Topological Portal to the Dark Sector

Davighi, AG, Selimovic; 2401.09528

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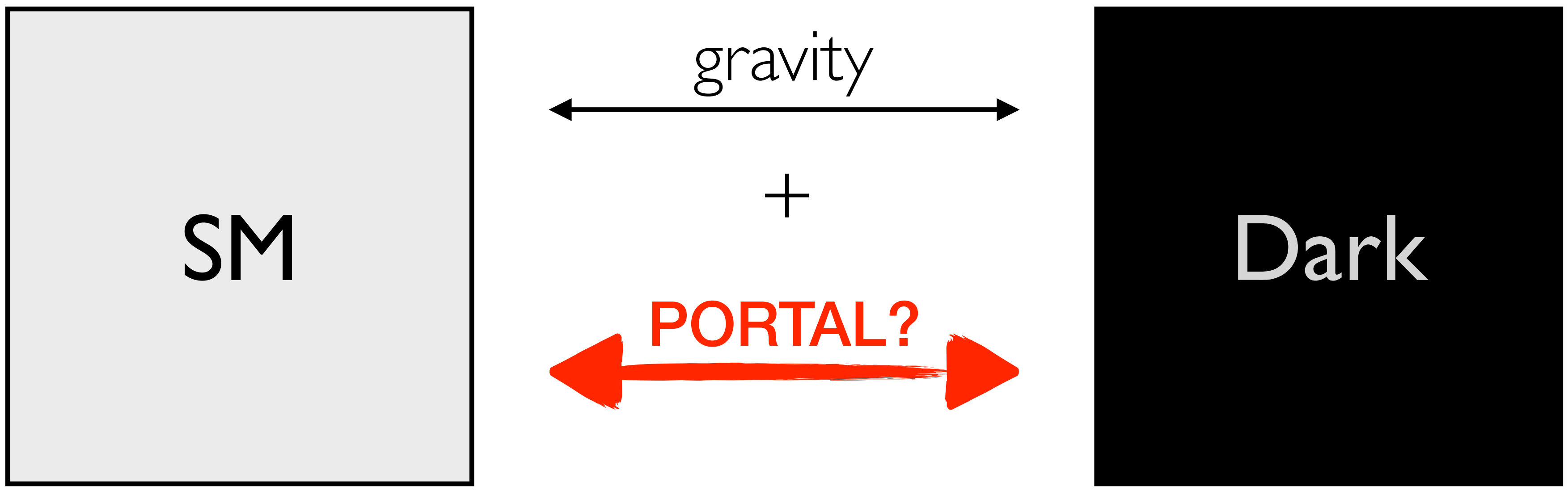
Motivation



- Dark matter revealed its presence through gravitational interactions.
- Portals to the dark sector are critical to probing its nature.
- They drive:
  - Cosmological history (Relic abundance),
  - Direct / Indirect detection,
  - Collider searches.
- Known portals are scarce.
  - Renormalizable: $H^\dagger H\, S^\dagger S$, $B_{\mu\nu} X^{\mu\nu}$, $\bar{L} H N$.
  - Higher-dimensional: $a G \wedge G$, …

Today

hep-th A novel portal topological interaction between QCD and Dark Pions!

hep-ph Elegant realization of the light thermal inelastic DM scenario.

hep-ex Novel signatures at Belle-II

Introduction

- χPT
- Chiral anomalies
- Dirac quantisation
- The WZW term

Chiral Lagrangian

- Low-energy limit of QCD
- Chiral symmetry breaking

$$G = SU(3)_L \times SU(3)_R$$

$$m_{u,d,s} < \Lambda \qquad \Big\downarrow \qquad \langle \bar{q}_L^i q_R^j \rangle \approx \Lambda^3 \delta^{ij}$$

$$\mathscr{H} = SU(3)_{L+R}$$

- Coset space = vacuum manifold

$$\langle\rangle_{ij} \to (L^\dagger R)_{ij} \qquad X = \frac{G}{\mathscr{H}} = SU(3)$$

- Goldstone (Pion) matrix

$$U(x) : M^4 \to SU(3)$$

$$G : U(x) \to L^\dagger U(x) R$$

Chiral Lagrangian

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$$U(x) : M^4 \to SU(3)$$

$$G : U(x) \to L^\dagger U(x) R$$

- χPT (non-linear effective action)

Weinberg '68, CCWZ '69

$$\mathscr{L} = \frac{f_\pi^2}{4} \operatorname{tr}\left(D_\mu U^\dagger D^\mu U \right) + \mathcal{O}(D_\mu^4)$$

$$U(x) = \exp\left(\frac{2i}{f_\pi} \pi(x) \right)$$

$$\pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

- Symmetries

1. $P_0 : \vec{x} \to -\vec{x}$
2. $(-1)^{N_\pi} : U \to U^\dagger \implies \pi^a \to -\pi^a$

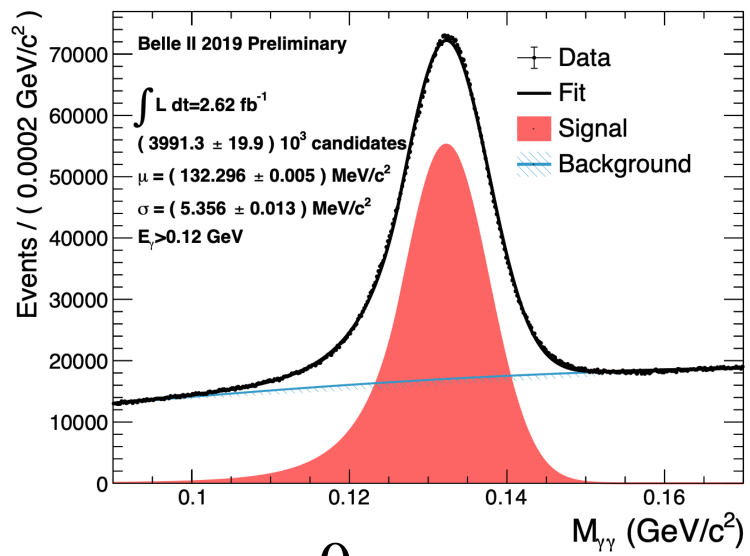
- CCWZ terms are invariant under both.
- QCD preserves only $P = P_0(-1)^{N_\pi}$
  e.g. $K^+ K^- \to (\phi) \to \pi^+ \pi^- \pi^0$

