Light Dark Portals at Future Lepton Collider

High energy μ's vs High Intensity e's

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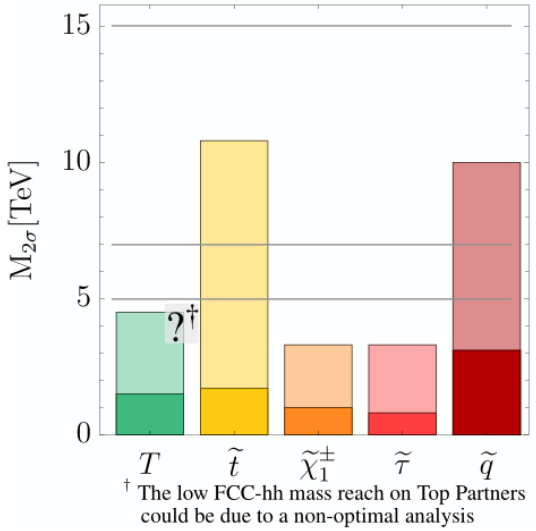
With – Edward Broadberry, Lorenzo Ricci, Gustavo Marques-Tavares

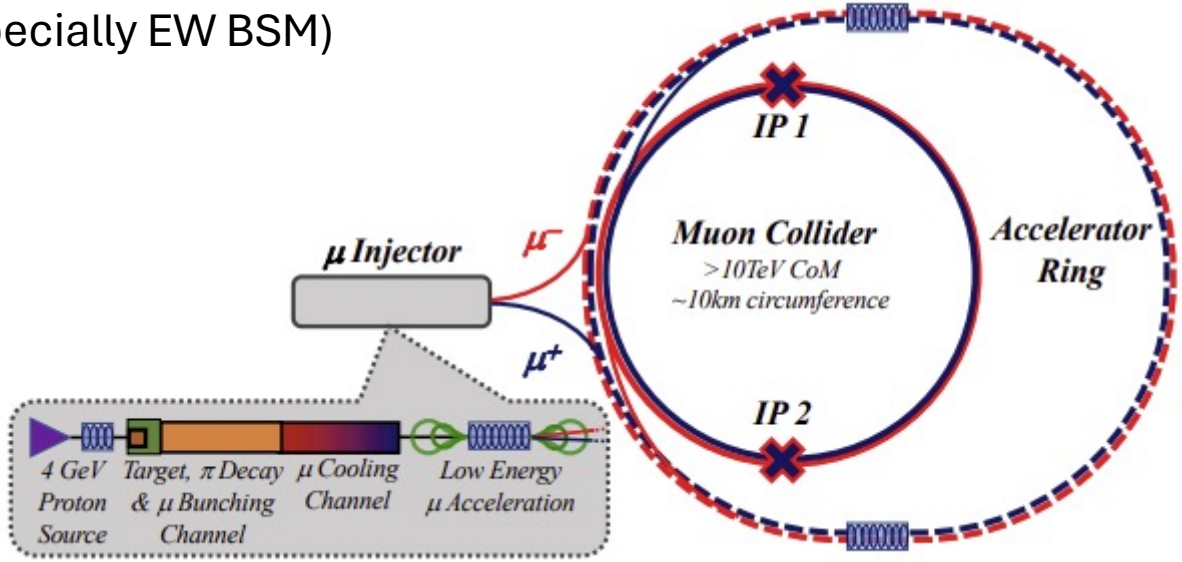
Muon Collider

- **High Energy**
  10 TeV $\mu\mu$ collider ~ 100 TeV pp collider (especially EW BSM)

- **High Precision**
  Clean environment

$$\mathcal{L}_{\text{int}} \sim 10\,\text{ab}^{-1}\left(\frac{\text{E}_{\text{cm}}}{10\text{TeV}}\right)^2$$





Towards a Muon Collider, Accettura, Carlotta et. al.

The physics case of a 3 TeV muon collider stage, de Blas, Jorge et. al.

Muon Collider

- A strong physics case –
  - EW BSM
  - Higgs Physics
    - Compositeness
    - Higgs Potential
    - Higgs Portal
  - Dark Matter
  - g-2
  - Etc.
  - **What else?**

