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

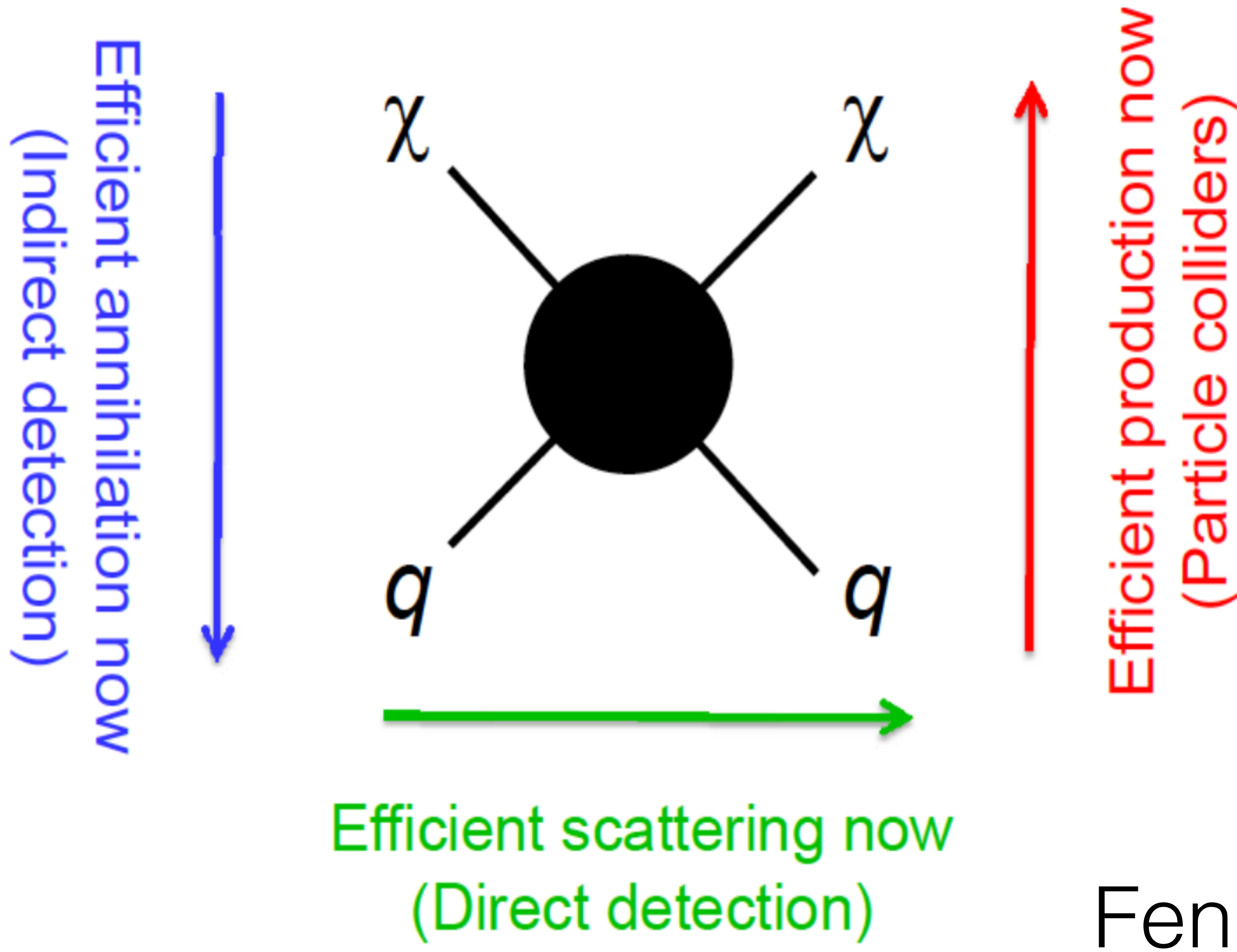
Myeonghun Park

기초과학연구원
Institute for Basic Science

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

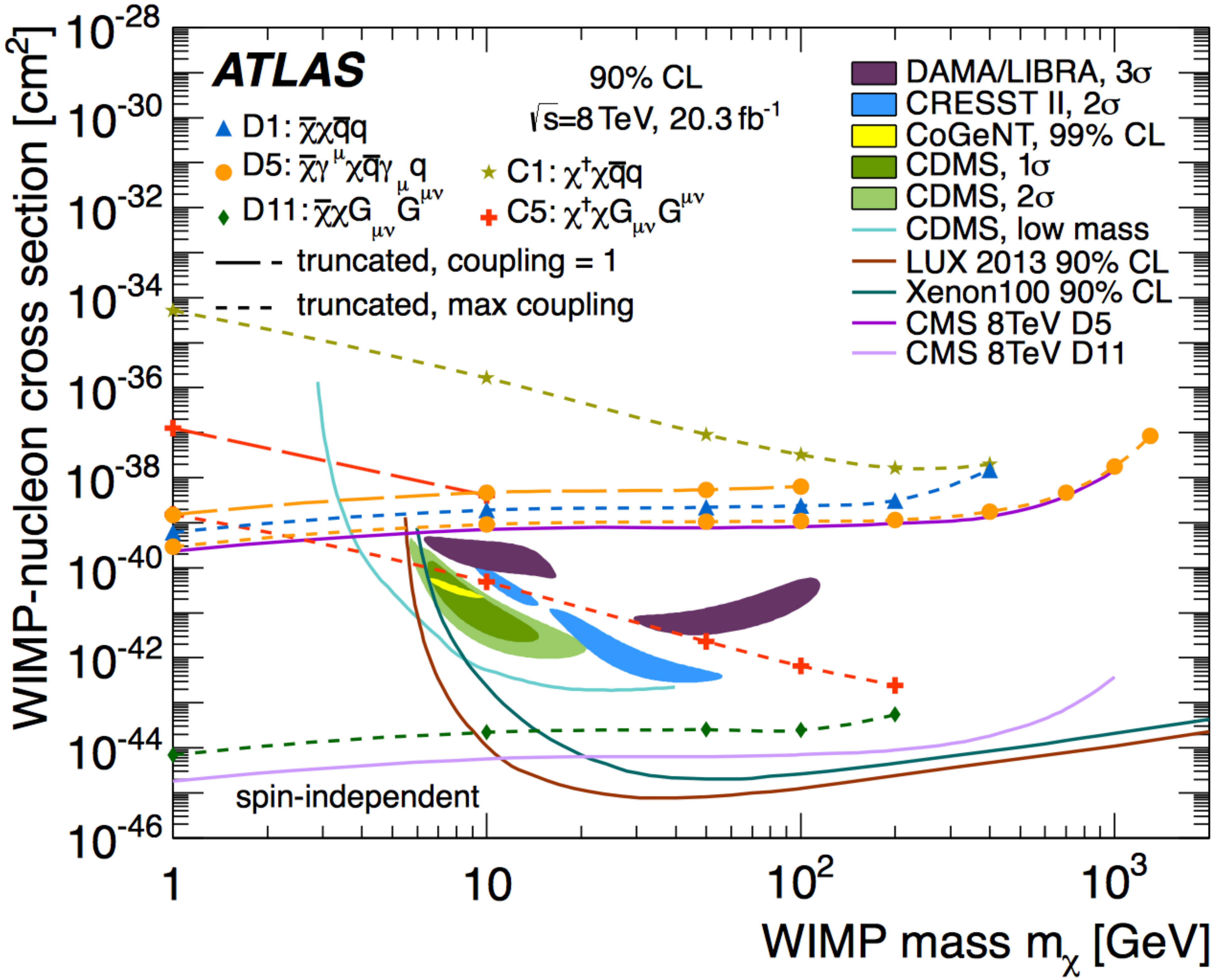
DM @ LHC 2017

All directional efforts!

