

Search for Excited Dark Matter with FASER AHCAL at LHC

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对撞机上新物理寻找研讨会

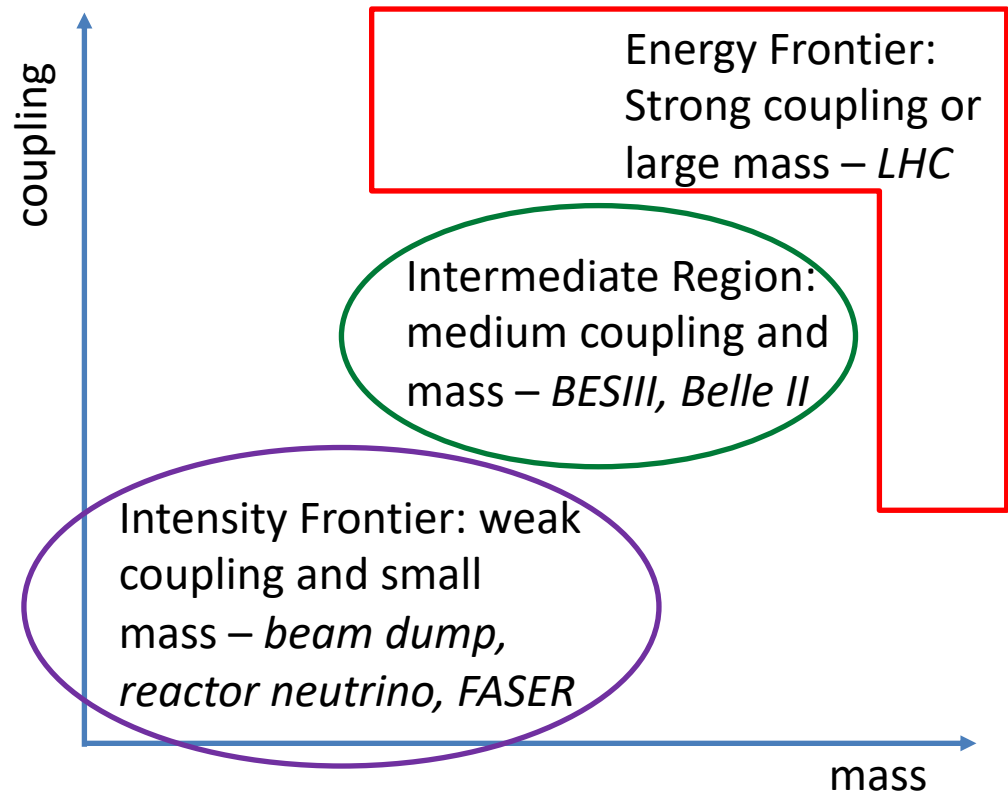
Nanjing University, Suzhou, 04/17/2026

Coupling and mass

Our universe and particle physics vary vastly in coupling and mass scales

Different scales of BSM demands different kinds of search strategy

- Weak coupling and small mass: search for their interaction with SM matter with large flux/target (Super-K, underground DM exp.)
- Medium coupling and mass: long-live particles (LLP), search for their decay which can be detected in dedicated low-energy detectors

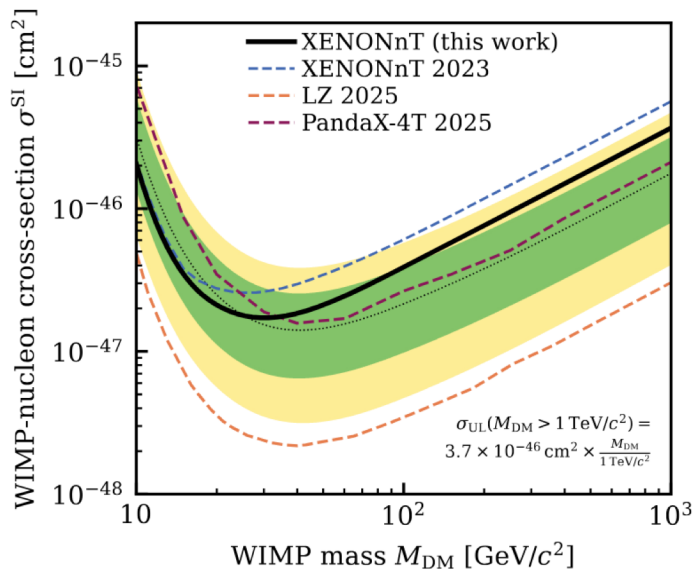


Sources of weakly interacting or LLP's: cosmology, fixed target or collider

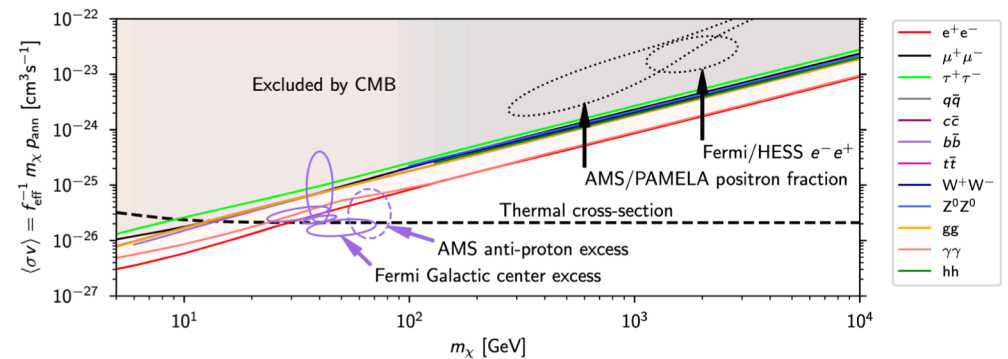
Dark matter limits

- There are a lot of evidences for dark matters from astronomical observations, but a direct detection has yet to be made
- The dark matters are in thermal equilibrium with SM particles in the early universe. A possible portal between the dark sector and the SM sector is the dark photon

[Phys. Rev. Lett. 135 (2025) 221003]



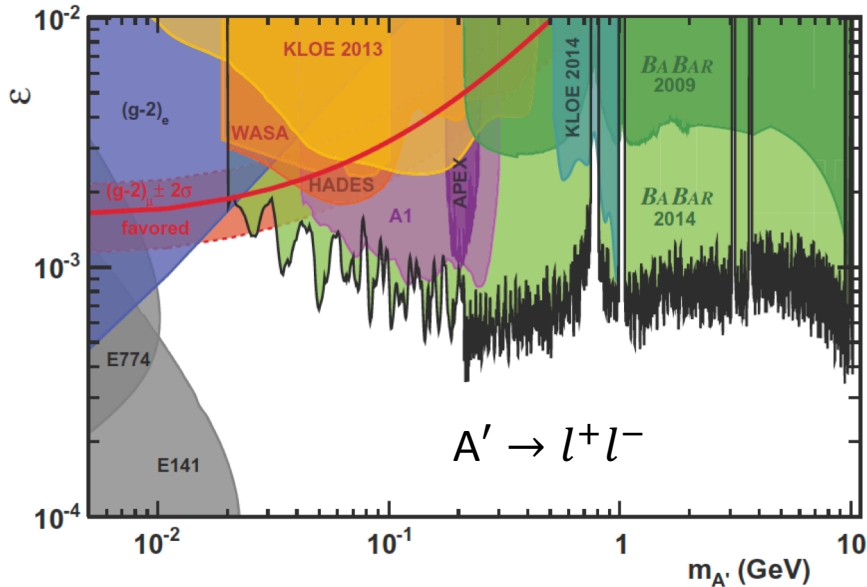
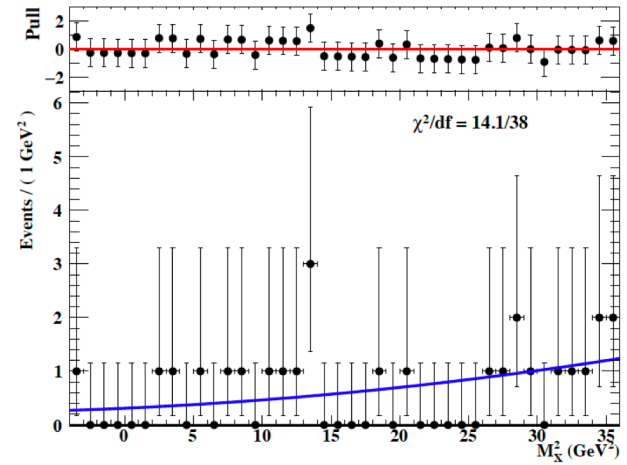
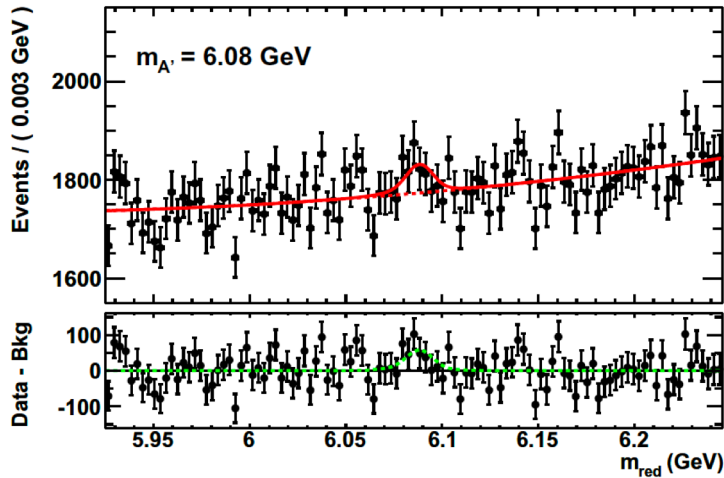
[A&A A6 (2020) 641]



