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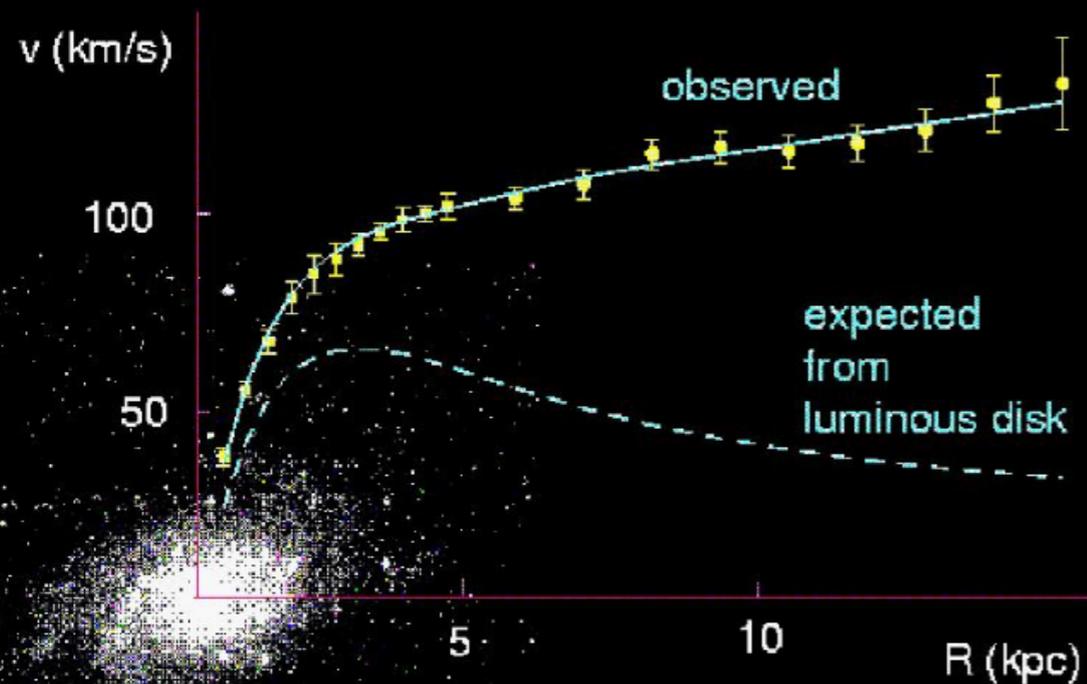
Myeonghun Park

ibS 기초과학연구원
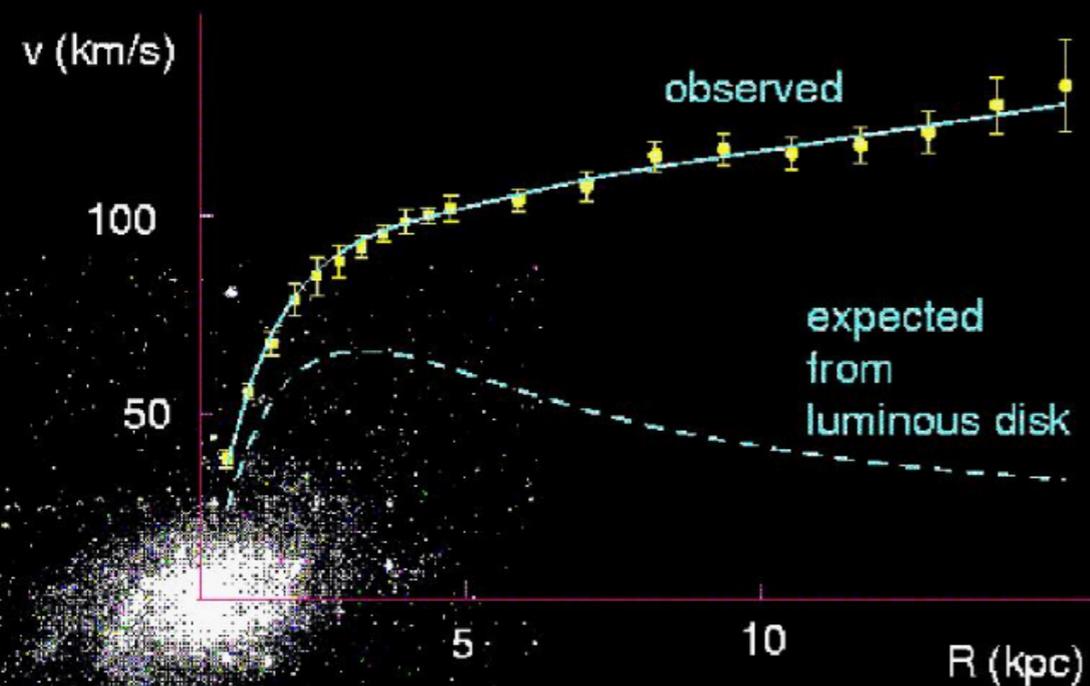Institute for Basic Science

Pheno 2017

Dark Matter is neutral

M33 rotation curve

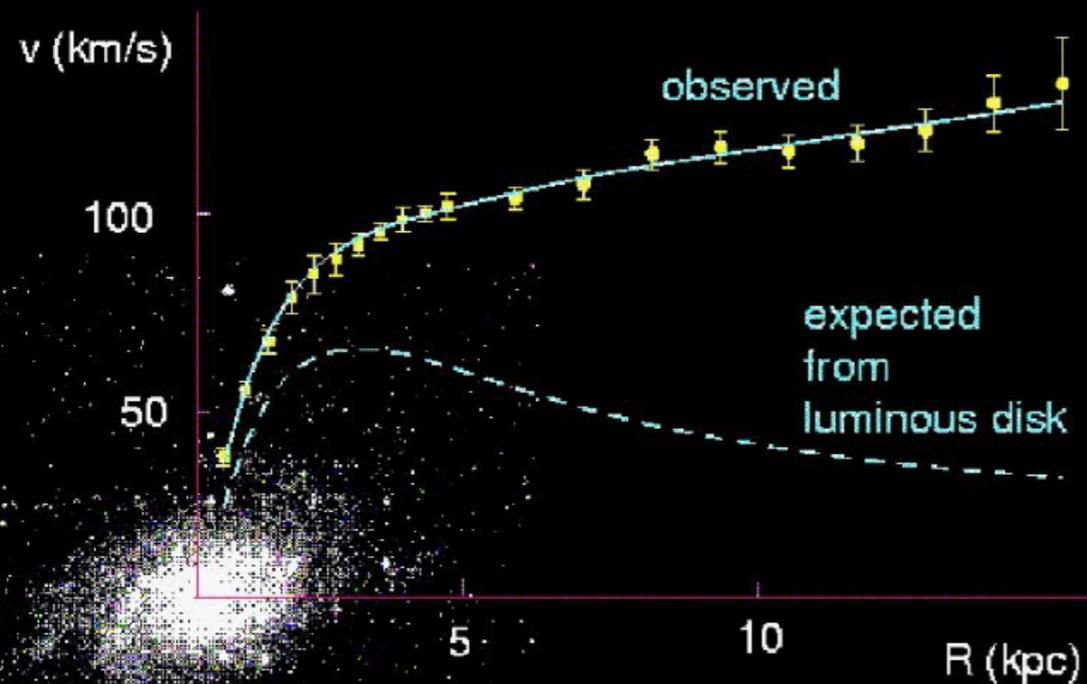- We know that we **can not** see dark matter directly

