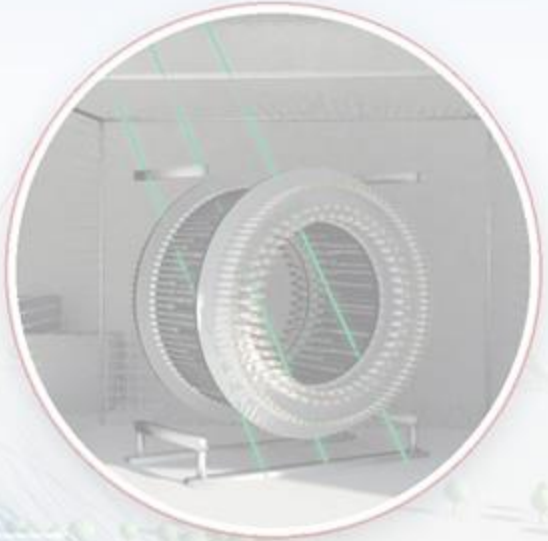
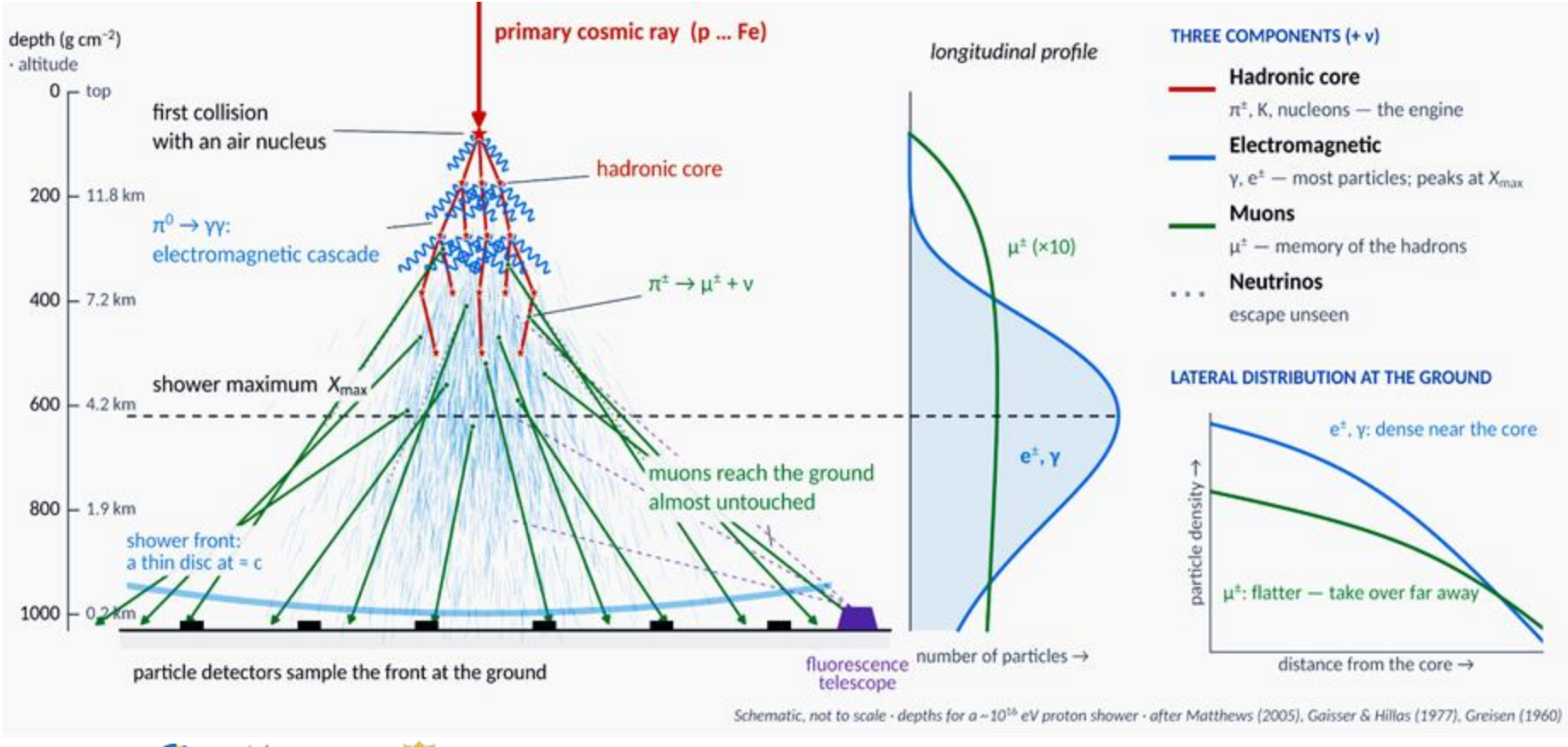
NEW-EXOTICA workshop, ECT* Trento



