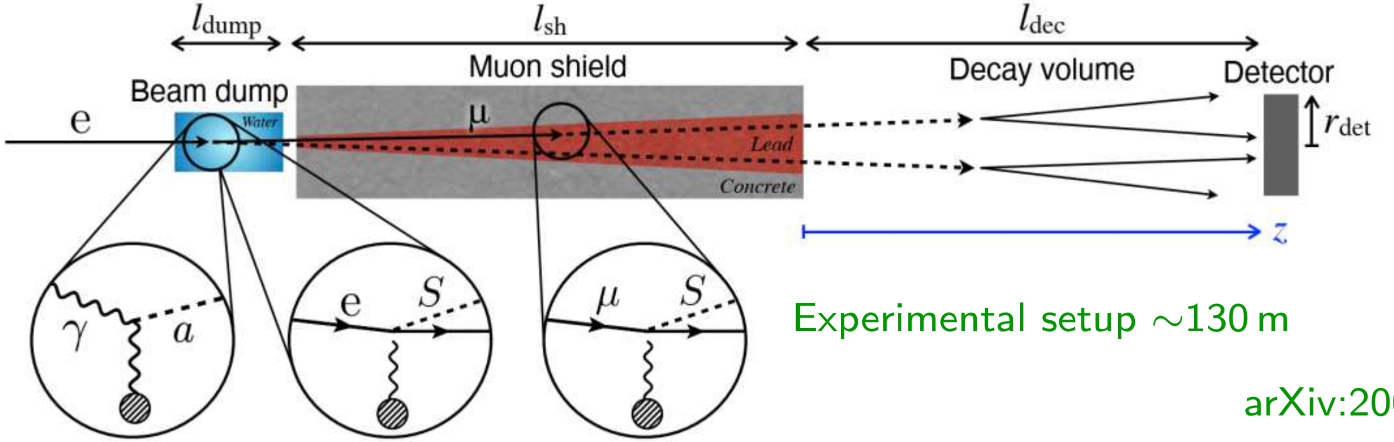
Electron and positron beams, with extreme intensities ($\sim 10^{22} e^{\pm}/y$)

Many beam dump points planned around the ILC facility



K.Yokoya @ LCWS'2021

Concept of main beam dump experiments searching for axion-like particles or new scalars:



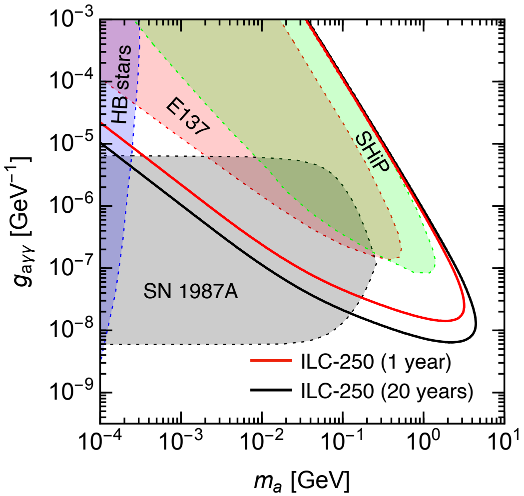
Experimental setup $\sim$130 m

arXiv:2009.13790

ILC beam-dump experiments

Looking for SM decays of new exotic particles produced in the beam dump

arXiv:2009.13790



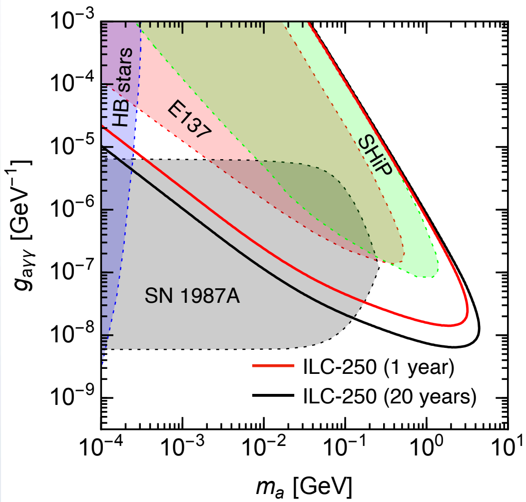
Axion-like particle model   looking for $a \to \gamma\gamma$

$$\mathcal{L} \ni -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2$$

An order of magnitude better sensitivity than other experiments

ILC beam-dump experiments

Looking for SM decays of new exotic particles produced in the beam dump
arXiv:2009.13790



