Weakly Interacting Stable Pions

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Santa Fe 2010 Summer Workshop

JHEP 1002, 049

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arXiv:1003.3006

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arXiv:1005.0008

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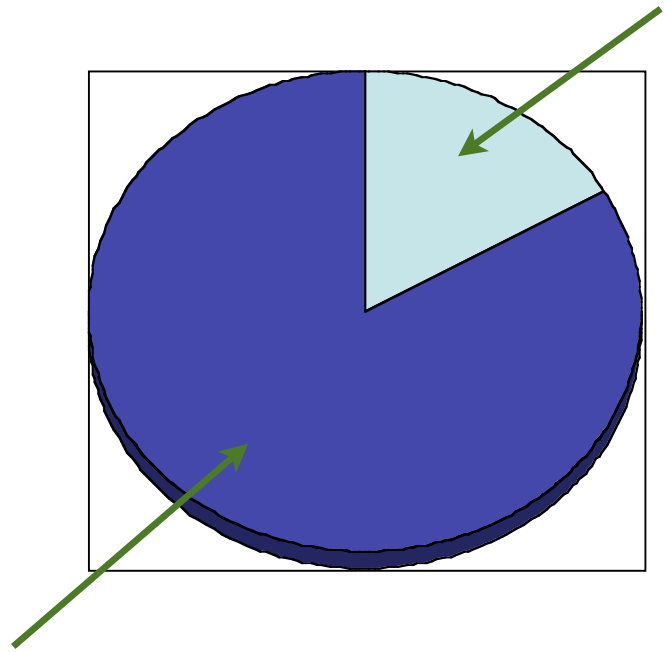
Outline

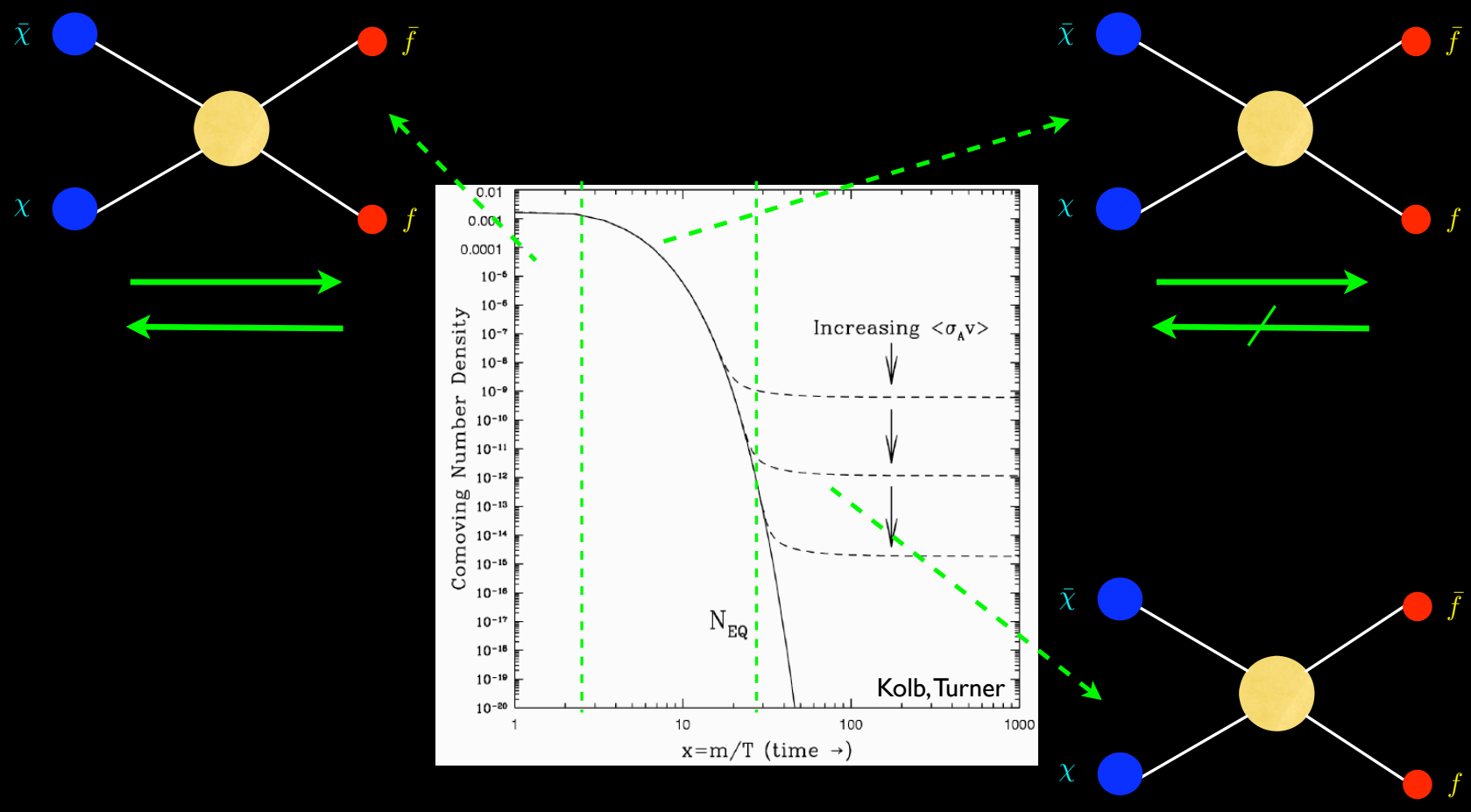
- The dark matter motivation
- Review properties of pions in the SM
- Stable "new" pion
- Collider signatures of topological "new" pion
- Conclusions

