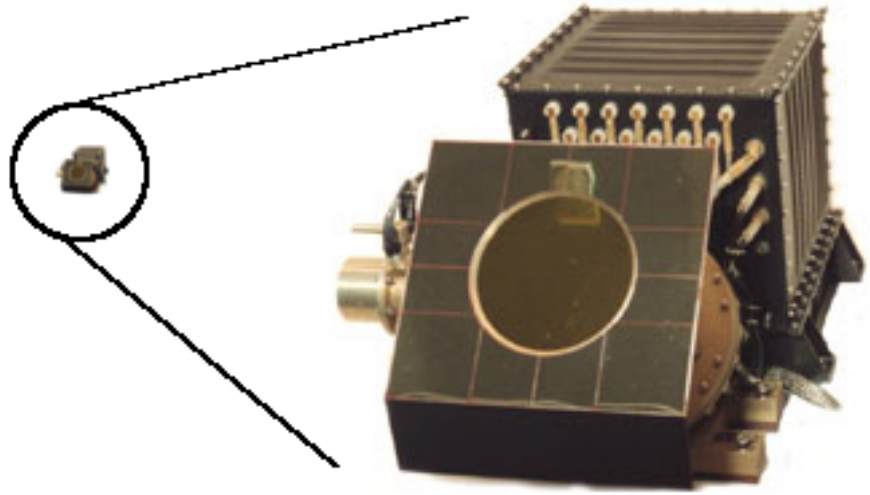
Solar Energetic Particle Events with Protons above 500 MeV between 1995 and 2015 Measured with SOHO/EPHIN

Patrick Kühl [1], N. Dresing [1], B. Heber [1], A. Klassen [1]

[1] Institute for Experimental and Applied Physics, University of Kiel

AMS Workshop Washington DC, Apr 25th, 2017

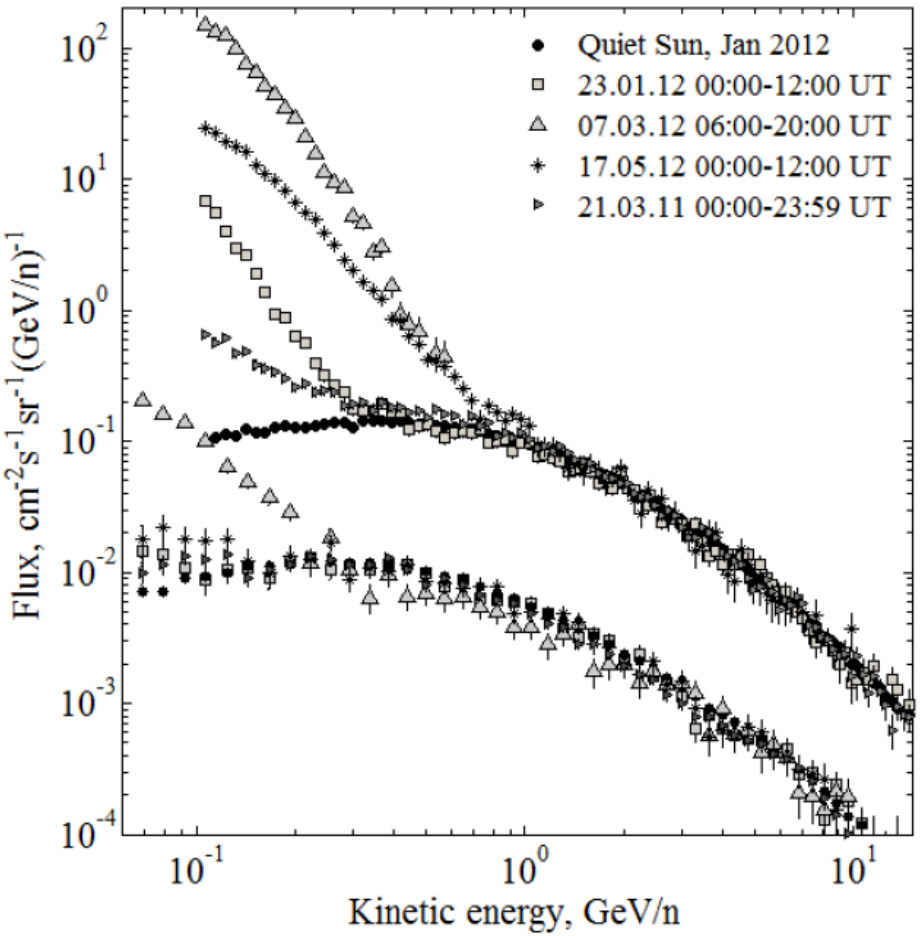

AMS-02
AMS-02



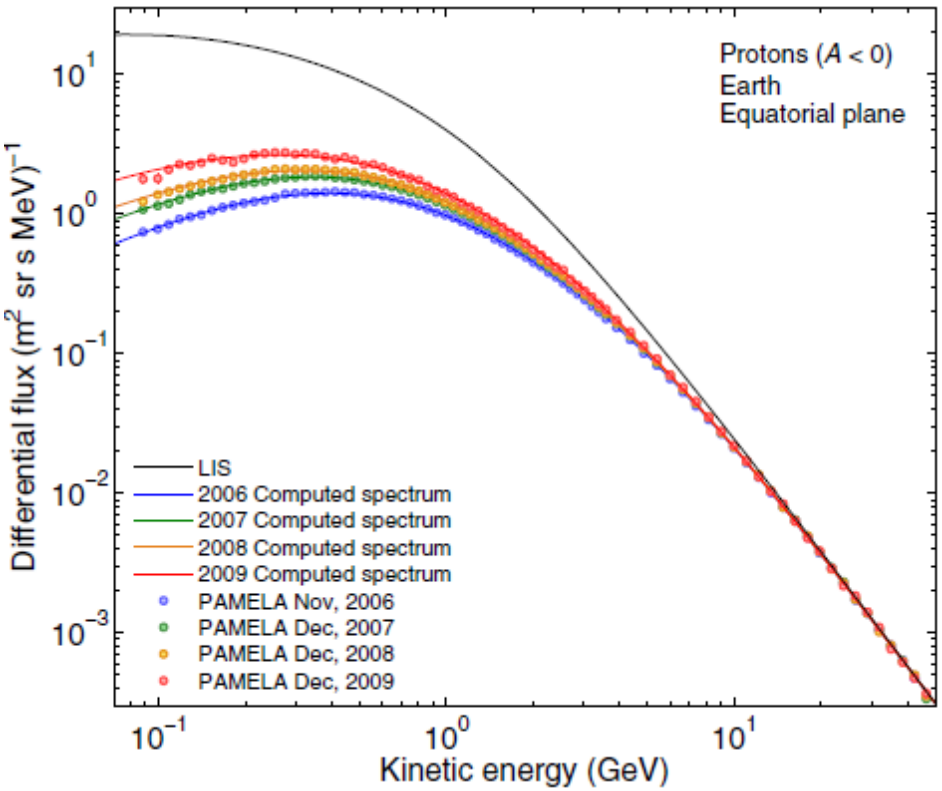
AMS-02	EPHIN
7500 kg	3.55 kg
500 x 400 x 300 cm^3	35 x 33 x 19 cm^3
10 Mbit/sec	172 bit/sec
4500 cm^2 sr	4.5 cm^2 sr
$\approx$ 0.4 - 1000 GeV	5 - 50 MeV
ISS	L1
May 2011	Dec 1995

AMS-02: Kountine, 2012; Bindi, 2015
EPHIN: Müller-Mellin et al., 1995

Scientific motivation



Bazilevskaya et al., 2013



Adriani et al., 2013

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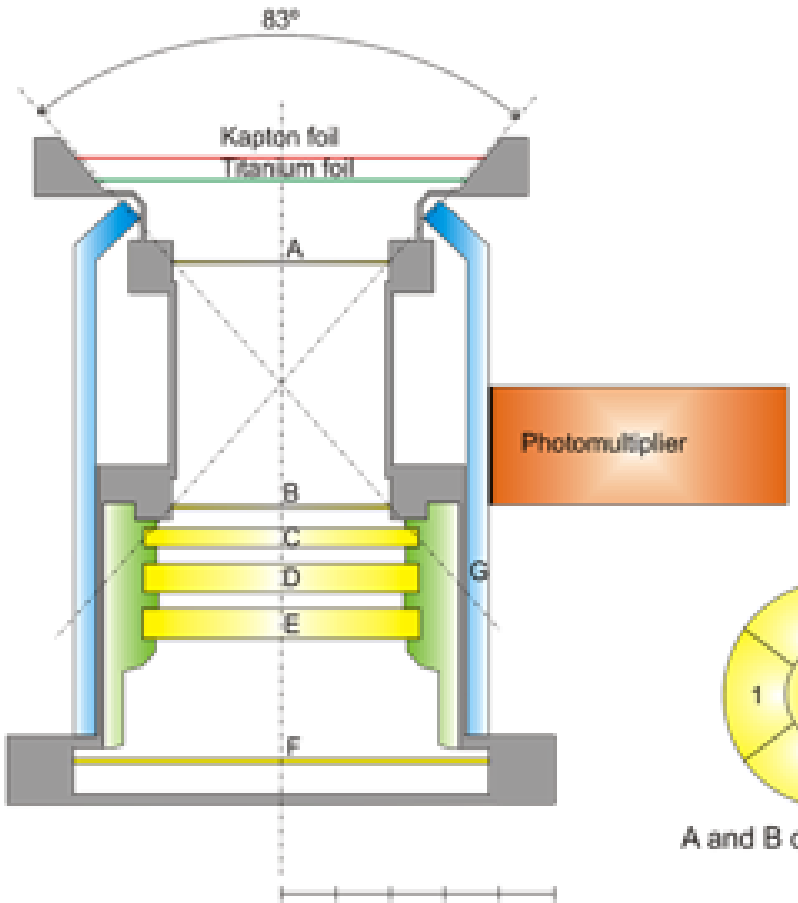
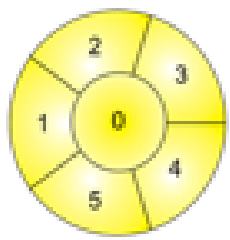
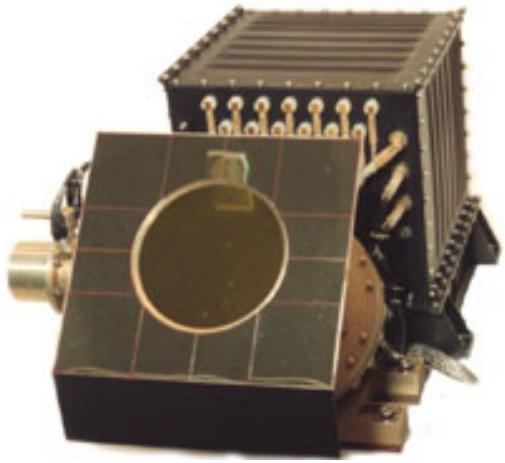
The EPHIN sensor head





