Dark Sector at CLIC

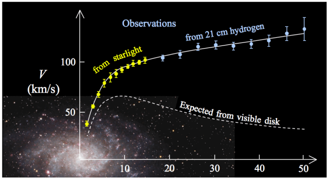
Michael Rauch | Physics at CLIC – July 18, 2017

INSTITUTE FOR THEORETICAL PHYSICS

Motivation

Strong indications for existence of Dark Matter (DM)

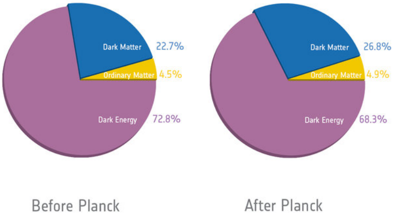
- Rotation curves of galaxies
- Galaxy clusters and gravitational lensing
- Cosmic microwave background



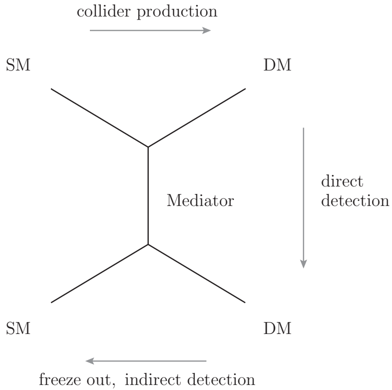
→ ΛCDM Model

⇒ Dark sector in many BSM extensions

- particle(s) without electric or colour charge
- protected by global symmetries
  → stable on astrophysical time scales
- often not completely decoupled
  ↔ interacts with SM by Z boson
  or mediator exchange



Feynman Diagram View

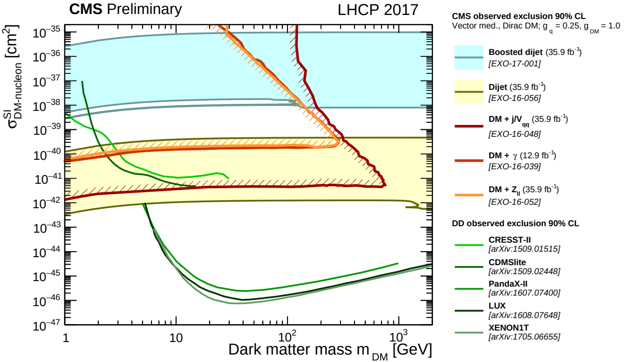


Detection of Dark Sector

Collider searches: LHC

- detection in mono-jet/mono-photon searches $pp \to j/\gamma + \not{E}_T$
- Sensitivity almost independent of DM mass
- $\to$ limits in low-mass region stronger than from direct detection experiments

$$1\text{fb} \mathrel{\widehat{=}} 10^{-39}\text{cm}^2$$

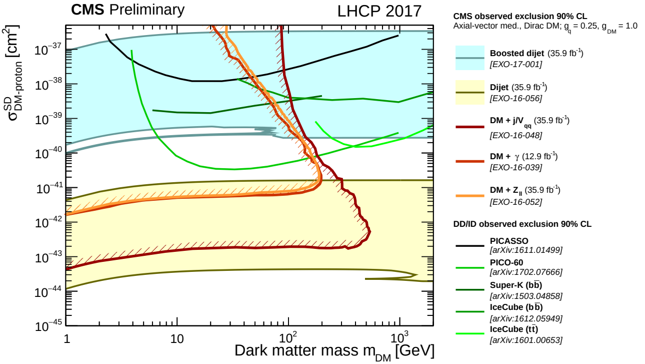


Detection of Dark Sector

Collider searches: LHC

- detection in mono-jet/mono-photon searches $pp \to j/\gamma + \not{E}_T$
- Sensitivity almost independent of DM mass
- $\to$ limits in low-mass region stronger than from direct detection experiments

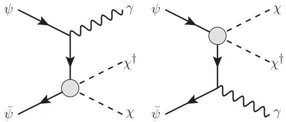
$$1\,\text{fb} \mathrel{\widehat{=}} 10^{-39}\,\text{cm}^2$$



