Leptophilic Composite Asymmetric Dark Matter and its Detection

Joint Workshop of the CEPC Physics, Software and New Detector Concept in 2022

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2022-05-25

Based on (*Phys.Rev.D 104,055008)* MZ

Outline

1.Motivation for Composite Asymmetric Dark Matter (ADM)

2.Model Introduction

3.Direct Search

4.Collider Search (LHC v.s. CEPC)

5.Conclusion

Motivation of composite ADM

$$\Omega_{\rm DM} : \Omega_{\rm B} \sim 5 : 1$$

We need a asymmetry between baryon and anti-baryon:
1)C and CP violation
2)B-number broken
3)deviation from equilibrium

Baryon mass comes from QCD confinement

WIMP:
Heavy Majorana particle freeze out

WIMP mass is given by hand (soft term in SUSY)

Motivation of composite ADM

$$\Omega_{\mathrm{DM}} : \Omega_{\mathrm{B}} \sim 5 : 1$$

So maybe the true story is like:

Baryon-anti-baryon asymmetry:
1)C and CP violation
2)B-number broken
3)deviation from equilibrium

DM-anti-DM asymmetry:
1)C and CP violation
2)D-number broken
3)deviation from equilibrium

Baryon mass and DM (dark baryon) mass comes from QCD confinement and Dark-QCD confinement respectively.

Model Introduction

Consider a scalar mediator Φ couple to "dark quark" and SM quark:

$$\mathcal{L} \supset \kappa \Phi \bar{q}' q$$

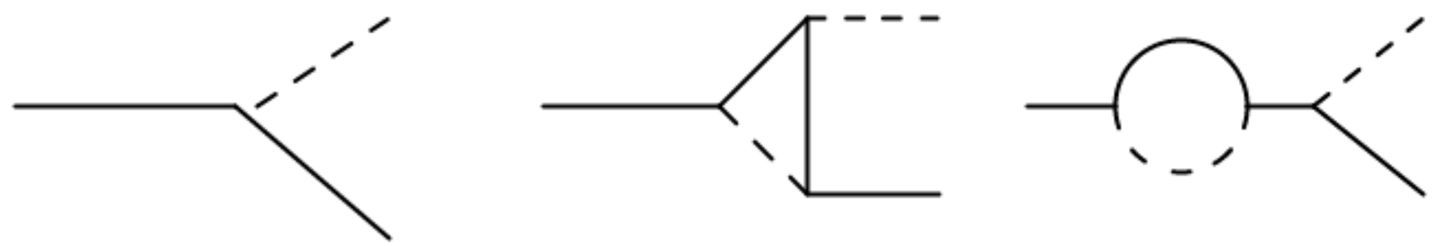
quark

dark quark

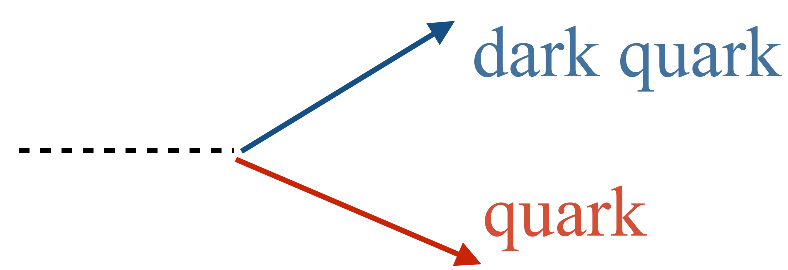
arXiv:1306.4676

Step 1: generate the asymmetry of mediator Φ. For example, CPV& out of equilibrium decay of heavy neutral particle:

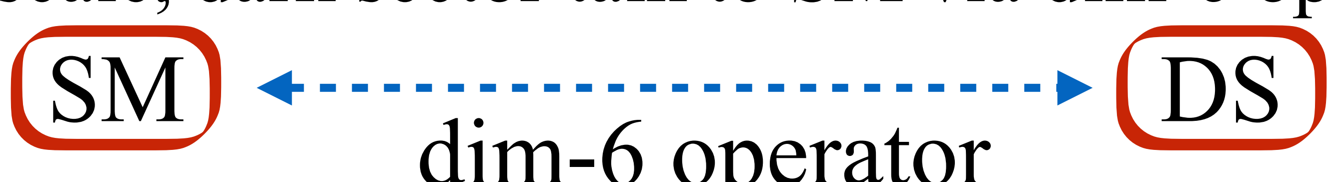
$$\mathcal{L} \supset k_i \bar{Y}_1 \Phi N_i + \text{h.c.}$$



Step 2: mediator Φ decay to "dark quark" and SM quark, and thus generate "dark baryon" and baryon asymmetry simultaneously:



At low energy scale, dark sector talk to SM via dim-6 operator:



Model Introduction

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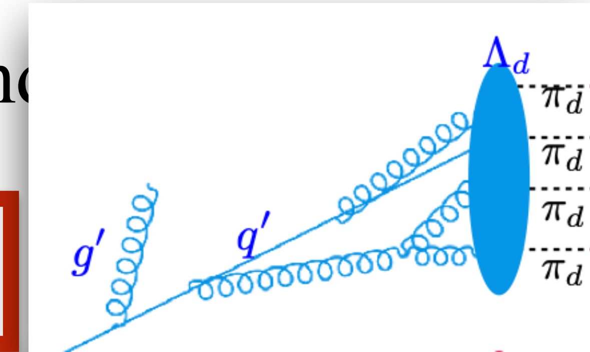
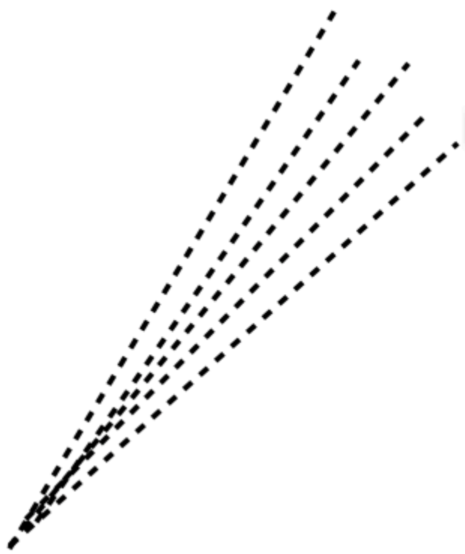
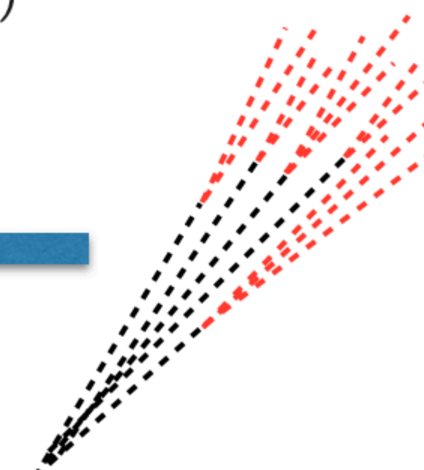


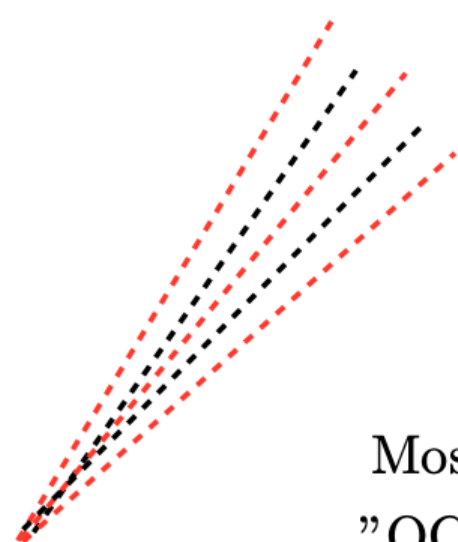
Unique signal: dark jet!



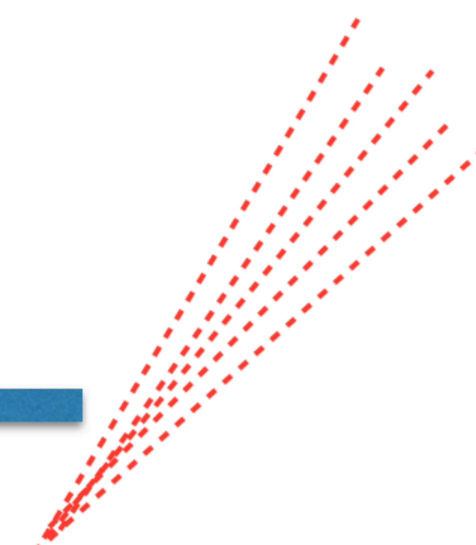
Most dark mesons are stable or stable enough.
Invisible Jet (Missing Energy)



Most dark mesons are long-lived.
Emerging Jet (Displaced Track)
JHEP **1505**, 059 (2015)



A fraction of dark mesons are stable.
Semi-visible Jet (Transverse Mass)
Phys. Rev. Lett. **115**, no. 17, 171804 (2015)



Most of dark mesons decay to visible particles promptly
"QCD-like" dark jet. We can use jet sub-structure (q/g)
Phys.Rev.D 100 (2019) 11, 115009 Myeonghun Park, MZ

Model Introduction

Another possibility: what if Φ couples to L + q\` instead of q + q\`:

$$\mathcal{L} \supset \kappa \Phi \bar{q}' l$$

lepton

dark quark

arXiv:2104.06988

Step 1: generate the asymmetry of mediator Φ. For example, CPV& out of equilibrium decay of heavy neutral particle:

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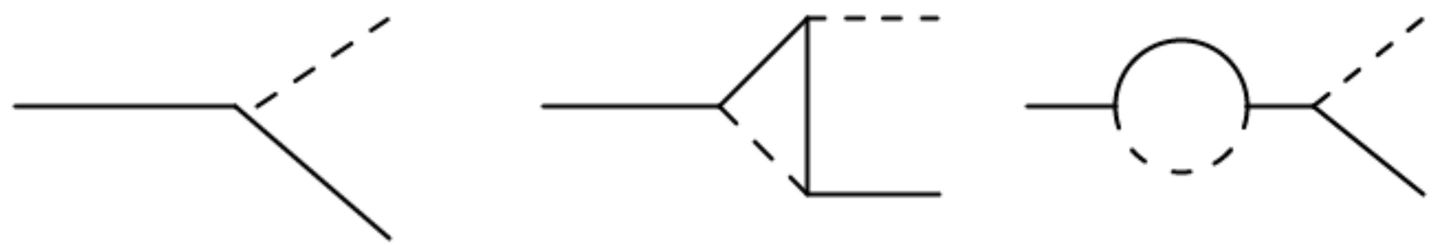

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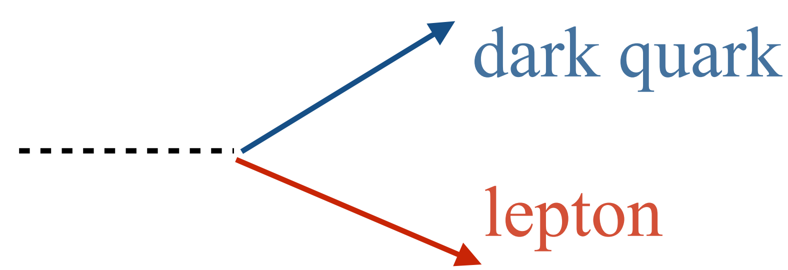
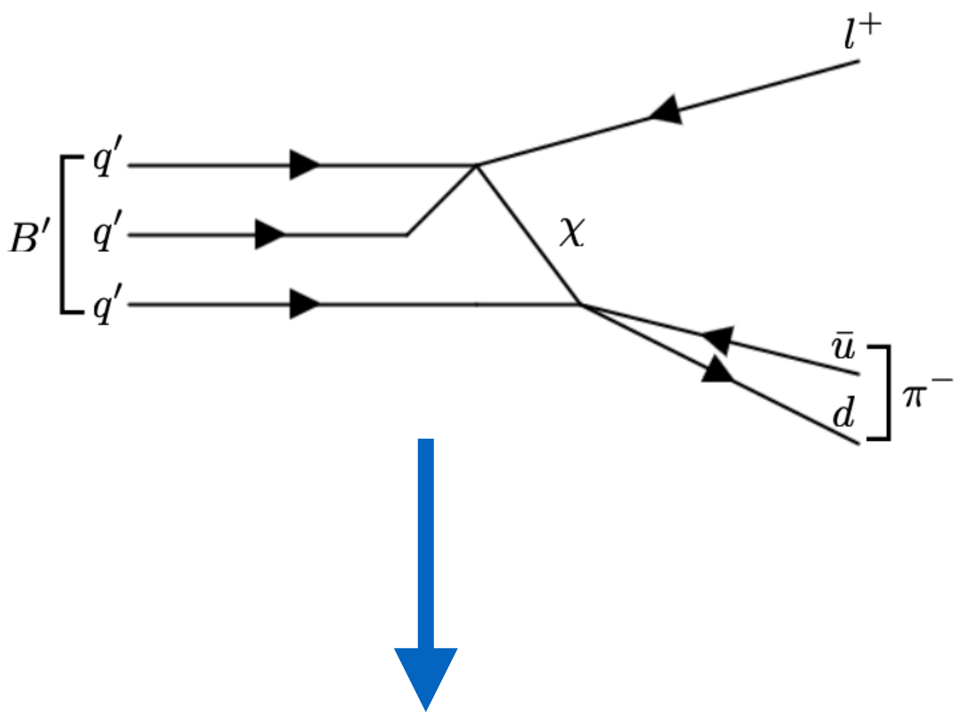


Step 3: lepton number transfer to baryon number via sphaleron process:

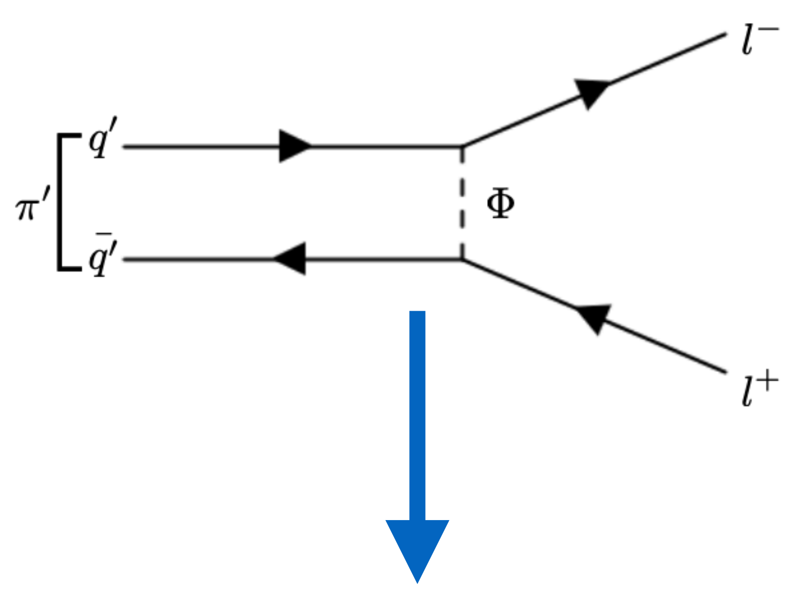
Model Introduction

At low energy scale, there are “dark baryon” and “dark pion”, both of them are not stable:

$$\mathcal{L} \supset \frac{\kappa^2}{m_\Phi^2} \left(\bar{q}'_L l_R\right) \left(\bar{l}_R q'_L\right) + \left[\frac{1}{m_\chi \Lambda_1^2 \Lambda_2^2} \left(\bar{q}'^C_L l_R\right) \left(\bar{q}'^C \gamma^\mu q'\right) \left(\bar{d}_R \gamma_\mu u_R\right) + h.c.\right]$$



Dark baryon decay via
dim-9 operator: life-time
is longer than age of universe



Dark pion decay via
dim-6 operator: life-time
is shorter than 1s (before BBN)

Direct Search

mediator Φ can be quite light: we only need Φ to decay before EWPT:

$$200GeV < m_\Phi < 100TeV$$

decay before EWPT

dark pion decay before BBN

Integrating out the mediator, dim-6 operator:

$$\frac{\kappa^2}{m_\Phi^2}\left(\bar{q}'_L e_R\right)\left(\bar{e}_R q'_L\right) = \frac{\kappa^2}{2m_\Phi^2}\left(\bar{q}'_L\gamma^\mu q'_L\right)\left(\bar{e}_R\gamma_\mu e_R\right)$$

Spin-independent cross-section between “dark baryon” and electron:

$$\mathcal{M} = \frac{\kappa^2}{8m_\Phi^2} g_{\mu\nu} J^\mu_{B'} J^\nu_e \qquad \bar{\sigma}_{eB'} \approx \frac{9\kappa^4\mu^2_{eB'}}{64\pi m_\Phi^4}$$

where $J^\nu_e = \bar{u}(p')\gamma^\nu u(p)$, and $J^\mu_{B'} = \left\langle B'(k')\left|\bar{q}'\gamma^\mu q'\right|B'(k)\right\rangle \approx 3\bar{u}(k')\gamma^\mu u(k)$.

If we choose $\kappa = 1$ and $m_\Phi = 300$ GeV, then $\bar{\sigma}_{eB'} \approx 5.6 \times 10^{-46}$ cm^2.

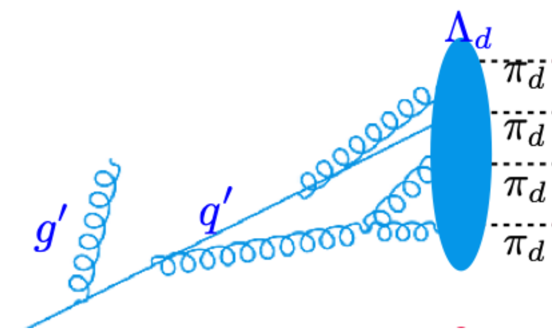
cross section is too small to be detected via direct search

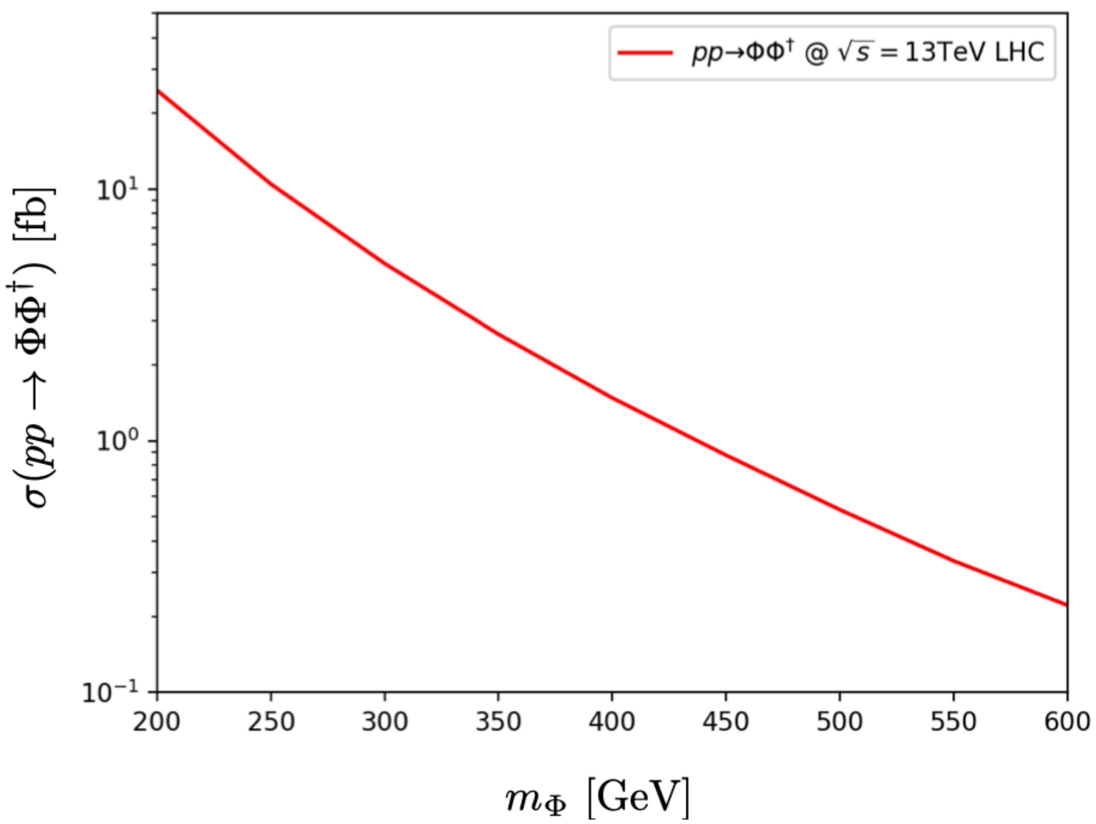
Collider Search (LHC)

