The extension of the dynamic range of AugerPrime

Gioacchino Alex Anastasi,
on behalf of the Torino group

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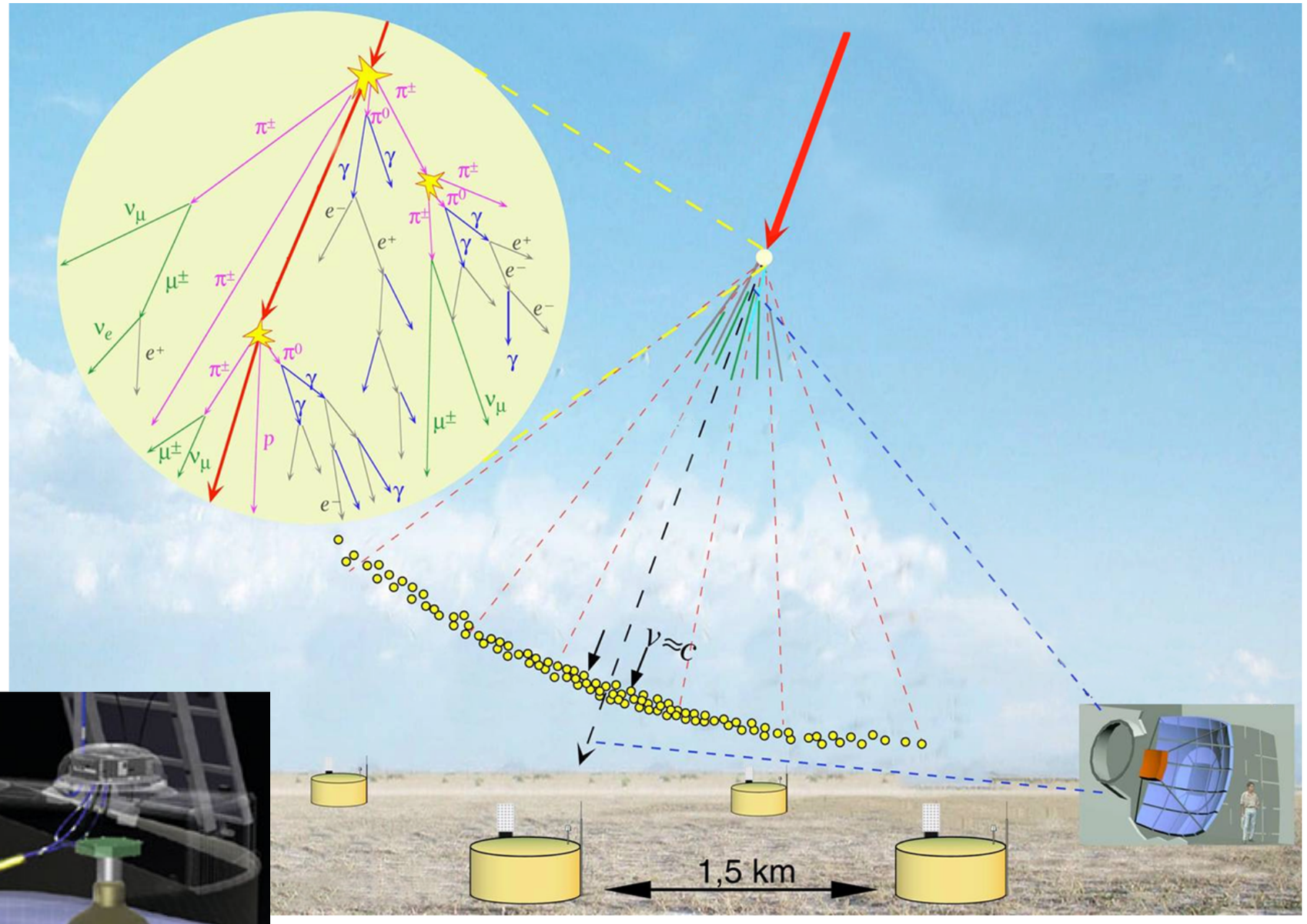
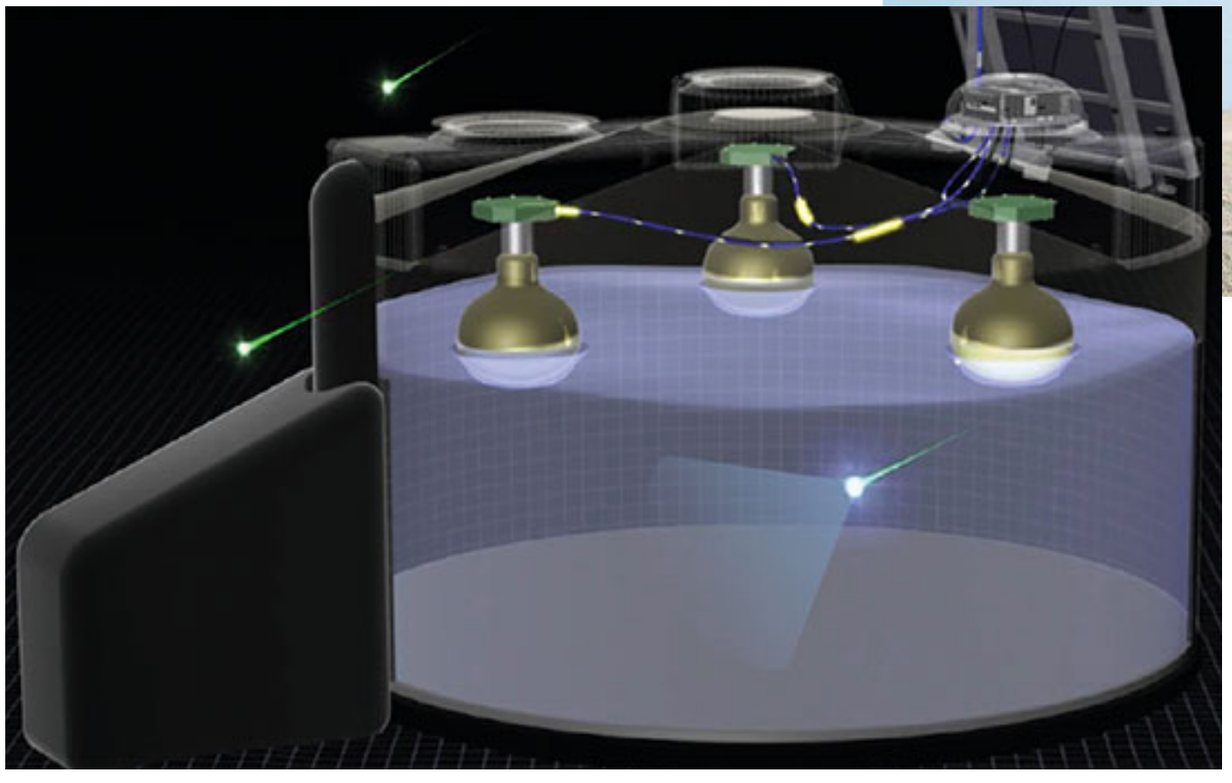
Measurements of detectors at ground level

A network of particle detectors samples the shower at ground level.

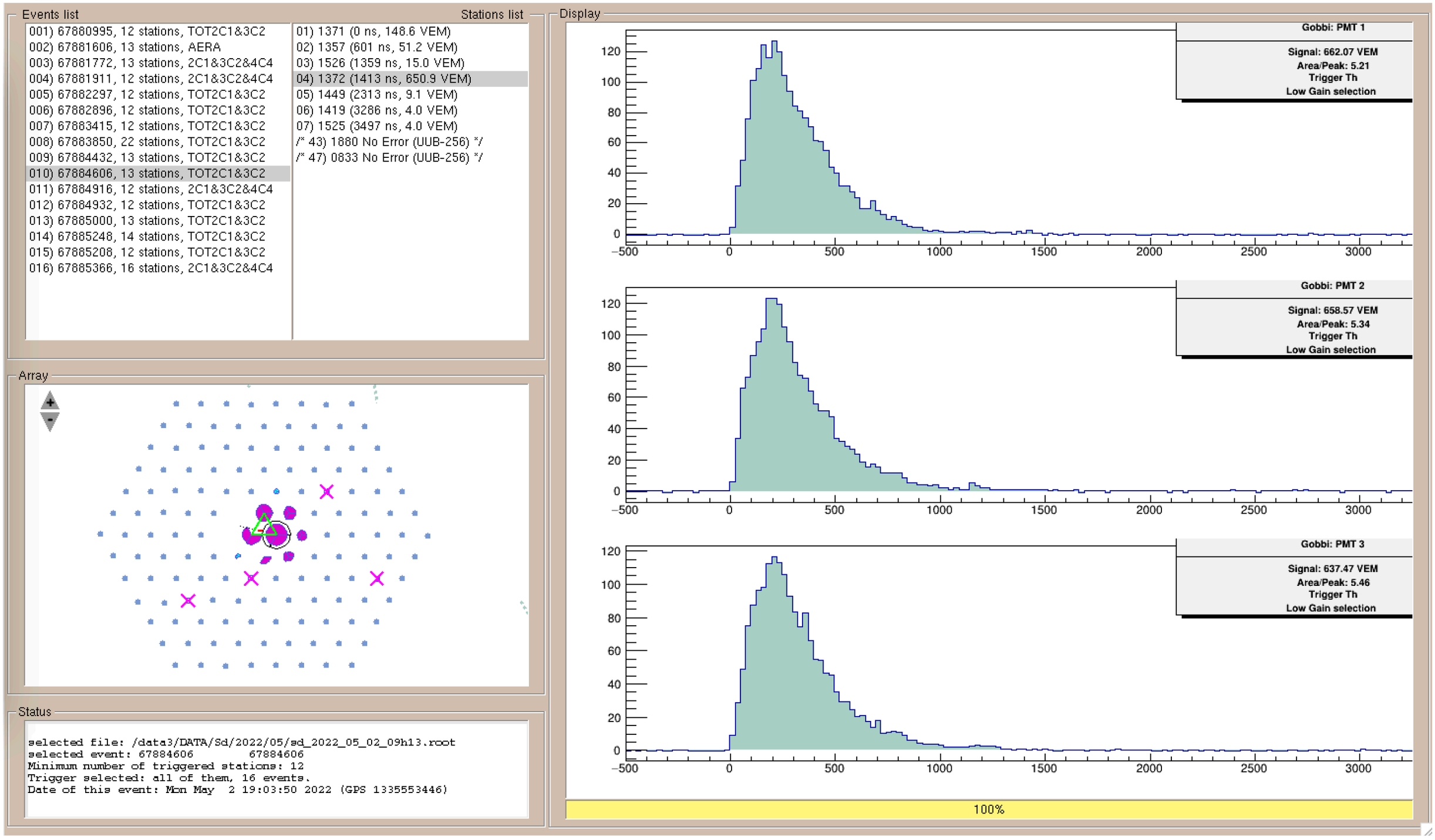
Physical measurement : energy released by secondary particles in each detector as a function of time.





