Examining dark sector mass origin at collider

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Based on arxiv:1612.02850 (Minho Kim,Hye-Sung Lee, Myeonghun Park, MZ)

Outline

1. A brief review of dark photon

2. Dark photon search @ LHC

3. Different dark photon shower

4. Discussion and conclusion

Dark photon model

Motivation of a Dark interaction(See P.Ko's talk)

Consider a dark U(1)'. Kinetic mixing between U(1) and U(1)` could be induced by some high energy scale physics:

$$\mathcal{L}_{\rm kin.mix.} = \frac{1}{2}\epsilon F^{\mu\nu} F'_{\mu\nu}.$$

This is the dark "portal" in this model. Dark photon will couple to SM charge flow through this portal.

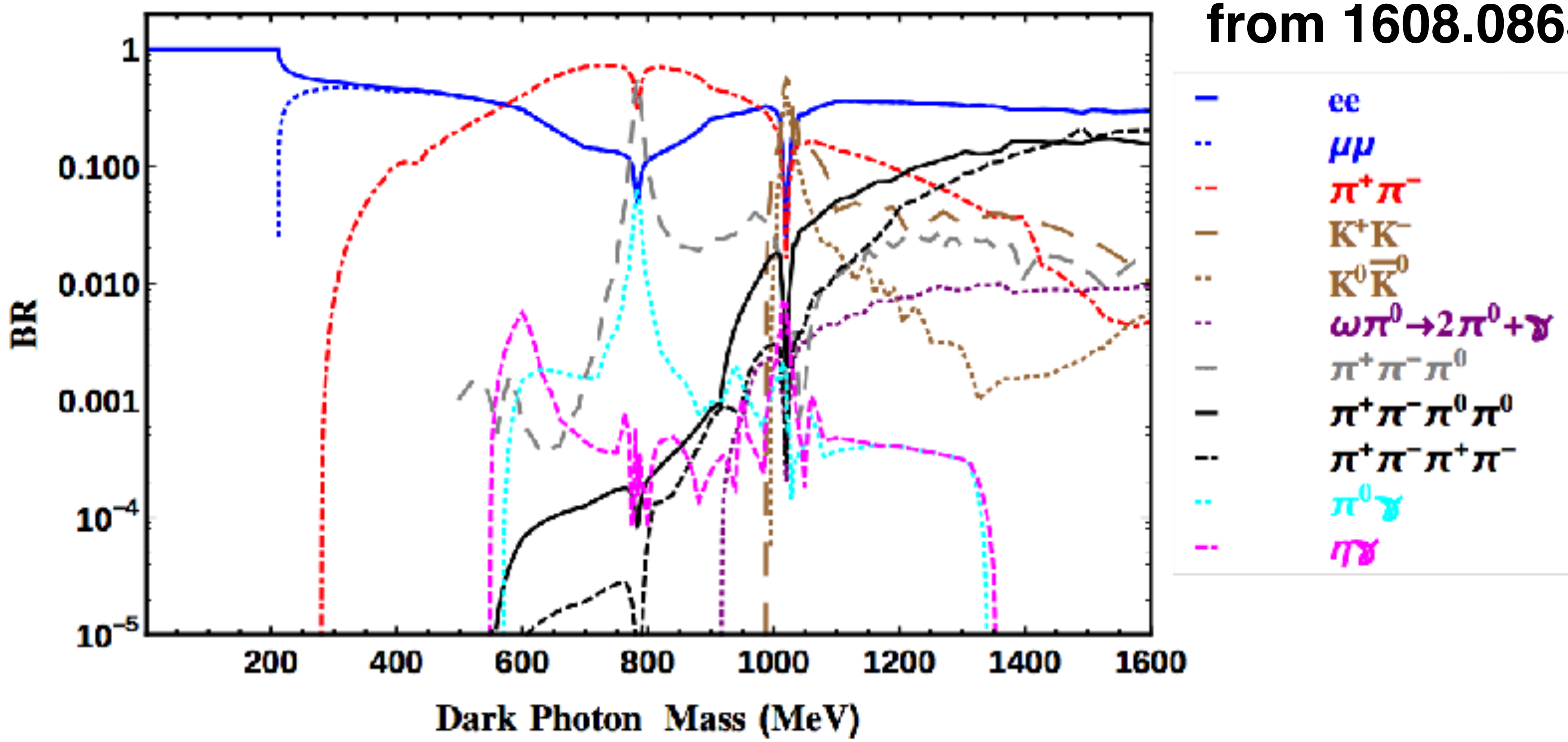
$$\mathcal{L}_{\rm int} = \epsilon\, e A'_\mu J^\mu_{\rm EM}\,,$$

The search of dark photon is independent.

Dark photon decay

The decay of dark photon only depend on its mass:

from 1608.08632



There are just two parameters in this simple extension:
kinetic mixing and **dark photon mass**.

