imagine the impossible

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Scalar dark matter interpretation of DAMPE e^+e^- peak structure with U(1) gauge interactions

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1711.11452 [Phys.Rev. D97 (2018) no.9, 095011]

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Outline

- First DAMPE e^+e^- result
- Scalar DM model with additional U(1)
  - $G_{SM}\times U(1)_{Y'}$
  - $G_{SM}\times U(1)_{Y'}\times U(1)_{Y''}$
- Peak explanations, constraints
- Summary

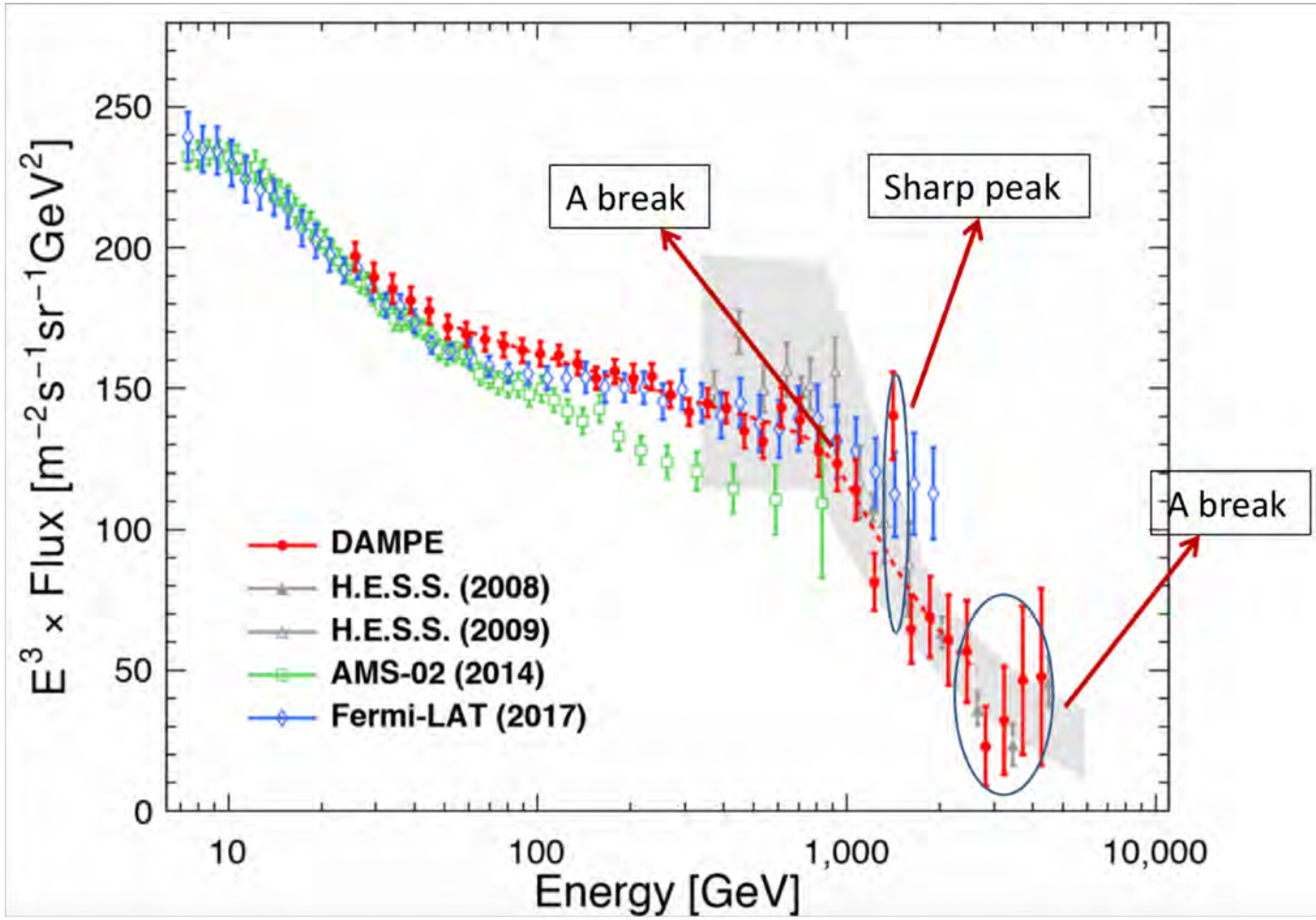
First DAMPE e^+e^- result

10.1038/nature24475

- Nov. 2017

- **DA**rk **M**atter **P**article **E**xplorer (DAMPE) experiment released new measurement of total cosmic e^+e^- flux between 25 GeV and 4.6 TeV.

- a spectral softening at ~0.9 TeV and a tentative peak at ~1.4 TeV



Peak at ~1.4 TeV: DM annihilation explanation

TABLE III: Mass of the DM particle, and mass and luminosity of the DM clump halo to fit the DAMPE data. The annihilation cross section is assumed to be 3×10^{-26} cm^{3}s^{-1}.

channel	1.0 kpc			0.3 kpc			0.1 kpc		
	m_χ/TeV	$M_{sub}/M_\odot$	$\mathcal{L}$/GeV^{2}cm^{-3}	m_χ/TeV	$M_{sub}/M_\odot$	$\mathcal{L}$/GeV^{2}cm^{-3}	m_χ/TeV	$M_{sub}/M_\odot$	$\mathcal{L}$/GeV^{2}cm^{-3}
e^+e^-	2.2	3.8×10^9	1.0×10^{67}	1.5	8.0×10^7	3.8×10^{65}	1.5	5.0×10^6	3.5×10^{64}
$e\mu\tau$	2.2	1.0×10^{10}	2.3×10^{67}	1.5	2.6×10^8	1.0×10^{66}	1.5	1.9×10^7	1.1×10^{65}

[Y. Qiang et al, 1711.10989]

- m_{DM} ~1.5 TeV
- $\langle \sigma v \rangle_0 \simeq 3{\times}10^{-26} cm^3/s$
- annihilation products
  - exclusively (democratically) into e^+e^- ($e^+e^-, \mu^+\mu^-, \tau^+\tau^-$)
- DM clump should be near earth, keeping E_{e^+,e^-} peak-like

4 conditions

- i: Indirect detection (ID)
  - large $\langle\sigma v\rangle_0 \geq 1\times10^{-26}cm^3/s$ with $v\sim10^{-3}c$ in today's Universe
  - satisfying other comic ray constraints

- ii: Relic density (RD)
  - large $\langle\sigma v\rangle_{FO} \geq 1\times10^{-26}cm^3/s$ with $v\sim0.1\ c$ in freeze-out (FO) era

- iii: Direct detection(DD)
  - small DM-nucleon scattering rate σ^{SI}_{DM-p} to pass DD bounds