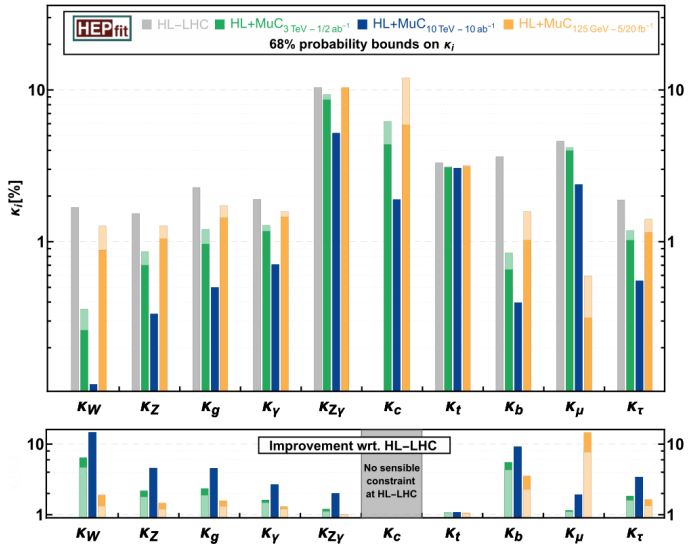
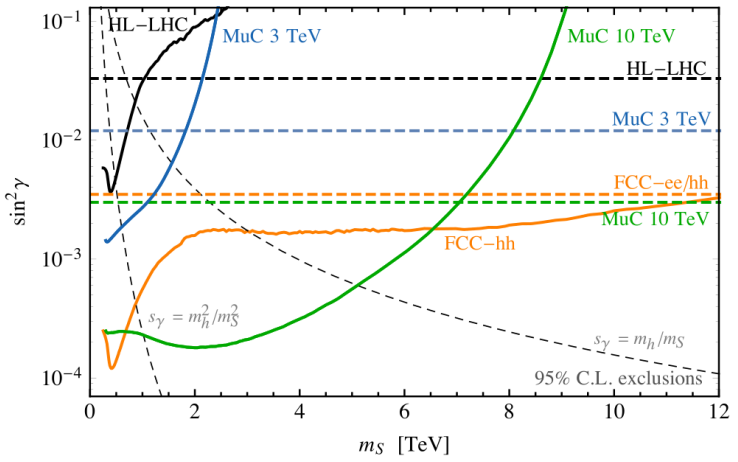


Fig. 82 Sensitivity to modified Higgs couplings in the κ framework. We show the marginalized 68% probability reach for each coupling modifier. For the 125 GeV MuC, light (dark) shades correspond to a luminosity of 5 (20) fb^{-1}. The same color code is used for the 3 TeV MuC with 1 or 2 ab^{-1}.



The physics case of a 3 TeV muon collider stage, de Blas, Jorge et. al.

Light Physics at Muon Collider

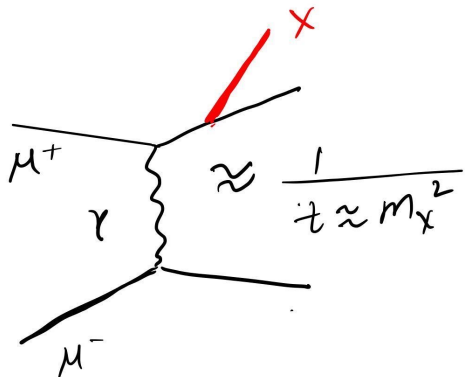
- Naively, direct search for invisible light new physics not the best idea
- Cross-section for s-channel production, when $m_{NP}^2 \ll s$, is roughly $\sigma_{prod} \sim \frac{1}{s}$
- Muon colliders overcome this because Luminosity scales $\sim s$

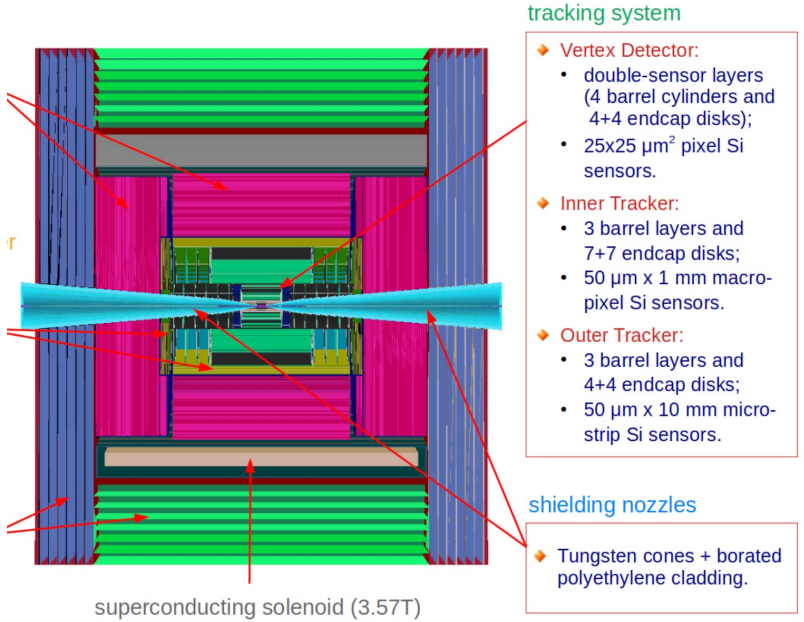
$$\frac{S}{\sqrt{B}} = \frac{\sigma_S \mathcal{L}}{\sqrt{\sigma_B \mathcal{L}}} \sim \frac{\frac{1}{s} \times s}{\sqrt{\frac{1}{s} \times s}}$$