$$\mathcal{L} \supset \bar{q}'(\not{D} - m_{q'})q' + (D_\mu \Phi)^\dagger (D^\mu \Phi) - m_\Phi^2 \Phi^\dagger \Phi - \frac{1}{4} G'^{\mu\nu} G'_{\mu\nu} - (\kappa \Phi \bar{q}'_L l_R + h.c.)$$

$$c\tau_0 = \frac{c\hbar}{\Gamma_{\pi'}} \approx 120 \text{ mm} \times \frac{1}{\kappa^4} \left(\frac{1 \text{ GeV}}{f_{\pi'}}\right)^2 \left(\frac{0.1 \text{ GeV}}{m_l}\right)^2 \left(\frac{1 \text{ GeV}}{m_{\pi'}}\right) \left(\frac{m_\Phi}{500 \text{ GeV}}\right)^4$$

perfect for LLP search!





Category	Observed events	Expected background
All events	285	231 ± 12 (stat) ± 62 (syst)
Type2–Type2 excluded	46	31.8 ± 3.8 (stat) ± 8.6 (syst)
Type2–Type2 only	239	241 ± 41(stat) ± 65(syst)

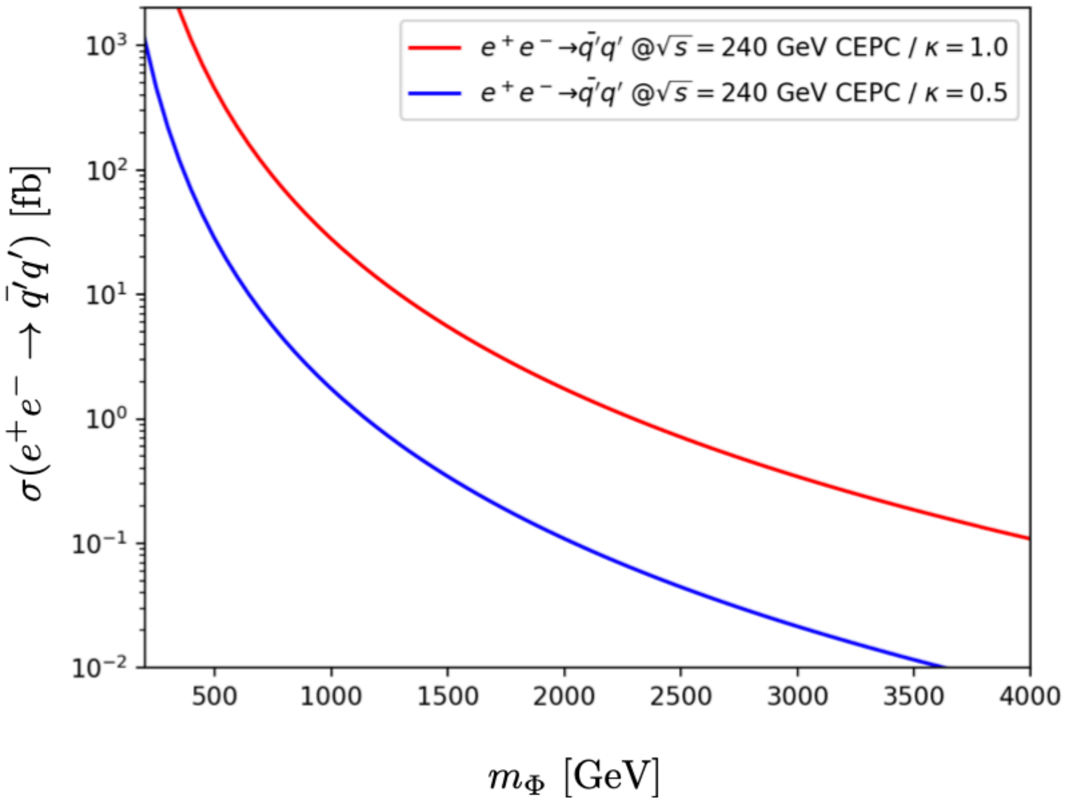
BKG is not negligible

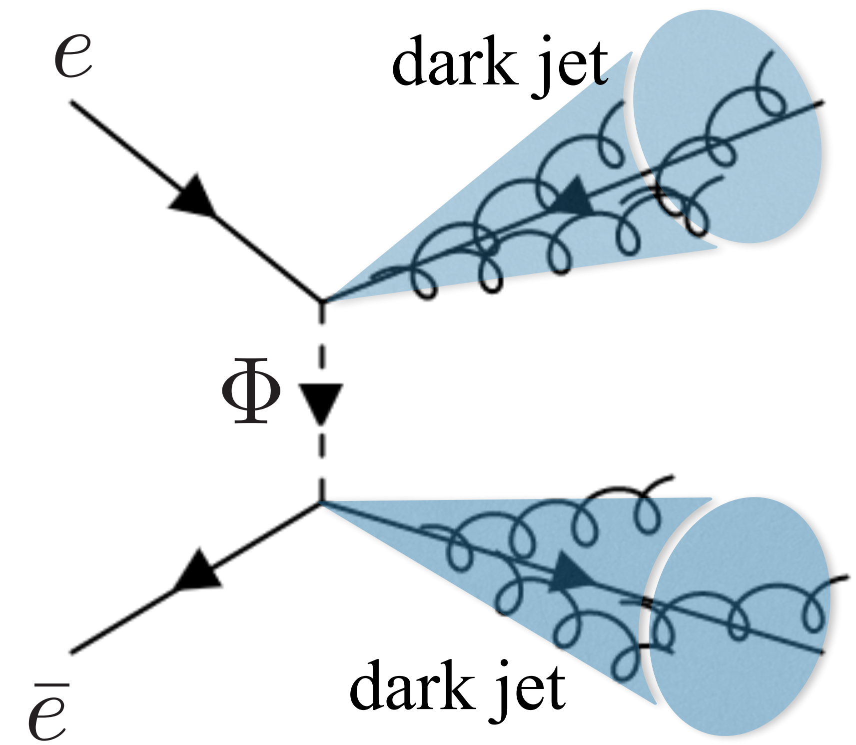
ATLAS-CONF-2016-042

but X-section is too small

Collider Search (CEPC)

$$\frac{\kappa^2}{m_\Phi^2}\left(\bar{q}'_L e_R\right)\left(\bar{e}_R q'_L\right) \quad \longrightarrow \quad \sigma(e^+e^- \to \bar{q}'q') \approx \frac{\kappa^4}{256\pi}\frac{s}{m_\Phi^4}$$





Collider Search (CEPC)

Cut flow for "displaced lepton jet" search:

(i) Dark pion π' decay at a place away from primary vertex, and then two daughter muons come out and leave tracks in detectors. Thus it is possible to reconstruct the displaced vertex (DV) from π' decay via daughter muons' tracks. Detailed discussion on DV tagging is given in the Appendix. All the muons that can be traced back to a DV will be labelled as displaced muon.[6]

(ii) We use all the displaced muons, with $p_T > 1$ GeV and $|\eta| < 3.0$, as input of jet clustering. We use anti-kt algorithm with jet radius $R = 0.4$ to do jet clustering. If there are 6, or more than 6, displaced muons inside a jet, then this jet will be tagged as a displaced muon jet (DMJ).

(iii) For a signal event, we require the number of DMJs to be greater than 2.

BKG estimation: BKG free! (thanks to Manqi)