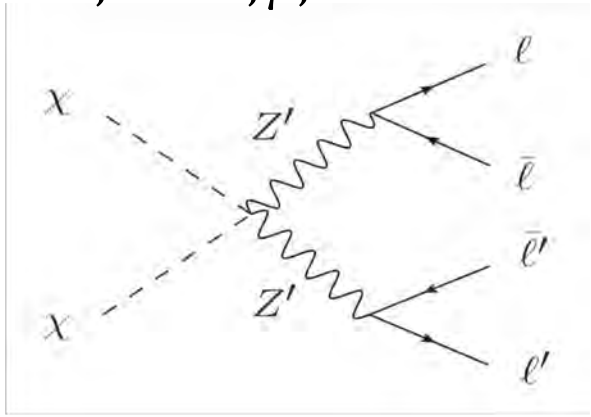
- iv: Collider
  - small signals to pass the relevant collider constraints

In this work

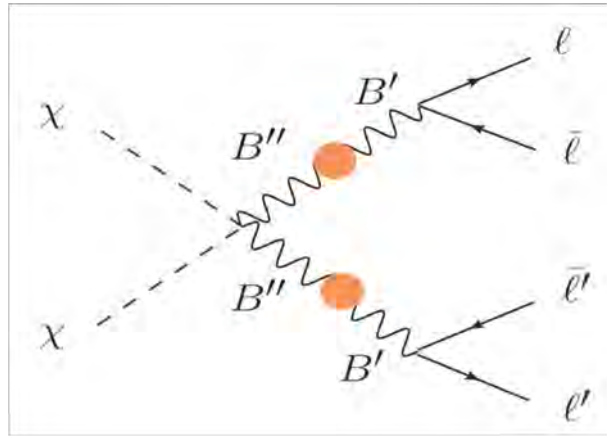
$m_\chi \sim m_{Z'} \sim 2\times1.5$ TeV

$l, l' = e, \mu, \tau$

- Minimal: $G_{SM}\times U(1)_{Y'}$
  - can explain the DAMPE peak ~1.4 TeV
  - excluded by (iv), i.e. LHC constraints on Z'



- Non-minimal: $G_{SM}\times U(1)_{Y'}\times U(1)_{Y''}$
  - $U(1)_{Y''}$ mixes with $U(1)_{Y'}$
  - can interpret DAMPE peak~1.4 TeV
  - can pass all four conditions (i)–(iv)



$$G_{SM} \times U(1)_{Y'}$$

Particle contents

- 3 RH neutrinos $\nu_{R,\{1,2,3\}}$
- 2 complex scalars ϕ_s, ϕ_χ

- $\langle \phi_s \rangle = v_s$
  - generate $m_{Z'}$
- $\langle \phi_\chi \rangle = 0$
  - has odd Z_2-parity
  - provide DM candidate

Name	Spin	Generation	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{Y'}$
H	0	1	1	2	$-\frac{1}{2}$	0
Q	1/2	3	3	2	$\frac{1}{6}$	$\frac{1}{3}$
d_R^*	1/2	3	$\bar{3}$	1	$\frac{1}{3}$	$-\frac{1}{3}$
u_R^*	1/2	3	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{1}{3}$
L_1	1/2	1	1	2	$-\frac{1}{2}$	3
$L_{\{2,3\}}$	1/2	2	1	2	$-\frac{1}{2}$	-3
$\ell_{R,1}^*$	1/2	1	1	1	1	-3
$\ell_{R,\{2,3\}}^*$	1/2	2	1	1	1	3
$\nu_{R,1}^*$	1/2	1	1	1	0	-3
$\nu_{R,\{2,3\}}^*$	1/2	2	1	1	0	3
ϕ_s	0	1	1	1	0	6
ϕ_χ	0	1	1	1	0	6

Lagrangian

- Lagrangian relevant for DAMPE interpretation

$$\mathcal{L} \supset |D'_\mu \phi_\chi|^2 + |D'_\mu \phi_s|^2 - V(H, \phi_\chi, \phi_s)$$
$$-\frac{1}{4}|F'_{\mu\nu}|^2 + g_{Y'} Z'_\mu (Y'_{f_R} \overline{f_R} \gamma^\mu f_R + Y'_{\nu_{R,i}} \overline{\nu_{R,i}} \gamma^\mu \nu_{R,i})$$

Fermion species: $f = u, d, \ell$

Covariant derivative: $D'_\mu = \partial_\mu - i g_{Y'} Y' Z'_\mu$

Field tensor: $F'_{\mu\nu} = \partial_\mu Z'_\nu - \partial_\nu Z'_\mu$

Scalar potential:

$$\begin{aligned} V(H, \phi_\chi, \phi_s) = {} & m_H^2 |H|^2 + m_{\phi_\chi}^2 |\phi_\chi|^2 + m_{\phi_s}^2 |\phi_s|^2 \\ & + \lambda_H |H|^4 + \lambda_{\phi_\chi} |\phi_\chi|^4 + \lambda_{\phi_s} |\phi_s|^4 \\ & + \lambda_{\chi H} |\phi_\chi|^2 |H|^2 + \lambda_{sH} |\phi_s|^2 |H|^2 \\ & + \lambda_{\chi s} |\phi_\chi|^2 |\phi_s|^2 + \lambda'_{\chi s} ((\phi_\chi^* \phi_s)^2 + \text{H.c.}) \end{aligned}$$

DM candidate

Name	Spin	Generation	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{Y'}$
ϕ_s	0	1	1	1	0	6
ϕ_χ	0	1	1	1	0	6

$$V(H,\phi_\chi,\phi_s) \supset \lambda'_{\chi s}((\phi_\chi^*\phi_s)^2 + \text{H.c.}) \supset \frac{1}{2}\lambda'_{\chi s} v_s^2 (\phi_{R,\chi}^2 - \phi_{I,\chi}^2)$$

$$\Delta m^2_{\chi',\chi} = m^2_{\chi'} - m^2_\chi = 2\lambda'_{\chi s} v_s^2$$

assuming $\lambda'_{\chi s} > 0$

DM is $\chi \equiv \phi_{I,\chi}$

ϕ_χ also generate $\chi' \equiv \phi_{R,\chi}$

$$\phi_s \to \frac{1}{\sqrt{2}}(\phi_{R,s} + i\phi_{I,s})$$

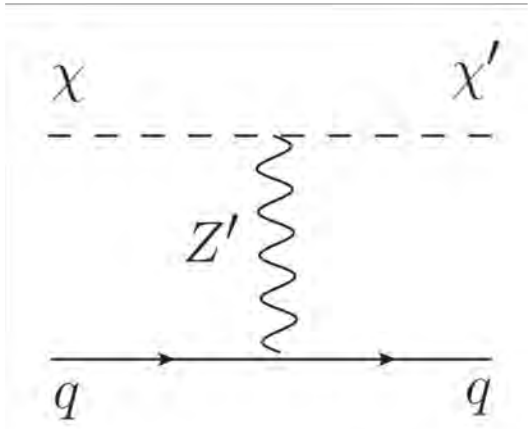
$$\phi_\chi \to \frac{1}{\sqrt{2}}(\phi_{R,\chi} + i\phi_{I,\chi})$$