A and B detectors

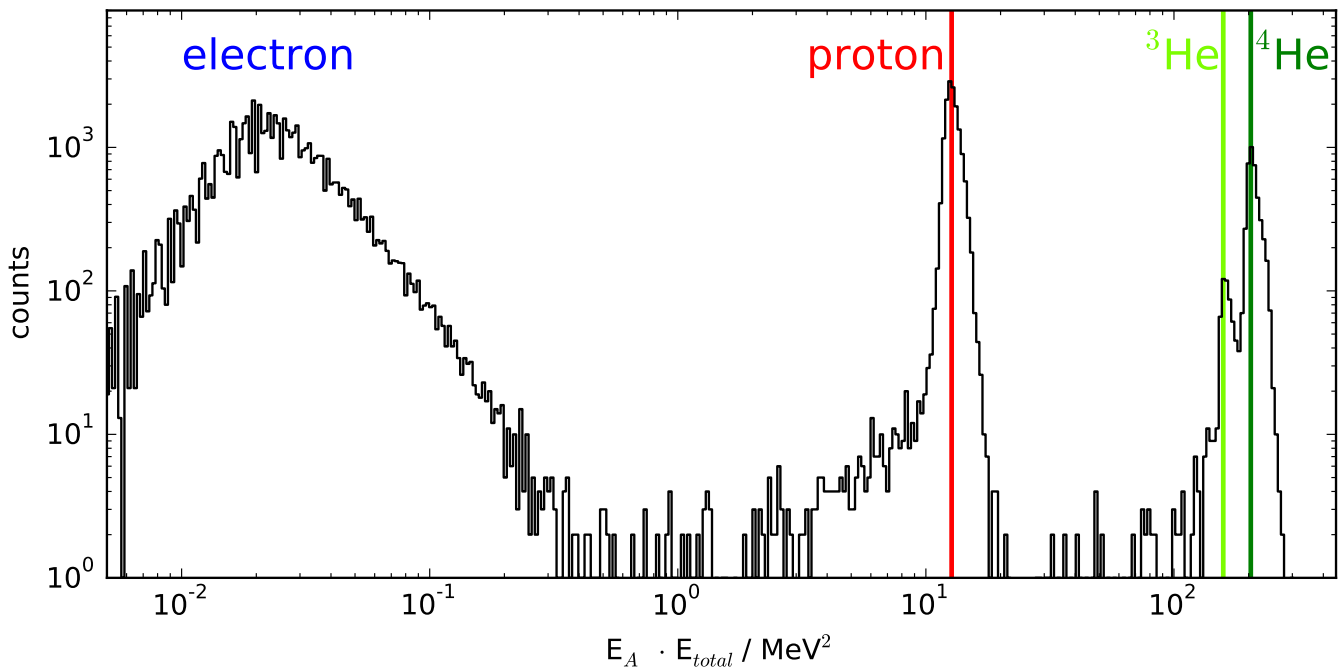


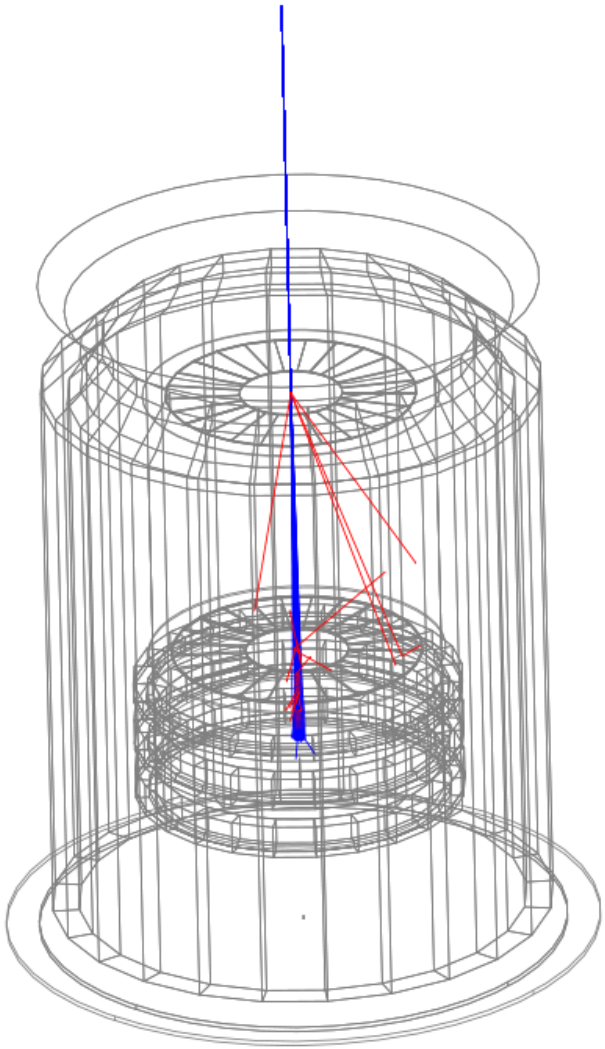
- stack of six solid state detectors
- enclosed by an anti-coincidence
- count rates of different channels
- energy loss in every detector for a statistical sample

dE/dx-E technique

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z_P^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left(\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right) \propto \frac{z_P^2}{\beta^2} \quad ; \quad \beta = \frac{v}{c}$$

$$E = \frac{1}{2} m v^2 \quad \rightarrow \quad dE/dx \cdot E \propto z^2 m$$





required information:

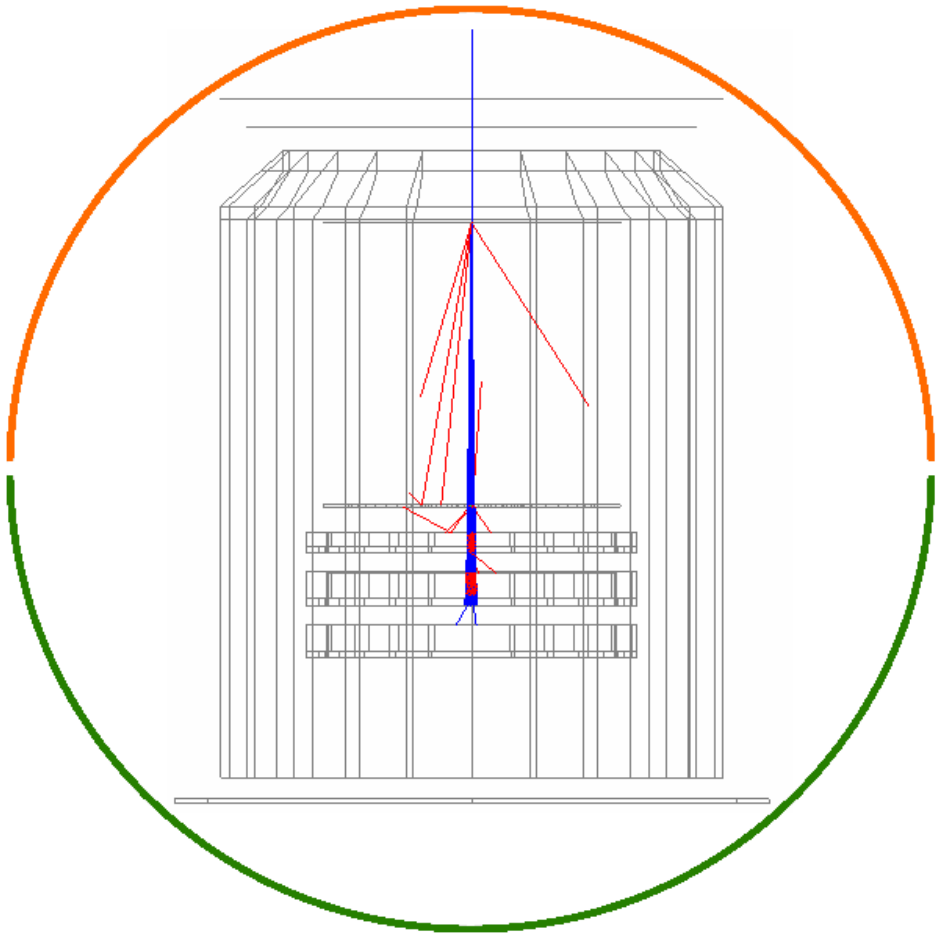
- particle identification
- total energy

available information:

- energy losses in all detectors

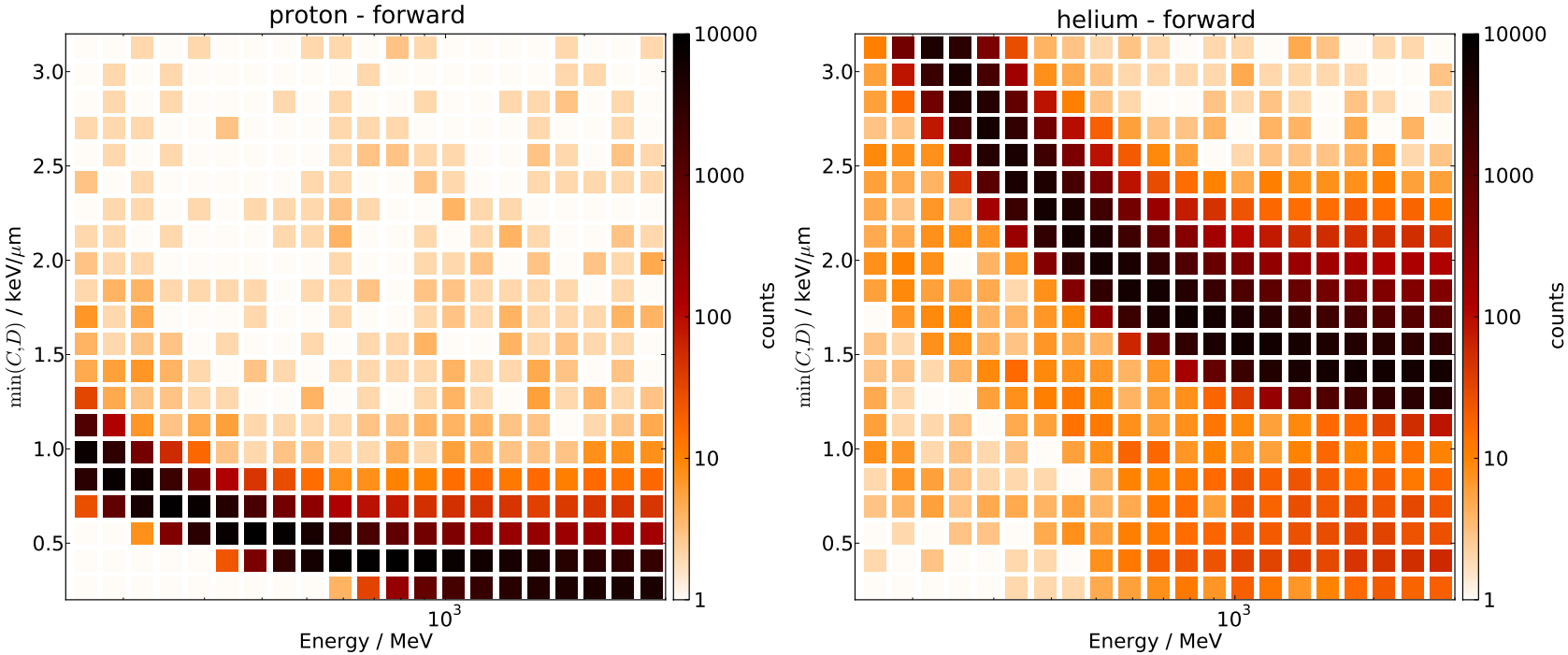
approach:

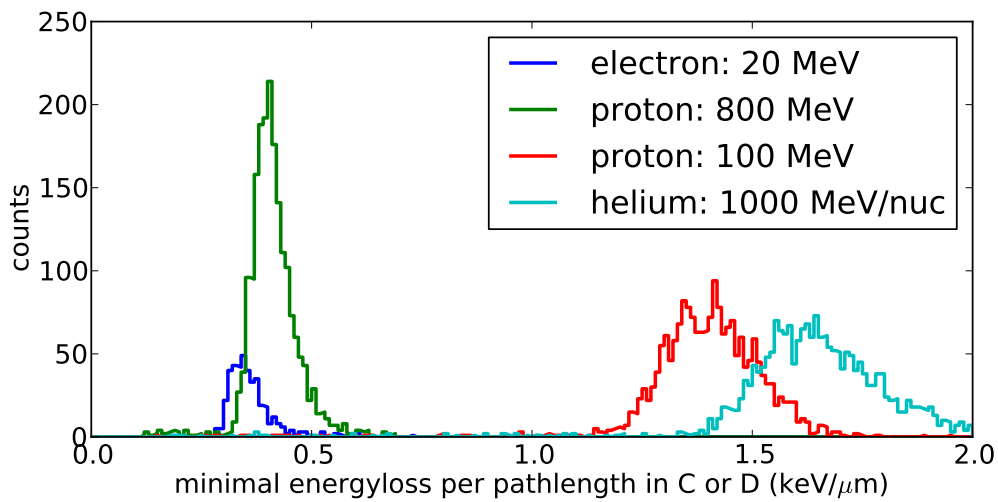
- GEANT4 Monte Carlo simulation

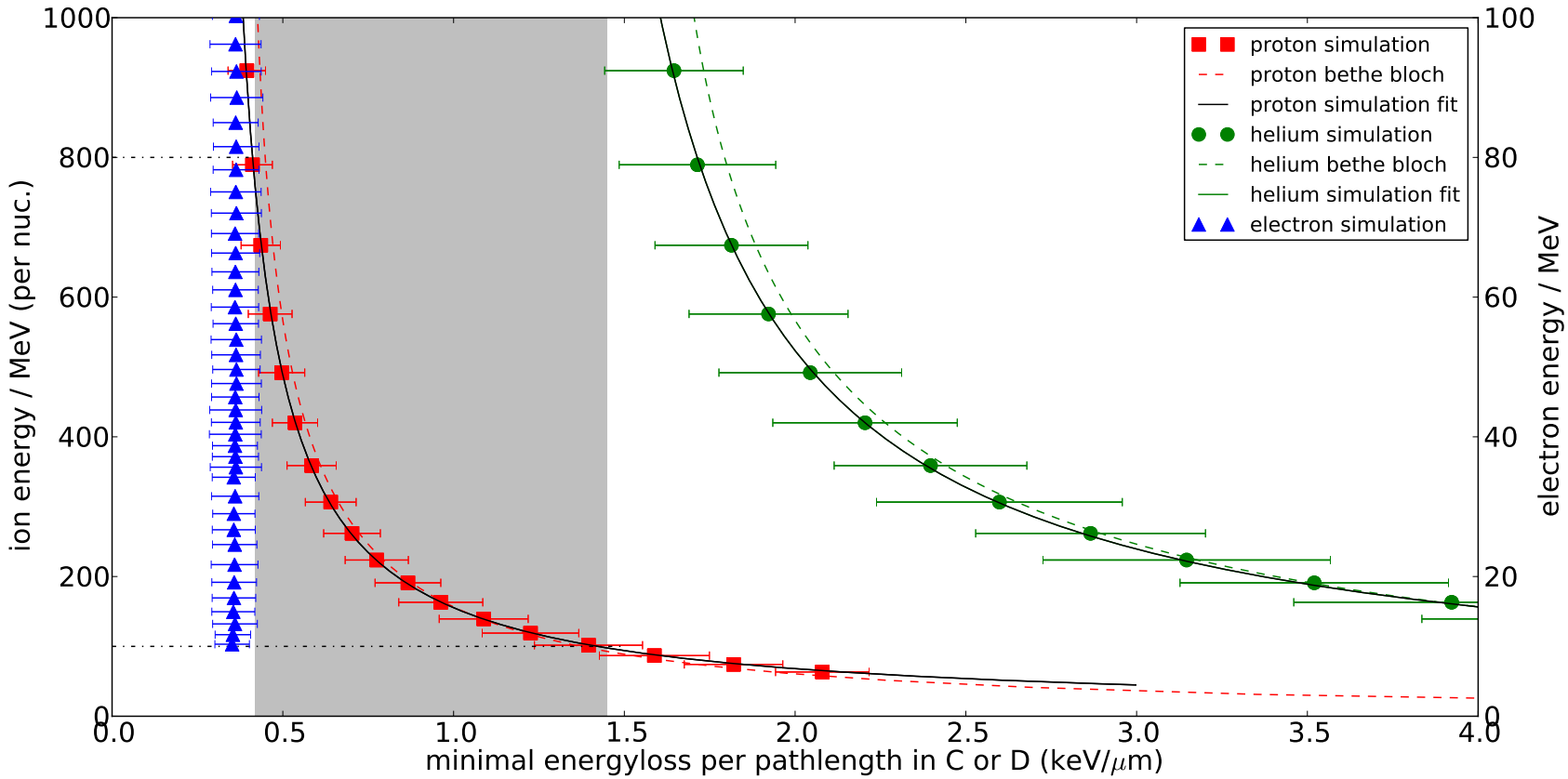


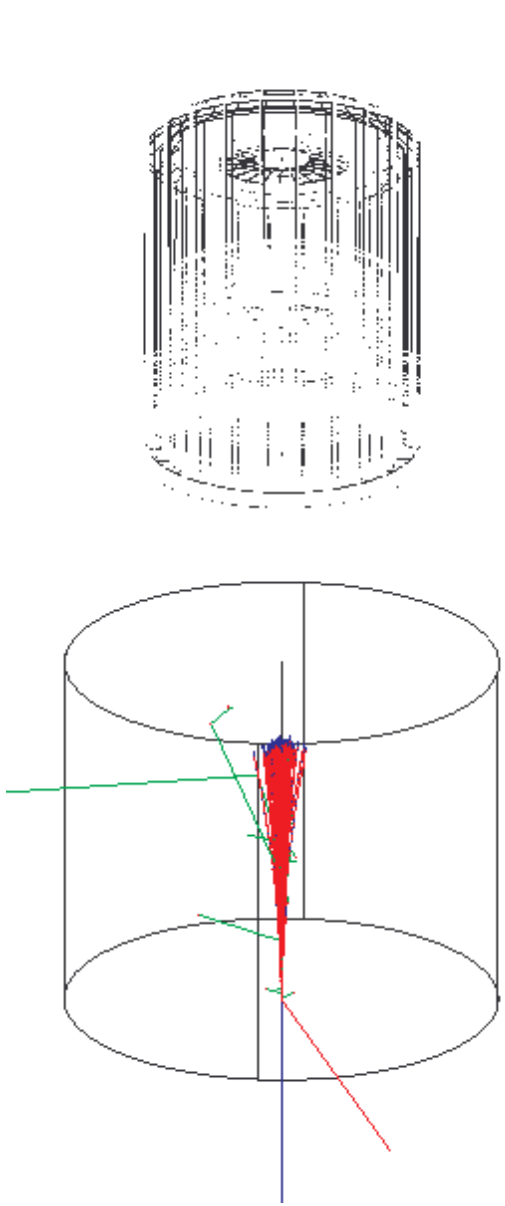
- forward penetrating particles
- backward penetrating particles

forward penetrating particles

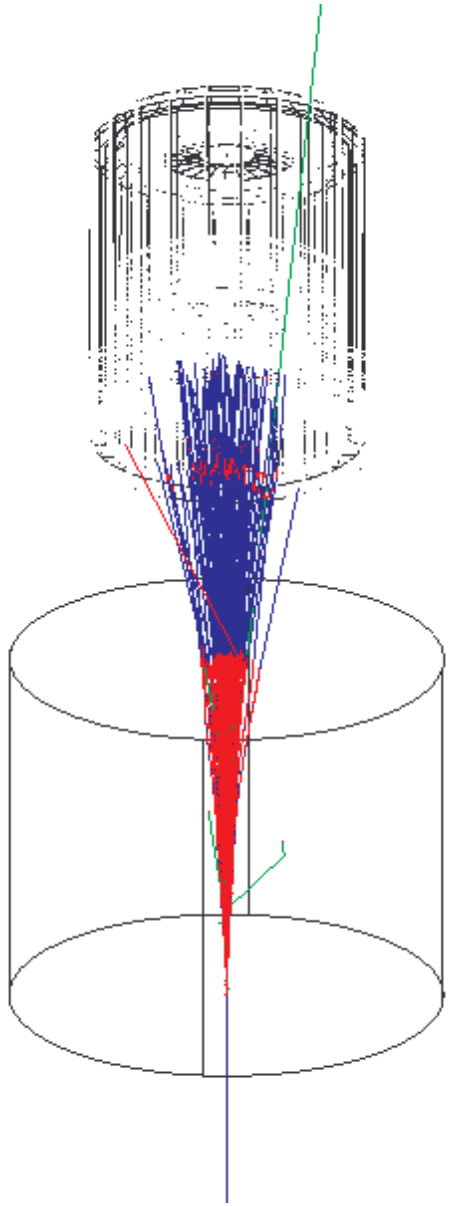




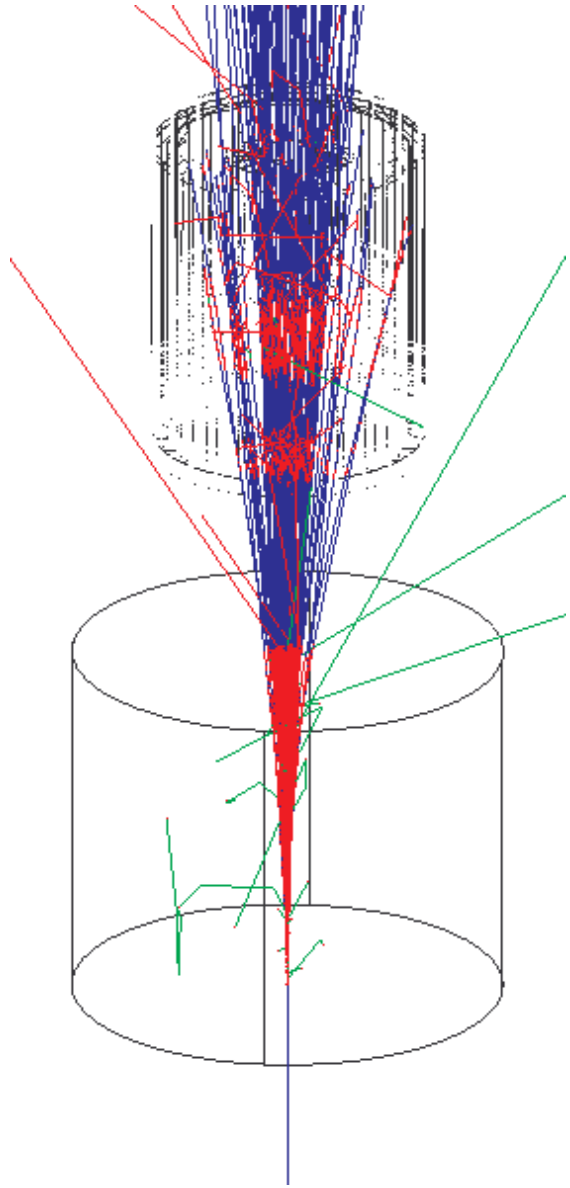

proton simulation
proton bethe bloch
proton simulation fit
helium simulation
helium bethe bloch
helium simulation fit
electron simulation
ion energy / MeV (per nuc.)
electron energy / MeV
minimal energyloss per pathlength in C or D (keV/μm)
0
200
400
600
800
1000
0
20
40
60
80
100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0