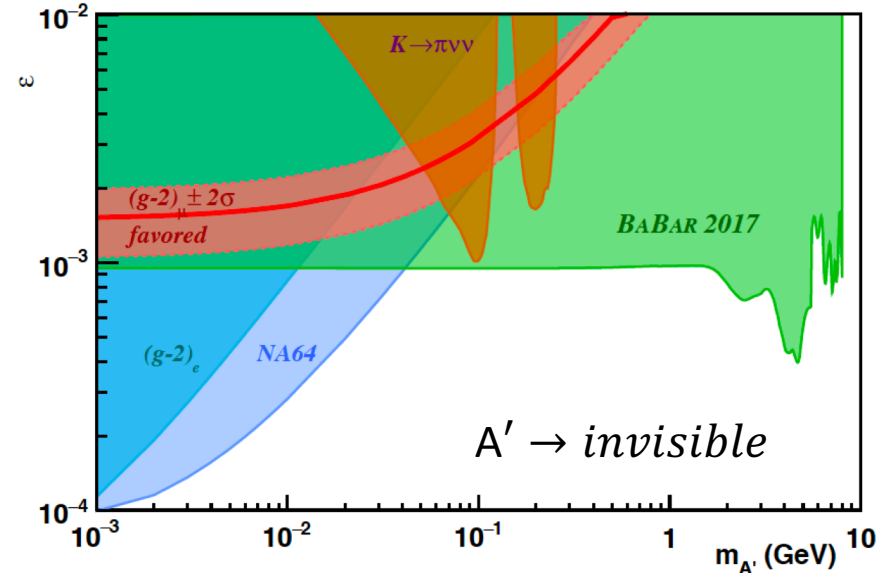
- 一方面，地下实验对大于10 GeV的暗物质粒子给出了强烈限制
- 另一方面，CMB数据排除了小于~10 GeV暗物质粒子的可能（S波湮灭）

- The tension can be relieved by inelastic dark models

Collider search – BaBar

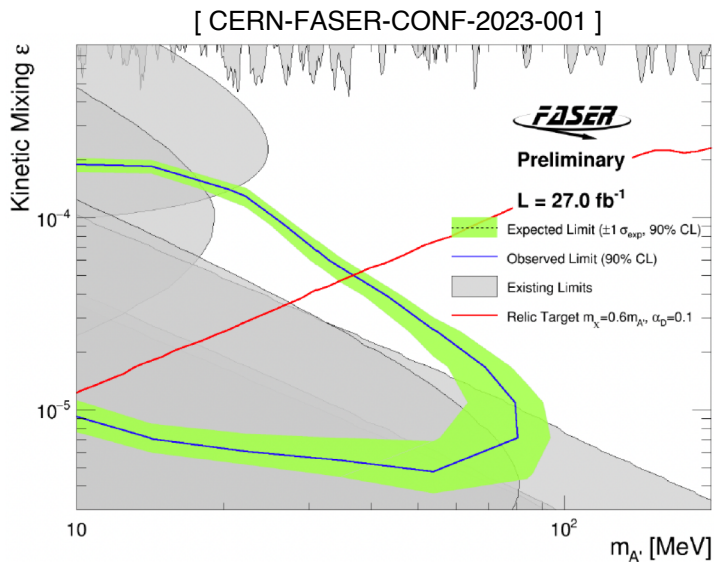
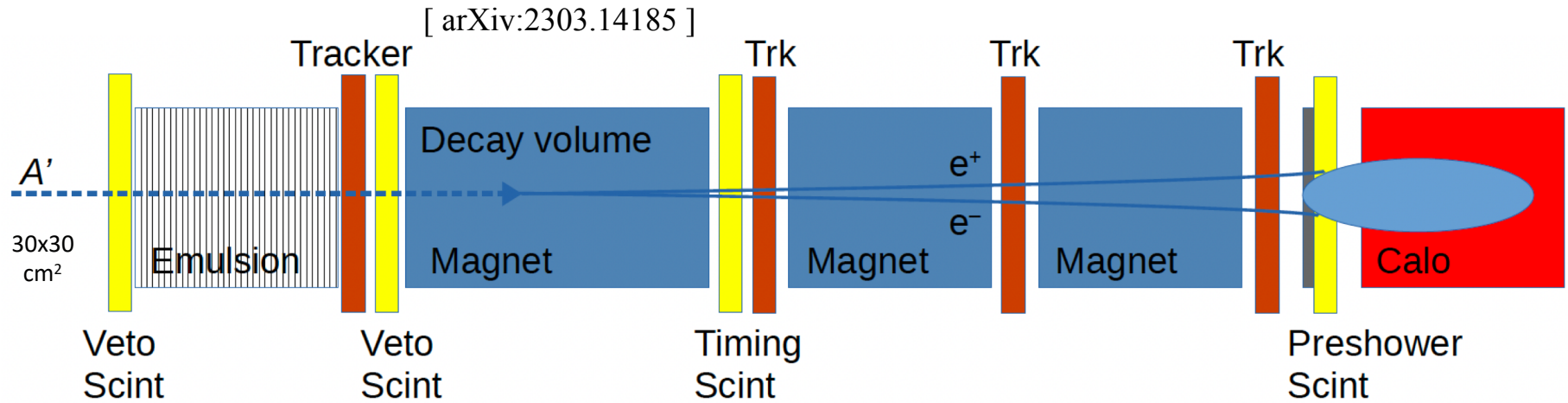


[Phys. Rev. Lett 113 (2014) 201801]

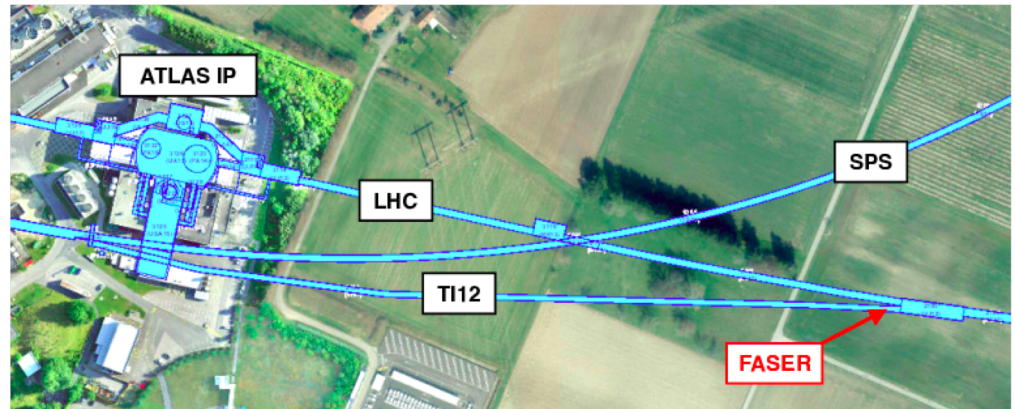


[Phys. Rev. Lett. 119 (2017) 131804]

Collider search – FASER



$$\bar{d} = c \frac{1}{\Gamma_{A'}} \gamma_{A'} \beta_{A'} \approx (80 \text{ m}) B_e \left[\frac{10^{-5}}{\epsilon} \right]^2 \left[\frac{E_{A'}}{\text{TeV}} \right] \left[\frac{100 \text{ MeV}}{m_{A'}} \right]^2$$



