Probing new physics at the FASER(2) detector

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Outline

1. The FASER and FASER2 detectors
2. Inelastic Dark Matter from Dark Higgs Boson Decays
3. Searches for TeV scale new physics - the quirk scenario
   - The timing analysis at the FASER

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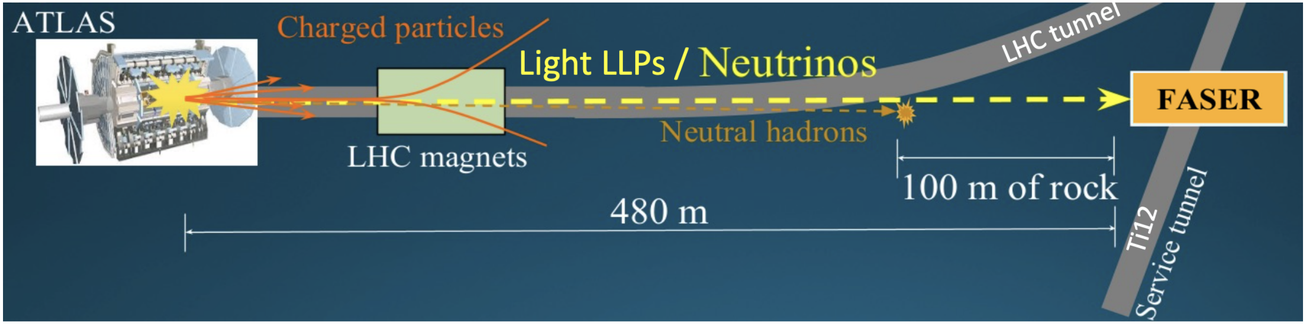
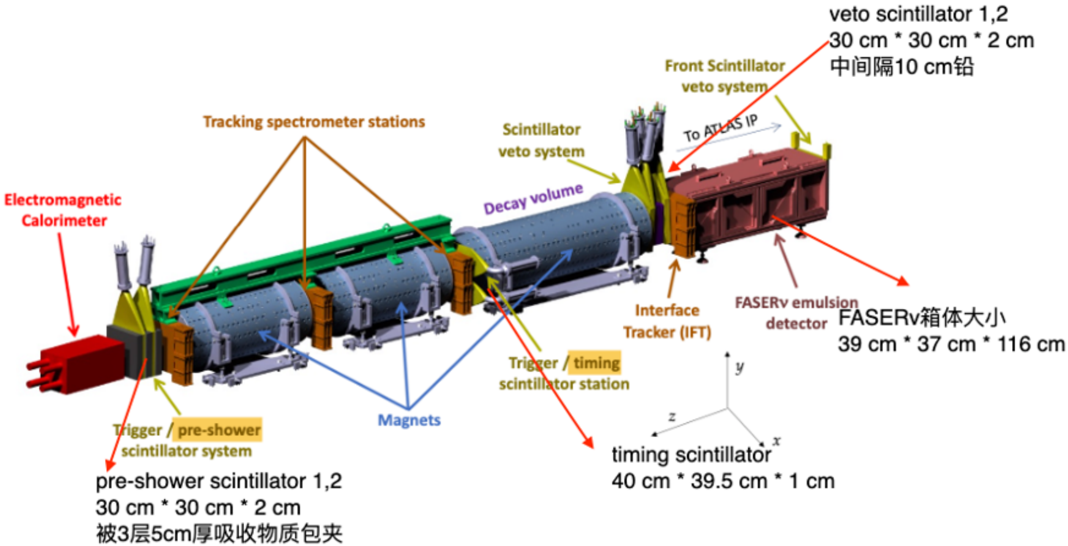
FASER detector





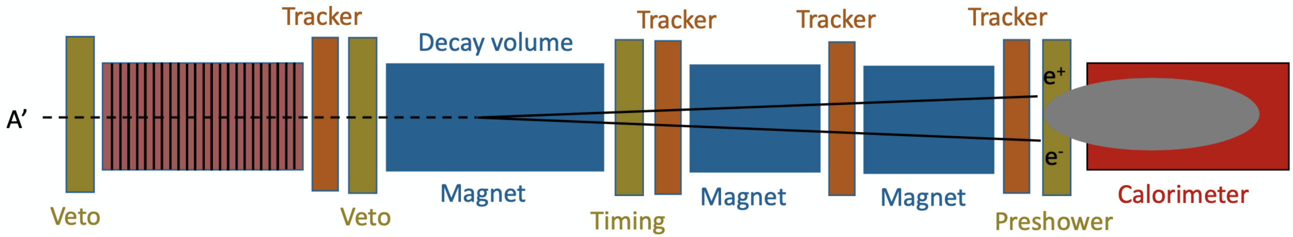
To wasted forward LHC events

$$\sigma_{\rm inel} \sim 75 \text{ mb}$$
$$N_\pi \sim 10^{17} \text{ at } 3 \text{ ab}^{-1}$$
$$\Lambda_{\rm QCD} \sim 250 \text{ MeV}$$
$$E \sim 100 \text{ GeV}$$
$$\theta \sim \Lambda_{\rm QCD}/E$$

Newly proposed small ($\sim 0.05\text{m}^3$) and inexpensive ($\sim$ 2M$) experiment detector to be placed few hundred meters downstream away from the ATLAS IP. Start taking LHC collision data in 2022.

Physics at the FASER detector

- The benchmark signal (light and long-lived dark photon from mesons decay and bremsstrahlung)



$$L = c\beta\tau\gamma \sim (100\ \mathrm{m})(\frac{10^{-5}}{\epsilon})^2(\frac{E_{A'}}{\mathrm{TeV}})(\frac{100\ \mathrm{MeV}}{m_{A'}})^2$$

- The main backgrounds
  - Muons with tracks pointing back to veto

    [5 layers reduce 10^8 muons to negligible]
  - Cosmic measured in runs with no beam

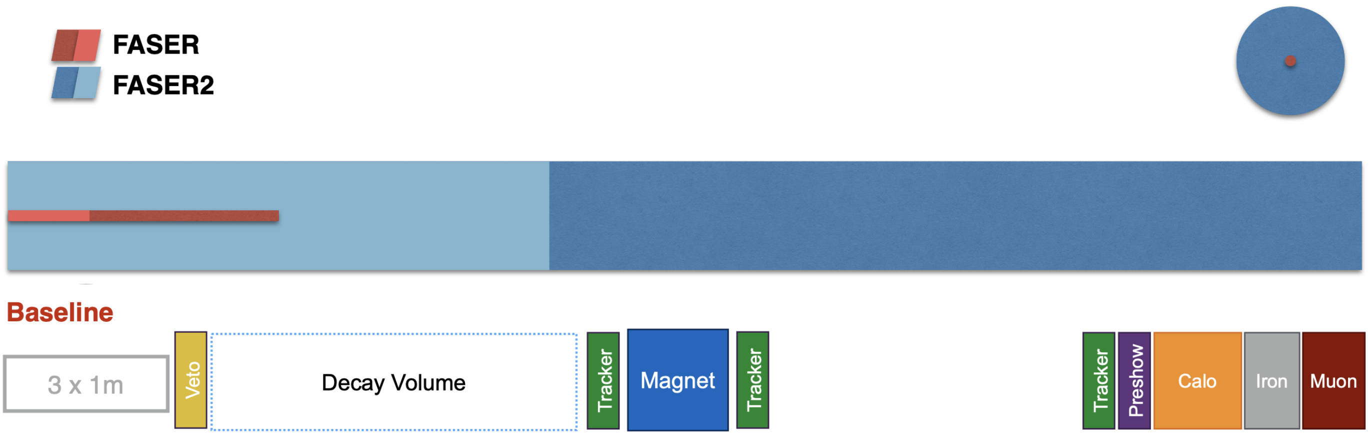
    [No event observed with ≥ 1 track or $E(\text{calo}) > 500$ GeV]
  - From neutrino interaction from vicinity of timing detector

