Bayesian analysis of Cosmic Ray Propagation Parameters :

antiproton-to-proton ratio is consistent with spatial-dependent Model prediction.

Jie Feng[1,2] and Nicola Tomassetti[3,4]

[1] *Academia Sinica, Taiwan*

[2] *Sun Yat-sen University, China*

[3] *Universita degli Studi di Perugia & INFN-Perugia, Italy*

[4] *LPSC, Université Grenoble-Alpes, CNRS/IN2P3, France*

Contents

- Spatial Dependent Propagation Model
- Bayesian analysis method
- Error break down of the antiparticles
- Estimation of the halo height

- **Spatial Dependent Propagation Model**
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Transport Equation

$Q = Q_{pri} + Q_{sec}.$

$Q_{pri} \propto R^{-\nu}$: *primary source term;*

$Q_{sec} = \sum_j \Gamma_j^{sp} \psi_j$: *secondary production term from spallation of j nuclei with rate* Γ_j^{sp}

$\Gamma = \beta c n \sigma$: *destruction rate for collisions of gas with density n at velocity* βc *and cross section* σ.

$$\frac{\partial \psi}{\partial t} = Q + \vec{\nabla} \cdot (D \vec{\nabla} \psi) - \psi \Gamma + \frac{\partial}{\partial E}(\dot{E} \psi)$$

$\dot{E} = -\frac{dE}{dt}$: *ionization and Coulomb losses*

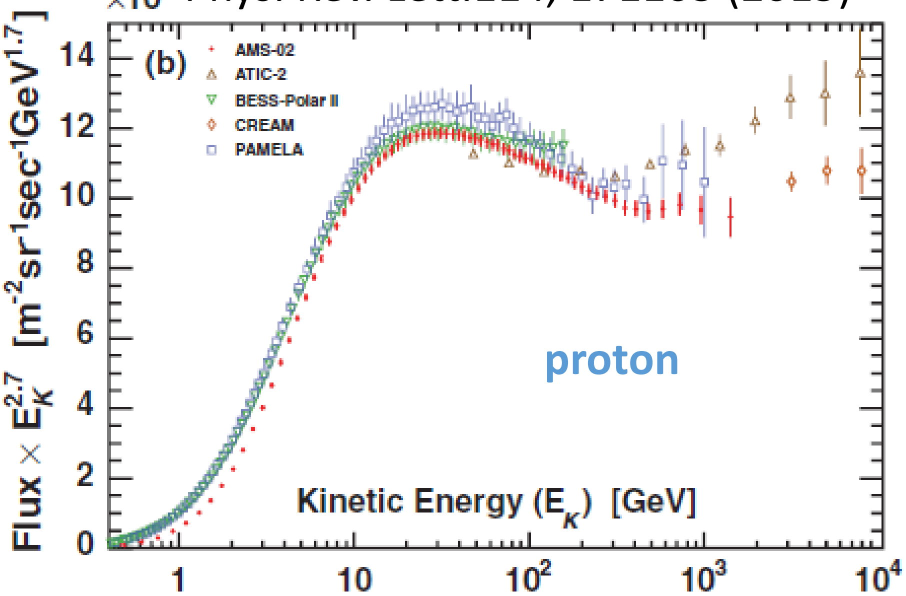
$D(R) \propto R^{\delta}$: *rigidity* $\left(R = \frac{p}{Z}\right)$ *dependent diffusion coefficient*

$\psi = \psi(E, r, z)$: *particle number density*

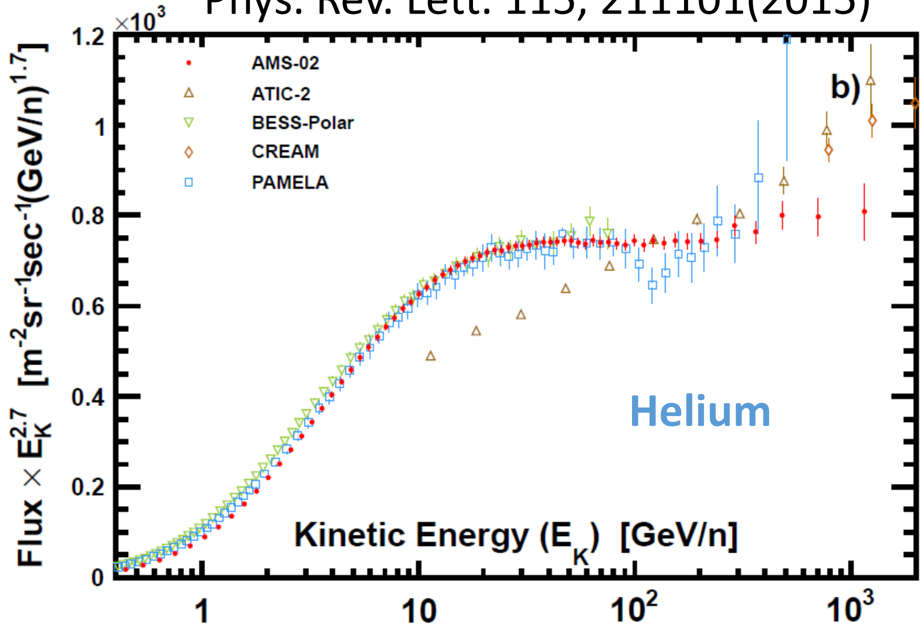
For homogeneous diffusion model, primary particles at high energies: $\psi(\mathrm{R}) \propto R^{-\nu-\delta}$, single power law.

High energy breaks in the H and He spectra

M. Aguilar et al., Phys. Rev. Lett.114, 171103 (2015)



M. Aguilar et al., Phys. Rev. Lett. 115, 211101(2015)



Current explanations:

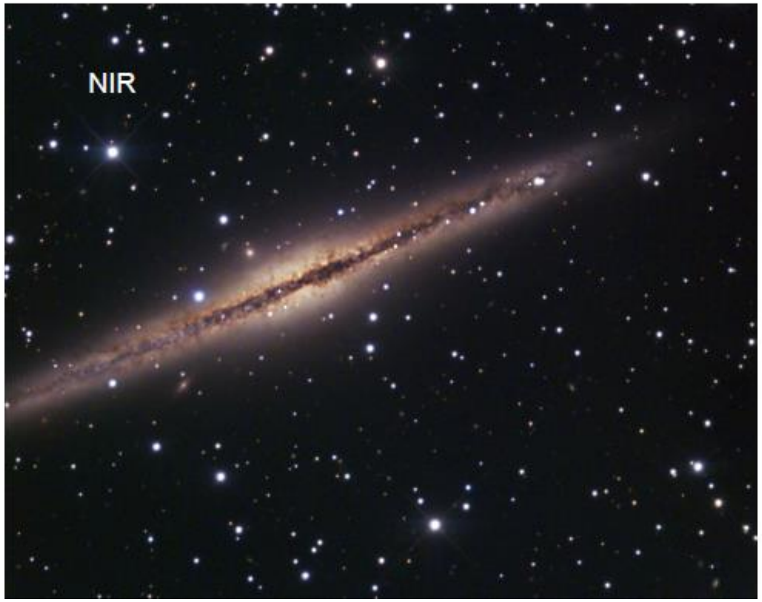
1) **multi-component populations**
2) **the CR injection, Q(R), non-linear effects in diffusive-shock-acceleration mechanisms**
3) **Nonlinear propagation or inhomogeneous diffusion coefficient D(R)**