"Missing terms?" Witten '83

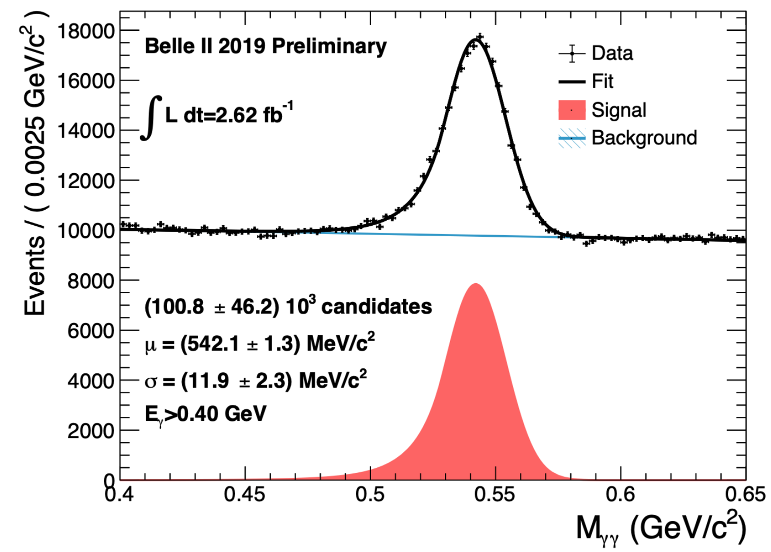
Chiral anomalies

Omnipresent

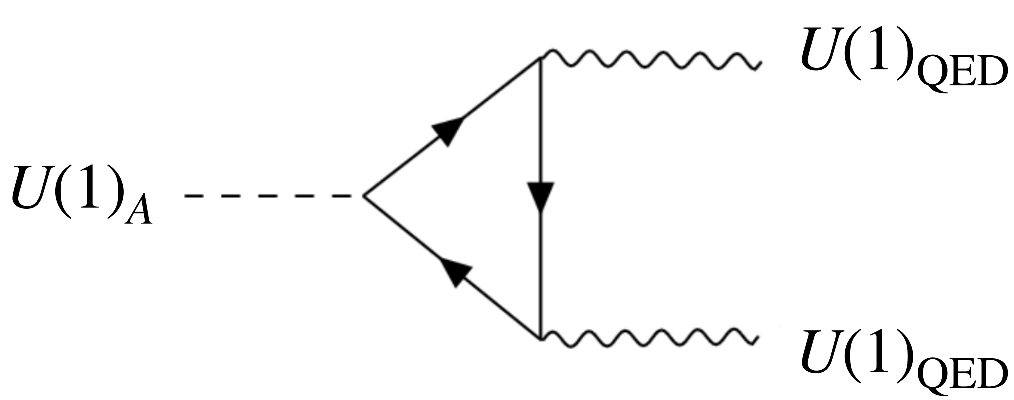
- Violates P_0 and $(-1)^{N_\pi}$ keeping P



$\pi^0 \to \gamma\gamma$



$\eta \to \gamma\gamma$



Mixed (ABJ) anomaly — Adler; Bell, Jackiw '69

$$\partial^\mu J^3_{A\,\mu} = \frac{N_c}{96\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

Anomaly matching ('t Hooft): Deep IR

Q: How does $\mathcal{L} = \frac{N_c e^2}{96\pi^2 f_\pi}\pi^0\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$ arise in a G-invariant EFT?

Wess, Zumino '71
Witten '83

Invariant action?

- An attempt to construct a G-invariant Lagrangian:

$$\epsilon^{\mu\nu\rho\sigma}\,\mathrm{tr}\left(U^\dagger\,(\partial_\mu U)U^\dagger\,(\partial_\nu U)U^\dagger\,(\partial_\rho U)U^\dagger\,(\partial_\sigma U)\right) = 0$$

P_0-odd

No G-invariant term in 4d violates P_0

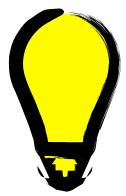
- But 4d covariant EOM exist: Witten '83

$$\frac{1}{2}f_\pi^2\,\partial_\mu(U^\dagger\partial^\mu U) = \frac{k}{48\pi^2}\epsilon^{\mu\nu\rho\sigma}\,U^\dagger\,(\partial_\mu U)U^\dagger\,(\partial_\nu U)U^\dagger\,(\partial_\rho U)U^\dagger\,(\partial_\sigma U)$$

P_0-odd

- How can we build an invariant action?

Invariant action?



Witten '83: Global aspects of current algebra

- The WZW action:
    - Extend $U(x)$ to a 5d bulk D whose boundary is a 4d spacetime
    - Action $S \sim \int_D \omega_5$ where $\omega_5 \sim \mathrm{tr}(U^{-1}dU)^5$ is a 5-form

<u>Properties of ω_5</u>:

- G-invariant
- Closed: $d\omega_5 = 0$
- Integral: The path integral phase e^{iS} *independent* of D (Topological)

(

Dirac quantisation

Consider a charge e moving on a unit sphere S_2 around a monopole g

EOM: $$m\frac{d\mathbf{v}}{dt} = e\mathbf{v} \times \mathbf{B}$$

$$\mathbf{B} = \frac{g\hat{r}}{4\pi r^2} \implies \int d\mathbf{S} \cdot \mathbf{B} = g$$

Symmetries of $\ddot{x}_i = \epsilon_{ijk} x_j \dot{x}_k$

- $SO(3)$ rotations
- LHS: P and T
- RHS: PT

Dirac quantisation

Consider a charge e moving on a unit sphere S_2 around a monopole g

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$$\nabla\times\mathbf{A} = \mathbf{B} = \frac{g\hat{r}}{4\pi r^2} \implies \int d\mathbf{S}\cdot\mathbf{B} = g$$

$$A_\phi^N = \frac{g\,(1-\cos\theta)}{4\pi r\sin\theta}$$

Dirac string

Rotational symmetry violated, thus

$$S = \int dt\left(\frac{1}{2}m\mathbf{v}^2 + e\mathbf{v}\cdot\mathbf{A}\right)$$

is not manifestly symmetric.