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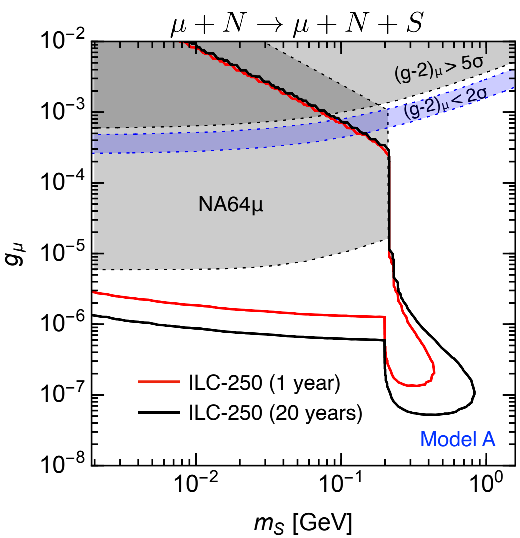


Light scalar coupled to charged leptons

$$\mathcal{L} \ni \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - \sum_{l=e,\mu,\tau} g_l S \bar{l} l$$

Model A: $g_l \propto m_l$

Sensitivity down to very small couplings

ILC beam-dump experiments

Significant interest in searches for sub-GeV DM with feeble couplings to SM

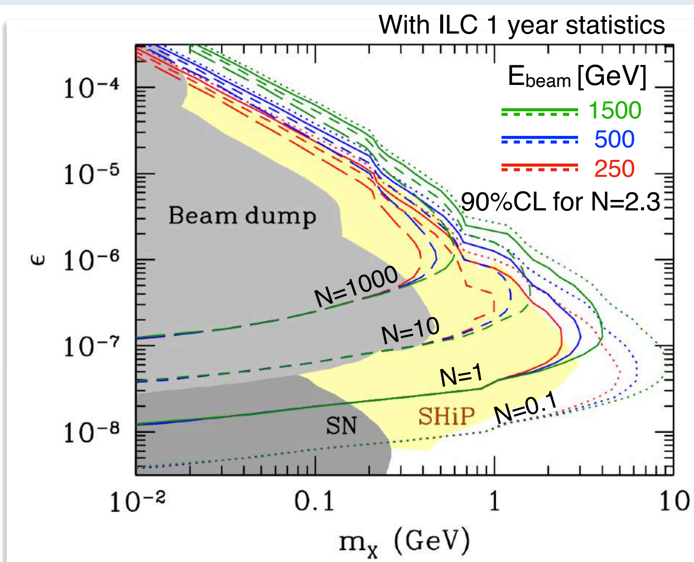
Benchmark model: dark photon mediating interactions of SM and DM

$$\mathcal{L}_{eff} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \overline{\chi}\left(i\not{D} - m_\chi\right)\chi$$

a) $m_{A'} < 2m_\chi$ dark photon decays visibly

- ✓ Main beam dump experiments can search on the large unexplored region.
- ✓ If SHiP will not be realized due to high-cost issues, ILC will be the only experiment that can access the small-coupling and high-mass region.

