Auger energy scale

V. Verzi

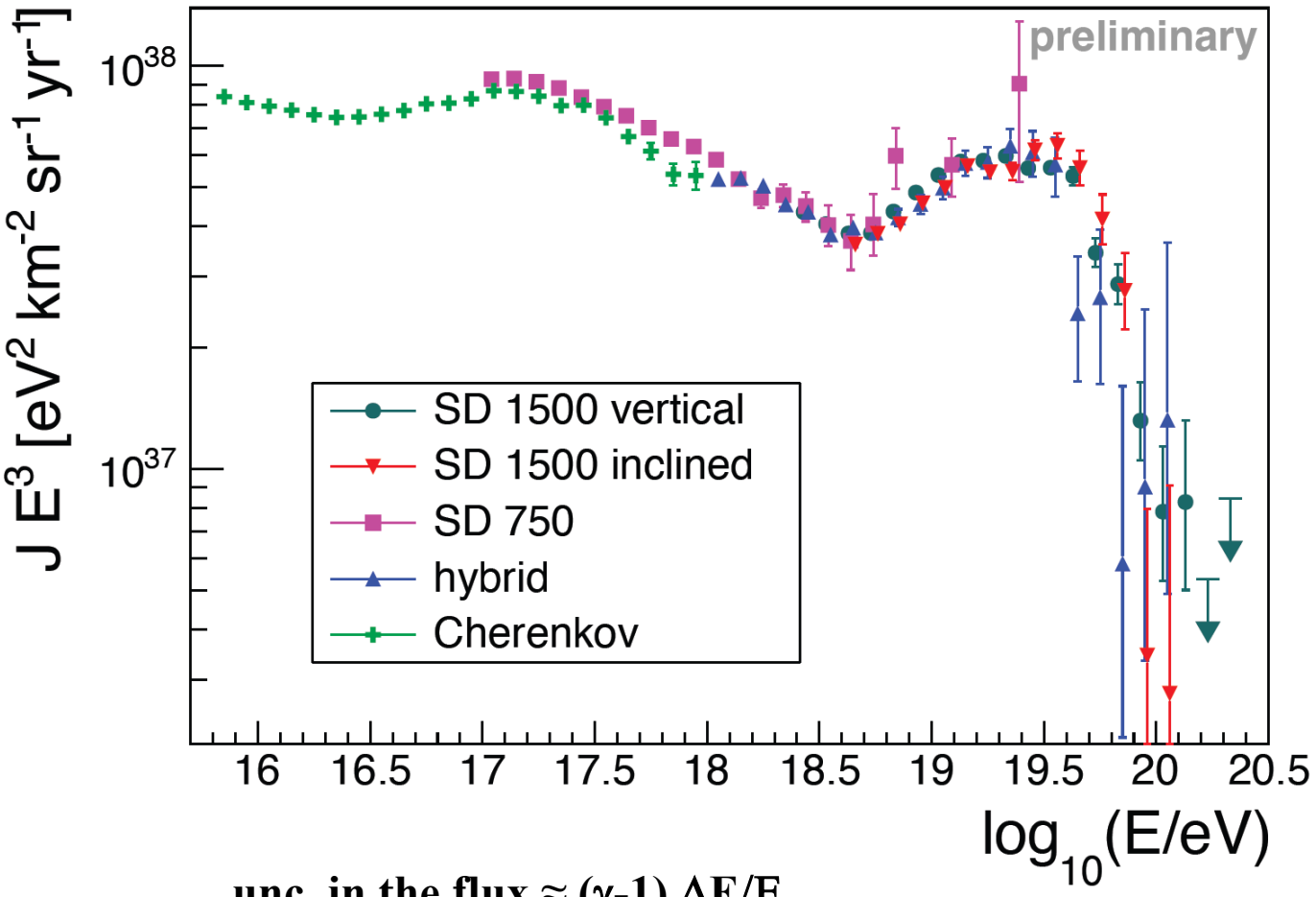
INFN, Roma “Tor Vergata”

Torino, 4 Febbraio 2025

Outline

- **status of the SD calibrations**
- **HEAT/CO cross calibration factors**
- **future prespectives**
  - **XY-Scanner (see also Gaetano)**
  - **radio**
  - **Auger vs TA: Aeolus and spectrum**
- **MC based SD energy calculation (see Francesco tomorrow)**

combined spectrum – ICRC 2021



unc. in the flux ≈ (γ-1) ΔE/E

SD 1500 vertical
SD 1500 inclined
hybrid
→ LL LM CO LA

SD 750 m
Cherenkov
→ HEAT CO

SD 433 m (ICRC 2023)
→ SD 750 m

consistency is important !

FD data sets

FD data set	data period	HECO - NSB	aerosols reference night	new constraint for L (GH fit)	new uncertainties in E_{FD} (resolution)
ICRC 2019	2004 - 2017				
ICRC 2019 + NSB	2004 - 2017	✓			
ICRC 2023	2004 - 2021	✓	✓	✓	
ICRC 2025	2004 - 2023	✓	✓	✓	✓

HECO – NSB Alberto S. et al. : GAP2024_029 PoS(ICRC2023)276 → see later

aerosols reference night Violet H. PoS(ICRC2023)300

new constraint for L (GH fit) GAP2022_050

new uncertainties in E_{FD} Foundations-FD online 18/12/2024

toward ICRC issue in SD timing solved (hybrids production by Lorenzo P.)
all databases are ready
within few days an offline tag → first look at the new data
→ energy calibration

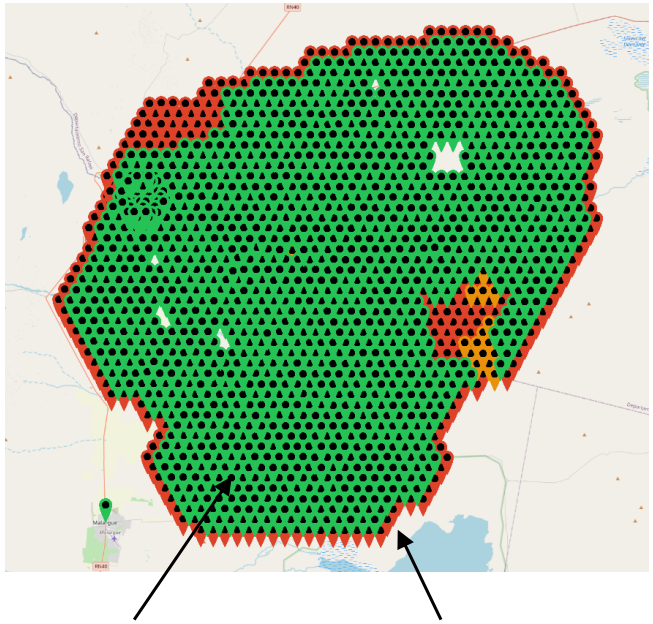
SD energy calibration

FD data set	data period	HECO - NSB	aerosols reference night	new constraint for L (GH fit)	new uncertainties in E_{FD} (resolution)
ICRC 2019	2004 - 2017				
ICRC 2019 + NSB	2004 - 2017	✓			
ICRC 2023	2004 - 2021	✓	✓	✓	
ICRC 2025	2004 - 2023	✓	✓	✓	✓

SD data set			calibrated with	to be calibrated with
1500 m	vertical	Offline	ICRC 2023	ICRC 2025
		Herald	ICRC 2019	-
	inclined	Offline		ICRC 2025
		Efit	ICRC 2019	-
750 m	new triggers	Offline (55^0)	ICRC 2023 (GAP2024_063)	ICRC 2025
		Herald (45^0 and 55^0)	ICRC 2019 + NSB	-
	ordinary triggers	Offline	ICRC 2023 (→AERA)	ICRC 2025

FD data: 2023

UUB (+ sPMT + SSD-PMT)
June 2023



upgraded stations **without SSD**

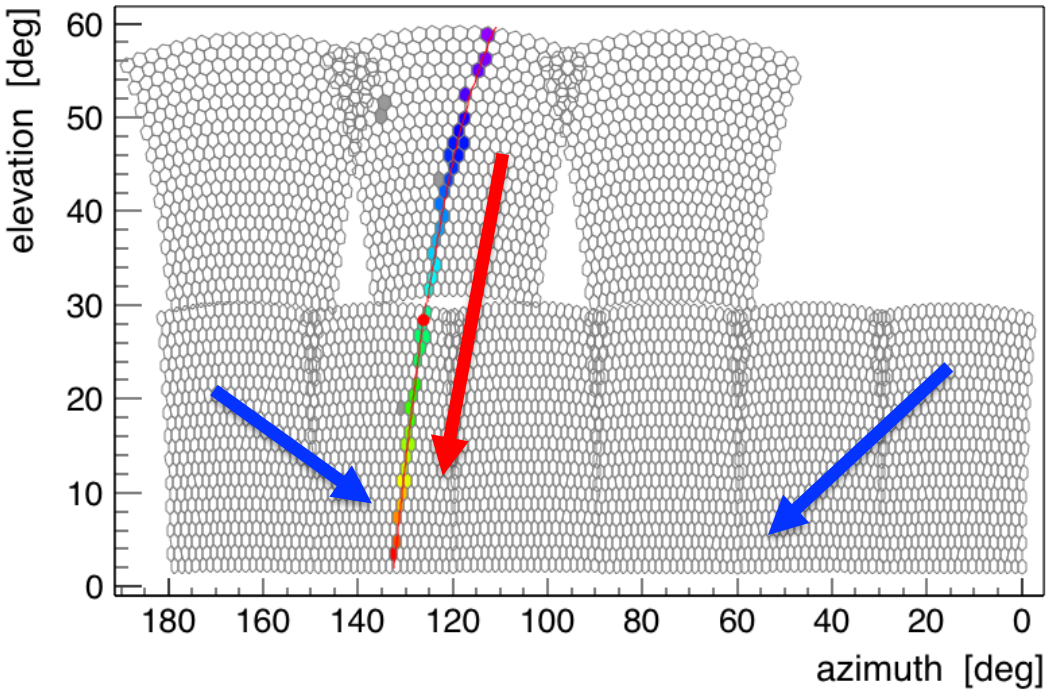
!isUUB for Phase 1 data set

2023: first FD data with UUB (account for UB-UUB time offset)

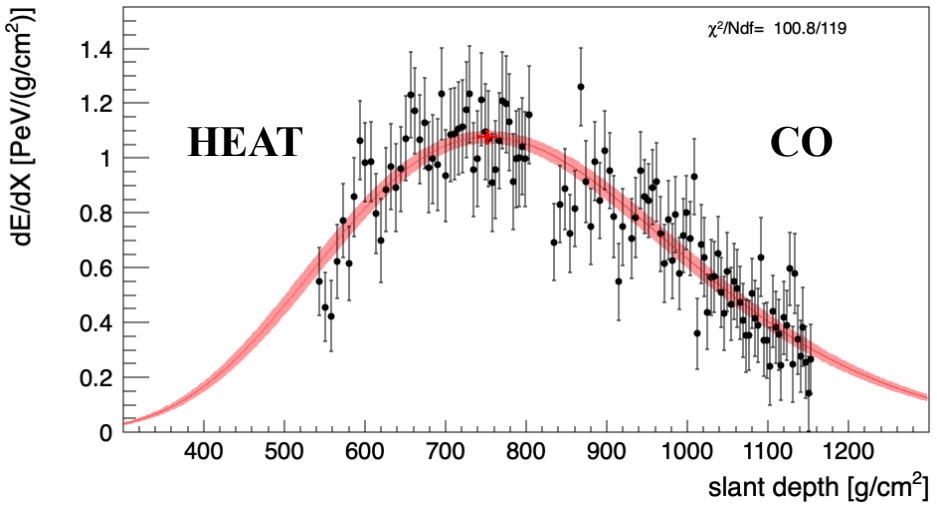
→ first AugerPrime events with FD profiles

HECO cross calibration factors

why they are important?



HEAT always in the first part of the profile



multi mirror events

- **HEAT-CO**
  → **important for X_{max} resolution and absolute scale**
- **'standard' telescopes**
  → **important only for X_{max} resolution**

note: similar situation for energy, but less critical in comparison to X_{max}

HECO cross calibration factors: old method - 2013

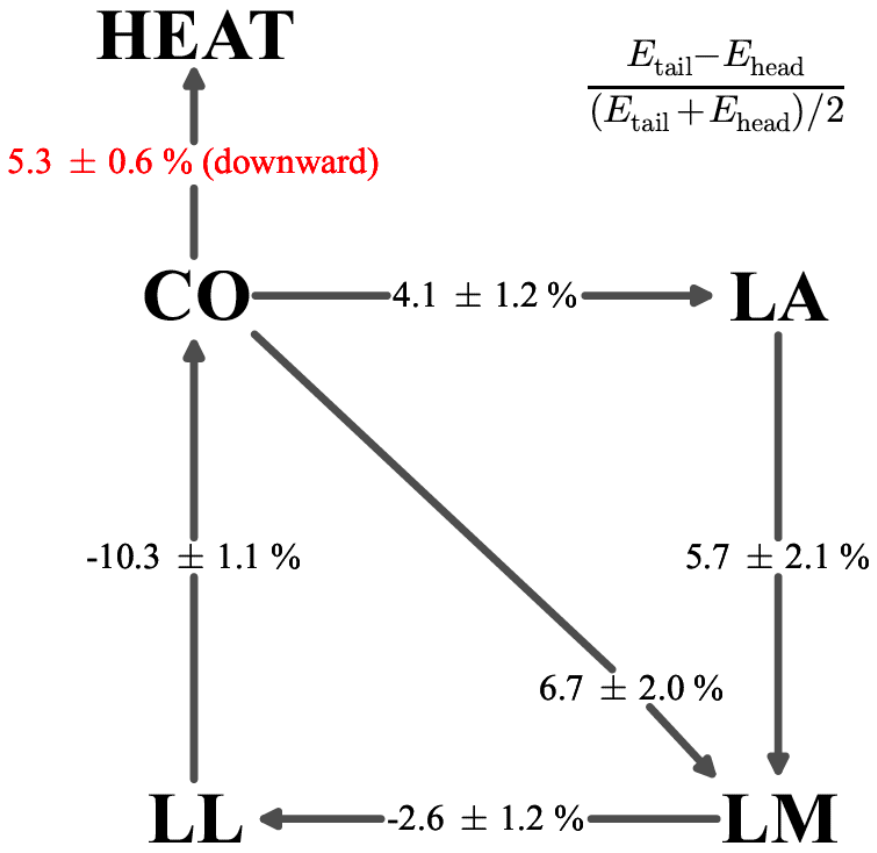
Alessio Porcelli (KIT)

GAP2014_058

from HEAT downward runs:
energy HEAT < CO by 5.3%

→ increase HEAT calib. constants by 5.3%

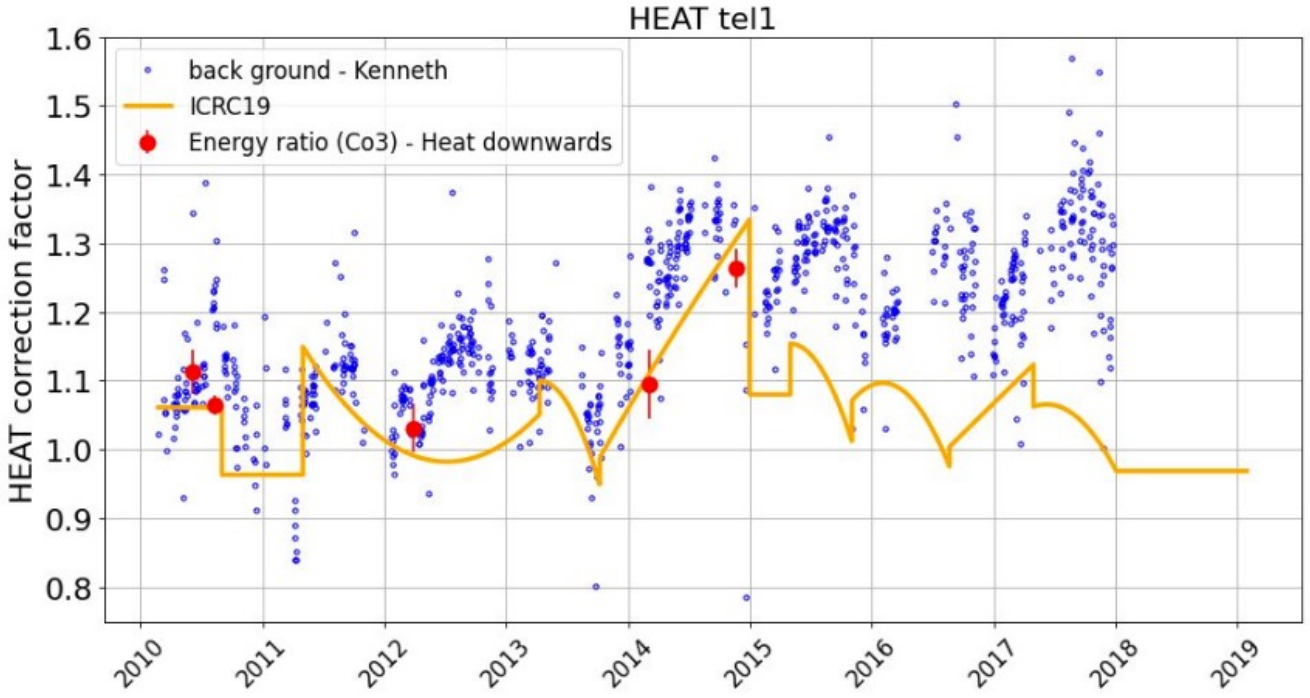
same factor at all times
same factor for all telescopes