150 MeV

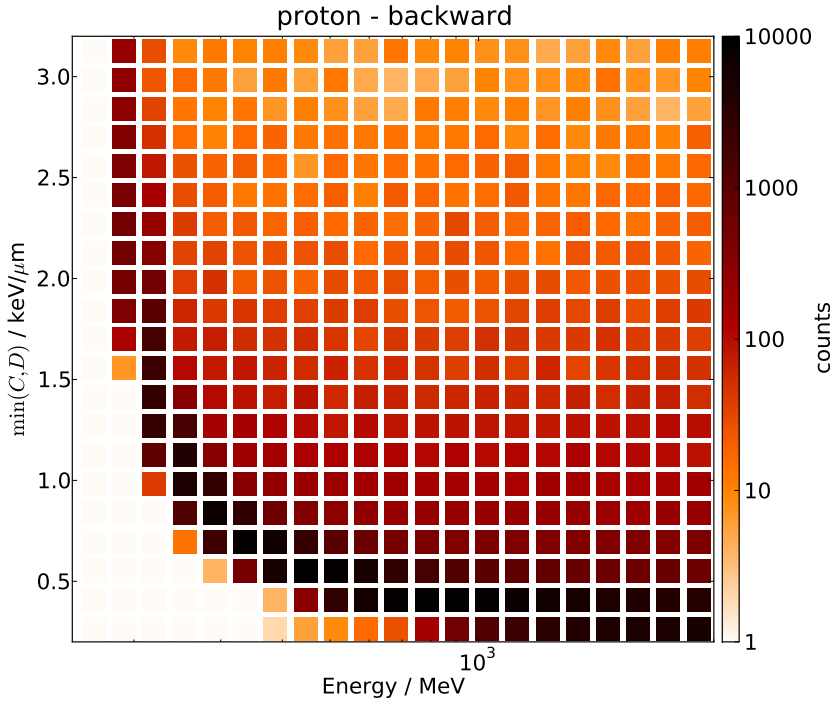


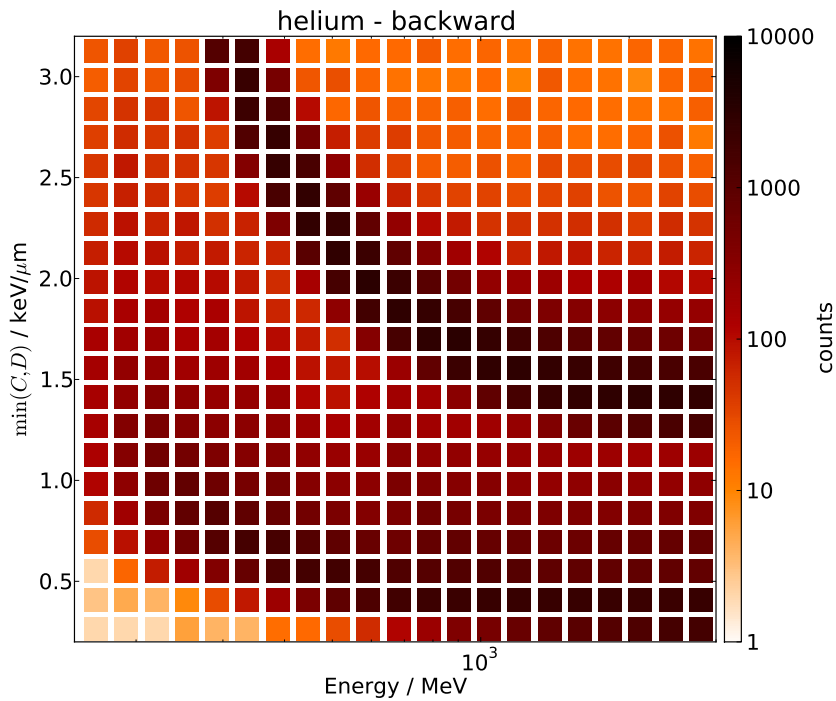
180 MeV

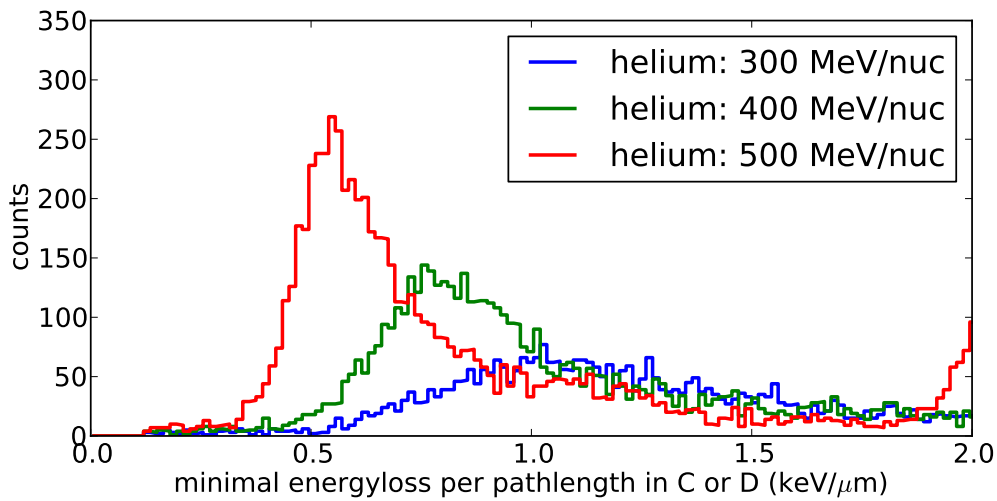


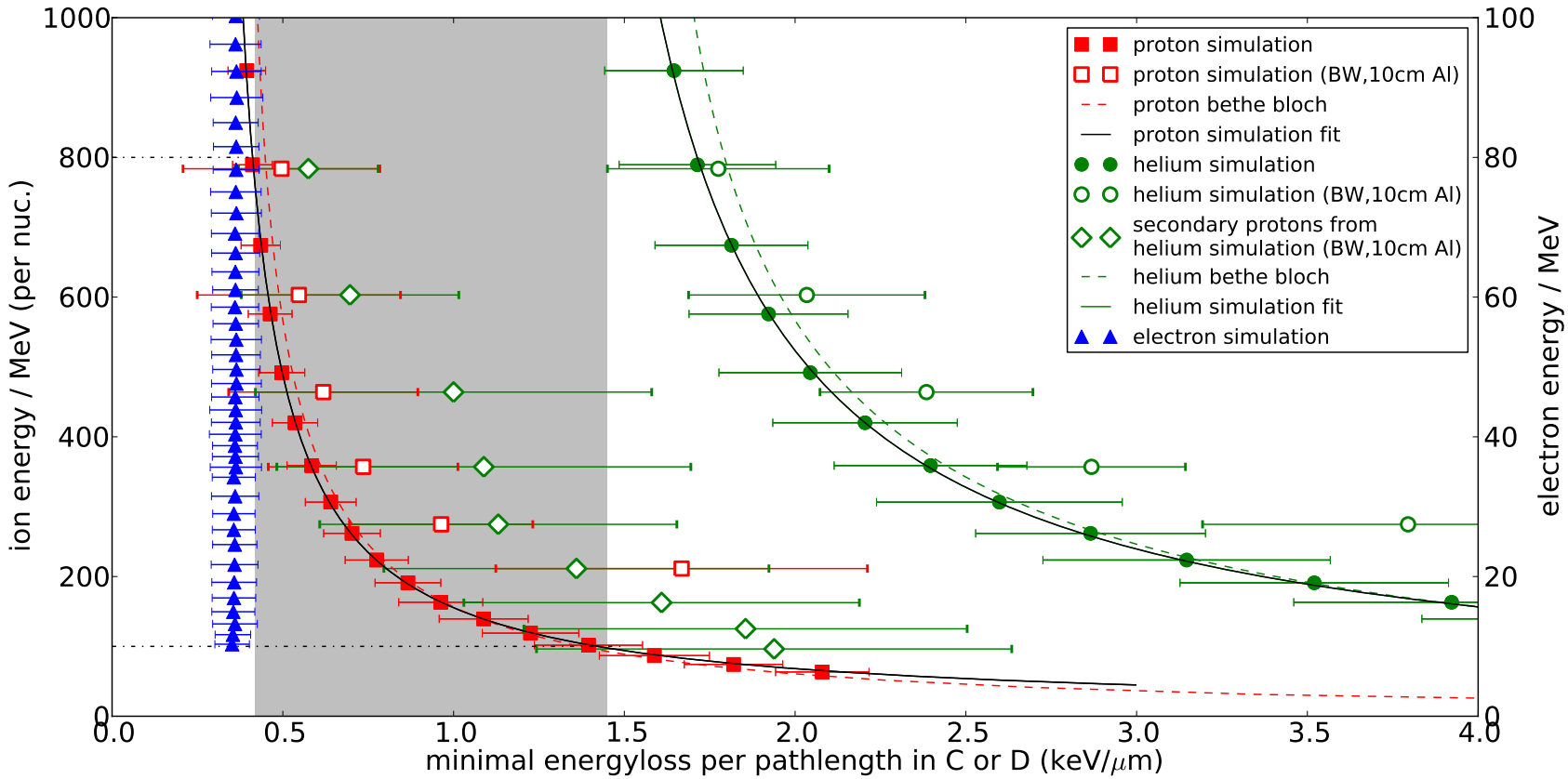
200 MeV

backward penetrating particles

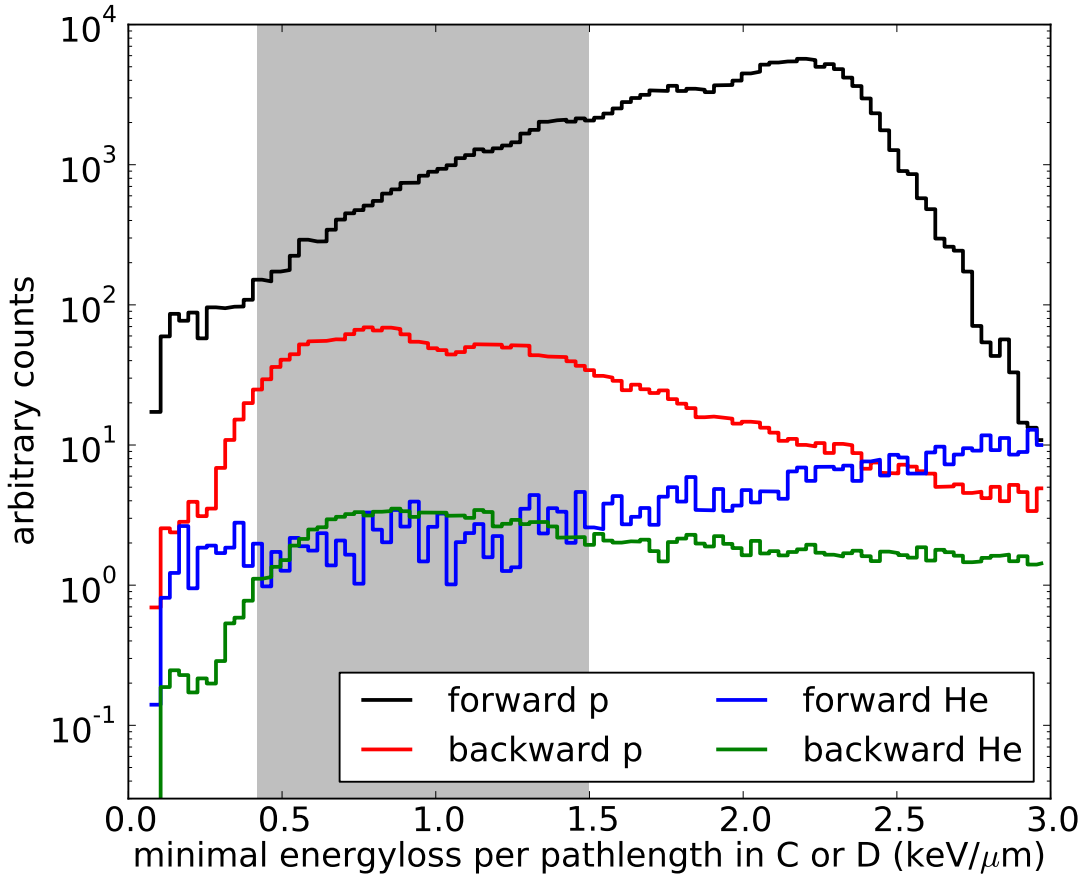






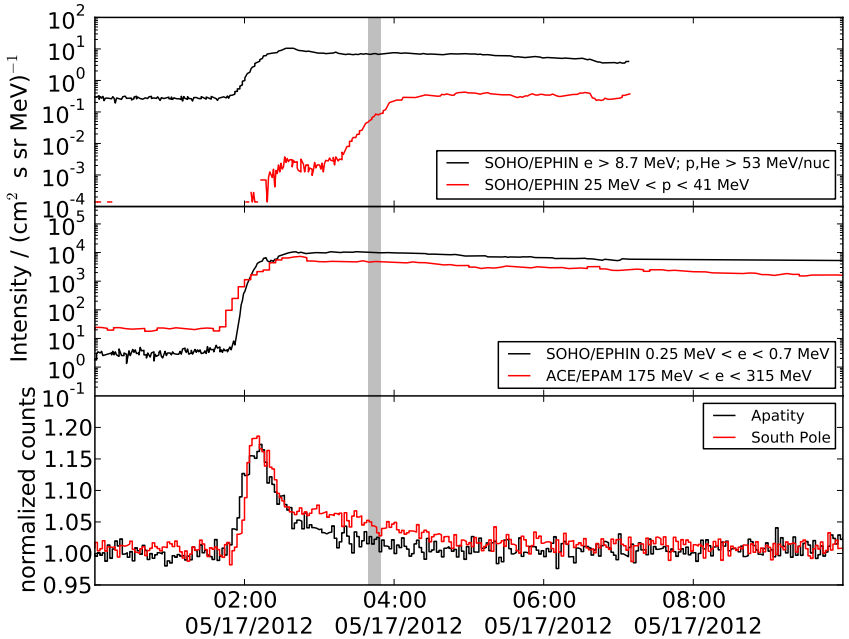

ion energy / MeV (per nuc.)
electron energy / MeV
minimal energyloss per pathlength in C or D (keV/μm)
0
200
400
600
800
1000
0
20
40
60
80
100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
proton simulation
proton simulation (BW,10cm Al)
proton bethe bloch
proton simulation fit
helium simulation
helium simulation (BW,10cm Al)
secondary protons from helium simulation (BW,10cm Al)
helium bethe bloch
helium simulation fit
electron simulation

