Probing the **chirality** of dark matter at colliders with dark photon showering

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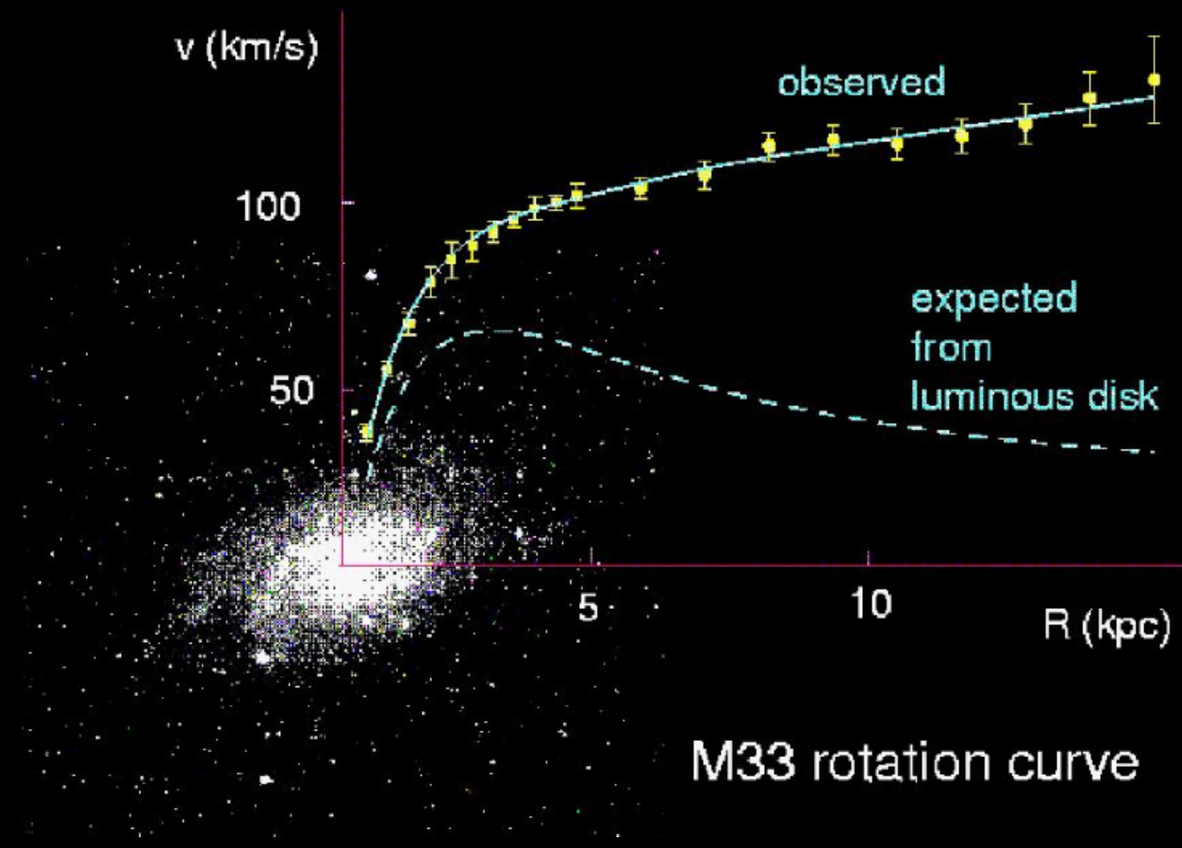
Based on arXiv:1612:02850
with Mengchao Zhang, Minho Kim and Hye-Sung Lee

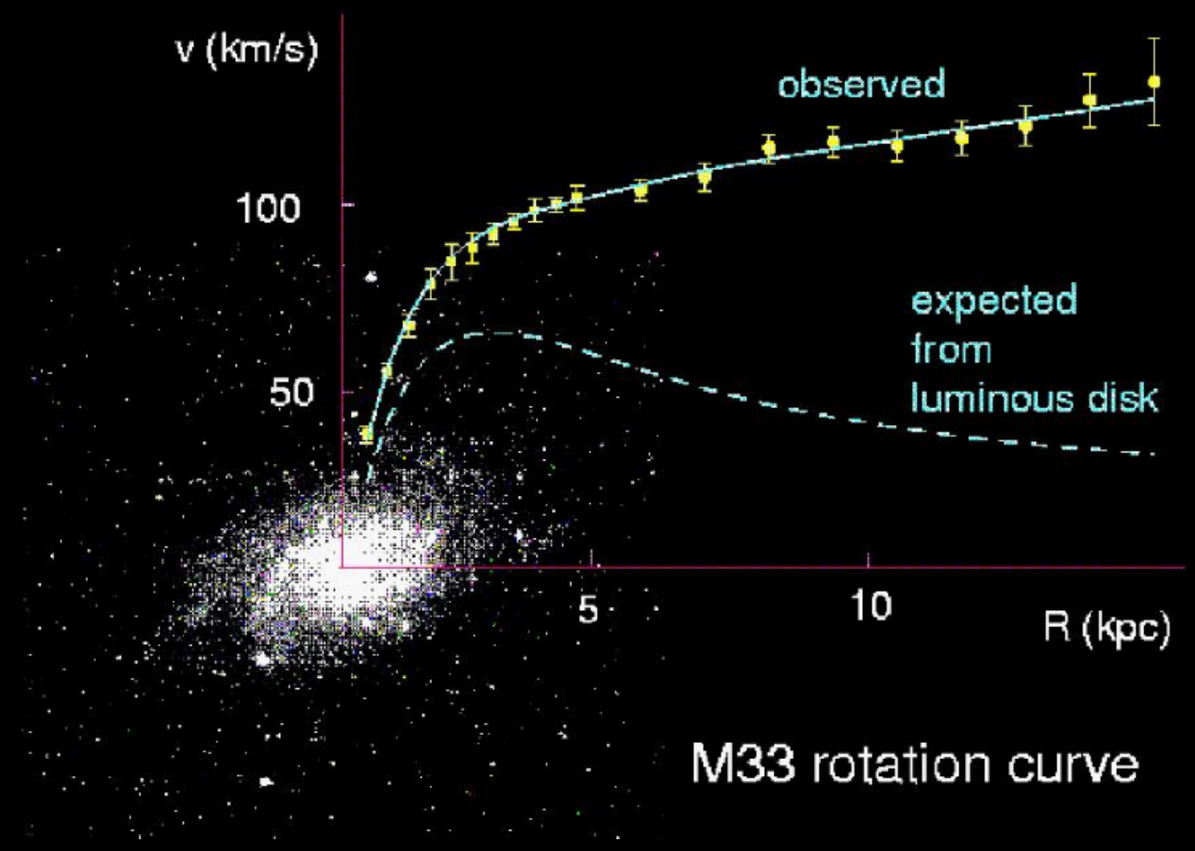
MC4BSM 2017

Dark Matter is neutral



- We know that we **can not** see dark matter directly

Dark Matter is neutral

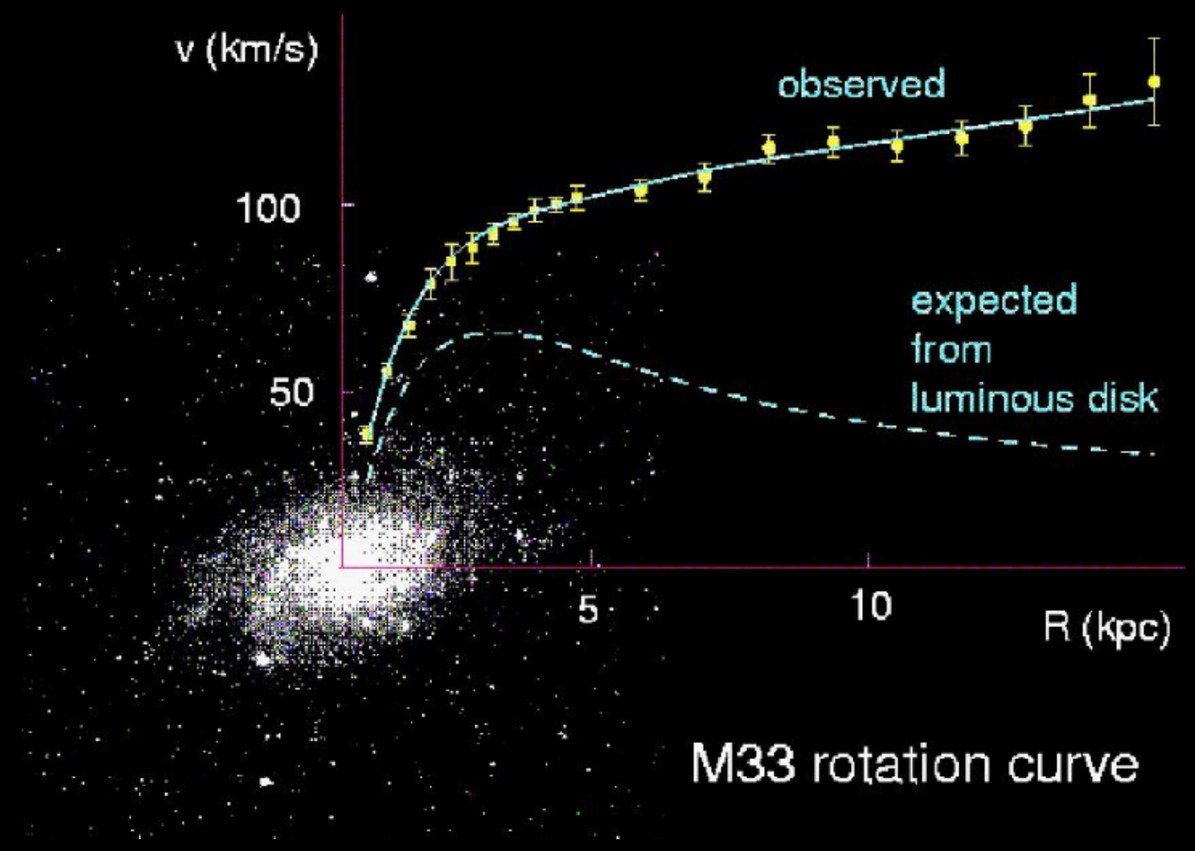


M33 rotation curve

- We know that we **can not** see dark matter directly

- Dark Matter is **Neutral** under **Standard Model $U(1)_{EM}$**

Is Dark Matter neutral under …?