Forward Detectors at Muon Collider

- μ interact very weakly and hence can pass through stuff and can be detected in the forward region
- Therefore, t-channel processes can be tagged efficiently

$$\frac{S}{\sqrt{B}} = \frac{\sigma_S \mathcal{L}}{\sqrt{\sigma_B \mathcal{L}}} \sim \frac{\frac{1}{m^2_{NP}} \times s}{\sqrt{\frac{1}{m^2_{SM}} \times s}}$$





- How effective is this? We look for dark portals…
- We also compare the reach to other future lepton colliders

Invisible Higgs from forward muons at a muon collider, Ruhdorfer, Maximilian et. al.

Higgs Width and Couplings at High Energy Muon Colliders with Forward Muon Detection , Li, Peiran et. al.

Dark Portals

- Well-motivated BSM paradigm

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{dark} + \mathcal{L}_{int}$$

- Possibilities at renormalizable level
  - Higgs Portal- $H^\dagger H S + H^\dagger H S^2$
  - Vector Portal - $B_{\mu\nu} F'^{\mu\nu}$ $\bar{\psi}\gamma^\mu \psi Z'_\mu$
  - Neutrino Portal- $L\tilde{H}N$ Work in Progress

Invisible Higgs from forward muons at a muon collider, Ruhdorfer, Maximilian et. al.

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Focus of this talk

Muon Collider is a Neutrino Collider!

Heavy Neutral Leptons at Muon Colliders, Li, Peiran and Liu, Zhen and Lyu, Kun-Feng

Hypercharge Portal

- A new U(1) gauge boson that kinetically mixes with hypercharge

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{\epsilon}{2c_W}\tilde{F}_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m_D^2\tilde{A}_\mu\tilde{A}^\mu + |D_\mu H|^2 - V(H).$$

- After canonical normalization and diagonalization leads to

$$\frac{e\epsilon}{1-r}Z'_\mu\left(J^\mu_{\text{em}} - \frac{r}{\cos^2\theta_W}J^\mu_Y\right) + \tilde{g}Z'_\mu J^\mu_D, \quad r = \frac{m_D^2}{m_Z^2} \Rightarrow \boxed{\mathcal{L} \supset \epsilon e Z'_\mu J^\mu_{\text{em}} \text{ for r} \ll 1}$$

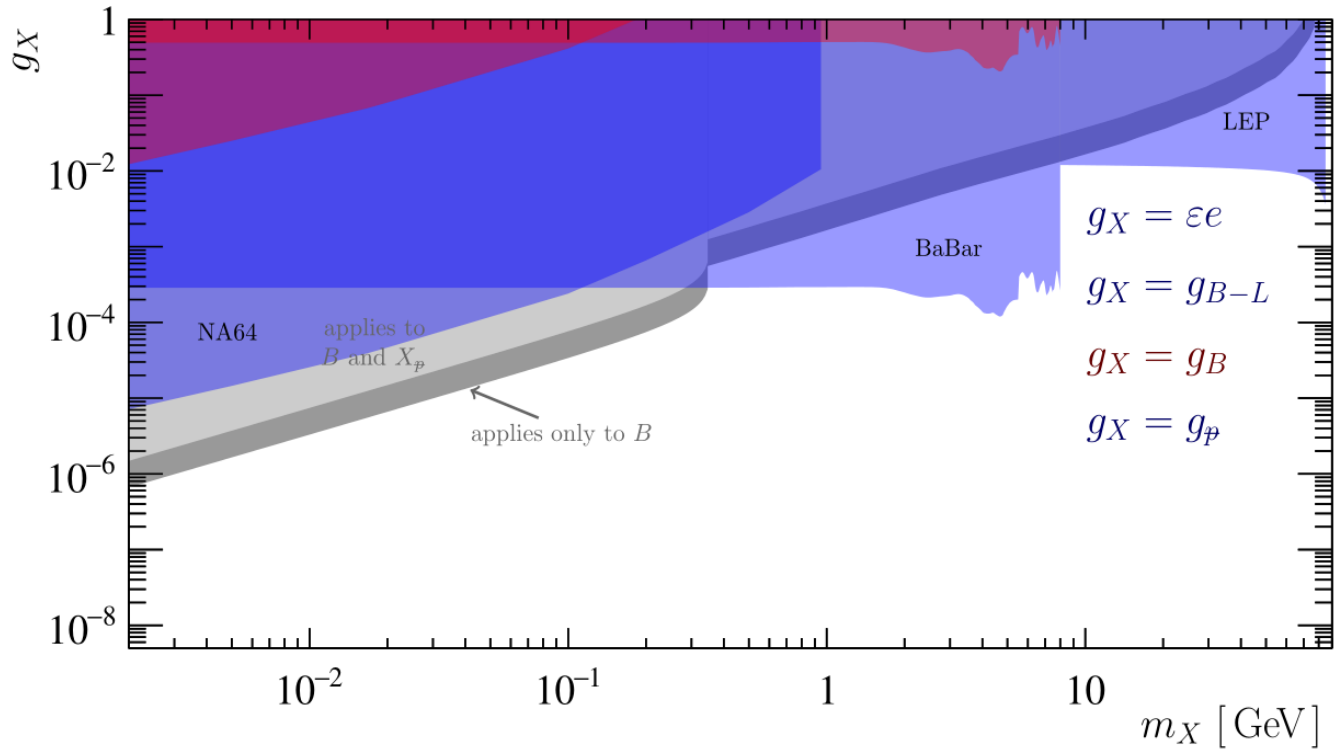
to $O(\epsilon)$.

