

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

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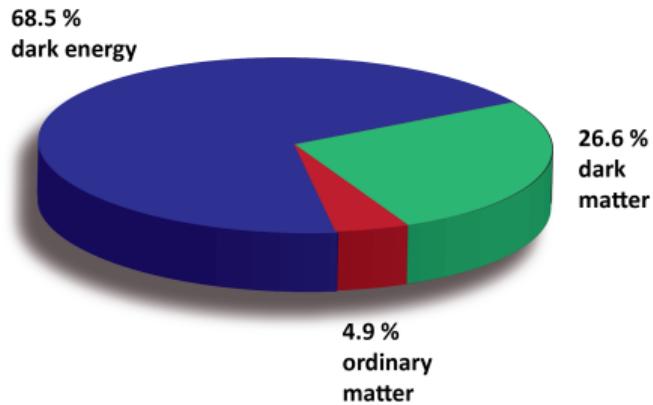
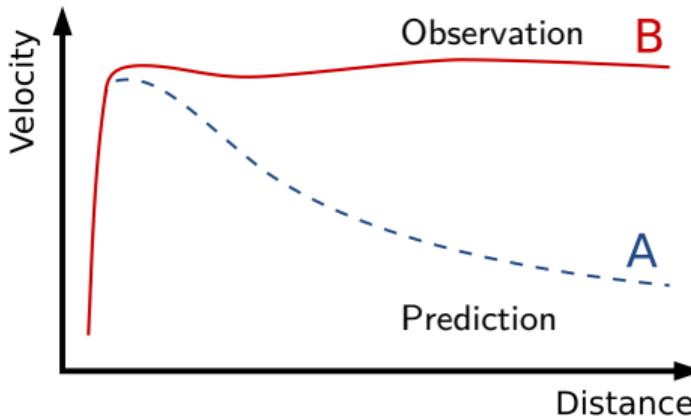
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HELMHOLTZ
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Motivation

arXiv:astro-ph/9909252

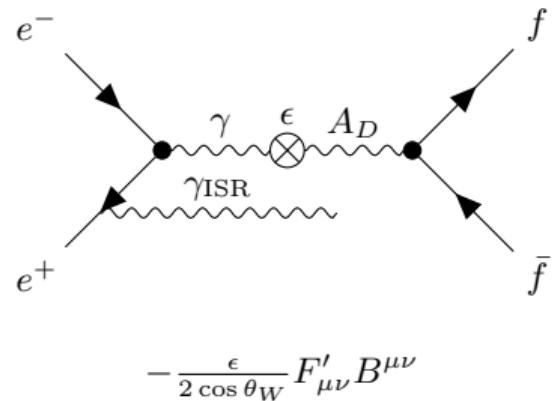


- Dark matter exists and interacts with ordinary matter (SM particles) at least via gravitation
- No DM candidate in SM
 - BSM
 - add Dark sector to SM \Rightarrow add a new gauge symmetry.



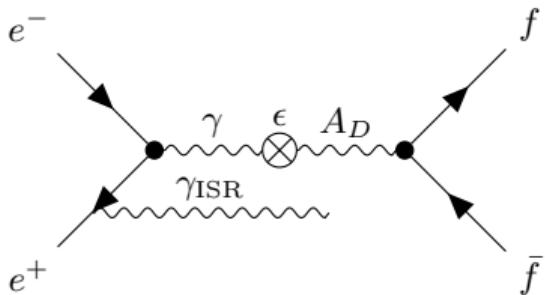
A minimal model of the dark sector

- ▶ 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
 - ▶ $e^+e^- \rightarrow A_D + \gamma_{\text{ISR}} \rightarrow f\bar{f} + \gamma_{\text{ISR}}$
- ▶ In this study
 - ▶ $e^+e^- \rightarrow A_D + \gamma_{\text{ISR}} \rightarrow \mu^+\mu^- + \gamma_{\text{ISR}}$
 - ▶ γ_{ISR} is always at the low angles
 - ▶ $\mu\bar{\mu}$ final state is the best measured final state
 - ▶ using the model of Curtin (UFO-files)