- We know that we **can not** see dark matter directly

- Dark Matter is Neutral under Standard Model $U(1)_{EM}$

- But it **does not** mean that Dark Matter is neutral under "**Dark Photon**"

- What would be the **phenomenological consequences** of “dark charged” dark matter ?

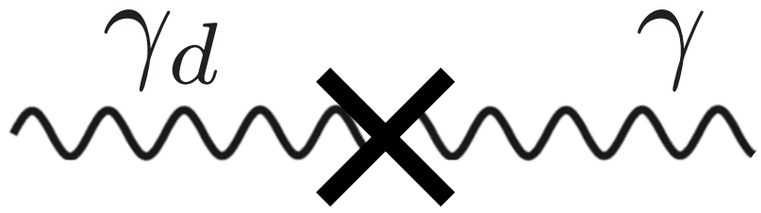
- How we can **check** whether dark matter is “dark charged” or not.

DM with dark charge

- Dark matter may have a dark-U(1) charge (good to have proper relic density)

- dark-U(1) can mix with SM U(1)-hyper through a Gauge-kinetic mixing : Gauge-invariant term

$$\mathcal{L} \ni \epsilon F'_{\mu\nu} F_Y^{\mu\nu}$$

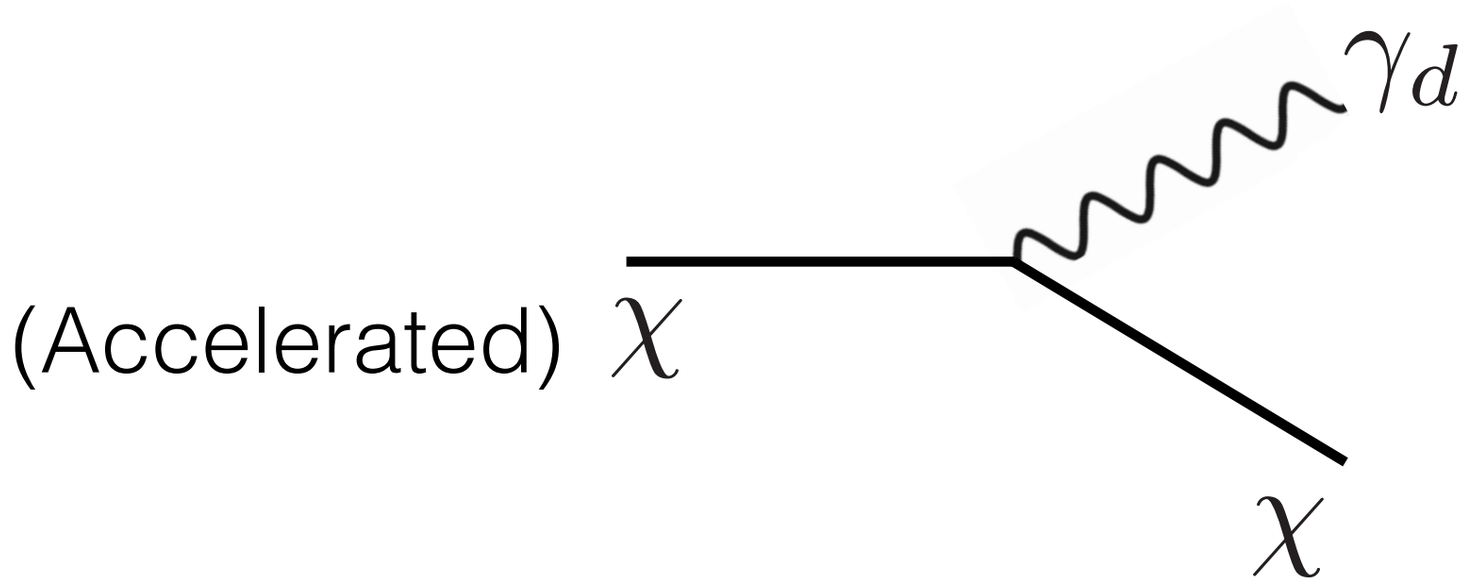


- If dark-U(1) is massless (unbroken), then a dark matter can have a milli-charged under SM U(1)

- If dark-U(1) is massive, dark matter would be totally neutral under SM U(1) (Holdom 1986)

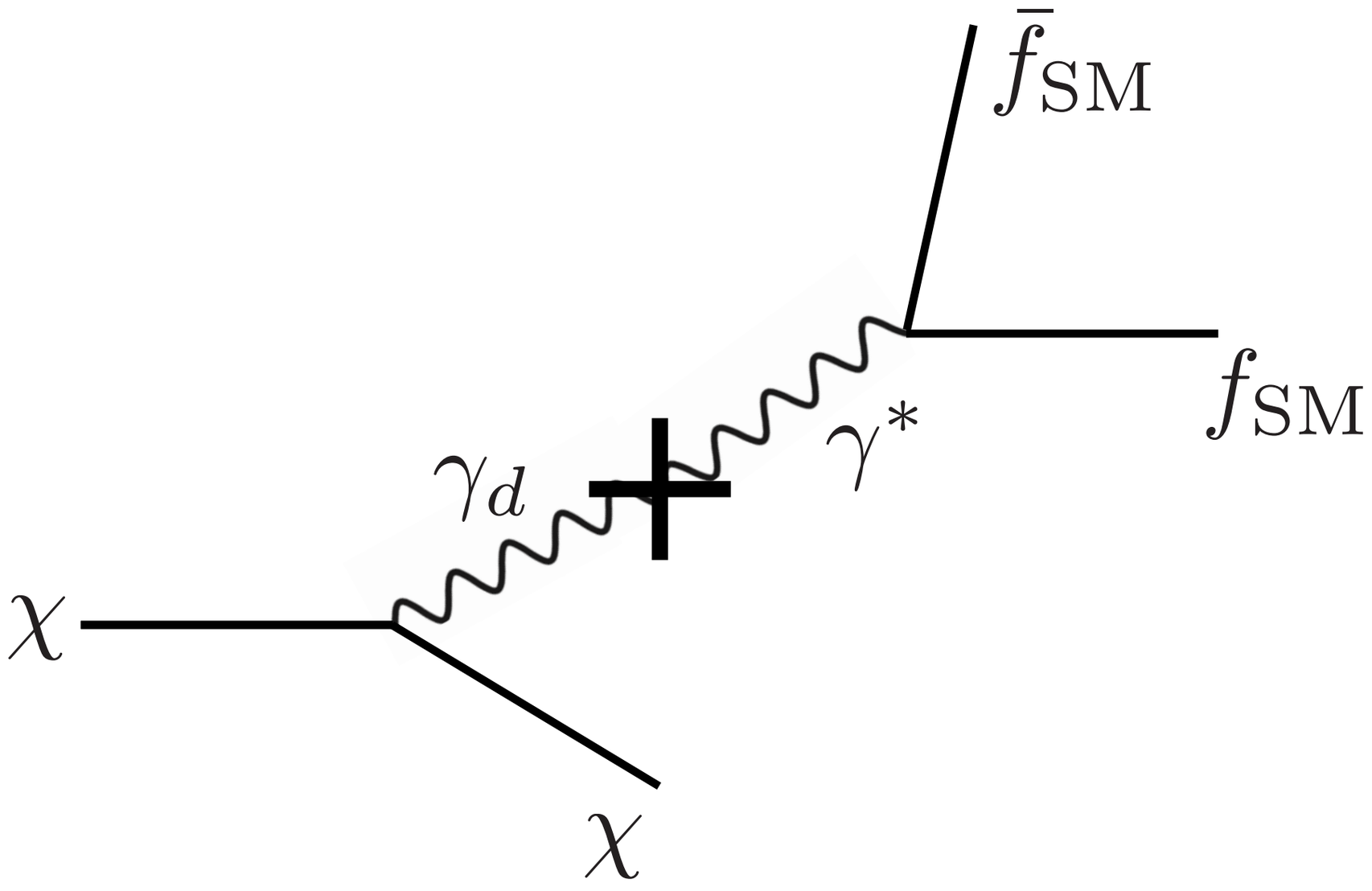
How can we observe?

- **Dark Showering**

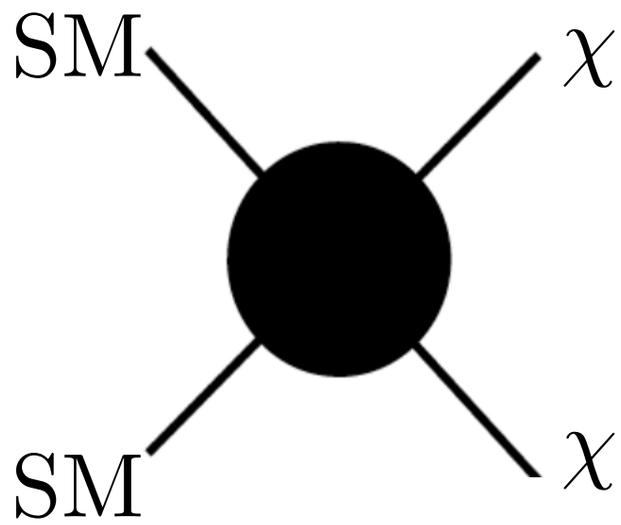


How can we observe?