Pierre Auger Observatory Surface Detector : Three 9-inch PMTs inside each tank collect the Cherenkov light produced by relativistic charged particles in water.

Signals inside the WCD



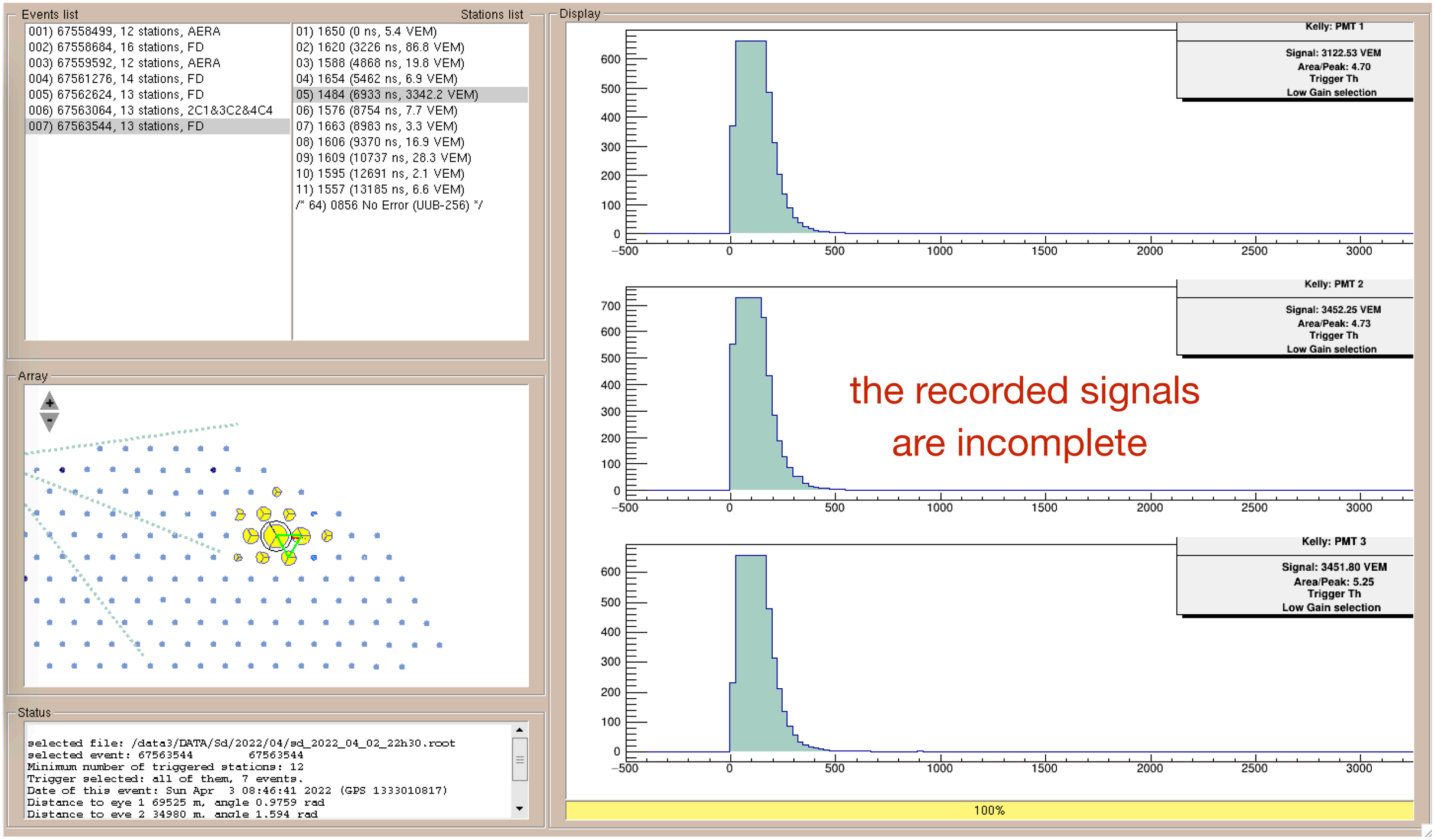
unit of measurement : VEM (*Vertical Equivalent Muon*)

