Fermion Portal Dark Matter at a Muon Collider

Pouya Asadi

pasadi@uoregon.edu

University of Oregon → UC Santa Cruz

Based on : 2312.03826, 2412.14235
With : Samuel Homiller, Aria Radick, Tien-Tien Yu

Talk Presented @ CIPANP 2025

June 11, 2025

On a High Energy Muon Collider (MuC)

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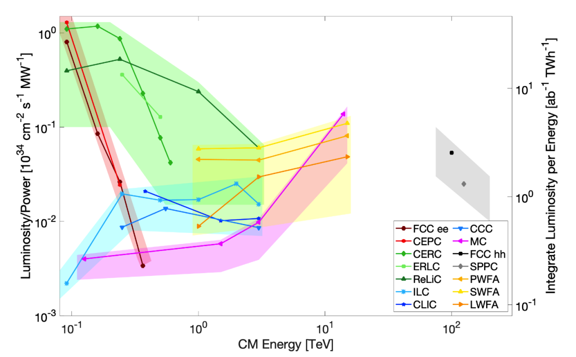

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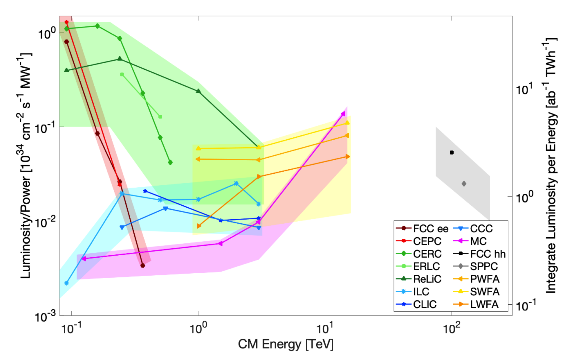

Trove of discussions: KITP workshop 2023.

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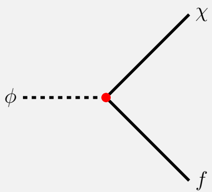

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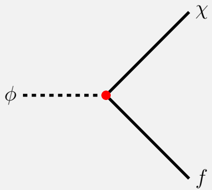

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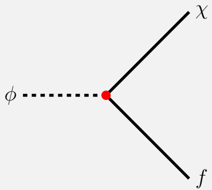

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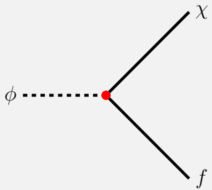

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  $\rightarrow$ Informing benchmark specs for the detector.

Relic Abundance: SuperWIMP + Freeze-in

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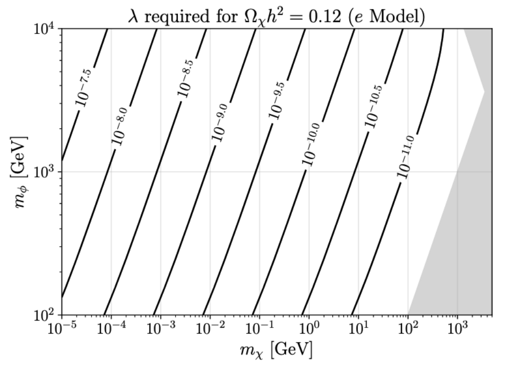

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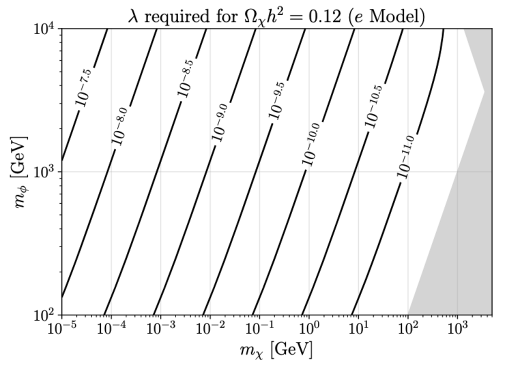

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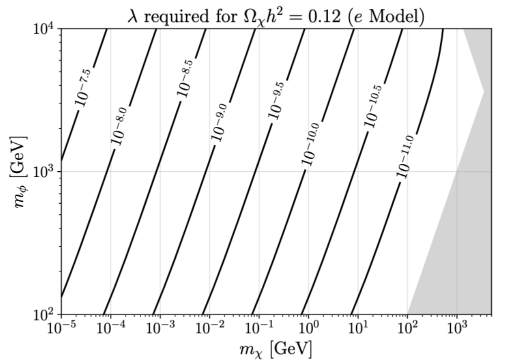
- Direct freeze-in supplements the abundance.