life time

decay pattern

The detection of dark photon

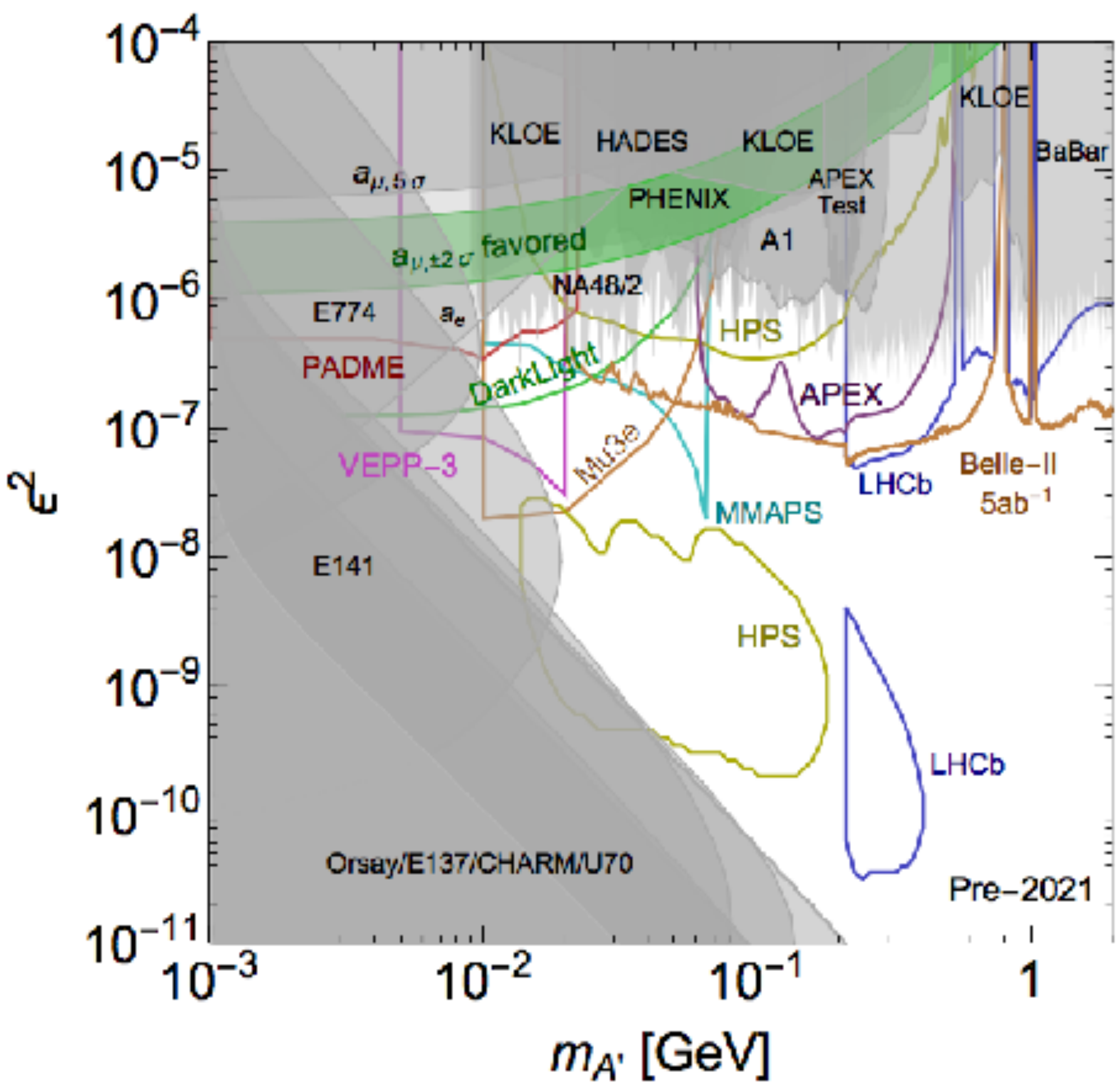
signal:

Fixed tagget expriment: $e^- N \to e^- N A'$

ep collision: $e^- e^+ \to \gamma A'$

meson rare decay: $\pi^0 \to \gamma A'$ $K \to \pi A'$

$A' \to visible$ or $A' \to missing$ (depend on mixing ϵ)

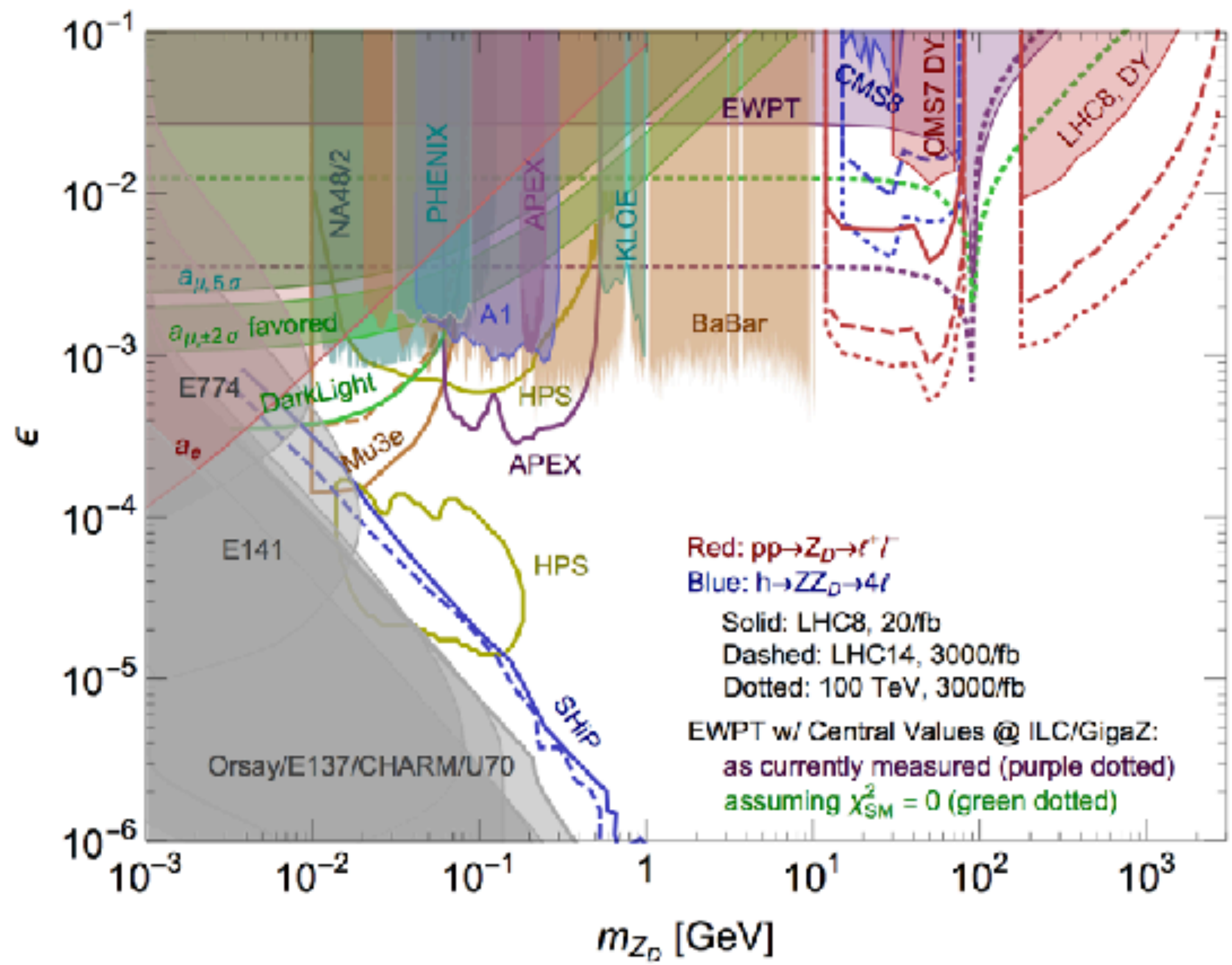


Gray region is the region excluded by current Exp.

from 1608.08632

PP collider ?

