

Fermion Portal Dark Matter at a Muon Collider

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Based on : 2312.03826, 2412.14235

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

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June 11, 2025

On a High Energy Muon Collider (MuC)

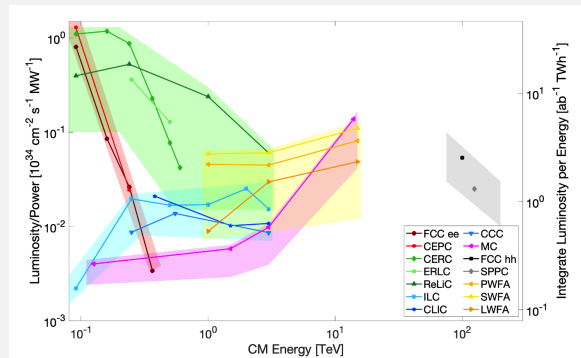
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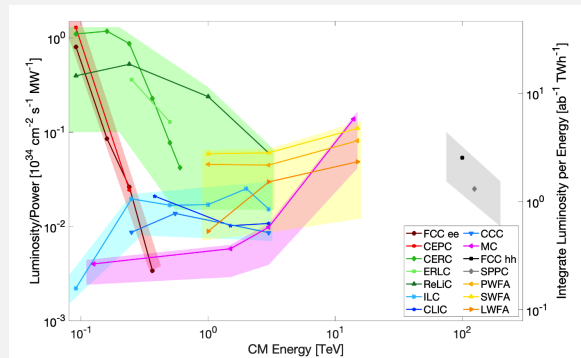
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[Trove of discussions: KITP workshop 2023.](#)

Freeze-in Fermion Portals

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

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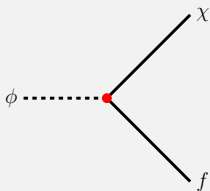
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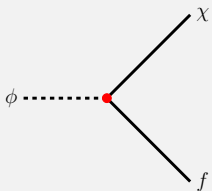
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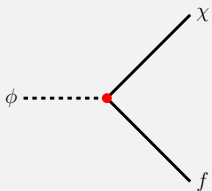


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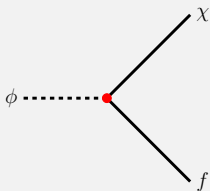


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 → Informing benchmark specs for the detector.

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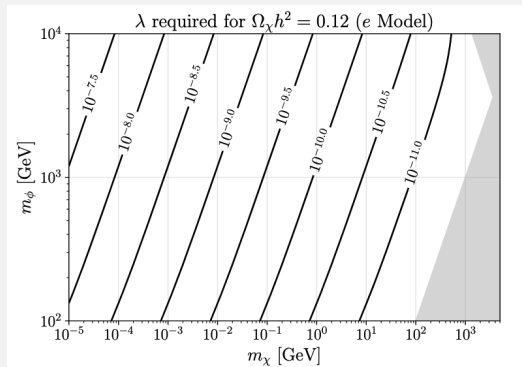
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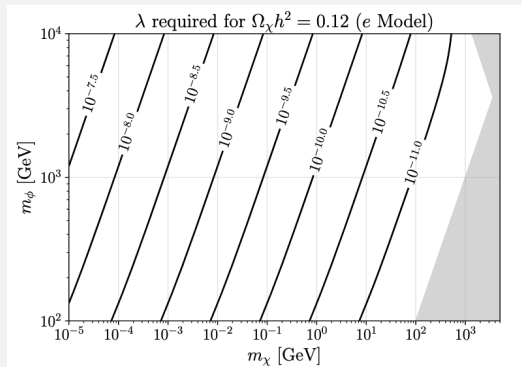
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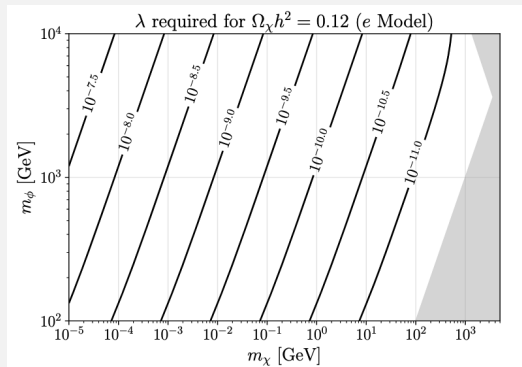
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- Direct freeze-in supplements the abundance.