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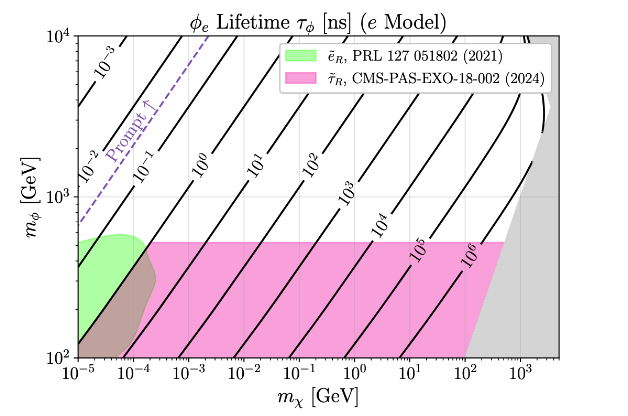

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The μ parton PDF should be included for an accurate calculation of the reach.

A Cut-and-Count Analysis for ϕ_f

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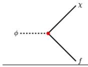
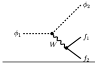
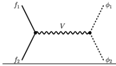
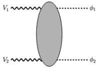
	$\phi_e \to e\chi$	$\phi_L^0 \to \nu\chi$ $\phi_L^- \to \ell^-\chi$	$\phi_u \to u\chi$	$\phi_Q^{2/3} \to u\chi$ $\phi_Q^{-1/3} \to d\chi$
		$\phi_L^- \to \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3} \to \phi_Q^{-1/3} e^+ \nu_e$
	$\mu\mu \to \phi_e\phi_e$	$\mu\mu \to \phi_L^+\phi_L^-$ $\mu\mu \to \phi_L^0\phi_L^0$	$\mu\mu \to \phi_u\phi_u$	$\mu\mu \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $\mu\mu \to \phi_Q^{1/3}\phi_Q^{-1/3}$
	$VV \to \phi_e\phi_e$	$VV \to \phi_L^+\phi_L^-$ $VV \to \phi_L^0\phi_L^0$ $VV \to \phi_L^0\phi_L^\pm$	$VV \to \phi_u\phi_u$	$VV \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $VV \to \phi_Q^{1/3}\phi_Q^{-1/3}$ $VV \to \phi_Q^{2/3}\phi_Q^{1/3}$

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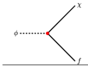
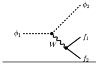
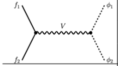
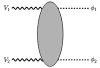
	$\phi_e \to e\chi$	$\phi_L^0 \to \nu\chi$ $\phi_L^- \to \ell^-\chi$	$\phi_u \to u\chi$	$\phi_Q^{2/3} \to u\chi$ $\phi_Q^{-1/3} \to d\chi$
		$\phi_L^- \to \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3} \to \phi_Q^{-1/3} e^+ \nu_e$
	$\mu\mu \to \phi_e\phi_e$	$\mu\mu \to \phi_L^+\phi_L^-$ $\mu\mu \to \phi_L^0\phi_L^0$	$\mu\mu \to \phi_u\phi_u$	$\mu\mu \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $\mu\mu \to \phi_Q^{1/3}\phi_Q^{-1/3}$
	$VV \to \phi_e\phi_e$	$VV \to \phi_L^+\phi_L^-$ $VV \to \phi_L^0\phi_L^0$ $VV \to \phi_L^0\phi_L^\pm$	$VV \to \phi_u\phi_u$	$VV \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $VV \to \phi_Q^{1/3}\phi_Q^{-1/3}$ $VV \to \phi_Q^{2/3}\phi_Q^{1/3}$

