Leptophilic Composite Asymmetric Dark Matter and its Detection

The 2021 International Workshop on the High Energy Circular Electron Position Collider

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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

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

So maybe the true story is like:

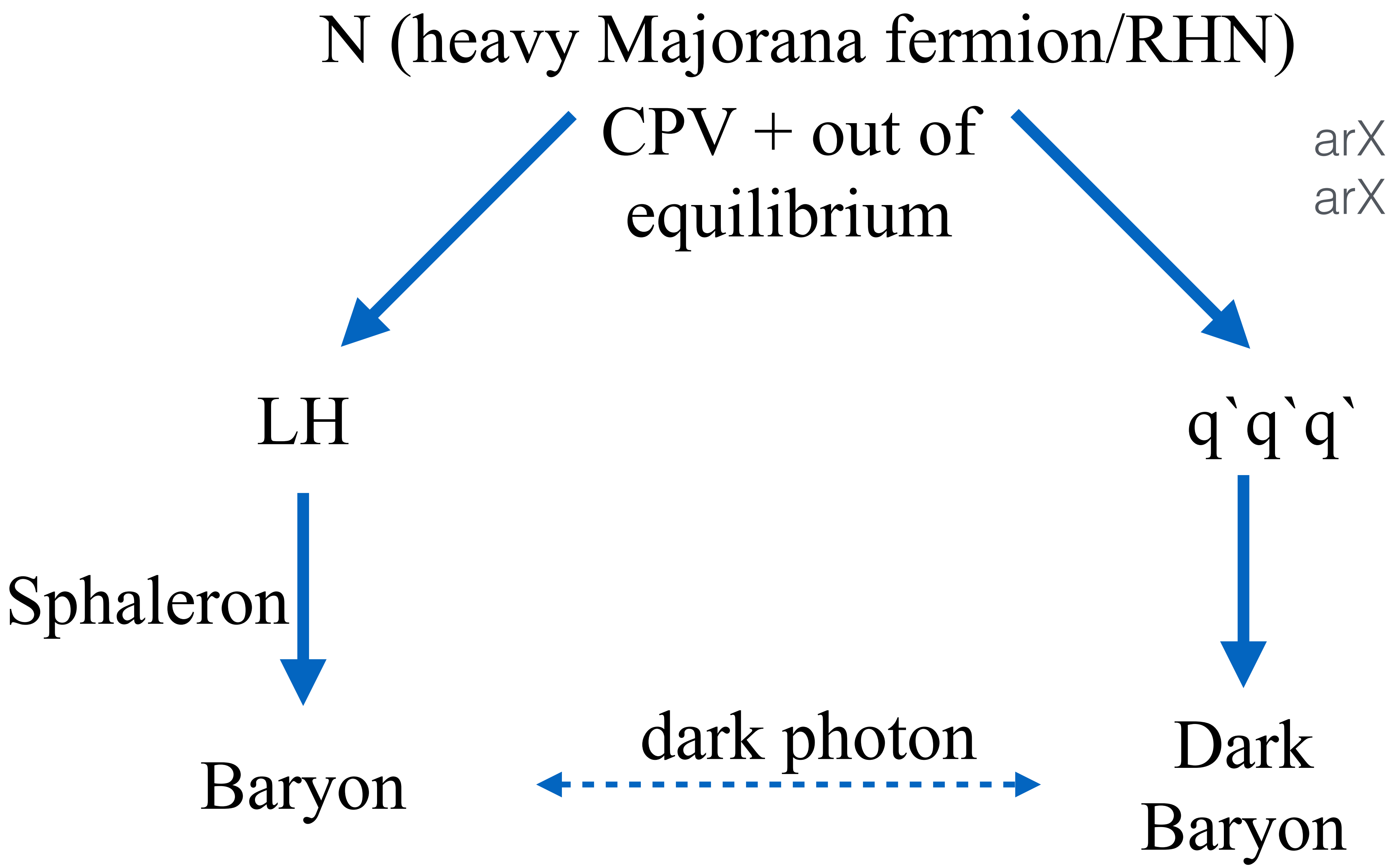
Baryon-anti-baryon asymmetry:
1)C and CP violation
2)B-number broken
3)deviation from equilibrium