Matter Pie of Our Universe



From WMAP

The WIMP "Miracle"



Relic Abundance $\Omega_{\rm DM} \sim \langle \sigma_A \, v \rangle^{-1}$

WIMP

- "WIMP Miracle" relates the DM relic abundance to the DM annihilation cross section.

$$\Omega_{\rm DM} \sim \langle \sigma_A \, v \rangle^{-1} \sim \frac{m_\chi^2}{g^4}$$

- Three conditions to have a viable thermal DM candidate.
  - DM is stable: requires an unbroken discrete or continuous symmetry.
  - DM interacts with SM particles: requires DM charged under SM gauge symmetries or via Higgs portal.
  - Not to overclose the universe and not ruled out by the current direct detection experiments.

Discrete and Continuous Symmetries in the SM

- Parity, Charge Conjugation, Time Reversal
- Baryon number and lepton number

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

π^0

$$I^G(J^{PC}) = 1^-(0^{-+})$$

Mass $m = 134.9766 \pm 0.0006$ MeV (S = 1.1)
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.4 \pm 0.6) \times 10^{-17}$ s (S = 3.0)
$c\tau = 25.1$ nm

Pions in the Standard Model

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
(u_L, d_L)	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3

two flavors

g_s gets strong at $\Lambda_{\rm QCD} \sim 1$ GeV

$$\langle \bar{u}_L\, u_R + \bar{d}_L\, d_R \rangle \neq 0$$

Chiral symmetry is spontaneously broken

$$SU(2)_L \times SU(2)_R \Downarrow SU(2)_V$$

Three pions are generated: π^+, π^- and π^0

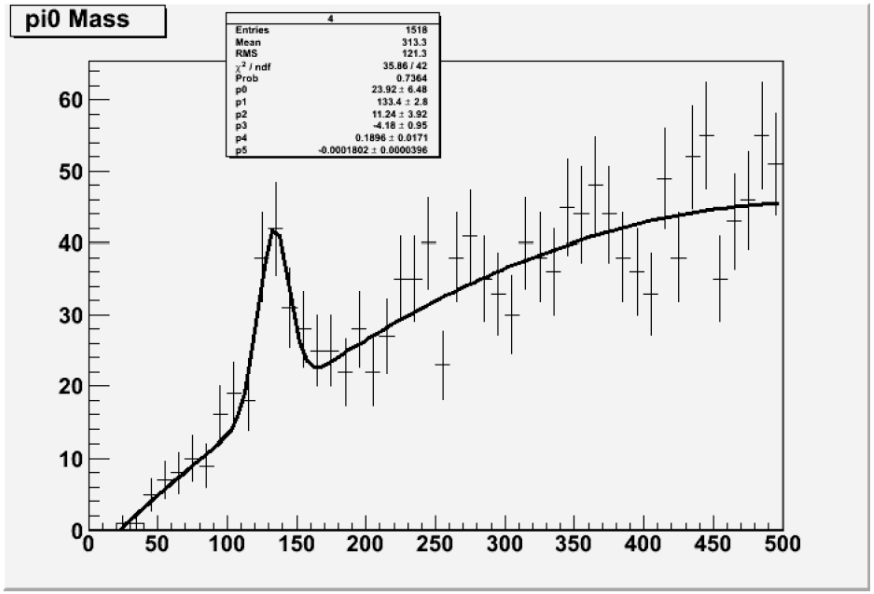
$$SU(2)_W \times U(1)_Y \to U(1)_{em}$$

The Discovery of Charged Pion

- Prediction of pion existence:
  Yukawa '1935
- Detected in cosmic rays captured in photographic emulsion:
  Cecil Powell et al. '1947
- Produced at Univ. of California's cyclotron in '1948

The Discovery of Neutral Pion

- At the Univ. of California's cyclotron in '1950
- In cosmic-ray balloon experiments at Bristol Univ. in '1950



Nov. 2009, LHC

G-parity in the SM

Selection Rules Imposed by Charge Conjugation.

L. MICHEL

European Council for Nuclear Research (CERN) - Theoretical Study Group (*)

(ricevuto il 24 Gennaio 1953)

Charge Conjugation, a New Quantum Number G, and Selection Rules Concerning a Nucleon-Antinucleon System.

T. D. LEE

Columbia University - New York, N.Y.

C. N. YANG

Institute for Advanced Study - Princeton, N.J.

(ricevuto il 30 Gennaio 1956)

Definition of the G-parity

$$\boxed{G = \mathcal{C} \exp[i\pi I_2]}$$

$$\pi^a \, \tau^a \xrightarrow{\mathcal{C}} \pi^a \, (\tau^a)^*$$

$$S \equiv e^{i\pi I_2} = i\sigma^2 \qquad S^\dagger \tau^a S = -(\tau^a)^* \qquad S^\dagger (\tau^a)^* S = -\tau^a$$

$$\pi^a \, \tau^a \xrightarrow{G} \pi^a \, S^\dagger \, (\tau^a)^* \, S = -\pi^a \, \tau^a$$

$$\pi^0 \xrightarrow{G} -\pi^0 \qquad \pi^\pm \xrightarrow{G} -\pi^\pm$$

G-parity in the SM

Lee, Yang 1956'

TABLE I. – *Selection Rules for* $\bar{p} + n \to m\pi$.

