In Search of a Hidden Sector: the Phenomenology of Dark Sector Models

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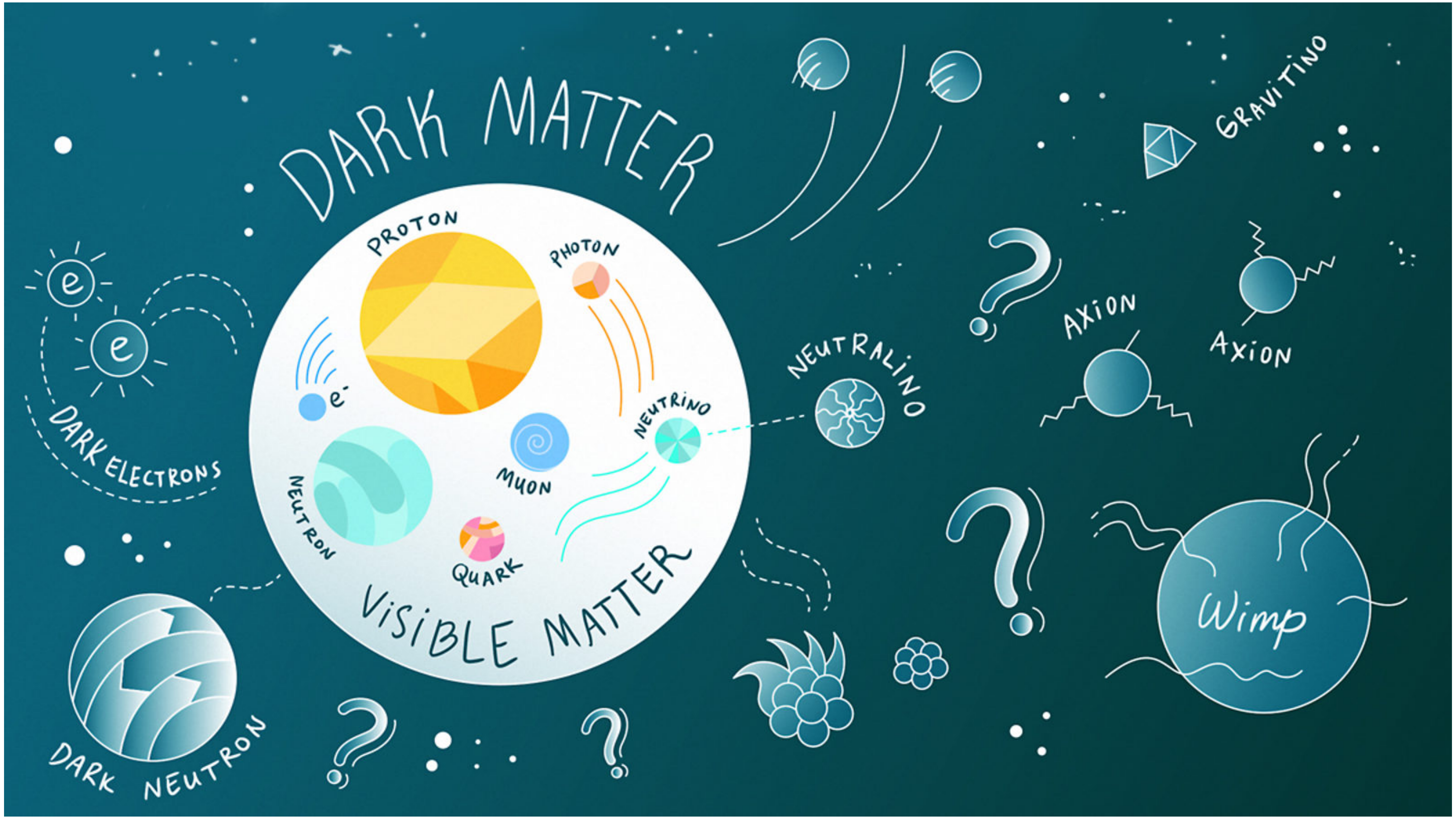


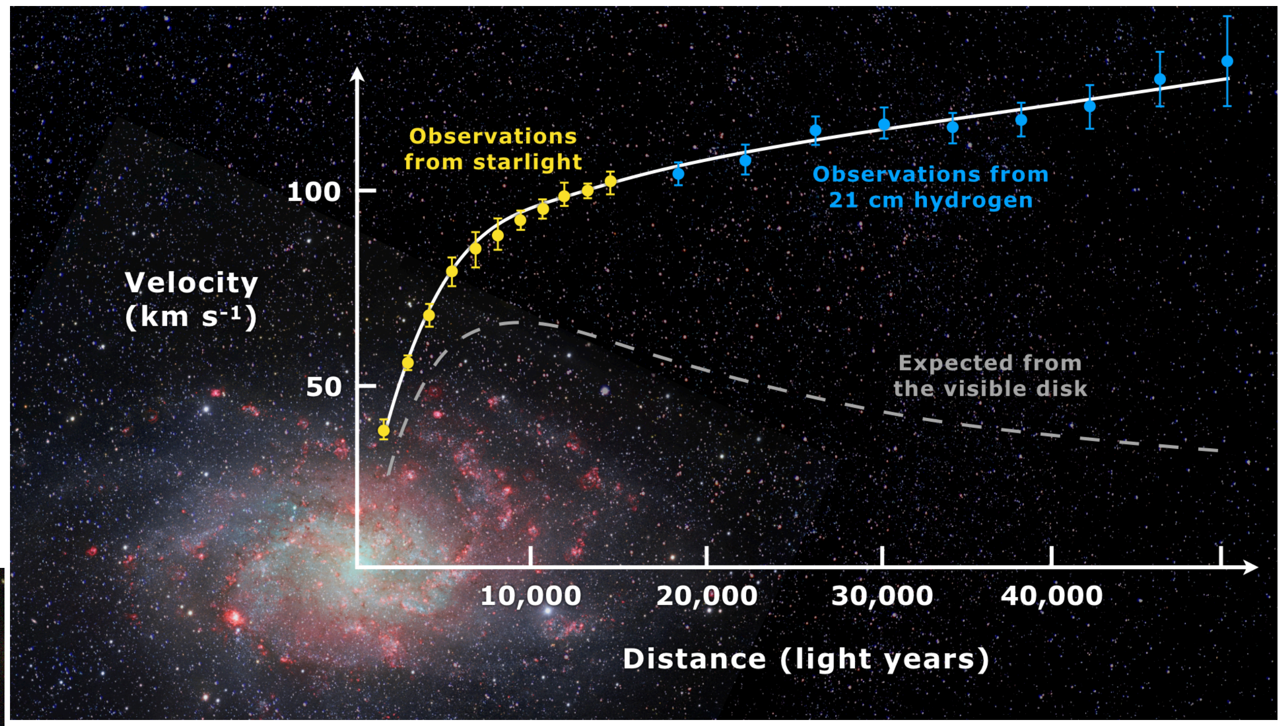
Taken from Symmetry, Illustration by Sandbox Studio, Chicago with Ana Kova

Question: What is Dark Matter, and why should we care?

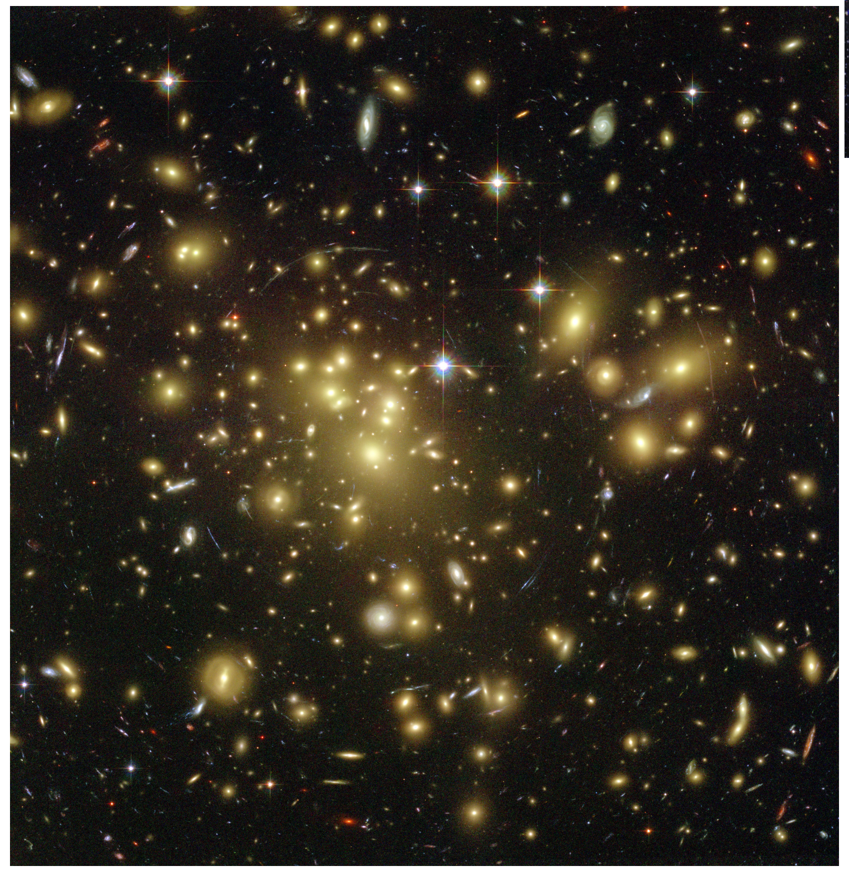
Why Should we Care?

There is ample observational evidence for the existence of dark matter!