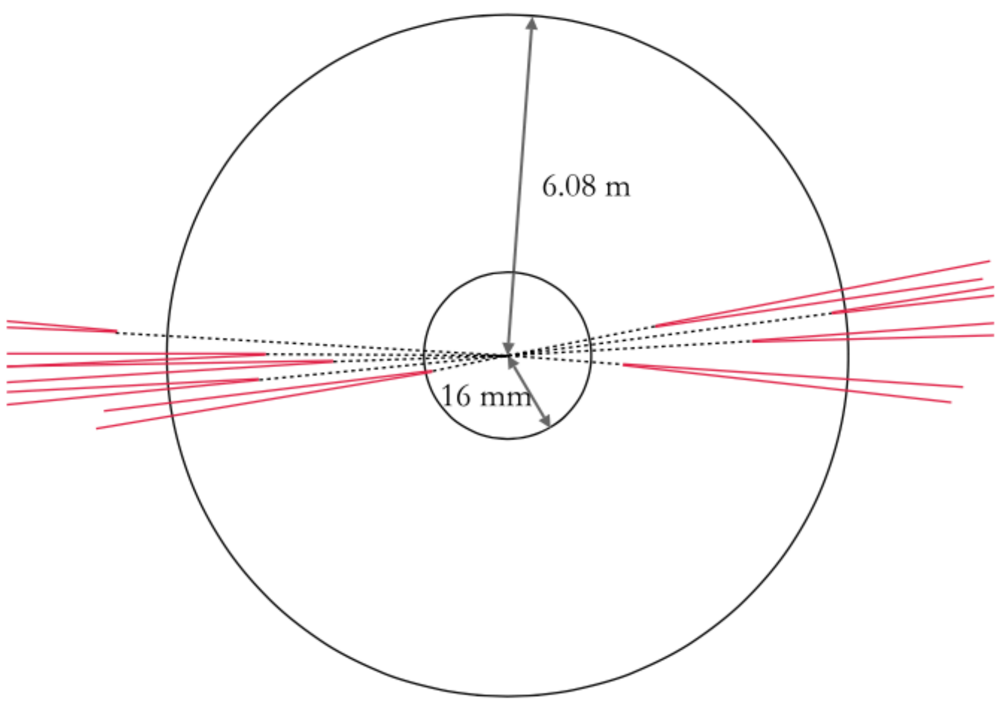


TABLE II. Physical size and spatial resolution of different detectors on CEPC. Here R_{in}, R_{out}, σ_{xy}, and σ_z are inner radius, outer radius, transverse spatial resolution, and longitudinal spatial resolution of different detectors respectively.

Detector	R_{in}	R_{out}	σ_{xy}	σ_z
Vertex detector	16 mm	60 mm	$(2.8 \sim 6)$ μm	$(2.8 \sim 6)$ μm
Silicon tracker	0.15 m	1.81 m	7.2 μm	86.6 μm
Hadron calorimeter	2.30 m	3.34 m	30 mm	30 mm
Muon system	4.40 m	6.08 m	2.0 cm	1.5 cm

displaced lepton jet tagging efficiency estimation

Collider Search (CEPC)

Tagging efficiency:

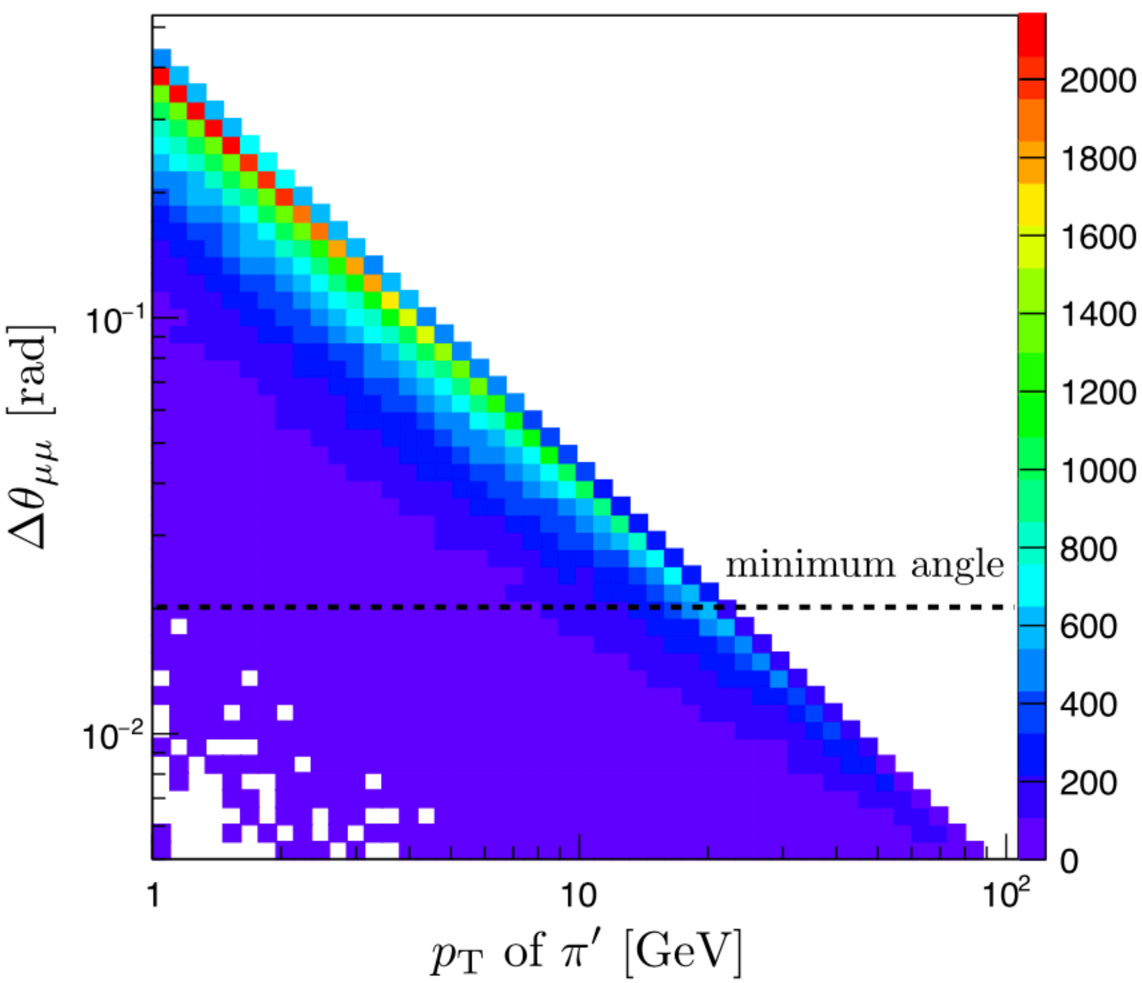
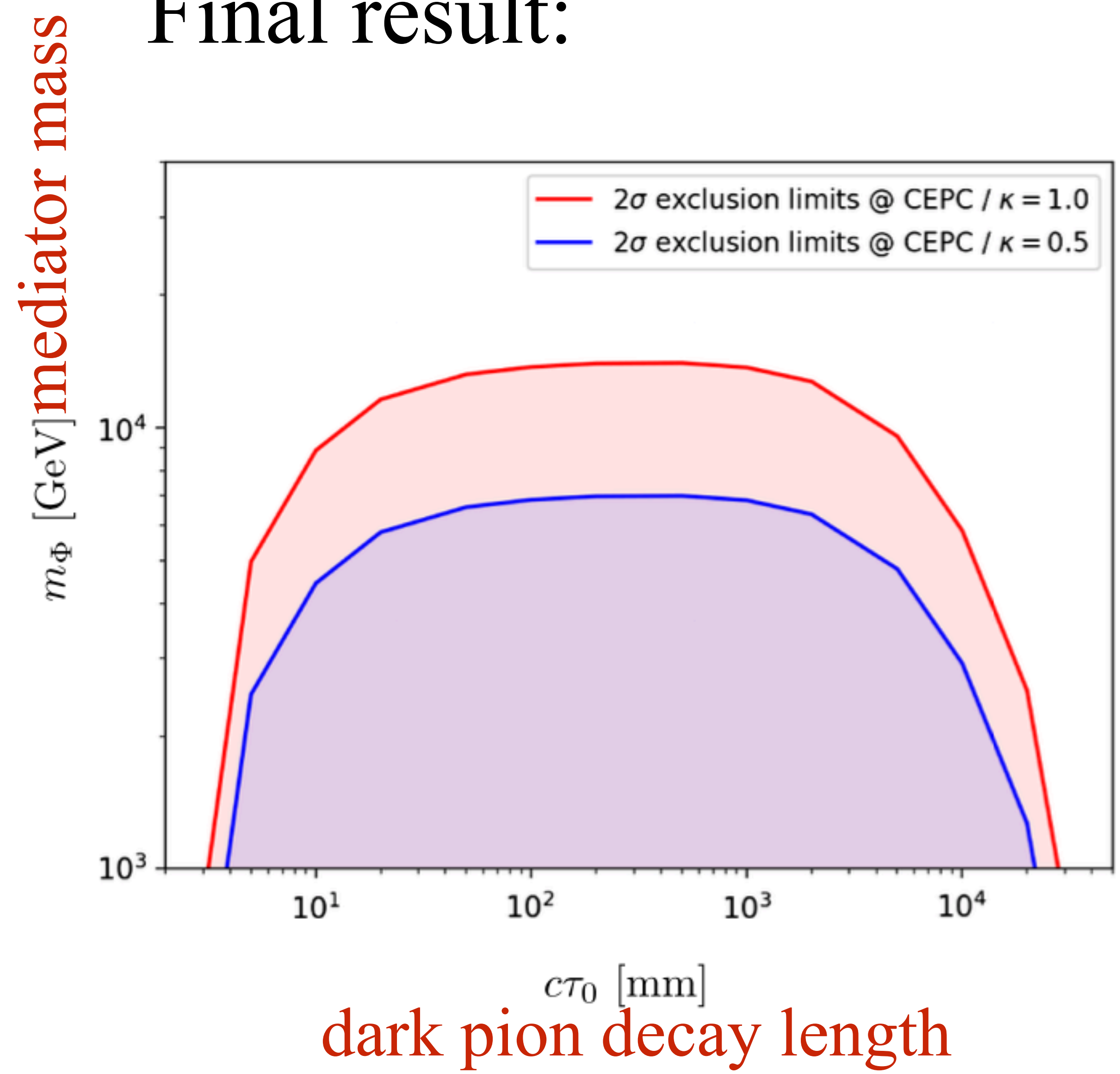


FIG. 6. Distribution of $\Delta\theta_{\mu\mu}$ and p_T of 300,000 π' produced by dark hadronization process at CEPC.

Final result:



Conclusion

Composite asymmetric dark matter is an attractive model.

A light mediator introduce unique collider signal: dark jet.

If this mediator is leptophilic:

1)Composite ADM is difficult to be detected by direct search.

2)Composite ADM is difficult to be detected at LHC.

3)Composite ADM is promising to be detected at CEPC.