Can we use the huge energy produced by LHC to study the dark photon phenomenology?
You can consider DY process pp->A'->ffbar or pp->h->ZA':

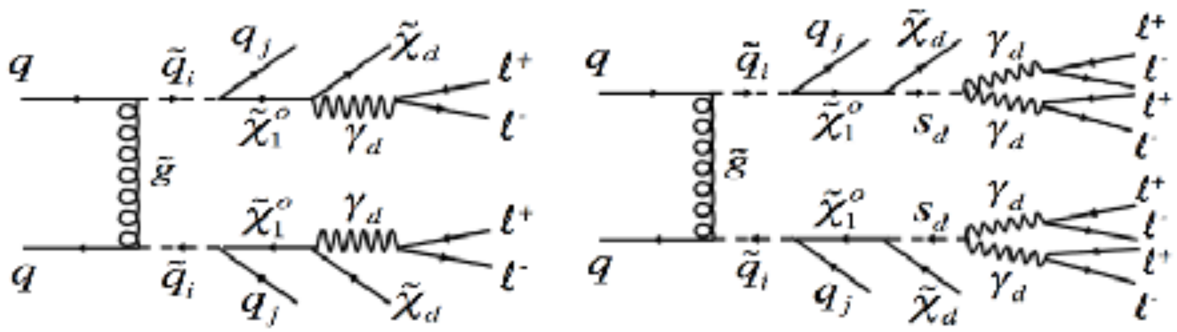


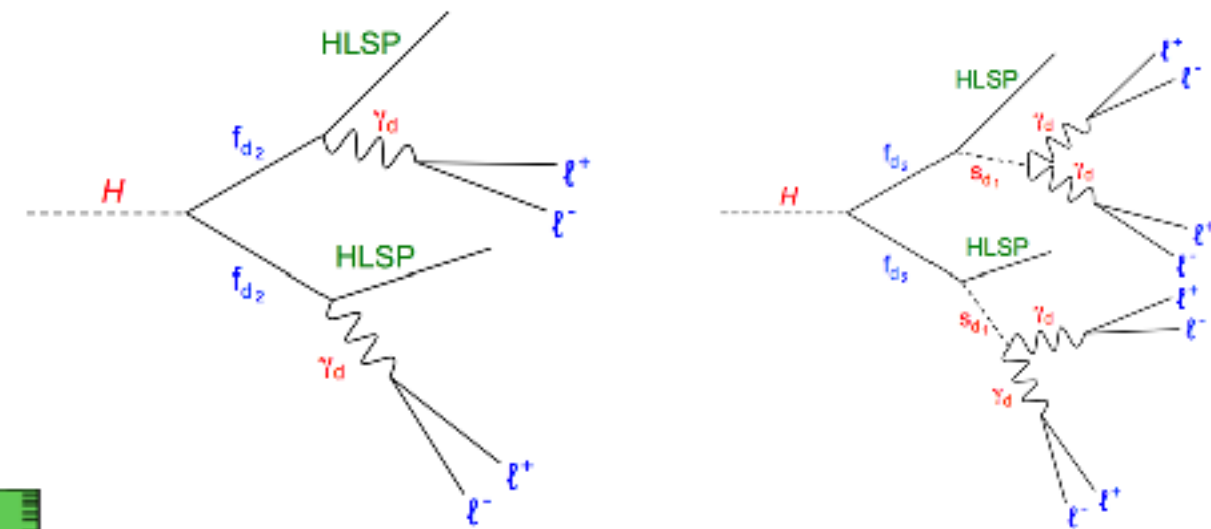
But the sensitive region is >10GeV

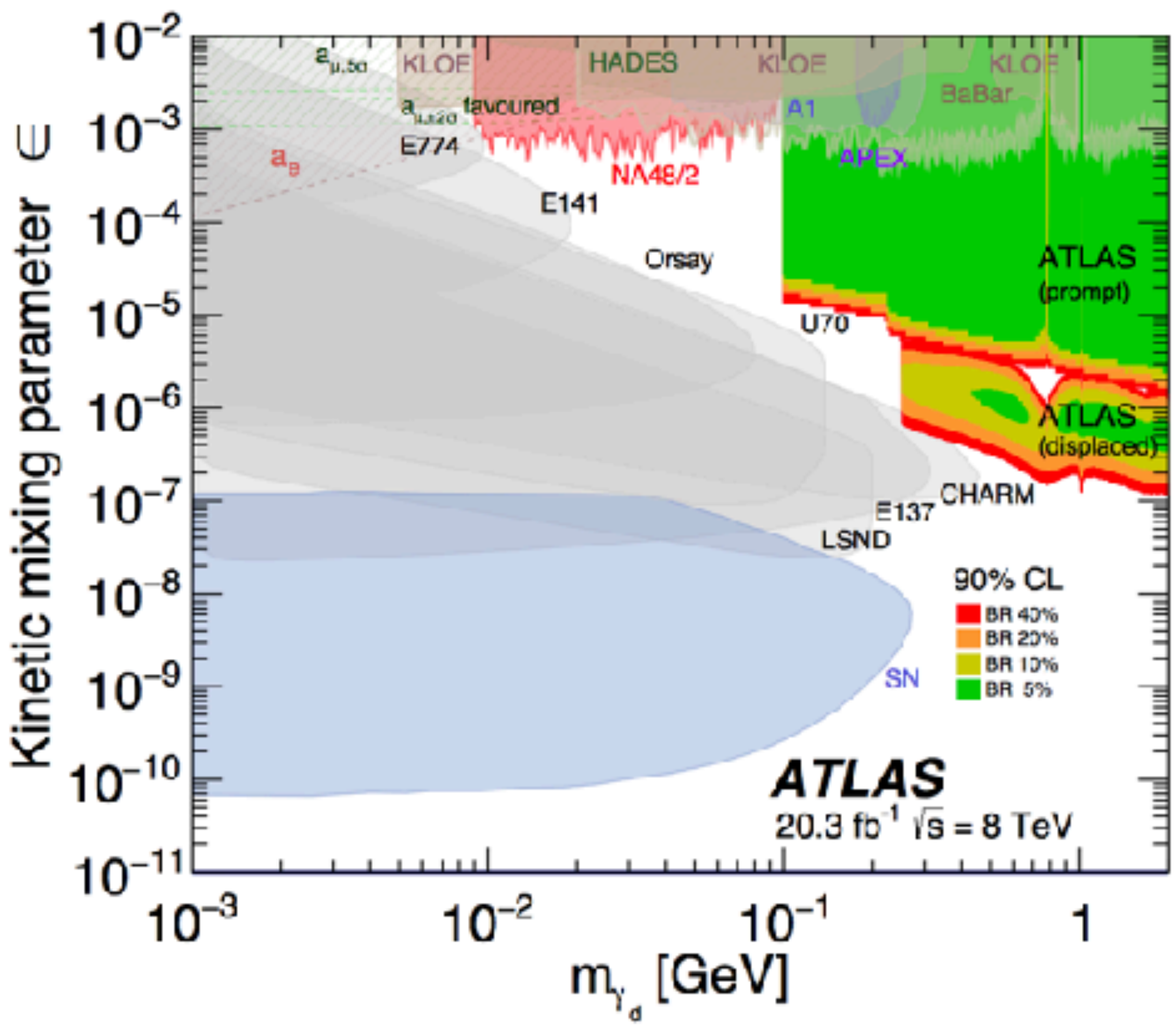
1412.0018

How to access Gev/Sub GeV region by High energy pp collider ?