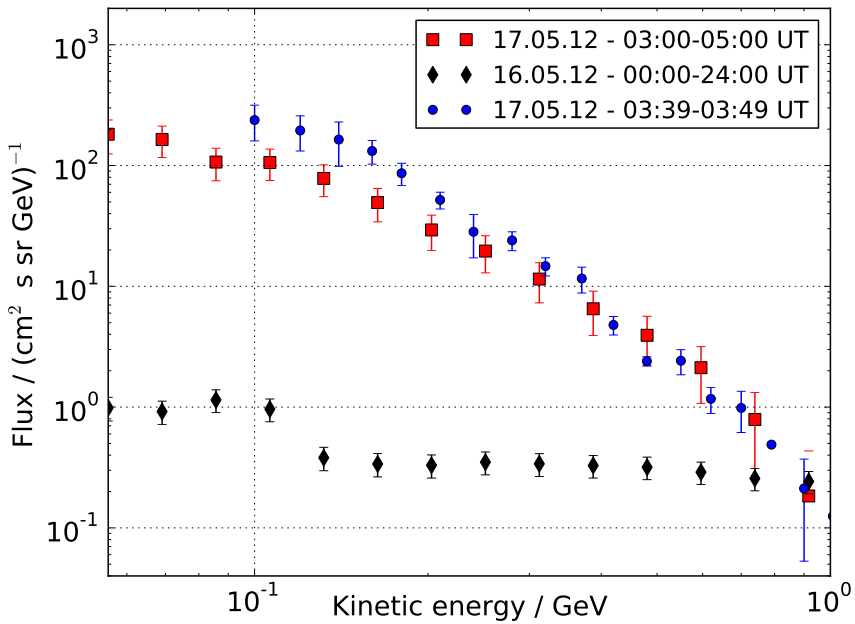
Exploiting Event Characteristics



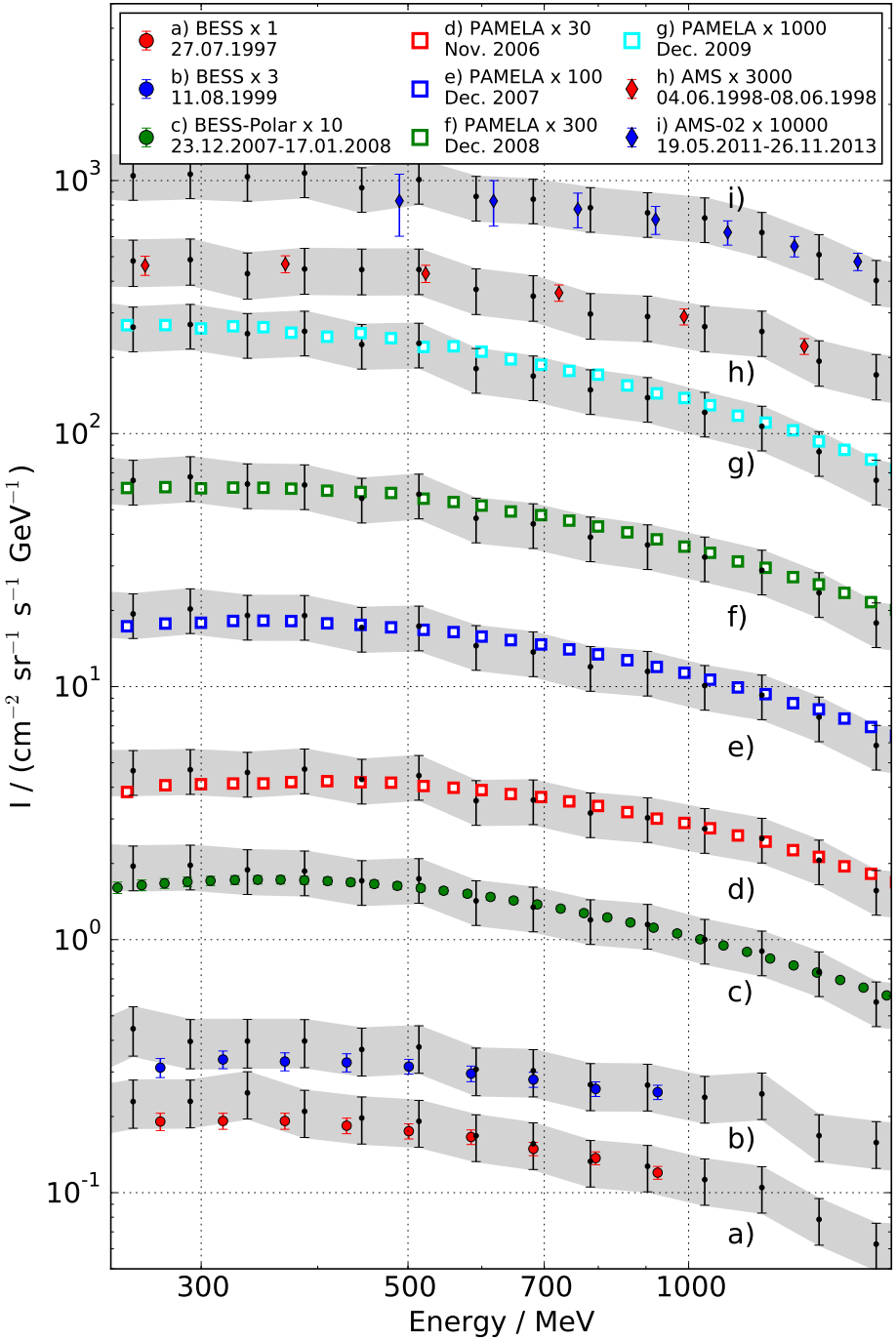
- artificial energy-loss histogram
- $I = I_0 \cdot E^{-\gamma}$, $\gamma = 3$ spectrum
- He/p = 10 %

GLE 71, May 17th, 2012



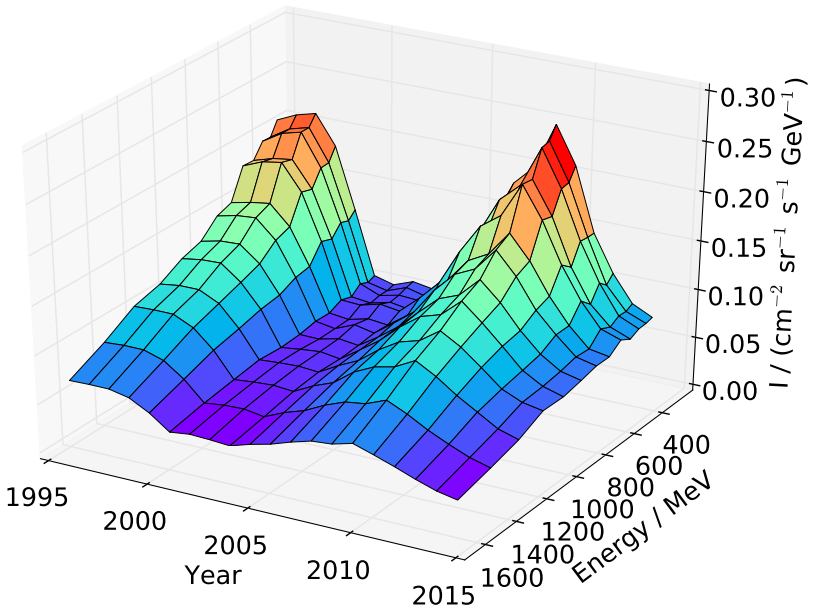


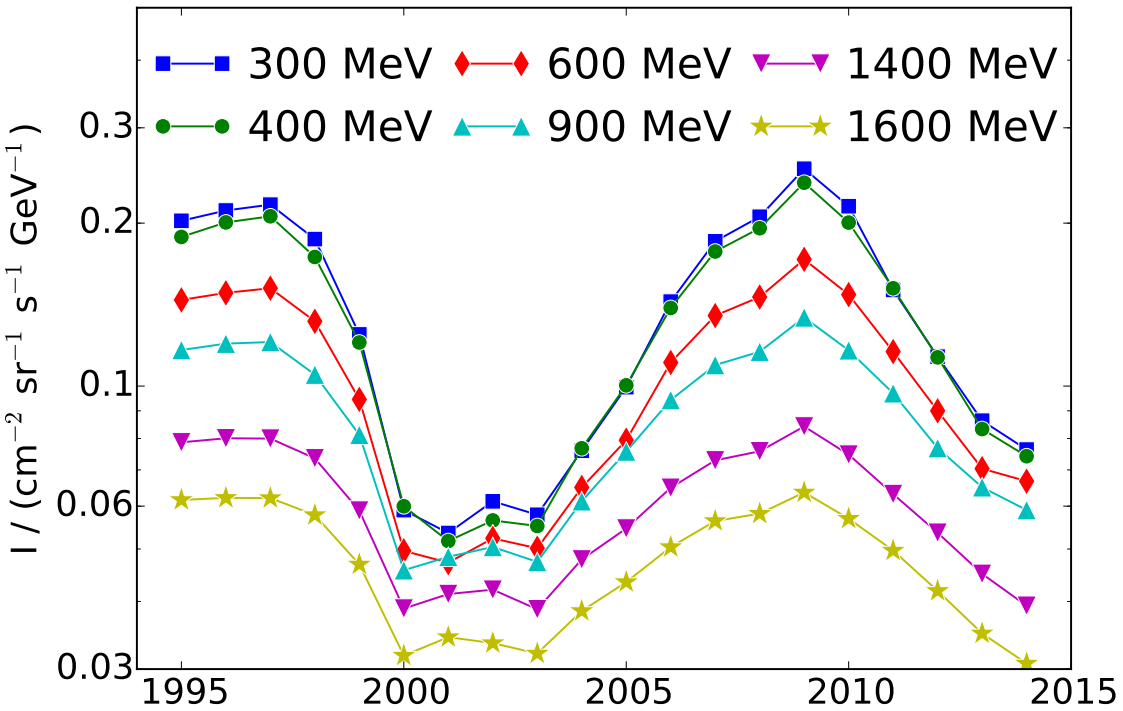
- agreement with PAMELA data (blue, Bazilevskaya et al. 2013)
- deviation less than two σ
- longer time period required due to statistical limitation
- possible electron contamination above 800 MeV



AMS-02	2011 - 2013	x 1 x 10^4
AMS	June 1998	x 3 x 10^3
PAMELA	Dec. 2009	x 1 x 10^3
PAMELA	Dec. 2008	x 3 x 10^2
PAMELA	Dec. 2007	x 1 x 10^2
PAMELA	Nov. 2006	x 3 x 10^1
BESS-Polar	Dec. 2007	x 1 x 10^1
BESS	Aug. 1999	x 3 x 10^0
BESS	July 1997	x 1 x 10^0