$$\phi_{R,s} \to v_s + \phi_{R,s}$$

Direct detection: easily satisfied

- tree-level scattering is ***in***elastic, induced by $Z' - \chi - \chi'$

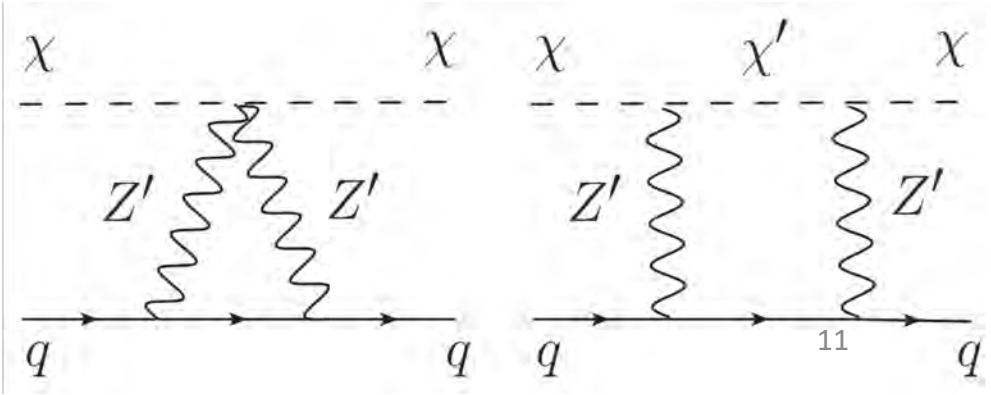
$$|D'_\mu \phi_\chi|^2 = \partial^\mu \phi_\chi \partial_\mu \phi_\chi^* + (g_{Y'} Y'_{\phi_\chi})^2 Z'^\mu Z'_\mu (\phi_{R,\chi}^2 + \phi_{I,\chi}^2) - 2 g_{Y'} Y'_{\phi_\chi} Z'_\mu (\phi_{R,\chi} \partial^\mu \phi_{I,\chi} - \phi_{I,\chi} \partial^\mu \phi_{R,\chi}),$$



- DM kinetic energy $E_{\chi,kin.} \sim$ 1 MeV $\quad \frac{1}{2} m_\chi v_\chi^2 \sim 0.5 \times (3 \times 10^3 \text{ GeV}) \times (10^{-3})^2 \sim 1 \text{ MeV}$
- Choosing $\Delta m_{\chi',\chi}$ >> 1 MeV forbids ***in***elastic scattering

$$\Delta m_{\chi',\chi}^2 = m_{\chi'}^2 - m_\chi^2 = 2\lambda'_{\chi s} v_s^2$$

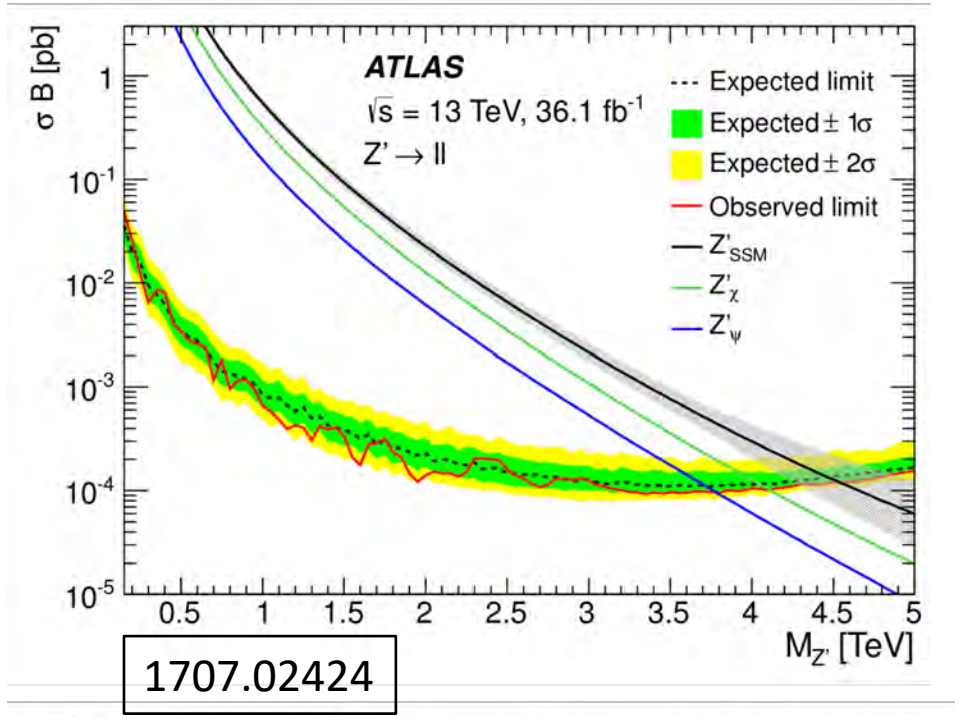
- elastic scatterings induced by loop
  - suppressed by loop factor



Collider constraints on Z'

- LEP: $e^+e^- \to Z' \to \mu^+\mu^-$
- $m_{Z'} \geq \frac{g_{Y'}}{0.1} \times 1.4$ TeV [Lee, Ma, 1001.0768]