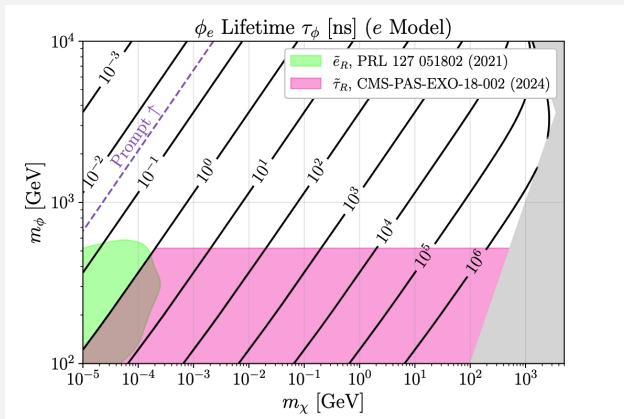


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The μ parton PDF should be included for an accurate calculation of the reach.

A Cut-and-Count Analysis for ϕ_f

Topology	e model	L model	u model	Q model
	$\phi_e \rightarrow e\chi$	$\phi_L^0 \rightarrow \nu\chi$ $\phi_L^- \rightarrow \ell^-\chi$	$\phi_u \rightarrow u\chi$	$\phi_Q^{2/3} \rightarrow u\chi$ $\phi_Q^{-1/3} \rightarrow d\chi$
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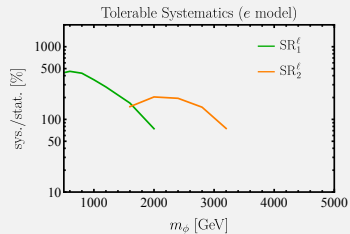
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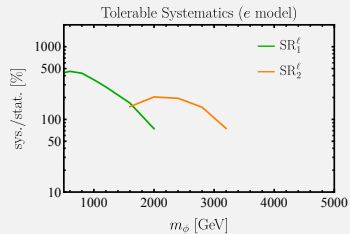
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Effective reduction of bkg.

Significance Plots and Tolerable Systematics

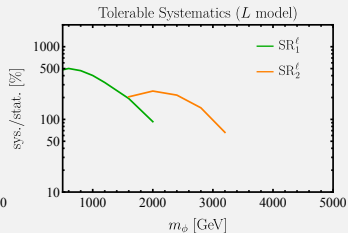
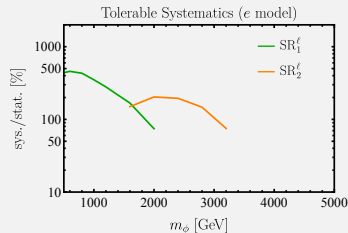


