Alpha Magnetic Spectrometer

A cosmic-ray observatory in space

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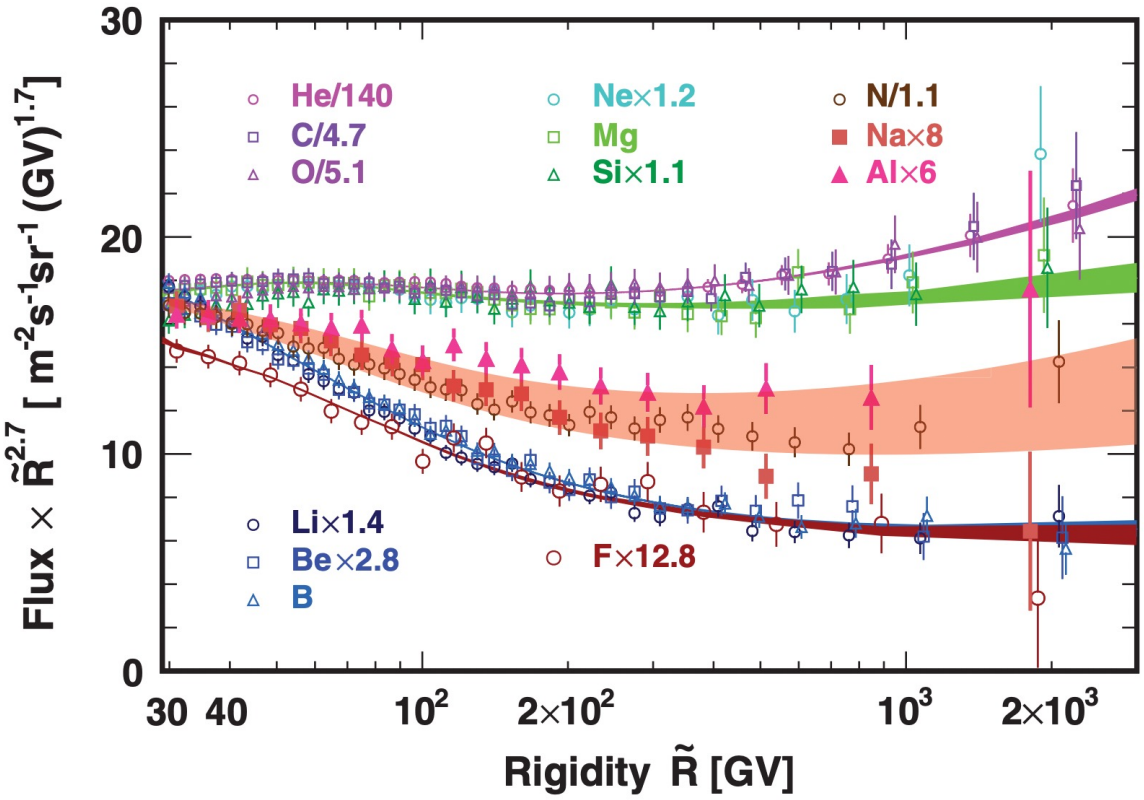
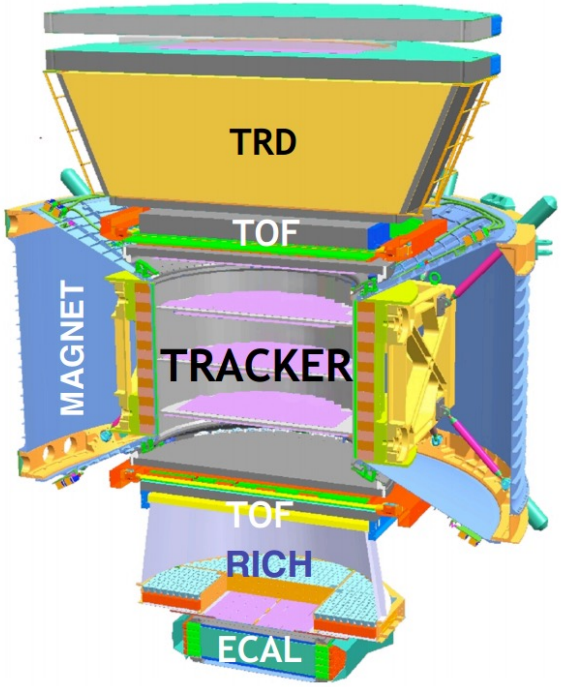
Alpha Magnetic Spectrometer

The **Alpha Magnetic Spectrometer** (AMS-02) is a state-of-the-art cosmic-ray detector installed on the ISS, continuously measuring the cosmic-ray flux. AMS has collected more than **202,000,000,000 cosmic ray events** up to this day, at a rate of about **45 million events per day**.

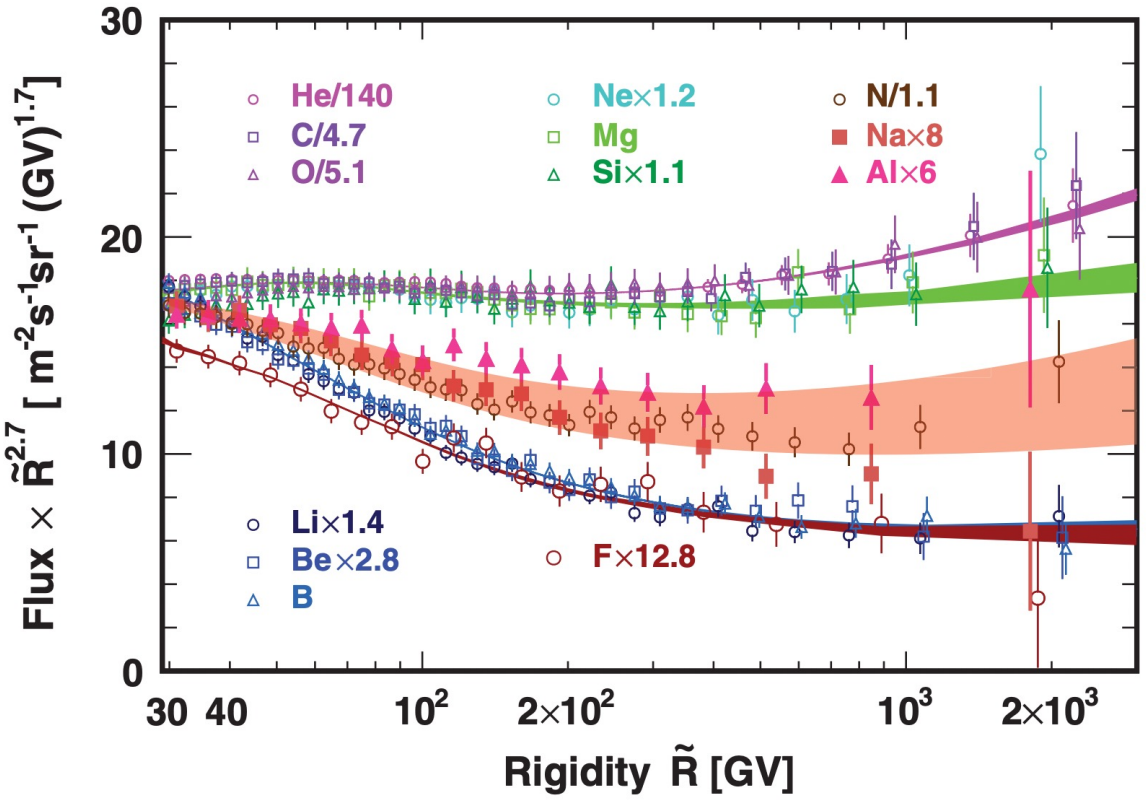


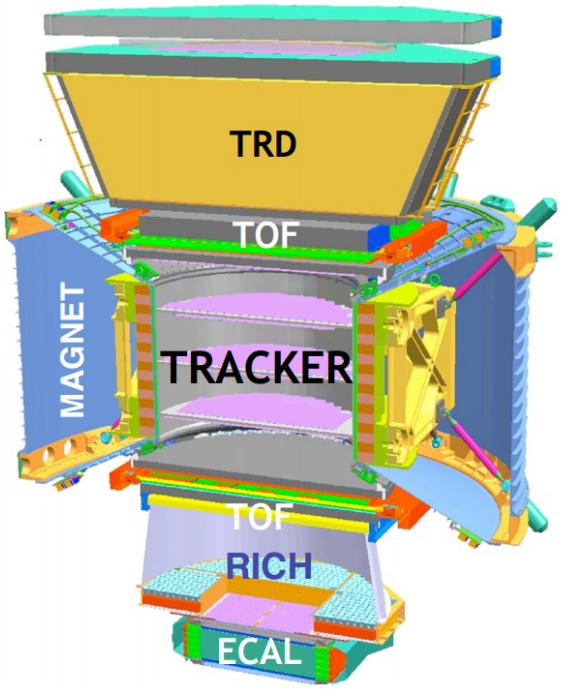


Alpha Magnetic Spectrometer

These results contribute to different fields of study:

- Dark matter origin
- Antimatter origin
- Astroparticle physics (Primary & Secondary CR)
- Solar physics
- Space environment physics & Space travel

