Cherenkov Transparency Coefficient Part 2: Array calibration

CTA CCF Meeting, Barcelona
October 2017

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Cherenkov Transparency Coefficient

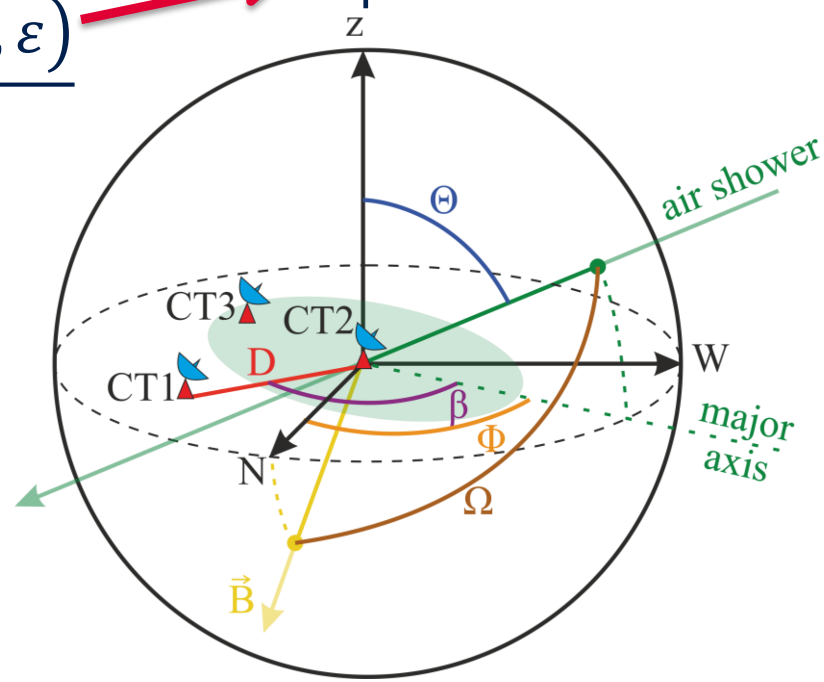
- CTC in CTA:
  - calibrate only within pairs of telescopes
  - apply for many pairs and constrain the calibration quantities

- transparency estimates for telescope pairs *(i, j)*:

$$\tau_{ij}(AOD) = \frac{R_{ij}(AOD, D, \theta, \beta, \vec{B}, \varepsilon)}{F(D, \theta, \beta, \vec{B}, \varepsilon)}$$

experiment

simulations

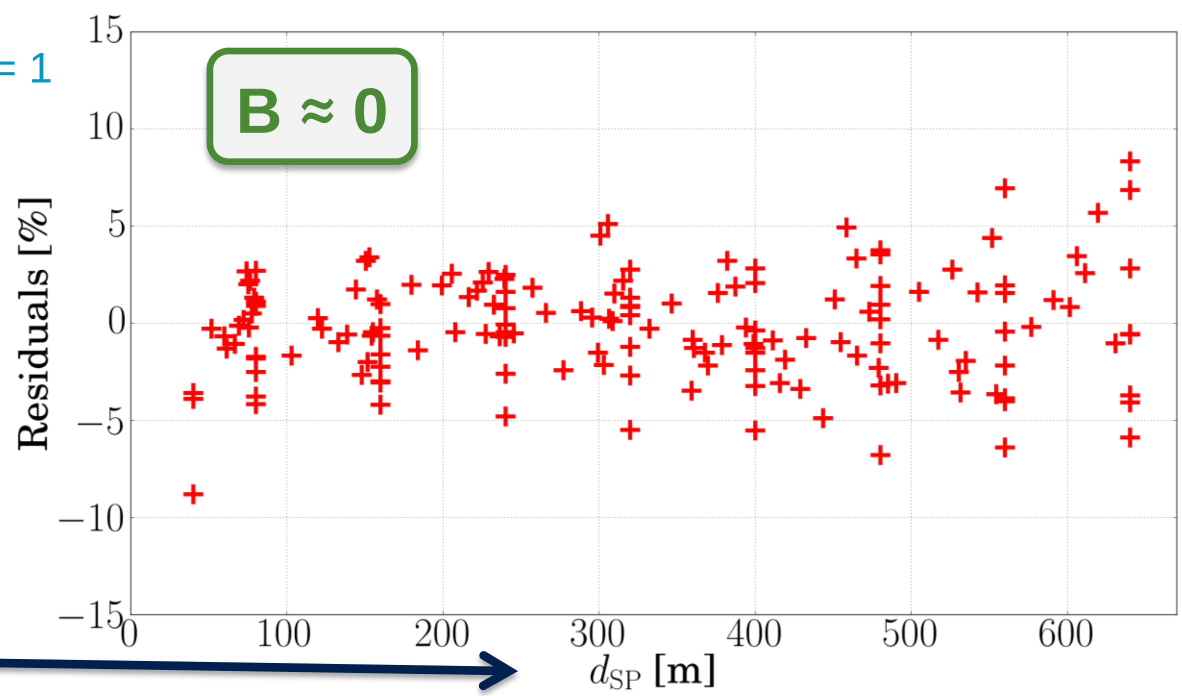


Geometrical configuration

Tuesday talk:

- stereo trigger rate depends on:
  - zenith angle (θ)
  - telescope separation (D)
  - telescope pair alignment w.r.t. shower direction (β)
- β – dependence eliminated if separation expressed in the shower plane:
  - d_{SP} (θ, β)
- fits of the remaining dependencies (θ, d_{SP}) provide the rate estimate $F(D, \theta, \beta)$ for:
  - magnetic field $B \approx 0$
  - telescope efficiencies $\varepsilon_1 = \varepsilon_2 = 1$
  - nominal atmosphere

$$\frac{R_{Fit} - R}{R}$$

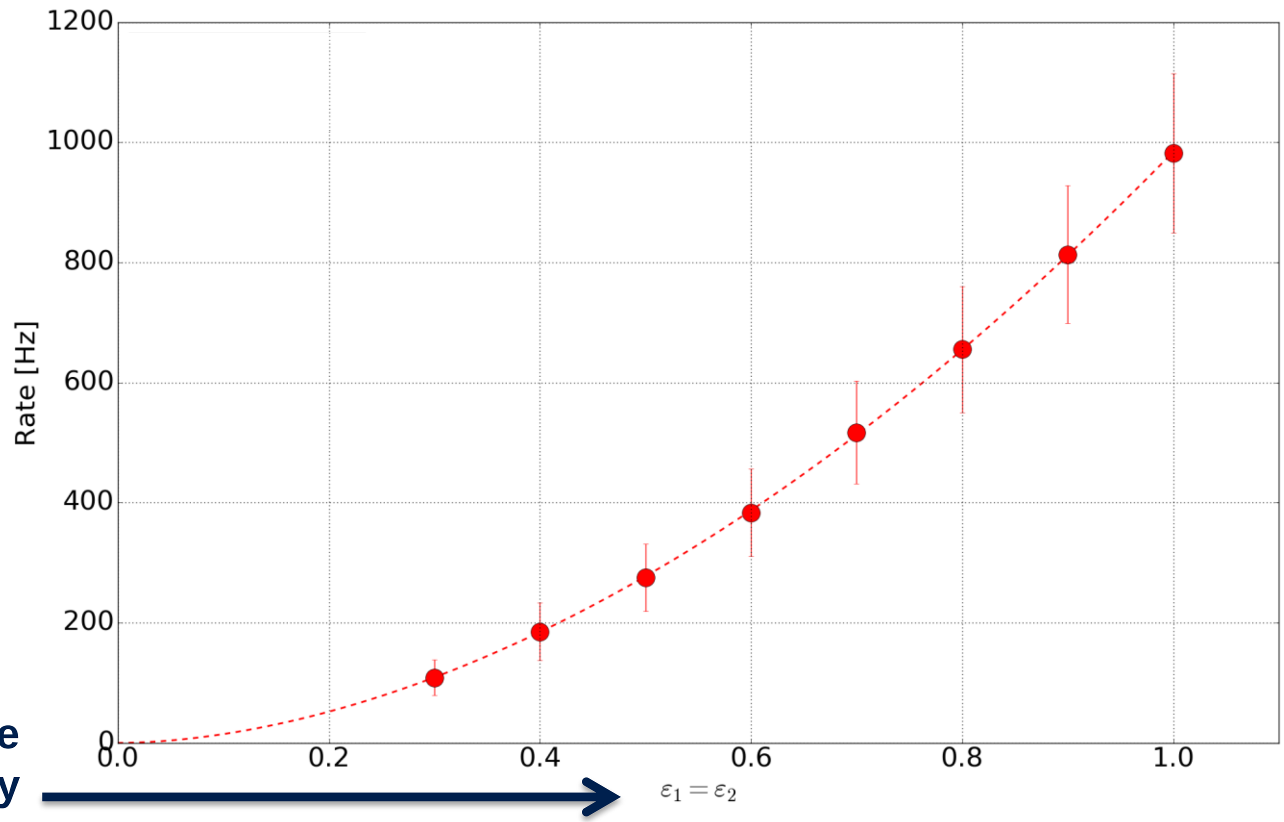


Telescope separation in the shower plane

Hardware dependence

- 2 MST-F in coincidence
- separation between telescopes: d_{SP} **= 150 m**
- telescope detection efficiencies: $\varepsilon_1, \varepsilon_2 \in$ **[0.1, 1.0]**