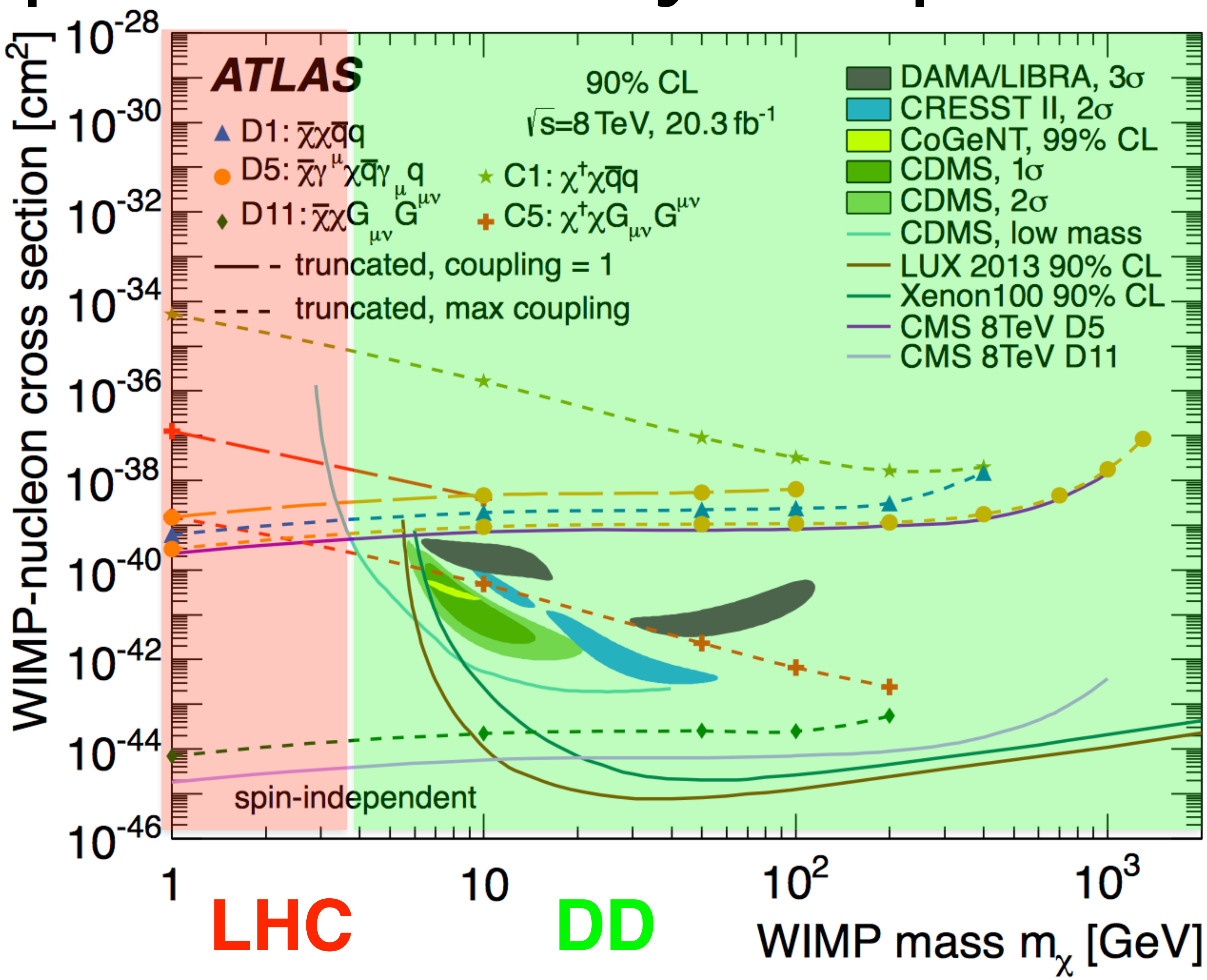


Feng (2008)

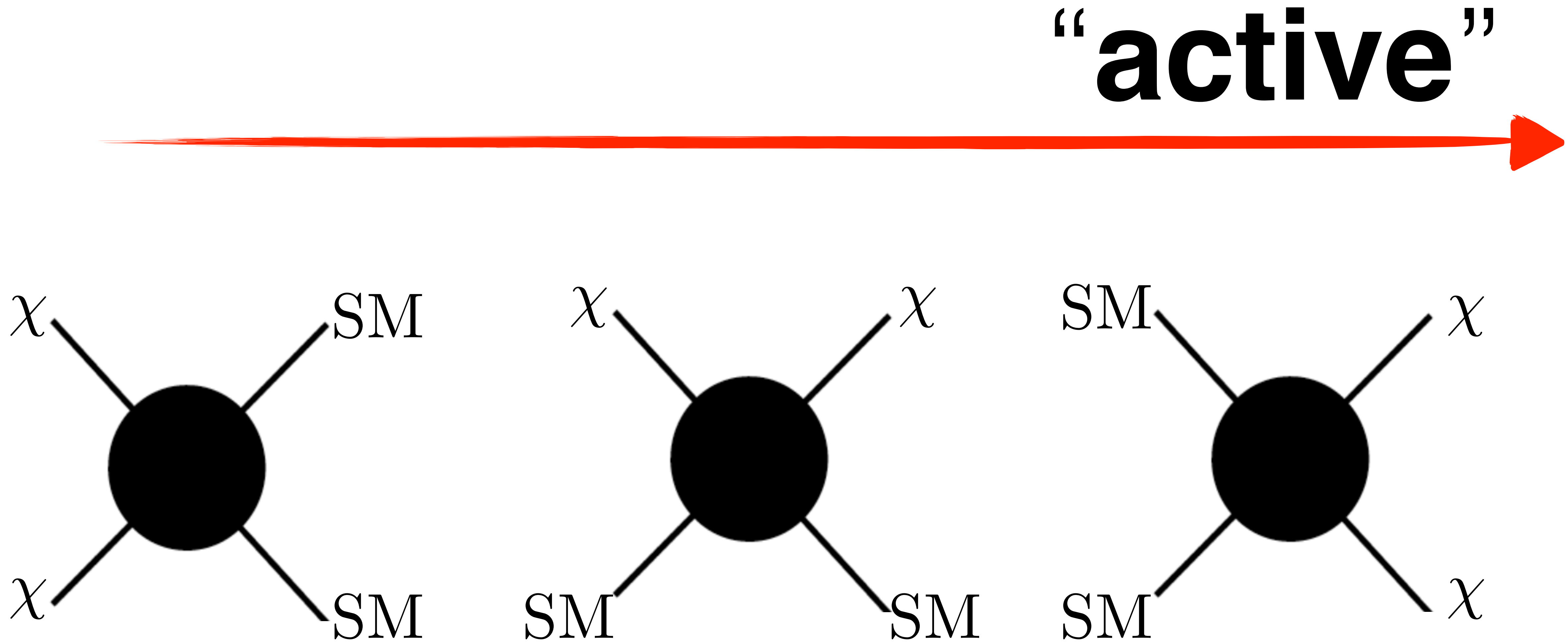
Complementary experiments



Complementary experiments



- A collider has a sensitivity in probing a light dark matter particle!
- There is a big difference among Collider / Indirect / Direct exps.



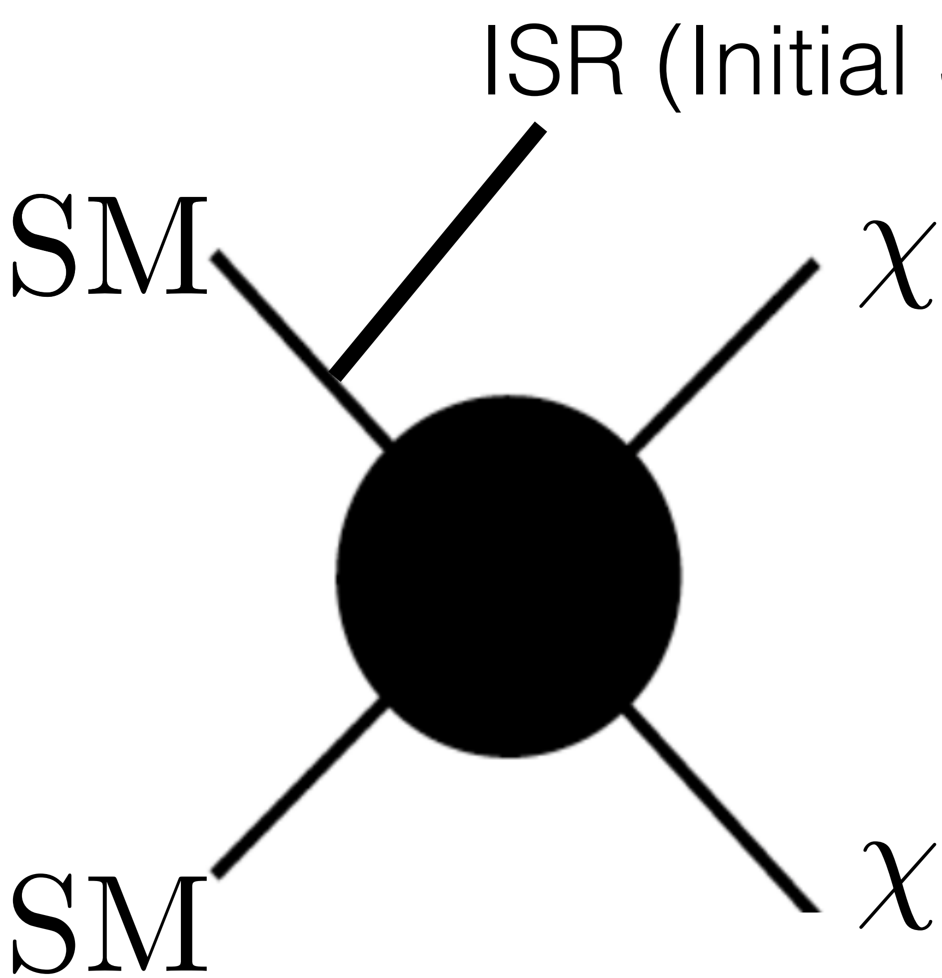
Dark matter Indirect searches

Dark matter Direct searches

Collider

Understanding details

- Once we tag "dark matter" events over backgrounds with ISR, ISR can talk about the details…



