Searching for Milli-Charged Dark Pions in MoEDAL MAPP

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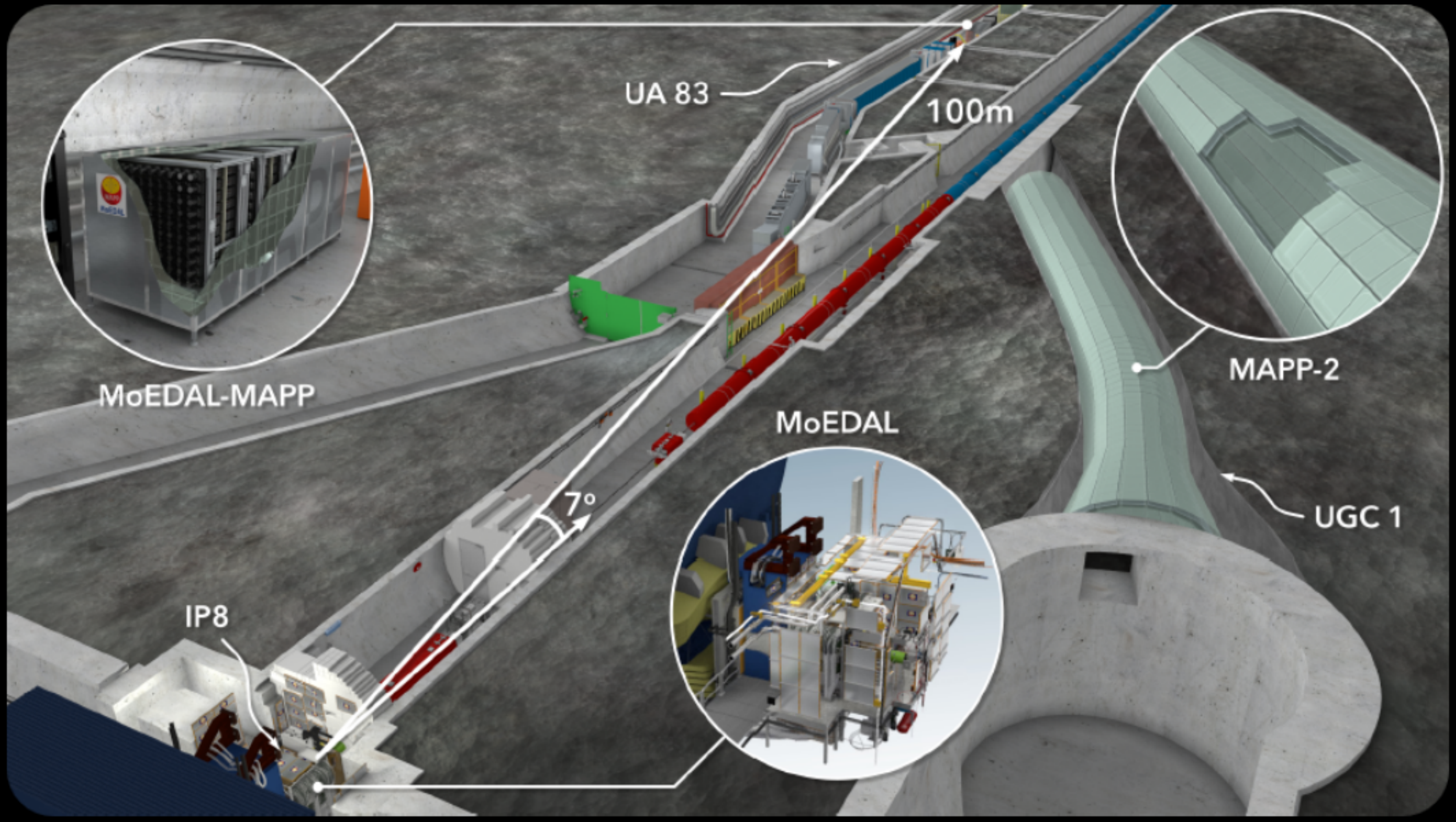
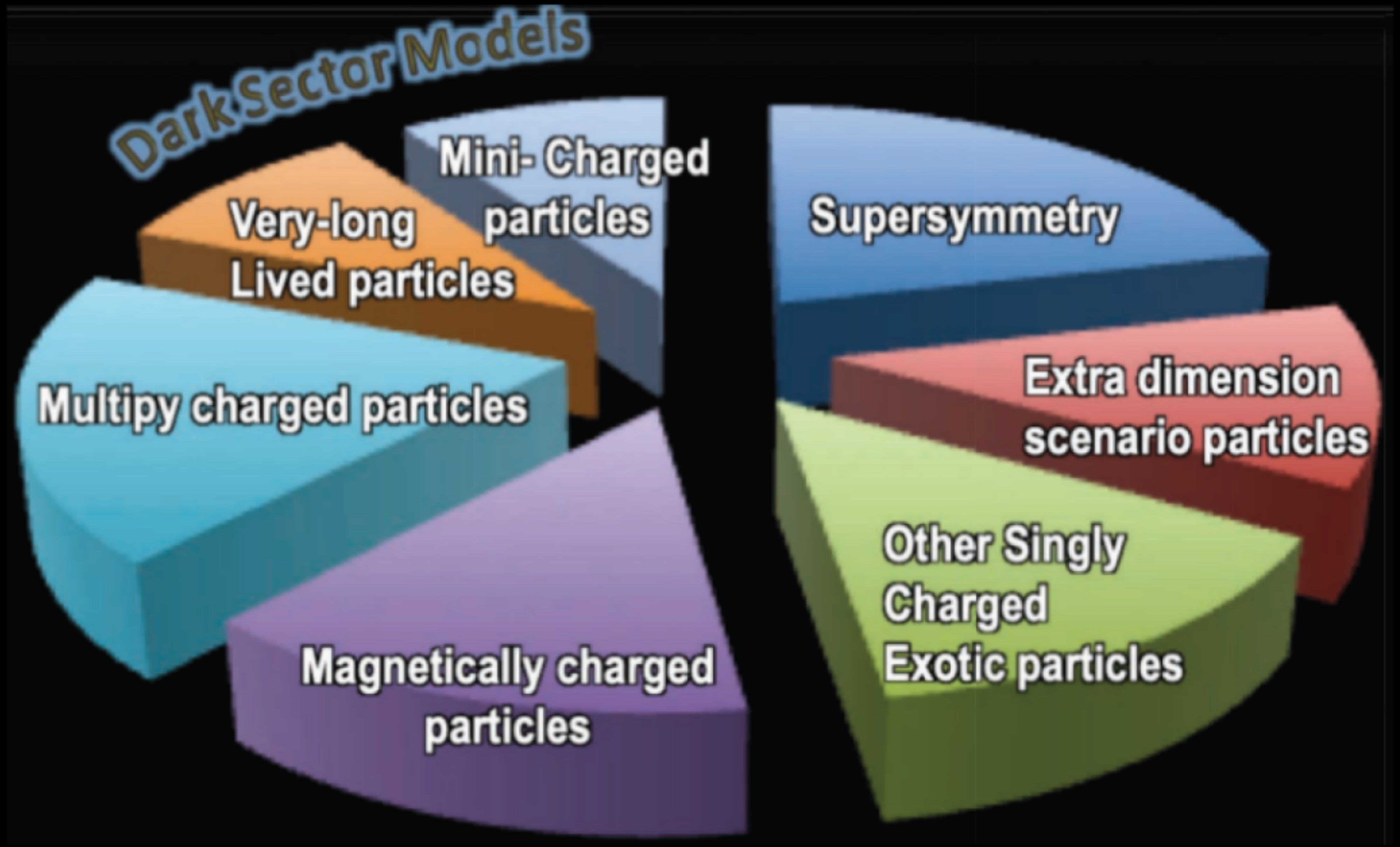
MoEDAL Apparatus for Penetrating Particles

- Designed to search for FIPs (Feebly Ionising Particles): mCPs and heavy neutrinos with an anomalously large EDM.
- Sensitive to charge and neutral LLPs.
- Optimized to search for FIPs.



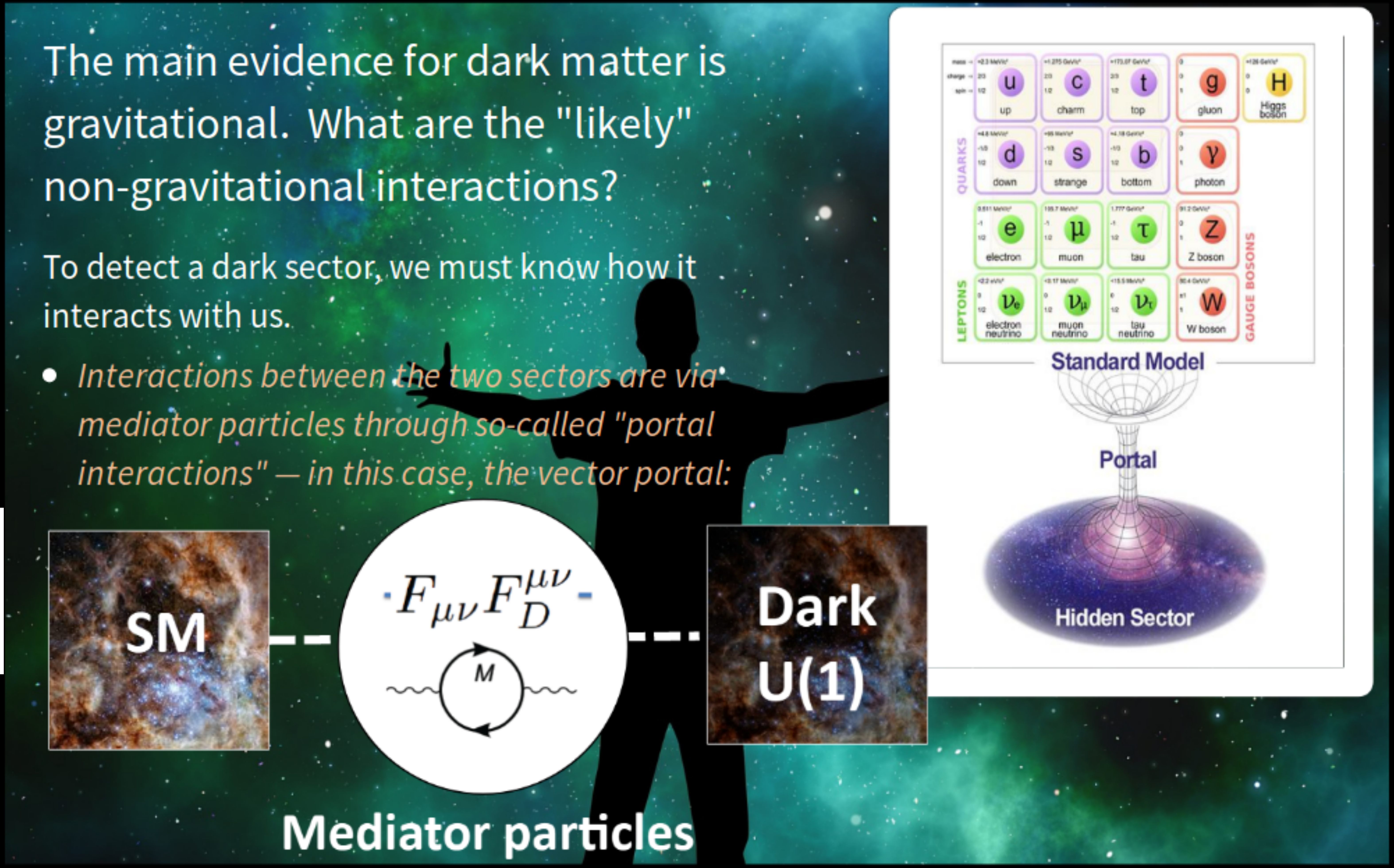


Milli-Charged Particles (mCP)