HECO cross calibration factors: old method - 2017

Jose Belido

showers with HEAT upward: minimize χ^2 of the dE/dX for HEAT upward events



time dependent factor
same factor for all telescopes

note: analysis always considered unsatisfactory

HECO cross calibration factors: NSB - 2021

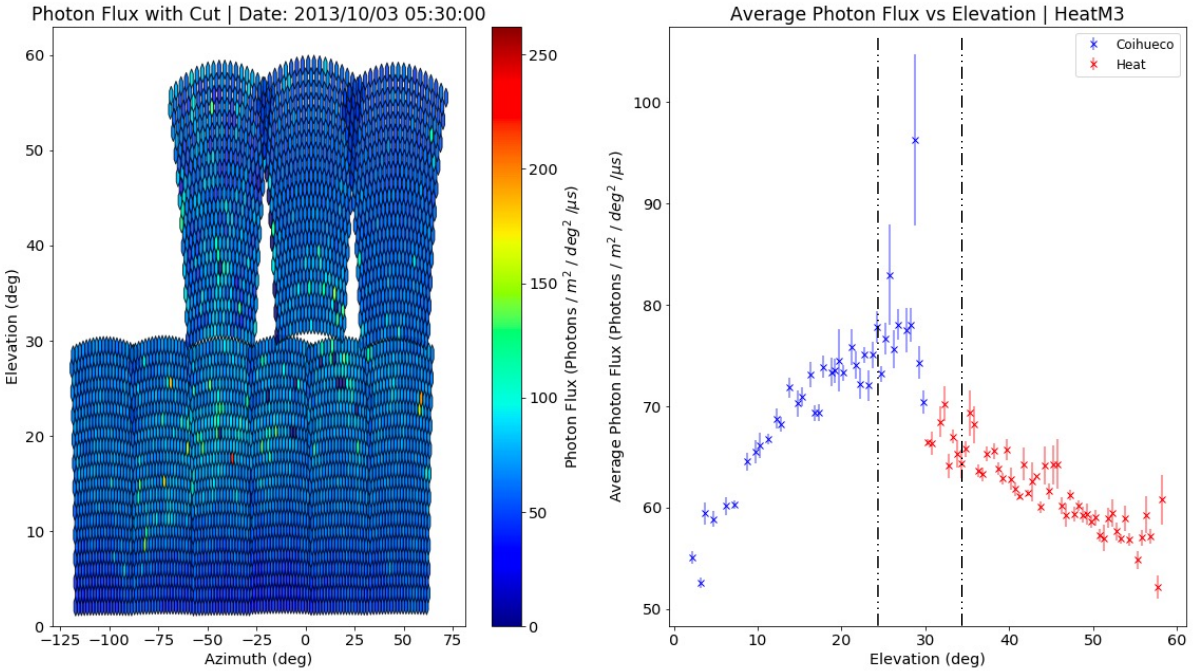
- measured every 30 s
- photons flux from ADC variance

HEAT upward

compare NSB measured in HEAT and CO between 25^0 and 35^0 in elevation

time dependent and felescope-wise factors

GAP2023-013

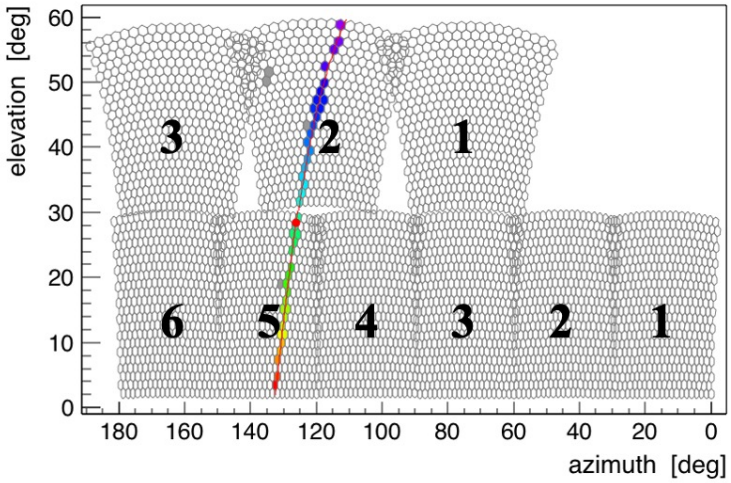


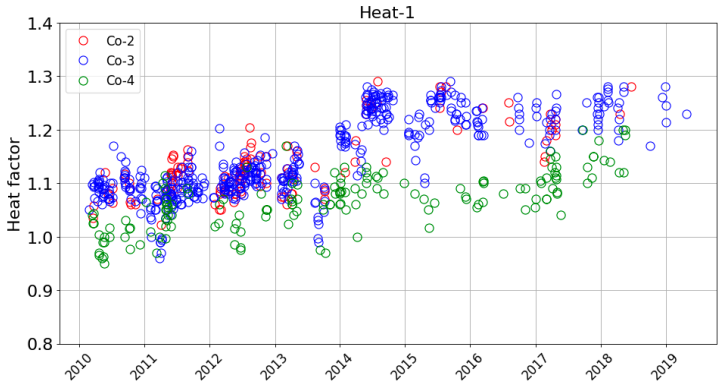
- **significant improvement with respect to previous analys**
- **new db: obviously a mistake**

take CO as reference
(shift only HEAT)

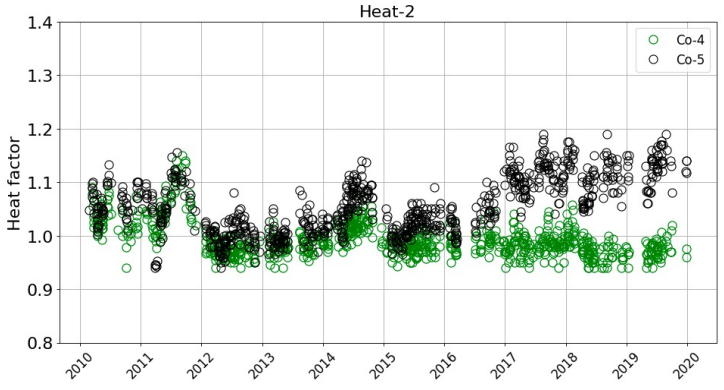
factors from:

- **HEAT 1 vs CO 3**
- **HEAT 2 vs average of CO 4 and CO 5**
- **HEAT 3 vs CO 6**

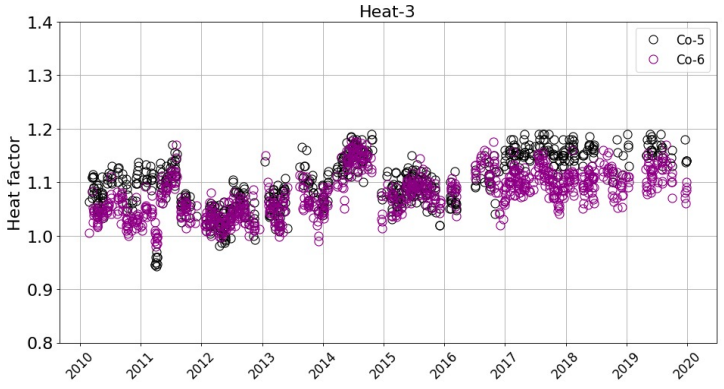




HEAT 1
vs
CO 2 3 4



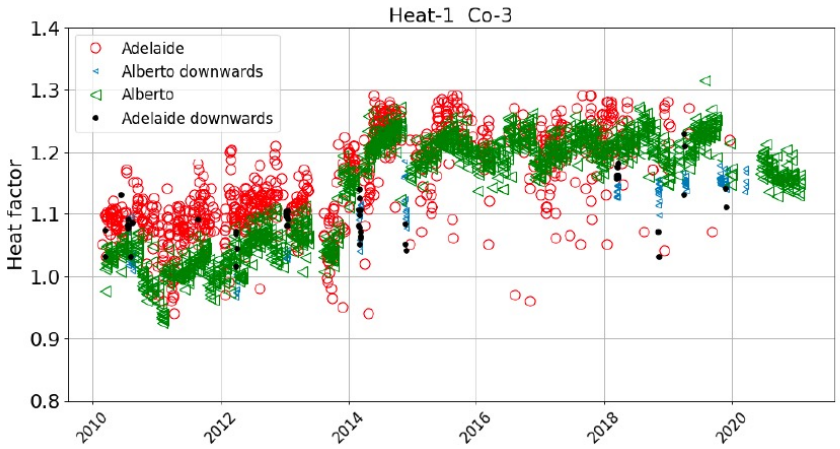
HEAT 2
vs
CO 4 5

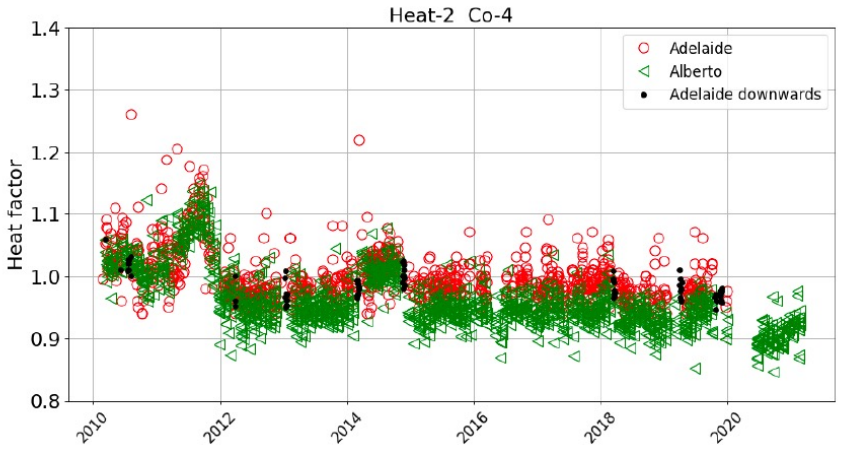


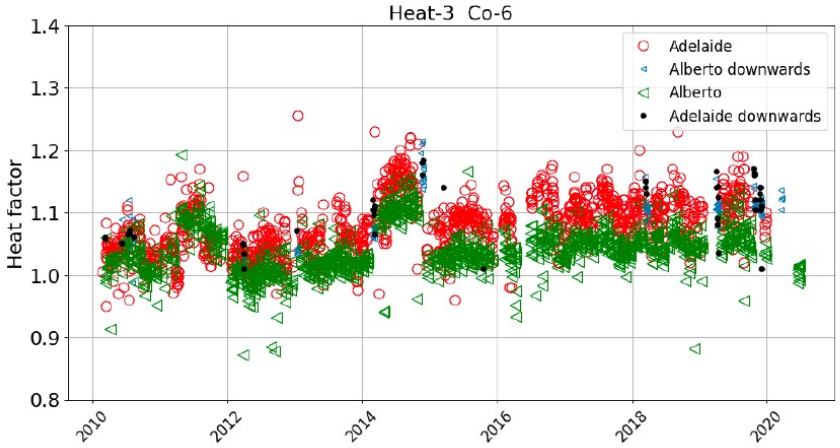
HEAT 3
vs
CO 5 6

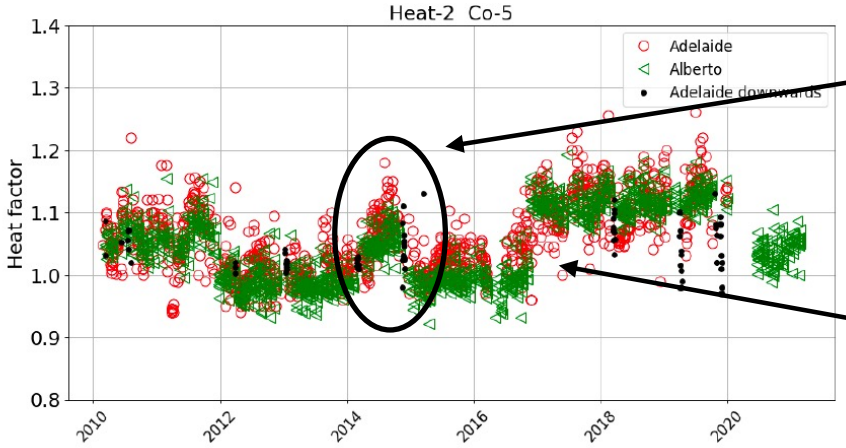
sensitivity looks good but not everything is clear

significant offset between Alberto's and Jose's analyses







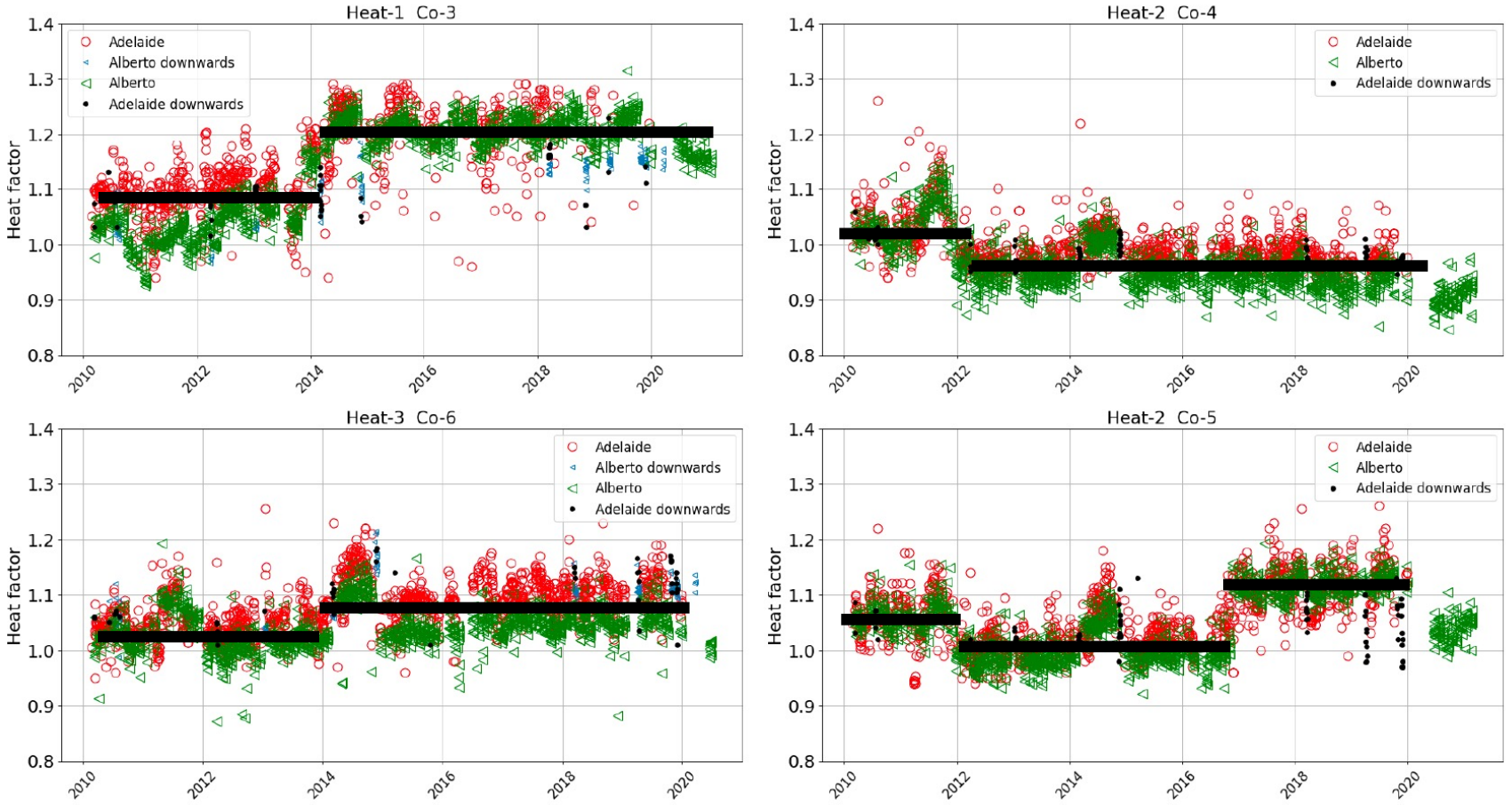


HEAT shutter not fully opened

cleaning of CO 5

do we really need to have daily measurements ?

