Fermion Portal Dark Matter at a Muon Collider

Pouya Asadi

pasadi@ucsc.edu

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!

Pouya Asadi

pasadi@ucsc.edu

UC Santa Cruz

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

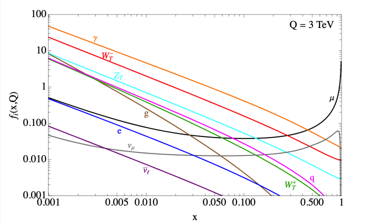
Talk Presented @ USMCC 2025

August 8, 2025

Muon Parton PDF

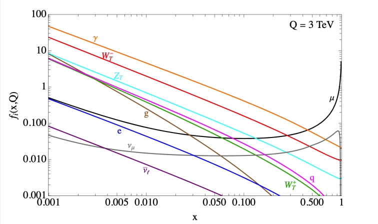
Muon Parton PDF

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



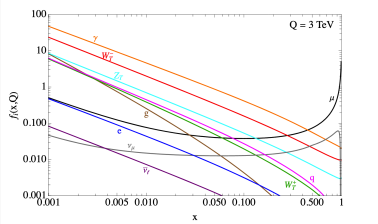
Muon Parton PDF

- Two major production channels (initial μ - VBF).
- μ parton PDF is not included in standard simulation pipelines yet.



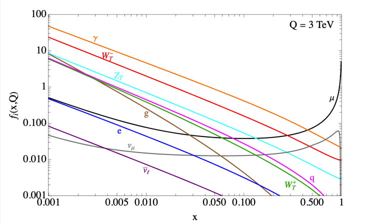
Muon Parton PDF

- Two major production channels (initial μ - VBF).
- μ parton PDF is not included in standard simulation pipelines yet.
- We included the μ parton PDF in our simulation.



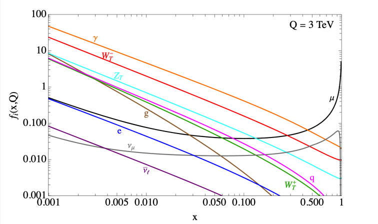
Muon Parton PDF

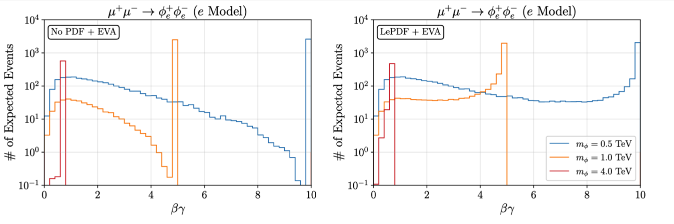
- Two major production channels (initial μ - VBF).
- μ parton PDF is not included in standard simulation pipelines yet.
- We included the μ parton PDF in our simulation.
- Including the μ parton PDF changes the kinematics:



Muon Parton PDF

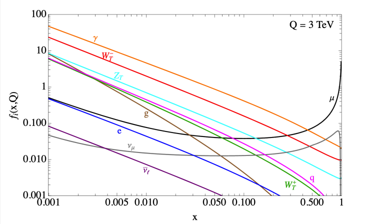
- Two major production channels (initial μ - VBF).
- μ parton PDF is not included in standard simulation pipelines yet.
- We included the μ parton PDF in our simulation.
- Including the μ parton PDF changes the kinematics:

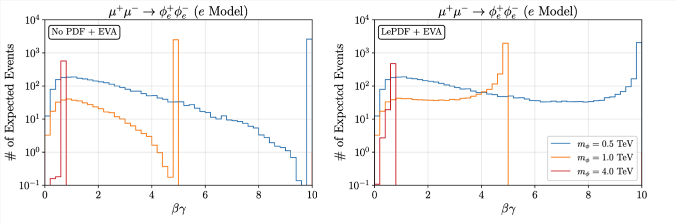




Muon Parton PDF

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

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

Implementing the μ Parton PDF

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

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

- $c_\mu^{L/R}(Q^2)$: determined from sum rules for (i) the total muon number and (ii) the total polarization (left/right).

Implementing the μ Parton PDF

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

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

- $c_{\mu}^{L/R}(Q^2)$: determined from sum rules for (i) the total muon number and (ii) the total polarization (left/right).

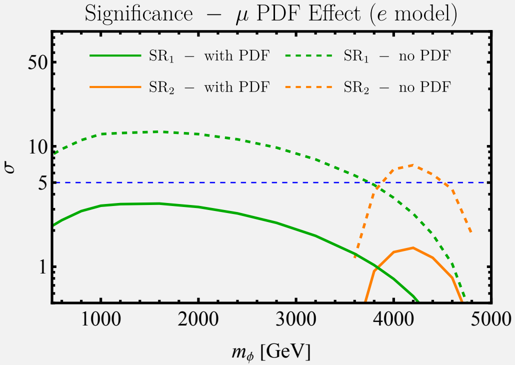
$$\begin{aligned}\frac{\mathrm{d}\mathcal{L}_{\mu^+\mu^-}}{\mathrm{d}\tau} &= \int_{\tau}^{1}\frac{\mathrm{d}x}{x} f_{\mu^+}(x,Q_f) f_{\mu^-}(\tau/x,Q_f) \\ &= \frac{\mathrm{d}\tilde{\mathcal{L}}_{\mu^+\mu^-}}{\mathrm{d}\tau} + c_{\mu^+}c_{\mu^-}\delta(1-\tau) + c_{\mu^+}\tilde{f}_{\mu^-}(\tau) + c_{\mu^-}\tilde{f}_{\mu^+}(\tau),\end{aligned}$$

Effect of Muon Parton PDF

- Including the PDF could diminish the mass reach.