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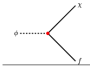
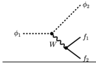
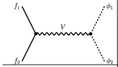
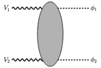
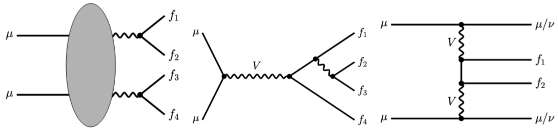
	$\phi_e \to e\chi$	$\phi_L^0 \to \nu\chi$ $\phi_L^- \to \ell^-\chi$	$\phi_u \to u\chi$	$\phi_Q^{2/3} \to u\chi$ $\phi_Q^{-1/3} \to d\chi$
		$\phi_L^- \to \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3} \to \phi_Q^{-1/3} e^+ \nu_e$
	$\mu\mu \to \phi_e\phi_e$	$\mu\mu \to \phi_L^+\phi_L^-$ $\mu\mu \to \phi_L^0\phi_L^0$	$\mu\mu \to \phi_u\phi_u$	$\mu\mu \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $\mu\mu \to \phi_Q^{1/3}\phi_Q^{-1/3}$
	$VV \to \phi_e\phi_e$	$VV \to \phi_L^+\phi_L^-$ $VV \to \phi_L^0\phi_L^0$ $VV \to \phi_L^0\phi_L^\pm$	$VV \to \phi_u\phi_u$	$VV \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $VV \to \phi_Q^{1/3}\phi_Q^{-1/3}$ $VV \to \phi_Q^{2/3}\phi_Q^{1/3}$



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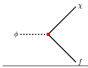
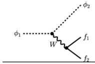
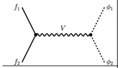
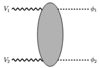
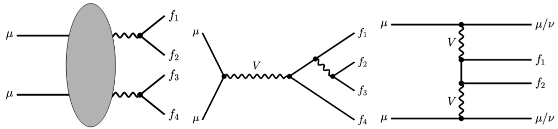
	$\phi_e \to e\chi$	$\phi_L^0 \to \nu\chi$ $\phi_L^- \to \ell^-\chi$	$\phi_u \to u\chi$	$\phi_Q^{2/3} \to u\chi$ $\phi_Q^{-1/3} \to d\chi$
		$\phi_L^- \to \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3} \to \phi_Q^{-1/3} e^+ \nu_e$
	$\mu\mu \to \phi_e\phi_e$	$\mu\mu \to \phi_L^+\phi_L^-$ $\mu\mu \to \phi_L^0\phi_L^0$	$\mu\mu \to \phi_u\phi_u$	$\mu\mu \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $\mu\mu \to \phi_Q^{1/3}\phi_Q^{-1/3}$
	$VV \to \phi_e\phi_e$	$VV \to \phi_L^+\phi_L^-$ $VV \to \phi_L^0\phi_L^0$ $VV \to \phi_L^0\phi_L^\pm$	$VV \to \phi_u\phi_u$	$VV \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $VV \to \phi_Q^{1/3}\phi_Q^{-1/3}$ $VV \to \phi_Q^{2/3}\phi_Q^{1/3}$



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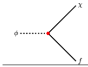
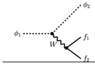
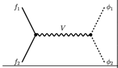
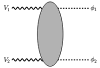
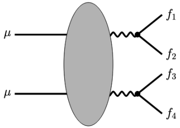
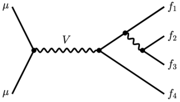
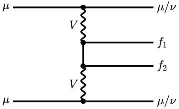
	$\phi_e \to e\chi$	$\phi_L^0 \to \nu\chi$ $\phi_L^- \to \ell^-\chi$	$\phi_u \to u\chi$	$\phi_Q^{2/3} \to u\chi$ $\phi_Q^{-1/3} \to d\chi$
		$\phi_L^- \to \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3} \to \phi_Q^{-1/3} e^+ \nu_e$
	$\mu\mu \to \phi_e\phi_e$	$\mu\mu \to \phi_L^+\phi_L^-$ $\mu\mu \to \phi_L^0\phi_L^0$	$\mu\mu \to \phi_u\phi_u$	$\mu\mu \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $\mu\mu \to \phi_Q^{1/3}\phi_Q^{-1/3}$
	$VV \to \phi_e\phi_e$	$VV \to \phi_L^+\phi_L^-$ $VV \to \phi_L^0\phi_L^0$ $VV \to \phi_L^0\phi_L^\pm$	$VV \to \phi_u\phi_u$	$VV \to \phi_Q^{2/3}\phi_Q^{-2/3}$ $VV \to \phi_Q^{1/3}\phi_Q^{-1/3}$ $VV \to \phi_Q^{2/3}\phi_Q^{1/3}$







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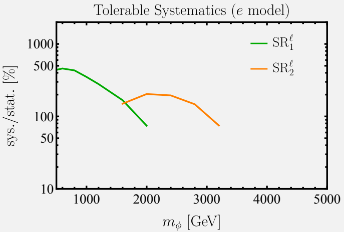
Effective reduction of bkg.