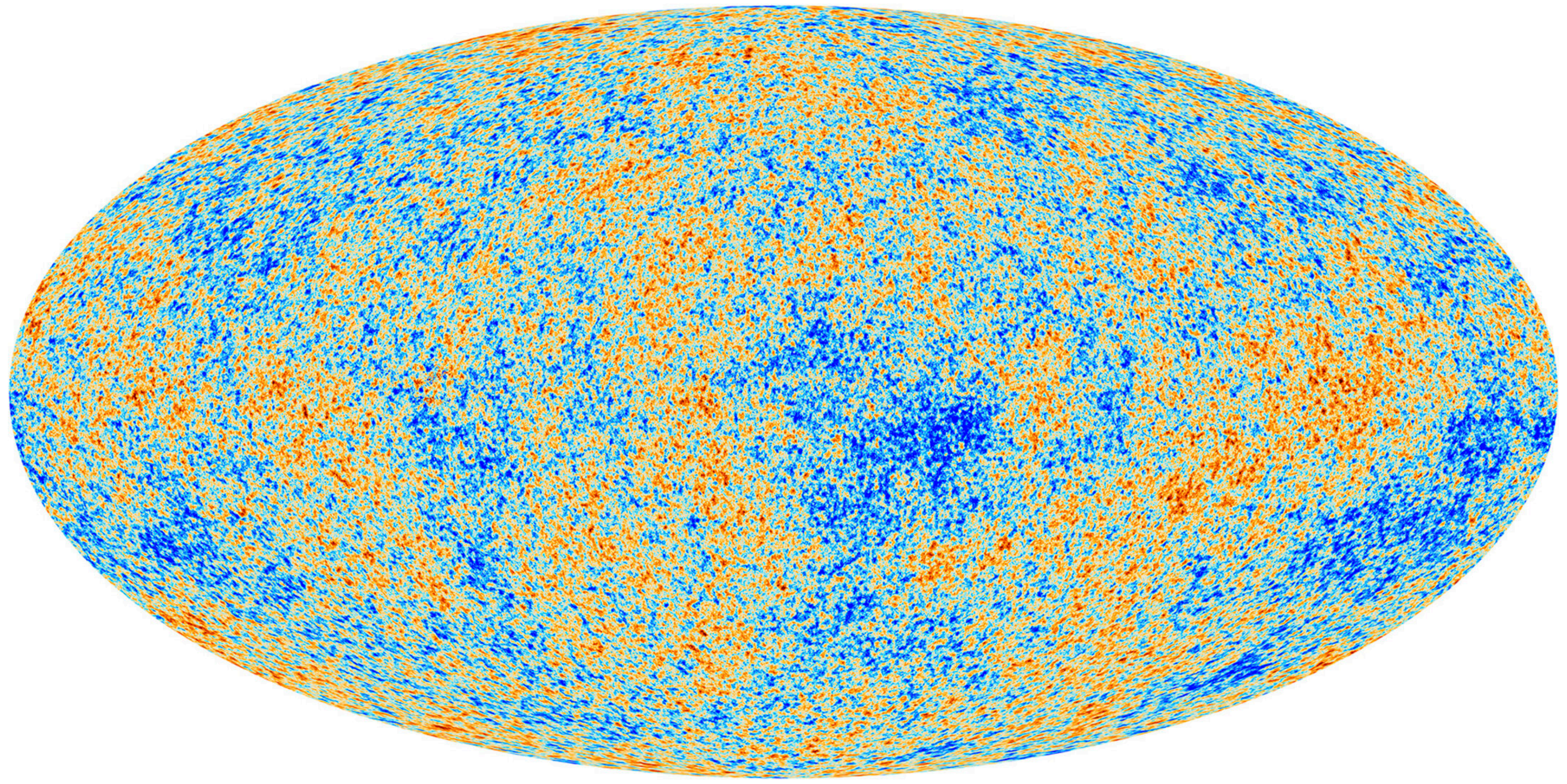
- Galactic Rotation Curves



- Galaxy Clusters



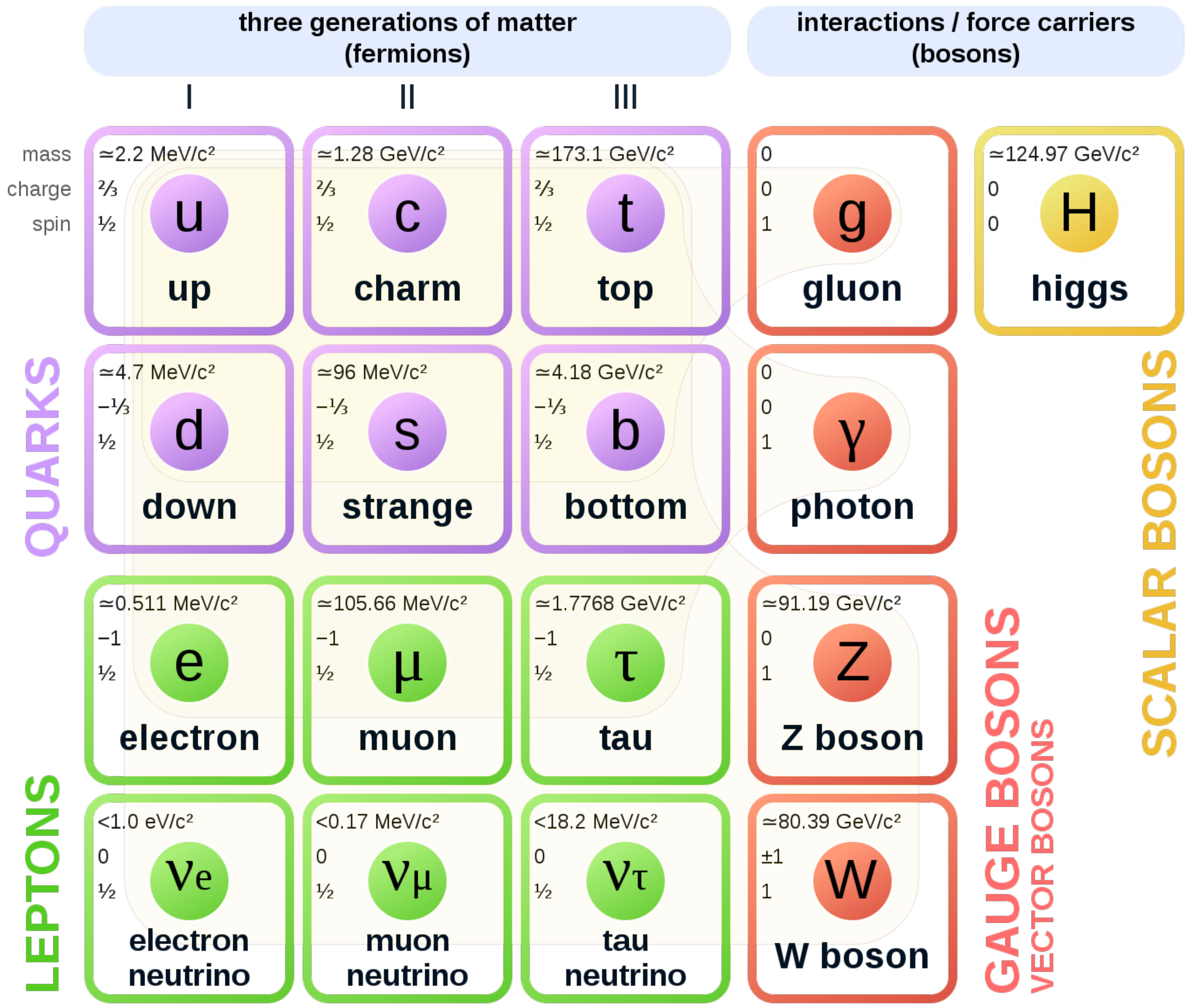
- CMB



What is Dark Matter?

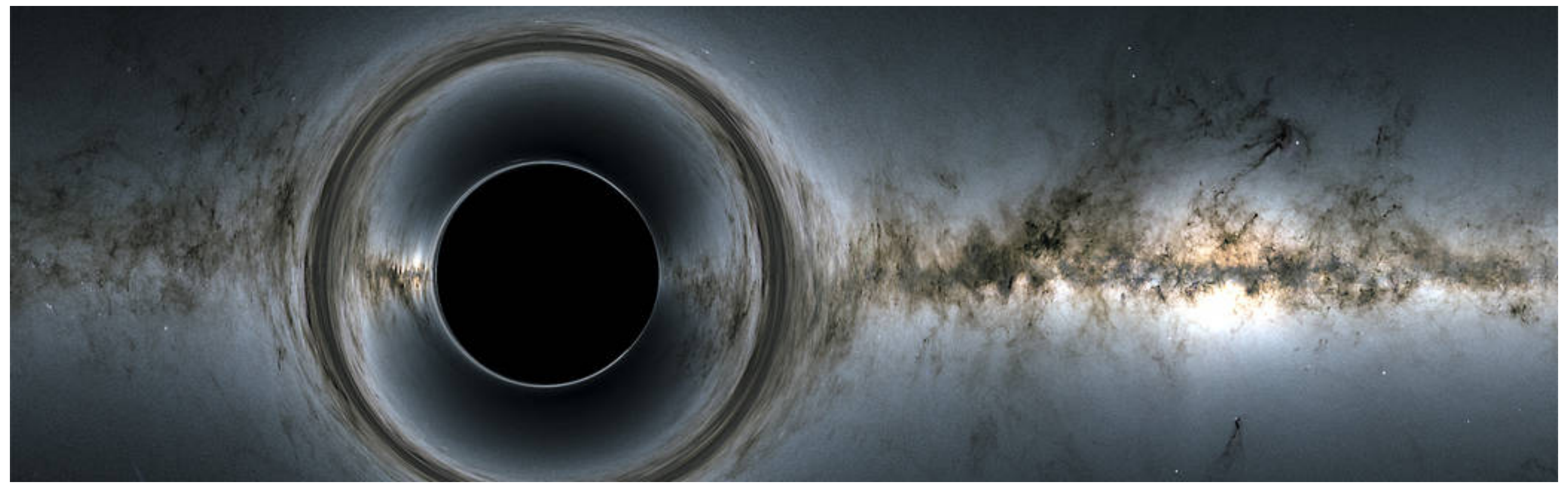
Luminous Matter (~5%)

Standard Model of Elementary Particles



Dark Matter (~26%)

?



Black Holes?

...and?

The Core-Cusp Problem

-In the CDM paradigm, dark matter particles interact with each other only gravitationally and do not collide.

-While the simulations using CDM produce distributions where the density sharply increases at the centre of the galaxies (“cusps”), observations of dwarf galaxies show constant central distributions (“cores”).

-A solution to the core-cusp problem is self-interacting dark matter (SIDM).

W. J. G. de Blok, Advances in Astronomy, vol. 2010, Article ID 789293, 2010. https://doi.org/10.1155/2010/789293

What is Dark Matter?