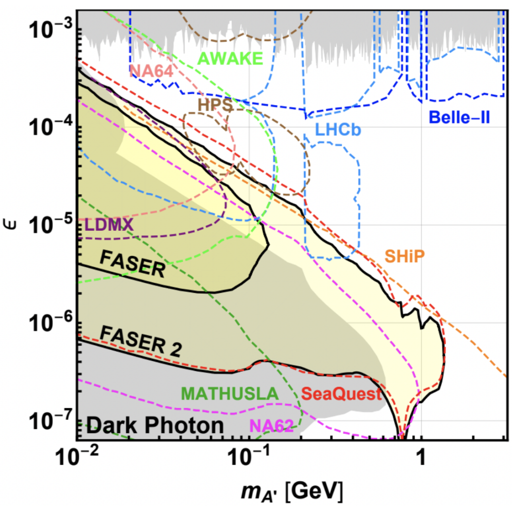
    [Events with $E(\text{calo}) > 500$ GeV, $(1.8 \pm 2.4) \times 10^{-3}/27\ \mathrm{fb}^{-1}$]
  - Neutral hadron from upstream muons interacting with rock
    [Event with $E(\text{calo}) > 500$ GeV pass

    though 8 interaction length (FASERν)

    $(2.2 \pm 3.1) \times 10^{-4}/27\ \mathrm{fb}^{-1}$]

FASER2 detector

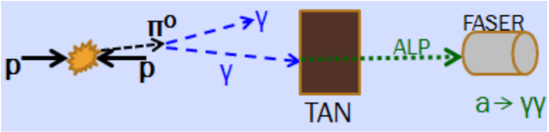


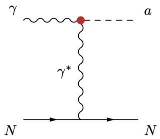


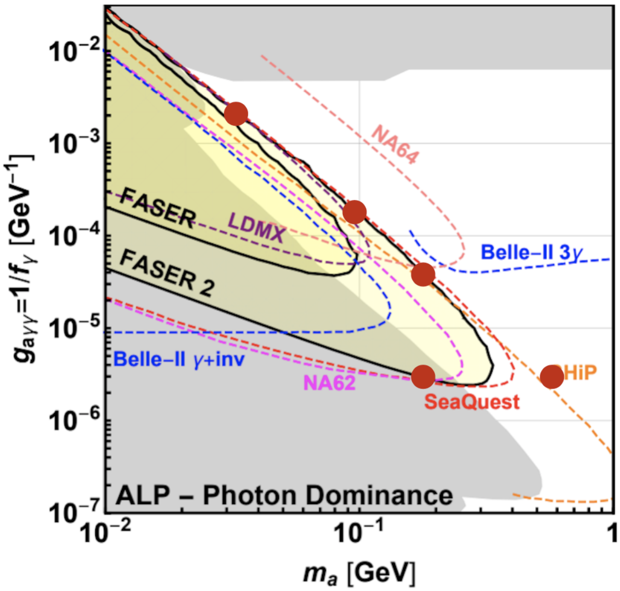
- For lower ϵ boundary, the total number of signal events in the detector scales as ϵ^4.
- For high ϵ boundary, the number of signal events becomes exponentially suppressed once the A' decay length drops below the distance to the detector.
- At around $m_{A'} = 0.7$ GeV, enhancement from the electromagnetic form factor of nucleons.

Photon Dominance

($\frac{1}{\Lambda} a V^{\mu\nu} \tilde{V}_{\mu\nu}$, Primakoff process)

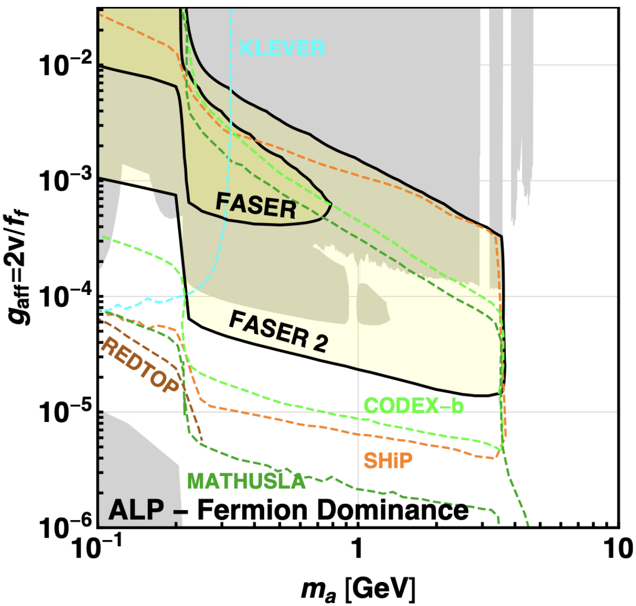






Fermion Dominance

($\frac{m_f}{\Lambda} a\bar{f}\gamma_5 f$, heavy meson decay $B \to X_s a$;
Through mixing with pion if $g_{add} \neq g_{auu}$)



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Outline

Inelastic dark matter model

BSM field content $(U(1)_X)$:

Dirac fermion $\chi : U(1)_X^{1/2}$, Complex scalar $S = \frac{1}{\sqrt{2}}(s + ia) : U(1)_X^{1/2}$, Higgs scalar $\phi : U(1)_X^1$

The Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM}^{\chi(S)} - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} - \frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu} + (D^\mu \varphi)^* (D_\mu \varphi) - V(H, \phi)$$

where

$$\mathcal{L}_{DM}^{\chi} = \bar{\chi}(i\not{D} - M_\chi)\chi + \left(y_L \overline{\chi_L^c} \chi_L \varphi + y_R \overline{\chi_R^c} \chi_R \varphi + h.c. \right)$$

$$\mathcal{L}_{DM}^{S} = (D^\mu S)^* (D_\mu S) - M_S^2 S^* S - \mu(\varphi S^* S^* + c.c.) - \lambda_S (S^* S)^2 - \lambda_{HS} (S^* S)(H^\dagger H) - \lambda_{\varphi S} (\varphi^* \varphi)(S^* S)$$

$$V = -\mu_H^2 H^\dagger H - \mu_\varphi^2 \varphi^* \varphi + \frac{\lambda_H}{2} (H^\dagger H)^2 + \frac{\lambda_\varphi}{2} (\varphi^* \varphi)^2 + \lambda_{H\varphi} (H^\dagger H)(\varphi^* \varphi)$$

DM scenarios (gauge symmetry breaking)