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)
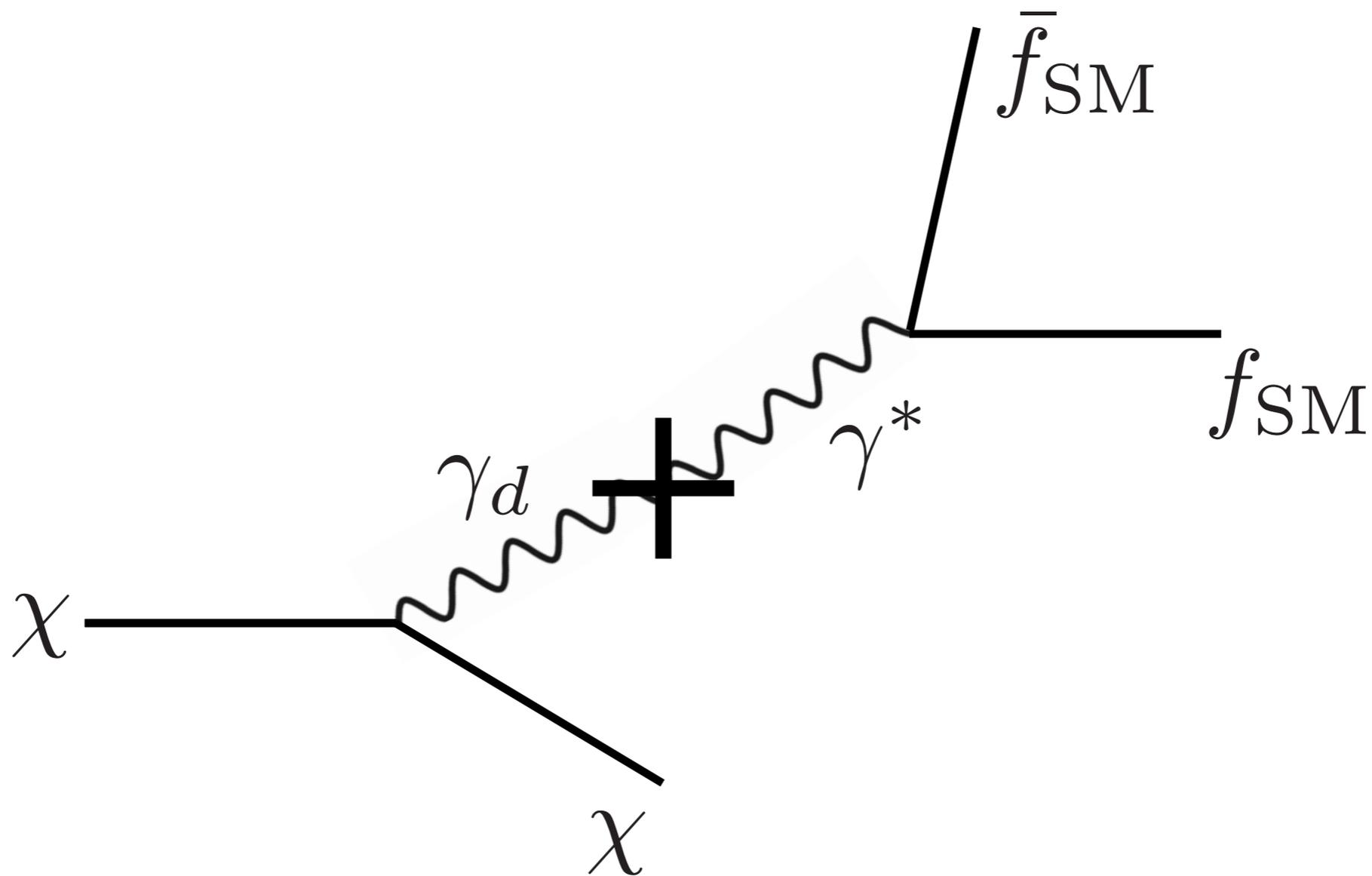
How can we observe?
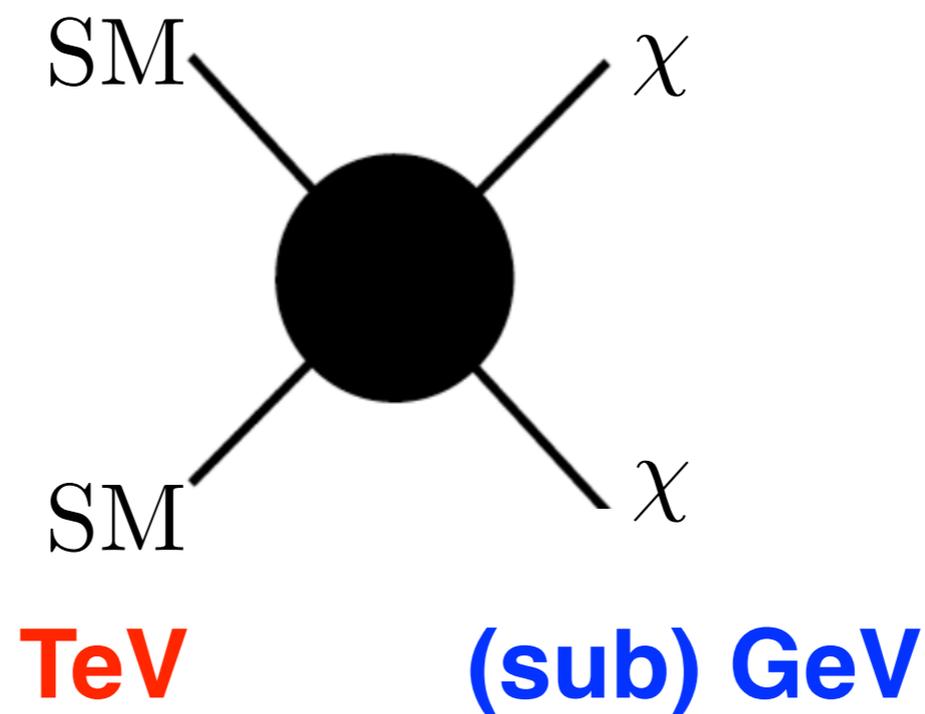
- **Dark Showering** (Dark Bremsstrahlung)

$$\gamma_d$$

(Accelerated) χ

χ
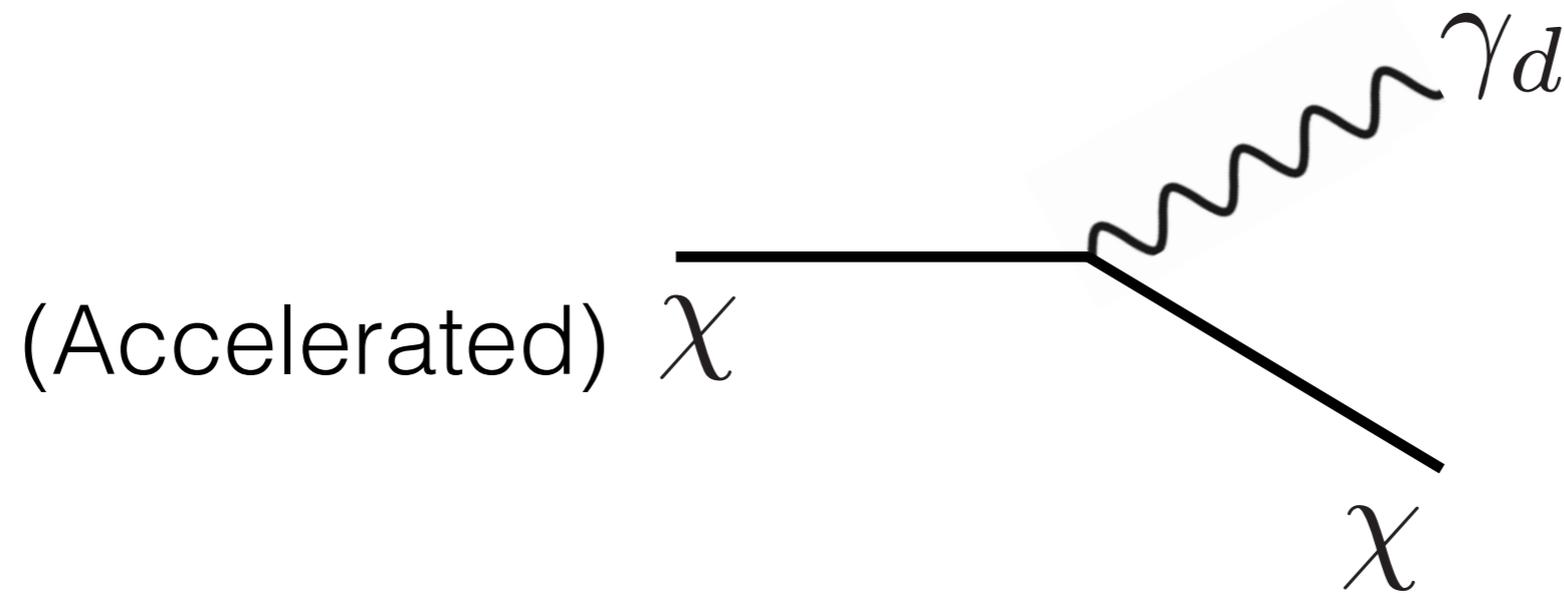
How can we observe?

- **Dark Showering** (Dark Bremsstrahlung)

