Dark Photon Searches at Future e^+e^- Colliders

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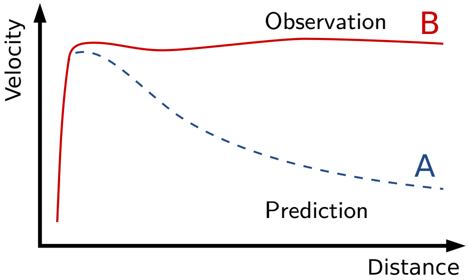
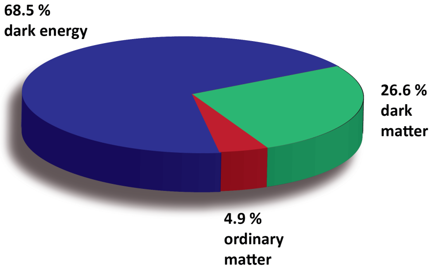
Motivation

arXiv:astro-ph/9909252



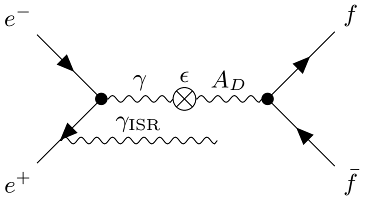


- Dark matter exists and interacts with ordinary matter (SM particles) at least via gravitation

- No DM condidate in SM
  - BSM
  - add Dark sector to SM $\Rightarrow$ add a new gauge symmetry.

A minimal model of the dark sector

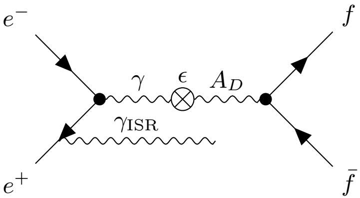
- Dark sector has a $U'(1)$ gauge-symmetry
- $U'(1)$ is spontaneously broken by dark Higgs
- Dark photon A_D as hypothetical gauge boson in dark sector
  - A_D can kinematically mix with ordinary photon
  - $e^+e^- \to A_D + \gamma_{\rm ISR} \to f\bar{f} + \gamma_{\rm ISR}$
- In this study
  - $e^+e^- \to A_D + \gamma_{\rm ISR} \to \mu^+\mu^- + \gamma_{\rm ISR}$
    - $\mu\bar{\mu}$ final state is the best measured final state



$$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

Dark photon A_D

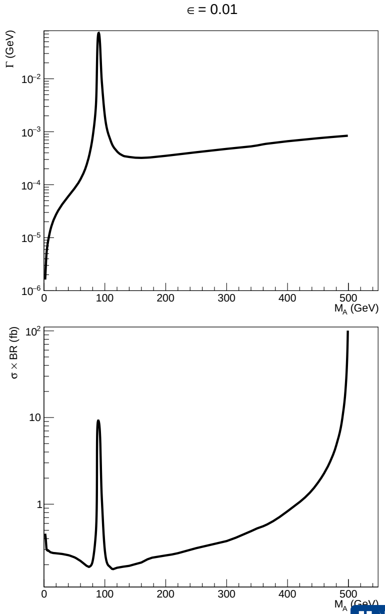
The only detectable sign of dark sector



$$\sigma \times BR \times \mathrm{L} = N^{Total}_{A_D}$$

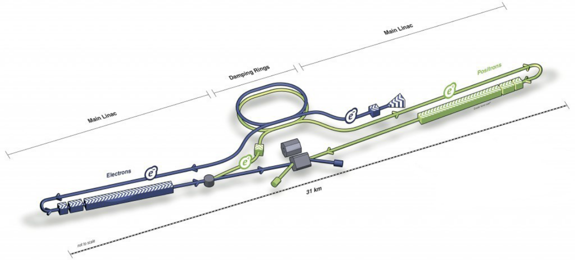
$$\sigma \times BR \propto \epsilon^2$$

- For (almost) any m_{A_D}: $\Gamma < 1\mathrm{MeV}$
  $\Rightarrow$ peak width given by detector resolution
- Heisenberg's uncertainty principle: $c\tau = \frac{1.97\times10^{-7}}{\Gamma_{\mathrm{Tot}}[\mathrm{GeV}]}\ \mu\mathrm{m}$
- Dark photon decays immediately ($\ll 1\mu\mathrm{m}$)