Fermion DM

$$\mathcal{L}_{M_\chi} = \frac{1}{2}(\overline{\chi_L^c}\ \overline{\chi_R}) \begin{pmatrix} m_L & M_\chi \\ M_\chi & m_R \end{pmatrix} \begin{pmatrix} \chi_L \\ \chi_R^c \end{pmatrix} + h.c.$$

$$\begin{aligned} \mathcal{L}^{\chi}_{A'-\mathrm{int}} =& g_X A'_\mu [\cos 2\theta_\chi (\bar\chi_1 \gamma^\mu \chi_1 - \bar\chi_2 \gamma^\mu \chi_2) \\ & + \sin 2\theta_\chi (\bar\chi_1 \gamma^\mu \chi_2 + \bar\chi_2 \gamma^\mu \chi_1)] \\ \mathcal{L}^{\chi}_{\phi-\mathrm{int}} =& \frac{1}{\sqrt{2}} y_L (c_\alpha \phi - s_\alpha h)(c_\chi^2 \overline{\chi_1^c}\chi_1 + c_\chi s_\chi \\ & \times(\overline{\chi_1^c}\chi_2 + \overline{\chi_1}\chi_2^c) + s_\chi^2 \overline{\chi_2^c}\chi_2) \\ & + \frac{1}{\sqrt{2}} y_R (c_\alpha \phi - s_\alpha h)(s_\chi^2 \overline{\chi_1^c}\chi_1 - c_\chi s_\chi \\ & \times(\overline{\chi_1^c}\chi_2 + \overline{\chi_1}\chi_2^c) + c_\chi^2 \overline{\chi_2^c}\chi_2) + h.c. \end{aligned}$$

Relic density:

nearly maximal mixing $\theta_\chi \sim \pi/4 - 0.05$

$$\chi_1\chi_1 \to A' \to \bar f f$$

$$\chi_1\chi_2 \to A' \to \bar f f$$

Scalar DM

$$\mathcal{L}_{M_S} = \frac{1}{2}\left(\tilde M_S^2 + \sqrt{2}\mu v_\varphi\right) s^2 + \frac{1}{2}\left(\tilde M_S^2 - \sqrt{2}\mu v_\varphi\right) a^2$$

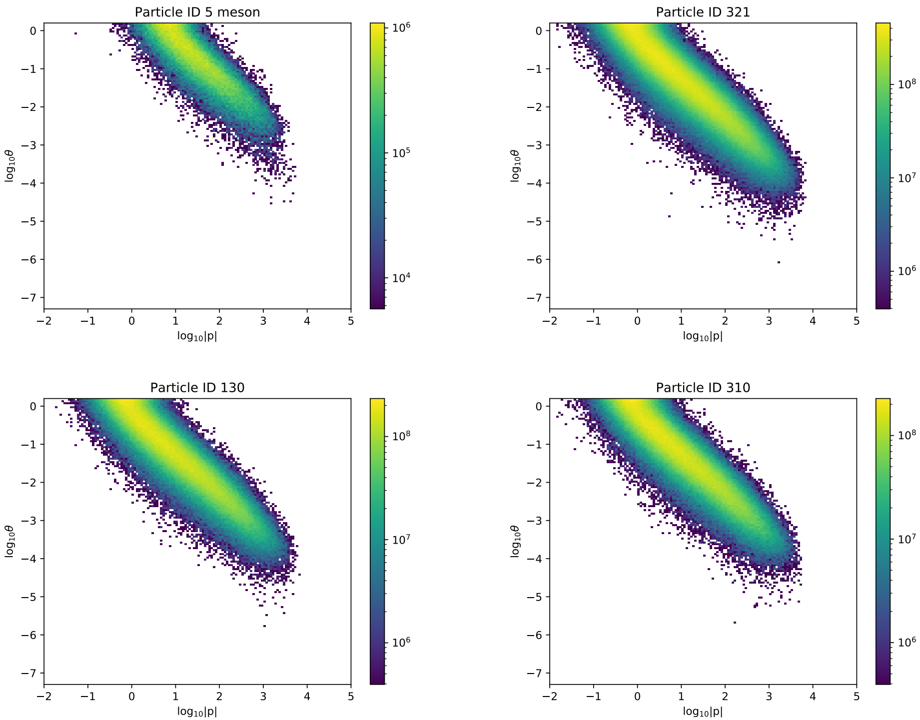
$$\begin{aligned} \mathcal{L}^{S}_{A'-\mathrm{int}} =& \frac{1}{2} g_X A'_\mu (s\partial^\mu a - a\partial^\mu s) \\ & + \frac{1}{8} g_X^2 A'_\mu A'^\mu (s^2 + a^2) \\ \mathcal{L}^{S}_{\phi-\mathrm{int}} =& -\frac{\mu}{\sqrt{2}}\tilde\phi (s^2 - a^2) - \frac{\lambda_{HS}}{4}(\tilde h^2 + 2v\tilde h) \\ & \times (s^2 + a^2) - \frac{\lambda_{\varphi S}}{4}(\tilde\phi^2 + 2v_\varphi \tilde\phi)(s^2 + a^2) \end{aligned}$$

Relic density:

$$sa \to A' \to \bar f f$$

Produced from the decay of the dark Higgs boson which can be produced from B and K meson decays

Meson cross section [pb]



$$\mathrm{Br}(B \to X_s \phi):$$

$$5.7\left(1-\frac{m_\phi^2}{m_b^2}\right)^2 \alpha^2$$

$$\mathrm{Br}(K^\pm \to \pi^\pm \phi)(321):$$

$$2.0 \times 10^{-3}\,\frac{2p_\phi^0}{m_{K^\pm}}\alpha^2$$

$$\mathrm{Br}(K_L \to \pi^0 \phi)(130):$$

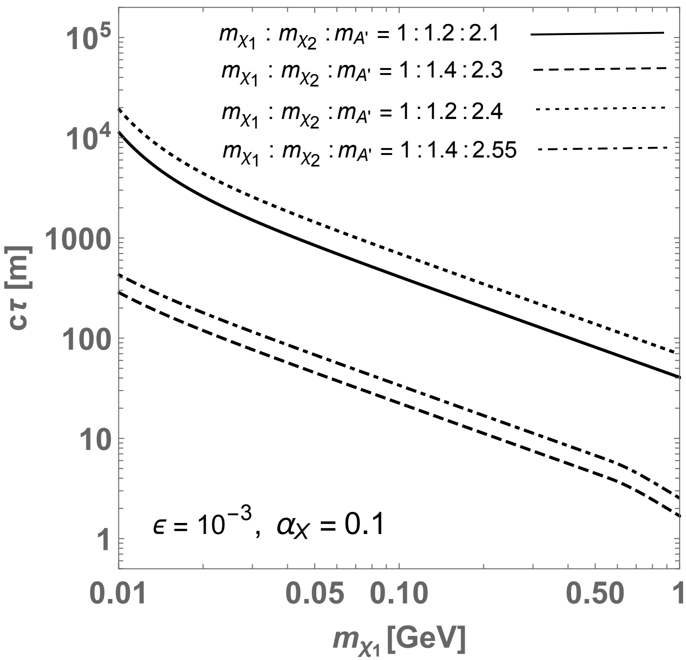
$$7.0 \times 10^{-3}\,\frac{2p_\phi^0}{m_{K_L^0}}\alpha^2$$