Energetic DM @ Colliders

SM χ

SM χ

TeV   **(sub) GeV**

- **Radiations** from **Energetic** "dark charged" particles will acquire certain level of energy, enough to be "**tagged**"
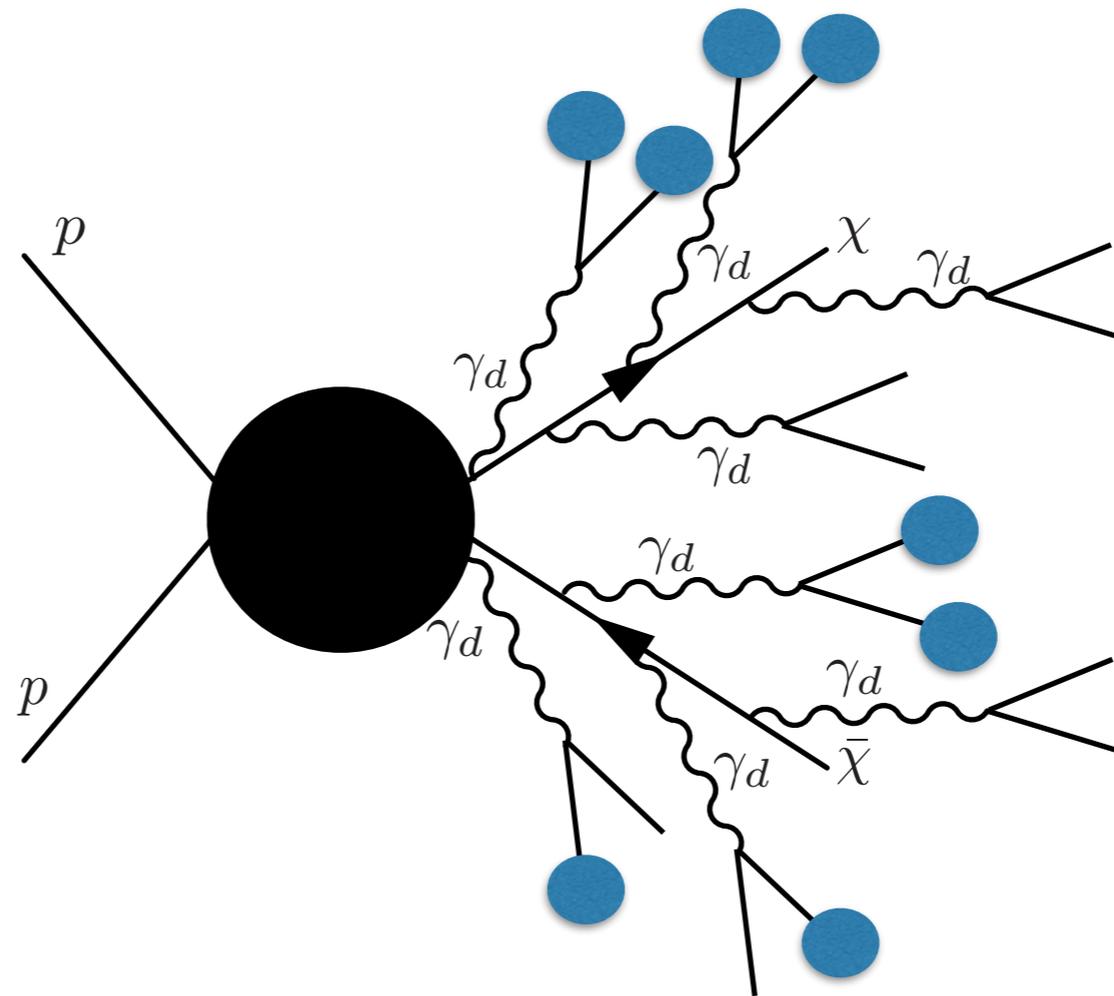
(<u>detectable effect</u>)

Energetic DM @ Colliders
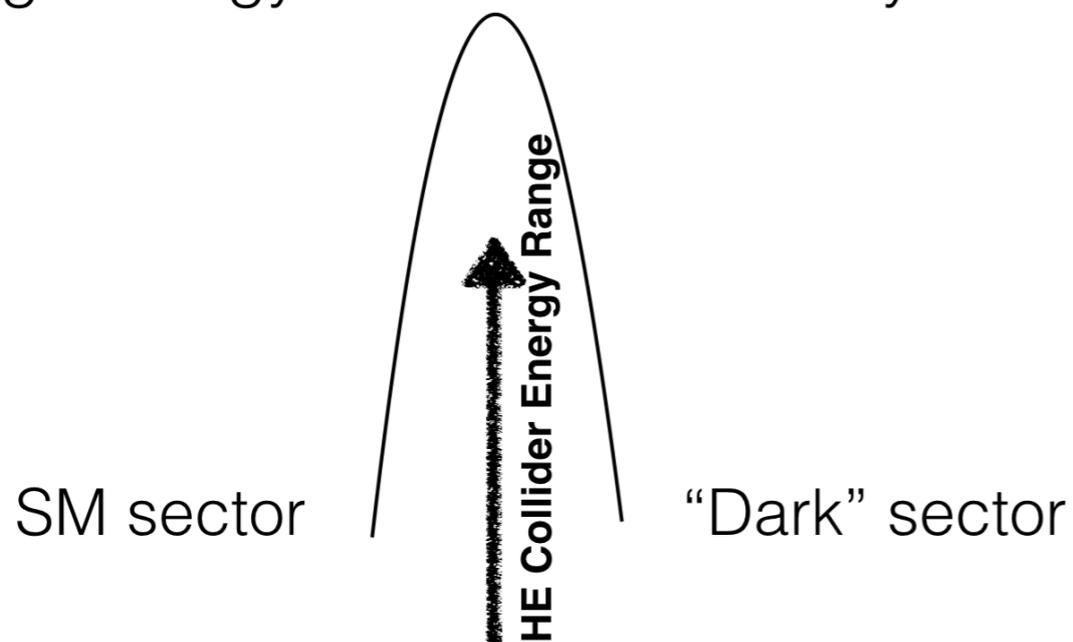

- **Radiations** from **Energetic** "dark charged" particles will acquire certain level of energy, enough to be "**tagged**"
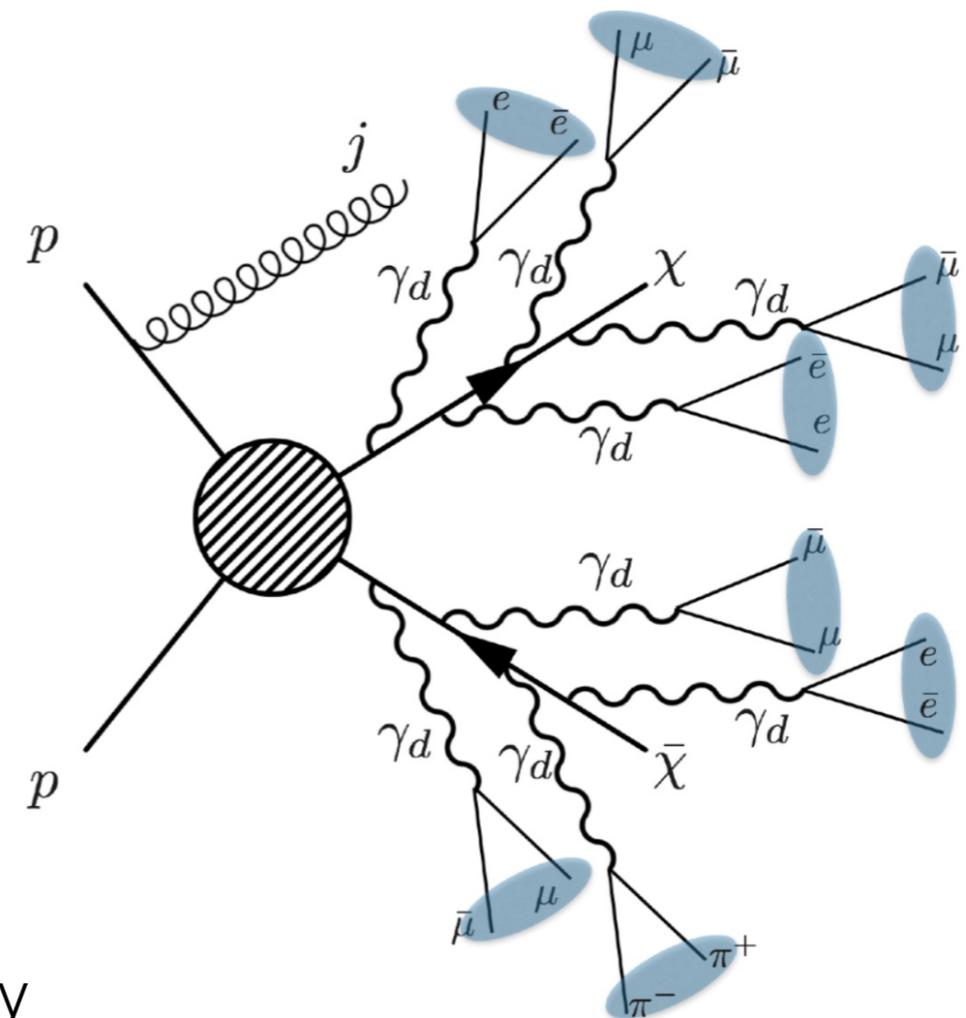
(<u>detectable effect</u>)

