Improved sensitivities of low-energy $U(1)_{B-L}$ model @ DUNE & FASER

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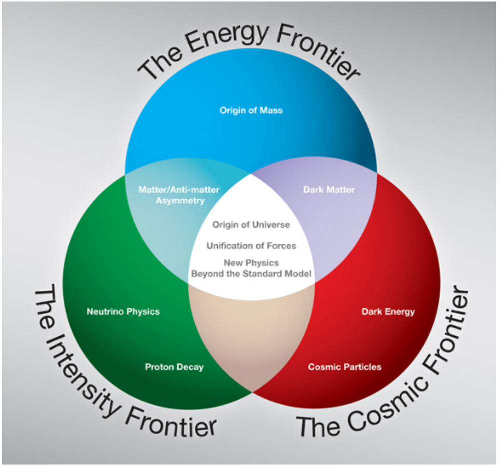
第四届高能物理理论与实验融合发展研讨会

based on
Dev, Dutta, Kelly, Mohapatra & YCZ, 2104.07681 [JHEP]
Zihao Guo, ~~Kevin Kelly~~ & YCZ, 25xy.abcde

Frontiers of particle physics & cosmology



High-Energy frontier
High-Intensity frontier
Cosmic frontier

Interdisciplinary:

- particle physics
- nuclear physics
- astronomy
- astrophysics & cosmology
- engineering & industry
- applications
- economy
- ...

High-Intensity frontier experiments

- High-luminosity meson factories:
  BES III, BaBar, Belle II...
- DM direct detection experiments:
  PandaX, CDEX, XENON1T, LZ...
- Long-lived particle experiments:
  FASER(ν), CODEX-b, MATHUSLA, SND, FPF, DUNE...
- Parity-violating electron scattering (PVES) experiments:
  MOLLER, P2, APV (^{225}Ra+), SoLID, Qweak...
- Muon precision measurements:
  FNAL $g-2$, MUonE, EMuS, COMET, MEG, Mu2e, Mu3e...
- $0\nu\beta\beta$ decay experiments:
  PandaX-III, CDEX-300ν, NνDEX, CUPID-CJPL, JUNO-bb...
- Coherent elastic neutrino-nucleus scattering (CEνNS) experiments:
  COHERENT, COνUS...
- Neutrino experiments:
  T2K, NOvA, JUNO, DUNE, Hyper-Kamiokande, IceCube...
- Observations of supernovae, neutron stars, Sun etc
  $\Longrightarrow$ ν's in JUNO...; GWs in TianQin, Taiji...
- ...

$U(1)_{B-L}$ model

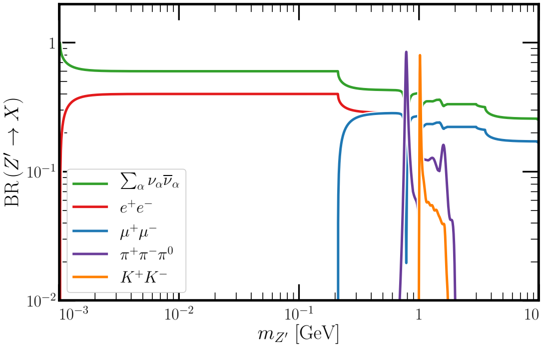
$U(1)_{B-L}$ models

- Global $U(1)_{B-L}$ model
  - Majoron (pseudo-Nambu-Goldstone boson) [Chikashige, Mohapatra & Peccei '80 PRL; '81 PLB; Aulakh & Mohapatra '82 PLB; Gelmini & Roncadelli '81 PLB; Schechter & Valle '82 PRD]
- Local: $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ [Marshak & Mohapatra '80 PLB; '80 PRL; Deshpande & Iskandar '80 NPB; Galison & Manohar '84 PLB]
  - Symmetry breaking $U(1)_{I_{3R}} \times U(1)_{B-L} \to U(1)_Y$
- Local: $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ [Buchmuller, Greub & Minkowski '91 PLB; Basso '11]
  - Neutrino portal (N): type-I seesaw
  - Vector portal (Z'): DM, collider pheno...
  - Scalar portal (S breaking $U(1)_{B-L}$): DM, collider pheno...