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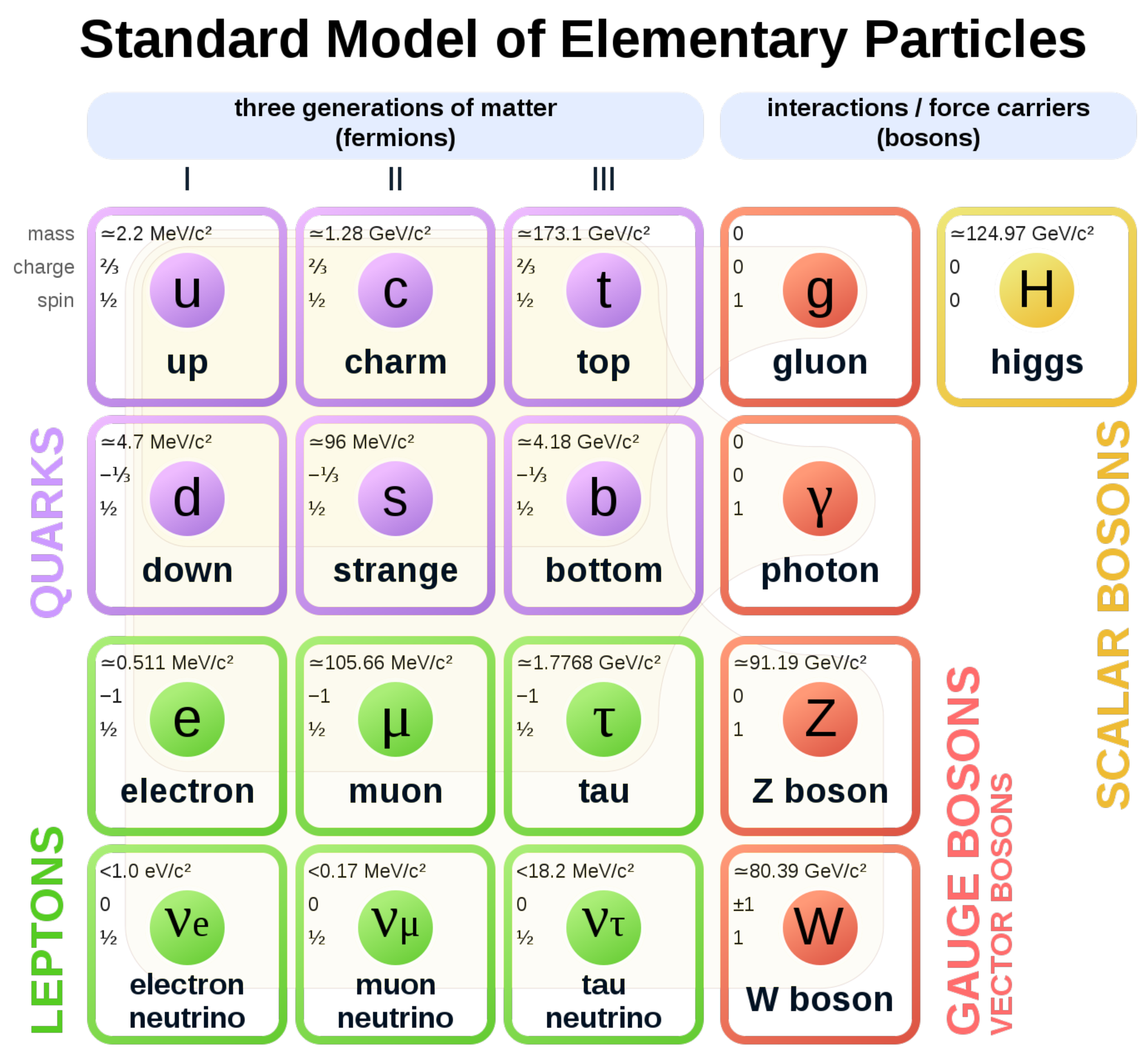
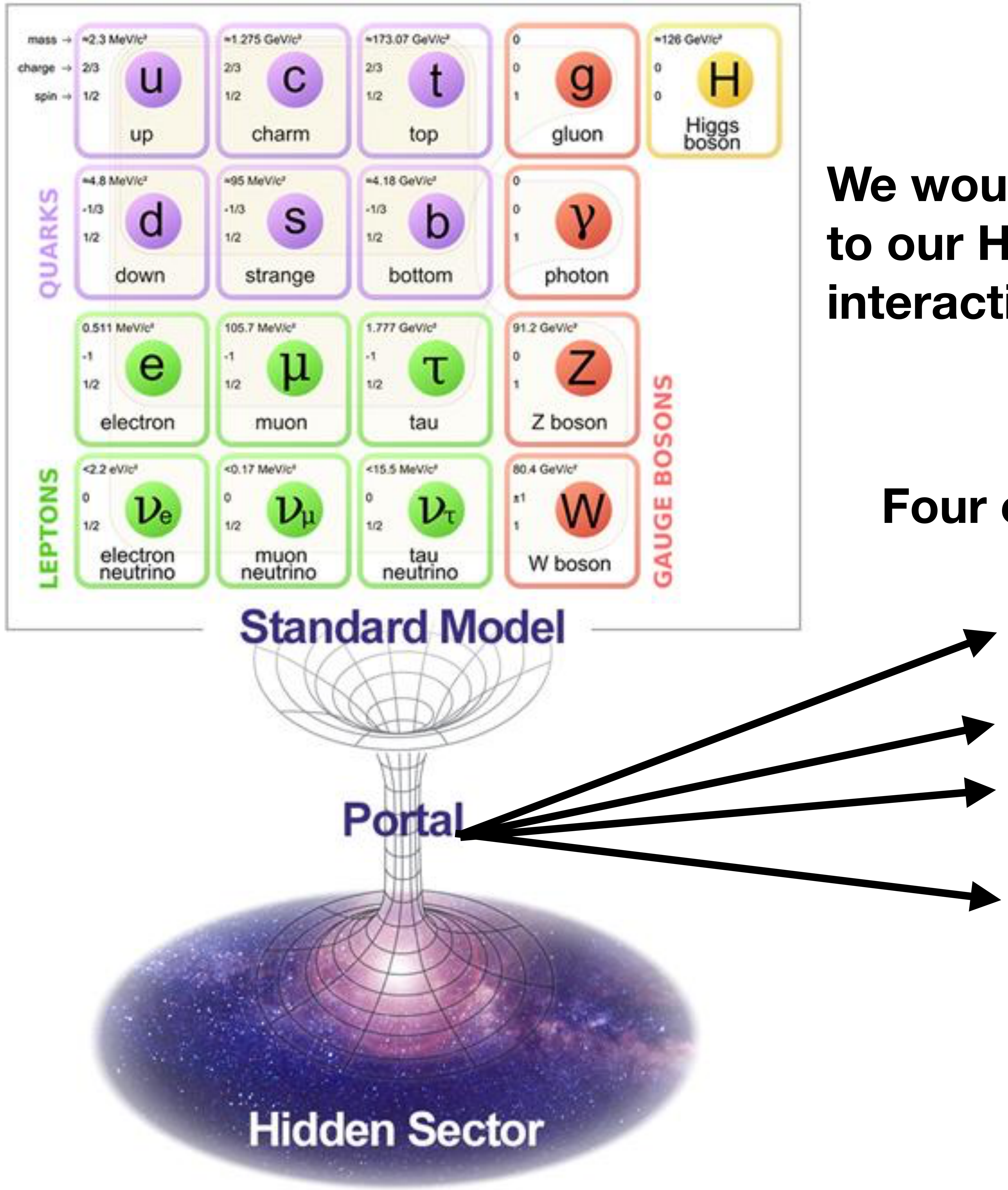


Dark Matter (~26%)

Dark or Hidden Sector!

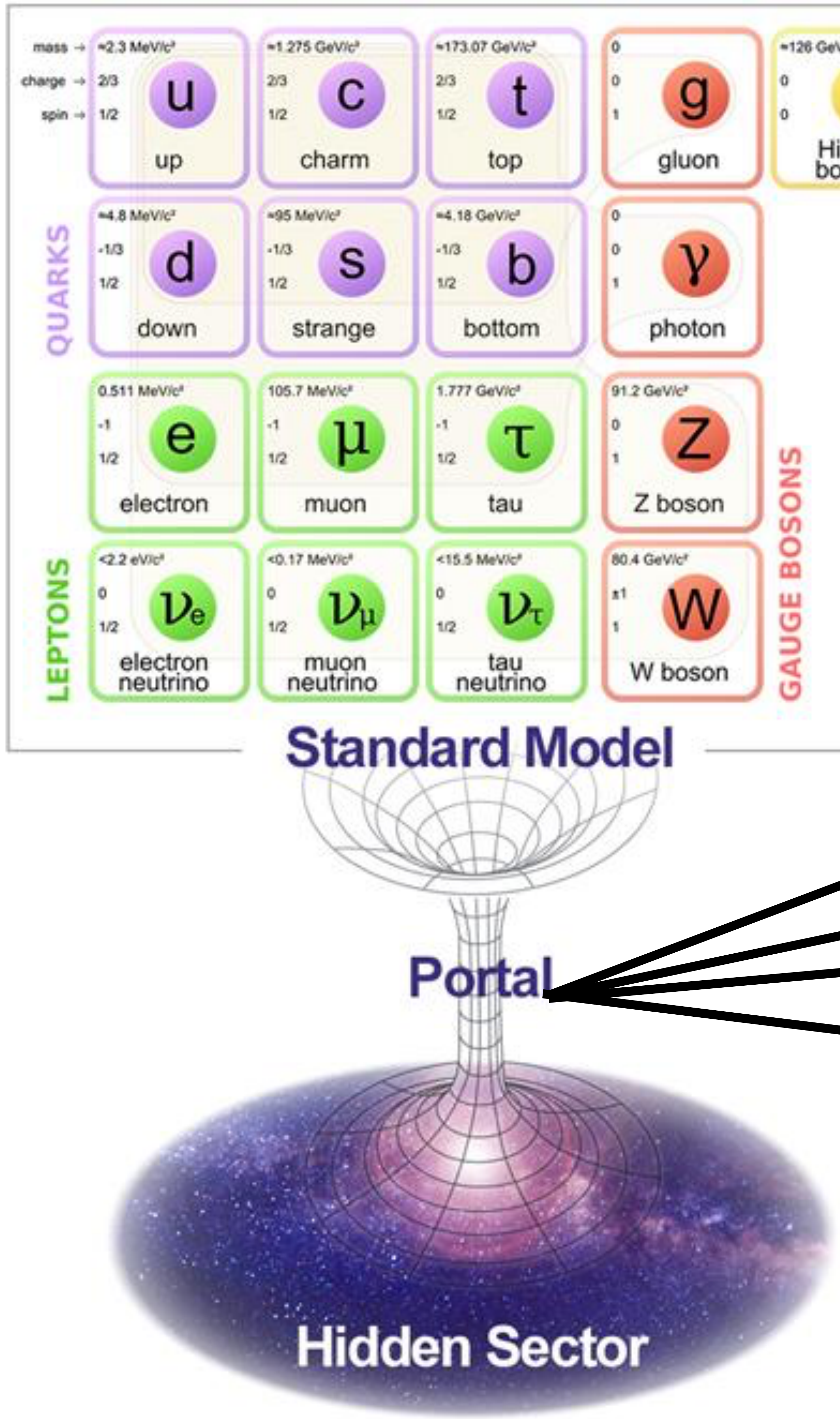
Is there a “dark” Standard Model?



We would like to connect the Standard Model to our Hidden Sector, this is done through a "portal" interaction or interactions.