2 – MST trigger rate



telescope efficiency

Hardware dependence

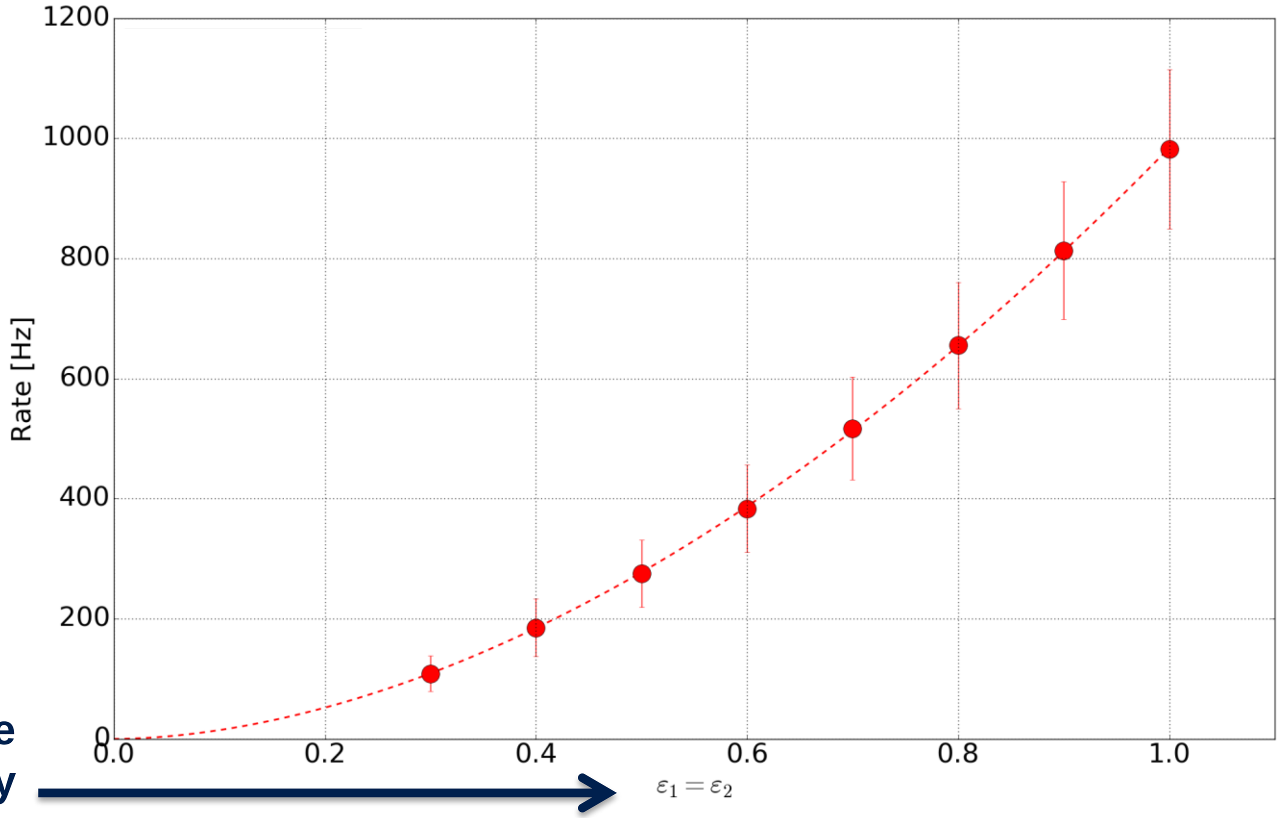
Original concept:

- $Rate \approx (E_{threshold})^{-1.7}$
- $E_{threshold} \approx \varepsilon^{-1}$

$\Big\}$ $\boldsymbol{Rate \approx \varepsilon^{1.7}}$

Holds approximately for stereo rates on condition: $\boldsymbol{\varepsilon_1 = \varepsilon_2 \equiv \varepsilon}$

2 – MST trigger rate



telescope efficiency

Hardware dependence

Original concept:

- $Rate \approx (E_{threshold})^{-1.7}$
- $E_{threshold} \approx \varepsilon^{-1}$

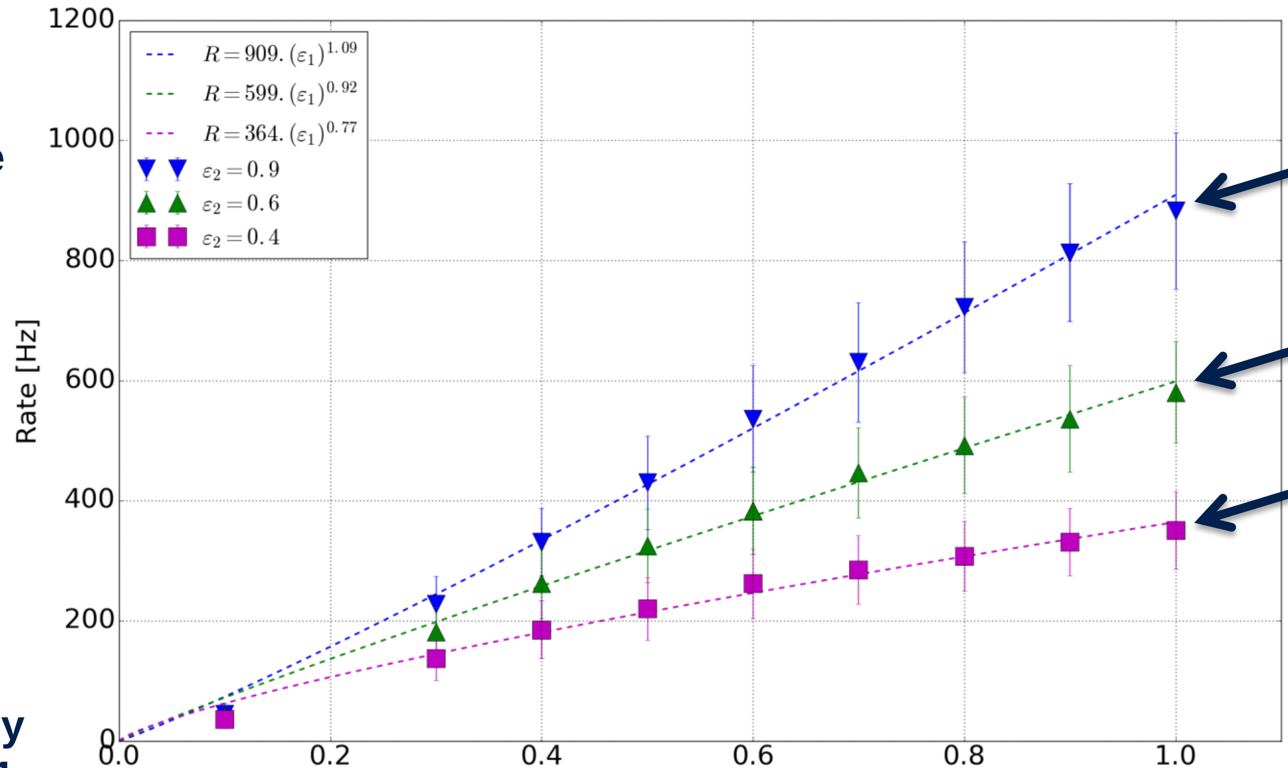
$\Big\}$ $Rate \approx \varepsilon^{1.7}$

What if $\varepsilon_1 \neq \varepsilon_2$?

Stereo trigger rates depend on efficiencies of all involved telescopes!

