

Fermion Portal Dark Matter at a Muon Collider

Pouya Asadi

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UC Santa Cruz

Based on : 2312.03826, 2412.14235

With : Samuel Homiller, Aria Radick, Tien-Tien Yu

Talk Presented @ USMCC 2025

August 8, 2025

Include the Muon PDF in the Simulation Pipeline!

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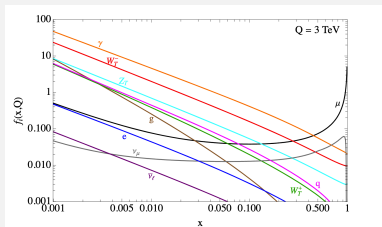
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Muon Parton PDF

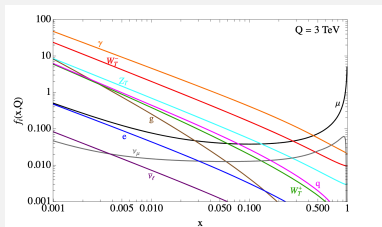
Muon Parton PDF

- Two major production channels (initial μ - VBF).



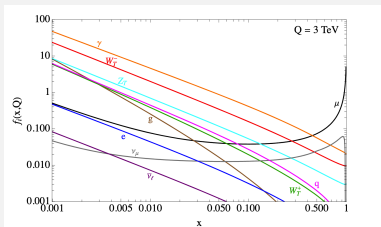
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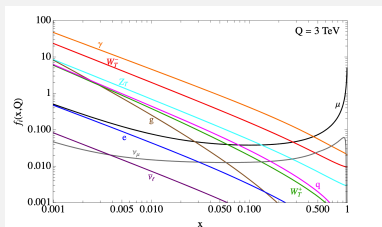
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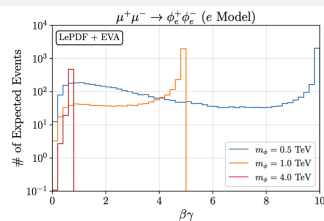
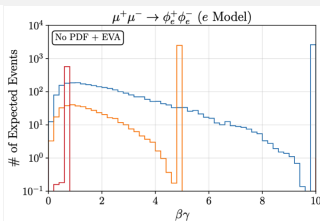
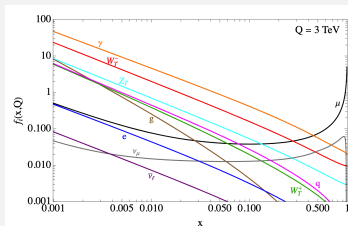
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- Including the μ parton PDF changes the kinematics:



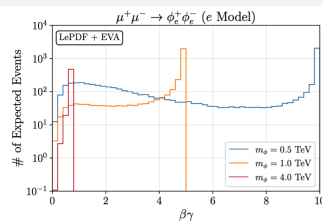
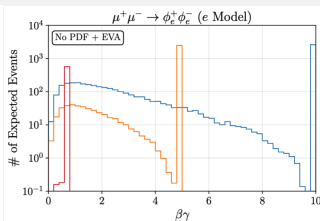
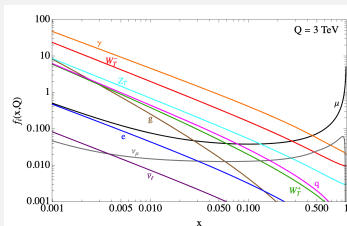
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Muon Parton PDF

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- μ parton PDF is not included in standard simulation pipelines yet.
- We included the μ parton PDF in our simulation.
- Including the μ parton PDF changes the kinematics:
 - filled up a gap,
 - decrease the peak.



Implementing the μ Parton PDF

- Each muon helicity is separately implemented as an LHAPDF file.

$$f_{\mu}^{L/R}(x, Q^2) \equiv \tilde{f}_{\mu}^{L/R}(x, Q^2) + c_{\mu}^{L/R}(Q^2)\delta(1-x).$$