A scalar inelastic dark matter model

Assume the following Lagrangian for a scalar inelastic dark matter model study

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu - \epsilon e Q_f X_\mu \bar{f} \gamma^\mu f + \quad [\text{arxiv:2001.04382}]$$

$$(D_\mu \phi)^* D^\mu \phi - \mu^2 \phi^* \phi - \frac{1}{2} \rho^2 (\phi\phi + \phi^* \phi^*),$$

"Majorana"-like mass term

where X is the dark photon, ϕ is a dark scalar, $D_\mu = \partial_\mu + i g_D X_\mu$ is the the covariant derivative. $U(1)_D$ can be broken to give X mass. Additionally, the last term explicitly violate $U(1)_D$

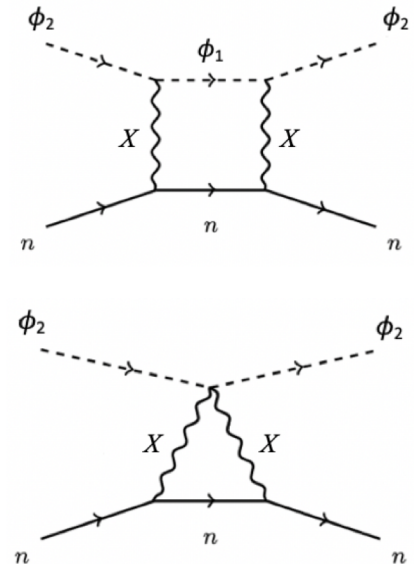
Substitute $(\phi_1 + i\phi_2)/\sqrt{2}$ for ϕ , we obtain

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu \phi_1 \partial^\mu \phi_1 + \frac{1}{2} \partial_\mu \phi_2 \partial^\mu \phi_2 - \frac{1}{2} (\mu^2 + \rho^2) \phi_1^2$$

$$- \frac{1}{2} (\mu^2 - \rho^2) \phi_2^2 - g_D X_\mu (\phi_2 \partial^\mu \phi_1 - \phi_1 \partial^\mu \phi_2)$$

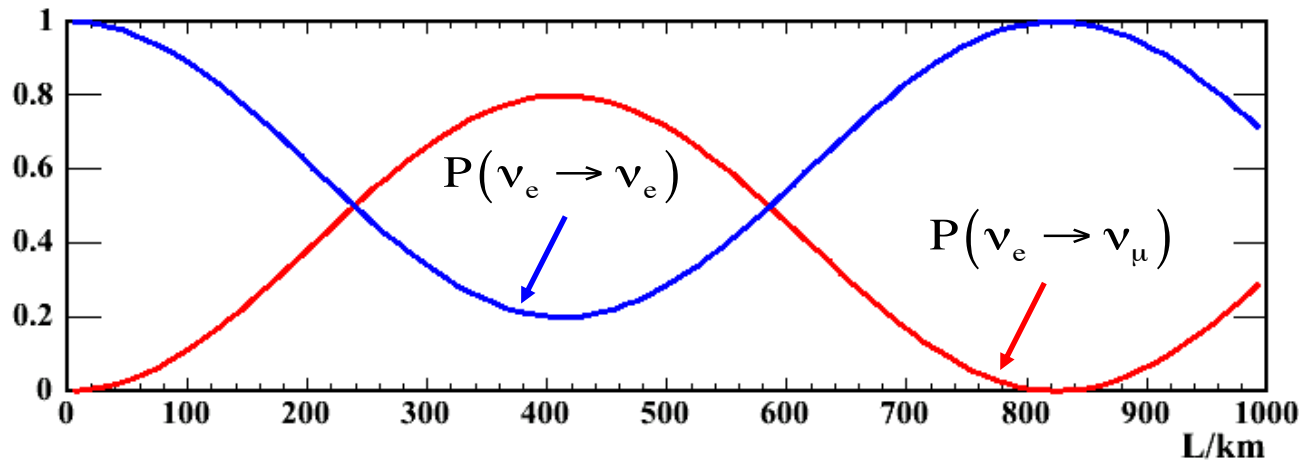
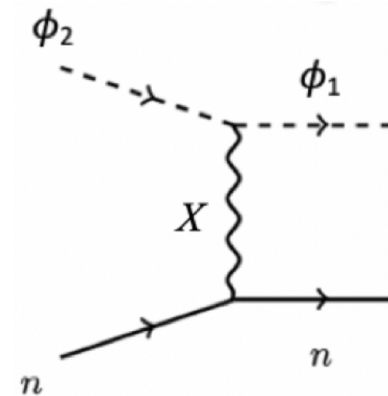
$$+ \frac{1}{2} g_D^2 X_\mu X^\mu (\phi_1^2 + \phi_2^2).$$

Mass splitting between ϕ_1 and ϕ_2 is realized: $m_1 = \sqrt{\mu^2 + \rho^2}$, $m_2 = \sqrt{\mu^2 - \rho^2}$. Interaction of ϕ_2 with SM particles is loop suppressed

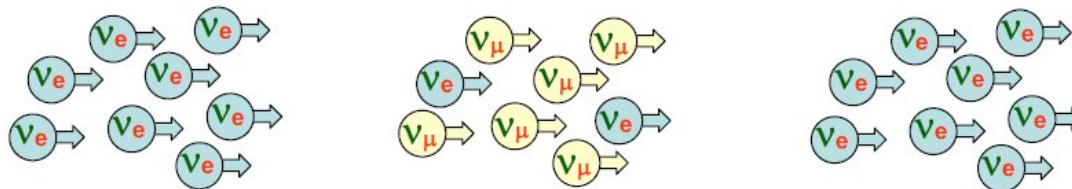


The tree diagram?

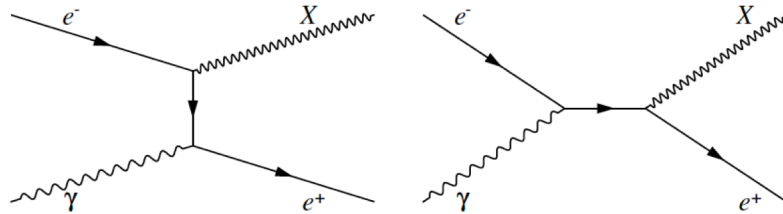
- ϕ_2 can interact directly with nucleus and turn into ϕ_1
- When the mass splitting between ϕ_1 and ϕ_2 is large and ϕ_2 is cold, this process does not happen
- The Missing Neutrino Mystery is an analogue of this scenario



$$\lambda_{\text{osc}} = \frac{4\pi\hbar E}{c^3 \Delta m^2}$$

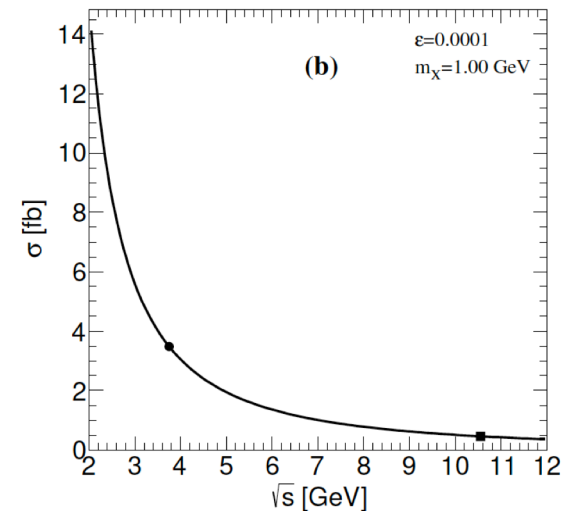
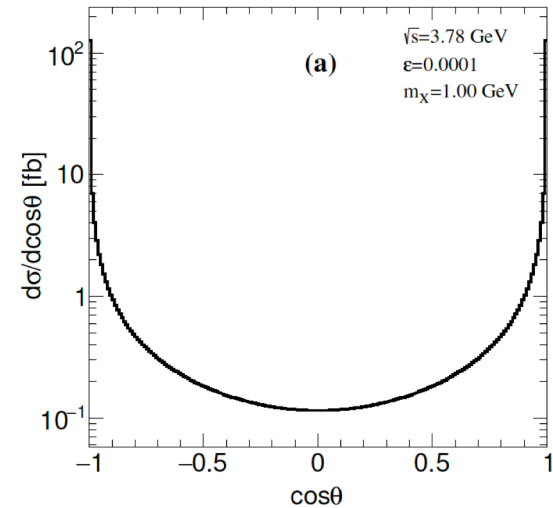