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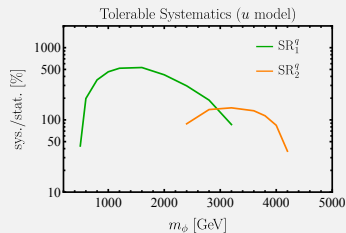
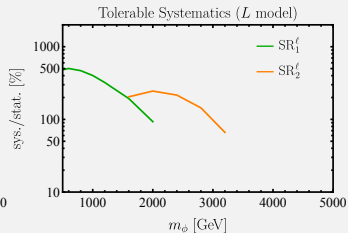
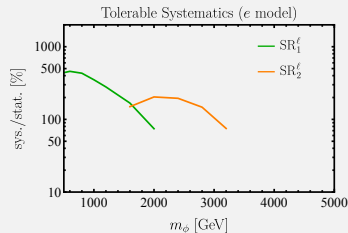
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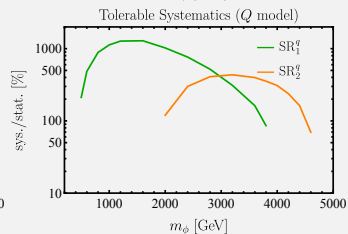
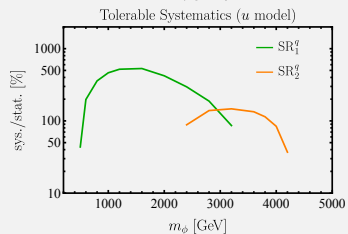
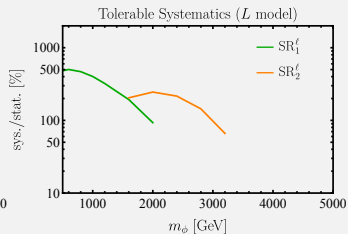
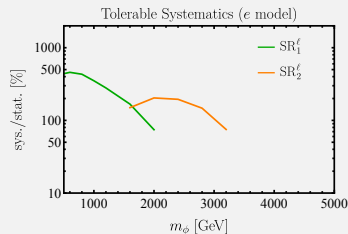
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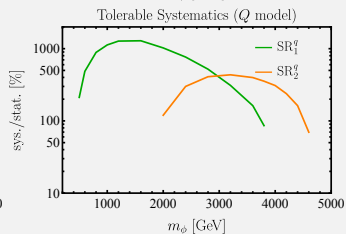
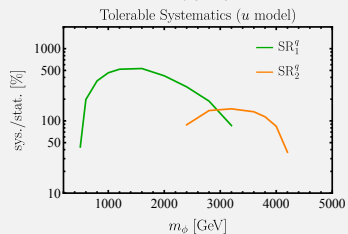
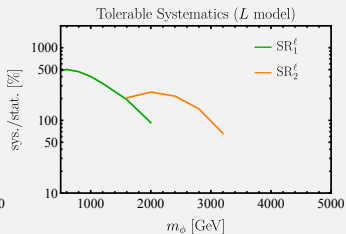
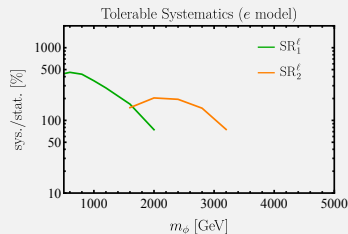
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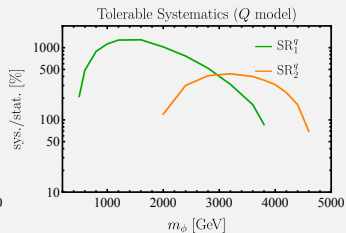
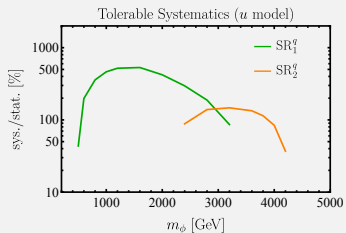
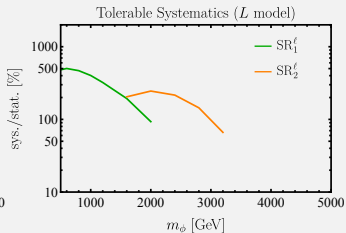
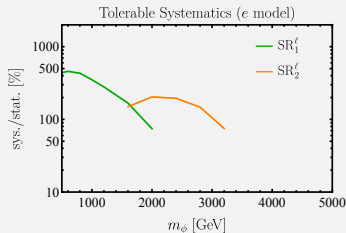
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Significance Plots and Tolerable Systematics



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- Large sys. tolerable.

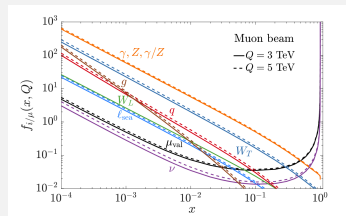
Significance Plots and Tolerable Systematics