Decay of Z'

Partial widths [hadron channels using R-ratio [Buschmann, Kopp, Liu & Machado '15 [JHEP]; Ilten, Soreq, Williams & Xue '18 [JHEP]; Bauer, Foldenauer & Jaeckel '18 [JHEP]]]

$$\Gamma(Z' \to f\bar{f}) = \frac{m_{Z'} g_{BL}^2 N_f^C S_f}{12\pi} \left(1 + \frac{2m_f^2}{m_{Z'}^2}\right) \sqrt{1 - \frac{4m_f^2}{m_{Z'}^2}}$$



Decay of Scalar S

- $h - S$ mixing induced decays [Donoghue, Gasser & Leutwyler '90 [NPB]; Djouadi '09 [Phys. Rept.]]

$$\Gamma(S \to \ell^+\ell^-) = \frac{G_F m_S m_\ell^2 \sin^2\vartheta}{4\sqrt{2}\pi}\left(1-\frac{4m_\ell^2}{m_S^2}\right)^{3/2}$$

$$\Gamma(S \to \pi^+\pi^-) = 2\Gamma(S \to \pi^0\pi^0) = \frac{G_F m_S^3 \sin^2\vartheta}{8\sqrt{2}\pi}\left(1-\frac{4m_\pi^2}{m_S^2}\right)^{1/2}\left|G(m_S^2)\right|^2$$

$$\Gamma(S \to \gamma\gamma) = \frac{G_F \alpha^2 m_S^3 \sin^2\vartheta}{128\sqrt{2}\pi^3}\left|\sum_f N_f^C Q_f^2 A_{1/2}(\tau_f) + A_1(\tau_W)\right|^2$$

- Gauge couling induced decay

$$\Gamma(S \to Z'Z') = \frac{g_{BL}^2 Q_S^2 m_S^3}{32\pi m_{Z'}^2}\left(1-\frac{4m_{Z'}^2}{m_S^2}\right)^{1/2}\left(1-\frac{4m_{Z'}^2}{m_S^2}+\frac{12m_{Z'}^4}{m_S^4}\right)$$

Benchmark points of S decay

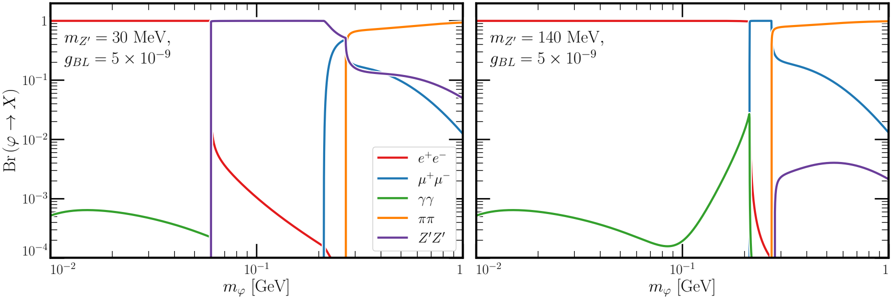


Figure: Decay BRs of S with $\sin\theta = 10^{-4}$.

Free parameters in the model

$$m_{Z'}\,, \quad m_S\,, \quad g_{BL}\,, \quad \sin\vartheta$$

Four different scenarios

- Pure Z' case
- Pure S case
- $S + Z'$ case (effects of $S \to Z'Z'$)
- Associate production of S & Z'

Z' @ DUNE

Bhupal Dev, Bhaskar Dutta, Kevin Kelly, Rabindra Mohapatra & YCZ,
2104.07681 [JHEP]
Light, Long-Lived $B - L$ Gauge and Higgs Bosons at the DUNE Near Detector

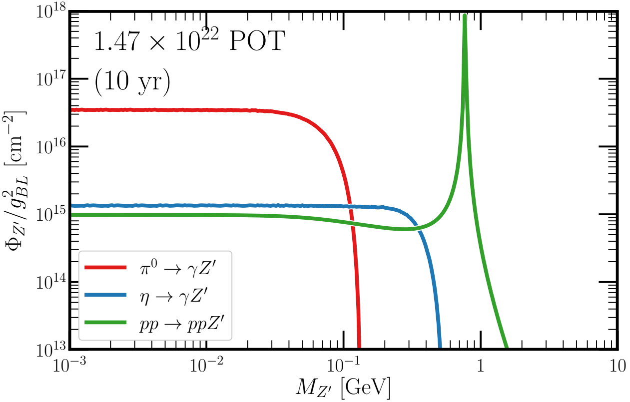
Z' Production channels

- Leading contributions: $\pi, \eta \to \gamma Z'$, $pN \to pNZ'$
  [Batell, Pospelov & Ritz '09 [PRD]]

$$\mathrm{BR}\left(\mathfrak{m} \to \gamma Z'\right) \quad = \quad 2\mathrm{BR}\left(\mathfrak{m} \to \gamma\gamma\right)\left(\frac{g_{BL}}{e}\right)^2 \left(1 - \frac{m_{Z'}^2}{m_{\mathfrak{m}}^2}\right)^3$$