besides the offsets, are we improving calA ?



test on showers extremely important

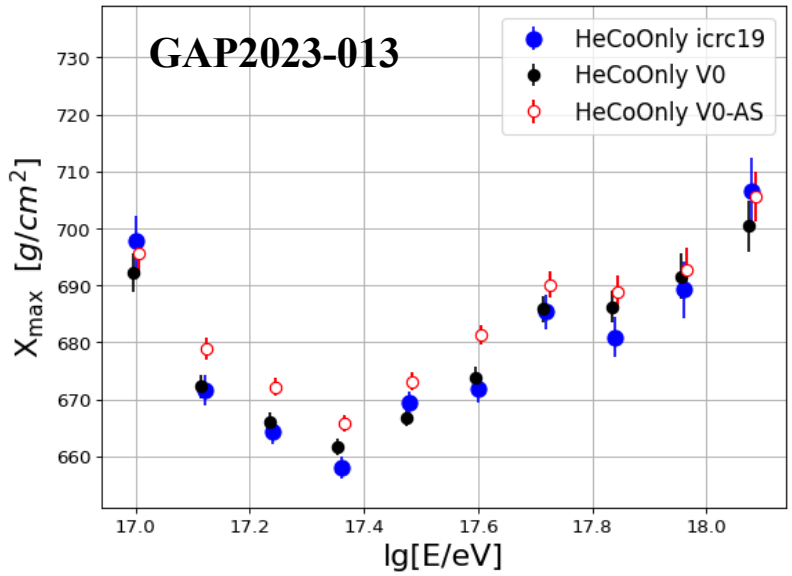
→ X_{max} vs time, RMS(X_{max}), …

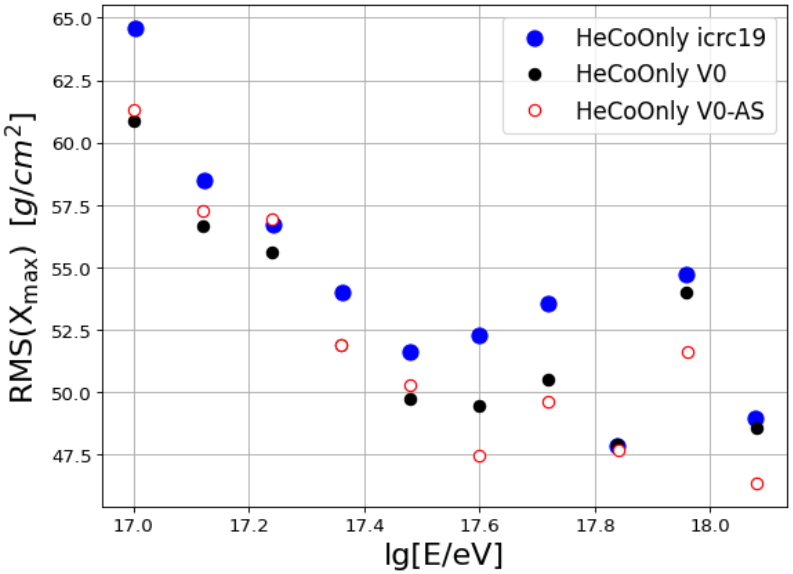
need to define the correct 'reference' to test how much we improve calA

GAP2023-013

reference is ICRC 2019
it is not good

- **uses old shower-based factors**
- **has a 60% offset corrected by Gae**

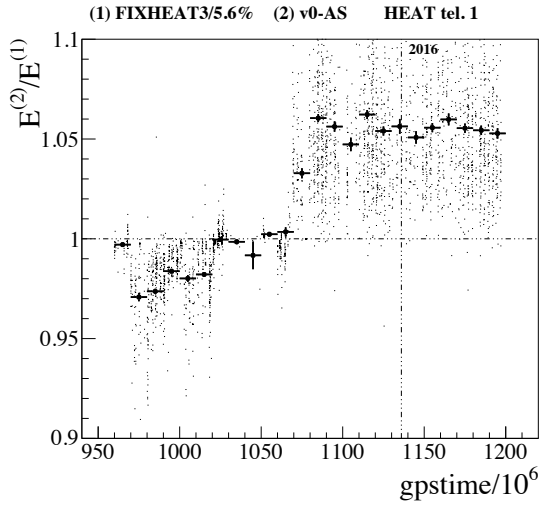


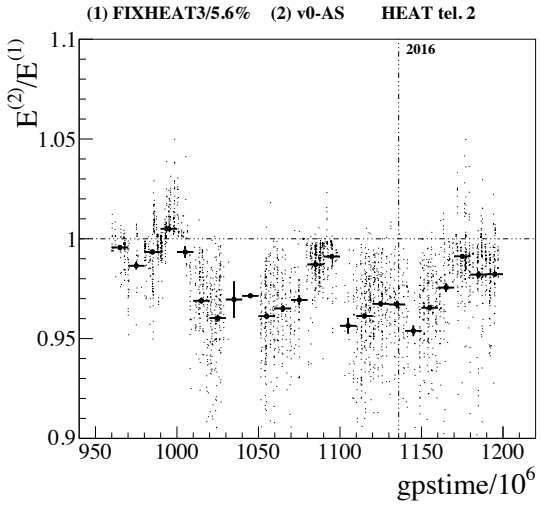


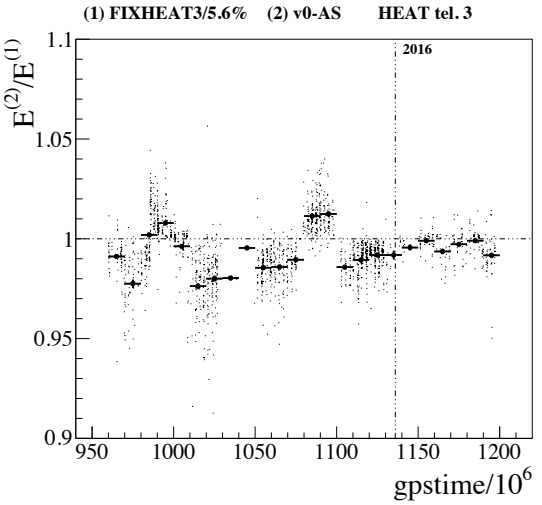
better reference: calA + 5.6% from A.Porcelli + Gae's correction

Lorenzo P. and VV

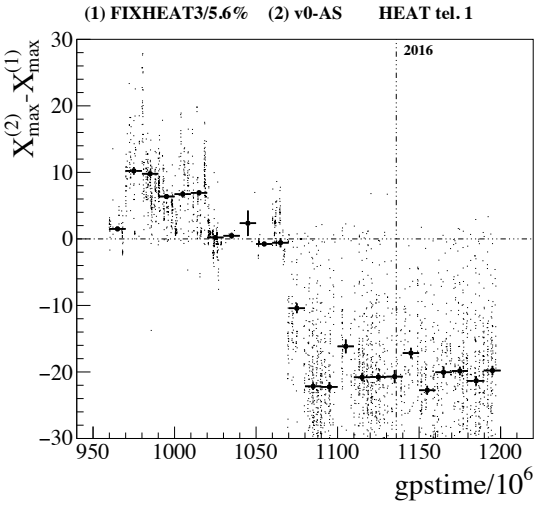
Energy

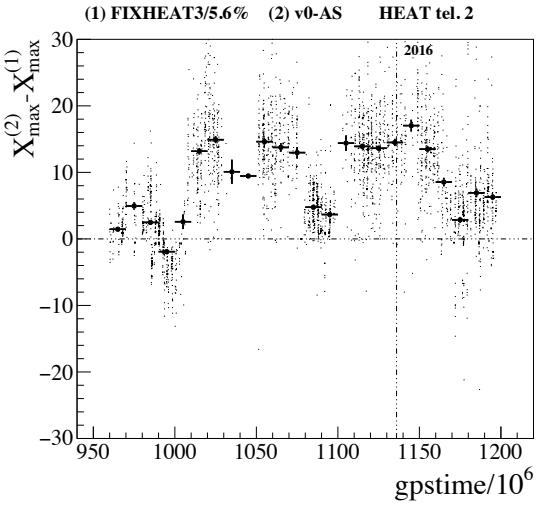


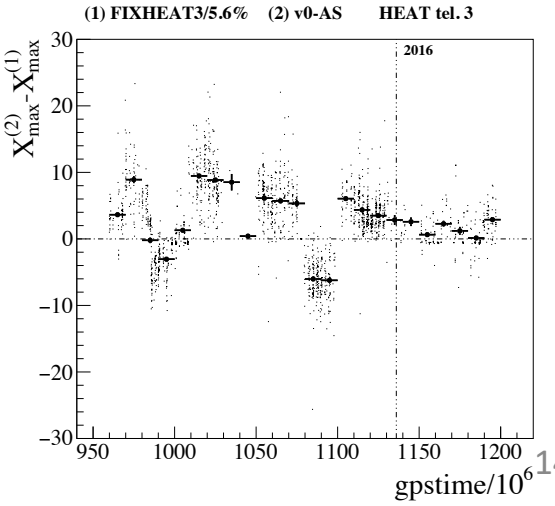




X_{max}







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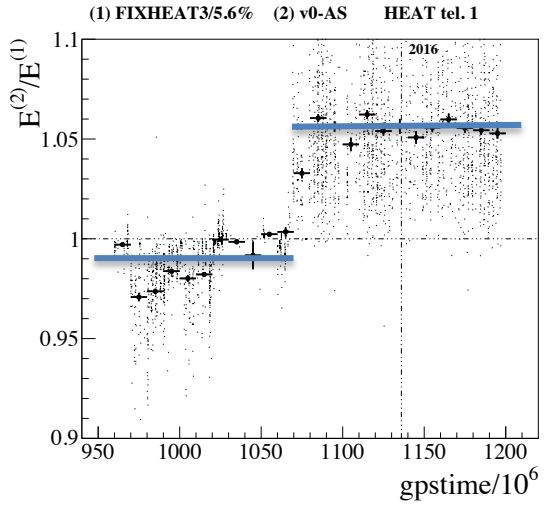
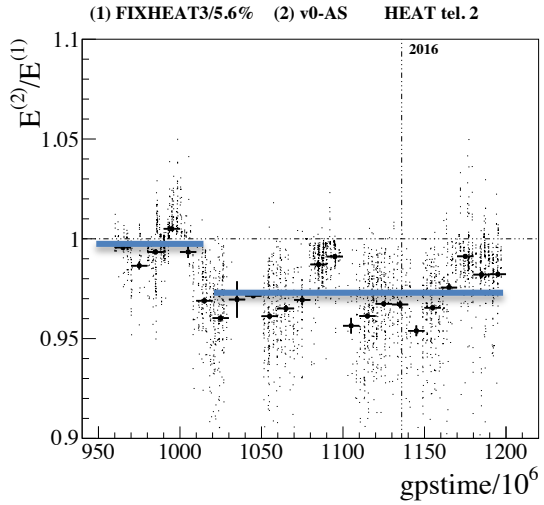
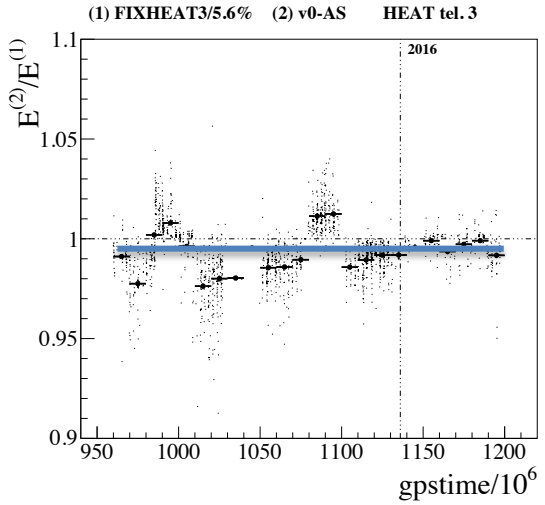
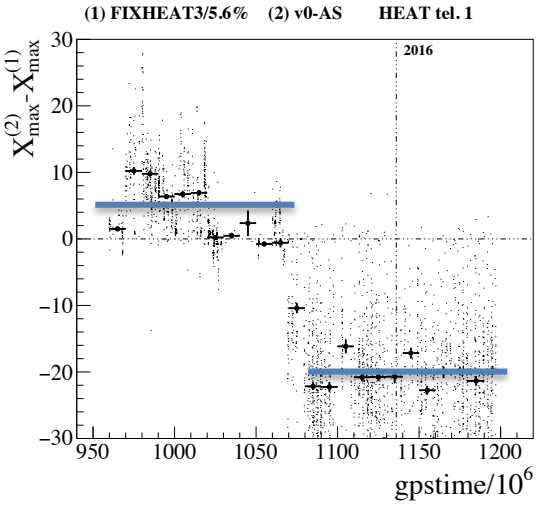
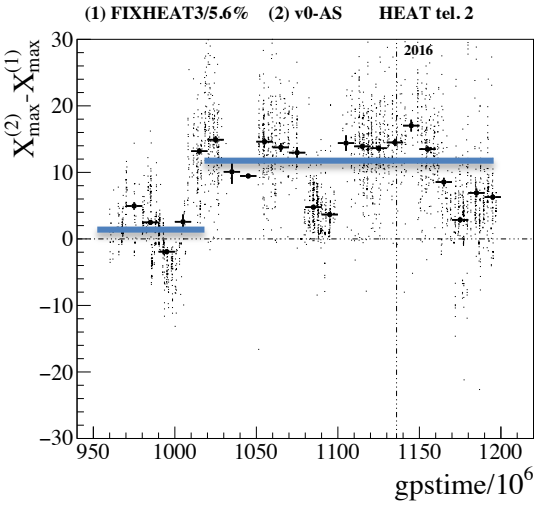


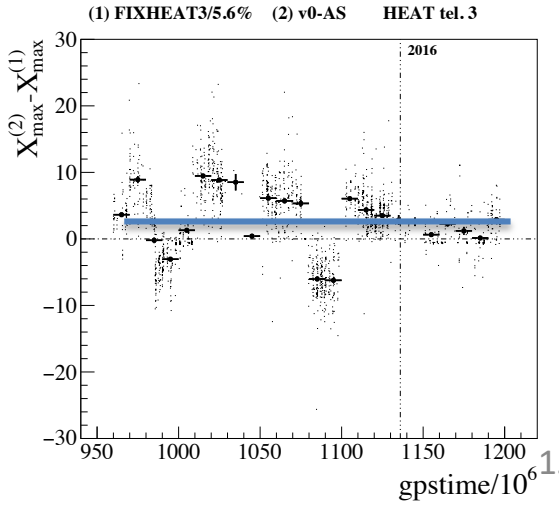




X_{max}







How to move forward ?

ICRC 2025 (2022-23):
extrapolation of older data (Gae)

analysis strategy:

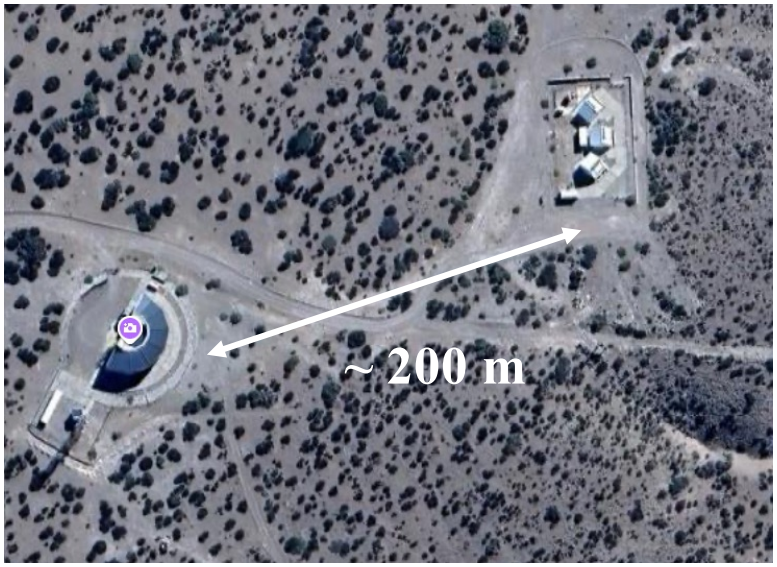
- HEAT downward to precisely address the offset

- HEAT upward to detect the time of the jump

- daily fluctuations ?