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

SM sector   "Dark" sector
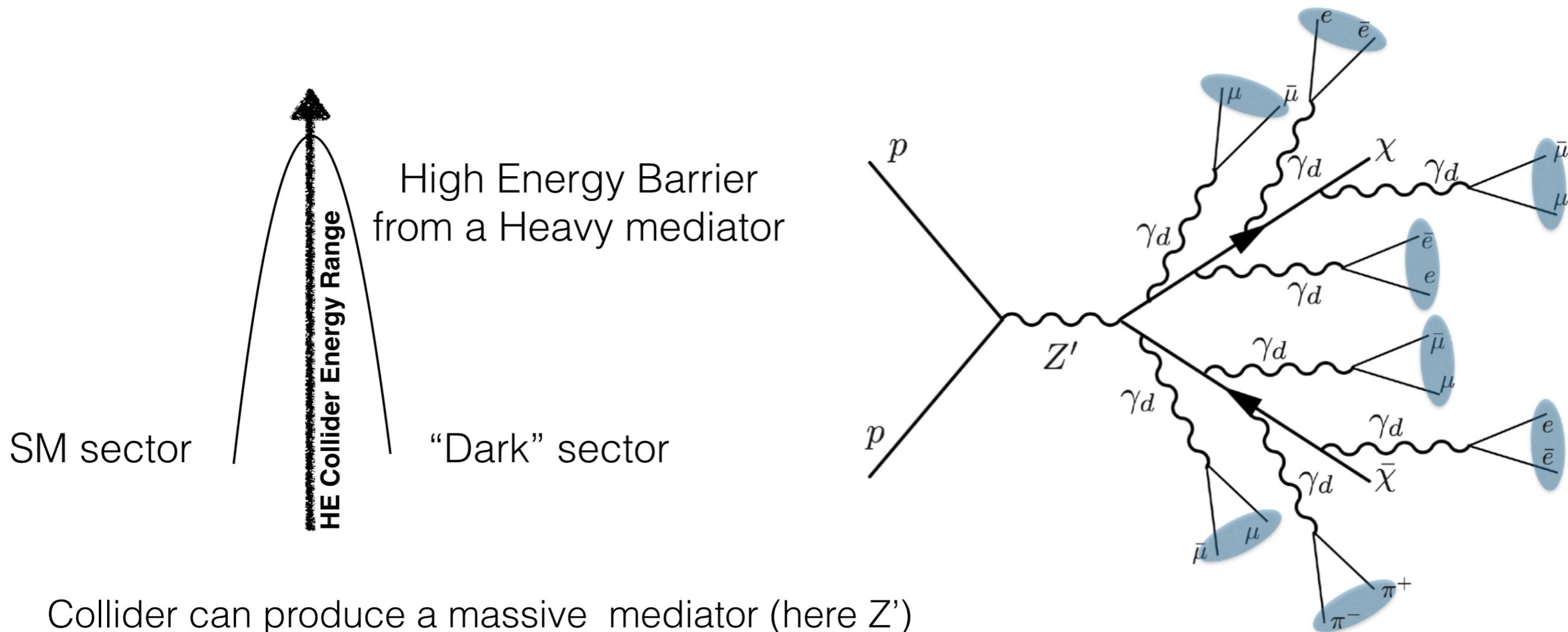
HE Collider Energy Range

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

Energetic DM @ Colliders

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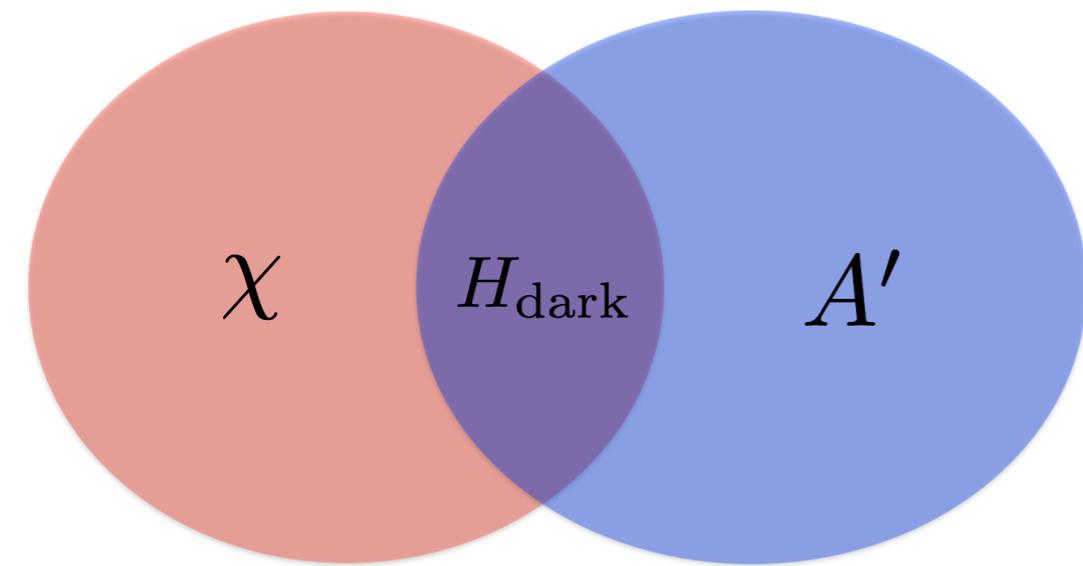 (2). Hard back-to-back boost from a heavy mediator

High Energy Barrier
from a Heavy mediator

HE Collider Energy Range

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**?

χ H_{dark} A'
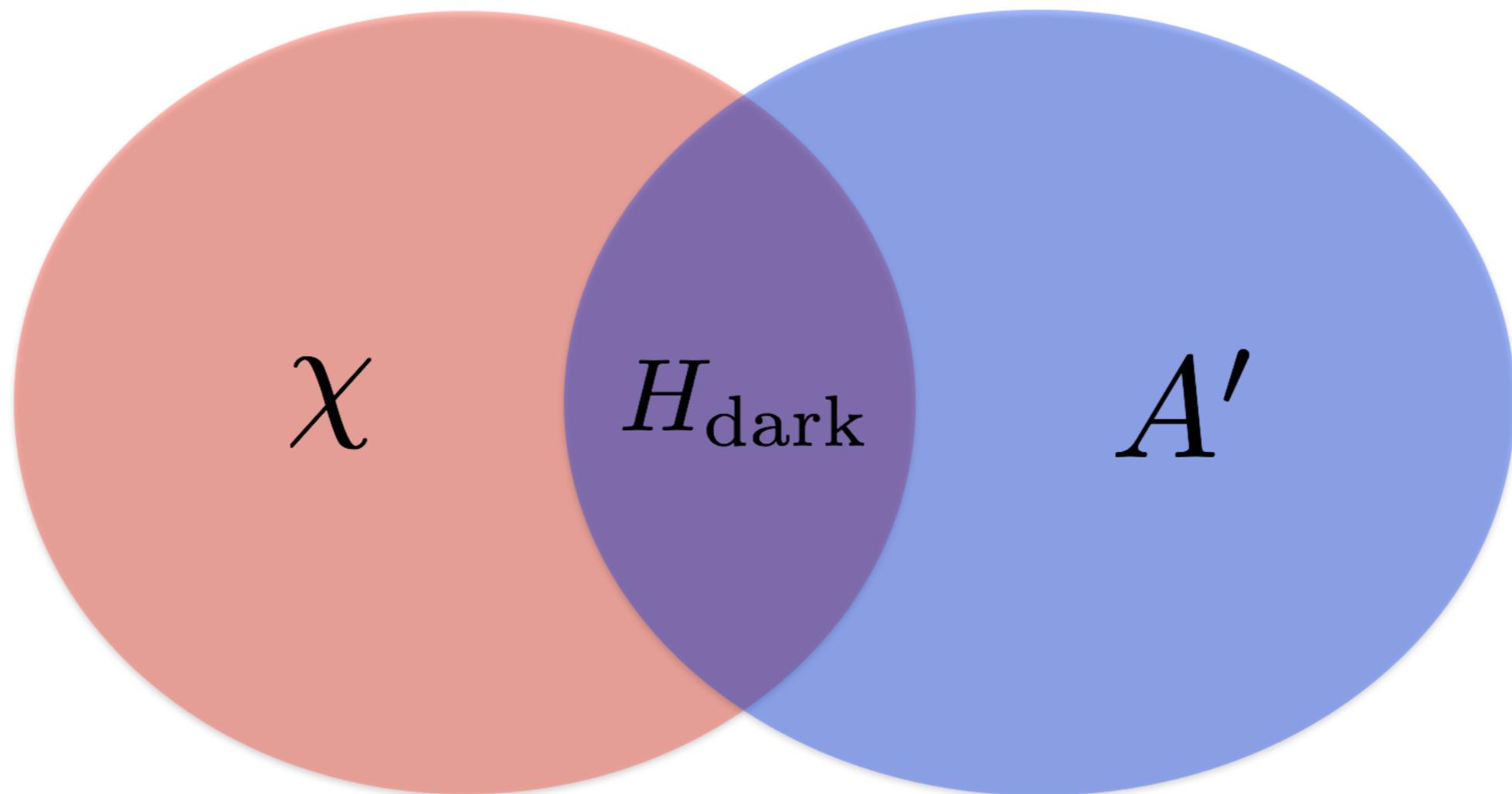
dark matter and dark-photon
share the same origin for their mass

dark matter and dark-photon
have their own mass mechanism

χ A'
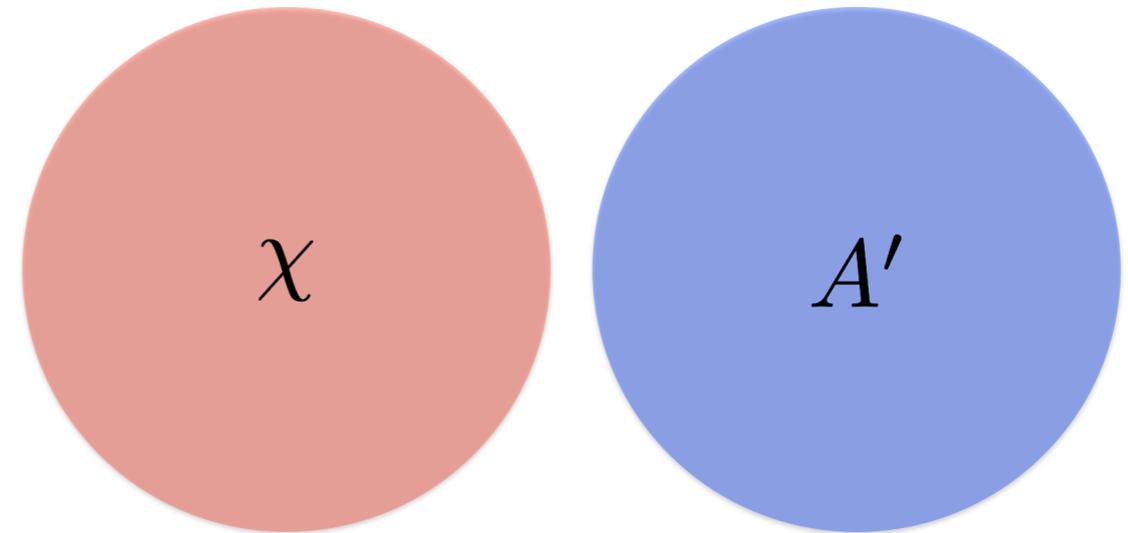
Can we see difference @ LHC ?