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

The most convenient model framework: extended Leptogenesis



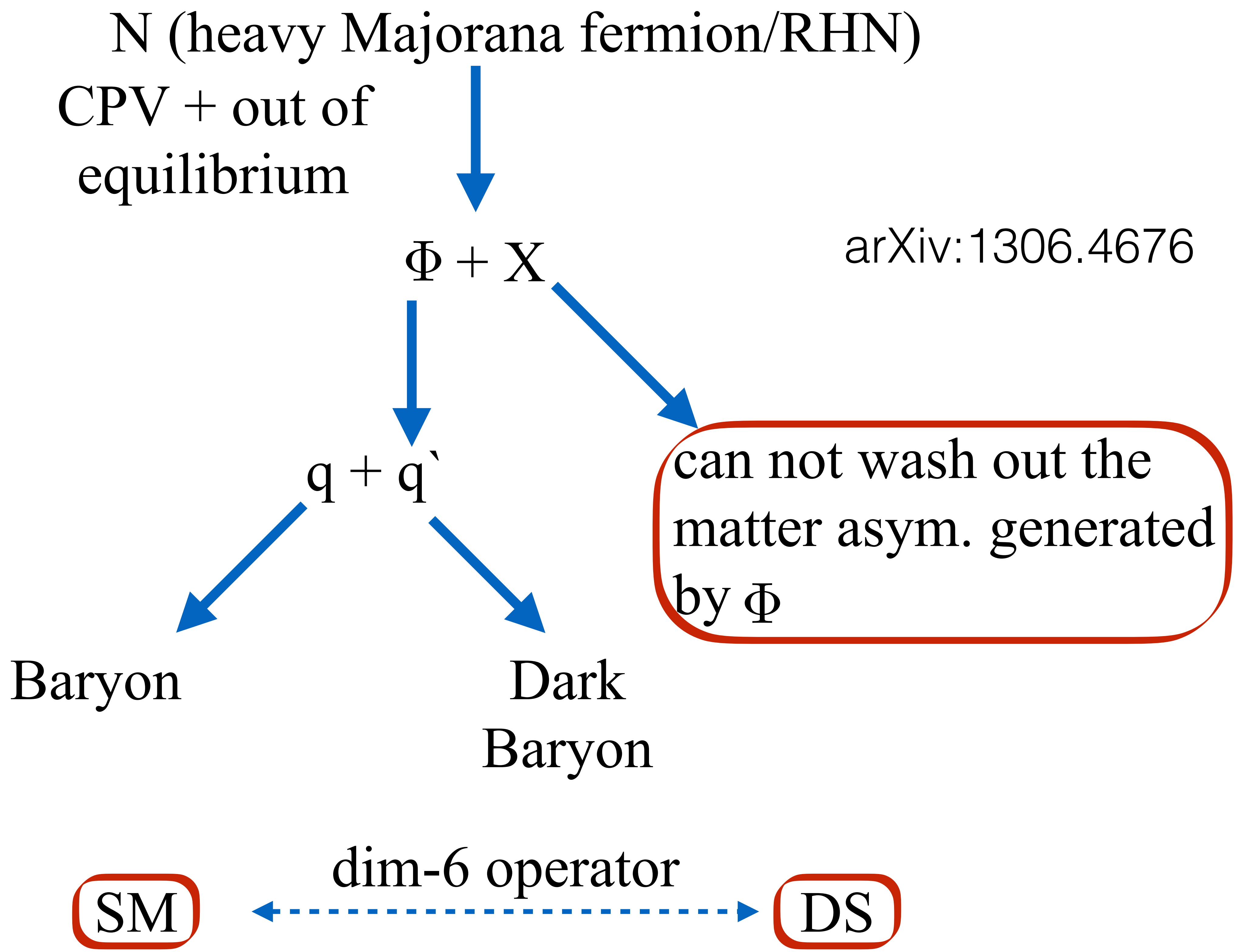
arXiv:1811.10232
arXiv:1907.03404

For collider physics, this model is not so attractive:
N is very heavy & dark photon is too common.