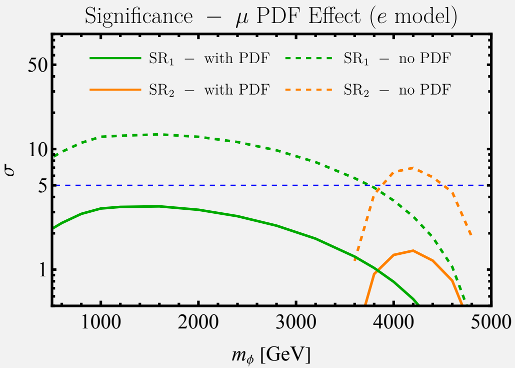
Effect of Muon Parton PDF

- Including the PDF could diminish the mass reach.



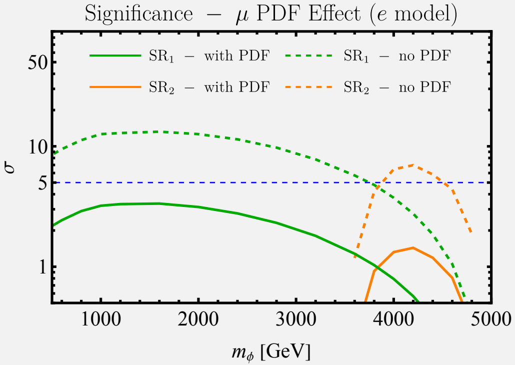
Effect of Muon Parton PDF

- Including the PDF could diminish the mass reach.
- The drop depends on the model and the cuts (SRs).



Effect of Muon Parton PDF

- Including the PDF could diminish the mass reach.
- The drop depends on the model and the cuts (SRs).



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

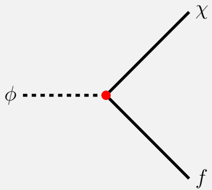
$$\mathcal{L} \supset \lambda \phi_f f^\dagger \chi + h.c.$$

f	Q	u	d	e	L
SM Charges	(**3**,**2**,1/6)	(**3**,**1**,2/3)	(**3**,**1**,-1/3)	(**1**,**1**,-1)	(**1**,**2**,-1/2)

Freeze-in Fermion Portals

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

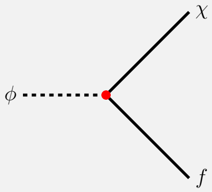
f	Q	u	d	e	L
SM Charges	($\mathbf{3}$,$\mathbf{2}$,1/6)	($\mathbf{3}$,$\mathbf{1}$,2/3)	($\mathbf{3}$,$\mathbf{1}$,-1/3)	($\mathbf{1}$,$\mathbf{1}$,-1)	($\mathbf{1}$,$\mathbf{2}$,-1/2)



Freeze-in Fermion Portals

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

f	Q	u	d	e	L
SM Charges	(**3**,**2**,1/6)	(**3**,**1**,2/3)	(**3**,**1**,-1/3)	(**1**,**1**,-1)	(**1**,**2**,-1/2)

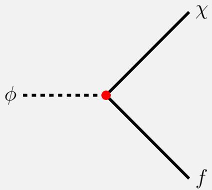


- Will study ϕ_f in the freeze-in limit at a 10 TeV MuC.

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)

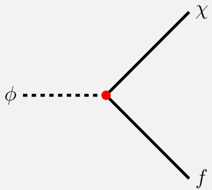


- Will study ϕ_f in the freeze-in limit at a 10 TeV MuC.
- Motivated dark matter model:

Freeze-in Fermion Portals

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

f	Q	u	d	e	L
SM Charges	(**3**,**2**,1/6)	(**3**,**1**,2/3)	(**3**,**1**,-1/3)	(**1**,**1**,-1)	(**1**,**2**,-1/2)

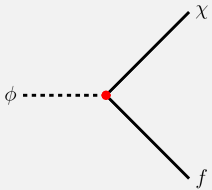


- Will study ϕ_f in the freeze-in limit at a 10 TeV MuC.
- Motivated dark matter model:
  $\rightarrow$ Informing benchmark specs for the detector.

Freeze-in Fermion Portals

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

f	Q	u	d	e	L
SM Charges	(**3**,**2**,1/6)	(**3**,**1**,2/3)	(**3**,**1**,-1/3)	(**1**,**1**,-1)	(**1**,**2**,-1/2)

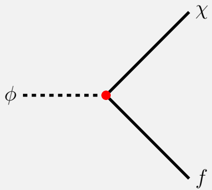


- Will study ϕ_f in the freeze-in limit at a 10 TeV MuC.
- Motivated dark matter model:
  $\rightarrow$ Informing benchmark specs for the detector.
  $\rightarrow$ Both prompt and LLP signals.