- Determine the properties of dark matter

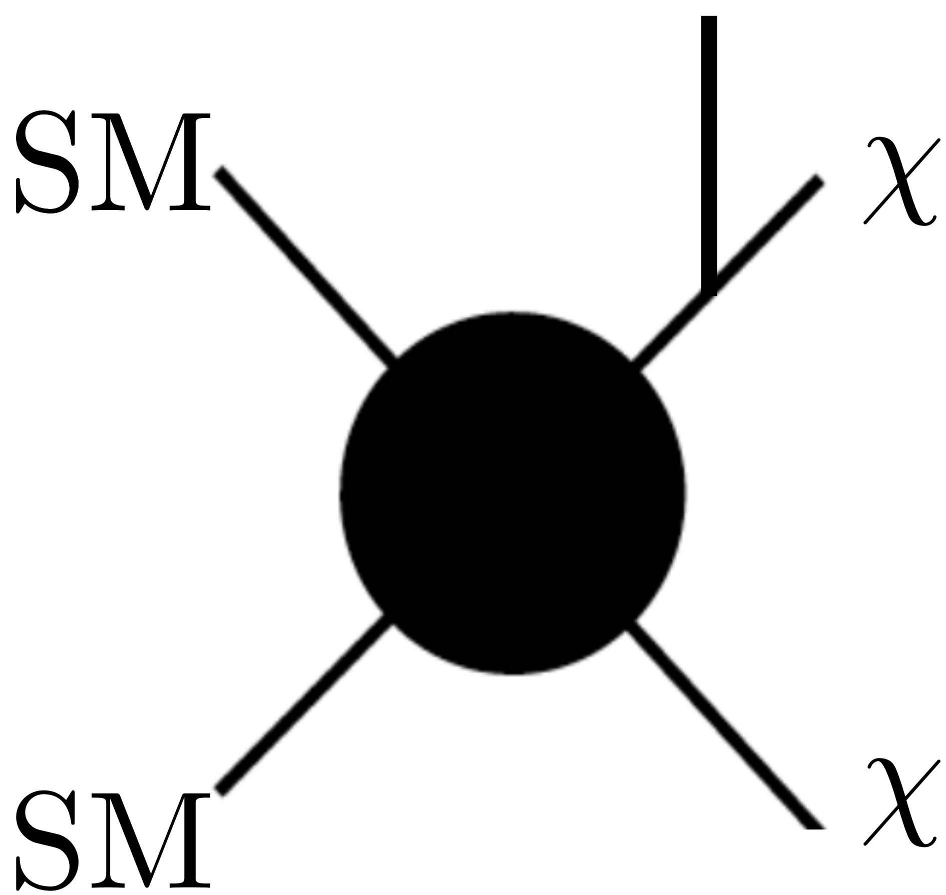
  - **Mass** spectrum (from kinematics)

  - **Spin** of dark matter / **Interaction** between SM and Dark (from MET, talk by Alexander Belyaev ~ ISR (photon, jet) PT, talk by Jonathan Feng)

Understanding details

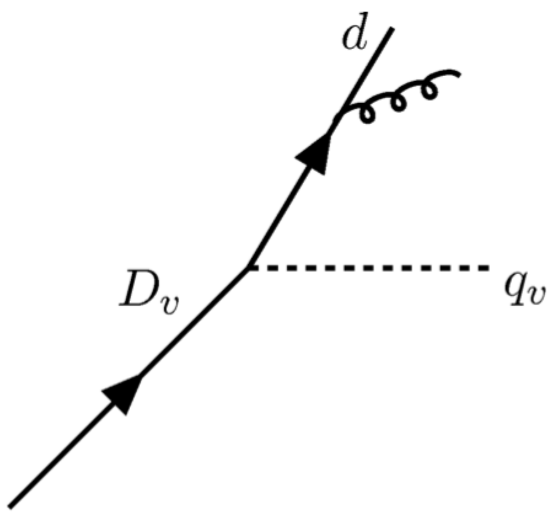
- FSR can talk about a gauge structure of Dark matter!

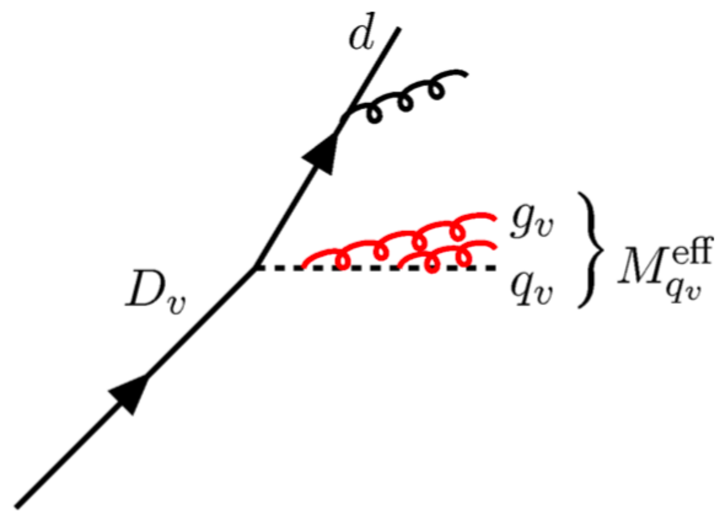
FSR (Final State Radiation)