signal released by a muon traversing the tank on a vertical trajectory

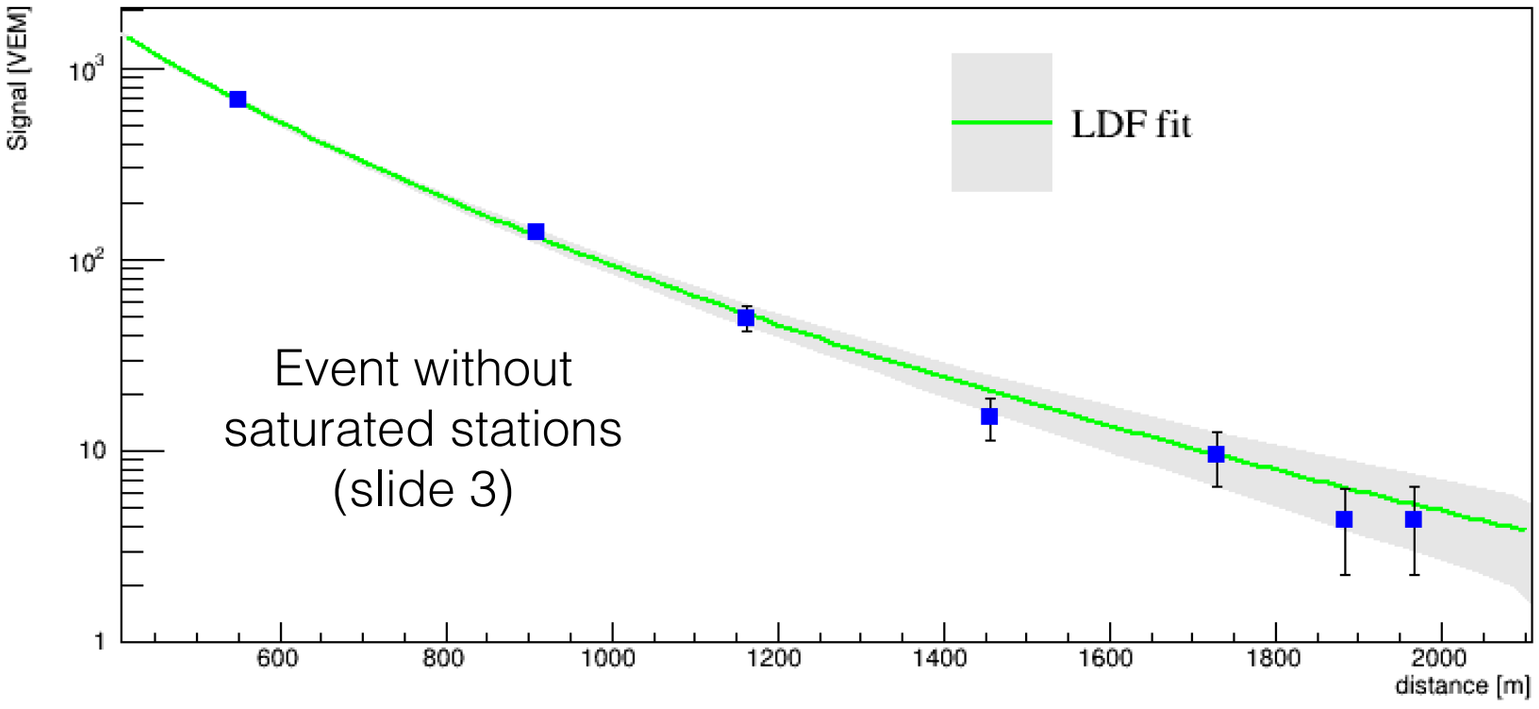
Saturated signals

Electronics saturation : overflow of the anode FADC dynamic range

Occurring for integrated signals ≳ 700 VEM



Lateral distribution function

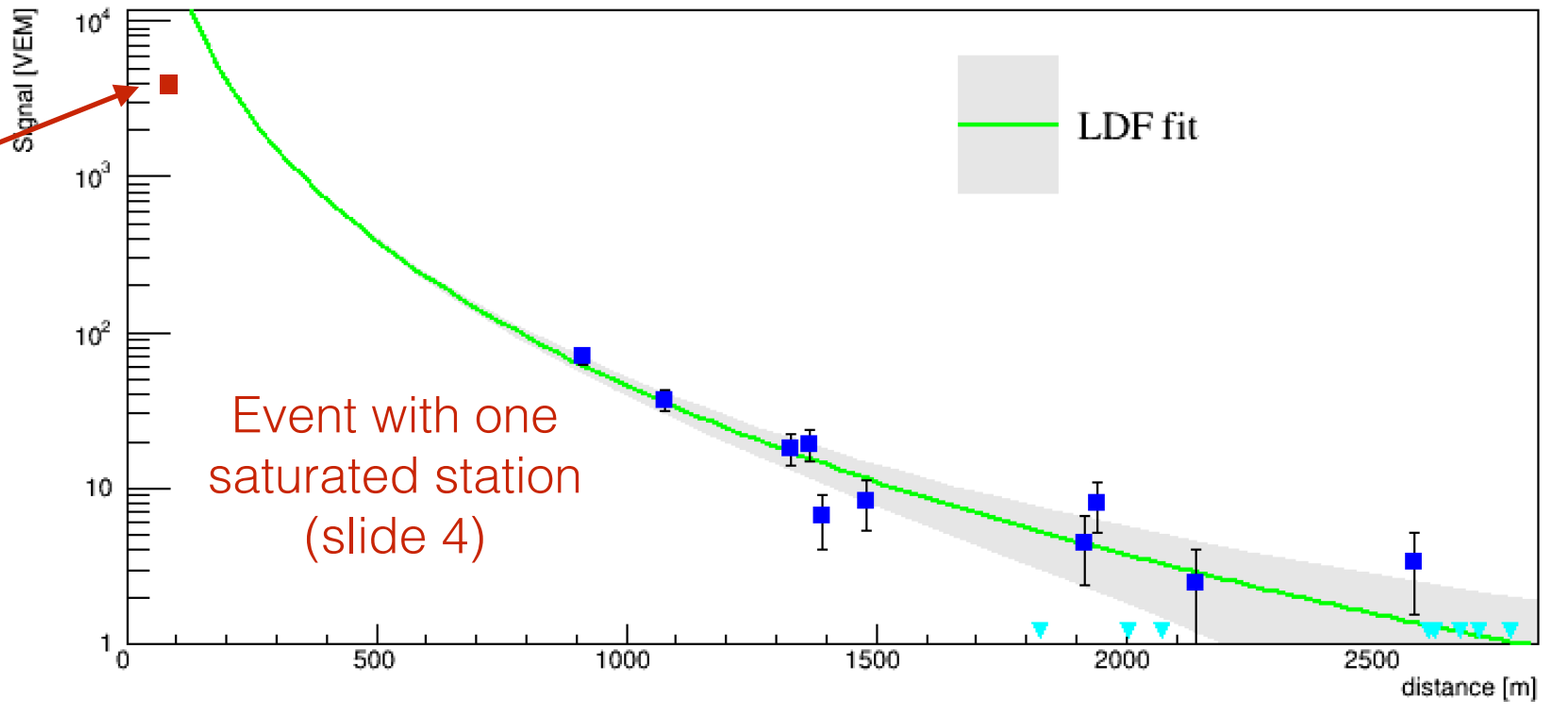


Signals as a function of the distance from the *core* (intersection between the shower direction of propagation and the ground).

LDF fit performed using well-established empirical parameterizations.

Station closer to the core (~ few hundreds of meters) often present saturated signal.

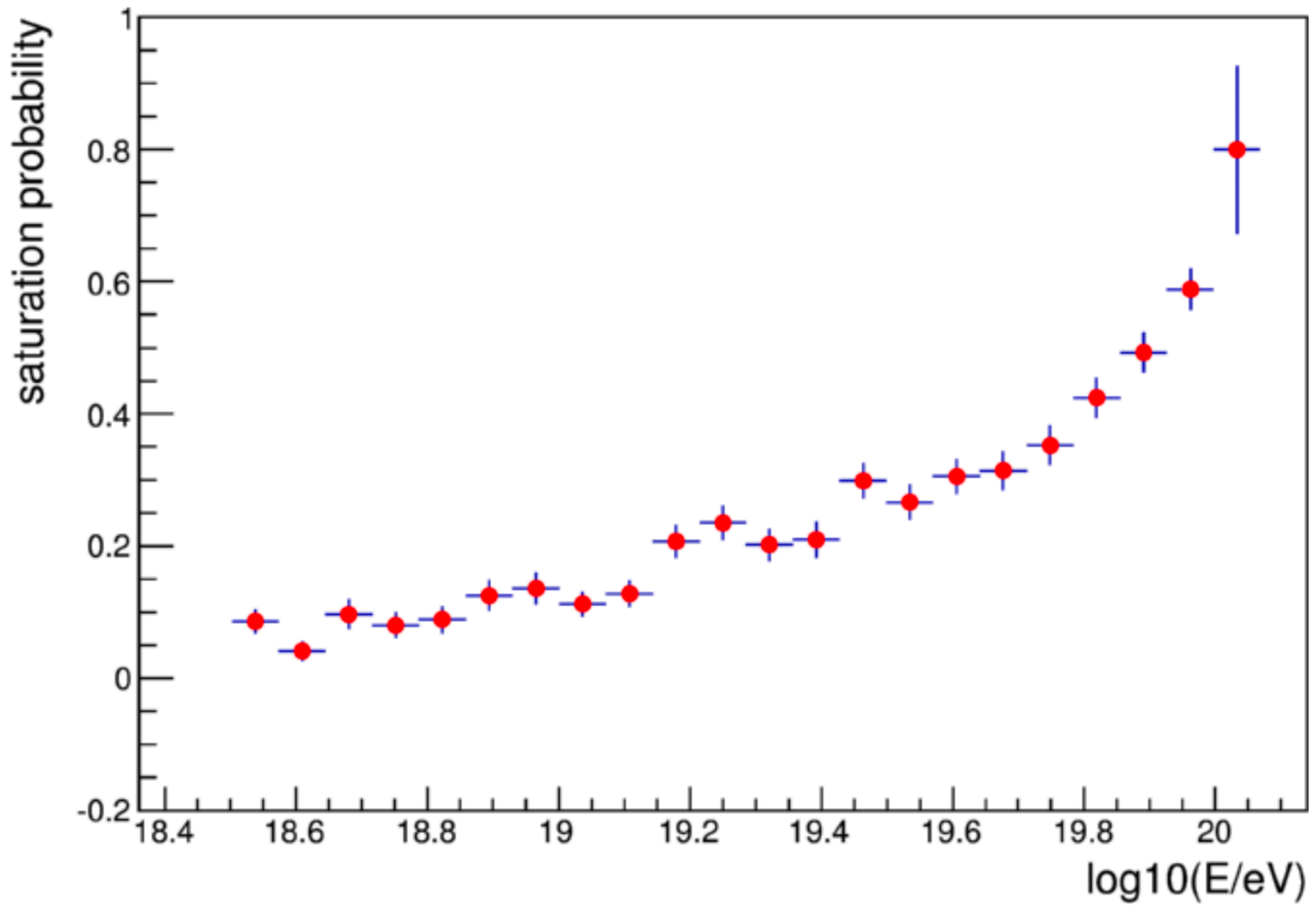
Particle densities largely unknown near the shower core.



Dynamic range extension

Station closest to the core saturated in more than 40% of events above 3×10^{19} eV, affecting the reconstruction accuracy.

➡ Extension of the dynamic range up to **at least 20,000 VEM** to measure very high energy events without saturation.