Discovering a Dark Sector

[Dreiner, Huck, Krämer, Schmeier, Tattersall]

- Extensive survey of different combinations
- scalar, fermion and vector dark matter
- process $e^+e^- \to \gamma\chi\chi$



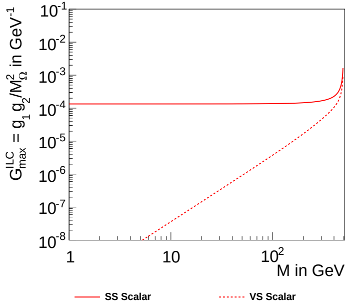
DM	Med.	Diagram	$-\mathscr{L}_{\rm UV}$ $-\mathscr{L}_{\rm eff}$
S	S		$g_\chi \chi^\dagger \chi \phi + \bar\psi(g_s + i g_p \gamma^5)\psi\phi$ $\frac{g_\chi}{M_\Omega^2} \chi^\dagger \chi \bar\psi (g_s + i g_p \gamma^5)\psi$
S	F		$\bar\eta(g_s + g_p\gamma^5)\psi\chi + \bar\psi(g_s - g_p\gamma^5)\eta\chi^\dagger$ $\frac{1}{M_\Omega}\left[(g_s^2 - g_p^2)\bar\psi\psi\chi^\dagger\chi + \frac{i}{M_\Omega}\chi^\dagger\bar\psi\left(g_s^2 + g_p^2 - 2g_s g_p\gamma^5\right)\gamma^\mu\partial_\mu(\psi\chi)\right]$
S	V		$g_\chi(\chi^\dagger\partial_\mu\chi - \chi\partial_\mu\chi^\dagger)Z^\mu + \bar\psi\gamma^\mu(g_l P_L + g_r P_R)\psi Z_\mu$ $\frac{g_\chi}{M_\Omega^2}\bar\psi\gamma^\mu(g_l P_L + g_r P_R)\psi\left(\phi^\dagger\partial_\mu\phi - \phi\partial_\mu\phi^\dagger\right)$
F	S		$\bar\chi\left(g_s + g_p\gamma^5\right)\chi\phi + \bar\psi\left(g_s + g_p\gamma^5\right)\psi\phi$ $\frac{1}{M_\Omega^2}\bar\chi\left(g_s + i g_p\gamma^5\right)\chi\bar\psi\left(g_s + i g_p\gamma^5\right)\psi$
F	V		$\bar\psi\gamma^\mu(g_l P_L + g_r P_R)\psi Z_\mu + \bar\chi\gamma^\mu(g_l P_L + g_r P_R)\chi Z_\mu$ $\frac{1}{M_\Omega^2}\bar\psi\gamma^\mu(g_l P_L + g_r P_R)\psi\,\bar\chi\gamma_\mu(g_l P_L + g_r P_R)\chi$
F	tS		$\bar\chi\left(g_s + g_p\gamma^5\right)\psi\phi + \bar\psi\left(g_s + g_p\gamma^5\right)\chi\phi$ $\frac{1}{M_\Omega^2}\bar\psi\left(g_s - g_p\gamma^5\right)\chi\bar\chi\left(g_s + g_p\gamma^5\right)\psi$
F	tV		$\bar\psi\gamma^\mu(g_l P_L + g_r P_R)\chi Z_\mu + \bar\chi\gamma^\mu(g_l P_L + g_r P_R)\psi Z_\mu$ $\frac{1}{M_\Omega^2}\bar\psi\gamma^\mu(g_l P_L + g_r P_R)\chi\bar\chi\gamma_\mu(g_l P_L + g_r P_R)\psi$
V	S		$-\chi^\mu\chi_\mu\phi + \bar\psi(g_s + i g_p\gamma^5)\psi\phi$ $-\frac{g_\chi}{M_\Omega^2}\chi^\mu\chi_\mu\bar\psi\left(g_s + i g_p\gamma^5\right)\psi$
V	F		$-\bar\eta\gamma^\mu(g_l P_L + g_r P_R)\chi_\mu + \bar\psi\gamma^\mu(g_l P_L + g_r P_R)\eta\chi_\mu^\dagger$ $\frac{1}{M_\Omega}\left[g_l g_r\bar\psi\gamma^\nu\gamma^\rho\psi\;\chi_\nu^\dagger\chi_\rho + \frac{i}{M_\Omega}\chi_\nu^\dagger\bar\psi\gamma^\nu\gamma^\mu\gamma^\rho\left(g_l^2 P_L + g_r^2 P_R\right)\partial_\mu(\psi\chi_\rho) +\right]$
V	V		$i g_\chi\left[Z_\mu\chi_\nu^\dagger\partial\chi^{\mu\nu} + Z_\mu\chi_\nu\partial\chi^{\mu\nu} + \chi_\mu^\dagger\chi_\nu\partial Z^{\mu\nu}\right] + \bar\psi\gamma_\mu(g_l P_L + g_r P_R)\psi$ $\frac{i g_\chi}{M_\Omega^2}\bar\psi\gamma^\mu(g_l P_L + g_r P_R)\psi\left[\chi^\nu\partial\chi_{\mu\nu}^\dagger - \chi^{\dagger,\nu}\partial\chi_{\mu\nu} + \partial^\nu\left(\chi_\nu^\dagger\chi_\mu - \chi_\mu^\dagger\chi_\nu\right)\right]$