State	Spin parity	I	G	$\pi^- + \pi^0$	$2\pi^- + \pi^+$	$\pi^- + 2\pi^0$	$2\pi^- + \pi^+ + \pi^0$	$\pi^- + 3\pi^0$	$3\pi^- + 2\pi^+$	$2\pi^- + \pi^+ + 2\pi^0$	$\pi^- + 4\pi^0$
$^1S_0$	0^-	1	—	×			—	—			
$^3S_1$	1^-	1	+		—	—			—	—	—
$^1P_1$	1^+	1	+	×	—	—			—	—	—
$^3P_0$	0^+	1	—	—	×	×	—	—			
$^3P_1$	1^+	1	—	×			—	—			
$^3P_2$	2^+	1	—	—			—	—			

× means strictly forbidden and — means forbidden so far as the isotopic spin is a good quantum number.

G-parity is broken in the SM

- The G-parity in the SM is broken by the chiral weak interaction and nonzero hypercharges of quarks.

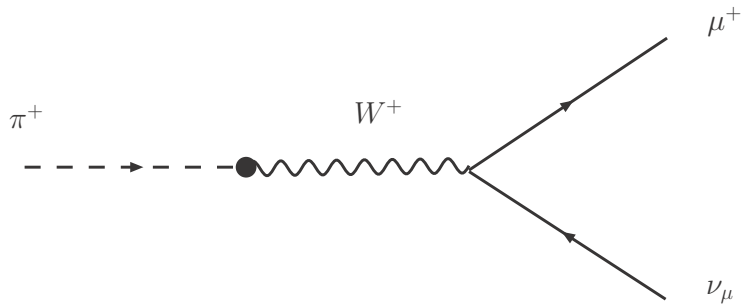
$$\mathcal{L} = \psi^\dagger_{L\,i}\,\bar{\sigma}\cdot(i\partial + \mathcal{A} + W^a\,\tau^a_{ij})\psi_{L\,j} + \psi^\dagger_{R\,i}\,\sigma\cdot(i\partial+\mathcal{A})\psi_{R\,i}$$

$$\begin{aligned}
\psi_{L\,i} &\xrightarrow{G} (-i\sigma^2)(\sigma^2)_{ij}\,\psi^*_{R\,j}\,,\\
\psi_{R\,i} &\xrightarrow{G} (i\sigma^2)(\sigma^2)_{ij}\,\psi^*_{L\,j}\,,\\
\mathcal{A} &\xrightarrow{G} \mathcal{A}^{\mathcal{C}} = -A^a(t^a)^*\,,\\
W^a\tau^a &\xrightarrow{G} (W^a\tau^a)^{\mathcal{C}} = \sigma^2(W^a\tau^a)\sigma^2
\end{aligned}$$

$$\mathcal{L} = \psi^\dagger_{R\,i}\,\bar{\sigma}\cdot(i\partial + \mathcal{A} + W^a\,\tau^a_{ij})\psi_{R\,j} + \psi^\dagger_{L\,i}\,\sigma\cdot(i\partial+\mathcal{A})\psi_{L\,i}$$

G-parity is broken. Pion-number is not conserved.

Decay of Charged Pions

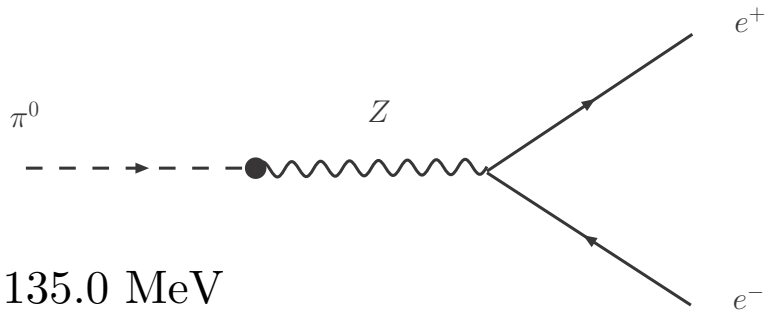


$m_{\pi^+} = 139.6$ MeV $\qquad$ $m_{\mu^+} = 105.7$ MeV

$$\Gamma(\pi^+ \to \mu^+ \nu_\mu) = \frac{G_F^2 f_\pi^2 m_\mu^2 (m_\pi^2 - m_\mu^2)^2}{16\pi m_\pi^3} = 2.6 \times 10^{-17} \text{ GeV}$$

$$\tau = 2.6 \times 10^{-8} \text{ s}$$

Decay of Neutral Pion



$$m_{\pi^0} = 135.0 \text{ MeV}$$

$$\Gamma(\pi^0 \to e^+e^-) = \frac{G_F^2 f_\pi^2 m_e^2 m_\pi}{16\pi} = 3.4 \times 10^{-21} \text{ GeV}$$

$$\tau = 2.0 \times 10^{-4} \text{ s}$$

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

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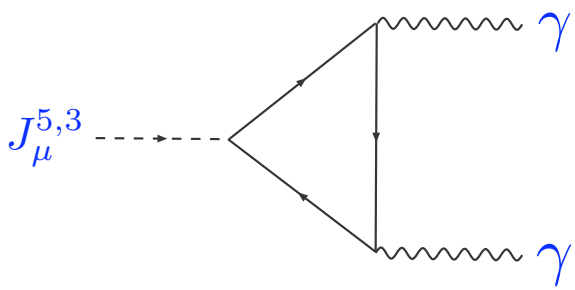
Chiral Anomaly