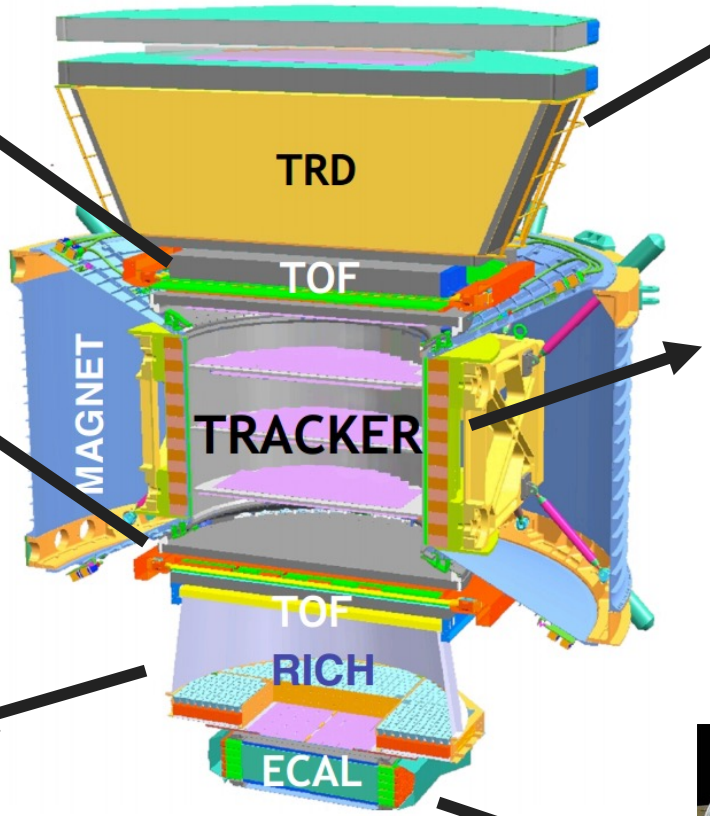




Inside View of AMS

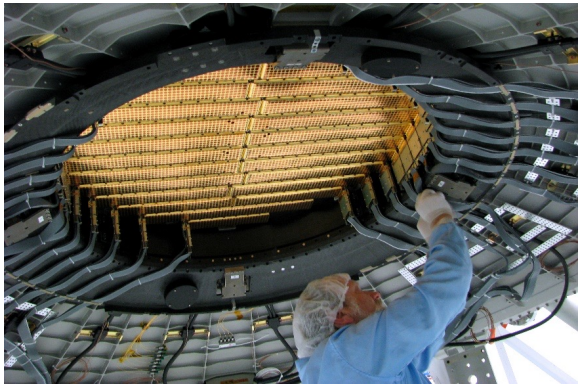
Lower
Time-of-flight
Detector

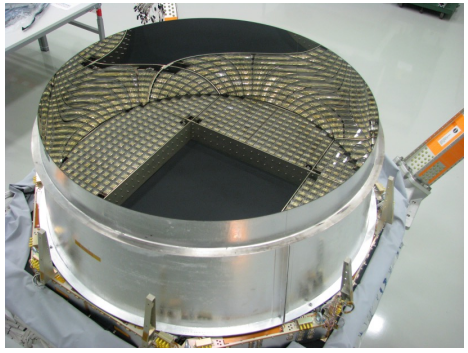
Upper
TOF



Transition
Radiation
Detector

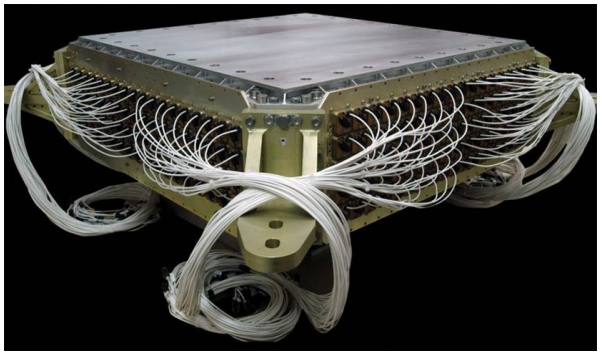
Silicon Tracker



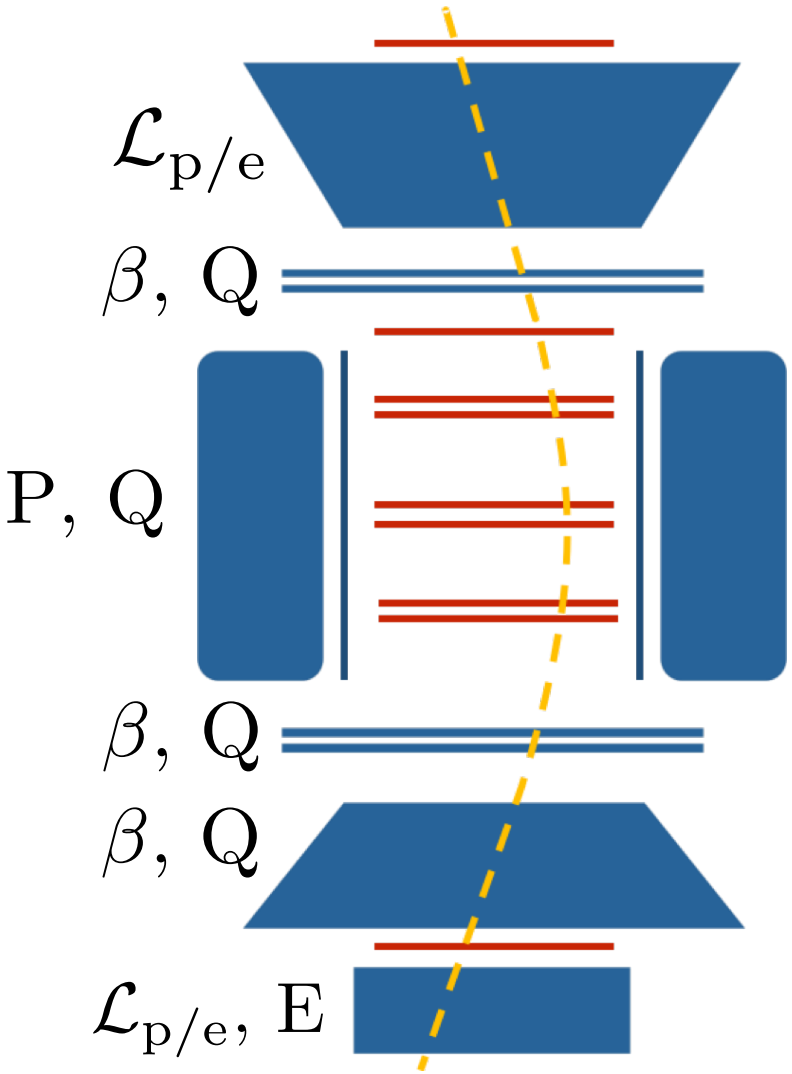


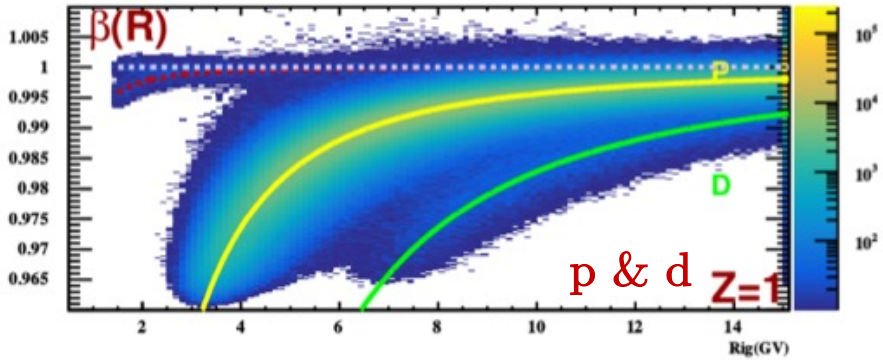
Ring-Imaging Cherenkov Detector

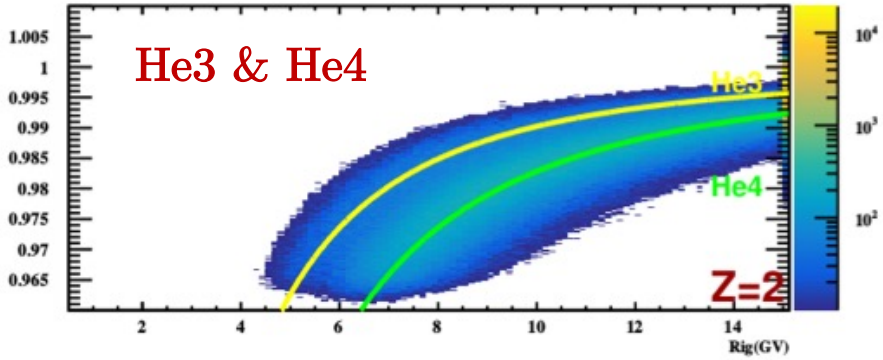
Electromagnetic
Calorimeter