- Subleading: $K_L \to \gamma Z'$
- Subleading: $\pi^+, K^+ \to \ell^+ \nu Z'$
  [Berryman, de Gouvea, Fox, Kayser, Kelly & Raaf '20 [JHEP]]
- Subleading: $K_S \to \pi^0 Z'$, $K^+ \to \pi^+ Z'$
  [Pospelov '08 PRD; Davoudiasl, Lee & Marciano '14 PRD]
- Subleading: $\Delta(1232) \to NZ'$

Production of Z' @ DUNE (near detector complex)



Fluxes of Z' @ DUNE

- Meson decay [$c_{\mathfrak{m}}$ the average number of mesons produced per POT; $A_{\rm det}$ the detector area; $\epsilon_{Z'}$ the geometrical acceptance factor]

$$\Phi_{\mathfrak{m}Z'} = \frac{c_{\mathfrak{m}} N_{\rm POT}}{A_{\rm det}} \epsilon(m_{Z'}) {\rm BR}\left(\mathfrak{m} \to \gamma Z'\right) .$$

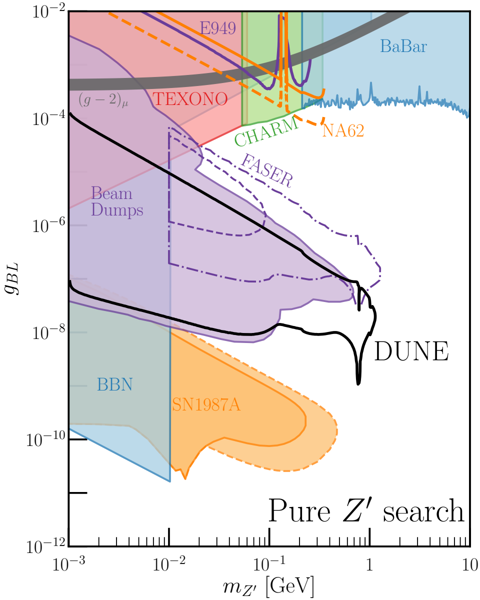
- Bremsstrahlung process [σ_{pN} the total proton-target cross section; $F_{1,N}$ form factor; w_{ba} photon splitting function]
  [Blumlein & Brunner '14 PLB; deNiverville, Chen, Pospelov & Ritz '17 PRD]

$$\Phi_{{\rm brem}Z'} = \frac{N_{\rm POT}}{A_{\rm det}\sigma_{pN}(s)} \left|F_{1,N}(m_{Z'}^2)\right|^2 \int {\rm d}z \int_{\rm det} {\rm d}p_T^2 \, \sigma_{pN} w_{ba}(z, p_T^2) .$$

- Number of signals

$$N_{\rm sig} = \int_{E_{\rm min}}^{E_{\rm max}} {\rm d}E_{Z'} \int_{A_{\rm det}} {\rm d}A \int_{D_{\rm det}}^{D_{\rm det}+L_{\rm det}} {\rm d}x \left[\frac{{\rm d}\Phi_{Z'}}{{\rm d}E_{Z'}} P_{\rm decay}(E_{Z'}, x)\right] .$$

DUNE sensitivity: pure Z' case



Consider only visible decays of Z'.

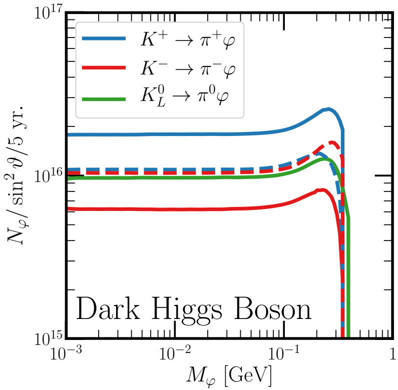
Lab limits from [Bauer, Foldenauer & Jaeckel '18 [JHEP]]

BBN & SN1987A limits from [Knapen, Lin & Zurek '17 [PRD]; Croon, Elor, Leane & McDermott '21 [JHEP]]

Comparing DUNE and FASER: DUNE events' energy is lower, thus probing smaller g_{BL}.