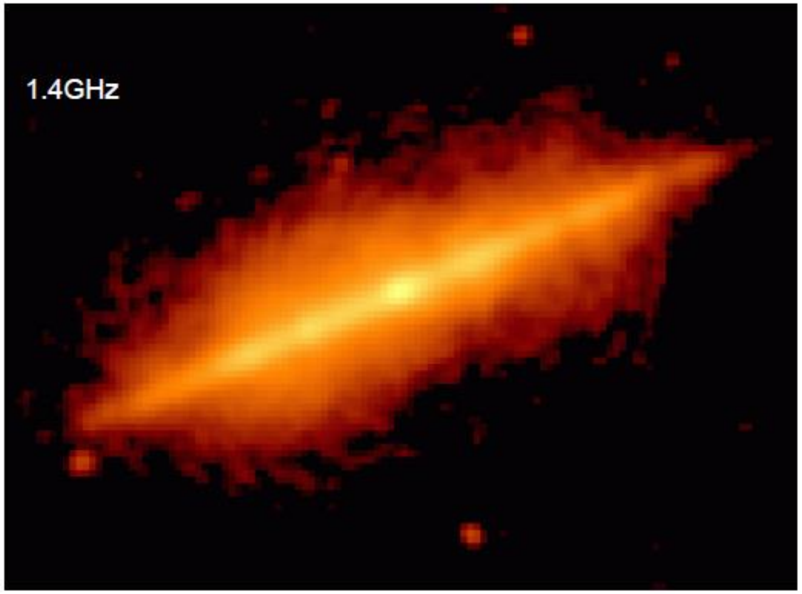
Introduction to Spatial dependent propagation model

Recent studies based on gamma-ray observations:

1) **Galactic wind (S. Recchia et al., arXiv:1604.07682)**
2) **Anomalous diffusion (A. D. Erlykin and A. W. Wolfendale, arXiv:1212.2760; C. Evoli and H. Yan, arXiv:1310.5732).**

NGC 891





Near Infrared **Radio**

Spatial dependent propagation model (Two-Halo-Model)

Diffusion Coefficient as a function of space:

$$D_{xx}(r,z,p) = \begin{cases} D_0 \beta^\eta \left(\frac{R}{R_0}\right)^\delta & |z| < \xi z_h \\ \chi D_0 \beta^\eta \left(\frac{R}{R_0}\right)^{\delta F(r,z)} & |z| > \xi z_h \end{cases}$$

$$F(r,z) = \begin{cases} 1 & |z| < \xi z_h \\ \left(\frac{1}{1+\exp\left(f(r)\right)} + \Delta\right)\left(\frac{z}{\xi z_h}\right)^n & |z| > \xi z_h \end{cases}$$

N.Tommassetti, arXiv: 1509.05775
Yi-Qing Guo, Zhen Tian, Chao Jin, arXiv: 1509.08227v1

- Spatial Dependent Propagation Model
- **Bayesian analysis method**
- Error break down of the antiparticles
- Estimation of the halo height

Bayesian analysis

- 8-parameter set: $\boldsymbol{\theta}$
- Observed data set: $\mathbf{D}$
- The posterior distribution

$$P(\theta|\mathbf{D}) = \frac{P(\mathbf{D}|\theta)P(\theta)}{P(\mathbf{D})}$$

- depends on the likelihood function $L(\theta) = P(\mathbf{D}|\theta)$ and on the prior probability distribution $P(\theta)$.

Markov Chain Monte-Carlo

- The transition probability to move from θ_n to θ_{n+1} in the parameter space:

$$T(\theta_n,\theta_{n+1})$$

- An arbitrary proposal density distribution:

$$q(\theta_n,\theta_{n+1})$$

- The probability to accept this new point:

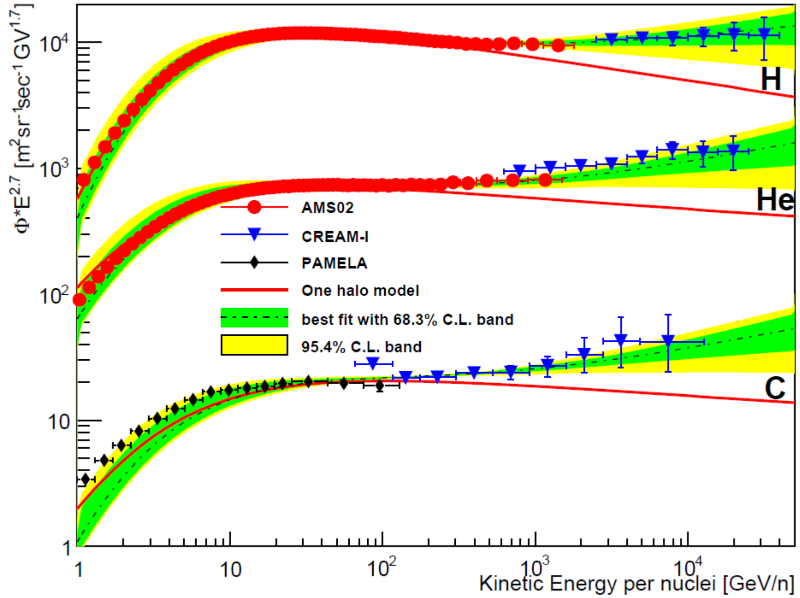
$$\alpha(\theta_n,\theta_{n+1}) = min\left\{1, \frac{P(\theta_{n+1})q(\theta_{n+1},\theta_n)}{P(\theta_n)q(\theta_n,\theta_{n+1})}\right\}$$

- We get

$$T(\theta_n,\theta_{n+1}) = \alpha(\theta_n,\theta_{n+1})q(\theta_n,\theta_{n+1})$$

