Radboud University

Towards Ultra-High-Energy Photon Detection With AugerPrime

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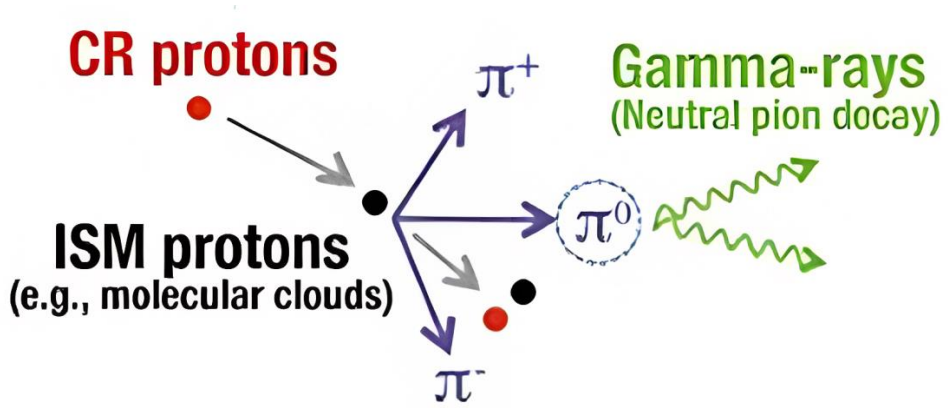
Photon Production & Propagation

GZK Limit



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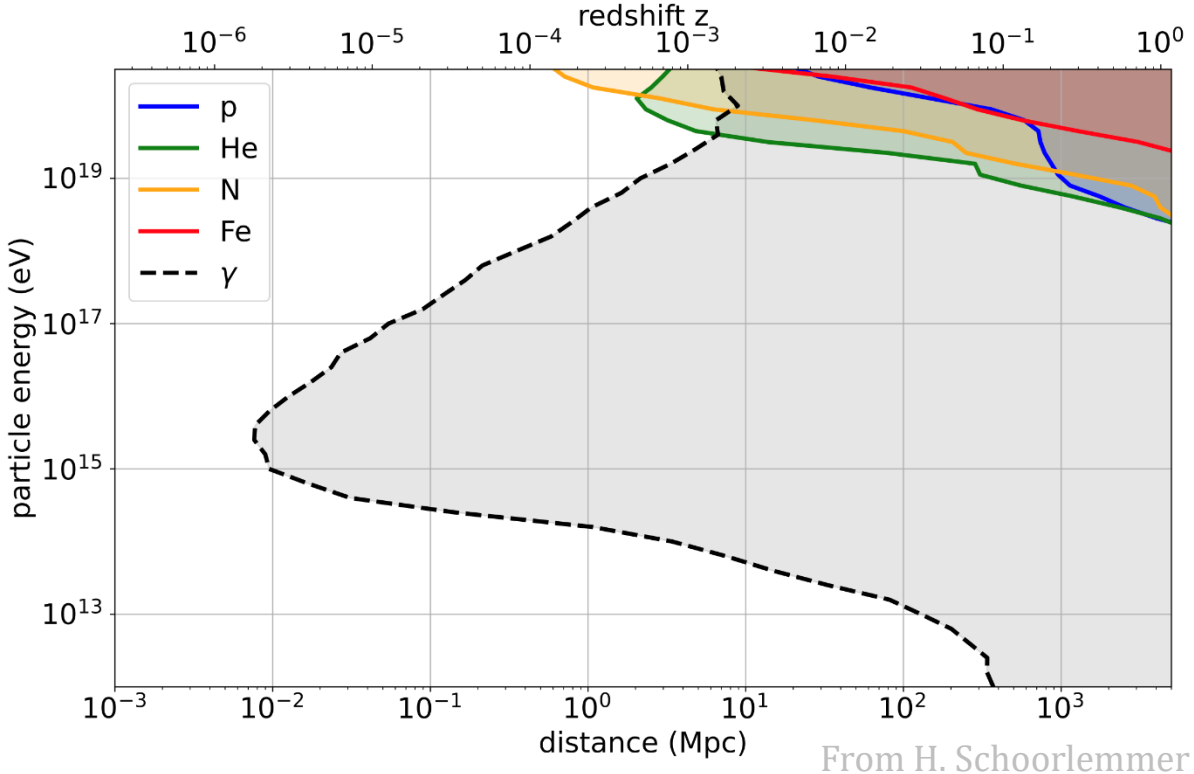


From H. Schoorlemmer

$$p + \gamma_{CMB} \rightsquigarrow p + \pi^0 \rightarrow p + 2\gamma$$

GZK Interaction threshold $\sim 5 \times 10^{19}$eV

The resulting photon energy ~ 1 order of magnitude less than the initial proton

Pierre Auger Observatory

Mariangela Settimo, "ILP day", Paris 13 March 2014

Based on 2 complementary and independent techniques

Fluorescence Detector (FD)
24 + 3 telescopes in 4 sites
10-15% duty cycle

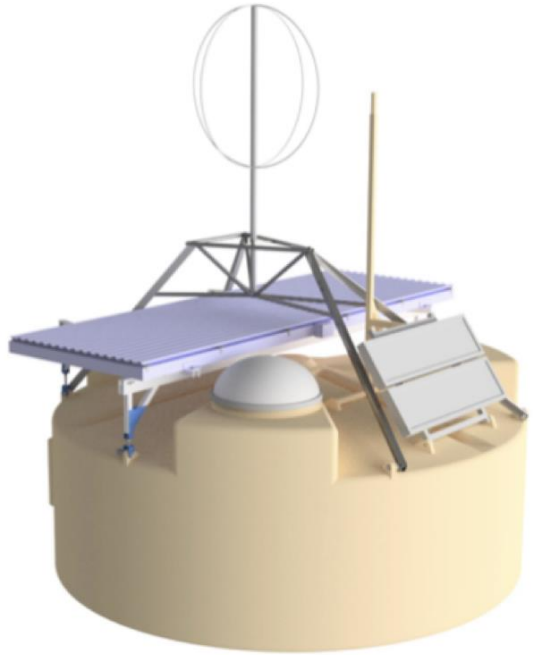
Real Event, E = 7 10^{19} eV

3000 km²

Malargüe (Argentina), 1400 m a.s.l.

Hybrid events:
observed at the same time by at least 1 fluorescence telescope + 1 SD

Surface Detector array (SD)
1600 + 60 water Cherenkov stations, 100% duty cycle **(WCD)**



AugerPrime Upgrade

Upgrade Each Detection Unit:
+ Radio Antenna
+ Surface Scintillator
+ Small photomultiplier