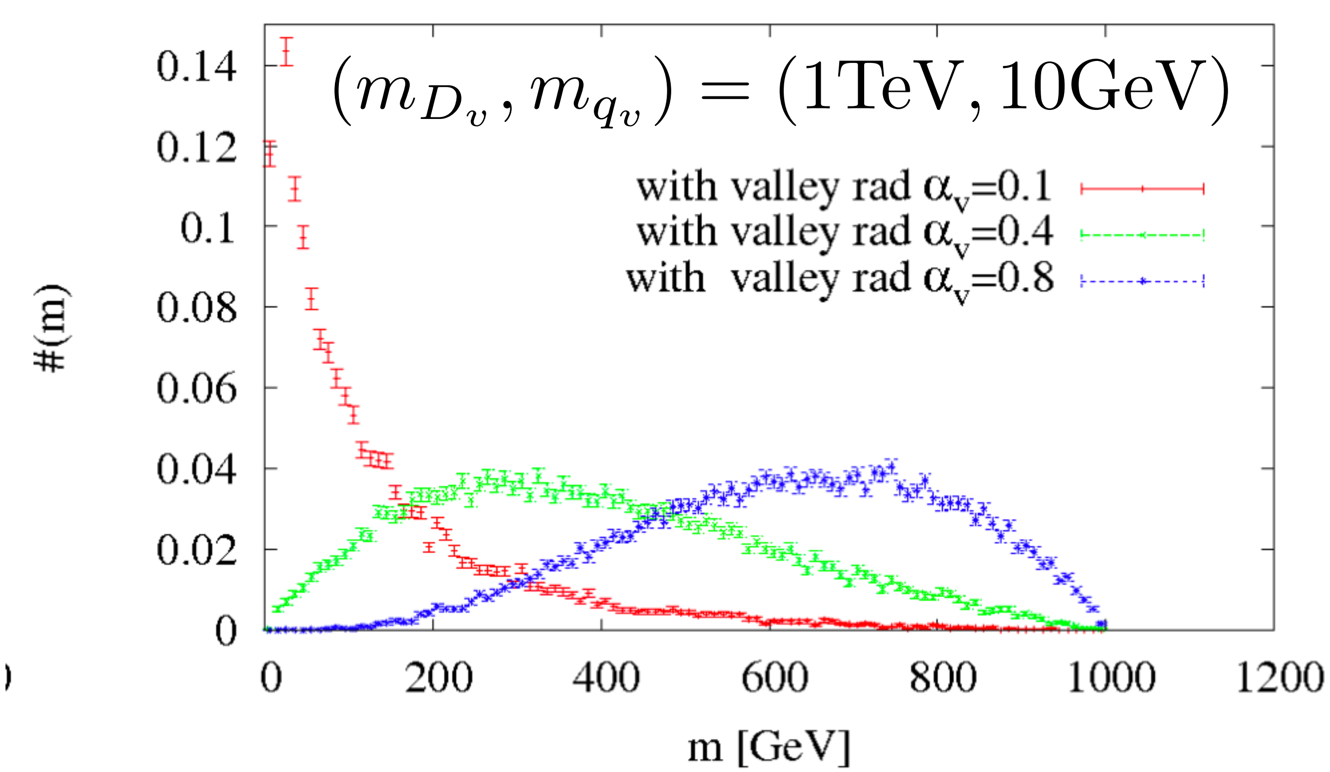
Understanding details

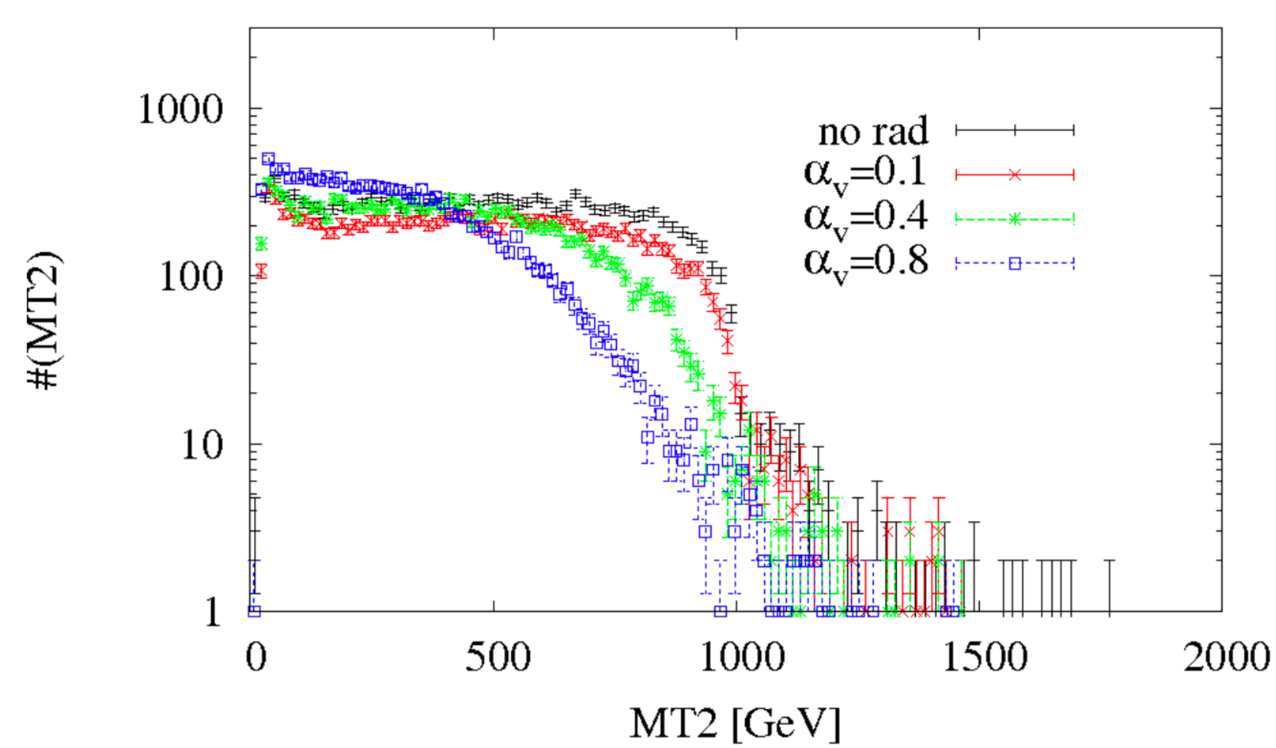
Lisa Carloni, Torbjorn Sjostrand (2010)



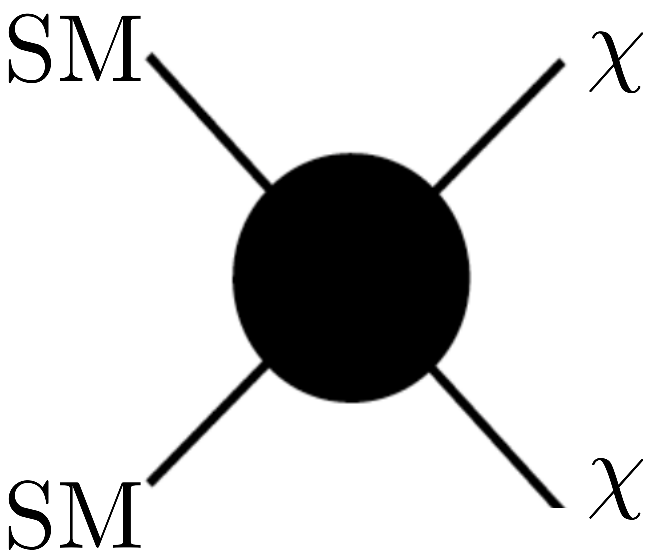


	$SU(3)_c$	$\times\ SU(3)_v$
Q_v	3	3
q_v	1	3





DM @ Colliders



TeV **(sub) GeV**

- Collider can **BOOST** dark matter particles!

- **Radiations** from **BOOSTED** "dark charged" particle will acquire certain level of energy, enough to be "**tagged**" (detectable effect)

DM with an abelian charge

- Dark matter may have a dark-U(1) charge (good to have proper relic, see a talk by Tongyan Lin)

- 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)

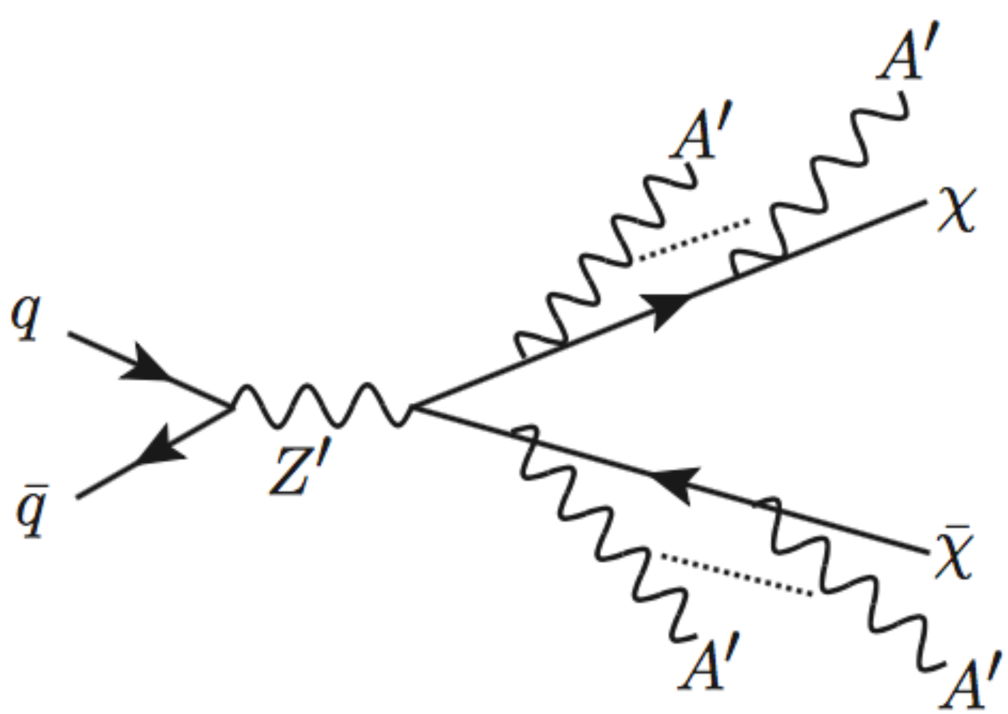
(see also J. Feng, J. Smolingsky and P. Tanedo 2016)

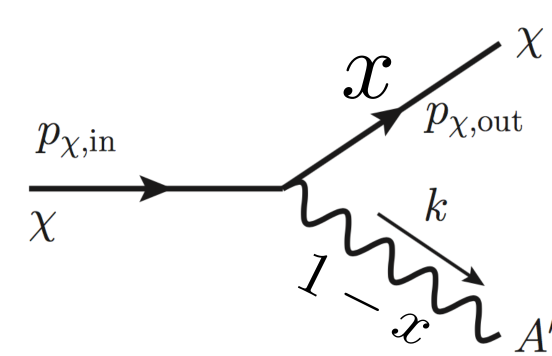
Highly boosted DM@collider

- For a vector-like Dark matter case:

M. Buschmann et.al arXiv:1505.07459

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





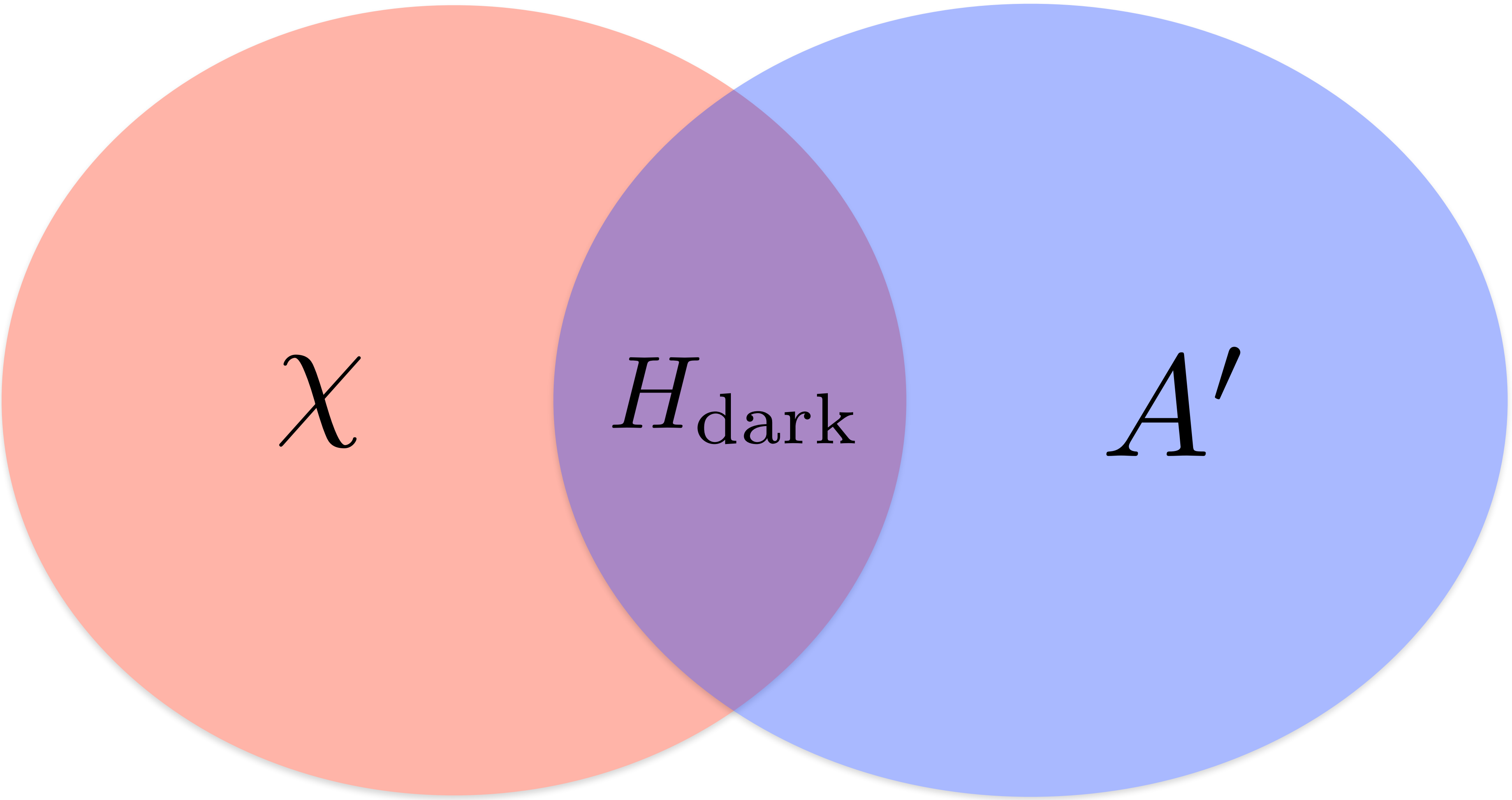
x is an energy fraction

Splitting function

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

What if

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



DM, dark gauge boson and a Dark Higgs

A'_μ	Φ	χ_L	χ_R	ψ_L	ψ_R
	Q'_Φ	Q'_{χ_L}	Q'_{χ_R}	Q'_{ψ_L}	Q'_{ψ_R}

$$Q'_\Phi = Q'_{\chi_R} - Q'_{\chi_L} = -(Q'_{\Psi_R} - Q'_{\Psi_L})$$

$$\mathcal{L}_{\text{vector+scalar}} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu} + |D_\mu \Phi|^2$$

$$\begin{aligned} \mathcal{L}_{\text{matter}} &= \bar{\chi}_L i\gamma^\mu D_\mu \chi_L + \bar{\chi}_R i\gamma^\mu D_\mu \chi_R + \bar{\psi}_L i\gamma^\mu D_\mu \psi_L \\ &+ \bar{\psi}_R i\gamma^\mu D_\mu \psi_R - y_\chi \bar{\chi}_L \Phi^* \chi_R - y_\chi \bar{\chi}_R \Phi \chi_L \\ &- y_\psi \bar{\psi}_L \Phi \psi_R - y_\psi \bar{\psi}_R \Phi^* \psi_L \end{aligned}$$

DM, dark gauge boson and a Dark Higgs

A'_μ	Φ	χ_L	χ_R	ψ_L	ψ_R
	Q'_Φ	Q'_{χ_L}	Q'_{χ_R}	Q'_{ψ_L}	Q'_{ψ_R}

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

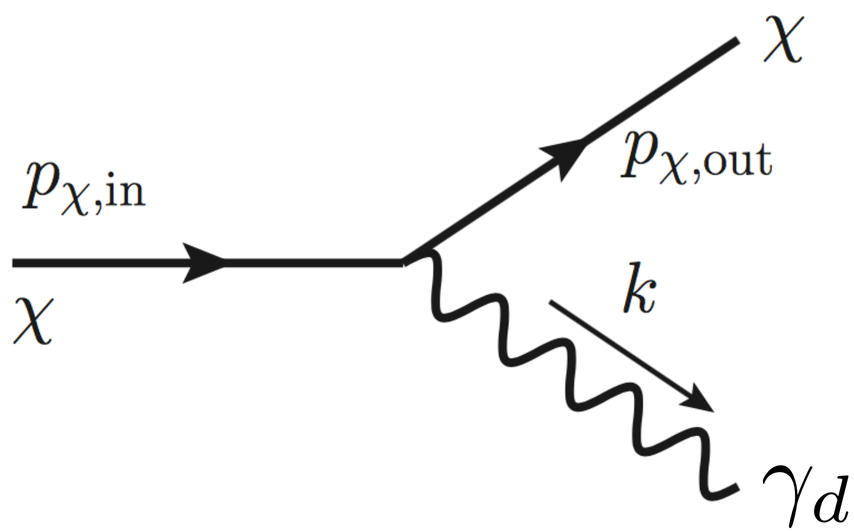
$$Q'_A = \frac{1}{2}(Q'_{\chi_R} - Q'_{\chi_L}) = \frac{Q'_\Phi}{2}$$

$$Q'_V = \frac{1}{2}(Q'_{\chi_R} + Q'_{\chi_L}) = \frac{Q'_\Phi}{2} + Q'_{\chi_L}$$

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

Showering process



Splitting function

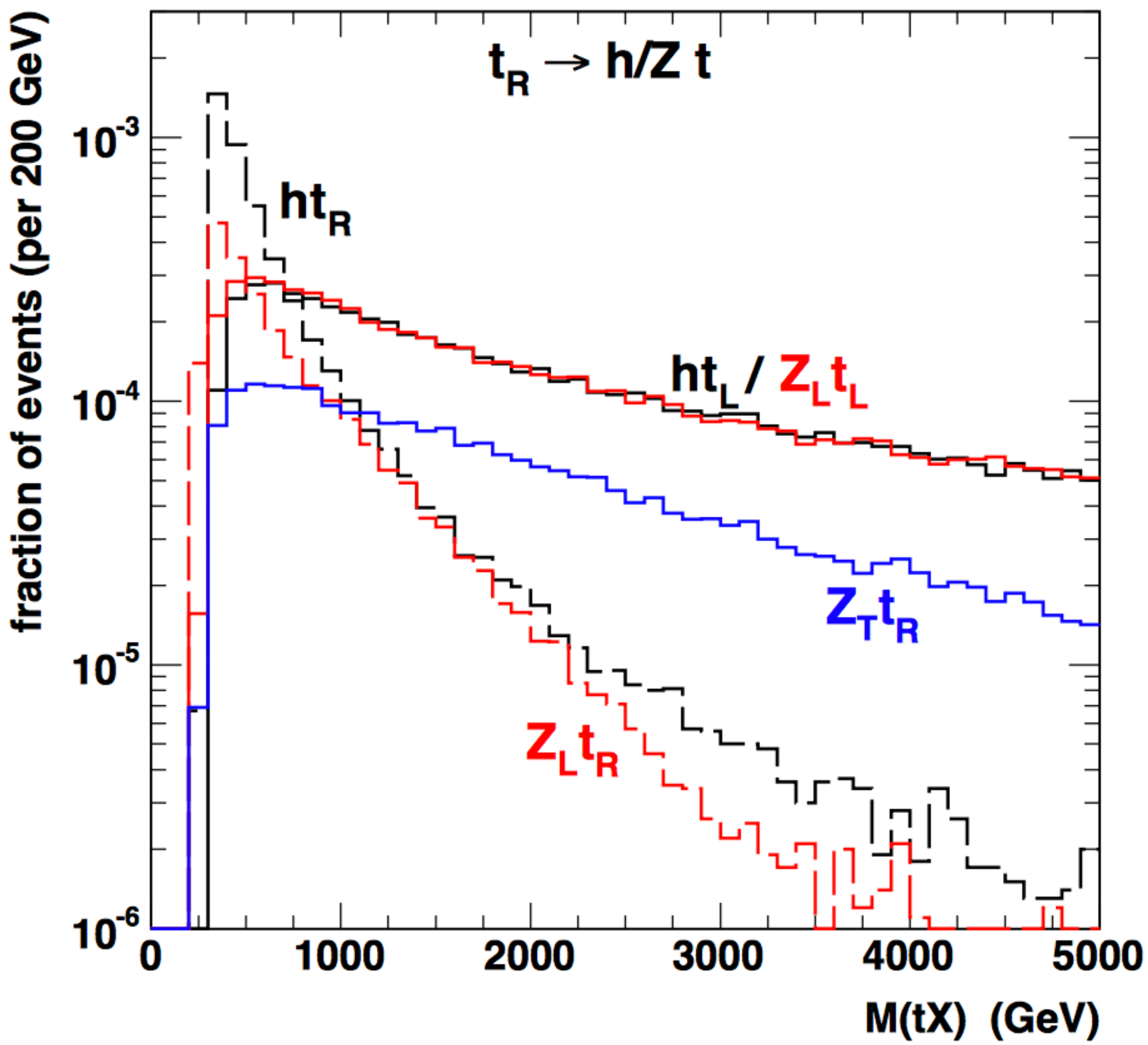
$$P_{\chi\to\chi\gamma_d}(x,t) \simeq Q_V'^2 \,\frac{1+x^2}{1-x}$$