Hypercharge portal (invisible)

- For $m_D^2 << m_Z^2$,

$$\mathcal{L} \supset \epsilon e Z'_\mu J^\mu_{\text{em}}$$

- We assume $\mathcal{B}(Z' \to \text{dark}) \approx 1$
- Existing constraints from LEP and BaBar



Serendipity in dark photon searches, Ilten et.al.

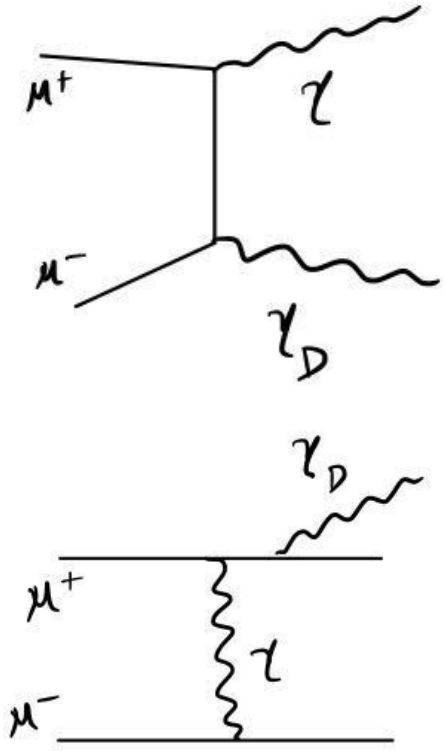
Hypercharge Portal at μ Collider

- We consider the following channels
  - Mono-photon **(conventional search)**

    $$\mu^+ + \mu^- \to \gamma + \gamma_D$$

  - t-channel **(forward search)**

    $$\mu^+ + \mu^- \to \mu^+ + \mu^- + \gamma_D$$



- Primary Backgrounds
  - Monophoton

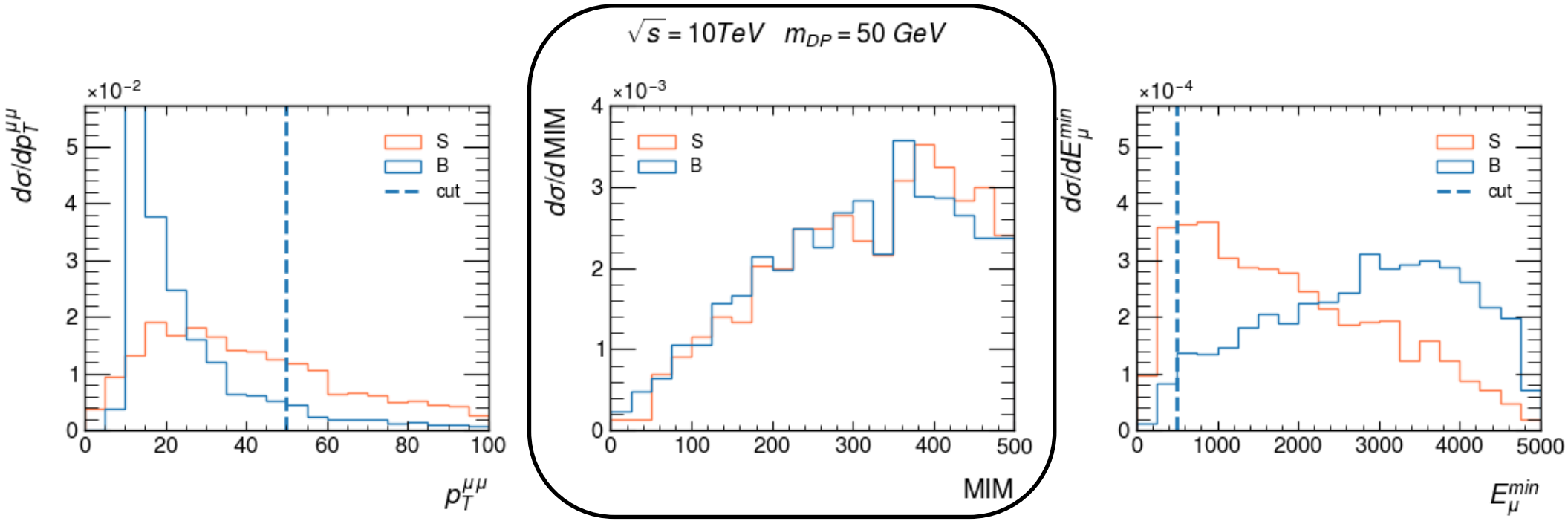
    $$\mu^+ + \mu^- \to \gamma + Z(\text{inv.})$$