2 – MST trigger rate

efficiency of MST 2 fixed:



$\varepsilon_2 = 0.9$

$\varepsilon_2 = 0.6$

$\varepsilon_2 = 0.4$

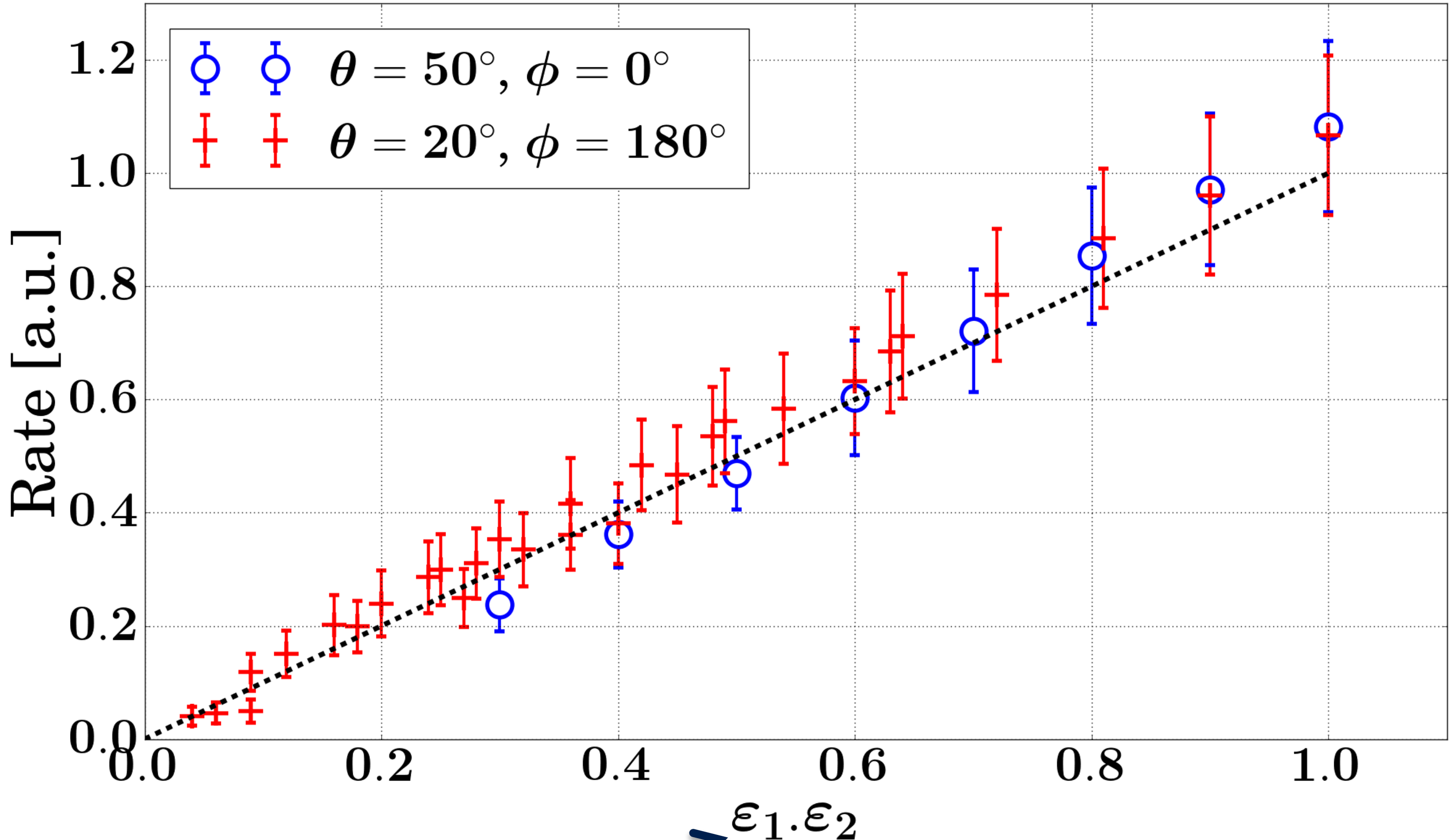
efficiency of MST 1

ε_1

Hardware dependence

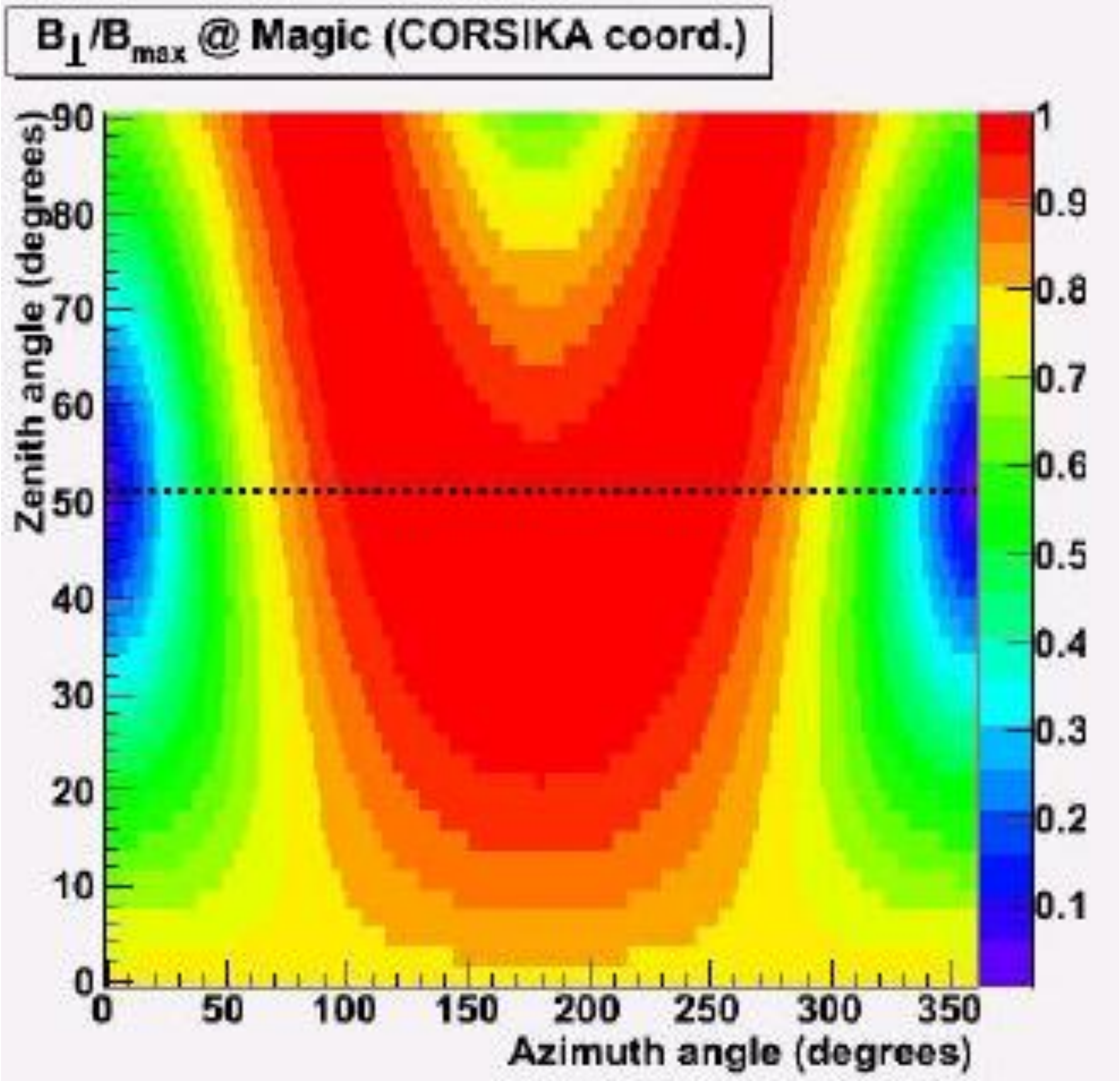
- assumption: *Rate = F* ($\varepsilon_1 . \varepsilon_2$)
  - superposition of all possibilities results in a linear-like behaviour