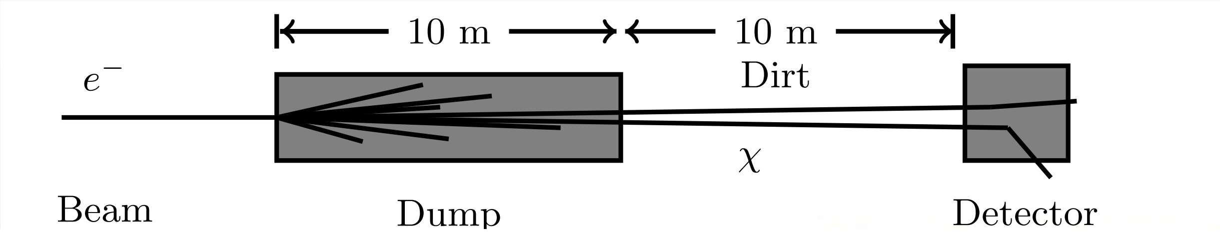
Sakaki@LCWS2021



ILC beam-dump experiments

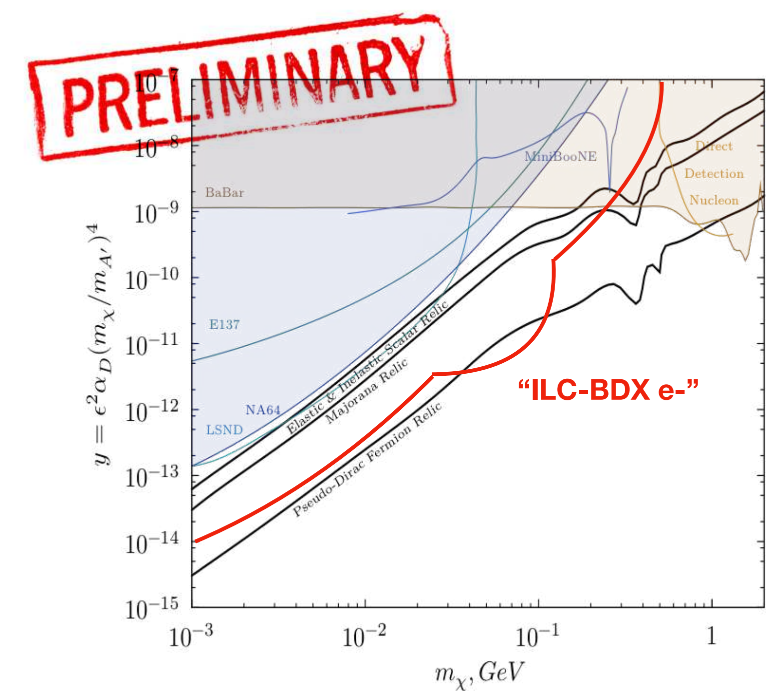
b) $m_{A'} > 2m_\chi$ dark photon decays invisibly

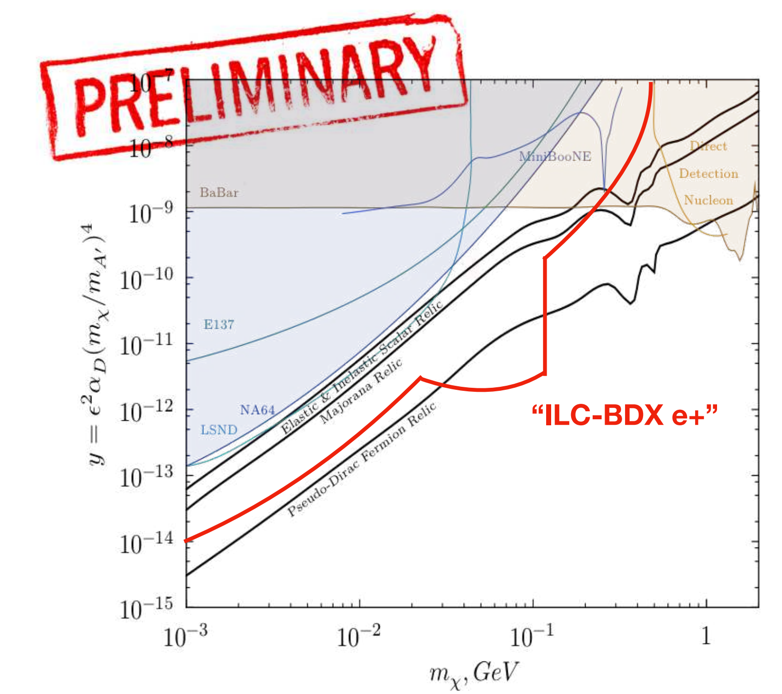
scenario compatible with DM thermal origin



$$e^- + \chi \to e^- + \chi$$

M. Perelstein @ LCWS2021





Experiment with extracted e+ beam

- Missing Mass technique: positron beam on thin target, $e^+e^- \to A' + \gamma$
- Detect photons ~10 m downstream at 0.5-2 deg. angle
- Reconstruct MM: $m^2_{\rm miss} = (p_{e^+} + p_{e^-} - p_\gamma)^2$
- Bump-hunt over SM bg: $2\gamma, 3\gamma, \;\text{brem}, \ldots$
- Setup similar to PADME experiment running at Frascati, with ~500 x beam energy and large increase in statistics