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

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

- We implemented this shower profile in PYTHIA 8

Lesson from SM



In High Energetic Top-quark case:

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

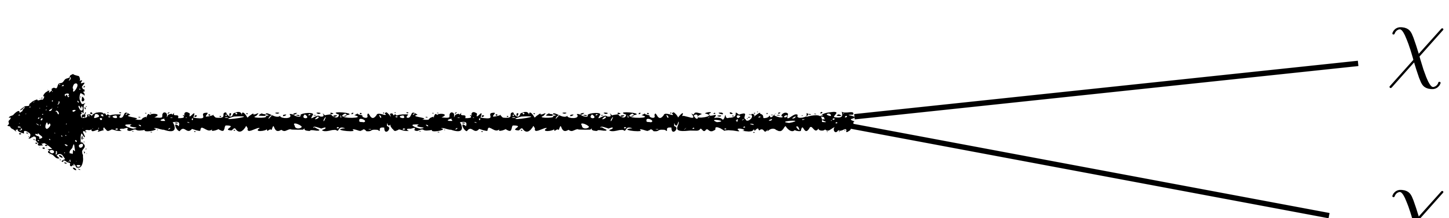
$$\mathcal{P}(t_R \to ht_L) \simeq \mathcal{P}(t_R \to Z_L t_L)$$

Junmou Chen, Tao Han and Brock Tweedie (2016)

DM production @ collider

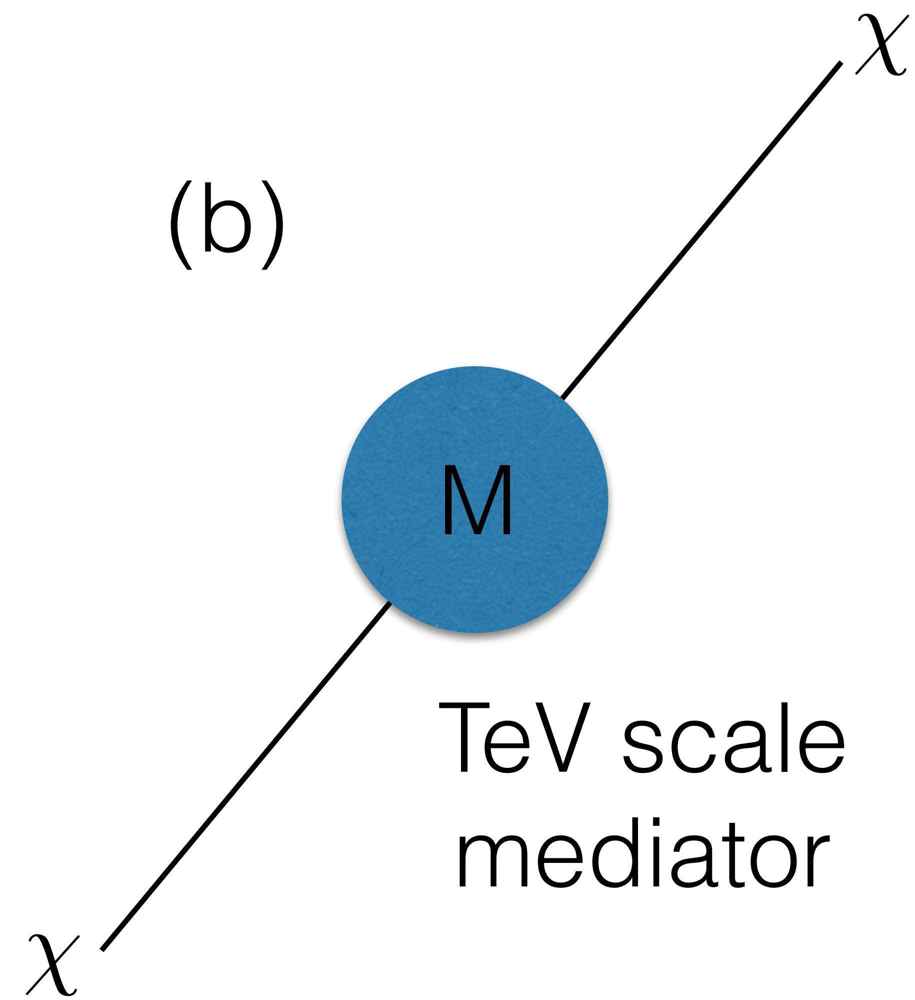
- To be more generic, we simulated “boosted” dark matter via
  (a). Hard recoil from High PT ISR jet
  (b). Hard back-to-back boost from a heavy mediator

(a)



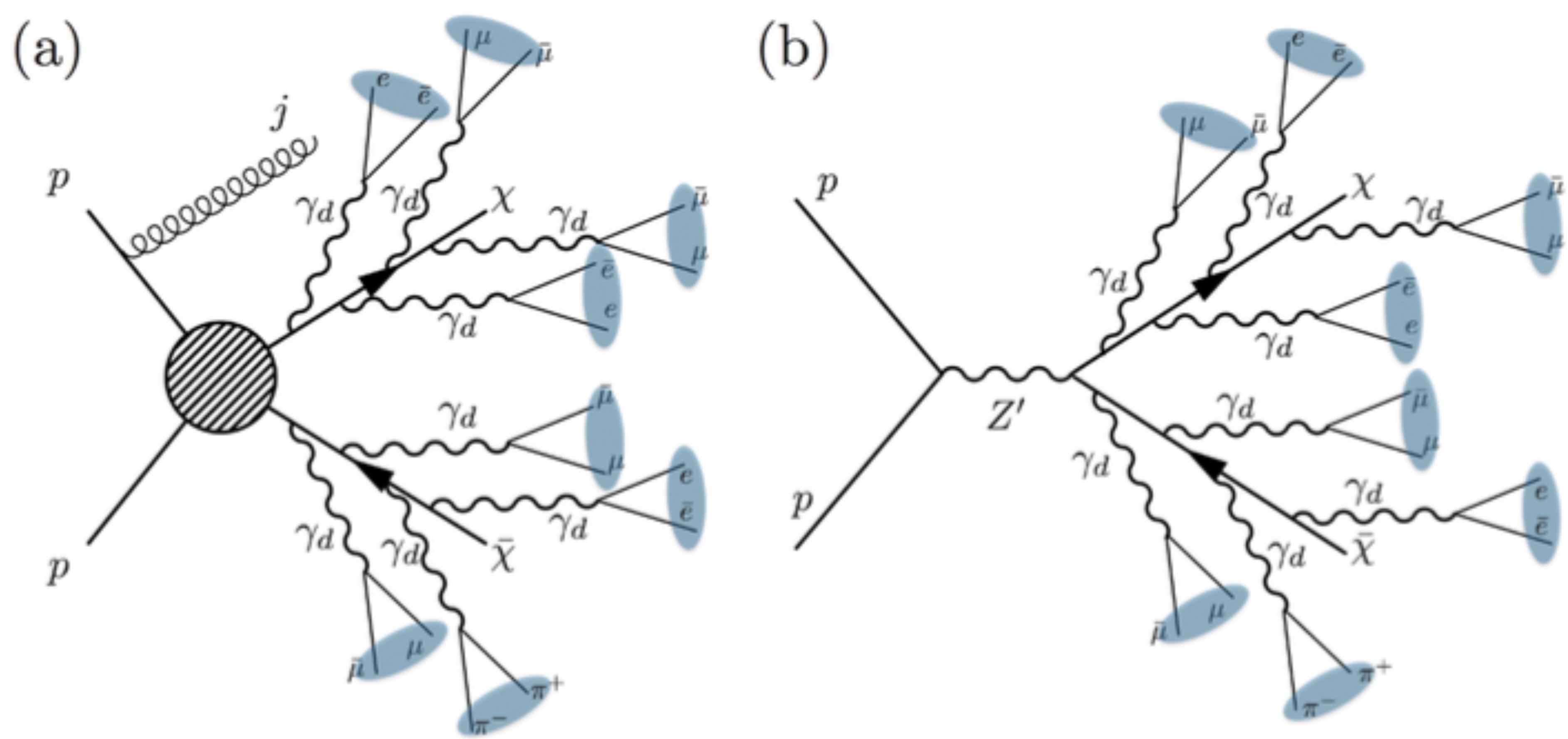
High PT ISR

(b)



DM production @ collider

- To be more generic, we simulated "boosted" dark matter via
  (a). Hard recoil from High PT ISR jet
  (b). Hard back-to-back boost from a heavy mediator