- **Dark Showering, decaying back to SM**



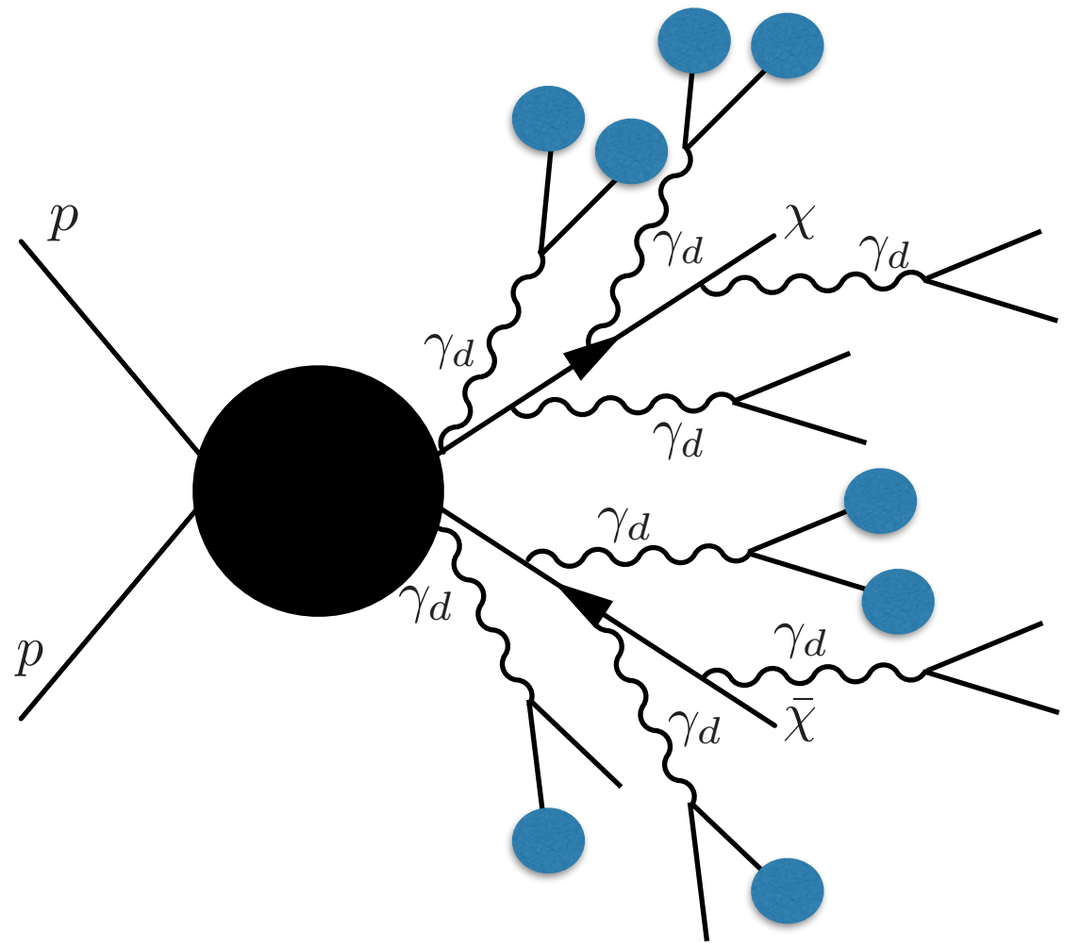
Energetic DM @ Colliders



TeV **(sub) GeV**

- **Radiations** from **Energetic** “dark charged” particles will acquire certain level of energy, enough to be “**tagged**” (detectable effect)

Energetic DM @ Colliders

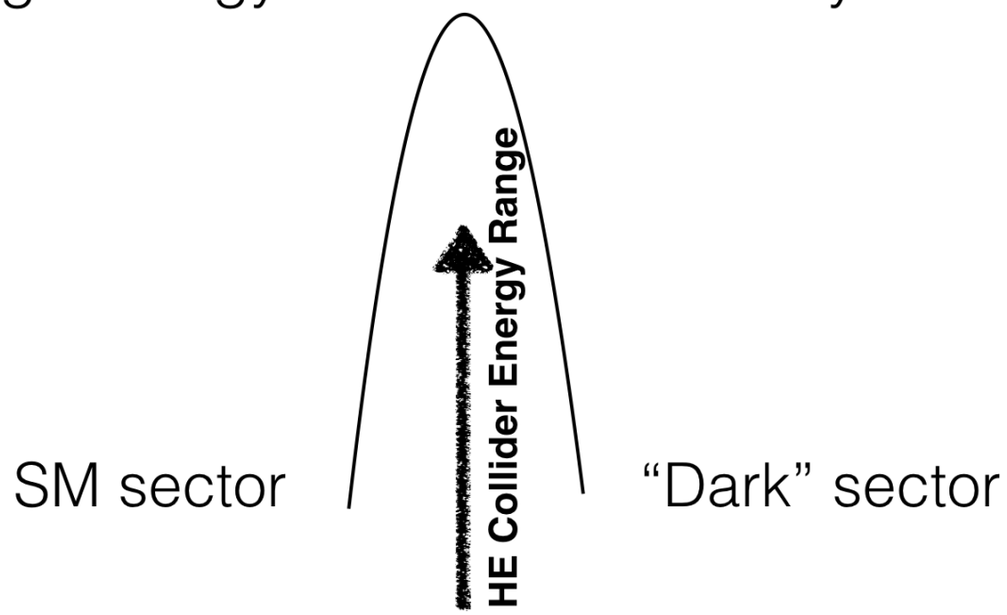


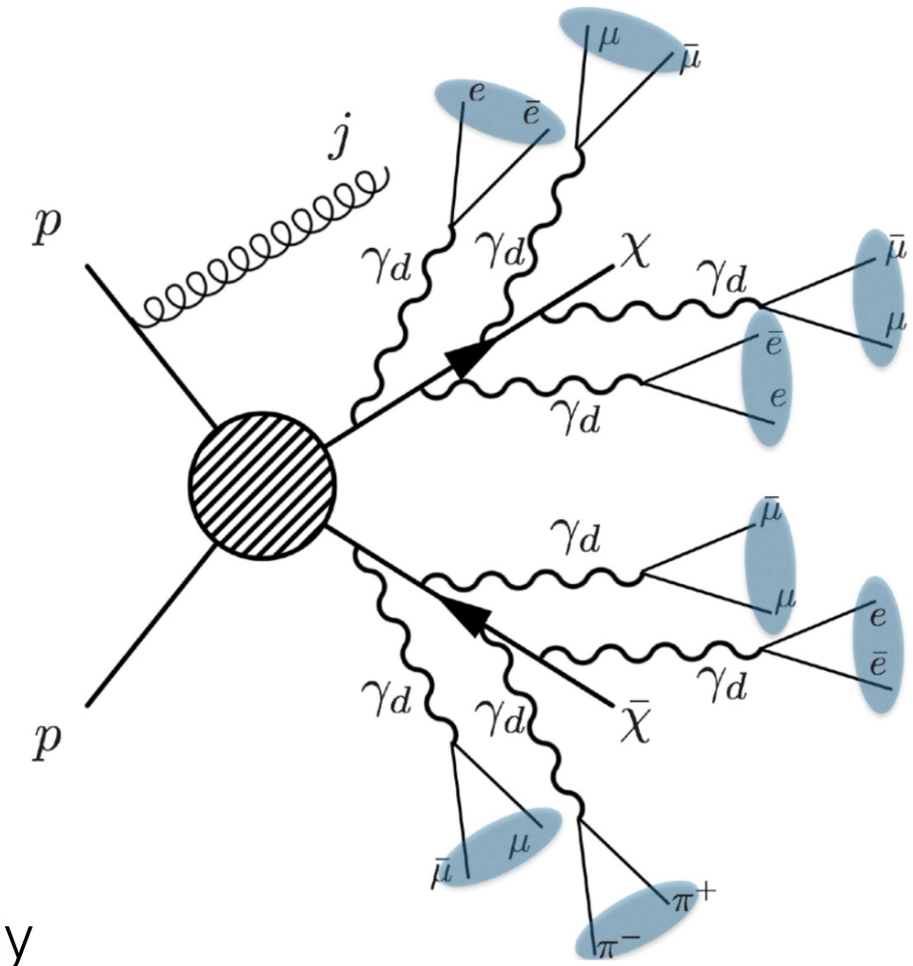
- **Radiations** from **Energetic** “dark charged” particles will acquire certain level of energy, enough to be “**tagged**” (detectable effect)

Energetic DM @ Colliders

- At Collider, we can BOOST dark matters
  (1). Hard recoil from High PT ISR jet

High Energy Barrier from a Heavy mediator

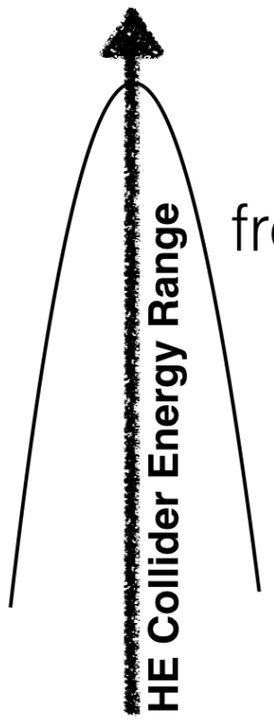




A Collider can not produce a mediator directly
(Effective operator)