Dark Photon in e^+e^-

- Why e^+e^-
  - Clean collision environment without QCD backgrounds at e^+e^- colliders.
  - Well-defined initial state.
  - Very sensitive to subtle signals.
- proposed colliders:
  - CLIC , FCC , CEPC , ILC .
  - ILC (International Linear Collider)
    - In this study considered International Large Detector (ILD)

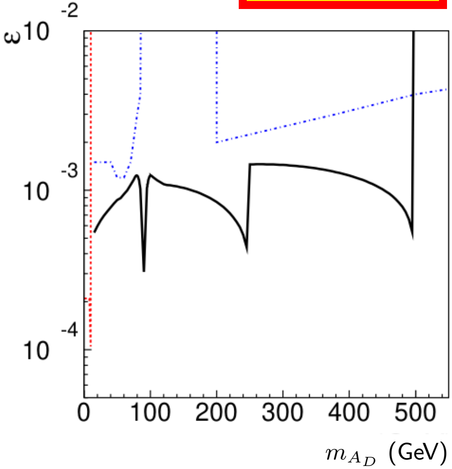


Exclusion limit projections for dark photon

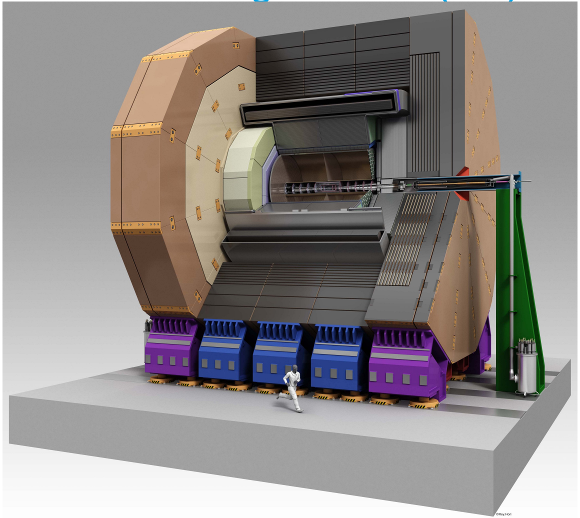
for **ILC**, BelleII and HL-LHC

- in a theory study:
  - reasonable assumption on the $m_{\mu\bar{\mu}}$ resolution
  - dependence of $m_{\mu\bar{\mu}}$ resolution on dark photon mass
- experimental approach:
  - exclusion limit at 95% confidence

arXiv:2111.09928

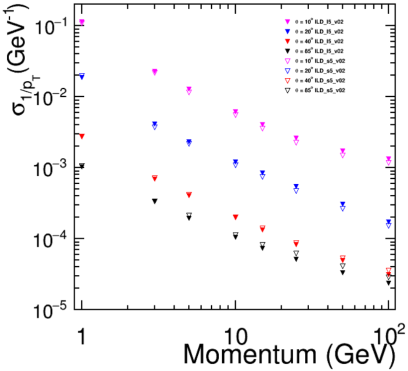


International Large Detector (ILD)

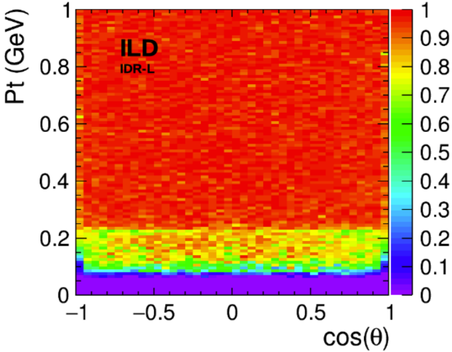


- **asymptotic momentum resolution:** $\boldsymbol{\sigma_{\frac{1}{p_T}} \sim 2 \times 10^{-5}}$ **GeV**$^{\boldsymbol{-1}}$
- impact parameter: $\sigma_{d_0} \sim 5\mu m$
- jet energy resolution: $\frac{\sigma_{E_j}}{E_j} \sim 3 - 4\%$
- designed and optimized for ParticleFlow
- hermeticity down to 5 mrad