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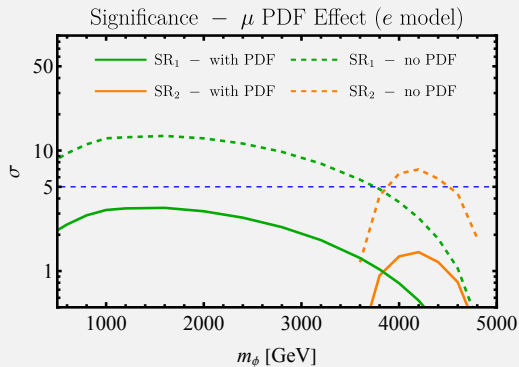
$$\begin{aligned} \frac{d\mathcal{L}_{\mu^+\mu^-}}{d\tau} &= \int_{\tau}^1 \frac{dx}{x} f_{\mu^+}(x, Q_f) f_{\mu^-}(\tau/x, Q_f) \\ &= \frac{d\tilde{\mathcal{L}}_{\mu^+\mu^-}}{d\tau} + c_{\mu^+}c_{\mu^-}\delta(1-\tau) + c_{\mu^+}\tilde{f}_{\mu^-}(\tau) + c_{\mu^-}\tilde{f}_{\mu^+}(\tau), \end{aligned}$$

Effect of Muon Parton PDF

- Including the PDF could diminish the mass reach.

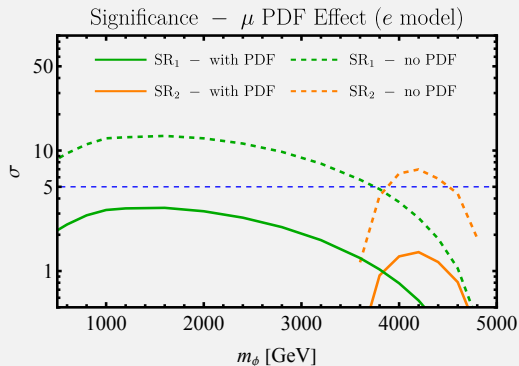
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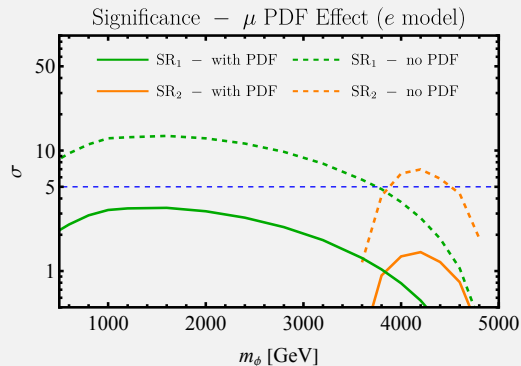
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- The drop depends on the model and the cuts (SRs).



Effect of Muon Parton PDF

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Include the μ parton PDF in your simulation pipeline!

Freeze-in Fermion Portals

$$\mathcal{L} \supset \lambda \phi_f f^\dagger \chi + h.c.$$

Freeze-in Fermion Portals

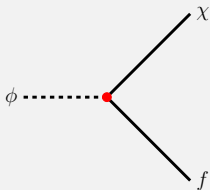
$$\mathcal{L} \supset \lambda \phi_f f^\dagger \chi + h.c.$$

f	Q	u	d	e	L
SM Charges	$(\mathbf{3}, \mathbf{2}, 1/6)$	$(\mathbf{3}, \mathbf{1}, 2/3)$	$(\mathbf{3}, \mathbf{1}, -1/3)$	$(\mathbf{1}, \mathbf{1}, -1)$	$(\mathbf{1}, \mathbf{2}, -1/2)$

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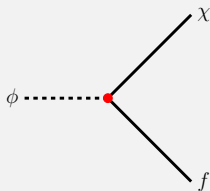


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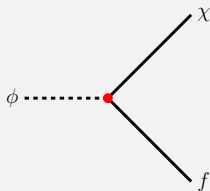
- Will study ϕ_f in the freeze-in limit at a 10 TeV MuC.



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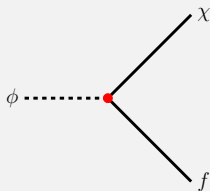


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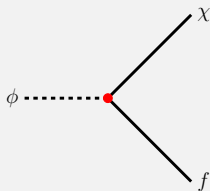


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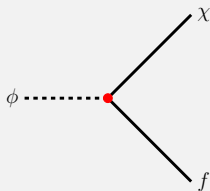


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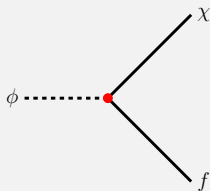


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 - Highlighting the effect of μ parton PDF.

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- Will study ϕ_f in the freeze-in limit at a 10 TeV MuC.
- Motivated dark matter model:
 - Informing benchmark specs for the detector.
 - Both prompt and LLP signals.
 - Highlighting the effect of μ parton PDF.
 - List useful kinematic cuts.