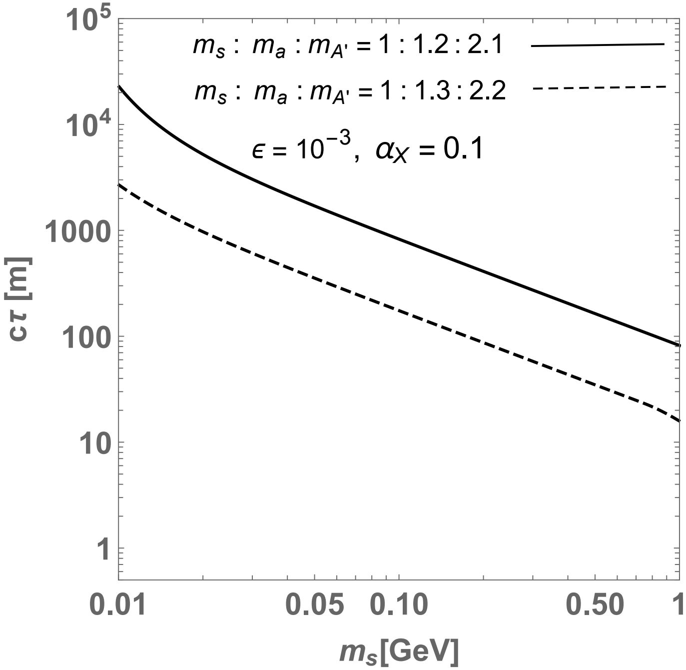
$$\mathrm{Br}(K_S \to \pi^0 \phi)(310):$$

$$2.2 \times 10^{-6}\,\frac{2p_\phi^0}{m_{K_S^0}}\alpha^2$$

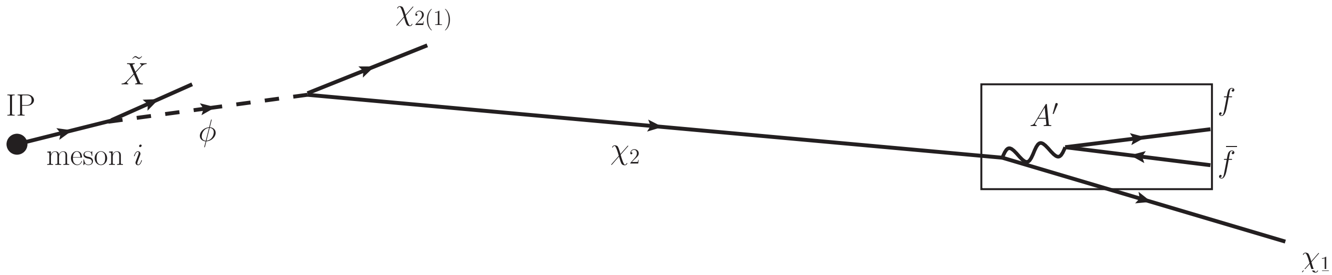
Decays

$$\chi_2[a] \to A'^*(\to \bar{f}f)\chi_1[s]$$





Signal rate

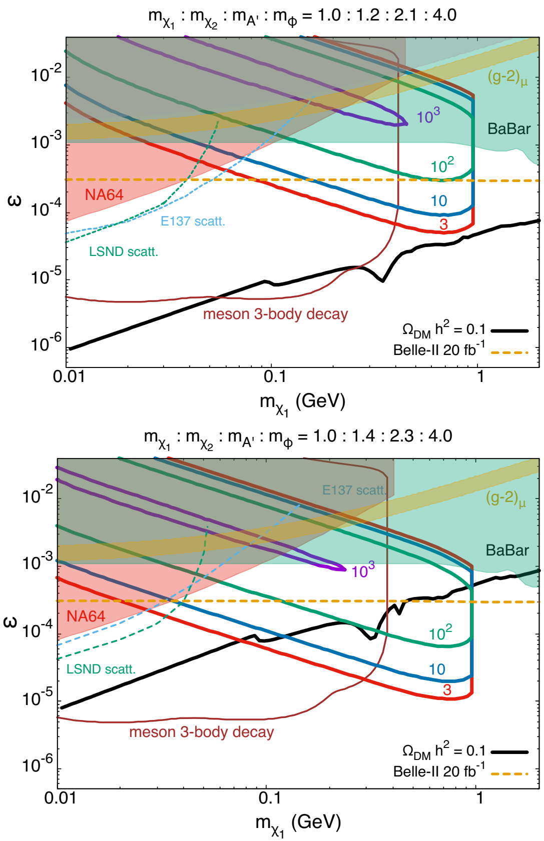


$$N_{\chi_2} = \mathcal{L} \sum_{i:\text{meson}} \int dp_i\, d\theta_i \frac{d\sigma_{pp\to iX}}{dp_i\, d\theta_i} \text{Br}(i \to \tilde{X}\phi)$$
$$\times \left[\sum_{j=1,2} \text{Br}(\phi \to (\chi_2)_1(\chi_2)_2) \mathcal{P}^{\text{det}}_{(\chi_2)_j}(\boldsymbol{p}_{(\chi_2)_j}, \boldsymbol{p}_\phi) + \text{Br}(\phi \to \chi_1\chi_2)\mathcal{P}^{\text{det}}_{\chi_2}(\boldsymbol{p}_{\chi_2}, \boldsymbol{p}_\phi) \right],$$
$$N_s = \mathcal{L} \sum_{i:\text{meson}} \int dp_i\, d\theta_i \frac{d\sigma_{pp\to iX}}{dp_i\, d\theta_i} \text{Br}(i \to \tilde{X}\phi) \sum_{j=1,2} \text{Br}(\phi \to (a)_1(a)_2)\mathcal{P}^{\text{det}}_{a_j}(\boldsymbol{p}_{a_j}, \boldsymbol{p}_\phi),$$

where

$$\mathcal{P}^{\text{det}}_i(\boldsymbol{p}_i, \boldsymbol{p}_\phi) = \frac{1}{\bar{d}_\phi \cos\theta_\phi} \int_{z_{\phi,\min}}^{z_{\phi,\max}} dz_\phi\, e^{-\frac{z_\phi}{\bar{d}_\phi \cos\theta_\phi}} \frac{1}{\bar{d}_i \cos\theta_i} \int_{z_{i,\min}}^{L_{\max}} dz_i\, e^{-\frac{z_i - z_\phi}{\bar{d}_i \cos\theta_i}}$$
$$\times\, \Theta(R - r_{i,R})\Theta(R - r_{i,F})$$

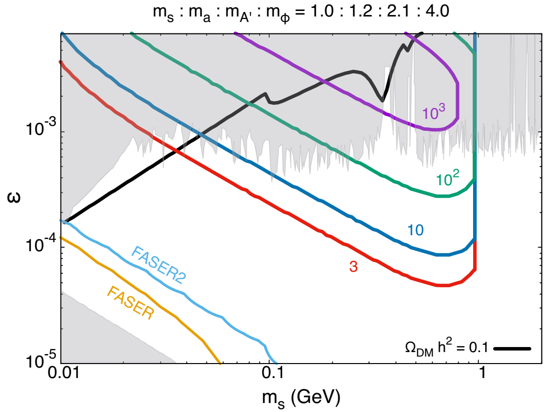
The sensitive region (fermion DM)

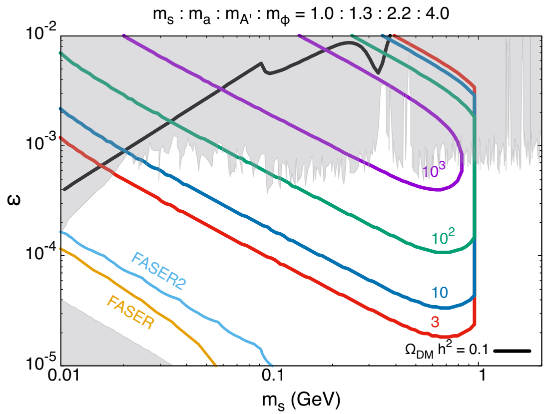


- Colored contours correspond to the expected number of the signal events events
- Cutoff at 1 GeV because the scalar boson mass is heavier than B meson
- The invisible decay search of the dark photon by NA64 (red) and BaBar (green)
- Orange band is the favored region of muon anomalous magnetic moment within 2σ
- The brown curve corresponds to 3 signal events from 3-body decays of π^0, η, η' into $\gamma\chi_1\chi_2$, it covers much smaller kinetic mixing due to higher light mesons production rate.