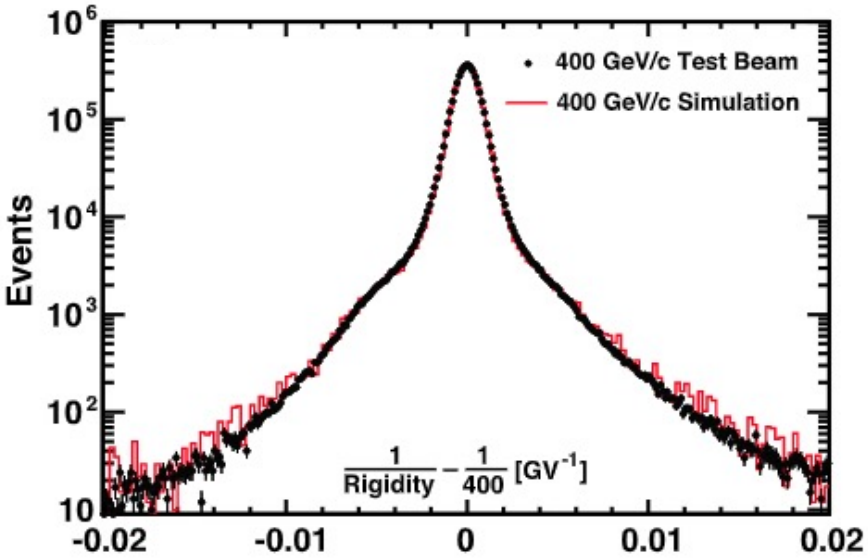


Particle separation

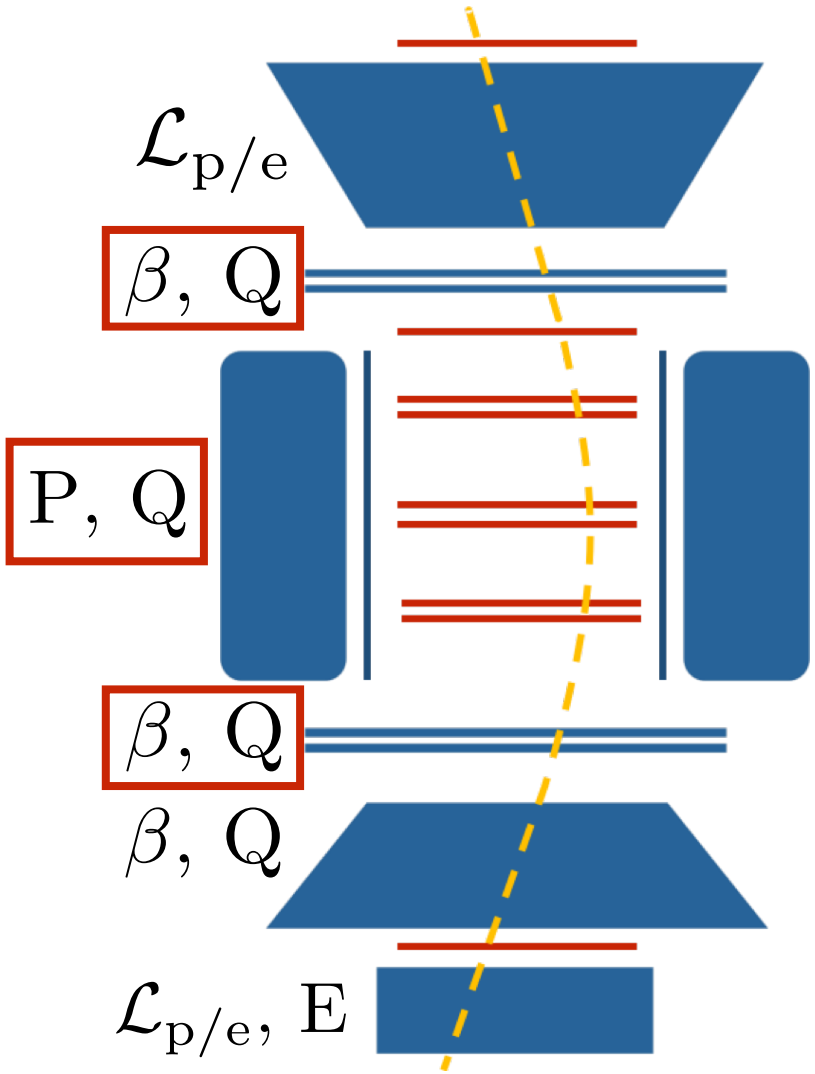


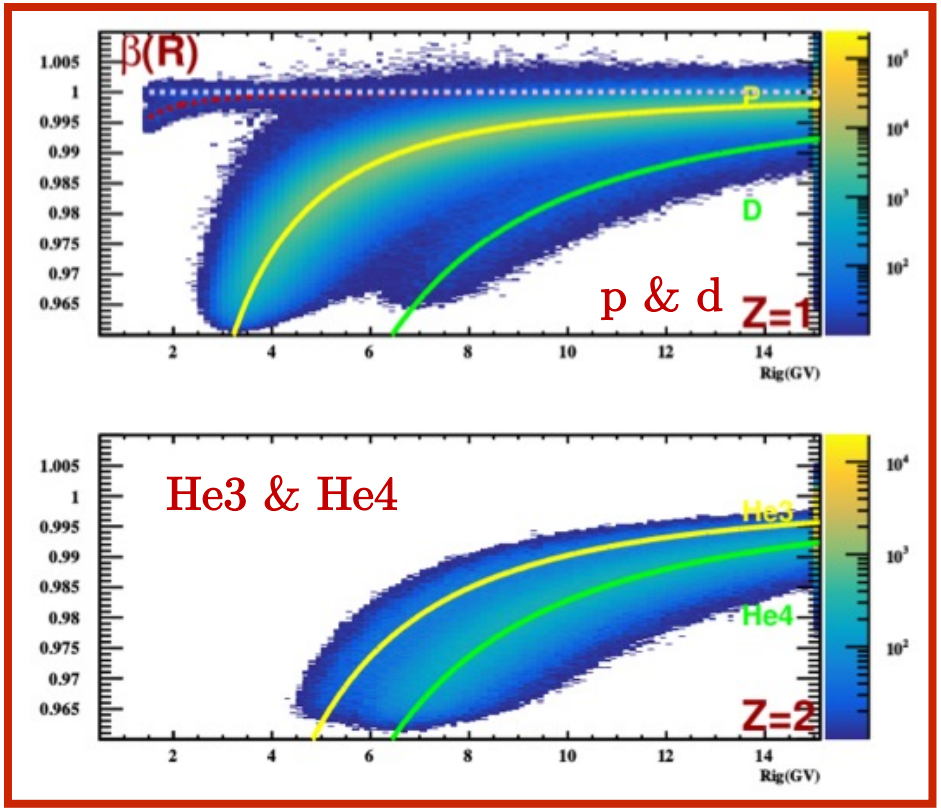


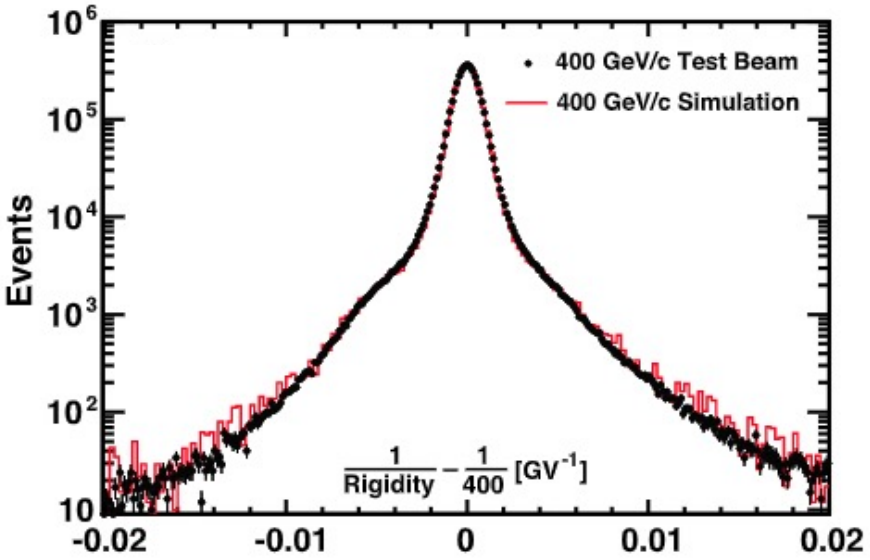




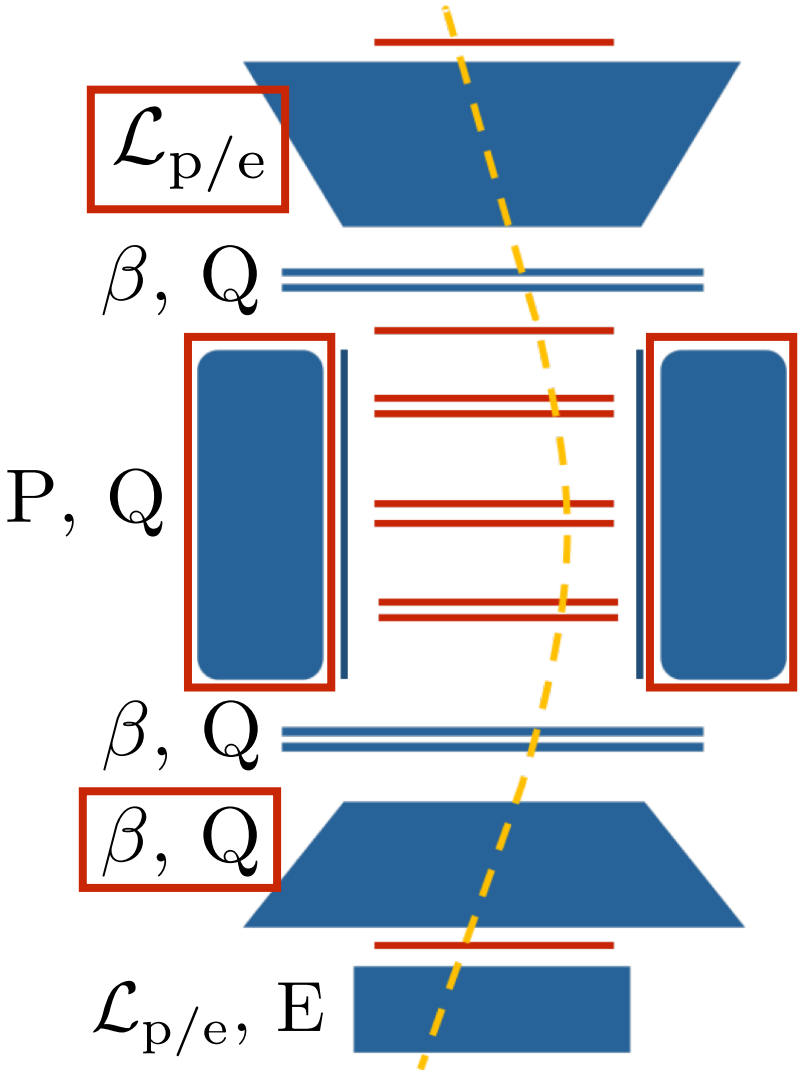
Particle separation

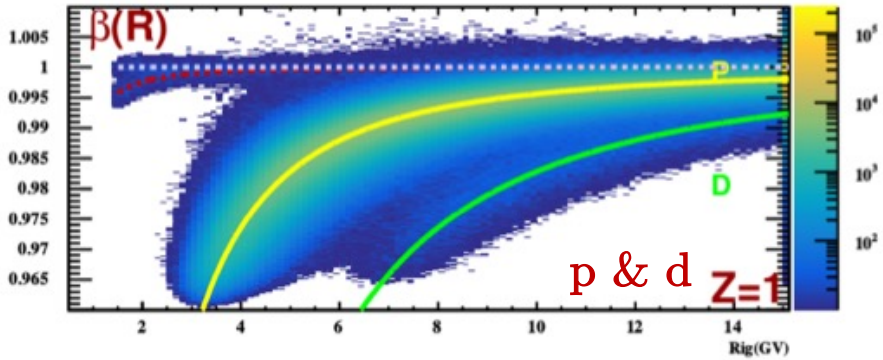


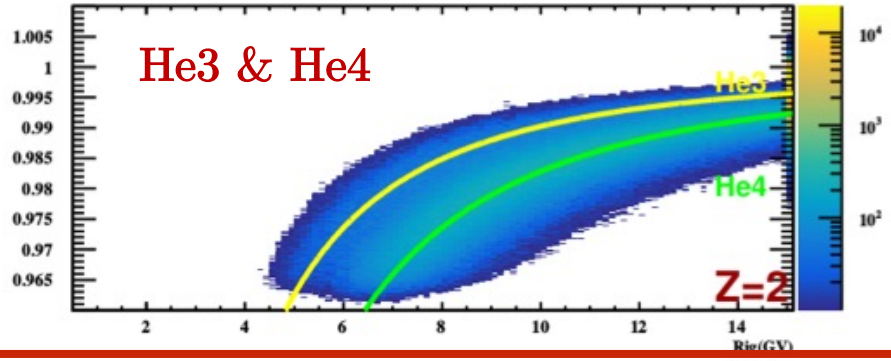


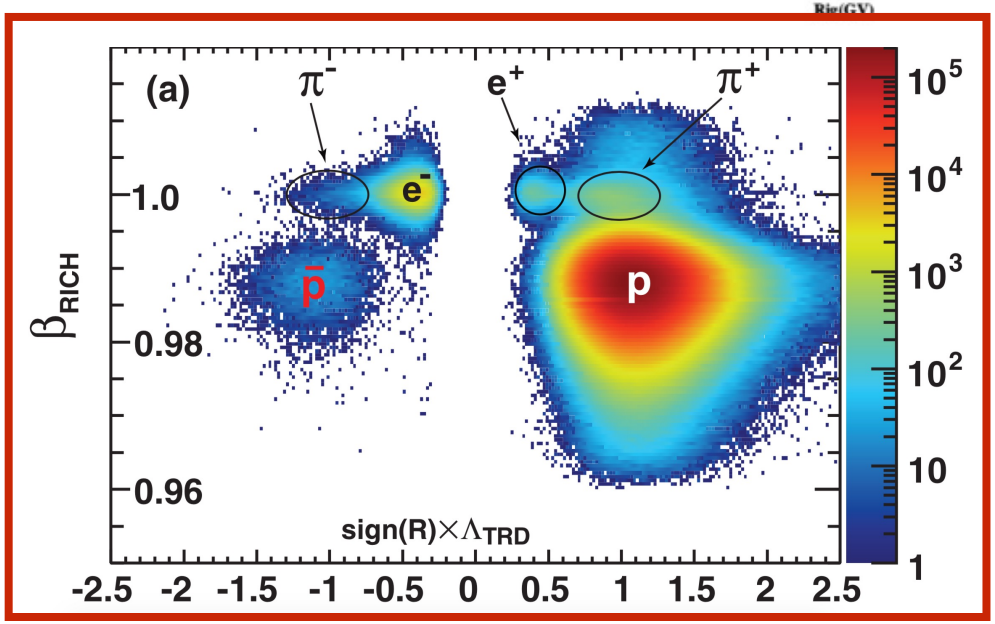


Particle separation

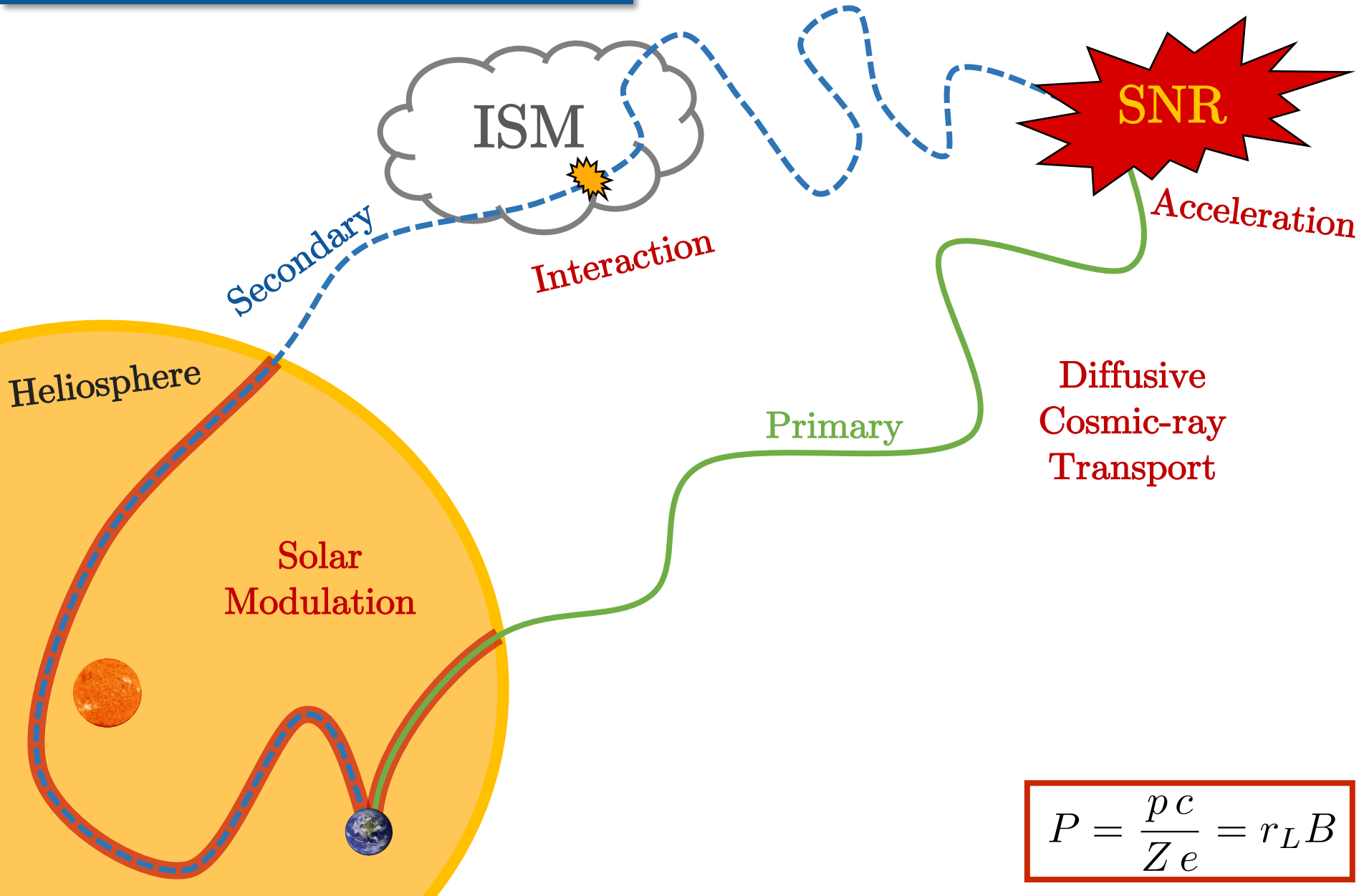








Cosmic ray origin