Chasing the Muon with repurposed J-PET detectors

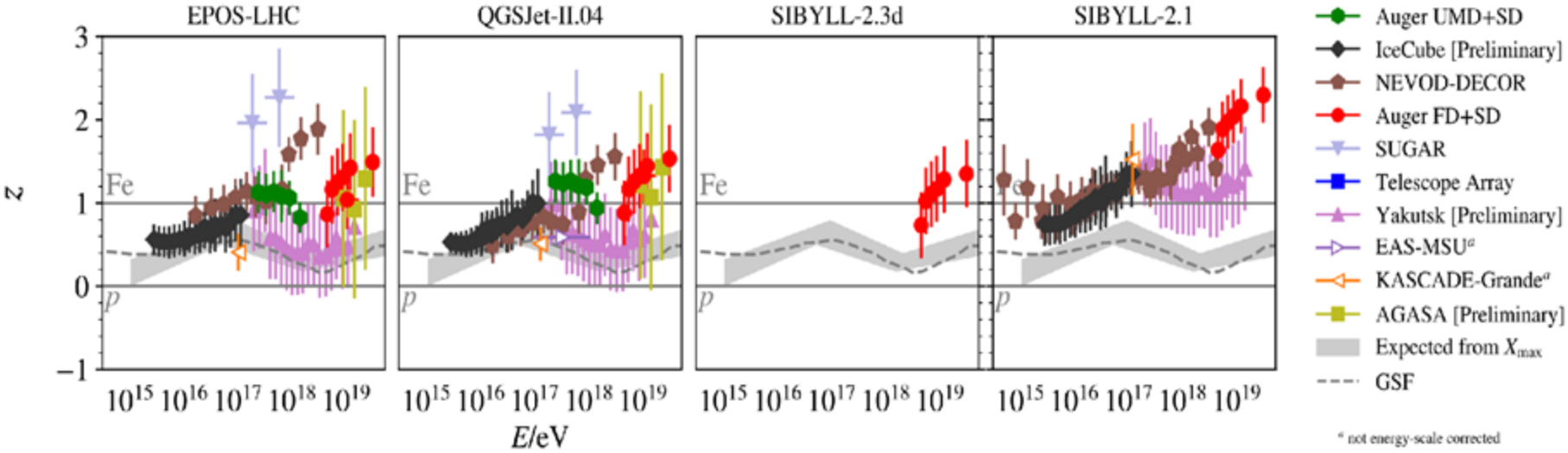
Negin Sadeghinejad
13 October 2026

Extensive Air Showers (EAS)



Schematic, not to scale · depths for a ~10^{16} eV proton shower · after Matthews (2005), Gaisser & Hillas (1977), Greisen (1960)

The muon puzzle



$$z = \frac{\log \rho_\mu - \log \rho_\mu^{\mathrm{p}}}{\log \rho_\mu^{\mathrm{Fe}} - \log \rho_\mu^{\mathrm{p}}} \quad \begin{matrix} \text{data} \\ \text{model (proton, iron)} \end{matrix}$$

z = 0: proton-like *z = 1: iron-like*

Above the band

the excess appears above ~ 10^{15} eV and grows with energy (8σ)