- It converges to a balance

$$P(\theta_{n+1})T(\theta_{n+1},\theta_n) = P(\theta_n)T(\theta_n,\theta_{n+1})$$



$$\delta = 0.149$$

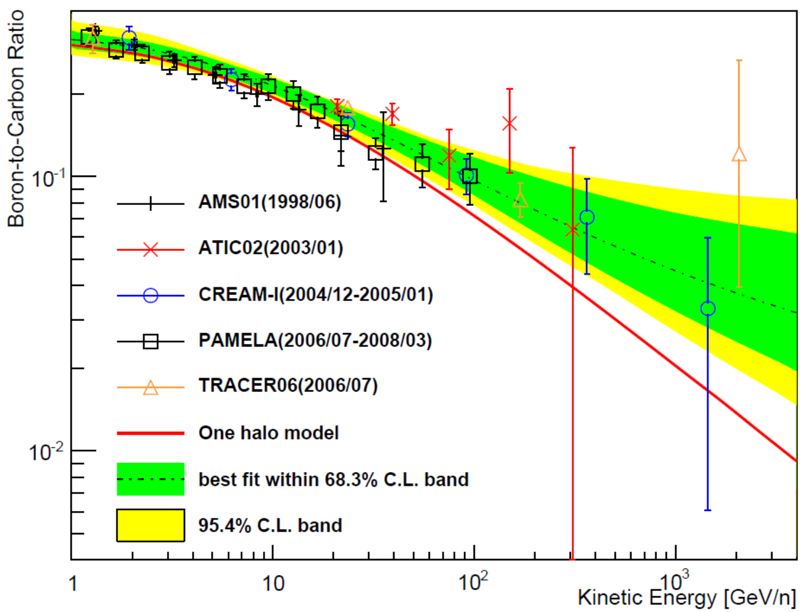
$$\delta + \Delta = 0.149 + 0.523$$

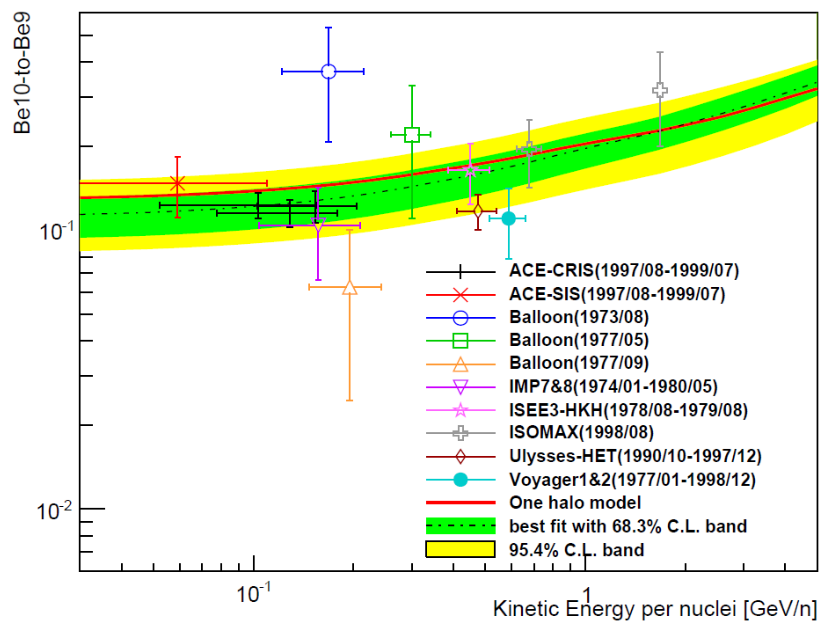
Data sample to constrain parameters:

1) H, He and C spectra

2) B/C

3)^{10}Be/^{9}Be





- Spatial Dependent Propagation Model
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- **Error break down of the antiparticles**
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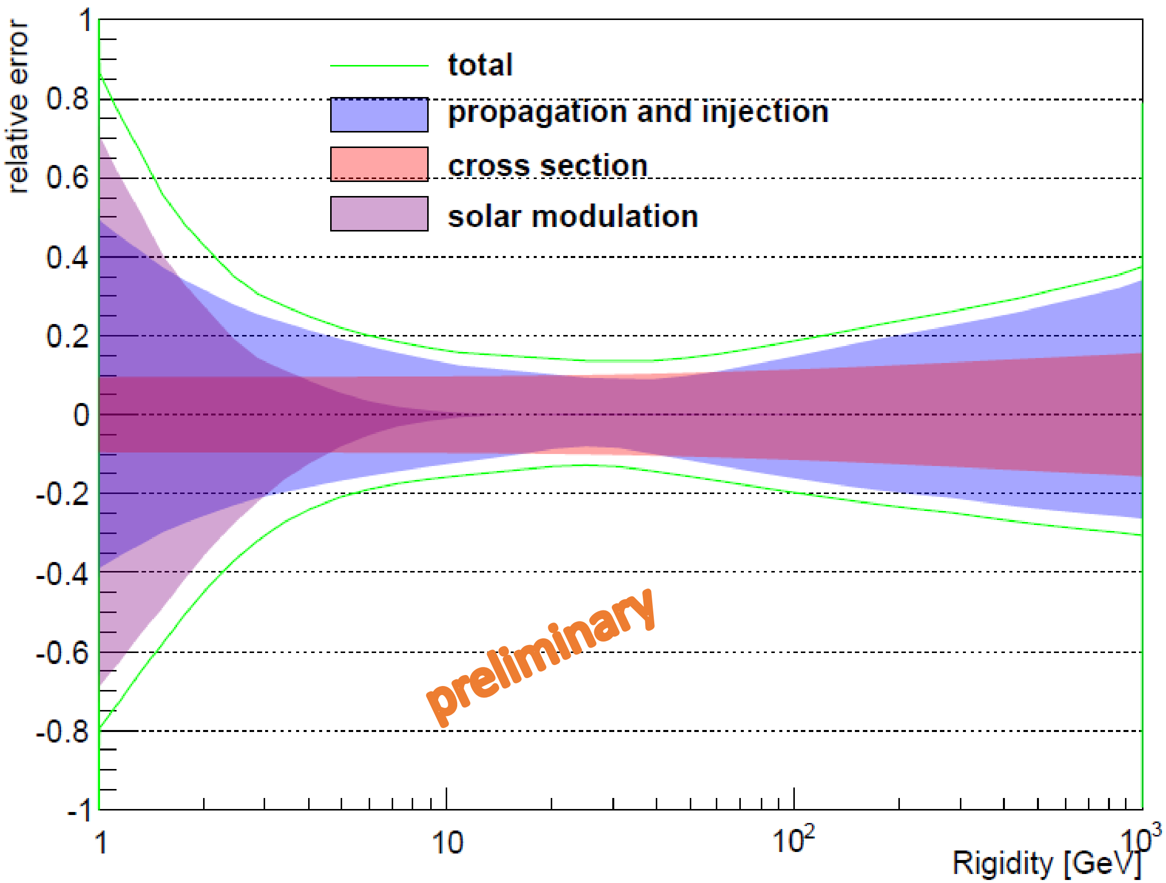
Error break down of ap/p