2 – MST trigger rate



efficiency of MST 1 * efficiency of MST2

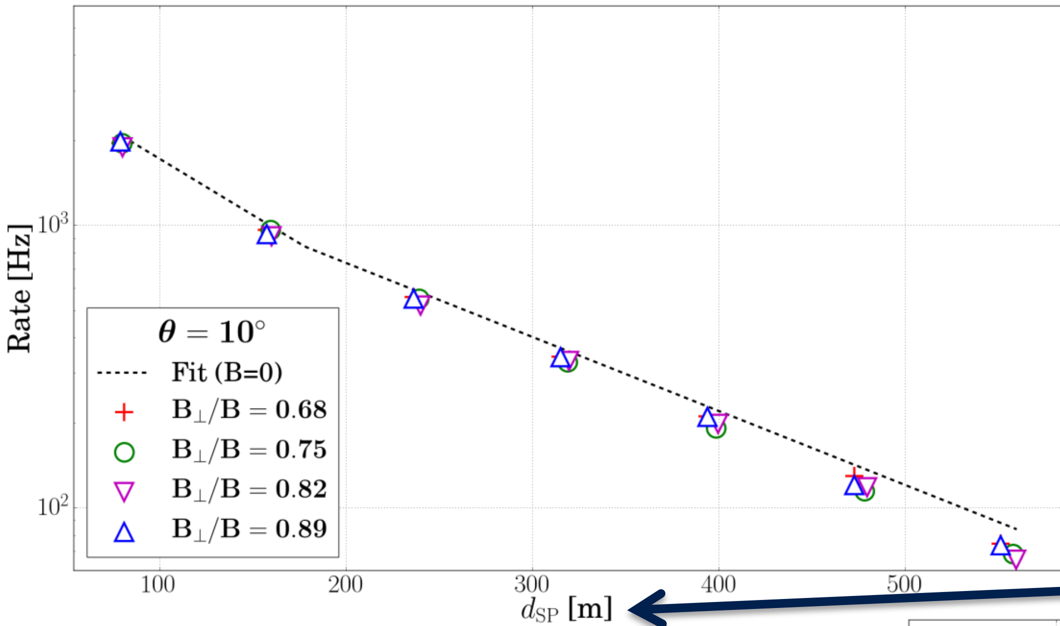
Earth's magnetic field



R. de los Reyes, Ph.D. thesis

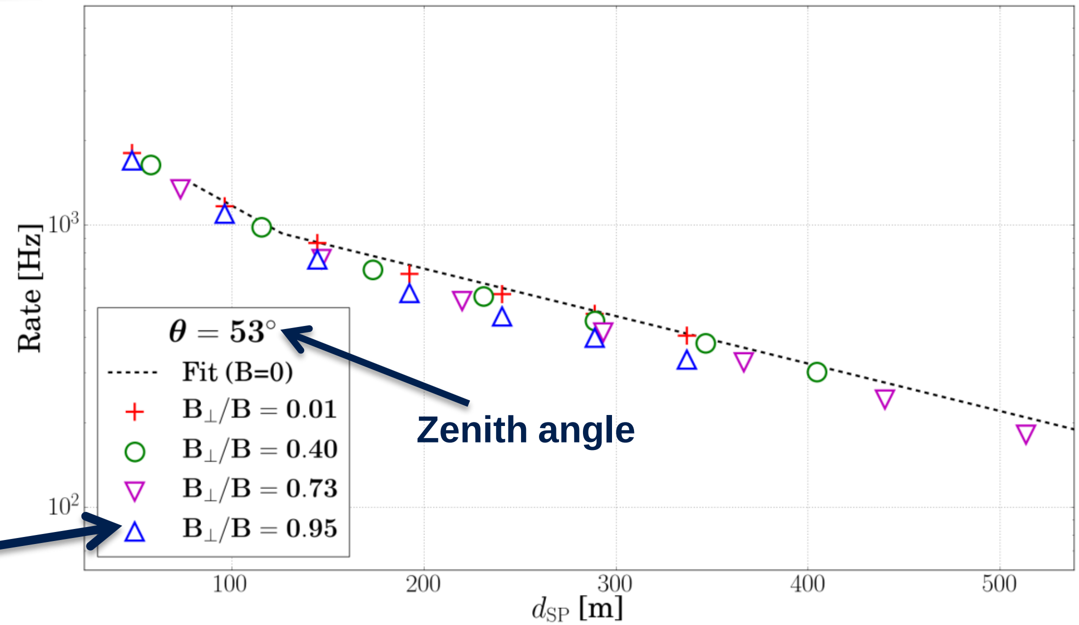
Earth's magnetic field

B ≠ 0



Telescope separation in the shower plane

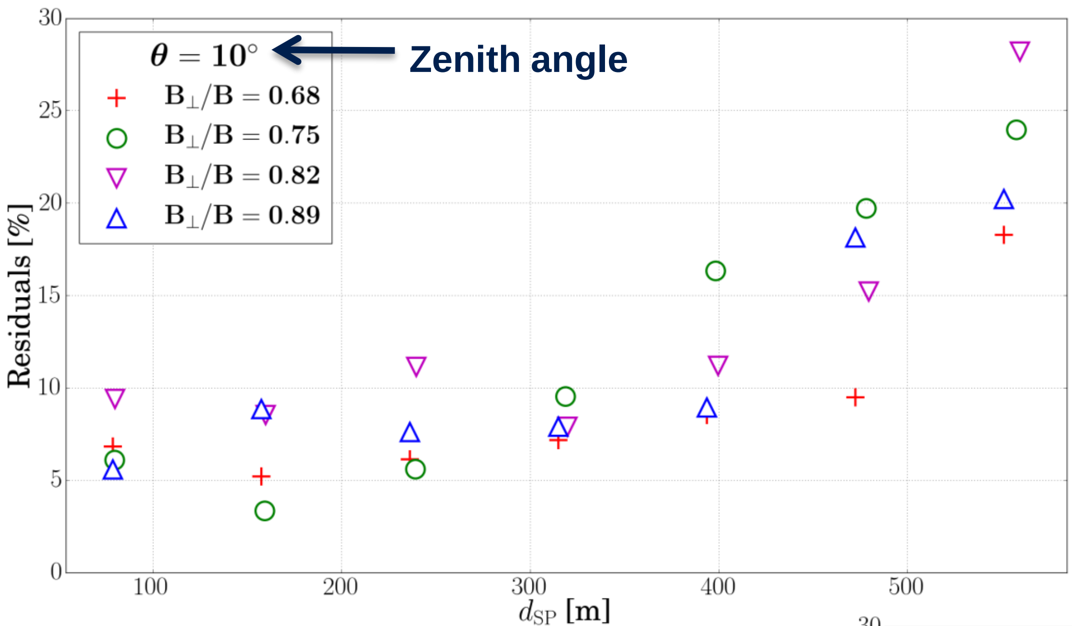
2 – MST trigger rate



Zenith angle

B-component perpendicular to the shower direction

Earth's magnetic field



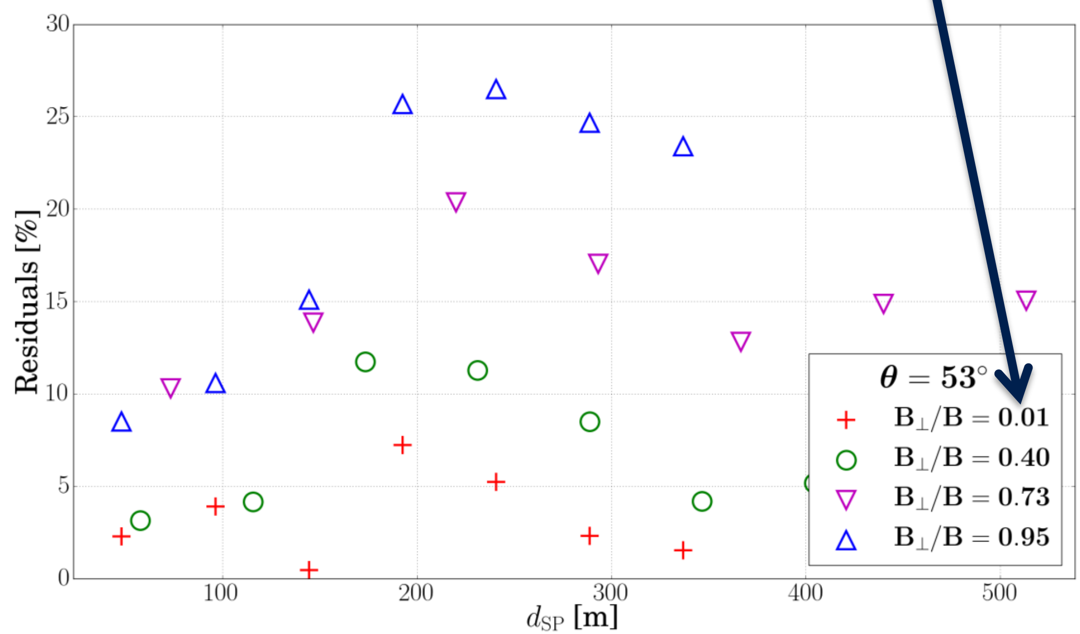
Zenith angle

B ≠ 0

B-component perpendicular to the shower direction

Telescope separation in the shower plane

$$\frac{R_{Fit}\,(B\approx 0) - R\,(B\neq 0)}{R\,(B\neq 0)}$$



Earth's magnetic field

- preliminary idea (ICRC):
  - deviations **R_{Fit} (B≈0) - R (B≠0)** are small for ***d_{SP}* < 200 m** (ascertained from 2 configurations (*θ, Φ*))
  - inter-calibration: **consider only telescope pairs less than 200 m apart and neglect the magnetic field effect**

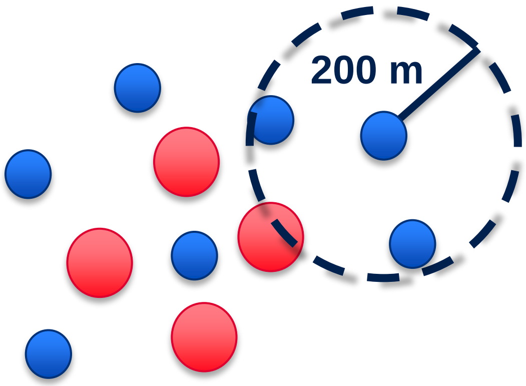
- works quite well for cases when **$B_\perp$ small**

- not so straightforward for **$B_\perp$ >> 0**?
  significant coupling of *B*, *D*, *θ, β* ?
  - at the moment, the biggest (final ?) obstacle
  - is it possible to decouple all dependencies as proposed?
  - look-up tables inevitable?