Significance Plots and Tolerable Systematics



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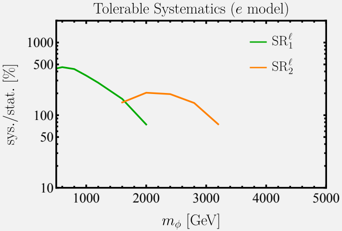

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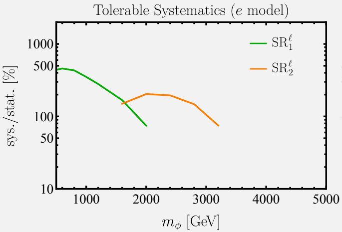

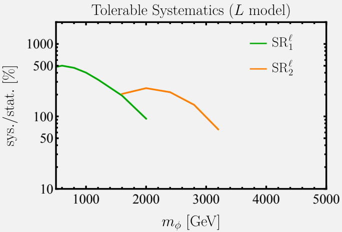

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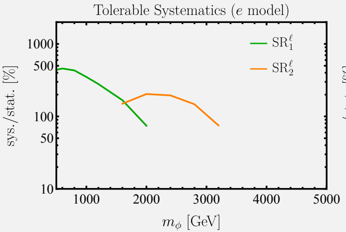

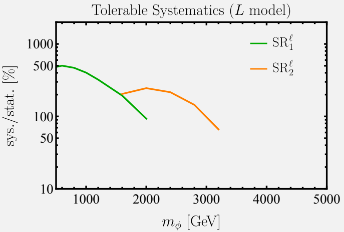

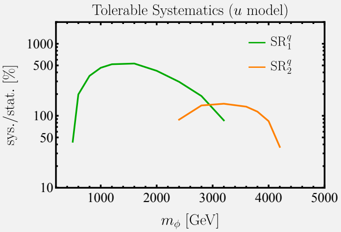

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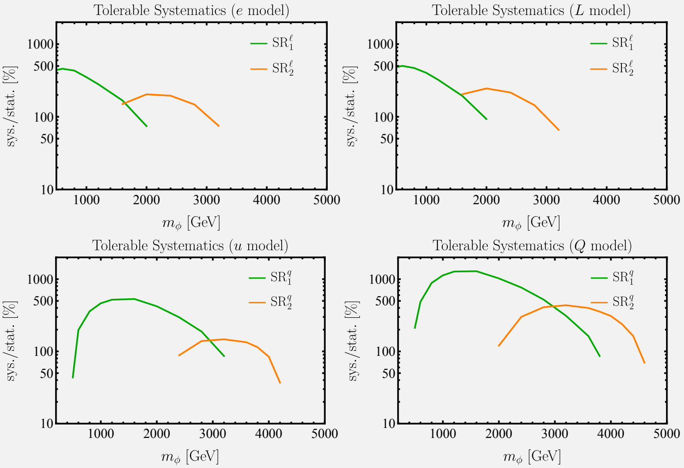

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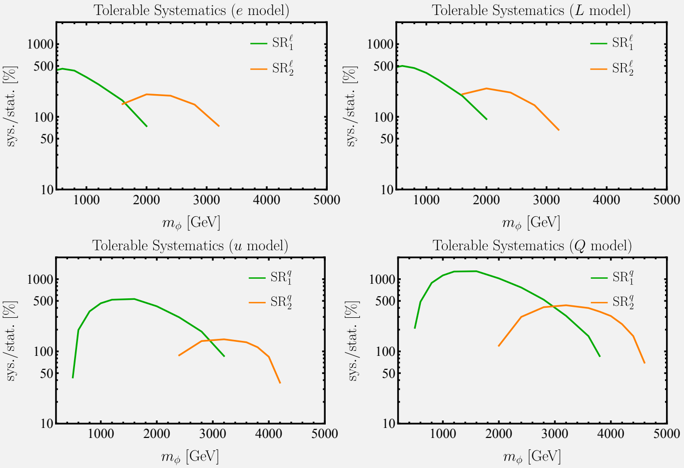