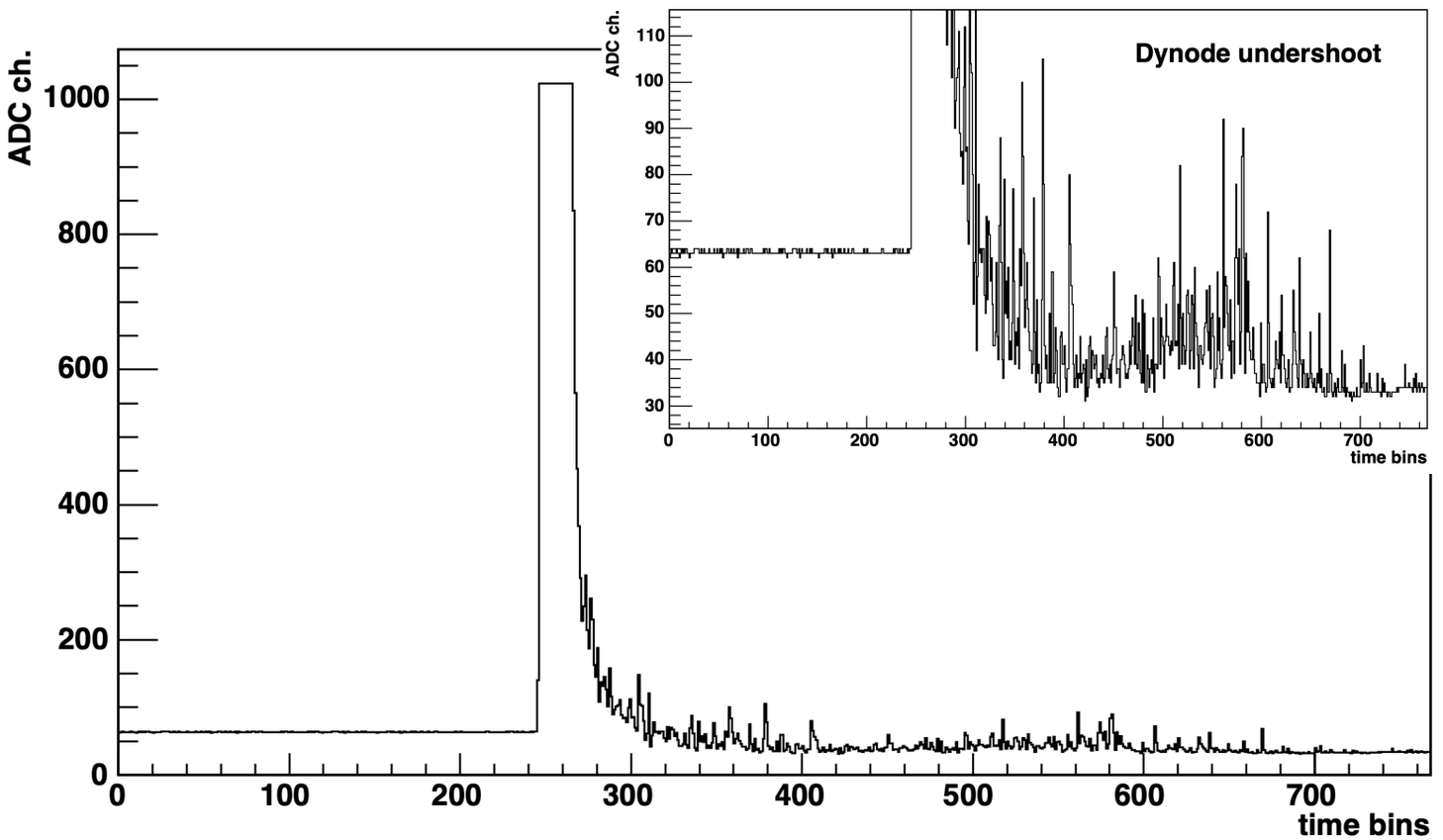
➡ Accuracy better than 15% required on the signals closer to the core :

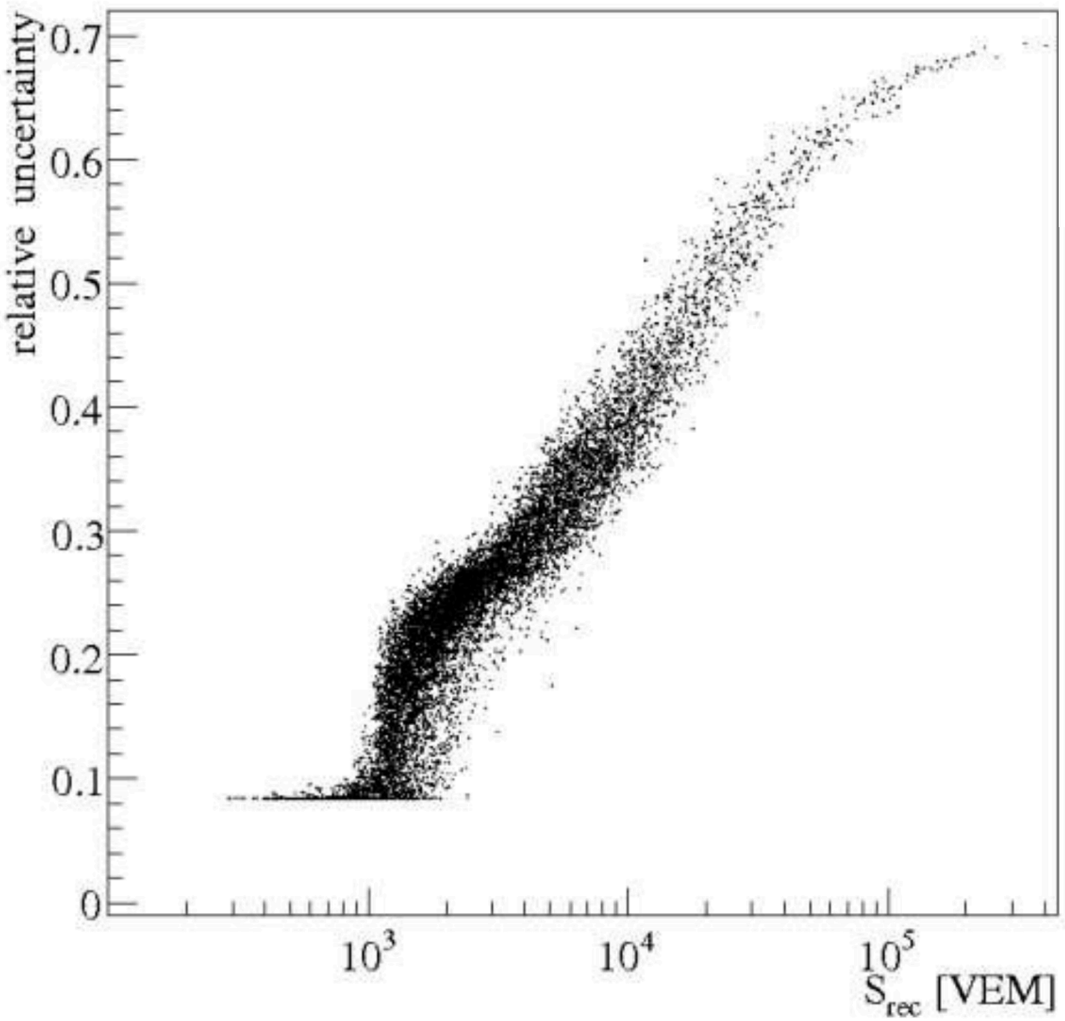
- to recover a precise information on energy ;
- to improve the knowledge of the LDF and thus of hadronic interactions ;
- for a direct comparison with muon detectors at high muon densities.

Before AugerPrime : signal recovery

Method exploiting the relation between the total signal charge at the PMT anode and the undershoot.

Not a measurement





Impossible to study and monitor the individual response to saturation of more than 5000 PMTs in the field.

Only average information available —> large uncertainties in the recovered signals

AugerPrime : the small PMT

1-inch photomultiplier (active area ~1/100 of the Large PMTs)

- direct measurement of very large amounts of light !