M. Perelstein @ LCWS2021

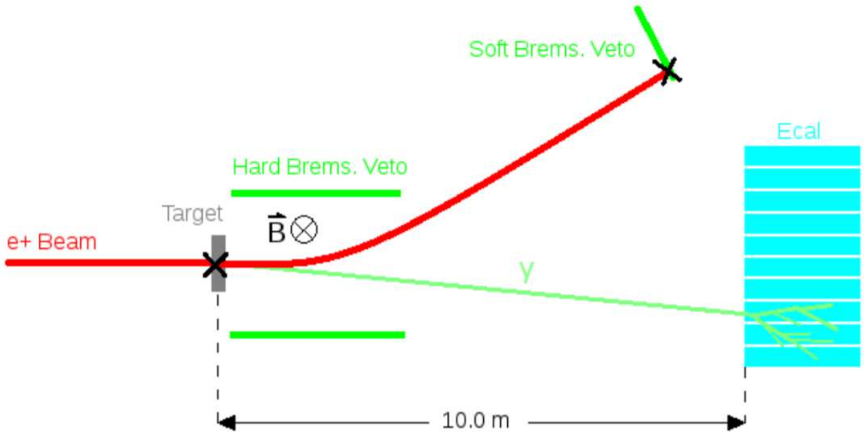


Figure: Marsicano et al, 2007.15081

Experiment with extracted e+ beams

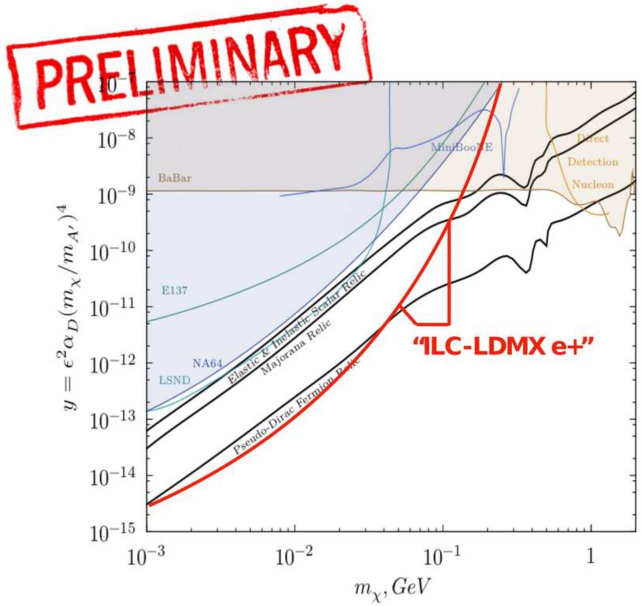
Searching for Dark Photons with extracted positron beams

$$e^+e^- \to A'\gamma$$

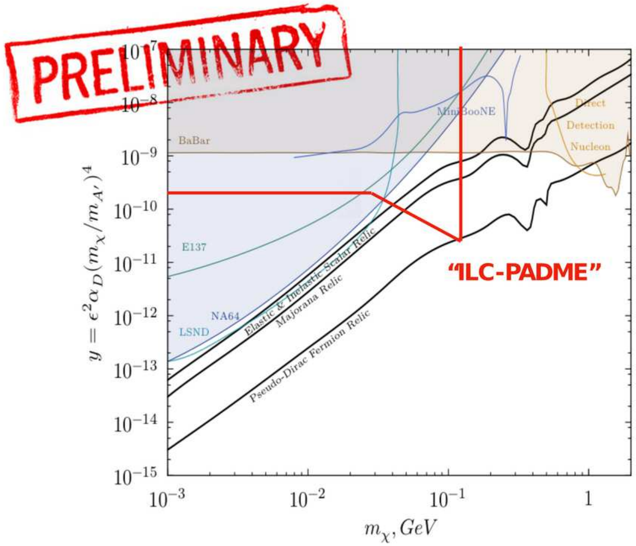
M. Perelstein @ LCWS2021

Missing energy reconstruction in thick active target

Thin target, missing mass reconstruction in dedicated detector



LDMX for SLAC: arXiv:1807.05884



PADME @ Frascati: arXiv:1910.00764

Sensitivity extending down to the minimum couplings allowed by relic density bounds

Conclusions

Conclusions

Linear e+e- colliders will offer many complementary options for DM searches

- Different scenarios can be constrained via precision Higgs studies
- Clean environment, kinematic constraints and polarised beams in e+e- collisions result in high sensitivity to different DM production scenarios
- Sensitivity extends to the TeV mass scales, order of magnitude higher than the collision energy
- Unprecedented intensities of high energy electron and positron beams for beam-dump and extracted-beam experiments enhance the value of linear colliders