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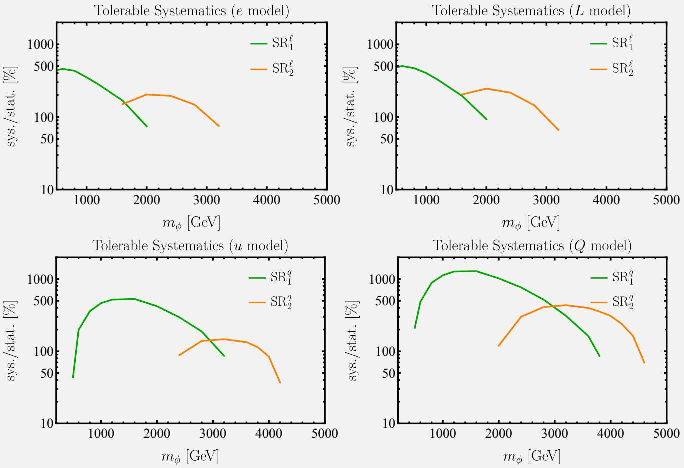
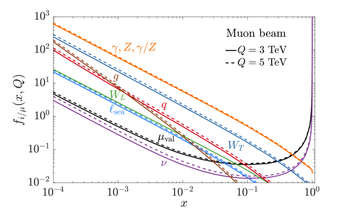


- Upto large masses discoverable.
- Large sys. tolerable.
- Why not the entire kinematically accessible region?

Muon Parton PDF

- Muons have a non-trivial PDF themselves. Diverges at $x \to 1$.



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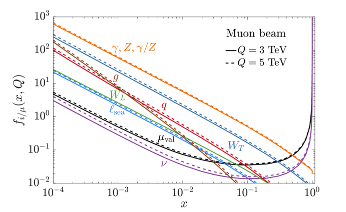

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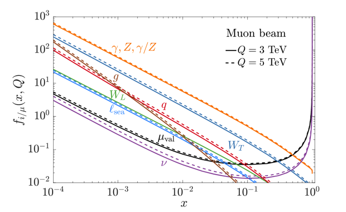

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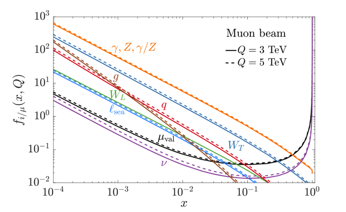

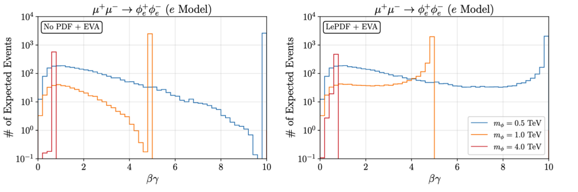

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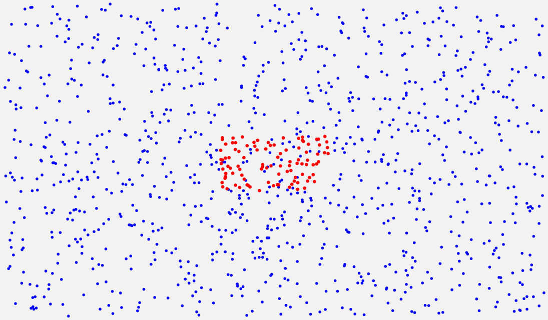

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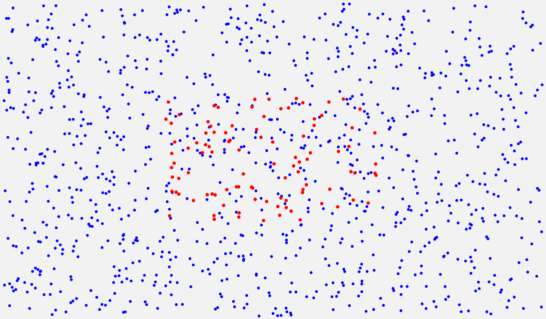

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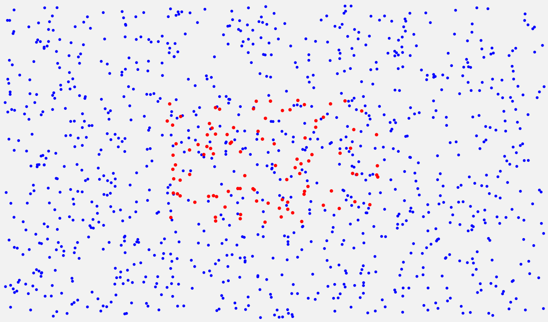

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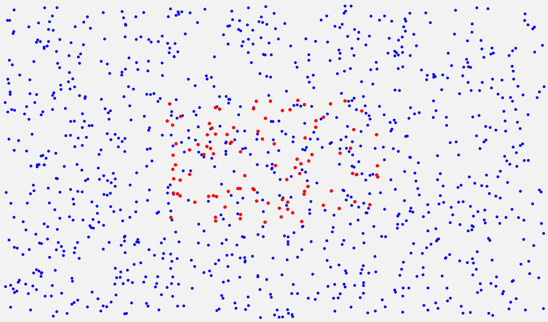
- Include the μ parton PDF in your analyses!