Inter-calibration

ICRC ’17 (arXiv:1709.01117)

- consider only telescope pairs which are less than 200 m apart



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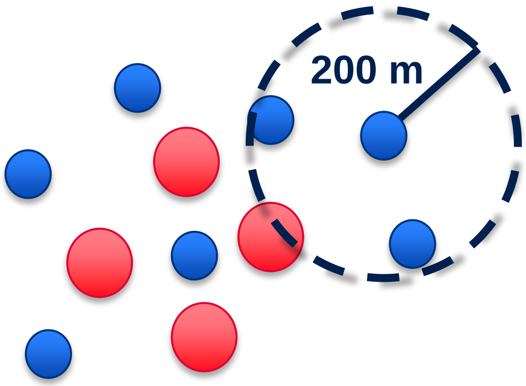

- for each pair (i,j) assume $\varepsilon_1 = \varepsilon_2 = 1$ and define:

$$\tau_{ij}(AOD) = \frac{R_{ij}\left(AOD, D, \theta, \beta, \vec{B}, \varepsilon\right)}{F\left(D, \theta, \beta, \vec{B}, \varepsilon\right)}$$

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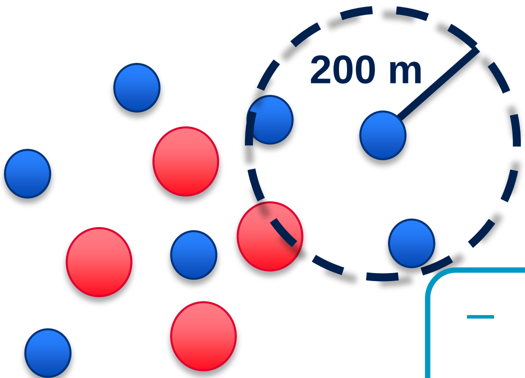

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- $\varepsilon_1 = \varepsilon_2 = 1$
- atmo. conditions uniform

→

- $\tau_{ij} = \tau_{kl} = T$ for all pairs
  (T = true atmo. transparency)

Inter-calibration

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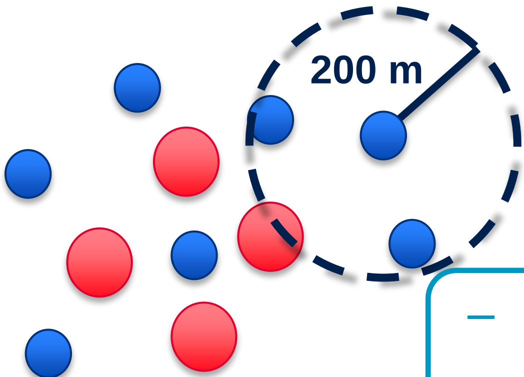

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Inter-calibration

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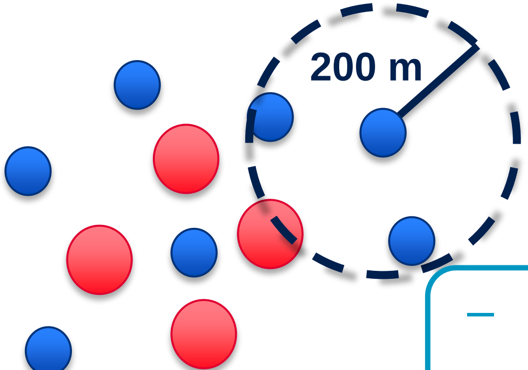

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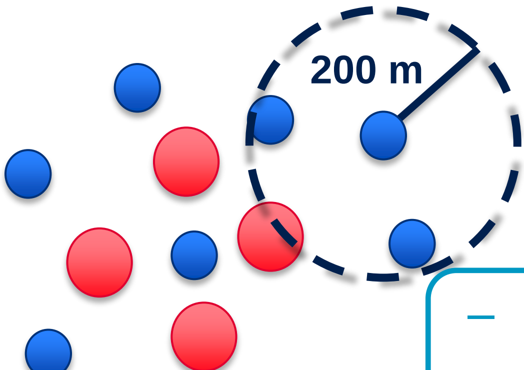
- quantify variations of efficiencies from nominal values as: $a_{ij/kl} = \dfrac{\tau_{ij} - \tau_{kl}}{\tau_{ij} + \tau_{kl}}$

Inter-calibration

ICRC '17 (arXiv:1709.01117)

- consider only telescope pairs which are less than 200 m apart



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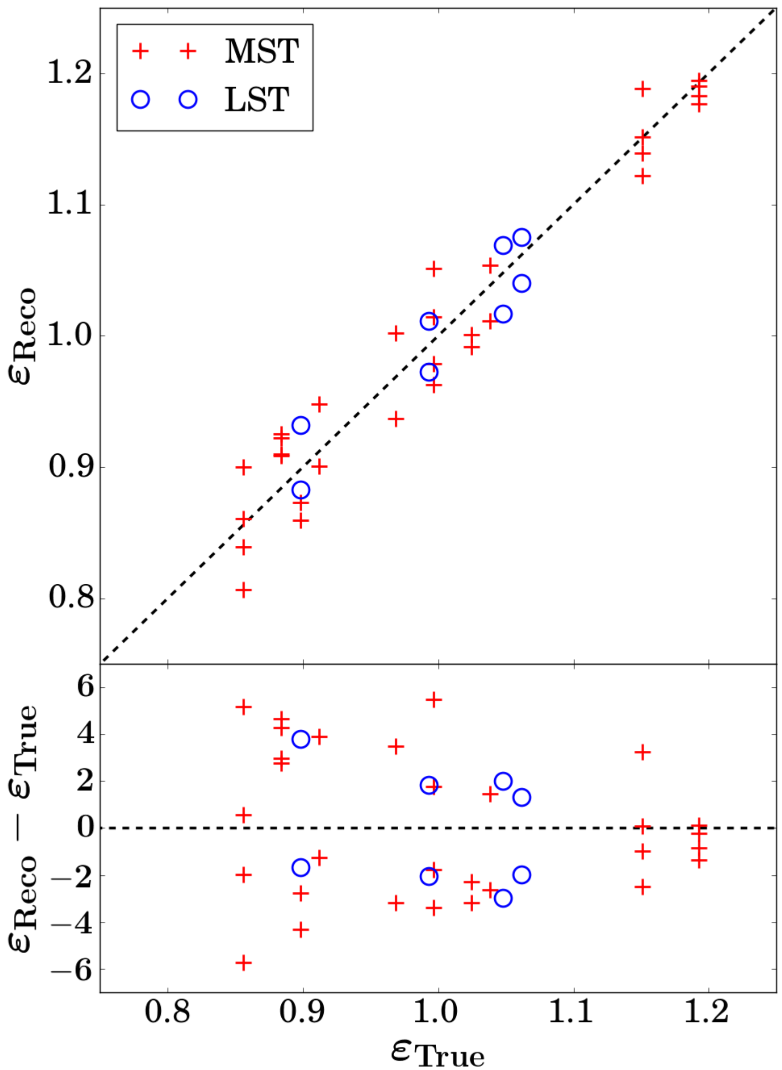
- quantify variations of efficiencies from nominal values as: $a_{ij/kl} = \dfrac{\tau_{ij} - \tau_{kl}}{\tau_{ij} + \tau_{kl}}$
- treat optical efficiencies $\boldsymbol{\varepsilon}$ as free parameters:

$$\chi^2 = \sum_{\text{pairs}} \frac{\left[a_{ij/kl} - \dfrac{\varepsilon_i.\varepsilon_j - \varepsilon_k.\varepsilon_l}{\varepsilon_i.\varepsilon_j + \varepsilon_k.\varepsilon_l}\right]^2}{\sigma^2_{ij/kl}}$$

Inter-calibration

ICRC '17 (arXiv:1709.01117)

- described procedure inspired by approach using reconstructed shower energies (A. Mitchell et al. 2015)



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$$\chi^2 = \sum_{\mathrm{pairs}} \frac{\left[a_{ij/kl} - \dfrac{\varepsilon_i.\varepsilon_j - \varepsilon_k.\varepsilon_l}{\varepsilon_i.\varepsilon_j + \varepsilon_k.\varepsilon_l} \right]^2}{\sigma^2_{ij/kl}}$$

- applied to the full CTA-N layout:
  - 3AL4M15-5-F
  - 3 configurations (θ, Φ)
  - randomly assigned telescope efficiencies from $\mathcal{N}(0.7, 0.1)$
  - inter-calibration separately for MST and LST sub-systems

To-do list

- solve the magnetic field issue
- parametrize the stereo trigger rate for SSTs
- cross-calibration of telescopes of different types