Dark photon A_D

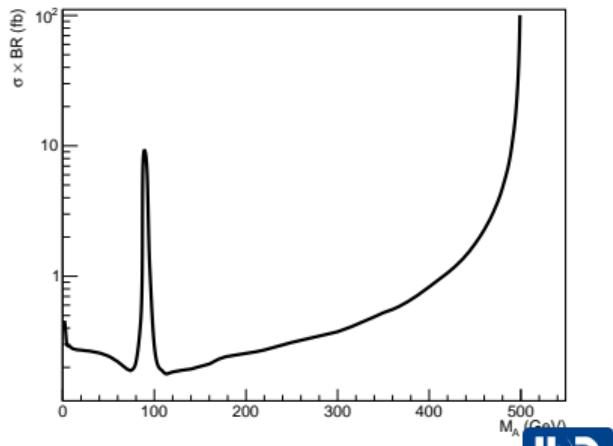
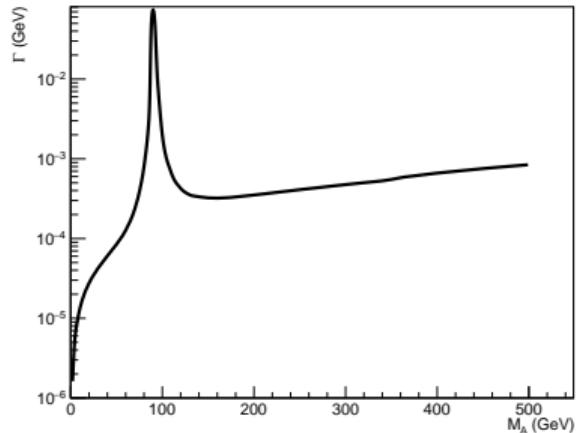
The only detectable sign of dark sector



$$\sigma \times BR \times L = N_{A_D}^{Total}$$

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

- ▶ For (almost) any m_{A_D} : $\Gamma < 1\text{MeV}$
 \Rightarrow peak width given by detector resolution
- ▶ Heisenberg's uncertainty principle: $c\tau = \frac{1.97 \times 10^{-7}}{\Gamma_{\text{Tot}}[\text{GeV}]} \mu\text{m}$
- ▶ Dark photon decays immediately ($\ll 1\mu\text{m}$)



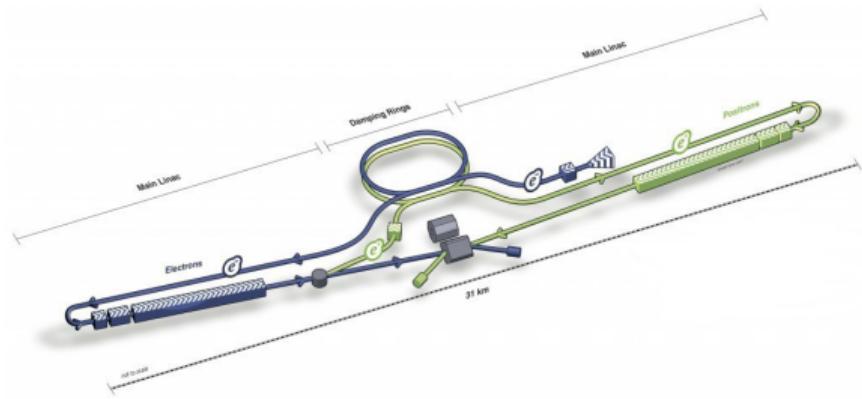
Dark Photon in e^+e^-

► e^+e^- colliders

- ▶ Clean collision environment without QCD backgrounds at e^+e^- colliders.
- ▶ Well-defined initial state.
- ▶ Very sensitive to subtle signals.

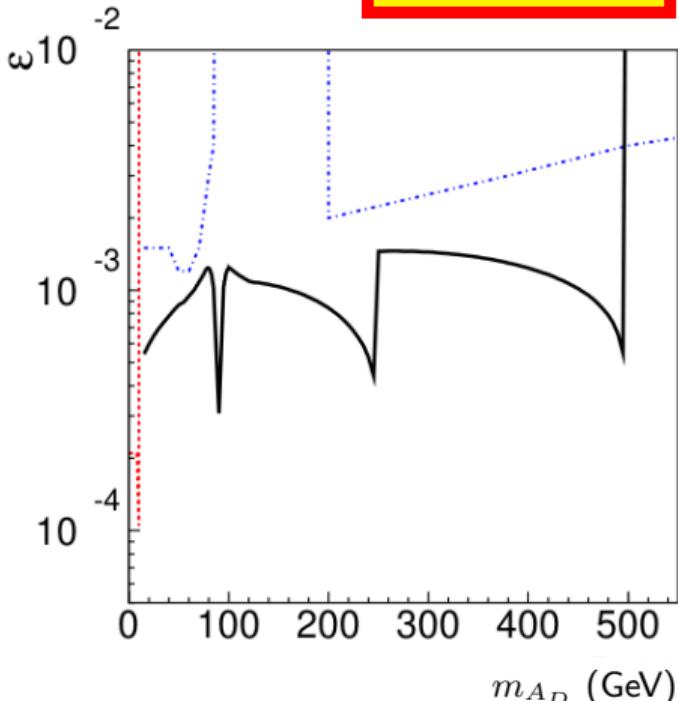
► proposed colliders:

- ▶ CLIC , FCC , CEPC , ILC .
- ▶ ILC (International Linear Collider)
 - ▶ In this study considered International Large Detector (ILD)



Exclusion limit projections for dark photon

arXiv:2111.09928

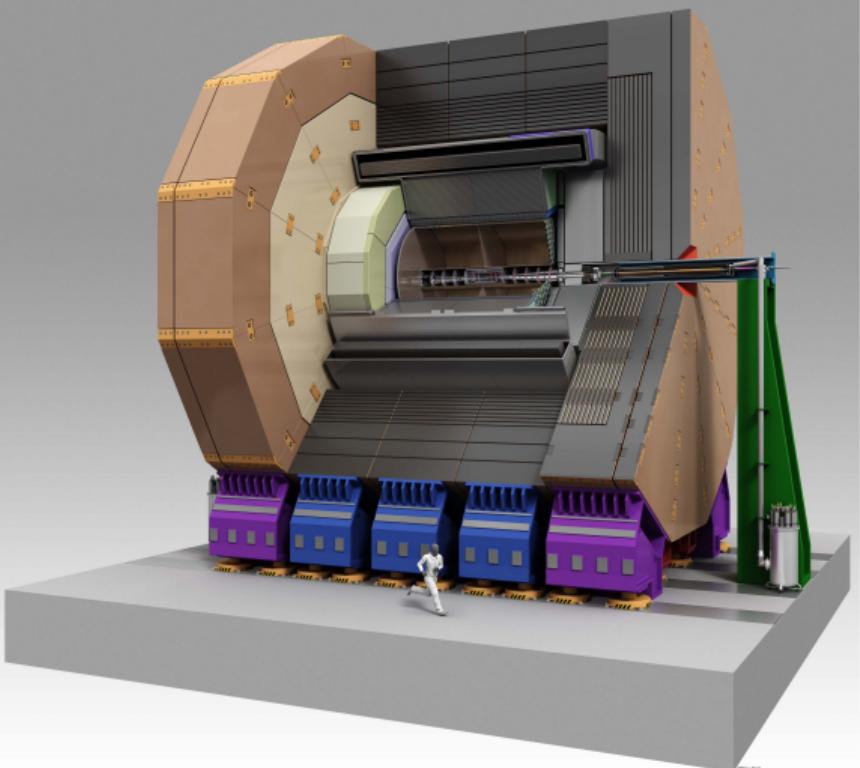


for ILC, BelleII and HL-LHC

- ▶ 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

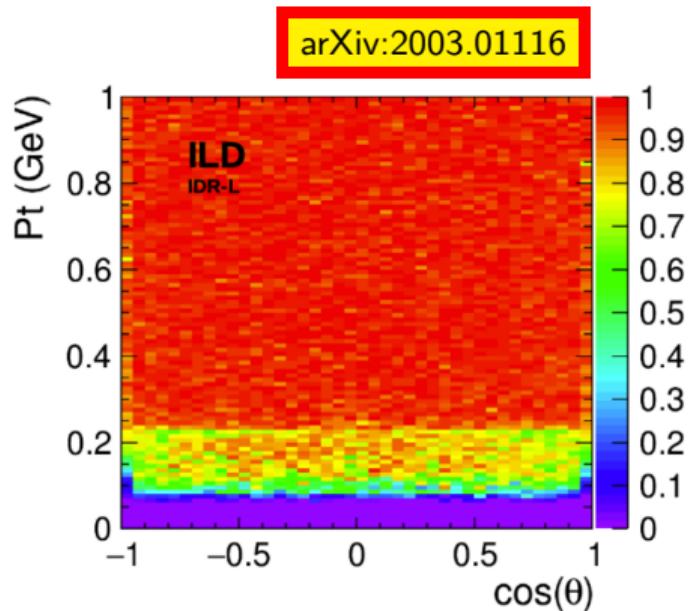
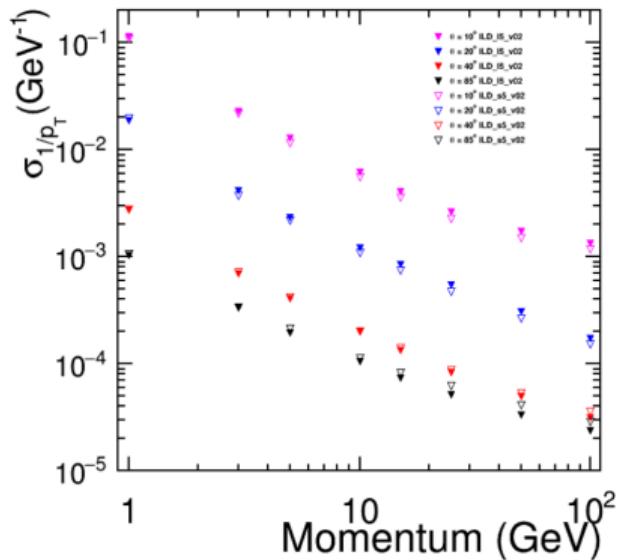