Photon Searches

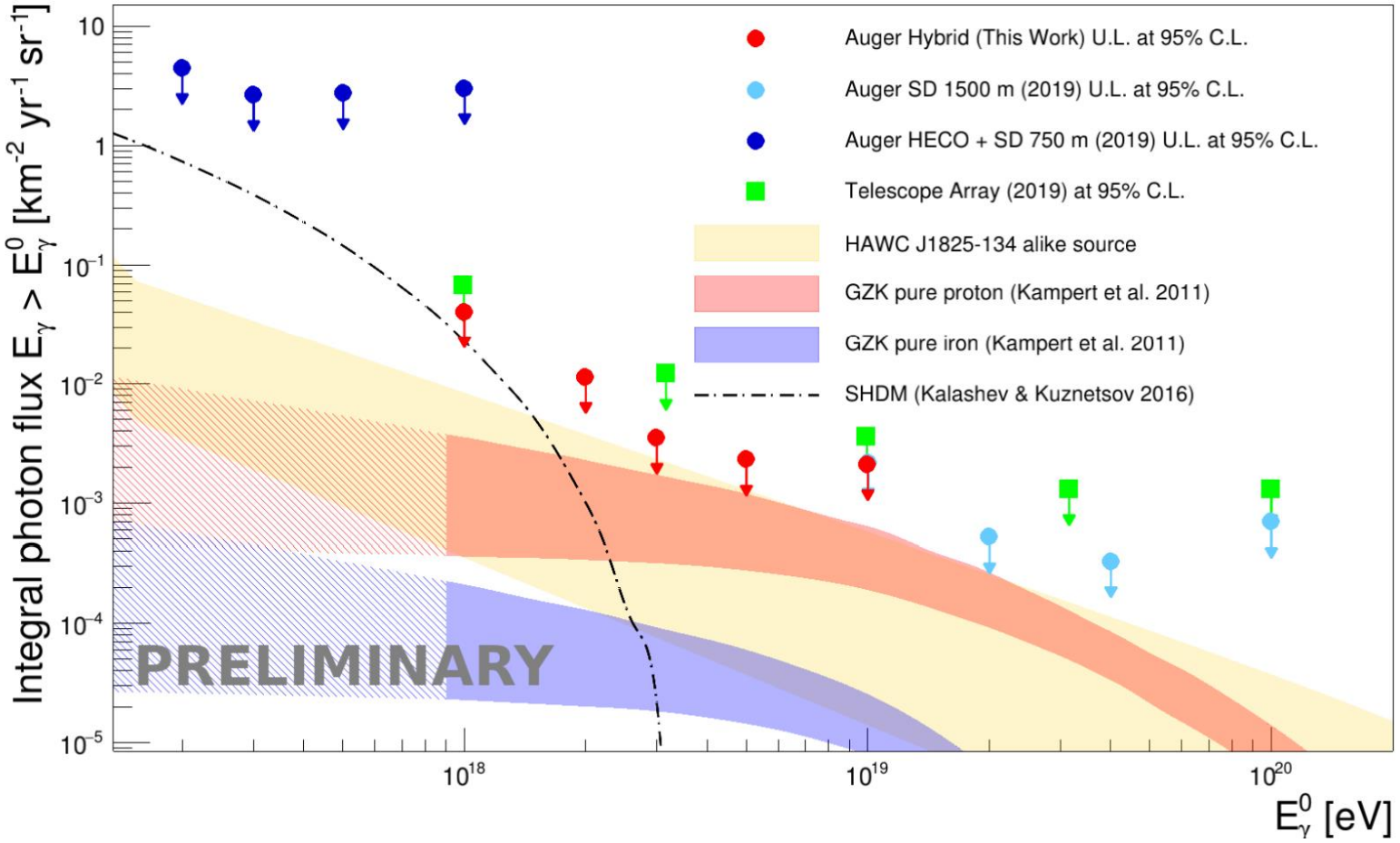
Pierre Auger Observatory's Searches

Year	Approach	Energy [eV]	Zenith angle [deg]
2022 (1)	WCD	$> 10^{19}$	$30 - 60$
2022 (2)	WCD infill + FD	$> 10^{17}$	< 60
2021 (8)	WCD , FD	$> 10^{19}$	$30 - 60$
2016 (3)	WCD + FD	$> 10^{18}$	< 60
2019 (4), 2015 (7)	WCD + FD	$> 10^{19}$	$30 - 60$
2008 (5), 2012 (6)	WCD	$> 10^{19}$	$30 - 60$

As almost all searches performed for $\mathbf{Zenith} < \mathbf{60^0}$.
The observables used not well defined for horizontal showers → Weak WCD signal

No Photon Detected So Far!

pos.sissa.it/395/373/

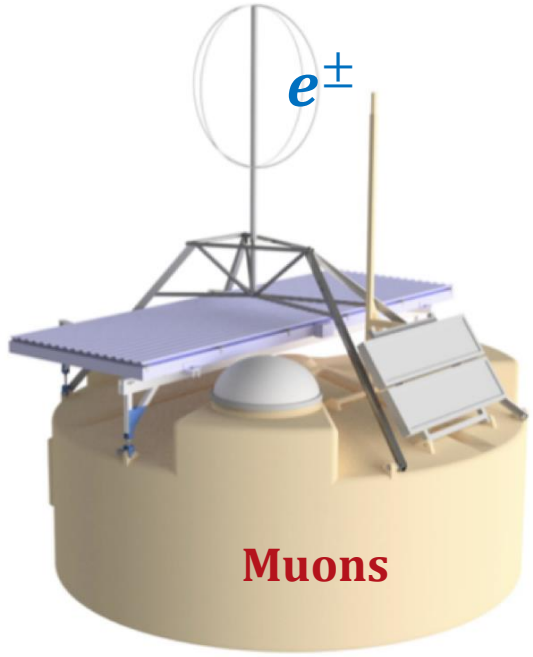


- GZK limit ($\sim 10^{19}$ eV) is real with some outlier i.e. heavy nuclei = UHECR not pure protons
- Limits are relatively close to the fluxes expected for photons originating from the GZK effect

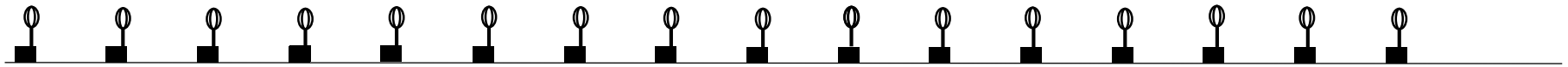
Radio In AugerPrime

Characteristic	Advantage compared to AugerPhase1
~ 100% duty cycle	More Statistics
Calorimetric energy of the primary particle	Direct measurement for shower's electromagnetic content
Primary mass sensitive	Electron / muon separation with Surface Detector
Efficient for inclined showers	Extends sky coverage

Radio SALLA Antenna measures radio emission between 30-80 MHz



Photons in AugerPrime



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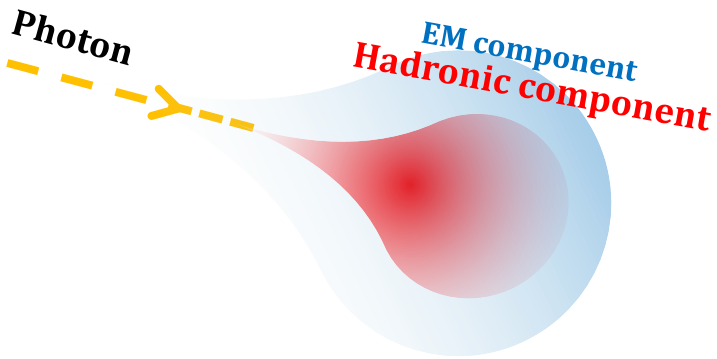

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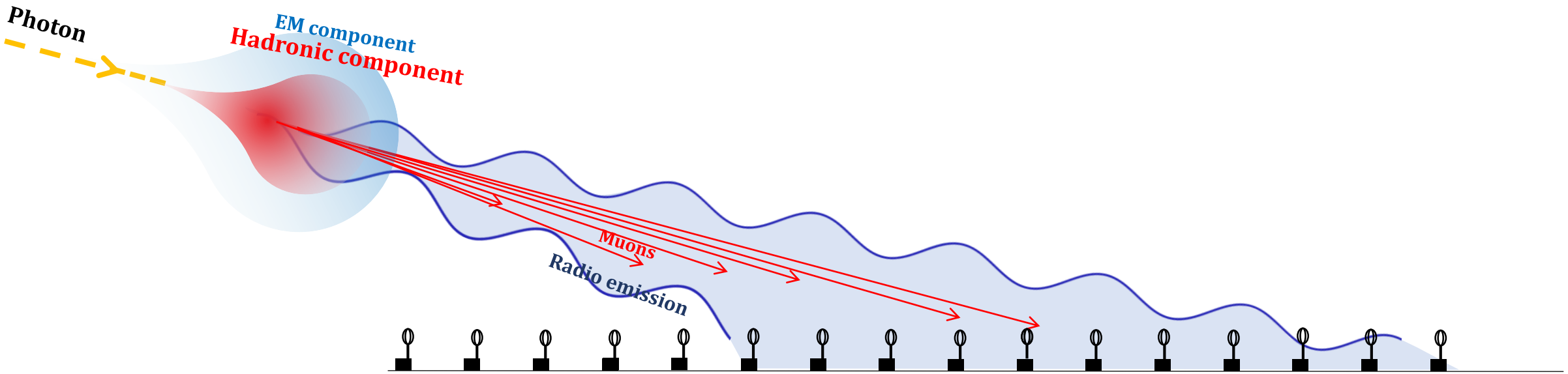
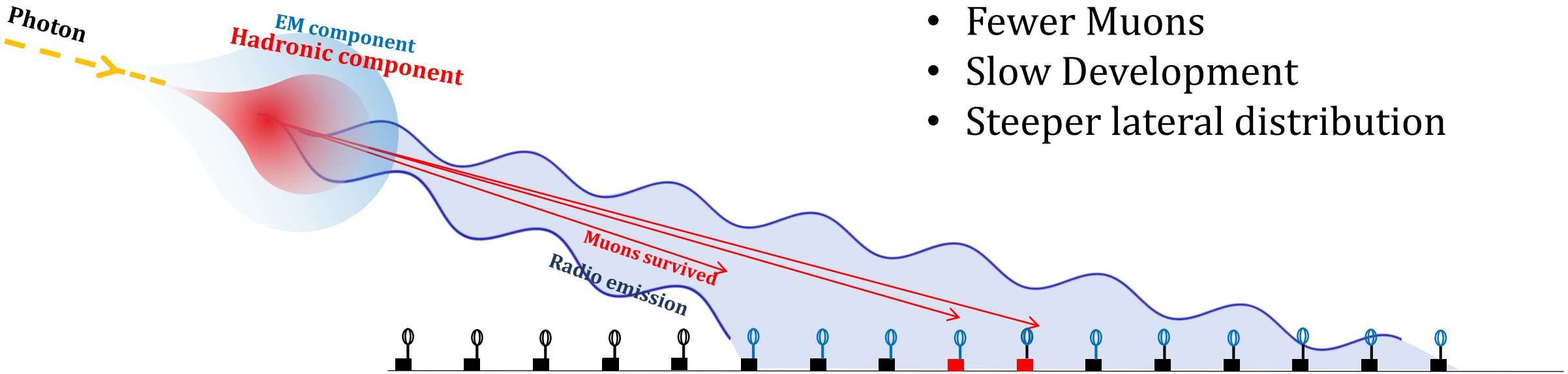


- The atmosphere is transparent to the radio frequencies. Inclined events have a large radio illuminated area, resulting in a higher number of stations capable of recording the radio emissions.

