

milliQan and FORMOSA

Update for the 2025 IIHE Annual Meeting

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charge quantization
dark sector

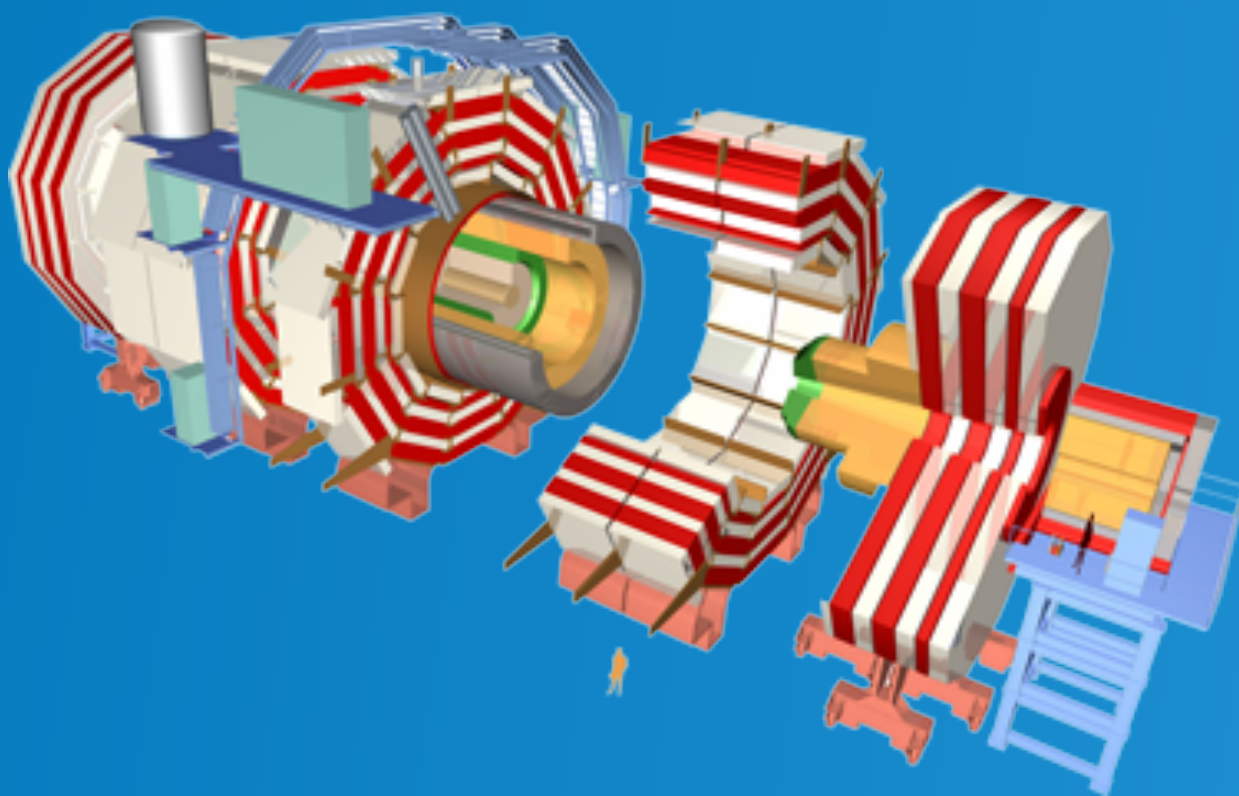
where

$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\mu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\mu^a g_\nu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\mu W_\mu^+ \partial_\nu W_\nu^- - \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - i g_{cw} (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\nu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\nu^+)) - \\ & i g_{sw} (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\nu^+) + A_\nu (W_\nu^+ \partial_\nu W_\mu^- - \\ & W_\mu^- \partial_\nu W_\nu^+)) - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\ & Z_\nu^0 Z_\mu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\nu A_\mu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2 A_\mu Z_\mu^0 W_\mu^+ W_\nu^-) - \frac{1}{2} \partial_\mu H \partial_\mu H - 2 M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \\ & \beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\ & g \alpha_h M (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \\ & \frac{1}{8} g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \\ & \frac{1}{2} i g (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\ & \frac{1}{2} g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\ & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+) - i g \frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + i g s_w M A_\mu (W_\mu^+ \phi^- - \\ & W_\mu^- \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4} g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8} g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\ & \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 Z_\mu^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w}{c_w} H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 s_w (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\ & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2} i g_s \lambda_{ij}^a (\bar{q}_i^a \gamma^\mu q_j^a) q_\mu^a - \bar{e}^\lambda (\gamma^\mu + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma^\mu + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^a (\gamma^\mu + \\ & m_u^a) u_j^a - \bar{d}_j^a (\gamma^\mu + m_d^a) d_j^a + i g s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda + \frac{2}{3} (\bar{u}_j^a \gamma^\mu u_j^a) - \frac{1}{3} (\bar{d}_j^a \gamma^\mu d_j^a)) + \\ & \frac{ig}{4c_w} Z_\mu^0 ((\bar{e}^\lambda \gamma^\mu (1 - \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^a \gamma^\mu (\frac{2}{3} s_w^2 - 1 - \gamma^5) u_j^a) + \\ & (\bar{u}_j^a \gamma^\mu (1 - \frac{8}{3} s_w^2 + \gamma^5) u_j^a)) + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U_{\lambda\kappa}^{lep} e^\kappa) + (\bar{u}_j^a \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^a)) + \\ & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\lambda U_{\lambda\kappa}^{lep} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^a C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^a)) + \\ & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\lambda (\bar{\nu}^\lambda U_{\lambda\kappa}^{lep} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U_{\lambda\kappa}^{lep} (1 + \gamma^5) e^\kappa) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U_{\lambda\kappa}^{lep} (1 + \gamma^5) \nu^\kappa) - m_\nu^\lambda (\bar{e}^\lambda U_{\lambda\kappa}^{lep} (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{M}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\ & \frac{g}{2} \frac{M}{M} H (\bar{e}^\lambda e^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \\ & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^L (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^a (\bar{u}_j^a C_{\lambda\kappa} (1 - \gamma^5) d_j^a) + m_u^a (\bar{u}_j^a C_{\lambda\kappa} (1 + \gamma^5) d_j^a) + \\ & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^a (\bar{d}_j^a C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^a) - m_u^a (\bar{d}_j^a C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^a) - \frac{g}{2} \frac{m_u^2}{M} H (\bar{u}_j^a u_j^a) - \\ & \frac{g}{2} \frac{m_d^2}{M} H (\bar{d}_j^a d_j^a) + \frac{ig}{2} \frac{m_u^2}{M} \phi^0 (\bar{u}_j^a \gamma^5 u_j^a) - \frac{ig}{2} \frac{m_d^2}{M} \phi^0 (\bar{d}_j^a \gamma^5 d_j^a) + \bar{C}^a \partial^2 C^a + g_s f^{abc} \partial_\mu \bar{C}^a C^b g_\mu^c + \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^- (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\ & \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- + \\ & \partial_\mu \bar{X}^- X^+) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^- + \\ & \partial_\mu \bar{X}^- X^+) - \frac{1}{2} g M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} i g M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2c_w} i g M (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + i g M s_w (\bar{X}^a X^- \phi^+ - \bar{X}^a X^+ \phi^-) + \\ & \frac{1}{2} i g M (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) . \end{aligned}$$