- Hypothetical non-SM particles that have an effective charge less than that of the charge of an electron e.

$$\mathcal{L}_{\text{mix}} = \frac{\kappa_m}{2} B_{\mu\nu} A'^{\mu\nu}$$

Effective Charge: $\kappa_m e'$



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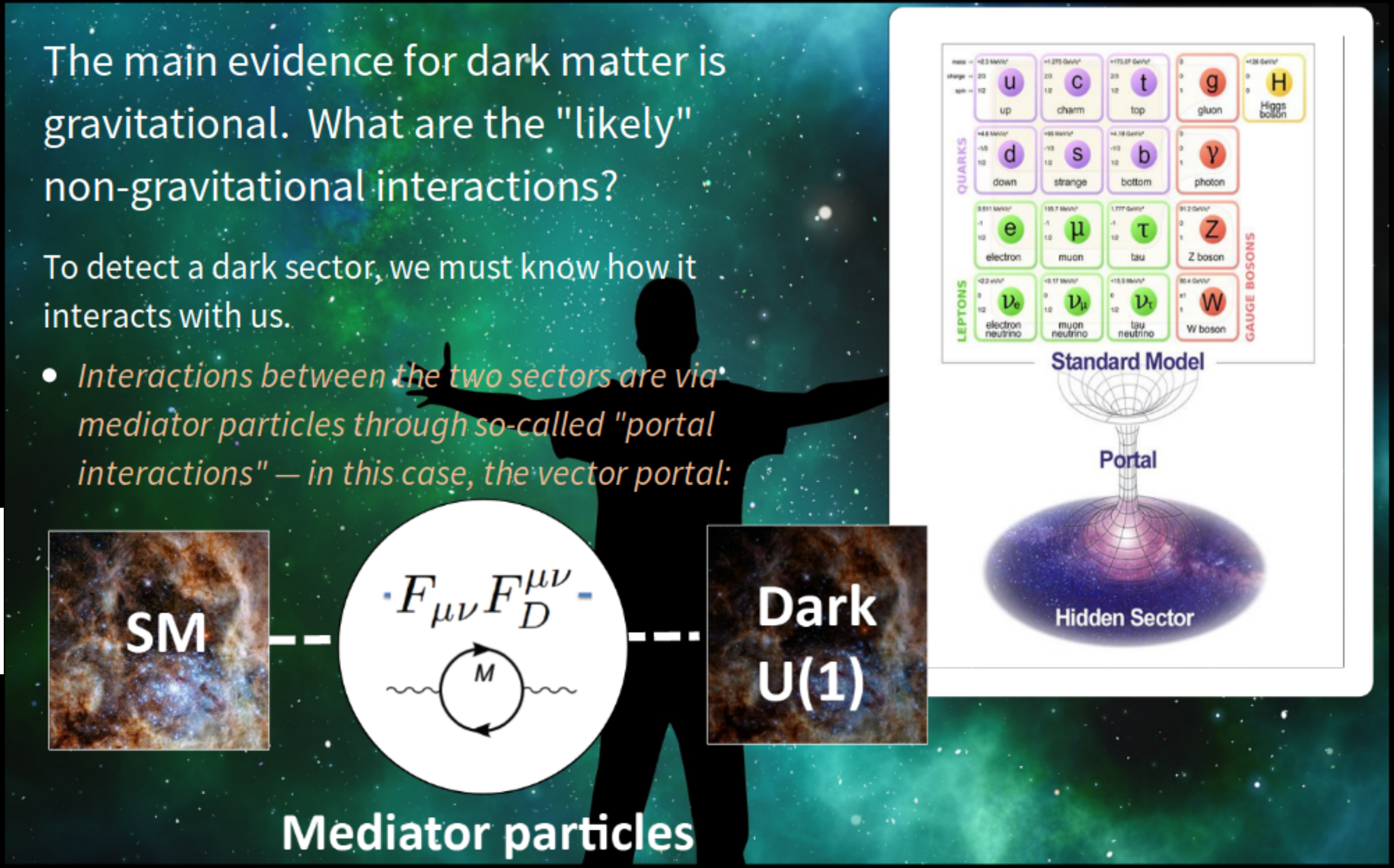

Strongly Interacting Dark Matter

WIMP DM annihilation: $m_{DM} \sim \alpha_{ann}(T_{eq}M_{Pl})^{1/2} \sim \text{TeV},$ $a_{ann} \simeq 1/30$

Hochberg et. al. Mechanism for Thermal Relic DM of Strongly Interacting Massive Particles

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Thermal relic DM can be produced even if $a_{ann} \simeq 0$

Enable a 3->2 annihilation process:

$$m_{DM} \sim \alpha_{eff}(T_{eq}^2 M_{Pl})^{1/3} \sim 100\ \text{MeV},$$

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Strongly Self-Interacting Dark Matter

- Pion-like DM: $m_q << \Lambda_D$ Motivated from Chiral Perturbation Theory

Hochberg et. al. Mechanism for Thermal Relic DM of Strongly Interacting Massive Particles

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Pion-like Dark Matter

Lagrangian for a Pion-like DM model is:

$$\mathcal{L} = \frac{f_\pi^2}{4} Tr[(D_\mu U)^\dagger D^\mu U] + \frac{Bf_\pi^2}{2} Tr(M^\dagger U + U^\dagger M) + \mathcal{L}_{WZW} + \mathcal{L}_{mix} + \ldots$$

$$U = e^{i\frac{\Pi}{f_\pi}}, \Pi = \pi^a \lambda^a$$

$$\frac{\Pi}{\sqrt{2}} = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\pi_8 & \pi_+ & K_+ \\ -\pi_- & \frac{1}{\sqrt{2}}\pi_3 + \frac{1}{\sqrt{6}}\pi_8 & K_0 \\ K_- & \bar{K}_0 & -\sqrt{\frac{2}{3}}\pi_8 \end{pmatrix}$$

$$M = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

S. Scherer, Introduction to chiral perturbation theory, Adv. Nucl. Phys. 27 (2003) 277

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$$\mathcal{L}_{\text{mix}} = \frac{\kappa_m}{2} B_{\mu\nu} B'^{\mu\nu}$$

- We get rid of this term by performing field re-definitions and modify the covariant derivative of both the dark sector and the Standard Model.

$$\mathcal{L}_{WZW} = \frac{2N_C}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} Tr[\Pi\partial_\mu\Pi\partial_\nu\Pi\partial_\rho\Pi\partial_\sigma\Pi]$$

- Allows for a 3 -> 2 annihilation process, resulting in DM self-interactions and helps explaining DM abundance.

$$i\frac{ne^2}{48\pi^2}\epsilon^{\mu\nu\rho\sigma}\partial_\nu A_\rho A_\sigma Tr[2Q^2(U\partial_\mu U^\dagger - U^\dagger\partial_\mu U) - QU^\dagger Q\partial_\mu U + QUQ\partial_\mu U^\dagger]$$

Cosmological Limit

Upper Limit: $m_\pi / F \lesssim 2\pi$

For higher F, we can cover larger masses.

Hochberg et. al. Model for Thermal Relic DM of Strongly Interacting Massive Particles

Cosmological Limit

Upper Limit: $m_\pi/F \lesssim 2\pi$

For higher F, we can cover larger masses.

Lower Limit: $\frac{\sigma}{m_\pi} \lesssim 1\ \mathrm{cm}^2/\mathrm{g} \simeq 1.78 \times 10^{12}\ \mathrm{pb/GeV}$

Always maintained in our simulations

Free parameters in our model: F and the mass of the dark Z boson

Hochberg et. al. Model for Thermal Relic DM of Strongly Interacting Massive Particles