Symmetries of $\ddot{x}_i = \epsilon_{ijk}x_j\dot{x}_k$

- $SO(3)$ rotations
- LHS: P and T
- RHS: PT

Dirac quantisation

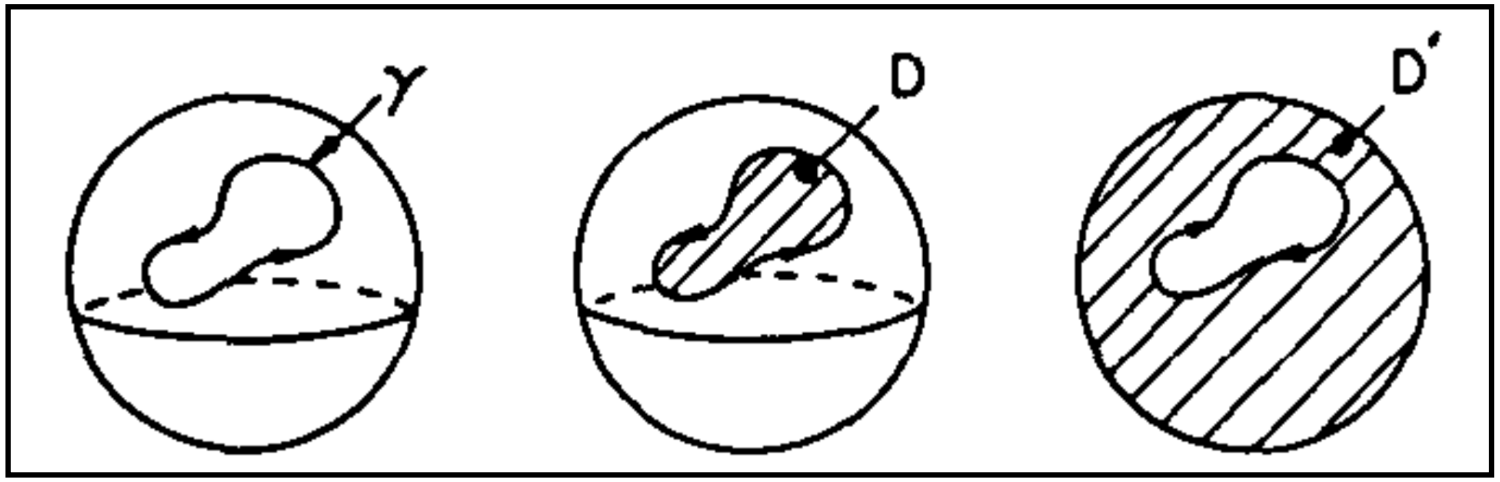
Consider a charge e moving on a unit sphere S_2 around a monopole g

In QM, a phase of a closed orbit

$$\alpha = \oint_\gamma \mathbf{A} \cdot d\mathbf{x} = \int_D d\mathbf{S} \cdot \mathbf{B}$$

- $SO(3)$-invariant 2-form $F_{ij} \sim \epsilon_{ijk} x^k / |x|^3$ but D is not unique.

Witten '83



$\pi_1(S^2) = 0$

Thus, $e^{ie\alpha} = e^{ie\alpha'}$, implies

$$eg = 2\pi n, \quad n \in Z$$

"integrality condition"

$\pi_2(S^2) = Z$

)

The WZW action

- Compactify the spacetime to a large 4d sphere S^4 (fields asymptote at infinity)

Witten '83

- The goldstone matrix $U(x) : S^4 \to SU(3)$

$$S = \frac{f_\pi^2}{4} \int d^4x \ \mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U) + \boxed{k \int_D d^5y \ \omega} \qquad \partial D = \mathbf{S}^4$$

- $U(y) : S^5 \to SU(3)$, unique 5-form:

$$\omega = -\frac{i}{240\pi^2} \epsilon^{\mu\nu\rho\sigma\tau} \mathrm{tr} \left(U^\dagger \frac{\partial U}{\partial y^\mu} U^\dagger \frac{\partial U}{\partial y^\nu} U^\dagger \frac{\partial U}{\partial y^\rho} U^\dagger \frac{\partial U}{\partial y^\sigma} U^\dagger \frac{\partial U}{\partial y^\tau} \right)$$

1. G-invariant
2. Closed: $d\omega = 0$

Tong, Gauge Theory

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Tong, Gauge Theory

1. G-invariant
2. Closed: $d\omega = 0$

- $\pi_4(SU(3)) = 0$, $\partial D = S^4$.
- Ambiguity in the choice of D. Phase independence of D

$\Longrightarrow$

$$\exp\left(ik \int_D d^5y \ \omega\right) = \exp\left(-ik \int_{D'} d^5y \ \omega\right)$$

opposite orientation

$$D \cup D' = \mathbf{S}^5 \quad \exp\left(ik \int_{\mathbf{S}^5} d^5y \ \omega\right) = 1$$

$$\int_{\mathbf{S}^5} d^5y \ \omega = 2\pi n \qquad \text{winding } n \in \mathbf{Z}$$

$$\pi_5(SU(3)) = Z$$

$$k \in \mathbf{Z}$$

3. Integral

The WZW action

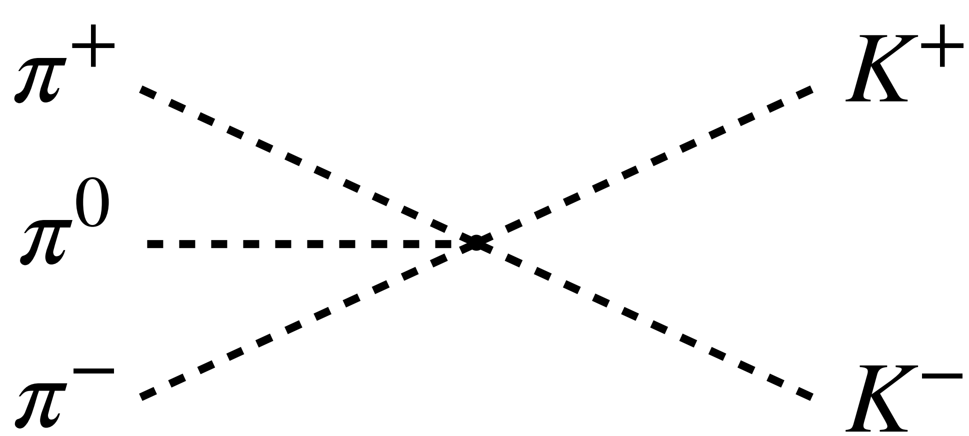
Witten '83

- Expand $U^\dagger \partial_\mu U = \frac{2i}{f_\pi}\partial_\mu \pi + \mathcal{O}(\pi^2)$

$$\int_D d^5y\, \omega = \frac{2}{15\pi^2 f_\pi^5}\int_D d^5y\, \epsilon^{\mu\nu\rho\sigma\tau}\partial_\mu \,\mathrm{tr}\left(\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\partial_\tau\pi\right) + \mathcal{O}(\pi^6)$$

$$= \frac{2}{15\pi^2 f_\pi^5}\int_{\mathbf{S}^4} d^4x\, \epsilon^{\nu\rho\sigma\tau}\,\mathrm{tr}\left(\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\partial_\tau\pi\right) + \mathcal{O}(\pi^6)$$

- Use Stoke's theorem $\Longrightarrow$



- Violates $(-1)^{N_\pi}$
- Phenomenology dominated by gauging, next slide

Gauging the WZW

Witten '83

$$Q = \begin{pmatrix} \frac{2}{3} & 0 & 0 \\ 0 & -\frac{1}{3} & 0 \\ 0 & 0 & -\frac{1}{3} \end{pmatrix}$$

- Gauge $U(1)_{\text{QED}} \supset SU(3)_{L+R}$
- $U \to U + i\epsilon[Q, U]$

- Gauging must take place in 4d where no manifest G-invariance
- Non-trivial derivation using Noether method ($\delta S \sim \int \partial_\mu \epsilon J^\mu$).