Millicharged particles in EW scale dark sector

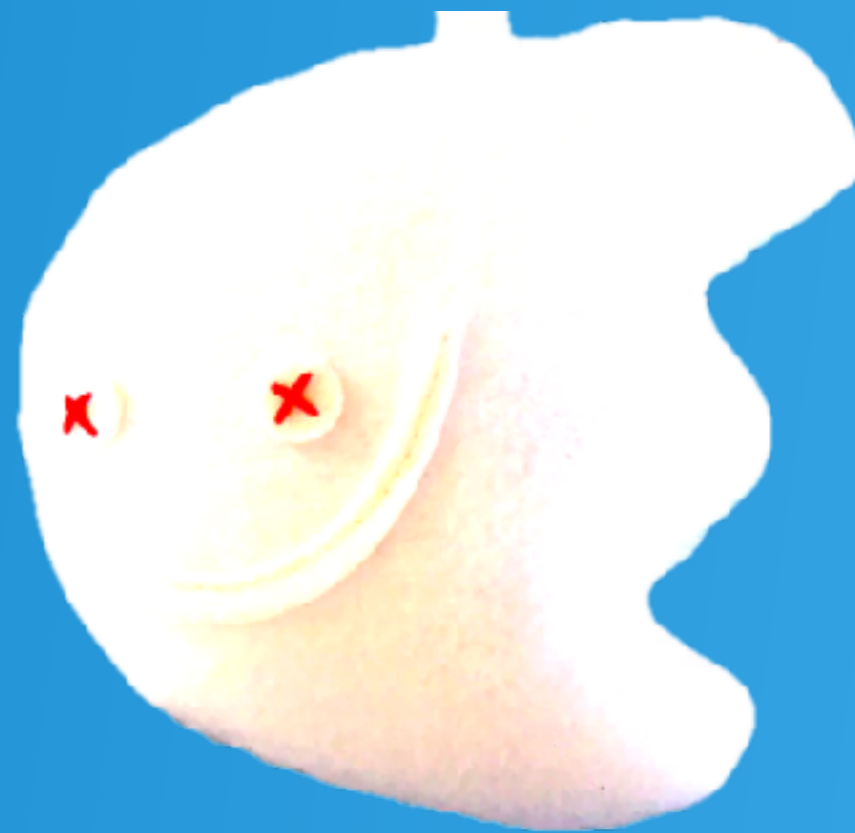


pseudoscalar meson decay
or vector meson decay



gives

off-shell photon



kinetic mixing $U(1)'$
with EW physics

naturally millicharged particle



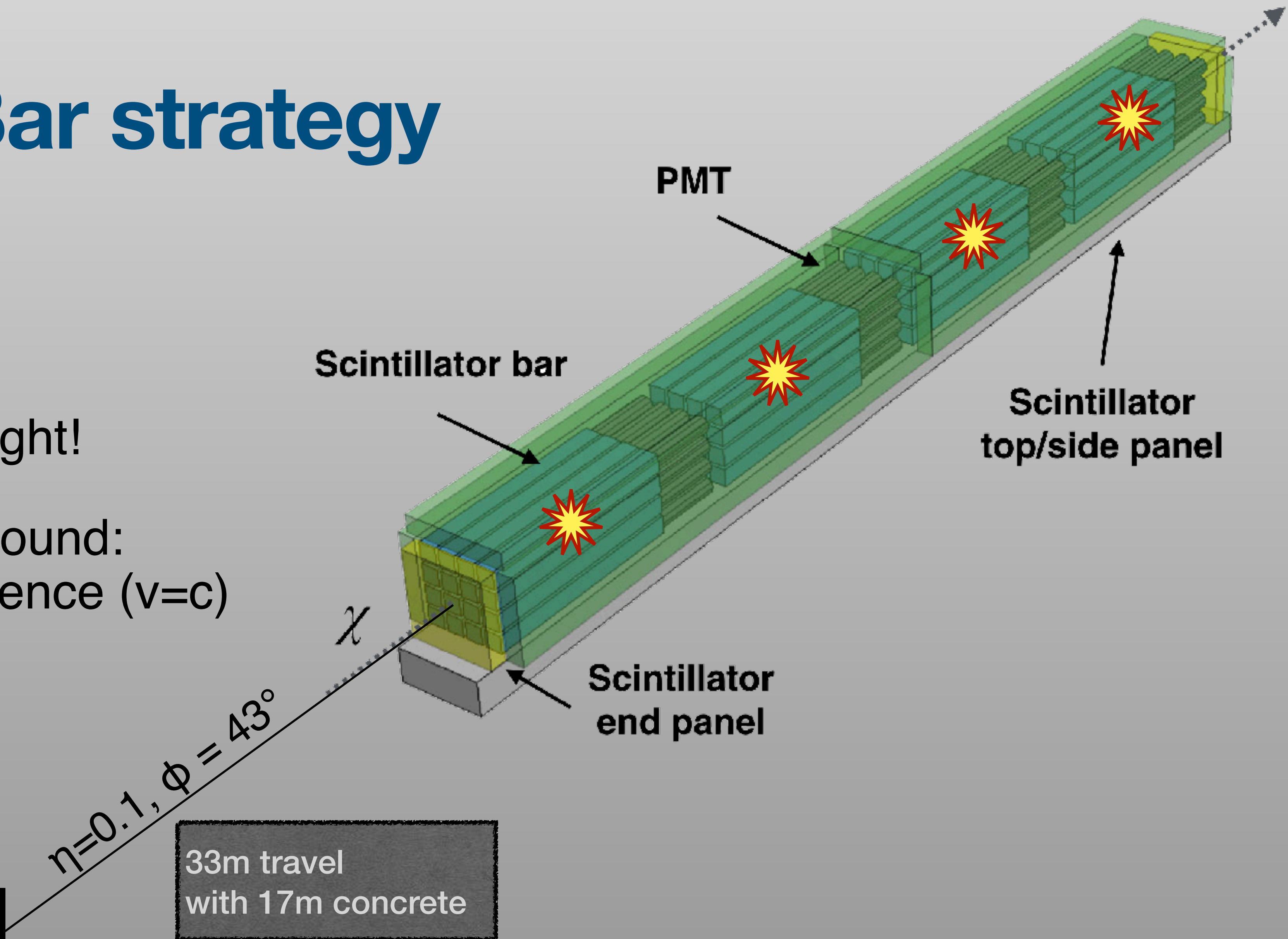