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

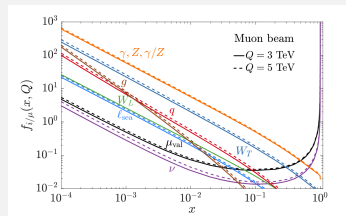
Muon Parton PDF

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



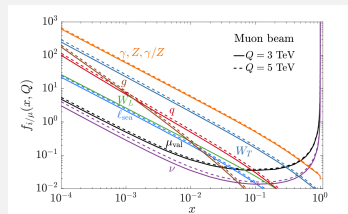
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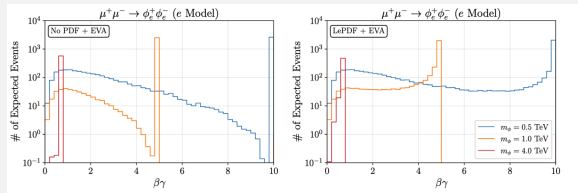
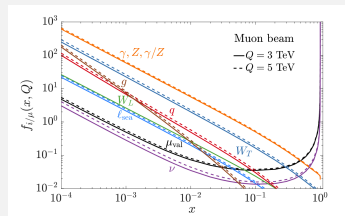
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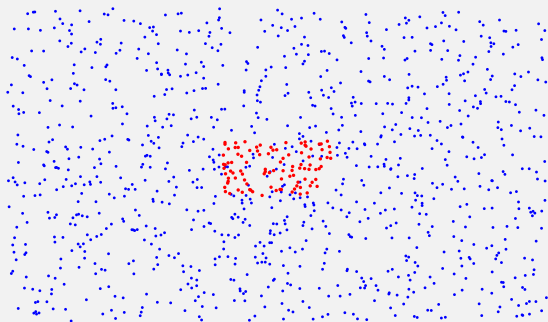


Effect of Muon Parton PDF

- Including the PDF diffuses the signals cluster - detrimental in a fishing expedition!

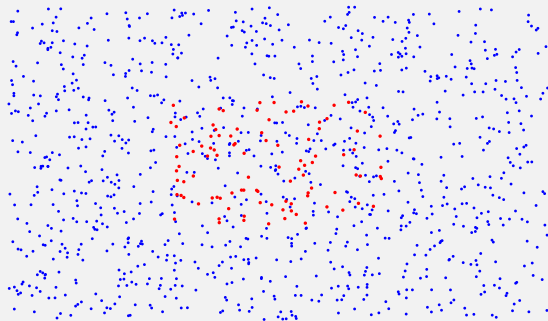
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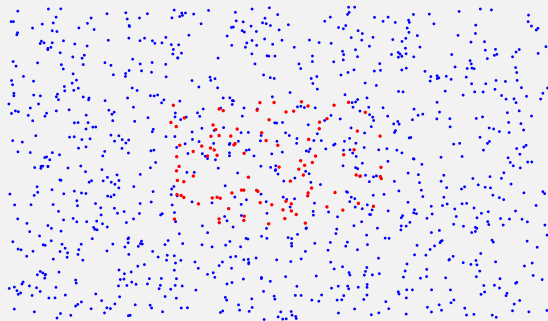
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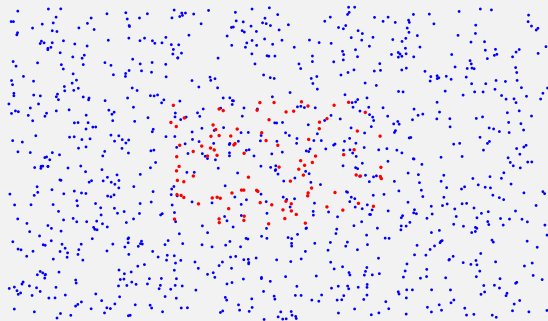
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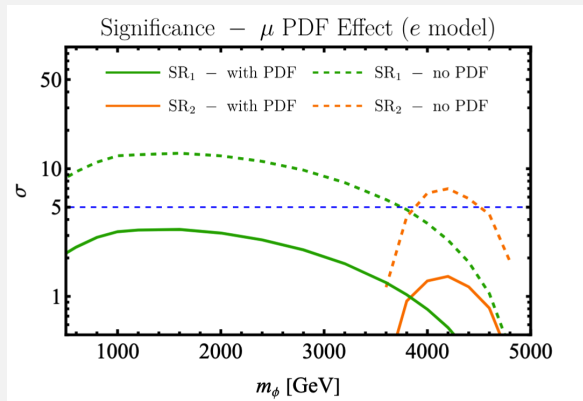
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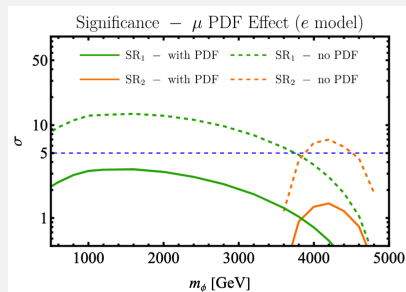
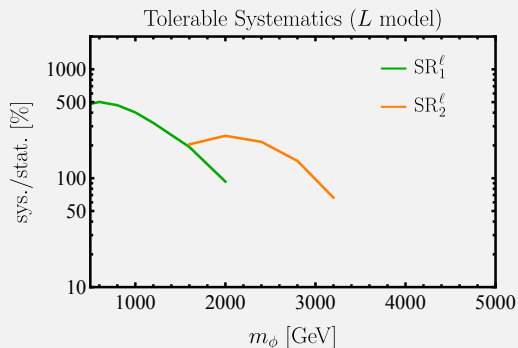
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Summary