Kinetic mixing as a minimal portal is not enough, you need to consider other mediator:







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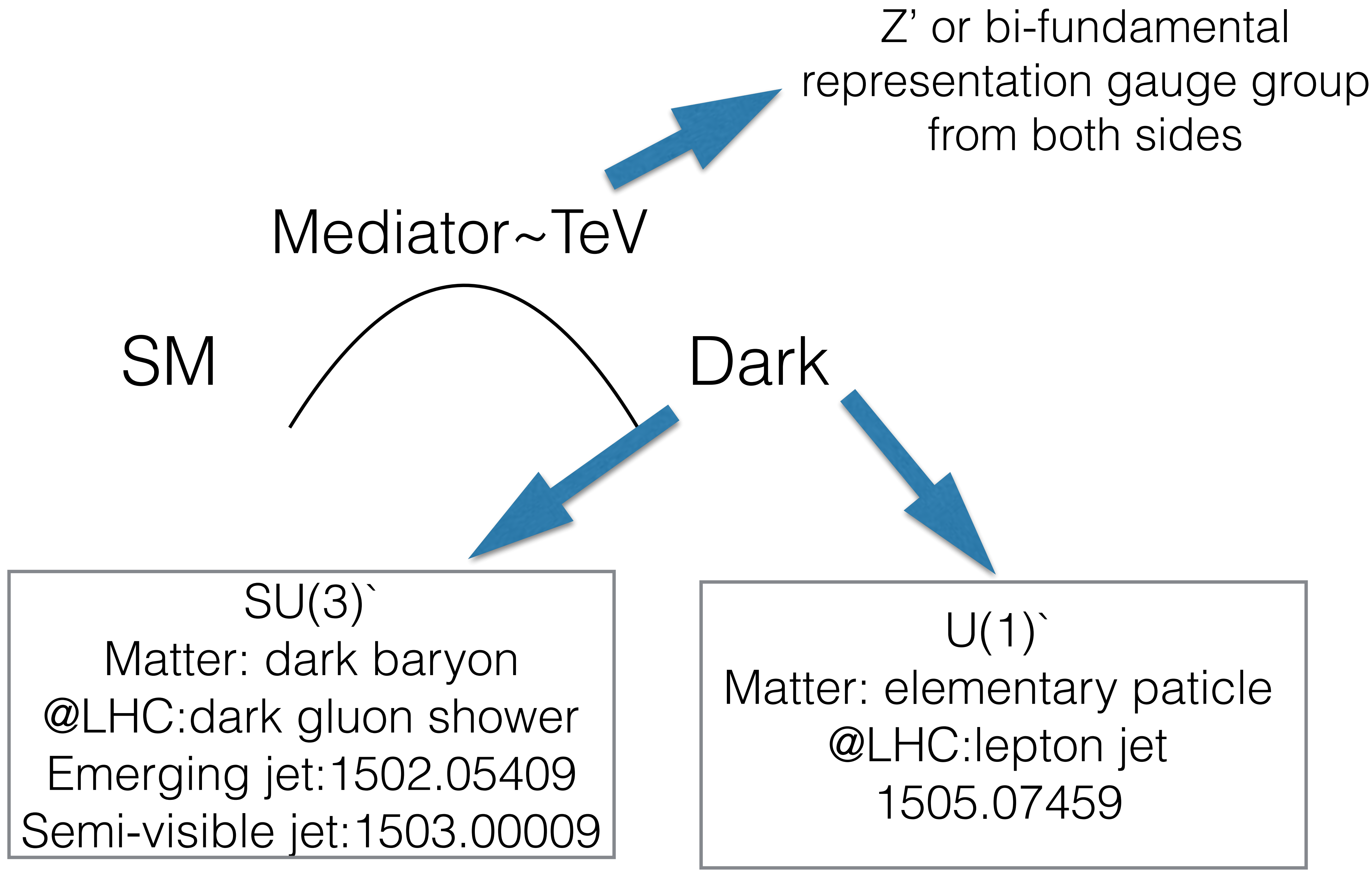
Those dark photon come from decay. But dark photon can also come from dark sector shower