$\alpha_X = 0.1$, $m_\phi = 4 \times m_{\chi_1}$, $\alpha_H = 10^{-4}$.

The sensitive region (scalar DM)





$\alpha_X = 0.1,\ m_\phi = 4 \times m_{\chi_1},\ \alpha_H = 10^{-4}.$

- Grey upper region is excluded by BaBar, NA48 and LSND while the lower region is excluded by NuCal.
- Relic density only through the coannihilation mechanism requires to large kinetic mixing

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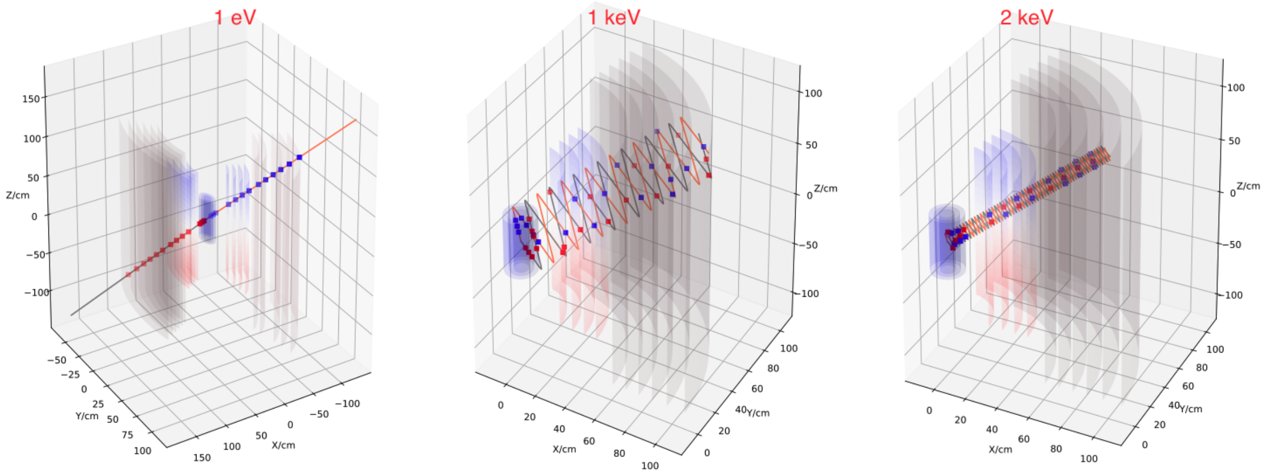
Introduction to quirk particle

Definition: particles that are charged under both the Standard Model (SM) gauge group and a new confining gauge group. The mass of the lightest quirk is much larger than the confinement scale (Λ) of the new gauge group. String tension $\propto \Lambda^2$

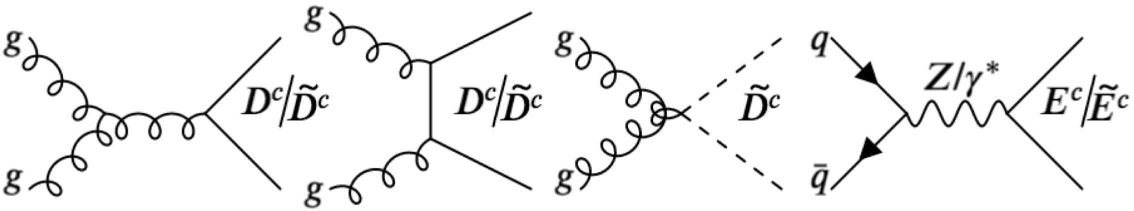
- $\Lambda < 10$ eV: string tension is negligible compared to the magnetic force HSCP.
- $\Lambda \in [100 \text{ eV}, 1 \text{ keV}]$: quirk track dropped in event reconstruction E_T^{miss}.
- $\Lambda \in [10 \text{ keV}, 10 \text{ MeV}]$: oscillation amplitude of the quirk is microscopic Ultra-boosted, high ionization.
- $\Lambda > 10$ MeV: the quirk pair system will oscillate intensively after production and annihilate into SM particles quickly resonance.