Q^2

naturally millicharged antiparticle

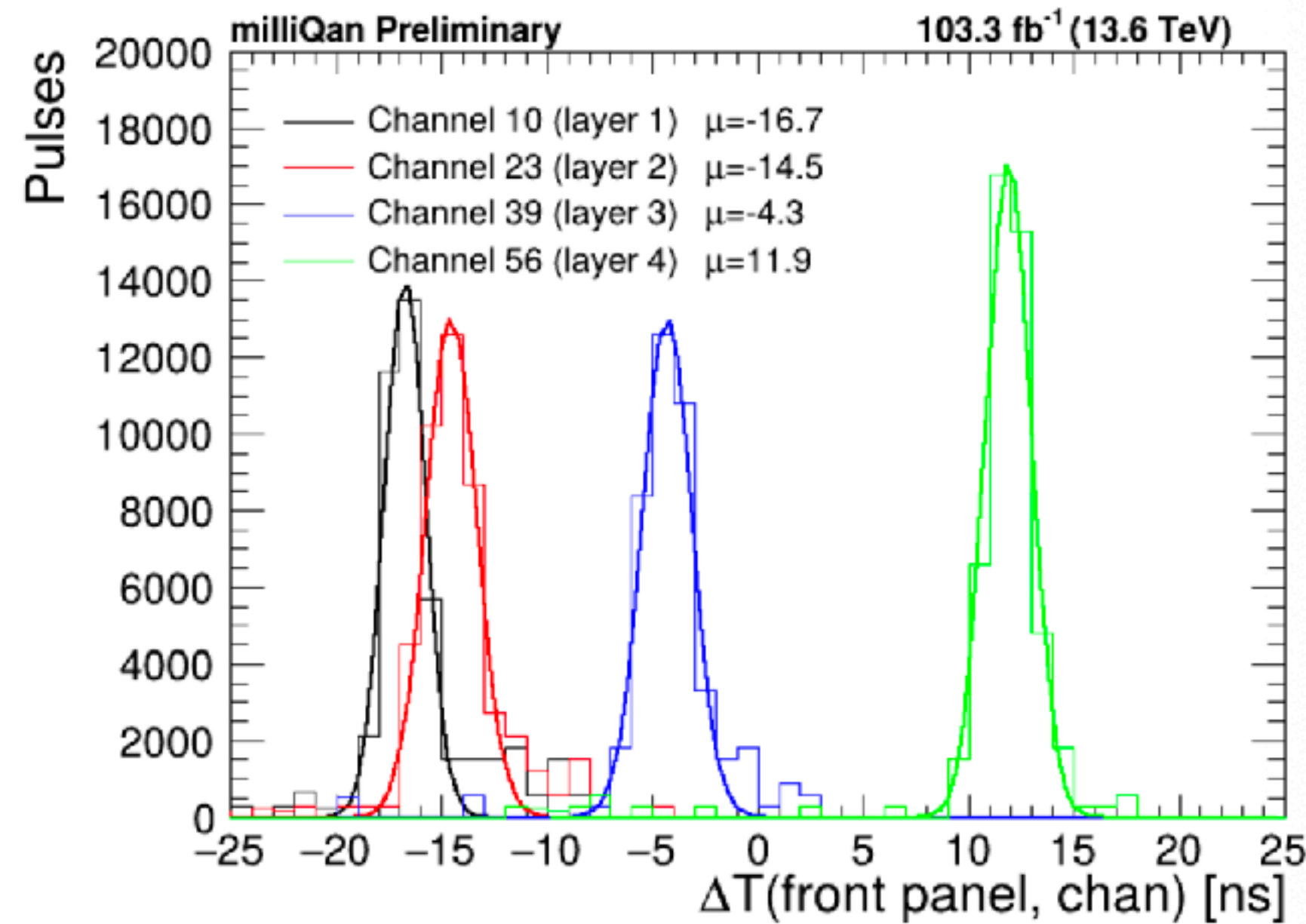


The milliQan Bar strategy

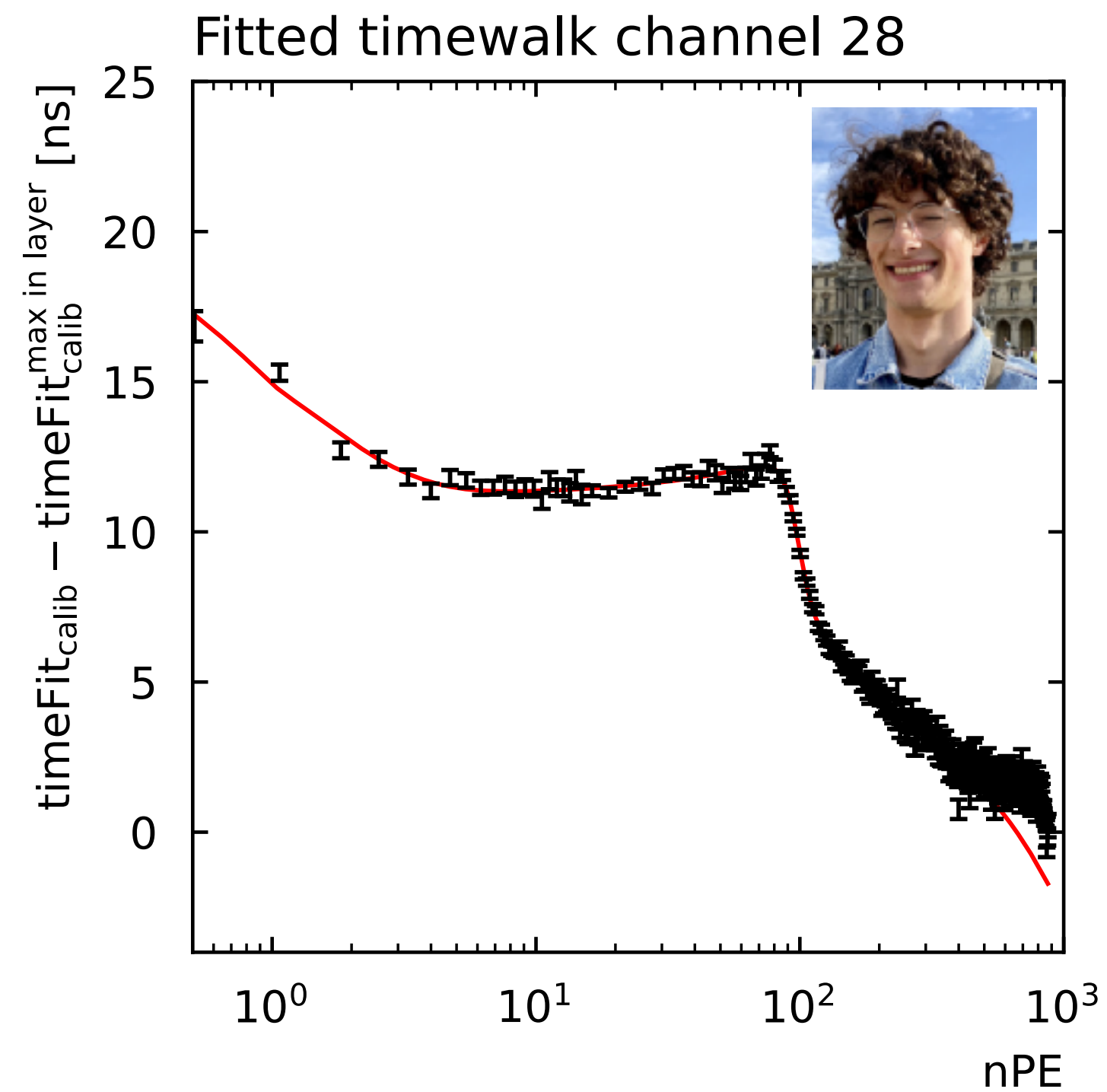
- mCP deposits very little light!
- Suppress random background:
require 4 in a row coincidence ($v=c$)
- Align to CMS IP