$$P = \frac{p\,c}{Z\,e} = r_L B$$

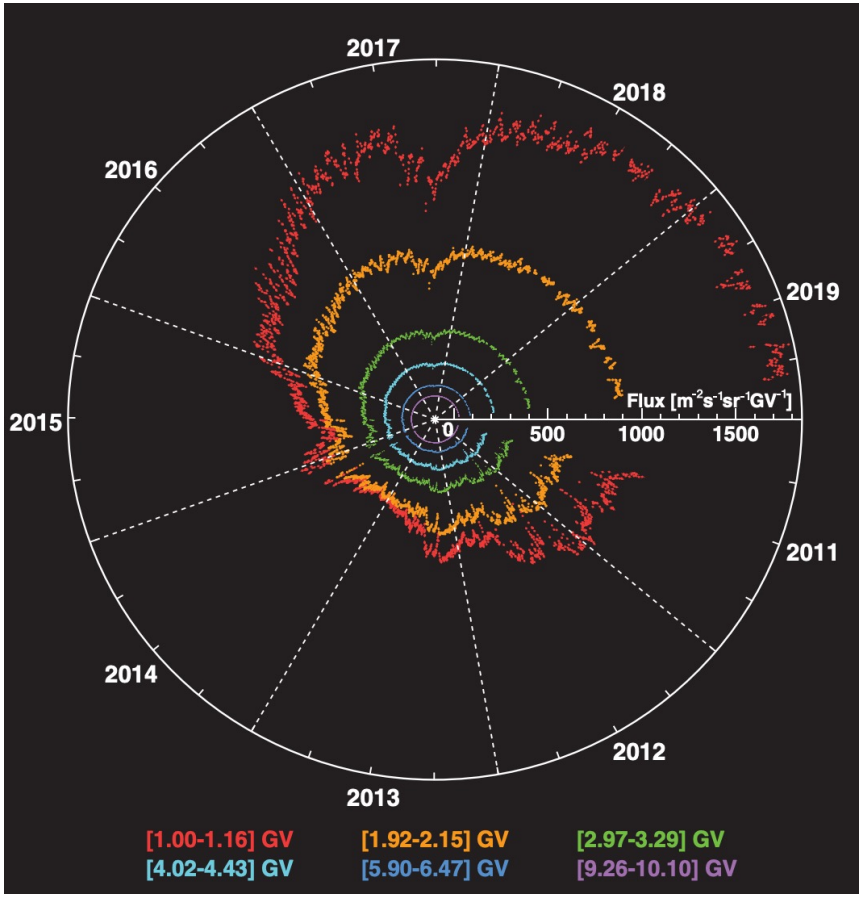
Low-Energy Cosmic-Ray Flux

Low Energy Physics

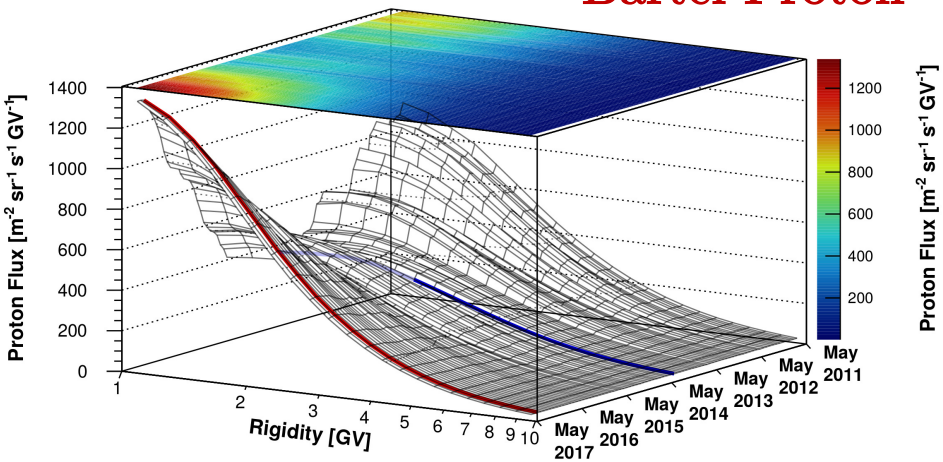
Physics channels

- Time-resolved CR fluxes
  - Daily (solar events)
  - Bartel (solar rotation)
  - Yearly (solar activity cycle, solar magnetic reversal)
- Flux ratios (p/He, e^+/e^-, $^3He/^4He$,...)
- Long-term observations
  - Neutron monitors
  - Satellites (Voyager, Parker probes, balloon, ...)
  - Solar Observables