Tracking efficiency and momentum resolution of ILD



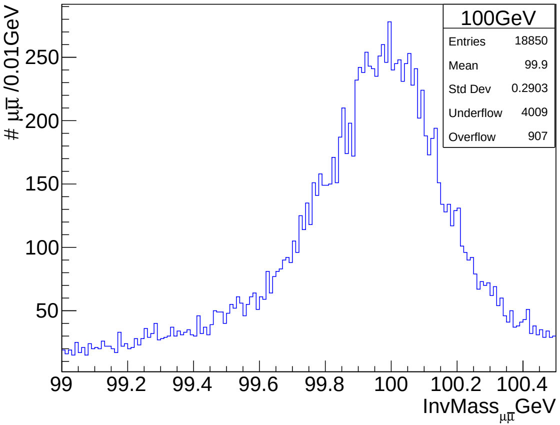
arXiv:2003.01116



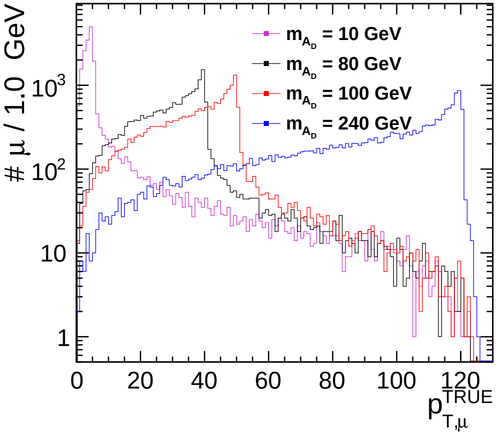
- Excelent momentum resolution of ILD for single μ events
- Perfect track finding efficiency (>95%) even in forward region with $P_t \geq 250$ MeV

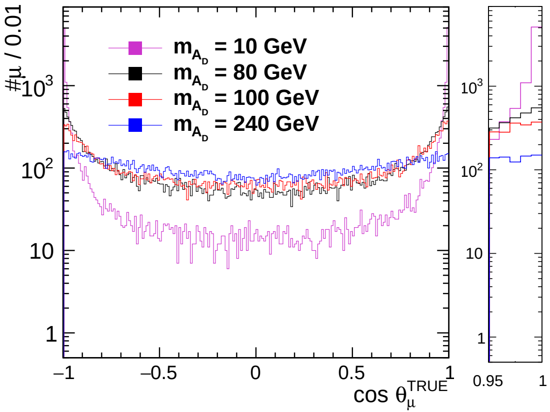
Data Sample

- $e^+e^- \to A_D \to \mu\bar{\mu}$ samples generated using WHIZARD event generator at $\sqrt{s}$=250 GeV. arXiV:1412.0018
  - Use the model of Curtin at al, described in UFO-files (Unified Feynrules Output): as input to Whizard
  - In terms of particle contents, couplings, vertices allowed
- Assumed A_D mass[GeV]: {10,20,30,...,80,100,...,240}
- 10k event samples per polarization configuration ($e^-_L e^+_R / e^-_R e^+_L$) per A_D mass
- Full simulation of ILD detector using GEANT4
- Reconstructed using iLCSoft (version: v02-02-03) (using Pandora ParticleFlow Algorithm)



p_T and $\cos\theta$ of muons

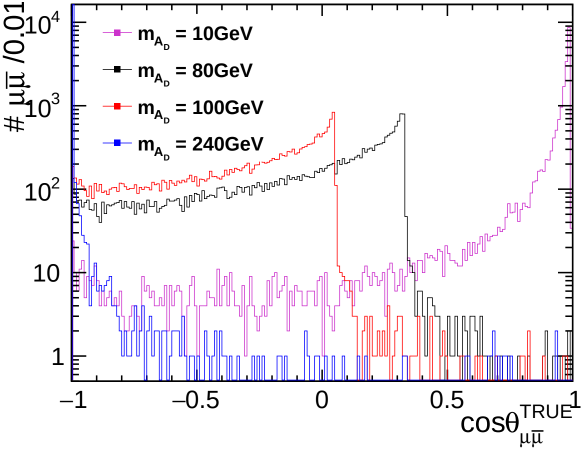




Dark photon detection is highly dependent on m_{A_D}:

- large mass dark photons: high p_T μ's $\Rightarrow$ worse momentum (and mass) resolution
- low mass dark photons: Thrust axis is along beam-pipe $\Rightarrow$ hard to detect