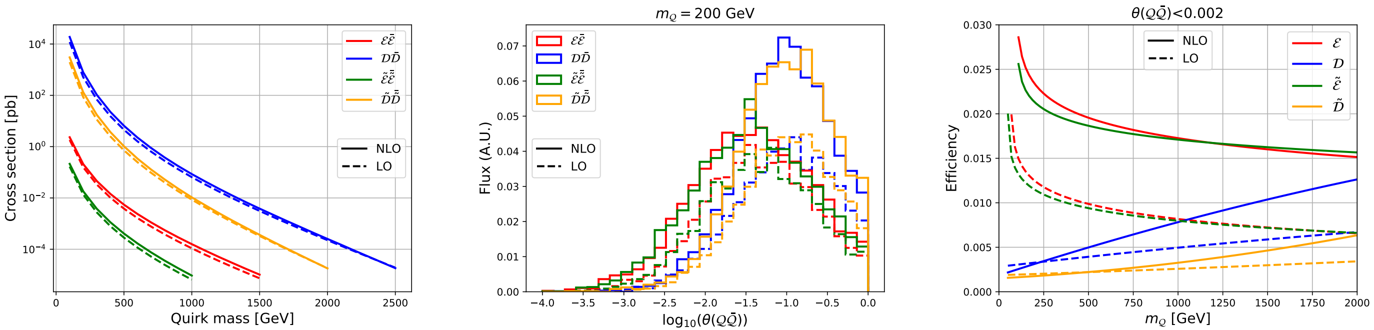


The quirk production at the LHC

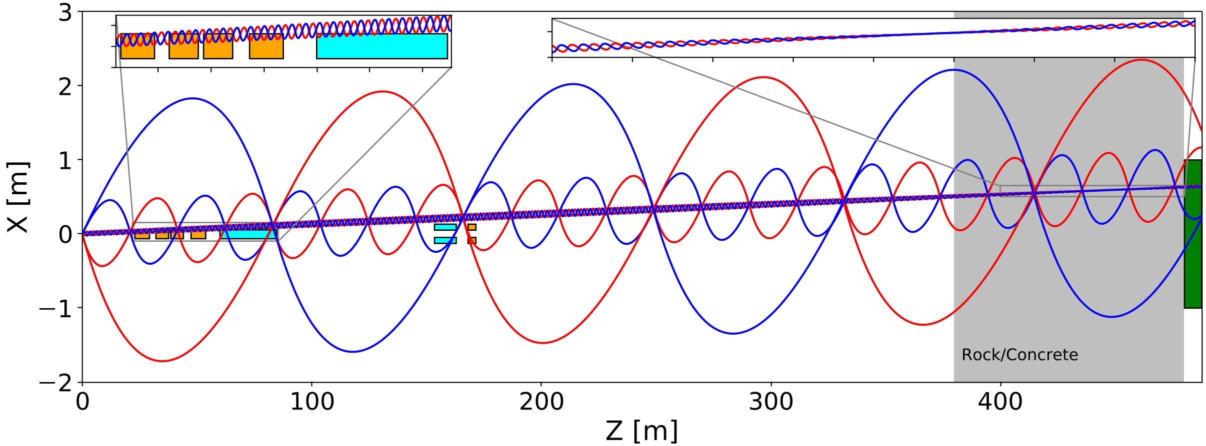
Representation under $SU(N_{\rm IC}) \times SU_C(3) \times SU_L(2) \times U_Y(1)$

$$\tilde{\mathcal{D}} : (N_{\rm IC} = 2, 3, 1, -1/3)\,, \quad \tilde{\mathcal{E}} : (N_{\rm IC} = 2, 1, 1, -1)$$
$$\mathcal{D} : (N_{\rm IC} = 2, 3, 1, -1/3)\,, \quad \mathcal{E} : (N_{\rm IC} = 2, 1, 1, -1)$$





The quirk trackctory to FASER



$$\frac{\partial(m\gamma\vec{v})}{\partial t} = \vec{F}_s + \vec{F}_{\text{ion}}$$

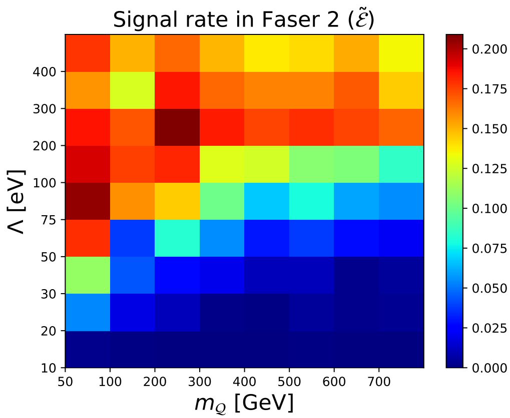
$$\vec{F}_s = -\Lambda^2\sqrt{1-\vec{v}_\perp^2}\,\hat{s} - \Lambda^2\frac{v_\parallel\vec{v}_\perp}{\sqrt{1-\vec{v}_\perp^2}}$$

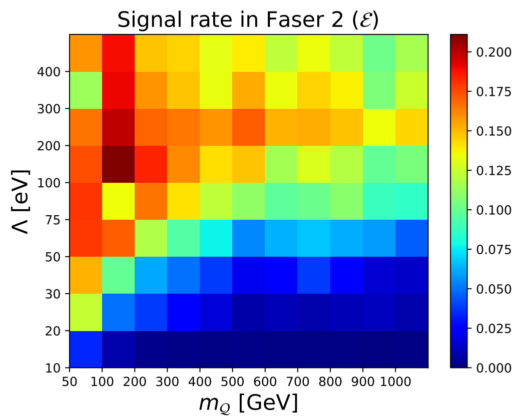
$$\vec{F}_{\text{ion}} = \frac{dE}{dx}\hat{v}$$

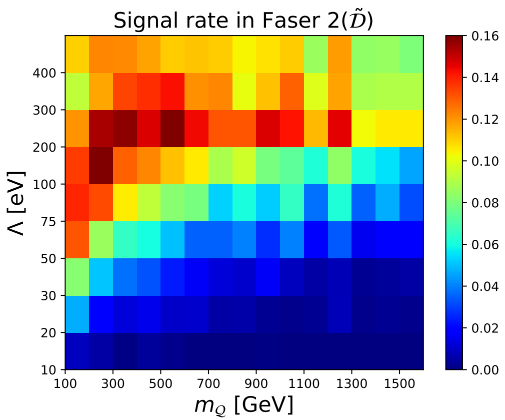
- $m_{\mathcal{Q}} = 800$ GeV
- $\vec{p}_1 = (-132.146, 121.085, 1167.35)$ GeV
- $\vec{p}_2 = (136.381, -123.865, 2061.56)$ GeV
- $\Lambda = 50$ eV, 100 eV, 400 eV

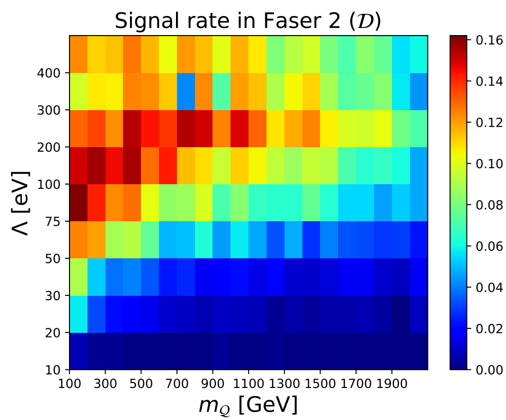
The fraction of quirk reaching the FASER2 detector

In the event sample which satisfies $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.005$ that have at least one quirk entering the FASER 2 tracker