Freeze-in Fermion Portals

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

f	Q	u	d	e	L
SM Charges	(**3**,**2**,1/6)	(**3**,**1**,2/3)	(**3**,**1**,-1/3)	(**1**,**1**,-1)	(**1**,**2**,-1/2)

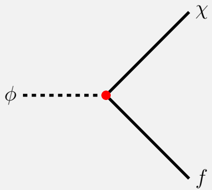


- Will study ϕ_f in the freeze-in limit at a 10 TeV MuC.
- Motivated dark matter model:
  $\rightarrow$ Informing benchmark specs for the detector.
  $\rightarrow$ Both prompt and LLP signals.
  $\rightarrow$ Highlighting the effect of μ parton PDF.

Freeze-in Fermion Portals

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

f	Q	u	d	e	L
SM Charges	(**3**,**2**,1/6)	(**3**,**1**,2/3)	(**3**,**1**,-1/3)	(**1**,**1**,-1)	(**1**,**2**,-1/2)



- 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

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

- SuperWIMP:

Relic Abundance: SuperWIMP + Freeze-in

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

- SuperWIMP:
  - ϕ_f freezes out via gauge interactions. Decays to dark matter χ.

Relic Abundance: SuperWIMP + Freeze-in

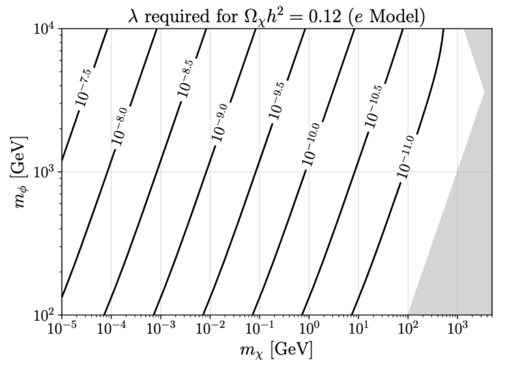
$$\mathcal{L} \supset \lambda \phi_f f^\dagger \chi + h.c.$$

- SuperWIMP:
  - ϕ_f freezes out via gauge interactions. Decays to dark matter χ.
  - Overclosure $\rightarrow$ an upper-bound on dark matter mass.

Relic Abundance: SuperWIMP + Freeze-in

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

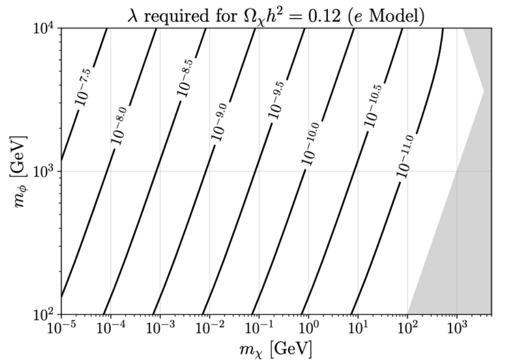
- SuperWIMP:
  - ϕ_f freezes out via gauge interactions. Decays to dark matter χ.
  - Overclosure $\rightarrow$ an upper-bound on dark matter mass.



Relic Abundance: SuperWIMP + Freeze-in

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

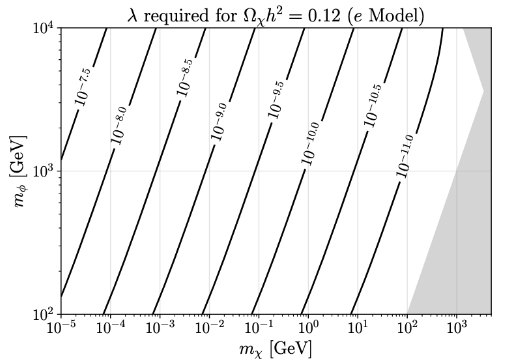
- SuperWIMP:
  - ϕ_f freezes out via gauge interactions. Decays to dark matter χ.
  - Overclosure → an upper-bound on dark matter mass.
- Lower bound on χ mass (astro.) → completely bounded space.



Relic Abundance: SuperWIMP + Freeze-in

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

- 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.