S production @ DUNE

Berryman, de Gouvêa, Fox, Kayser, Kelly & Raaf '20 [JHEP]; Batell, Pospelov & Ritz '11 [PRD]



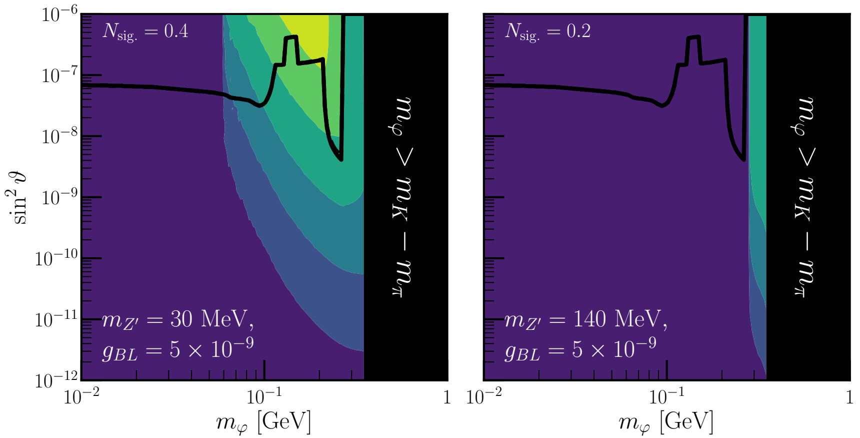
$$\Gamma(K^\pm \to \pi^\pm S) \simeq \frac{m_{K^\pm} |y_{sd}|^2 \sin^2\vartheta}{64\pi} \times \frac{m_{K^\pm}^2}{m_S^2} \lambda(m_{K^\pm}, m_{\pi^\pm}, m_S)\,,$$

$$\Gamma(K_L \to \pi^0 S) \simeq \frac{m_{K_L} (\mathrm{Re}\, y_{sd})^2 \sin^2\vartheta}{64\pi} \times \frac{m_{K^0}^2}{m_S^2} \lambda(m_{K_L}, m_{\pi^0}, m_S)\,,$$

$$y_{sd} = \frac{3\sqrt{2} G_F m_t^2 V_{ts}^* V_{td}}{16\pi^2} \frac{m_S}{\sqrt{2} v_{\mathrm{EW}}}$$

$pp \to ppS$ process contribution is comparatively small. [Batell, Berger & Ismail '19 [PRD]]

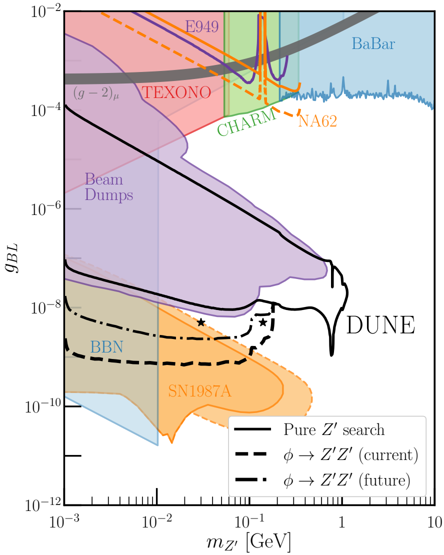
Numbers of Z' @ DUNE in presence of S



Much more Z' can be produced from $S \to Z'Z'$.

Color change: a factor of 10

Effects of $S \to Z'Z'$ on Z' prospects @ DUNE



Consider only visible decays of Z'.