Photons in AugerPrime

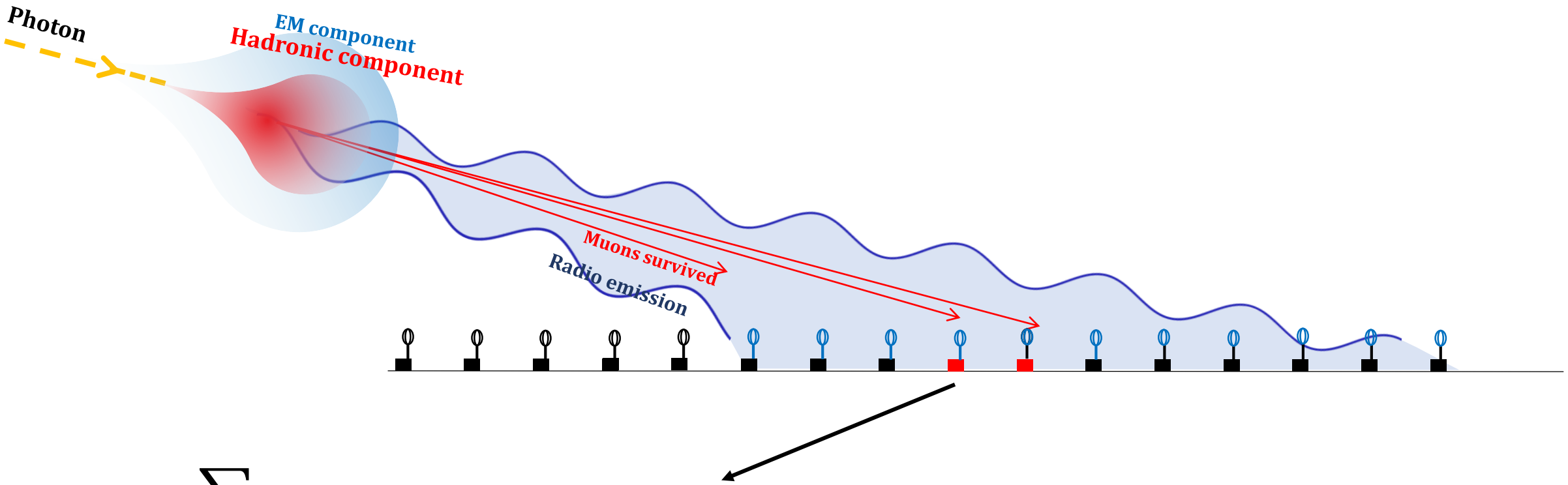


Photon shower footprint:

- Deep Xmax ~ 1000 g/cm^2
- Fewer Muons
- Slow Development
- Steeper lateral distribution

- The atmosphere is transparent to the radio frequencies. Inclined events have a large radio illuminated area, resulting in a higher number of stations capable of recording the radio emissions.
- Only a few WCDs are triggered by the surviving muons that reach the observation level.

Basic Photon Search in AugerPrime Using Radio

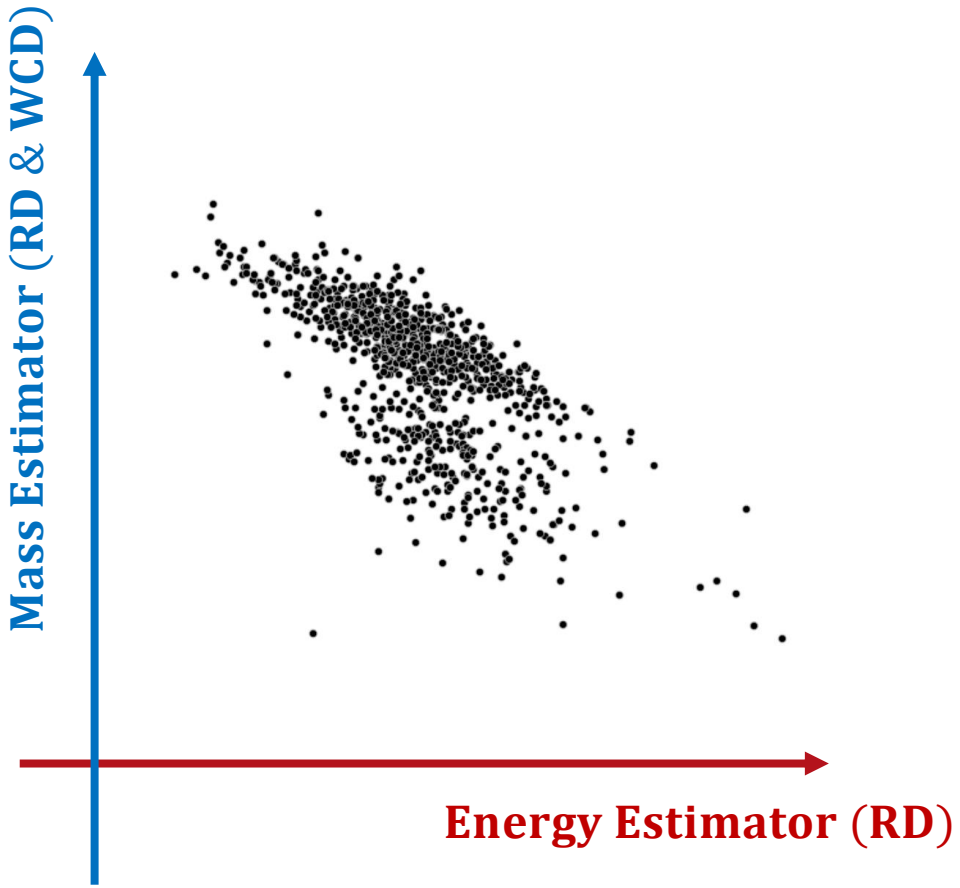


$$S_{RD} = \sum_n E_{max} \sim 1.6 \times 10^4 \ \mu V/m$$

$$S_{WCD} = \sum_n \rho_\mu \sim 19.7 \ VEM$$

Basic Photon Search in AugerPrime

- Correlation of the sum of WCD signal with the sum of maximum electric field per event after reconstruction.