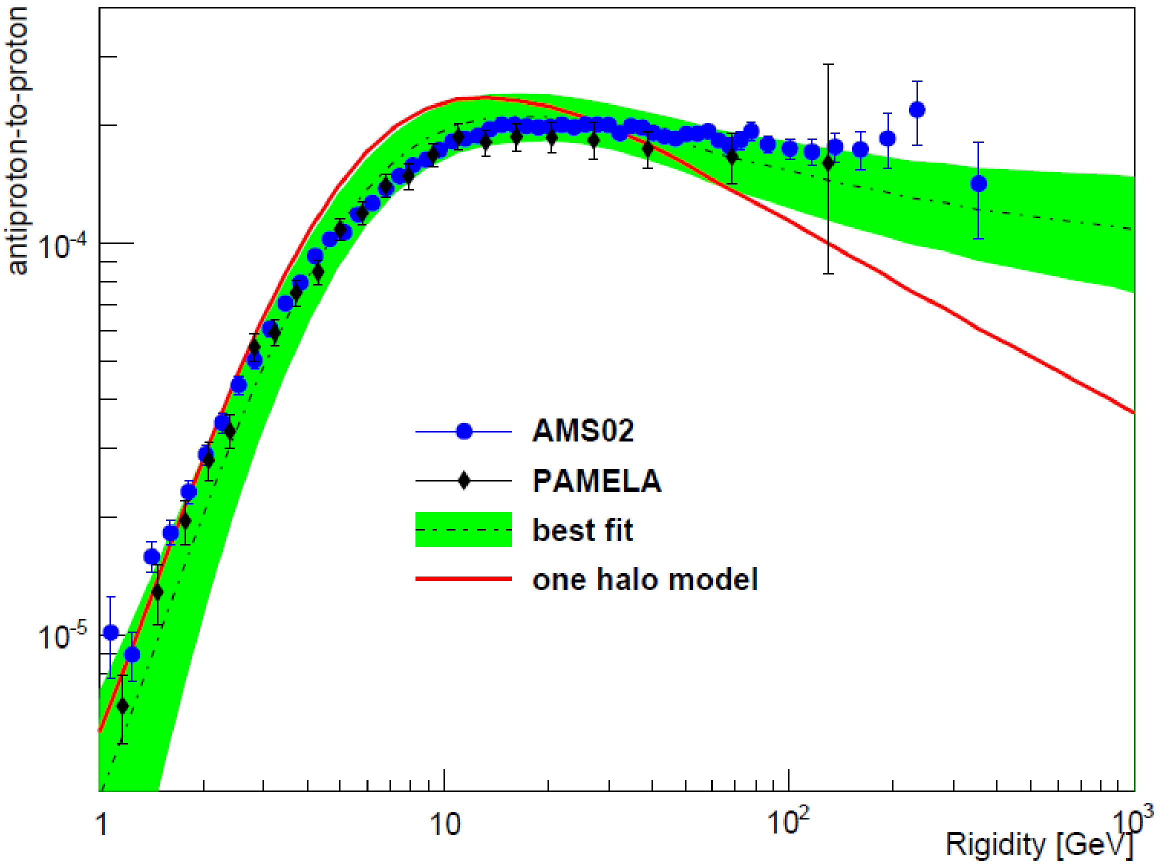


Propagation and injection error dominates the total error at high energies, which can be improved by B/C measured by AMS02, CALET and DAMPE.

Cross section is taken from EPOS LHC model.
Cross section error has a significant contribution , which can be improved by ground experiments.

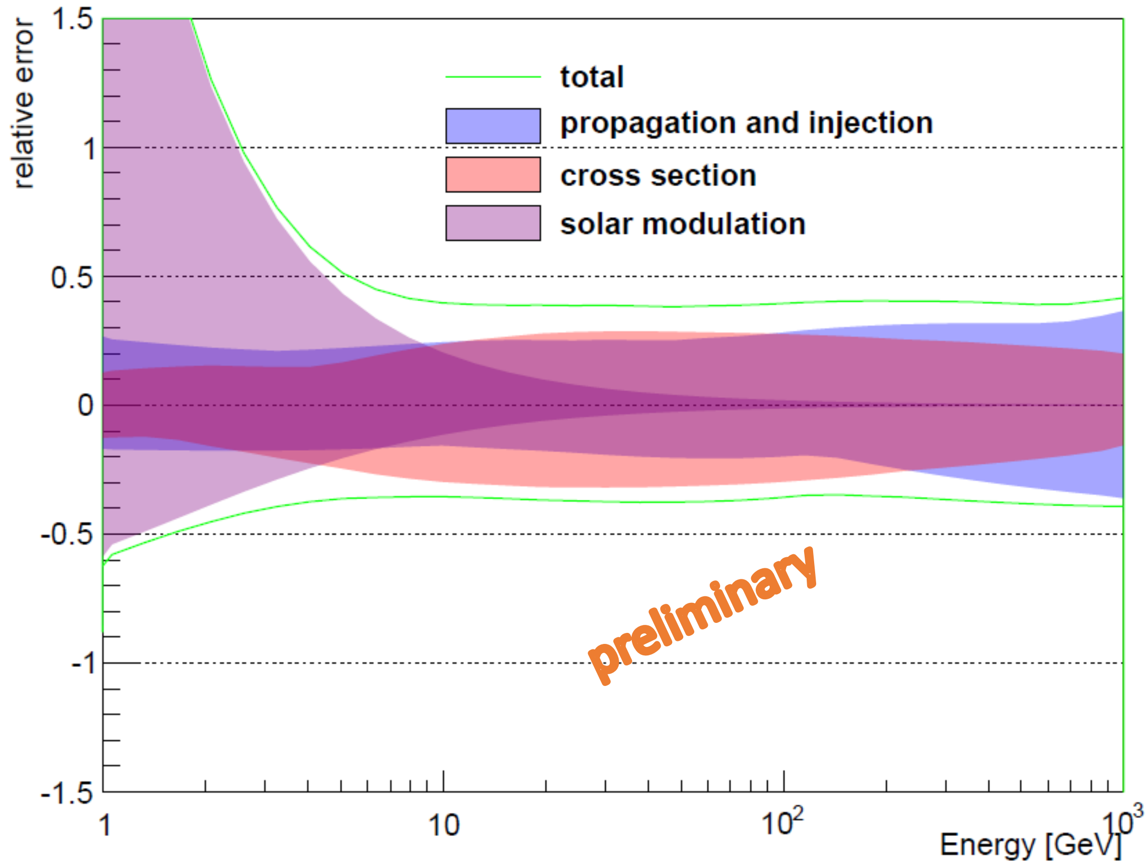
Solar modulation error is estimated by varying solar modulation potential from 200 MeV to 700 MeV

Prediction of ap/p with EPOS LHC



Ap/p prediction is consistent with measured data.