- LHC: $q\bar{q} \to Z' \to l^+l^-$
- Dedicated simulation



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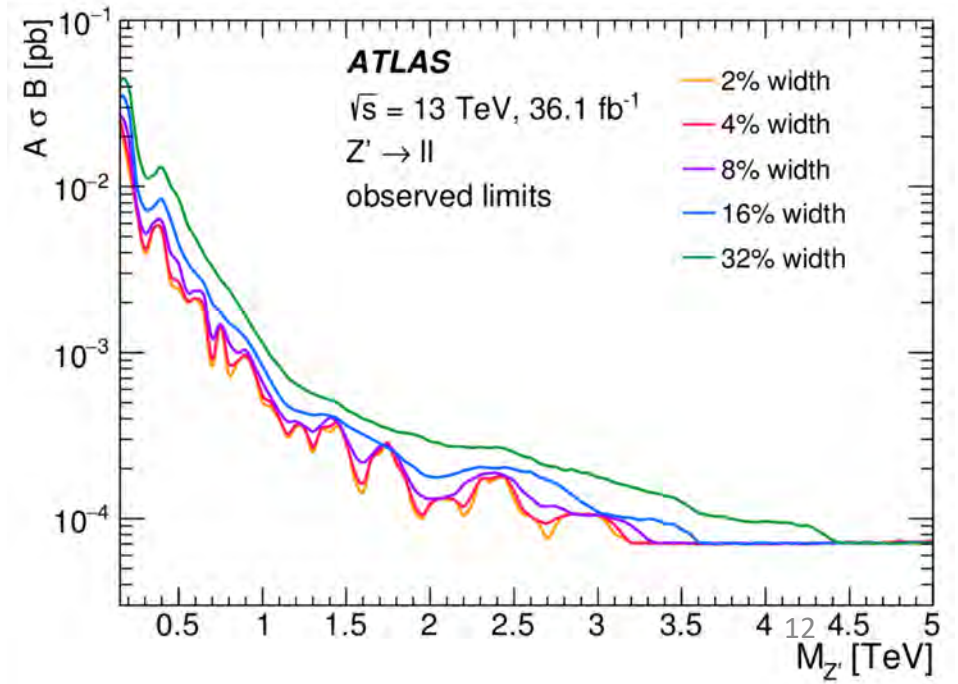
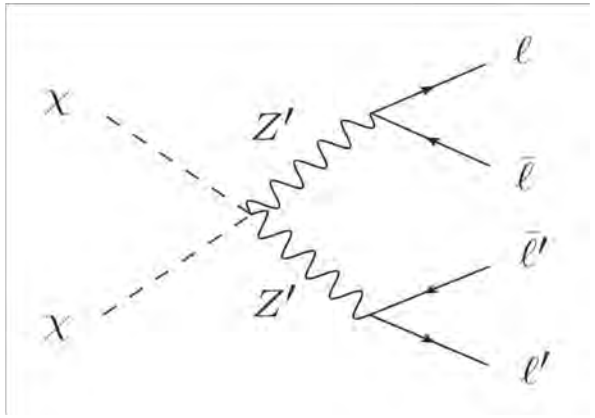
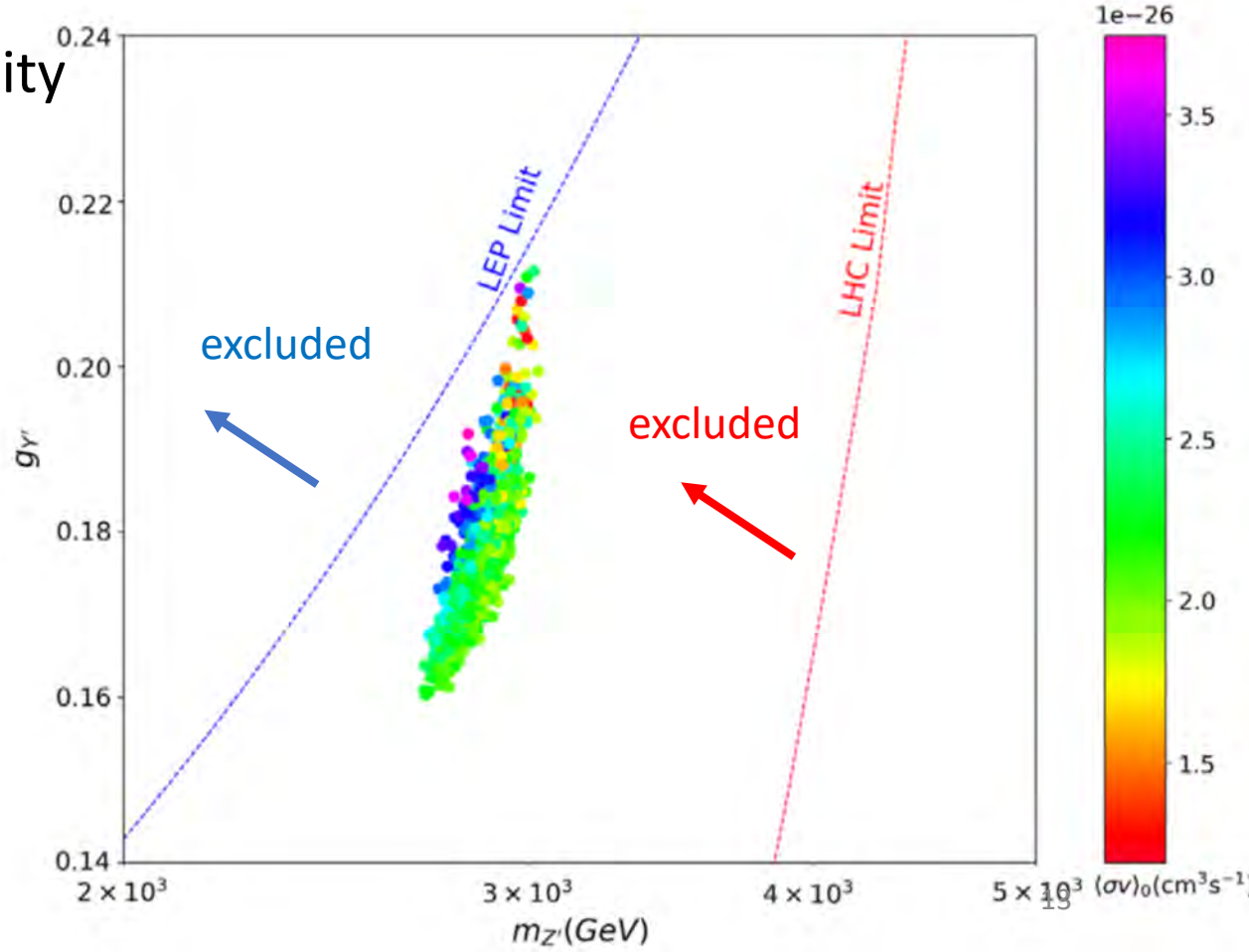


$G_{SM}\times U(1)_{Y'}$: Results



- $m_\chi \sim m_{Z'} \sim 2\times 1.5$ TeV $g_{Y'} \sim 0.2$
  - can produce observed DM relic density
  - can explain the DAMPE peak
  - can pass LEP bounds
  - fail to pass LHC bounds
- $\Delta m_{\chi',\chi}$ >> 1 MeV
  - can pass direct detection bounds



$$G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$$

Particle content

- 3 RH neutrinos $\nu_{R,\{1,2,3\}}$
- 3 complex scalars $\phi_s, \phi_\chi, \phi_d$

- $\langle \phi_s \rangle = v_s$
  - generate $m_{B'}$

$U(1)_{Y'}$

- $\langle \phi_d \rangle = v_d$
  - generate $m_{B''}$

$U(1)_{Y''}$

- $\langle \phi_\chi \rangle = 0$
  - has odd Z_2-parity
  - to generate DM

Name	Spin	Generation	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{Y'}$	$U(1)_{Y''}$
H	0	1	1	2	$-\frac{1}{2}$	0	0
Q	1/2	3	3	2	$\frac{1}{6}$	$\frac{1}{3}$	0
d_R^*	1/2	3	$\bar{3}$	1	$\frac{1}{3}$	$-\frac{1}{3}$	0
u_R^*	1/2	3	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{1}{3}$	0
L_1	1/2	1	1	2	$-\frac{1}{2}$	3	0
$L_{\{2,3\}}$	1/2	2	1	2	$-\frac{1}{2}$	−3	0
$\ell_{R,1}^*$	1/2	1	1	1	1	−3	0
$\ell_{R,\{2,3\}}^*$	1/2	2	1	1	1	3	0
$\nu_{R,1}^*$	1/2	1	1	1	0	−3	0
$\nu_{R,\{2,3\}}^*$	1/2	2	1	1	0	3	0
ϕ_s	0	1	1	1	0	6	0
ϕ_χ	0	1	1	1	0	0	Y''_{ϕ_χ}
ϕ_d	0	1	1	1	0	0	Y''_{χ_d}

Lagrangian

- Lagrangian relevant for DAMPE interpretation

$$\mathcal{L} \supset |D_\mu \phi_\chi|^2 + |D_\mu \phi_s|^2 + |D_\mu \phi_d|^2 - V(H, \phi_\chi, \phi_s, \phi_d) - \frac{1}{4}|F'_{\mu\nu}|^2 - \frac{1}{4}|F''_{\mu\nu}|^2 - \frac{\kappa}{2} F'^{\mu\nu} F''_{\mu\nu},$$