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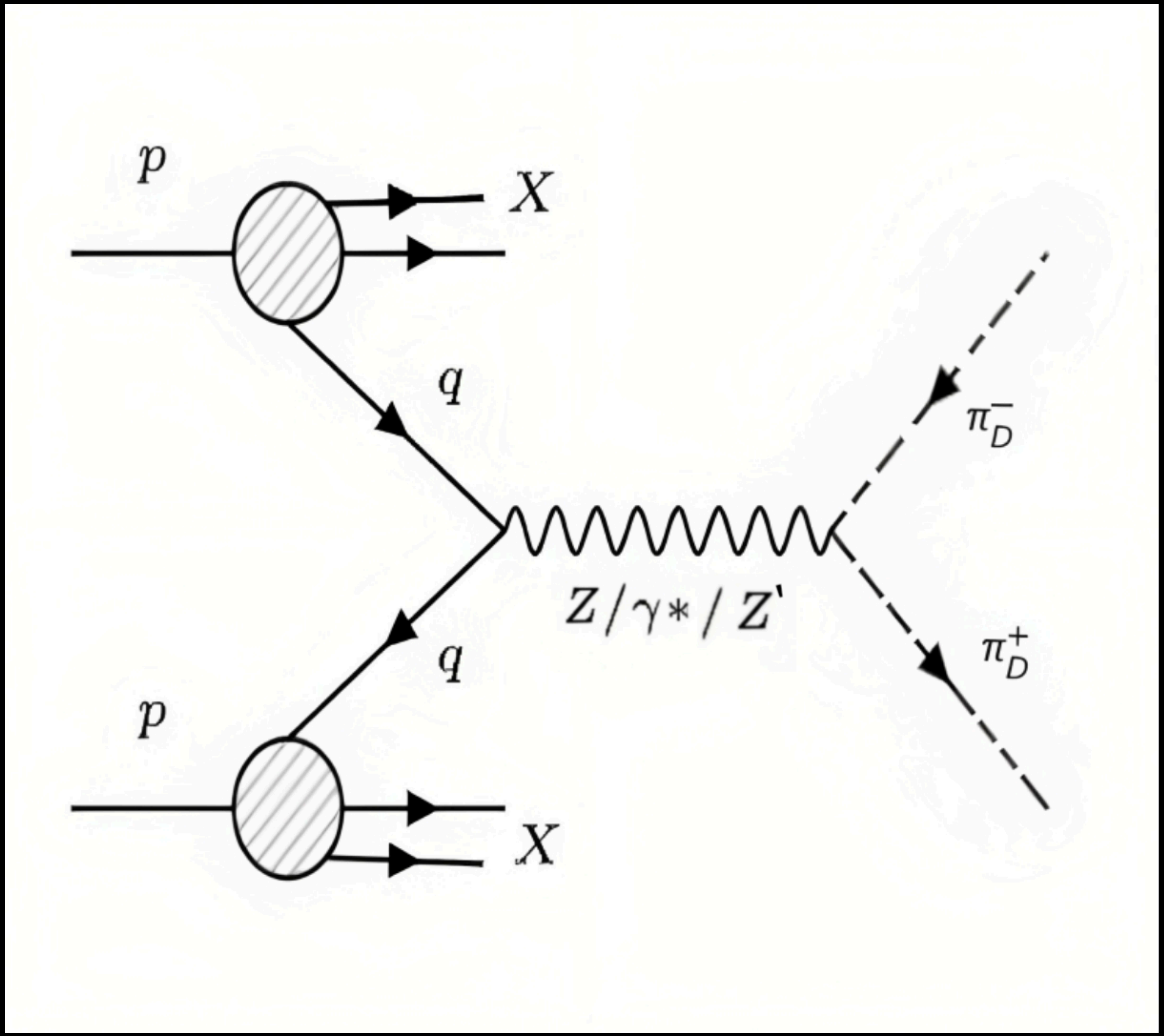
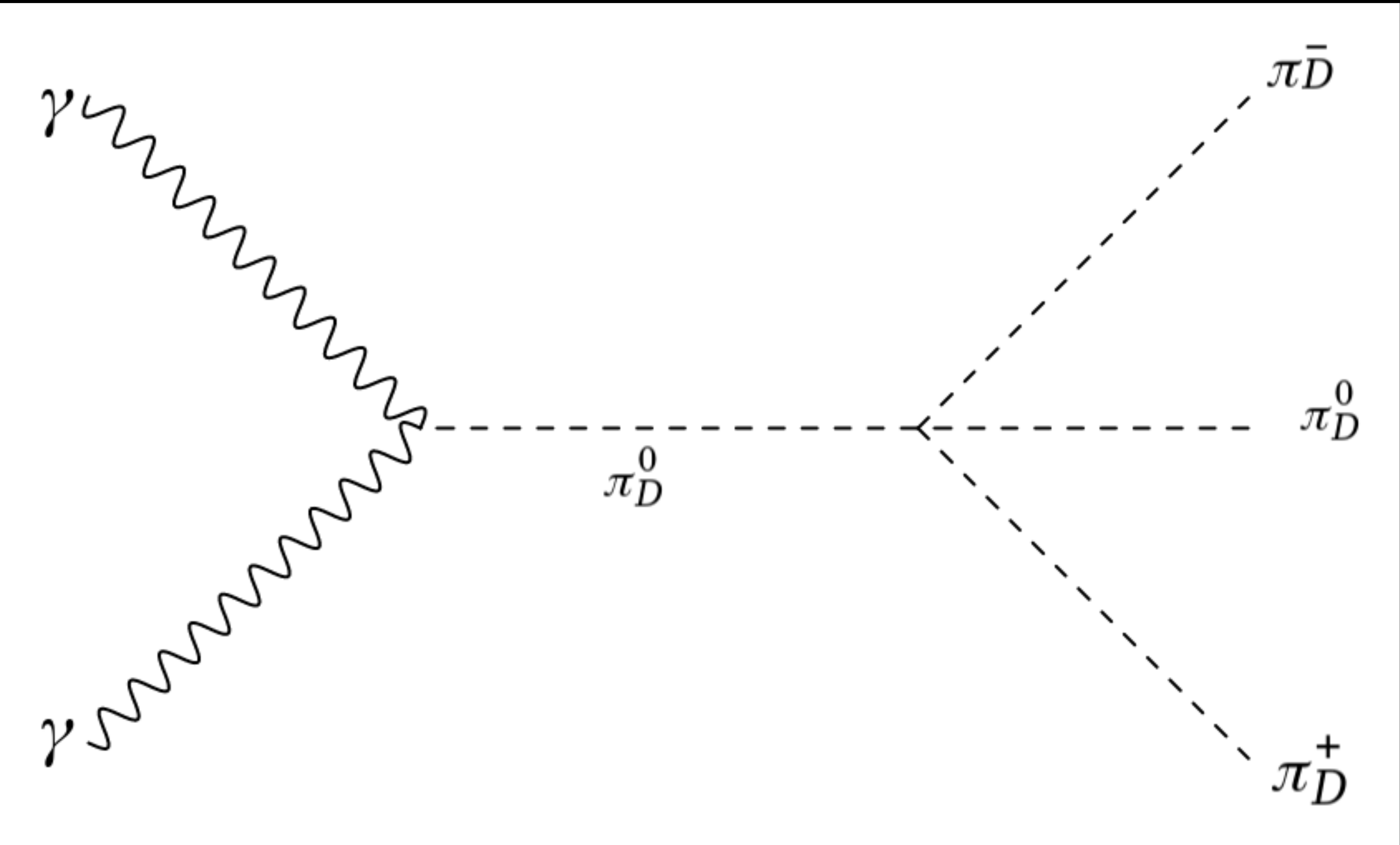
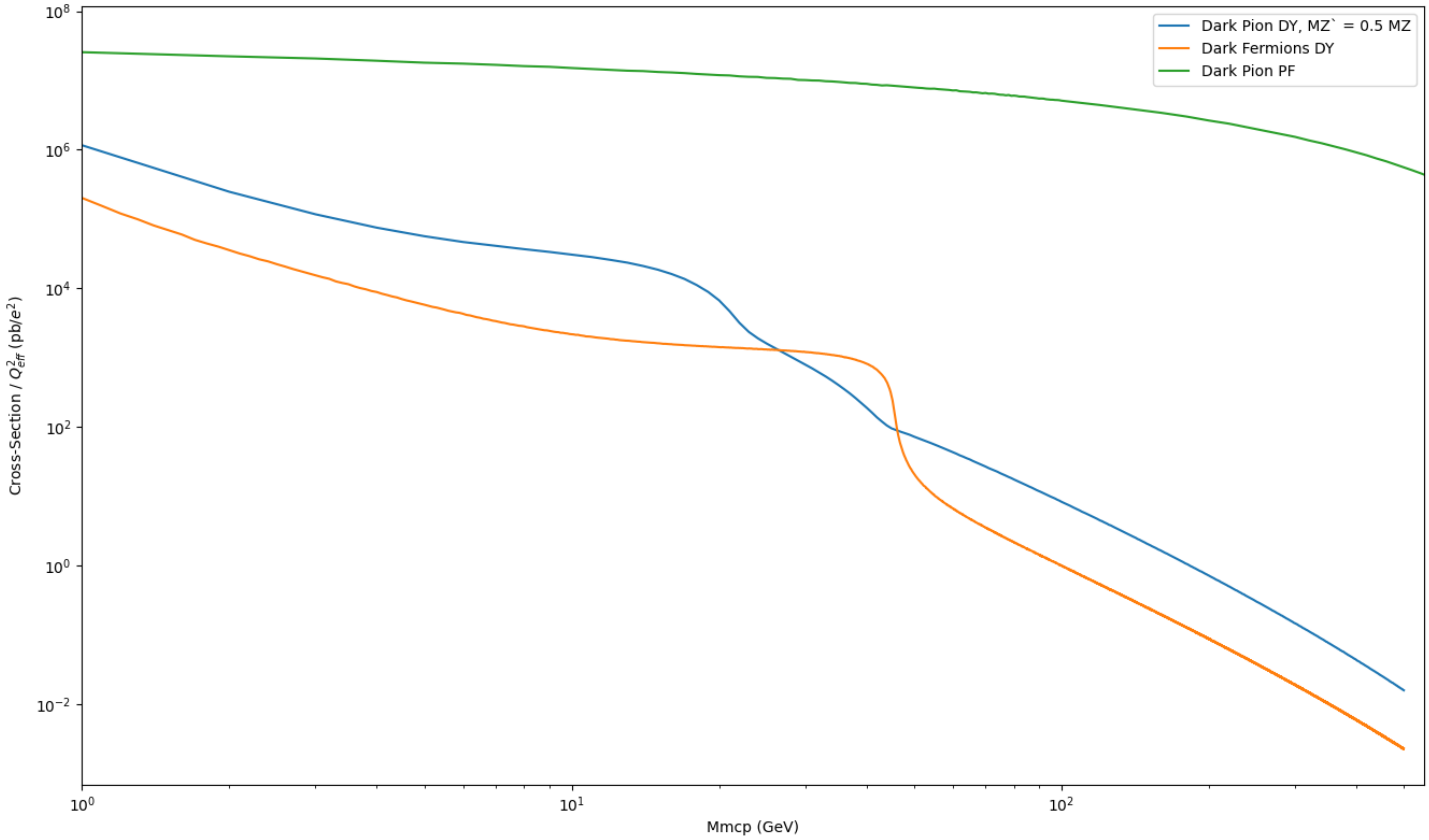