- (important) only one db for FD calibration

who? Bruce, Vladimir, Gae, …



special stereo showers

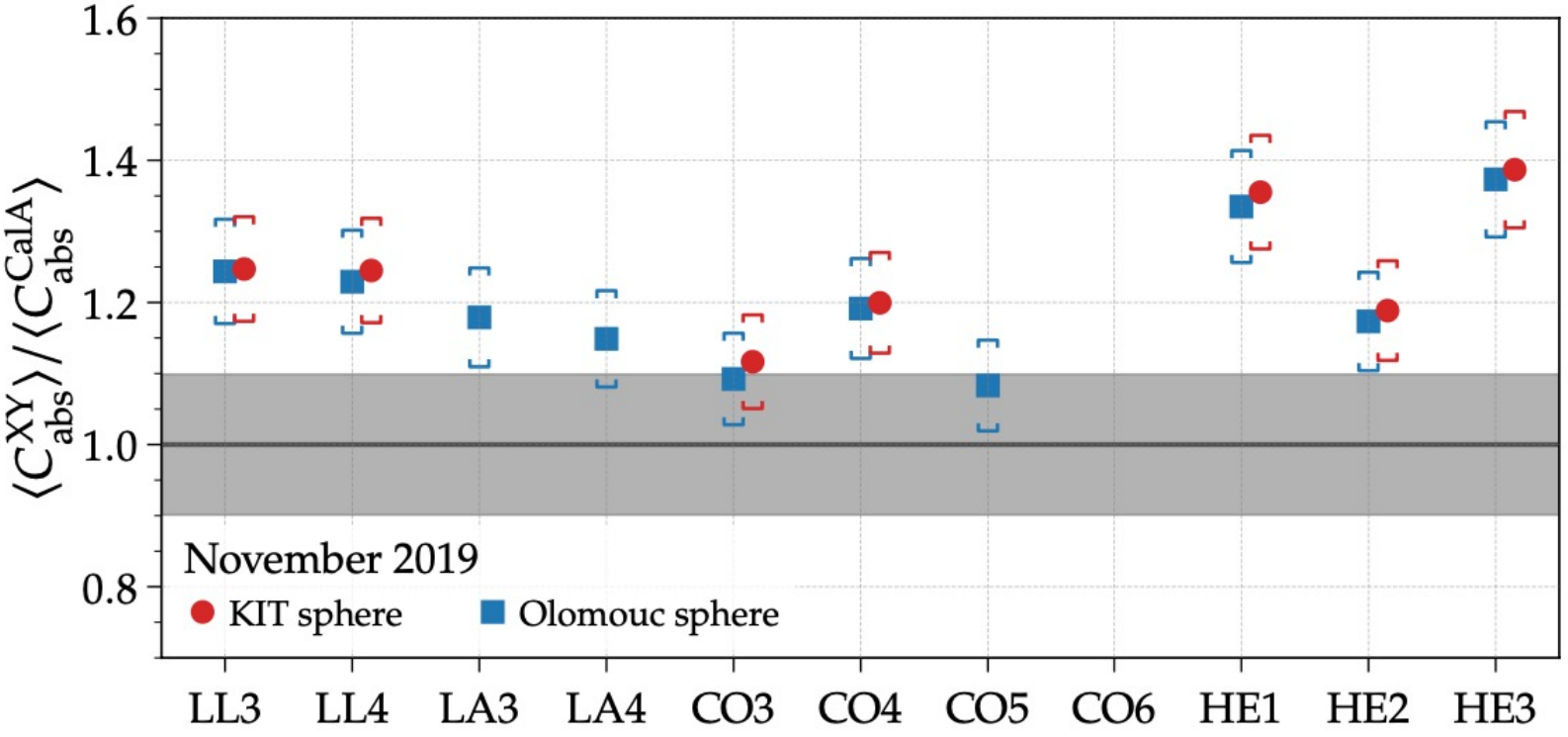
reconstruct them with same geometry and ζ_{opt}

→ a lot of statistics

see Gaetano's talk

XY-SCANNER

GAP2023_034
Christoph Schäfer
PhD thesis



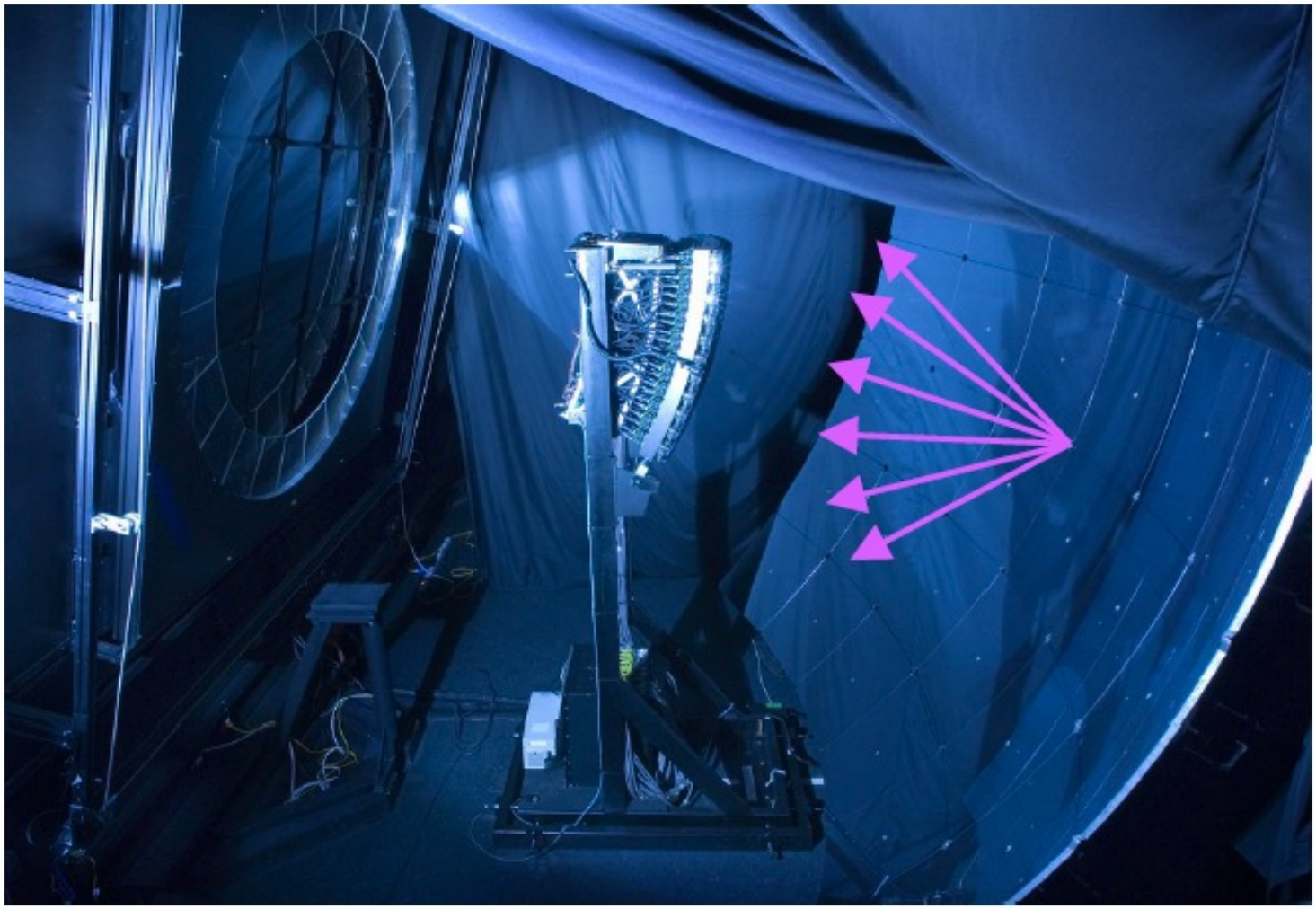
XY-Scanner
Drum+calA

Is the absolute calibration of the telescopes really off by 10%-30% ?

calA doesn't monitor filter and mirror (dust)

Drum 2010
XY-Scanner 2019

need to address the consistency of the two absolute calibration systems



Drum absolute calibration

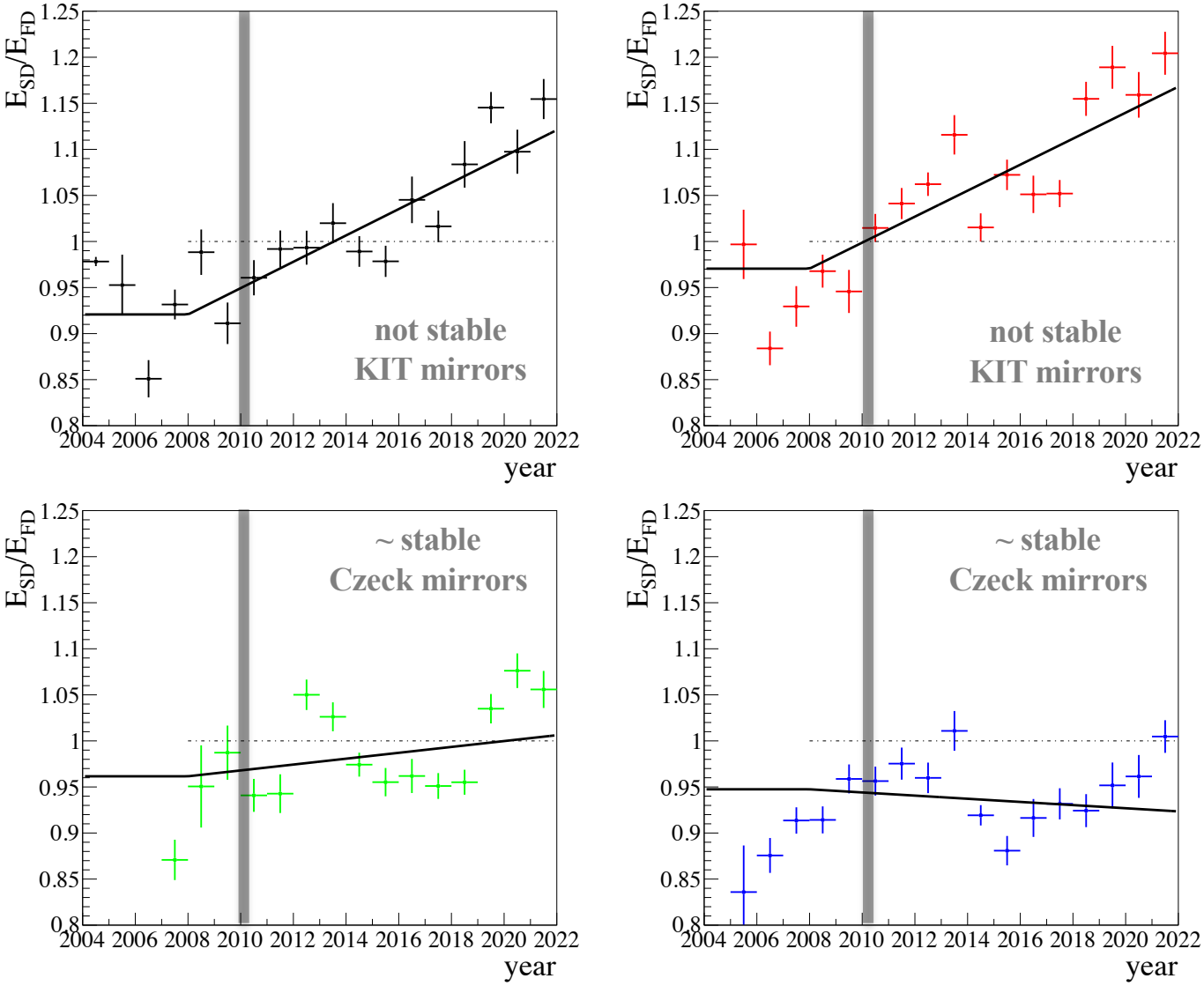
full trigger efficiency

sum over all mirrors within an eye

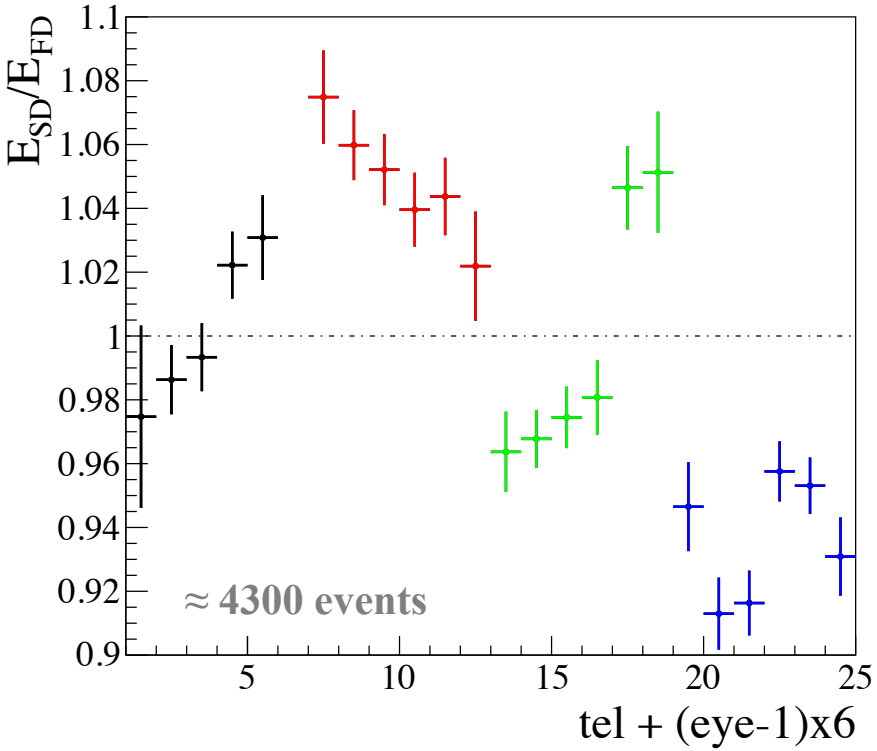
Czeck mirros cleaned in
2016 LA
2013 & 2016 CO