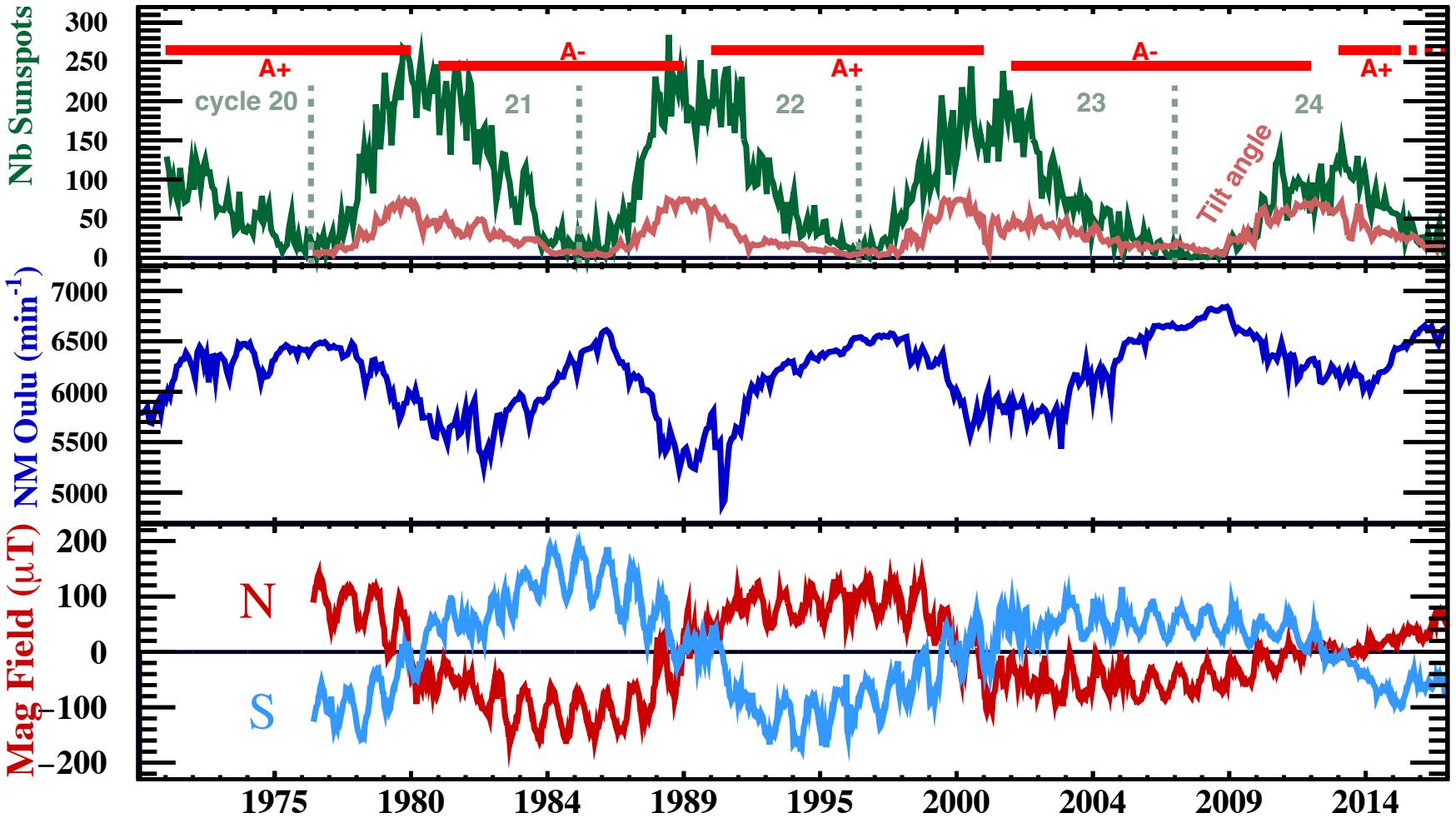
Daily Proton



Bartel Proton

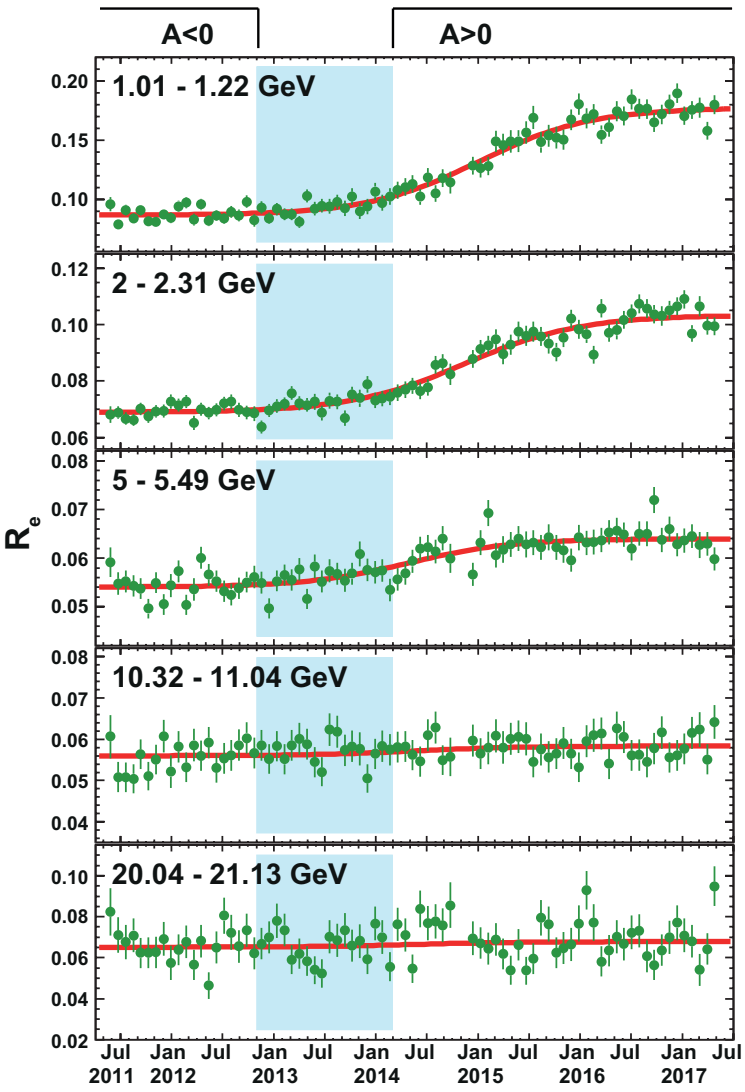


Solar Observables

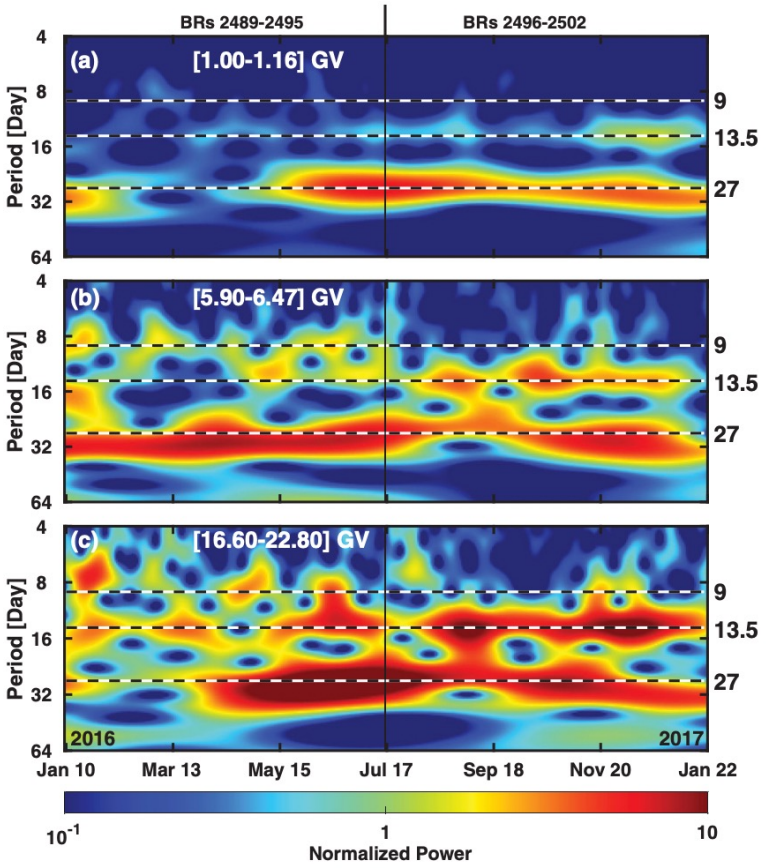


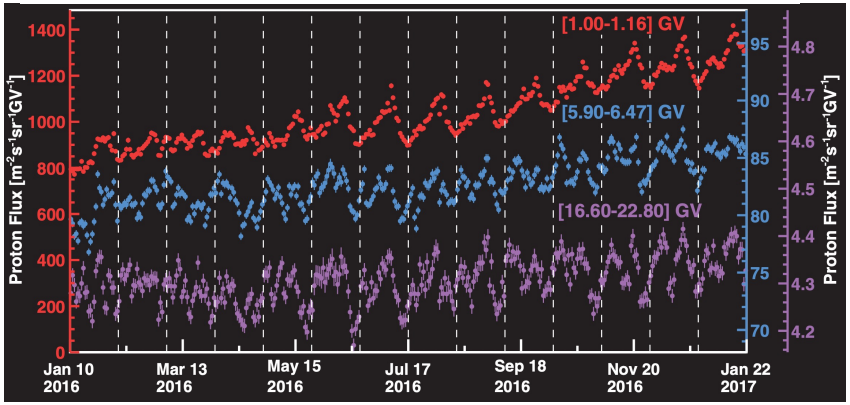
Time Variability

Electron Positron Ratio

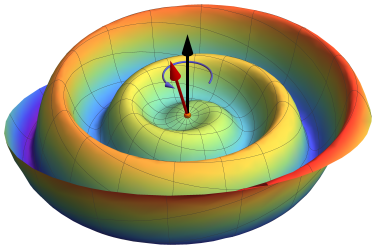


Daily Proton





Low Energy Physics

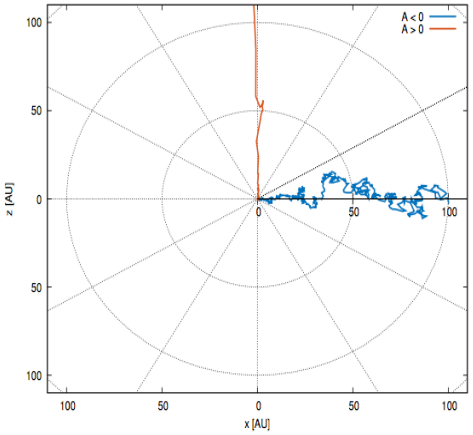


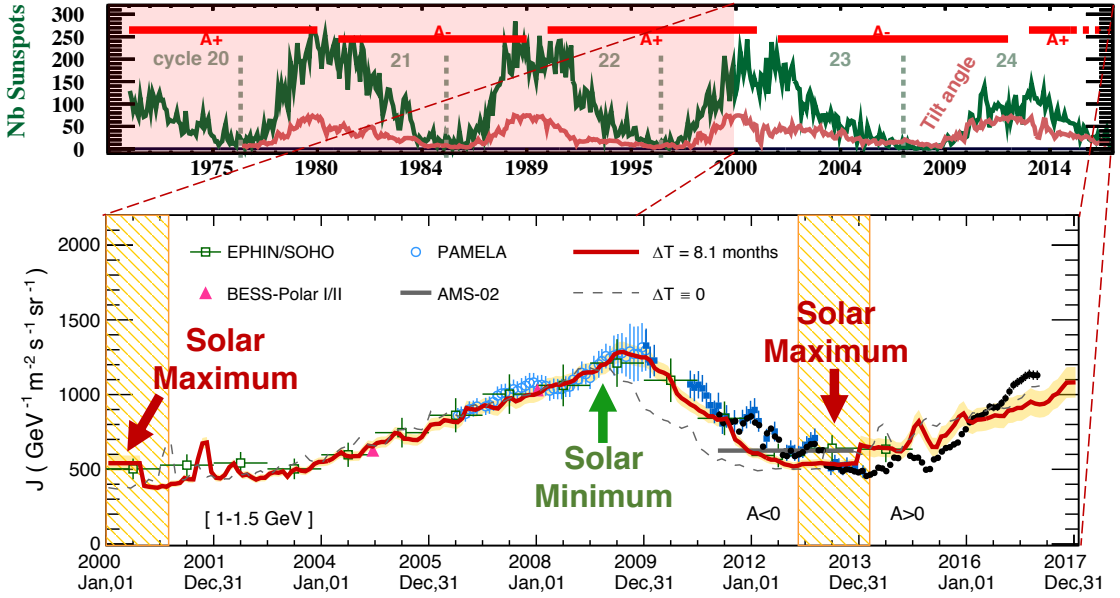
CR transport equation

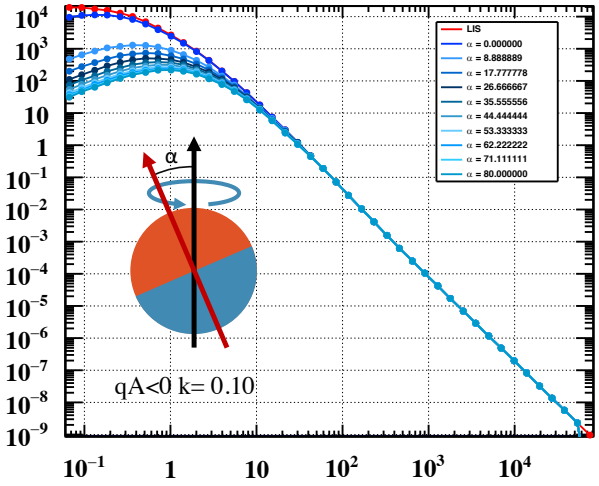
- Parker's equation

$$\frac{\partial f}{\partial t} = \underbrace{\nabla \cdot (\mathbf{K}_s \cdot \nabla f)}_{\text{diffusion}} - \underbrace{(\mathbf{V} + \langle \mathbf{v}_{dr} \rangle) \cdot \nabla f}_{\text{convection and drift}} + \underbrace{\frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{\text{adiabatic energy loss}} + \underbrace{Q(r, P, t)}_{\text{source/LIS}}$$

- Solar wind & heliospheric magnetic field
- Numerical & Stochastic resolution of the equation
  - 1D, 2D, Stochastic, Force-Field, ...