We need need unique signal for ADM

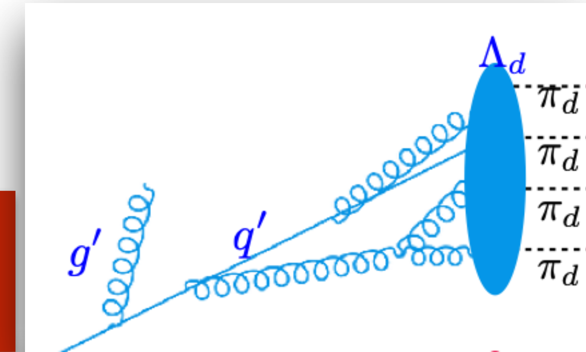
Model Introduction

Try to introduce a scalar mediator: Φ

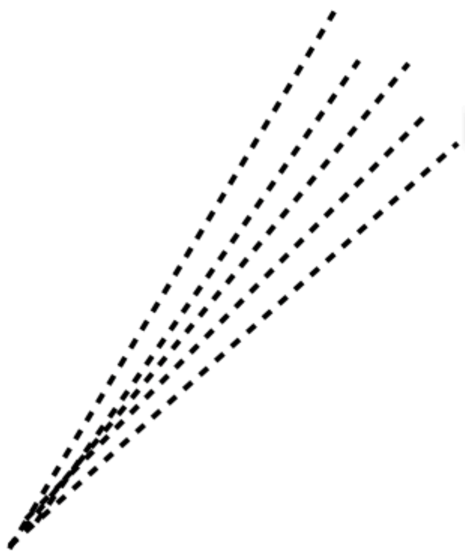


Model Introduction

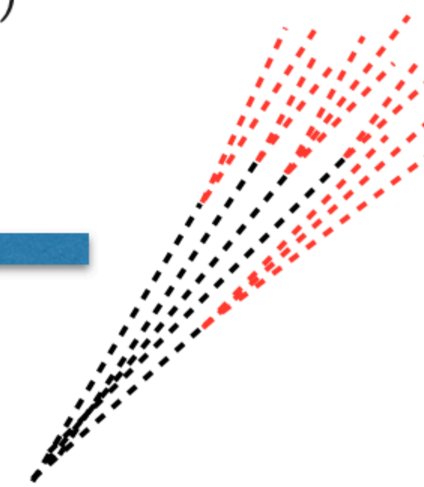
Try to introduce a scalar mediator: Φ



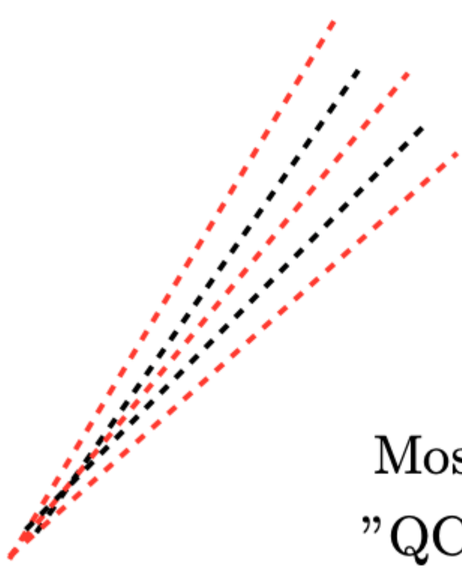
N **Unique signal: dark jet!**



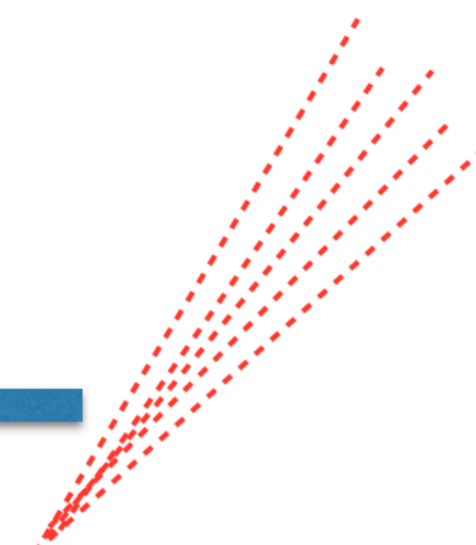