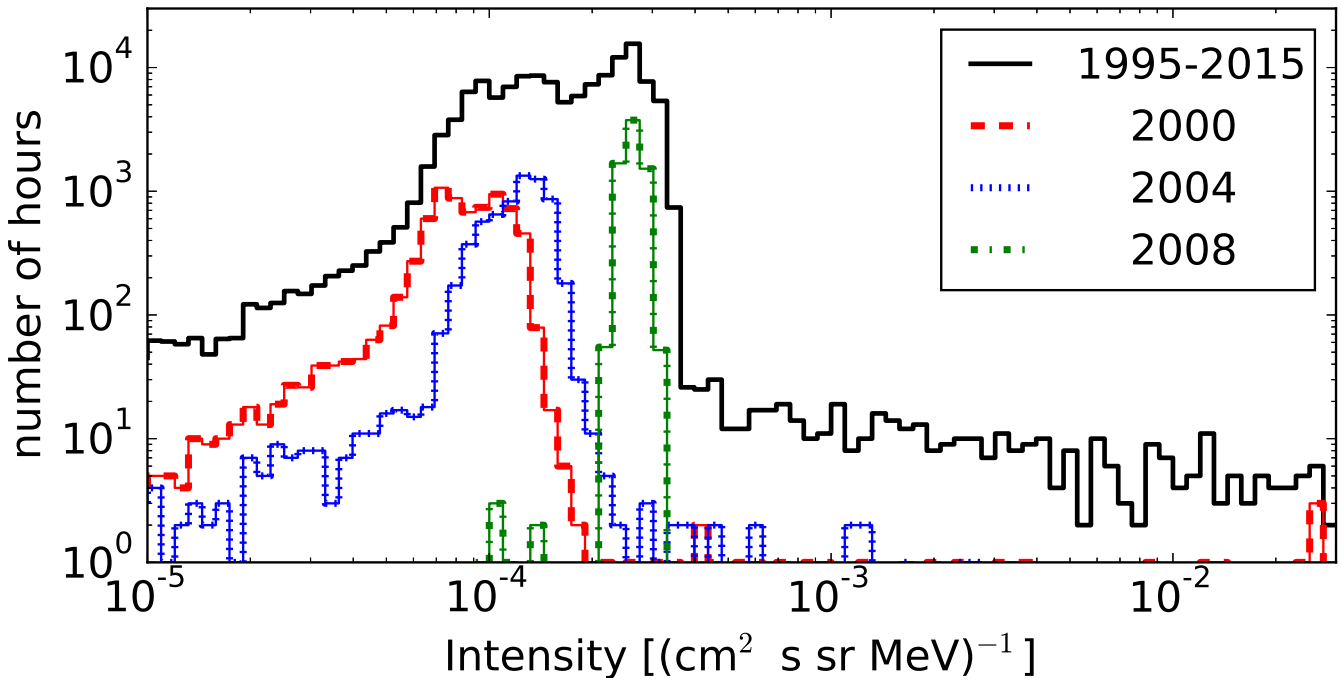
Solar Modulation - Annual Spectra



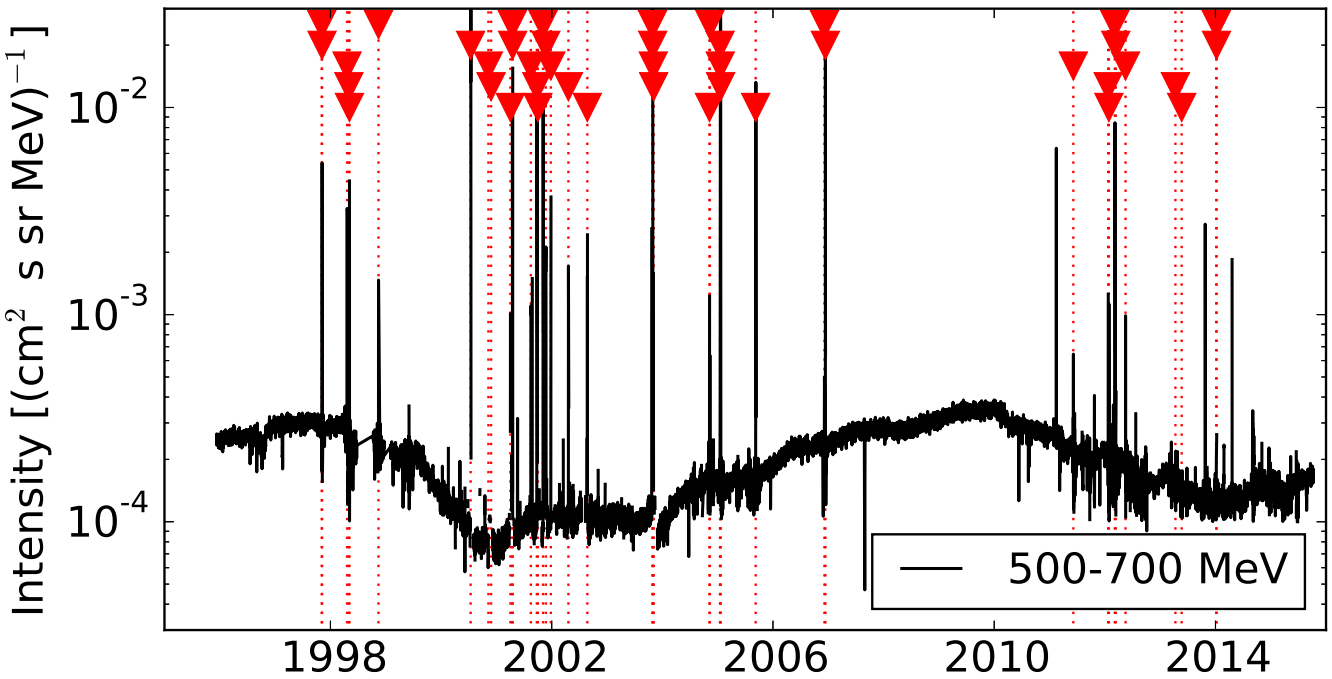


- annual GCR proton spectra from 250 MeV up to 1.6 GeV
- systematic uncertancies estimated with the FFS: below 20%
- statistical errors are in the order of $\approx$ 10%, 2% and 0.5% (for a given day, month/CR, year)

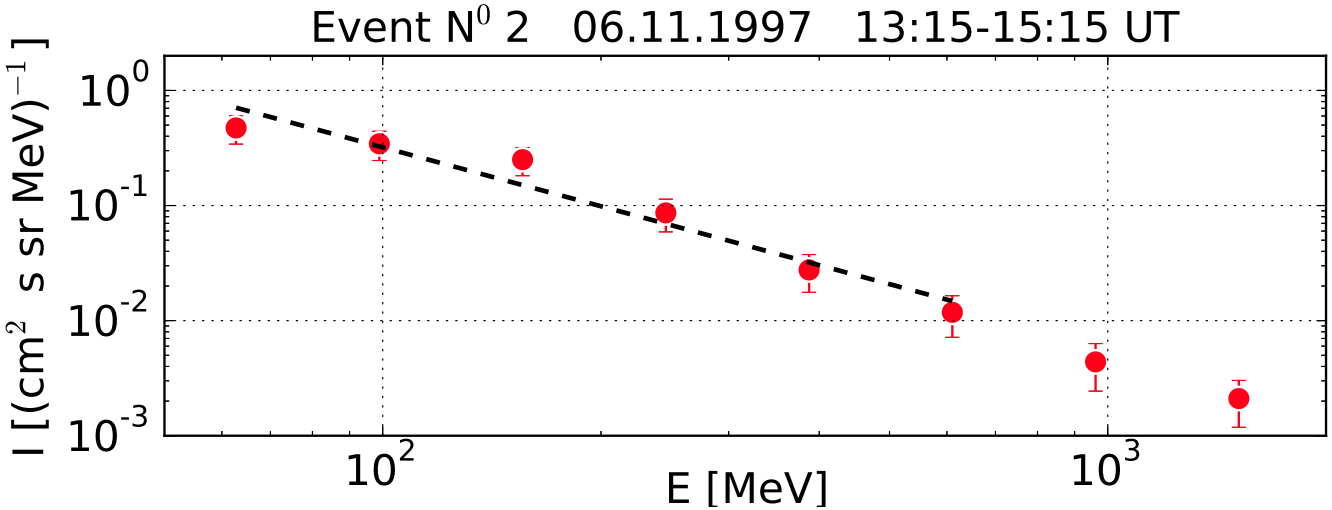
Identification of SEP events



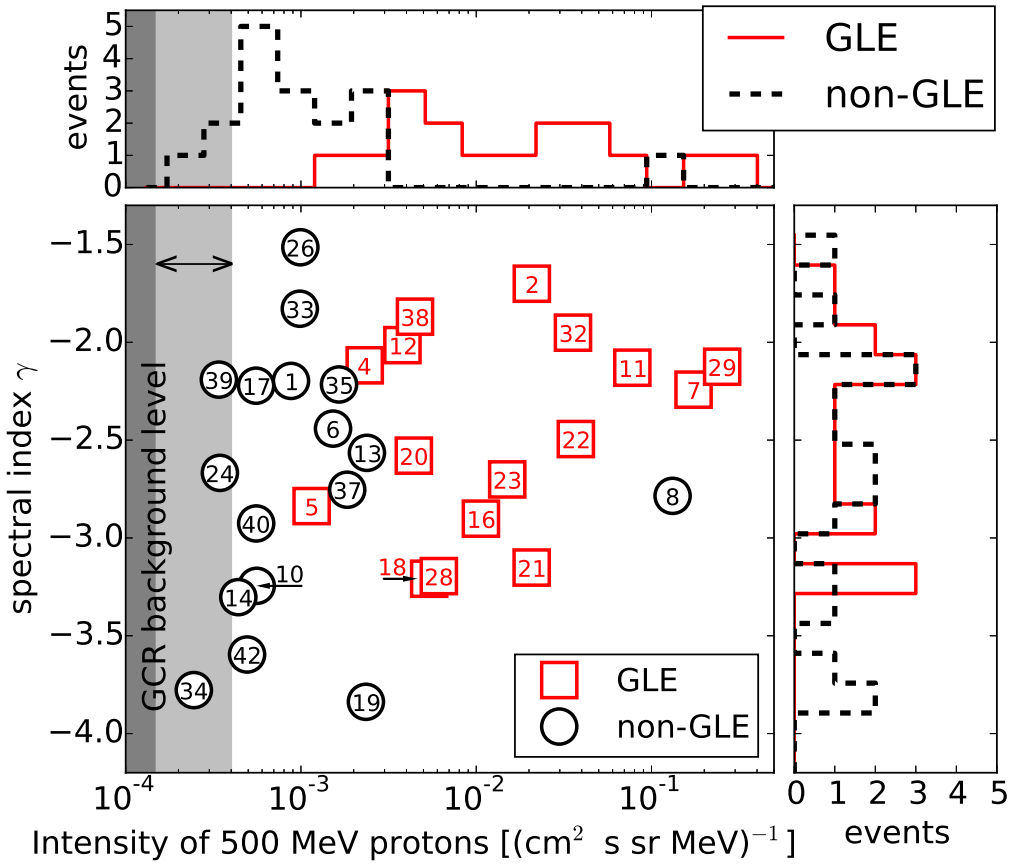
- hourly intensity of protons from 500 up to 700 MeV
- peak between 0.05 and 0.4 (cm^2 s sr MeV)$^{-1}$ due to GCR
- lower intensities: forbush decreases
- higher intensities: SEP candidates



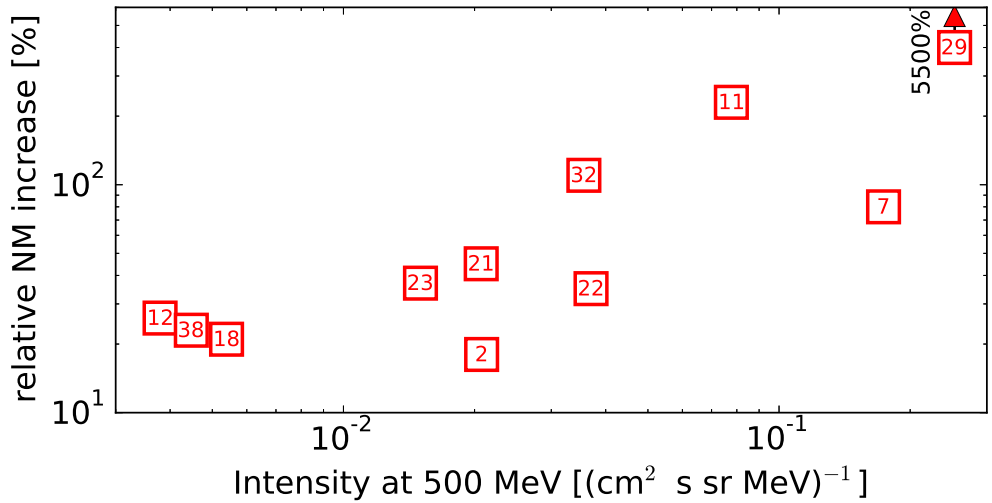
- 42 events with proton energies above 500 MeV
- 32 events in solar cycle 23; 10 events in solar cycle 24
- sanity check: GLEs 55 to 71 have been found
- exception: GLE 58 (datagap)



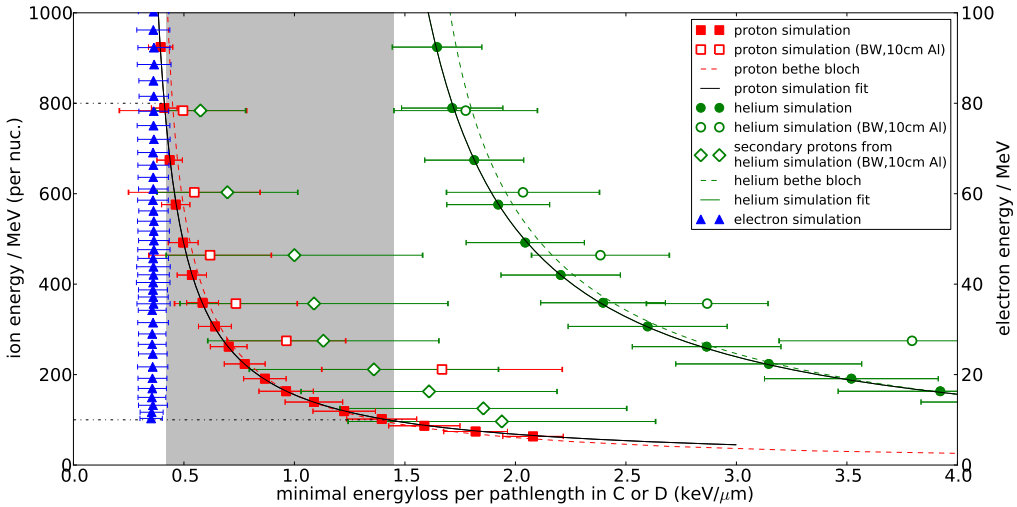
- define onset times (15 min resolution, 100-1000 MeV channel)
- derive spectrum in a two hour interval
  (starting 30 minutes after onset due to velocity dispersion)
- fit spectrum below 800 MeV with power-law
- (only for 33 events due to statistical limitations)