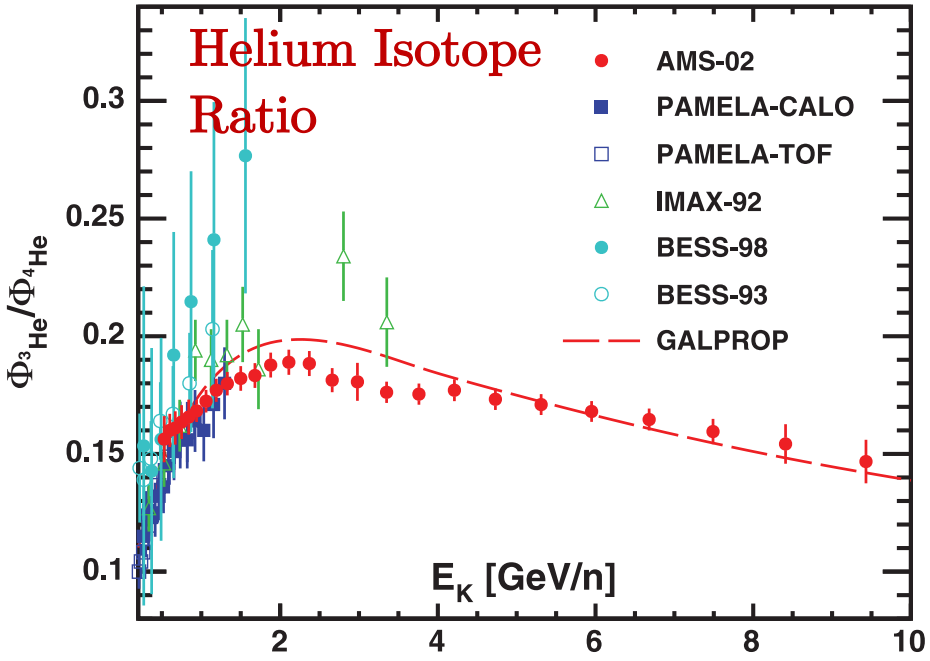


Light Isotope Separation

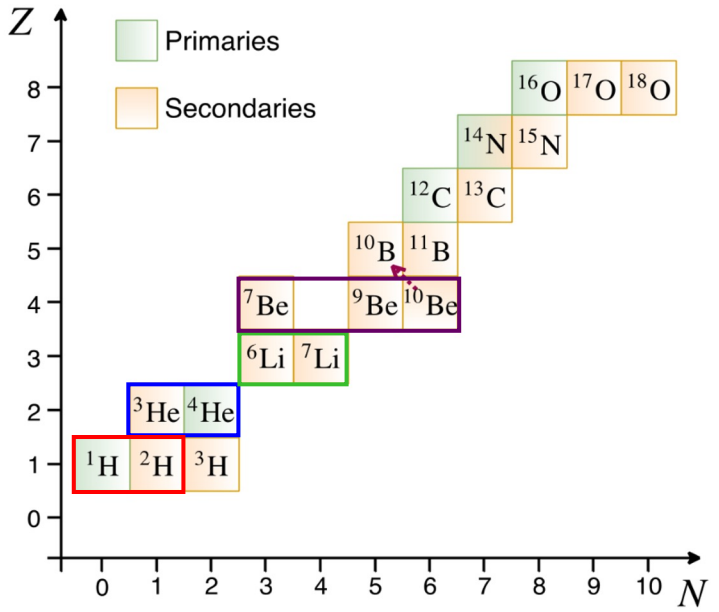
Isotope CR Flux

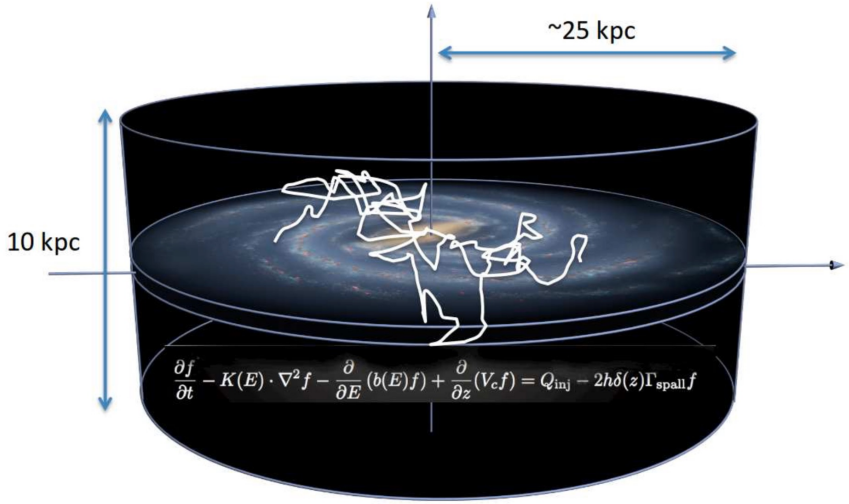
Cosmic rays as probes

- Light stable isotopes (D, ^{2}H, ^{3}He, ...)
  - CR propagation information
- Light radioactive isotopes (^{10}Be, ...)
- Secondary/Primary ratios
- Solar modulation physics
  - Velocity effect on diffusion
  - Drift velocities



Isotopes in light CR



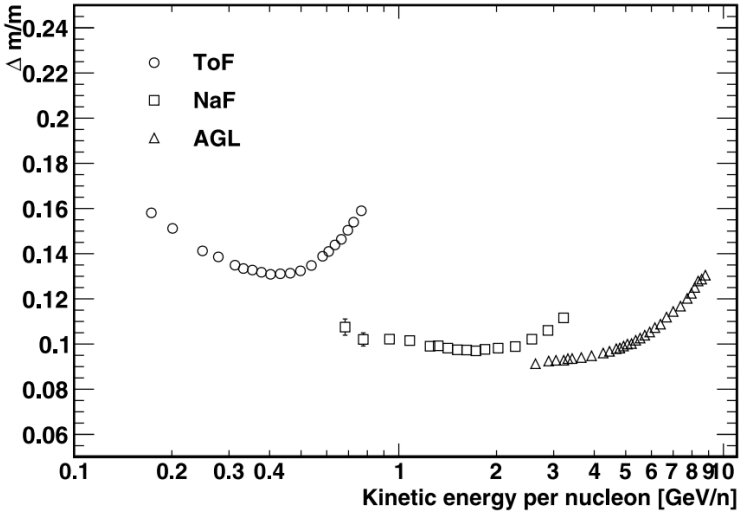


Isotopic separation

Detector physics

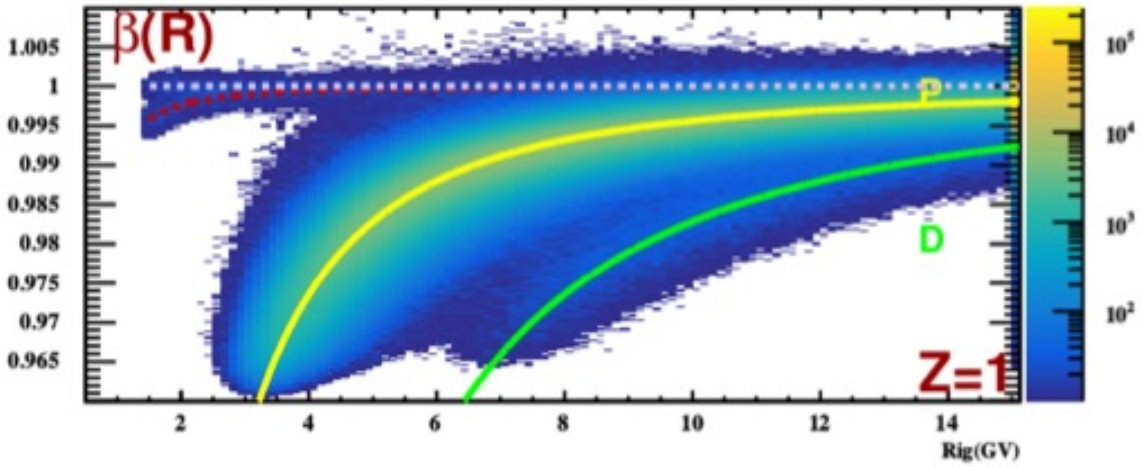
- Mass resolution
  - Rigidity & Velocity resolution
- Likelihood estimators
  - Folded rigidity template
  - Velocity resolution modelization

Mass resolution

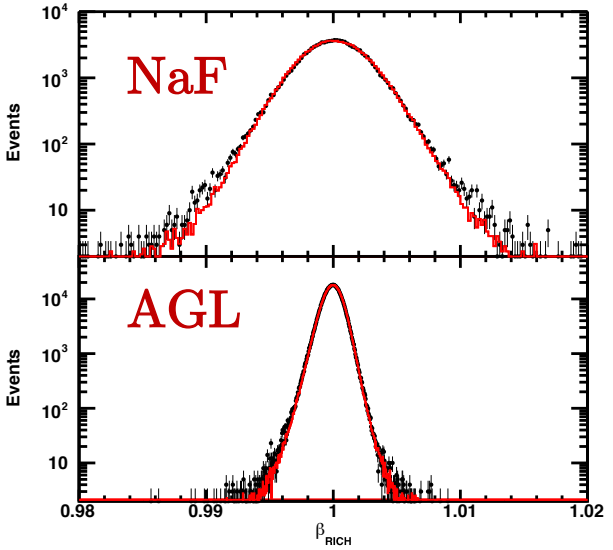


Mass measurement and resolution

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta R}{R}\right)^2 + \gamma^4 \left(\frac{\Delta \beta}{\beta}\right)^2 \qquad m = \frac{RZ}{\beta\gamma}$$



Helium - RICH

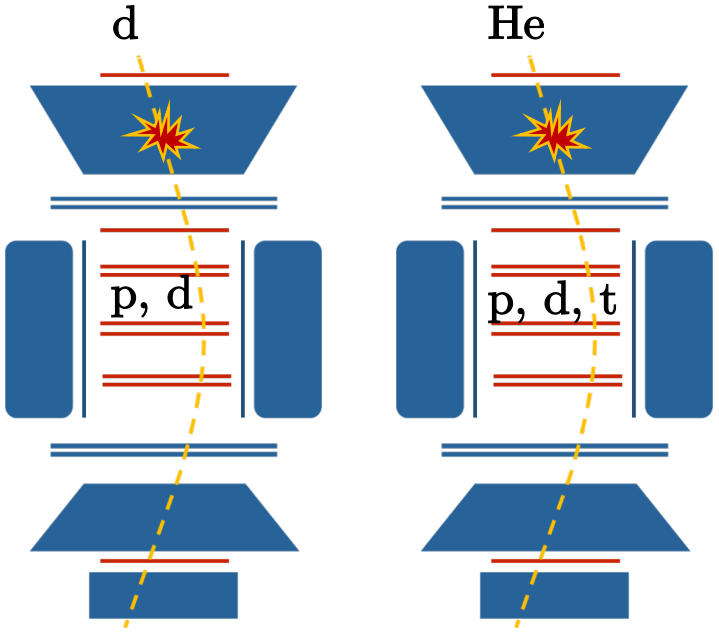


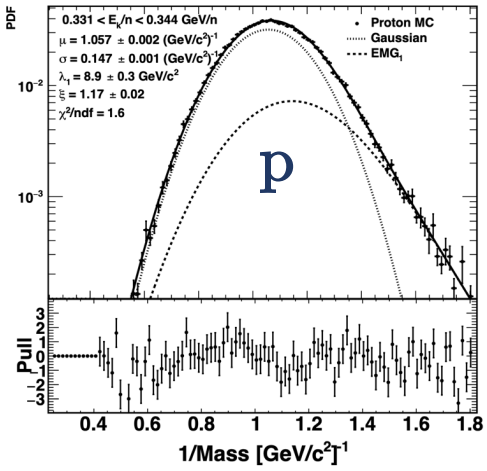
Deuteron separation

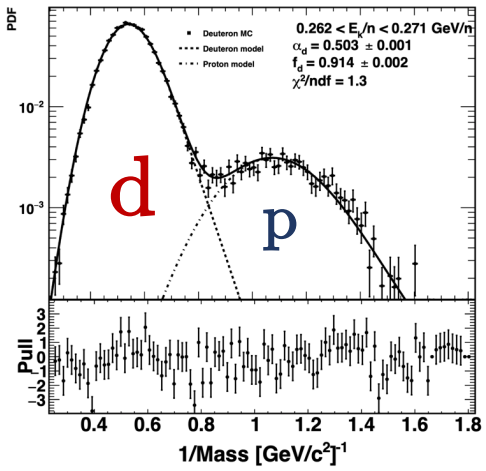
Isotopic separation

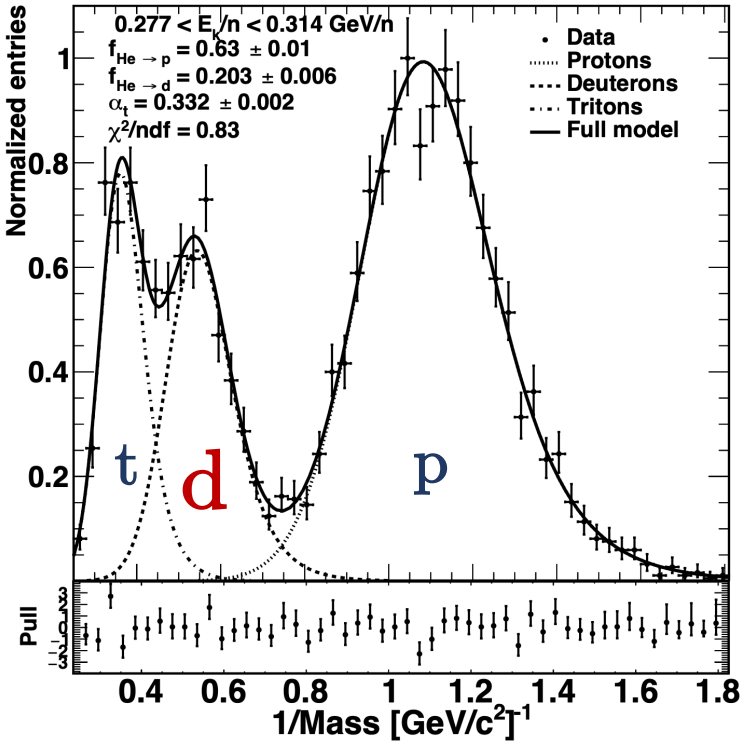
- Grants insight on galactic mass distribution
- Requires accurate mass separation
- Enables the exploration of advanced statistical tools and estimators