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- After trial and error $\quad J^\mu = \frac{1}{48\pi^2} \epsilon^{\mu\rho\sigma\tau} \mathrm{tr}\left(\{Q, U^\dagger\} \partial_\rho U \, U^\dagger \partial_\sigma U \, U^\dagger \partial_\lambda U \right)$

$$S_{WZW} = k \Bigg[\int_D d^5x \; \omega - e \int d^4x \; A_\mu(x) J^\mu + \frac{ie^2}{24\pi^2} \int d^4x \; \epsilon^{\mu\nu\rho\sigma} (\partial_\mu A_\nu) A_\rho \mathrm{tr}\left(\{Q^2, U^\dagger\} \partial_\sigma U + U^\dagger Q U Q U^\dagger \partial_\sigma U \right) \Bigg]$$

Gauging the WZW

Witten '83

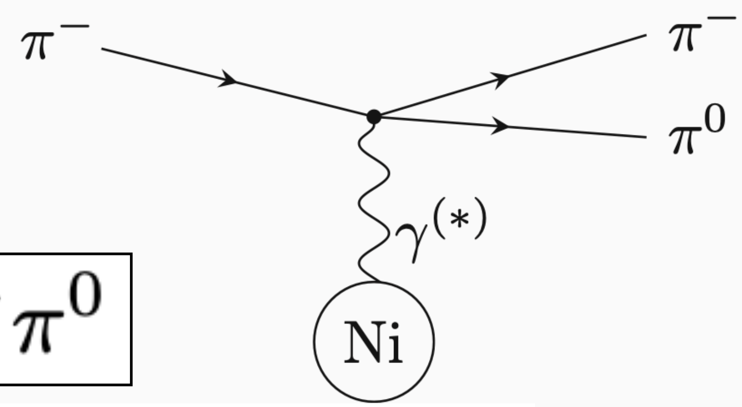
$$S_{WZW} = k\left[\int_D d^5x\ \omega - e\int d^4x\ A_\mu(x)\ \frac{1}{48\pi^2}\,\epsilon^{\mu\rho\sigma\tau}\mathrm{tr}\left(\{Q,U^\dagger\}\,\partial_\rho U\,U^\dagger\partial_\sigma U\,U^\dagger\partial_\lambda U\right)\right.$$
$$\left. + \frac{ie^2}{24\pi^2}\int d^4x\ \epsilon^{\mu\nu\rho\sigma}(\partial_\mu A_\nu)A_\rho\mathrm{tr}\left(\{Q^2,U^\dagger\}\,\partial_\sigma U + U^\dagger QUQU^\dagger\partial_\sigma U\right)\right]$$

$$\mathcal{L} = \frac{ke^2}{96\pi^2 f_\pi}\pi^0\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

$$k = N_c$$

Gauging the WZW

- COMPAS @ CERN 2310.09138



$$\pi^-\gamma \to \pi^-\pi^0$$

$$F_{3\pi}^{\rm theory} = \frac{eN_c}{12\pi^2 F_\pi^3} = (9.78 \pm 0.04)\ {\rm GeV}^{-3}$$

$$F_{3\pi}^{\rm preliminary} = (10.3 \pm 0.1_{\rm stat} \pm 0.6_{\rm syst})\ {\rm GeV}^{-3}$$

Witten '83

- VAAA anomaly: $\gamma\pi^+\pi^-\pi^0$

$$S_{WZW} = k\left[\int_D d^5x\ \omega - e\int d^4x\ A_\mu(x)\ \frac{1}{48\pi^2}\epsilon^{\mu\rho\sigma\tau}{\rm tr}\left(\{Q,U^\dagger\}\,\underline{\partial_\rho U}\ \underline{U^\dagger\partial_\sigma U}\ \underline{U^\dagger\partial_\lambda U}\right)\right.$$
$$\left. + \frac{ie^2}{24\pi^2}\int d^4x\ \epsilon^{\mu\nu\rho\sigma}(\partial_\mu A_\nu)A_\rho{\rm tr}\left(\{Q^2,U^\dagger\}\,\partial_\sigma U + U^\dagger QUQU^\dagger\partial_\sigma U\right)\right]$$

$$\mathcal{L} = \frac{ke^2}{96\pi^2 f_\pi}\pi^0\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

$$k = N_c$$

Invariant forms?

$$G = SU(3)_L \times SU(3)_R$$

$$X = \frac{G}{\mathcal{H}} = SU(3) \quad \Big\downarrow$$

$$\mathcal{H} = SU(3)_{L+R}$$

The only two G-invariant forms on X

$$\omega_5 \sim \mathrm{tr}(U^{-1}dU)^5$$

WZW

$$\omega_3 \sim \mathrm{tr}(U^{-1}dU)^3$$

What can we do with this?

The 3-form

$$\omega_3 \sim \mathrm{tr}(U^{-1}dU)^3$$

- It does not appear in the QCD action.
- However, it does appear in the topologically conserved current, **the baryon number!** Goldstone, Wilczek '81

Consider a static field configuration: $U(\mathbf{x}) : \mathbf{S}^3 \mapsto SU(N_f)$

$$B^\mu = \frac{1}{24\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{tr}\left(U^\dagger(\partial_\nu U)\,U^\dagger(\partial_\rho U)\,U^\dagger\,\partial_\sigma U\right)$$

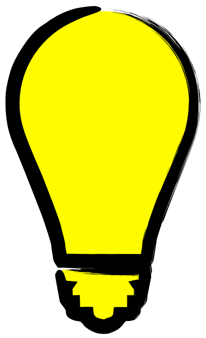
$\partial_\mu B^\mu = 0$ $\quad B = \int d^3x\ B^0$ Conserved winding no: $B \in \mathbf{Z}$

(antisymmetry) $\qquad \pi_3(SU(3)) = Z$

The global symmetry of QCD: $G \times U(1)_V$

The only candidate symmetry is $U(1)_V$!