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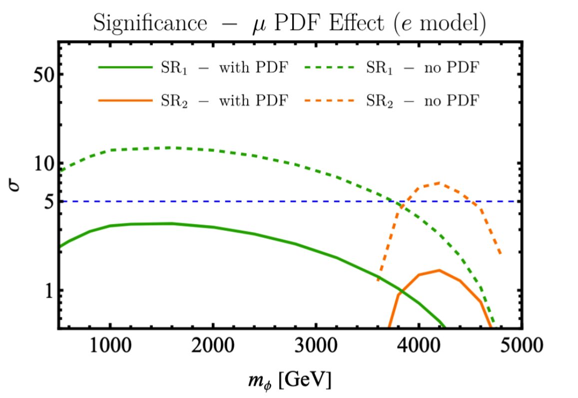
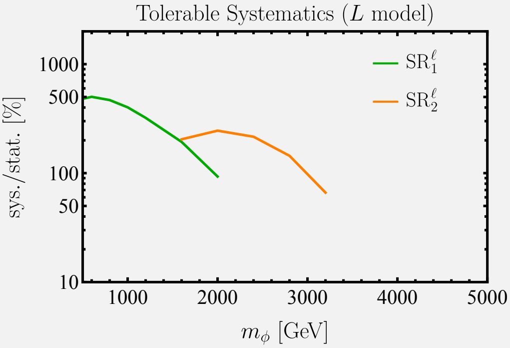
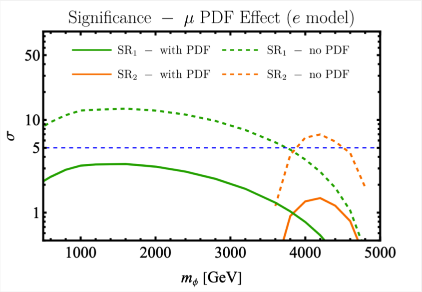


Summary

Search for fermion portal dark matter at a MuC. $\mathcal{O}(100\%)$ sys. tolerable.



μ parton PDF ought to be included for viable predictions.



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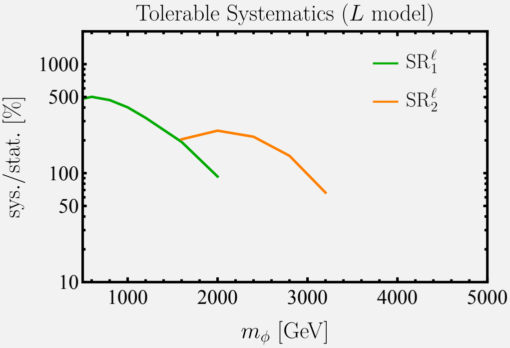
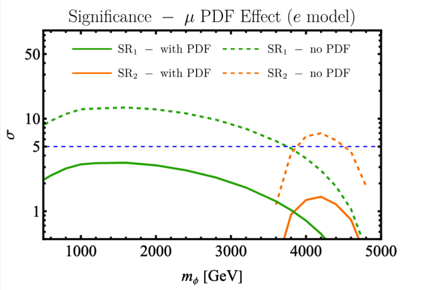