Relic Abundance: SuperWIMP + Freeze-in

$$\mathcal{L} \supset \lambda \phi_f f^\dagger \chi + h.c.$$

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Relic Abundance: SuperWIMP + Freeze-in

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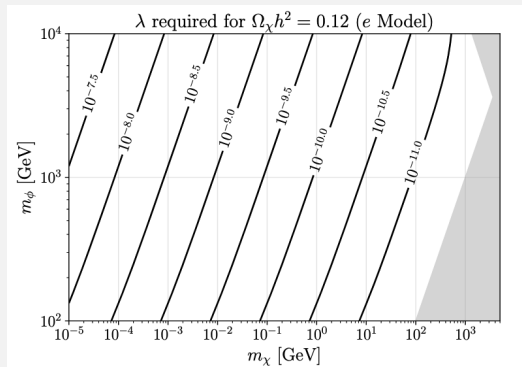
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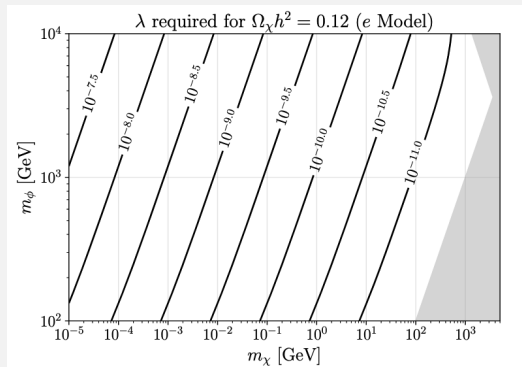
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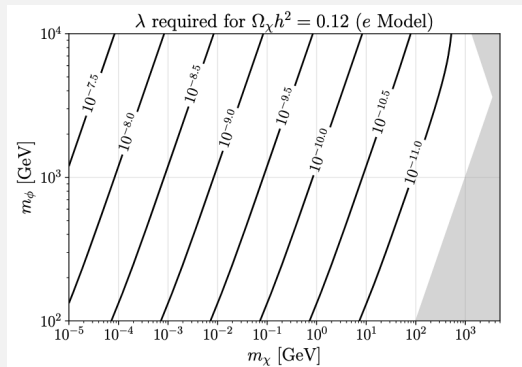
- SuperWIMP:
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- Lower bound on χ mass (astro.)
 $\rightarrow$ completely bounded space.



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- SuperWIMP:
 - ϕ_f freezes out via gauge interactions. Decays to dark matter χ .
 - **Overclosure** $\rightarrow$ an upper-bound on dark matter mass.
- Lower bound on χ mass (astro.)
 $\rightarrow$ **completely bounded space.**
- Direct freeze-in supplements the abundance.

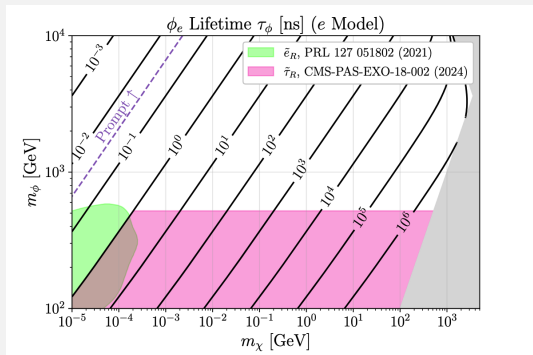


Prompt or Long-Lived

- The mediator can be long-lived: $\lambda \ll 1$.