KIT mirrors never cleaned

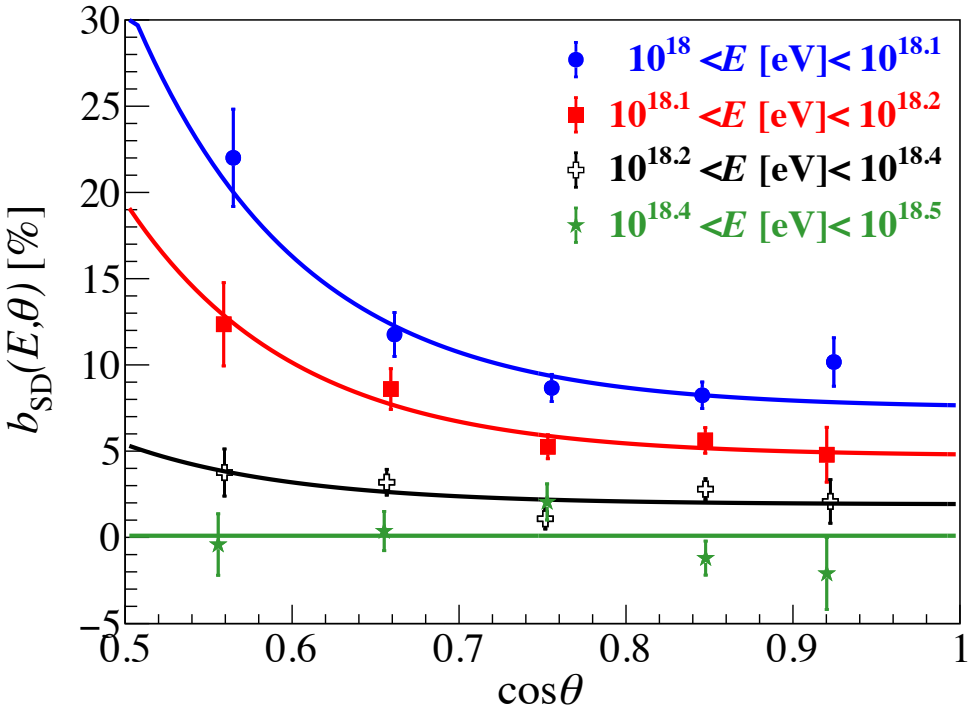
LL LM LA CO



full trigger efficiency



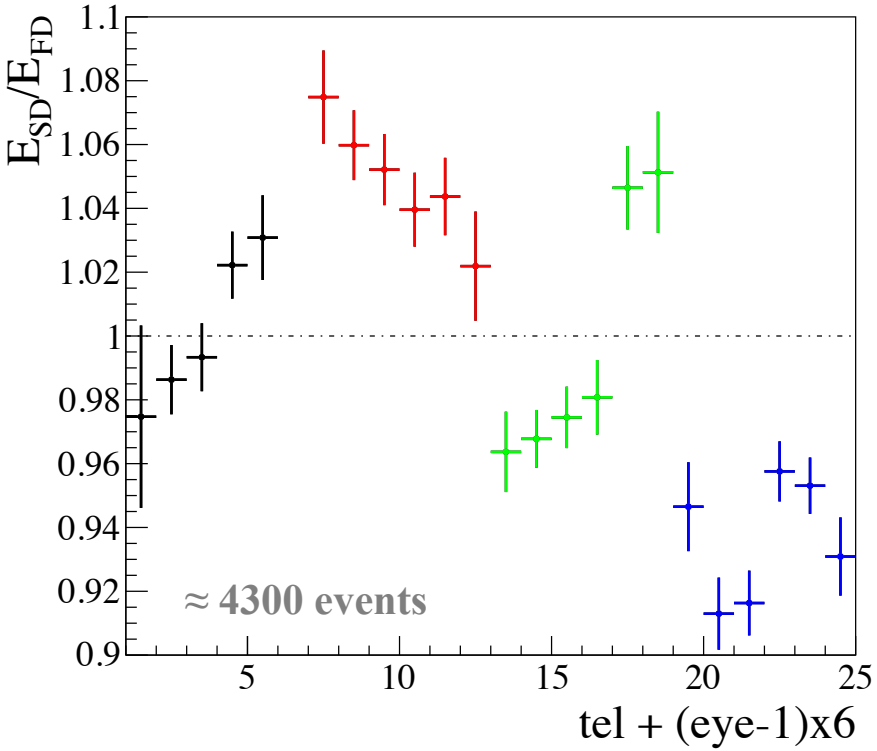
below full trigger efficiency



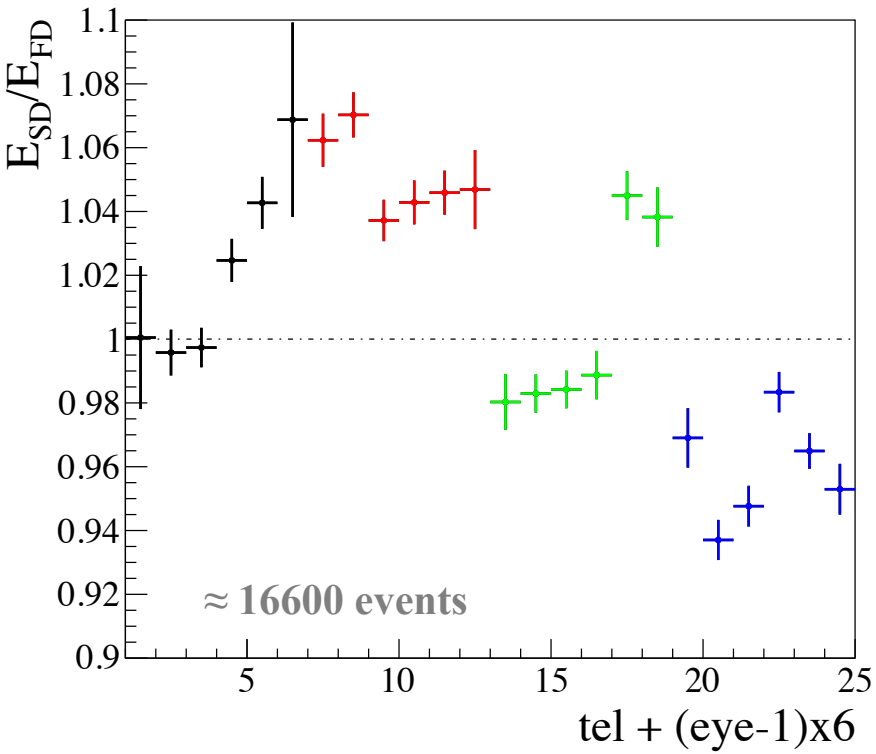
E_{SD}/E_{FD} vs time for each telescope ?

increase the statistics including events below full trigger efficiency - bias correction

full trigger efficiency



below full trigger efficiency



E_{SD}/E_{FD} vs time for each telescope ?

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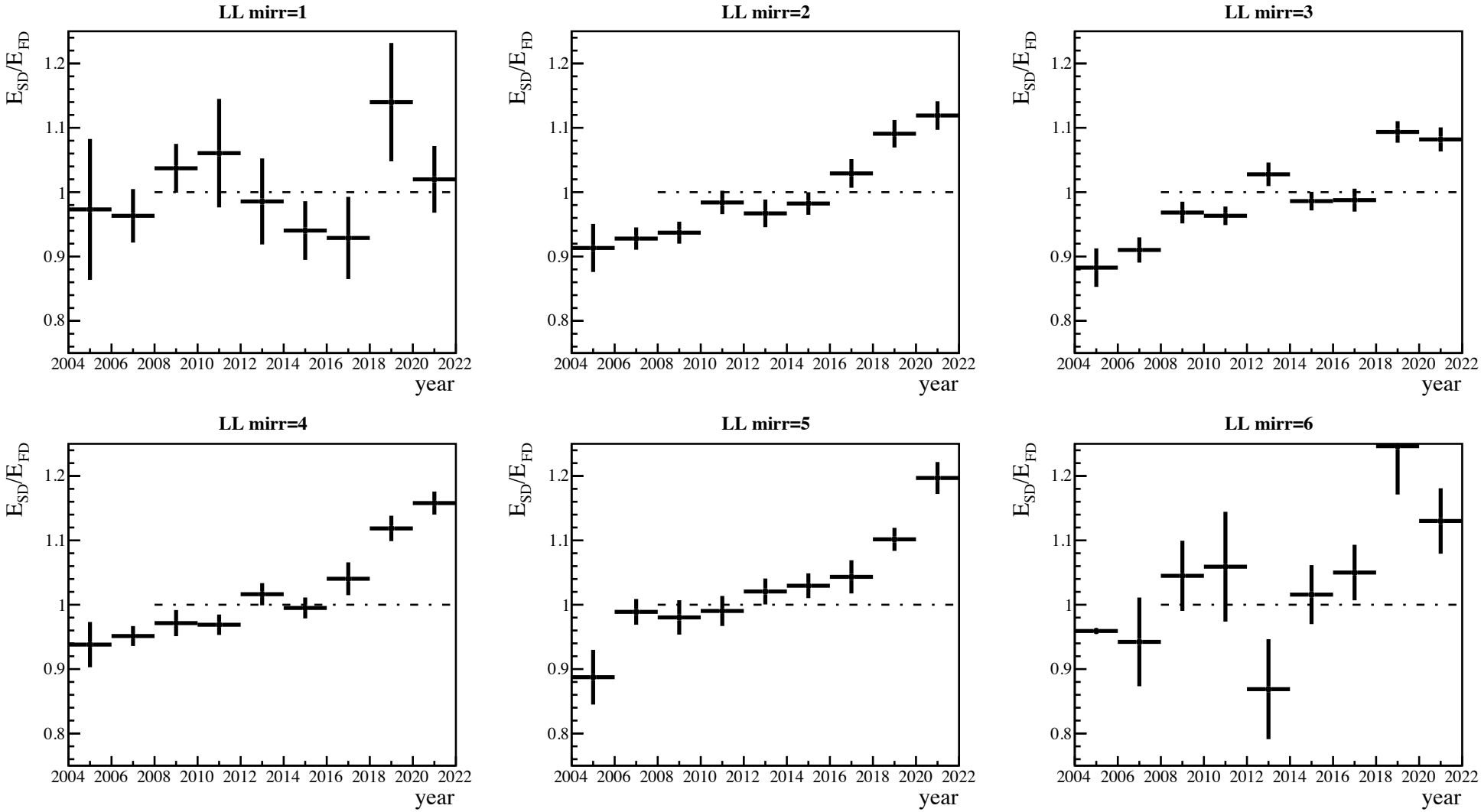
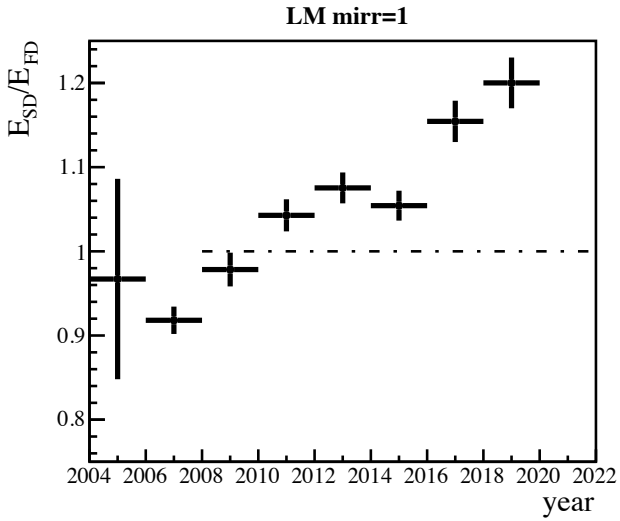

LL mirr=1
LL mirr=2
LL mirr=3
LL mirr=4
LL mirr=5
LL mirr=6
E_{SD}/E_{FD}
year
0.8
0.9
1
1.1
1.2
2004 2006 2008 2010 2012 2014 2016 2018 2020 2022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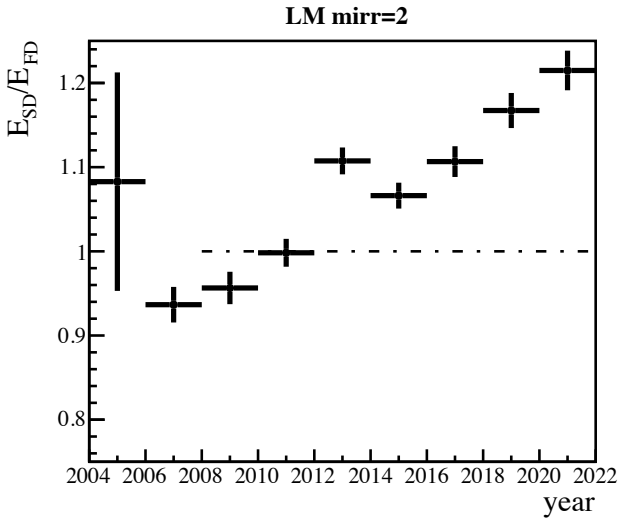
E_{SD}/E_{FD}
year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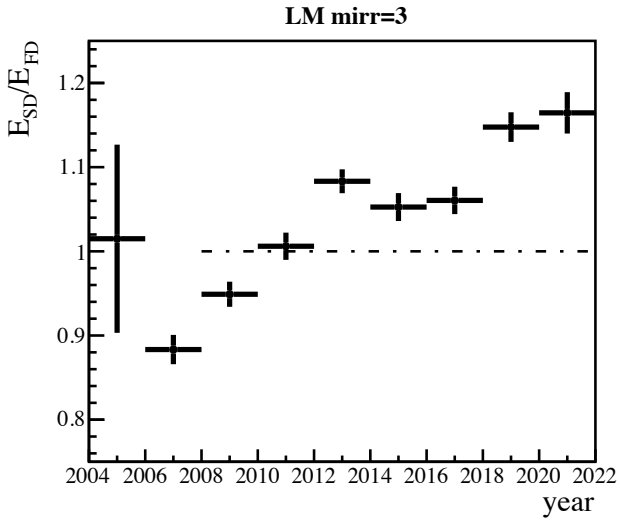
E_{SD}/E_{FD}
year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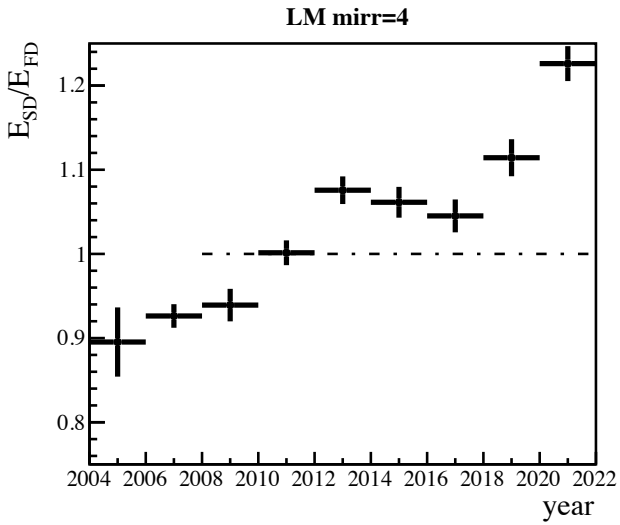
E_{SD}/E_{FD}
year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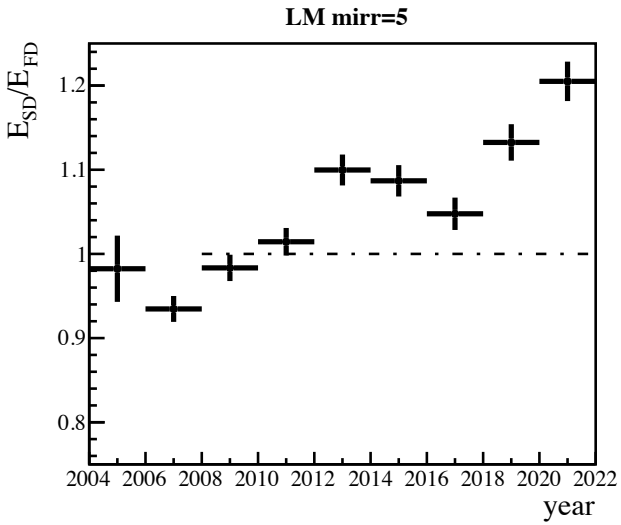
E_{SD}/E_{FD}
year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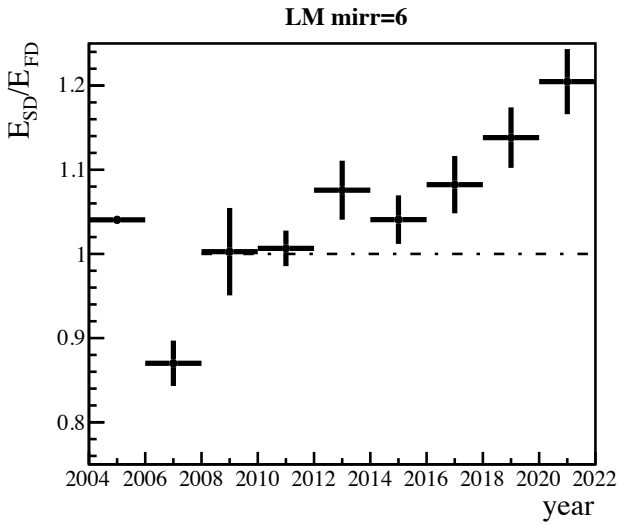
E_{SD}/E_{FD}
year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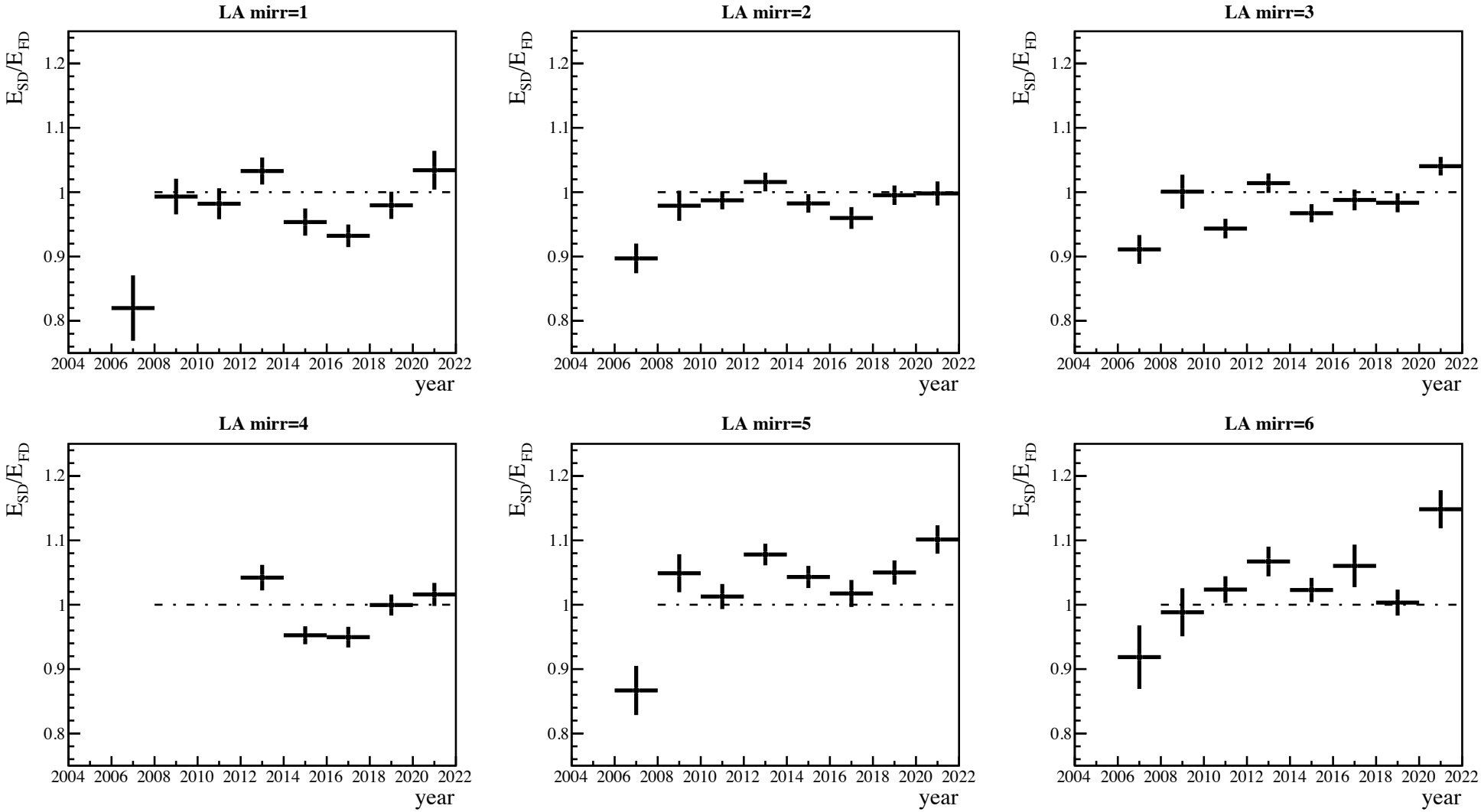
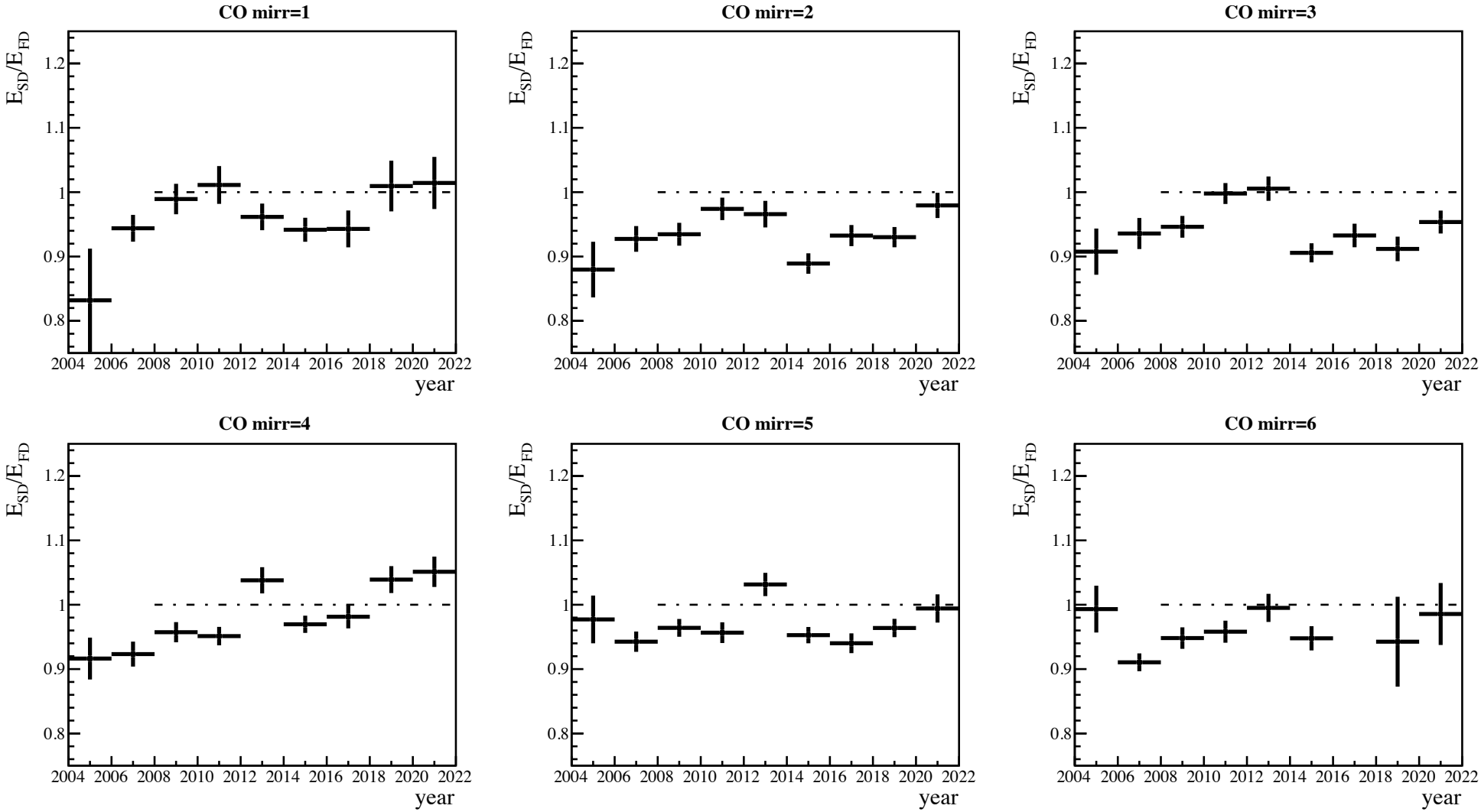
E_{SD}/E_{FD}
year