Drell-Yan production to two milli-charged dark pions

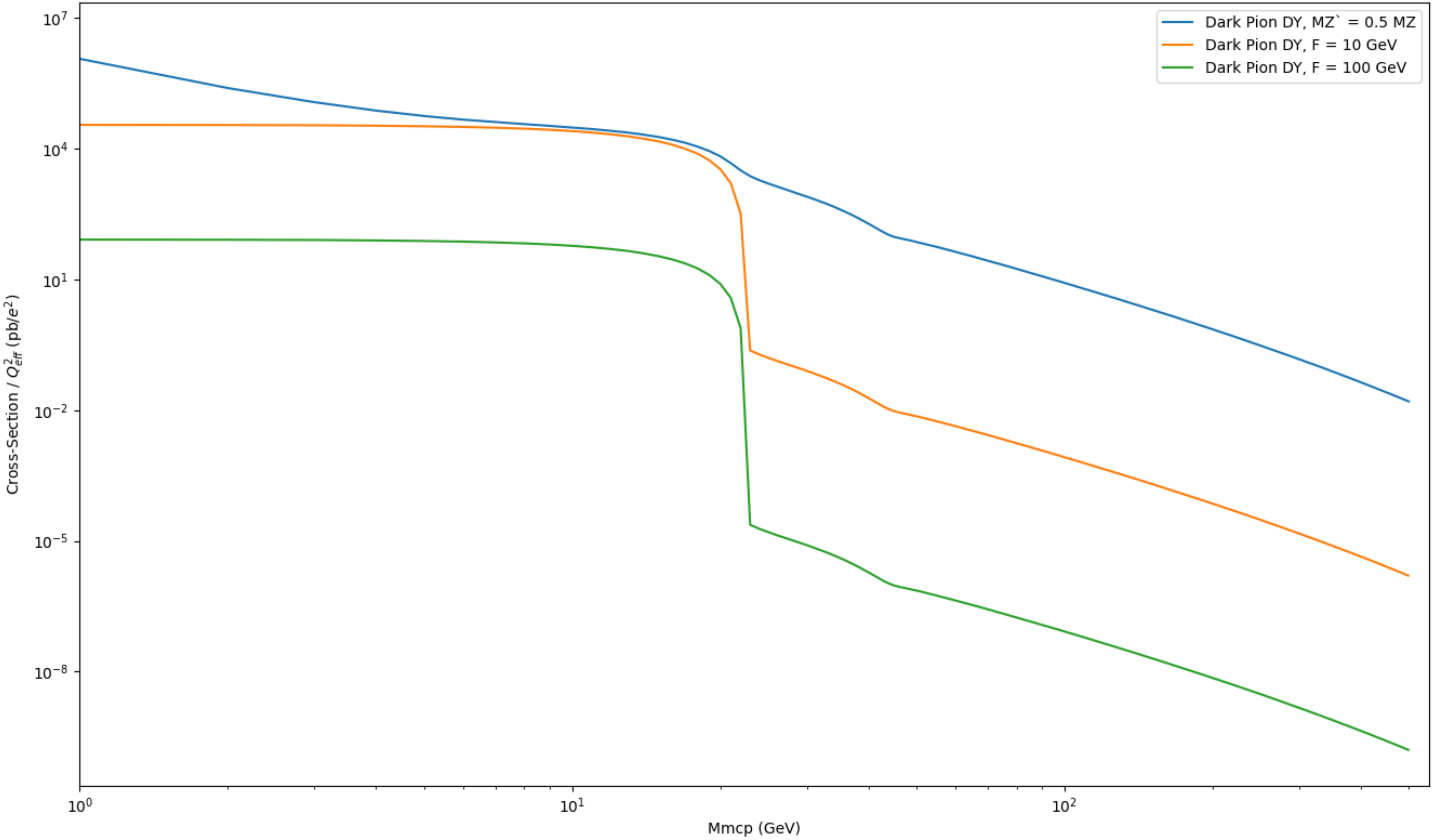


Photon fusion to three dark pions

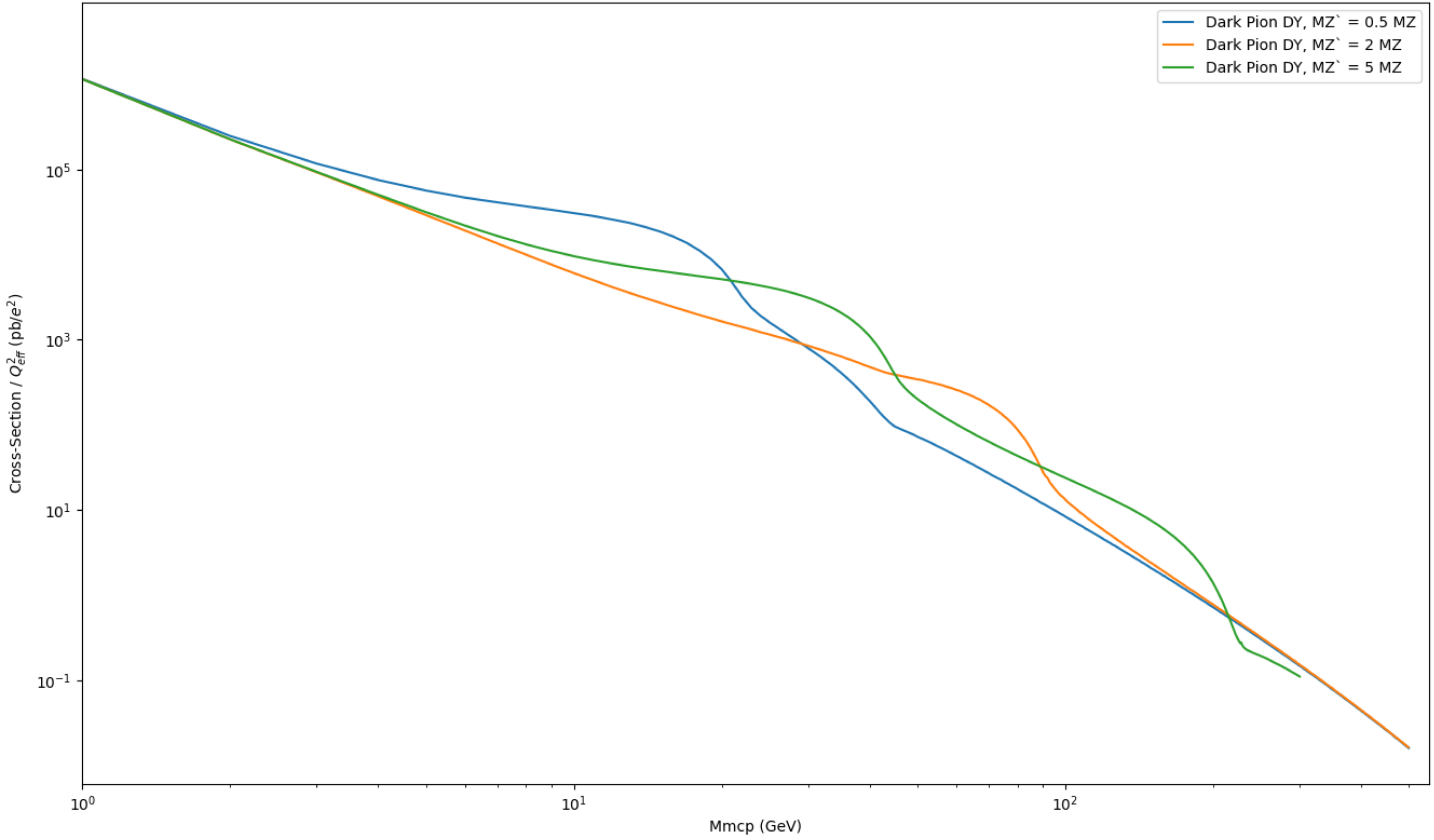
- arises from the WZW term



Dark Pion DY, MZ` = 0.5 MZ
Dark Fermions DY
Dark Pion PF
10^8
10^6
10^4
10^2
10^0
10^{-2}
Cross-Section / Q^2_{eff} (pb/e^2)
10^0
10^1
10^2
Mmcp (GeV)



Dark Pion DY, MZ` = 0.5 MZ
Dark Pion DY, F = 10 GeV
Dark Pion DY, F = 100 GeV
Cross-Section / Q_{eff}^2 (pb/e^2)
10^7
10^4
10^1
10^{-2}
10^{-5}
10^{-8}
10^0
10^1
10^2
Mmcp (GeV)



Dark Pion DY, MZ` = 0.5 MZ
Dark Pion DY, MZ` = 2 MZ
Dark Pion DY, MZ` = 5 MZ
Cross-Section / Q^2_{eff} (pb/e^2)
10^5
10^3
10^1
10^{-1}
10^0
10^1
10^2
Mmcp (GeV)

Preliminary Sensitivity Plot

- To generate a preliminary sensitivity plot of MAPP-1, we use the following formula for the estimated number of signal events:

$$N_{\mathrm{sig}} = N_\chi \times A \times P$$

- For a 95% C.L. N_{sig} equates to having 3 hits (Background free) in the detector.