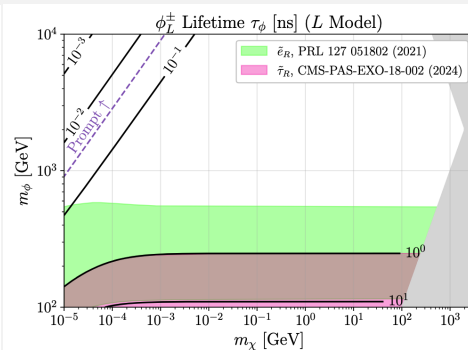
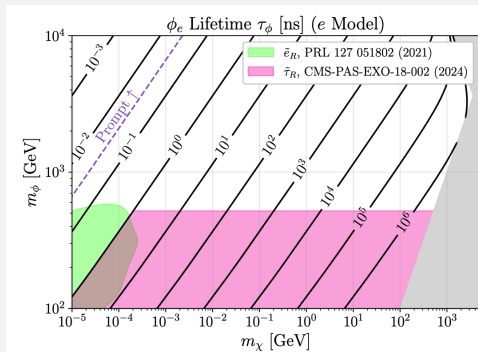
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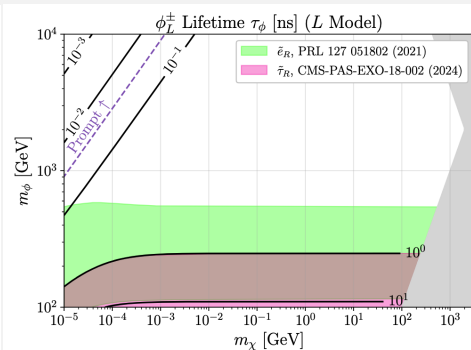
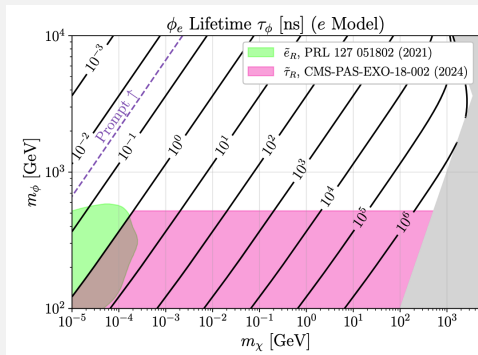
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- This talk: a cut-and-count analysis for the prompt region.

A Cut-and-Count Analysis for ϕ_f

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

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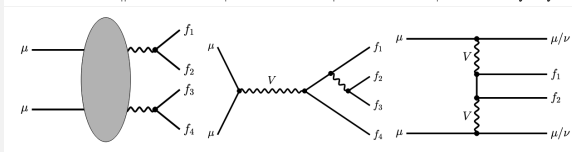
Topology	e model	L model	u model	Q model
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		$\phi_L^- \rightarrow \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3} \rightarrow \phi_Q^{-1/3} e^+ \nu_e$
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Signal: dijet/dilepton + MET

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Signal: dijet/dilepton + MET

Cut Variable	Background
$m_{\ell\ell,jj}$	ZZ
M_{T2}	WW
$\theta_{\ell\ell,jj}$	FSR
$E_{\ell,j}$	VBF
$\eta_{\ell,j}$	all

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Effective reduction of bkg.

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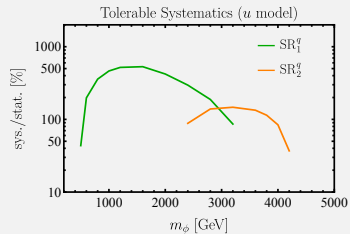
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	$\phi_e \rightarrow e\chi$	$\phi_L^0 \rightarrow \nu\chi$ $\phi_L^- \rightarrow \ell^-\chi$	$\phi_u \rightarrow u\chi$	$\phi_Q^{2/3} \rightarrow u\chi$ $\phi_Q^{-1/3} \rightarrow d\chi$
		$\phi_L^- \rightarrow \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3}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

Signal: dijet/dilepton + MET

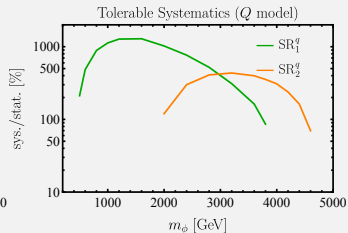
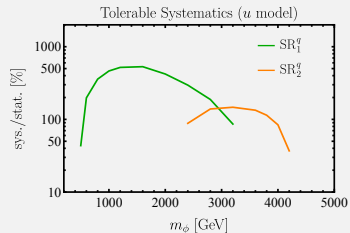
Cut Variable	Background
$m_{\ell\ell,jj}$	ZZ
M_{T2}	WW
$\theta_{\ell\ell,jj}$	FSR
$E_{\ell,j}$	VBF
$\eta_{\ell,j}$	all

Effective reduction of bkg.
Our cuts zero in on μ parton PDF
at $x \rightarrow 1$.