Everywhere

nine experiments on six continents see it; all three High-Energy Hadronic Interaction (HEHI) models, and their variants, miss it

J. Albrecht et al., Astrophys. Space Sci. 367, 27 (2022): the trend is seen for all models tested

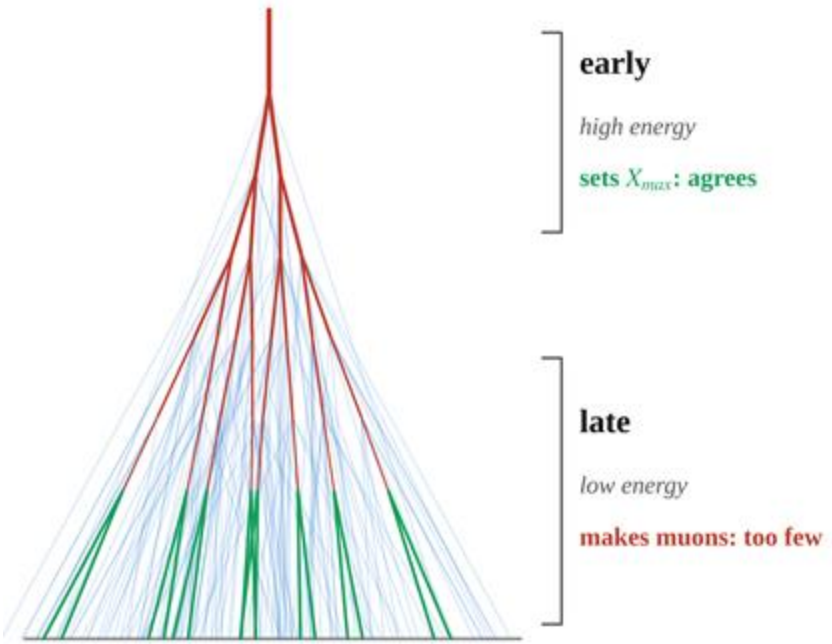
Nine experiments, one excess

	Experiment	Site	Altitude	Muon detector	Muons seen
	Pierre Auger · UMD + SD	Argentina · S. America	1.4 km	buried scintillators (2.3 m) + water-Cherenkov tanks	> 1 GeV (vertical)
	IceCube (IceTop) [p]	South Pole · Antarctica	2.8 km	ice-Cherenkov tanks on the surface	GeV muons, far from axis
	NEVOD-DECOR	Russia · Europe	≈ 0.2 km	2000 m^3 water-Cherenkov tank + 70 m^2 tracking array	muon bundles, θ > 55°
	Pierre Auger · FD + SD	Argentina · S. America	1.4 km	water-Cherenkov tanks + fluorescence telescopes	hadronic ground signal
	SUGAR	Australia	0.25 km	muon detectors buried 1.5 m deep	> 0.75 GeV
	Telescope Array	USA · N. America	1.4 km	unshielded plastic scintillators, 3 m^2	~70 % muon purity (far)
	Yakutsk [p]	Russia · Asia	0.1 km	large-area muon detectors	—
	EAS-MSU [a]	Russia · Europe	0.15 km	underground stations, 40 m w.e.	> 10 GeV
	KASCADE-Grande [a]	Germany · Europe	0.1 km	scintillators under 20 X_0 of shielding	—
	AGASA [p]	Japan · Asia	0.67 km	counters under 30 cm iron or 1 m concrete	> 0.5 GeV

Markers as in the z-plot · [a] not energy-scale corrected · [p] preliminary at the time of the analysis · energy scales of all experiments cross-calibrated

Different detectors, altitudes and muon energies, on six continents — all see the same excess.
What they share is the simulation.

What is missing in the simulations?