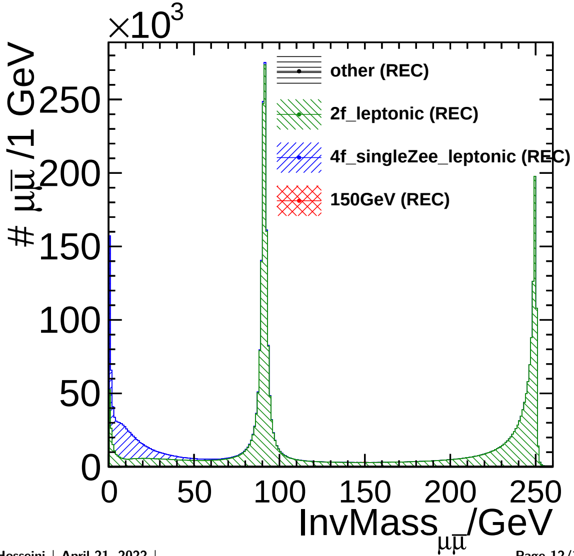
Opening angle of di-muons



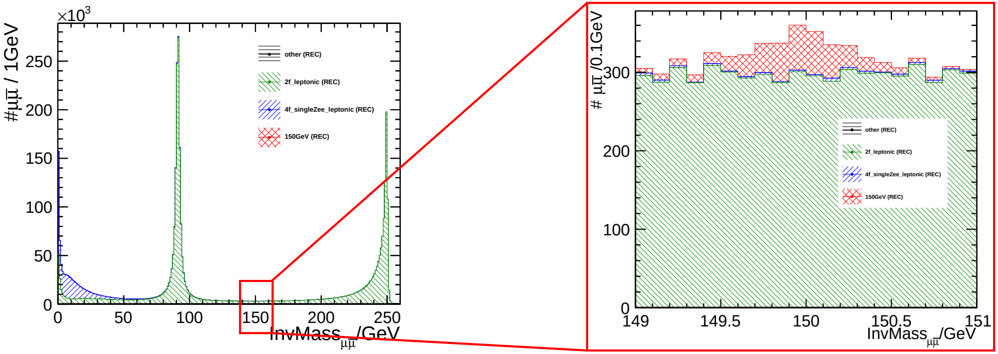
Decay products in high mass are back-to-back ⇒ easy to distinguish

Dark photon invariant mass in presence of SM background

- Dark photon signal: m_{A_D}=150 GeV
  $\sigma_{e_L^- e_R^+}$=0.66 fb, $\sigma_{e_R^- e_L^+}$=7.46 fb
- $\sqrt{s}$ = 250 GeV
- $e^- e^+$ Pol: $(\pm 80\%\ ,\ \mp 30\%)$
- Normalized to $\mathcal{L}_{\text{int}} = 900\ \text{fb}^{-1}$ per polarization
- Standard Model Background:
  - 2f-leptonic
  - 4f single Zee-leptonic
  - **rest SM-background**
- Observable (even small) signal in presence of SM-background



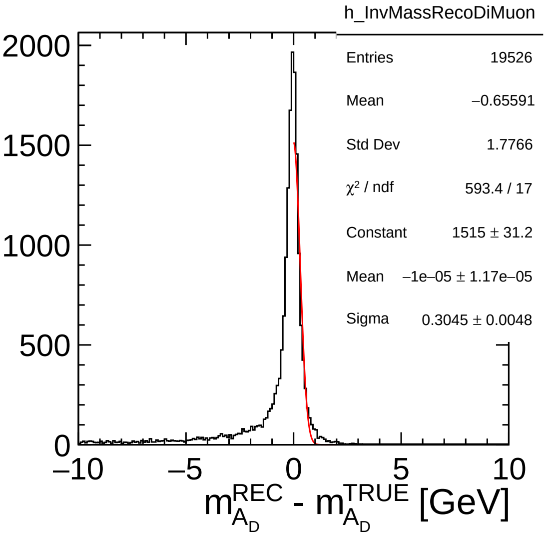
Dark photon invariant mass in presence of SM background



- Adjust search window width $\Rightarrow$ Get highest $\frac{N_{signal}}{N_{background}}$

A_D search window

- search for a narrow $\mu^+\mu^-$ resonance in $e^+e^- \to A_D + \gamma_{\rm ISR} \to \mu^+\mu^- + \gamma_{\rm ISR}$
- better mass resolution (σ_m) $\Rightarrow$ more narrow search window
- σ_m: width of mass residual ($=m^{REC}_{A_D} - m^{TRUE}_{A_D}$; $m^{REC}_{A_D} = m^{\rm inv}_{\mu^+\mu^-}$)
- more narrow search window $\Rightarrow$ lower background
- mass resolution dominated by detector resolution ($\Gamma \sim 1$ MeV)