International Large Detector (ILD)



- ▶ **asymptotic momentum resolution:**
 $\sigma_{\frac{1}{p_T}} \sim 2 \times 10^{-5} \text{ GeV}^{-1}$
- ▶ **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

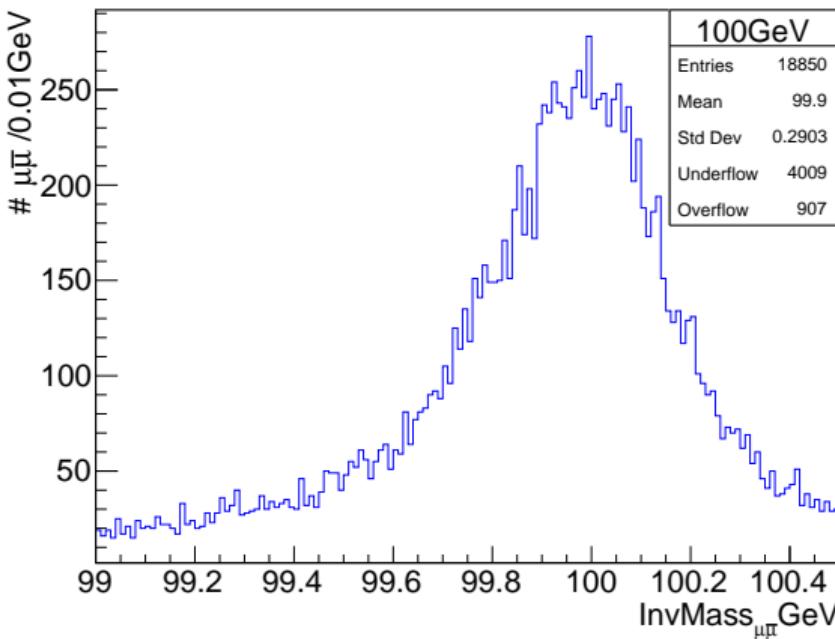


- Excellent momentum resolution of ILD for single μ events
- Perfect track finding efficiency ($>95\%$) even in forward region with $P_t \geq 250$ MeV