Most dark mesons are stable or stable enough.
Invisible Jet (Missing Energy)



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



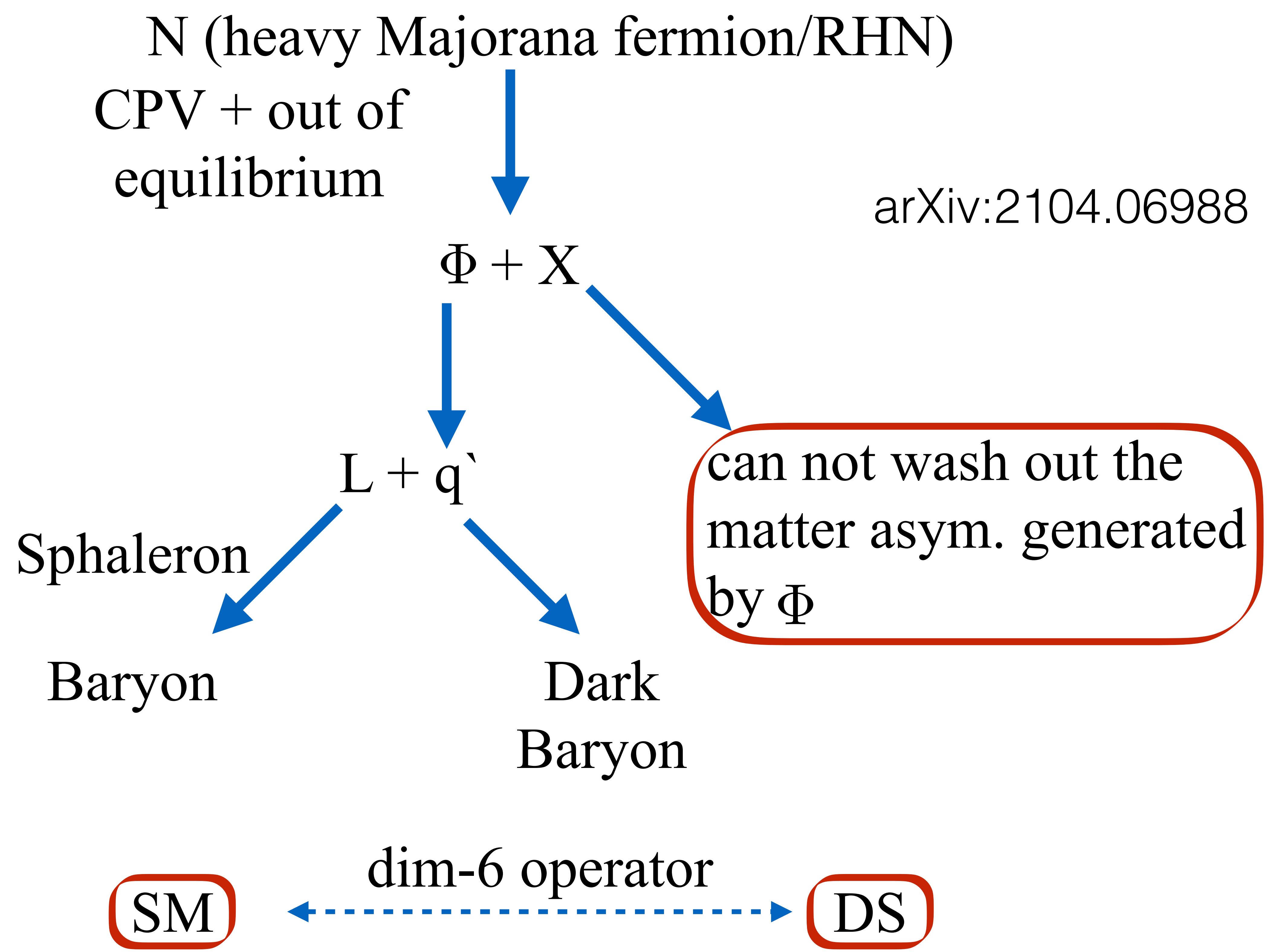
A fraction of dark mesons are stable.
Semi-visible Jet (Transverse Mass)
Phys. Rev. Lett. **115**, no. 17, 171804 (2015)



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`



Model Introduction

particle table:

	$SU(3)'$	$SU(3)$	$U_Y(1)$	Spin	L	B	B'
N_1/N_2	1	1	0	1/2	0	0	0
Φ	3	1	1	0	-1	0	1/3
χ	3	1	1	1/2	-1	0	1/3
q'	3	1	0	1/2	0	0	1/3
l_R	1	1	-1	1/2	1	0	0
d_R	1	3	-1/3	1/2	0	1/3	0
u_R	1	3	2/3	1/2	0	1/3	0

Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{2}\sum_{i=1,2} M_{N_i}\overline{N}_i N_i^C - m_\Phi^2 \Phi^\dagger \Phi - m_\chi \bar{\chi}\chi - m_{q'}\bar{q}'q' + \mathcal{L}_{\text{kinetic}}$$

$$- \sum_{i=1,2} \lambda_i \overline{N}_i \chi \Phi^\dagger - \kappa \Phi \bar{q}'_L l_R - \frac{1}{\Lambda_1^2}\left(\bar{q}'^C \chi\right)\left(\bar{q}'^C_L l_R\right) - \frac{1}{\Lambda_2^2}\left(\bar{\chi}\gamma^\mu q'\right)\left(\bar{d}_R \gamma_\mu u_R\right) + h.c.$$

break dark baryon number conservation

break lepton number conservation

Model Introduction

Stage I: out-of-equilibrium & CP violated decay of N_1

$$\epsilon \equiv \frac{\Gamma(N_1 \to \chi\Phi^\dagger) - \Gamma(N_1 \to \bar{\chi}\Phi)}{\Gamma(N_1 \to \chi\Phi^\dagger) + \Gamma(N_1 \to \bar{\chi}\Phi)} \qquad \epsilon \simeq -\frac{3}{16\pi}\frac{M_{N_1}}{M_{N_2}}\frac{\mathrm{Im}\left[(\lambda_2^*\lambda_1)^2\right]}{|\lambda_1|^2}$$

$$Y_{\Delta\Phi} = -Y_{\Delta\chi} = Y_{N_1} \times \epsilon \times \eta$$

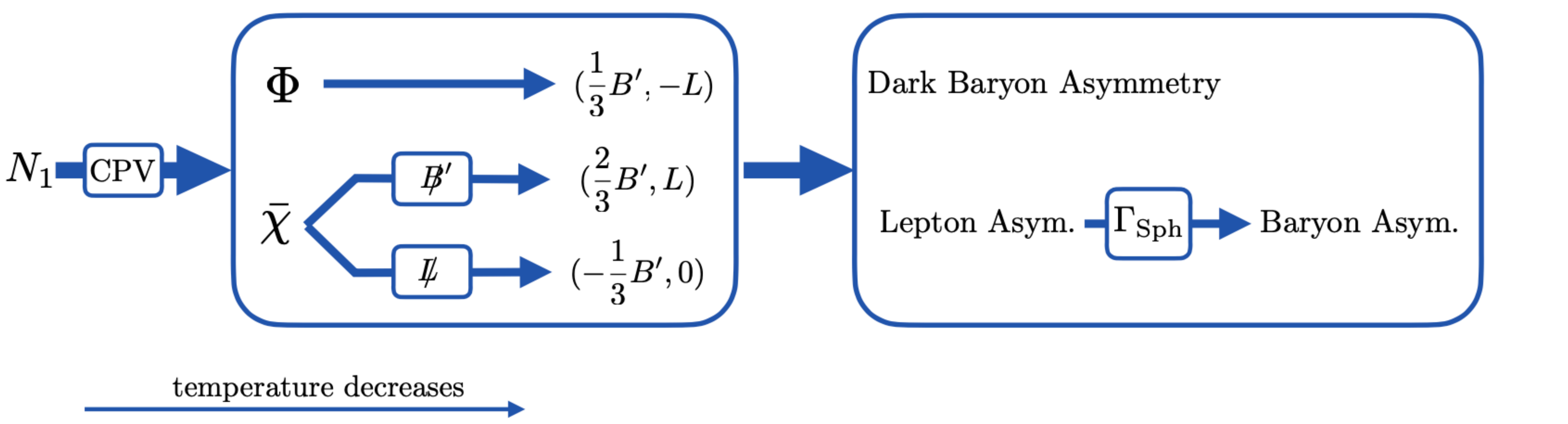
Stage II: Φ and χ decay to leptons and dark quarks

denote $\chi \to \bar{q}' q'^C \bar{l}_R$ and $\chi \to q' \bar{d}_R u_R$ by $Br_\chi(\not{B}')$ and $Br_\chi(\not{L})$

$$Y_{\Delta l_R} \simeq -Y_{\Delta\Phi} - Br_\chi(\not{B}') \times Y_{\Delta\chi} = -Br_\chi(\not{L}) \times Y_{\Delta\Phi}$$
$$Y_{\Delta q'} \simeq Y_{\Delta\Phi} + (Br_\chi(\not{L}) - 2Br_\chi(\not{B}')) \times Y_{\Delta\chi} = 3Br_\chi(\not{B}') \times Y_{\Delta\Phi}$$