✓ **X_{max} agrees**
the first, most energetic interactions look right

✗ **Muons do not**
the effect acts in the late, low-energy generations, or it is small and adds up over many generations

Grows with energy
more generations, more room to accumulate

Something in soft, forward hadron physics is missing
candidates: less energy to π^0, more strangeness, …, spin polarization (our hypothesis)

A. Porcelli et al., Universe 11, 180 (2025), Sec. 1.1 · J. Albrecht et al. (2022)

Our hypothesis: spin polarization in the cascade

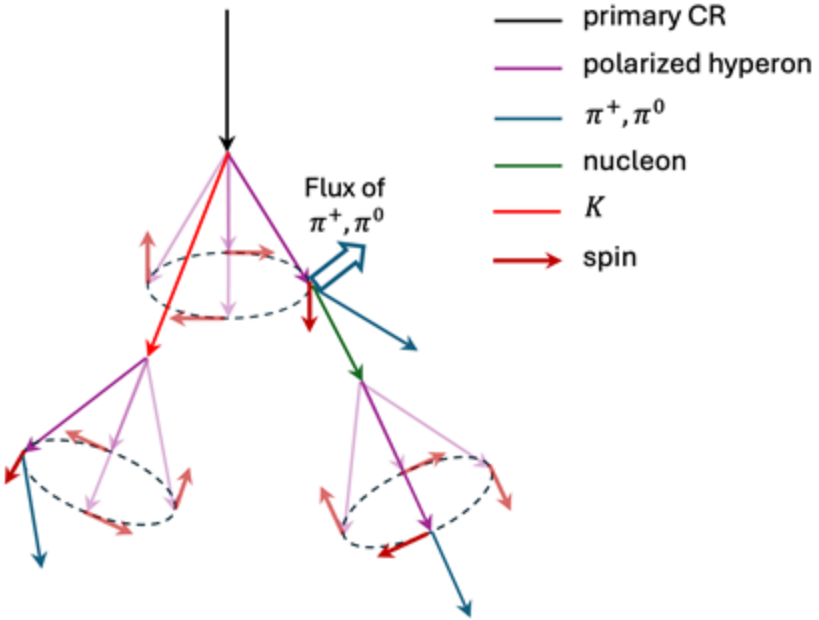


figure: μPPET group, "Spin asymmetries in EAS" (2026)

1 Polarize

collisions in the cascade can produce transversely polarized particles (e.g. Λ hyperons)

2 Kick

their next collision sends secondaries more to one side: single-spin asymmetry, up to ~40 %

3 Shift

over many generations, muons arrive at a different angle around the shower axis

A. Porcelli et al., Universe 11, 180 (2025) · B. Lundberg et al., PRD 40, 3557 (1989) · E.C. Aschenauer et al., EPJA 52, 156 (2016)

J-PET: a PET scanner repurposed for cosmic rays

Big Barrel → muon tracker

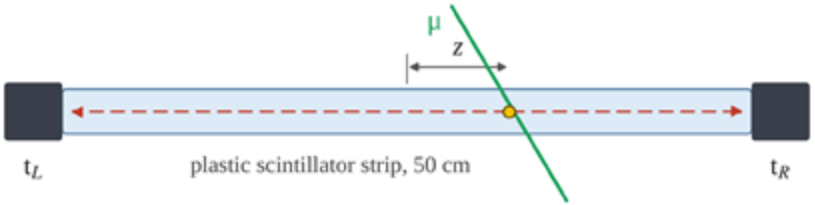


- 192 plastic strips (50 cm) in 3 layers, PMT read-out
- shielded room: only muons reach it; track angle ≈ 1°

Modular → Modular Array on the roof



- 24 modules × 13 plastic strips (50 cm), SiPM read-out
- paired into stations in cages; shower direction 0.25°–1.5°



Why it works for cosmic rays

$z = v\,(t_L - t_R) / 2$ → where it crossed (a few mm)