Four commonly discussed portal interactions:

- Scalar Portal: Dark Higgs
- Pseudoscalar Portal: Axion-like Particle
- Neutrino Portal: Heavy Neutral Lepton
- Vector Portal: Dark Photon



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Vector Portal: Dark Photon

The Lagrangian for a dark fermion , χ, coupling to a dark photon that kinetically mixes with the standard model is:

$$\mathcal{L}_D = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + \frac{1}{4}\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu} + \frac{\kappa}{2}B_{\mu\nu}\mathcal{A}^{\mu\nu}$$

$\mathcal{A}_\mu$:U(1)$_D$ gauge field

B_μ:U(1)$_Y$ gauge field

Under the field redefinition: $\mathcal{A}_\mu \rightarrow \mathcal{A}'_\mu - \kappa B_\mu$

$$\longrightarrow \quad \bar{\chi}(i\gamma^\mu\partial_\mu - e'\gamma^\mu\mathcal{A}'_\mu + \kappa e'\gamma^\mu B_\mu - m_\chi)\chi + \frac{1}{4}\mathcal{A}'_{\mu\nu}\mathcal{A}'^{\mu\nu}$$

B. Holdom, Phys.Lett. B166, 196 (1986).

Vector Portal: Dark Photon

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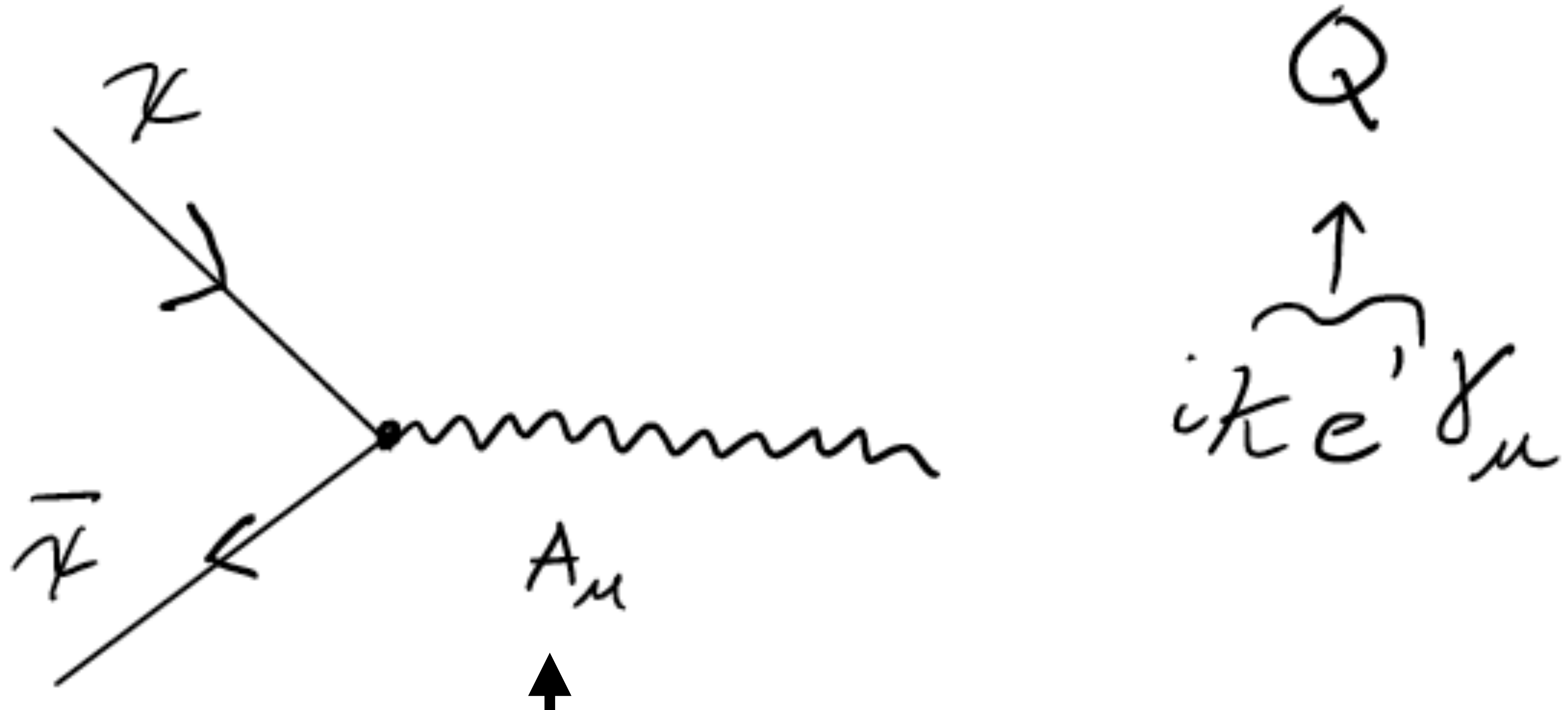

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B. Holdom, Phys.Lett. B166, 196 (1986).

A More General Case: Dark Photon+Dark Z

Standard Model Lagrangian

Dark Sector Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm DS} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu}$$

Hypercharge Gauge Field

“Dark” Hypercharge: dark Abelian vector field

Three possible phases can be considered:

-Okun phase: B'_μ is purely massive

-Holdom phase: B'_μ is massless

-Mixed phase: Both massless and massive dark gauge fields are present

"Dark" Photon

SM Z

SM Photon

$$\kappa B'_{\mu\nu}B^{\mu\nu} = \kappa\cos(\theta_W)\cos(\theta_{W'})A_1^\mu A_{2\mu} + \kappa\sin(\theta_W)\sin(\theta_{W'})Z_1^\mu Z_{2\mu} - \kappa\sin(\theta_W)\cos(\theta'_W)Z_1^\mu A_{2\mu} - \kappa\cos(\theta_W)\sin(\theta'_W)A_1^\mu Z_{2\mu}$$

"Dark" Z

Weinberg angle

"Dark" Weinberg angle

E. Izaguirre and I. Yavin, Phys Rev D 92 , 035014 (2015)

After field redefinitions, to order κ, one gets:

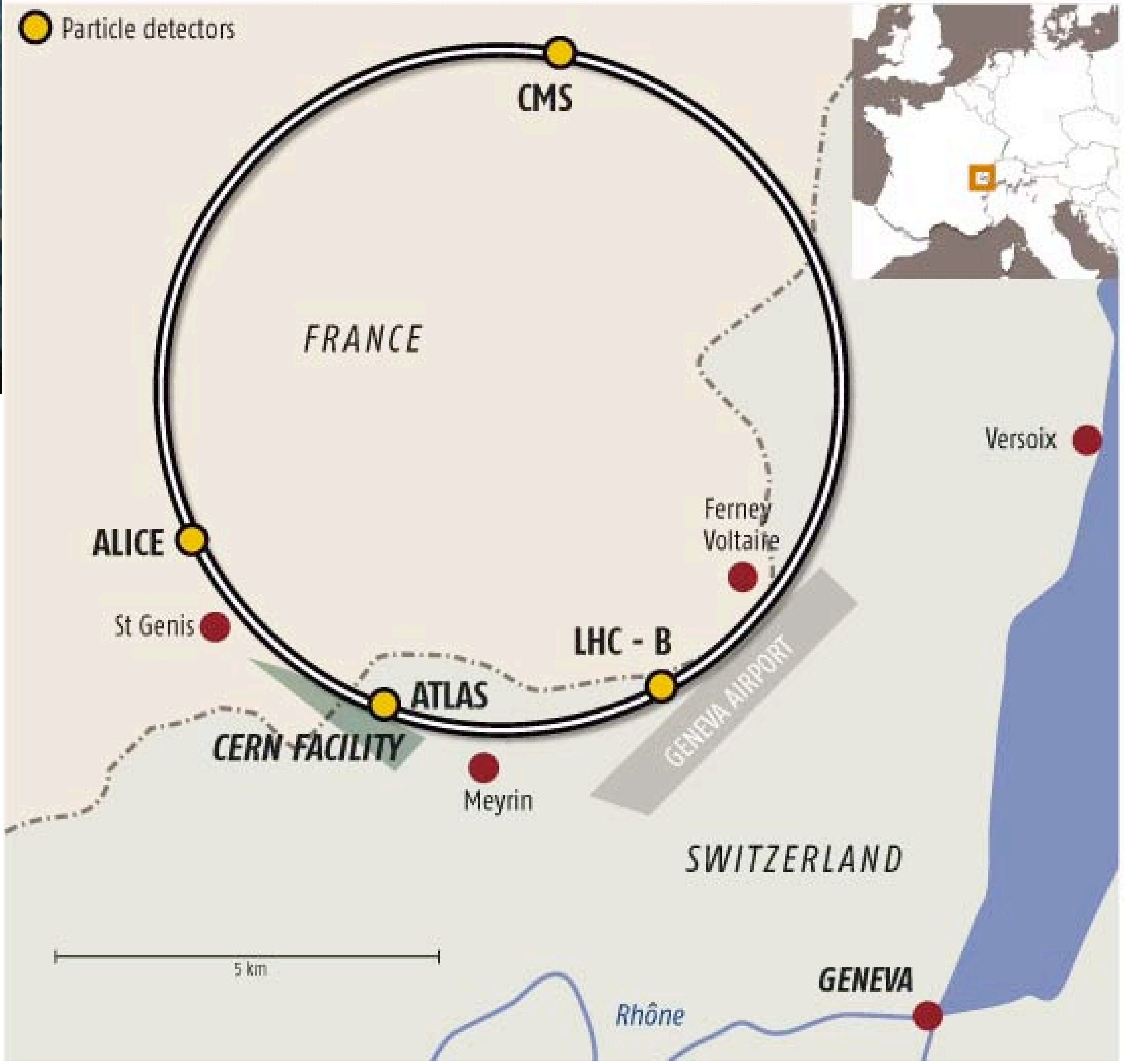
$$\mathscr{L} \supset A \cdot \left[eJ_{EM} - \kappa \cos(\theta_W)\cos(\theta_{W'})J_{EM'} \right]$$ → Photon now couples to dark EM current

$$\mathscr{L} \supset Z \cdot \left[\frac{g_2}{\cos(\theta_W)} J_Z + e'\kappa \sin(\theta_W)\cos(\theta_{W'})J_{EM'} - g_2' \tan(\theta_{W'})\kappa \sin(\theta_W) \left\{ \frac{M_Z^2}{M_Z^2 - M_{Z'}^2} \right\} J_{Z'} \right]$$ → Z now couples to dark EM current **and** dark Z current

$$\mathscr{L} \supset Z' \cdot \left[\frac{g_2'}{\cos(\theta_{W'})} J_{Z'} + e'\kappa \sin(\theta_W)\cos(\theta_{W'})J_{EM} + g_2 \tan(\theta_W)\sin(\theta_{W'})\kappa \left(\frac{M_{Z'}^2}{M_Z^2 - M_{Z'}^2} \right) J_Z \right]$$ → Dark Z now couples to EM current **and** Z current