Adjusting the gain, extension of a factor ~32 easily achieved

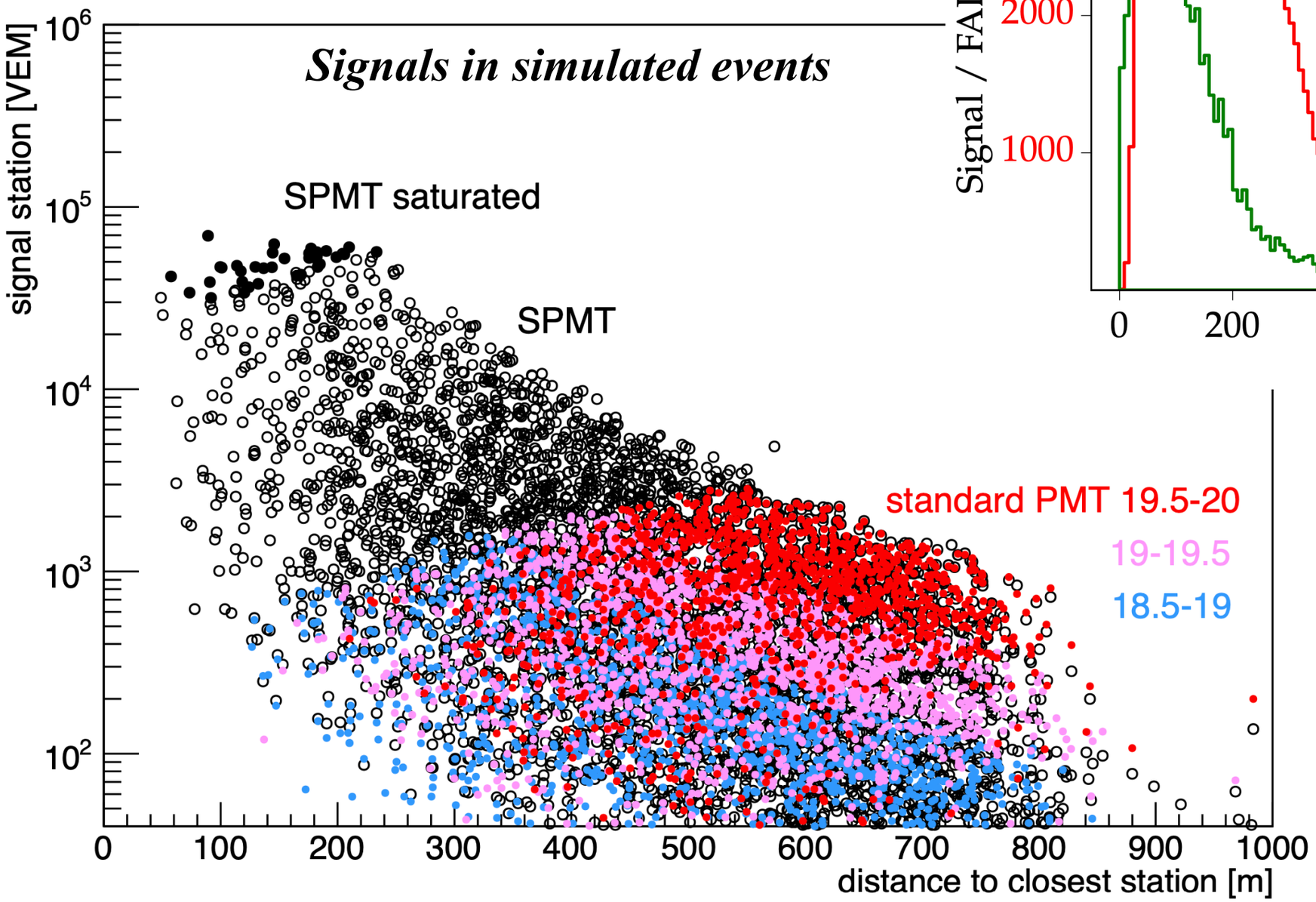
- signals from ~700 VEM to > 20,000 VEM without saturation

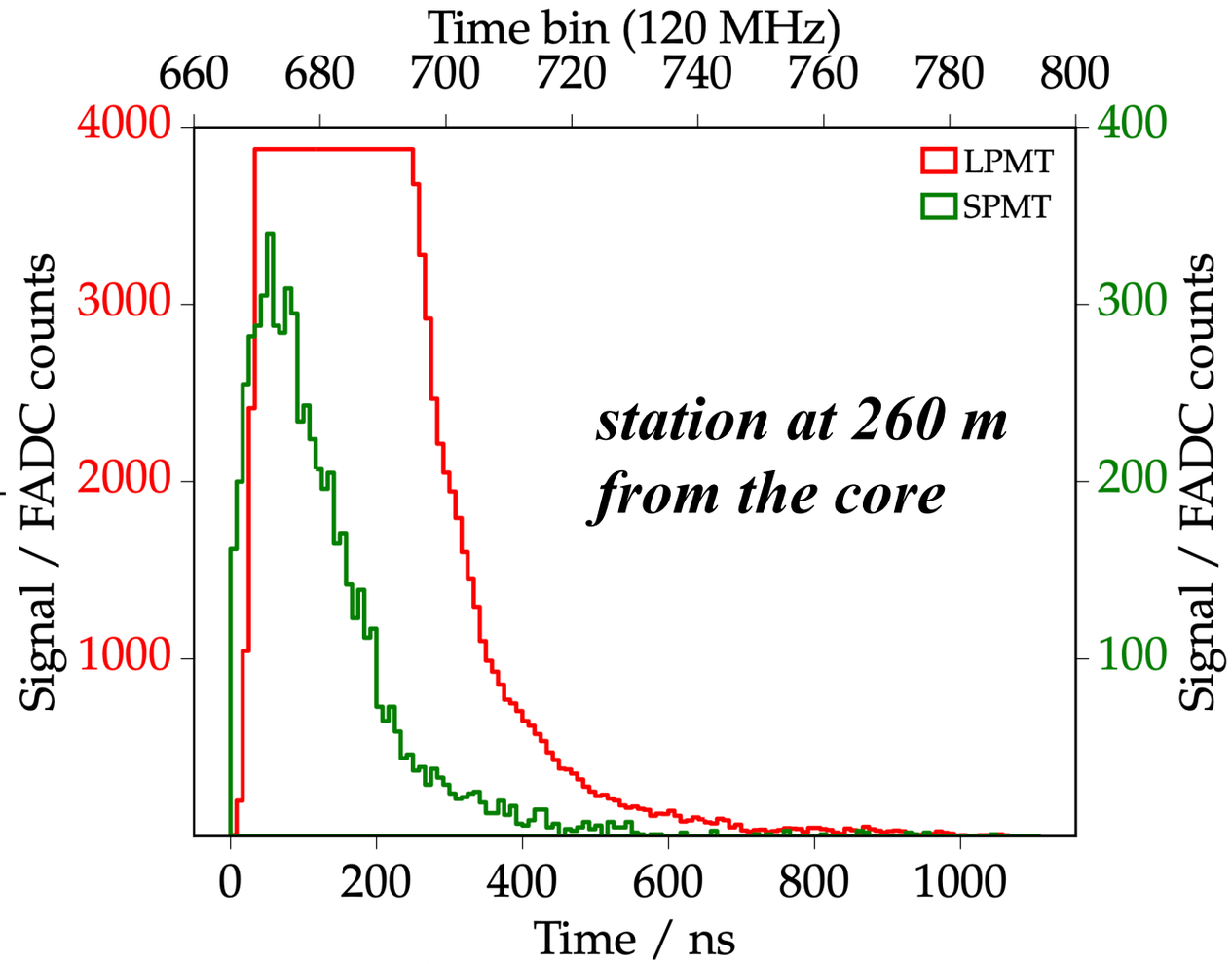
SPMT cross-calibrated using the VEM-calibrated signals of the three Large PMTs in the region of superposition

- accuracy better than 10% above ~1000 VEM

SPMT measurement

Measurement of complete signals at distances as close as ~250 m from the shower core.