Assuming zero backgrounds & 10 signal events [Berryman, de Gouvêa, Fox, Kayser, Kelly & Raaf '20 [JHEP]]

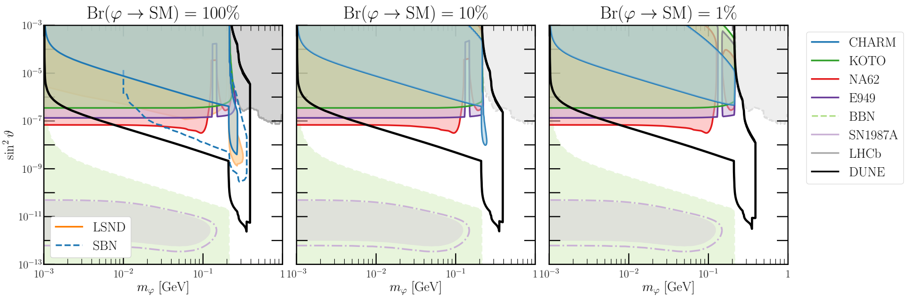
Lab limits from [Bauer, Foldenauer & Jaeckel '18 [JHEP]]

BBN & SN1987A limits from [Knapen, Lin & Zurek '17 [PRD]; Croon, Elor, Leane & McDermott '21 [JHEP]]

Improving the pure Z' case by up to **a factor of 45**.
dashed line: current S limits;
dot-dashed line: future S limits.

Effects of $S \to Z'Z'$ on S prospects @ DUNE

Dev, Mohapatra & YCZ '20 [PRD]; Egana-Ugrinovic, Homiller & Meade '20 [PRL]



Effects of $S \to Z'Z'$:

- Modifying its branching fraction into visible particles;
- Shortening its lifetime.

SN1987A limits from [Dev, Mohapatra & YCZ '20 [JCAP]; Dev, Fortin, Harris, Sinha & YCZ '21 [JCAP]]

Associate production of S and Z'

- Channels:

$$\pi^0 \to \gamma + Z' + S\,, \quad K \to \pi + Z' + S\,, \quad \rho \to Z' + S$$

- If S is produced from gauge coupling to Z'

$$\text{flux} \propto g_{BL}^4 \quad \text{too small!}$$

- If S is produced from Yukawa coupling to mesons

$$\text{flux} \propto \sin^2\vartheta g_{BL}^2 \quad \text{too small!}$$

Z' @ FASER(2)

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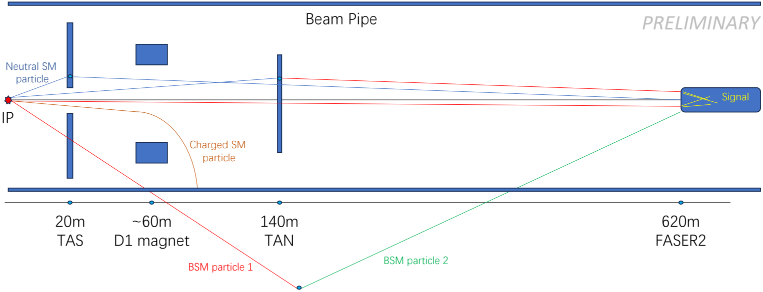
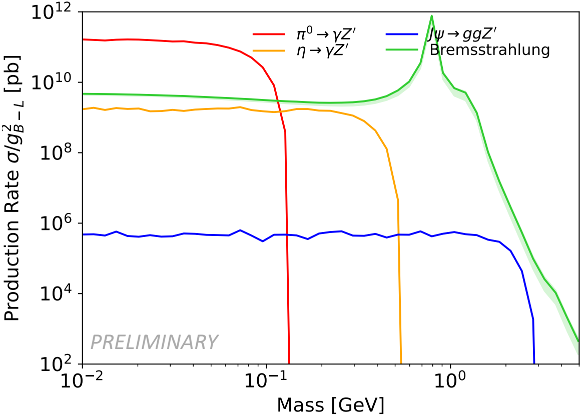
Long-lived particles at FASER(2)

FASER collaboration, 1901.04468



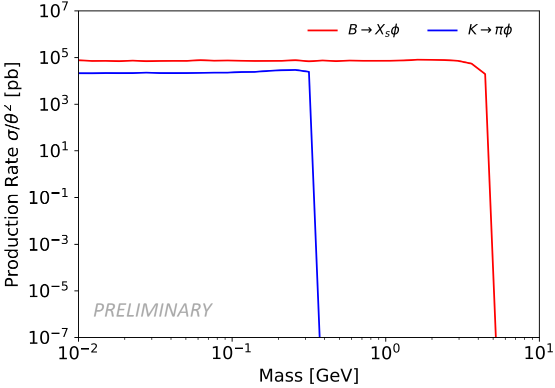
Production of Z' @ LHC (ATLAS)



- Dominant channels: $\pi^0 \to \gamma Z'$, $pp \to ppZ'$.
- Subdominant channels: $\eta \to \gamma Z'$, $J/\psi \to ggZ'$.
- See [Kling, Reimitz & Ritz 2509.09437] for form factors for the bremsstrahlung process.