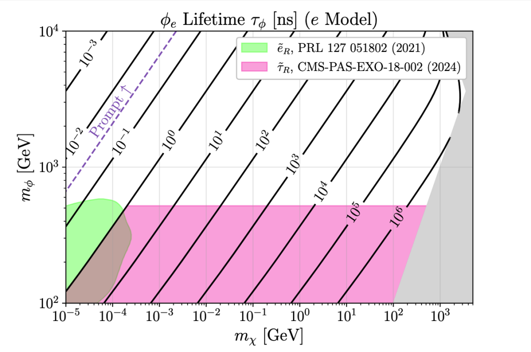


Prompt or Long-Lived

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

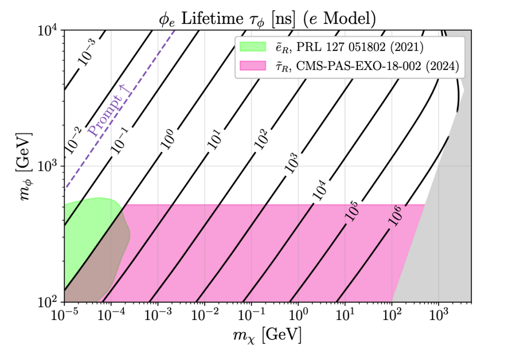
Prompt or Long-Lived

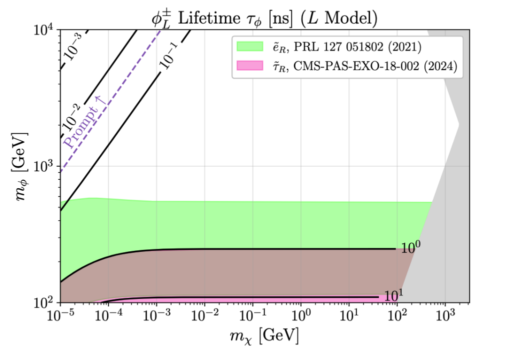
- The mediator can be long-lived: $\lambda \ll 1$.



Prompt or Long-Lived

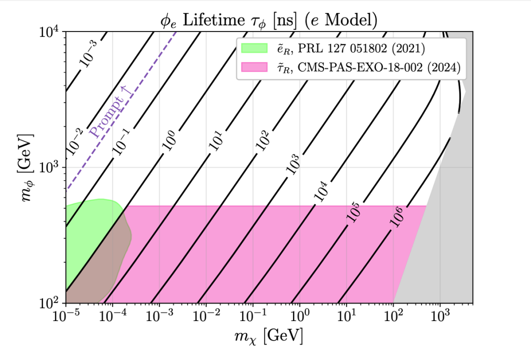
- The mediator can be long-lived: $\lambda \ll 1$.

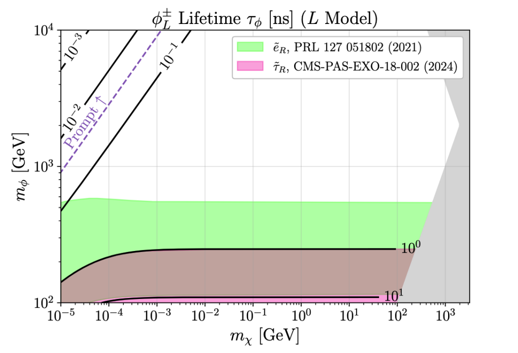




Prompt or Long-Lived

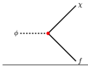
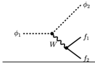
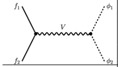
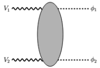
- The mediator can be long-lived: $\lambda \ll 1$.



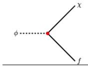
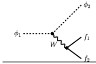
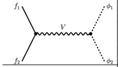
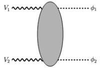


- This talk: a cut-and-count analysis for the prompt region.

A Cut-and-Count Analysis for ϕ_f

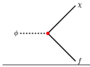
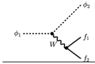
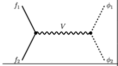
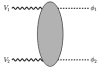
Topology	e model	L model	u model	Q model
	$\phi_e \to e\chi$	$\phi_L^0 \to \nu\chi$ $\phi_L^- \to \ell^-\chi$	$\phi_u \to u\chi$	$\phi_Q^{2/3} \to u\chi$ $\phi_Q^{-1/3} \to d\chi$
		$\phi_L^- \to \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3} \to \phi_Q^{-1/3} e^+ \nu_e$
	$\mu\mu \to \phi_e\phi_e$	$\mu\mu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

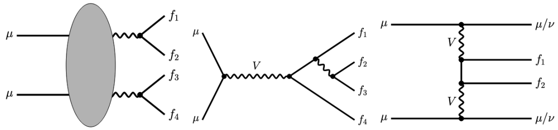
A Cut-and-Count Analysis for ϕ_f

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

Signal: dijet/dilepton + MET

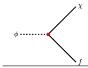
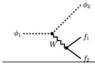
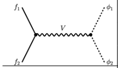
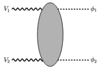
A Cut-and-Count Analysis for ϕ_f

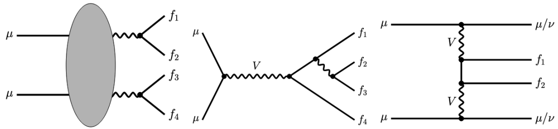
Topology	e model	L model	u model	Q model
	$\phi_e \to e\chi$	$\phi_L^0 \to \nu\chi$ $\phi_L^- \to \ell^-\chi$	$\phi_u \to u\chi$	$\phi_Q^{2/3} \to u\chi$ $\phi_Q^{-1/3} \to d\chi$
		$\phi_L^- \to \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3} \to \phi_Q^{-1/3} e^+ \nu_e$
	$\mu\mu \to \phi_e\phi_e$	$\mu\mu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