Covariant derivative:

$$D_\mu \phi = [\partial_\mu + iY'_\phi (g_{Y'Y'} B'_\mu + g_{Y'Y''} B''_\mu) + iY''_\phi (g_{Y''Y'} B'_\mu + g_{Y''Y''} B''_\mu)]\phi,$$

Field tensor:

$$F'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu$$

$$F''_{\mu\nu} = \partial_\mu B''_\nu - \partial_\nu B''_\mu$$

Scalar potential:

$$\begin{aligned} V(H, \phi_\chi, \phi_s, \phi_d) &= m_H^2 |H|^2 + m_{\phi_\chi}^2 |\phi_\chi|^2 + m_{\phi_s}^2 |\phi_s|^2 + m_{\phi_d}^2 |\phi_d|^2 \\ &+ \lambda_H |H|^4 + \lambda_{\phi_\chi} |\phi_\chi|^4 + \lambda_{\phi_s} |\phi_s|^4 + \lambda_{\phi_d} |\phi_d|^4 \\ &+ \lambda_{\chi H} |\phi_\chi|^2 |H|^2 + \lambda_{sH} |\phi_s|^2 |H|^2 + \lambda_{dH} |\phi_d|^2 |H|^2 \\ &+ \lambda_{\chi s} |\phi_\chi|^2 |\phi_s|^2 + \lambda_{\chi d} |\phi_\chi|^2 |\phi_d|^2 + \lambda_{sd} |\phi_s|^2 |\phi_d|^2 \end{aligned}$$

Mixing of new gauge bosons

- Under interaction basis $\{B', B''\}$
  - mass matrix is

$$D_\mu \phi = [\partial_\mu + iY'_\phi (g_{Y'Y'} B'_\mu + g_{Y'Y''} B''_\mu) + iY''_\phi (g_{Y''Y'} B'_\mu + g_{Y''Y''} B''_\mu)]\phi,$$

$$M_V^2 = 36 \times \begin{pmatrix} g_{Y'}^2 v_s^2 + \varepsilon^2 v_d^2 & \varepsilon(g_{Y'} v_s^2 + g_{Y''} v_d^2) \\ \varepsilon(g_{Y'} v_s^2 + g_{Y''} v_d^2) & \varepsilon^2 v_s^2 + g_{Y''}^2 v_d^2 \end{pmatrix}$$

$$g_{Y'} \equiv g_{Y'Y'}$$

$$g_{Y''} \equiv g_{Y''Y''}$$

$$\varepsilon \equiv g_{Y'Y''} = g_{Y''Y'}$$

- after diagonalization, we have $\{Z', Z''\}$

DM candidate

Name	Spin	Generation	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{Y'}$	$U(1)_{Y''}$
ϕ_s	0	1	1	1	0	6	0
ϕ_χ	0	1	1	1	0	0	Y''_{ϕ_χ}
ϕ_d	0	1	1	1	0	0	Y''_{χ_d}

- If $Y''_{\phi_\chi} = Y''_{\phi_d}$
  - similar to $G_{SM}\times U(1)_{Y'}$ with $\phi_s \to \phi_d$
  - DM is $\chi \equiv \phi_{I,\chi}$

- if $Y''_{\phi_\chi} \neq Y''_{\phi_d}$
  - no $\lambda'_{\chi d}[(\phi^*_\chi \phi_d)^2 + h.c.]$ term
  - DM is complex scalar ϕ_χ

$G_{SM}\times U(1)_{Y'}$

Name	Spin	Generation	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{Y'}$
ϕ_s	0	1	1	1	0	6
ϕ_χ	0	1	1	1	0	6

- DM candidate

$$V(H,\phi_\chi,\phi_s) \supset \lambda'_{\chi s}((\phi^*_\chi\phi_s)^2 + \text{H.c.}) \supset \frac{1}{2}\lambda'_{\chi s} v_s^2 (\phi^2_{R,\chi} - \phi^2_{I,\chi})$$

$$\Delta m^2_{\chi',\chi} = m^2_{\chi'} - m^2_\chi = 2\lambda'_{\chi s} v_s^2$$

assuming $\lambda'_{\chi s} > 0$

DM is $\chi \equiv \phi_{I,\chi}$

ϕ_χ also generate $\chi' \equiv \phi_{R,\chi}$

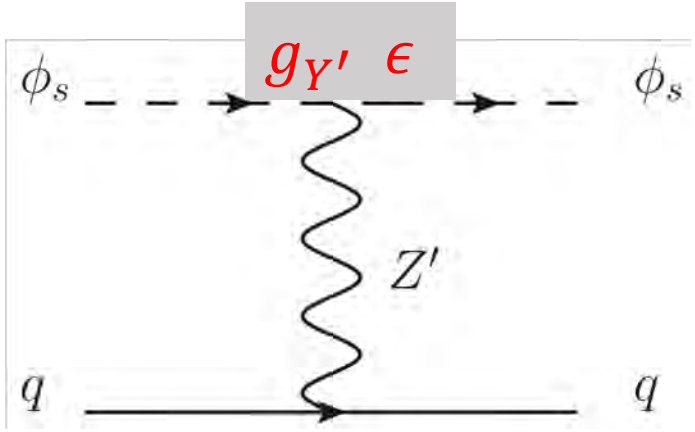
$$\phi_s \to \frac{1}{\sqrt{2}}(\phi_{R,s} + i\phi_{I,s})$$