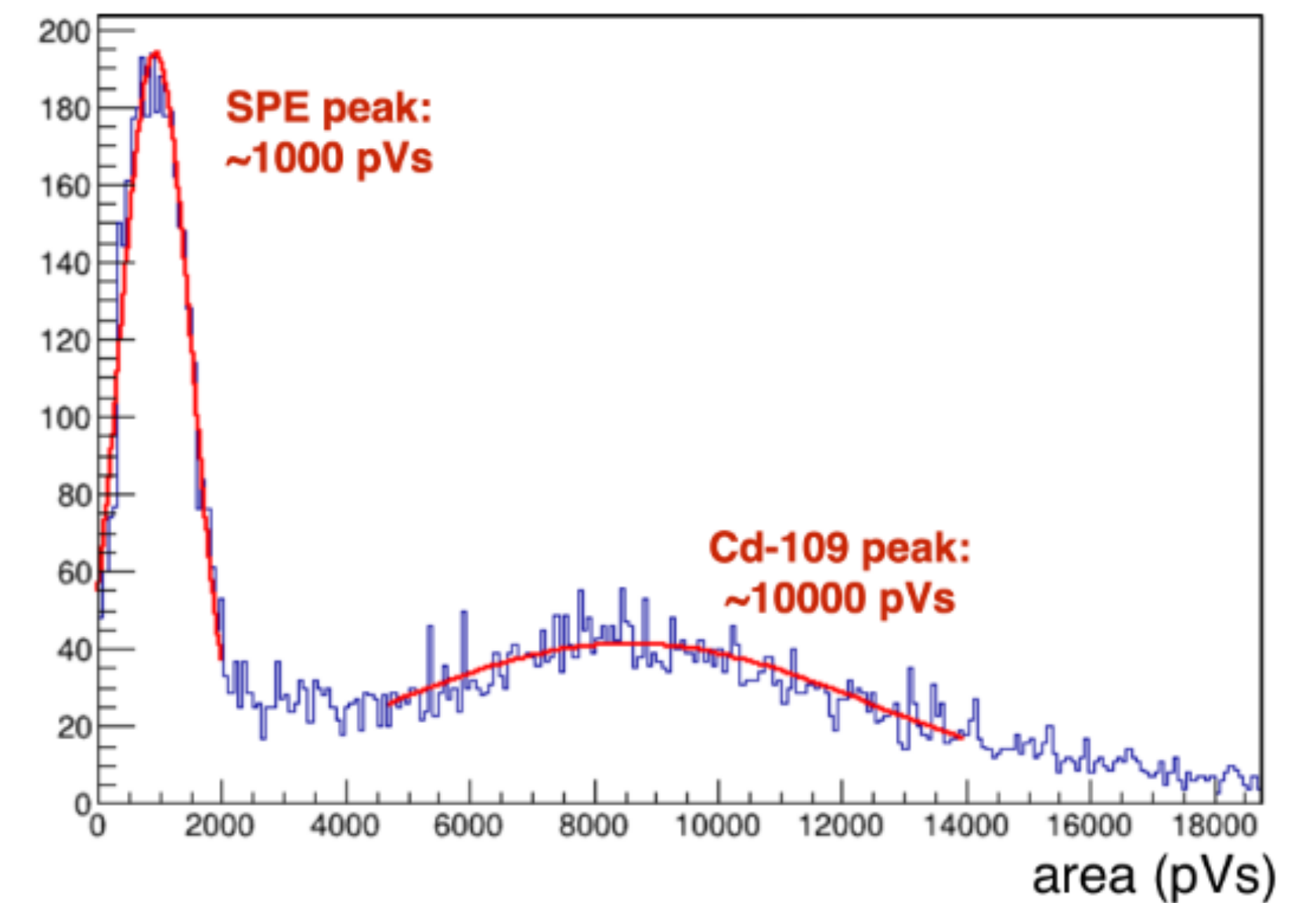
Key calibrations for analysis



suppress background: tight timing cut (20ns):
calibrate with beam muons



correct timing for low-energy timewalk:
calibrate with shower products

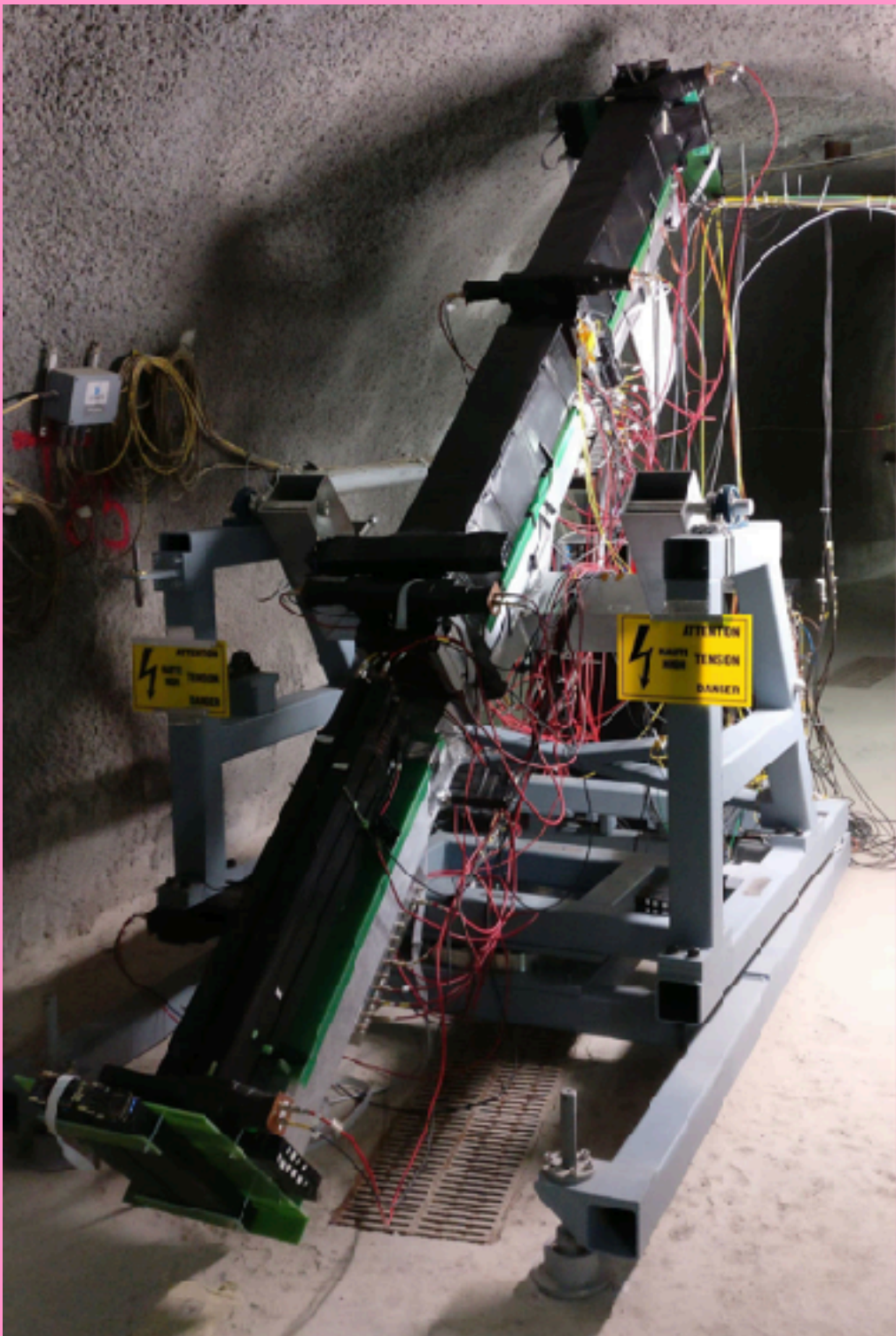


For gen MC to pulse injection:
calibrate reponse with Cd-109 Xrays

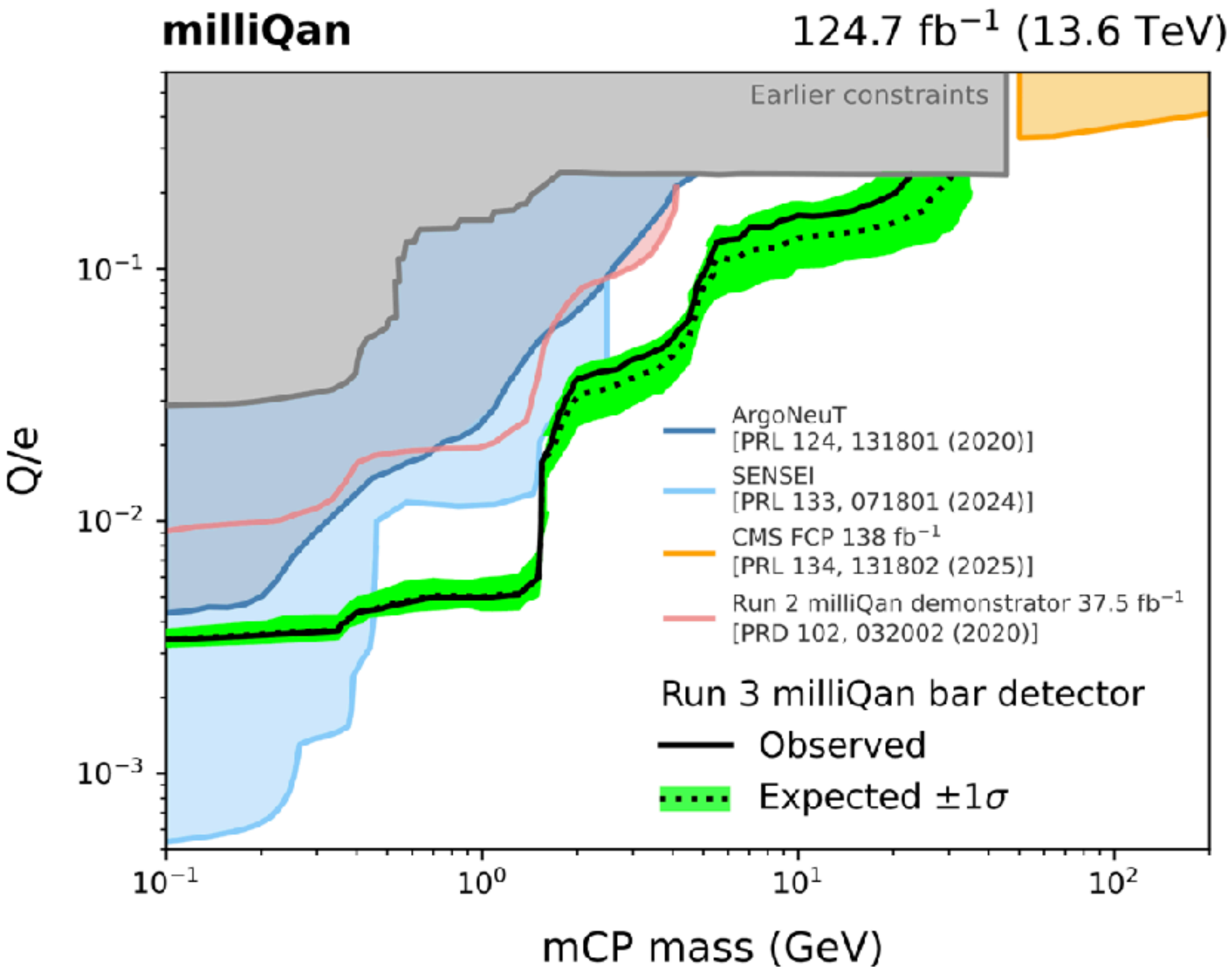
Leading limits for mCPs!