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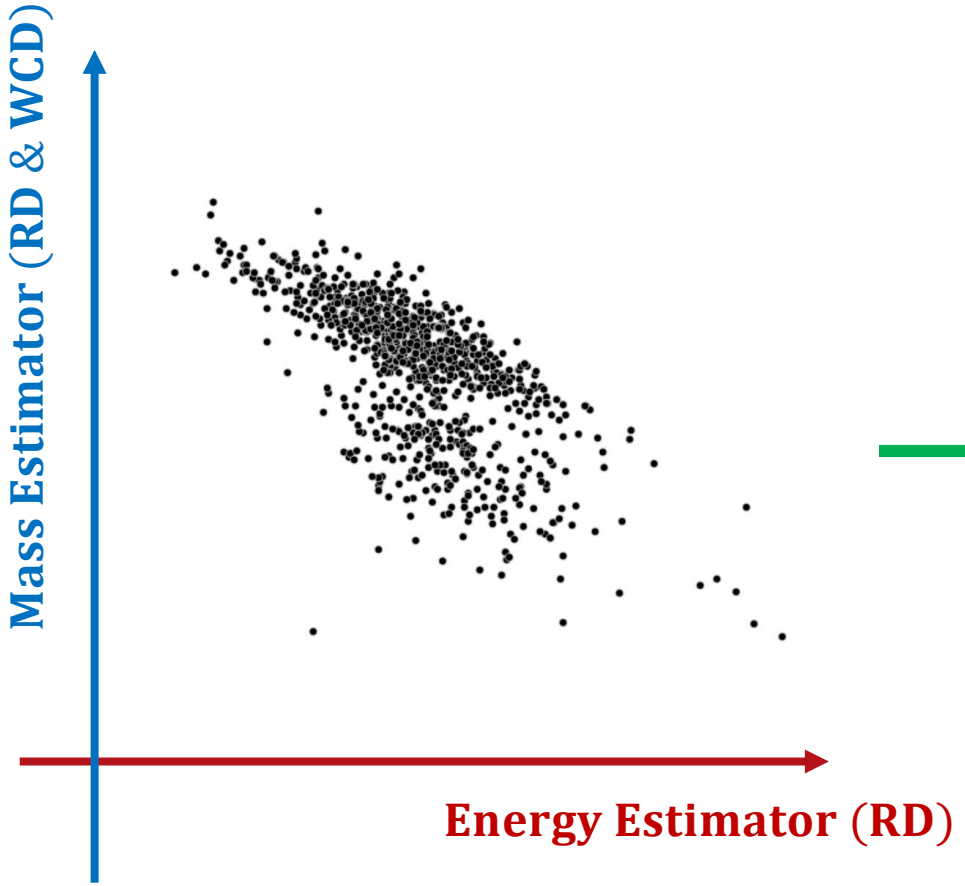
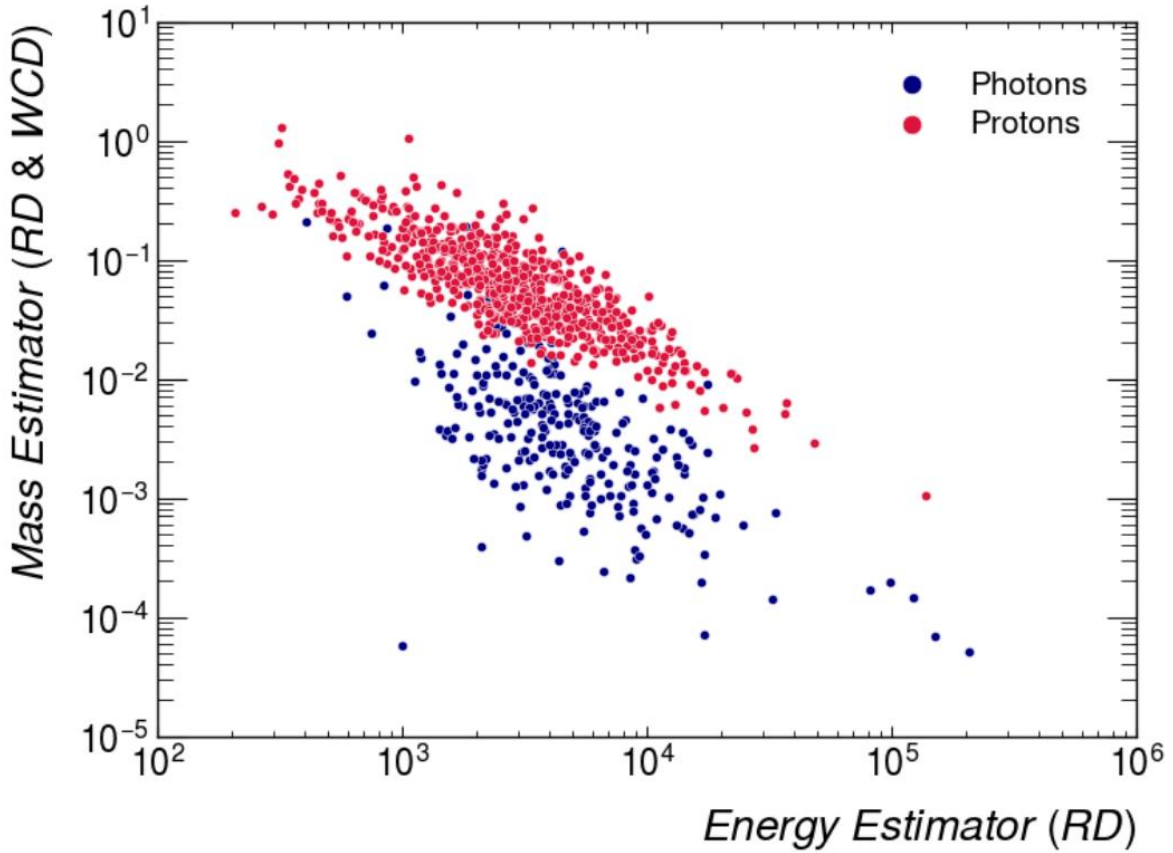
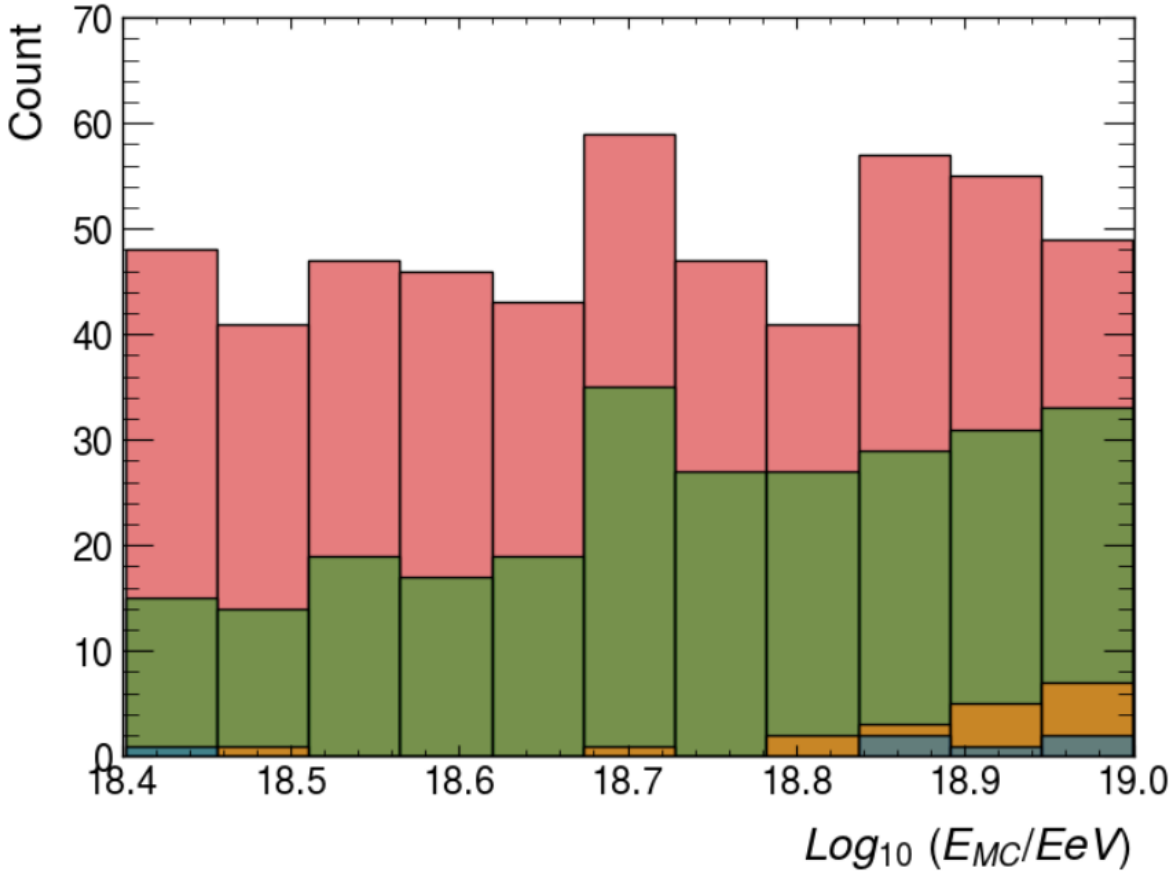




Toward Triggering on Radio Signals For Photons

- We have studied the possibility of implementing a RD trigger.
- Hybrid trigger mainly enhance the trigger of neutral primaries with poor muon content.
- A New Hybrid Trigger RD + WCD → 14 × more than trigger on WCD alone.

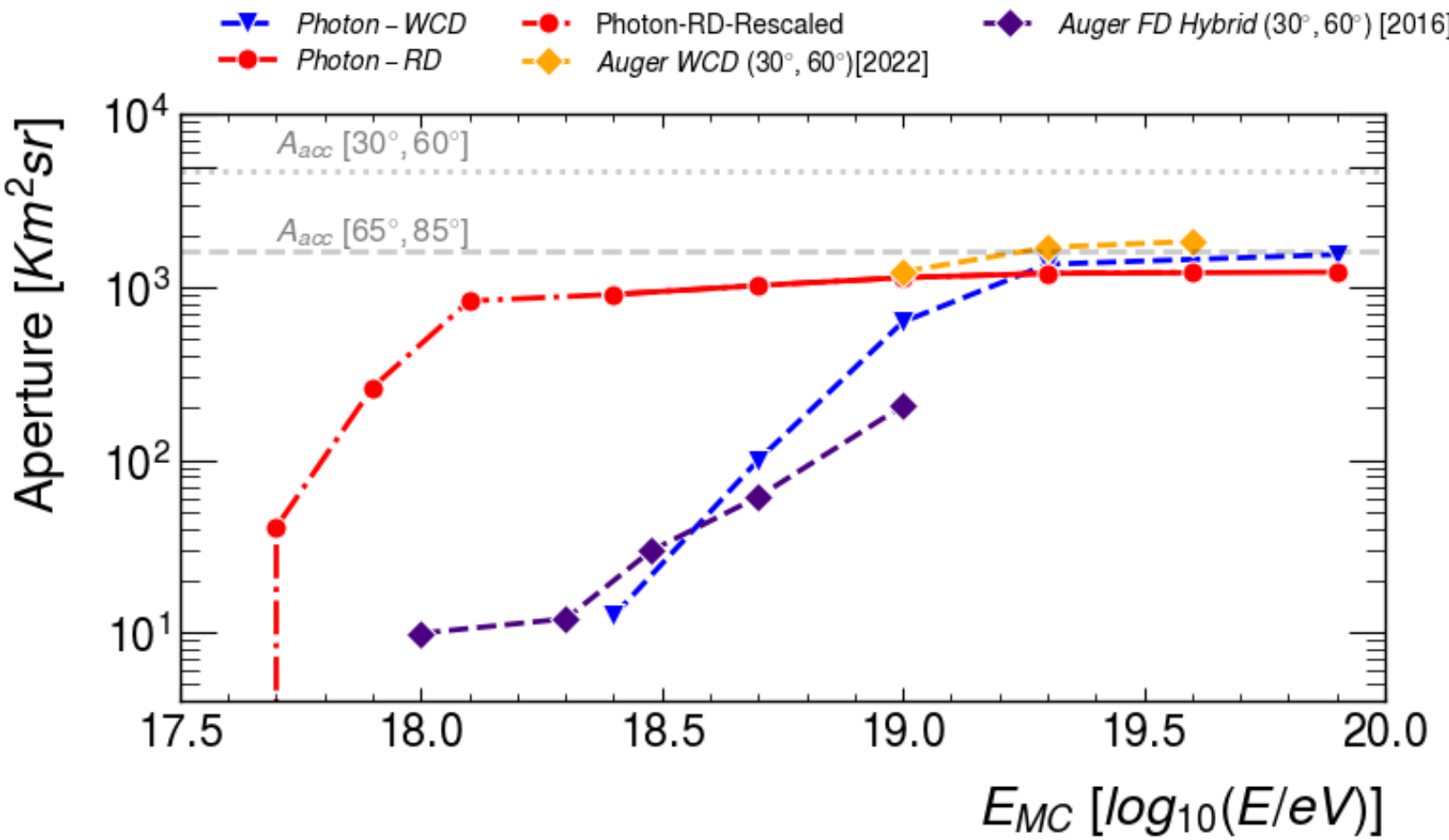


Reconstruction
- Slave-mode trigger *
- WCD only Trigger
- **RD + WCD Trigger**
- All Simulations

* Slave-mode: When WCD trigger, ask for radio data (currently implemented)

Expected Performance

- Radio array will be sensitive at low energies as well as significant increase for higher energies compared to Water Cherenkov array.
- Extend the sky coverage and declination range.