Dark photon production at e^+e^- colliders



$$\frac{d\sigma}{d\cos\theta} = 2\pi\epsilon^2\alpha^2 \frac{(s + m_X^2)^2 + (s - m_X^2)^2 \cos^2\theta}{s(s - m_X^2)(s \sin^2\theta + 4m_e^2)}$$

- Two main features of dark photon production:
 - X is produced mainly in the forward direction
 - Production rates decreases with increasing collision energy
- Can produce larger X mass than fixed target



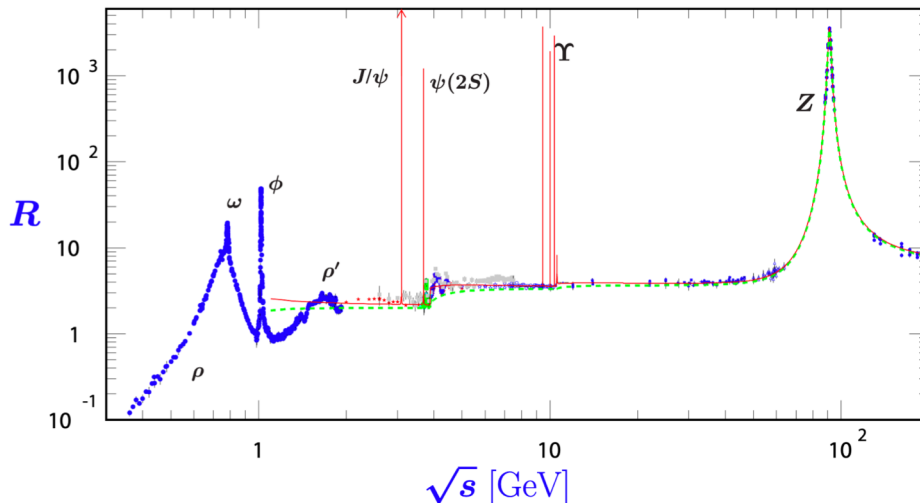
Dark photon decay rates

We assume g_D is much larger than ϵ , so X predominantly decays into DM

$$\Gamma(X \rightarrow f\bar{f}) = \frac{1}{3} \epsilon^2 Q_f^2 \alpha m_X \left(1 + \frac{2m_f^2}{m_X^2} \right) \left(1 - \frac{4m_f^2}{m_X^2} \right)^{\frac{1}{2}}$$

$$\Gamma(X \rightarrow \phi_1\phi_2) = \frac{g_D^2}{48\pi} m_X \left[1 - \frac{2(m_1^2 + m_2^2)}{m_X^2} + \frac{m_1^4 + m_2^4 - 2m_1^2 m_2^2}{m_X^4} \right] \left[1 - \frac{(m_1 + m_2)^2}{m_X^2} \right]^{\frac{1}{2}} \left[1 - \frac{(m_1 - m_2)^2}{m_X^2} \right]^{\frac{1}{2}}$$

<http://pdg.lbl.gov/2019/hadronic-xsections/hadron.html>

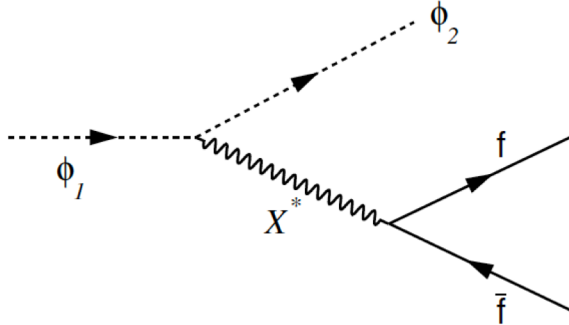


For $f=u/d/s$, the partial width can be calculated with the R -data:

$$R(\sqrt{s}) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

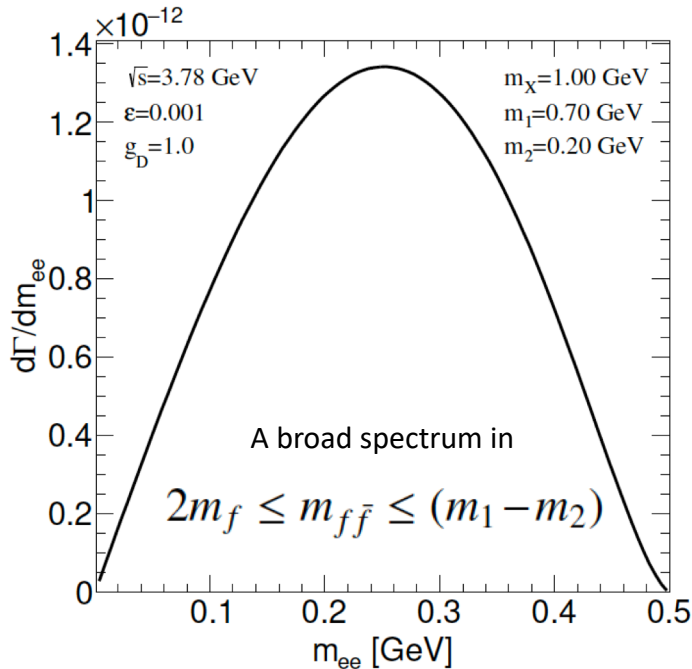
$$\Gamma_{had} = \Gamma_{\mu\mu} \cdot R(\sqrt{s} = m_X)$$

Heavy DM particle decay



The differential decay width:

$$d\Gamma(\phi_1 \rightarrow \phi_2 f \bar{f}) = \frac{\epsilon^2 Q_f^2 \alpha g_D^2}{8\pi^2 m_1^3 (m_{f\bar{f}}^2 - m_X^2)^2} \left[(m_{f\bar{f}}^2 - m_f^2)(m_1^2 + m_2^2 + m_f^2 - m_{f\bar{f}}^2 - m_{f\phi_2}^2) - m_1 m_2 \right] dm_{f\bar{f}}^2 dm_{f\phi_2}^2$$



After integrating out one mass:

$$\frac{d\Gamma_{\phi_1}}{dm_{f\bar{f}}} = \frac{\epsilon^2 Q_f^2 \alpha g_D^2}{24\pi^2 m_1^3 (m_{f\bar{f}}^2 - m_X^2)^2 m_{f\bar{f}}^2} \left[(m_1^2 - m_2^2 - m_{f\bar{f}}^2)^2 (m_{f\bar{f}}^2 + 2m_f^2) - 4m_2^2 m_{f\bar{f}}^4 - 8m_2^2 m_f^2 m_{f\bar{f}}^2 \right] (m_{f\bar{f}}^2 - 4m_f^2)^{\frac{1}{2}} \left[(m_1^2 - m_2^2 - m_{f\bar{f}}^2)^2 - 4m_2^2 m_{f\bar{f}}^2 \right]^{\frac{1}{2}}$$

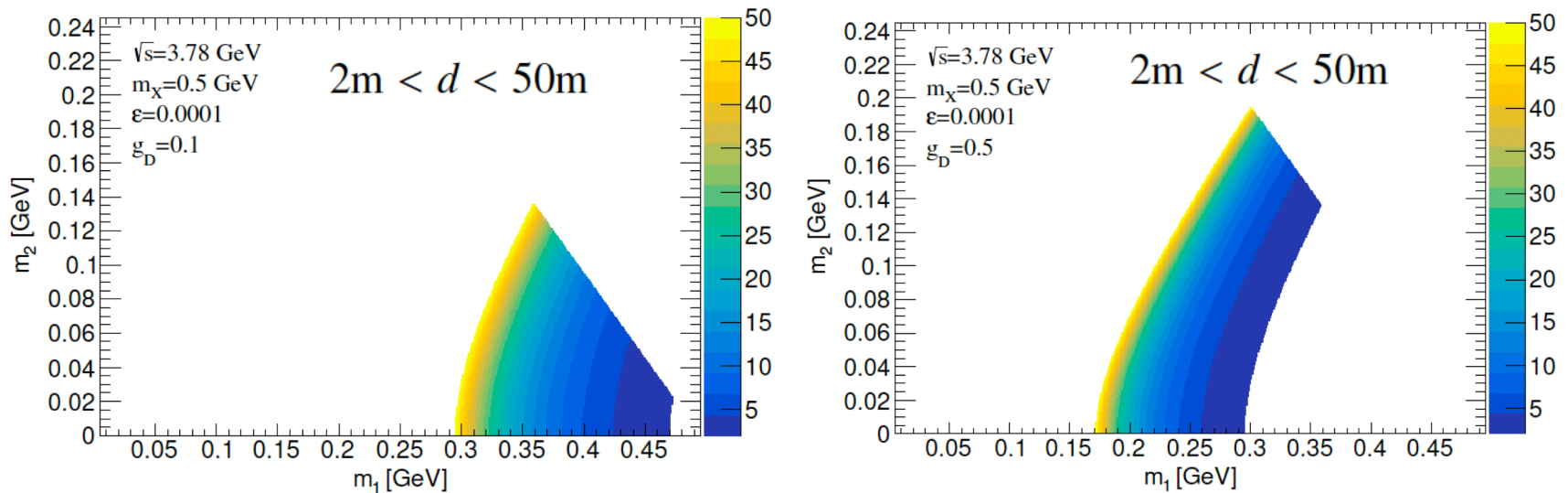
Decaying into lighter charged particles (e.g., electron-positron pair) is preferred due to phase space