Exclusion Limits

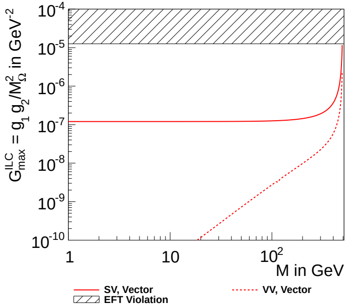
[Dreiner *et al.*]

Setup: $\sqrt{s} = 1$ TeV, $\mathcal{L} = 500$ fb^{-1}

scalar mediator



vector mediator



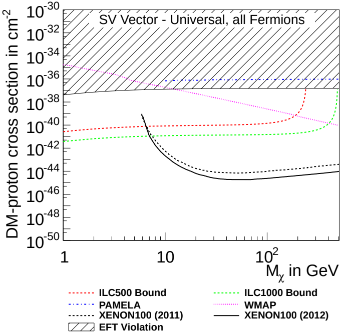
coupling reach ($G = \frac{g_1 g_2}{M_{\text{Mediator}}}$): 10^{-4} GeV / 10^{-7} GeV^2

fairly independent of mass up to kinematic threshold
except vector DM: much stronger limit for small DM mass

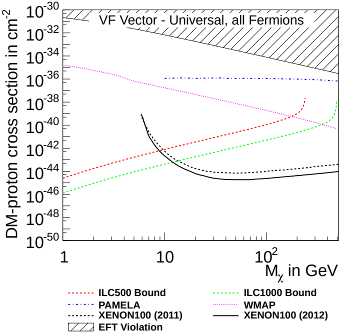
Comparison with Direct Detection

[Dreiner *et al.*]

scalar DM, vector mediator



vector DM, fermion mediator



low-mass range ($\lesssim$ 10 GeV): competitive with astrophysical bounds in many models

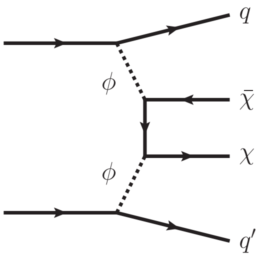
high-mass range ($\gtrsim$ 100 GeV): difficult to push into unexcluded regions

Determining Properties of a Dark Sector

- Mono-jet / Mono-photon searches:
  WIMP recoils against high-p_T jet/photon
- $\Rightarrow$ Only total amount of $\not\!\!E_T$ can be measured,
  i.e. differential c.s. for one observable
- $\rightarrow$ Limited tool for determining properties

$\Rightarrow$ Test other processes

Vector-Boson Fusion



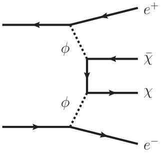
(ϕ: mediator,
χ: DSP (dark sector particle))