Consider Hidden Valley Model

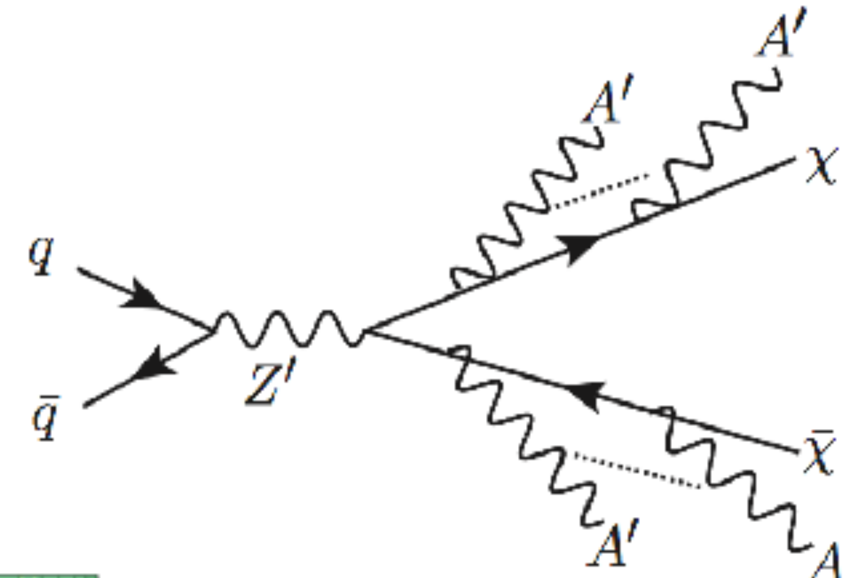


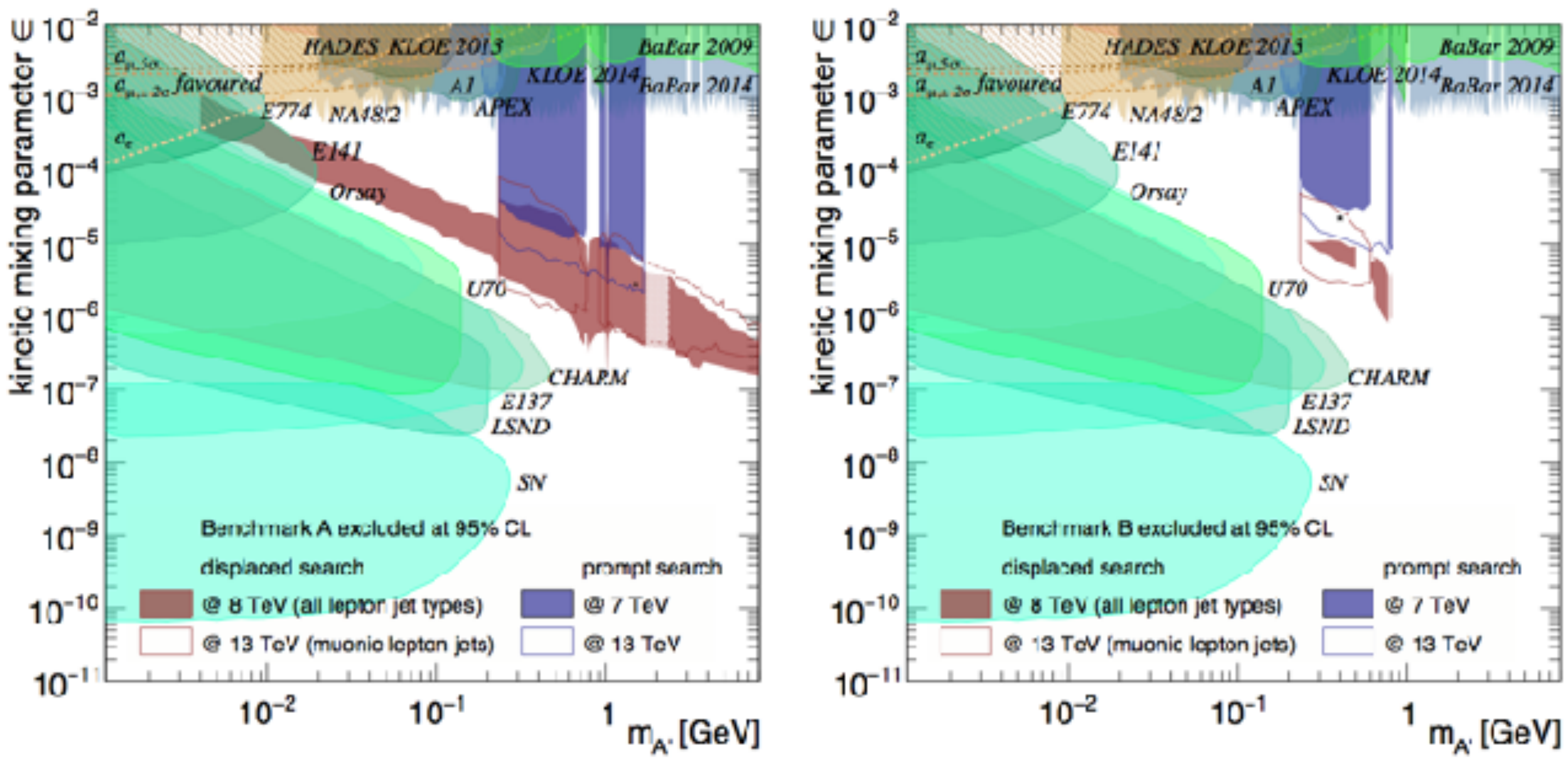
Previous Study

Lagrangian of light dark sector:

$$\mathcal{L}' = \bar{\chi}\left(i\partial\!\!\!/ - m_\chi + ig' A\!\!\!/'\right)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

+ TeV scale Leptophobic Z'





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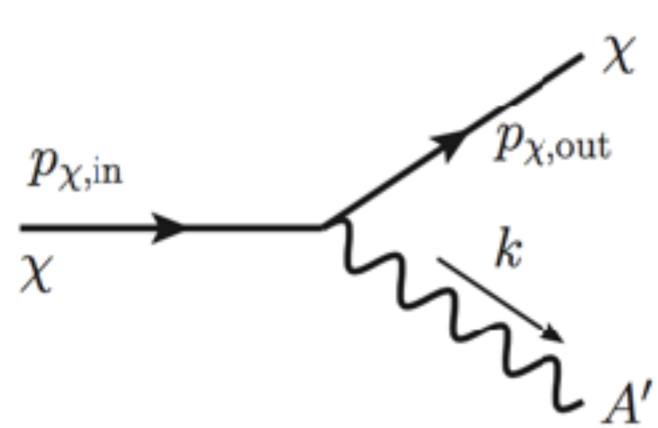
Reconsider dark photon shower

The L in light dark sector:

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

Higgs or Stueckelberg

Dark matter is vector like, you write down the mass term directly.



x

$1 - x$

Splitting Kernel: $P_{\chi\to\chi}(x) = \dfrac{1+x^2}{1-x}$

x and 1-x is the energy distribution

The Splitting Kernel only include the contribution from transverse polarization.

This is also the Hidden Valley shower implemented in Pythia8.

Consider some difference

You can ask two questions in here:

1.What is the contribution of longitudinal mode?

2.What if the the dark matter is chiral and there is a Higgs mechanism in the light dark sector.

Tame the longitudinal mode by gauge choice

Polarization vector of Longitudinal mode proportional to $\frac{E}{m}$

Naive calculation will overestimate the contribution from L-mode

Huge cancelation happens in here (like $W_L W_L \to W_L W_L$)

How to avoid such cancelation and get a physical behavior for one simple Feynman graph?

Tame the longitudinal mode by gauge choice

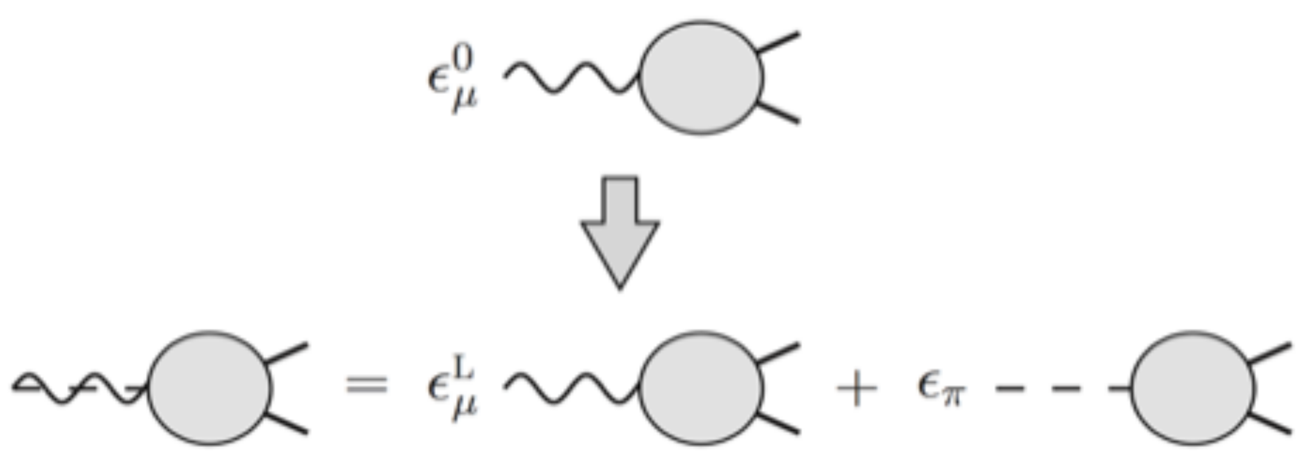
A more clever gauge choice:

0202142: light cone gauge

1611.00788: Goldstone Equivalence Gauge

$$\mathcal{L}_{\text{fix}} = -\frac{1}{2\xi}\big(n^{\mu}(k)\,W_{\mu}(k)\big)\big(n^{\nu}(k)\,W_{\nu}(-k)\big), \qquad (\xi \to 0)\ .$$

1309.6055: Use BRST symmetric transition



$$\epsilon^{L}_{\mu}(\mathbf{p}) \equiv \epsilon^{0}_{\mu}(\mathbf{p}) + i\,\epsilon^{s}_{\mu}(\mathbf{p}) = -\frac{m}{E_{\mathbf{p}} + |\mathbf{p}|}\left\{1,\ \frac{\mathbf{p}}{|\mathbf{p}|}\right\}$$ ← Suppressed by energy

$$\epsilon_{\pi}(\mathbf{p}) \equiv -i\,.$$ ← Goldstone equivalent theorem

New model and new splitting kernel

Chiral dark matter + Dark Higgs mechamism

$$\mathcal{L}_{Higgs} = i\overline{\chi}_L(\partial\!\!\!/ + ig'A\!\!\!/')\chi_L + i\overline{\chi}_R(\partial\!\!\!/)\chi_R - y\left(\overline{\chi}_L\phi\chi_R + \overline{\chi}_R\phi^*\chi_L\right)$$
$$-\frac{1}{4}(F'_{\mu\nu})^2 + |(\partial_\mu + ig'A'_\mu)\phi|^2 - V(\phi).$$

New model and new splitting kernel

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$$-\frac{1}{4}(F'_{\mu\nu})^2 + |(\partial_\mu + ig' A'_\mu)\phi|^2 - V(\phi).$$

$$\mathcal{L}_{SSB} = \overline{\chi}(i\partial\!\!\!/ - m_\chi)\chi - g' A_\mu \overline{\chi}(\gamma^\mu P_L)\chi - iy\frac{\varphi}{\sqrt{2}}\overline{\chi}\gamma^5\chi$$
$$-\frac{1}{2}A'_\mu\left(-g^{\mu\nu}\partial^2 + (1-\frac{1}{\xi})\partial^\mu\partial^\nu - m^2_{A'}g^{\mu\nu}\right)A'_\nu$$
$$+\frac{1}{2}(\partial_\mu\varphi)^2 - \frac{\xi}{2}m^2_{A'}\varphi^2 + \cdots .$$

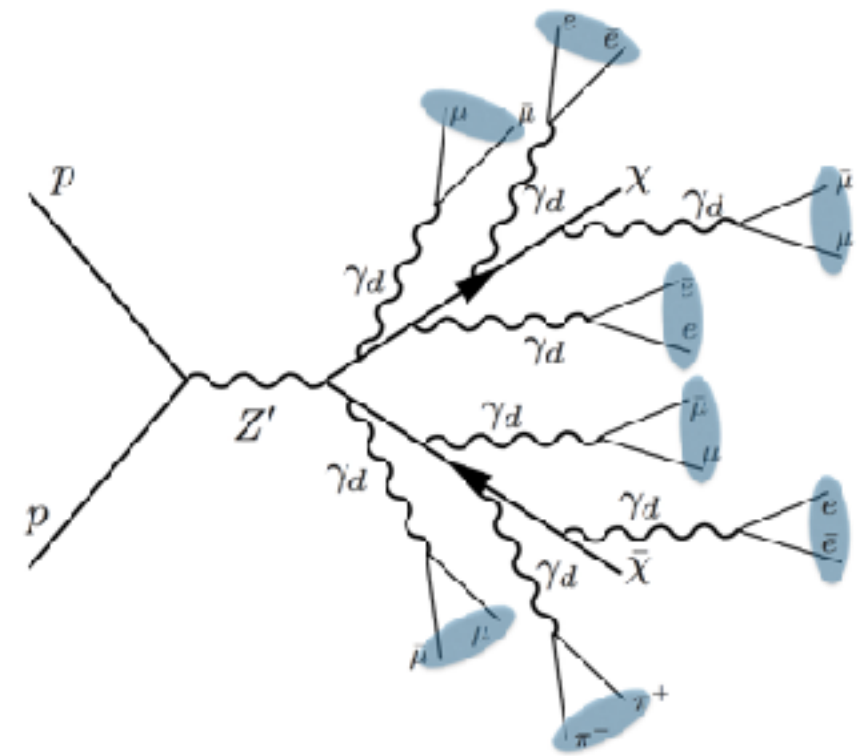
Then

$$P_{\chi\to\chi}(x) = \frac{1+x^2}{1-x} \quad\Rightarrow\quad P_{\chi\to\chi}(x) = \frac{1}{2}\frac{1+x^2}{1-x} + \frac{1}{2}\frac{m^2_\chi}{m^2_{A'}}$$

splitting kernel change

Show some difference

We also consider a Leptophobic Z':