Flight length of the excited DM

The flight length of an excited DM with Lorentz boost factor γ_1 :

$$d = \frac{\gamma_1 \beta_1}{\sum_f \Gamma_{\phi_1 \rightarrow \phi_2 f \bar{f}}}$$

Decay either too fast or too late will cause no events being detected in a detector. Need to scan the sensitive phase space regions



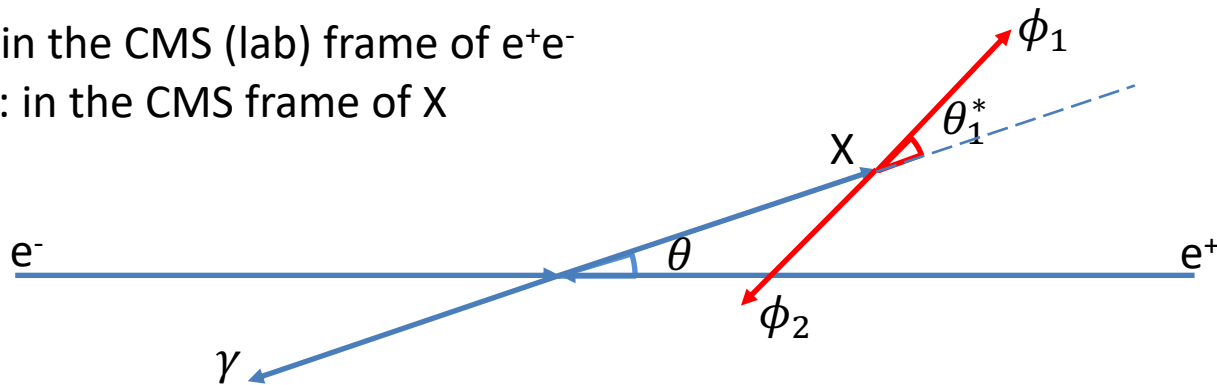
Angular distributions

The angular distributions in the lab frame with full correlation between production and decay of X:

$$\begin{aligned} \frac{d\sigma}{d\Omega d\Omega_1^*} \propto & \frac{1}{s(s \sin^2 \theta + 4m_e^2)} \left\{ (s + m_X^2)^2 + (s - m_X^2)^2 \cos^2 \theta \right. \\ & - \left[(s - m_X^2)^2 + (s + m_X^2)^2 \cos^2 \theta \right] \cos^2 \theta_1^* \\ & + 4m_X \sqrt{s} (s + m_X^2) \sin \theta_1^* \cos \theta_1^* \cos \phi_1^* \sin \theta \cos \theta \\ & \left. - 4m_X^2 s \sin^2 \theta_1^* \cos^2 \phi_1^* \sin^2 \theta \right\} \end{aligned}$$

Ω : in the CMS (lab) frame of e^+e^-

Ω_1^* : in the CMS frame of X



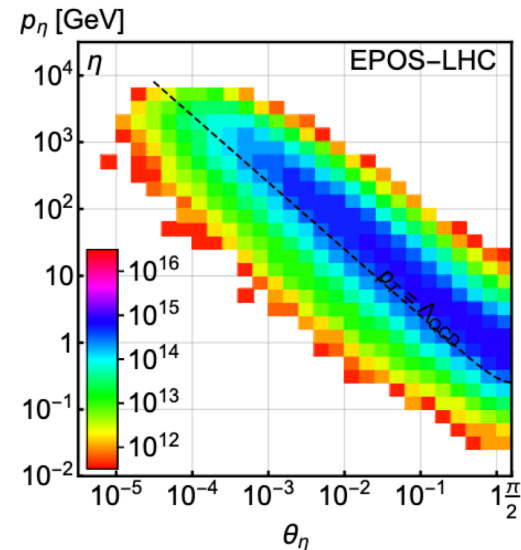
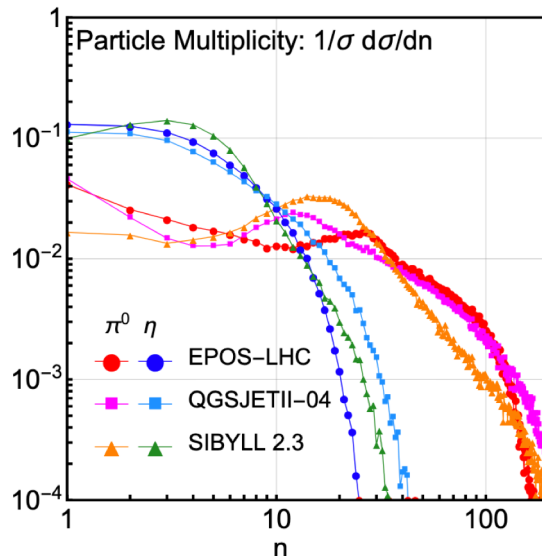
Dark photon production at LHC

- The main production modes for X at LHC are through meson decay, proton bremsstrahlung, and direct production via parton-parton collision
- For X mass below 0.5 GeV, the main production modes are through π^0 and η meson decays

$$B(\pi^0 \rightarrow A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \rightarrow \gamma\gamma),$$

$$B(\eta \rightarrow A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\eta}^2}\right)^3 B(\eta \rightarrow \gamma\gamma),$$

[Phys. Rev. D97, 035001 (2018)]



Excited DM helicity angle

In helicity formalism, for a particle of spin (J,M) decaying into two particles in (θ, φ) direction with helicities (λ, ν) , the decay amplitude can be expressed as

$$\begin{aligned}\mathcal{M}_{\lambda\nu}^J(\theta, \varphi; M) &\propto \langle \theta\varphi\lambda\nu | JM\lambda\nu \rangle \langle JM\lambda\nu | \mathcal{M} | JM \rangle \\ &\propto F_{\lambda\nu}^J D_{M\delta}^{J*}(\varphi, \theta, 0)\end{aligned}$$

where $\delta = \lambda - \nu$, $D_{M\delta}^{J*}$ is the Wigner D-function and $F_{\lambda\nu}^J \propto \langle JM\lambda\nu | \mathcal{M} | JM \rangle$. If parity is conserved, we have

$$F_{\lambda\nu}^J = \eta_J \eta_1 \eta_2 (-1)^{J-s_1-s_2} F_{-\lambda, -\nu}^J$$

where η_J, η_1, η_2 are the intrinsic parities of mother and two daughters. For the sequential decays in our case ($\eta \rightarrow A'\gamma \rightarrow \phi_1\phi_2\gamma$) we have