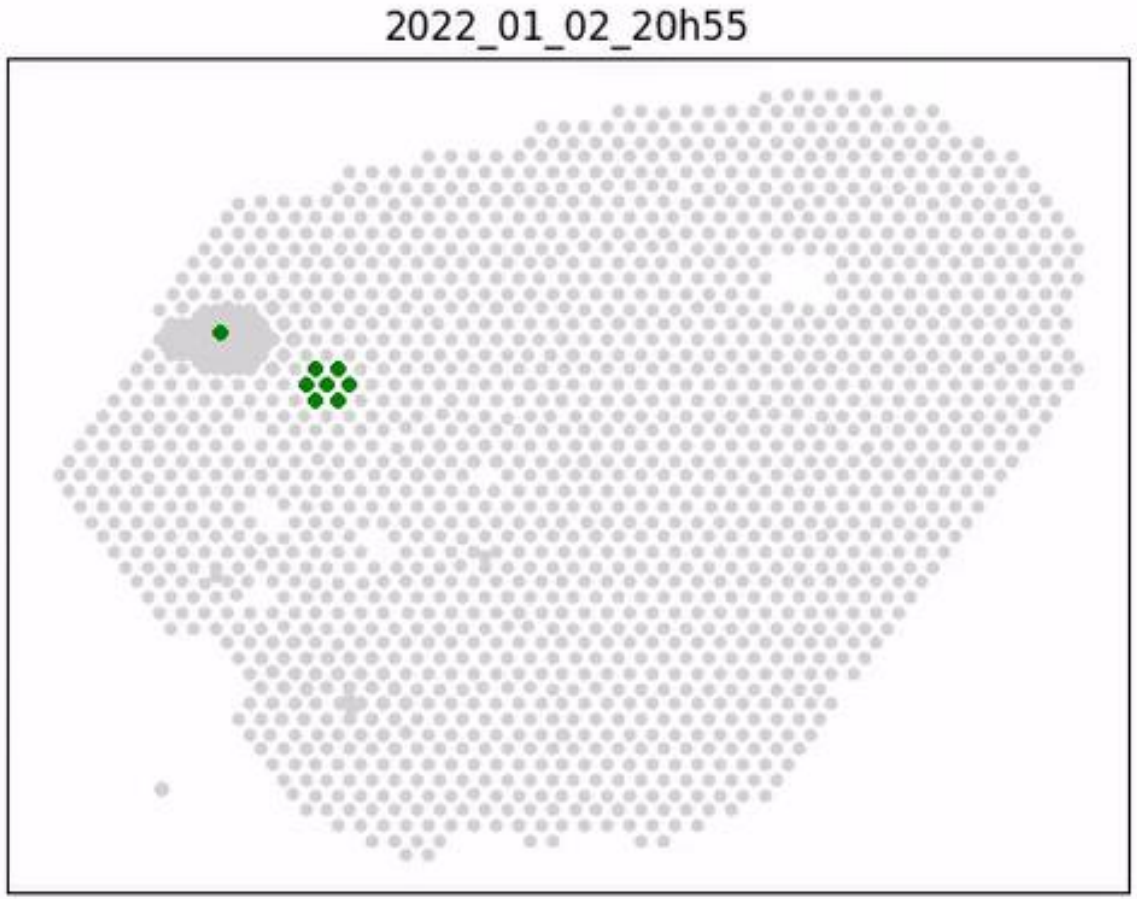
Conclusion

- Radio trigger under development, significant improvements expected from simulation study.
- Significant contribution to photon sensitivity and sky coverage.
- The first phase of Radio array is operating and actively taking data with 40 stations since end of May.
- The full Radio array ~ 1600 stations will be deployed by the end of the year.

Backup

Backup: Rd Data

- 40 Active stations in the field
- Operating in a slave-mode (If WCD trigger, ask for Radio data)



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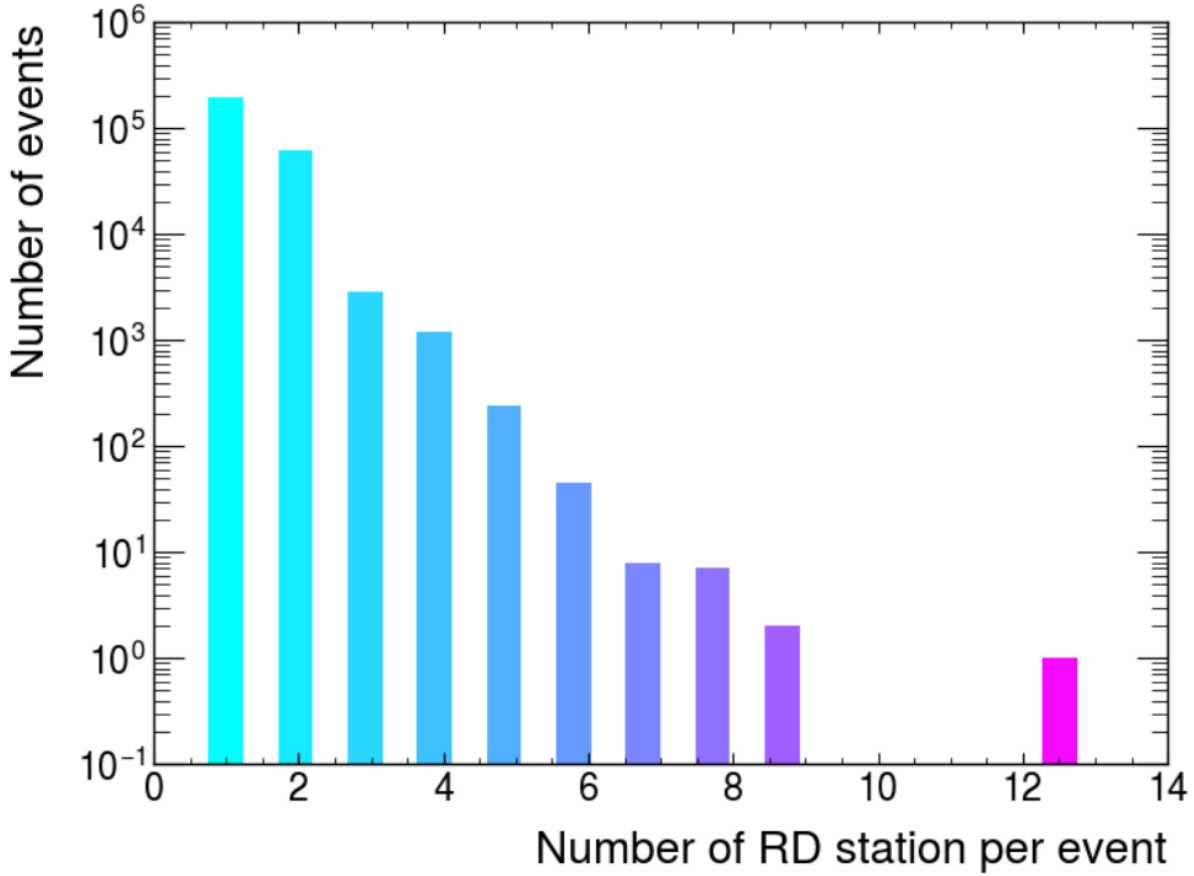
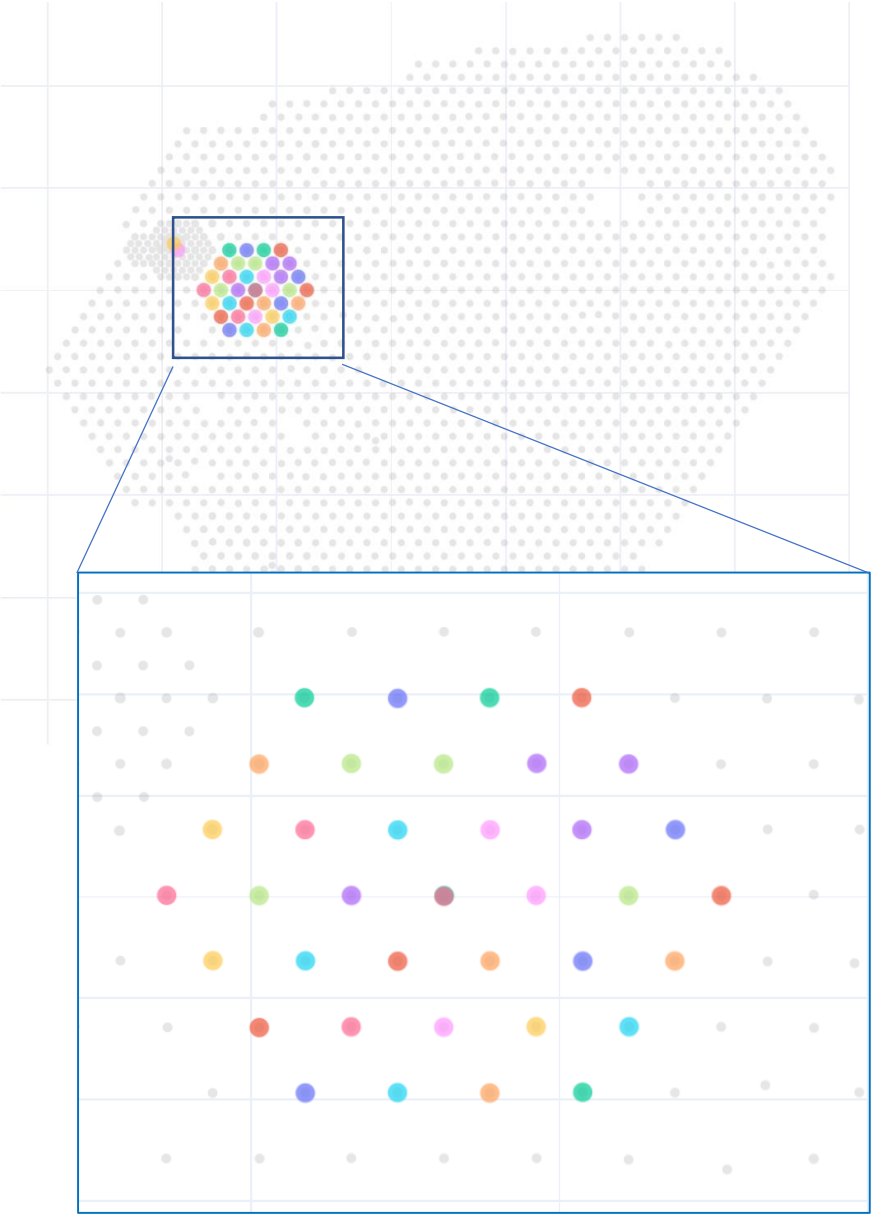
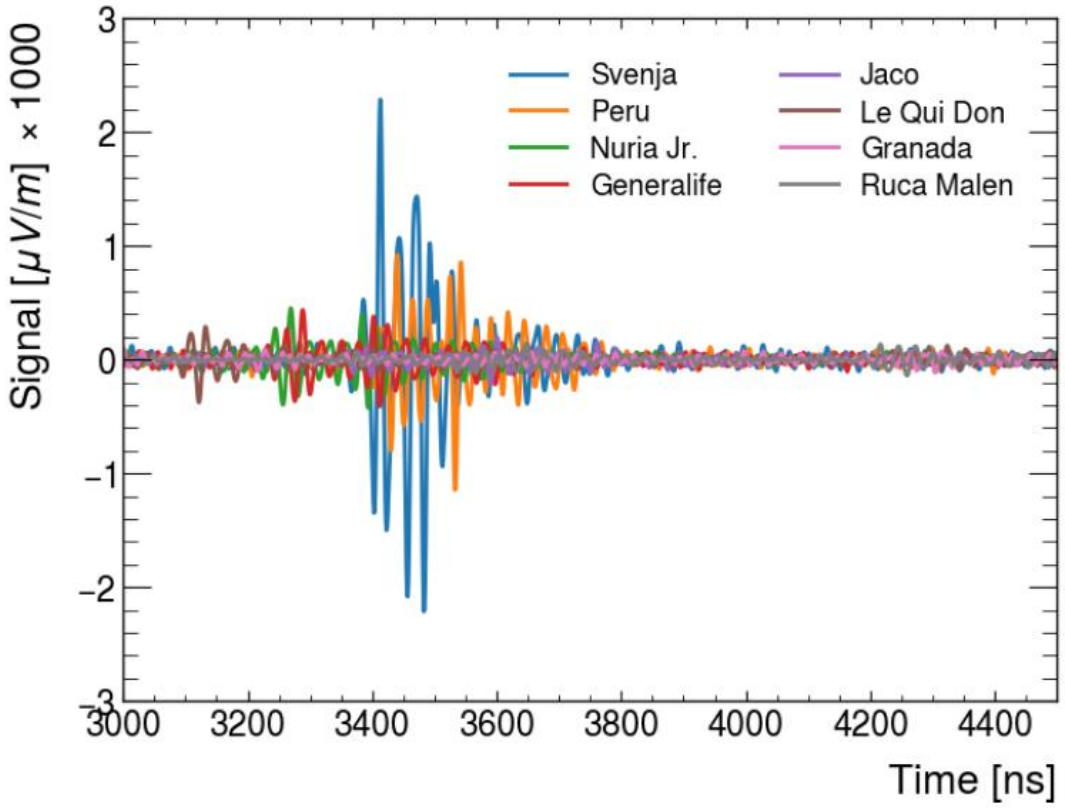