DM, dark gauge boson and a Dark Higgs

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

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

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

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

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

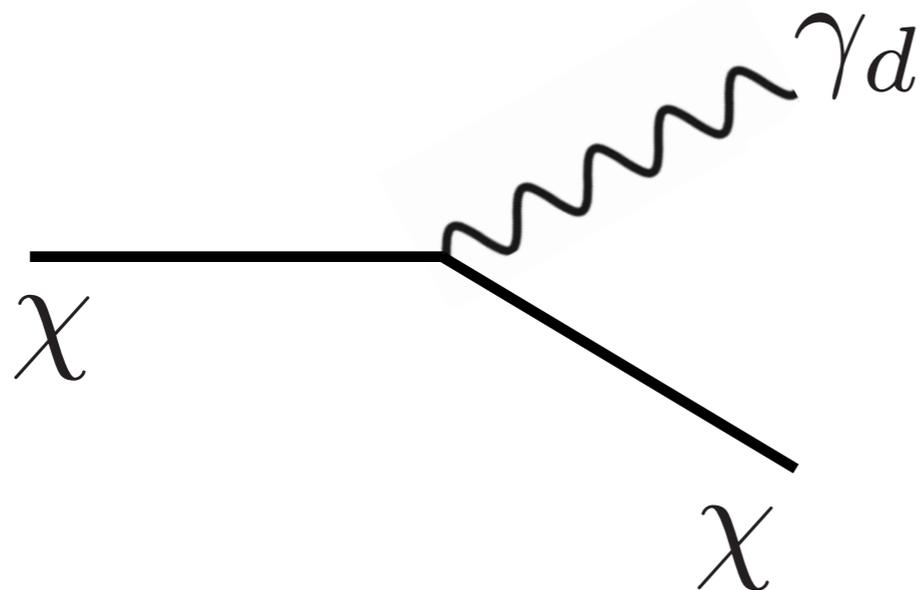Thus we always have the axial coupling
between DM and a Dark photon
if a dark photon and dark matter share the origin of mass

Additional Showering process

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 $\quad x = \frac{E_{\chi,\mathrm{out}}}{E_{\chi*}}$

Splitting function

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

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

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

Benchmark points

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

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

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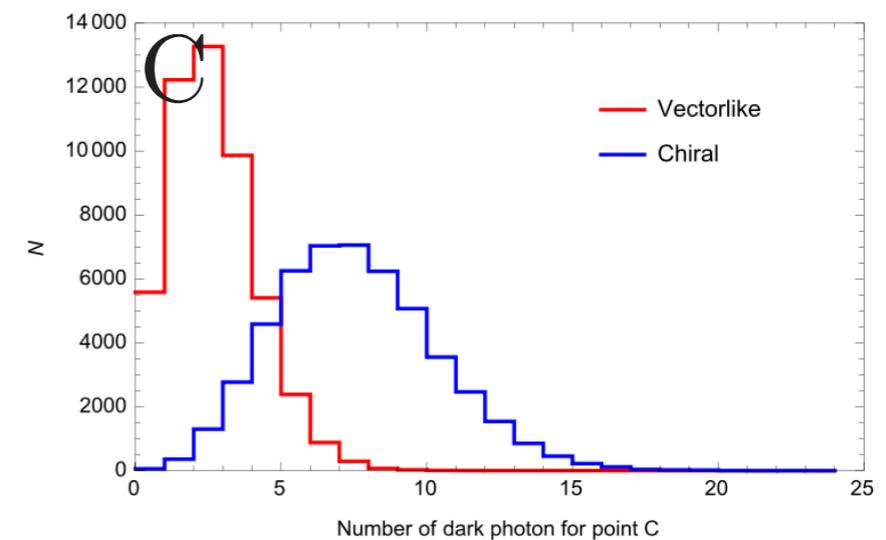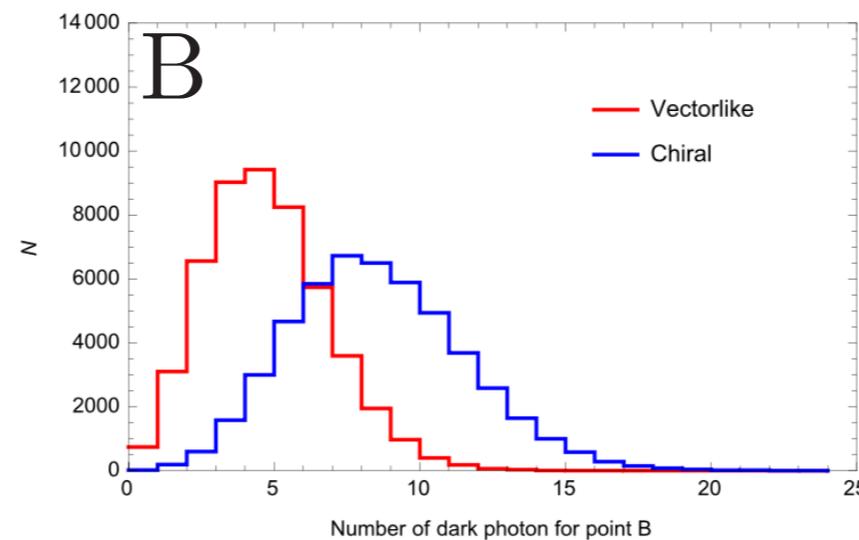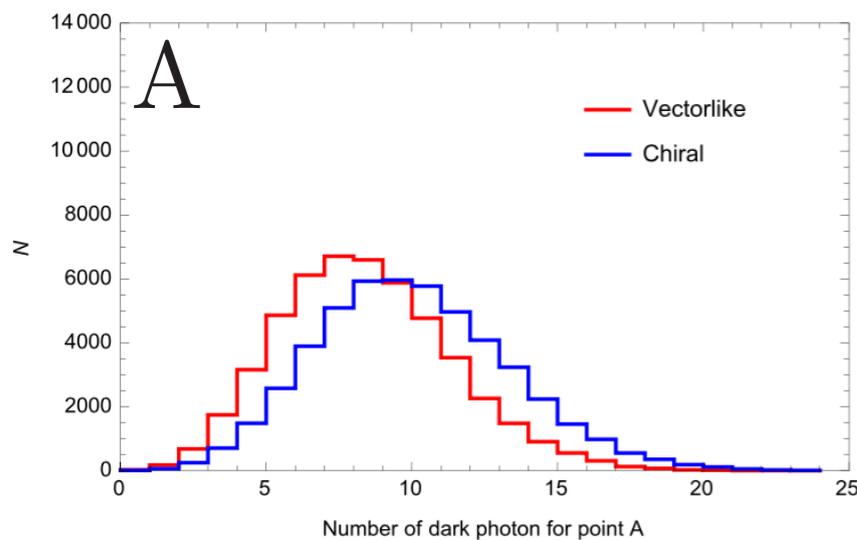
$$\downarrow$$