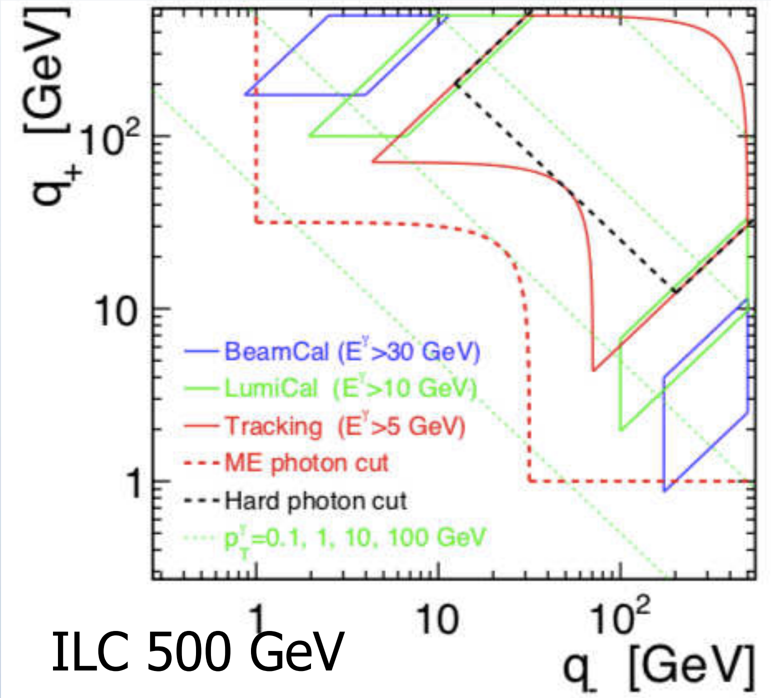
Additional slides

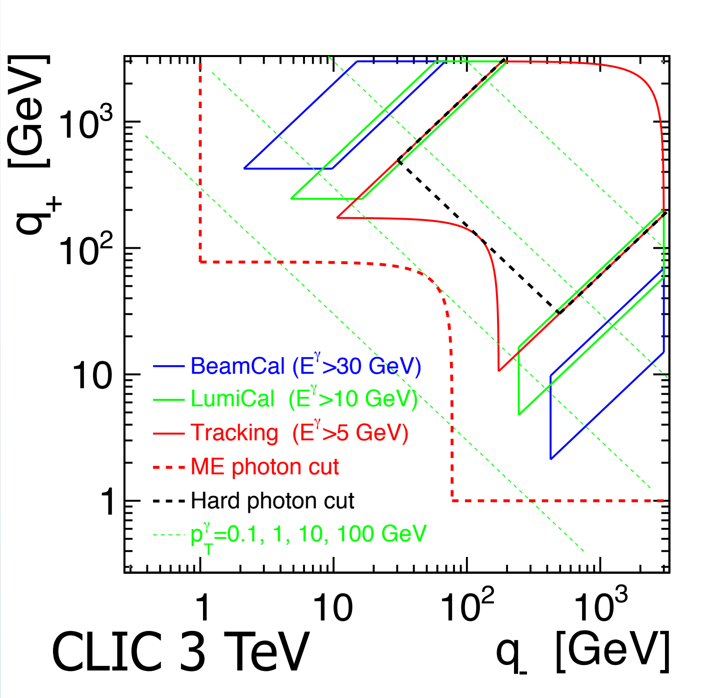
Merging ISR and ME photons

Define for each photon $$q_- = \sqrt{4E_0E_\gamma}\,\sin\frac{\theta_\gamma}{2}, \quad q_+ = \sqrt{4E_0E_\gamma}\,\cos\frac{\theta_\gamma}{2}$$

for events with only one photon these variables would correspond to virtualities of electron and/or positron after photon emission