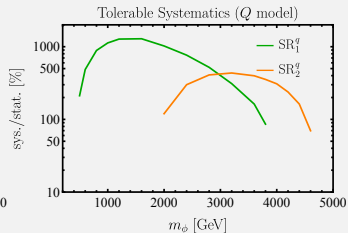
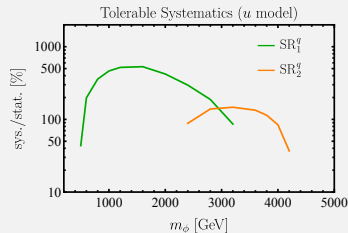
Significance Plots and Tolerable Systematics



Significance Plots and Tolerable Systematics

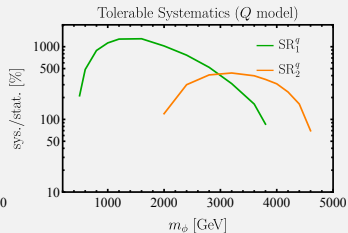
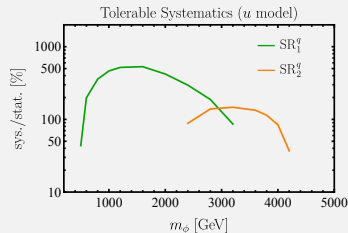


Significance Plots and Tolerable Systematics



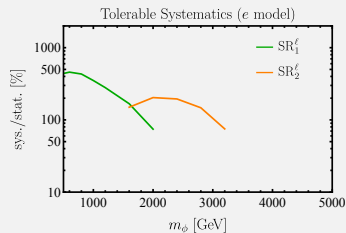
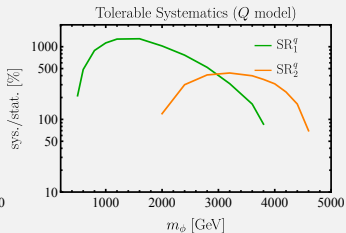
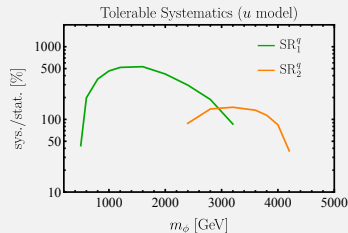
- Upto large masses discoverable.

Significance Plots and Tolerable Systematics



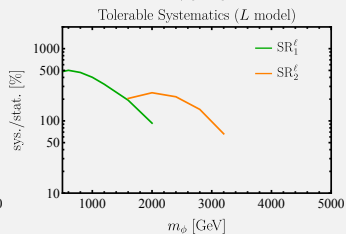
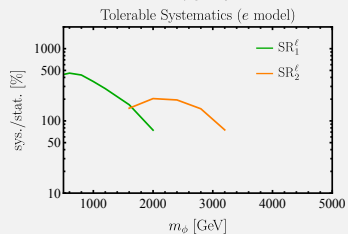
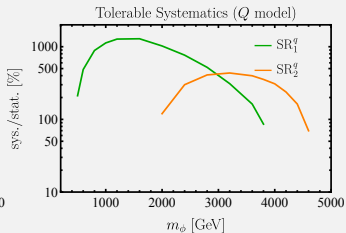
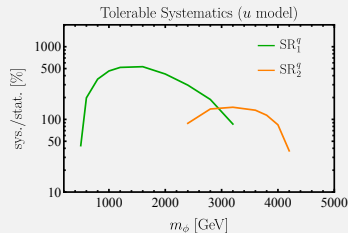
- Upto large masses discoverable.
- Large sys. tolerable.

Significance Plots and Tolerable Systematics



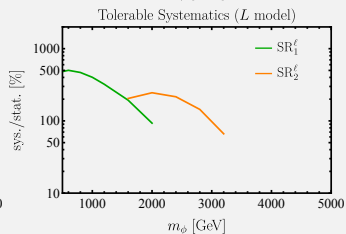
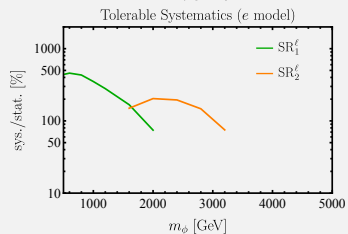
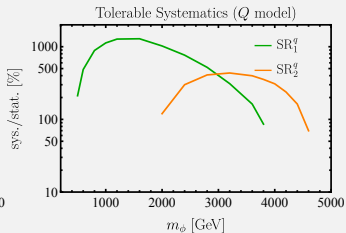
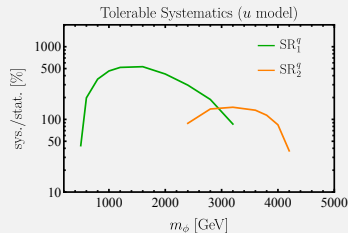
- Upto large masses discoverable.
- Large sys. tolerable.