- Recorded: $(124.7 \pm 3.8) \text{ fb}^{-1}$ with $(0.16 \pm 0.01) \text{ muons/pb}^{-1}$
- Under Background only hypothesis: no excess

Signal region	Prediction	Observation
SR1	$0.10^{+0.12}_{-0.07}$	0
SR2	$0.87^{+0.33}_{-0.26}$	2

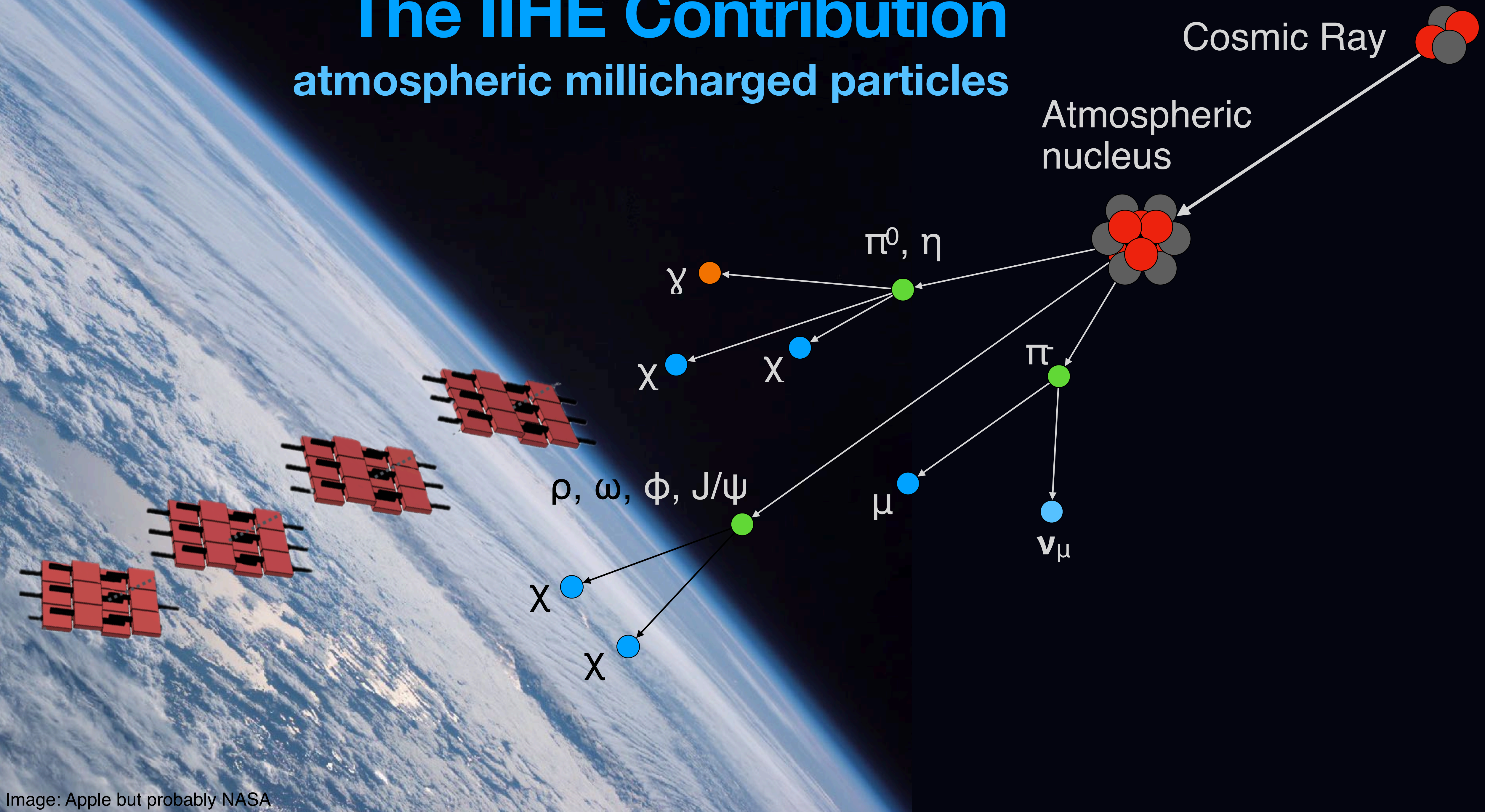


95% confidence level S+B limit



The IHE Contribution

atmospheric millicharged particles

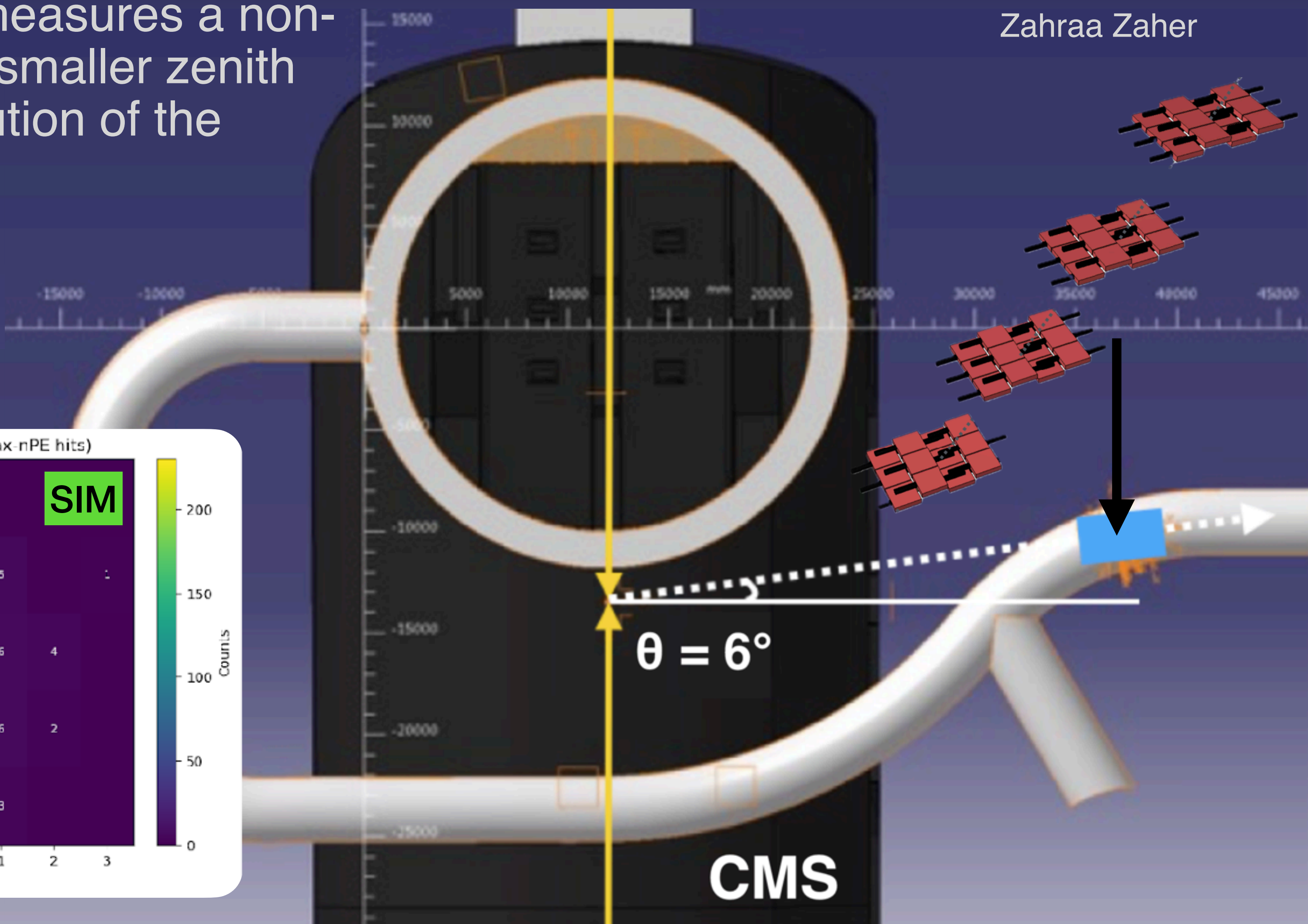