E. Izaguirre and I. Yavin, Phys Rev D 92 , 035014 (2015)

The Experimental Context

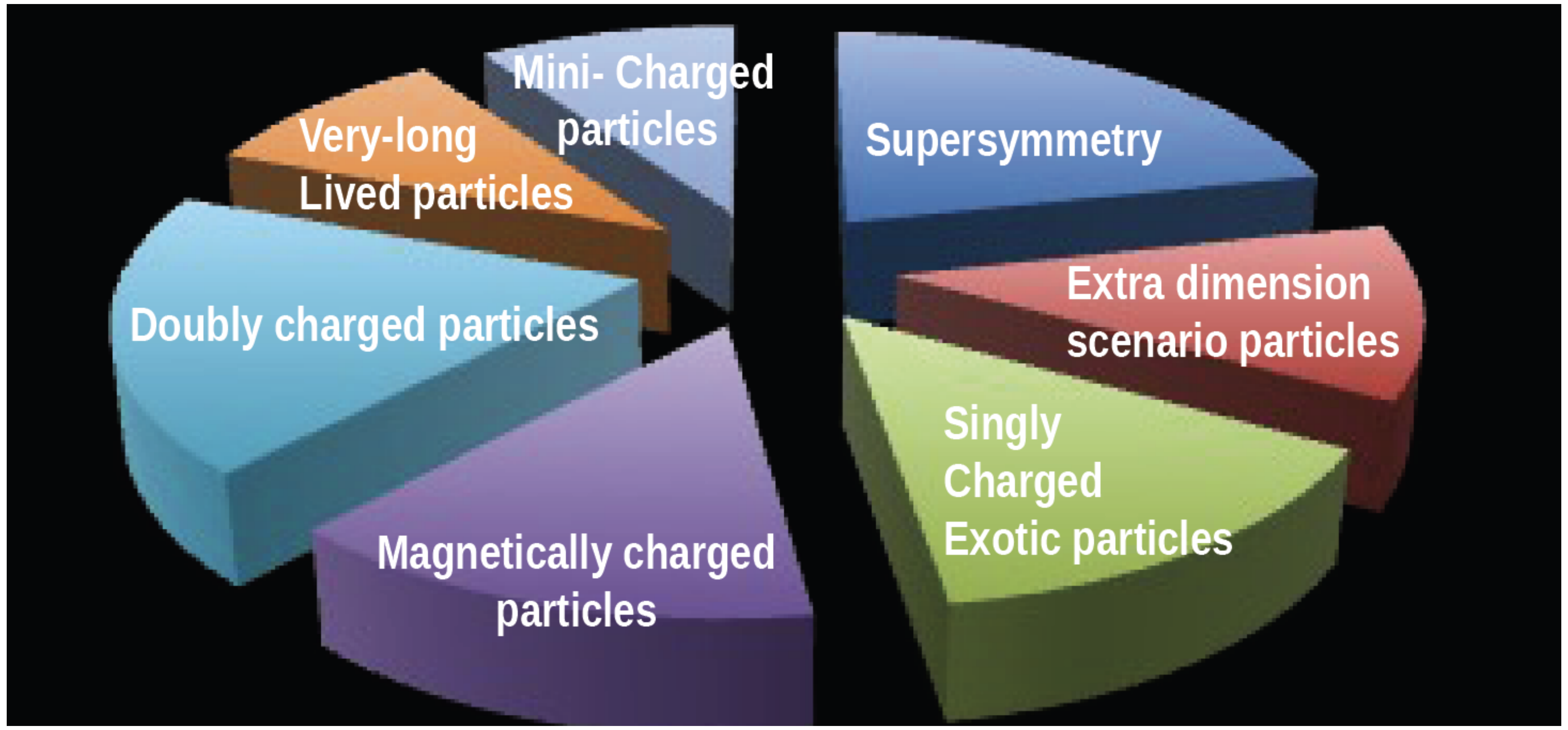


Large

Hadron

Collider

MoNopoles and Exotics Detector At the LHC

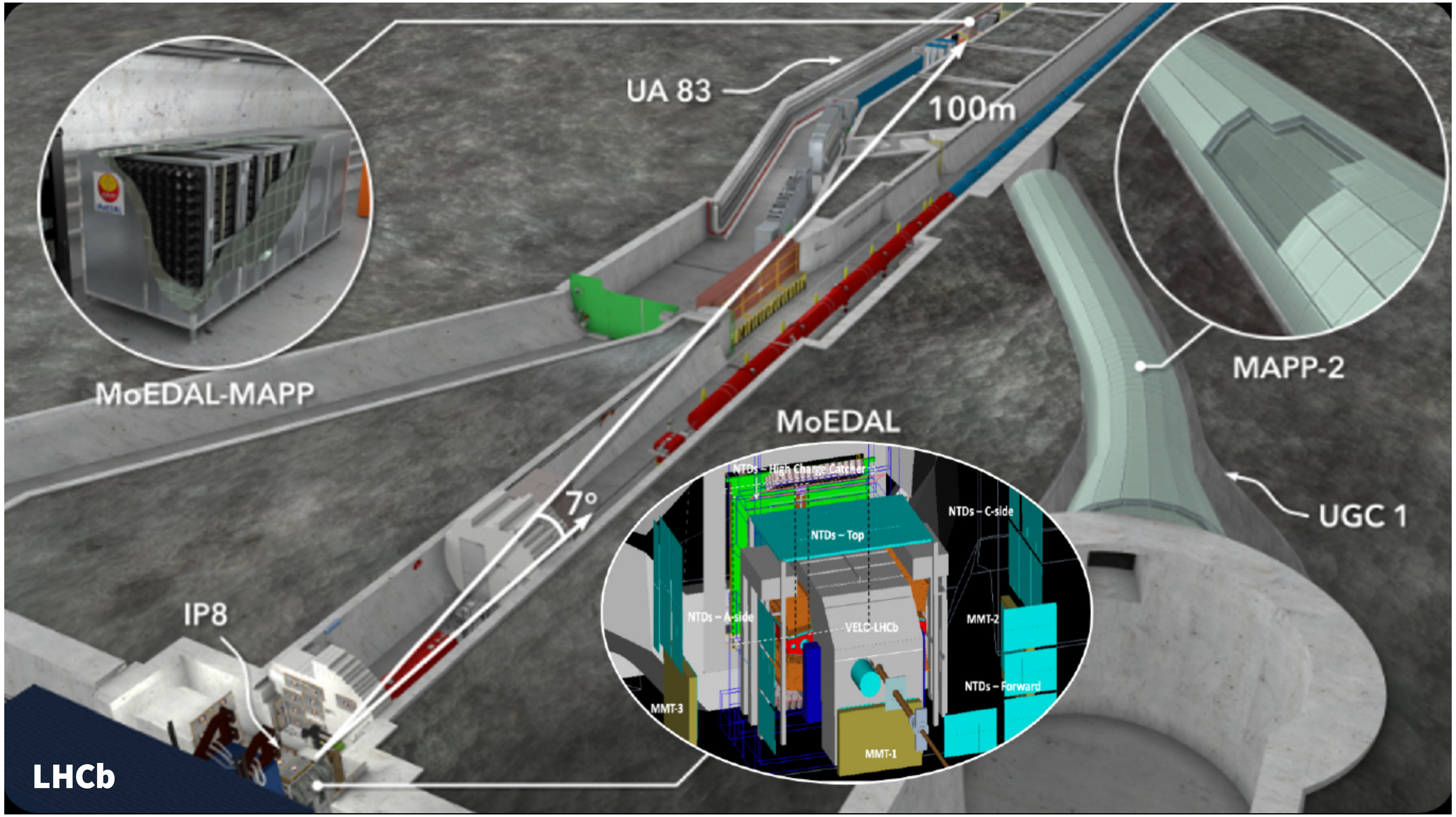


International Journal of Modern Physics A, September 2014, Vol. 29, No. 23

MoEDAL is sensitive to many new physics scenarios!

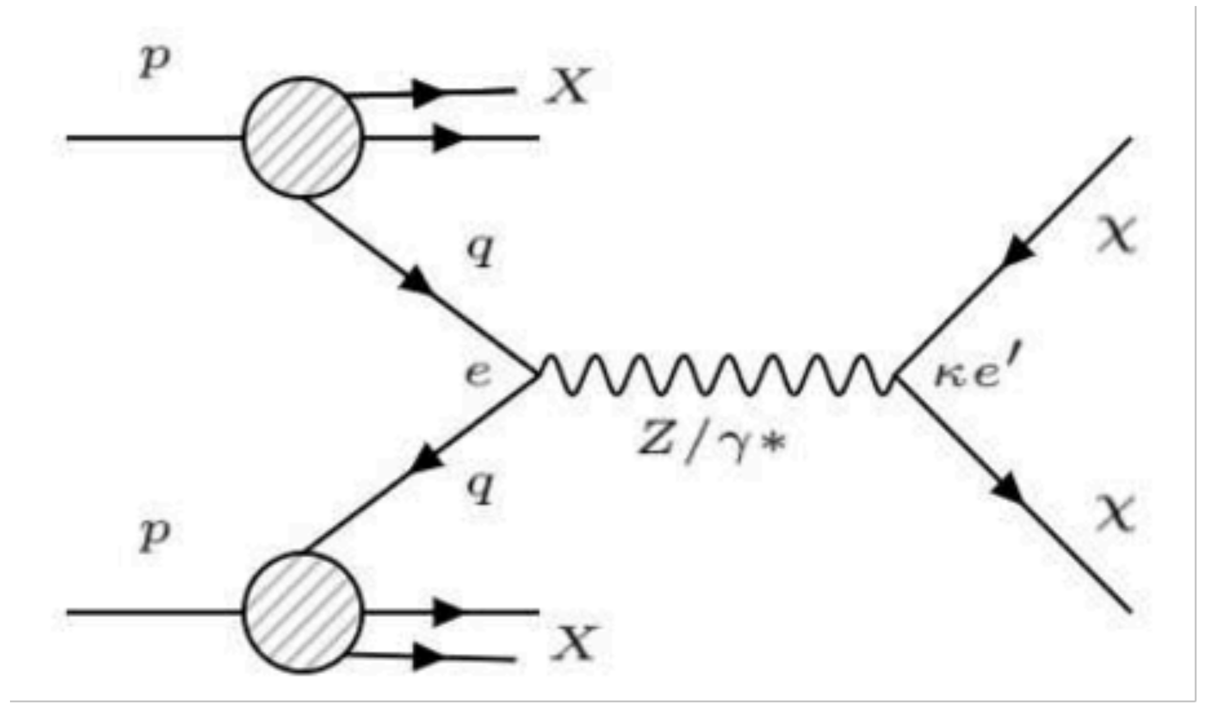
For what follows we will focus on the search for milli-charged particles.