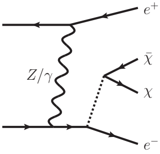
- proven as great tool already in Higgs phenomenology
- Predominant background:
  $pp \rightarrow Zjj \rightarrow \nu\bar{\nu}jj$
  (both QCD and VBF-EW)
- couplings very constrained from mono-jet searches
- $\leftrightarrow \mathcal{O}$(electro-weak coupling) required for useful phenomenology

[see also An, Wang, Zhang]

Moving to e^+e^- colliders

$\rightarrow$ Try same topology at e^+e^- collider



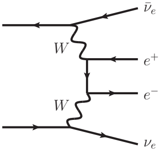


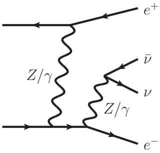
Signature: e^+e^- pair $+\not{E}_T$

e^+e^- collider clean environment:

- almost no exp. systematics
- smaller theory uncertainties
- $\Rightarrow$ mostly statistics limited

Main backgrounds:





Model Setup

Simple effective model used for study:

- DSP χ: Dirac fermion
- Mediator ϕ: scalar or vector

Mediator couples to electrons only (results for leptons-only basically identical)

$\rightarrow$ Interaction terms appearing in the Lagrangian:

	scalar	vector
e	$i\, g_{ee\phi,S}\; \bar{e}e\; \phi_S$	$i\, g_{ee\phi,V}\; \bar{e}\gamma_\mu e\; \phi_V^\mu$
χ	$i\, g_{\chi\chi\phi,S}\; \bar{\chi}\chi\; \phi_S$	$i\, g_{\chi\chi\phi,V}\; \bar{\chi}\gamma_\mu \chi\; \phi_V^\mu$

Define effective mass:

$$M_* = \frac{M_\phi}{\sqrt{g_{ee\phi} g_{\chi\chi\phi}}}$$

Heavy mediator can be integrated out:

$$g_{ee\phi} \frac{1}{q^2 - M_\phi^2} g_{\chi\chi\phi} \overset{q^2 \ll M_\phi^2}{=} g_{ee\phi} \frac{1}{-M_\phi^2} g_{\chi\chi\phi} = -\frac{1}{M_*^2}$$

$\rightarrow$ effective dimension-6 operators: $\bar{e}e\,\bar{\chi}\chi$, $\bar{e}\gamma_\mu e\,\bar{\chi}\gamma^\mu\chi$

Model setup

Benchmark points for study:

[Andersen, MR, Spannowsky]

model	mediator mass	mediator spin	DSP mass	M_*
LSL	8 GeV	0 (scalar)	5 GeV	30 GeV
LVL	8 GeV	1 (vector)	5 GeV	30 GeV
LSH	8 GeV	0 (scalar)	120 GeV	27.4 GeV
LVH	8 GeV	1 (vector)	120 GeV	21 GeV
HSL	200 GeV	0 (scalar)	5 GeV	1250 GeV
HVL	200 GeV	1 (vector)	5 GeV	1250 GeV
HSH	200 GeV	0 (scalar)	120 GeV	332.4 GeV
HVH	200 GeV	1 (vector)	120 GeV	511.8 GeV

$\rightarrow$ light mediator

$\Rightarrow$ full momentum dependence in propagator required

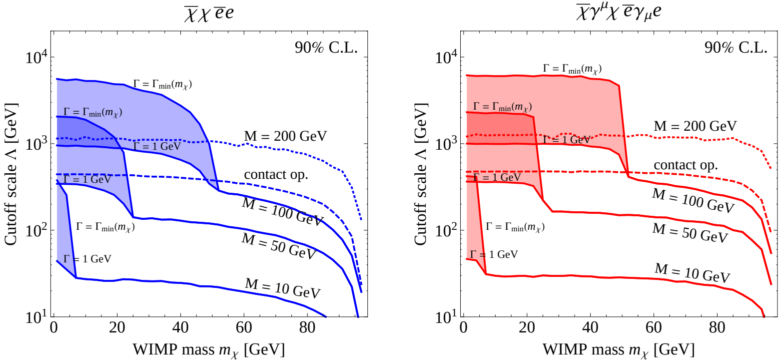
$\rightarrow$ M_* used as effective coupling constant

Technical setup:

- Event Simulation: MadGraph/MadEvent 4.5.1
- Mediator width: BRIDGE [Meade, Reece]
  (width small: < 1 GeV)

Benchmark Couplings

M_* values for light DSP from [Fox, Harnik, Kopp, Tsai] ($\Lambda \equiv M_*$)



for heavy DSP strong constraints from direct detection experiments
$\rightarrow$ e^+e^- cross sections too small
$\leftrightarrow$ DSP stable on collider time scales, but not on astrophysical ones
$\rightarrow$ for simplicity: similar c.s. as in light DSP case

Cross sections

- Cuts: $p_{T,e} > 10$ GeV, $|\eta_e| < 2.5$, $\not{p}_T > 50$ GeV
- Integrated cross sections for ILC, $\sqrt{s} = 500$ GeV:

model	cross section in fb		
	unpolarized	$++$-polarized	$+-$-polarized
SM	115.8	49.1	36.4
LSL	1.60	1.79	1.40
LVL	15.07	12.80	17.02
LSH	1.45	1.80	1.10
LVH	10.00	7.64	12.33
HSL	1.17	1.43	0.92
HVL	0.85	0.71	0.89
HSH	1.18	1.45	0.90
HVH	0.85	0.64	0.98

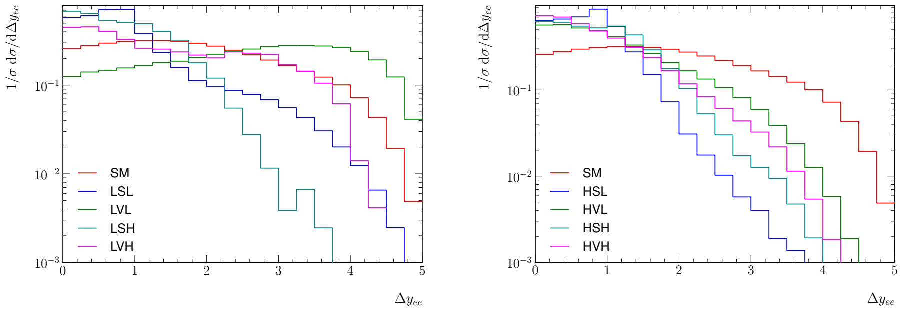
- Linear collider setup allows beams to be polarized:
  80% for e^- beam (first index)
  30% for e^+ beam (second index)
- $\rightarrow$ significant background reduction possible
  $-+$ and $--$ combinations lead to background enhancement $\Rightarrow$ not considered
- $\leftrightarrow$ opposite polarization than required for Higgs

Differential Distributions

Rapidity difference of the two leptons Δy_{ee}

[Andersen, MR, Spannowsky]

Light mediator — Heavy mediator



Clearly distinct shape between different contributions

$\rightarrow$ Explanation?

Regge Theory

Karlsruher Institut für Technologie

- (non-relativistic part) developed by T. Regge in 1957
- analytic behaviour of scattering amplitudes as function of angular momentum
- angular momentum can be any complex value

$$A(z) \propto z^{\ell(E^2)} \qquad z \gg 1$$

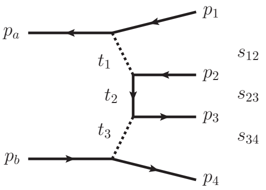
- relativistic: $z \gg 1 \longrightarrow$ large momentum transfer t [Mandelstam]
- apply to crossed channel $s \leftrightarrow t$

$$A \propto s^{\ell(t)} \qquad s \gg |t|$$

- Theory of strong interactions in 1960's
- $\rightarrow$ largely replaced by QCD nowadays

- $\rightarrow$ phenomenological tool for large-energy scattering

Multi-Regge kinematic limit



Multi-Regge kinematic limit:

invariant mass between final-state particles large compared to propagating momentum and masses

$$s_{ij} \gg |t_i|, m_{\phi,\chi}$$

$\Rightarrow$ VBF cuts

$$\mathcal{M}^{p_a p_b \to p_1 p_2 p_3 p_4} \to s_{12}^{\alpha_1(t_1)}\ s_{23}^{\alpha_2(t_2)}\ s_{34}^{\alpha_3(t_3)}\ \gamma$$