Signal: dijet/dilepton + MET

A Cut-and-Count Analysis for ϕ_f

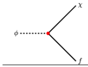
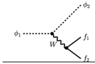
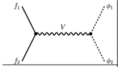
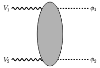
Topology	e model	L model	u model	Q model
	$\phi_e \to e\chi$	$\phi_L^0 \to \nu\chi$ $\phi_L^- \to \ell^-\chi$	$\phi_u \to u\chi$	$\phi_Q^{2/3} \to u\chi$ $\phi_Q^{-1/3} \to d\chi$
		$\phi_L^- \to \phi_L^0 \ell^- \bar{\nu}$		$\phi_Q^{2/3} \to \phi_Q^{-1/3} e^+ \nu_e$
	$\mu\mu \to \phi_e\phi_e$	$\mu\mu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

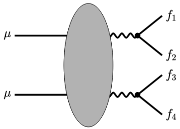


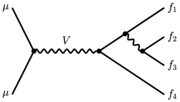
Signal: dijet/dilepton + MET

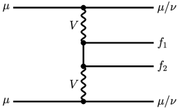
Cut Variable	Background
$m_{\ell\ell,jj}$	ZZ
M_{T2}	WW
$\theta_{\ell\ell,jj}$	FSR
$E_{\ell,j}$	VBF
$\eta_{\ell,j}$	all

A Cut-and-Count Analysis for ϕ_f

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





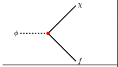
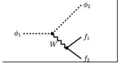
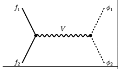
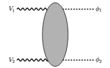


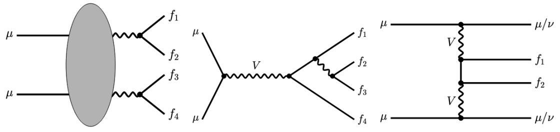
Signal: dijet/dilepton + MET

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.

A Cut-and-Count Analysis for ϕ_f

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

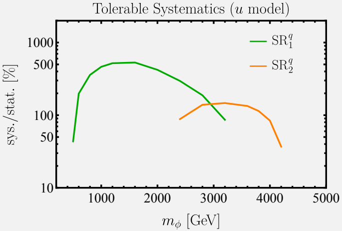


Signal: dijet/dilepton + MET

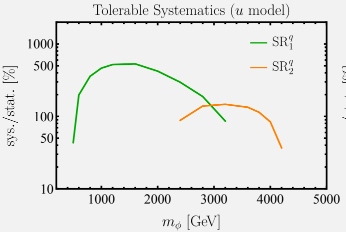
Cut Variable	Background
$m_{\ell\ell,jj}$	ZZ
M_{T2}	WW
$\theta_{\ell\ell,jj}$	FSR
$E_{\ell,j}$	VBF
$\eta_{\ell,j}$	all

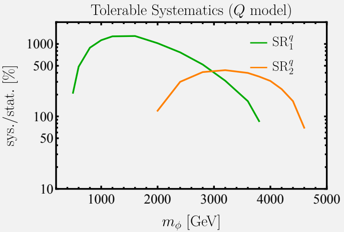
Effective reduction of bkg.
Our cuts zero in on μ parton PDF at $x \to 1$.

Significance Plots and Tolerable Systematics

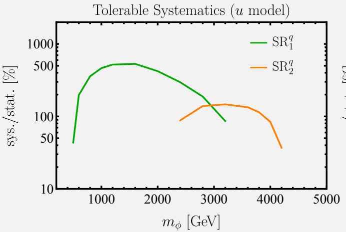


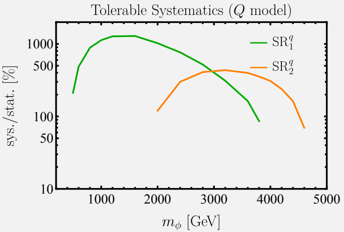
Significance Plots and Tolerable Systematics





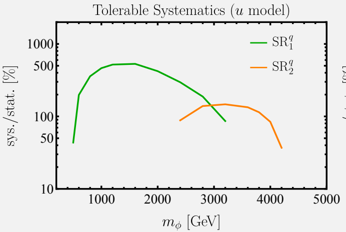
Significance Plots and Tolerable Systematics

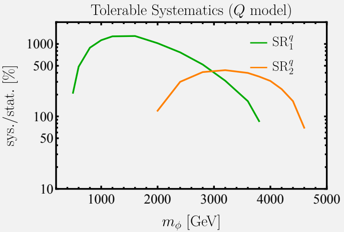




- Upto large masses discoverable.