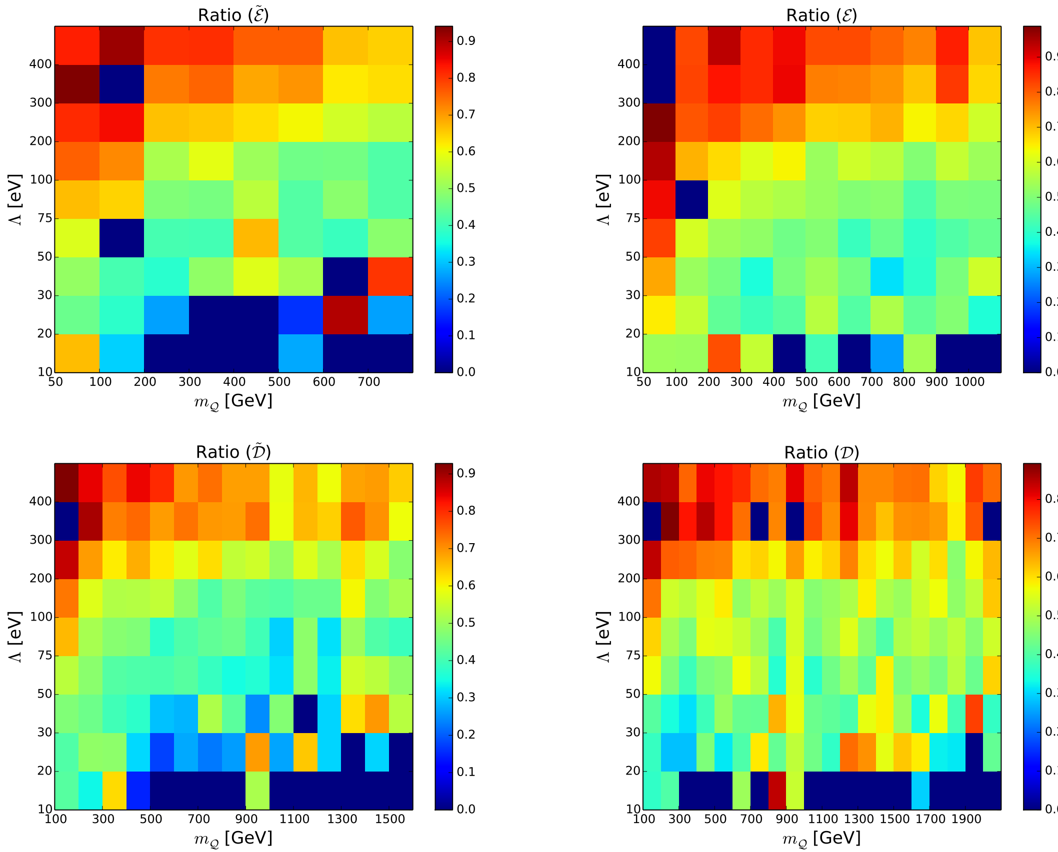




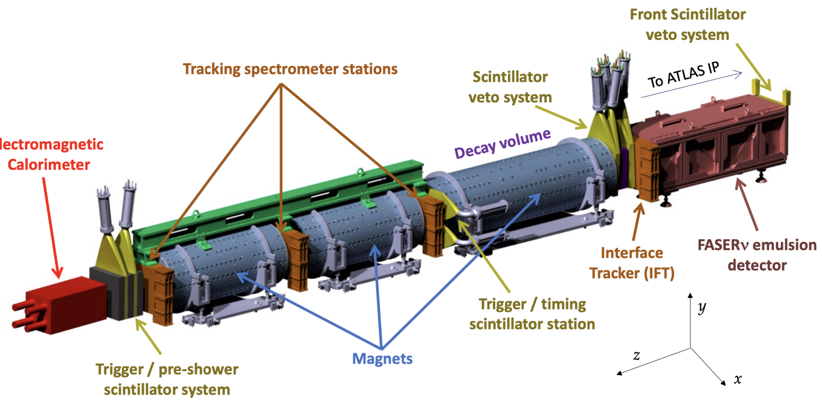


Reach the FASER2 through osillation

The ratio between the number of events with $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.002$ and $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.005$ in initial state



The timing ability of FASER detector



- All of the scintillators can measure the timing.
- The scintillators have extremely high time precision, but have no spatial resolution. It takes about 1 ns for the signal to get from one side of the scintillator to the other, so one can only determine the timing to 1 ns. If we have simultaneous tracking information, we could determine the location of the track, and the timing can probably be improved to the 0.1 ns level.
- The standard deviation on the difference in timing between the front veto scintillator and the back pre-shower detector is 350 ps.

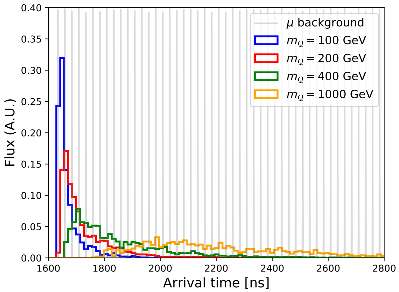
Two timing analyses

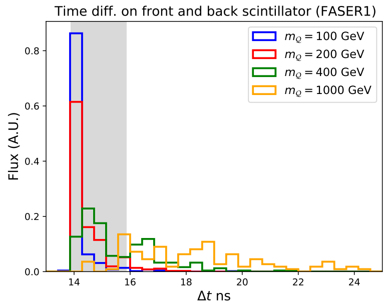
Arrival time at the timing scintillator

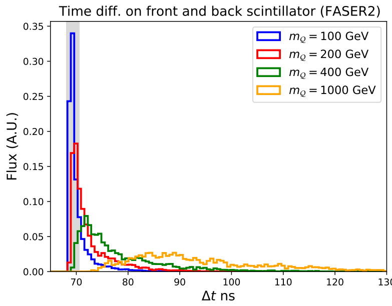
- Both quirks in the quirk pair should reach the timing scintillator.
- The arrival time of the quirk pair needs to be outside the muon window with [-3,3] ns. The muon arrival time is obtained by assuming the muon is travelling with the speed of light from the interaction point.
- The total momenta of both quirk should be greater than 100 GeV.

Time difference between the quirk passing through the front scintillator and the back scintillator

- At least one quirk can pass through both the front scintillator and the back scintillator.
- Comparing with the particle with a speed of light, the quirk time difference at the front scintillator and the back scintillator should be at least 2 ns larger.