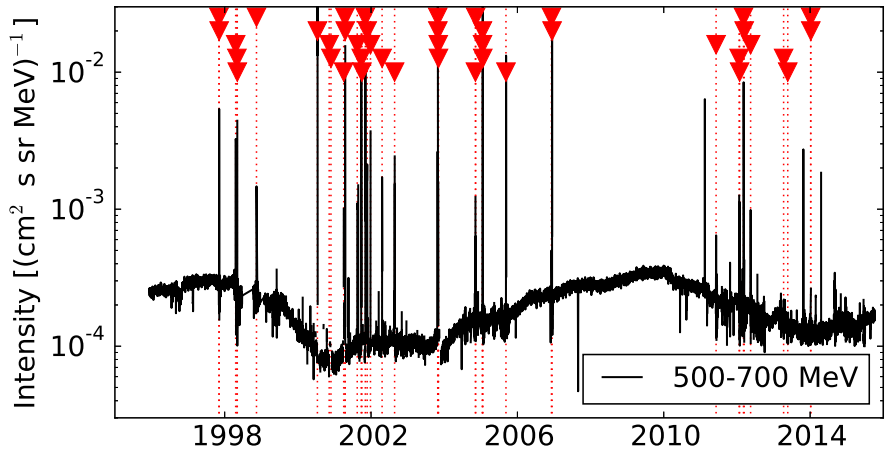


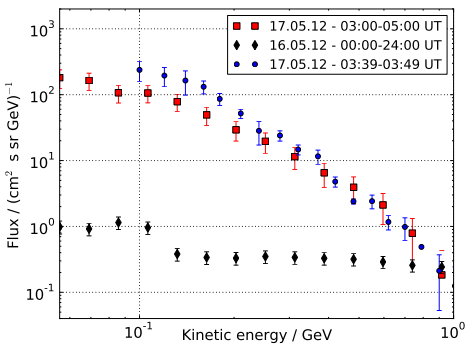
- GLE intensities: above $2{\cdot}10^{-3}$ $(\mathrm{cm}^2\ \mathrm{s\ sr\ MeV})^{-1}$ (Nitta et al. 2012)
- GLE spectral indices: between -2 and -3 (Mewaldt et al. 2012)
- Why is event 5 (GLE 57, May 5th, 1998) a GLE?
  Why is event 8 (Nov 9th, 2000) not a GLE? (Thakur et al. 2016)

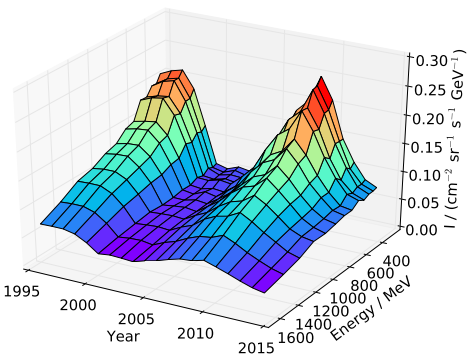


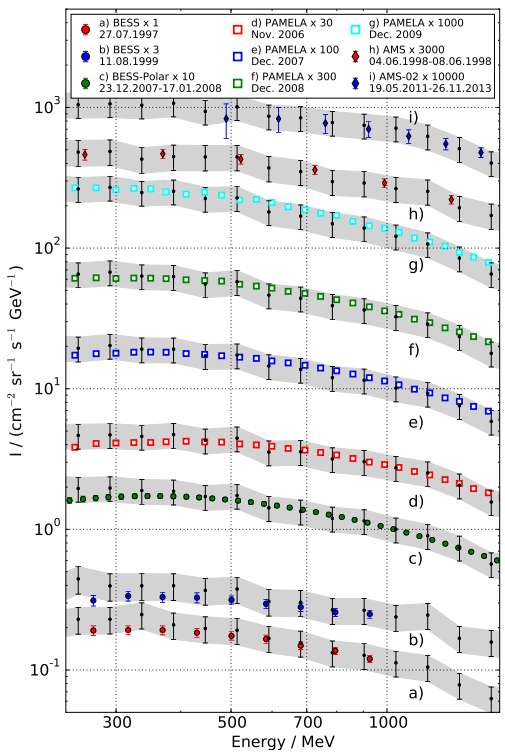
- NM count rate from McCracken, Moraal and Shea, 2012
- clear correlation (except for lowest intensities)
- event 29 (GLE 69, January 2005) is rather extreme
- scattering rather large, although spectral indices are similar
- asymptotic viewing direction? (Smart, Shea and Flückinger 2000)
  cutoff rigidities due to geomagnetic disturbances? (Danilova 1999)
  spectral break at higher energies?

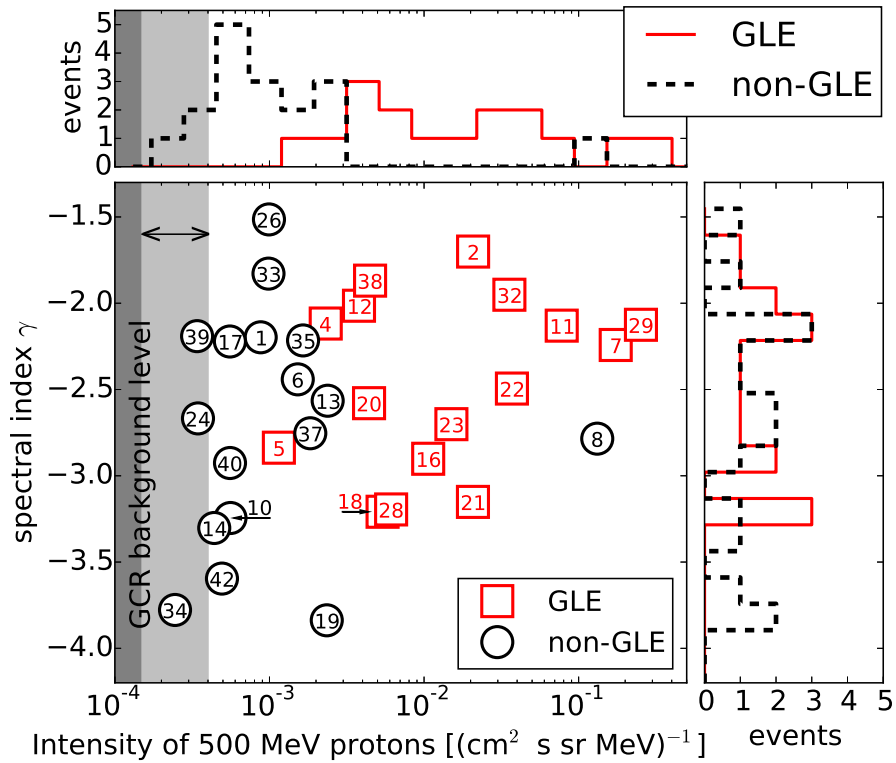

proton simulation
proton simulation (BW,10cm Al)
proton bethe bloch
proton simulation fit
helium simulation
helium simulation (BW,10cm Al)
secondary protons from helium simulation (BW,10cm Al)
helium bethe bloch
helium simulation fit
electron simulation
ion energy / MeV (per nuc.)
electron energy / MeV
minimal energyloss per pathlength in C or D (keV/μm)


Intensity [(cm² s sr MeV)⁻¹]
500-700 MeV

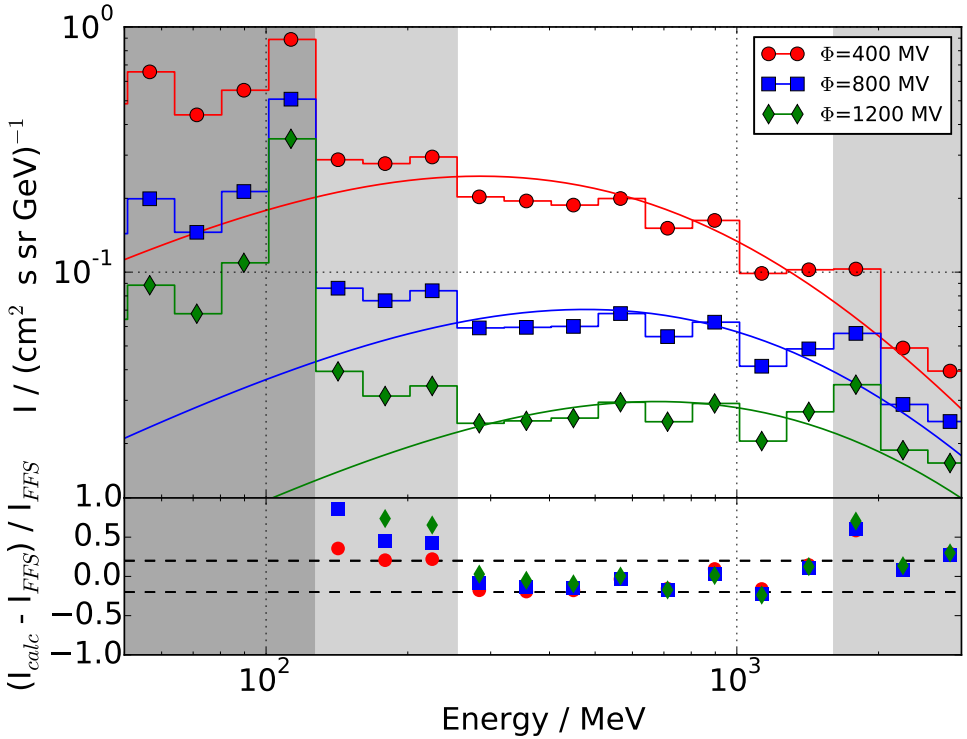

17.05.12 - 03:00-05:00 UT
16.05.12 - 00:00-24:00 UT
17.05.12 - 03:39-03:49 UT
Flux / (cm² s sr GeV)⁻¹
Kinetic energy / GeV


I / (cm⁻² sr⁻¹ s⁻¹ GeV⁻¹)
Year
Energy / MeV


a) BESS x 1 27.07.1997
b) BESS x 3 11.08.1999
c) BESS-Polar x 10 23.12.2007-17.01.2008
d) PAMELA x 30 Nov. 2006
e) PAMELA x 100 Dec. 2007
f) PAMELA x 300 Dec. 2008
g) PAMELA x 1000 Dec. 2009
h) AMS x 3000 04.06.1998-08.06.1998
i) AMS-02 x 10000 19.05.2011-26.11.2013
I / (cm⁻² sr⁻¹ s⁻¹ GeV⁻¹)
Energy / MeV


GLE
non-GLE
events
spectral index γ
GCR background level
Intensity of 500 MeV protons [(cm² s sr MeV)⁻¹]