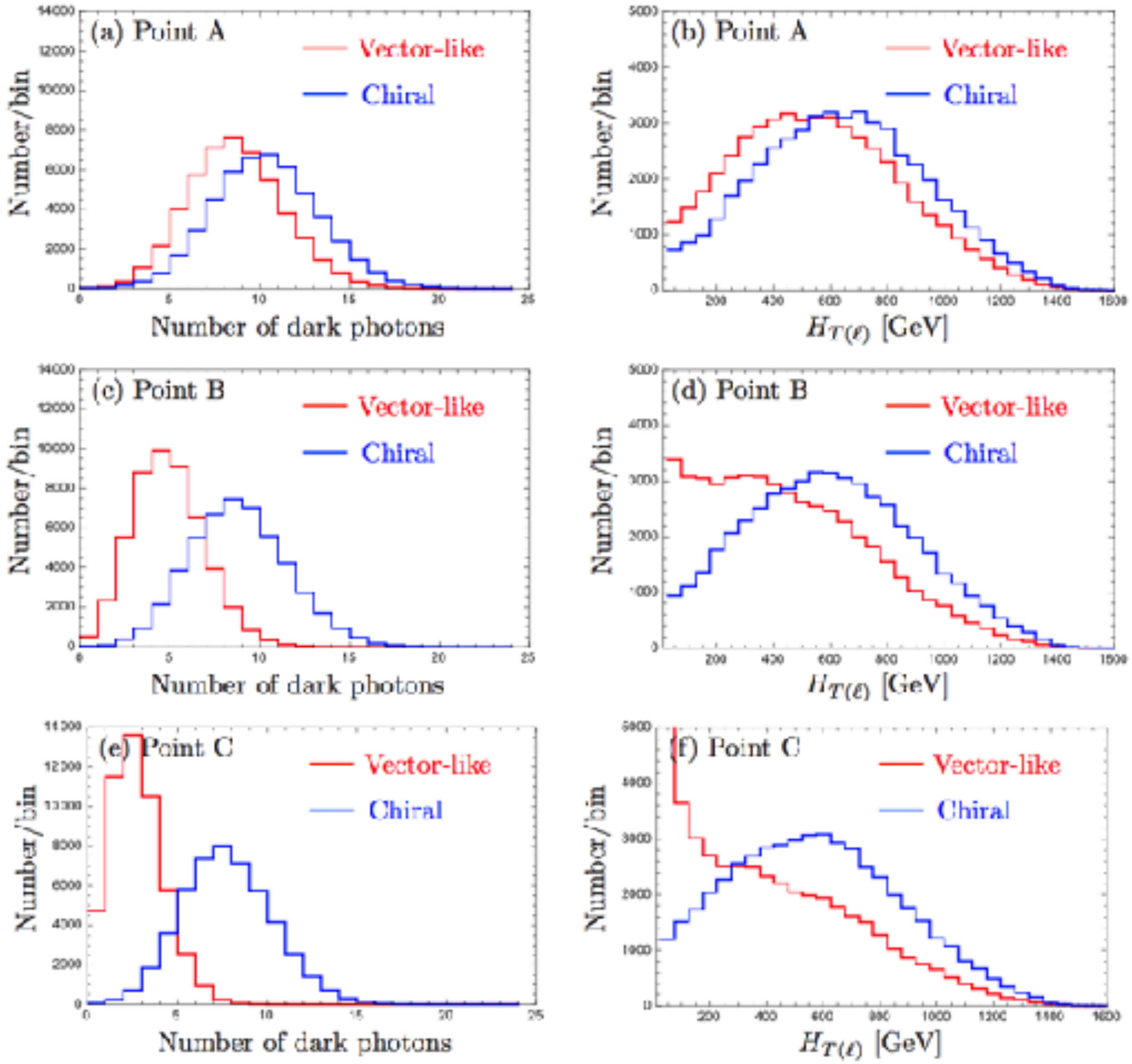
And 3 benchmark points:

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		

Show some difference

Shower strength compare:

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		



$$H_{T(\ell)} = \sum_{i=\mu^\pm, e^\pm} |p_{T\,i}|.$$ is the pT scalar sum of all leptons

How to distinguish different model?

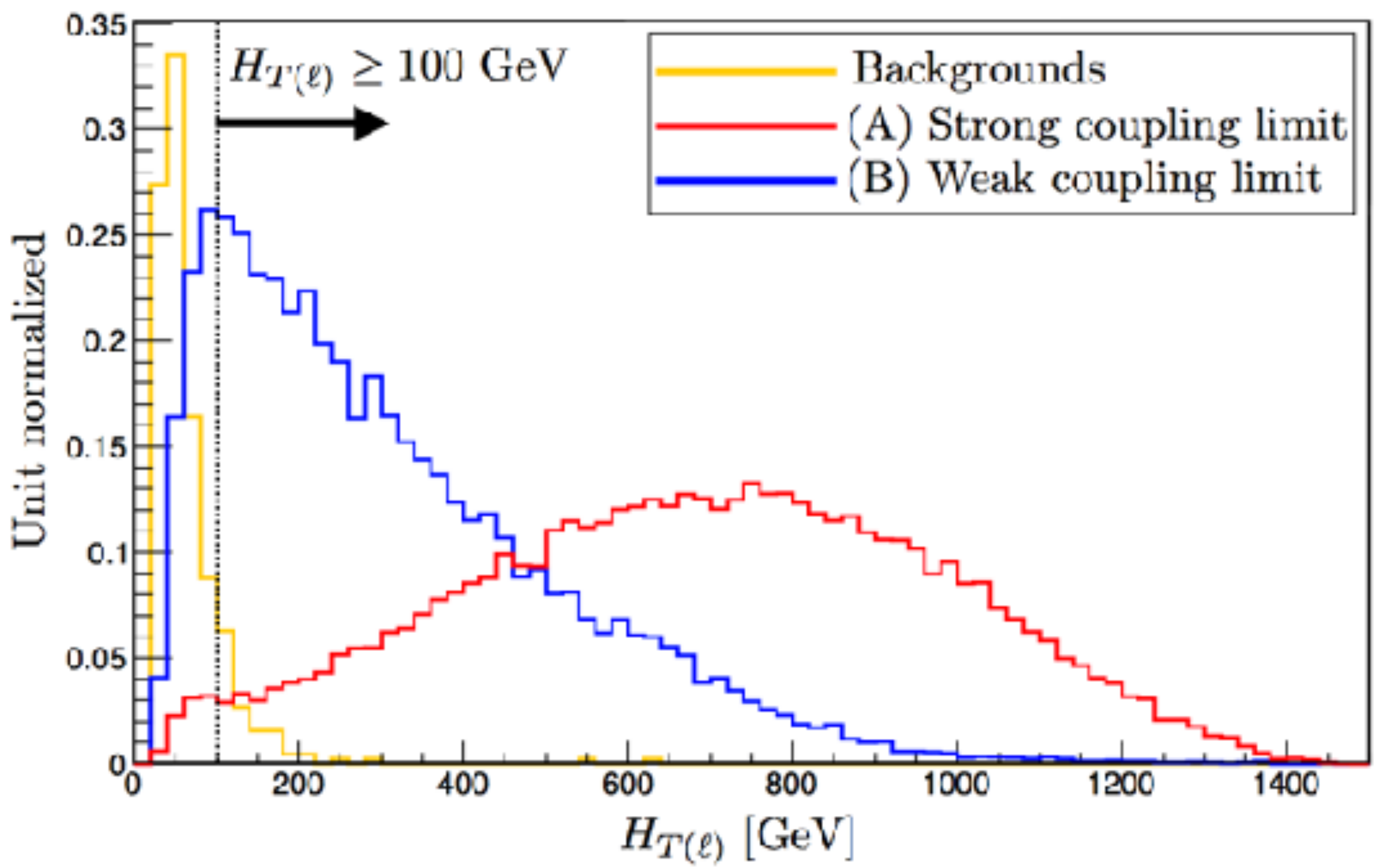
We don’t prepare to do another recast this work, we try to answer another question: how to distinguish these two models?