LA mirr=1
LA mirr=2
LA mirr=3
LA mirr=4
LA mirr=5
LA mirr=6
E_{SD}/E_{FD}
year
0.8
0.9
1
1.1
1.2
2004 2006 2008 2010 2012 2014 2016 2018 2020 2022

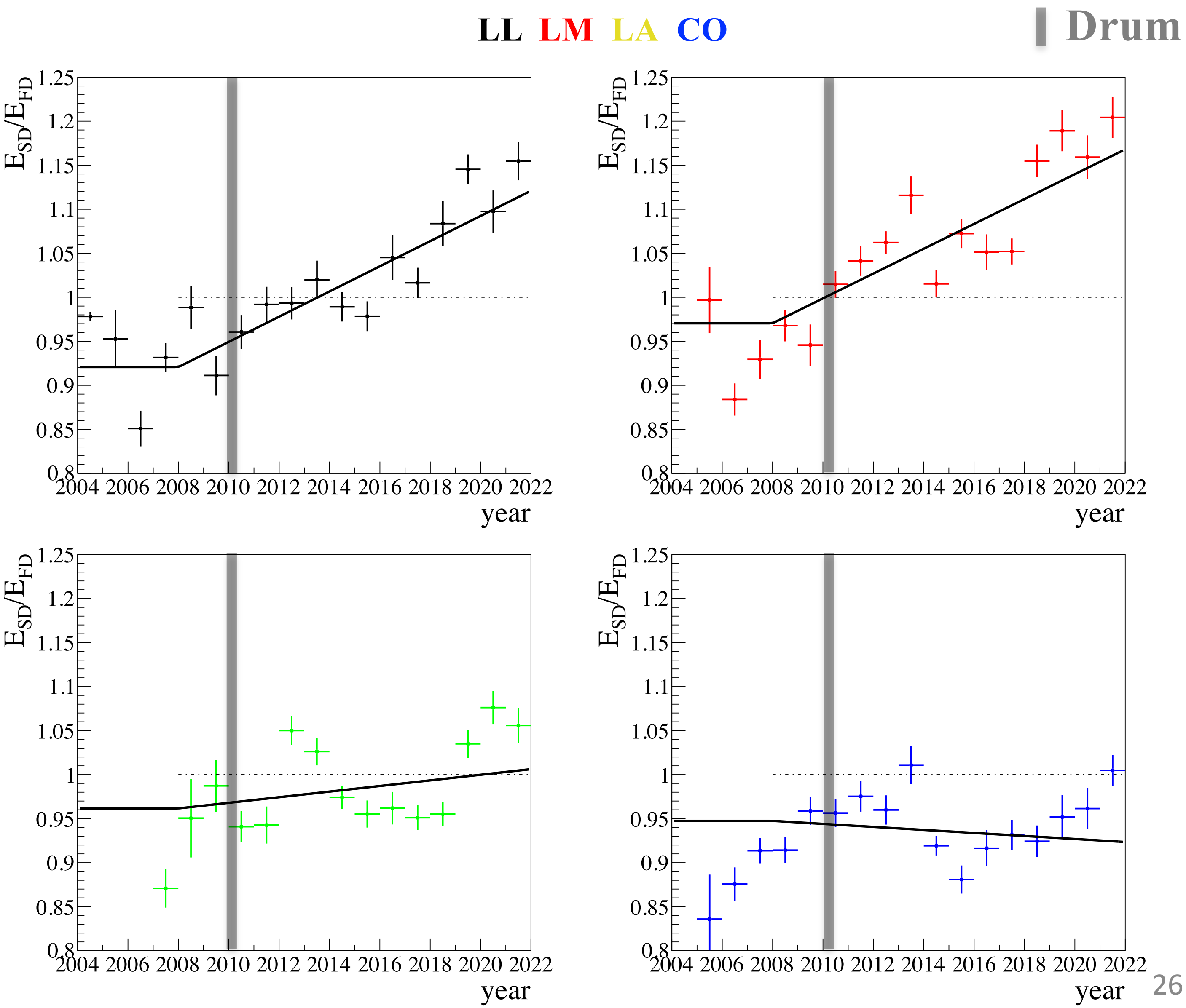

CO mirr=1
CO mirr=2
CO mirr=3
CO mirr=4
CO mirr=5
CO mirr=6
E_{SD}/E_{FD}
year
0.8
0.9
1
1.1
1.2
2004 2006 2008 2010 2012 2014 2016 2018 2020 2022

XY-SCANNER vs DRUM

Going back in time: analysis very preliminary but promising

LL LM → drift
LA CO → ~ stable

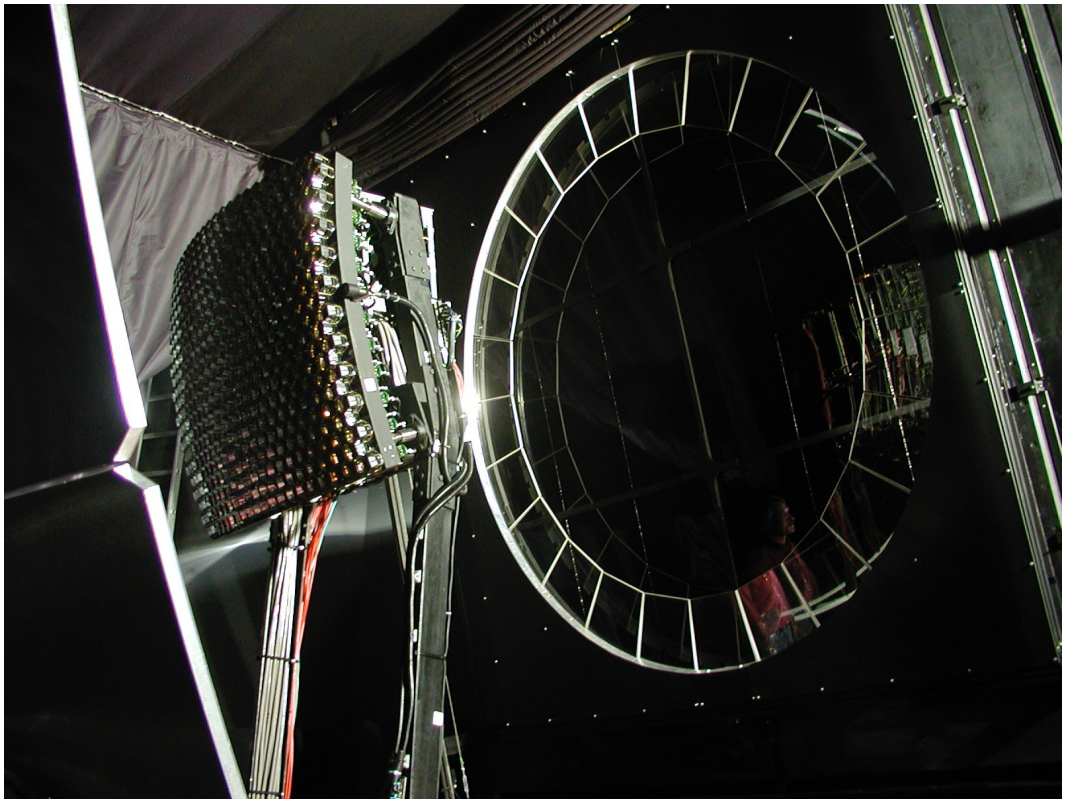
multi mirror events ?
atmosphere ?
FoV cut ?



RADIO

VS

FD

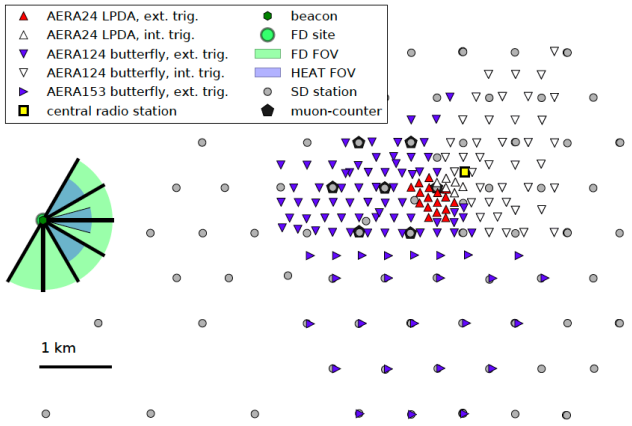


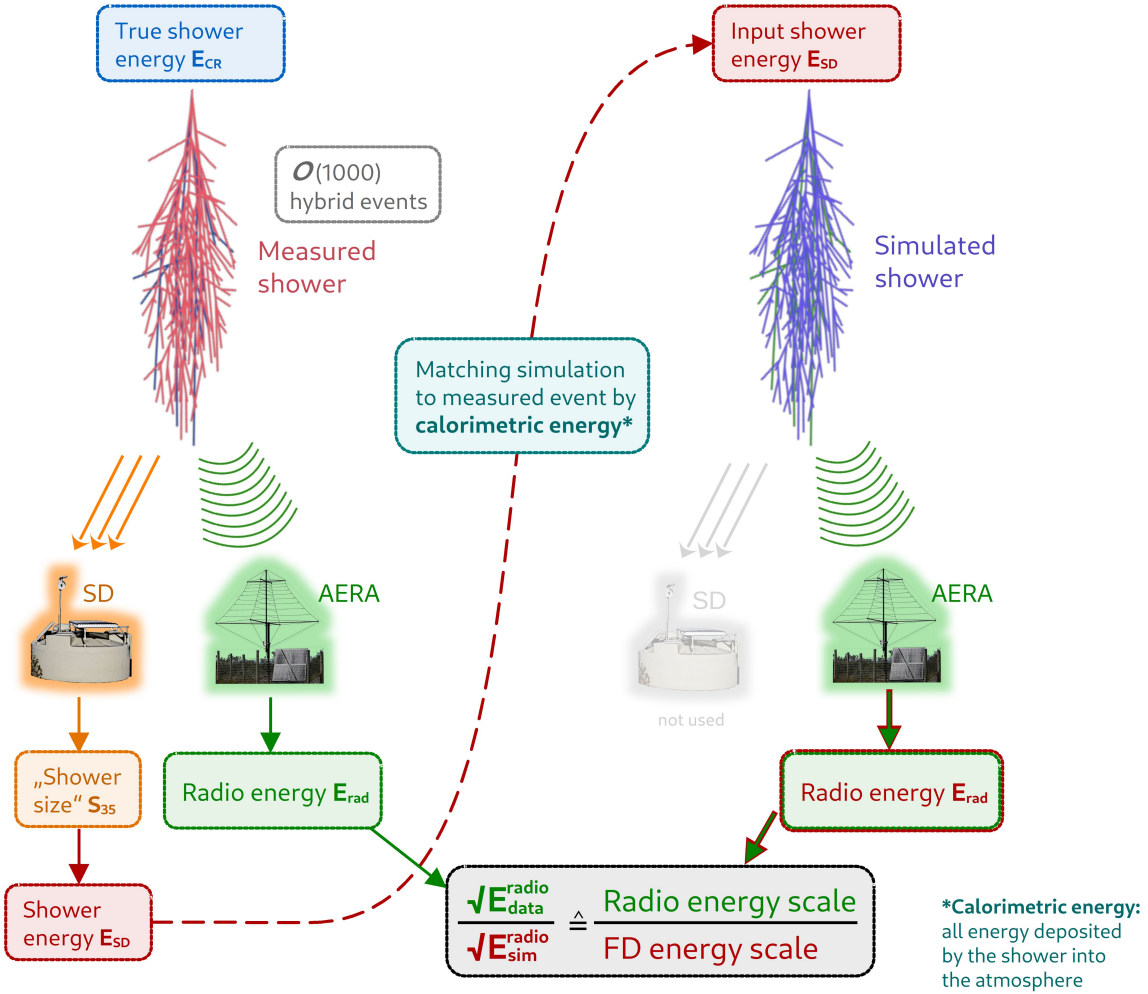
RADIO vs FD Energy scale

Max Büsken, Malargüe Nov 2024

events detected by RD and SD 750 m

E(radio) from simulations with input E_{SD}





***Calorimetric energy:** all energy deposited by the shower into the atmosphere

RADIO vs FD Energy scale

Max Büsken, Malargüe Nov 2024

after an umblinding

$$\frac{E_{\mathrm{CR}}^{\mathrm{Radio}}}{E_{\mathrm{CR}}^{\mathrm{FD}}} = \sqrt{\frac{E_{\mathrm{rad}}^{\mathrm{data}}}{E_{\mathrm{rad}}^{\mathrm{sim}}}}$$

p: $10^{0.0479} = 1.117 \pm 0.009$

Fe: $10^{0.0504} = 1.123 \pm 0.009$

→ Average: **1.120 ± 0.009**

Radio energy scale is **12.0% ± 0.9%** higher than FD energy scale

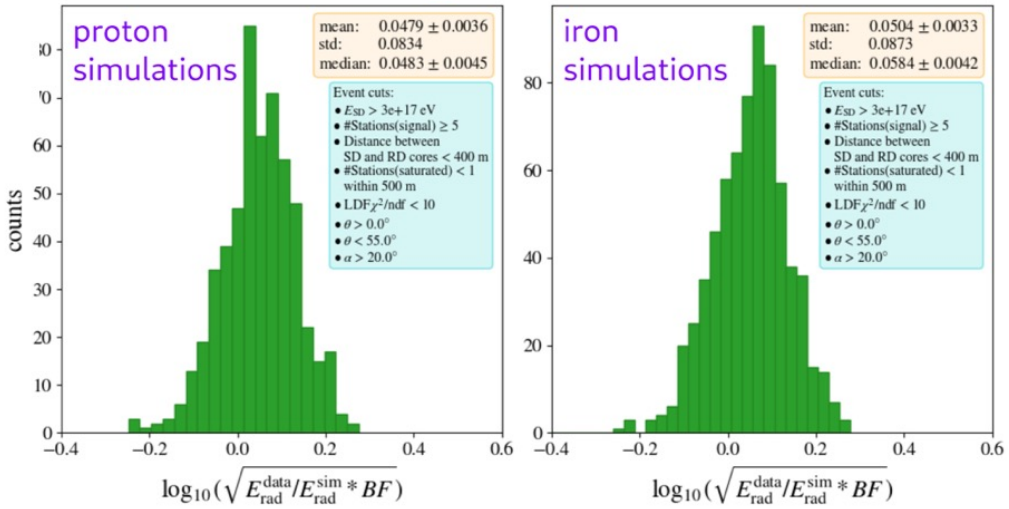
→ a **1 EeV** shower on the FD energy scale has **1.12 EeV** on the radio energy scale

$$\frac{RADIO}{FD} = 12\% \pm 1\% \pm 20\%$$

syst.