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

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

Different showering pattern @ collider

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

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

$(\alpha' << 1)$ limits

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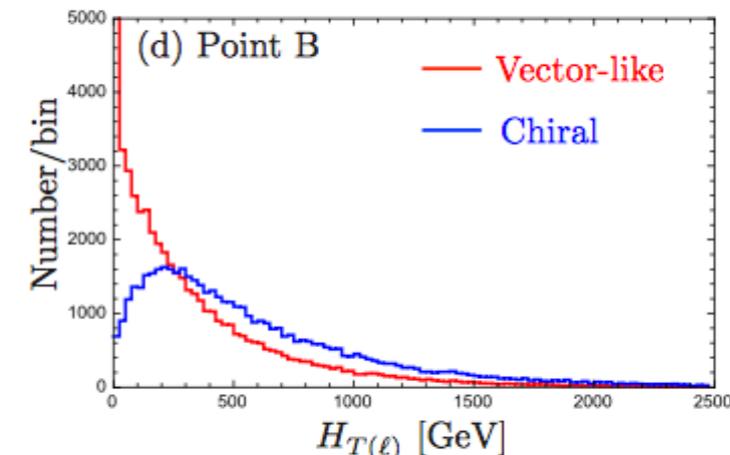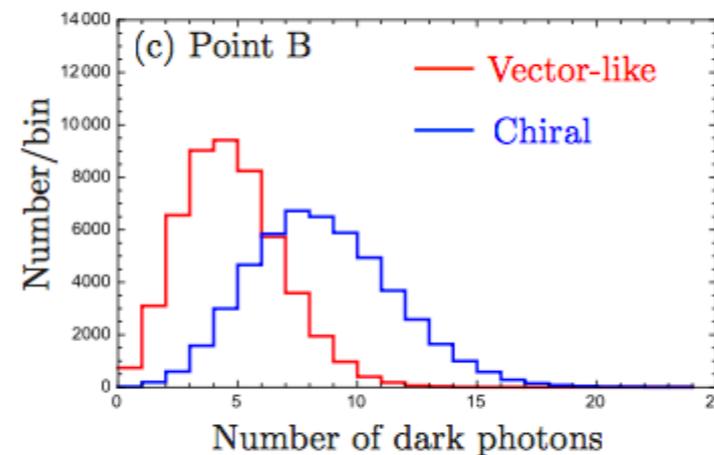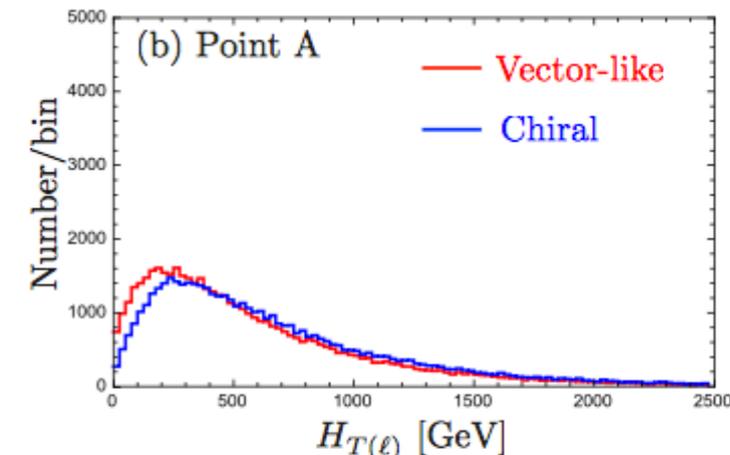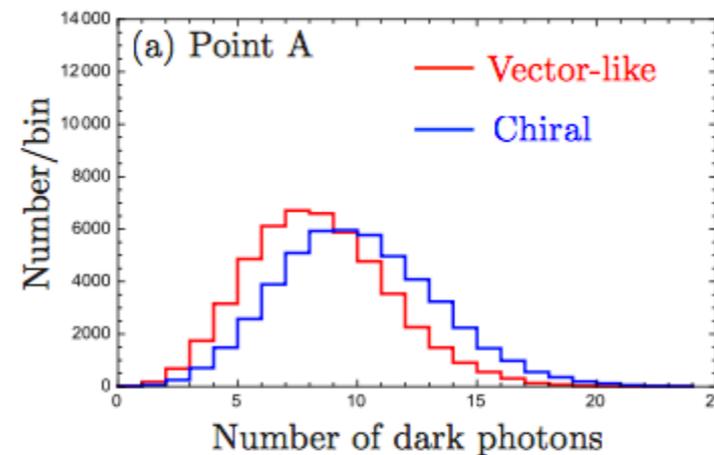
$$P_{\chi \to \chi \gamma_d}(x, t) \simeq (Q_V'^2 + Q_A'^2) \frac{1 + x^2}{1 - x} + 2Q_A'^2 \frac{m_\chi^2}{m_{\gamma_d}^2} \quad , \quad \alpha' \, P_{\chi \to \chi \gamma_d} \sim \frac{m_{\gamma_d}^2}{v_s^2} \frac{m_\chi^2}{m_{\gamma_d}^2} \sim y_\chi^2$$

Quantify the difference

- We use the transverse energy deposits from leptonic decay modes

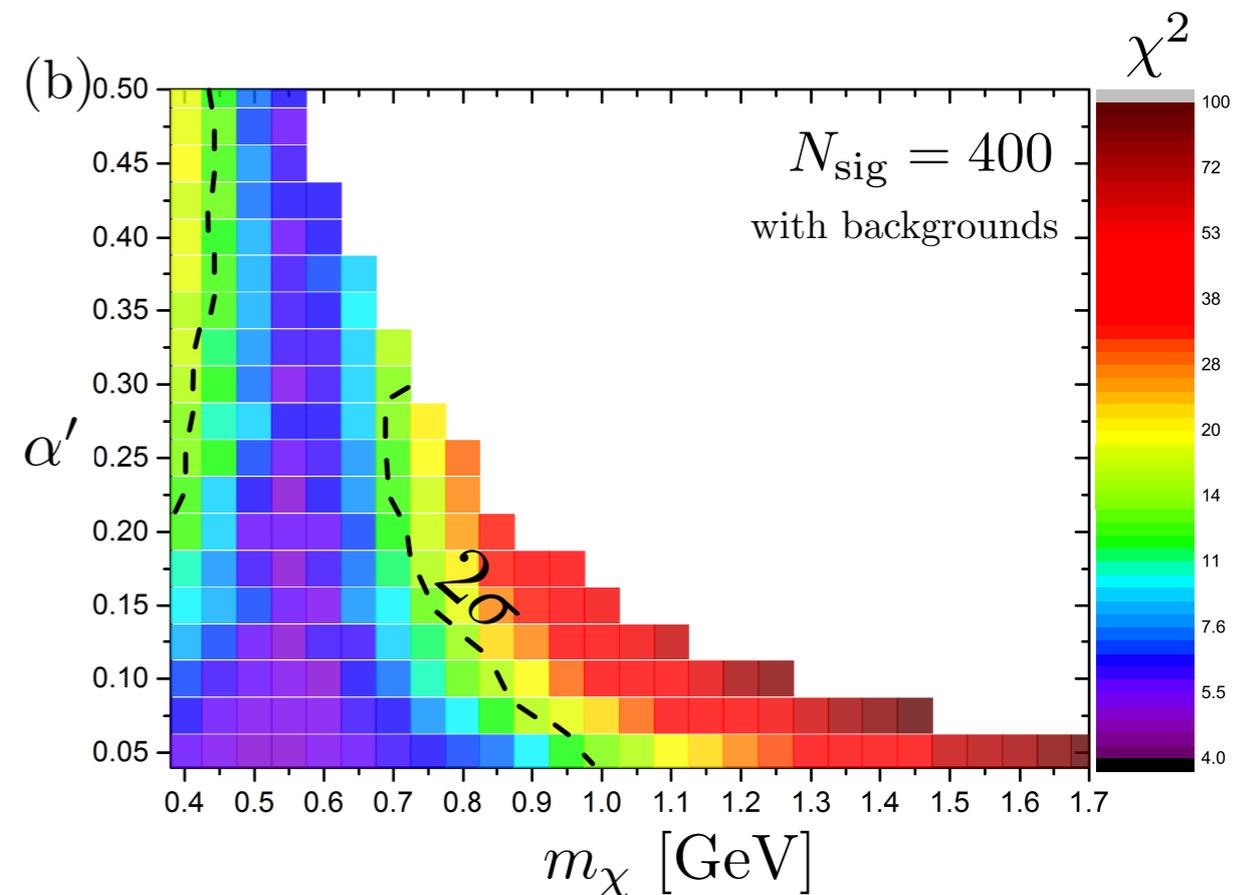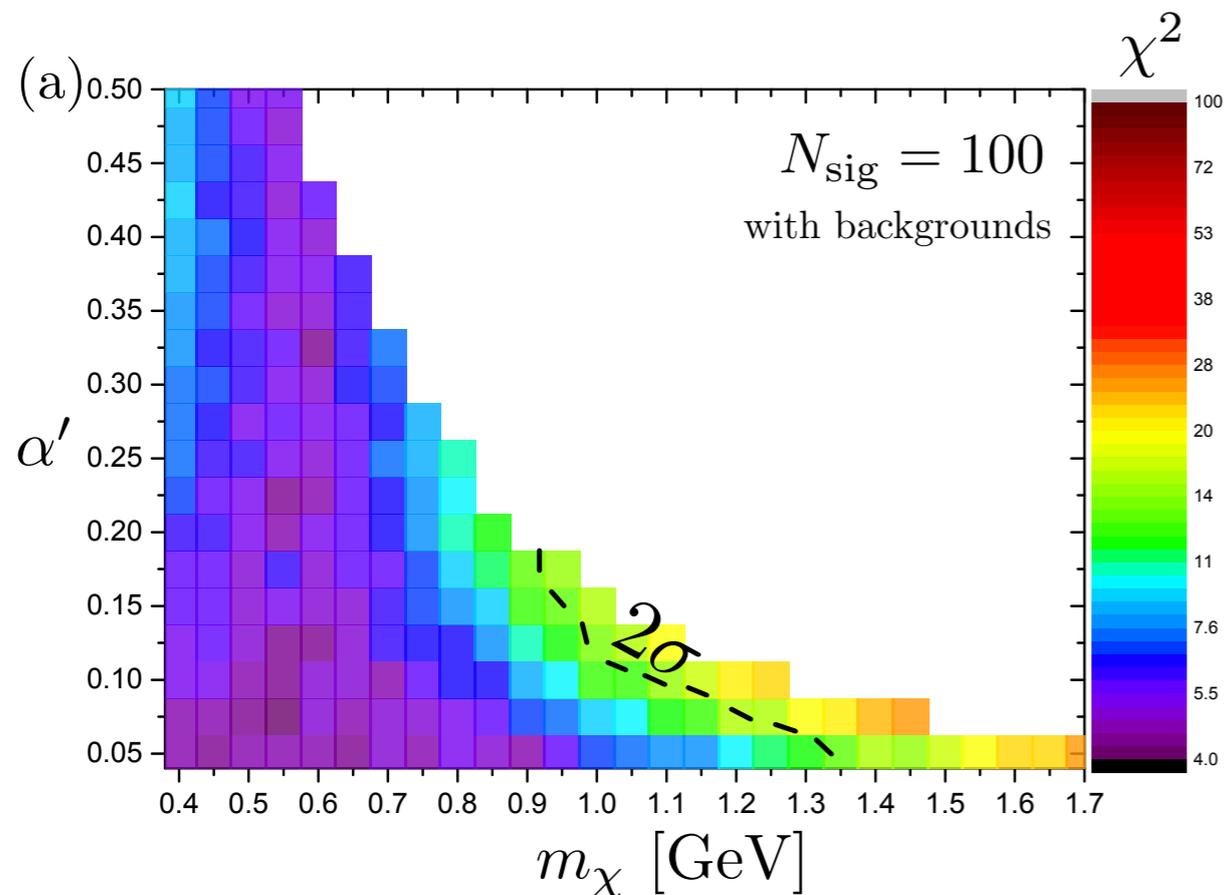| Benchmark Points (BP)	A	B	C
α'	0.3	0.15	0.075
m_χ (GeV)	0.7	1.0	1.4
m_{γ_d} (GeV)	0.4		