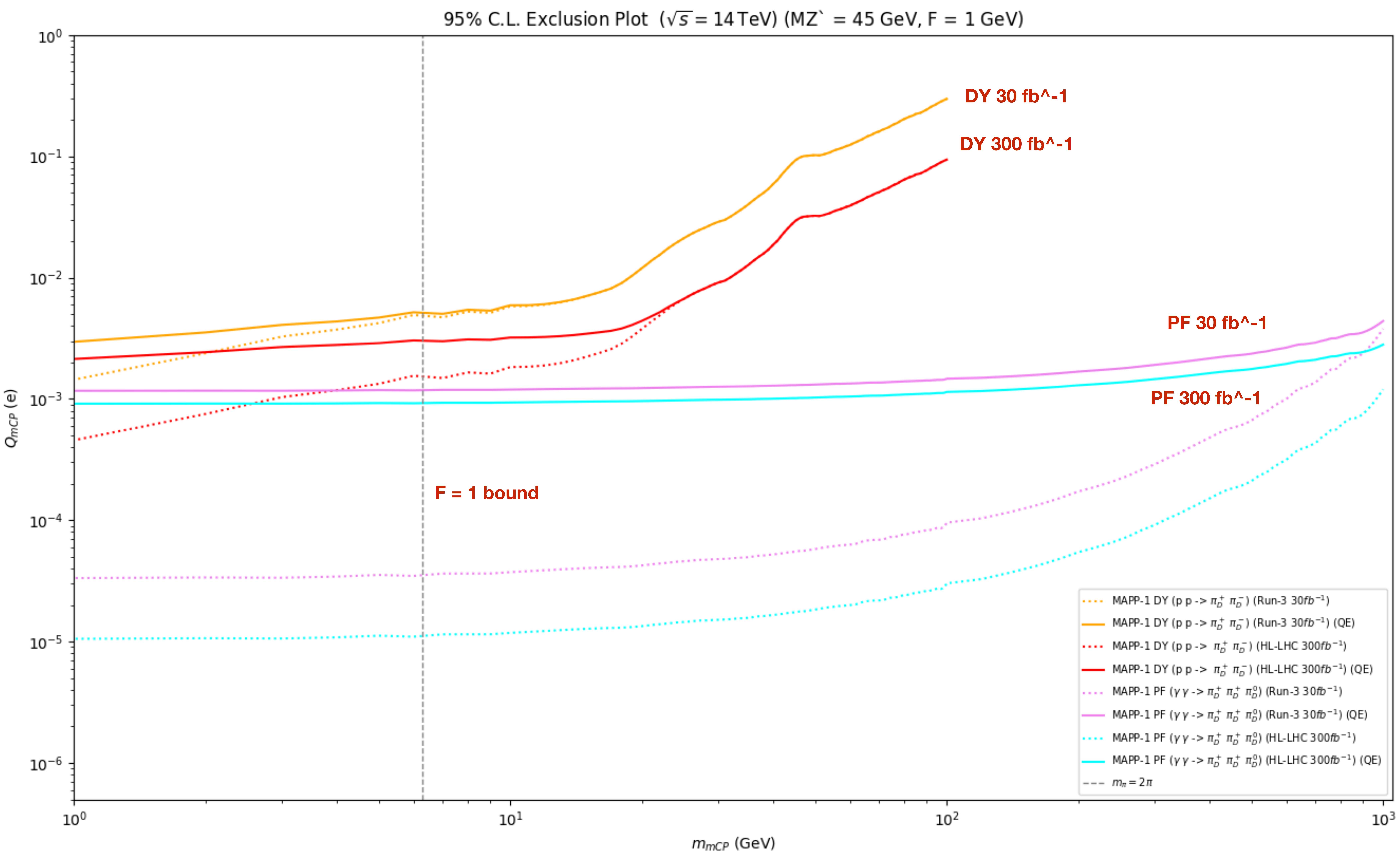
$$N_\chi = \sigma L$$

$$A = \frac{\text{number of particles that traverse the full detector}}{\text{number of particles that are produced}}$$

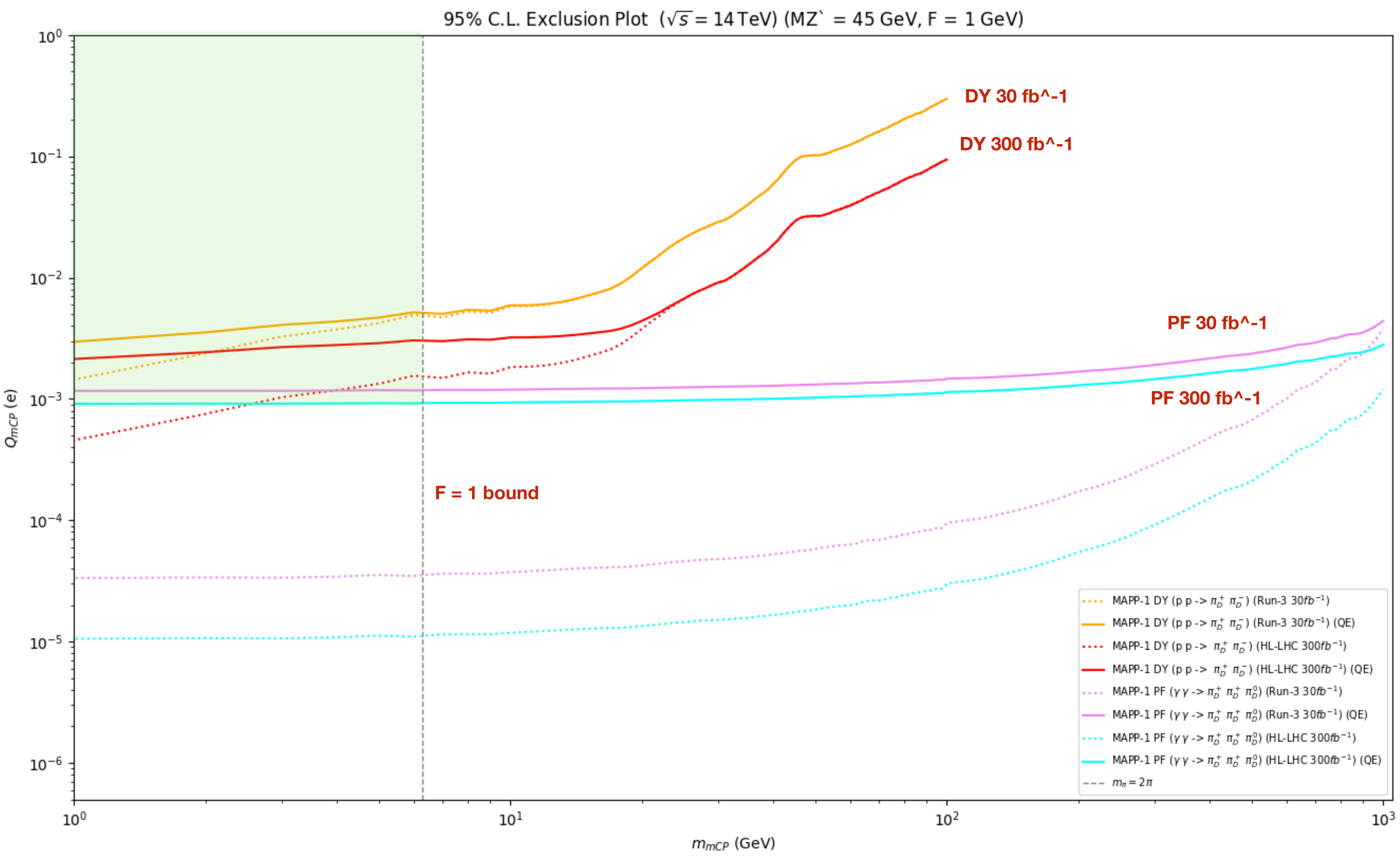
- P is the detection probability for a through-going particle. $P = (1 - e^{-N_{PE}})^n$

$N_{PE} \propto Q^2 N_\gamma \mathrm{QE}$ With a 20% Q.E. and $N_\gamma \simeq 6.824 \times 10^5$ we get $N_{PE} \simeq 1.365 \times 10^5\ Q^2$

Kalliokoski, M. et. al 10.1007/JHEP04(2024)137.



95% C.L. Exclusion Plot ($\sqrt{s} = 14\,\text{TeV}$) (MZ` = 45 GeV, F = 1 GeV)
DY 30 fb^-1
DY 300 fb^-1
PF 30 fb^-1
PF 300 fb^-1
F = 1 bound
Q_{mCP} (e)
m_{mCP} (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^0
10^1
10^2
10^3
MAPP-1 DY (p p -> π_D^+ π_D^-) (Run-3 30fb^{-1})
MAPP-1 DY (p p -> π_D^+ π_D^-) (Run-3 30fb^{-1}) (QE)
MAPP-1 DY (p p -> π_D^+ π_D^-) (HL-LHC 300fb^{-1})
MAPP-1 DY (p p -> π_D^+ π_D^-) (HL-LHC 300fb^{-1}) (QE)
MAPP-1 PF ($\gamma\gamma$ -> π_D^+ π_D^+ π_D^0) (Run-3 30fb^{-1})
MAPP-1 PF ($\gamma\gamma$ -> π_D^+ π_D^+ π_D^0) (Run-3 30fb^{-1}) (QE)
MAPP-1 PF ($\gamma\gamma$ -> π_D^+ π_D^+ π_D^0) (HL-LHC 300fb^{-1})
MAPP-1 PF ($\gamma\gamma$ -> π_D^+ π_D^+ π_D^0) (HL-LHC 300fb^{-1}) (QE)
$m_\pi = 2\pi$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Q_{mCP} (e)
m_{mCP} (GeV)
DY 30 fb^-1
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PF 30 fb^-1
PF 300 fb^-1
F = 1 bound
MAPP-1 DY (p p -> π_D^+ π_D^-) (Run-3 30fb^{-1})
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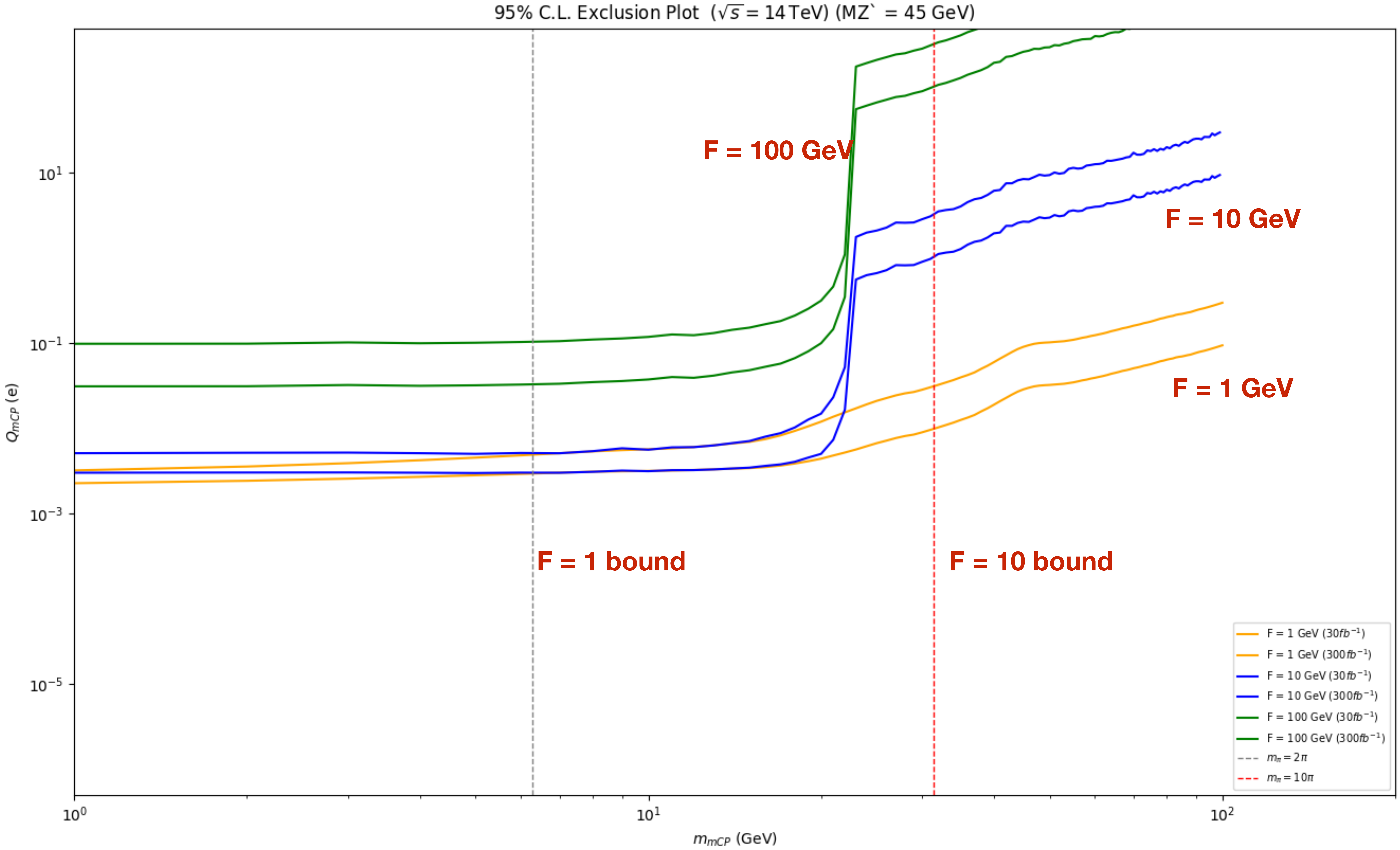