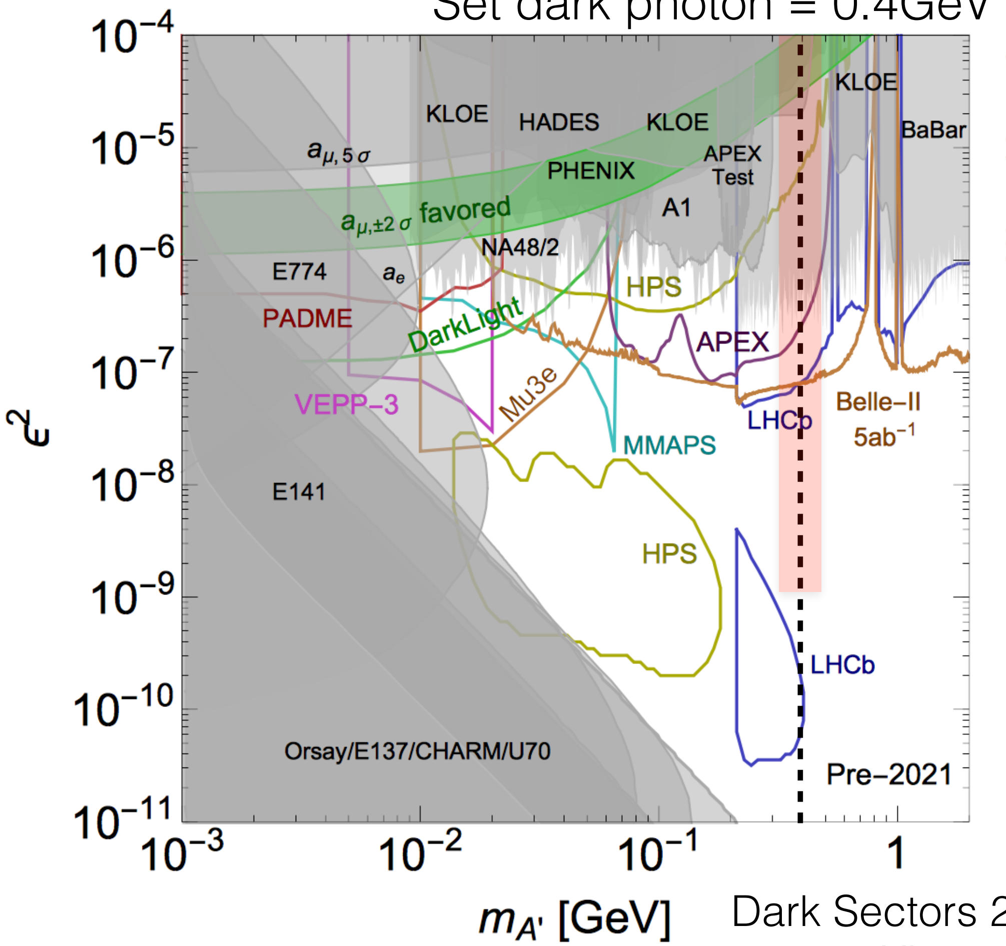
LHC can not produce a mediator directly (Effective operator)

LHC can produce a massive mediator (here Z')

Benchmark points

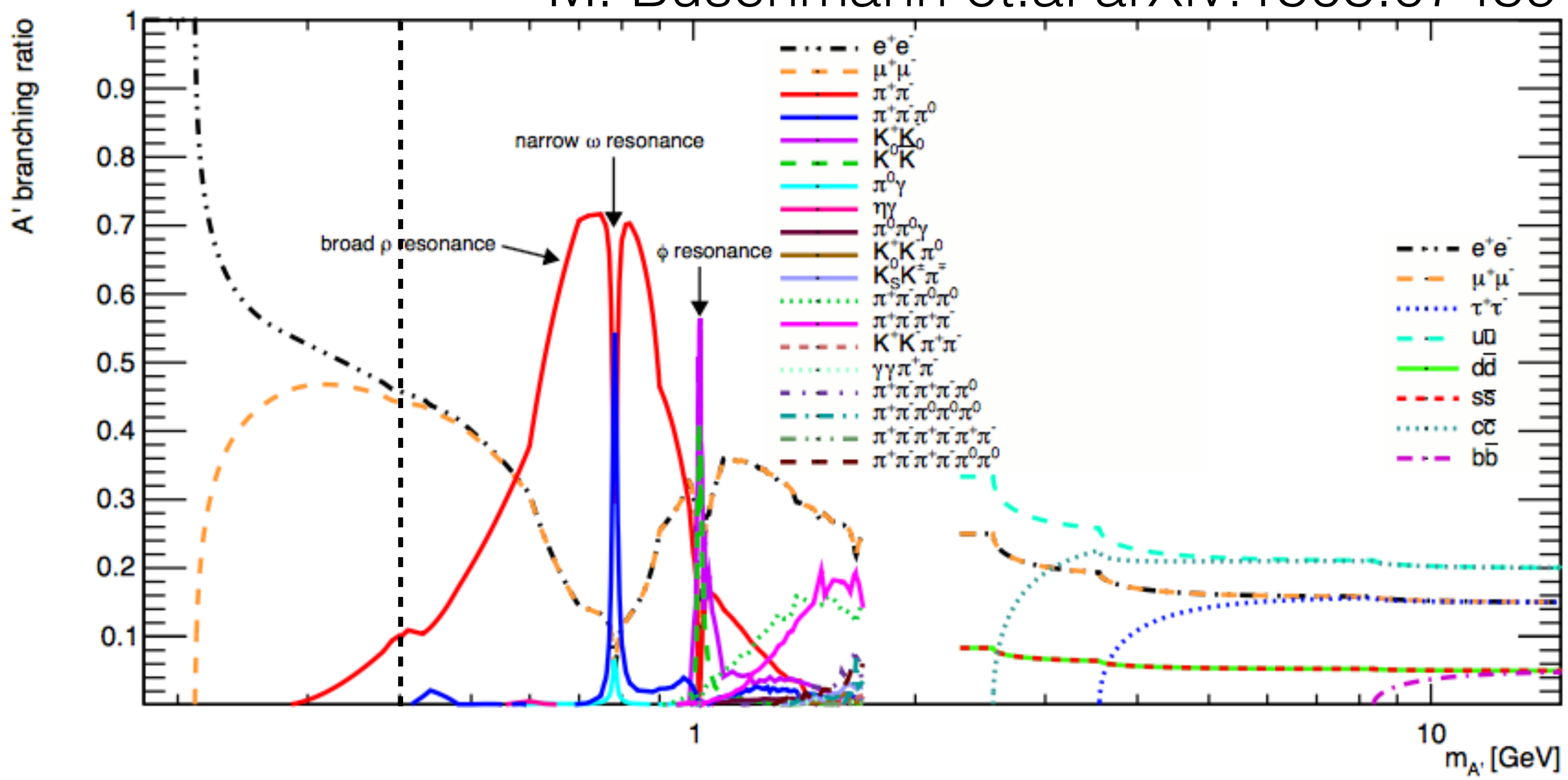
- We choose a bench mark point for
  - the prompt decays of a dark photon
  - Non-negligible decay mode into muons-pair to tag!

Set dark photon = 0.4GeV



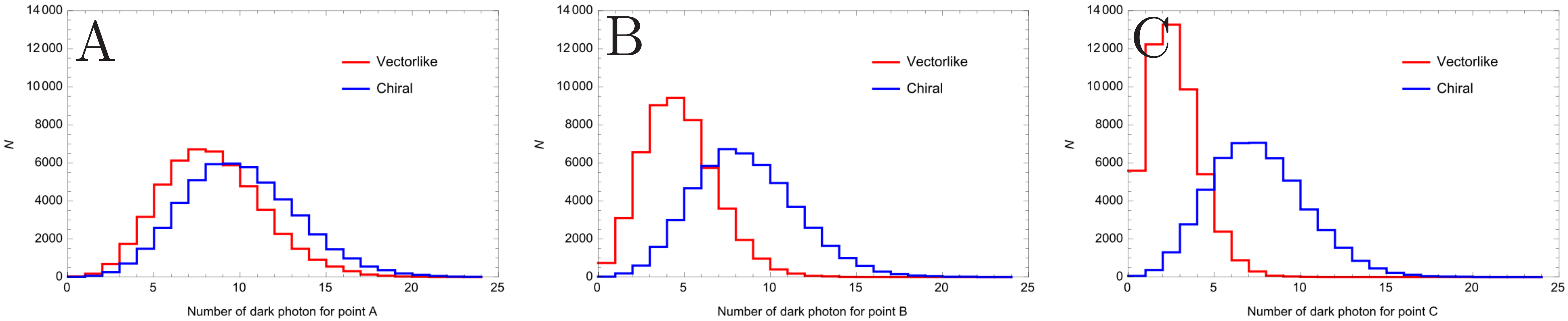
Dark Sectors 2016 Workshop
arXiv:1608.08632

M. Buschmann et.al arXiv:1505.07459



Different showering pattern @ collider

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



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	

TABLE I. Benchmark points we have chosen. They obey the perturbative limit of $\alpha' \frac{m_\chi^2}{m_{\gamma_d}^2} \lesssim 1$.