$$H_{T(\ell)} = \sum_{i=\mu^\pm,e^\pm} |p_{T_i}|$$
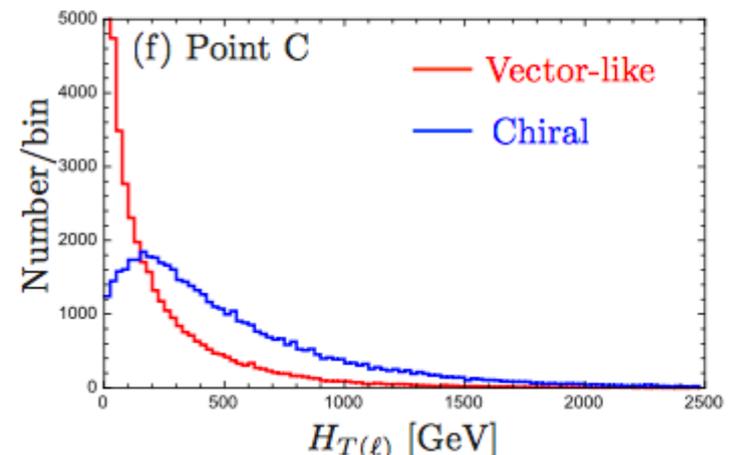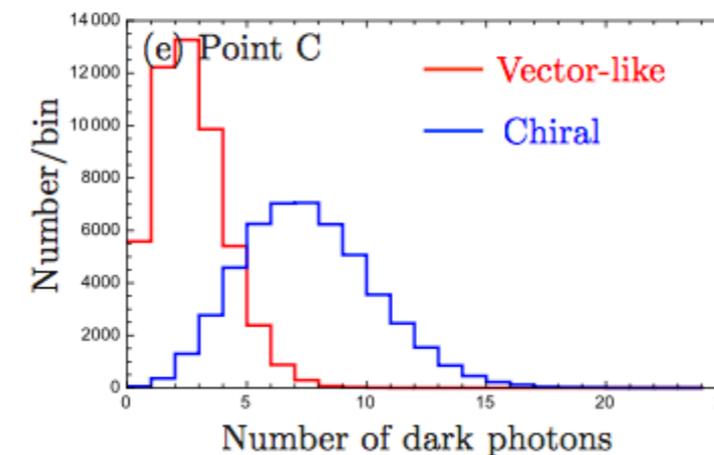
-Due to GBET, the energy spectrum of leptons from a **longitudinal mode** is larger compared to the case of leptons from a transverse mode

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**
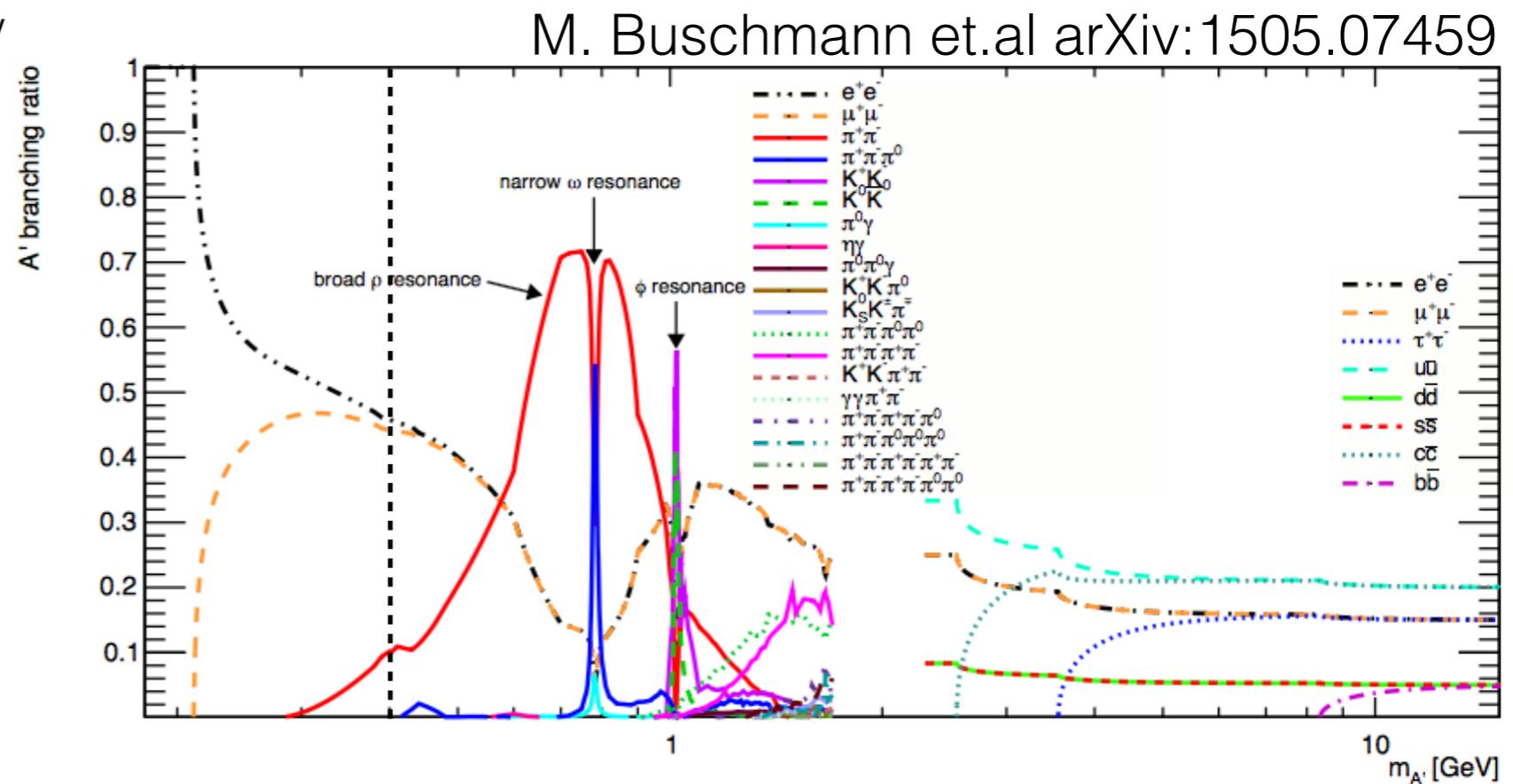
Back up