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

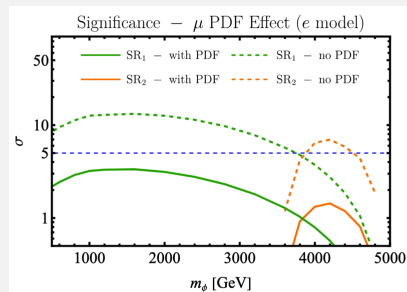
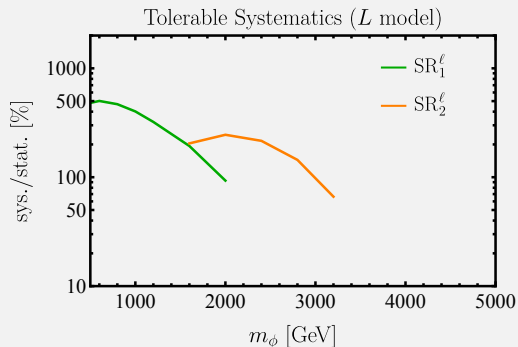
μ parton PDF ought to be included for viable predictions.



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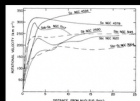
THANK YOU!

Back up

- Evidence For DM
- Exact Cuts
- Event Distribution Histograms
- μ PDF Implementation
- LLP Signal Yields

Evidence for DM

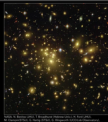
1. Rotation Curves



Rubin, Ford & Thonnex 1970

What we learn:
mass fraction
distribution

2. Cluster Dynamics



What we learn:
mass fraction
distribution



Coma 1981

3. Cluster Gas



What we learn:
mass fraction
distribution

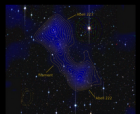
~90% of the luminous
matter in a cluster is
hot gas

4. Strong Gravitational Lensing



What we learn:
mass fraction
distribution

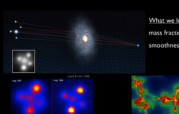
5. Weak Gravitational Lensing



Clowes et al. 2016

What we learn:
distribution
shape
structure

6. Cosmological Microlensing

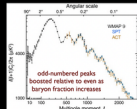


What we learn:
mass fraction
smoothness



Journal of Astrophysics

7. CMB Acoustic Peaks

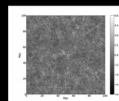


Harrison et al. 2013

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



Planck A91, Tensar Simulation

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

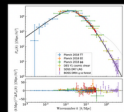


NASA/Cosmos et al. 2016

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

Difficult to explain
without
collisionless matter

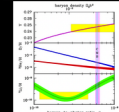
8. Matter Power Spectrum



Chabrier et al. 2019

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

11. Big Bang Nucleosynthesis

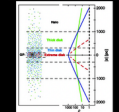


PDG 2018

What we learn:
amount of
baryonic matter

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

12. Local Stellar Motions



Bauer 2000

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)