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

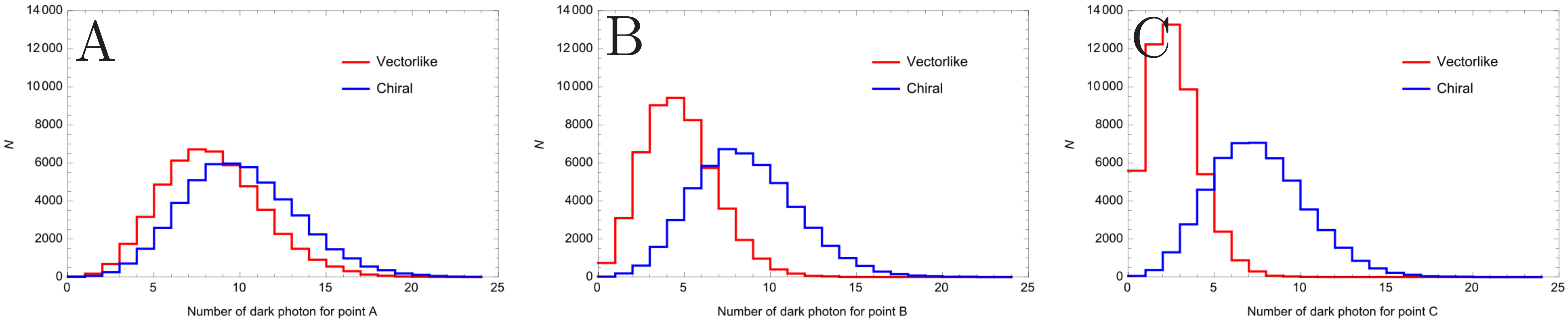
$$m_{\gamma_d} = g' Q'_\phi v_s$$

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

Different showering pattern @ collider

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

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



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		

@LHC, we may see the difference among various mechanism behind the mass of dark matter & a dark-photon

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

-($\alpha' << 1$) limits

$$\alpha' P_{\chi\to\chi\gamma_d} \sim \frac{m_{\gamma_d}^2}{v_s^2}\,\frac{m_\chi^2}{m_{\gamma_d}^2} \sim y_\chi^2$$

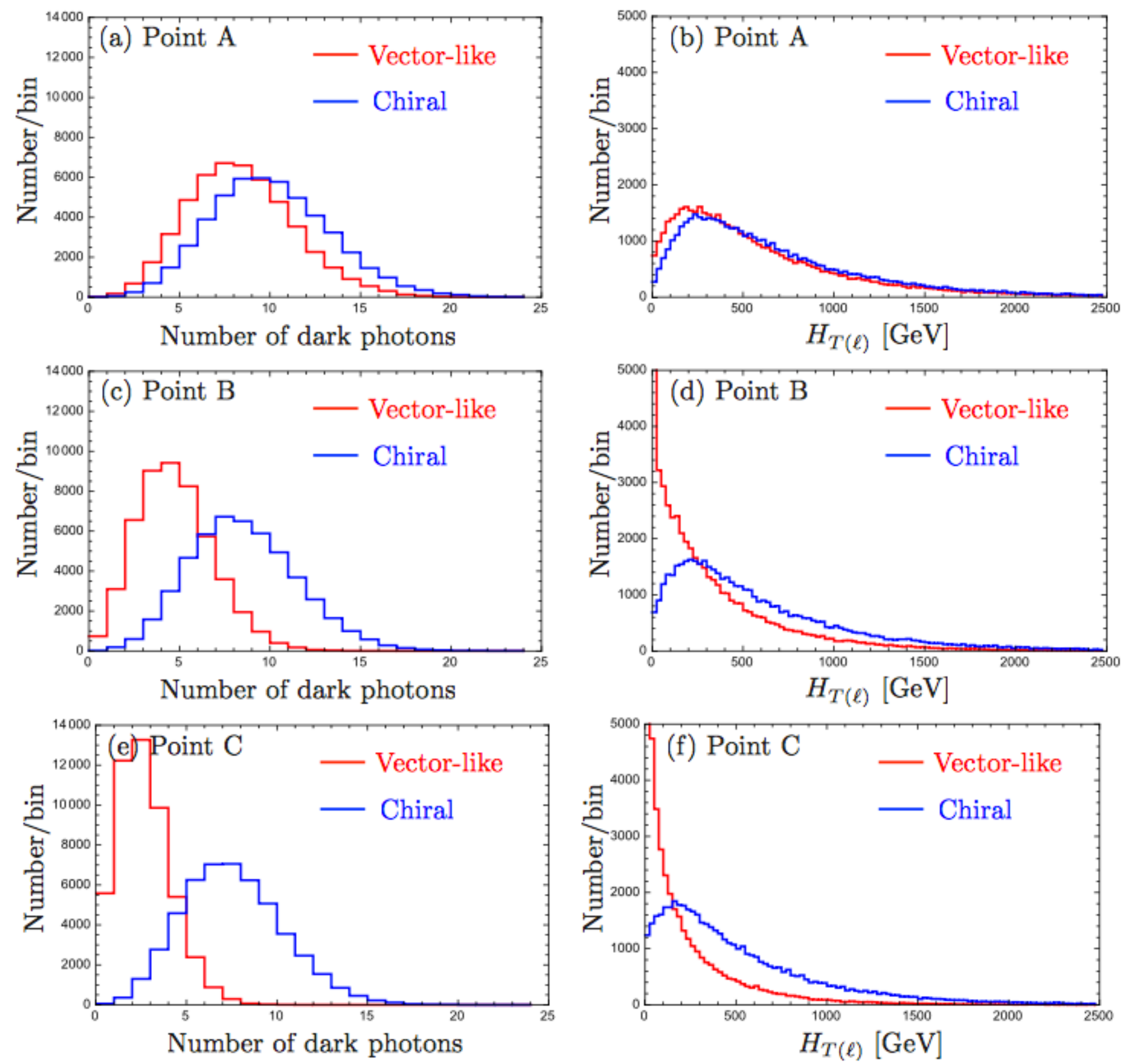
Quantify the difference

- 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		

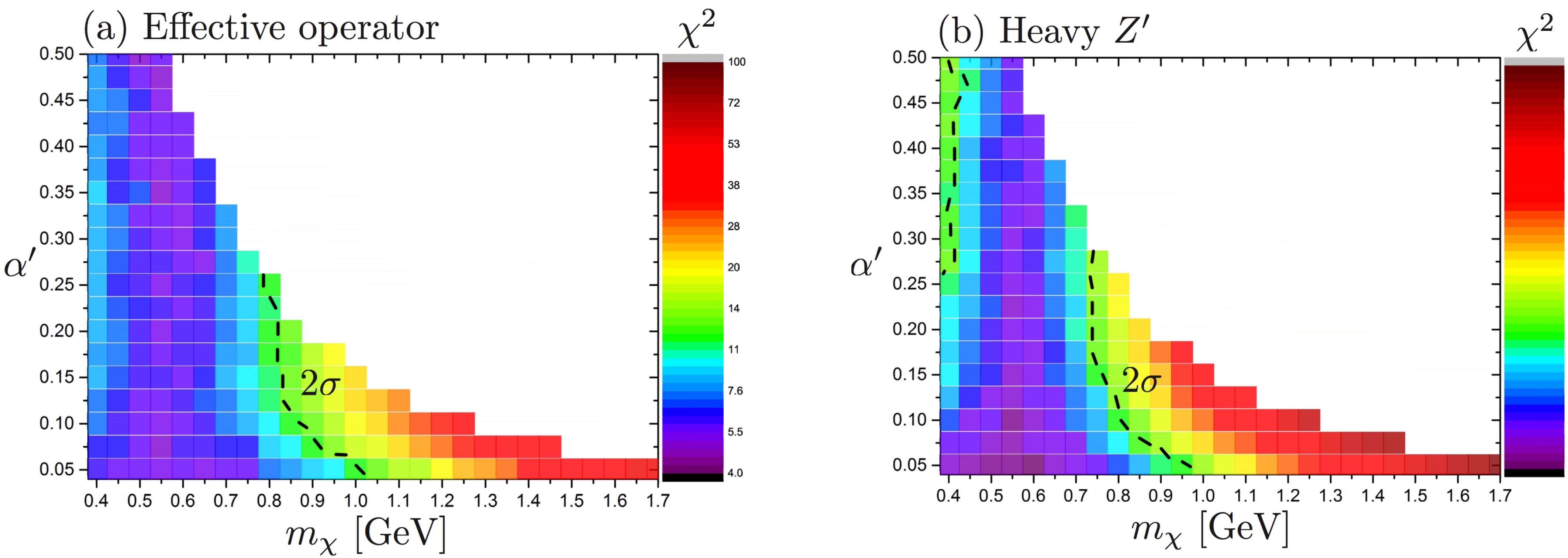
$$H_{T(\ell)} = \sum_{i=\mu^\pm, e^\pm} |p_{T\,i}|$$

-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 200 signal events after cuts to reduce BKG

(As BKG does not interfere with signal,
we can subtract BKG distribution)

Conclusion

- Collider 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 “**boosted**” dark matter.

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