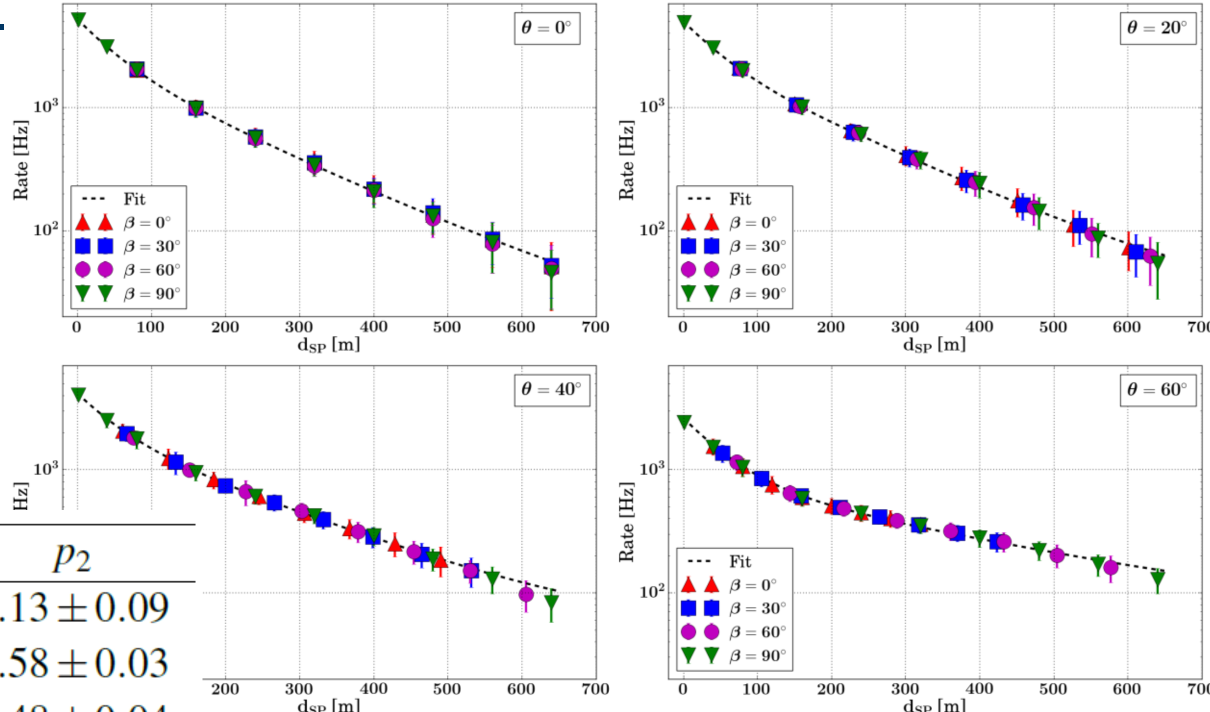
Summary

Feasibility study of the CTC for array calibration:

- quantification of the influence of the zenith & azimuth angles, telescope alignment (Tuesday)
- updated hardware dependence correction
- ongoing study of the Earth’s magnetic field influence
- inter-calibration performing well for the $B \approx 0$ case
- preliminary results presented at ICRC ’17 (poster)
- cross-calibration under study

Back-up

Back-up

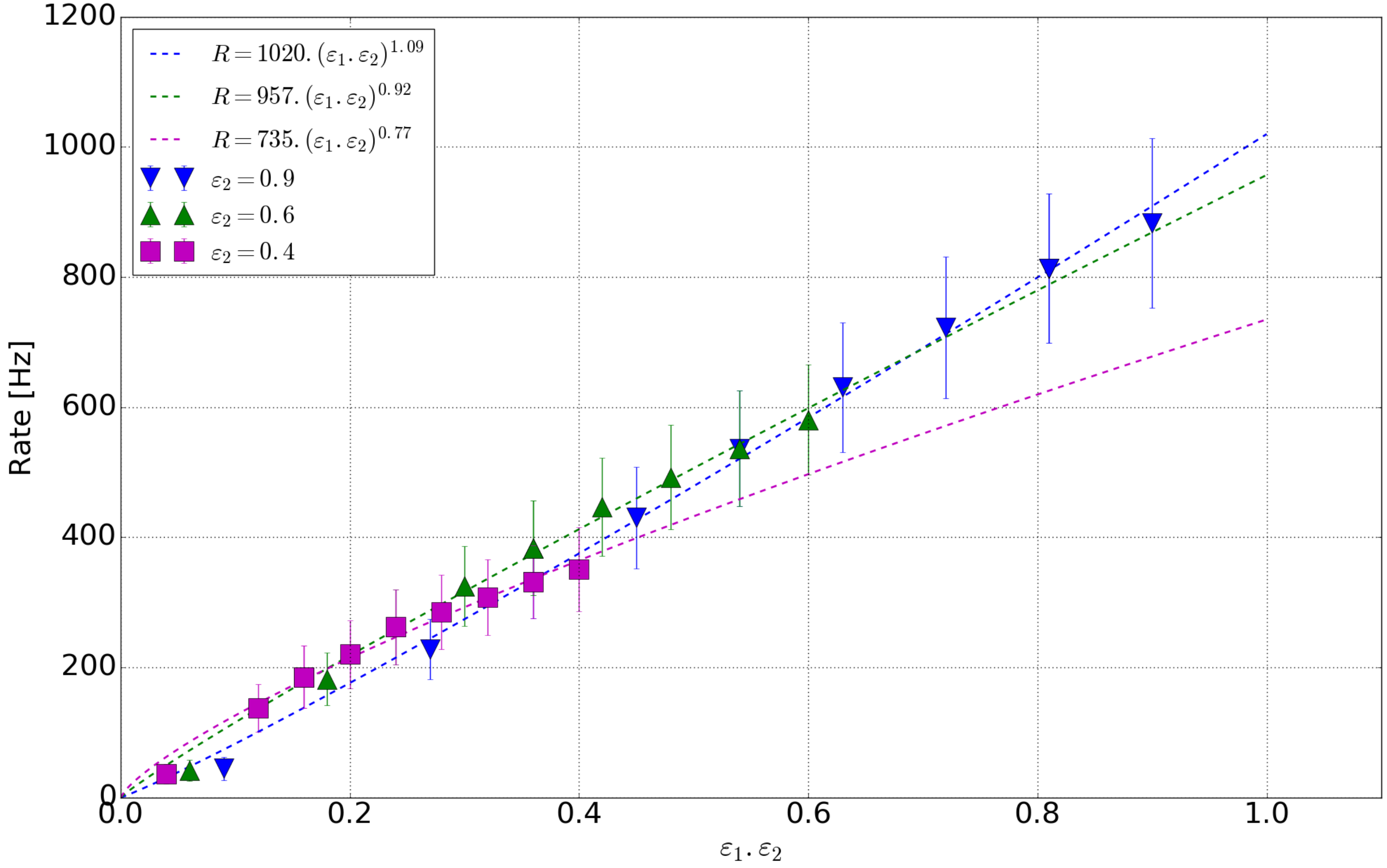


P	p_0	p_1	p_2
A_0	934 ± 14	15.9 ± 9.9	1.13 ± 0.09
A_2	$(7.4 \pm 0.4)\mathrm{e}^{-3}$	-3.7 ± 0.4	0.58 ± 0.03
A_3	184 ± 9	-6.5 ± 2.2	0.48 ± 0.04

Table 1: Fit results of the parameters of the Eq.(2.2) to the relation $P = p_0 \cdot [1 + \exp(p_1 \cdot (\cos\theta - p_2))]^{-1}$. A_1 can be described by the expression $p_0 \cdot [\cos(p_1 \cdot \theta - p_2)] + p_3$, where $p_0 = (5.9 \pm 0.5)\mathrm{e}^{-4}$, $p_1 = 6.2 \pm 0.3$, $p_2 = 53.9 \pm 7.4$, $p_3 = (8.63 \pm 0.03)\mathrm{e}^{-3}$ and θ is given in degrees.