To be more specific:
If we have measured the spectrum and gauge coupling in the light dark sector, can we use the shower of dark photon to distinguish the mass origin of dark matter?

Consider seriously

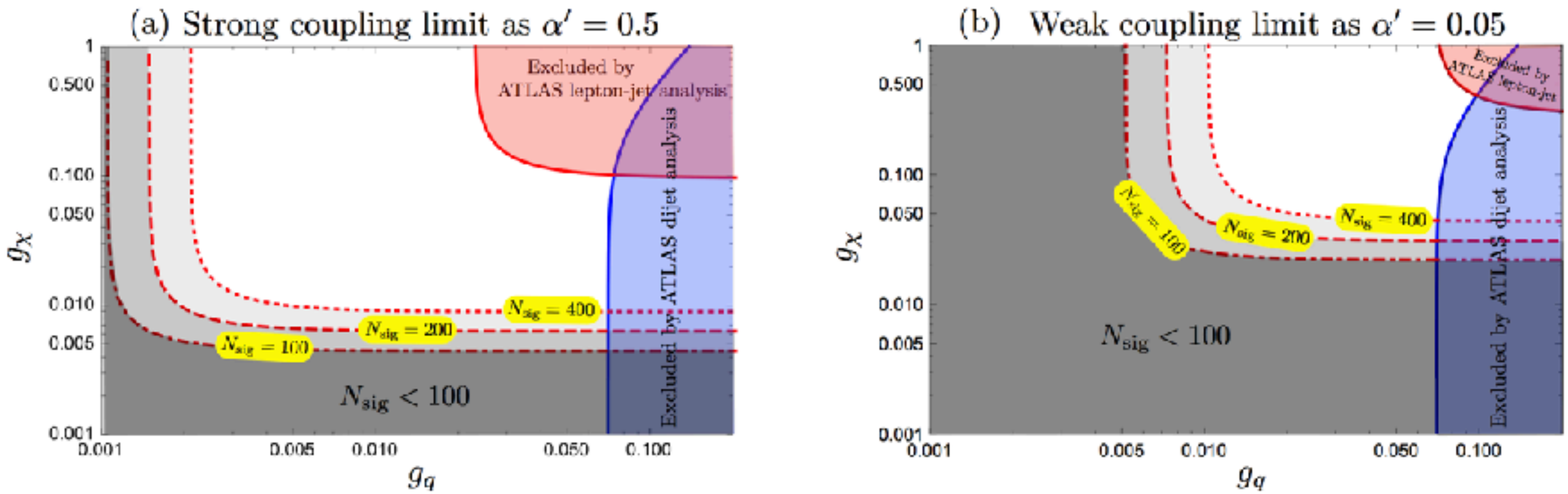
Maybe we can use the distribution of H_T(l) to distinguish the nature of dark matter and the mass origin of dark sector. Then we need to consider:
1.What is the parameter space allowed by current limit.(A recast to dijet and lepton-jet reports)
2.Sufficient signal should be produced at future collider. A efficient cut-flow need to be used to cut BKG.

Cut-flow for future search:
lepton-jet, isolation, mass window of lepton jet, H_T(l) cut.
Here is the H_T(l) distribution after front cut:

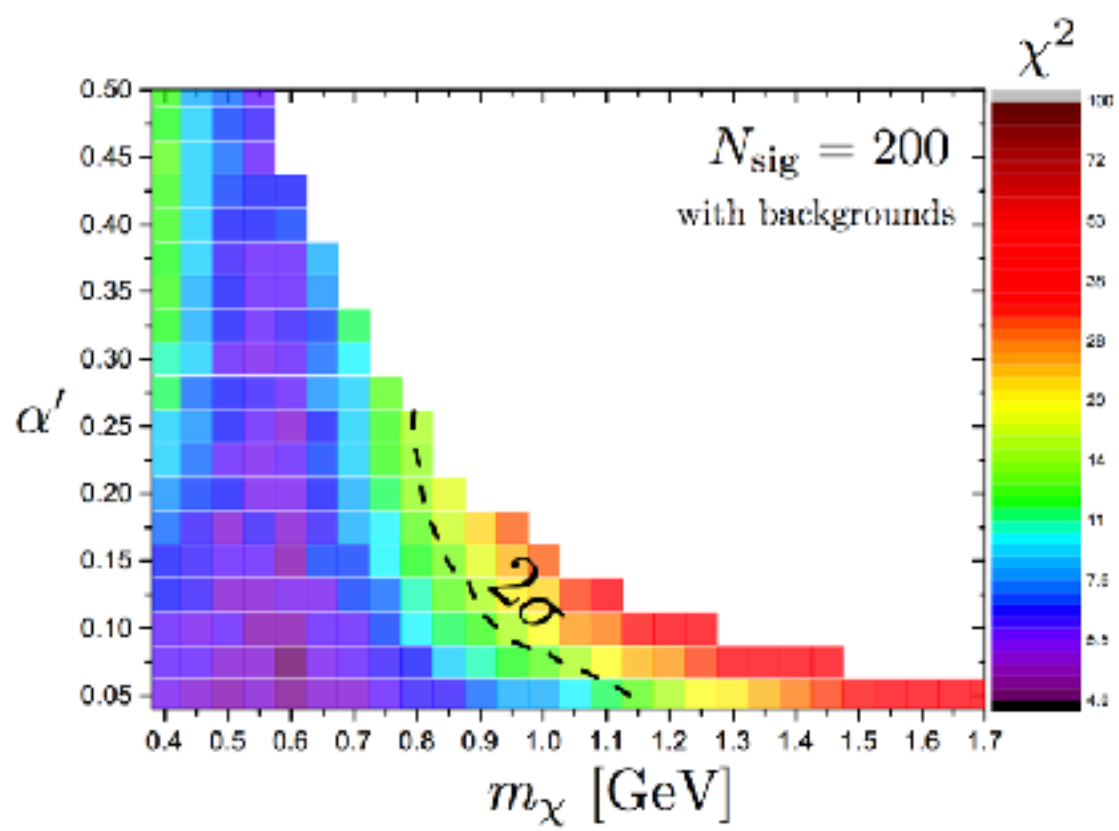


Final results

Allowed parameter space:



Some region can be distinguished.



Conclusion

Light dark matter with a U(1)’ gauge coupling is a popular dark sector setting. And different dark matter model(vector-like/chiral) will induce different dark shower. In this work we propose such different shower can be used to distinguish dark matter mass origin(if there is a dark sector Higgs mechanism)