Error break down of positron flux

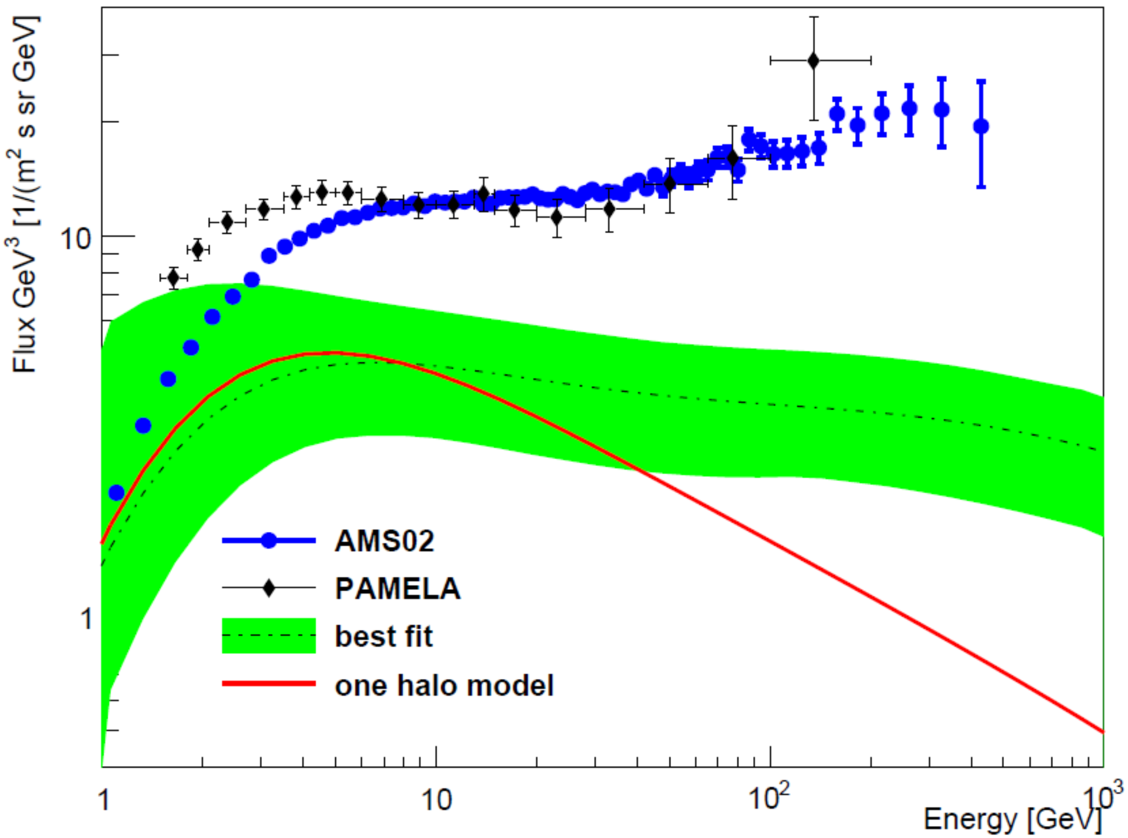


Propagation and injection error dominates the total error at high energies, which can be improved by B/C measured by AMS02, CALET and DAMPE.

Cross section is taken from (T. Delahaye, et al. arXiv:0809.5268)

Solar modulation error is estimated by varying solar modulation potential from 200 MeV to 700 MeV

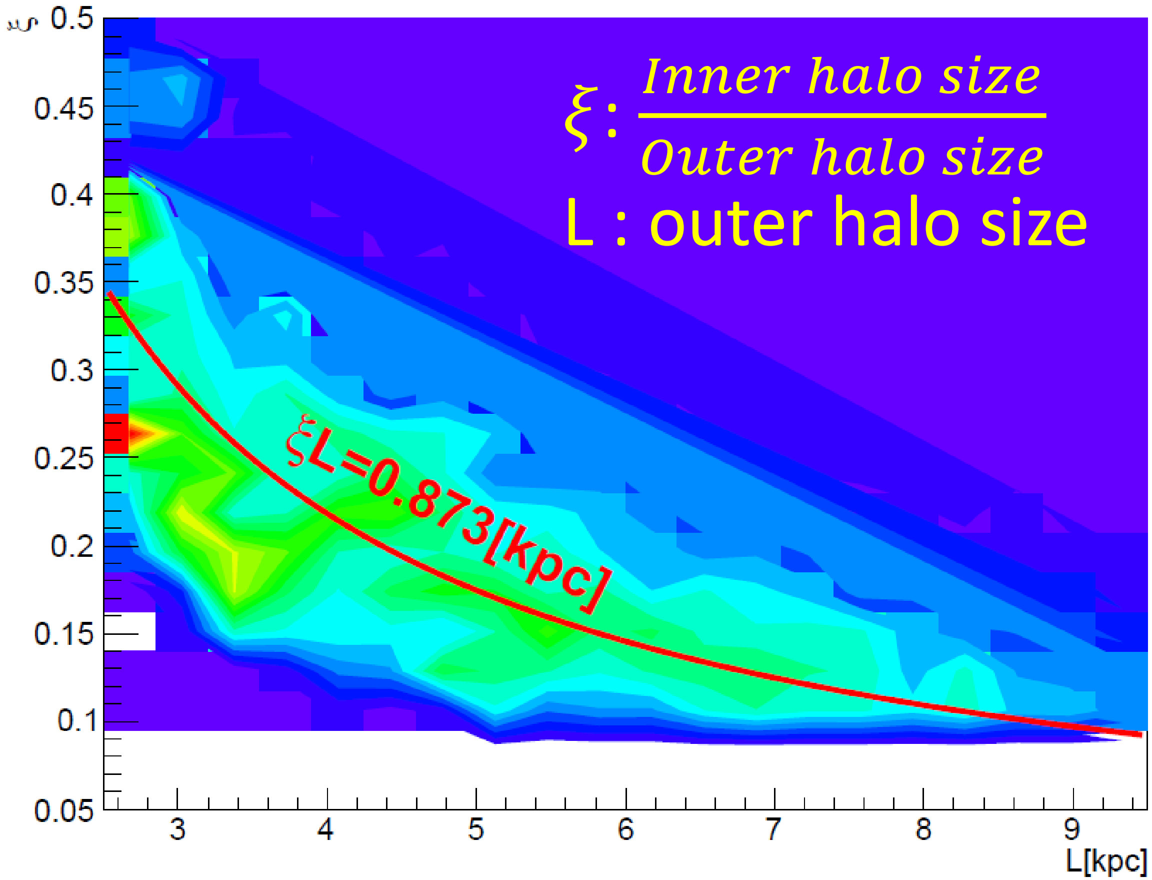
Prediction of positron flux



Positron prediction of two-halo-model is harder than that of one-halo-model.
Extra component is needed.