detector coverage in $q_-,\ q_+$ plane

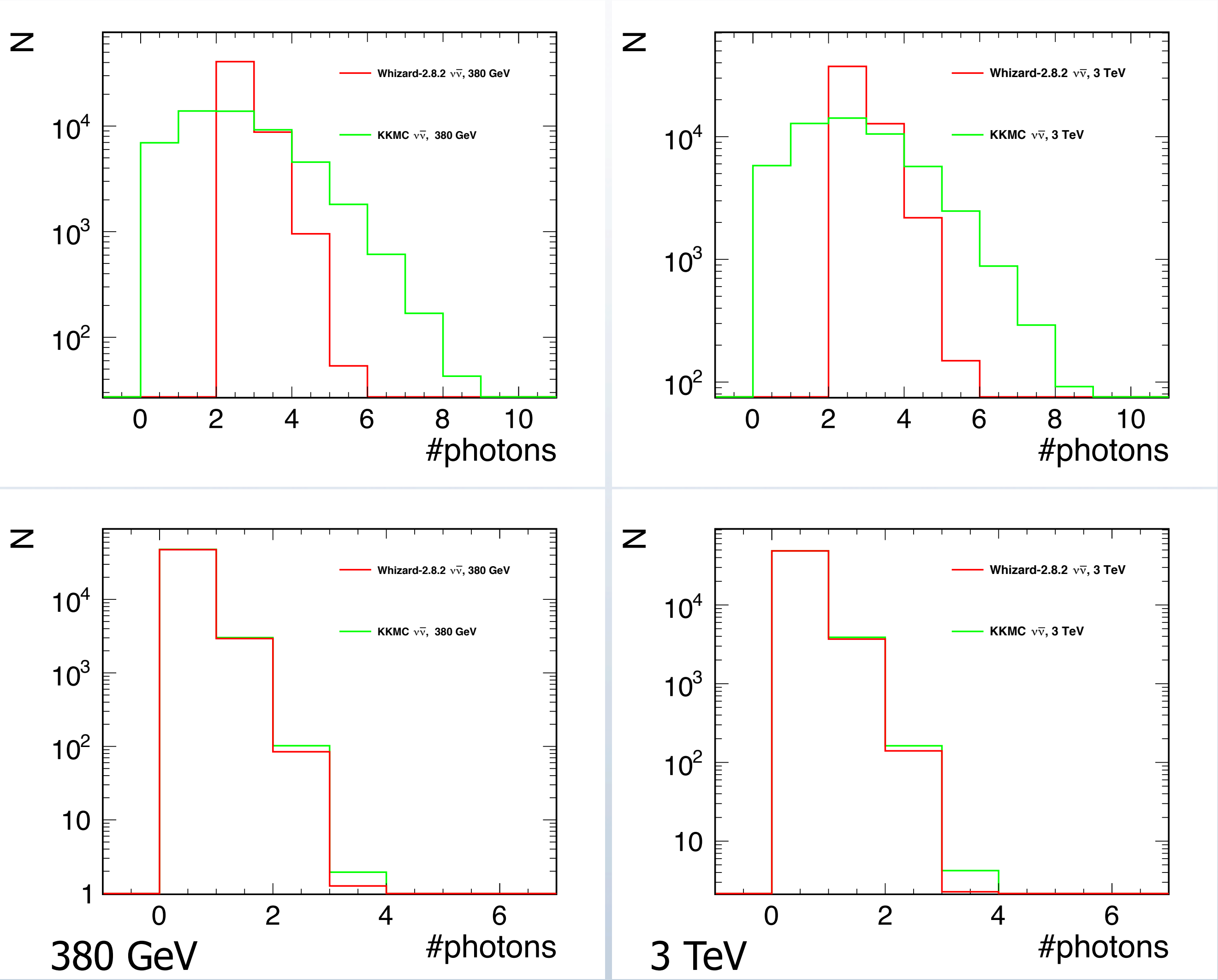




$$E_{min} = 1\ \mathrm{GeV}, \quad q_{min} = 1\ \mathrm{GeV}$$

Comparison with *KK* MC: photon multiplicity

*KK*MC: soft photon resummation in CEEX + exact O(Born + $\alpha^{3/2}$)