$$J_\mu^{5,a} = \bar{\psi}\gamma_\mu\gamma_5\tau^a\psi$$ Classically Conserved

[Adler and Bell, Jackiw'1969]



broken at quantum level

$$\partial^\mu J_\mu^{5,3} = \mathcal{A} = -\frac{N_c\, e^2}{48\pi^2}\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

$$\frac{\pi^0}{f_\pi}\mathcal{A} \Rightarrow \pi^0 \to \gamma\gamma$$

$$\Gamma(\pi^0 \to 2\gamma) = \frac{\alpha^2 m_\pi^3}{64\pi^3 f_\pi^2}$$

matches experimental data

Why not to use the G-parity to explain the stability of the dark matter particle?

Dark Matter Sector

Dark QCD

dark quarks, dark pions,
dark baryons,
...

dark G-parity is unbroken

dark pion is the LGP

Dark QCD

Introduce a new QCD-like strong dynamical gauge group with a confinement scale at TeV

$\Lambda_{\rm QCD} \sim 1$ GeV

To keep the dark G-parity:

- Make "dark quarks" vector-like under SU(2) weak gauge interaction.
- Choose zero hypercharge for "dark quarks".

New G-parity Odd Pions

	$SU(N)_h$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$\hat{\psi}_{L,R}$	N	1	2	0

$$SU(2)_L \quad \times \quad SU(2)_R$$
$$\Downarrow$$
$$SU(2)_V \quad = \quad SU(2)_W$$

quark-level

$$\hat{\psi} \xrightarrow{G} S\,\hat{\psi}^{\mathcal{C}} = S\,i\,\gamma^2\,\hat{\psi}^*$$
$$\hat{A}^b\,T^b \xrightarrow{G} (\hat{A}^b\,T^b)^{\mathcal{C}} = -\hat{A}^b\,(T^b)^*$$
$$W^a \xrightarrow{G} W^a$$

$$S = i\tau^2$$

pion-level

$$\Pi^a \xrightarrow{G} -\Pi^a$$

$\Pi^a : (3)_0$ Stable

General Weak Representations

Richard Hill, YB
1005.0008

	$SU(N)_h$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$\psi_{L,R}$	N	1	$2j+1$	0

$$SU(2j+1)_L \times SU(2j+1)_R \times U(1)_B \to SU(2j+1)_V \times U(1)_B$$

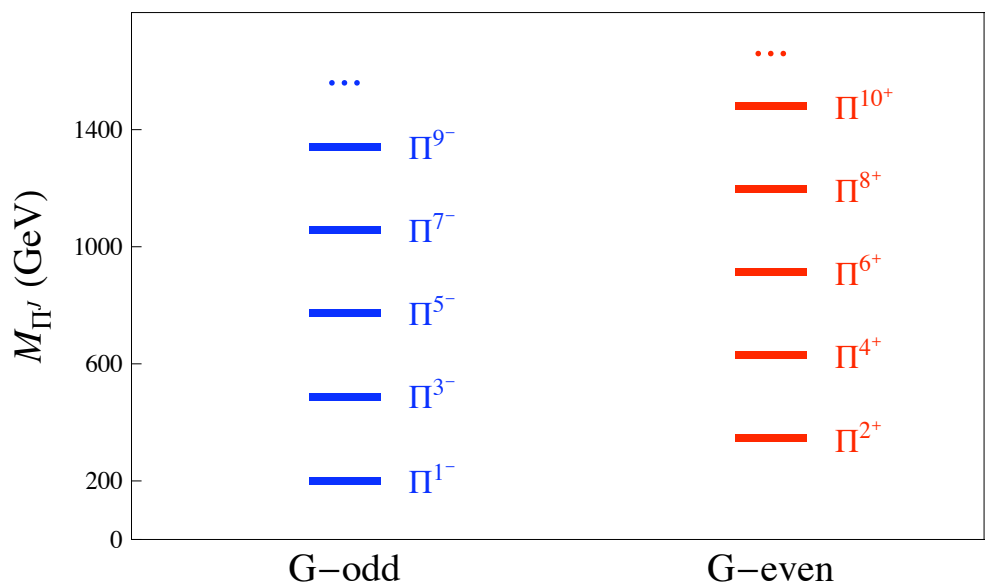
$$[\mathrm{I},\, \mathrm{G}] = 0$$

pions

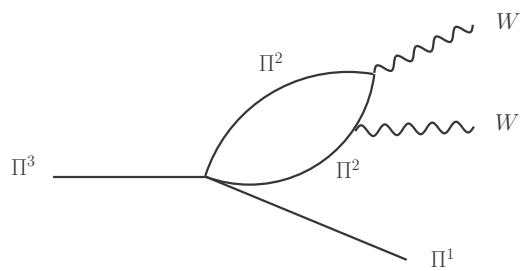
$$(2j+1)^2 - 1 = \sum_{J=1}^{2j} (2J+1)$$