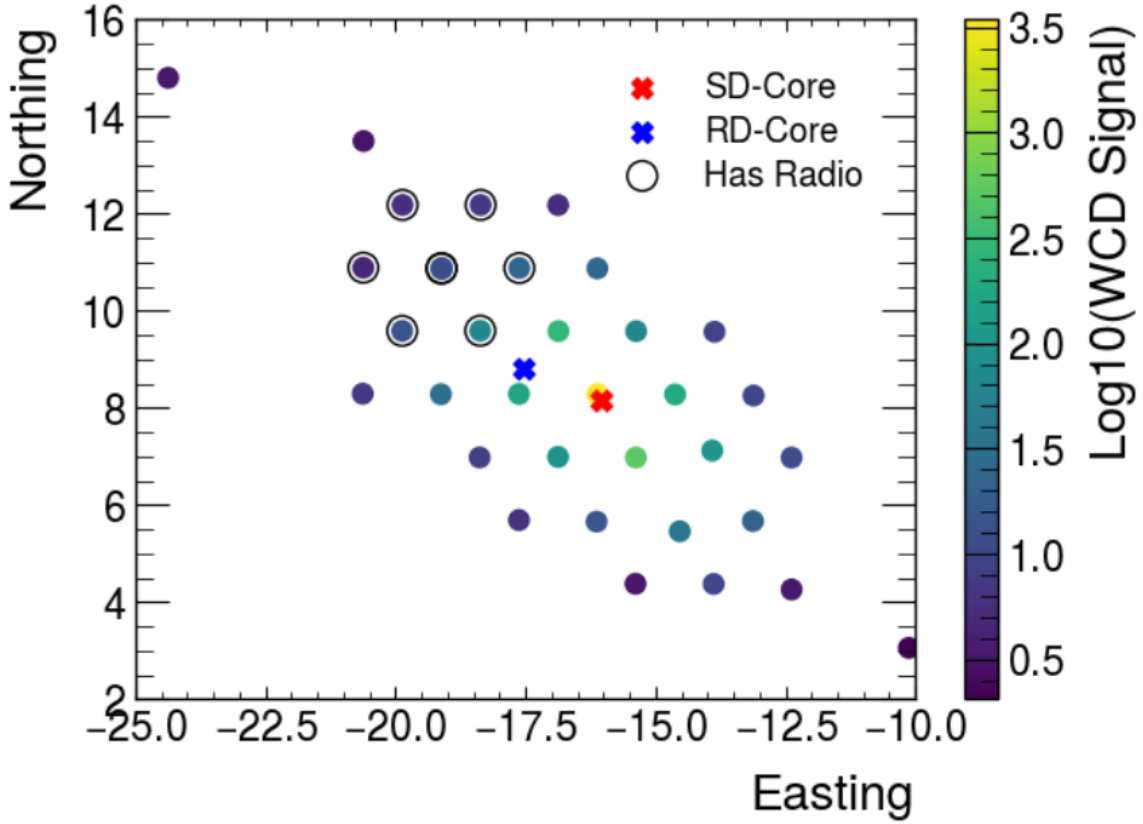


Backup: Rd Data

Event example recorded
by Radio and WCD

SD reconstruction (30 signals)
$E = (1.17 \pm 0.04) \times 10^{20}$ eV
$(\theta, \phi) = (57 \pm 0.1, 315 \pm 0.1)$