Energetic DM @ Colliders

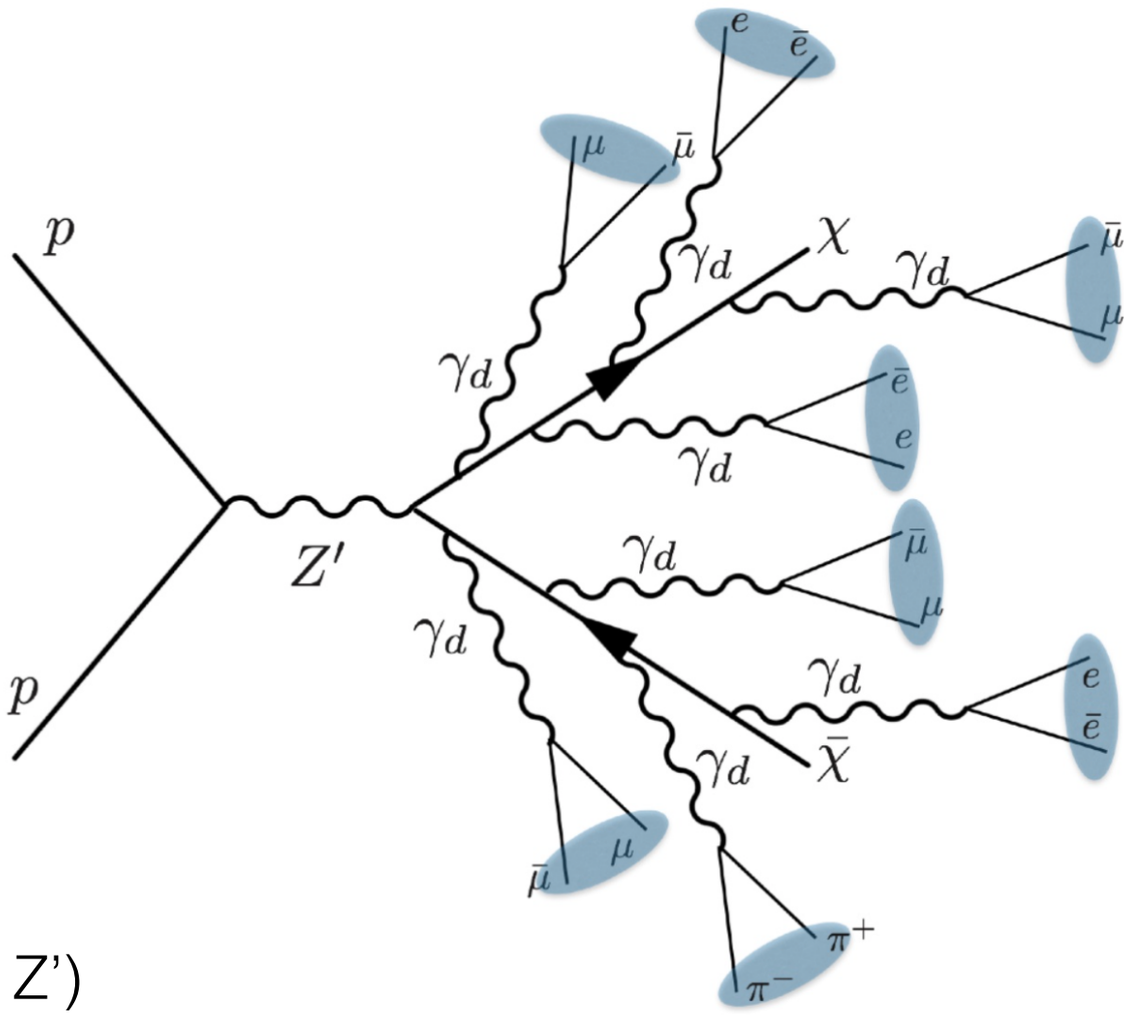
- At Collider, we can BOOST dark matters
  (2). Hard back-to-back boost from a heavy mediator



High Energy Barrier
from a Heavy mediator

SM sector

“Dark” sector

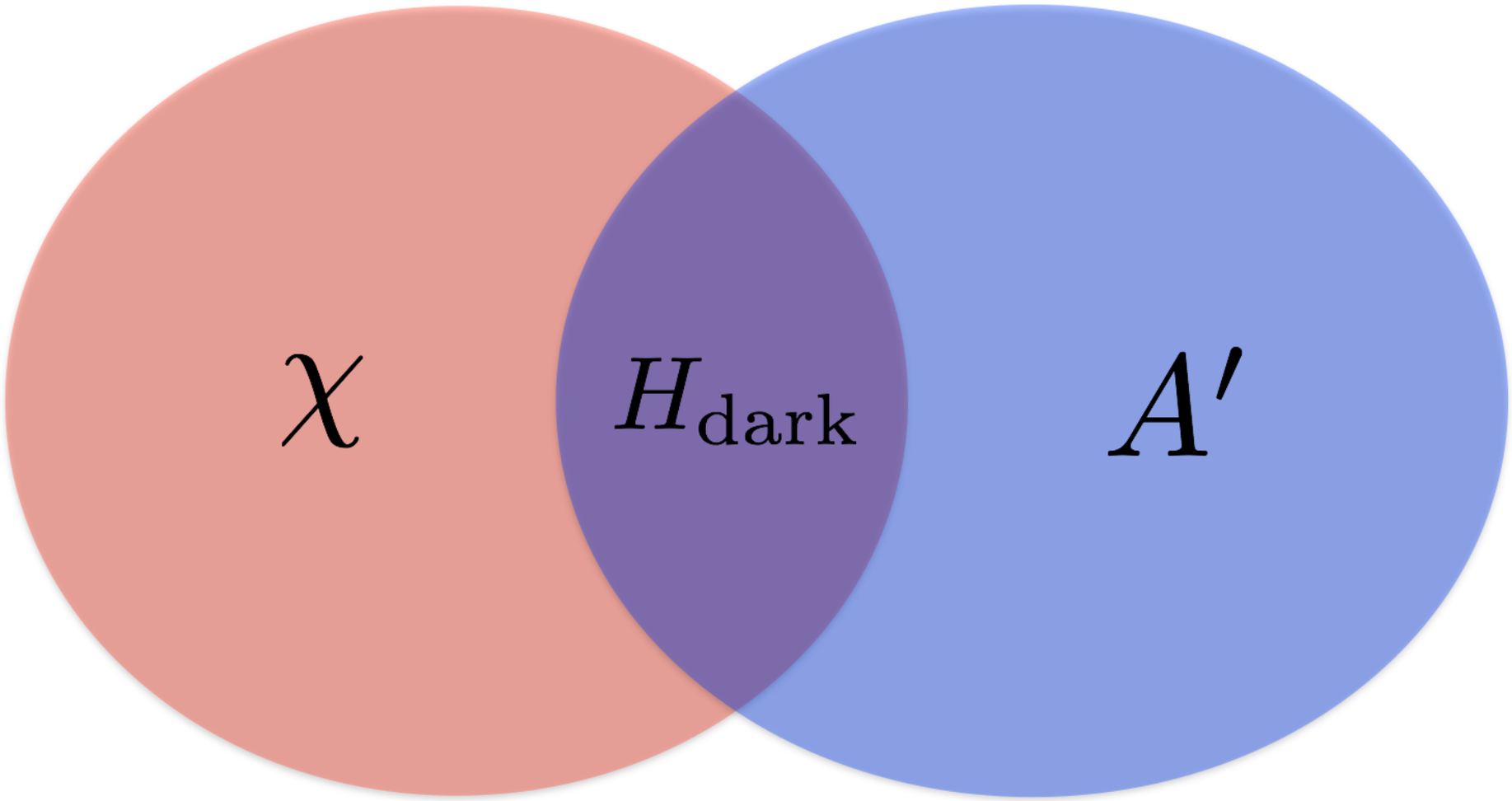


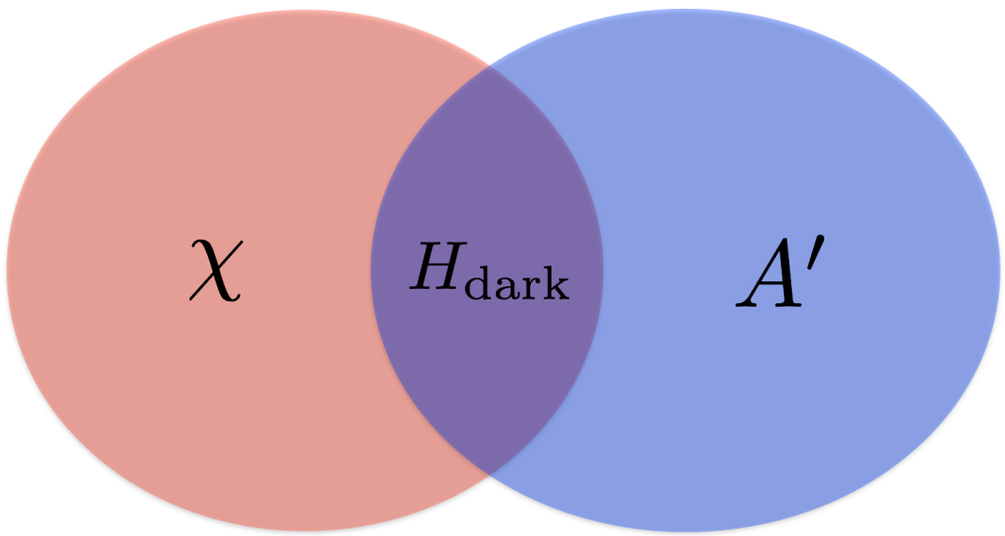
Collider can produce a massive mediator (here Z’)

Can we do more than tagging ?