  - t-channel

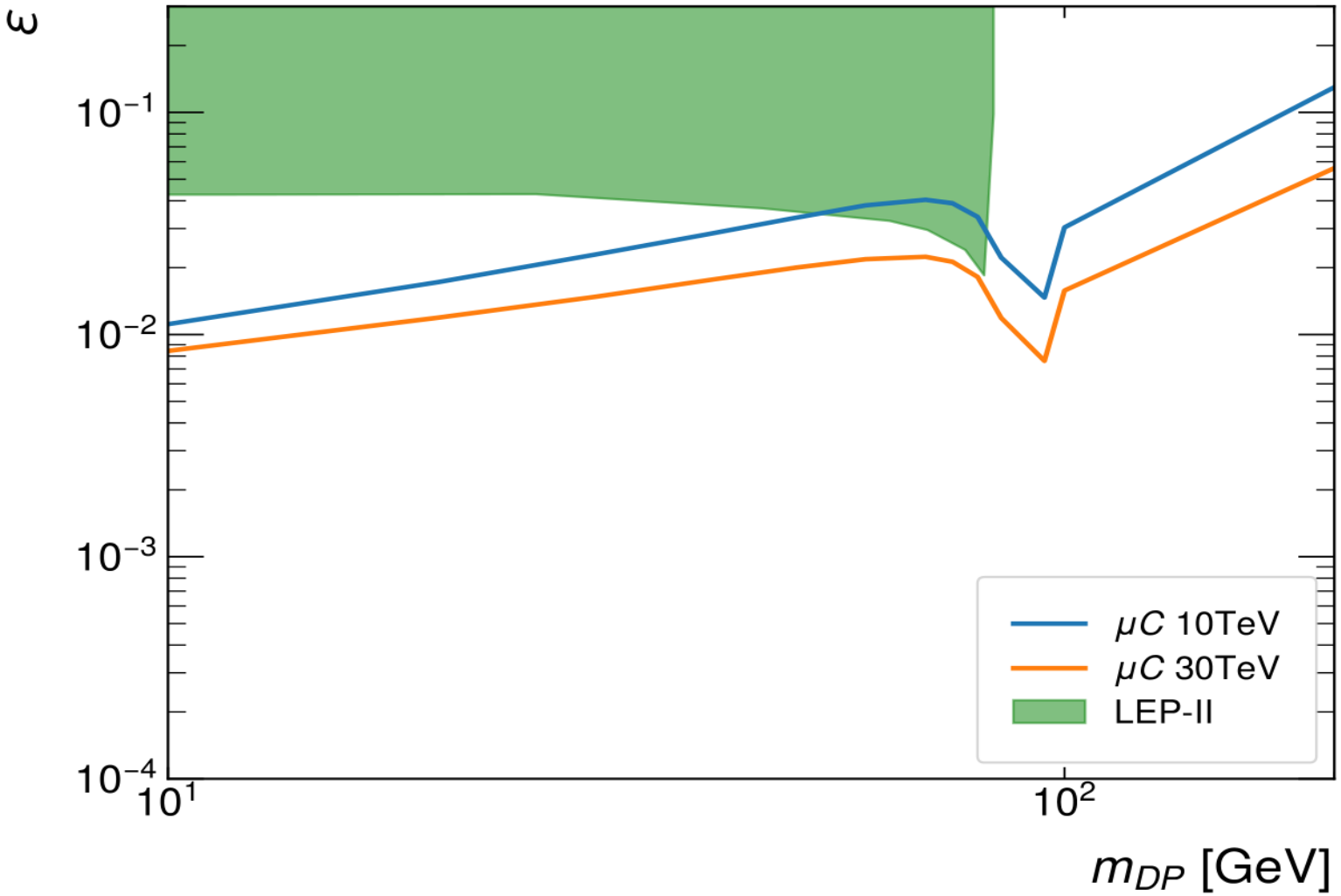
$$\mu^+ + \mu^- \to \mu^+ + \mu^- + \gamma/X\,(\text{forward, undetected})\ \text{or}\ \mu^+ + \mu^- + Z(\text{inv.})$$

Hypercharge portal at μ collider

- Spectrum with detector effects using De10lphes



Hypercharge portal at μ collider



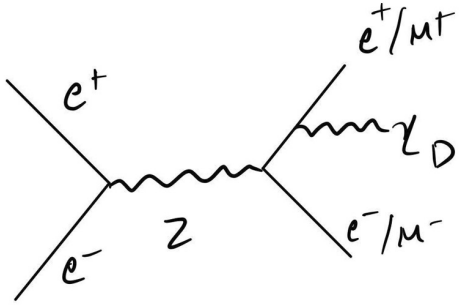
Serendipity in dark photon searches, Ilten et.al.