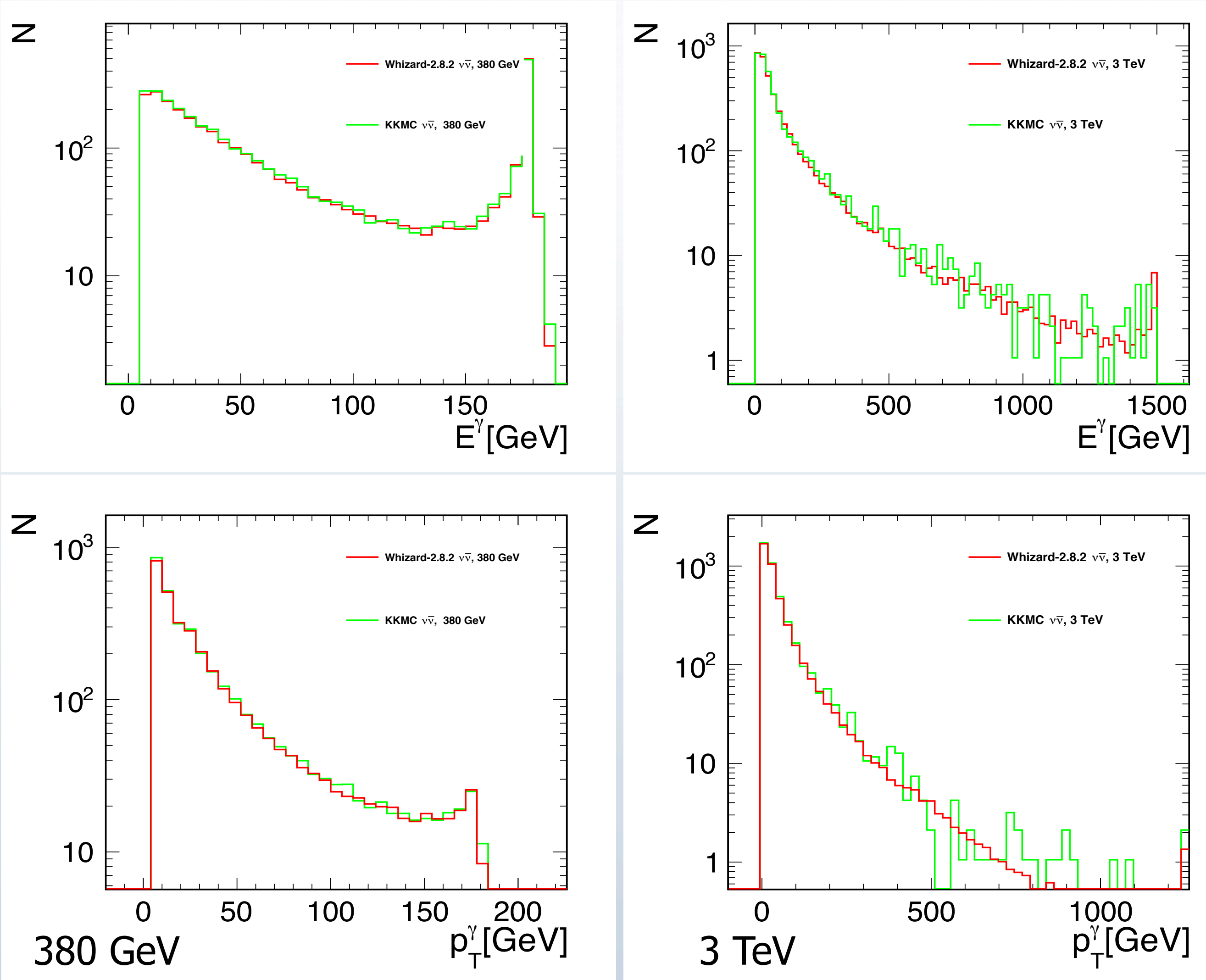


all photons

after hard photon selection

distributions normalised to # events expected for 1/fb

Comparison with *KK* MC: photon p_T



after hard photon selection

Simplified DM model

Dark matter particles, X_i, couple to the SM particles via an mediator, Y_j.

Each simplified scenario is characterized by one dark matter candidate and one mediator from the set listed below:

	particle	mass	spin	charge	self-conjugate	type
DM	X_R	m_{X_R}	0	0	yes	real scalar
	X_C	m_{X_C}	0	0	no	complex scalar
	X_M	m_{X_M}	$\frac{1}{2}$	0	yes	Majorana fermion
	X_D	m_{X_D}	$\frac{1}{2}$	0	no	Dirac fermion
	X_V	m_{X_V}	1	0	yes	real vector
mediator	Y_R	m_{Y_R}	0	0	yes	real scalar
	Y_V	m_{Y_C}	1	0	yes	real vector
	T_C	m_{T_C}	0	1	no	charged scalar

mono-photons: systematic uncertainty

systematic uncertainties: following ILD study arXiv:2001.03011
CLIC mono-photon study arXiv:2103.06006

- integrated luminosity uncertainty 0.26% (ILD), 0.2% (CLIC)
- neutrino background normalisation 0.2% (th+exp)
- Bhabha background normailsation 1% (th+exp)
- uncertainty on beam polarisation 0.02-0.08% (ILD), 0.2% (CLIC)
- luminosity spectra shape uncertainty

nuisance parameters in the model fit: 11 (ILD H-20 secnario), 7 (CLIC)

Limits on production cross sections calculated with CL_s using RooFit v3.60

mono-photons: analysis framework

JK, W. Kotlarski, K. Mękała, P. Sopicki, A.F. Żarnecki, arXiv:2107.11194

Event selection

On generator level:

- 1, 2 or 3 ME photons

  nonradiative events for signal only (for normalisation)

- all ME photons with

  $q_{\pm} > 1\,GeV \quad \& \quad E^{\gamma} > 1\,GeV$

  rejected are events with

  $q_{\pm} > 1\,GeV \quad \& \quad E^{\gamma} > 1\,GeV$

  for any of the ISR photons

- at least one ME photon with

  $p_T^{\gamma} > 2\,GeV \;\; \& \;\; 5^{\circ} < \theta^{\gamma} < 175^{\circ}$ (ILC 500 GeV)

  $p_T^{\gamma} > 5\,GeV \;\; \& \;\; 7^{\circ} < \theta^{\gamma} < 173^{\circ}$ (CLIC 3 TeV)

Delphes framework used for detector simulation and event reconstruction.