More than observing
a dark charged particle

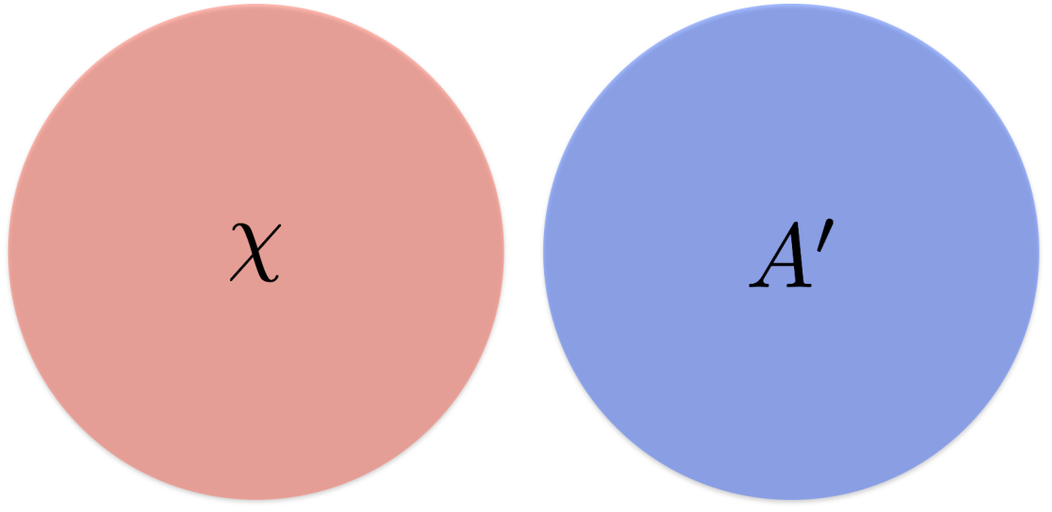
Do dark matter and a dark-photon **share** the same **origin** for their **mass**?





dark matter and dark-photon
share the same origin for their mass

dark matter and dark-photon
have their own mass mechanism



Can we see difference @ LHC ?

Case of a vector-like DM

- Malte Buschmann et.al, (arXiv:1505.07459)

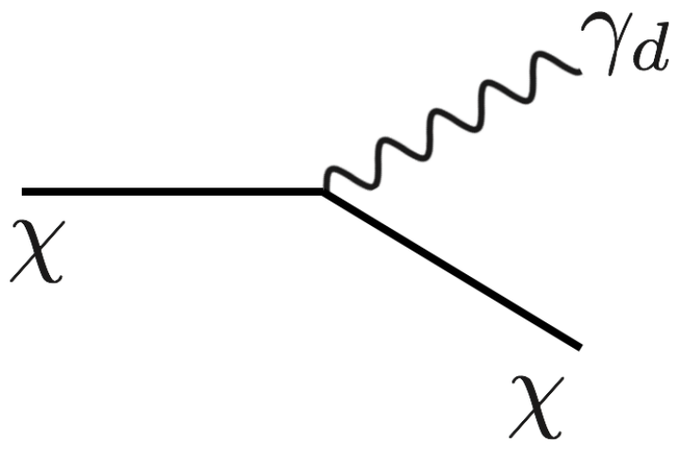
$$\mathcal{L}_{\text{dark}} \equiv \bar{\chi}(i\partial\!\!\!/ - m_\chi + i g_{A'} A\!\!\!/')\chi - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m^2_{A'} A'_\mu A'^\nu - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

- vector-like

- Higgs or Stueckelberg

Differential probability of a splitting process

$$\propto \frac{\alpha'}{2\pi} \mathrm{d}x \frac{\mathrm{d}t}{t} P_{\chi \to \chi\, \gamma_d}(x,t)$$



With $x = \frac{E_{\chi,\text{out}}}{E_{\chi,\text{in}}}$

Splitting function

$$P_{\chi \to \chi\gamma_d}(x,t) \simeq Q'^2_V \frac{1+x^2}{1-x}$$

-Splitting kernel contains only transverse modes in a HE limit
(This is also the Hidden Valley shower implemented in Pythia8)

DM, dark gauge boson and a Dark Higgs

A'_μ	Φ	χ_L	χ_R	ψ_L	ψ_R
	Q'_Φ	$Q'_{\chi L}$	$Q'_{\chi R}$	Q'_{ψ_L}	Q'_{ψ_R}

$$\mathcal{L}_{\text{matter}} \ni -g' Q'_V A'_\mu \bar{\chi} \gamma^\mu \chi - g' Q'_A A'_\mu \bar{\chi} \gamma^\mu \gamma_5 \chi$$

$$Q'_A = \tfrac{1}{2}(Q'_{\chi R} - Q'_{\chi L}) = \frac{Q'_\Phi}{2}$$

$$Q'_V = \tfrac{1}{2}(Q'_{\chi R} + Q'_{\chi L}) = \frac{Q'_\Phi}{2} + Q'_{\chi L}$$

$$\mathcal{L} \ni y_\chi \bar{\chi}_L \Phi^* \chi_R + h.c.$$

Thus we always have the axial coupling between DM and a Dark photon

if a dark photon and dark matter share the origin of mass

Extra contribution

- A dark Higgs $\Phi = \frac{1}{\sqrt{2}}(\phi_1 + i\,\phi_2)$

  with $\phi_1 = v_s + h_D \quad , \; \phi_2 = \varphi$

$$\mathcal{L}_{\rm matter} \quad \ni \quad \overline{\chi}(i\partial\!\!\!/ - m_\chi)\chi - g' A_\mu \overline{\chi}(Q'_{\chi_L}\gamma^\mu P_L + Q'_{\chi_R}\gamma^\mu P_R)\chi$$

$$-\frac{1}{2}A'_\mu\left(-g^{\mu\nu}\partial^2 + (1-\frac{1}{\xi})\partial^\mu\partial^\nu - m^2_{\gamma_d}g^{\mu\nu}\right)A'_\nu$$

$$-iy\frac{\varphi}{\sqrt{2}}\overline{\chi}\gamma^5\chi + \frac{1}{2}(\partial_\mu\varphi)^2 - \frac{\xi}{2}m^2_{\gamma_d}\varphi^2 + \cdots .$$

Longitudinal mode ~ Goldstone + $\mathcal{O}\left(\frac{m_{\gamma_d}}{E}\right)$

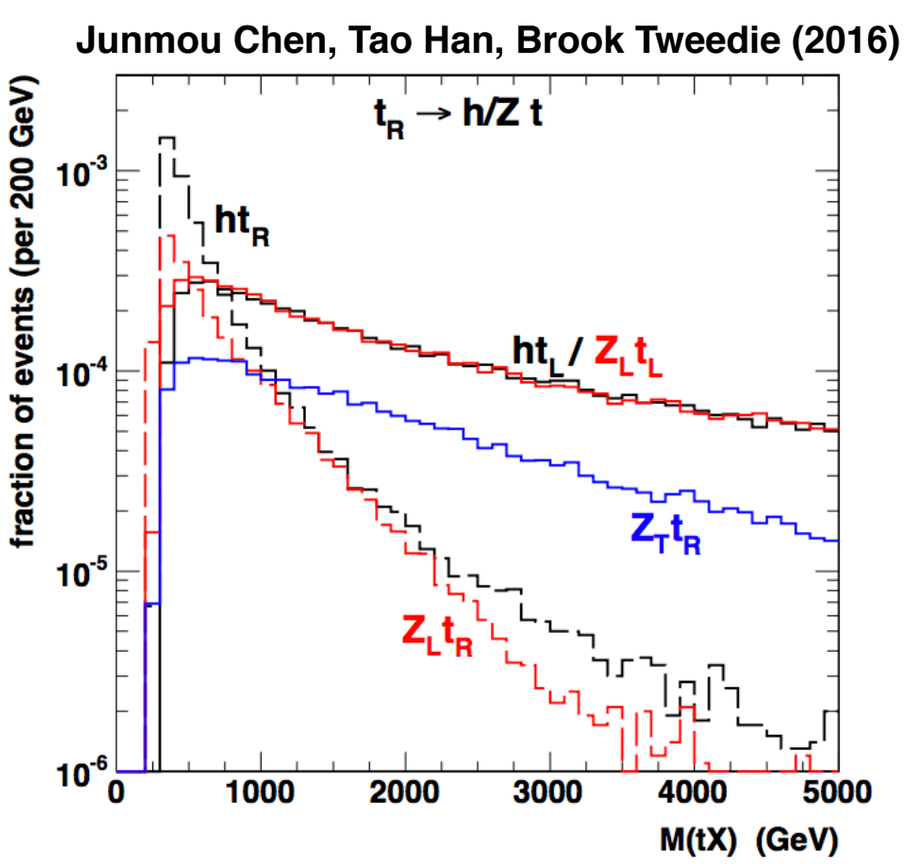
Andrea Wulzer (arXiv:1309.6055)

Lesson from SM (Tame the longitudinal polarization)

- Goldstone Equivalence Gauge (arXiv:1611.00788) by Junmou Chen, Tao Han, Brook Tweedie

Talk by Junmou in other session after my time :)

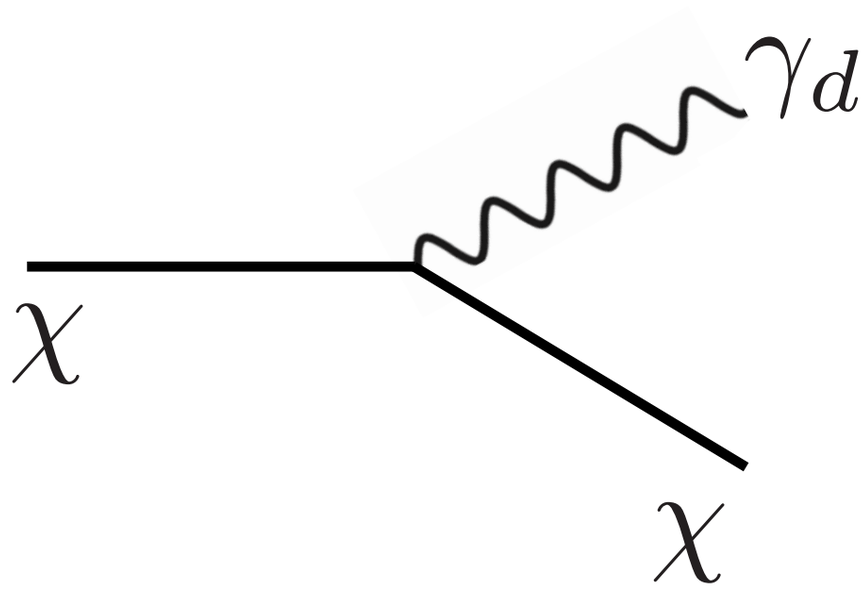
- No bad longitudinal polarization behavior ~ E/m at the level of individual Feynman diagrams