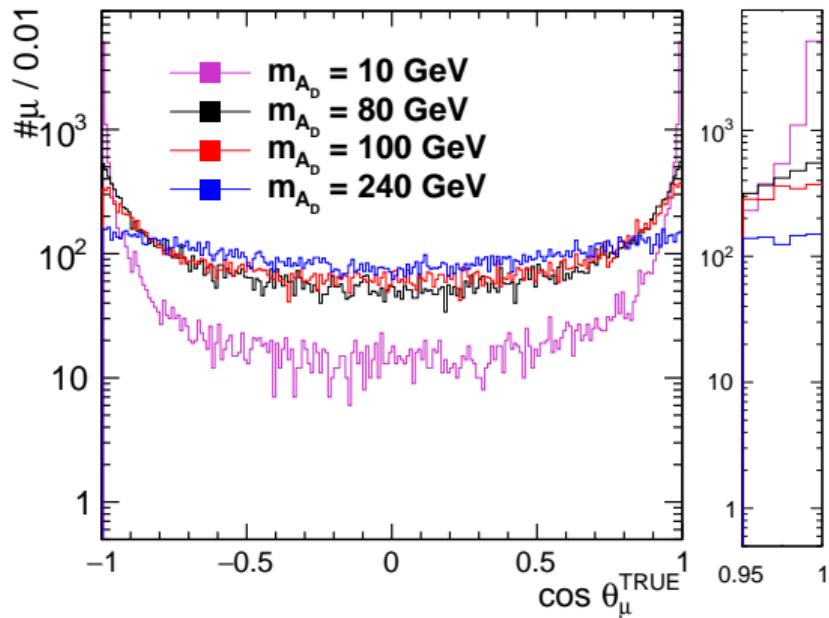
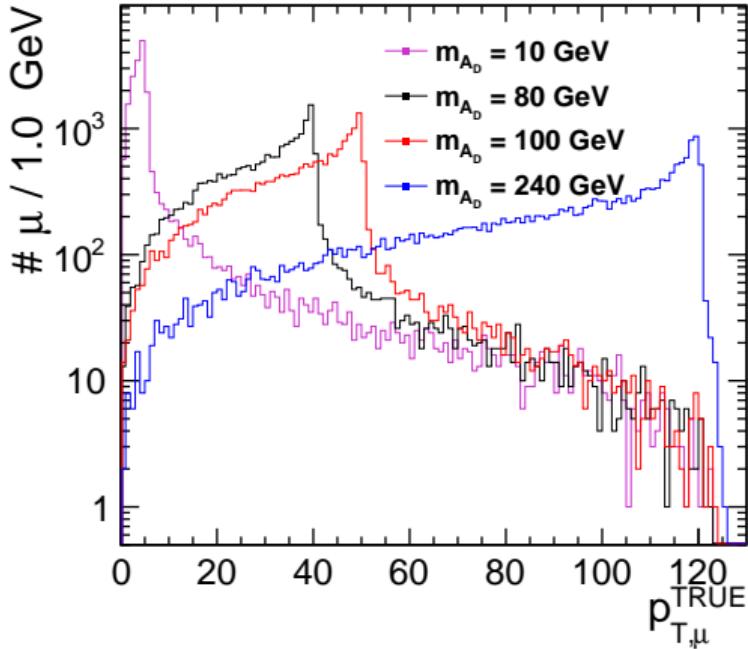


Data Sample

- ▶ $e^+e^- \rightarrow A_D \rightarrow \mu\bar{\mu}$ samples generated using WHIZARD event generator at $\sqrt{s}=250$ GeV.
 - ▶ Use the model of Curtin et al, described in UFO-files (Unified FeynRules Output): as input to Whizard arXiv:1412.0018
 - ▶ 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 PFA)



p_T and $\cos \theta$ of muons

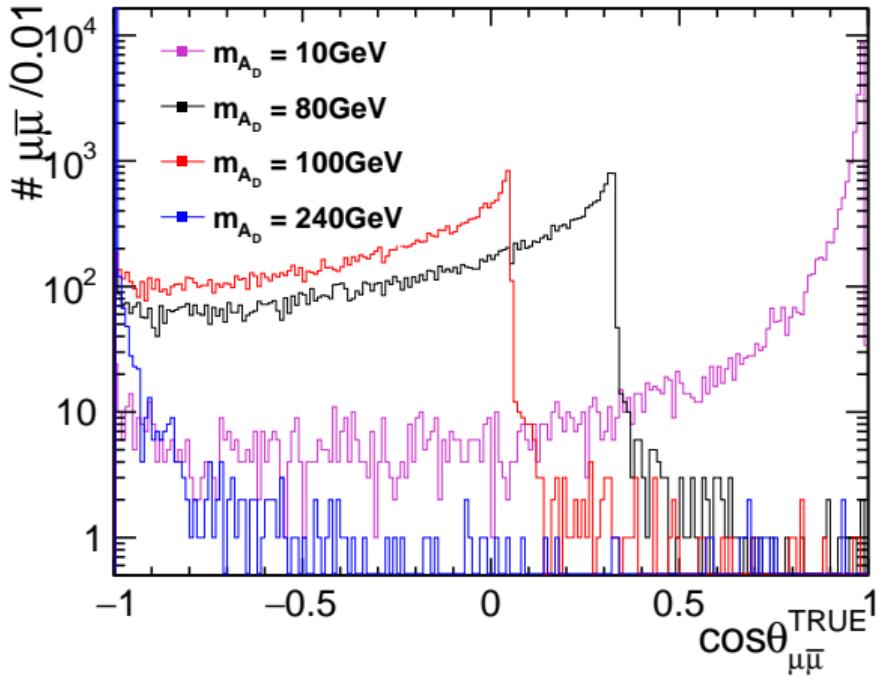


Dark photon detection is highly dependent on m_{A_D} :

- ▶ large mass dark photons: high p_T μ 's \Rightarrow worse momentum (and mass) resolution
- ▶ μ 's close to beam-pipe \Rightarrow hard to detect