Stage III: generate baryon and dark baryon asymmetries

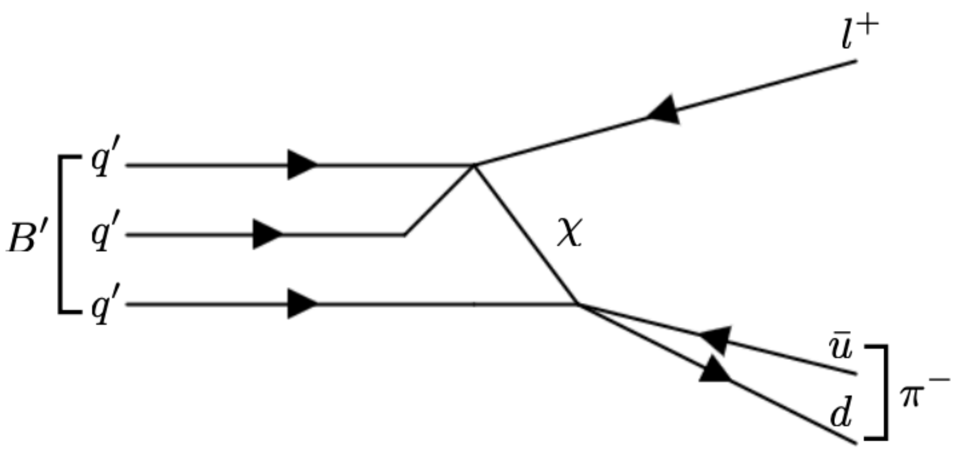
$$Y_{\Delta B'} = \frac{1}{3}Y_{\Delta q'} \simeq Br_\chi(\not{B}') \times Y_{\Delta\Phi} \qquad Y_{\Delta B} = \frac{28}{79}Y_{\Delta B-L} = -\frac{28}{79}Y_{\Delta l_R} \simeq \frac{28}{79}Br_\chi(\not{L}) \times Y_{\Delta\Phi}$$

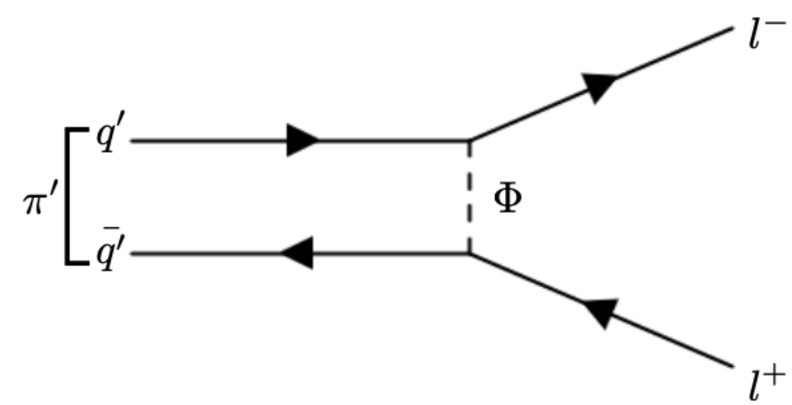


Model Introduction

Stability of dark baryon B' and dark pion π'

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





Very long-lived

Decay before BBN

Direct Search

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

$$\mathcal{M}=\frac{\kappa^2}{8m_\Phi^2}g_{\mu\nu}J^\mu_{B'}J^\nu_e$$

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

$$\bar{\sigma}_{eB'}\approx\frac{9\kappa^4\mu^2_{eB'}}{64\pi m_\Phi^4}$$

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

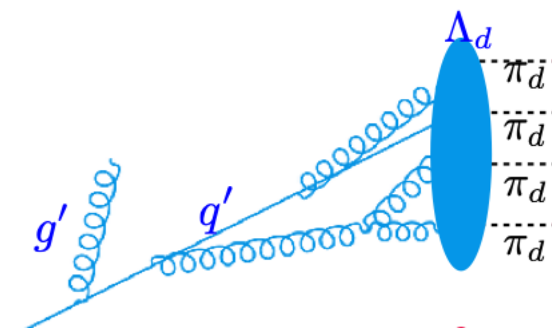
cross section is too small to be detected

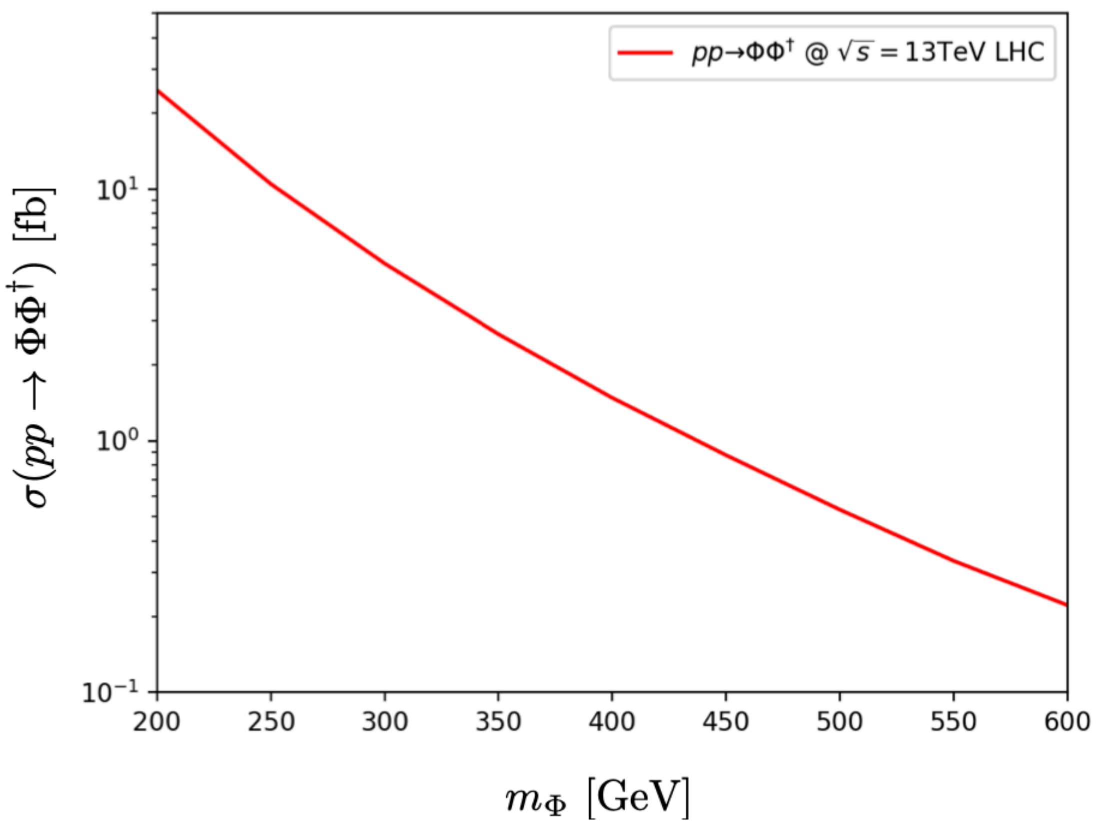
Collider Search (LHC)