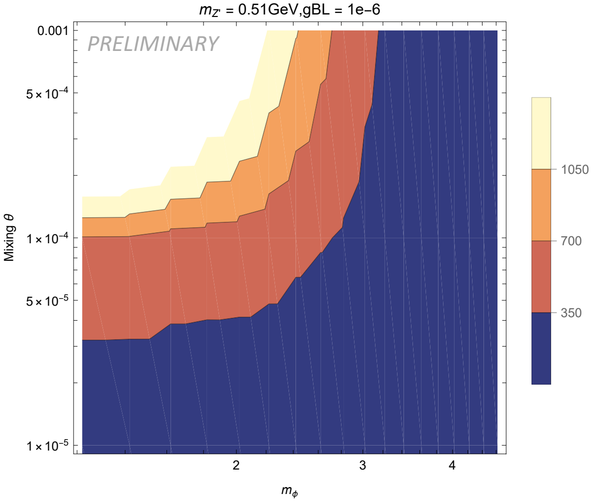
S production @ LHC

Feng, Galon, Kling & Trojanowski '17 [PRD]; Boiarska+ '19 [JHEP]

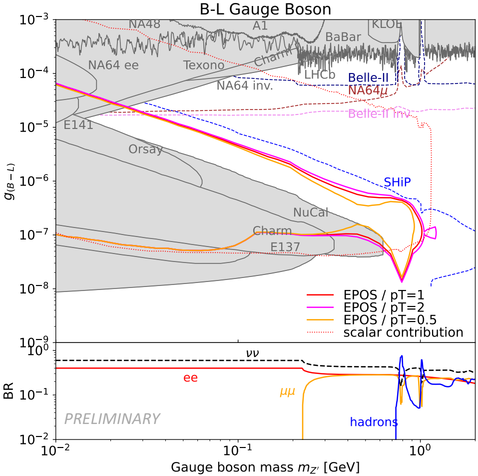


- Dominant channels $B \to X_s S$.
- Subdominant channels $K \to \pi S$, $pp \to ppS$.

Z' production @ FASER2 from S



Improved Z' prospects @ FASER2



$m_S = 2$ GeV & $\sin\theta = 10^{-4}$.

Consider only visible decays of Z'.

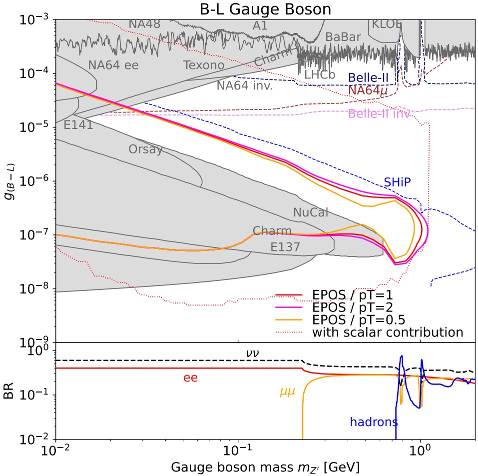
Assuming no SM backgrounds.

Assuming 3 signal events.

Z' sensitivities:
- solid lines: pure Z' case;
- **dotted line: Z' from S decay.**

The scalar S can improve significantly the FASER2 sensitivities of Z'.

Improved Z' prospects @ FASER2



$m_S = 2$ GeV & $\sin\theta = 10^{-4}$.

Consider only visible decays of Z'.

Assuming no SM backgrounds.

Assuming 3 signal events.

Z' sensitivities:
- solid lines: pure Z' case;
- **dotted line: pure $Z' \oplus S$ decay.**

The scalar S can improve significantly the FASER2 sensitivities of Z'.

Conclusion

- The light scalar and gauge bosons can have very rich phenomenologies at the high-intensity experiments such as DUNE & FASER(2).
- The gauge coupling $SZ'Z'$ can broaden the Z' prospects at DUNE & FASER2 by up to one order of magnitude.
- The decay $S \to Z'Z'$ reduces to some extent the sensitivity of S at DUNE & FASER(2).

Thank you very much!