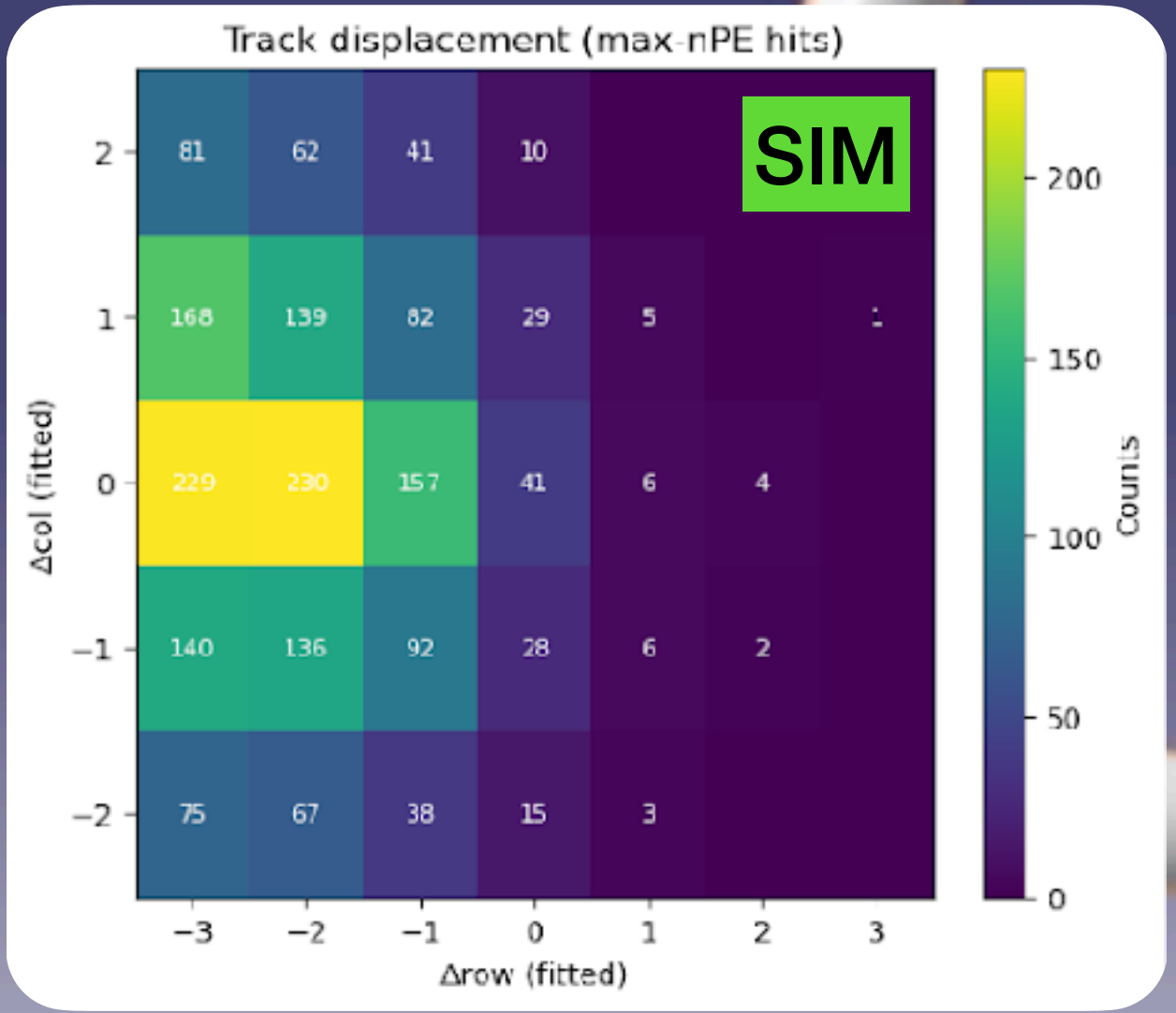
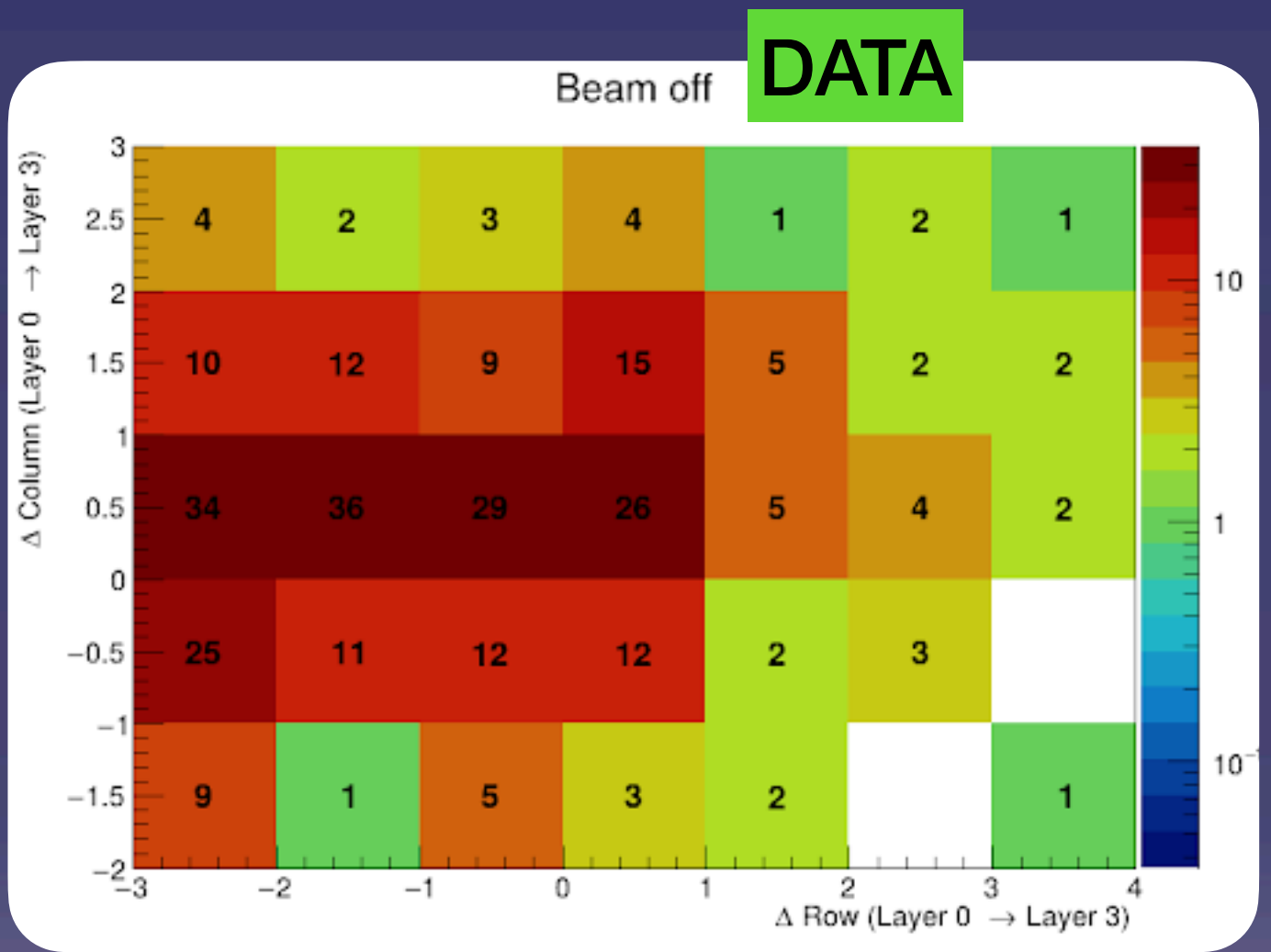


Muon background at the Slab detector

Zahraa studies cosmic track deviation while though the Slab detector. The asymmetric detector measures a non-uniform angular distribution which favors smaller zenith angles consistent with the $\cos^2(\theta)$ distribution of the cosmic flux. This was simulated as well.