95% C.L. Exclusion Plot ($\sqrt{s}$ = 14 TeV) (MZ` = 45 GeV)
Q_{mCP} (e)
m_{mCP} (GeV)
F = 100 GeV
F = 10 GeV
F = 1 GeV
F = 1 bound
F = 10 bound
F = 1 GeV ($30fb^{-1}$)
F = 1 GeV ($300fb^{-1}$)
F = 10 GeV ($30fb^{-1}$)
F = 10 GeV ($300fb^{-1}$)
F = 100 GeV ($30fb^{-1}$)
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$m_\pi = 2\pi$
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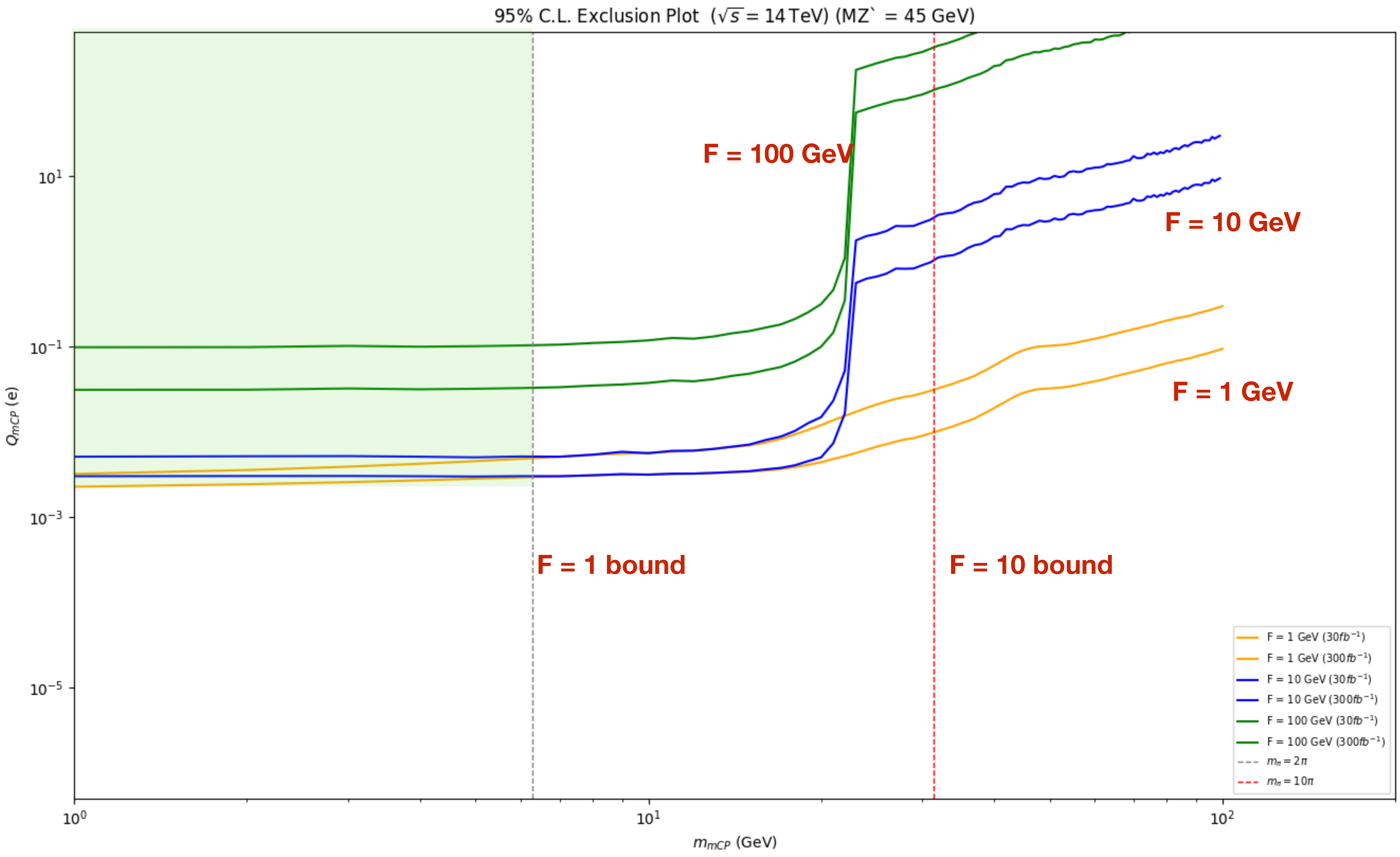

95% C.L. Exclusion Plot ($\sqrt{s}$ = 14 TeV) (MZ` = 45 GeV)
Q_{mCP} (e)
m_{mCP} (GeV)
10^1
10^{-1}
10^{-3}
10^{-5}
10^0
10^1
10^2
F = 100 GeV
F = 10 GeV
F = 1 GeV
F = 1 bound
F = 10 bound
F = 1 GeV ($30 fb^{-1}$)
F = 1 GeV ($300 fb^{-1}$)
F = 10 GeV ($30 fb^{-1}$)
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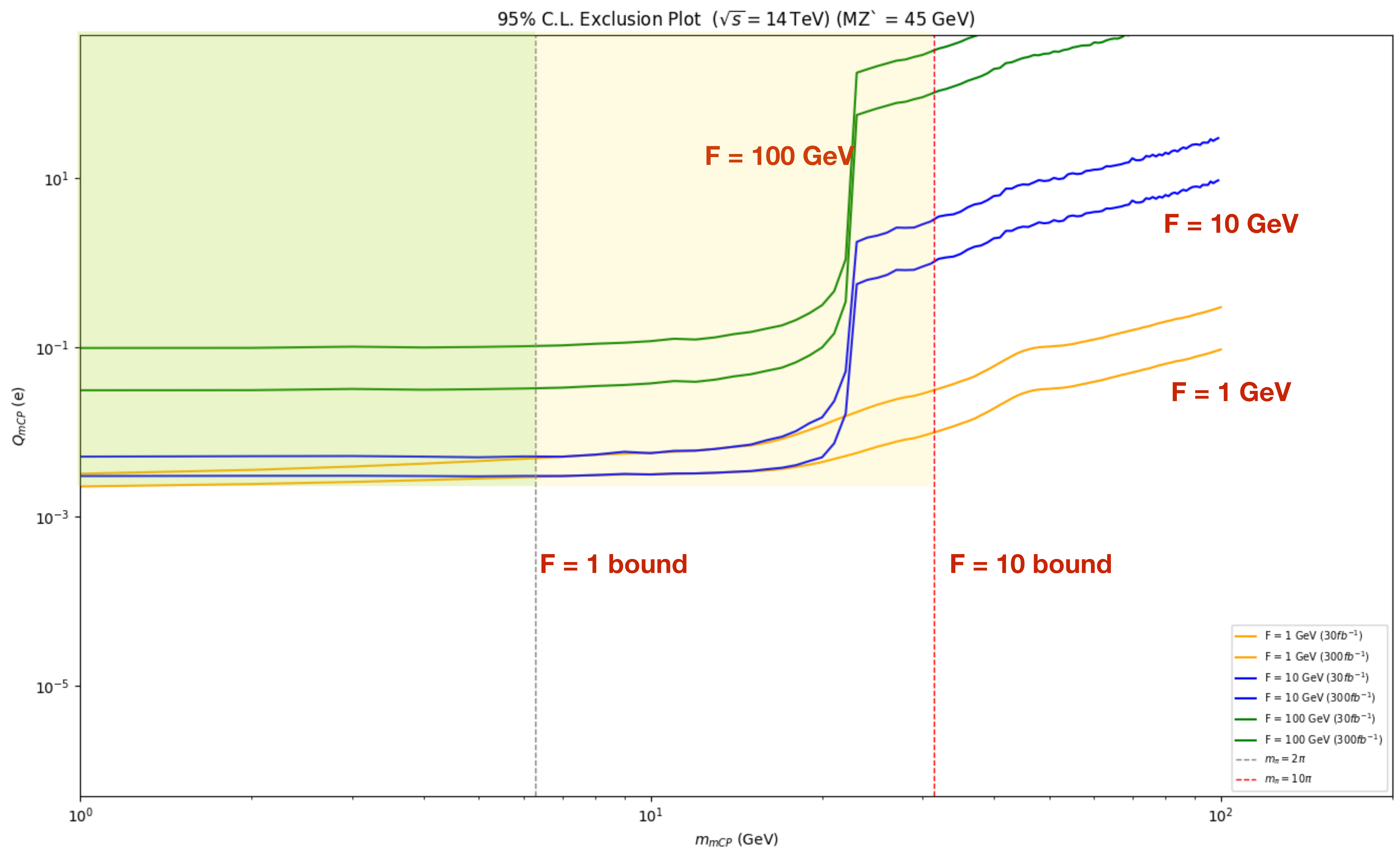