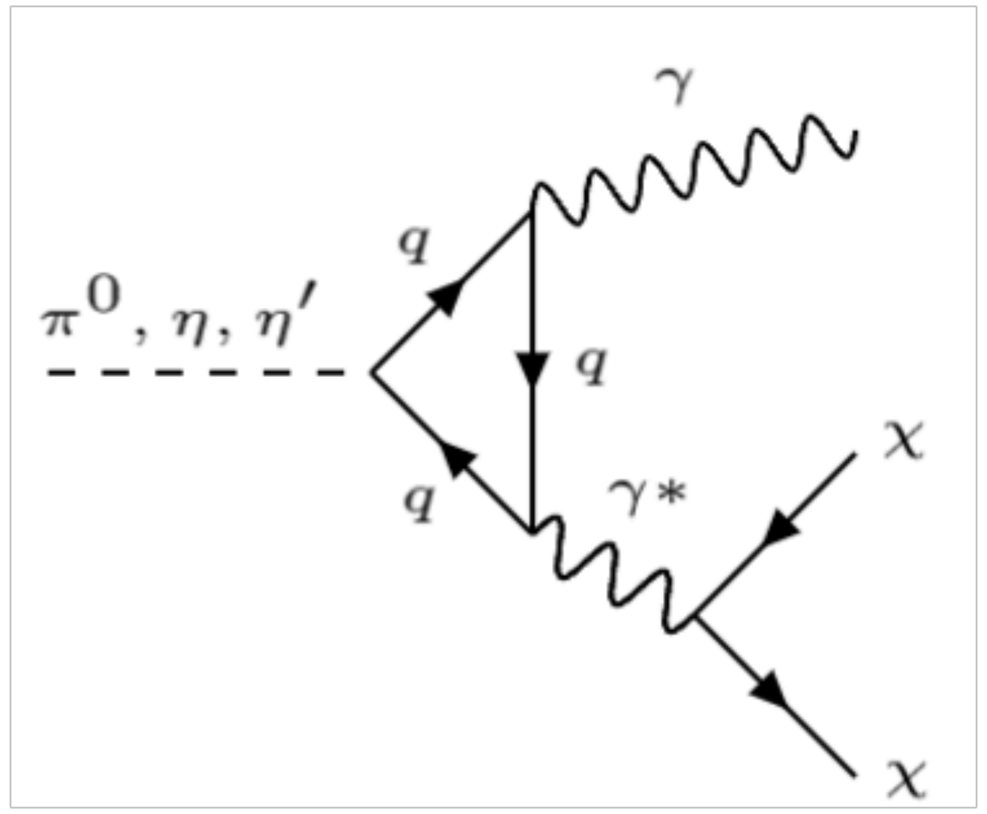
MoEDAL Apparatus for Penetrating Particles

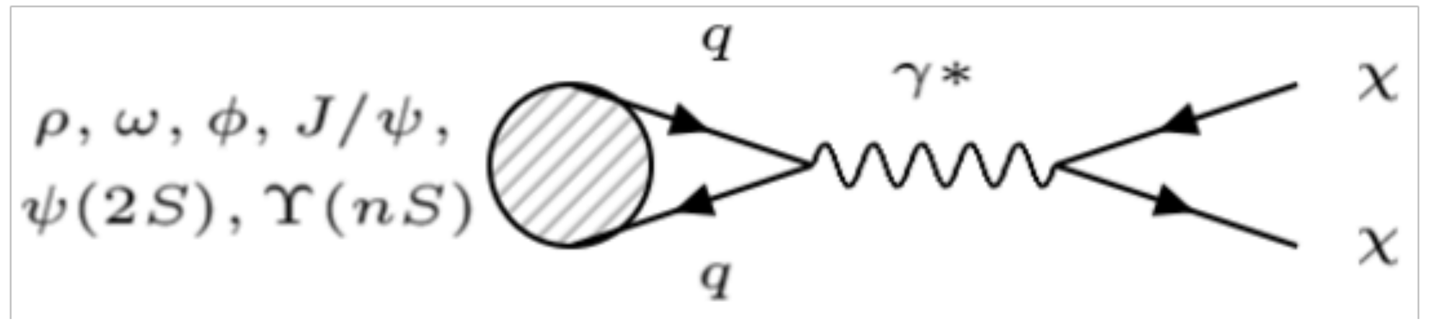


Postdoc: Michael Staelens

Holdom Phase: Milli-Charged Fermions

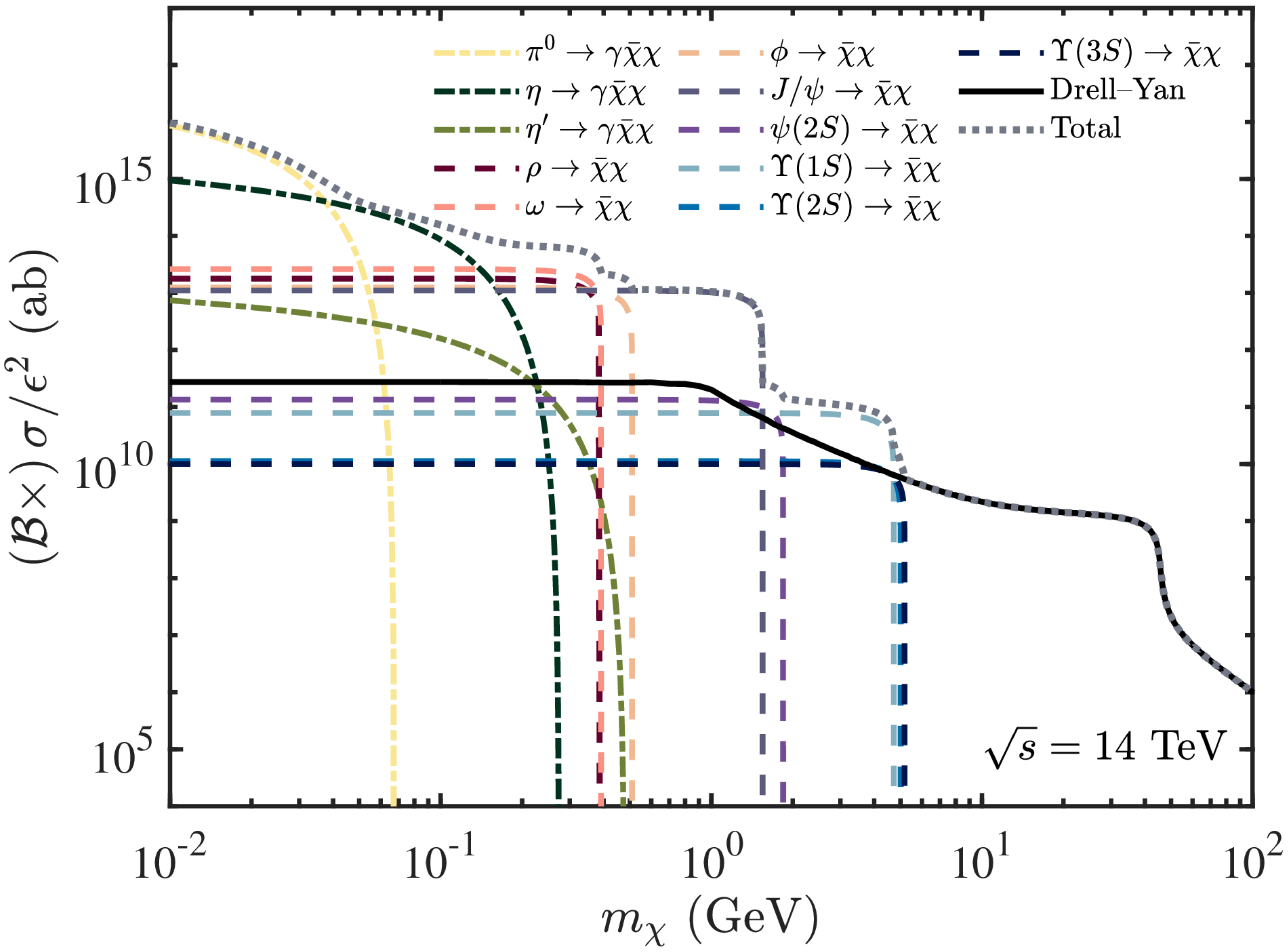






M. Kalliokoski, V.A. Mitsou, M. de Montigny, A. Mukhopadhyay, P.-P. A. Ouimet, J. Pinfold, A. Shaa, M. Staelens, J. High Energ. Phys. 2024, 137 (2024).

Charge-normalized milli-charged fermion production cross-sections at $\sqrt{s} = 14$ TeV. Meson decays are scaled by their respective branching ratios.



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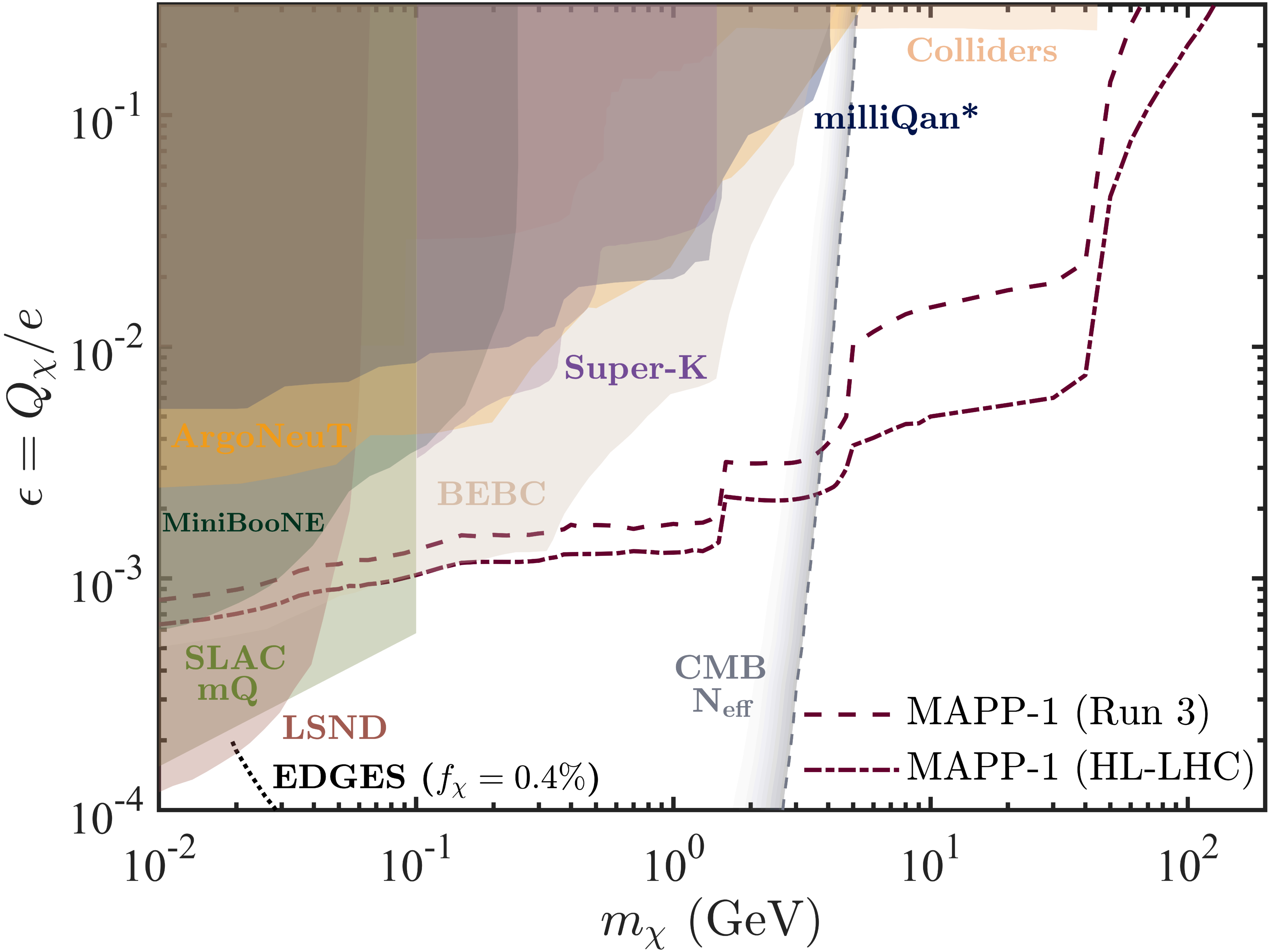
Projected 95% confidence level exclusion limits for MAPP-1 for milli-charged fermion produced in pp collisions.