Goldstone boson Equivalent (GET) show the growth single-logarithmically with energy

$$\mathcal{P}(t_R \to h t_L) \simeq \mathcal{P}(t_R \to Z_L t_L)$$

Additional Showering process



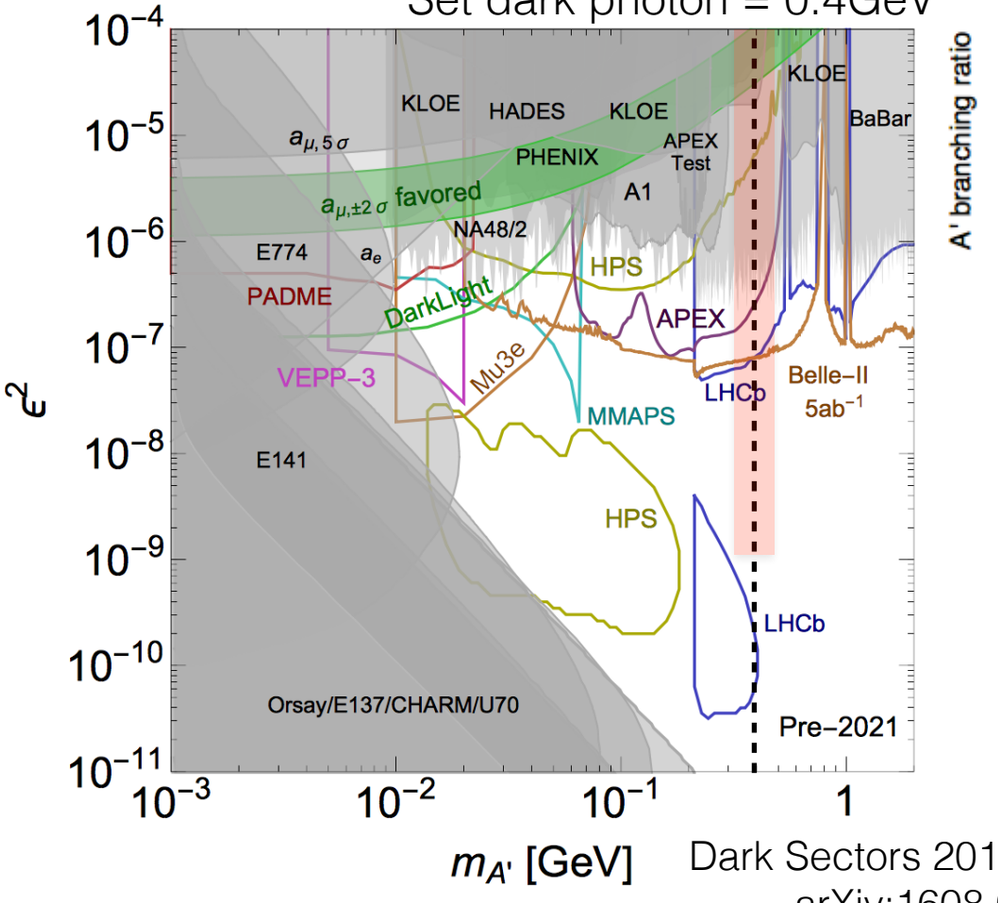
- In a **chiral** case, the **longitudinal** component of a dark photon couples to a dark matter

$$P_{\chi\to\chi\gamma_d}(x,t) \simeq \left(Q'^2_V + Q'^2_A\right)\frac{1+x^2}{1-x} + 2Q'^2_A\,\frac{m^2_\chi}{m^2_{\gamma_d}}$$

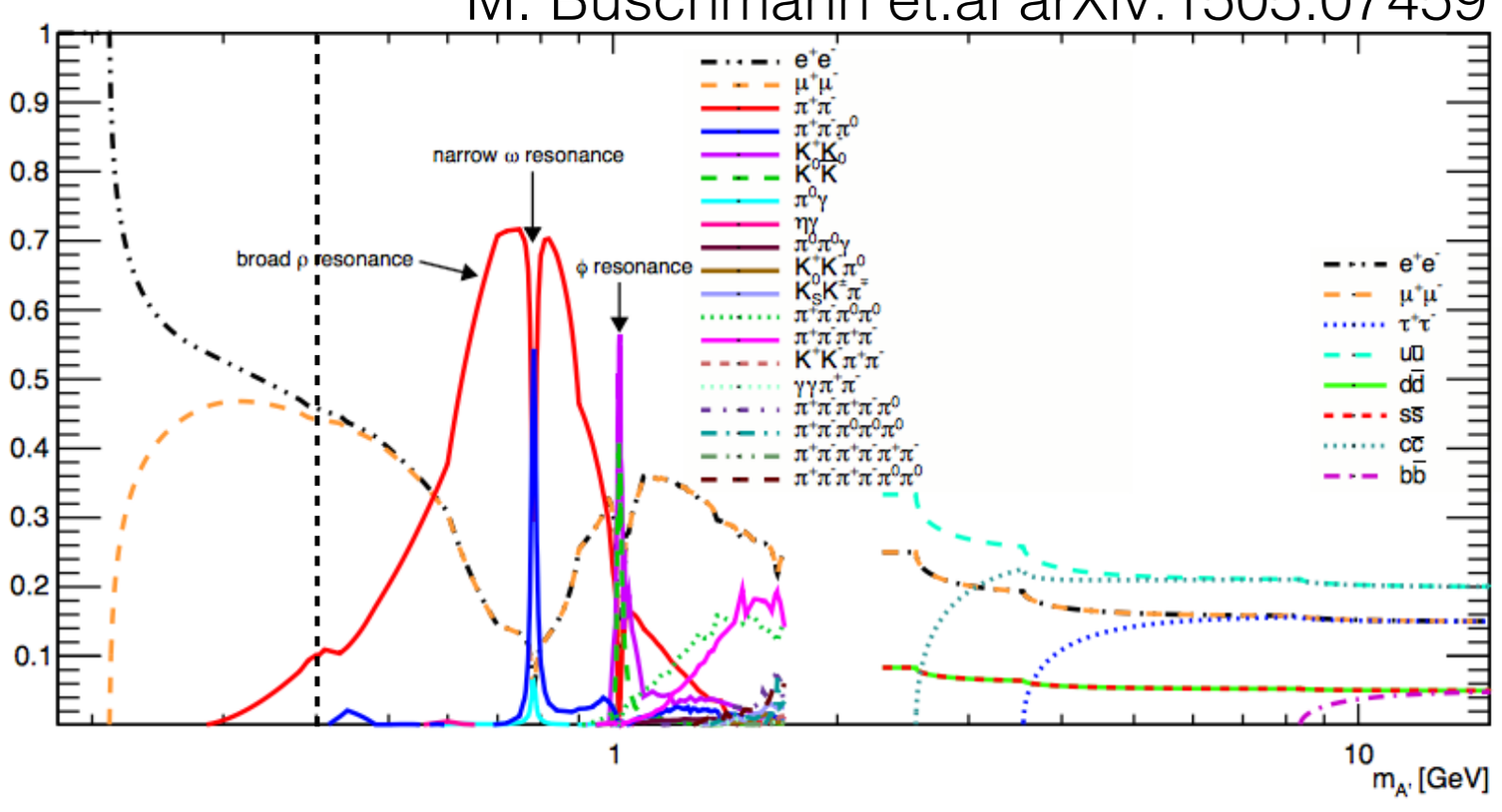
Benchmark points

- We choose a bench mark point for
  - the prompt decays of a dark photon
  - Non-negligible decay mode into muons-pair to tag!

Set dark photon = 0.4GeV



M. Buschmann et.al arXiv:1505.07459



Dark Sectors 2016 Workshop
arXiv:1608.08632

Benchmark points

- As dark matter and dark photon gets the mass from dark Higgs

$$m_{\gamma_d} = g' Q'_\phi v_s$$

$$m_\chi = y_\chi v_s / \sqrt{2}$$

$$\downarrow$$

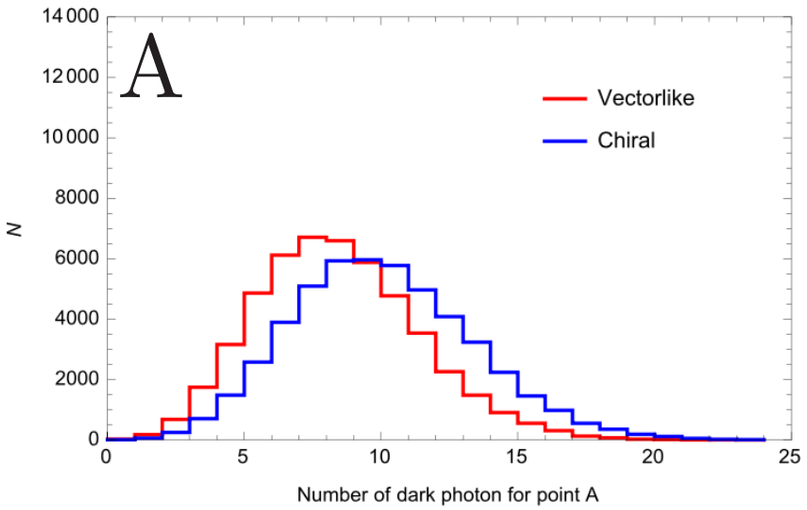
$$\left(y_\chi/\sqrt{2}\right)^2 \lesssim 4\pi$$