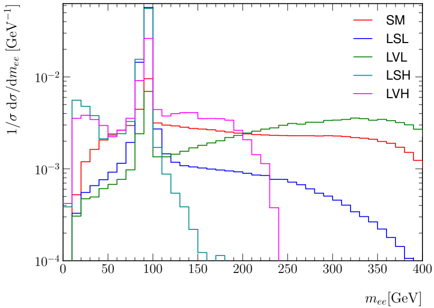
- $p_1, \ldots, p_4$ rapidity-ordered
- $\gamma = \gamma(\text{couplings}, t_i, \frac{s_{ij}}{\prod s_{kl}})$
- α_i = spin J_i of t-channel particle i (+ radiative corrections)
- Remember: $s_{ij} = 2\, p_{T,i}\, p_{T,j}\, (\cosh(y_i - y_j) - \cos(\phi_i - \phi_j))$

$\Rightarrow$ If messenger masses negligible
distinguish messenger spin by looking at m_{ee} or $\Delta\phi_{jj}$

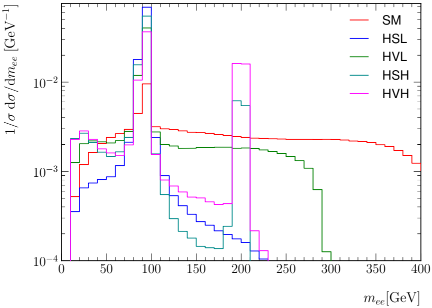
Differential Distributions (cont.)

Invariant mass of the two leptons m_{ee}

Light mediator



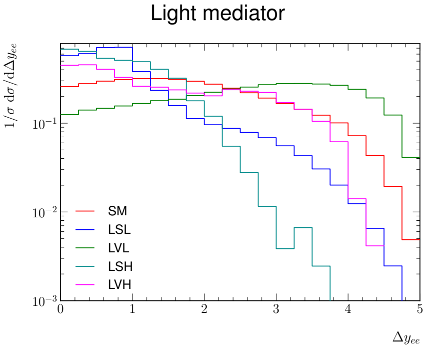
Heavy mediator

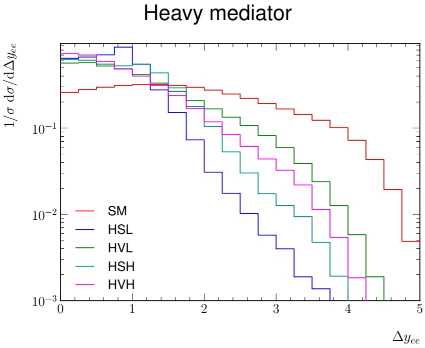


- Light mediator (L••)
  scalar (LS•) suppressed compared to vector exchange (LV•) at large m_{ee}
- Heavy mediator (H••)
  impact of mass significant for fixed DSP mass

Differential Distributions (cont.)

Rapidity difference of the two leptons Δy_{ee}





- Light mediator (L••)
  scalar (LS•) suppressed compared to vector exchange (LV•) at large Δy_{ee}
- Heavy mediator (H••)
  vector-scalar hierarchy at large Δy_{ee} still holds despite heavy mass

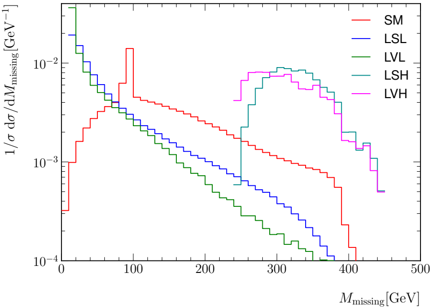
$\Rightarrow$ Polarised beams and vector mediator: S/B $\sim$ 27% at large Δy

Differential Distributions (cont.)