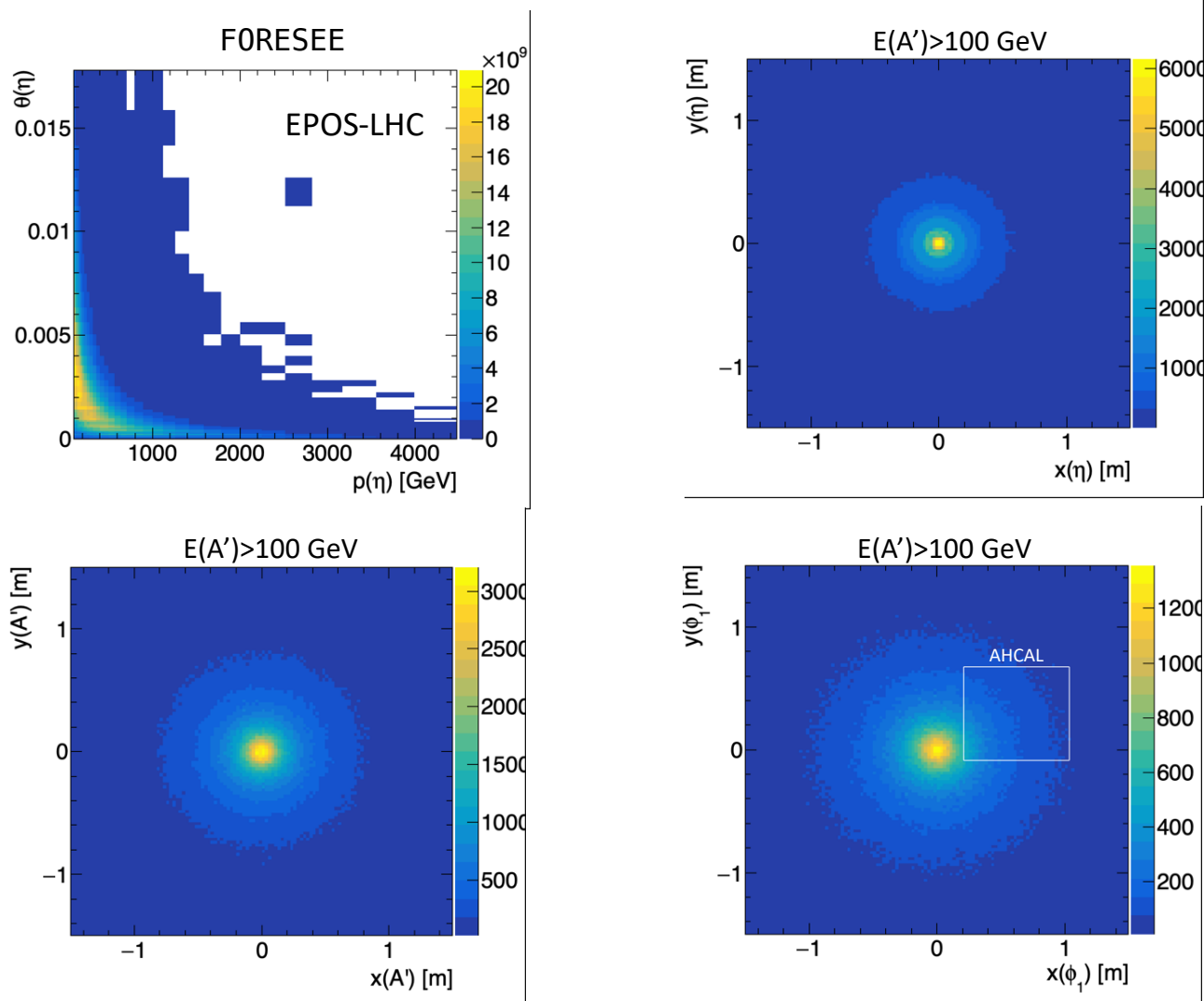
$$\mathcal{M} \propto F_{1\nu}^0 D_{0,1-\nu}^{0*}(\varphi, \theta, 0) A'_{00}{}^{11} D_{10}^{1*}(\varphi_1, \theta_1, 0) + F_{-1\nu}^0 D_{0,-1-\nu}^{0*}(\varphi, \theta, 0) A'_{00}{}^{11} D_{-10}^{1*}(\varphi_1, \theta_1, 0)$$

$$|\mathcal{M}|^2 \propto |d_{10}^1(\theta_1)|^2 + |d_{-10}^1(\theta_1)|^2 \propto \sin^2 \theta_1$$

Therefore, the decay of η is isotropic, and θ_1 is defined for ϕ_1 in the rest frame of A' . The $\sin^2 \theta_1$ behavior means the opening angle between ϕ_1 and ϕ_2 is largest

Distributions at AHCAL

- The distributions of η , A' ($m_{A'}=250$ MeV) and ϕ_1 ($m_{\phi_1}=10$ MeV, $m_{\phi_2}=5$ MeV) in the plane at AHCAL, perpendicular to Line of Sight (LoS)



Dark photon by proton bremsstrahlung

- When $m(A') \lesssim 1$ GeV, A' can be also produced via proton bremsstrahlung $pp \rightarrow pA'X$. We use the Weizsacker-Williams approximation for the cross section (in the fixed target frame)

$$\sigma_{pp \rightarrow pA'X} = \int dz \int dp_T^2 w(z, p_T^2) \sigma_{pp}(s')$$

The splitting function is defined as [Phys. Rev. D97, 035001 (2018)]

$$w(z, p_T^2) = \frac{\epsilon^2 \alpha}{2\pi H} \left\{ \frac{1 + (1-z)^2}{z} - 2z(1-z) \left(\frac{2m_p^2 + m_{A'}^2}{H} - z^2 \frac{2m_p^4}{H^2} \right) + 2z(1-z)(z + (1-z)^2) \frac{m_p^2 m_{A'}^2}{H^2} + 2z(1-z)^2 \frac{m_{A'}^4}{H^2} \right\},$$

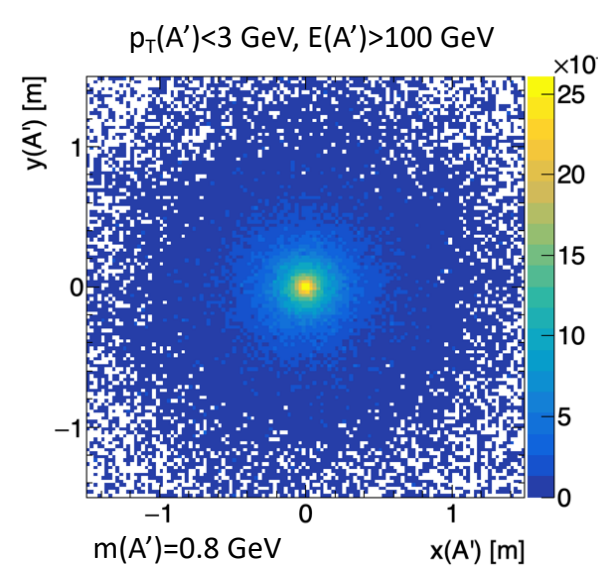
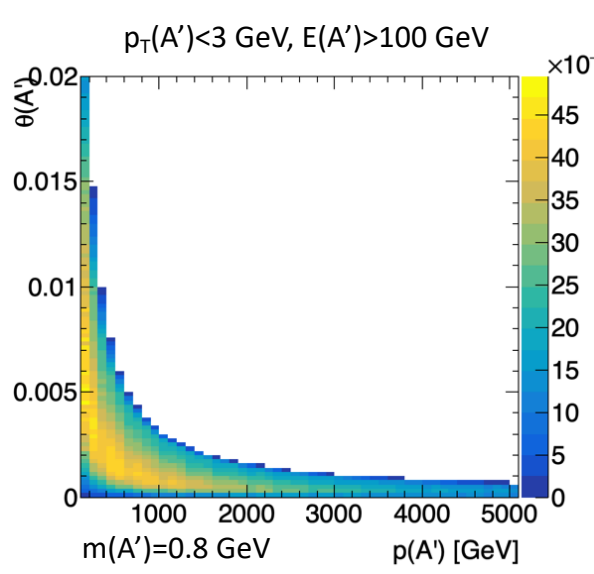
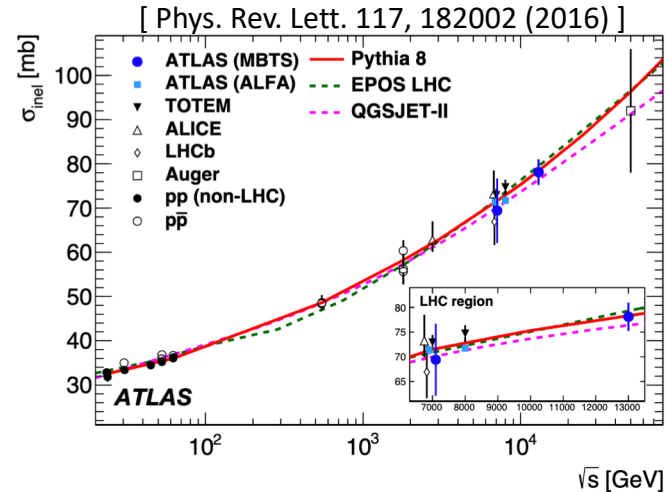
And the parameter H is defined as $H = p_T^2 + (1-z)m_{A'}^2 + z^2 m_p^2$