What else can we do with this?



$$\omega_5^{\text{PORTAL}} = \omega_3^{\text{QCD}} \wedge \omega_2^{\text{DARK}}$$

Davighi, AG, Selimovic; 2401.09528

The topological portal

- Formulation
- Relic abundance
- Direct/Indirect detection
- Collider searches

The setup

- We formulate a low-energy EFT for pions and dark pions

$$X = \frac{SU(3)_L \times SU(3)_R \times K}{SU(3)_{L+R} \times H} \cong SU(3) \times \frac{K}{H}$$

Dark sector coset

The setup

- We formulate a low-energy EFT for pions and dark pions

$$X = \frac{SU(3)_L \times SU(3)_R \times K}{SU(3)_{L+R} \times H} \cong SU(3) \times \frac{K}{H}$$

Dark sector coset

- Properties of $\omega_5^{\mathrm{PORTAL}} = \omega_3^{\mathrm{QCD}} \wedge \omega_2^{\mathrm{DARK}}$
  - Closed: $d\omega_5^{\mathrm{PORTAL}} = 0$ implies $d\omega_2^{\mathrm{DARK}} = 0$ since $d\omega_3^{\mathrm{QCD}} = 0$
  - G-invariance: Product structure implies ω_2^{DARK} is K-invariant
  - Integrality: Cycles factorize; normalize ω_2^{QCD} and ω_2^{DARK} separately

Which dark coset fits?

Cosetology

Searching for a closed, invariant, and integral K/H 2-form

- Consider following cosets (motivated by QCD-like theories):

$$\frac{K}{H} = \left\{ \frac{SU(N)_L \times SU(N)_R}{SU(N)_{L+R}}, \frac{SU(N)}{SO(N)}, \frac{SU(2N)}{Sp(2N)} \right\}$$

- All these are *symmetric* spaces $\Longrightarrow$
  K-invariant forms on K/H are in 1-to-1 with cohomology classes

see e.g. Davighi, Gripaios, Randal-Williams, 2011.05768

The portal $\exists$ iff $H^2(K/H) \neq 0$

de Rham cohomology $H^k(M)$ - the set of closed modulo exact k-forms on M

Cosetology

- Unique choice of the dark coset!

QCD

Davighi, AG, Selimovic; 2401.09528

p	1	Portal 2	3	4	SIMP 5
$H^p(SU(2))$	0	0	$\mathbb{R}$	–	–
$H^p(SU(n)),\ n \geq 3$	0	0	$\mathbb{R}$	0	$\mathbb{R}$
$H^p(SU(2)/SO(2))$	0	$\mathbb{R}$	–	–	–
$H^p(SU(3)/SO(3))$	0	0	0	0	$\mathbb{R}$
$H^p(SU(4)/SO(4))$	0	0	0	$\mathbb{R}$	$\mathbb{R}$
$H^p(SU(n)/SO(n)),\ n \geq 5$	0	0	0	0	$\mathbb{R}$
$H^p(SU(2n)/Sp(2n)),\ n \geq 2$	0	0	0	0	$\mathbb{R}$

The SIMP mechanism $(3 \to 2)$

Hochberg et al, 1402.5143, 1411.3727

(mutually exclusive)

The portal

- Take $K/H = SU(2)/SO(2) \cong S^2$

Two dark pions

$$\Omega_2 = \epsilon_{ij} d\chi_i \wedge d\chi_j/(8\pi f_D^2)$$

- the volume form on S^2

$\chi_1/f_D \in [0,\pi], \ \chi_2/f_D \in [0,2\pi)$

- The portal

$$\omega_{\text{portal}} = \frac{n}{24\pi^2} \text{Tr} \left(U^{-1} dU\right)^3 \wedge \Omega_2 \,, \quad n \in \mathbb{Z}$$

The portal

- Take $K/H = SU(2)/SO(2) \cong S^2$ Two dark pions

$$\Omega_2 = \epsilon_{ij} d\chi_i \wedge d\chi_j / (8\pi f_D^2)$$

- the volume form on S^2

$\chi_1/f_D \in [0,\pi],\ \chi_2/f_D \in [0,2\pi)$

- The portal

$$\omega_{\rm portal} = \frac{n}{24\pi^2} \mathrm{Tr}\left(U^{-1}dU\right)^3 \wedge \Omega_2\,, \quad n \in \mathbb{Z}$$

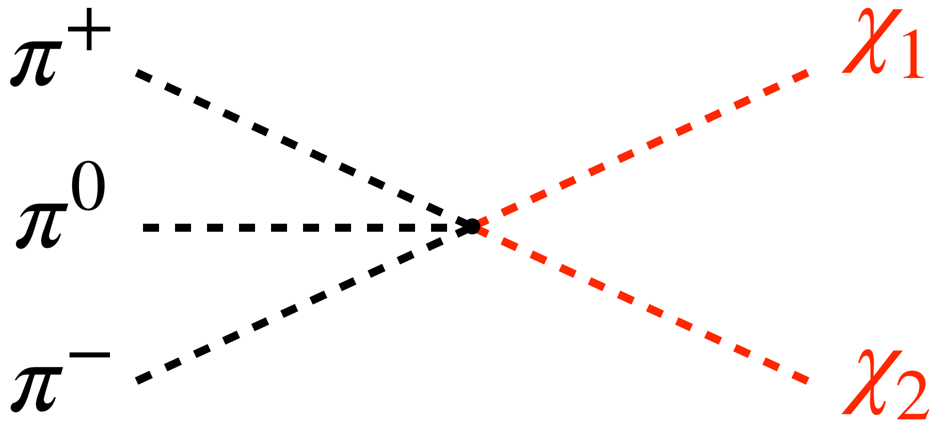
- Expanding $U^{-1}dU \Longrightarrow$ $\omega_{\rm portal} = \frac{n}{96\pi^3 f_\pi^3 f_D^2} f_{abc}\epsilon_{ij} d\pi_a d\pi_b d\pi_c d\chi_i d\chi_j$

- Use Stoke's theorem

$$\mathcal{L}^{e=0}_{\rm portal} = \frac{in\epsilon^{\mu\nu\rho\sigma}}{48\pi^2 f_\pi^3 f_D^2} f_{abc}\epsilon_{ij}\pi_a \partial_\mu \pi_b \partial_\nu \pi_c \partial_\rho \chi_i \partial_\sigma \chi_j$$