FCC-ee

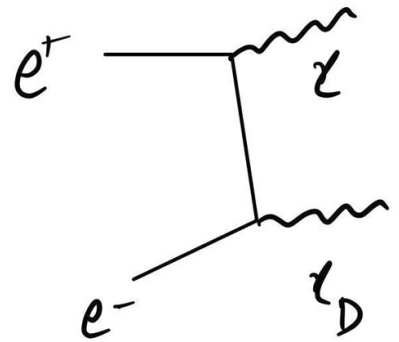
- Rare Z decay, 10^{12} Zs!! For $m_D \ll M_Z$,

$$\Delta\Gamma^{\mathrm{FCC}}_{Z\to\tau^+\tau^-} \lesssim \frac{\epsilon^2\alpha\Gamma_Z}{4\pi}\mathcal{B}(Z\to l^+l^-) \quad \Rightarrow \quad \epsilon \gtrsim 10^{-2}$$

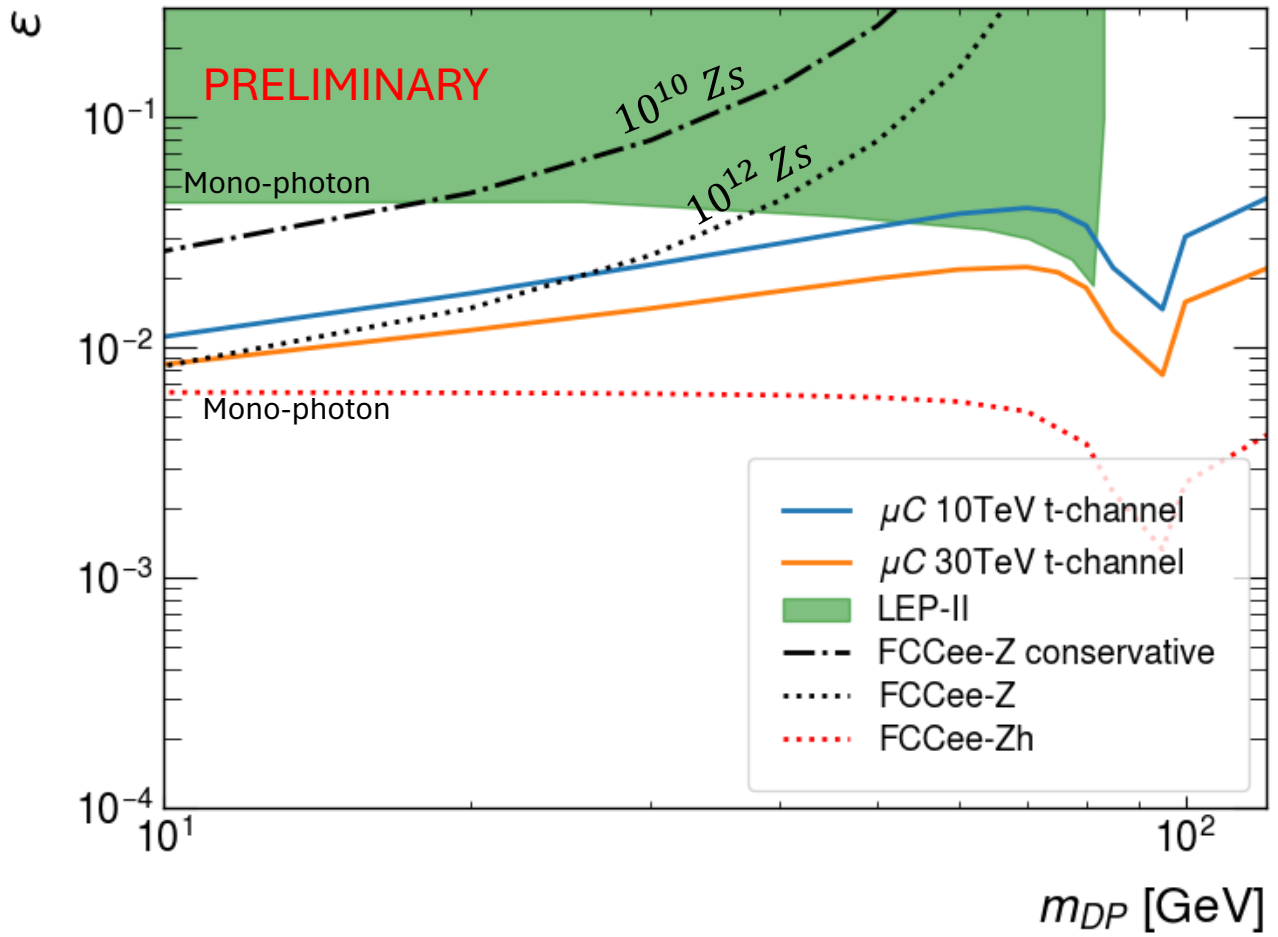
$$\left(\Delta\Gamma^{\mathrm{FCC}}_{Z\to\tau^+\tau^-} \approx \Delta\Gamma^{\mathrm{LEP}}_{Z\to\tau^+\tau^-}\sqrt{\frac{N^{\mathrm{LEP}}}{N^{\mathrm{FCC}}}}\right)$$