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F = 10 GeV
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F = 1 bound
F = 10 bound
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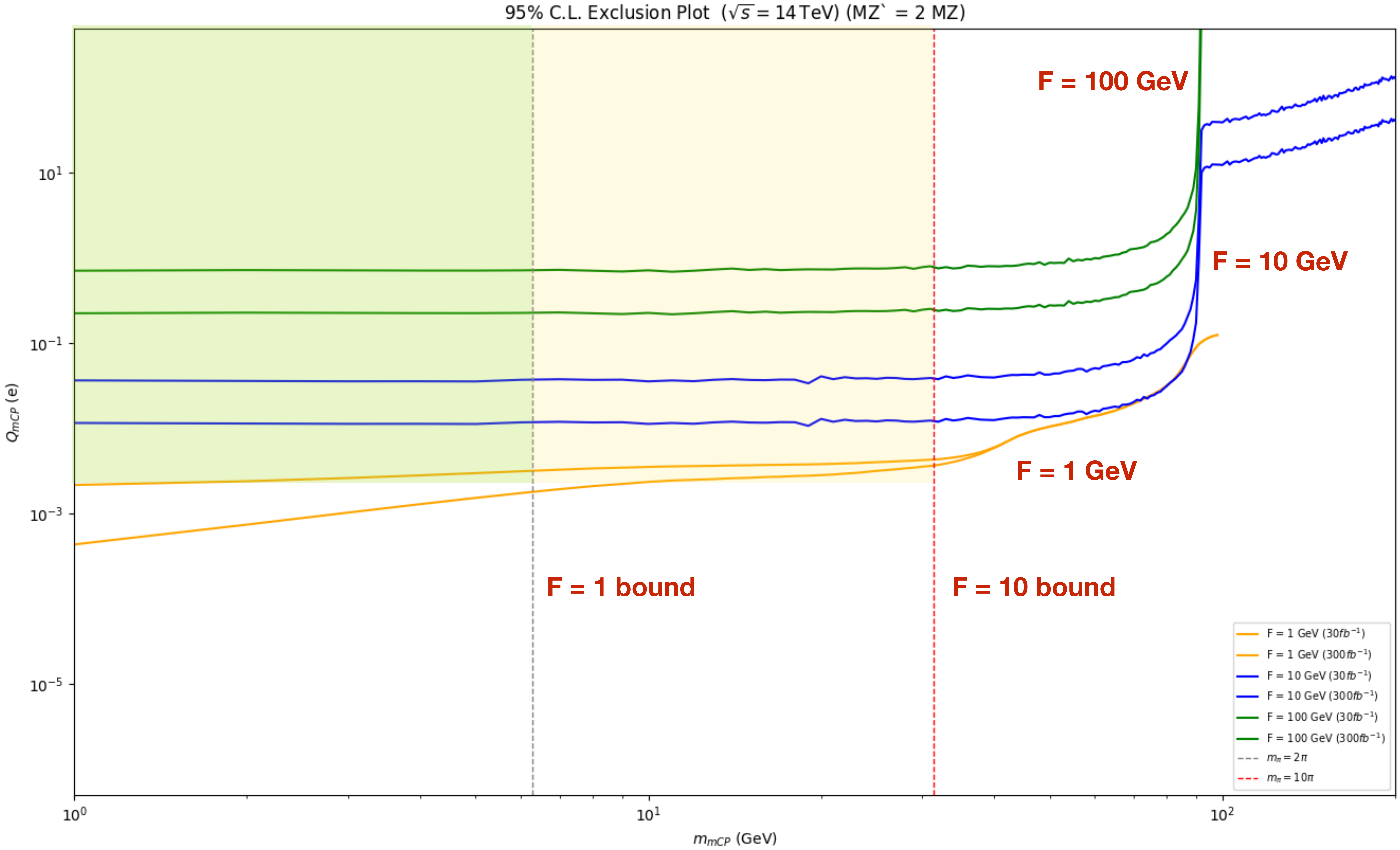
m_{mCP} (GeV)
F = 1 GeV (30fb^{-1})
F = 1 GeV (300fb^{-1})
F = 10 GeV (30fb^{-1})
F = 10 GeV (300fb^{-1})
F = 100 GeV (30fb^{-1})
F = 100 GeV (300fb^{-1})
$m_\pi = 2\pi$
$m_\pi = 10\pi$



95% C.L. Exclusion Plot ($\sqrt{s}$ = 14 TeV) (MZ` = 2 MZ)
F = 100 GeV
F = 10 GeV
F = 1 GeV
F = 1 bound
F = 10 bound
Q_{mCP} (e)
m_{mCP} (GeV)
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{0}
10^{1}
10^{2}
F = 1 GeV (30fb^{-1})
F = 1 GeV (300fb^{-1})
F = 10 GeV (30fb^{-1})
F = 10 GeV (300fb^{-1})
F = 100 GeV (30fb^{-1})
F = 100 GeV (300fb^{-1})
$m_{\pi} = 2\pi$
$m_{\pi} = 10\pi$

Summary and Future Work

- Looked at a strongly interacting dark pions model and studied its sensitivity in the context of MoEDAL MAPP.
- Studied the free parameters in our model and saw how they effect the bounds.
- GEANT4 simulation, specifically with the SUMMA model is WIP.

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Thank You

Collaborators

James Pinfold (University of Alberta)

Pierre-Philippe Ouimet (University of Regina)

Michael Staelens (Okanagan College)

Questions?

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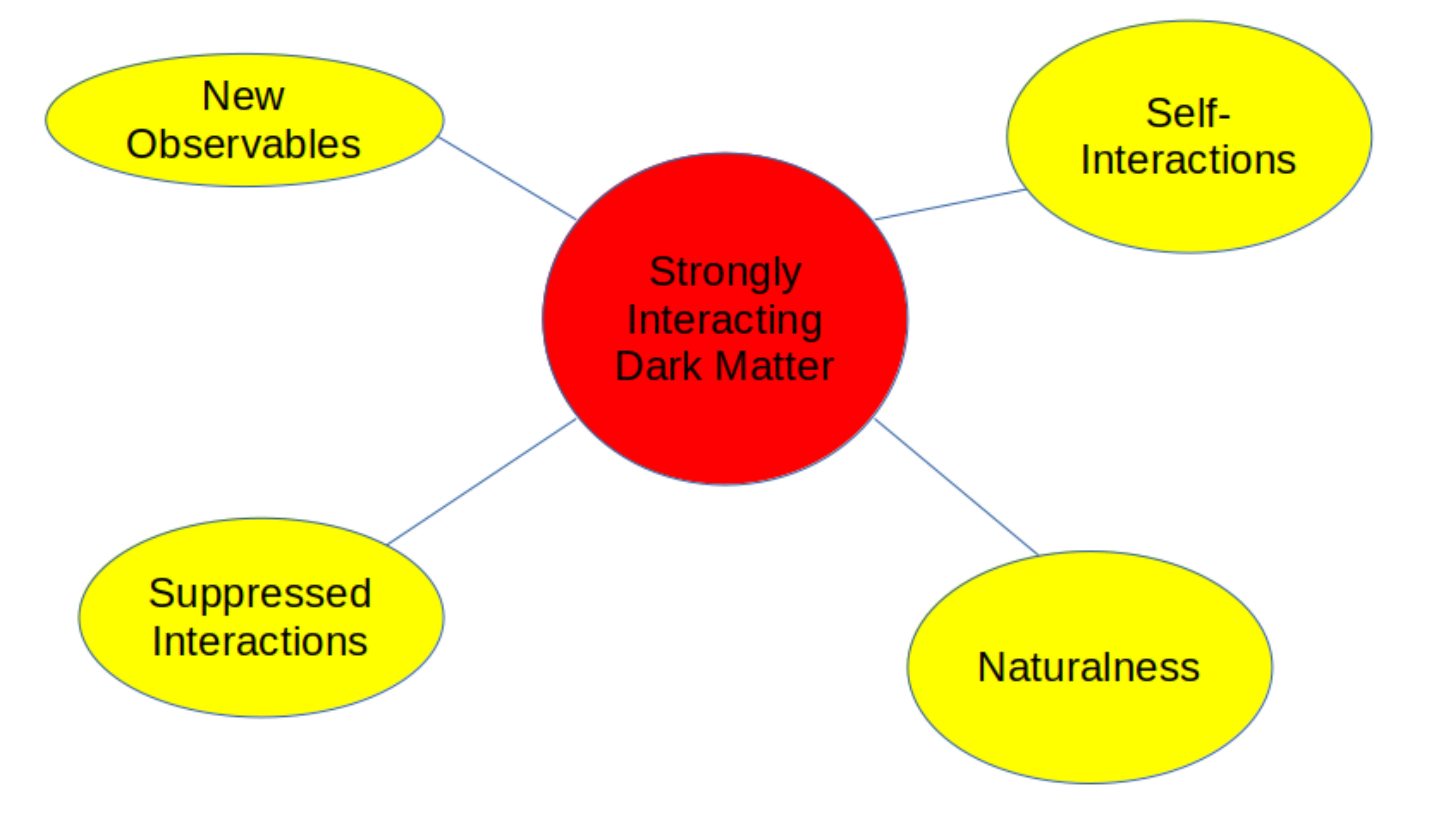
Strongly Interacting Dark Matter



- Pion-like DM: $m_q << \Lambda_D$
- Quarkonia-like DM: $m_q >> \Lambda_D$
- Intermediate or mixed regime
- Baryon-like DM
- Dark Glueballs