The portal

$$\mathcal{L}^{e=0}_{\rm portal} = \frac{i n \epsilon^{\mu\nu\rho\sigma}}{48\pi^2 f_\pi^3 f_D^2} f_{abc}\epsilon_{ij}\pi_a\partial_\mu\pi_b\partial_\nu\pi_c\partial_\rho\chi_i\partial_\sigma\chi_j$$



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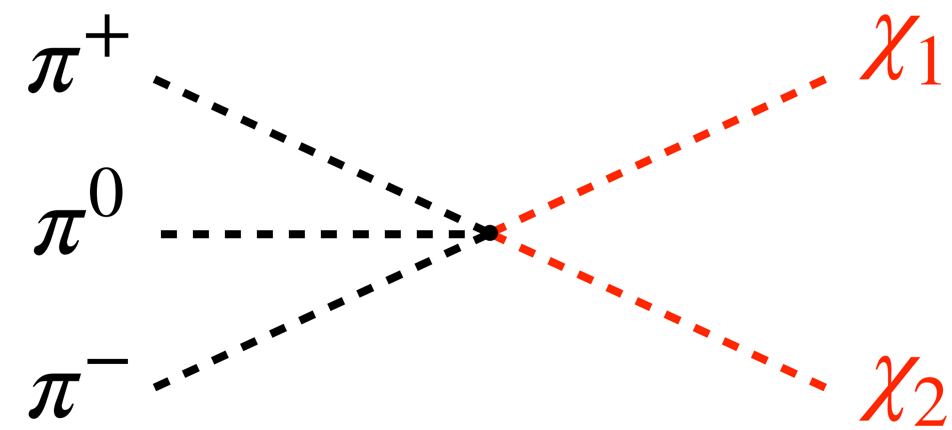
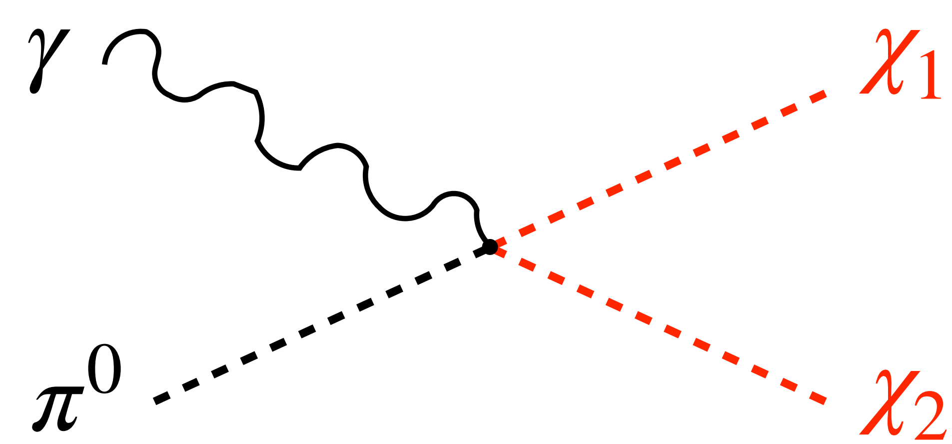


- As before, QED gauging drives the phenomenology

$$U(1)_Q \subset SU(3)_{L+R}$$

$$\frac{1}{f_\pi^2}\partial_\mu\pi^+\partial^\mu\pi^- \rightsquigarrow eF^{\mu\nu}$$



The portal

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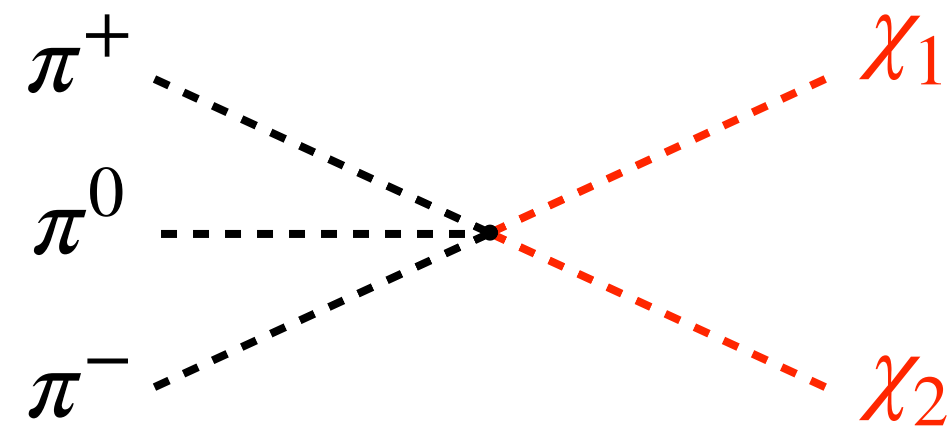

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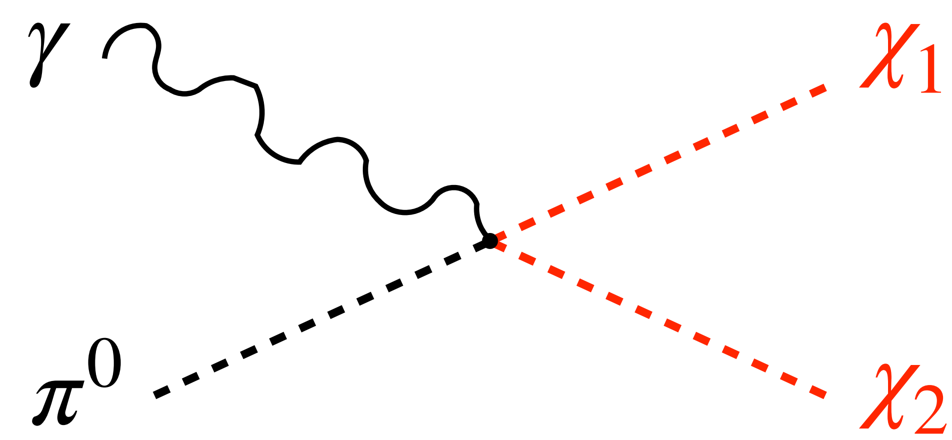
$$\frac{1}{f_\pi^2}\partial_\mu\pi^+\partial^\mu\pi^- \rightharpoondown eF^{\mu\nu}$$