Significance Plots and Tolerable Systematics



- Upto large masses discoverable.
- Large sys. tolerable.

Significance Plots and Tolerable Systematics

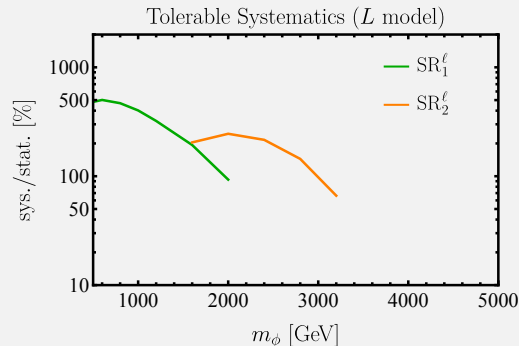
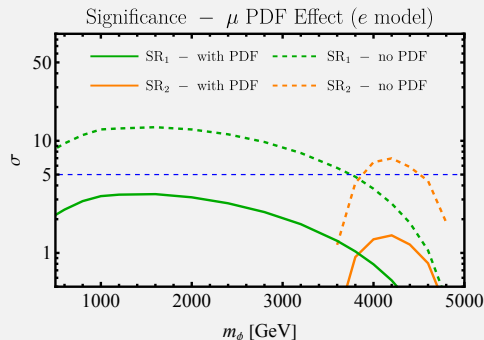


- Upto large masses discoverable.
- Large sys. tolerable.
- The μ parton PDF prevents us from discovering the entire kinematically-accessible mass range.

Summary

μ parton PDF ought to be included for viable mass reach predictions.

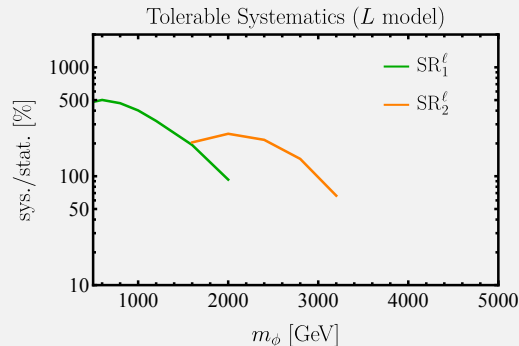
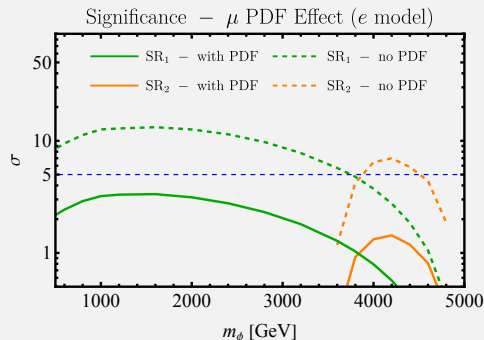
Search for fermion portal dark matter at a MuC. $\mathcal{O}(100\%)$ sys. tolerable.



Summary

μ parton PDF ought to be included for viable mass reach predictions.

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



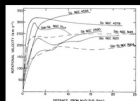
THANK YOU!

Back up

- Evidence For DM
- PDF Effect
- Exact Cuts
- Branching Ratios
- Histograms
- μ parton PDF and Cross Section
- c_μ Running
- LLP Signal Yields

Evidence for DM

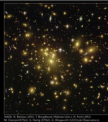
1. Rotation Curves



Rubin, Ford & Thonnex 1976

What we learn:
mass fraction
distribution

2. Cluster Dynamics



What we learn:
mass fraction
distribution



Chen 1993

3. Cluster Gas



What we learn:
mass fraction
distribution

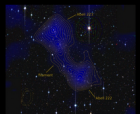
~90% of the luminous
matter in a cluster is
hot gas

4. Strong Gravitational Lensing



What we learn:
mass fraction
distribution

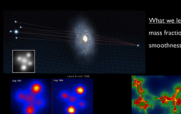
5. Weak Gravitational Lensing



Clowe et al. 2006

What we learn:
distribution
shape
structure

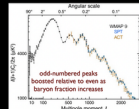
6. Cosmological Microlensing



What we learn:
mass fraction
smoothness

Johnston-Warner 2015

7. CMB Acoustic Peaks

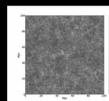


Harrison et al. 2013

What we learn:
ratio of DM/
collisional
matter
thermal history

odd-numbered peaks
boosted relative to even as
baryon fraction increases

9. Large Scale Structure



Pied-Aigle, Tisserand 2010

What we learn:
ratio of DM/
collisional
matter
thermal history

Excellent agreement
between simulations
and galaxy distribution
on the largest scales