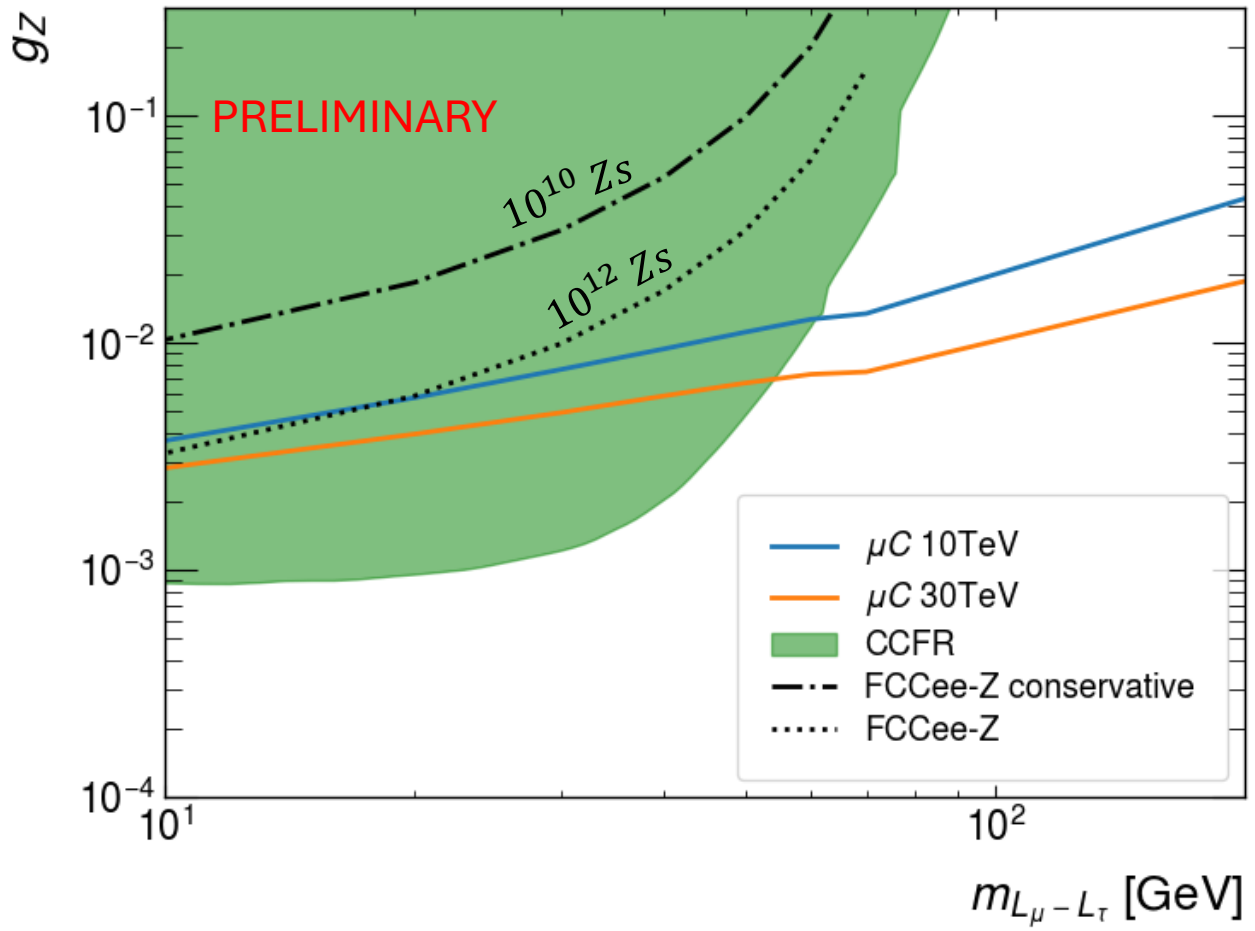
- Mono-γ search at the ZH threshold ~ $10\ ab^{-1}$