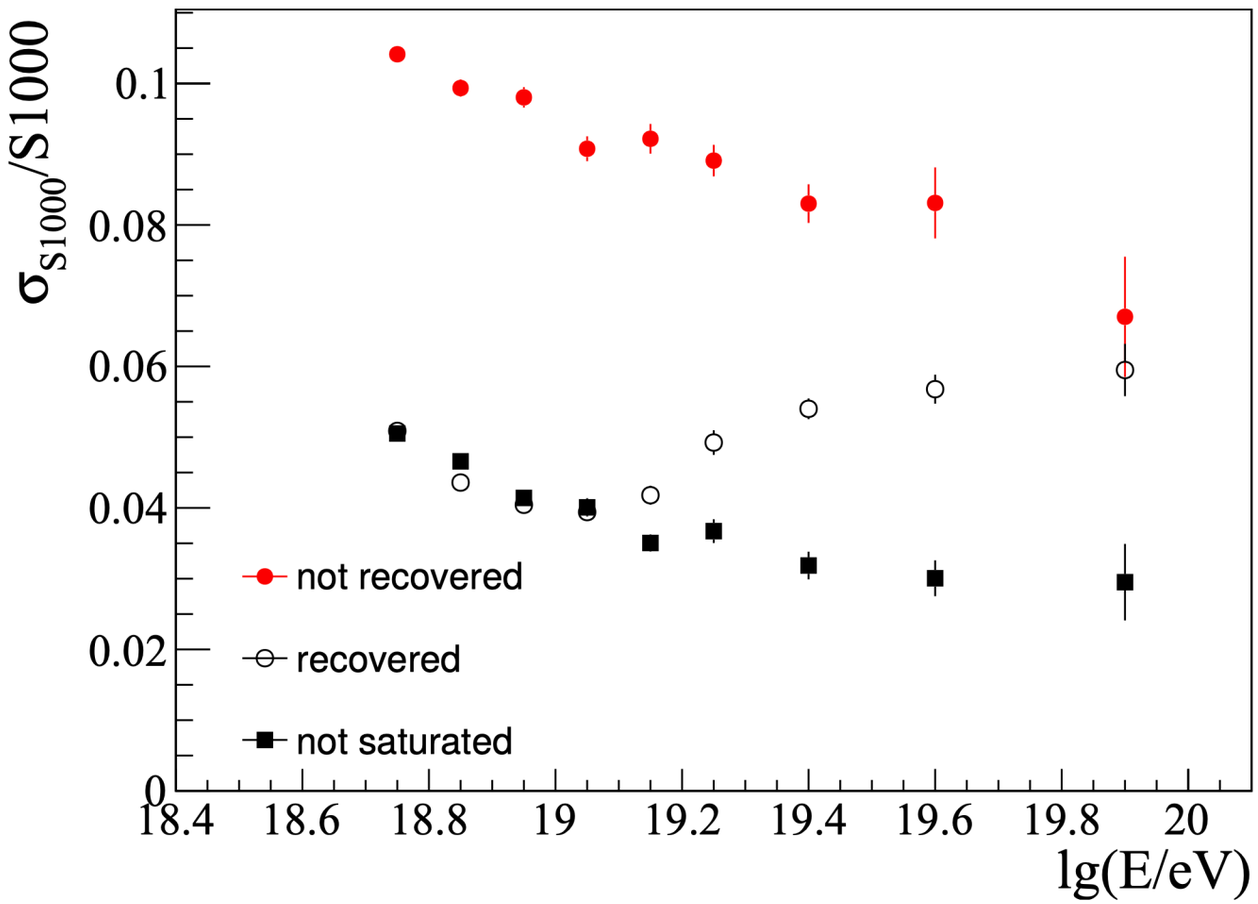


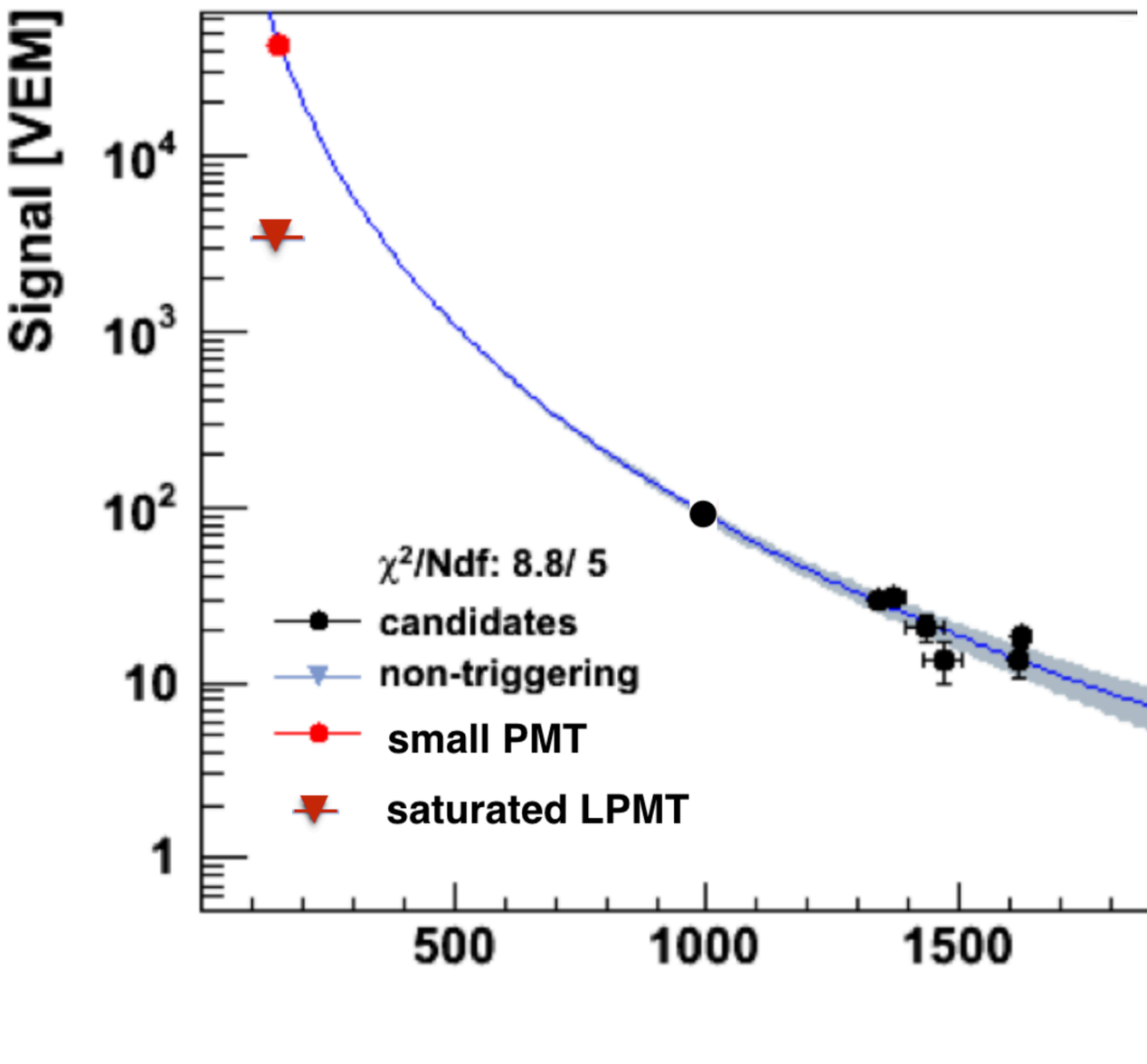


Few % of signals, very near to the core and at very high energies, are expected to saturate.

Using the SPMT signals

Resolution on S1000 (reconstructed parameter directly related to the primary energy) better than 4% above $10^{19.5}$ eV.





Unambiguous determination of particle density down to ≲ 300 m from the core.

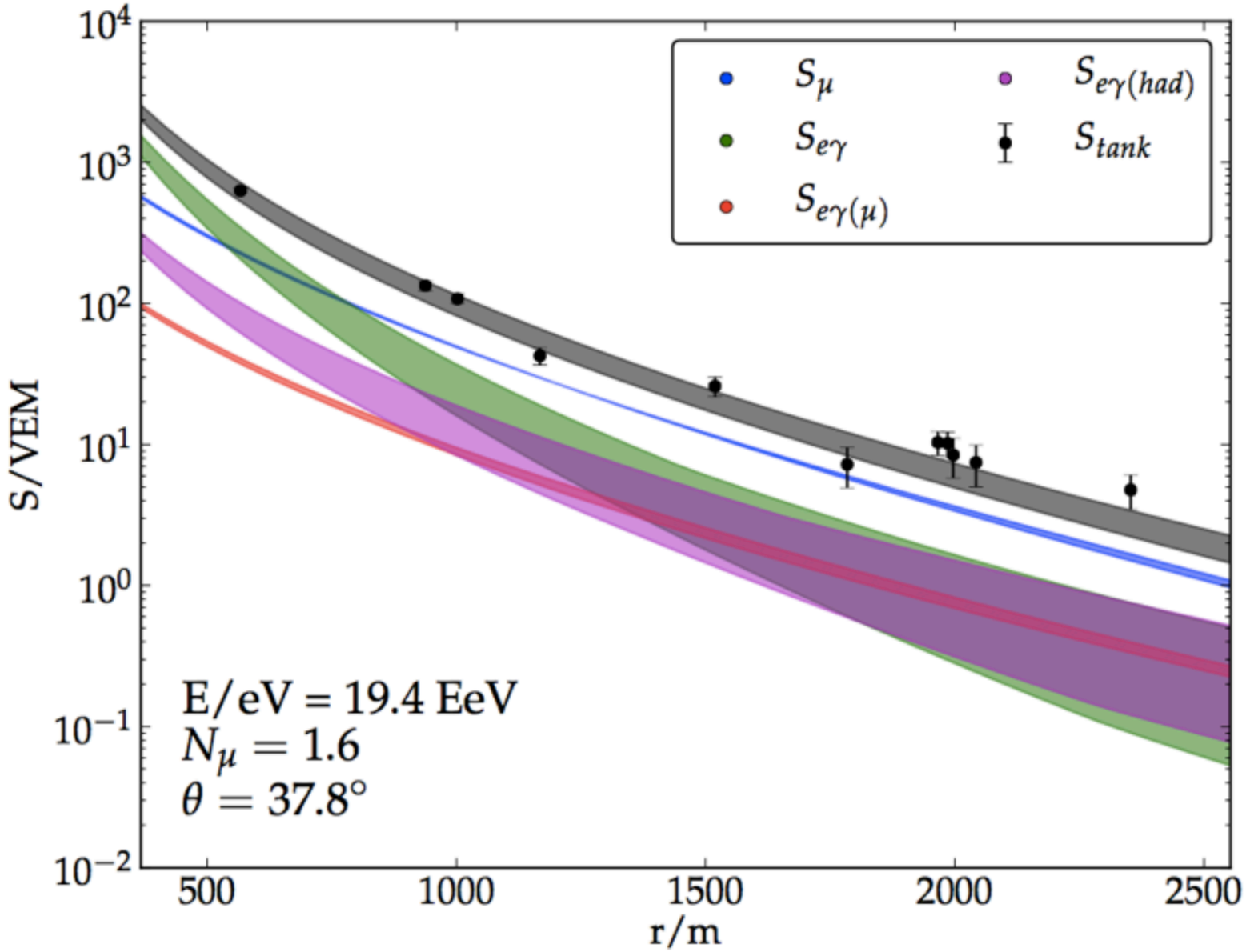
LDF and Universality

Universal features among showers considering four components :
(a) muonic component, (b) purely electromagnetic, (c) electromagnetic component stemming from muon interactions and muon decay,
(d) electromagnetic component from low-energy hadrons.