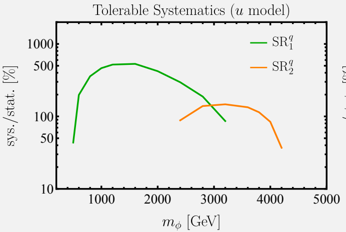
Significance Plots and Tolerable Systematics

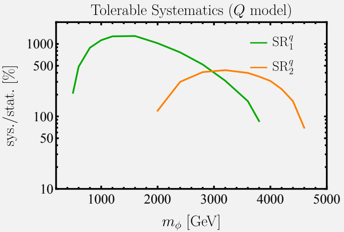


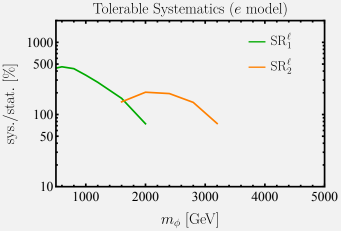


- Upto large masses discoverable.
- Large sys. tolerable.

Significance Plots and Tolerable Systematics

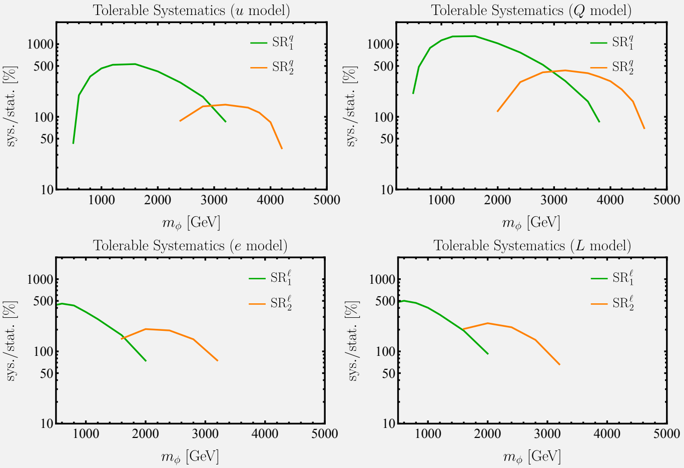






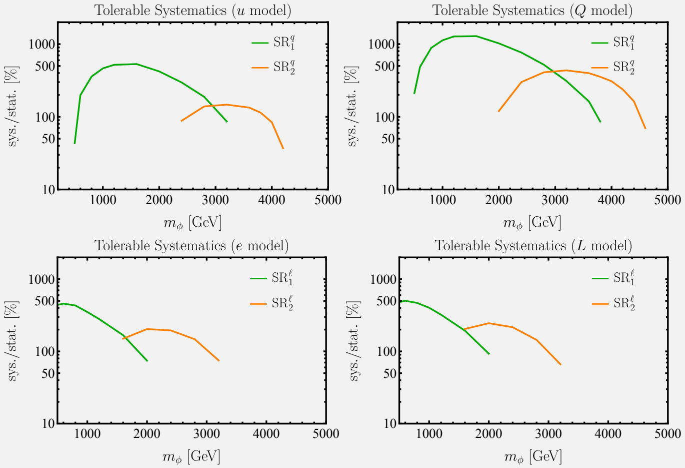
- Upto large masses discoverable.
- Large sys. tolerable.

Significance Plots and Tolerable Systematics



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

Significance Plots and Tolerable Systematics

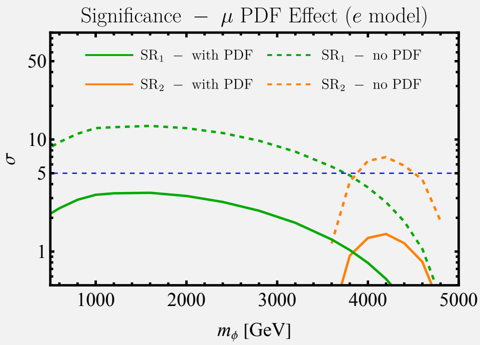


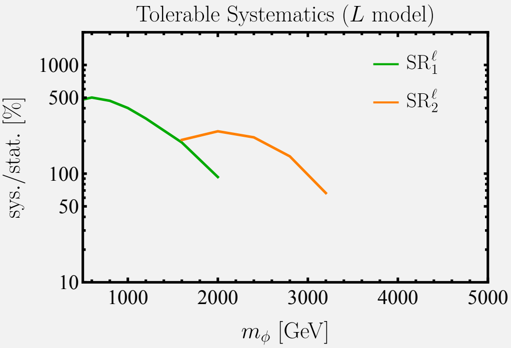
- Upto large masses discoverable.
- Large sys. tolerable.
- The μ parton PDF prevents us from discovering the entire kinematically-accessible mass range.

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.

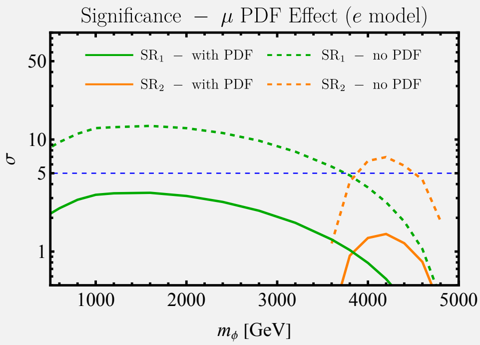


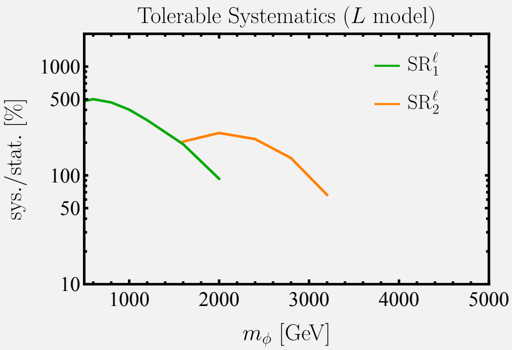


Summary

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.