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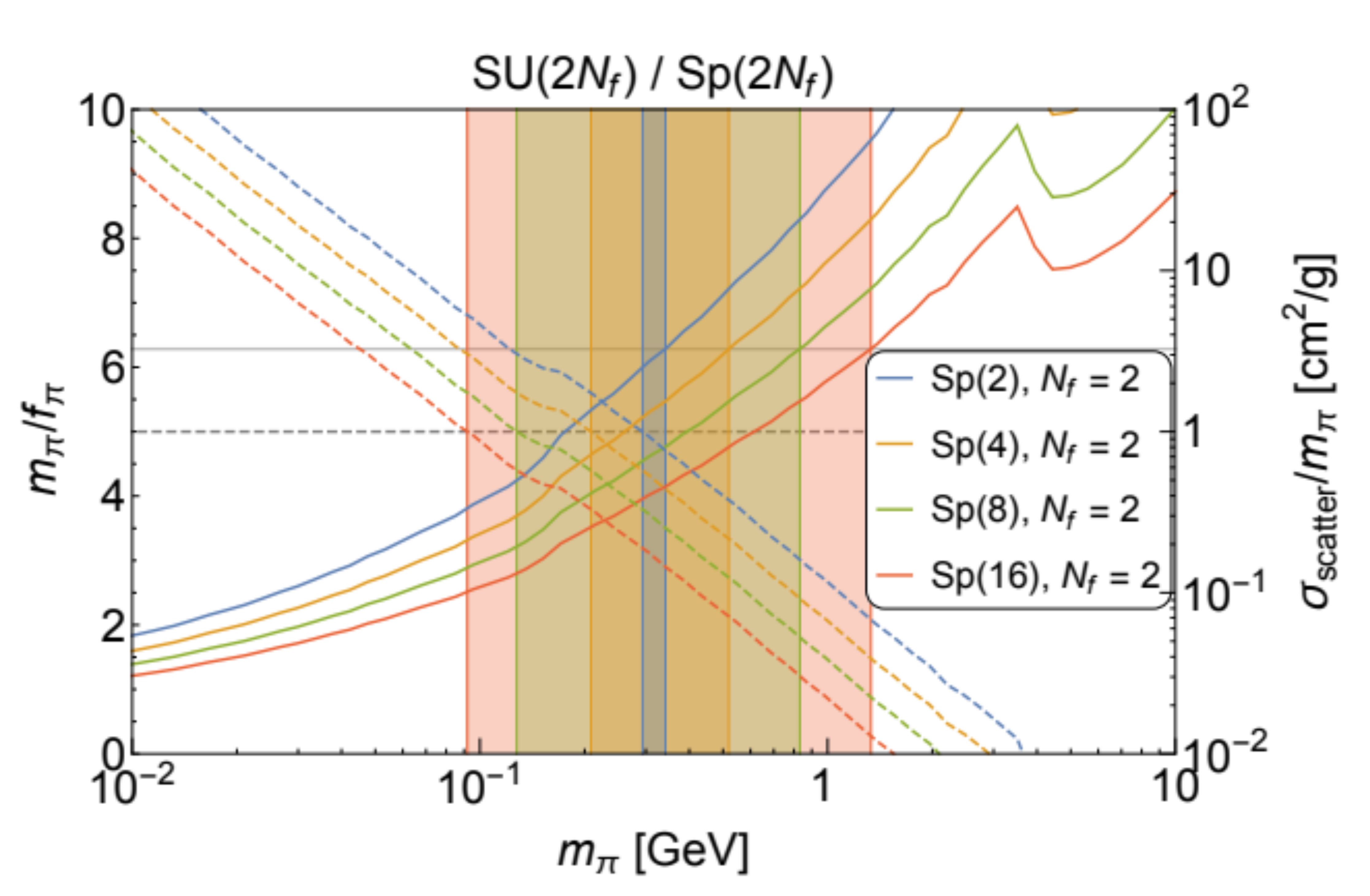

The solution to the Boltzmann equation of the 3 → 2 system, yielding the measured dark matter relic abundance for the pions

$$\frac{\sigma_{\text{scatter}}}{m_{\text{DM}}} \lesssim 1\ \text{cm}^2/\text{g}\,,$$

constrained by bullet-cluster and halo shape constraints

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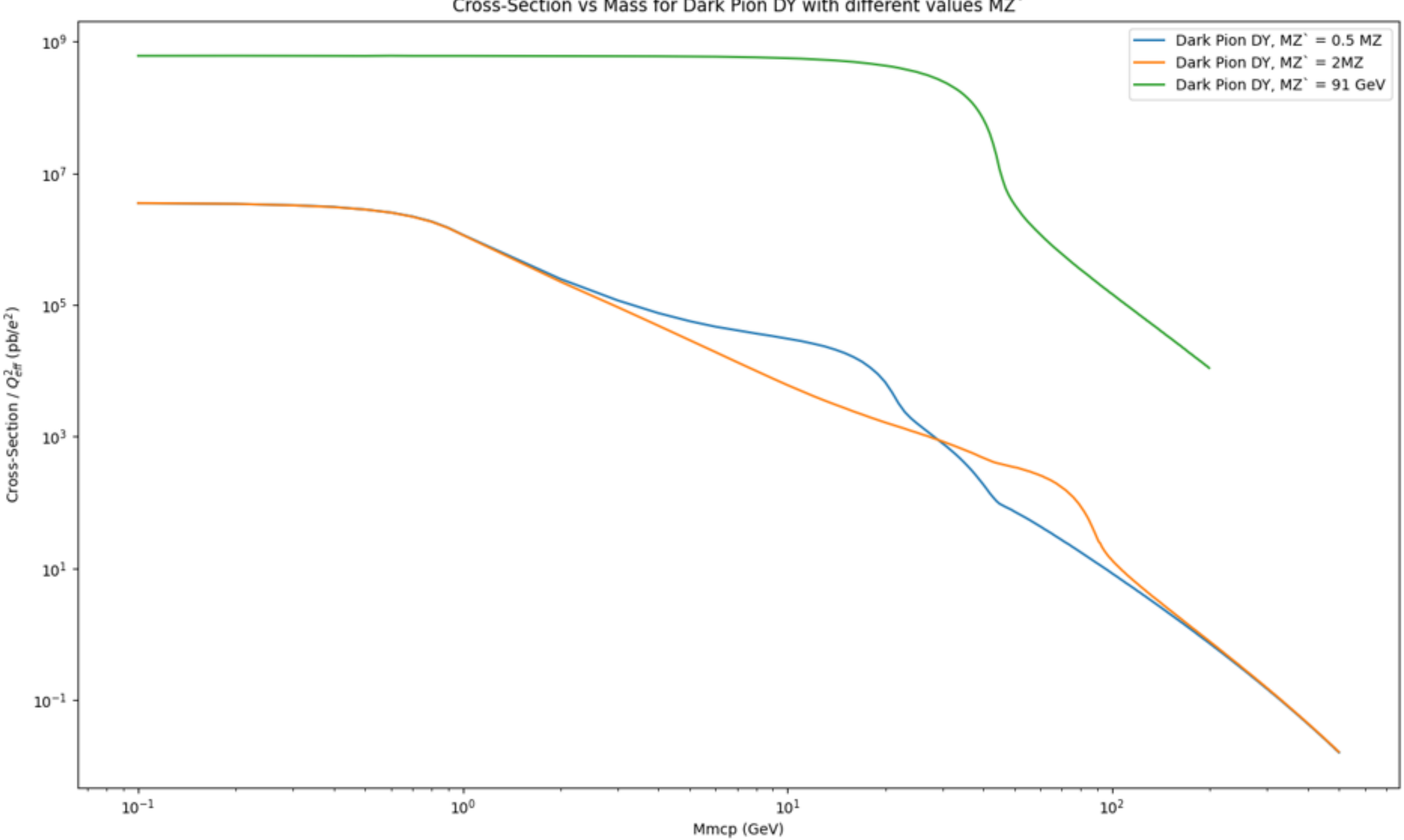
$$\mathbf{M} = \frac{M_1^2 + M_2^2}{M_1^2 - M_2^2}$$

We have this term in the WZW Lagrangian

Essentially enforces that Z and Z' cannot have the same mass

Cross-Section and sensitivity will become lower if MZ' >> MZ or MZ' << MZ

$$
\begin{aligned}
D_\mu\phi = \partial_\mu\phi + ig_D Q\phi \Bigg[& A'_\mu - \kappa cc' A_\mu + \left(\kappa sc' + \frac{1}{2}\kappa ss't'\mathbf{M} + \frac{1}{2}\kappa ss't' - (\kappa cs')^2 t'\right) Z_\mu \\
& + \left(\frac{1}{2}(\kappa s)^2 s'c'\mathbf{M} - \frac{(\kappa s)^2 c'}{2} - (\kappa c)^2 c's' - t' + \frac{1}{8}(\kappa ss')^2 t'\mathbf{M} + \frac{(\kappa ss')^2 t'}{4}\mathbf{M} - \frac{3(\kappa ss')^2 t'}{8}\right) Z'_\mu \Bigg] \\
& g_D\lambda_3 \left[\left(\frac{3(\kappa s)^2 s'}{8c'} - \frac{\kappa s}{2c'}\mathbf{M} - \frac{\kappa s}{2c'} - \frac{(\kappa c)^2 s'}{2c'}\right) Z_\mu \right] \\
& + \left(\frac{1}{s'c'} - \frac{(\kappa s)^2 s'}{8c}\mathbf{M}^2 - \frac{(\kappa s)^2 s'}{4c'}\mathbf{M}\right) Z'_\mu \Bigg] \\
& - ig_D\phi Q \Bigg[A'_\mu - \kappa_{cc'} A_\mu + \left(\kappa sc' + \frac{1}{2}\kappa ss't'\mathbf{M} + \frac{1}{2}\kappa ss't' - (\kappa cs't')^2\right) Z_\mu \\
& + \left(\frac{1}{2}(\kappa s)^2 s'c'\mathbf{M} - \frac{(\kappa s)^2 c'}{2} - (\kappa c)^2 c's' - t' + \frac{1}{8}(\kappa ss')^2 t'\mathbf{M} + \frac{(\kappa ss')^2 t'}{4}\mathbf{M} - \frac{3(\kappa ss')^2 t'}{8}\right) Z'_\mu \Bigg] \\
& \equiv \mathcal{D}_\mu\phi
\end{aligned}
$$



Cross-Section vs Mass for Dark Pion DY with different values MZ`
Dark Pion DY, MZ` = 0.5 MZ
Dark Pion DY, MZ` = 2MZ
Dark Pion DY, MZ` = 91 GeV
Cross-Section / Q^2_{eff} (pb/e^2)
Mmcp (GeV)
10^9
10^7
10^5
10^3
10^1
10^{-1}
10^{-1}
10^0
10^1
10^2

Background Considerations:

- MAPP-1 is naturally shielded from cosmic muons by 110 m rock overburden and 47 m of materials (concrete) from IP8 to its location.
- Background from muons originating from IP8 and its subsequently generated secondaries to be 1 out of 40,000 bunch-crossings
- Dark current in the PMTs can also result in signal-like events; however, the four-fold coincidence design employed essentially eliminates this BG source
- We assume a mean DCR of 500 Hz based on PMT Specifications. Assuming a 3-year trigger live time, a negligible result of 0.008 total signal-like events is obtained.