10. Galaxy/Cluster Collisions

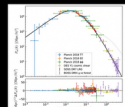


MASSIVE et al. 2016

What we learn:
distribution
separation from
collisional
matter
self-interaction

Difficult to explain
without
collisionless matter

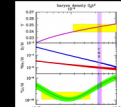
8. Matter Power Spectrum



Chabrier et al. 2019

What we learn:
ratio of DM/
collisional
matter
thermal history

11. Big Bang Nucleosynthesis

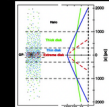


PDG 2018

What we learn:
amount of
baryonic matter

Remaining mystery:
lithium abundance
(but still need low
baryon fraction)

12. Local Stellar Motions



Bica 2010

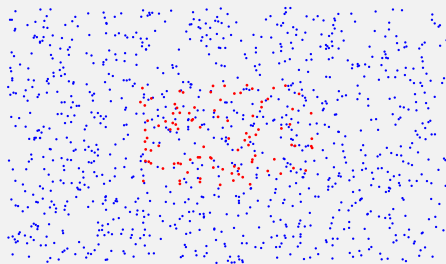
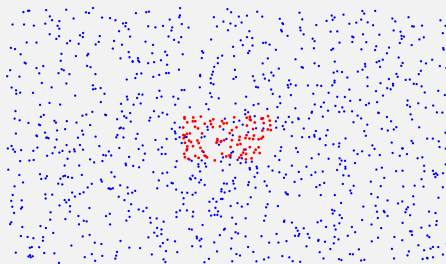
What we learn:
local dark
matter density

Estimate:
 $\rho_{DM} \sim 0.3 \text{ GeV/cm}^3$
 $\sim 0.008 \text{ M}_{\odot}/\text{pc}^3$

via Katie Mack (Aspen Center for Physics Colloquium 2019)

Effect of Muon Parton PDF

- Including the PDF diffuses the signals cluster - detrimental in a fishing expedition!
- It will diminish the mass reach.



Exact Cuts

Leptons

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

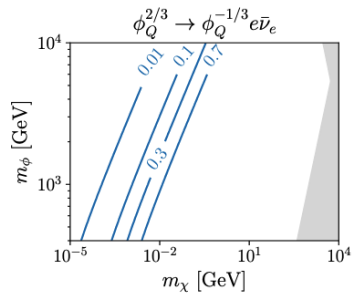
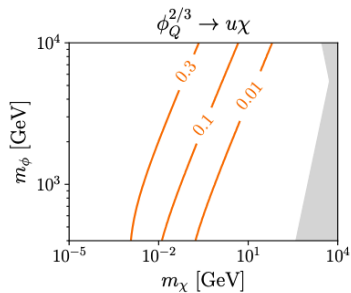
$$\left\{ m_{\ell\ell} \geq 300 \text{ GeV}, \theta_{\ell\ell} \geq \frac{13\pi}{18}, |\eta_\ell| \leq 0.2, M_{T2} \geq 800 \text{ GeV}, E_\ell \geq 1800 \text{ GeV} \right\}$$