Additional information on primary composition disentangling the muonic and EM components !

Required to efficiently constrain the LDF fit :

- unsaturated stations at $r < 700\ m$
- signal accuracy equal or better than 20%
  (~ difference S_{EM} - S_{μ})

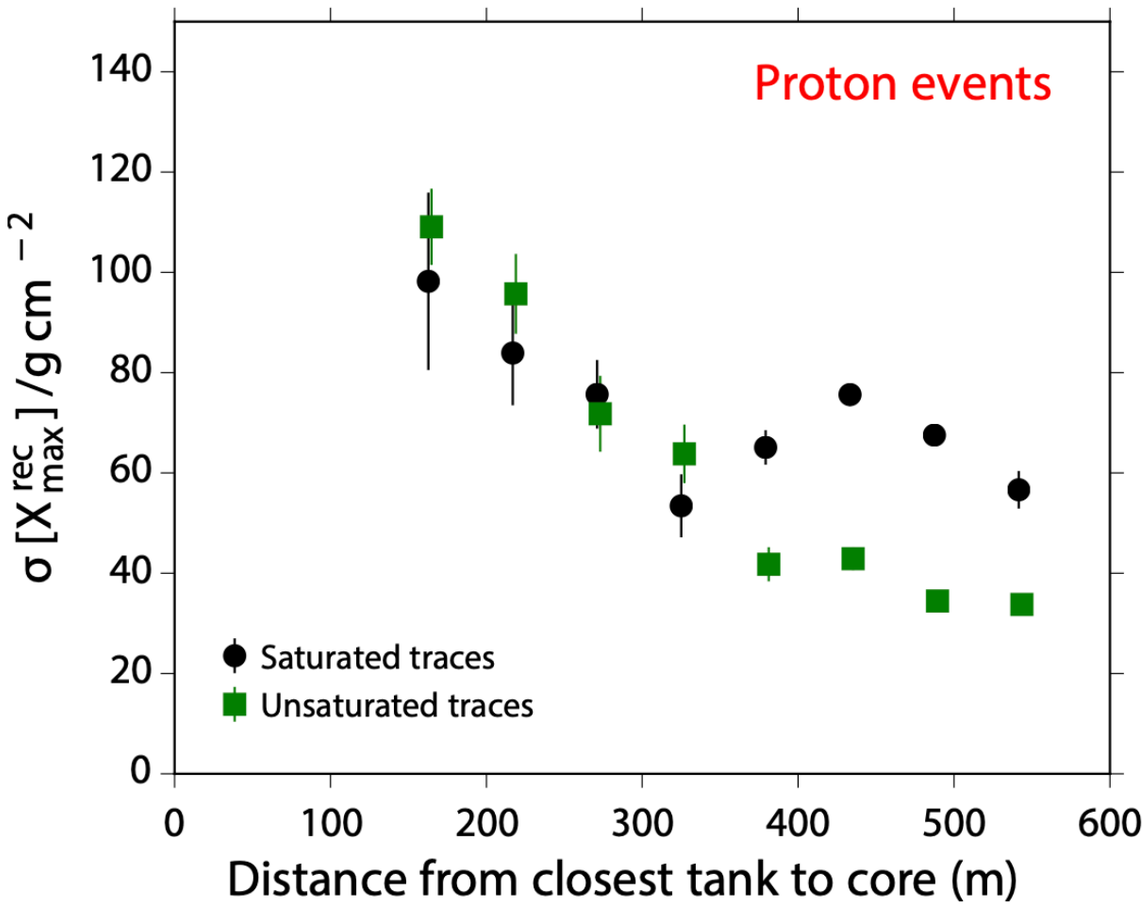


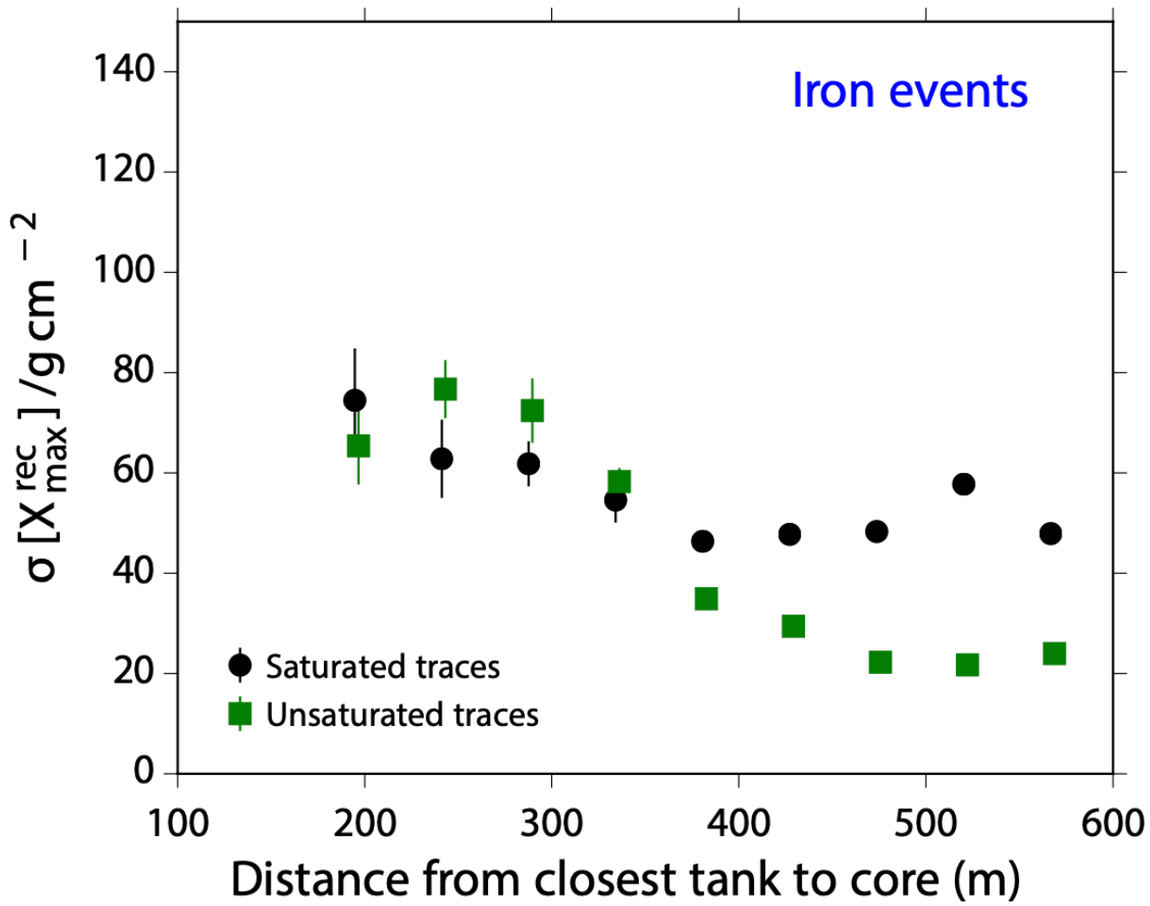
X_{max} resolution

Atmospheric depth of the maximum in the shower development (X_{max})

- information about the composition of primary cosmic rays ;
- high accuracy with fluorescence detector measurements;
- estimated from SD measurements with dedicated analyses.

Resolution over X_{max} from SD only data significantly improves having unsaturated measurements near the core.