A_D search window

with full detector resolution

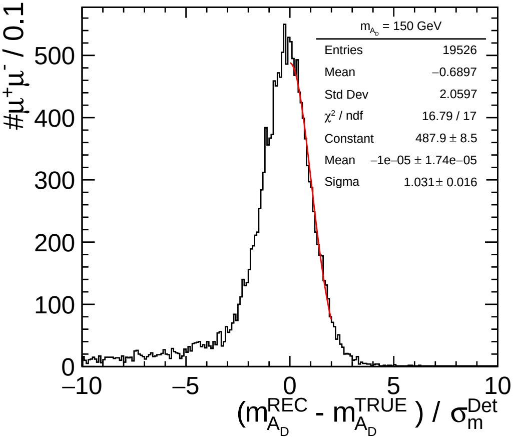
- Normalized Residual of dark photon mass:

  $= \frac{m_{A_D}^{\mathrm{REC}} - m_{A_D}^{\mathrm{TRUE}}}{\sigma_m^{\mathrm{Det}}}$

  σ_m^{Det}: uncertainty on $m_{\mu^+\mu^-}^{\mathrm{inv}}$ obtained from detector resolution

- Propagate CovMatrix of μ^+ and μ^- to $m_{\mu\bar{\mu}}$ uncertainty

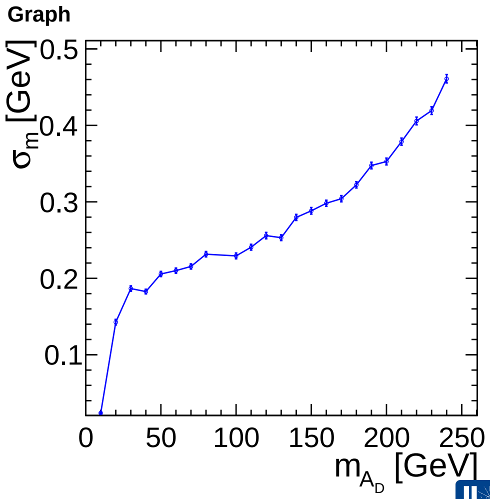
  $\mathrm{CovMat}(\vec{p}_{\mu^+}, E_{\mu^+}) \oplus \mathrm{CovMat}(\vec{p}_{\mu^-}, E_{\mu^-}) \Rightarrow \sigma_m^{\mathrm{Det}}$



ILD mass resolution

- adjust asymmetric search window $\propto$ dark photon mass

  $\Rightarrow$ goal: get highest N_{signal} / $N_{\text{background}}$



Conclusion

- Future e^+e^- collider experiments have capability to produce and detect dark photon
- ILD as a detector optimise for particle flow reconstruct individual particles with an excellent momentum and impact parameter resolution
- Excelent momentum resolution of ILD ($\sigma_{\frac{1}{p_T}}$) allows to search for dark photon in a very narrow window with the minimum background

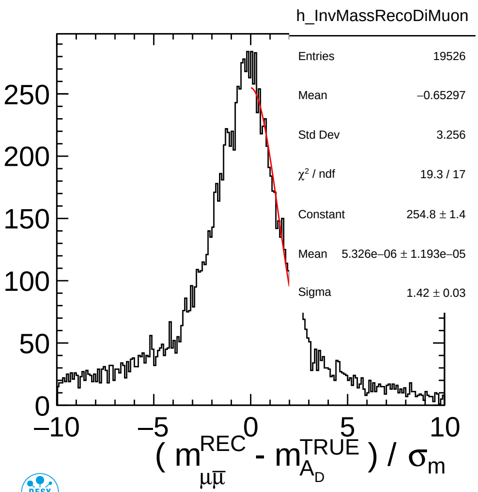
Outlook

- apply σ_m for optimizing width of search window to get CL95% signal of dark photon in ILD
- determin minimum ϵ^2 as a function of m_{A_D} $\Rightarrow$ get an observable signal

BACKUP

A_D search window

with detector momentum resolution $\sigma_{\frac{1}{p_T}}$



- with **only** asymptotic momentum resolution of ILD:

  $\sigma_{\frac{1}{p_T}} = 2 \times 10^{-5}$

- derived uncertainty on reconstructed $m_{\mu\bar{\mu}}$:

  $$\sigma_{m_{\mu\bar{\mu}}} = \sigma_{\frac{1}{p_T}} \times \sqrt{(\frac{dm_{\mu\bar{\mu}}}{dp_{T,\mu}})^2 \times p_{T,\mu}^4 + (\frac{dm_{\mu\bar{\mu}}}{dp_{T,\bar{\mu}}})^2 \times p_{T,\bar{\mu}}^4}$$

- underestimated uncertainty on $m_{\mu\bar{\mu}}$ by $\sim 40\%$