Run 3: $\sqrt{s} = 13.6$ TeV, $L^{\text{int}}_{\text{LHCb}} = 30\ \text{fb}^{-1}$

HL-LHC: $\sqrt{s} = 14$ TeV, $L^{\text{int}}_{\text{LHCb}} = 300\ \text{fb}^{-1}$



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Graduate Student: Shafakat Arifeen

Mixed Phase: Milli-Charged Scalars

We use a model inspired by chiral effective theories of QCD:

$$\mathcal{L}_{\text{int}}^{2\phi} = \frac{1}{F_0^2}\text{Tr}(D_\mu\phi D^\mu\phi) + \frac{BF_0^2}{2}\text{Tr}\left(2M - \frac{M\phi^2}{2}\right)$$

$$\begin{aligned}\mathcal{L}_{\text{int}}^{4\phi} = \frac{1}{4F_0^2}\text{Tr}\Big(&-\frac{1}{6}(\mathcal{D}_\mu\phi\mathcal{D}^\mu\phi\phi^2 + \mathcal{D}_\mu\phi\phi\mathcal{D}^\mu\phi\phi + \mathcal{D}_\mu\phi\phi^2\mathcal{D}^\mu\phi) \\ &+ \frac{1}{4}(\mathcal{D}_\mu\phi\phi + \phi\mathcal{D}_\mu\phi)(\mathcal{D}^\mu\phi\phi + \phi\mathcal{D}^\mu\phi) \\ &- \frac{1}{6}(\mathcal{D}_\mu\phi\phi^2\mathcal{D}^\mu\phi + \phi\mathcal{D}_\mu\phi\phi\mathcal{D}^\mu\phi + \phi^2\mathcal{D}_\mu\phi\mathcal{D}^\mu\phi)\Big) \\ &+ \frac{B_0F_0^2}{2}\text{Tr}\left(\frac{\mathcal{M}\phi^4}{24F_0^4}\right)\end{aligned}$$

$$\phi = \begin{pmatrix} \pi_D^0 + \frac{1}{\sqrt{3}}\eta_D & \sqrt{2}\pi_D^+ & \sqrt{2}K_D^+ \\ \sqrt{2}\pi_D^- & -\pi_D^0 + \frac{1}{\sqrt{3}}\eta_D & \sqrt{2}K_D^0 \\ \sqrt{2}K_D^- & \sqrt{2}\bar{K}_D^0 & -\frac{2}{\sqrt{3}}\eta_D \end{pmatrix}$$

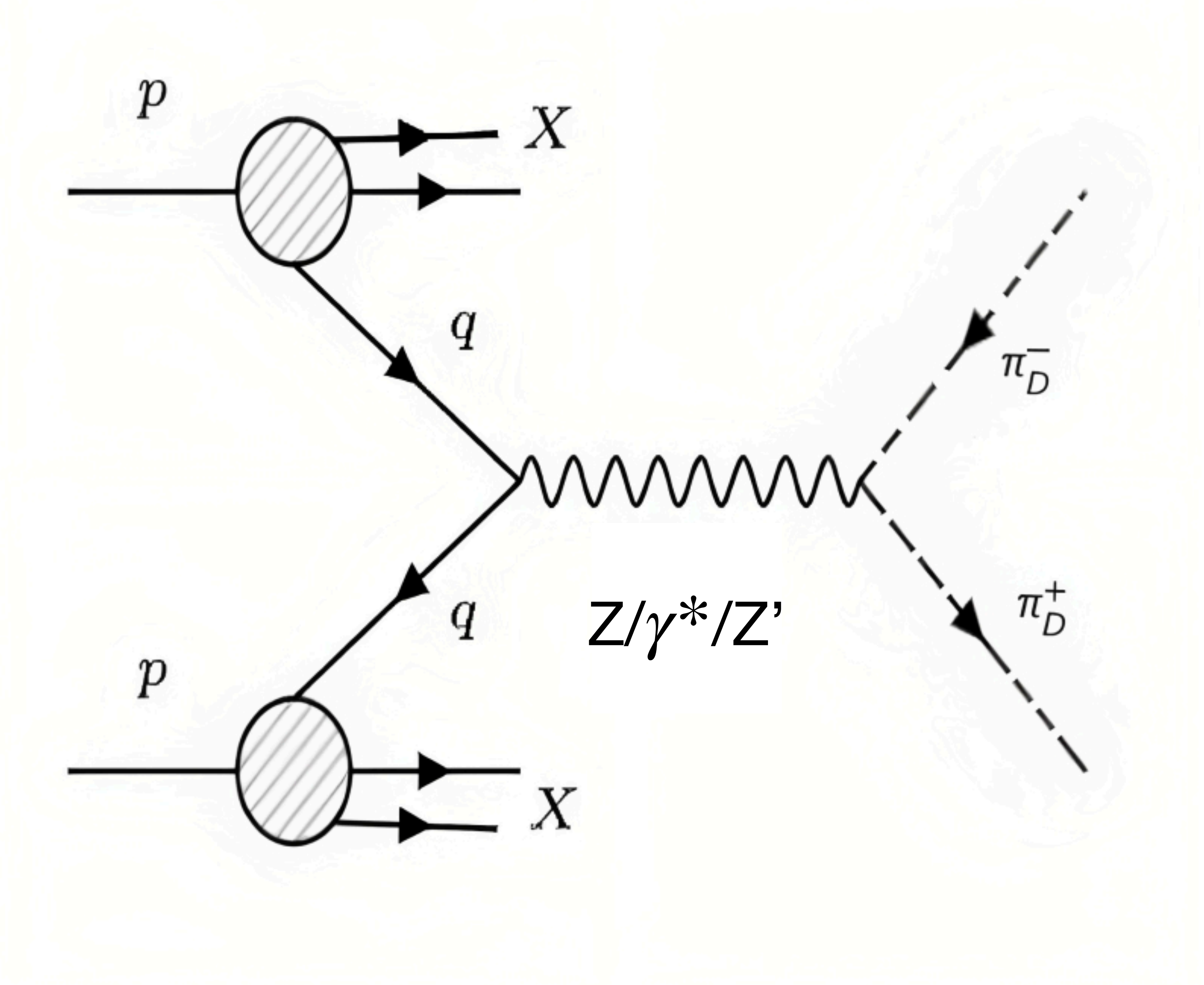
To which we add a Wess-Zumino-Witten like term:

$$n\mathcal{L}_{WZW}^{\text{ext}} = -en(A'_\mu - \kappa\cos\theta_W\cos\theta_{W'}A_\mu)J^\mu$$
$$+ i\frac{ne^2}{48\pi^2}\epsilon^{\mu\nu\rho\sigma}\partial_\nu(A'_\rho - \kappa\cos\theta_W\cos\theta_{W'}A_\rho)(A'_\sigma - \kappa\cos\theta_W\cos\theta_{W'}A_\sigma)$$
$$\times \operatorname{Tr}\left[2Q^2(U\partial_\mu U^\dagger - U^\dagger\partial_\mu U) - QU^\dagger Q\partial_\mu U + QUQ\partial_\mu U^\dagger\right]$$