$$\phi_\chi \to \frac{1}{\sqrt{2}}(\phi_{R,\chi} + i\phi_{I,\chi})$$

$$\phi_{R,s} \to v_s + \phi_{R,s}$$

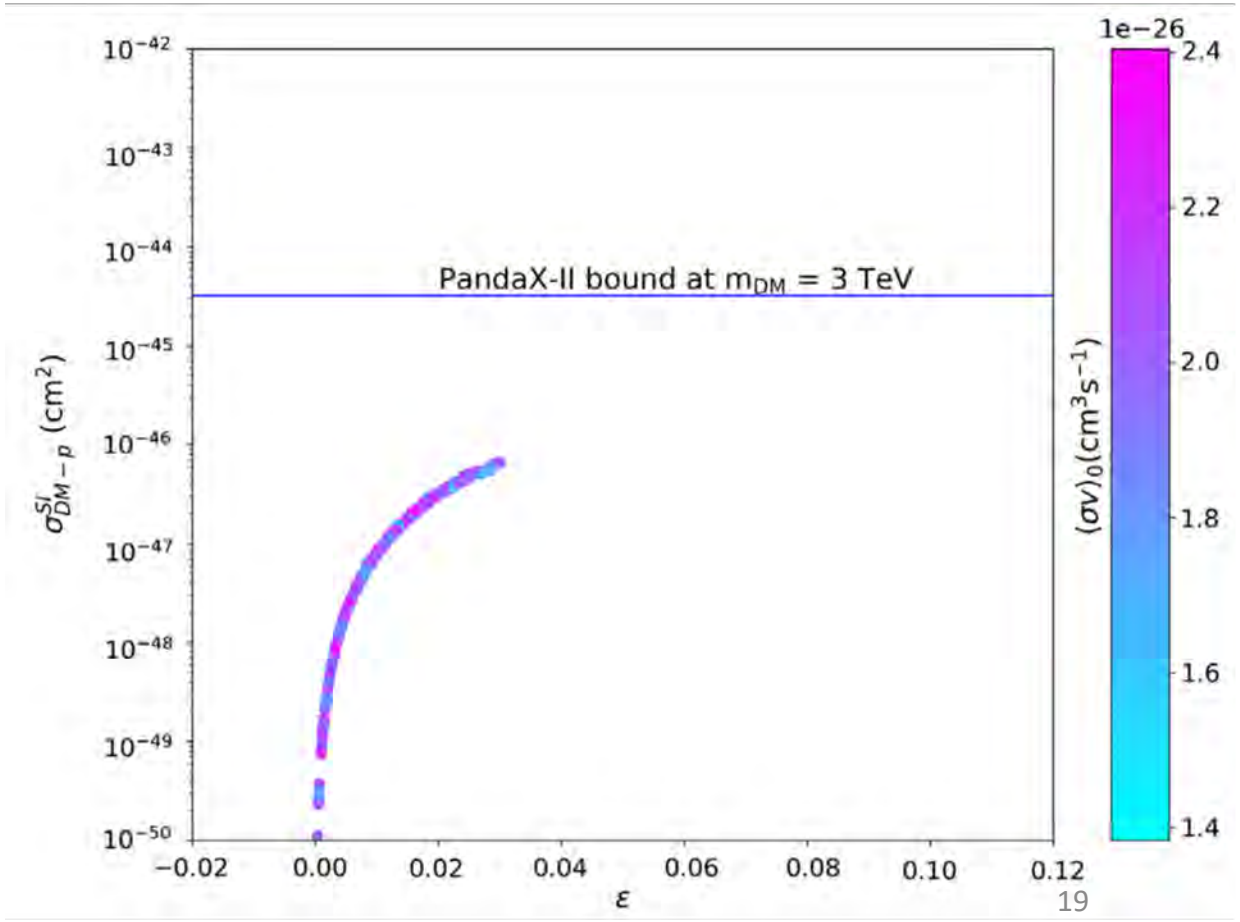
- Direct detection can be satisfied by heavy $m_{Z'}$ or small ε
  - we ignore $\lambda'_{\chi d}$ term for $Y''_{\phi_\chi} = Y''_{\phi_d}$
  - DM is complex scalar ϕ_χ

Direct detection: easily satisfied

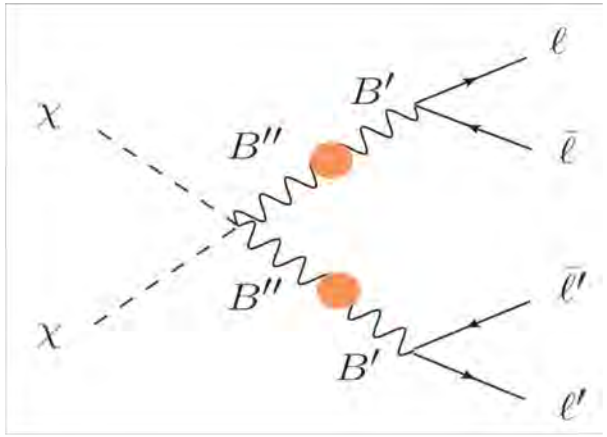


- tree-level scattering is elastic
- σ^{SI}_{DM-p} can be suppressed by
  - heavy Z'
  - small ε

- for $g_{Y'} = 0.1,\ m_{Z'} > 4$ TeV
  $\varepsilon < 0.04$ is sufficient

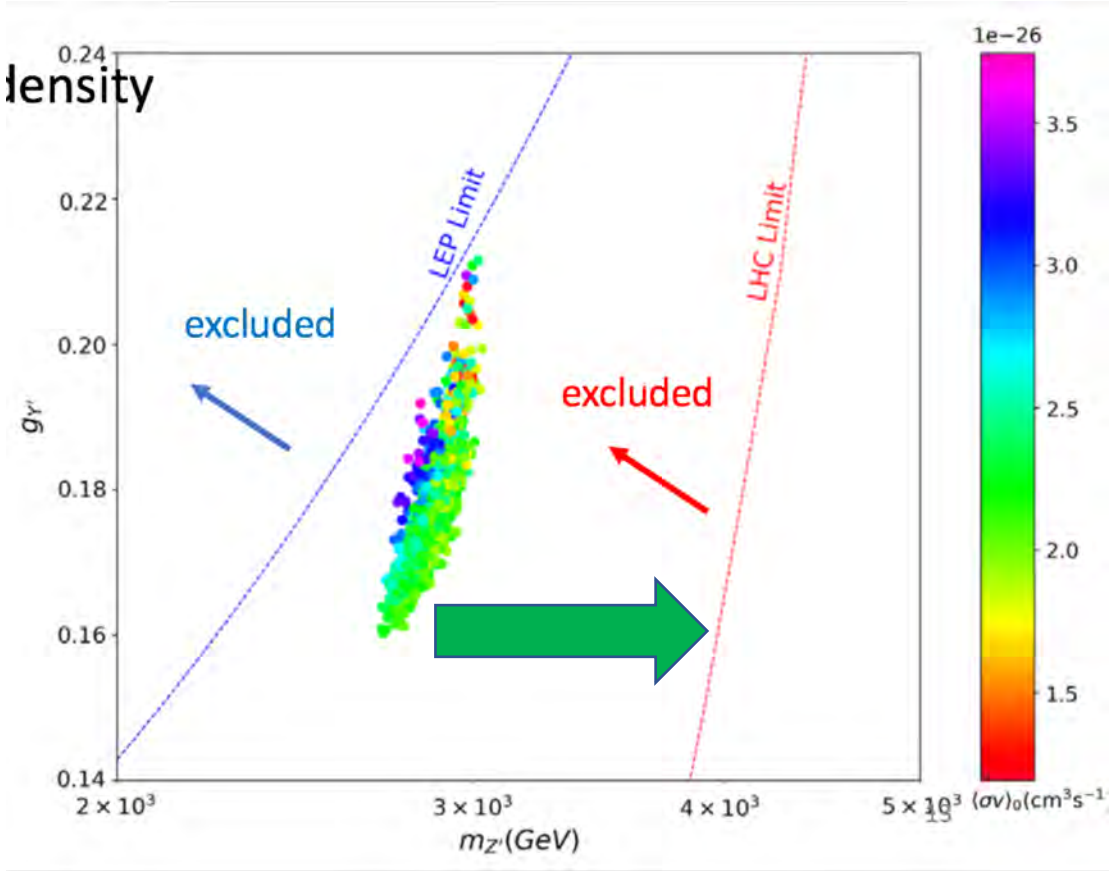


$G_{SM}\times U(1)_{Y'}\times U(1)_{Y''}$: Summary

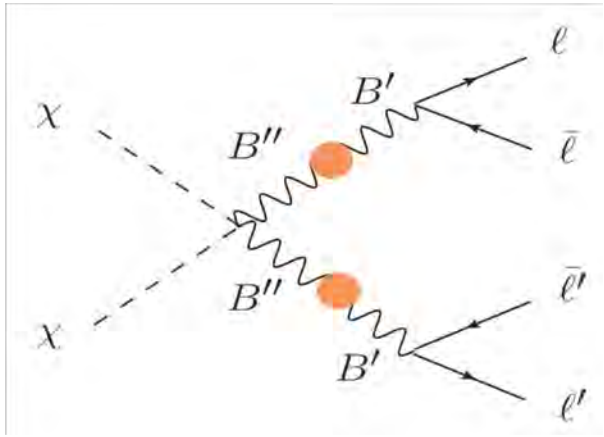


- $m_\chi \sim m_{Z''} \sim 2\times 1.5$ TeV $g_{Y''} \sim 0.2$
  - can produce observed DM relic density (ii)
  - can explain DAMPE peak (i)