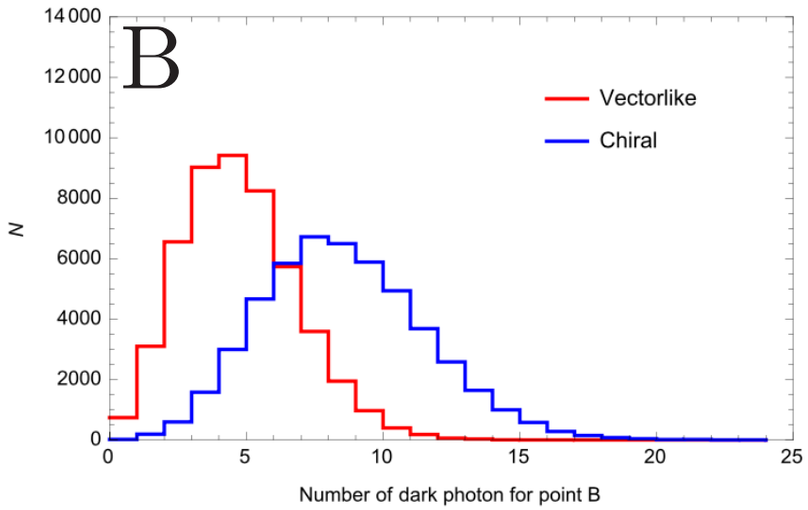
$$\alpha' \frac{m_\chi^2}{m_{\gamma_d}^2} \lesssim 1$$

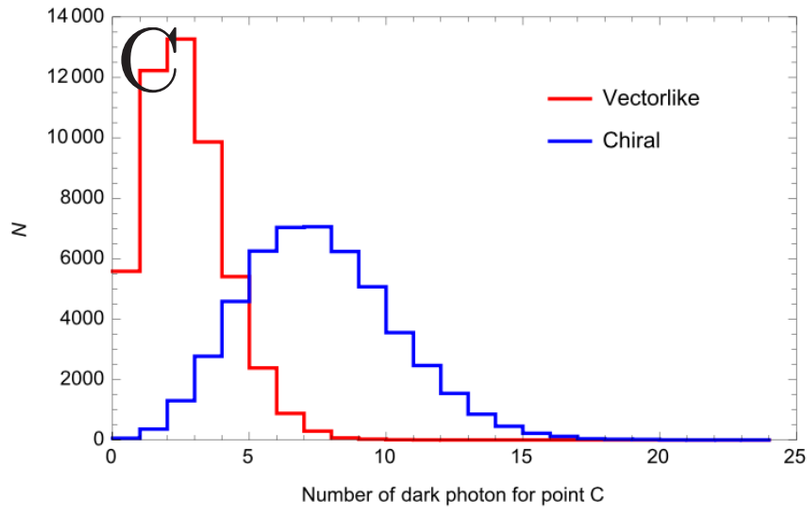
Different showering pattern @ collider

Benchmark Points (BP)	A	B	C
α'	0.3	0.15	0.075
$m_\chi\,(\mathrm{GeV})$	0.7	1.0	1.4
$m_{\gamma_d}\,(\mathrm{GeV})$	0.4		

Vector : (Q'L, Q'R) = (1,1)
Chiral: (Q'L, Q'R) = (1,0)







$(\alpha' << 1)$ limits

From

$$P_{\chi\to\chi\gamma_d}(x,t) \simeq \left(Q_V'^2 + Q_A'^2\right)\frac{1+x^2}{1-x} + 2Q_A'^2\,\frac{m_\chi^2}{m_{\gamma_d}^2}\quad,\quad \alpha'\,P_{\chi\to\chi\gamma_d} \sim \frac{m_{\gamma_d}^2}{v_s^2}\,\frac{m_\chi^2}{m_{\gamma_d}^2} \sim y_\chi^2$$

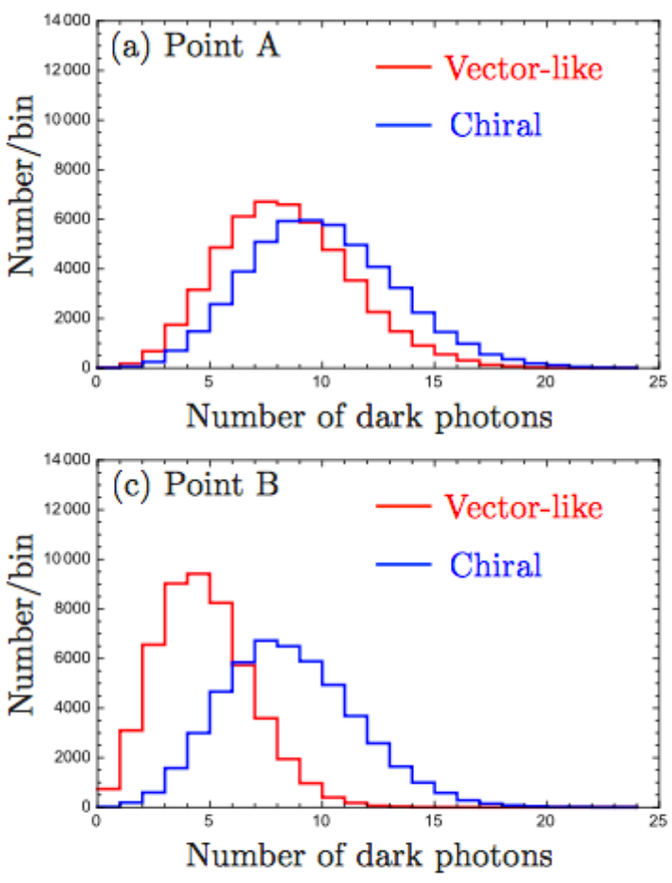
Quantify the difference

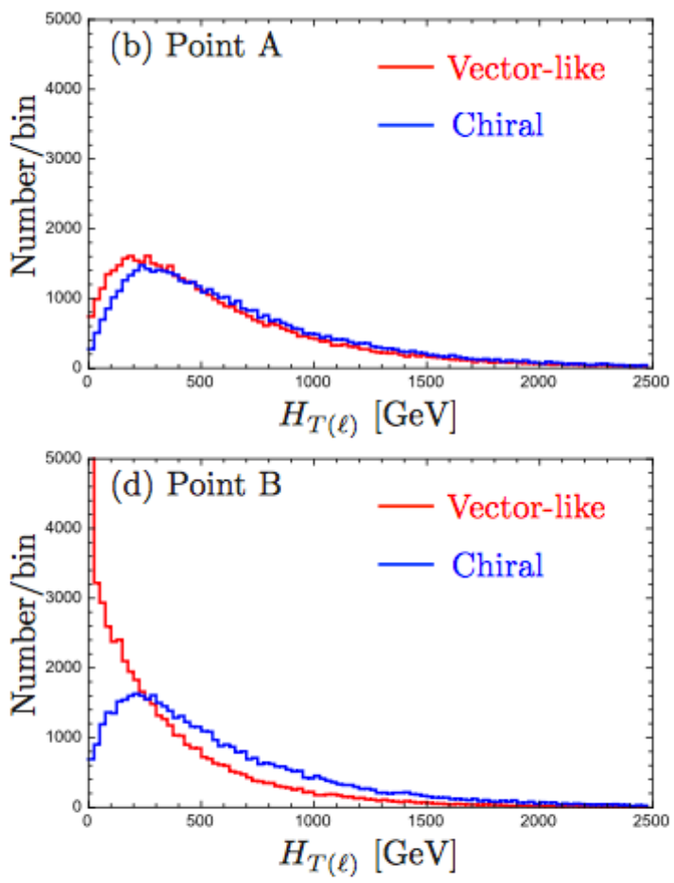
- We use the transverse energy deposits from leptonic decay modes

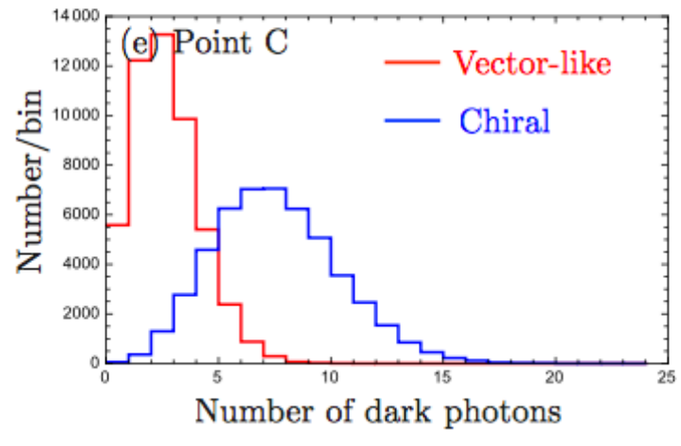
Benchmark Points (BP)	A	B	C
α'	0.3	0.15	0.075
m_χ (GeV)	0.7	1.0	1.4
m_{γ_d} (GeV)	0.4		

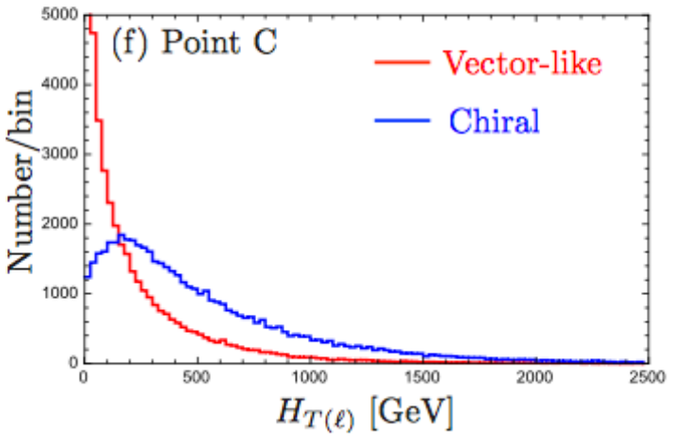
$$H_{T(\ell)} = \sum_{i=\mu^\pm, e^\pm} |p_{T\,i}|$$

-Due to GBET, the energy spectrum of leptons from a **longitudinal mode** is larger compared to the case of leptons from a transverse mode