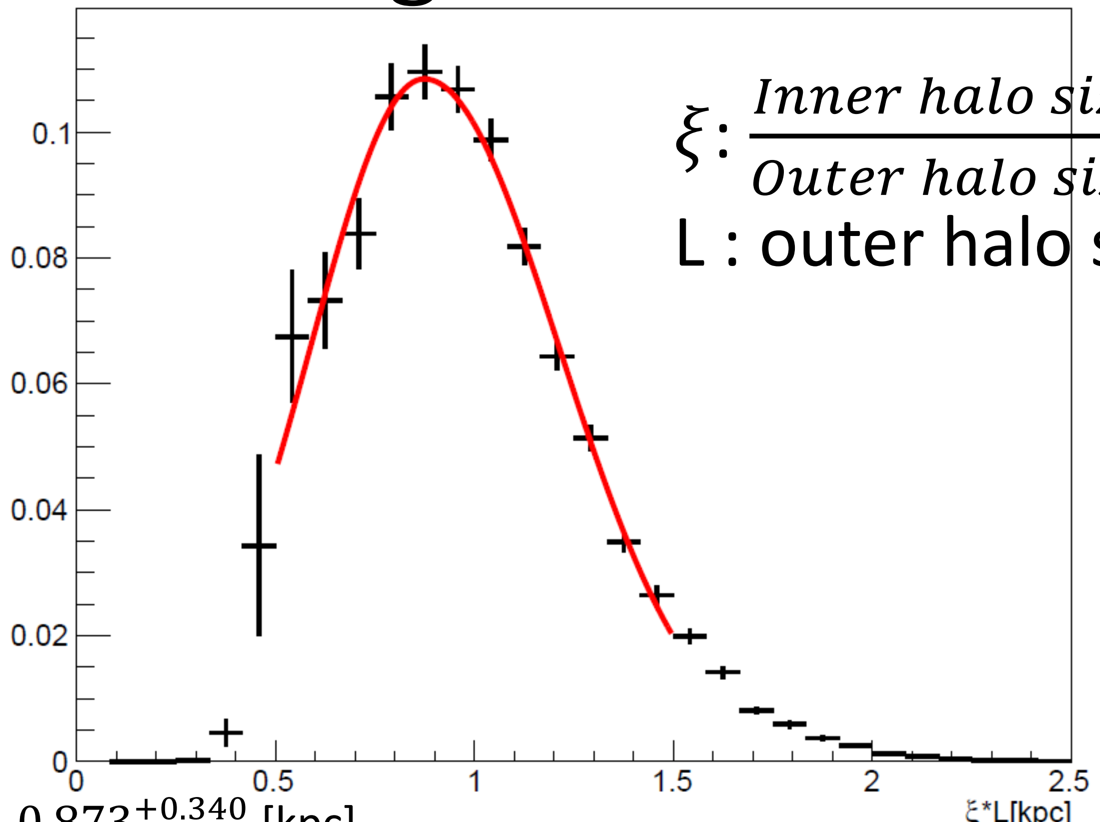
- Spatial Dependent Propagation Model
- Validation of antiproton production cross section
- Error break down of the antiparticles
- **Estimation of the halo height**

Outer halo height



The result of L does not converge.

Inner halo height



$\xi: \frac{Inner\ halo\ size}{Outer\ halo\ size}$

L : outer halo size

Inner halo height: $0.873^{+0.340}_{-0.286}$ [kpc]

1) The inner halo height = ξL can converge mainly due to Be-10 to Be-9 low energy data.
For $R = 4\ GeV,\ L_{10} \sim 0.5\ [kpc] < 0.873[kpc]$

2) We need high energy(>200 GeV/n) Be/B data to constrain L_{outer}.

3) x-ray and γ-ray observation may help to constrain the size of the outer halo.