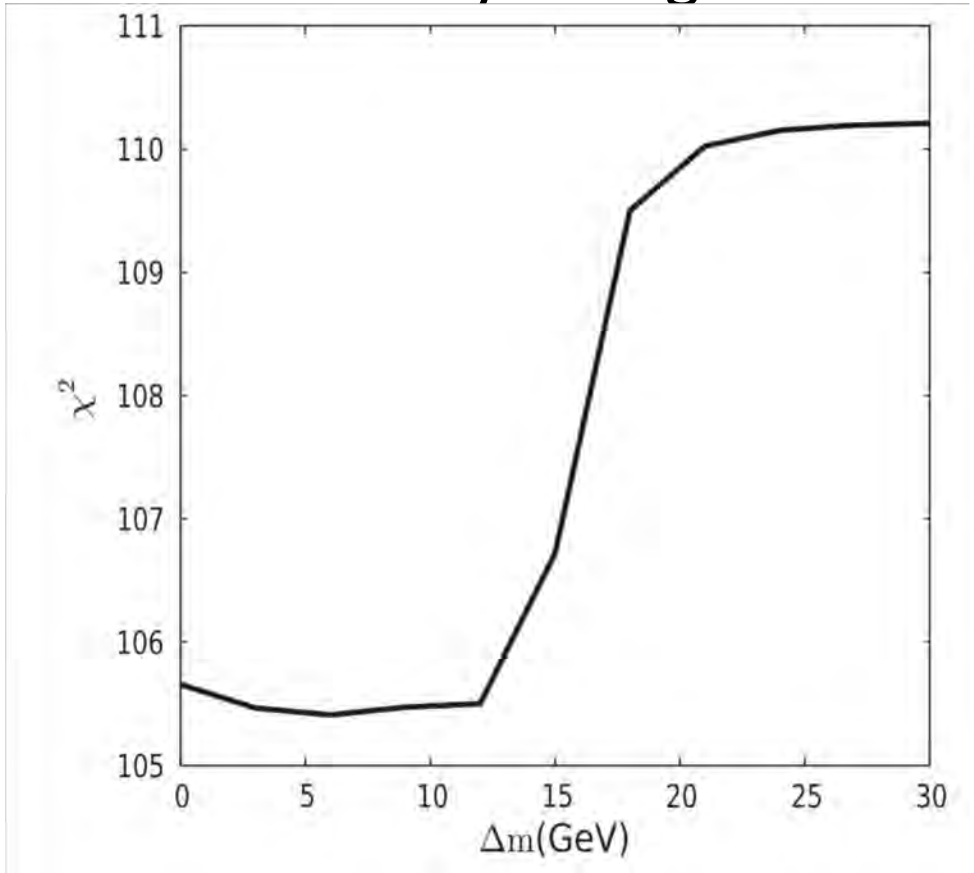
- $g_{Y'} = 0.1,\ m_{Z'} > 4$ TeV, $\varepsilon < 0.04$
  - can pass direct detection bounds (iii)
  - can pass LEP bounds (iv)
  - can pass LHC bounds (iv)



$\Delta m \equiv m_{\chi} - m_{Z''}$



- larger Δm generate more box-shape e^+e^- spectrum
- $\Delta m < 17$ GeV is identified by fitting the e^+e^- spectrum at 95% C.L.



Summary

- Nov. 2017, DAMPE released first results of total e^+e^- flux
  - 25 GeV ~ 4.6 TeV
  - a spectral softening at ~0.9 TeV
  - a tentative peak at ~1.4 TeV.

- $G_{SM}\times U(1)_{Y'}$
  - can explain DAMPE peak ~1.4 TeV
  - excluded by LHC constraints on Z'

- $G_{SM}\times U(1)_{Y'}\times U(1)_{Y''}$
  - can interpret DAMPE peak ~1.4 TeV
  - pass all four conditions (i)–(iv)

- Next DAMPE results in ~1 year

Thank you for the attention

Back up

Parameters of $G_{SM}\times U(1)_{Y'}$

For the numerical calculations, we use SARAH [23] to implement the model, SPHENO [24,25] to calculate the mass spectrum and MICROMEGAS [19,20] to calculate the DM relic abundance in which the threshold effects may be important for $m_\chi \sim m_{Z'}$ [26]. We set $\lambda_{\phi_\chi} = \lambda_{\chi s} = \lambda_{\chi H} = \lambda_{sH} = 0$ and scan the following parameters space using the package EASYSCAN-HEP [27], which is based on the Markov chain Monte Carlo sampling technique [28],

$$0 \le \lambda_{\phi_s},\quad g_{Y'},\quad \lambda'_{\chi s} \le 1,$$
$$2.9\,\text{TeV} \le m_{\phi_\chi} \le 3.1\,\text{TeV},\quad 1\,\text{TeV} \le v_s \le 5\,\text{TeV}. \quad (9)$$

In the mass spectrum calculation, we have included the radiative correction to m_χ; i.e., we have $m_\chi \neq m_{\phi_\chi}$ even with $\lambda_{\chi s} = \lambda'_{\chi s} = 0$. We further impose the constraints [29]

$$m_\chi \in (3000 \pm 10)\ \text{GeV},\qquad m_{Z'} \in (2.7, 3)\ \text{TeV},$$
$$m_{\phi_{R,s}}, m_{\chi'} > 3\ \text{TeV},\qquad \langle\sigma v\rangle_0 \gtrsim 1\times 10^{-26}\ \text{cm}^3/\text{s},$$
$$\Omega_\chi h^2 \in 0.1187 \pm 0.01198, \quad (10)$$

where both of the two physical scalars $S \equiv \phi_{R,s}$ and χ' are required to be heavier than 3 TeV so that they do not significantly affect the explanation of the DAMPE peak. The scalar S may decay into $Z'^{(*)}Z'^{(*)}$ or neutrinos via the new Yukawa interactions under $U(1)_{Y'}$ such as $\phi_s\overline{\nu^c_{R,1}}\nu_{R,23}, \phi_s\nu^c_{R,i}\nu^c_{R,i}$ [18], and the scalar χ' may decay via $\chi' \to \chi + Z'^{(*)}$ through the $U(1)_{Y'}$ gauge interaction.