Exact Cuts

Leptons

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

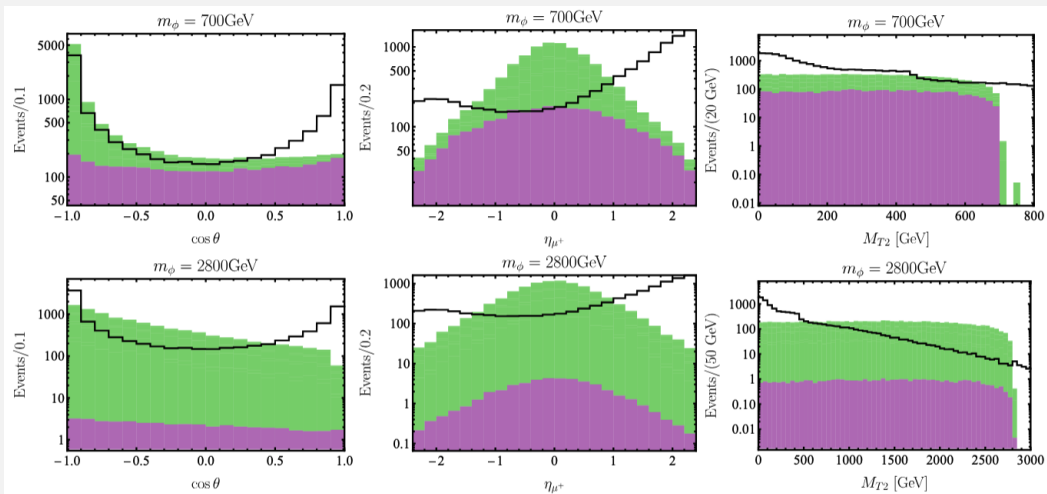
$$\left\{ m_{\ell\ell} \geq 300 \text{ GeV}, \theta_{\ell\ell} \geq \frac{13\pi}{18}, |\eta_\ell| \leq 0.2, M_{T2} \geq 800 \text{ GeV}, E_\ell \geq 1800 \text{ GeV} \right\}$$

Quarks

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

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

Histograms



Hurdles in Implementing PDFs

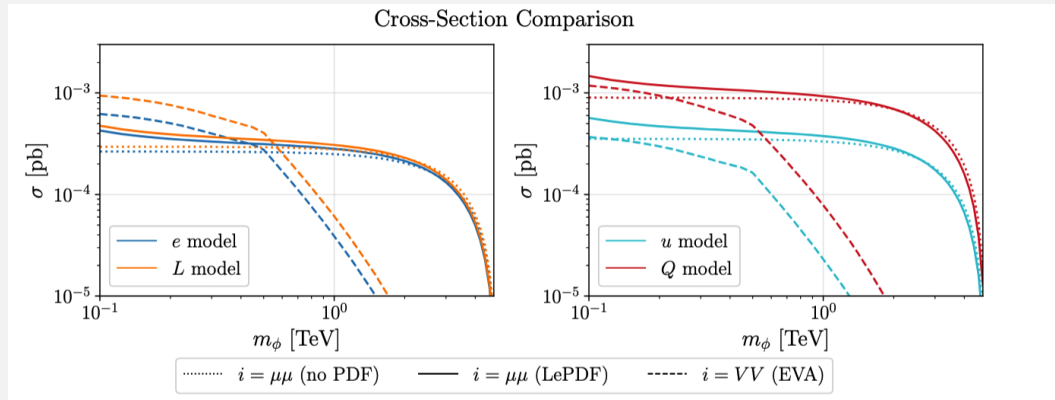
- Chirality matters!
- Interference PDFs (γ, Z, H).
- μ PDF itself (integrable divergence at $x \rightarrow 1$).

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.

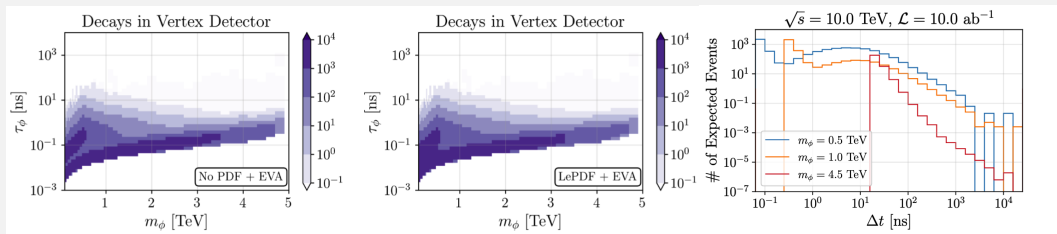
$$\begin{aligned}
 \frac{d\mathcal{L}_{\mu^+\mu^-}}{d\tau} &= \int_\tau^1 \frac{dx}{x} f_{\mu^+}(x, Q_f) f_{\mu^-}(\tau/x, Q_f) \\
 &= \frac{d\tilde{\mathcal{L}}_{\mu^+\mu^-}}{d\tau} + c_{\mu^+}c_{\mu^-}\delta(1 - \tau) + c_{\mu^+}\tilde{f}_{\mu^-}(\tau) + c_{\mu^-}\tilde{f}_{\mu^+}(\tau),
 \end{aligned}$$

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.