Zahraa Zaher



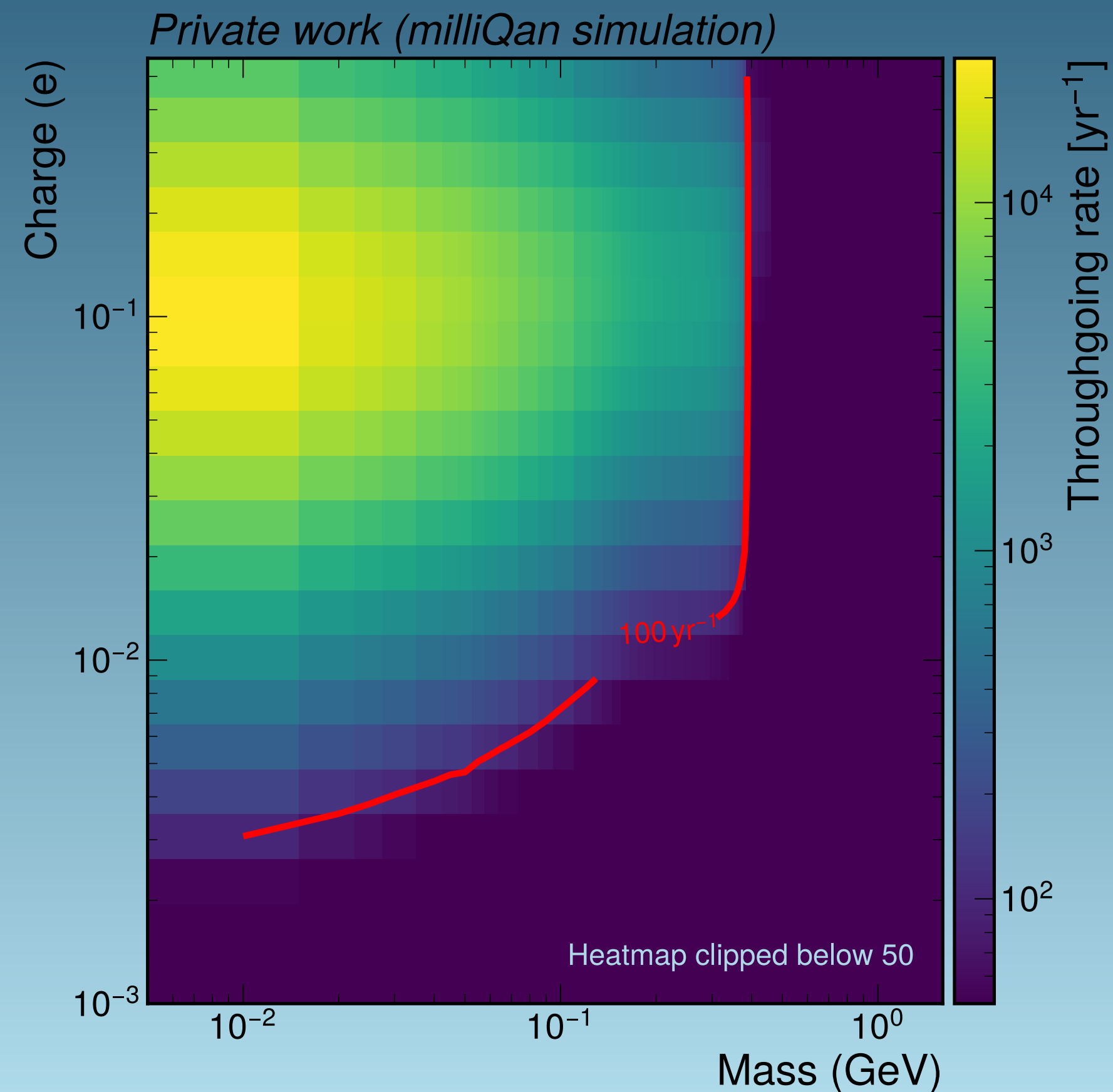
Atmospheric mCPs analysis + trigger design