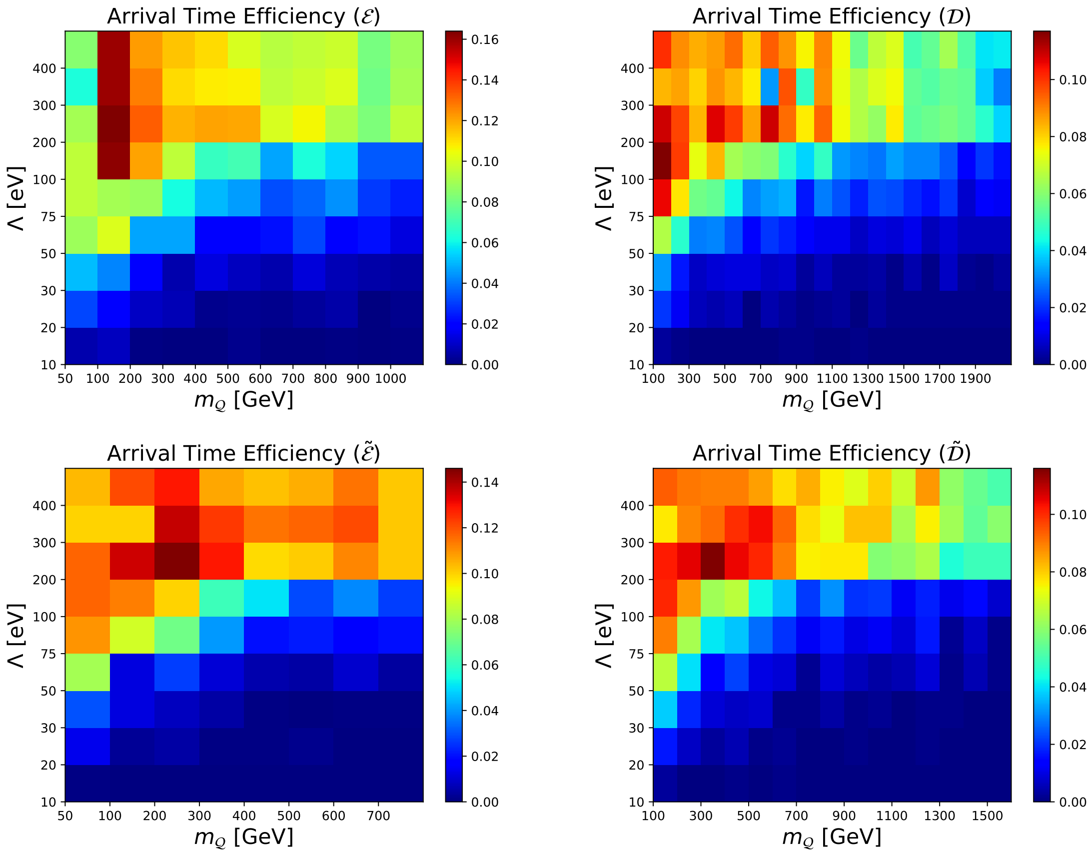






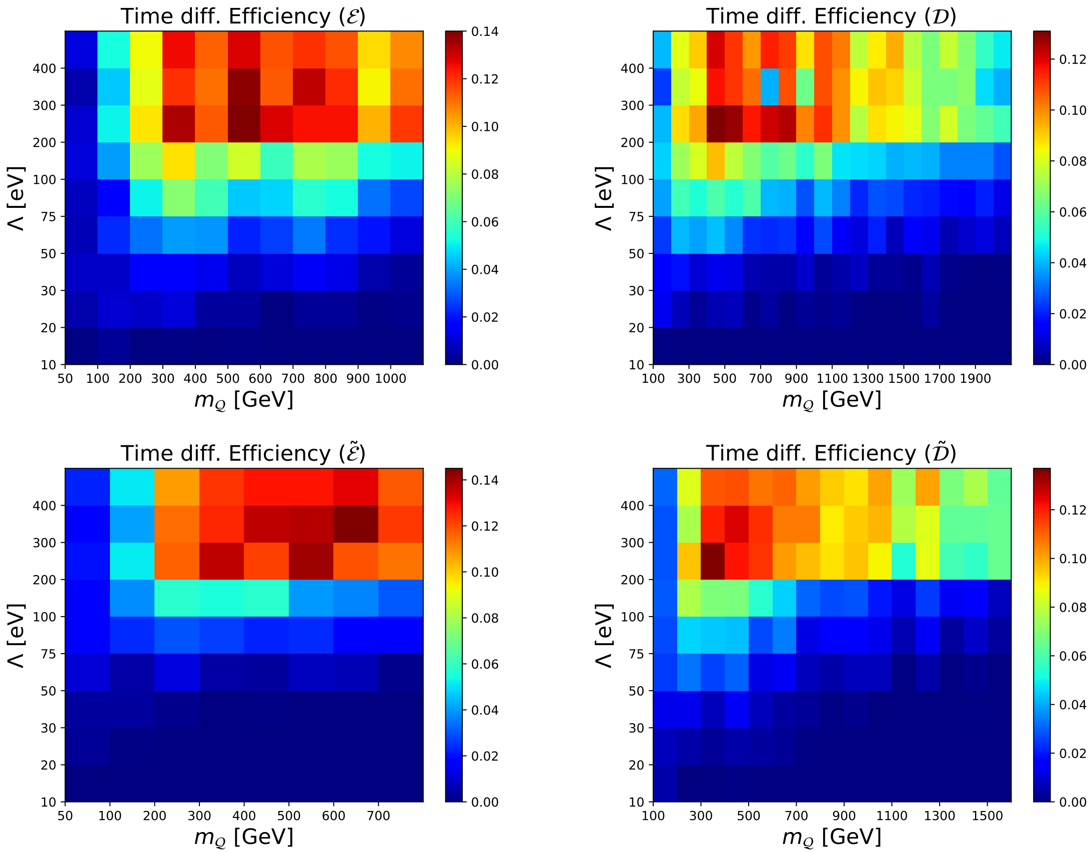
Efficiencies of arrival time analysis

On event sample with $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.005$

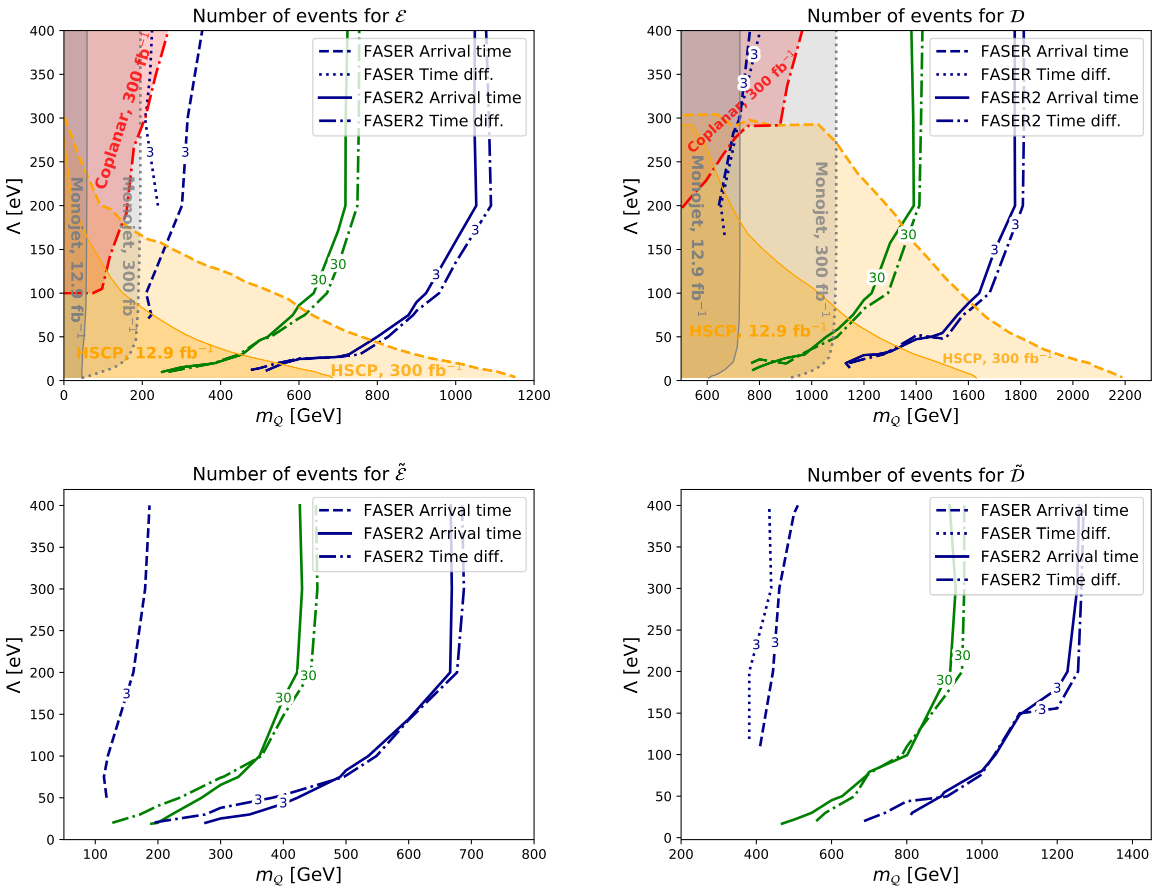


Efficiencies of time difference analysis

On event sample with $p_T(\mathcal{Q}\mathcal{Q})/|p(\mathcal{Q}\mathcal{Q})| < 0.005$



The sensitivities of two timing analyses



Conclusion

- FASER detector is a small but powerful detector to supplement the LHC main detectors.
- Sensitive to sub-GeV new physics, with BSM particles produced from meson decay and bremsstrahlung
- Quirk is a well-motivated new physics scenario, in models with neutral naturalness.
- The timing ability of FASER enables a sensitive probe to TeV scale quirk particle, which is one of the few heavy scenarios that could be probed at FASER.


Thank you!
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