Opening angle of di-muons

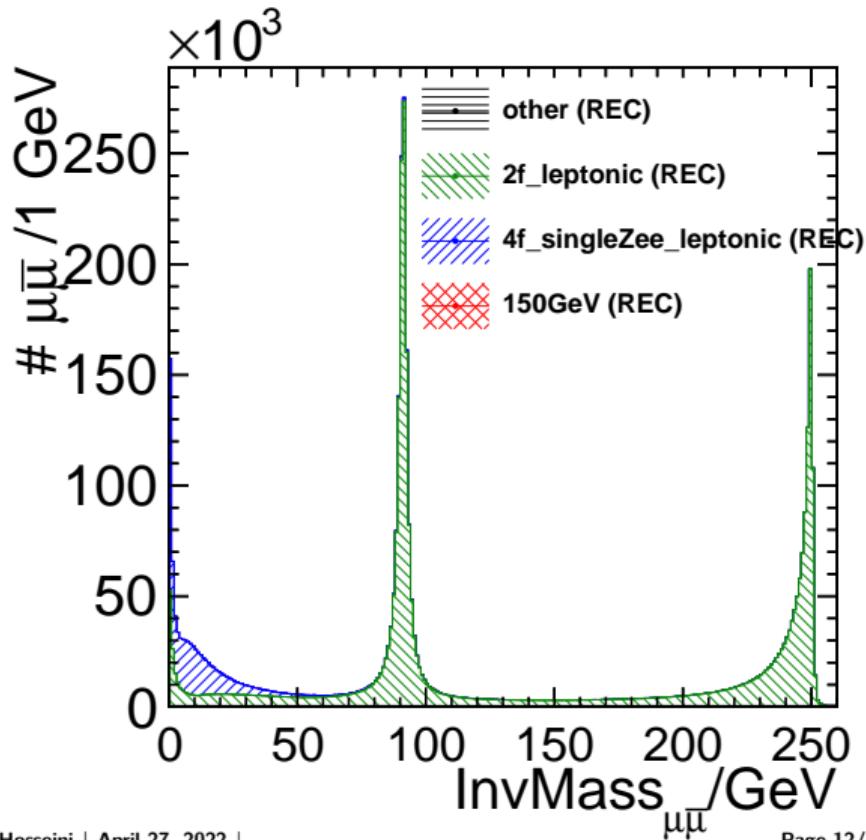


Decay products in high mass are back-to-back \Rightarrow easy to distinguish

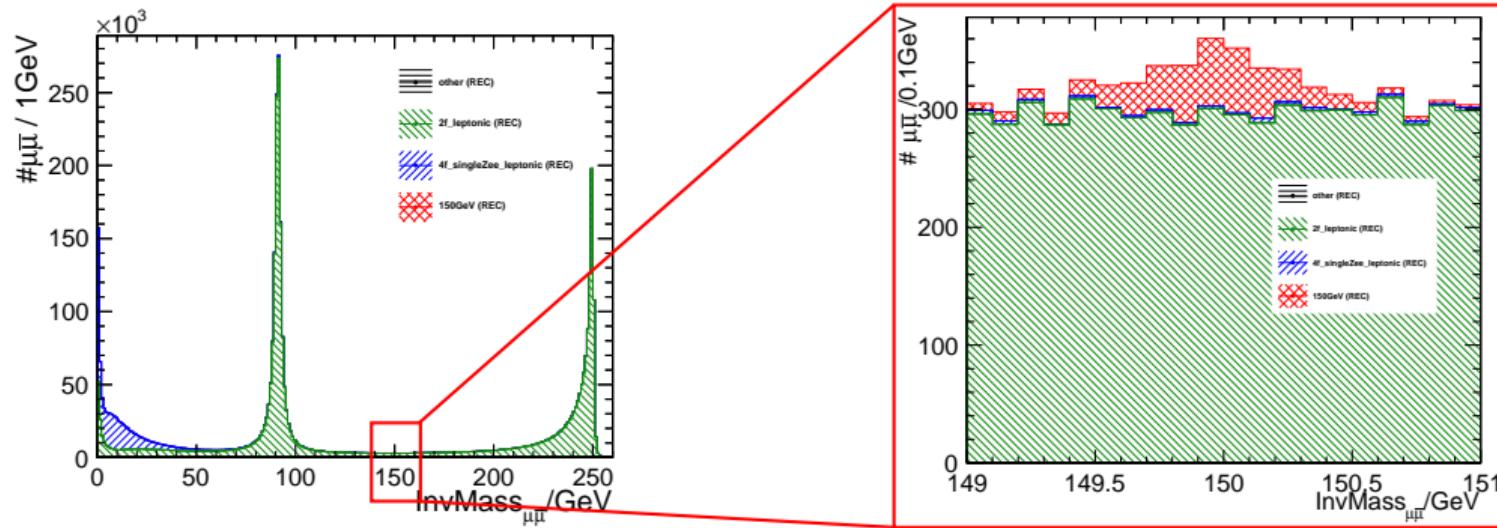


Dark photon invariant mass in presence of SM background

- ▶ 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

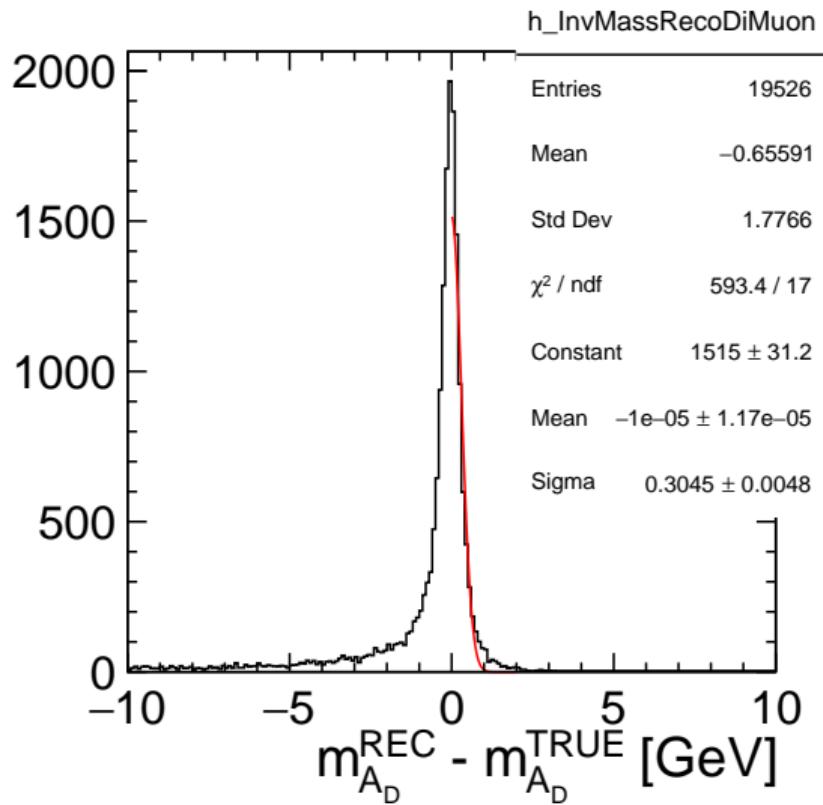


- ▶ Adjust search window width \Rightarrow Get highest $\frac{N_{signal}}{N_{background}}$



A_D search window