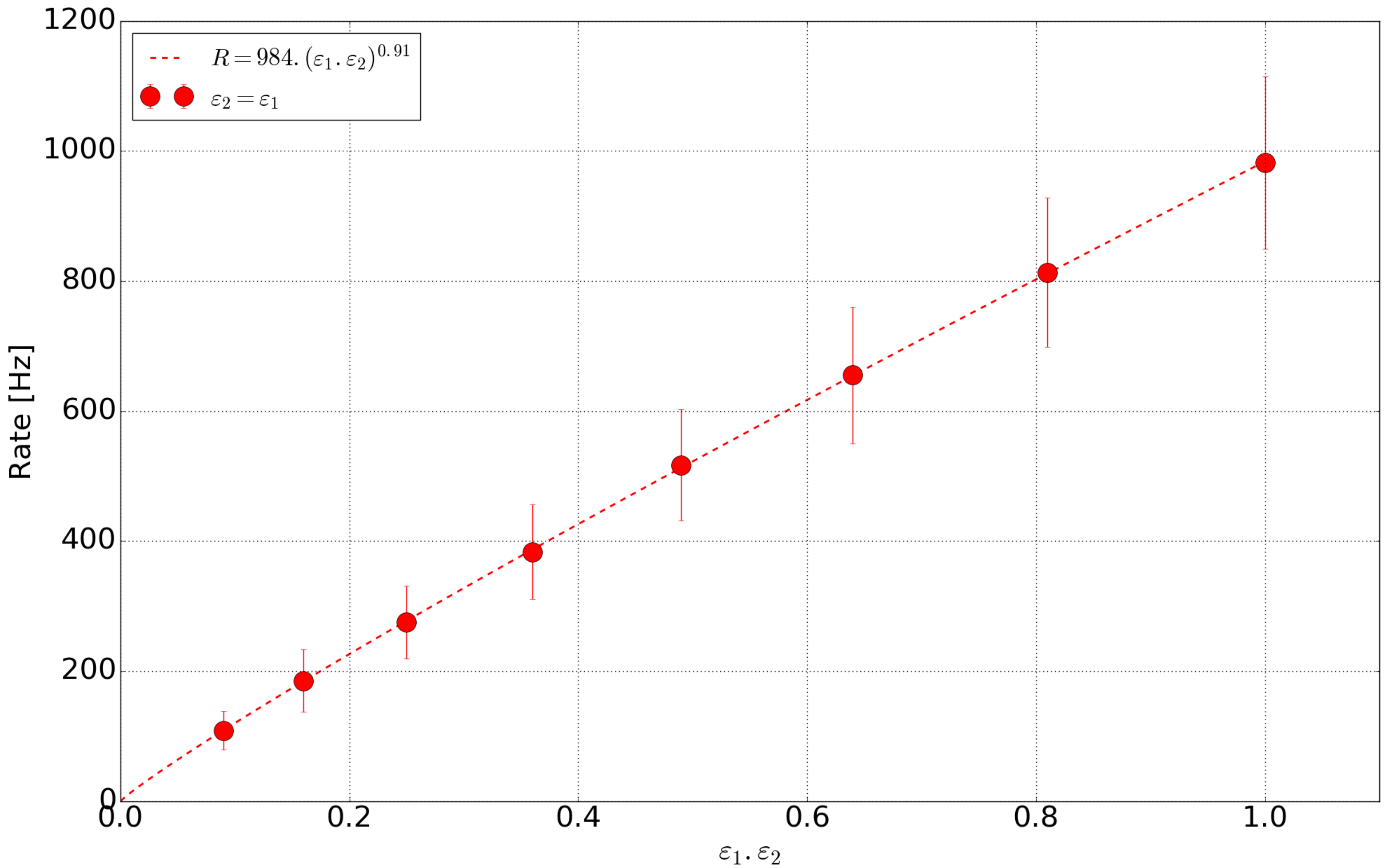
$$R_{\mathrm{Fit}}(d_{\mathrm{SP}}) = \begin{cases} A_0 \cdot e^{A_1 \cdot (d_{\mathrm{SP}} - A_3)}, & \text{if } d_{\mathrm{SP}} < A_3 \\ A_0 \cdot e^{A_2 \cdot (d_{\mathrm{SP}} - A_3)}, & \text{if } d_{\mathrm{SP}} > A_3. \end{cases}$$

Back-up



$R = 1020.\,(\varepsilon_1.\,\varepsilon_2)^{1.09}$
$R = 957.\,(\varepsilon_1.\,\varepsilon_2)^{0.92}$
$R = 735.\,(\varepsilon_1.\,\varepsilon_2)^{0.77}$
$\varepsilon_2 = 0.9$
$\varepsilon_2 = 0.6$
$\varepsilon_2 = 0.4$
Rate [Hz]
1200
1000
800
600
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
$\varepsilon_1.\,\varepsilon_2$

Back-up



$R = 984.\,(\varepsilon_1\,.\,\varepsilon_2)^{0.91}$
$\varepsilon_2 = \varepsilon_1$
1200
1000
800
600
400
200
0
Rate [Hz]
0.0
0.2
0.4
0.6
0.8
1.0
$\varepsilon_1\,.\,\varepsilon_2$

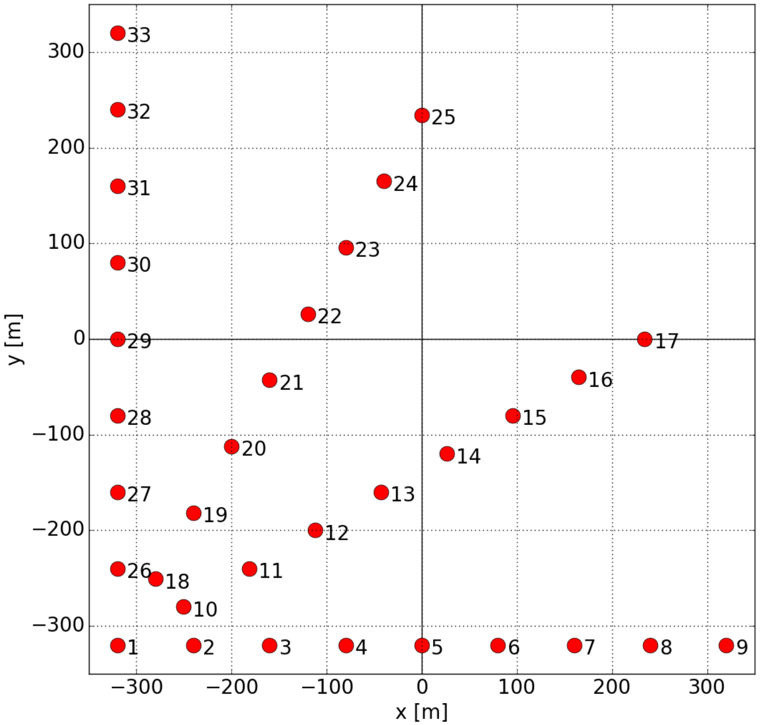
Monte Carlo simulations

- CORSIKA (v. 6990) + sim_telarray (21/12/2016)
- primary particles: **protons**
- energy range: **4 GeV – 100 TeV**
- site: **La Palma**
- atmospheric profile: **atm. 36**
- aerosols: **atm_trans_2147_1_3_0_0_0**
- number of showers: **250000**
- core re-scattering: **20**
- telescopes: **MST-F**, **LST**
- array layout: **3AL4M15-5-F + some “testing” layouts**
- jobs: **> 50**

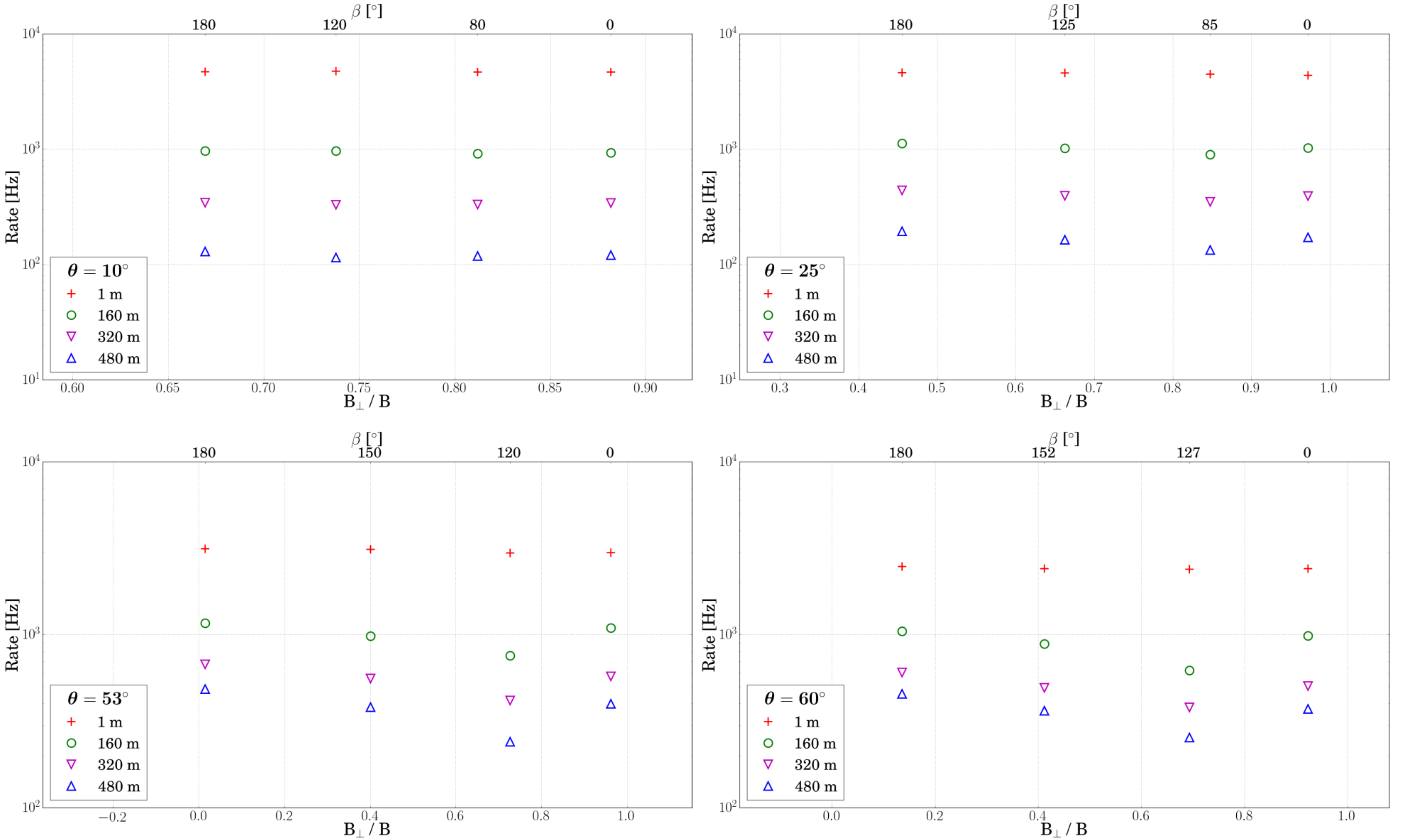
Monte Carlo simulations

- fixed azimuth $\boldsymbol{\Phi = 0^o}$ (i.e. along the x-axis)
- zenith angle $\boldsymbol{\theta \in [0^o,60^o]}$
- fixed magnetic field $\boldsymbol{B \approx 0}$
- telescope separation $\boldsymbol{D \in [1\text{ m}, 640\text{ m}]}$
- telescope alignment w.r.t.