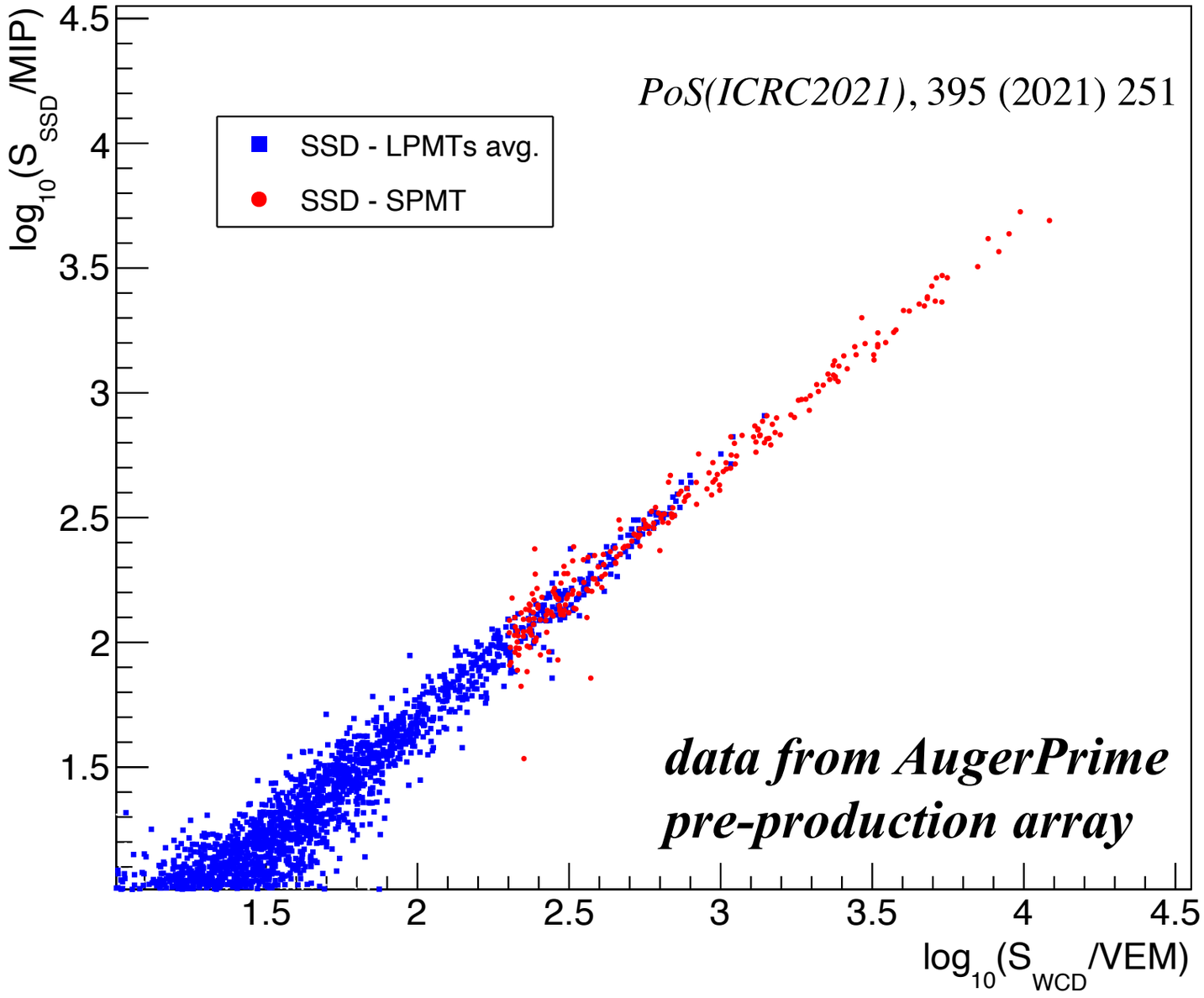


SSD and WCD signals

WCDs (Water-Cherenkov Detectors) and SSDs (Scintillator Surface Detectors) have different responses to the muonic and e.m. components, giving two complementary measurements of the shower.

The dampened channel of the SSD allows the measurement of unsaturated signals at distances as close as ~300 m from the core.

The dynamic range of both detectors is similar to benefit the most from the combined information.



Summary and conclusions

- Before the *AugerPrime* upgrade, half of events with energy > $10^{19.5}$ eV had at least one saturated station.

- The installation of the SPMT together with the upgraded electronics :
  - extends the linear non-saturated range of 32 times, corresponding to particle densities as high as several thousand per m^2 ;
  - allows the measurement of full signals from all stations down to ~250 m from the shower core and up to the highest energies.

- The matching dynamic ranges of SSDs and WCDs will help in separating the shower components and infer new information about the primary cosmic ray composition at the highest energies.

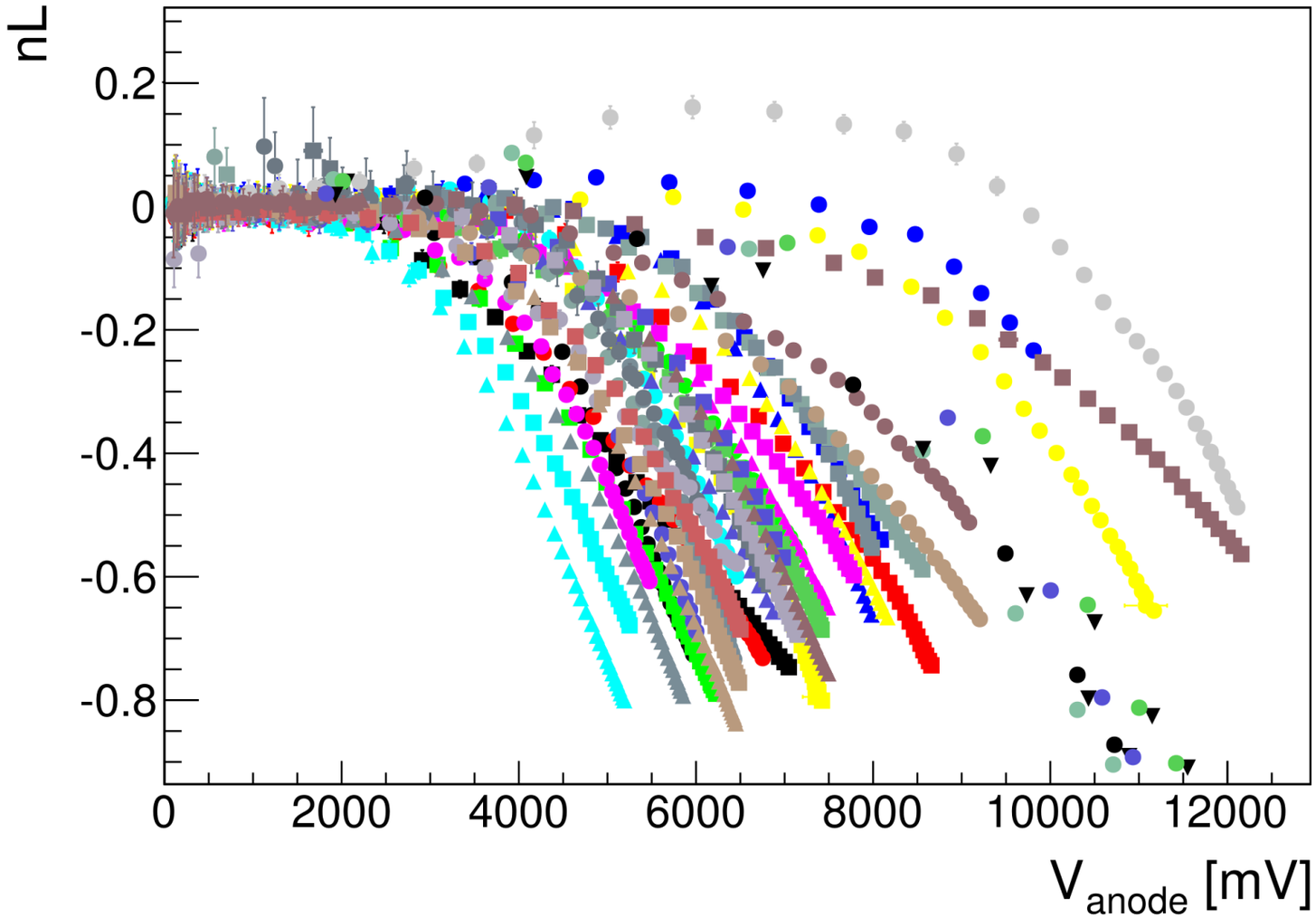
Backup

Photomultiplier saturation

The overflow of the FADC in the pre-AugerPrime electronics (dynamic range of 10 bit) corresponds roughly to 50 mA, with 1 VEM roughly equal to ~90 photoelectrons and a typical gain of 2×10^5.

The signal rises rapidly when approaching the shower core and the Large PMT response for anode currents greater than 100 mA is no longer linear.

Measurements of non-linearity and saturation for several Large PMTs. Values of nL close to zero correspond to the linear regime of the PMT response while a value of -1 indicates total saturation of the output voltage.
Resistive load is 50 Ω, i.e.
12 V corresponds to 240 mA.



Dynamic range - WCD PMTs

Range	Intent	Dynamic Range																					
bits		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
LowGain	VEM	AnodeX32																					
HighGain	Showers						Anode																
VeryHighGain	Cores											SPMT											
Ipeak (mA)		0.0006					0.02		0.08			1.2						40					
Vpeak (mV)		0.03					1		3.9			64						2000					
Ipeak SPMT (mA)												0.02						1.25				40	
Vpeak SPMT (mV)												1						64				2000	
Npart (VEM)		0.01					0.3		1.2			10						600				20000	

The Large PMTs signal is split into an amplified (x32) range for single muon resolution and a HighGain range for measurements of shower signals.
Events closer to the core have a larger signal that is collected by the small PMT and input into a dedicated VeryHighGain range, increasing the pre-AugerPrime dynamic range by a factor of 32 and up to more than 20 kVEM.

Dynamic range - SSD

Range	Intent	Dynamic range																		
bits		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
LowGain	MIP	AnodeX32																		
HighGain	Showers								Anode/4											
Ipeak (mA)		0.0006				0.01			0.1				1.25			10				160
Vpeak (mV)		0.03				0.5			4				62.5			500				8000
Npart (MIP)		0.07				1.2			10				156			1250				20000

The signal from the SSD PMT is split into two ranges (LowGain and HighGain).

Using an amplification factor of 32 for the low gain signal the ***MIP*** (Minimum Ionizing Particle) signal can be studied, while by reducing the signal of a factor 4 the linearity range can be stretched up to 20 kMIP, matching the WCD range.