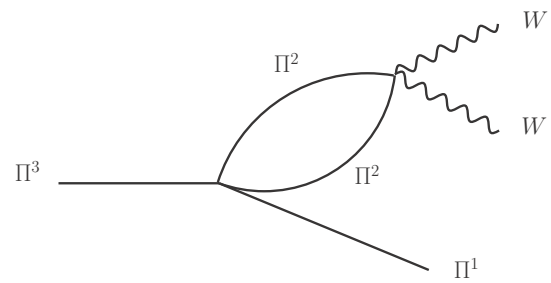
$$M^2_{\Pi^J} \sim C_2(J)\, g_2^2\, f^2_\Pi$$

weak SU(2) is unbroken



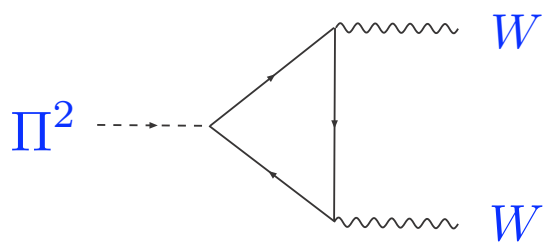
General Weak Representations





$$\Gamma(\Pi^{(3M)} \to \Pi^{(1M')} + 2W) \sim \alpha_2^2 m_\Pi^5/(4\pi)^5 f_\Pi^4$$

$$\Pi^J \to \Pi^{J-2} + W + W$$



$$\Gamma(\Pi^{(2M)}) \sim \alpha_2^2 m_\Pi^3/(4\pi)^3 f_\Pi^2$$

Lightest G-odd particle

From electromagnetic radiative corrections

$$m_{\Pi^{(JQ)}} - m_{\Pi^{(J0)}} \approx \alpha_2 Q^2 m_W \sin^2 \frac{\theta_W}{2}$$

Especially $m_{\Pi^{(1\pm1)}} - m_{\Pi^{(10)}} \approx 170\,\mathrm{MeV}$

$$\Gamma(\Pi^{(1\pm1)} \to \Pi^{(10)} + \pi^\pm) = \frac{4G_F^2}{\pi}\Delta^2\sqrt{\Delta^2 - m_\pi^2}\, f_\pi^2$$

The charged parts have decay length: $c\tau \approx 5\,\mathrm{cm}$

behave as a long-lived charged particle at colliders

The current constraints set $m_{\Pi^1} > 88\ \mathrm{GeV}$

Π^{10} is the LGP

Relic Abundance and Detection

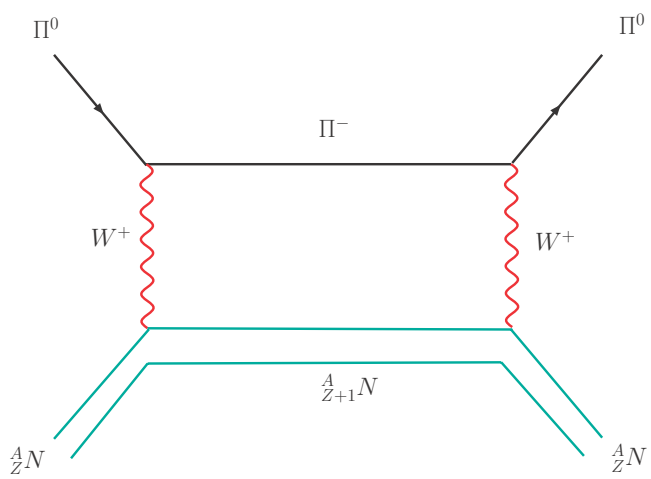
Annihilation Cross section:

$$\sigma(\Pi^0\Pi^0 \to WW) \approx \frac{g_2^4}{4\pi\, m_\Pi^2}$$

To satisfy the relic abundance $m_\Pi \sim 1 - 2\ \mathrm{TeV}$

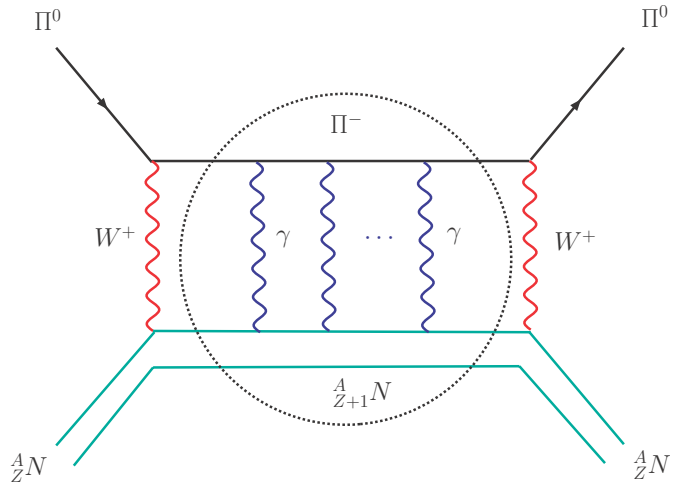
Not to over-close the universe $0.1 \lesssim m_\Pi \lesssim 1\ \mathrm{TeV}$

Direct Detection



$10^{-45}\ \mathrm{cm}^2$

Resonant Effects



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The typical binding energy is O(10) MeV