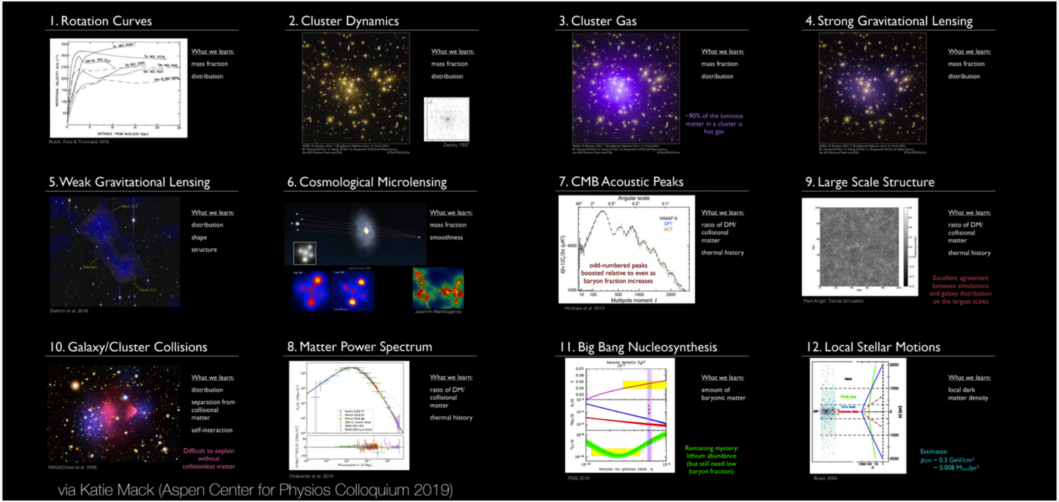


THANK YOU!

Back up

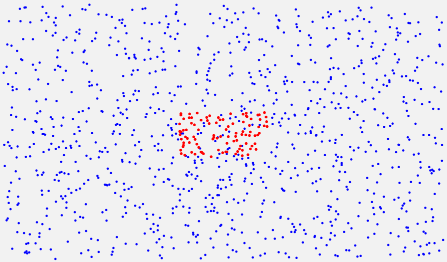
- Evidence For DM
- PDF Effect
- Exact Cuts
- Branching Ratios
- Histograms
- μ parton PDF and Cross Section
- c_μ Running
- LLP Signal Yields

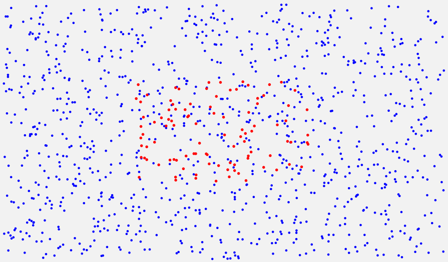
Evidence for DM



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

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

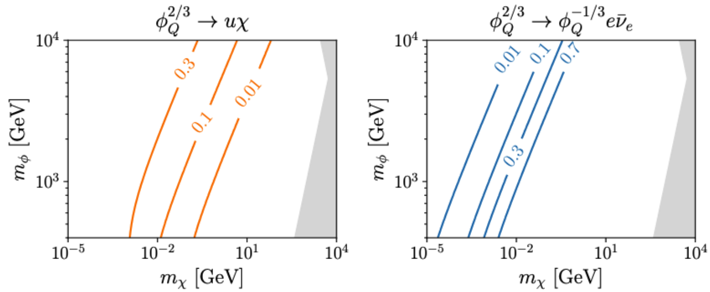
$$\left\{ m_{\ell\ell} \geqslant 300 \text{ GeV}, \theta_{\ell\ell} \geqslant \frac{13\pi}{18}, |\eta_\ell| \leqslant 0.2, M_{T2} \geqslant 800 \text{ GeV}, E_\ell \geqslant 1800 \text{ GeV} \right\}$$