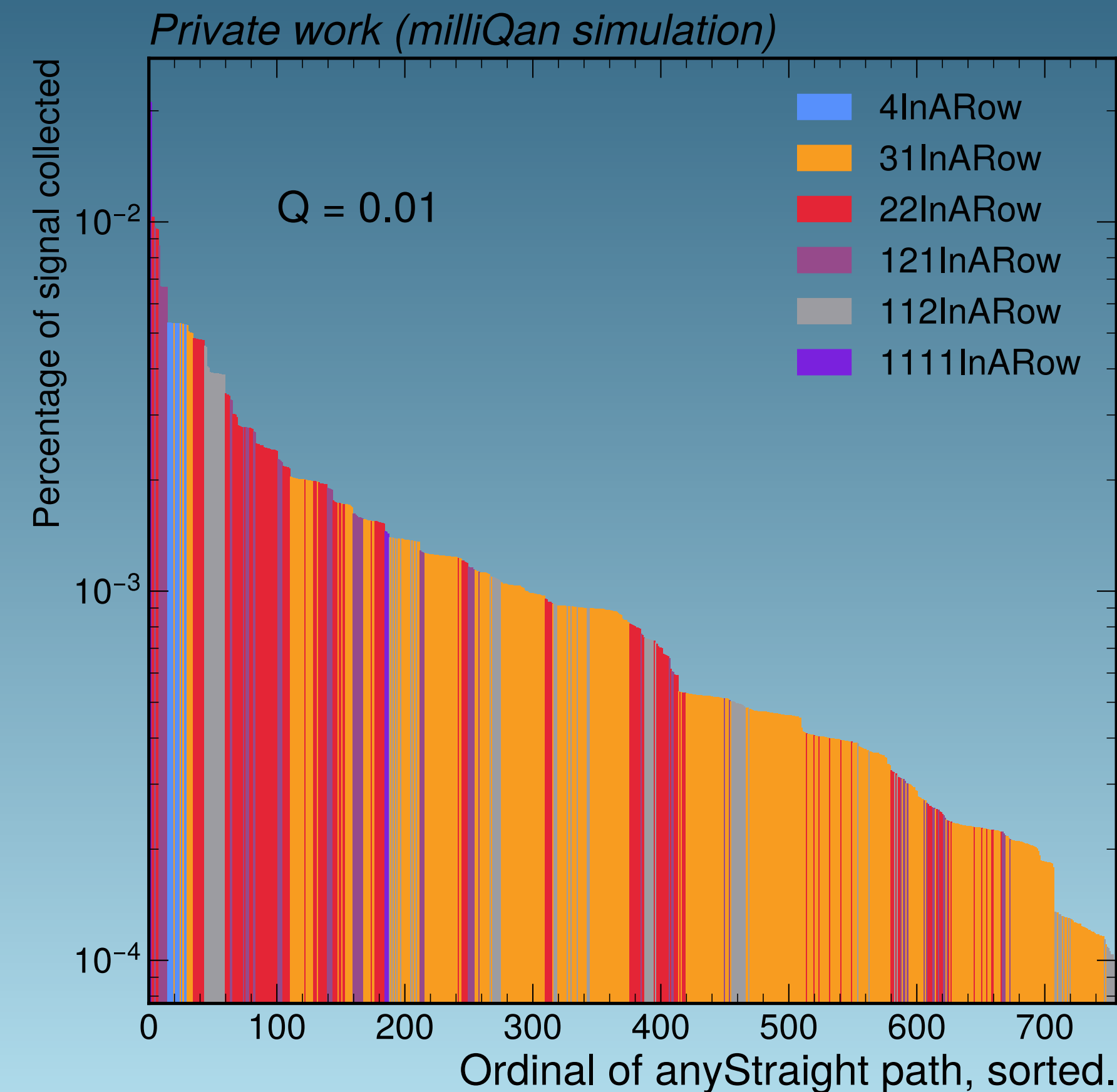
Tiepolo Wybouw

Analysis status:
sensitivity to meson decay mCPs

Trigger designed using MC



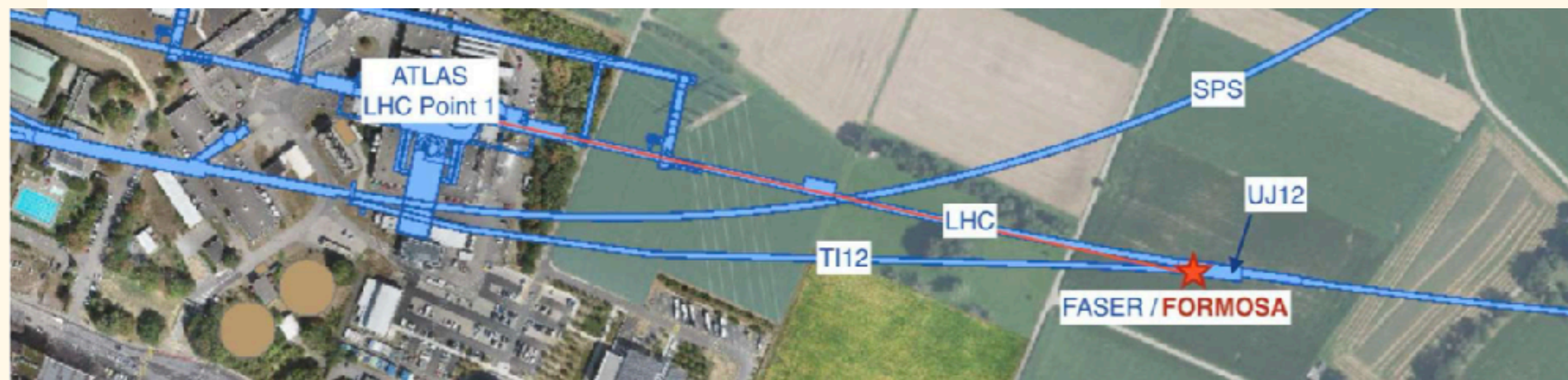
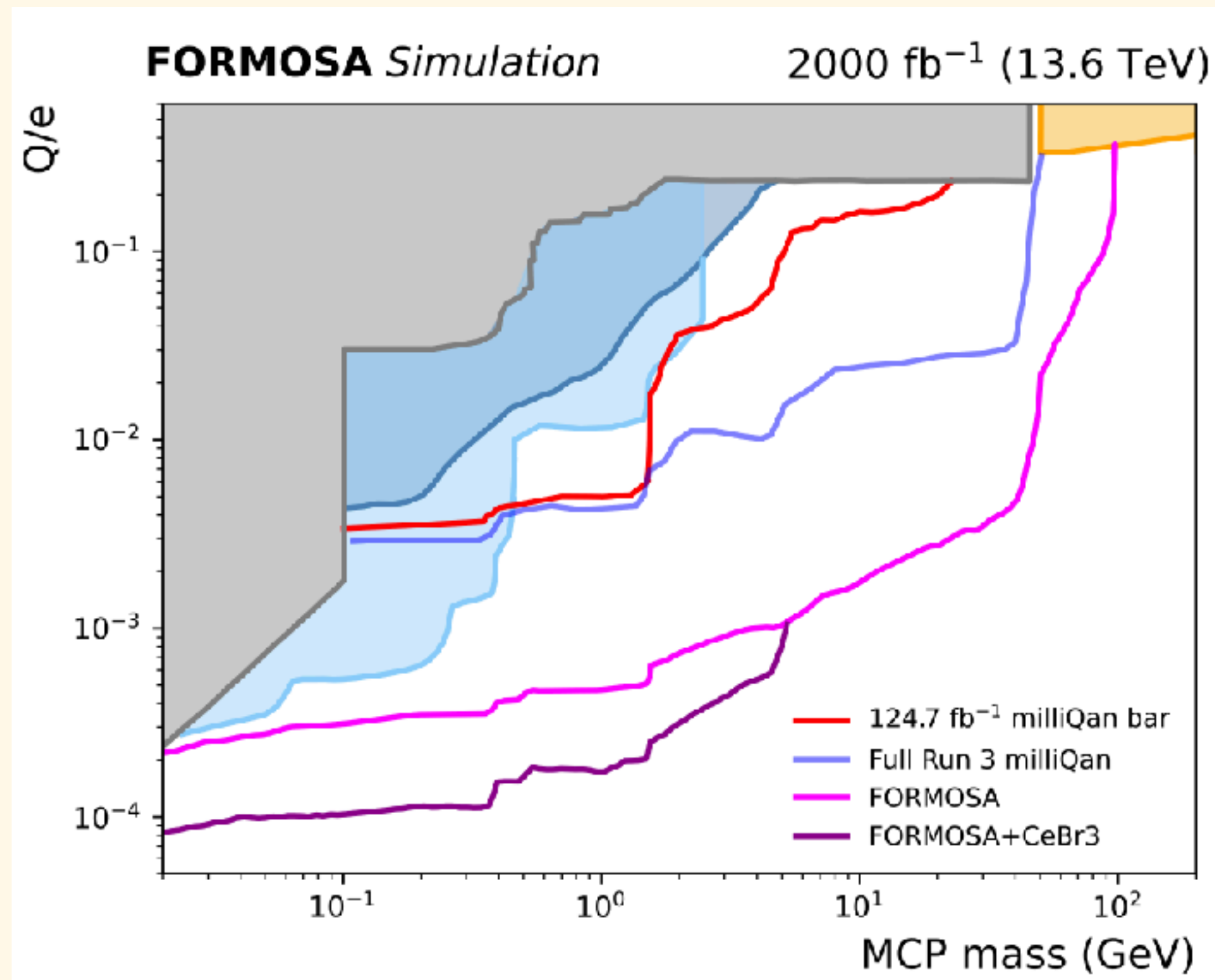
Next steps:
SIM (CORSIKA + propagation)



Next steps:
Implement! + timing calibrations for Slab

FORMOSA

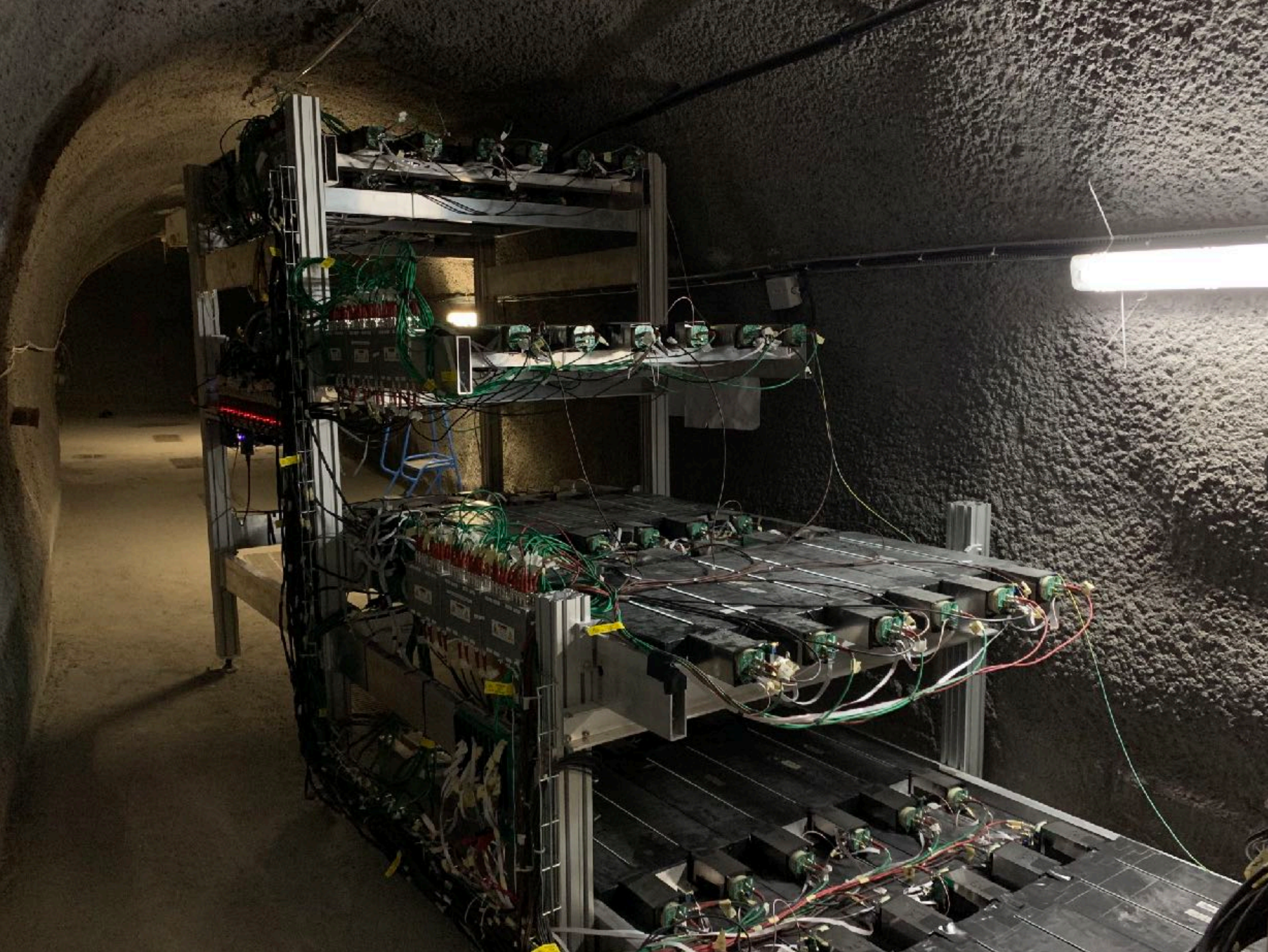
milliQan's sister experiment



Part of FPF with input to ESPPU!

FORMOSA Side Panel wrapping and trigger board install





Steven



Zahraa



Tiepolo

So long and thanks for all the slides