- ▶ search for a narrow $\mu^+ \mu^-$ resonance in
 $e^+ e^- \rightarrow A_D + \gamma_{\text{ISR}} \rightarrow \mu^+ \mu^- + \gamma_{\text{ISR}}$
- ▶ better mass resolution (σ_m) \Rightarrow more narrow search window
- ▶ σ_m : width of mass residual ($= m_{A_D}^{\text{REC}} - m_{A_D}^{\text{TRUE}}$;
 $m_{A_D}^{\text{REC}} = m_{\mu^+ \mu^-}^{\text{inv}}$)
- ▶ 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

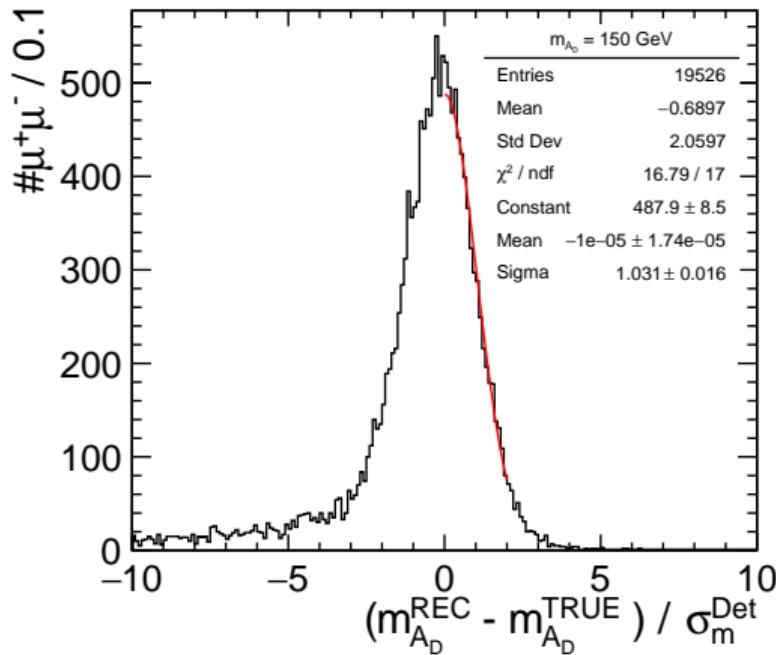
- Normalized Residual of dark photon mass:

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

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

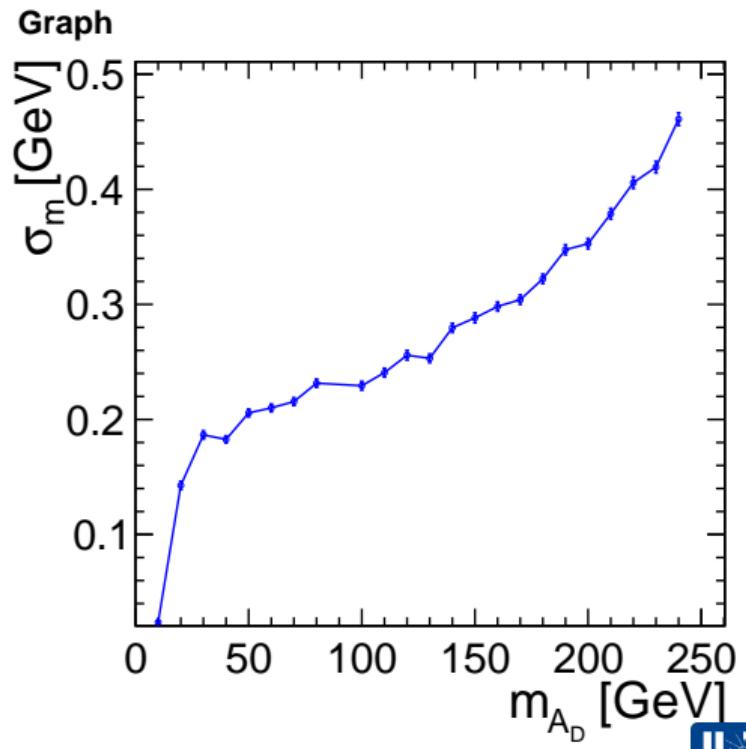
- Propagate CovMatrix of μ^+ and μ^- to $m_{\mu\bar{\mu}}$ uncertainty

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



ILD mass resolution

- ▶ adjust search window \propto dark photon mass
- ⇒ goal: get highest $N_{\text{signal}} / N_{\text{background}}$



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
- ▶ Excellent momentum resolution of ILD ($\sigma_{\frac{1}{pT}}$) 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
- ▶ determine minimum ϵ^2 as a function of m_{A_D} \Rightarrow get an observable signal

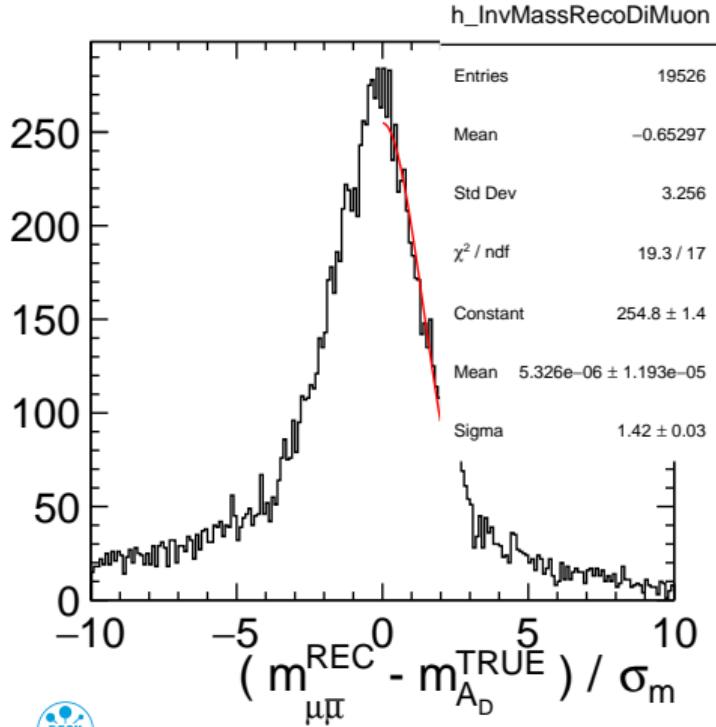


BACKUP



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 $m_{\mu\bar{\mu}}$:

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

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