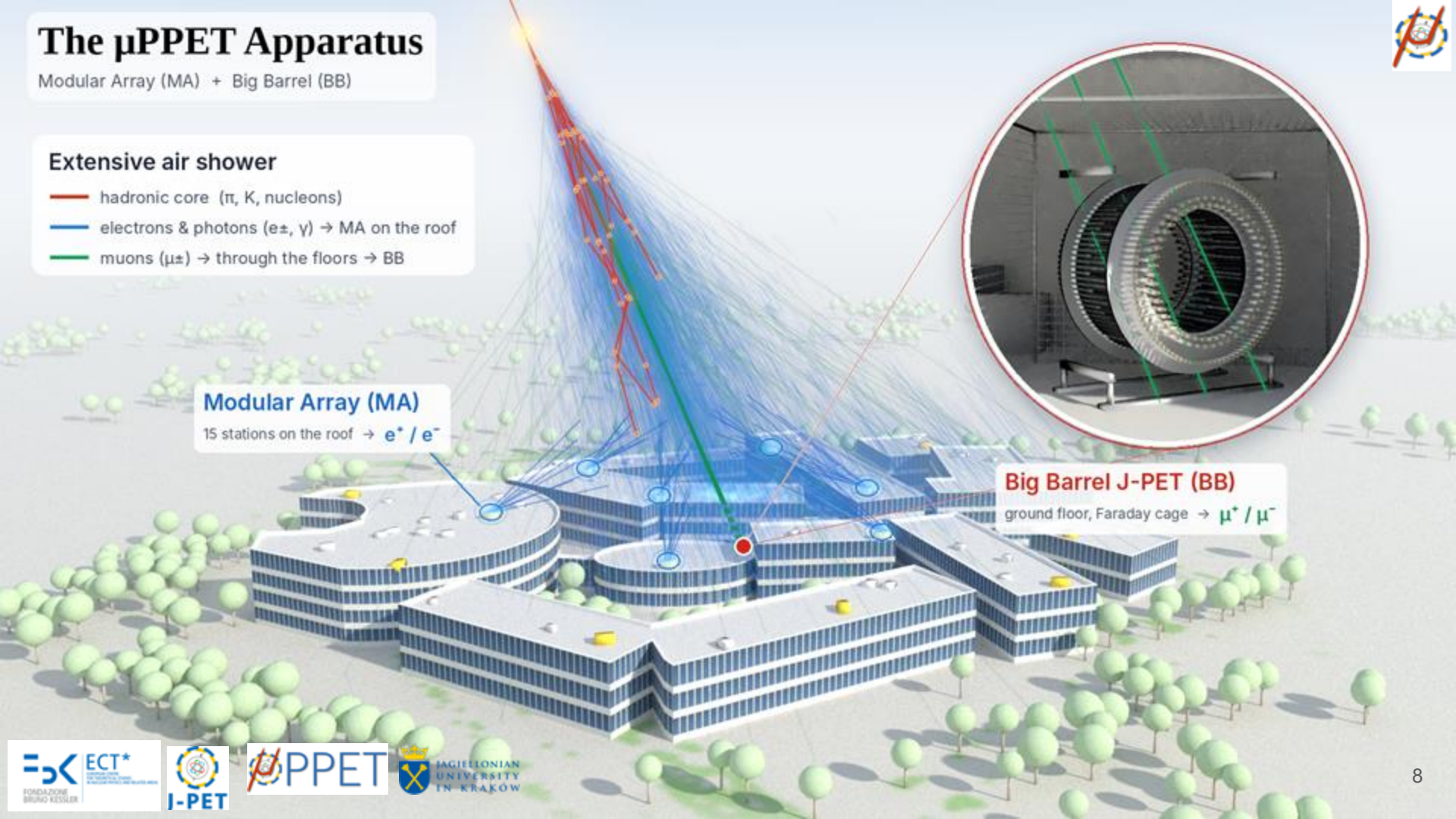
$t = (t_L + t_R) / 2$ → when

plastic: cheap, light, easy to move and rearrange

J-PET in medical imaging: P. Moskal et al., Sci. Adv. 10, eadp2840 (2024); Sci. Adv. 11, eads3046 (2025)

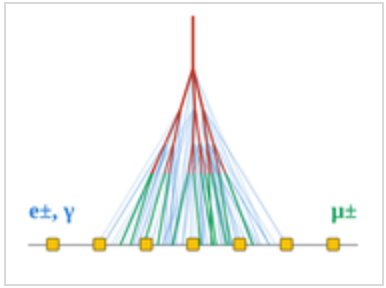
The µPPET Apparatus

Modular Array (MA) + Big Barrel (BB)