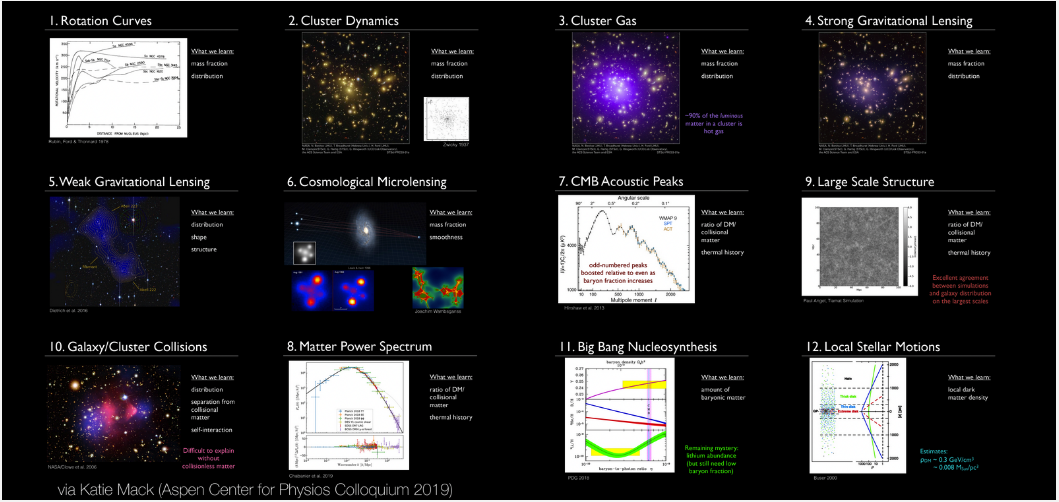
THANK YOU!

Back up

- Evidence For DM
- Exact Cuts

- Event Distribution Histograms
- μPDF Implementation
- LLP Signal Yields

Evidence for DM



Exact Cuts

Leptons

$$\left\{m_{\ell\ell} \geqslant 300\ \text{GeV}, \theta_{\ell\ell} \geqslant \frac{8\pi}{9}, |\eta_\ell| \leqslant 0.3, M_{T2} \geqslant 150\ \text{GeV}, E_\ell \geqslant 600\ \text{GeV}\right\}$$

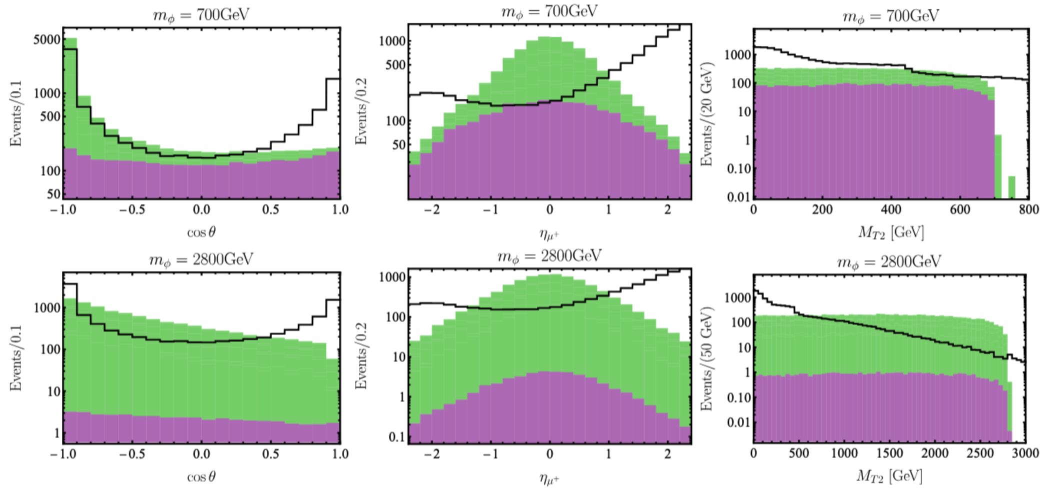
$$\left\{m_{\ell\ell} \geqslant 300\ \text{GeV}, \theta_{\ell\ell} \geqslant \frac{13\pi}{18}, |\eta_\ell| \leqslant 0.2, M_{T2} \geqslant 800\ \text{GeV}, E_\ell \geqslant 1800\ \text{GeV}\right\}$$

Quarks

$$\left\{m_{jj} \geqslant 3600\ \text{GeV}, \theta_{jj} \geqslant \frac{7\pi}{9}, |\eta_j| \leqslant 0.5, M_{T2} \geqslant 400\ \text{GeV}, E_j \geqslant 900\ \text{GeV}\right\}$$

$$\left\{m_{jj} \geqslant 1500\ \text{GeV}, \theta_{jj} \geqslant \frac{\pi}{4}, |\eta_j| \leqslant 0.7, M_{T2} \geqslant 1600\ \text{GeV}, E_j \geqslant 1600\ \text{GeV}\right\}$$