The approximation is valid if $E_{A'}, E_p, E_{p'} \gg m_{A'}, m_p, p_T$, and

$$|q_{\min}^2| \approx \frac{1}{4 E_p^2 z^2 (1-z)^2} [p_T^2 + (1-z)m_{A'}^2 + z^2 m_p^2]^2 < \Lambda_{\text{QCD}}^2$$

Dark photon by proton bremsstrahlung

- The partonic inelastic cross section $\sigma_{pp}(s')$ from experiments
- The collinearity and energy of A' are similar to the meson decay. The total cross section is substantial. Extra form factor will further suppress $m(A') \gtrsim 1$ GeV



Dark photon by parton collisions

- When $m(A') \gtrsim 1$ GeV, A' is dominantly produced by parton-parton interaction process $q\bar{q} \rightarrow gA'$ and its crossed diagram $qg \rightarrow qA'$. For the $q\bar{q}$ initiated process, the e^+e^- formula for $e^+e^- \rightarrow \gamma A'$ can be reused

$$\frac{d\sigma}{d\cos\theta} = 2\pi\epsilon^2\alpha^2 \frac{(s + m_X^2)^2 + (s - m_X^2)^2 \cos^2\theta}{s(s - m_X^2)(s \sin^2\theta + 4m_e^2)}$$

with the following modifications

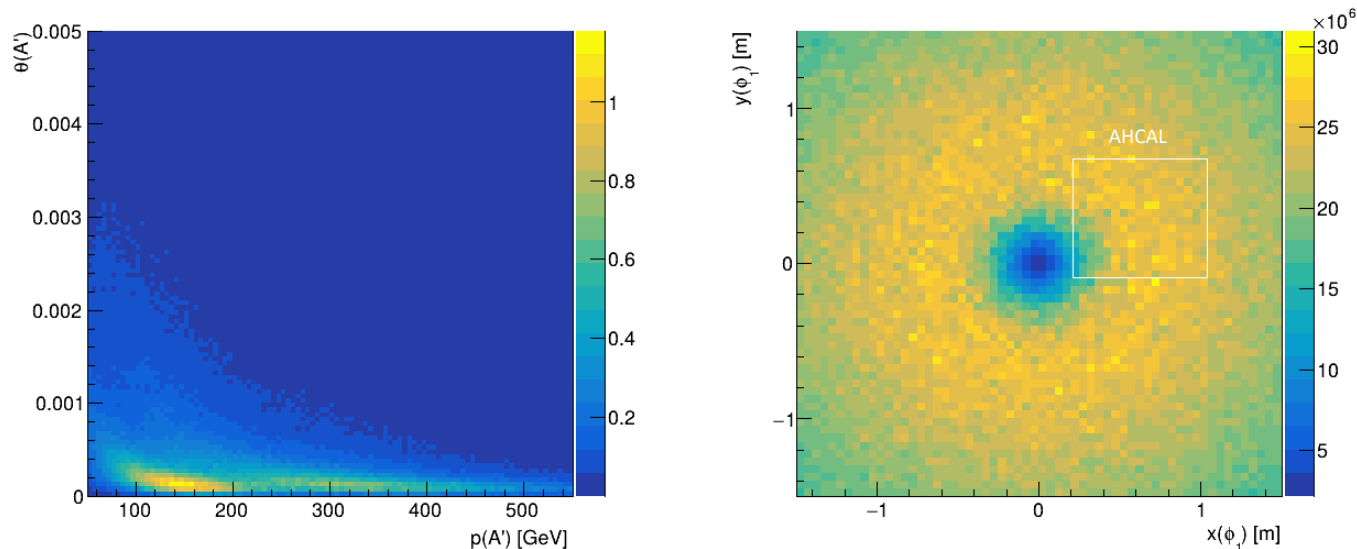
- Replace one α by $\alpha_S(Q^2)$ where Q is the gluon energy in partonic CM frame, replace m_e by the quark (u & d) \overline{MS} mass, and multiply by the quark charge squared
- To avoid infrared divergence at $s = m_{A'}^2$, and to keep perturbative QCD valid, we impose a lower cutoff of 1 GeV on the gluon energy
- Multiply by a color factor of 4/9 (sum over final gluon colors and average over initial quark colors)
- Convolute the partonic cross section with the NNPDF23LO PDF from 10^{-8} to 1
- Smear each parton with an intrinsic p_x and p_y of 0.2 GeV in Gaussian width

Dark photon by $q\bar{q} \rightarrow gA'$

- For $m(A') = 3 \text{ GeV}$, $m(\phi_1) = 1.0 \text{ GeV}$, $m(\phi_2) = 0.8 \text{ GeV}$, $\epsilon = 10^{-4}$, $p(A') > 50 \text{ GeV}$ and $\theta(A') < 0.005$ in the lab frame, the cross sections for different initial states:

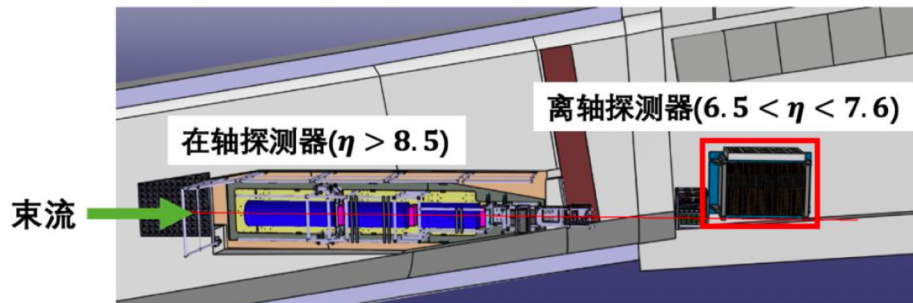
Initial state	$u\bar{u}$	$\bar{u}u$	$d\bar{d}$	$\bar{d}d$
$\sigma \text{ (fb)}$	561	31	53	9

- The A' energy is peaking around 150 GeV, and there is a hole at LoS (where FASER is located). On the other hand, AHCAL can cover a large part of signal



Signal and AHCAL

- Signal acceptance $\propto e^{-L/d} \frac{\Delta L}{d}$ (d is ϕ_1 flight length). If the mass splitting between ϕ_1 and ϕ_2 is small, the opening angle between e^+ and e^- is small and the signal is a single EM shower inside AHCAL with no hadronic recoil
- If the mass splitting is large (\sim GeV level), the signal is two EM showers originating from the same vertex inside AHCAL with no hadronic recoil
- AHCAL consists of 39 layers of absorber and 40 layers of scintillator. The sensitive volume is $76 \times 83 \times 116 \text{ cm}^3$. Its center is located at $(62.5, 29.3) \text{ cm}$ with LoS as the origin. The pixel granularity is $4 \times 4 \text{ cm}^2$, and the energy threshold is $\sim 100 \text{ MeV}$

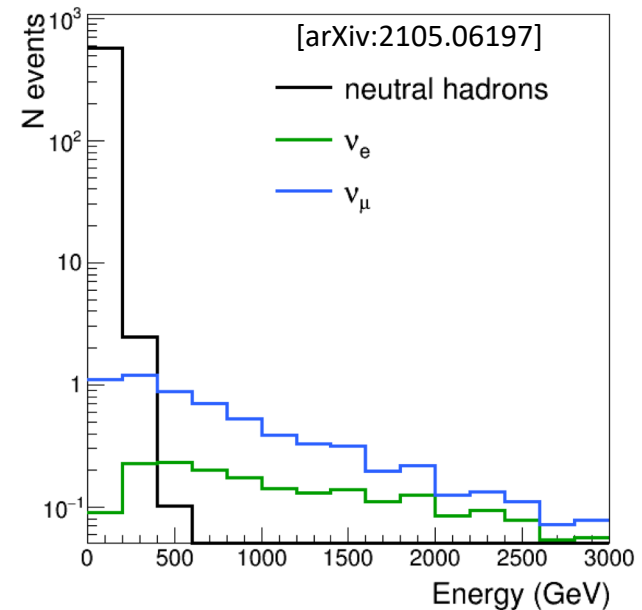


Backgrounds

- FASER and AHCAL are naturally shielded from cosmic muons, and particles produced at IP are largely shielded by $\sim 100\text{m}$ of rock, except for large momentum muons and neutrinos
- Muons produce neutral hadrons, mainly $K_S \rightarrow \pi^+\pi^-/\pi^0\pi^0$, $K_L \rightarrow \pi^+\pi^-\pi^0$, $\Lambda \rightarrow p\pi^-/n\pi^0$, in upstream rock, which can mimic neutrino interactions. Hadrons and π^0 in the final state can be separated by their shower profiles. $K_S \rightarrow \pi^0\pi^0$ can be vetoed by its mass window. But since AHCAL is several meters away from rock wall, the main components are actually K_L and **neutron**