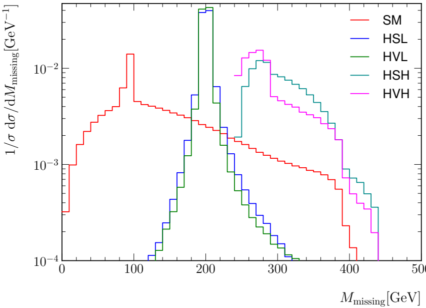
Invariant mass of missing momentum M_{missing}
(lower bound: $2 \cdot$ DSP mass)

[see also Chacko, Cui, Hong]

Light mediator



Heavy mediator

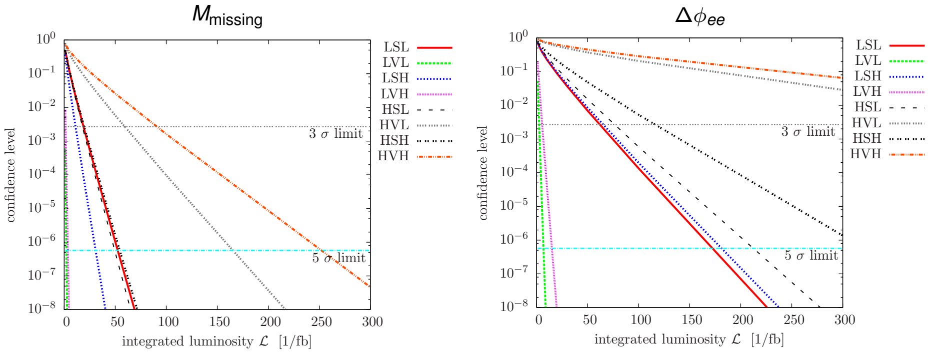


- No distinction of scalar/vector mediator
- Pronounced peak if $m_\phi > 2m_\chi$ (H•L, on-shell mediator production)
- allows mass distinction
  $\rightarrow$ complementary to m_{ee}, Δy_{ee}
- for CP-even vs. CP-odd coupling study $\Delta\phi_{ee}$ in addition

Excluding Models

Binned log-likelihood hypothesis test with CL_S method

ILC, $\sqrt{S} = 500$ GeV, $+-$ beam polarization



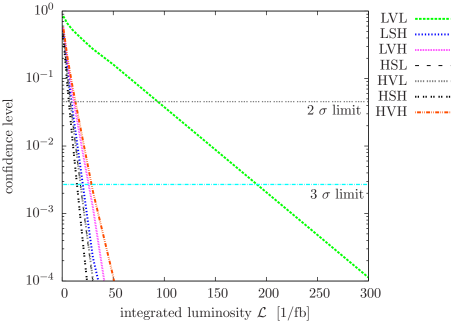
- Single variable test only
- LVL, LVH large c.s. $\rightarrow$ 5σ-excluded with 10 fb^{-1}
- 300 fb^{-1} sufficient for all considered scenarios

Discriminating Models

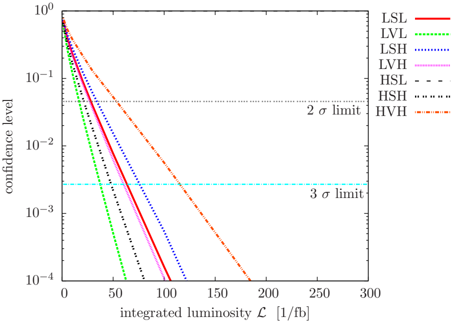
Binned log-likelihood hypothesis test with CL_S method

ILC, $\sqrt{S}$ = 500 GeV, $+-$ beam polarization, $\sigma = 2.5\% \times \sigma_{\text{SM bkgd.}}$

LSL model



HVL model



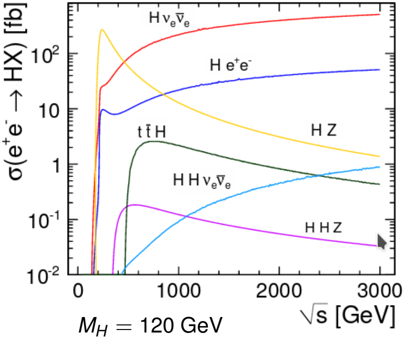
- Single variable test only
- Good prospects for distinguishing scenarios