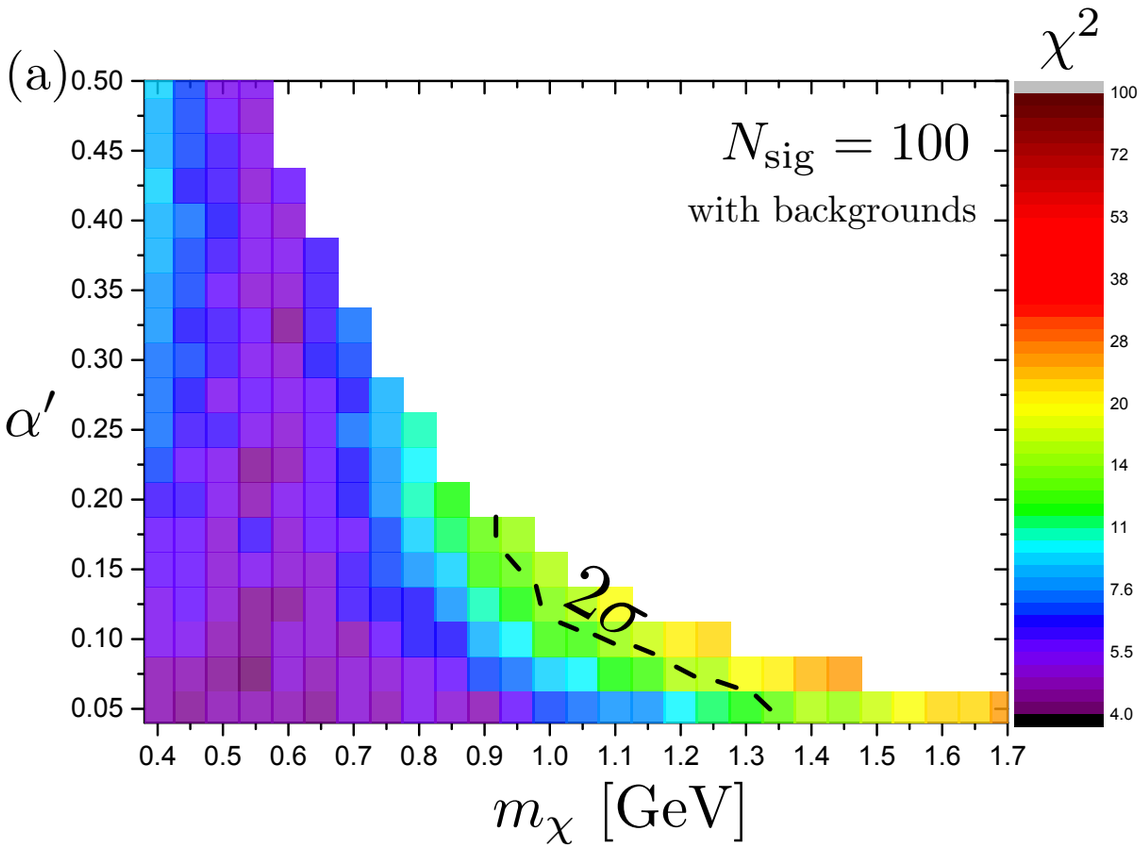


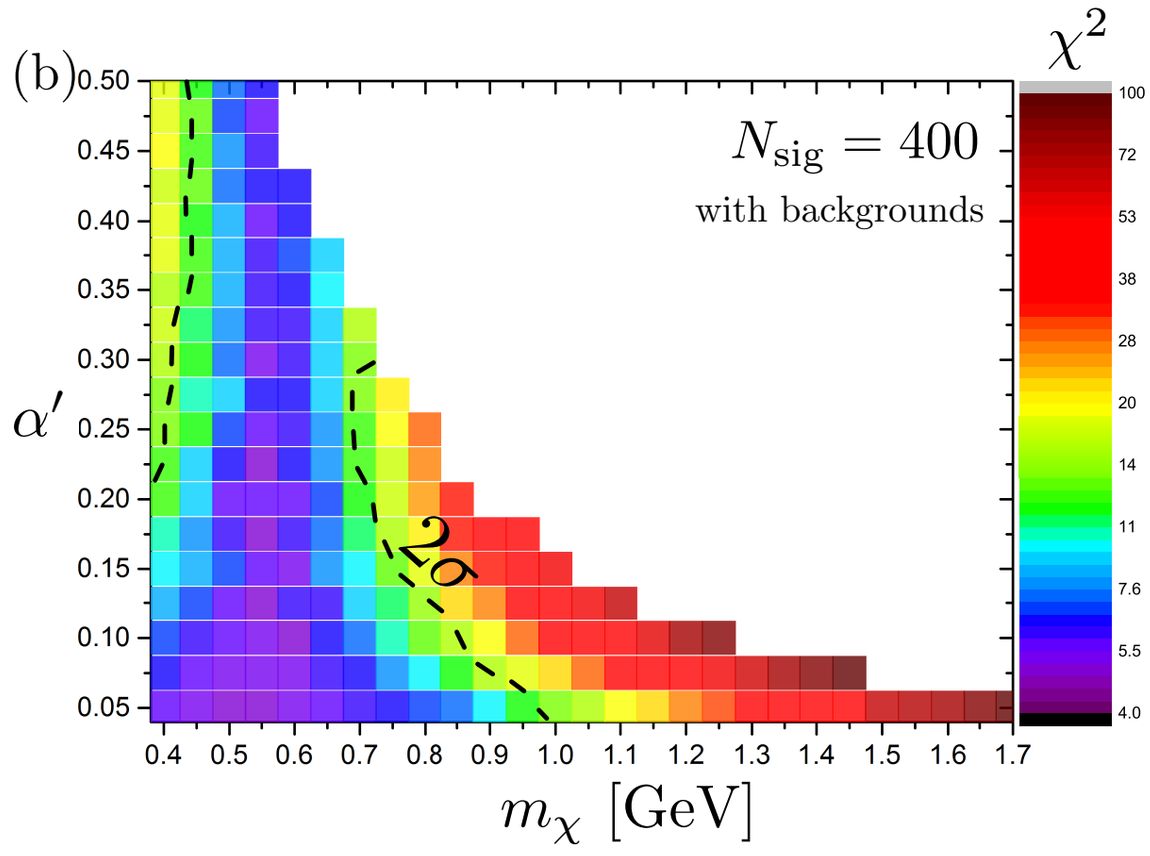




Checking chirality@ Collider

- After triggering signal events by tagging a collimated muon-jet (a jet only with muons)





with 100 , 400 signal events after cuts to reduce BKG

Number of BKG ~ O(1)

Conclusion

- High Energy Collider program is an **active** experiment
  - to find dark sector (dark matter).
  - to measure properties of a dark sector.

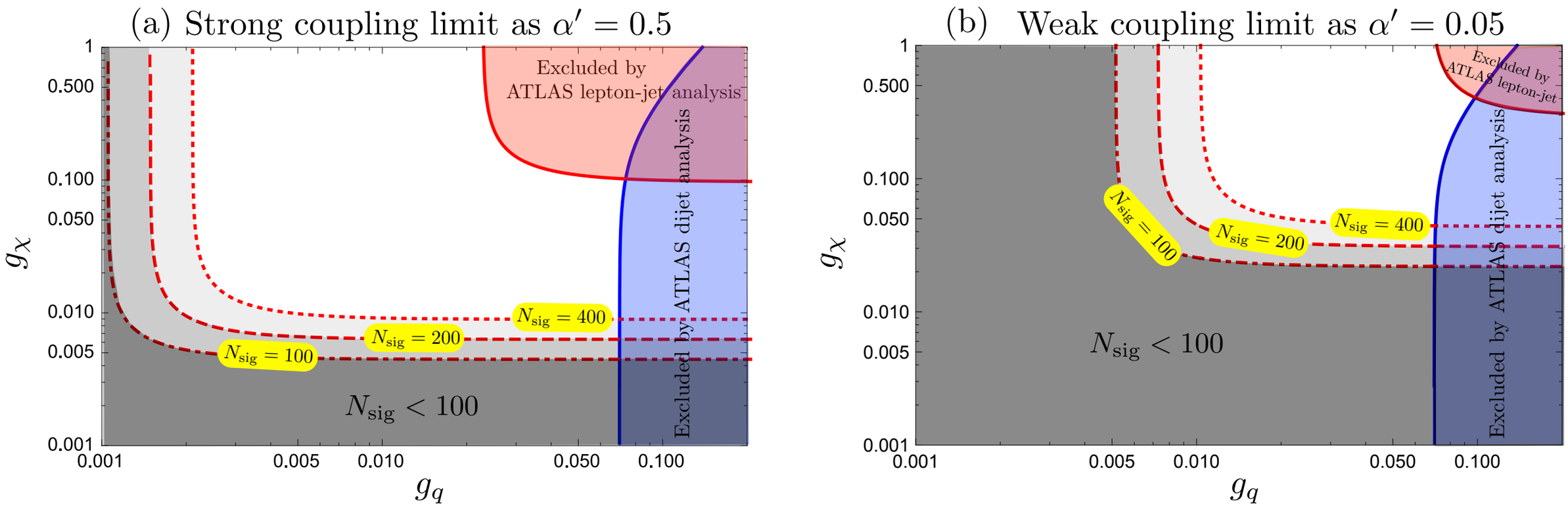
- The **mass origin** in dark sector (like SM-Higgs mechanism) can strongly affect the dark photon showering in “**Energetic**” dark matter.

- Collider can probe the nature of dark matter by examine the **pattern** of dark photon **showering**

Back up

Constraints from LHC

with $M_{Z'} = 1.5$ TeV and $m_{\gamma_d} = 0.4$ GeV



Benchmark case	α'	m_χ(GeV)	Model	ϵ_S(%)
(a) strong coupling limit	0.50	0.5	vector-like	3.68
(b) weak coupling limit	0.05	0.45	chiral	0.41