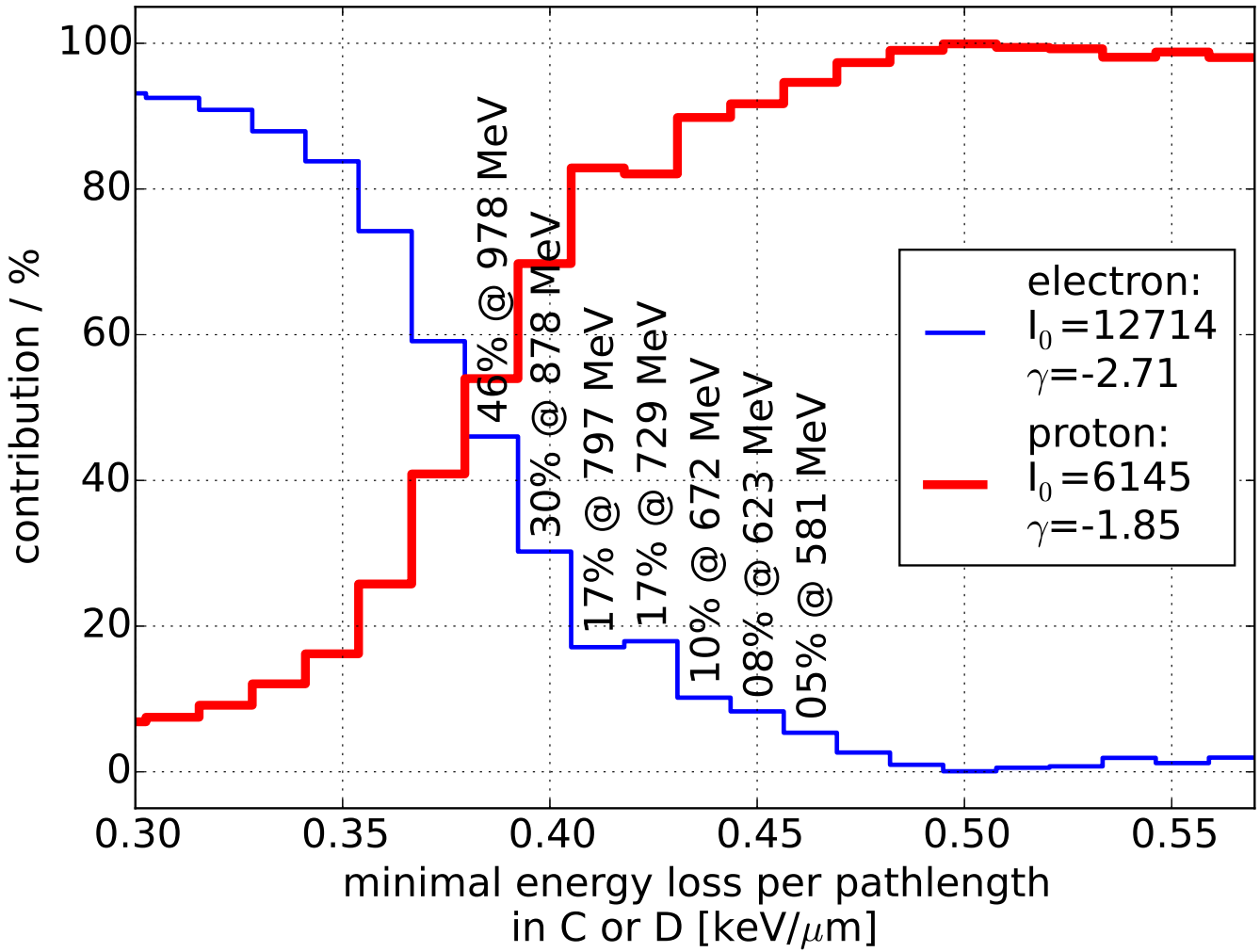
Solar Modulation - error estimation

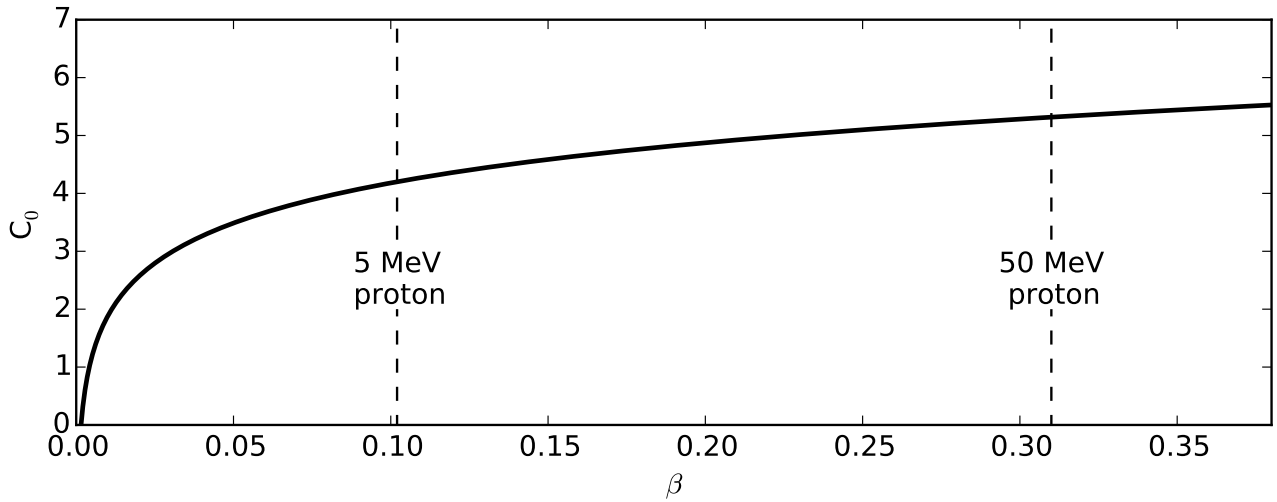


- simulation using expected GCR spectra
- Force Field Solution
- various modulation parameter to mimic different solar activities

- $<$ 160 MeV : Helium MIPs contribution
- 160 - 250 MeV : backward protons contribution
- 250 MeV - 1.6 GeV : systematic uncertancies below 20%
- $>$ 1.6 GeV : energy loss converges (proton MIPs), electrons

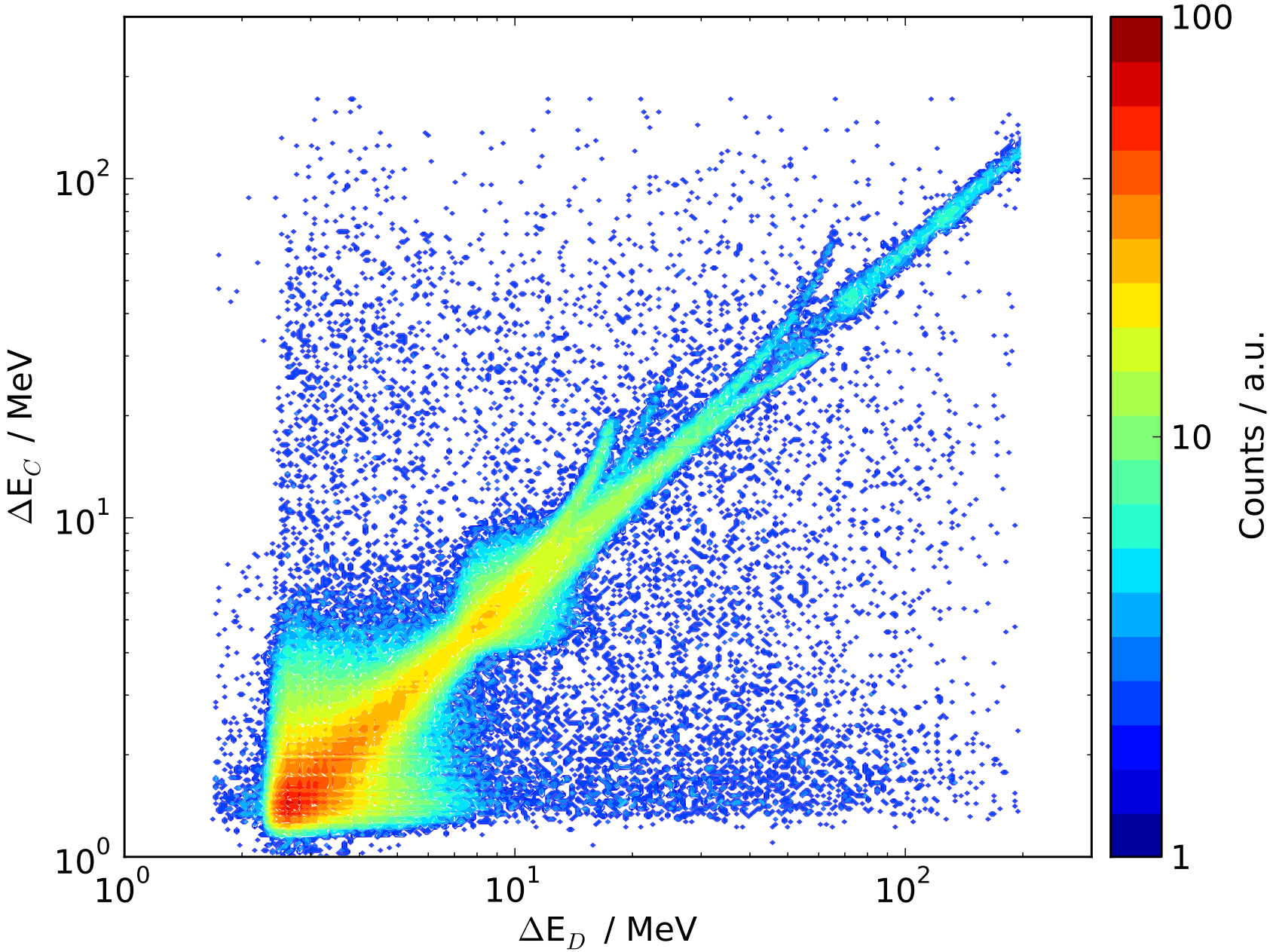
- statistical errors are in the order of $\approx$ 10%, 2% and 0.5% (for a given day, month/CR, year)

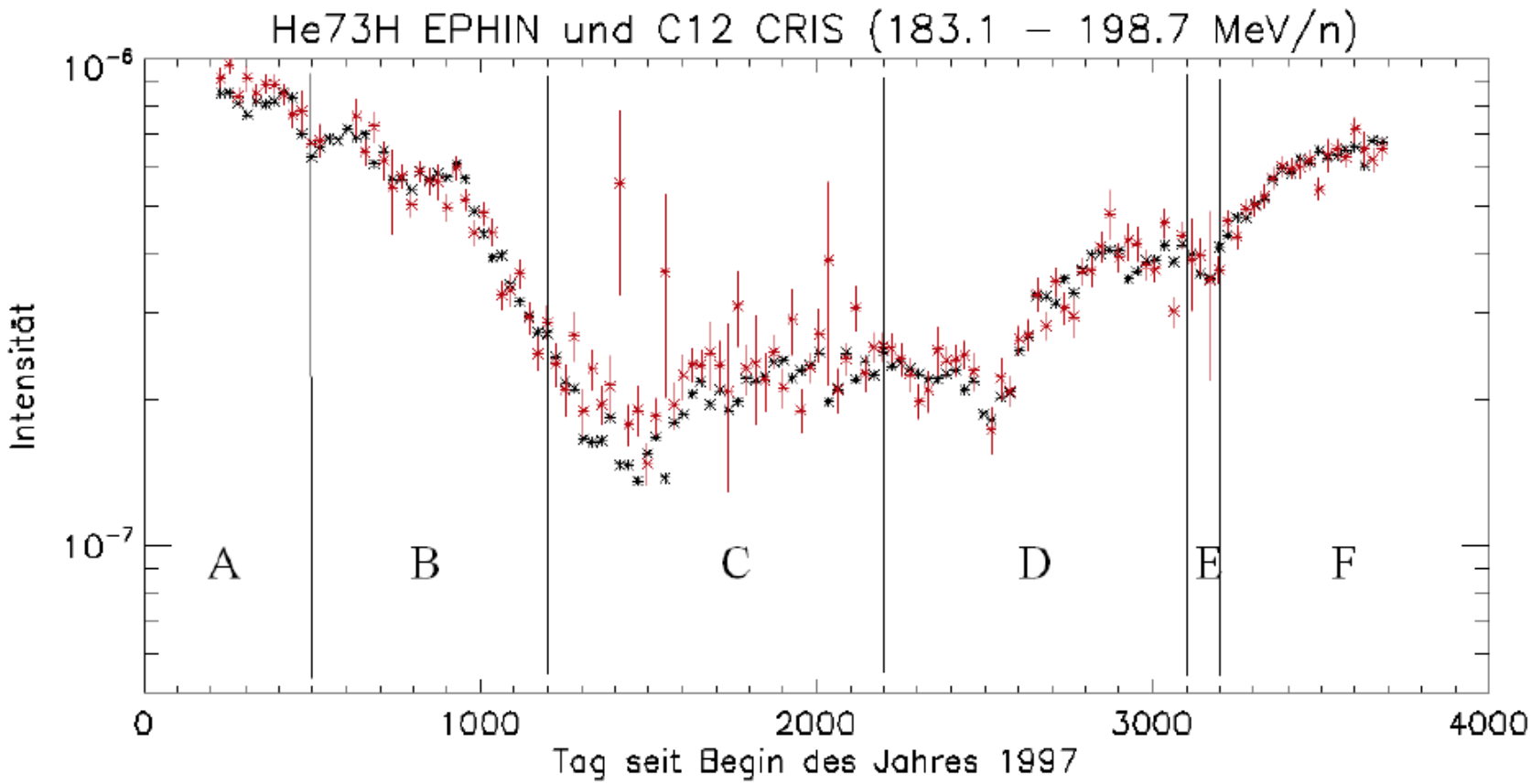

100
80
60
40
20
0
contribution / %
0.30
0.35
0.40
0.45
0.50
0.55
minimal energy loss per pathlength
in C or D [keV/μm]
46% @ 978 MeV
30% @ 878 MeV
17% @ 797 MeV
17% @ 729 MeV
10% @ 672 MeV
08% @ 623 MeV
05% @ 581 MeV
electron:
I0=12714
γ=-2.71
proton:
I0=6145
γ=-1.85



$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z_P^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left(\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right)$$

$$C_0 = \left(\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right)$$


10^2
10^1
10^0
ΔE_C / MeV
10^0
10^1
10^2
ΔE_D / MeV
100
10
1
Counts / a.u.



183 - 198 MeV/nuc Carbon (ACE/CRISS, black) and backward Helium (SOHO/EPHIN, red) [Labrenz 2014, priv. comm.]