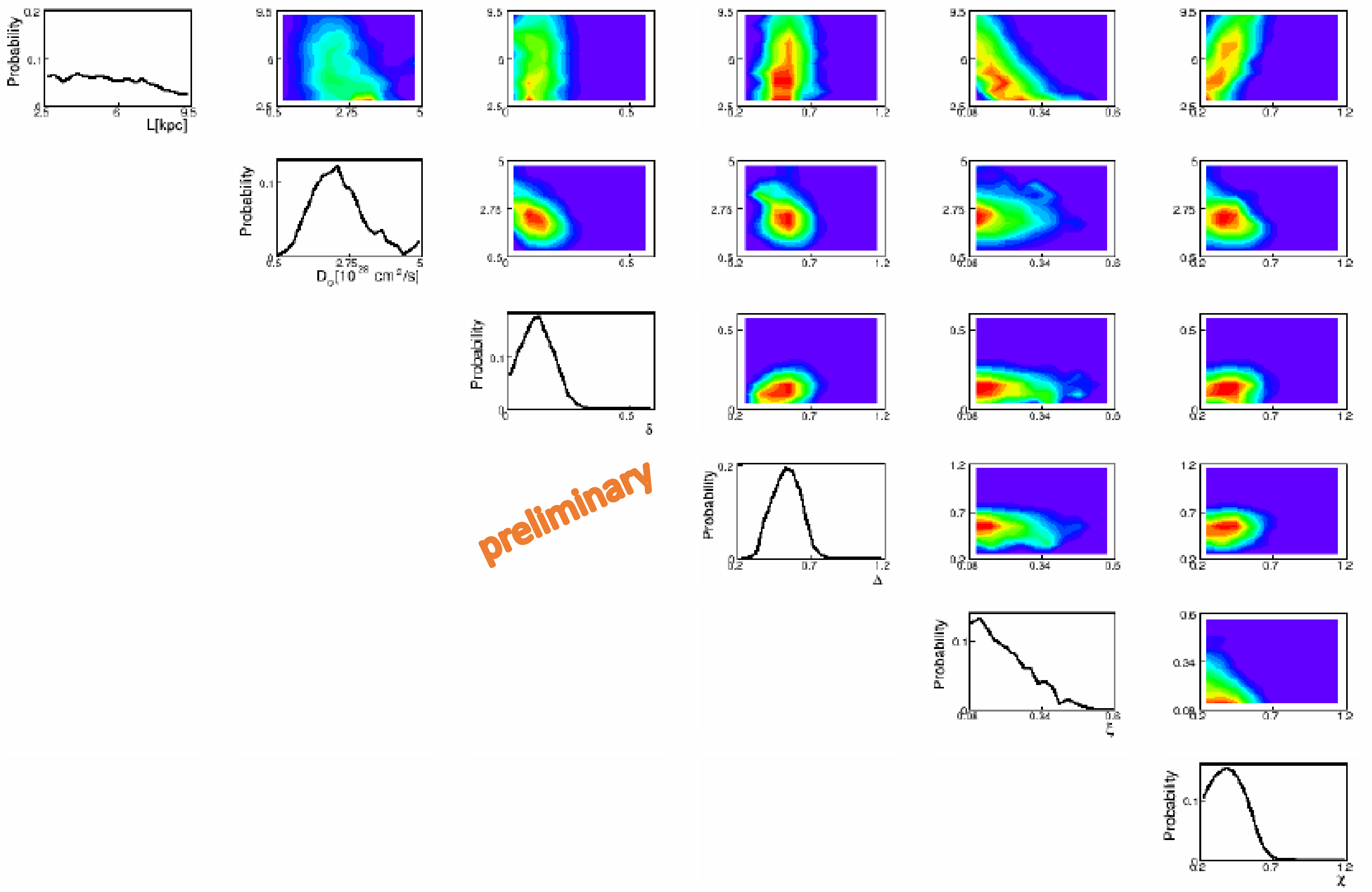
Summaries

- Antiparticles predicted by Spatial-Dependent-Model is presented:
- 1) antiproton-to-proton ratio prediction is consistent with the measured data.
- 2) positron flux prediction is lower than data. Extra component is needed.

- The error break down of the antiparticles is shown. The total error is dominated by propagation and cross section errors.

- Disk height is around ~1 kpc.

- Backup slides


Probability
L[kpc]
D0[10^28 cm^2/s]
δ
Δ
χ
preliminary

A fast scan

- the following variables fixed :

$\eta = -0.4$

$D_0\beta^\eta(\frac{R}{R_0})^\delta$, η is a factor
(D.Gaggero et al., arXiv:1311.5575)

$\phi = 0.5\ GeV$

Solar modulation potential
(A. Ghelfi et al., arXiv:1607.01976)

$n = 5$

Smooth function variable
(Y. Q. Guo et al. arXiv:1509.08227)

$R_0 = 0.25\ GeV$

Normalization Energy.

The following variables fitted

Variable	Definition
L	Halo height.
D_0	Diffusion coefficient
χ	Ratio between outer and inner Diffusion coefficients
δ	Diffusion index of outer
ξ	Halo height/Galaxy disk height.
Δ	Diffusion index difference between inner and outer
$\Delta\nu$	Injection index difference between proton and other nuclei(He, C and O), decided by proton, Helium and Carbon fluxes.
ν	Proton injection index

Antiproton production in Cosmic rays from collisions

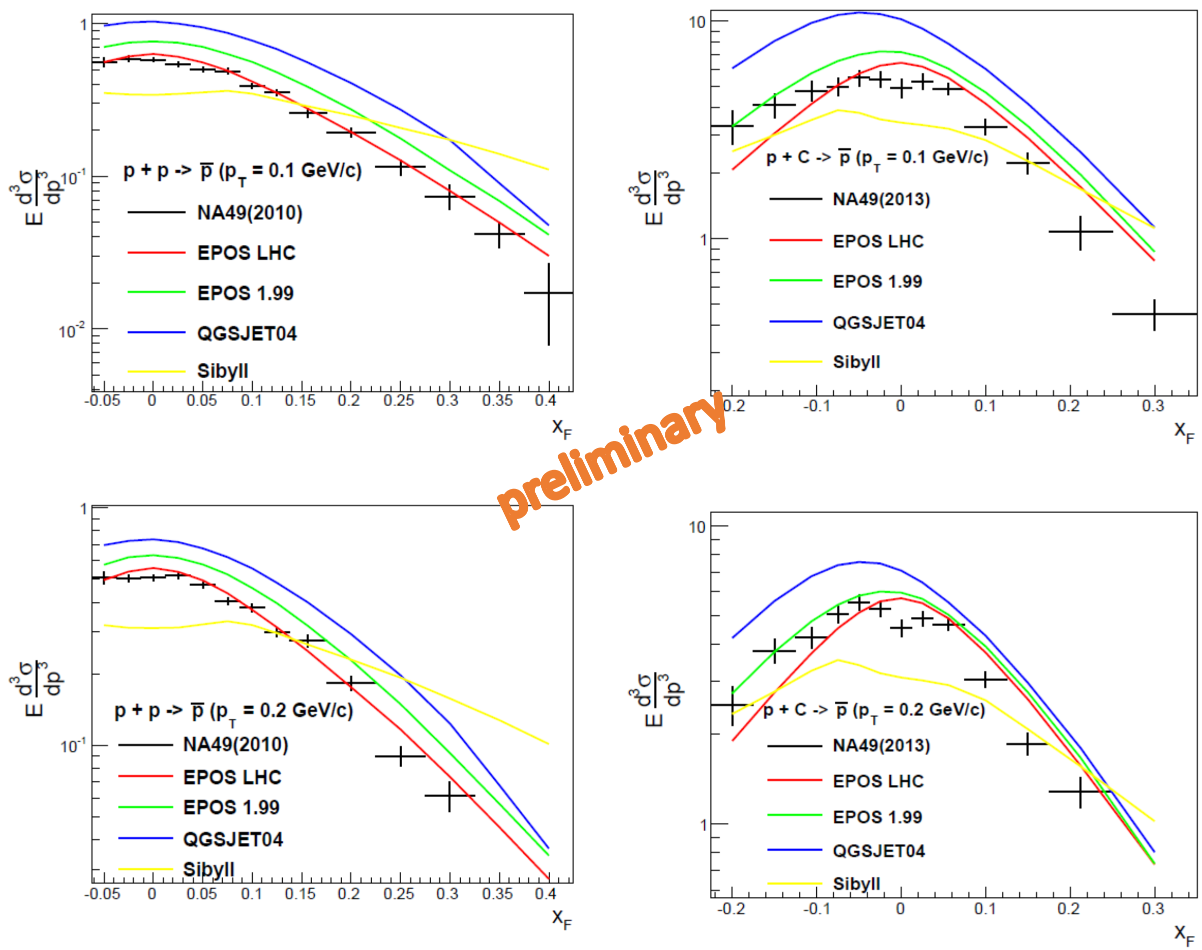
- In space, four channels mainly contribute directly to antiproton production.
- p + p(ISM) -> ap + X
- p + He(ISM) -> ap + X
- He + p(ISM) -> ap + X
- He + He(ISM) -> ap + X

- On the ground experiments:
- 1) p+p data can be used to check the p+p models.
- 2) p+C, p+Pb, Pb+Pb data can be used as a cross check of p+He.