Backup: Expected Performance

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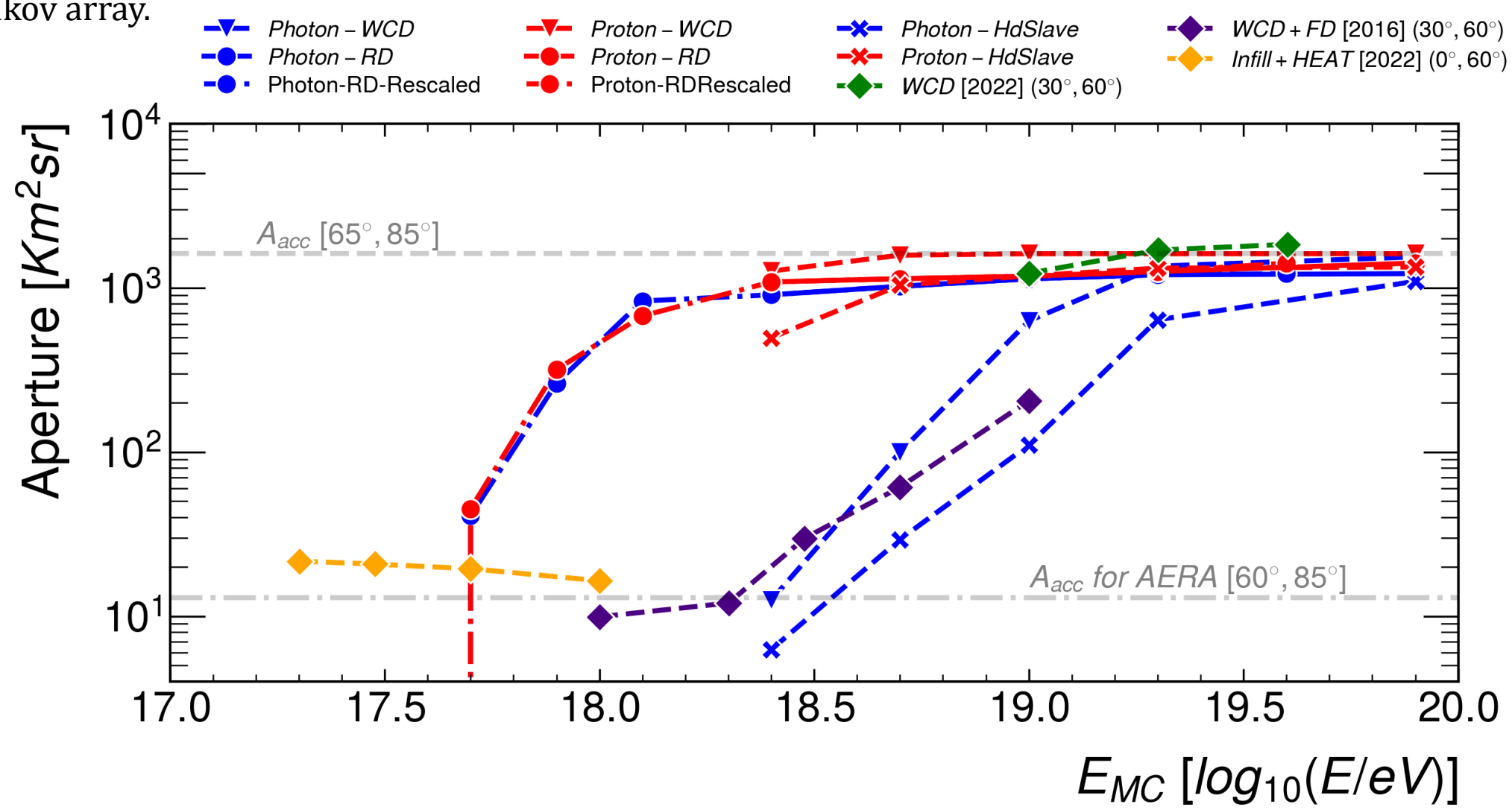
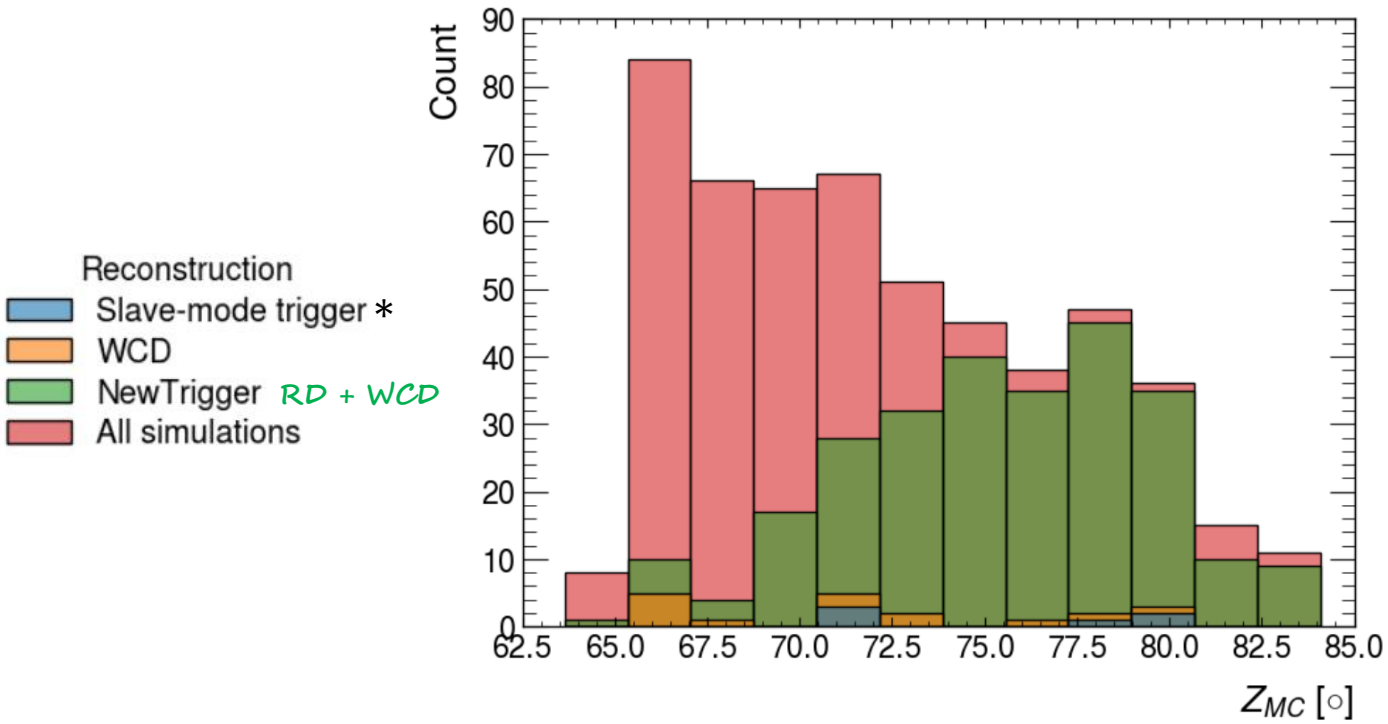


Backup: Event Radio Trigger ‘Photons’

- A New Hybrid Trigger RD + WCD

- 50% of Events with T3,
- 85% of reconstructable events (RD-only)
- 14 × more than standard WCD trigger.



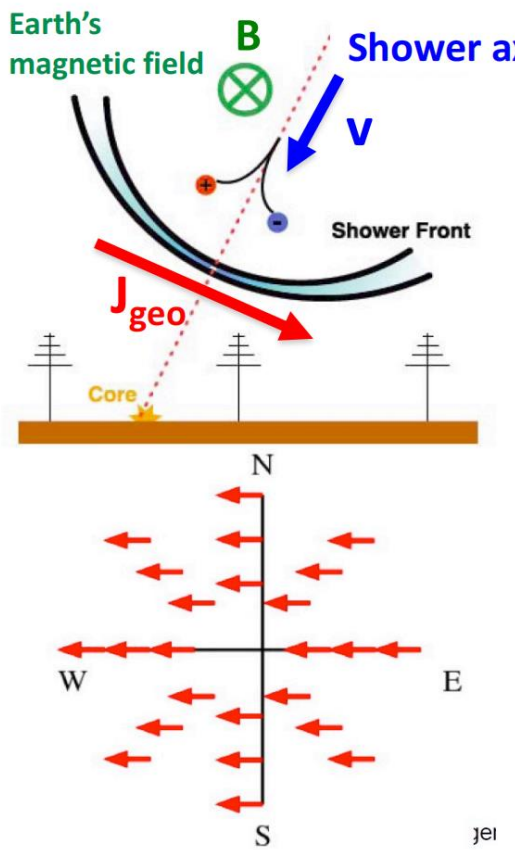
* Slave-mode: When WCD trigger, ask for radio data

Backup

Radio Emission Mechanisms

Geomagnetic mechanism

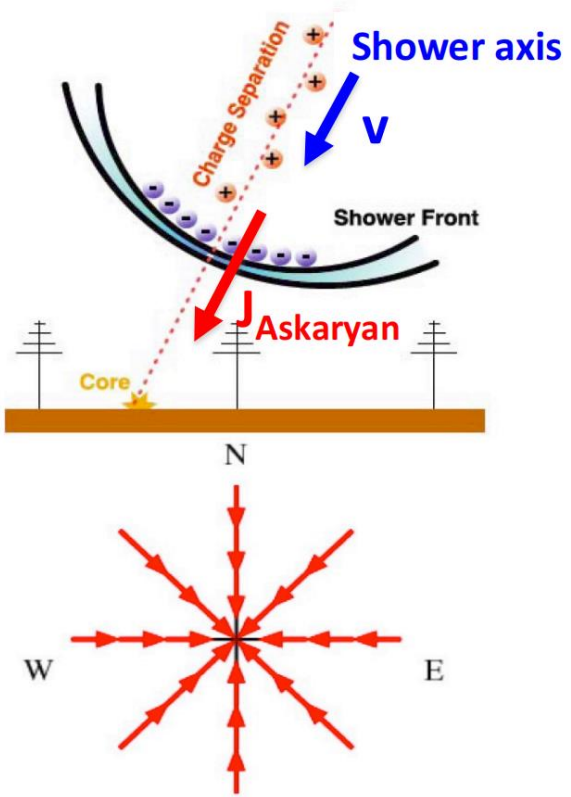
Separation of e- & e+ in the magnetic field (**B**) of the Earth induces **electric current** (J_{geo}) parallel to (**v x B**). **Electric field:** ~ B sinα (α = angle between **B** and **v**).