Parameters of $G_{SM}\times U(1)_{Y'}\times U(1)_{Y''}$

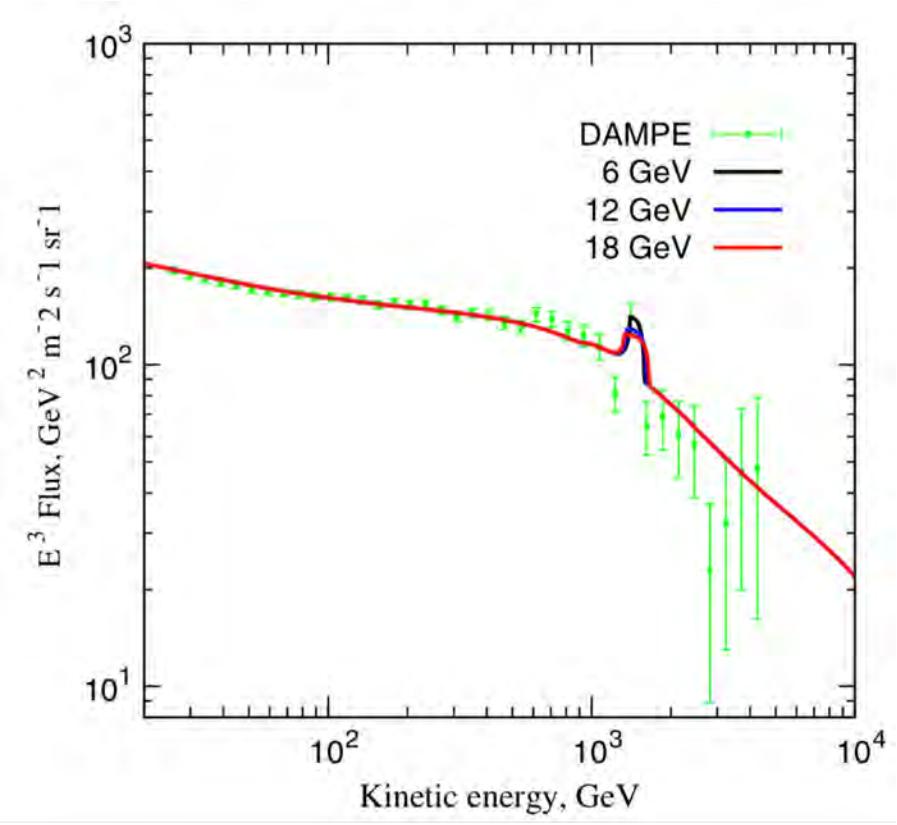
As what we did in previous section, we explore the parameter space of the nonminimal framework $G_{\rm SM}\times U(1)_{Y'}\times U(1)_{Y''}$ to interpret the DAMPE peak. First, we set $\lambda_{\{\chi,s,d\},H}=\lambda_{\phi_\chi}=\lambda_{\chi s}=\lambda_{\chi d}=\lambda_{sd}=0$, $g_{Y'}=0.1$ to simplify our analysis and also to ensure that the H-dominated CP-even scalar acts as the SM Higgs boson. Then, we scan the parameter space

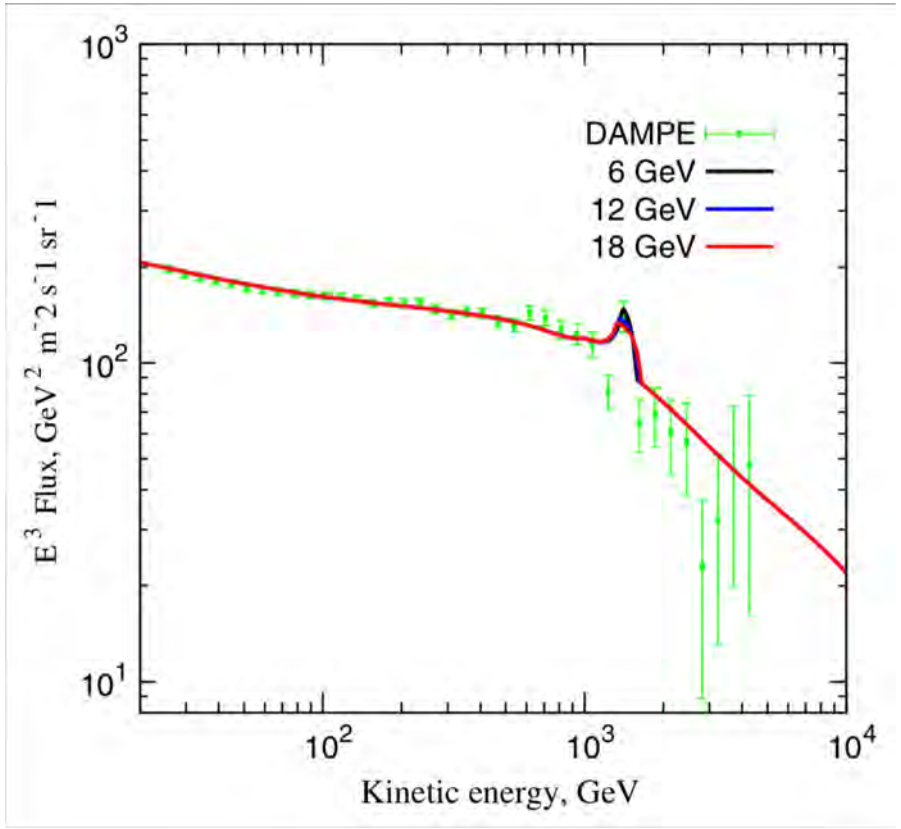
$$0\le\lambda_{\phi_s},\quad \lambda_{\phi_d},\quad g_{Y''},$$
$$\varepsilon\le 1,\quad 2.9\ \text{TeV}\le m_{\phi_\chi}\le 3.1\ \text{TeV},$$
$$6(2)\ \text{TeV}\le v_s(v_d)\le 10(5)\ \text{TeV}$$

with the following requirements:

$$m_\chi\in(3000\pm 10)\ \text{GeV},\qquad m_{Z''}\in(2.7,3)\ \text{TeV},$$
$$m_{\phi_{R,s}},m_{\phi_{R,d}}>3\ \text{TeV},\qquad m_{Z'}>4\ \text{TeV},$$
$$\Omega_\chi h^2\in 0.1187\pm 0.01198,\qquad \langle\sigma v\rangle_0\gtrsim 1\times 10^{-26}\ \text{cm}^3/\text{s}.$$

e^+e^- spectrum





The top panel corresponds to the choice $\langle\sigma v\rangle_0 = 3.2 \times 10^{-26}$ cm^3 s^{-1}, $M_{\rm Halo} = 1.9 \times 10^7$ m$_\odot$ (the subhalo mass), and $l = 0.1$ kpc (the distance of the subhalo away from our solar system), while the bottom panel corresponds to $\langle\sigma v\rangle_0 = 1.2 \times 10^{-26}$ cm^3 s^{-1}, $M_{\rm Halo} = 3.0 \times 10^8$ m$_\odot$, and $l = 0.2$ kpc.