Quarks

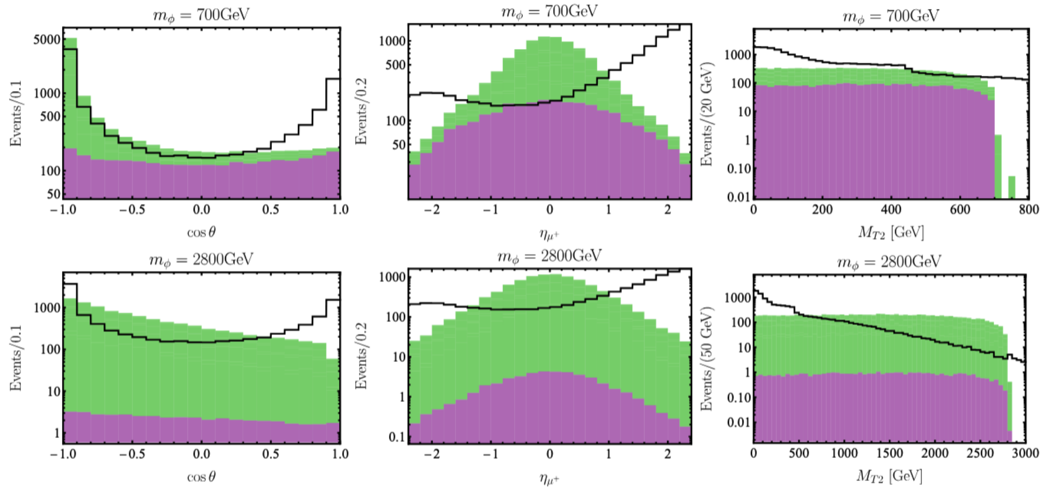
$$\left\{ m_{jj} \geqslant 3600 \text{ GeV}, \theta_{jj} \geqslant \frac{7\pi}{9}, |\eta_j| \leqslant 0.5, M_{T2} \geqslant 400 \text{ GeV}, E_j \geqslant 900 \text{ GeV} \right\}$$

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

Branching Ratios



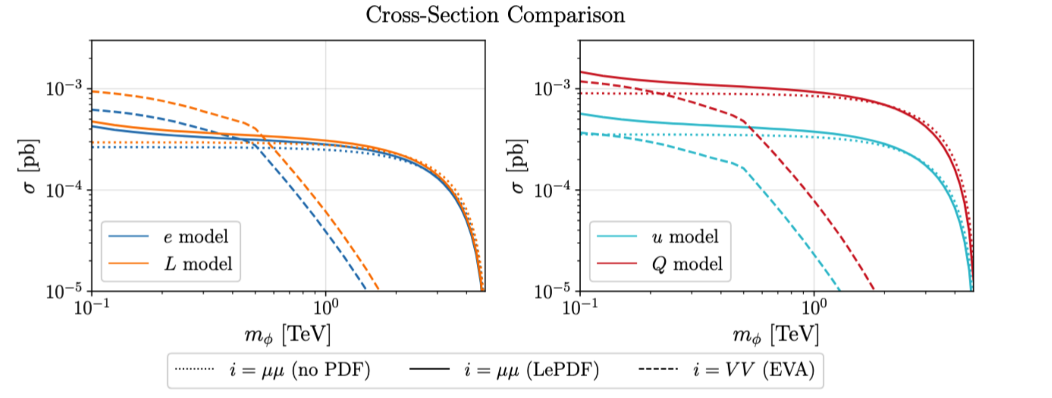
Histograms


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

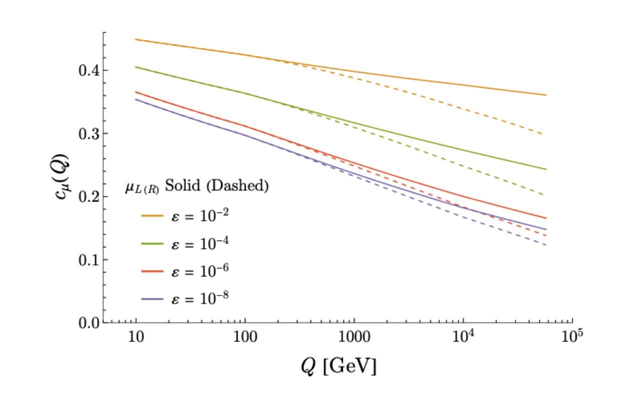
Hurdles in Implementing PDFs

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

Total Cross Section

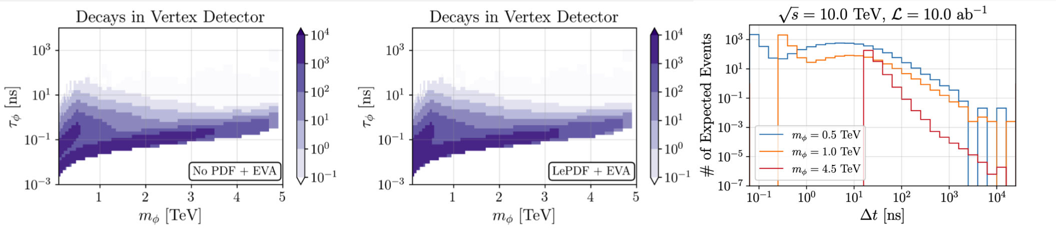


c_μ Running


$c_\mu(Q)$
0.4
0.3
0.2
0.1
0.0
10
100
1000
10^4
10^5
Q [GeV]
$\mu_{L(R)}$ Solid (Dashed)
$\varepsilon = 10^{-2}$
$\varepsilon = 10^{-4}$
$\varepsilon = 10^{-6}$
$\varepsilon = 10^{-8}$

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.