Charge-excess (Askaryan) mechanism

~ 20% **excess e- over e+** because shower drags atomic e- of atmosphere into shower flow, mainly due to Compton:

γ e-(medium) ⟶ γ e-(shower)



Approx. polarization pattern on shower plane around shower axis

Backup

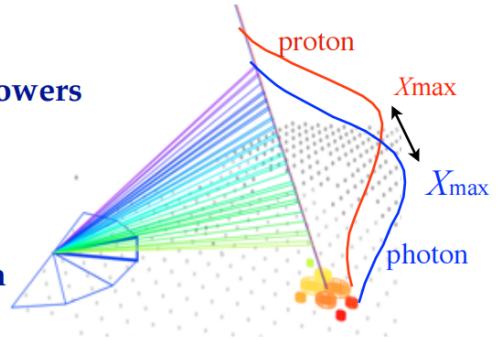
How to Identify a photon using WCD

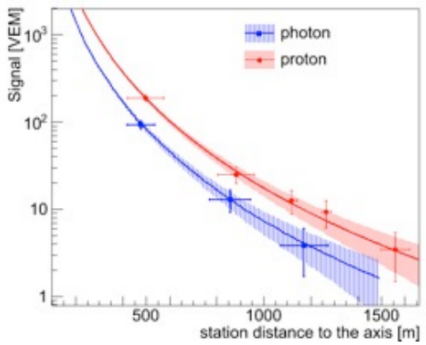
Photon identification

Hybrid events ($E > 10^{18}$ eV):

- Deeper development of the air showers *(larger Xmax)*

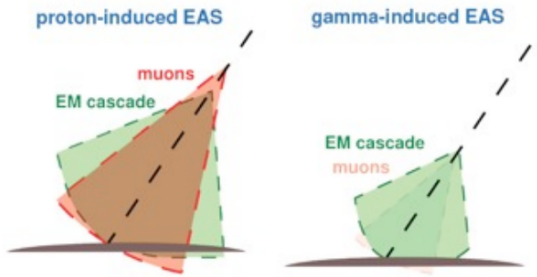
- Smaller detected signal in SD and steeper lateral distribution function



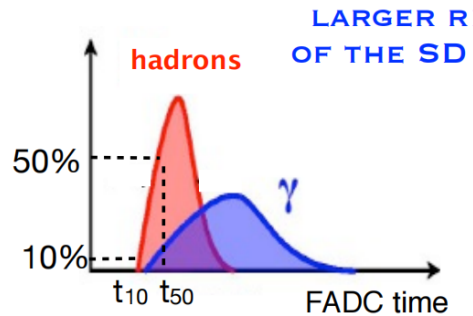


SD events ($E > 10^{19}$ eV):

Deeper shower development and smaller number of muons



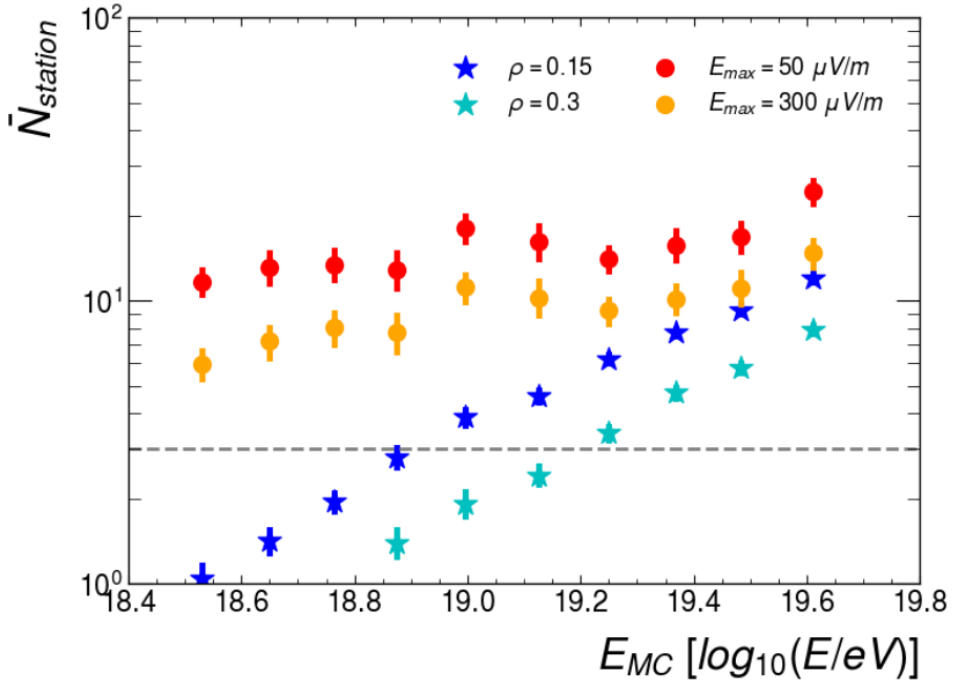
SMALLER RADIUS OF CURVATURE

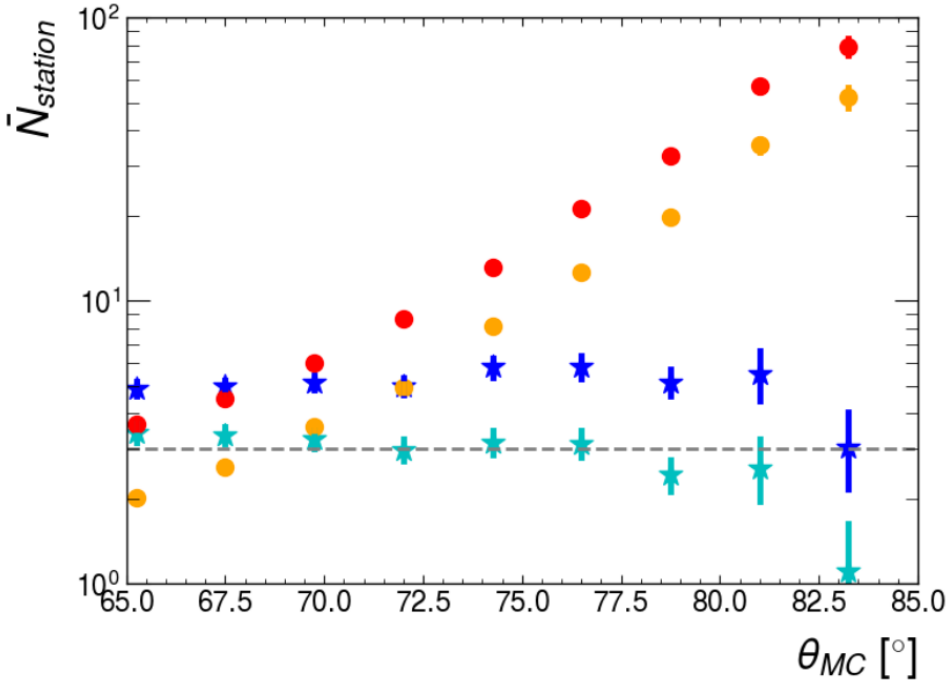


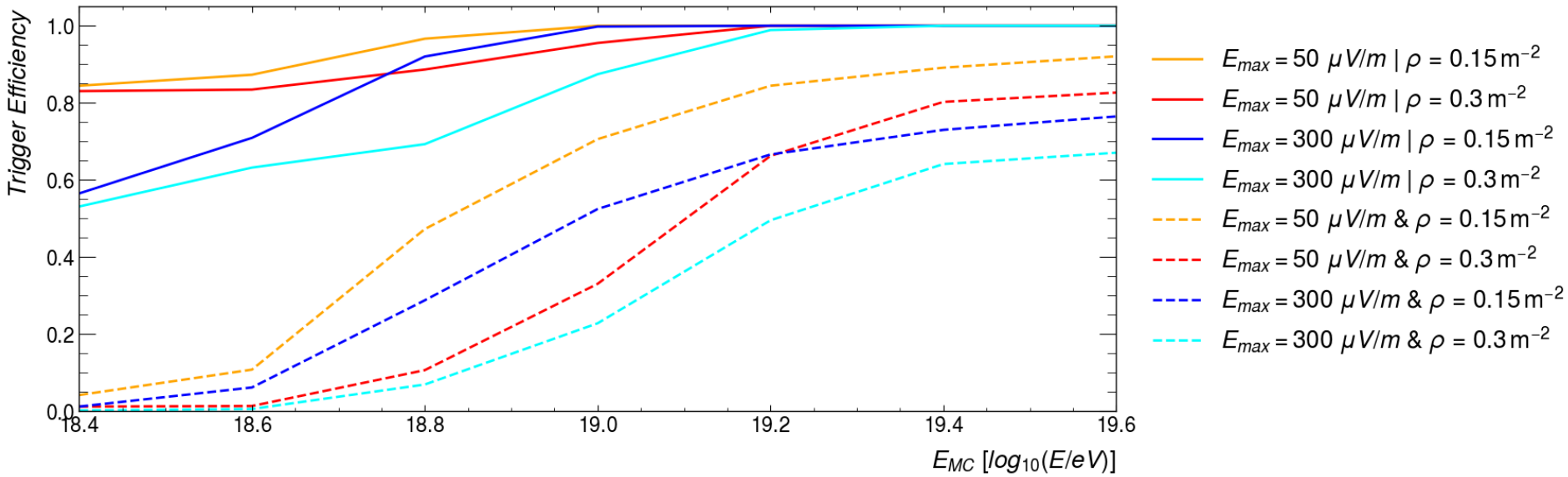
Risetime: $t_{1/2} = t_{50\%} - t_{10\%}$

Backup

Simulation's Trigger Efficiency







Backup

Rescaling Photon Simulations to Lower Energies