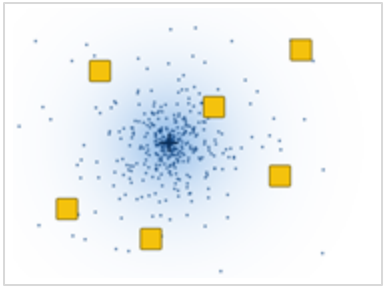
How we estimate what we will see

1 CORSIKA simulation



CORSIKA, 10^4 – 10^8 GeV

2 Footprint



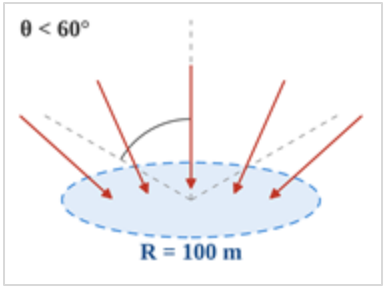
particle density at each station

3 Classification



fraction fired → **efficiency**

4 Counting

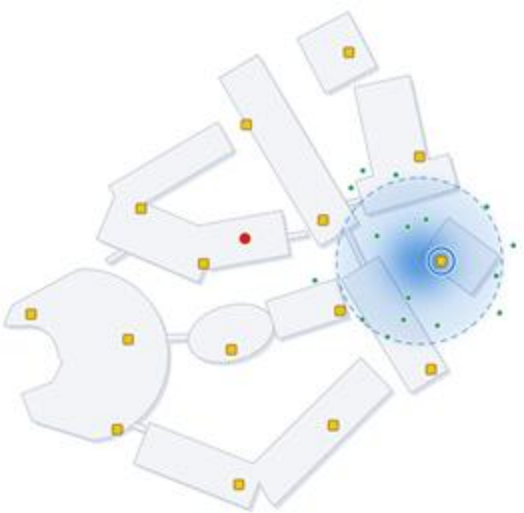


flux **Φ(E)** → events / month

$$N_{showers} = \int dE \int dA \int d\Omega \cos\theta \int_{month} dt \;\; \mathbf{\Phi(E)}$$

$$N_{class} = \mathbf{Efficiency_{class}} \times N_{showers}$$

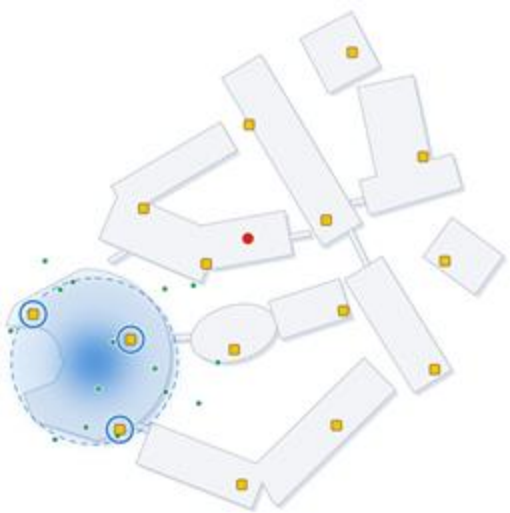
Definition of the event classes



Brass

TRIGGER ≥ 1 MA

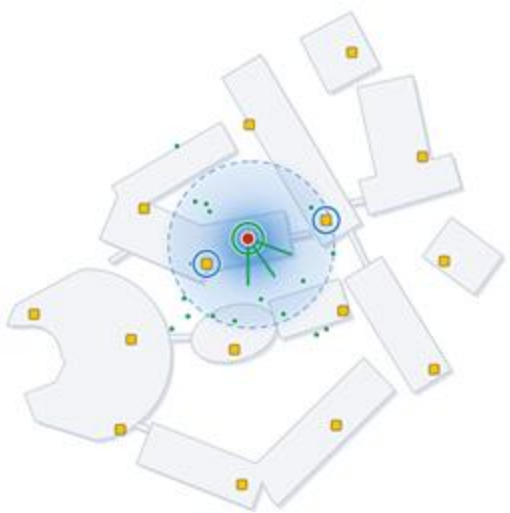
GIVES a shower happened → rates, calibration, monitoring