Benchmark points

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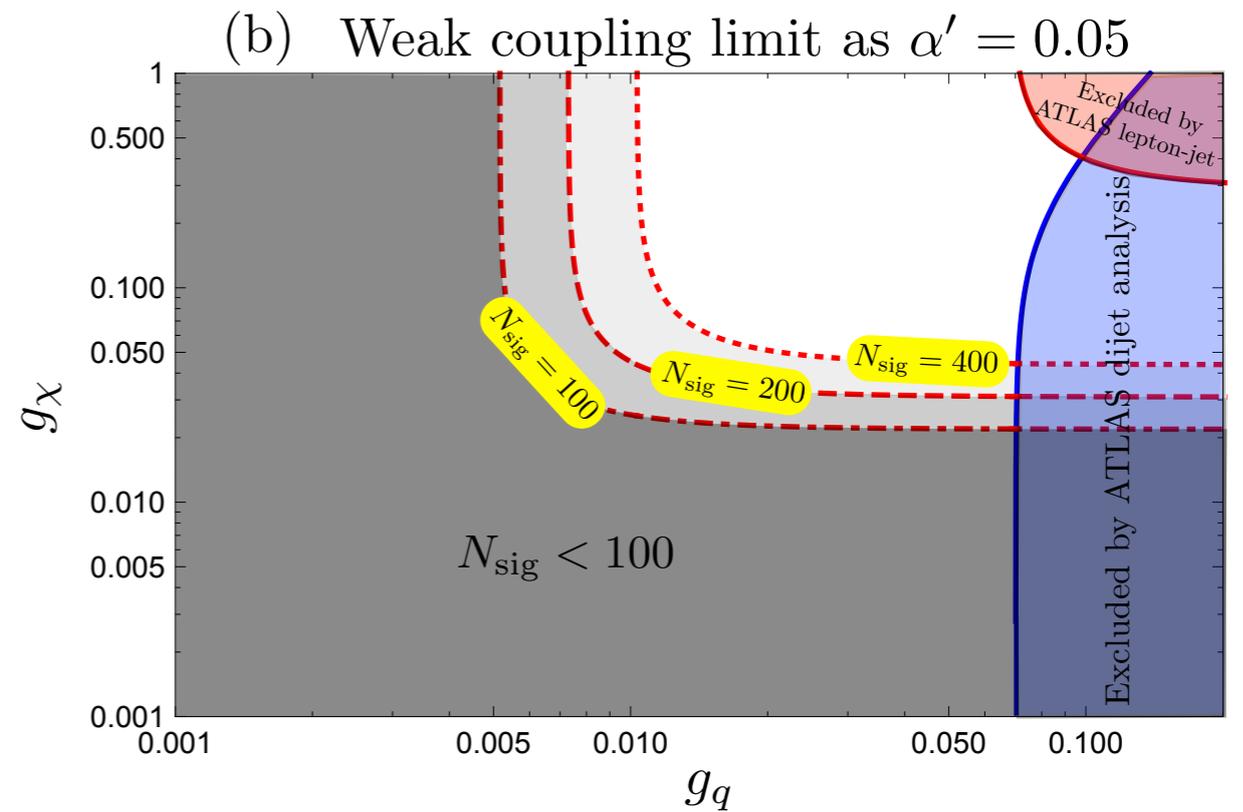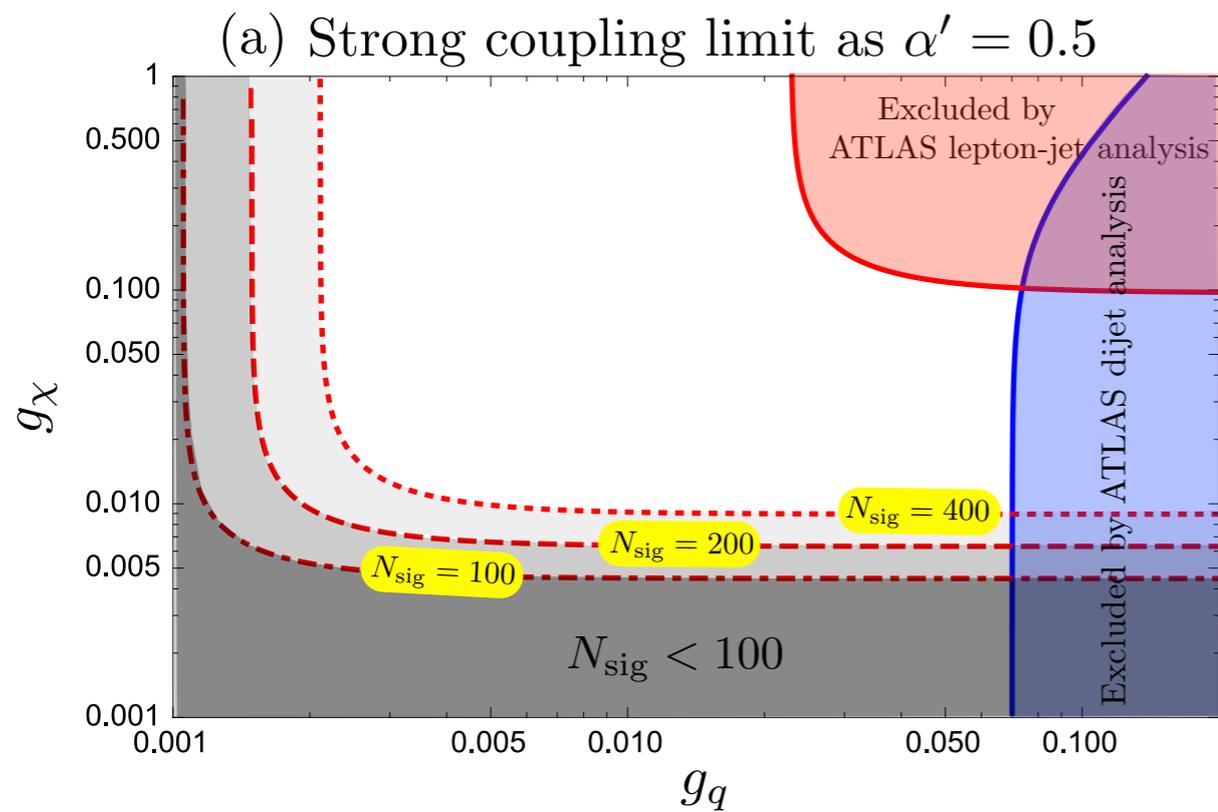 - Non-negligible decay mode into muons-pair to tag!

Set dark photon = 0.4GeV

M. Buschmann et.al arXiv:1505.07459
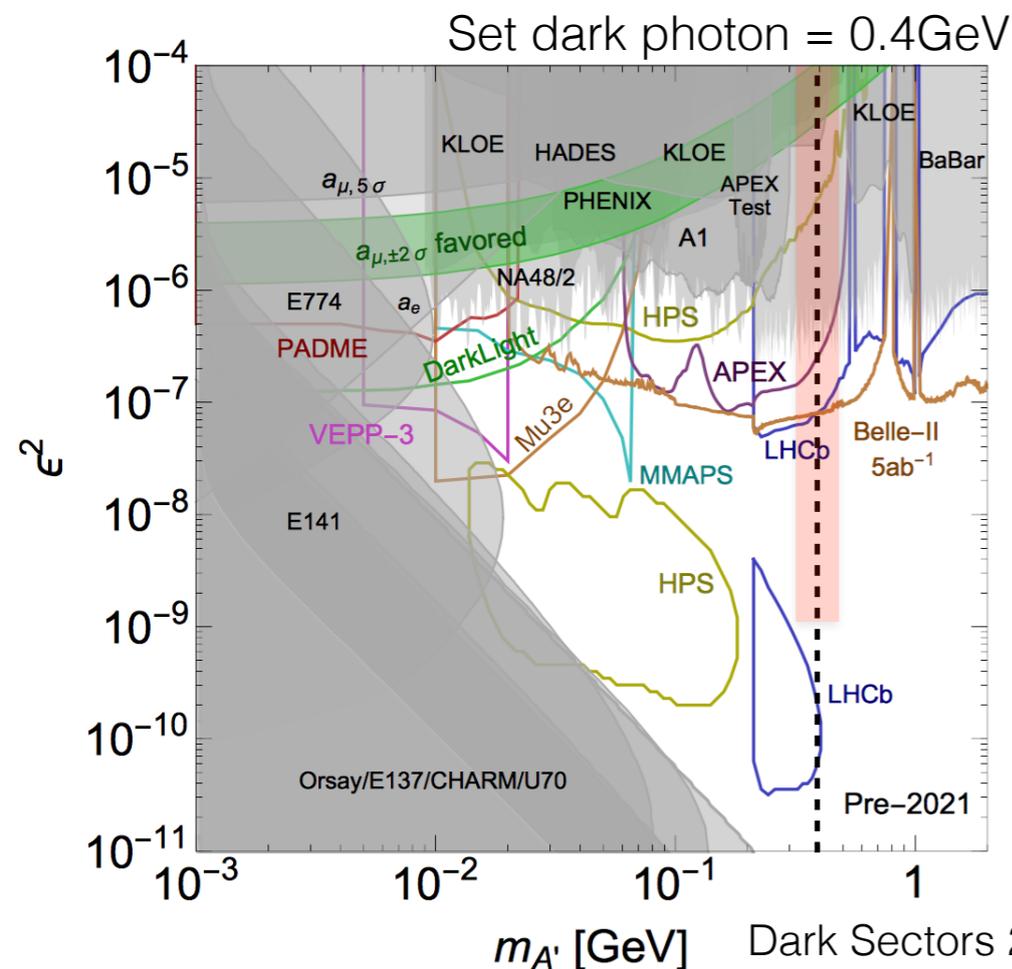
Dark Sectors 2016 Workshop
arXiv:1608.08632

Constraints from LHC

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

(a) Strong coupling limit as $\alpha' = 0.5$

(b) Weak coupling limit as $\alpha' = 0.05$

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