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

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

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)

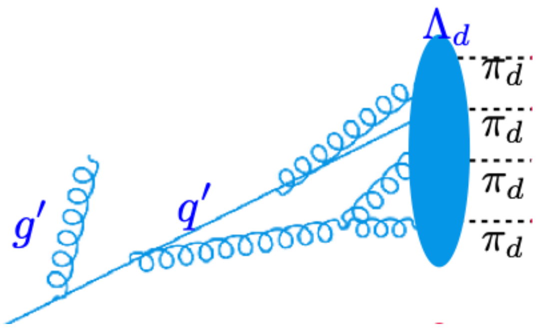
BKG is not negligible

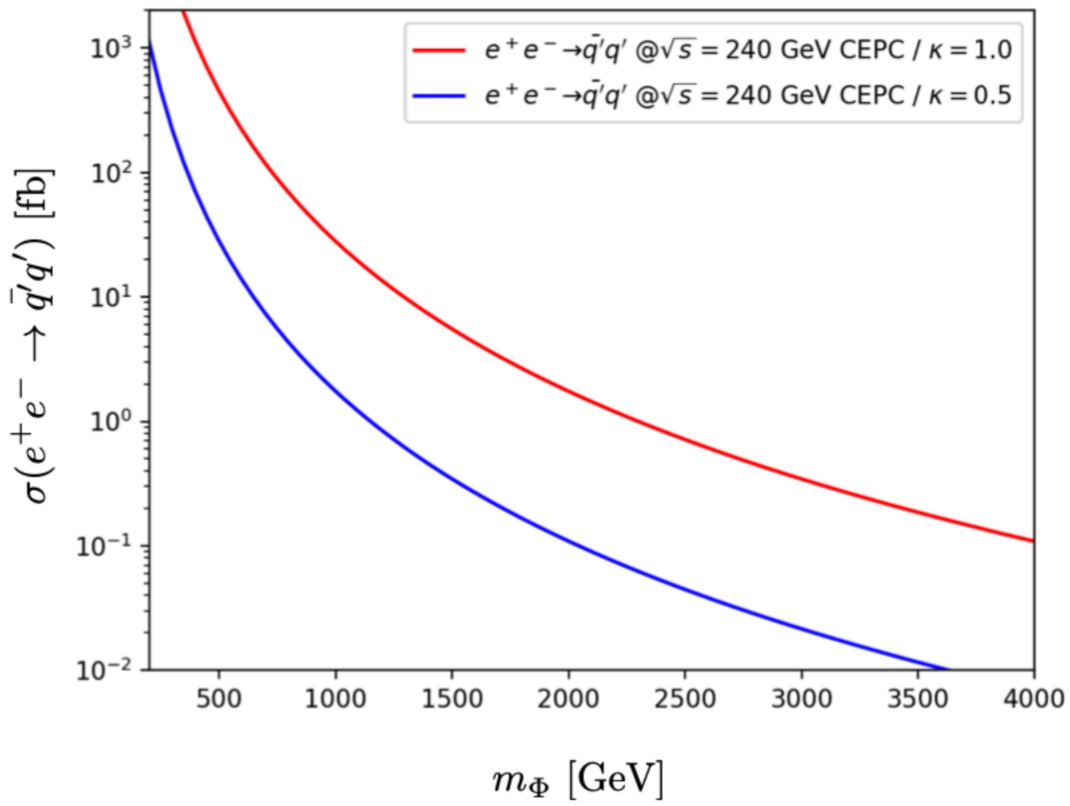
ATLAS-CONF-2016-042

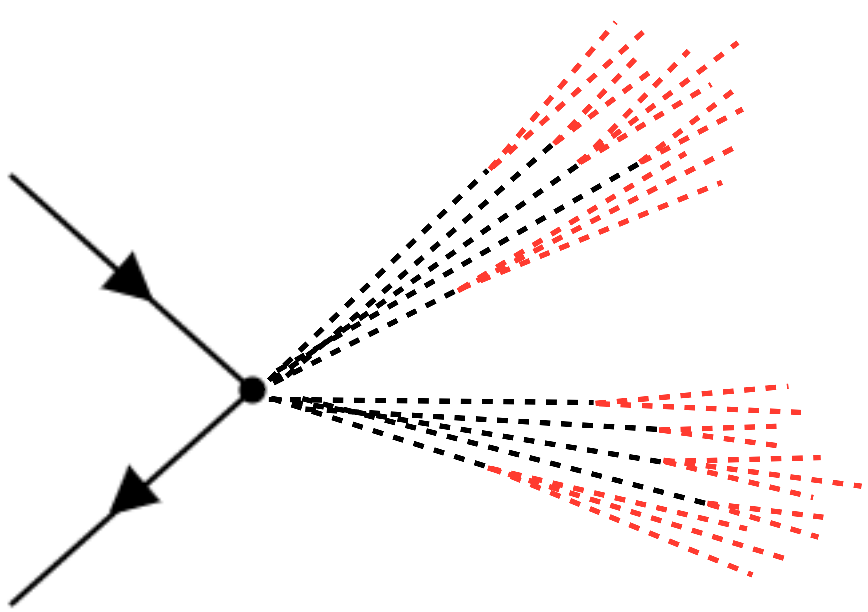
but X-section is too small

Collider Search (CEPC)

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







Displaced lepton-jet

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)

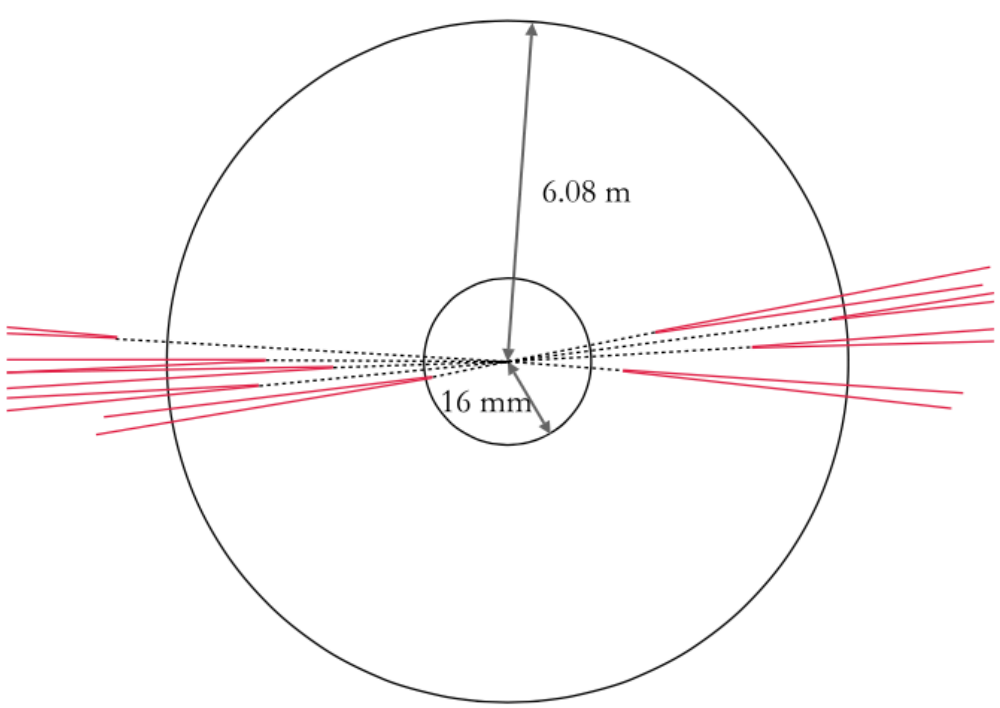


TABLE II. Physical size and spatial resolution of different detectors on CEPC. Here $R_{\rm in}$, $R_{\rm out}$, σ_{xy}, and σ_z are inner radius, outer radius, transverse spatial resolution, and longitudinal spatial resolution of different detectors respectively.

Detector	$R_{\rm in}$	$R_{\rm out}$	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:

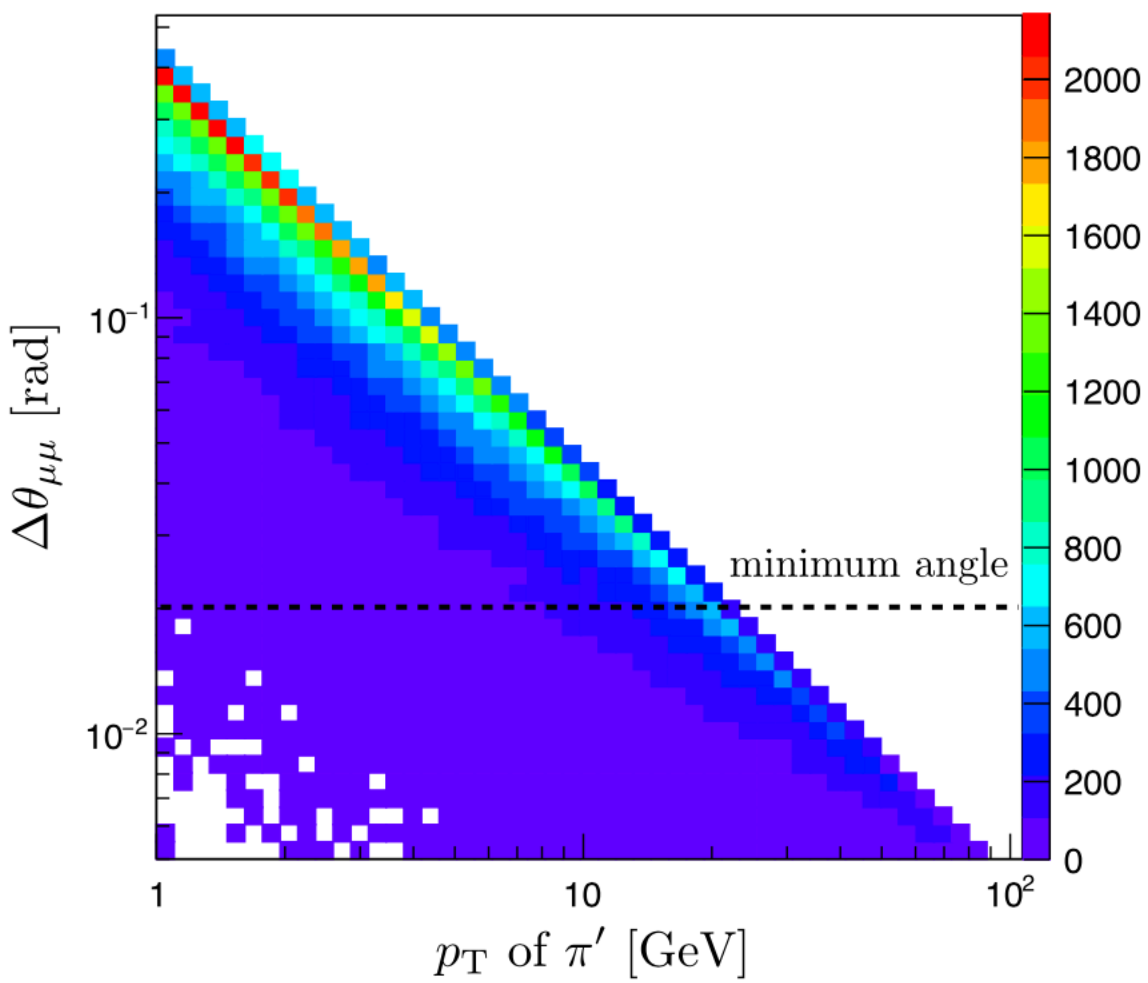
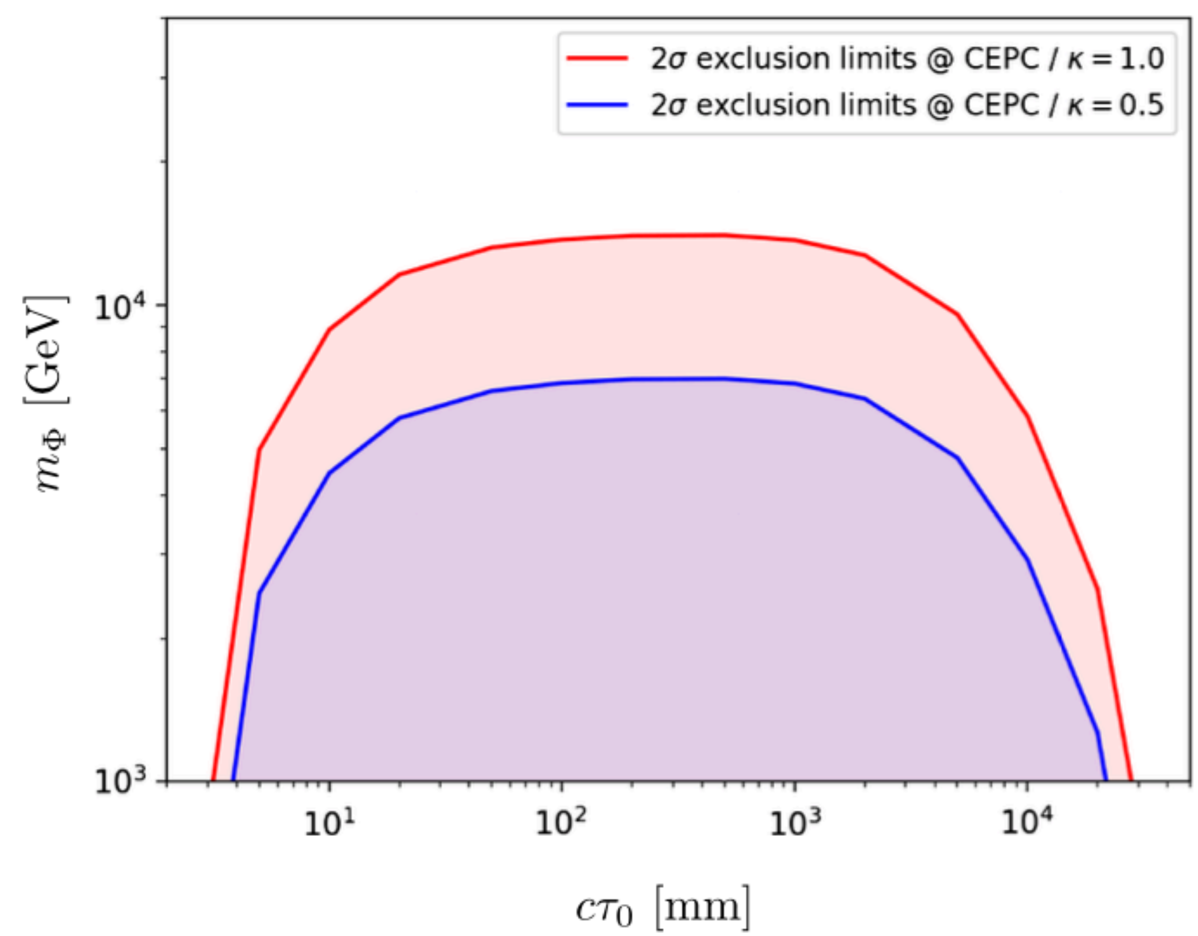


FIG. 6. Distribution of $\Delta\theta_{\mu\mu}$ and p_T of 300,000 π' produced by dark hadronization process at CEPC.

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.