$$M^{\text{Total}}(1/m) = f_1 M_p + \underbrace{f_2 M_d + f_3 M_{d\to p}}_{M_d^{\text{Total}}} + \underbrace{f_4 M_{\text{He}\to d} + f_5 M_{\text{He}\to p} + f_6 M_{\text{He}\to t}}_{M_{\text{He}\to X}}$$









Typical challenges in CR detection

Analysis of massive datasets (45 million events per day)

- Efficient selection frameworks
- Development of regularization frameworks
- Parallelization of workload

Development of advanced statistical and computational tools

- Iterative-Bayesian unfolding with prior regularization
- Likelihood methods
- Optimization
- Parametric and Non-parametric regularization

Numerical resolution of Parker Equation (Solar Modulation)

- Development of numerical solvers
- Stochastic Differential Equation solvers

(Time, Frequency) spectral analysis

- Filtered Fourier Transform
- Wavelet Transform
- Cross-correlation and PCA
- Hilbert-Huang Transform & Empirical Mode Decomposition

Conclusions

- **Cosmic-ray physics is multidisciplinary...**
  - Particle Physics
  - Detector physics
  - Cosmic-ray transport
    - Plasma physics, Diffusion, ...
  - Computational physics
  - Advanced Statistics
  - Data analysis
  - Machine learning

- **There is more to be done in...**
  - Detector studies (RICH, Tracker, ECAL, ...)
  - Observation of solar events on daily flux
  - Time-resolved isotope fluxes
  - Frequency-domain analysis
  - Selection of higher charge events
  - Machine learning classifiers
  - Geomagnetic field as a velocity selector
  - Velocity resolution model

Our doors are always open…

Questions?

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LIP

TÉCNICO LISBOA

Backup

Low Energy Physics

Cosmic rays as probes

- Propagation models (around the Sun)
  - Diffusion (velocity effects)
  - Charge sign effects
- Parametrizations & correlation with solar observables
- Forbush decrease & solar events
- Decoupling solar effects from CR flux

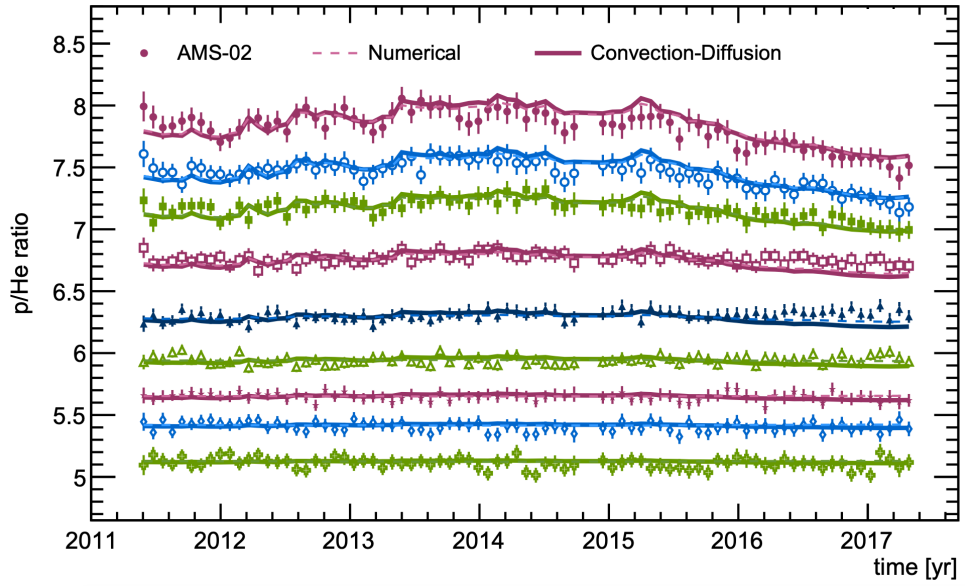
$$K_\perp = 0.02 K_\parallel$$

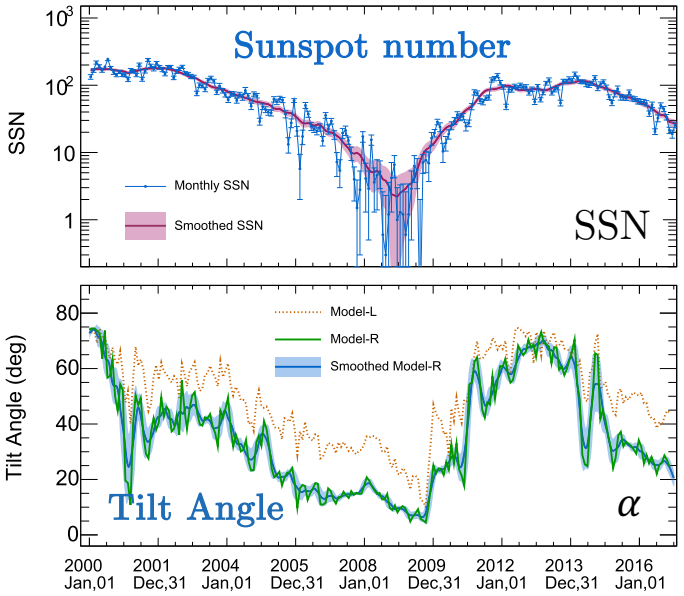
$$K_\parallel = k_0(t) \frac{A}{3B} \beta \, (P/1\,\mathrm{GV})$$

$$\mathrm{SSN} = \mathrm{SSN}(t)$$

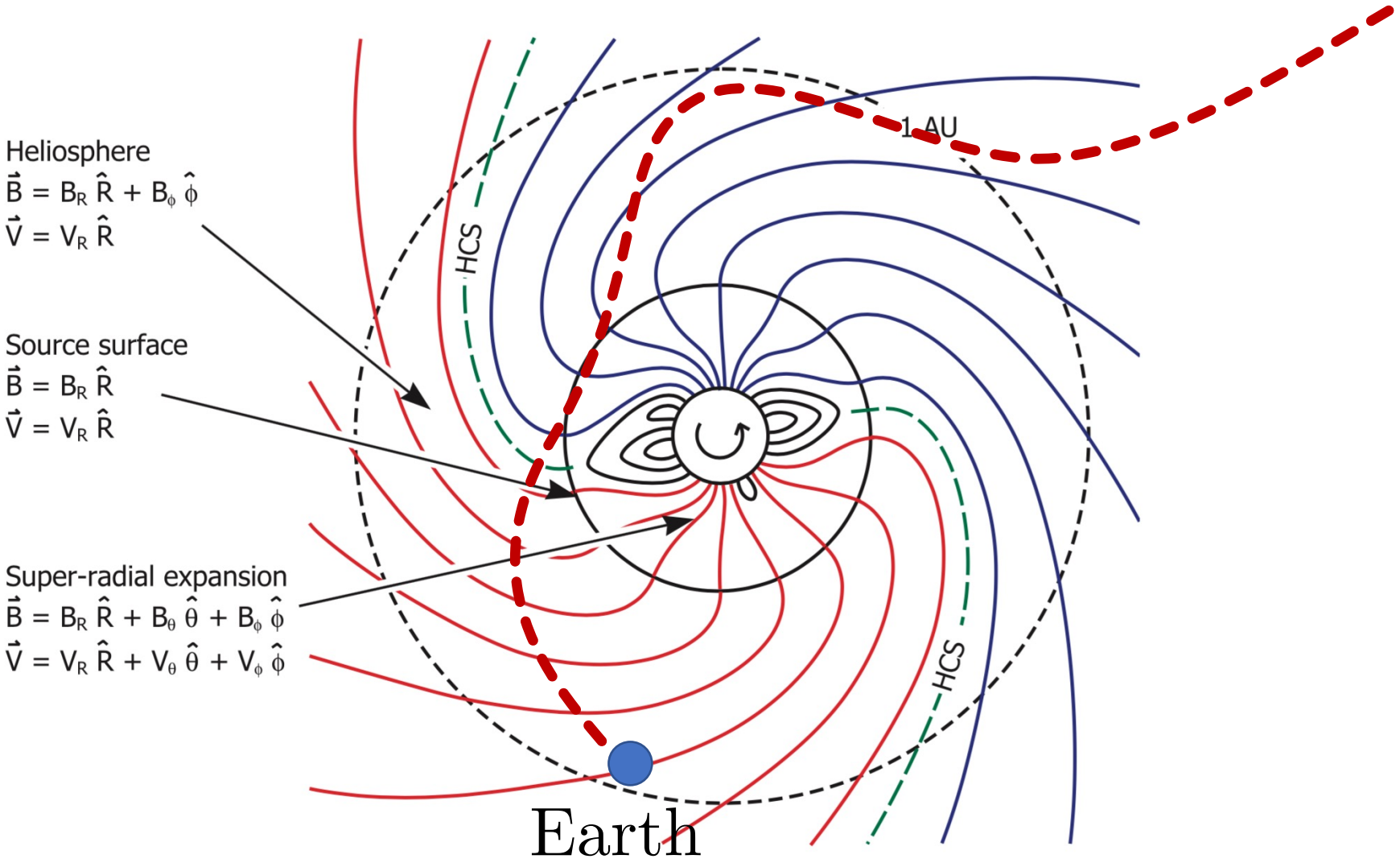
Parametrization of diffusion parameter

Proton-helium ratio





Solar Modulation



Alpha Magnetic Spectrometer

To estimate the proton flux some key ingredients are necessary:

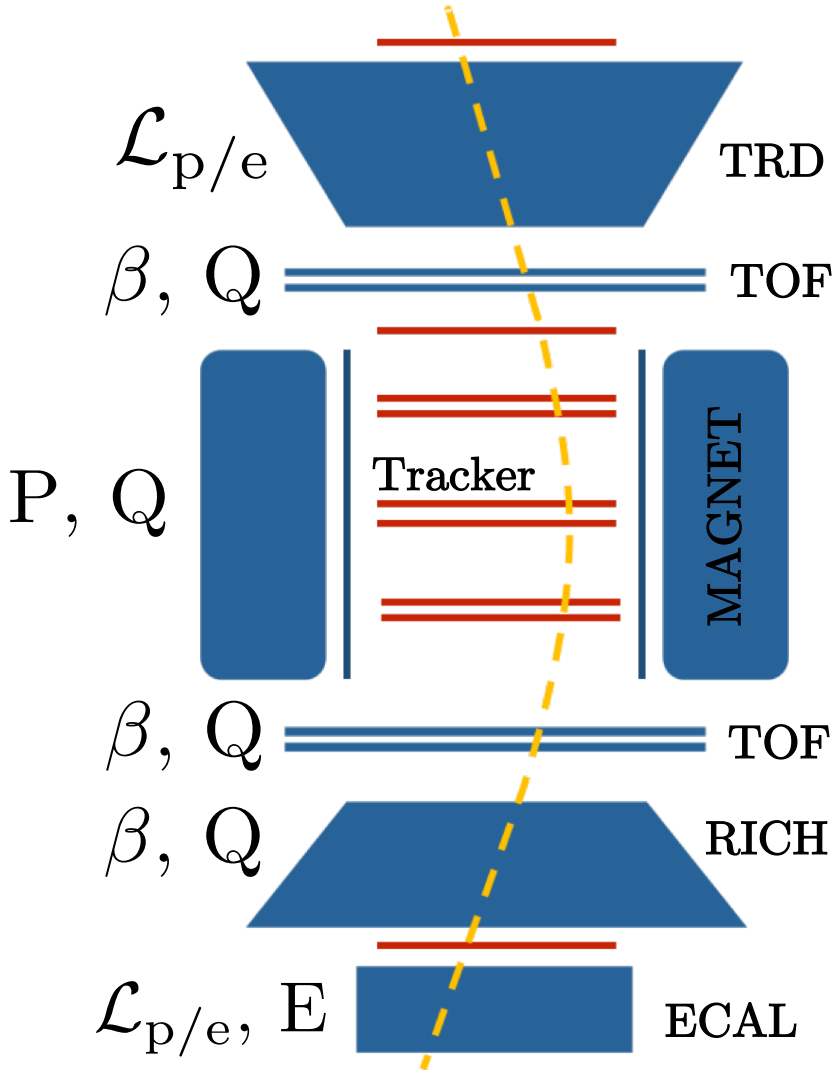
- **Accurate particle detection**
- **Exposure time**
- **Trigger Efficiency**
- **Detector acceptance and efficiency**

$$\varphi(P) = \frac{N_{\text{part}}(P)}{\Delta t(P)\, Acc_0\, \varepsilon_{\text{geom}}(P)\, \varepsilon_{\text{det}}(P)\, \Delta P}$$

$$\varphi(P) = \frac{N_{\text{part}}(P)}{\Delta t(P)\, Acc_{\text{eff}}(P)\, C_{\text{MC}}^{\text{DATA}}(P) \Delta P}$$

Measurements are usually written as a function of kinetic energy or magnetic rigidity:

$$P = \frac{p\,c}{Z\,e} = r_L B$$

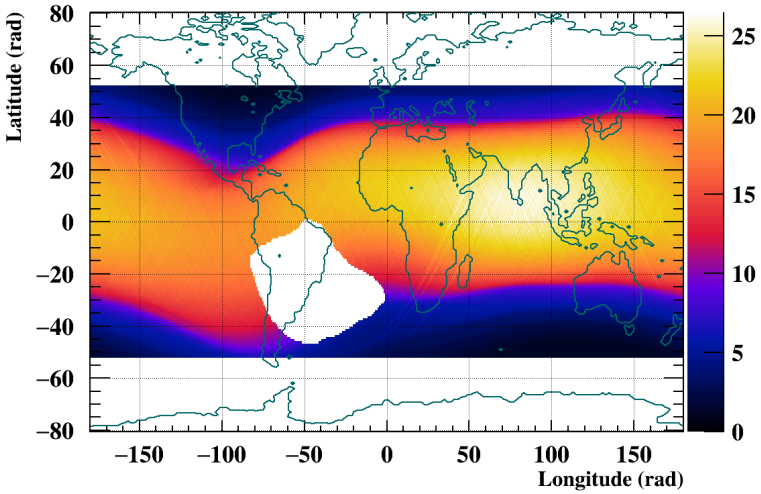


Isotopic separation

Other innovative methods

- Geomagnetic Cutoff Estimator
  - Using earth's magnetic field
  - Building β pdf's from slices of rigidity
- Iterative-Bayesian unfolding with prior regularization, using multiple detector measurements
- Machine learning algorithms
  - BDT, MLP, ...
  - Classifier distribution as template
  - Classification techniques
  - Selection of physical variables

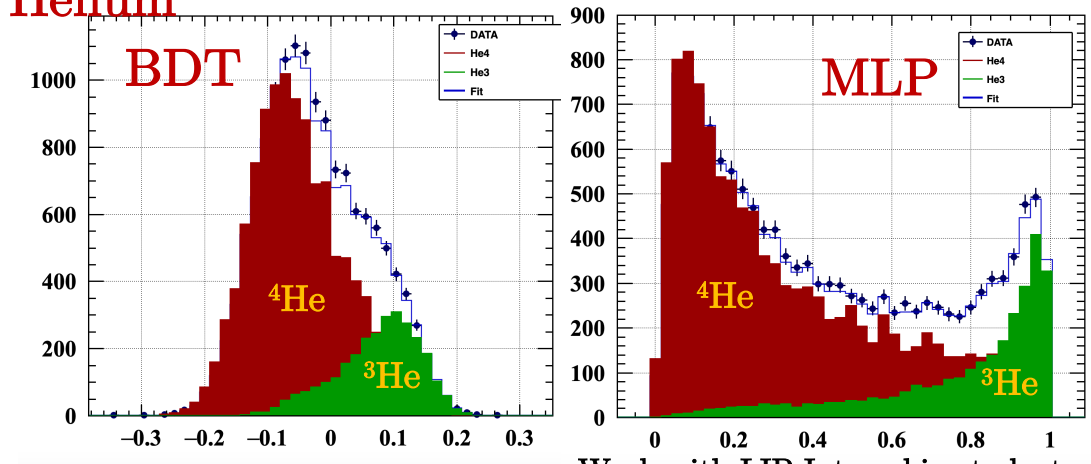
Geomagnetic Cutoff

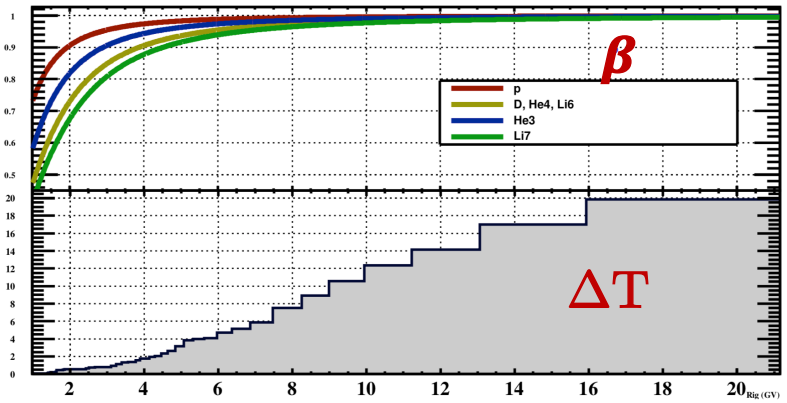


$P_{\mathrm{Cutoff}}(\varphi,\theta)$

$P(\mathrm{GV})$

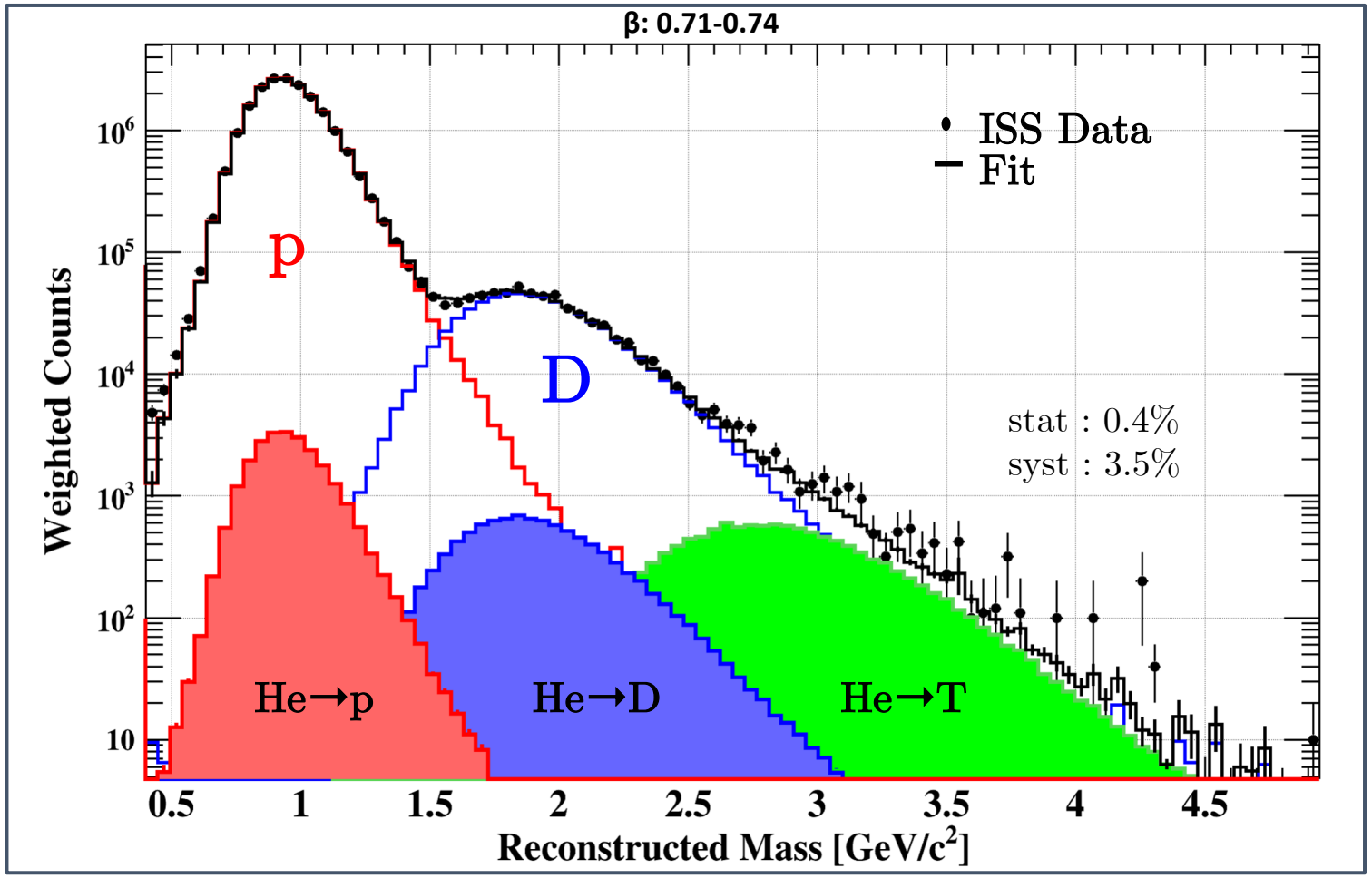
Helium





Work with LIP Internship students

Backup


β: 0.71-0.74
ISS Data
Fit
p
D
stat : 0.4%
syst : 3.5%
He→p
He→D
He→T
Weighted Counts
Reconstructed Mass [GeV/c²]
10⁶
10⁵
10⁴
10³
10²
10
0.5
1
1.5
2
2.5
3
3.5
4
4.5