Hypercharge portal at future lepton colliders



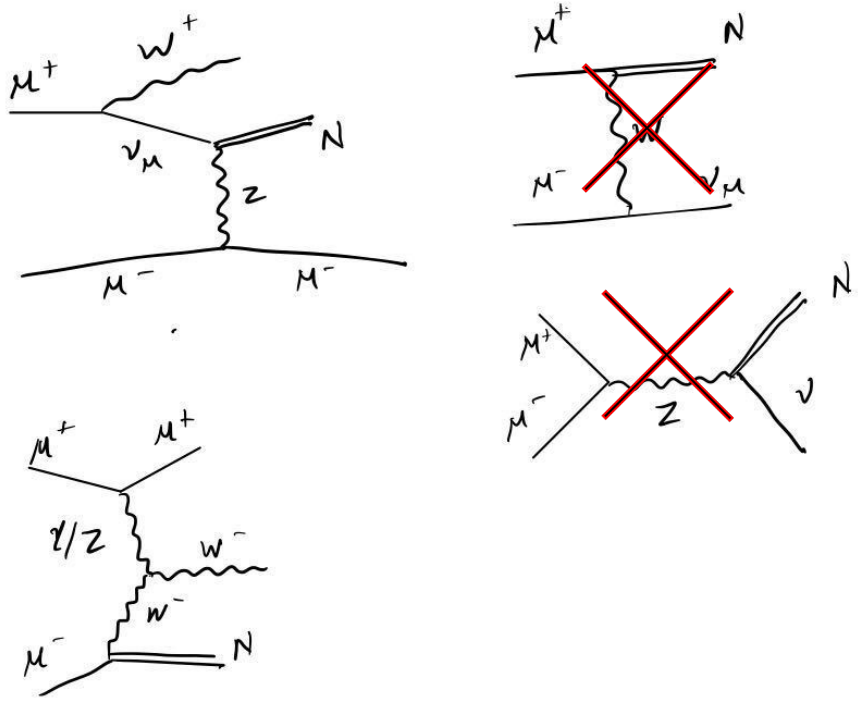
$L_\mu - L_\tau$ portal at future lepton colliders



Neutrino Trident Production: A Powerful Probe of New Physics with Neutrino Beams, Altmannshofer et.al.

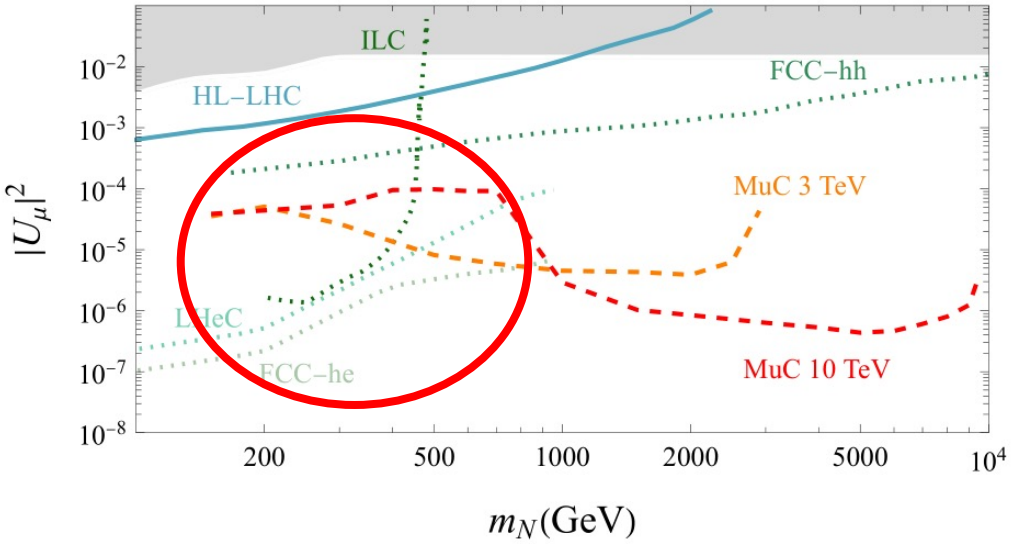
Other Portals

- Neutrino Portal (invisible) – Results very soon



VBF like processes forward detectors can help

Reducing cosmological small scale structure via a large dark matter-neutrino interaction: constraints and consequences, Bertoni et.al.



Heavy Neutral Leptons at Muon Colliders, Li, Peiran and Liu, Zhen and Lyu, Kun-Feng

Conclusions

- Future Lepton Collider are great probe of light invisible new physics
- Despite the high center of mass energy, a muon collider can explore new regions of parameter space for “light” dark portals
- FCC-ee would be one of the best probe for Dark Photons
- Perhaps, forward detector could also improve sensitivity to Neutrino Portals and Higgs Portal
- Watch out for our paper 2406.XXXX

Questions?