- Prescription

Yonekura, 2009.04692

Shift $\omega_3^{\rm QCD}$ by

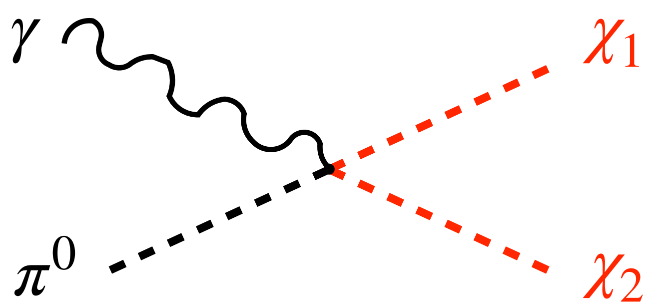
$\frac{-e}{4\pi^2} F \wedge {\rm Tr}\,(Qg^{-1}dg)$

$$\mathscr{L} = \frac{ne\,\epsilon^{\mu\nu\rho\sigma}}{16\pi^2 f_\pi f_D^2}\left(\pi^0 + \frac{\eta}{\sqrt{3}}\right) F_{\mu\nu}\partial_\rho\chi_1\partial_\sigma\chi_2$$

The leading portal in the EFT power counting. The next term

$$\frac{1}{f_\pi^2 f_D^2}(D_\mu\pi_a D^\mu\pi^a)(\partial_\nu\chi_i\partial^\nu\chi^i)$$

DM relic abundance



- Solving Boltzmann eqs. numerically

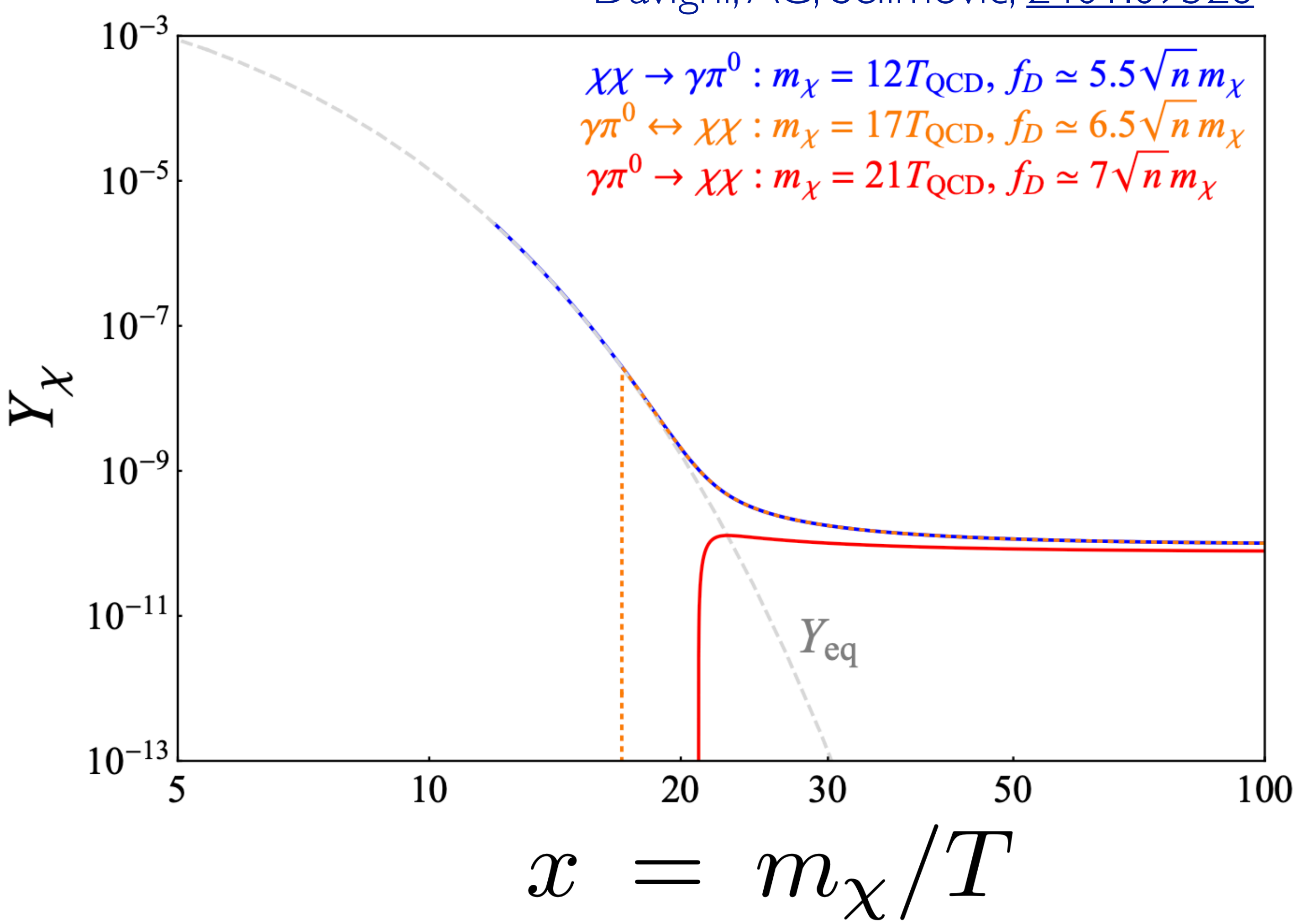
$m_{\chi_1} = m_{\chi_2}$ $\chi_1 + \chi_2$ yield

$$\frac{dY_\chi}{dx} = -\sqrt{\frac{\pi g_*}{45}}\frac{M_P m_\chi}{x^2}\langle\sigma v\rangle\left(Y_\chi^2 - Y_{eq}^2\right)$$

$$\langle\sigma v\rangle = \frac{\int_{4m_\chi^2}^{\infty}\sigma\sqrt{s}(s-4m_\chi^2)\,\mathrm{K}_1(\sqrt{s}/T)\,\mathrm{d}s}{8m_\chi^4 T\,\mathrm{K}_2^2(m_\chi/T)}$$

$$\sigma = \frac{n^2}{1536\,\pi^4}\frac{\alpha_Q}{f_\pi^2 f_D^4}s^{3/2}\sqrt{s-4m_\chi^2}$$

Davighi, AG, Selimovic; 2401.09528



- Quick thermalization — all we need is the theory at the freeze-out!
- Our EFT applies when the freeze-out occurs after the QCD phase transition

DM relic abundance

- Consistent EFT description: $m_\chi \lesssim 23 T_{\rm QCD} \approx 3.7\,\mathrm{GeV}$
- Relic abundance fits for $f_D \sim \mathcal{O}(5.5-7) \times \sqrt{n}\, m_\chi$

  $\Longrightarrow \chi_{1,2}$ indeed the lightest dark states

  Dark number conservation (Z_2 symmetry) ensures the stability of the lightest dark pion.