rather than higher …
better to say consistent …

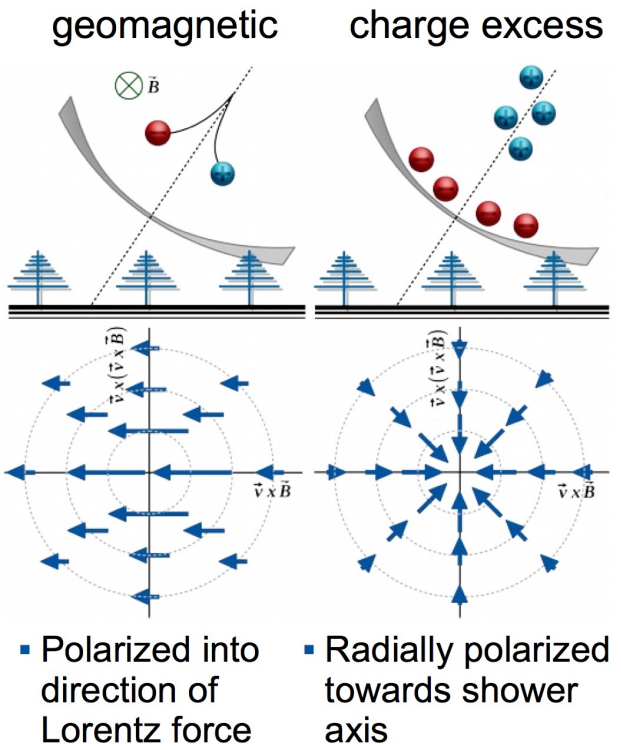
log10(Ratios)



note:

- **E_{SD} is not E_{FD}**
- **SD 750 m spectrum not seen**
- **bias from mass composition ?**

	FLUORESCENCE	RADIO
yield	measured in lab	QED
emission	isotropic	forward
simulation	no	yes
atmospheric attenuation	yes	no
duty cycle	15%	100% (inclined showers)



FD - data driven reconstruction

FY measured in lab

$$n_{ADC} \sim \frac{dE}{dX}\, Y_{fluo}\, \frac{A}{r^2}\, T_{atm}\, C_{calib}$$

- n_{ADC}: number of photons $\propto dE/dX$
- $\frac{dE}{dX}$
- Y_{fluo}: fluorescence yield
- $\frac{A}{r^2}$: isotropic emission
- T_{atm}: atmospheric attenuation
- C_{calib}: telescope calibration

Radio - MC
need to sum the electric field at ground generated by all particles during the shower development

Systematic uncertainties

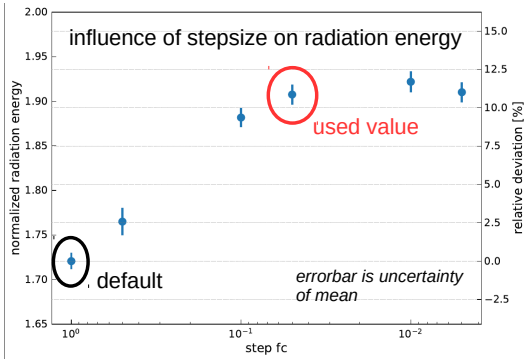
Source of uncertainty	Size
Experimental uncertainties	**9.8 %**
Galactic calibration	6.1 %
Antenna response pattern	5 %
LDF model	0.5 %
Atmosphere	<1.25 %
Ground conditions	<1.8 %
Quiet sun	0.5 %
Simulation primary bias	0.5 %
Signal loss during reconstruction	1.6 %
Mass composition bias wrt. Auger mix	5 %
Theoretical uncertainties	**5.2 % / ~10.1 %**
Microscopic description of radio emission	5.0 % / ~10 %
Choice of hadronic interaction model	0.13 %
Air refractivity	1.0 %
Thinning	<0.15 %
Energy thresholds of shower particles	<0.5 %
Stat. uncertainty of energy scale comparison	**0.9 %**
Total absolute scale uncertainty	**11.2 % / ~14.1 %**

Christian Glaser - 2017

NEW

Theoretical Calculation of Radiation Energy

- **New production:** Same as in *Glaser et al. JCAP09(2016)024* but more precise and tailored to Auger environment
  - yearly average Malargüe atmosphere and refractivity
  - simulation of full 2D footprint
    - reduced uncertainty of radiation energy
  - CoREAS 7.57 (QGSJetII-04 and Urqmd)
  - step size reduced by a factor 20 → +11% in E_{rad} (+5.5% in E_{CR})
  - 1.6M core hours
- Many additional checks regarding stability of prediction
  - step size was the only relevant parameter
  - SAL publication in preparation *(Gottowik et al.)*

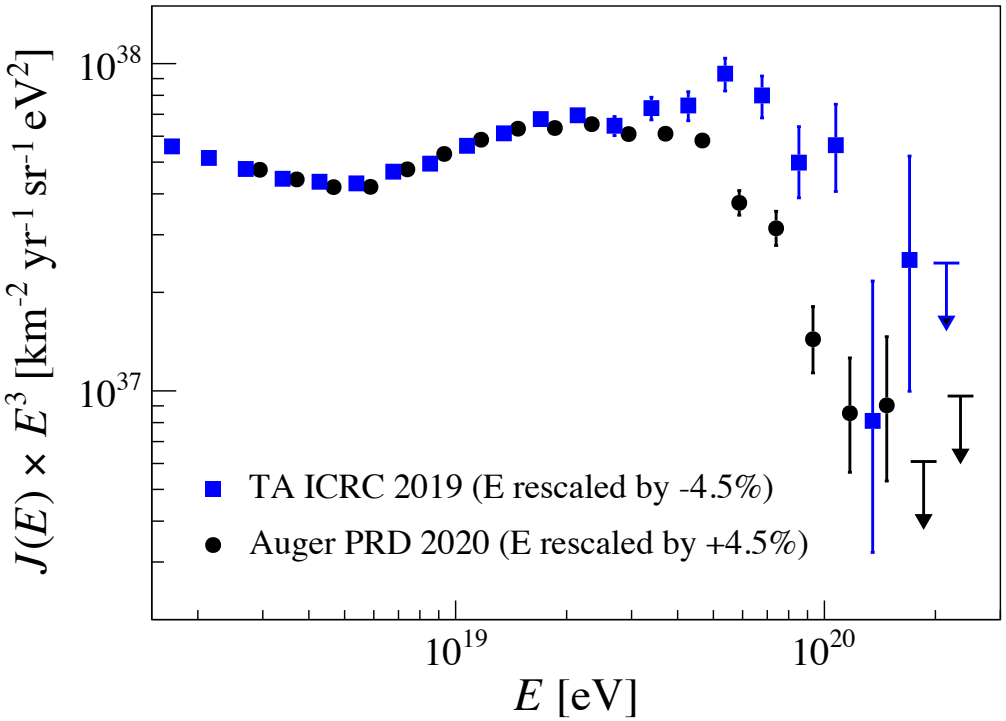


weak point: theoretical calculation

- **no measurements in lab**
- **step size effect emblematic**

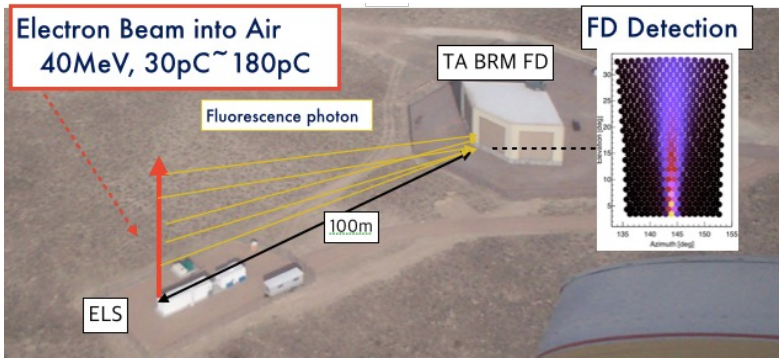
AUGER vs TA

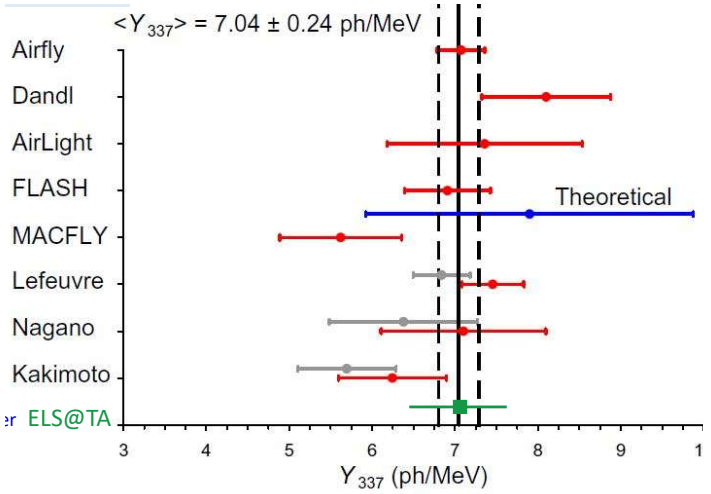
surprisingly agreement once using same FY and E_{inv}



other systematics (TA exposure) ?

TA: remarkable test using a Linac acc.



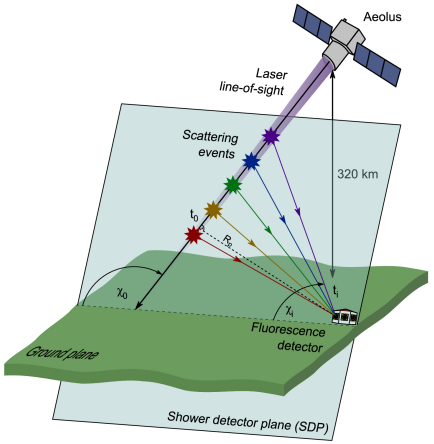


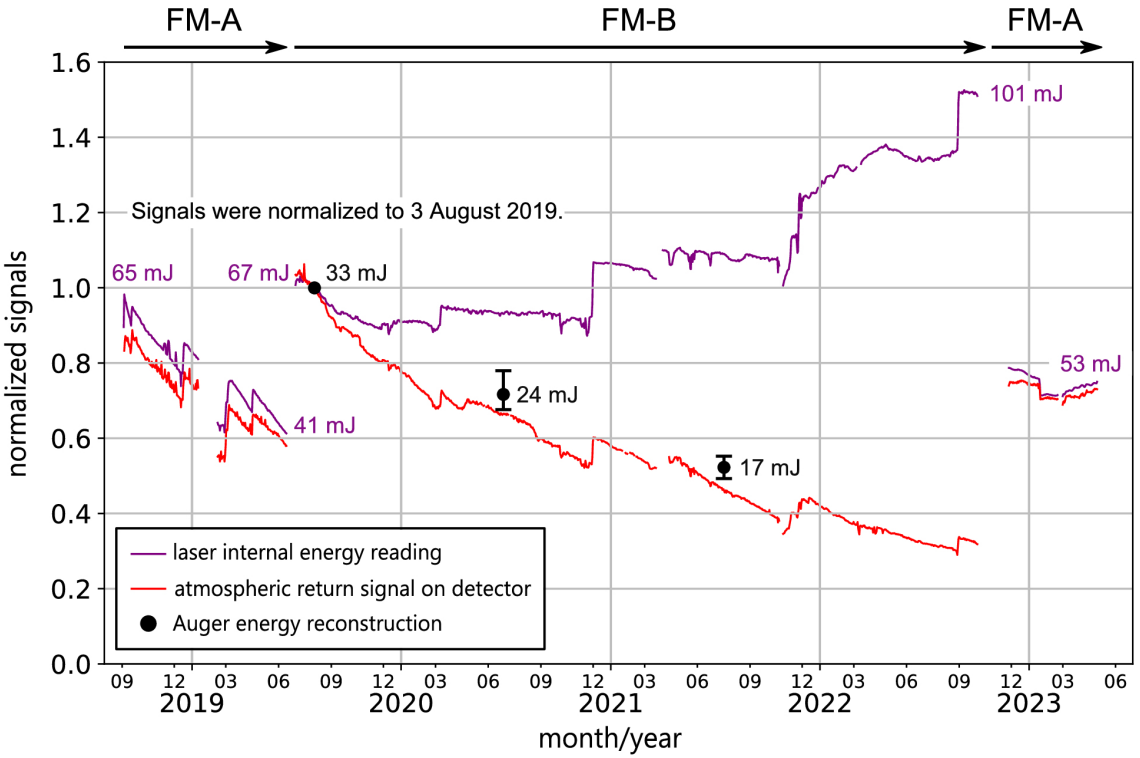
Laser shots from ALEOUS satellite

will be visible in Auger and TA

- **FD calibration + atmosphere**
- **light collection (MS+halo) ?**

not an easy task





Optica 11 (2024) 263-272

- no useful information on reconstruction in supplementary material
- F. Knapp Master's thesis not available

O U T L O O K

- **ICRC 2025: phase 1 data set**
  - **vertical, inclined, hybrid spectra**
  - **energy scale paper**
- **HEAT/CO cross calibration factors**
  - **strategy for a final solution**
- **near future (demanding)**
  - **XY-Scanner**
  - **radio**
  - **Auger vs TA spectrum, Aeolus, …**

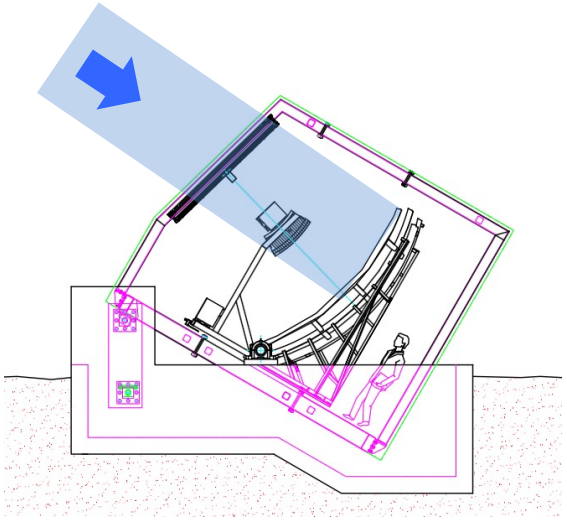
  (μ number excess, spectrum, …)