Antiproton production in Cosmic rays from decays

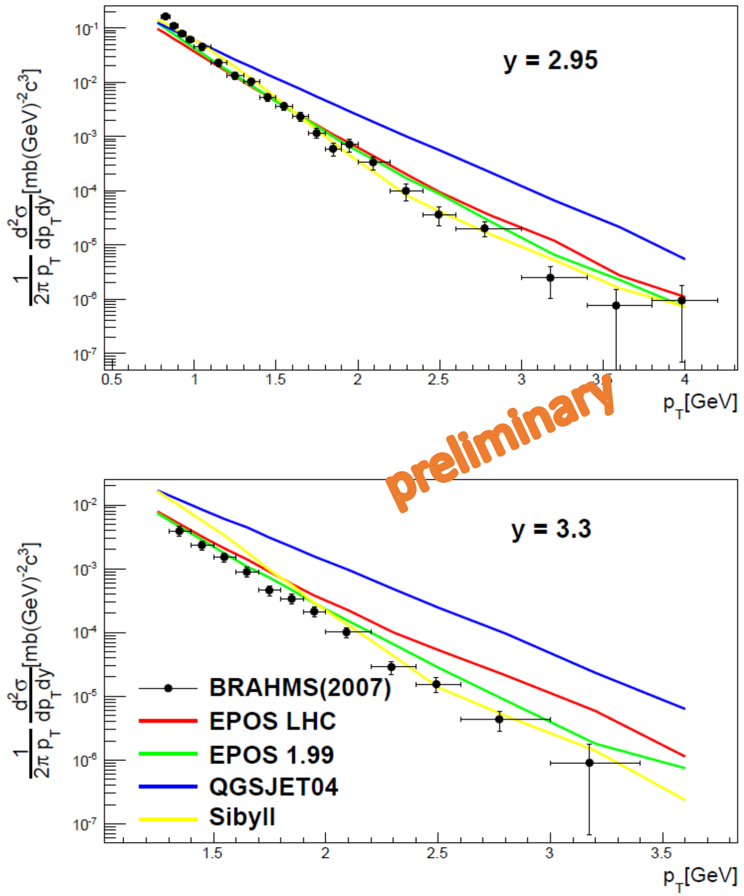
- Anti-n -> anti-p + e+ + nu
- Its life time is 881.5(15) s when βγ = 0 and ~10^5 s when βγ ~ 100.
- Compared to propagation time 10^5 yr, this lifetime is negligible.

NA49:
158 GeV/c proton beam



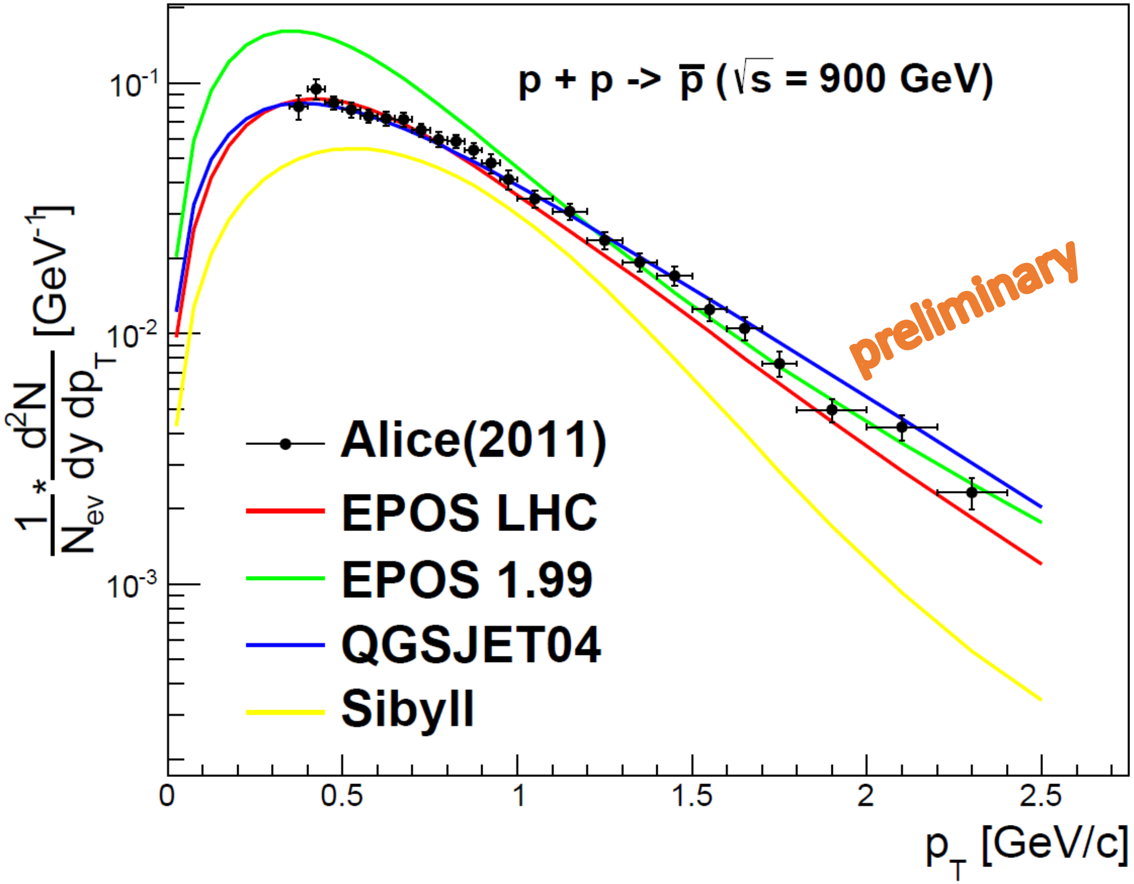
EPOS LHC is the best model.

BRAHMS:
20000 GeV/c proton beam



EPOS LHC and EPOS 1.99 behave good.

ALICE:
405000 GeV/c proton beam



EPOS LHC and QGSJET04 perform well.

jie.feng@cern.ch

- EPOS LHC is chosen as a reference model.

- We give an error estimation of this model according to the chi2 between this model and experimental data.

Antiproton production cross section uncertainties.