Silver

TRIGGER ≥ 3 MA

GIVES shower direction from the timing · charge separation



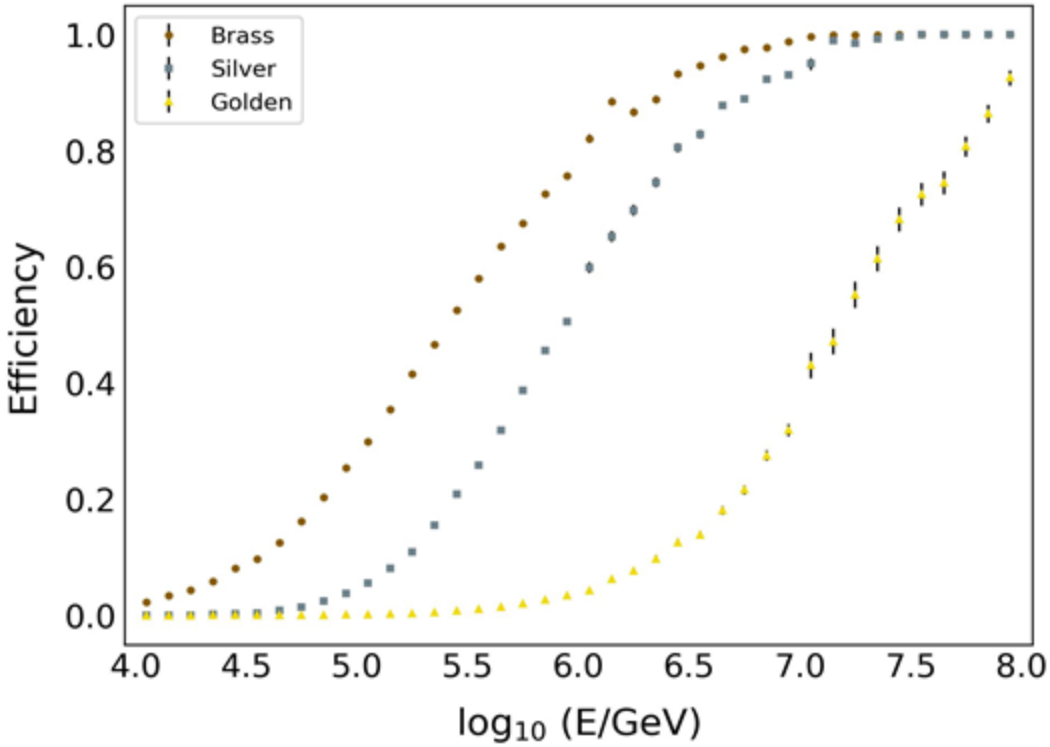
Golden

TRIGGER ≥ 2 MA + BB

GIVES electrons and muons of the same shower — what the puzzle needs

MA station · Shower footprint · muon · Big Barrel (BB)