If the mass splitting, $\Delta = m_{\Pi^-} - m_{\Pi^0} = O(10\ \mathrm{MeV})$

for example, add the operator $\epsilon^{abc}\Pi^a\Pi^b(H^\dagger t^c H)$

The resonance effects become important

DAMA/LIBRA results can be explained

Binding Energy is Element Dependent

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CDMS ZEPLIN XENON

${}^{A}_{Z}N$	${}^{23}_{11}Na$	${}^{28}_{14}Si$	${}^{74}_{32}Ge$	${}^{127}_{53}I$	${}^{129}_{54}Xe$	${}^{133}_{55}Cs$	${}^{184}_{74}W$
${}^{A}_{Z+1}N$	${}^{23}_{12}Mg$	${}^{28}_{15}P$	${}^{74}_{33}As$	${}^{127}_{54}Xe$	${}^{129}_{55}Cs$	${}^{133}_{56}Ba$	${}^{184}_{75}Re$
Δm (MeV)	3.8	13.8	2.1	0.15	0.7	0.01	1.0
S_n (MeV)	13.1	14.5	8.0	7.3	9.6	7.2	6.5
E_b (MeV)	5.8	7.5	13.5	19.1	19.4	19.6	23.3

DAMA KIMS CRESST

- The rDM can reconcile the apparent contradiction between DAMA and other experiments like CDMS, XENON, KIMS, ZEPLIN and CRESST.

Discussions

- The G-parity is unbroken from all renormalizable operators.
- Two dim-five operators violate G-parity:

$$B_{\mu\nu}\bar{\hat{\psi}}\sigma^{\mu\nu}\hat{\psi}/\Lambda_{\rm UV} \qquad\qquad H^\dagger t^a H\bar{\hat{\psi}}J^a\hat{\psi}/\Lambda_{\rm UV}$$

- Introducing a Peccei-Quinn symmetry, the LGP can still have a lifetime longer than the age of our universe.
- Hidden sector baryons are also stable. However, they only contribute a very small fraction of the dark matter density:

$$\frac{\Omega_B}{\Omega_\Pi} \sim \frac{\langle\sigma v\rangle_\Pi}{\langle\sigma v\rangle_B} \sim 4\pi\,\alpha_2^2 \sim 10^{-2}$$

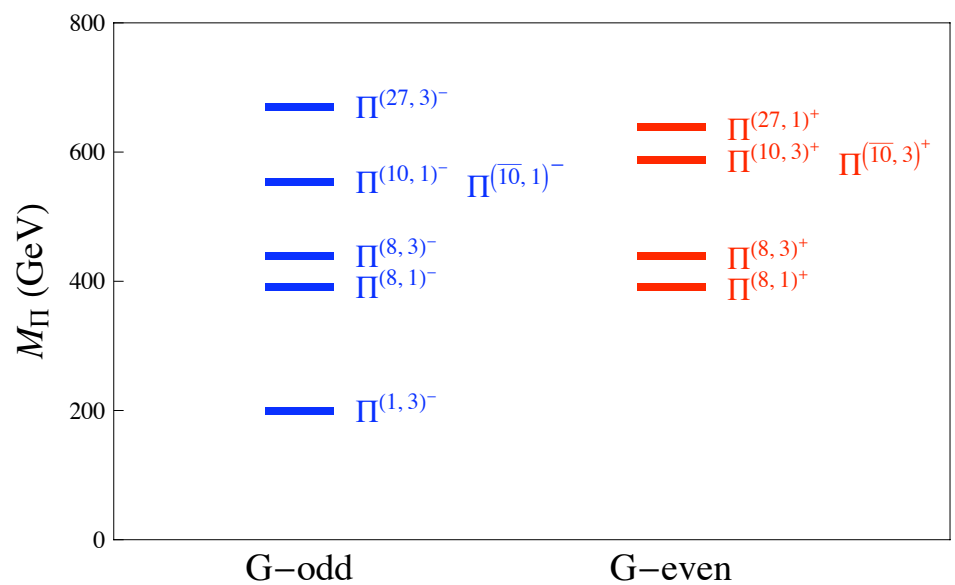
Extension to Color SU(3)

Richard Hill, YB
1005.0008

	$SU(N)_h$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$\psi_{L,R}$	N	8	2	0

only possible for real representation

$$8 \times 8 = 8_A + 10_A + \overline{10}_A + 1_S + 8_S + 27_S$$



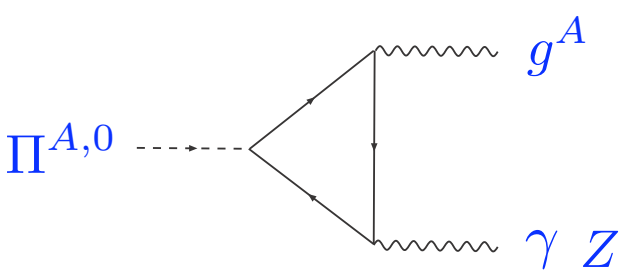
Topological Pions

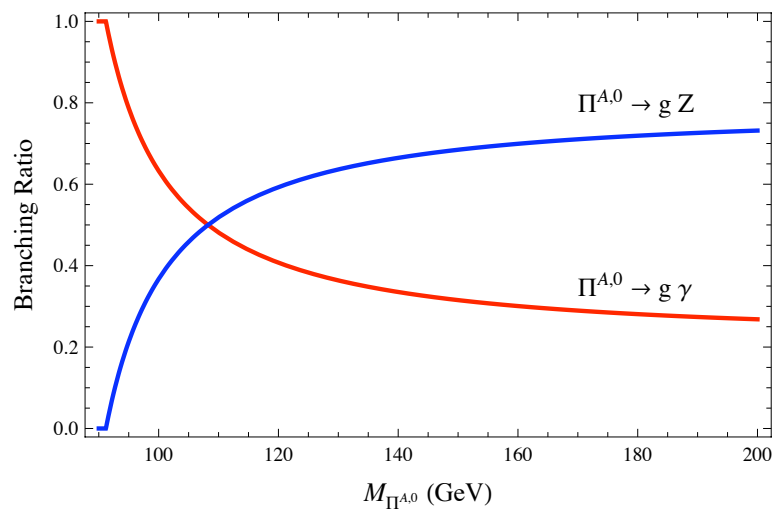
vector-like representation:

[Kilic, Okui, Sundrum: 0906.0577]

A case study at colliders $\Pi^{(8,3)^+}$

They only decay via anomalies

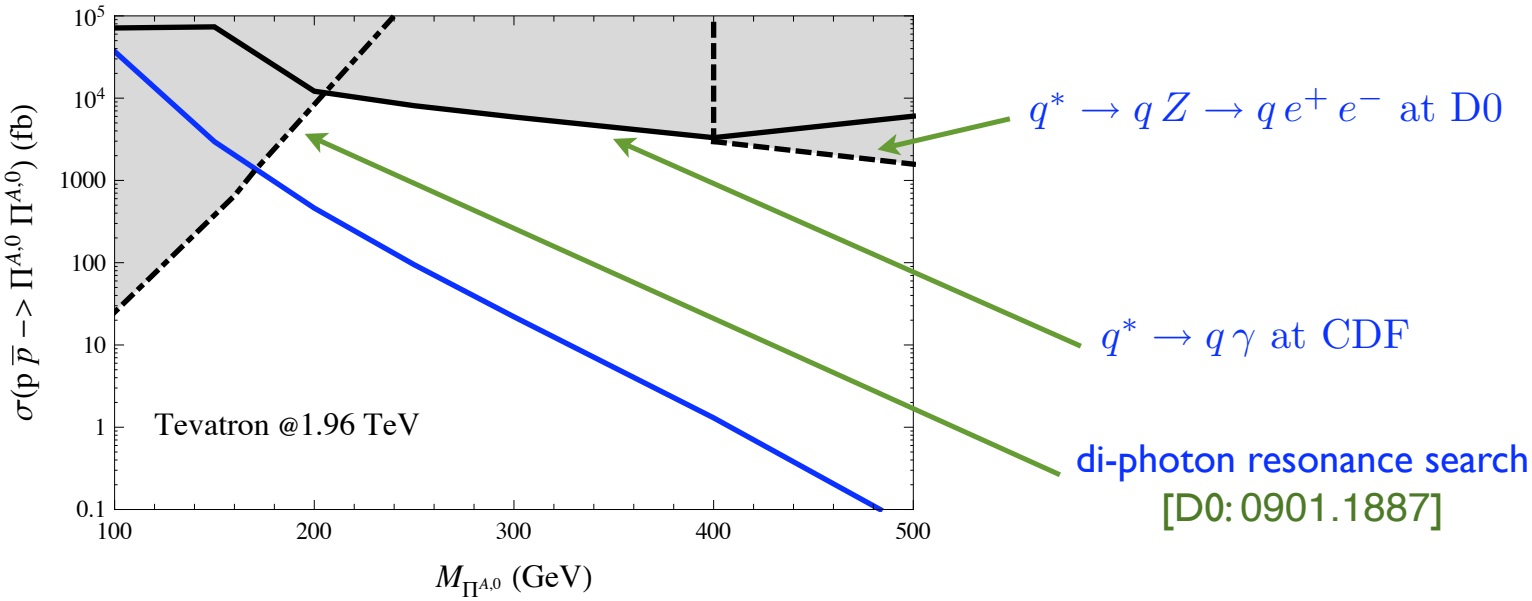




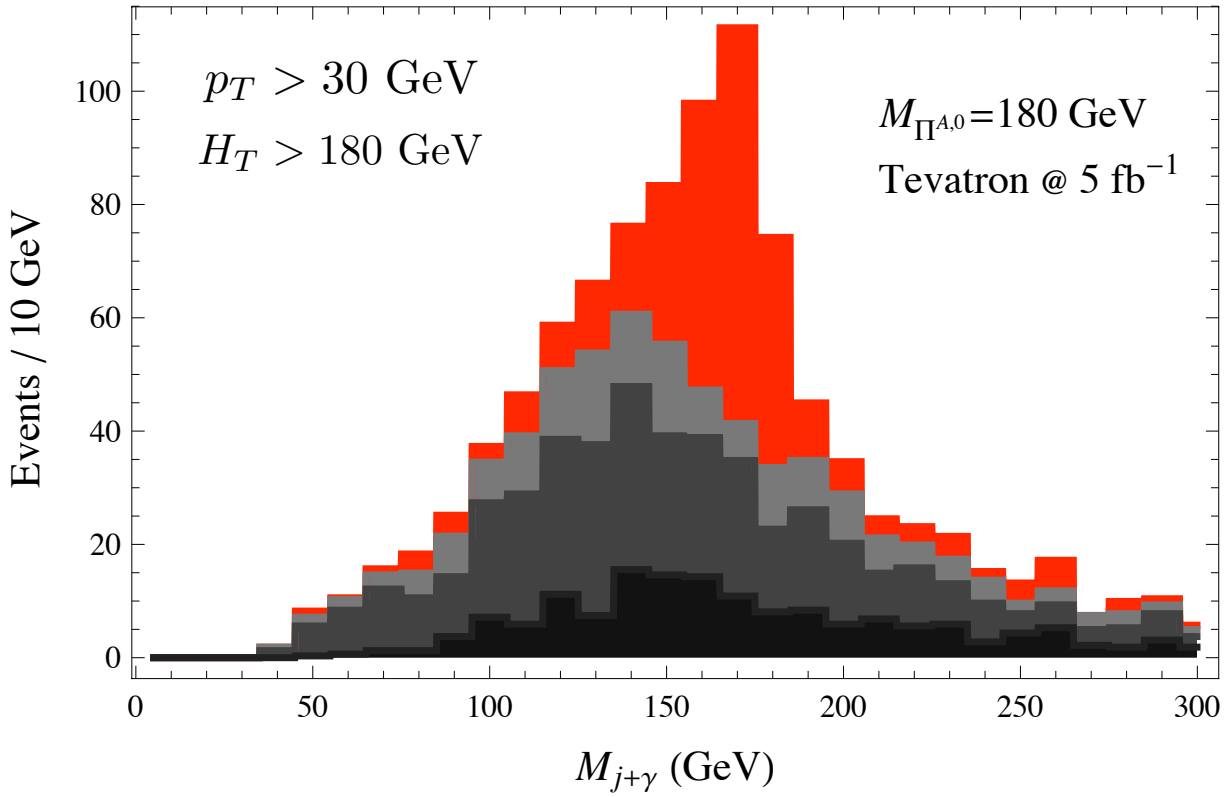
Width: $\mathcal{O}(1\ \mathrm{MeV})$

Topological Pions

pair produced at colliders



Reconstruction



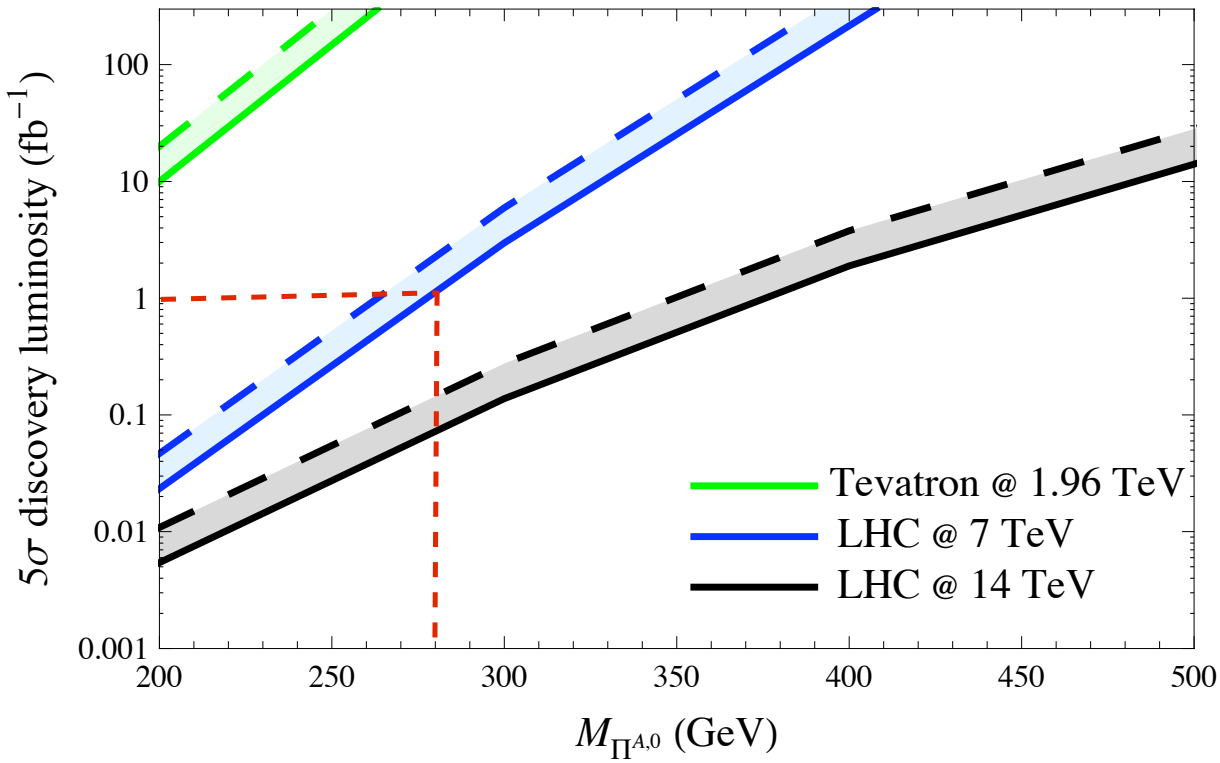
BG: $n\,j + 2\,\gamma$

BG: $n\,j + 1\,\gamma +$ jet fakes

ATLAS physics TDR

Discovery Potential

Martin and YB: 1003:3006



$$p_T^1 > M_\Pi/3\,,\; p_T^2 > M_\Pi/6\,,\; H_T > \max(M_\Pi\,, 3\,M_\Pi - 600\ \text{GeV})$$

Conclusions

- An unbroken and nontrivial discrete symmetry emerges in a class of models with vector-like SM gauging of fermions with QCD-like strong dynamics.
- The dark matter particle, LGP, could be a stable pion emerges in this class of models.
- The mechanism leads to testable and distinct dark matter and LHC phenomenologies.
- New pions decaying into gluon plus photon (anomaly induced) may be found with the early data of the LHC.