Histograms



$m_\phi = 700$GeV
Events/0.1
$\cos\theta$
Events/0.2
η_{μ^+}
Events/(20 GeV)
M_{T2} [GeV]
$m_\phi = 2800$GeV
Events/(50 GeV)

Hurdles in Implementing PDFs

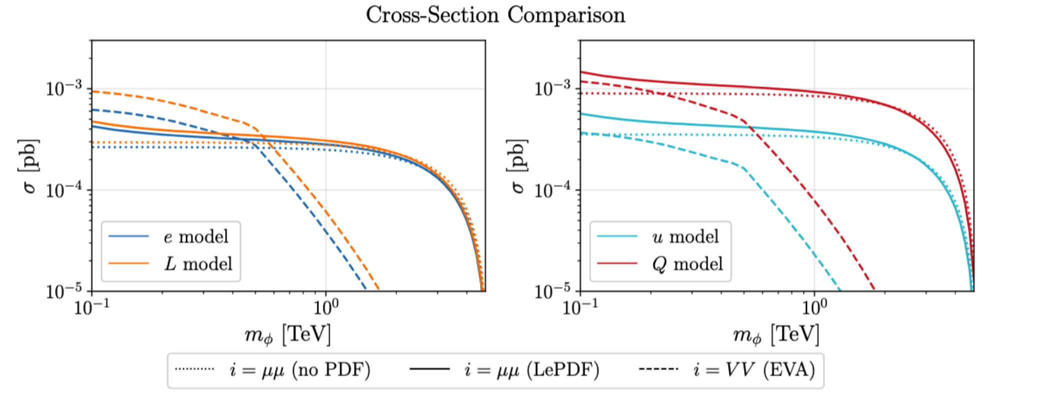
- Chirality matters!
- Interference PDFs (γ, Z, H).
- μ PDF itself (integrable divergence at $x \to 1$).

Implementing the μ Parton PDF

- Each muon helicity is separately implemented as an LHAPDF file.
- $f_\mu(x, Q^2) \equiv \tilde{f}_\mu(x, Q^2) + c_\mu(Q^2)\delta(1-x)$.
- $c_{L/R,\mu}(Q^2)$: determined from sum rules for (i) the total muon number and (ii) the total polarization (left/right).
- $c_\mu(Q^2)$ varies with Q^2.
- 2 polarization $\times$ ($x = 1$ or $x < 1$) per beam: 8 runs.

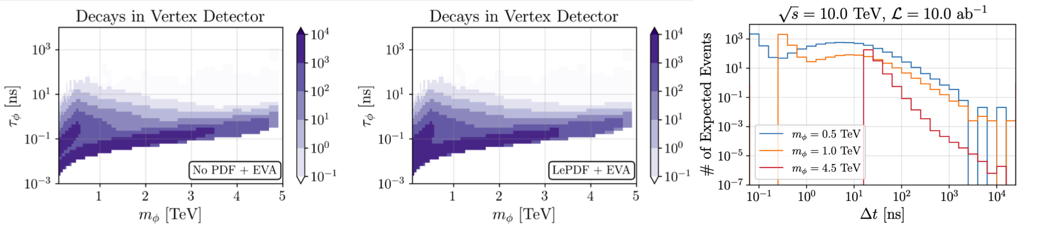
$$\begin{aligned}
\frac{\mathrm{d}\mathcal{L}_{\mu^+\mu^-}}{\mathrm{d}\tau} &= \int_\tau^1 \frac{\mathrm{d}x}{x} f_{\mu^+}(x, Q_f) f_{\mu^-}(\tau/x, Q_f) \\
&= \frac{\mathrm{d}\tilde{\mathcal{L}}_{\mu^+\mu^-}}{\mathrm{d}\tau} + c_{\mu^+} c_{\mu^-} \delta(1-\tau) + c_{\mu^+} \tilde{f}_{\mu^-}(\tau) + c_{\mu^-} \tilde{f}_{\mu^+}(\tau),
\end{aligned}$$

Total Cross Section



LLP Signals

- VBF or μ: Two production channels with different kinematics
- SM bkg is reducible, *e.g.* by arriving timing data.



- Remaining bkg: detector response. Requires extensive GEANT4 simulation.
- Displaced lepton/jet signal yield reported in each detector component.

LLP Signals

- Max $\mathcal{O}(1000)$ events. Especially heavy stable charged particles or R-hadron.