CLIC Prospects

No detailed studies yet – work for the future

- discovery reach
  - biggest improvements from collider data for low-DM-mass regime
  - $\rightarrow$ collider center-of-mass energy less relevant
  - $\leftrightarrow$ improved precision for vector DM

- property determination
  - from vector-boson-fusion process
  - $\rightarrow$ higher energy beneficial
  - $\rightarrow$ better signal-background separation
  - $\rightarrow$ increased significance



[CLIC Conceptual Design Report]

Conclusions

- mono-photon searches helpful for discovering dark sector
- competitive in particular in low-mass region

- not well suited for studying properties
  $\rightarrow$ VBF-like topologies
- VBF cross sections grows with energy
- polarized beams help further in SM background suppression

- differing distributions allow distinction

  M_{missing}: mass scale and hierarchies of mediator and DSP
  m_{ee} and Δy_{ee}: mediator spin
- latter explained by multi-Regge kinematic limit

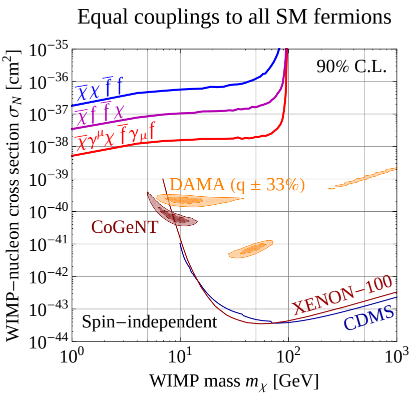
$\rightarrow$ CLIC ideal collider for studying dark sector

Detection of Dark Sector

Collider searches: LEP

- detection in mono-photon searches
  $e^+e^- \to \gamma + \not{E}_T$
- no official results
  only theorists' reinterpretation of mono-photon searches
  [Fox, Harnik, Kopp, Tsai]
- high sensitivity in low-mass region
- superseded by LHC results
  if χ couples to all fermions
- still competitive
  if χ couples to leptons only

$1\,\text{fb} \mathrel{\hat{=}} 10^{-39}\text{cm}^2$

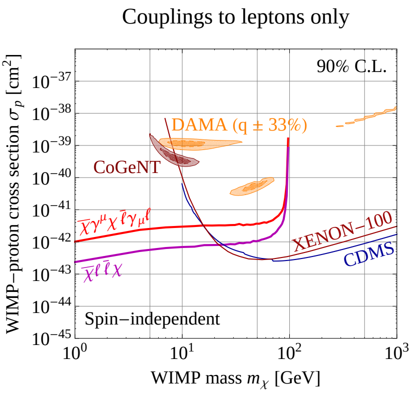


Detection of Dark Sector

Collider searches: LEP

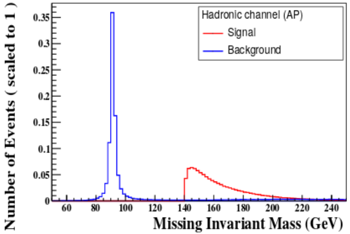
- detection in mono-photon searches
  $e^+e^- \to \gamma + \not{E}_T$
- no official results
  only theorists' reinterpretation of mono-photon searches
  [Fox, Harnik, Kopp, Tsai]
- high sensitivity in low-mass region
- superseded by LHC results
  if χ couples to all fermions
- still competitive
  if χ couples to leptons only

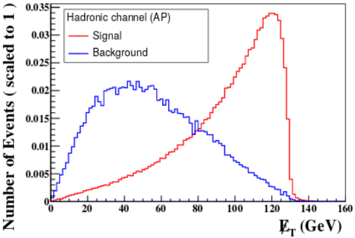
$1\text{fb} \widehat{=} 10^{-39}\text{cm}^2$



Another useful variable

[Chacko, Cui, Hong]





- studied scenario:
  Higgs portal with $m_{\text{DM}} > m_H/2$
- here: $m_{\text{DM}} = 70$ GeV, $\sqrt{s} = 350$ GeV
- main channel:
  ZH associated production
- main backgrounds:
  ZZ production, *W*-fusion
- missing invariant mass provides good separation power
- need to know $\sqrt{s}$
  $\rightarrow$ only possible at e^+e^- collider