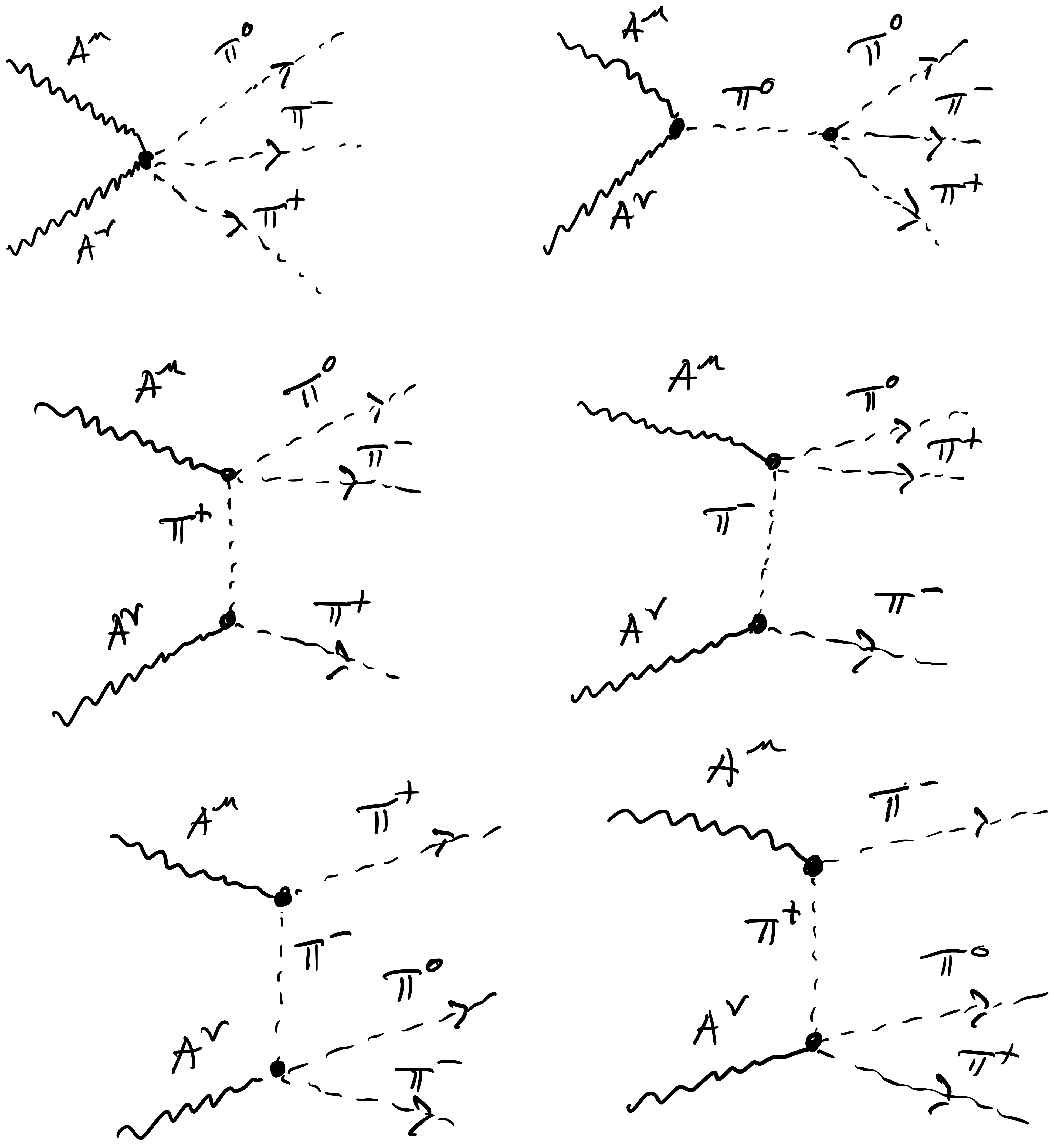
$$U(x) = \exp\left(i\frac{\phi(x)}{F_0}\right)$$

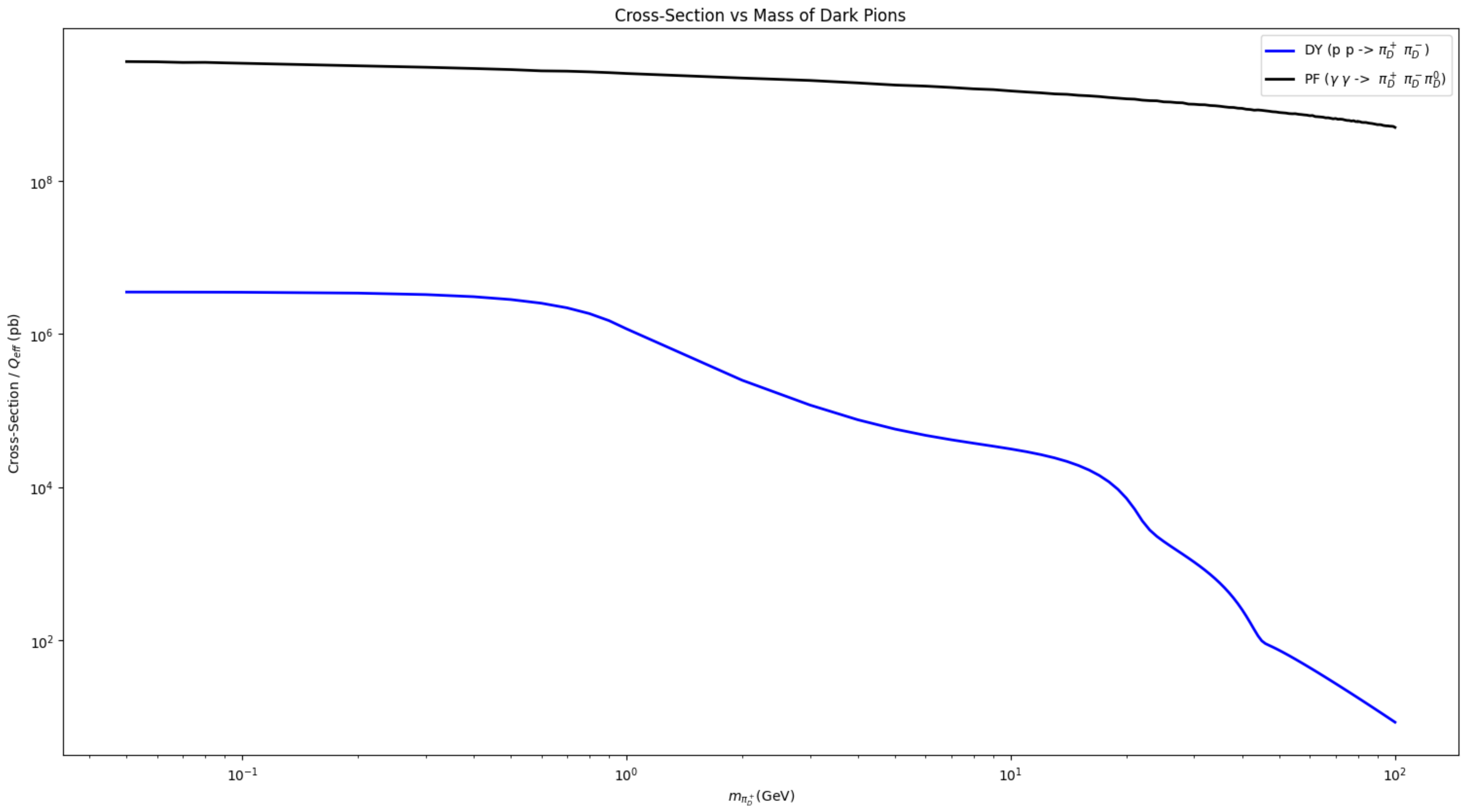
$$J^\mu = \frac{\epsilon^{\mu\nu\rho\sigma}}{48\pi^2}\operatorname{Tr}\left(Q\partial_\nu UU^\dagger\partial_\rho UU^\dagger\partial_\sigma UU^\dagger + QU^\dagger\partial_\nu UU^\dagger\partial_\rho UU^\dagger\partial_\sigma U\right)$$

Case 1: Drell-Yan production of milli-charged scalars



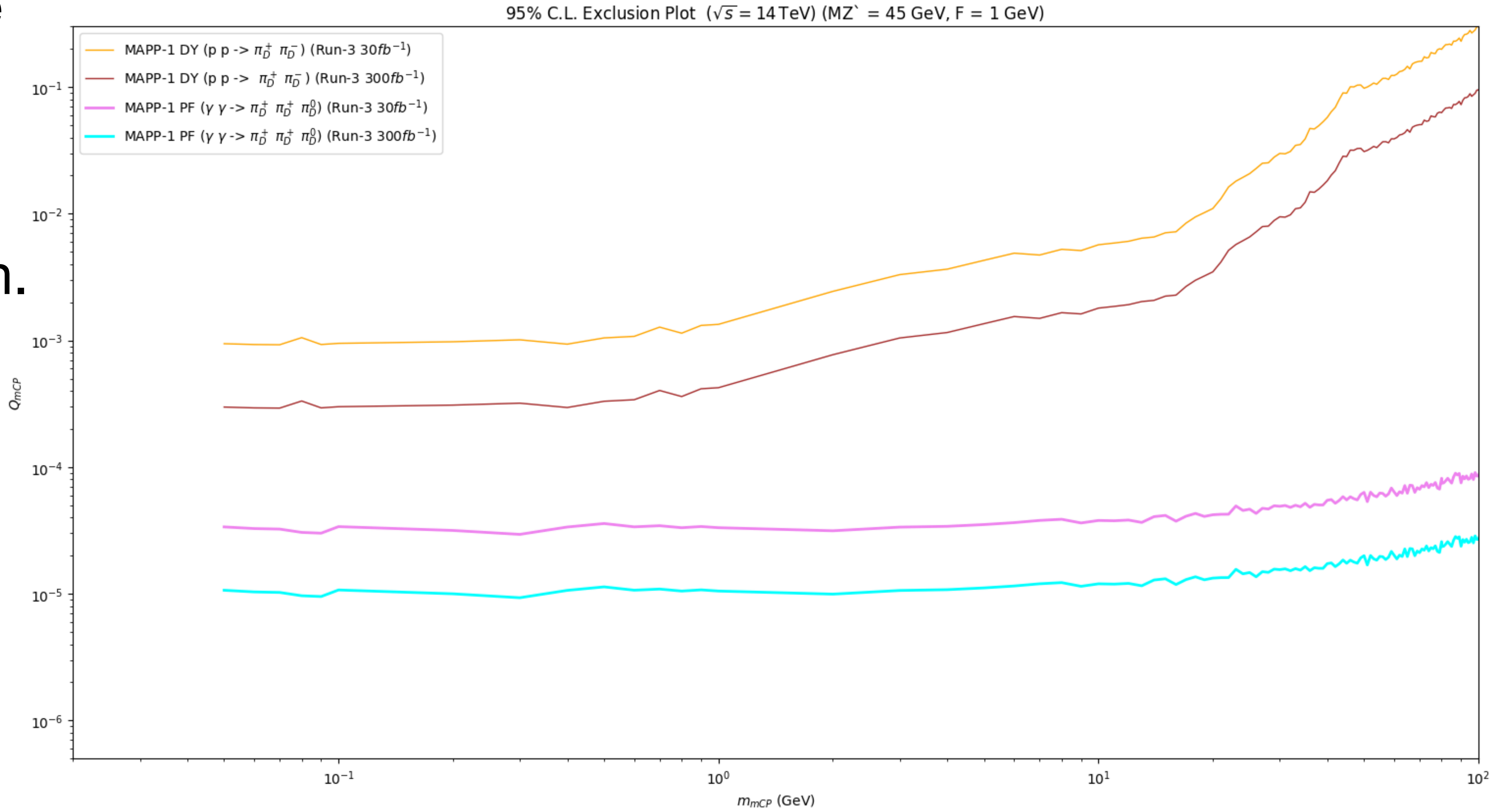
Case 2: photo-fusion production of milli-charged scalars





Cross-Section vs Mass of Dark Pions
DY (p p -> π_D^+ π_D^-)
PF (γ γ -> π_D^+ π_D^- π_D^0)
10^8
10^6
10^4
10^2
Cross-Section / Q_{eff} (pb)
10^{-1}
10^0
10^1
10^2
$m_{\pi_D^+}$(GeV)

Projected 95% confidence level exclusion limits for MAPP-1 for milli-charged scalars produced in pp collisions and photo-fusion.



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Conclusion

- Hidden sector models offer a rich and interesting phenomenology that is accessible at accelerators.
- Indications are that MAPP-1 will access novel parameter space in the search for mCP.
- Much work yet remains to be done!