Quarks

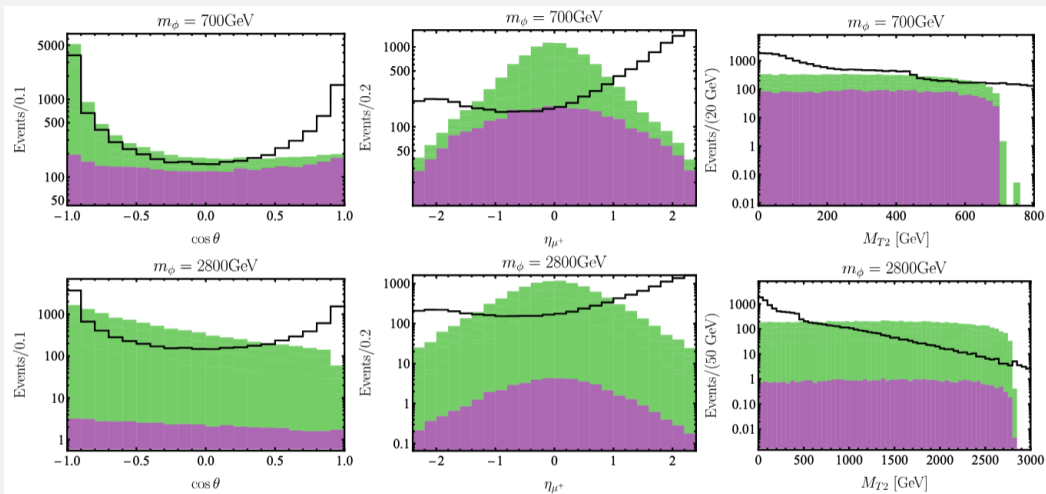
$$\left\{ m_{jj} \geq 3600 \text{ GeV}, \theta_{jj} \geq \frac{7\pi}{9}, |\eta_j| \leq 0.5, M_{T2} \geq 400 \text{ GeV}, E_j \geq 900 \text{ GeV} \right\}$$

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

Branching Ratios



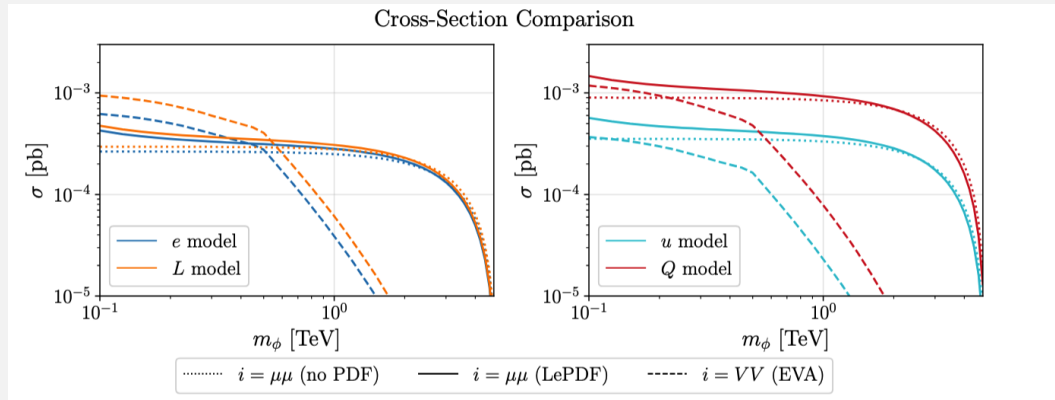
Histograms



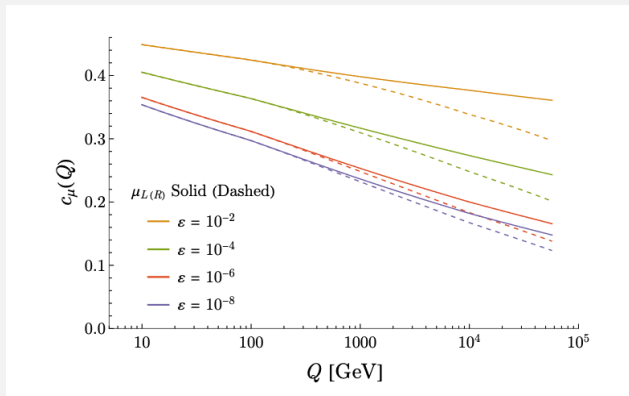
Hurdles in Implementing PDFs

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

Total Cross Section

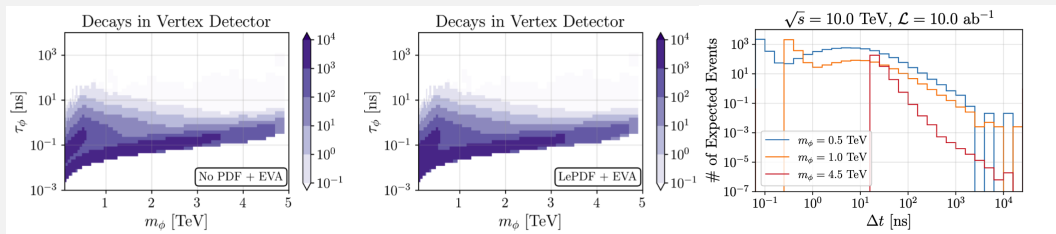


c_μ Running



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.