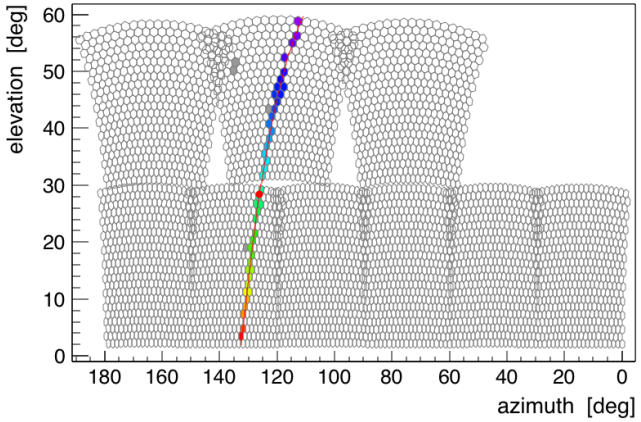
Dust mainly on the lower part of the mirrors

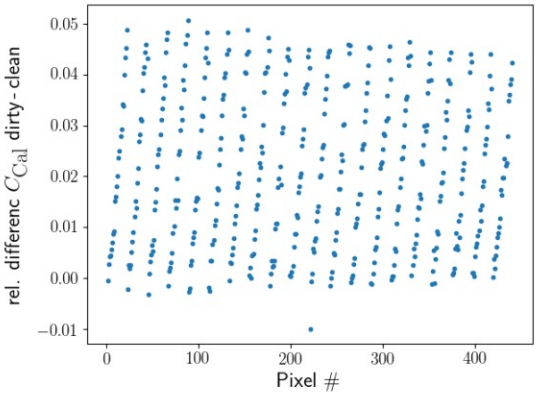
see presentation by Bruce
https://indico.nucleares.unam.mx/event/1409/session/12/contribution/87
credits also to Alberto

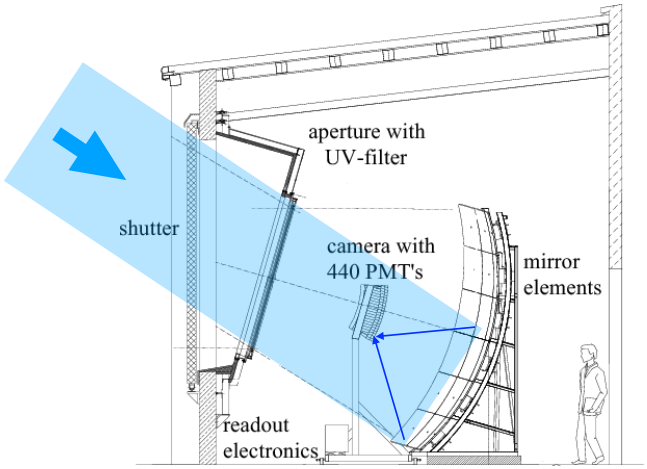
Field of view common to HEAT and CO
- maximum effect of dust in CO pixels
- minimum effect of dust in HEAT pixels

→ a double effect going in the direction to underestimate the energies from HEAT (with respect to CO)









ABSOLUTE FLUORESCENCE YIELD

measured in lab

nowadays measured with a <4% uncertainty (AIRFLY)

emission process well understood but too large uncertainty in the theoretical prediction

grey points - old measurements affected by a known bias:

some δ rays escape the detector f.o.v.
→ underestimation of Y_{337}

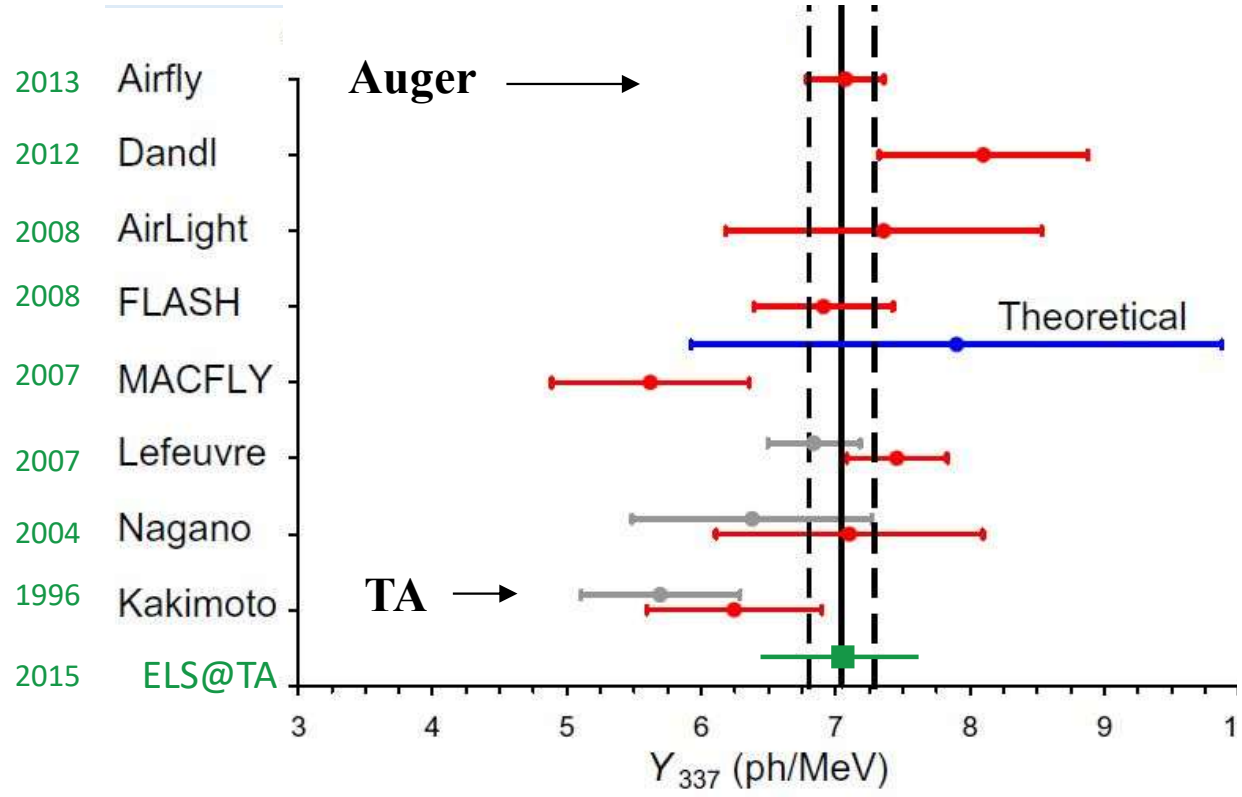


figure from J. Rosado, F. Blanco and F. Arqueros, ApP 55(2014) 51-62
ELS@TA added by M. Fukushima, GCOS workshop 2022

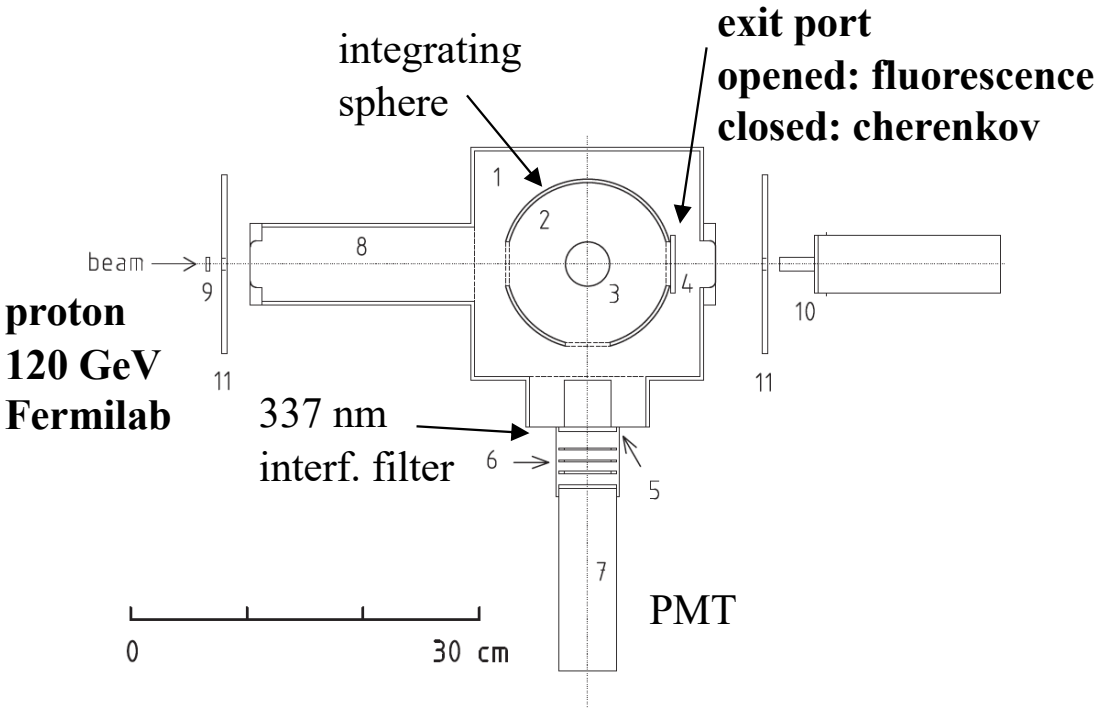
AIRFLY

Absolute Yield (337 nm)

Astropart. Phys. 42 (2013) 90

precise measurement by normalizing to a well know process (avoid absolute PMT calibration)

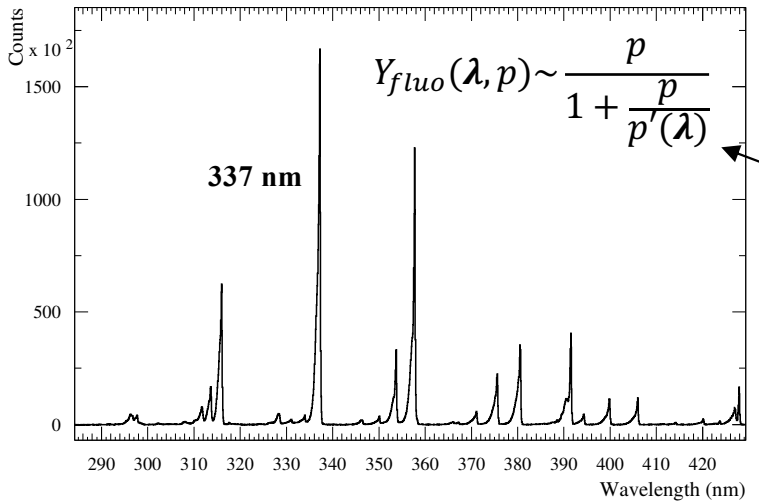
$$Y_{fluo} \sim Y_{cher} \frac{N_{fluo}}{N_{cher}}$$



Wavelength spectrum and quenching effects

Astropart. Phys. 28 (2007) 41

relative measurements



$$Y_{fluo}(\lambda, p) \sim \frac{p}{1 + \frac{p}{p'(\lambda)}}$$

$$\frac{\sqrt{T}}{\sigma}$$

0,1 nm resolution

AWA and VdG (Argonne)

- **spectrum**
- **dependence on pressure, humidity and temperature**

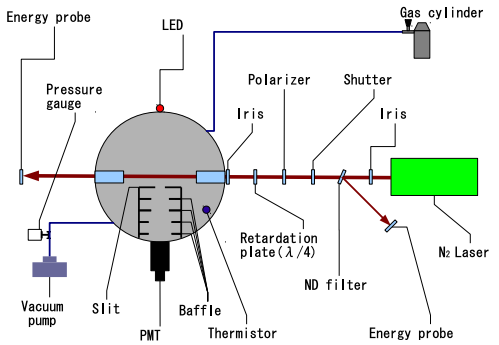
uncertainty in shower energy from FY < 4%

ABSOLUTE TELESCOPE CALIBRATION

Auger: calibrate the full telescope illuminating uniformly the camera with a calibrated source

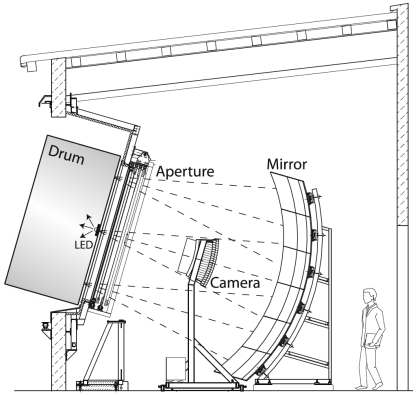
TA: ‘piece to piece’ calibration. Absolute PMT calibration with Rayleigh scattered light from nitrogen laser

TA CRAYS



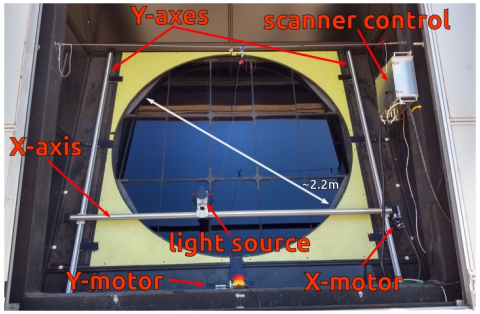
S. Kawana et al., Nucl. Instrum. Meth. A 681 (2012) 68

AUGER DRUM



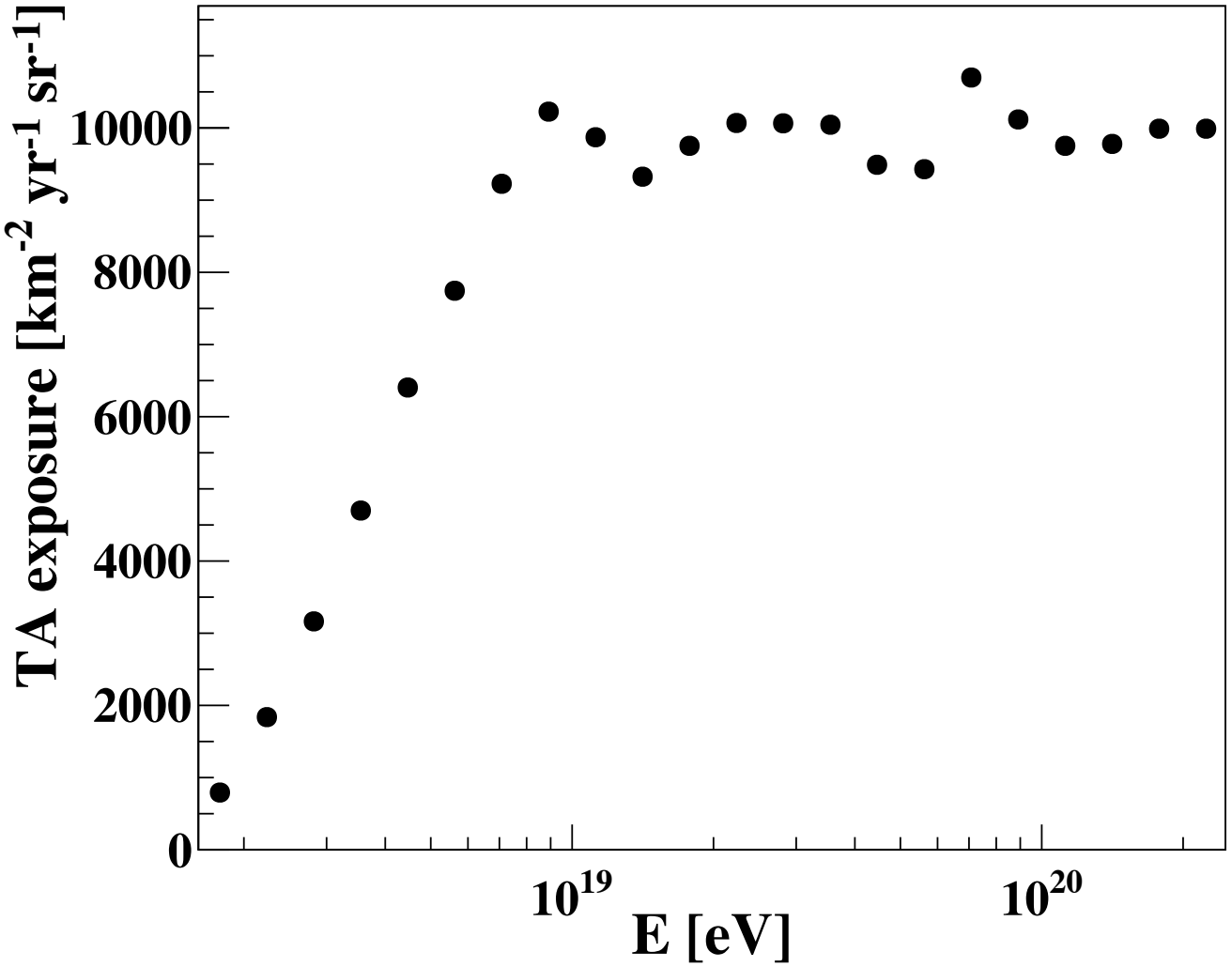
J. T. Brack et al., JINST 8 (2013) P05014

AUGER X-Y SCANNER



Christoph M. Schäfer PoS (ICRC2023) 305

uncertainty in shower energy from absolute telescope calibration ~ 10%


TA exposure [km^{-2} yr^{-1} sr^{-1}]
0
2000
4000
6000
8000
10000
10^{19}
10^{20}
E [eV]