Require:

- single photon with

  $p_T^{\gamma} > 3\,GeV \;\; \& \;\; |\eta^{\gamma}| < 2.8$ (ILC)

  $p_T^{\gamma} > 10\,GeV \;\; \& \;\; |\eta^{\gamma}| < 2.6$ (CLIC)

- no other activity in the detector

  other reconstructed objects

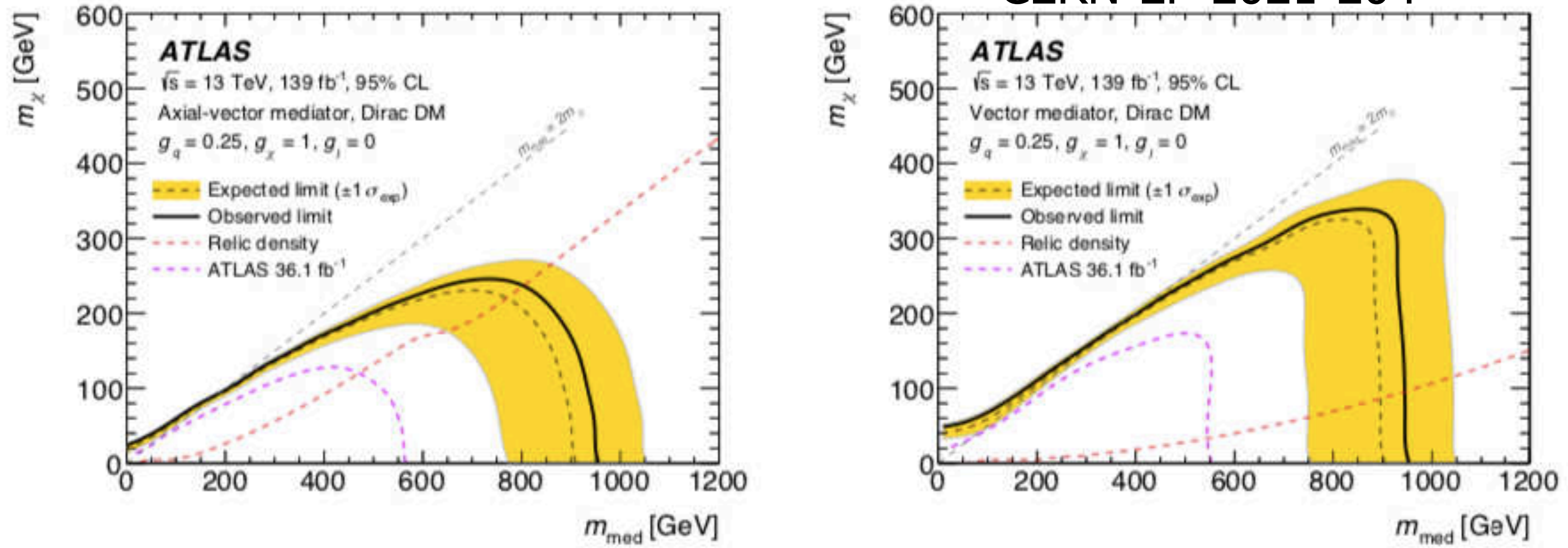
  - no electrons
  - no LumiCal photons
  - no BeamCal photons
  - no jets

Detector response simulated in the Delphes framework:

ILCgen for ILC, CLICdet extended to include BeamCal and LumiCal

Mono-Z search at the LHC

CERN-EP-2021-204



pp-> Z(ll)$\chi\chi$

(a) (b)

Figure 4: Exclusion limits for simplified DM models with $g_\chi = 1.0$, $g_q = 0.25$, and $g_\ell = 0$, when assuming (a) an axial-vector mediator or (b) a vector mediator. The region below the solid black line is excluded at the 95% CL. The dashed black line indicates the expected limit in the absence of signal, and the yellow band the corresponding $\pm 1\sigma$ uncertainty band. The dashed red line labelled 'Relic density' corresponds to combinations of DM and mediator mass values that are consistent with a DM density of $\Omega h^2 = 0.118$ and a standard thermal history, as computed in Ref. [13]. Below the line, annihilation processes described by the simplified model mostly predict too high a relic density while regions with too low a relic density are mostly found for m_{med} closer to the DM mass. The dashed magenta line indicates the previous ATLAS result from a 36.1 fb^{-1} dataset [21].

BR(H->inv) < 19%   at 95% C.L.