Trigger efficiency vs. primary energy



Efficiency rises with energy

bigger showers fire more stations

Brass ≈ 100 % above $10^{6.5}$ GeV

→ *the array sees every shower within 100 m*

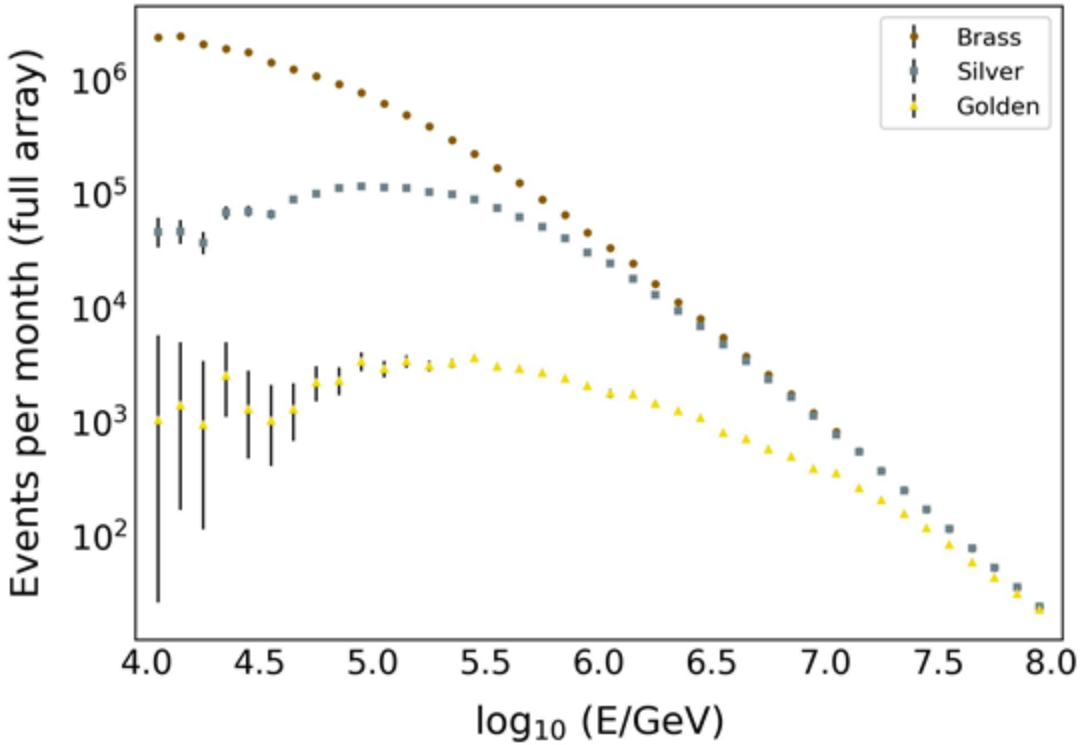
Silver ≈ 100 % above 10^{7} GeV

Golden 50 % at $10^{7.2}$, 90 % at 10^{8} GeV

Golden reaches 50 % at ≈ 10^{7} GeV, just where the muon excess appears

CORSIKA, 10^{4}–10^{8} GeV · footprints within R = 100 m, θ < 60° · trigger level: scintillator efficiency not yet included · preliminary

Expected events per month



Brass ≈ 2×10^6 per bin at 10^4 GeV
→ *exposure, livetime, calibration*

Silver ≈ 10^5 per bin near 10^5 GeV
→ *shower reconstruction*

Golden ≈ 10^3 per bin at peak

Enough Golden events every month !

per $\Delta\log_{10}$(E/GeV) = 0.1 bin · full array · R = 100 m, θ < 60°, 30 days · flux: PDG power law, · trigger level · preliminary

Summary and outlook

Where we are

- Two repurposed J-PET scanners: the Modular Array on the roof gives the shower axis, the Big Barrel in a shielded room gives the muon direction
- Simulated resolution: muon angle ≈ 1° in the Big Barrel; shower direction ≈ 0.25°–1.5° from the Modular Array
- Three trigger classes; the array fires on every shower above ≈ 3 PeV (Brass); Golden (≥ 2 MA + BB) gives the muon angle relative to the shower axis
- Golden: 50 % efficiency at ≈ 16 PeV, where the muon excess appears; ≈ 3×10^3 events per month per bin at the peak

Next steps

Hardware finish the cage endurance tests, install the stations on the roof, synchronize the array with the Big Barrel

Simulation Geant4 model of cages and scintillators; fold the station efficiency into the trigger efficiency;

Reconstruction μPPETeer framework; graph neural network for the shower direction; physics-informed neural network for muon identification in the Big Barrel

Physics simulations with spin polarization → compare the muon-angle distributions with data

Golden events will test whether spin polarization changes the angle of the muons in air showers



Thank you

The µPPET TEAM

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