- A small explicit breaking of K needed to give $m_\chi \neq 0$, as in QCD
- For a small mass splitting — **co-annihilations**

$$\Delta := \frac{\Delta m_\chi}{m_{\chi_1}} \qquad \Longrightarrow \qquad f_D(\Delta) \approx f_D(0)\, e^{-\frac{x_{\rm max}\Delta}{4}}$$ (Boltzmann suppression)

Direct & Indirect DM detection

- $\chi_2 \to \chi_1 \gamma \pi^0$ before the onset of BBN when $\Delta m_\chi > m_\pi$
- Dark matter is composed only of χ_1
    - **Indirect detection**:
      2-form antisymmetrization: $\chi_1 \wedge \chi_2$
      $\chi_1 \chi_1$ annihilations highly suppressed
      Evades limits from CMB anisotropies on elastic s-wave scattering, Planck, 1807.06209
    - **Direct detection**:
      $\chi_1 \to \chi_2$ inelastic up-scattering kinematically forbidden
      $\chi_1 \to \chi_1$ highly suppressed

The antisymmetrization inherent to forms provides an elegant and natural realization of the *light thermal inelastic DM* scenario!

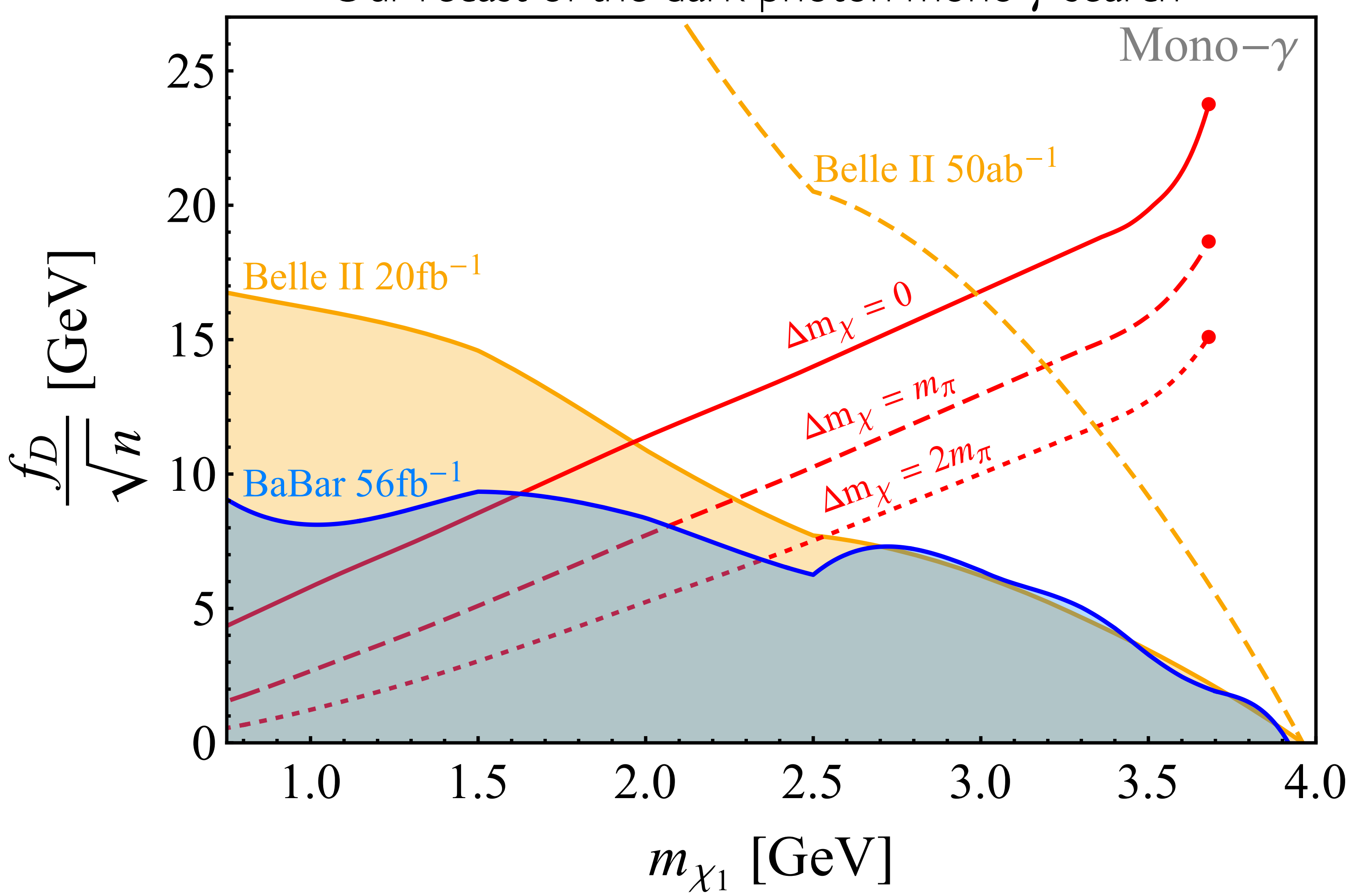
hep-ph/0101138, hep-ph/0402065, 0807.2250, 0910.3698, 1305.3575, 1508.03050, 1904.09994, 1911.03176, 2405.08081, + …

Collider searches

- Production $e^+e^- \to \gamma^* \to \chi_1\chi_2\pi^0$
- Signatures

Δm_χ	$\lesssim 1.7 m_{\pi^0}$	$\gtrsim 1.7 m_{\pi^0}$
Signature	$\pi^0 + \not{E}_T$	$\pi^0 + \not{E}_T + \mathrm{DV}(\pi^0\gamma\not{E}_T)$

Our recast of the dark-photon mono-γ search



- Novel signatures yet to be explored by the experiment
- New analysis is needed, in particular for the displaced vertex
- Excellent prospects at Belle-II
- If the signal is found, look for η

Outlook

- A well-rounded EFT tale

$$\omega_5^{\text{PORTAL}} = \omega_3^{\text{QCD}} \wedge \omega_2^{\text{DARK}}$$

hep-th

Light thermal inelastic DM

hep-ph

Belle-II

hep-ex

- The open question:

UV completion?

Alhambra of Granada

Thank you

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https://physik.unibas.ch/en/persons/admir-greljo/

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