  the shower direction $\boldsymbol{\beta \in [0^o,90^o]}$
- fixed telescope efficiencies $\boldsymbol{\varepsilon = 1.0}$
- **fixed atmosphere**



Earth's magnetic field



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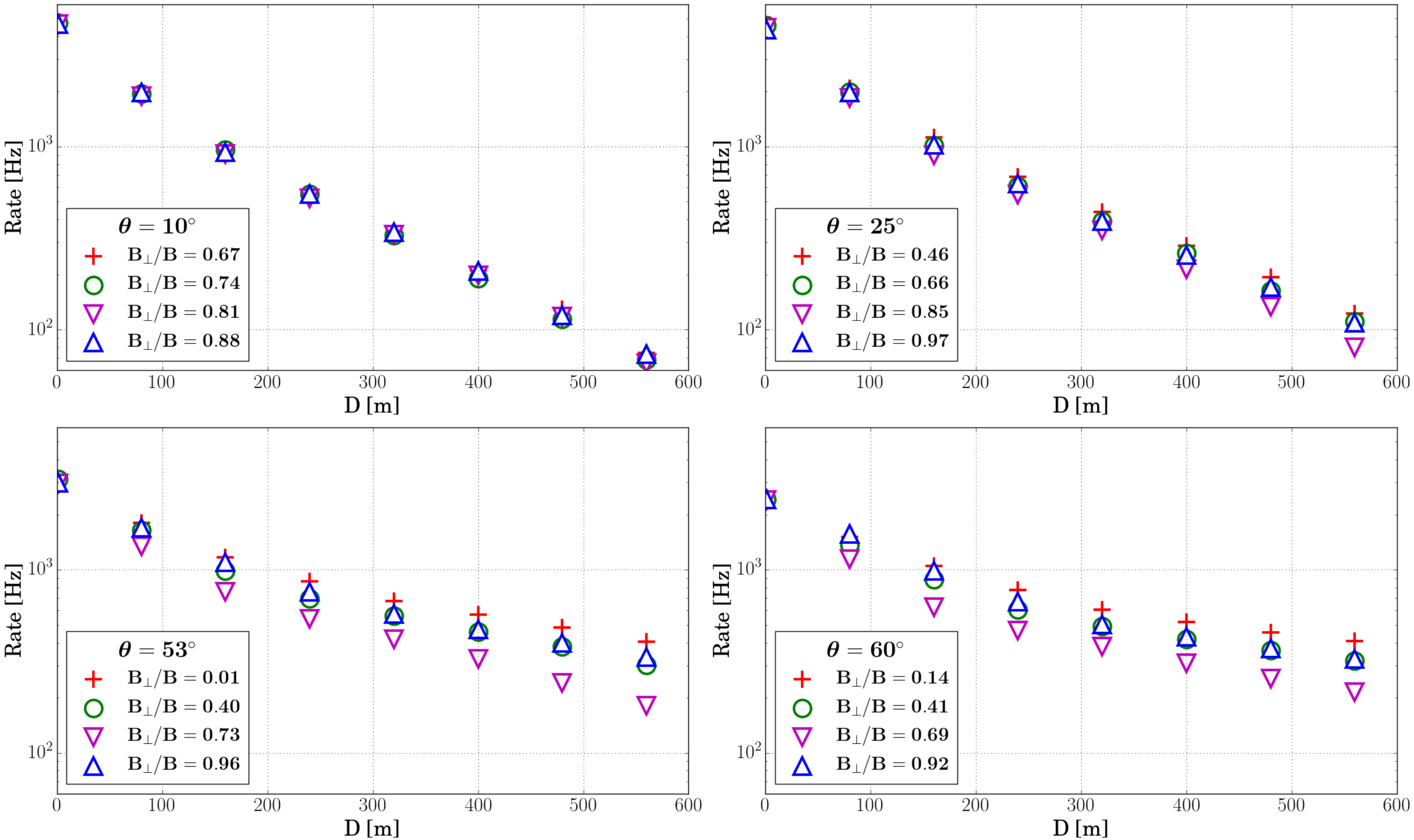
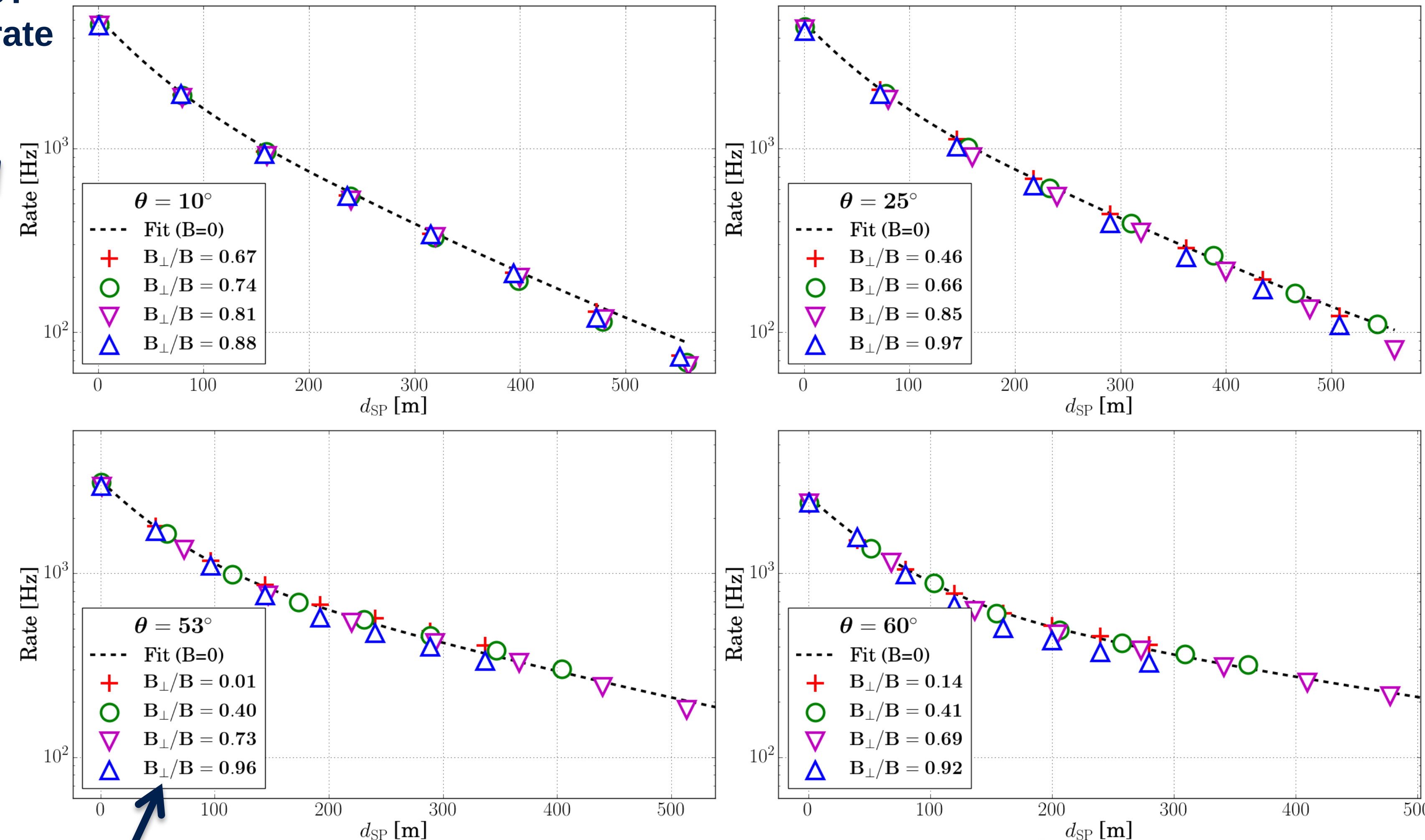


Earth's magnetic field

$\vec{B} \neq 0$

2 – MST trigger rate



B-component perpendicular to the shower direction

Telescope separation in the shower plane