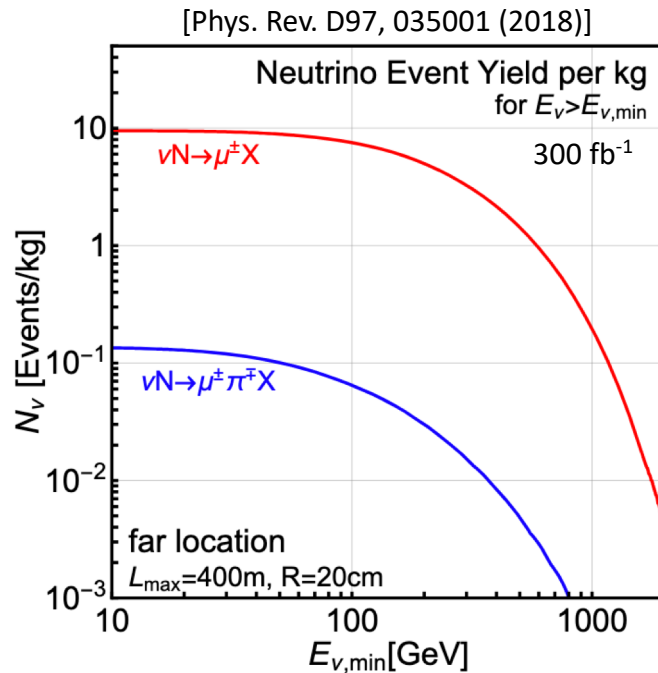
The production rates of neutral hadrons per incident muon (arXiv:2105.06197)

	Negative Muons	Positive Muons
K_L	3.3×10^{-5}	9.4×10^{-6}
K_S	8.0×10^{-6}	2.3×10^{-6}
n	2.6×10^{-5}	7.7×10^{-6}
\bar{n}	1.1×10^{-5}	3.2×10^{-6}
Λ	3.5×10^{-6}	1.8×10^{-6}
$\bar{\Lambda}$	2.8×10^{-6}	8.7×10^{-7}

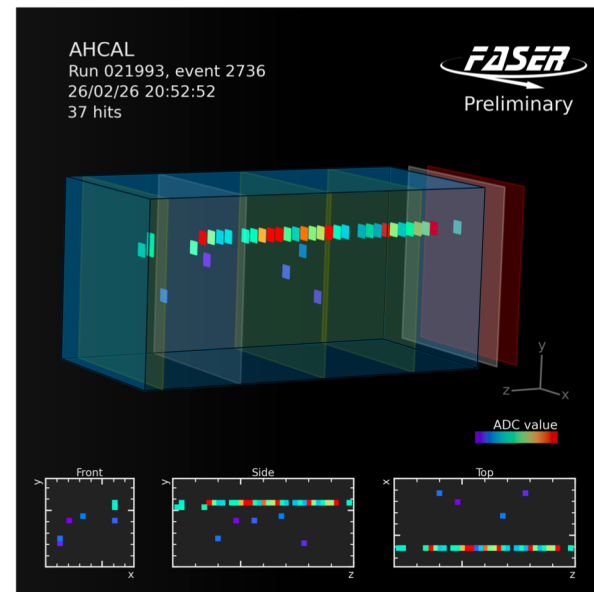


Backgrounds

- A typical neutrino process is $\nu_\mu N \rightarrow \mu^- \pi^+ X$. The muon gives a long track in AHCAL, while the pion is typically much softer and gives a small hadronic shower. With energy threshold of AHCAL down to ~ 100 MeV, the hadronic recoil can be efficiently detected. Neutrino events are rare and are another type of signal we want to detect
- Muons, typically penetrating the whole detector, are easy to veto



The first LHC muon recorded in AHCAL



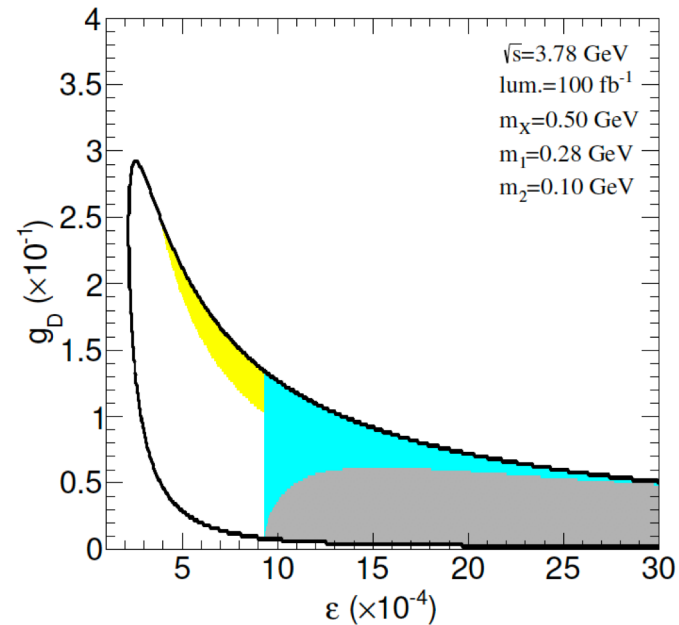
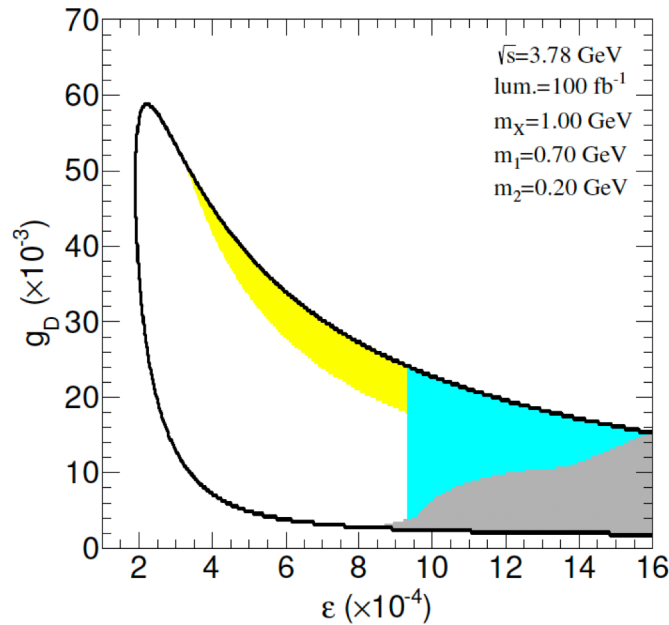
Summary

- Excited dark matter model is a good candidate to resolve some experimental tension and explain the non-observation of DM
- At LHC, while the low mass dark photon ($m \lesssim 1$ GeV) is covered by FASER, the high mass one ($m \gtrsim 1$ GeV) is mainly produced by parton interactions, and the excited DM can be best detected by an off-axis detector such as AHCAL
- With $\sim 50 \text{ fb}^{-1}$ data collected this year at 13.6 TeV, expect to put a strong limit on this model
- Calculation is still going on with the gluon initiated crossed process of $qg \rightarrow qA'$, and the final sensitivity plot to be completed

Backup Slides

Signal sensitivity at BESIII

- Signal yield: $N_{sig} = \mathcal{L}\sigma(e^+e^- \rightarrow \gamma X)BR(X \rightarrow \phi_1\phi_2)\epsilon_A \left(e^{-\frac{6}{d}} - e^{-\frac{6+L}{d}} \right)$. Sensitivity for at least one signal event:



- The grey areas have been excluded by BaBar

Either $\epsilon > \frac{\epsilon_1}{\sqrt{BR(X \rightarrow ll)}}$ causing too large $X \rightarrow ll$, or $\epsilon > \epsilon_2 e^{1/d}$ spoiling the mono-photon topology

- The cyan is the original literal exclusion on ϵ from $X \rightarrow$ invisible search at BaBar
- Yellow is the region with a $d < 2$ m