Implications of AMS-02 results for dark matter and Cosmic-ray propagation

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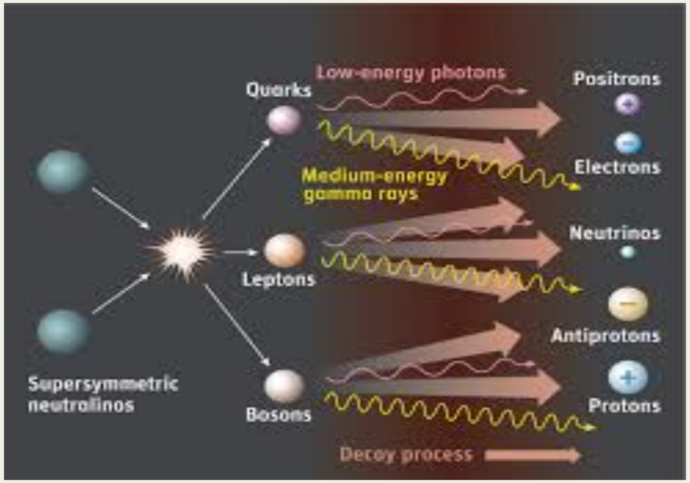
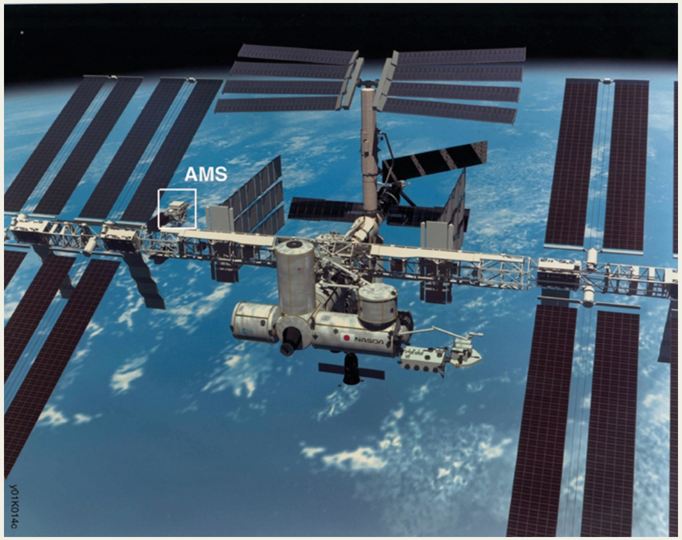
H.B.Jin, Y.L.Wu, YFZ, Phys.Rev. D92 (2015) 5, 055027 [arXiv:1504.04601]
H.B.Jin, Y.L.Wu, YFZ, JCAP 1509 (2015) 09, 049 [arXiv:1410.0171]
H.B.Jin, Y.L.Wu, YFZ, JCAP 1311, 026 (2013) [arXiv:1304.1997[]

DSU2015,YITP, Tyoto

DM indirect detections





Advantages

- Tiny cross section compensated by huge volume of Galactic DM halo
- Distinct spectral feature and morphology

  line vs. continuum,

  peaky vs. featureless power law,

  extended signal in space vs. point-like source.
- A number of anomalies observed:

  CR positrons, GC gamma-rays, X-rays

Difficulties

- Information loss during CR propagation

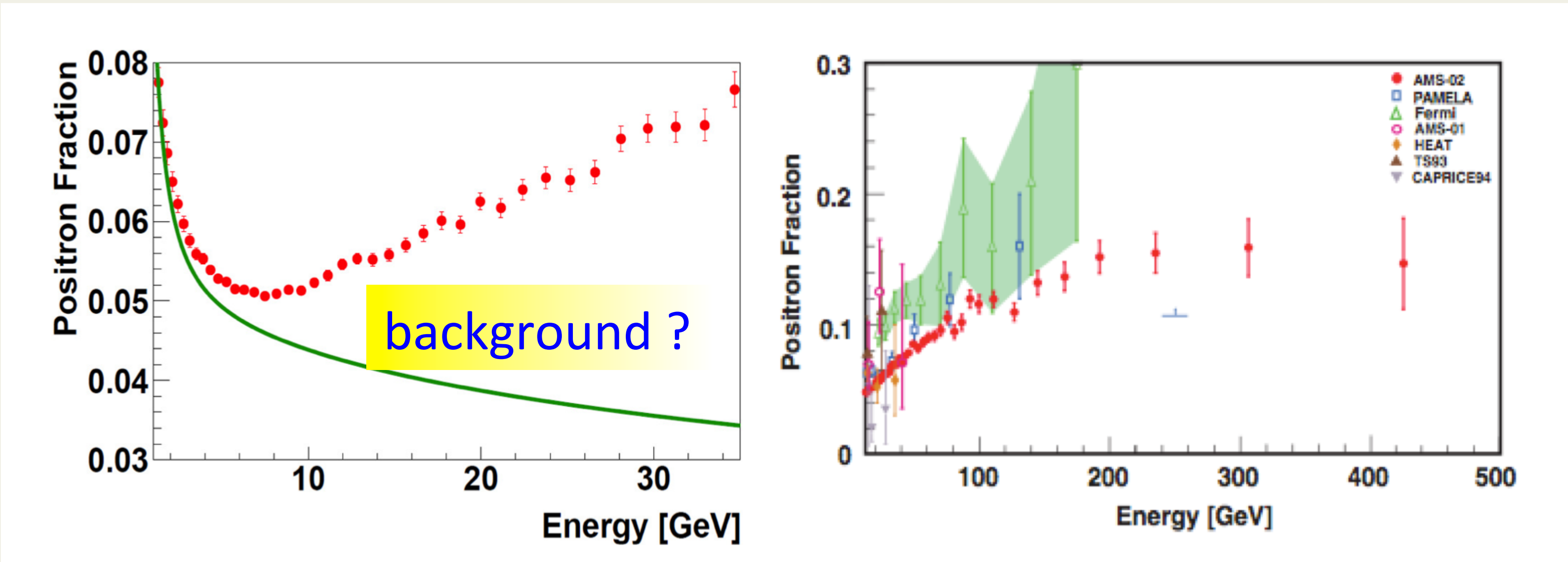
  spectrum change du to E-dependent propagation, convection, re-acceleration, E-loss

  anisotropic source -->isotropic signals
- Large uncertainties in Theoretical predictions

  propagation models, Solar modulation
- Always difficult to rule out astrophysical contributions

AMS-02 is measuring the CRs with unprecedented precisions

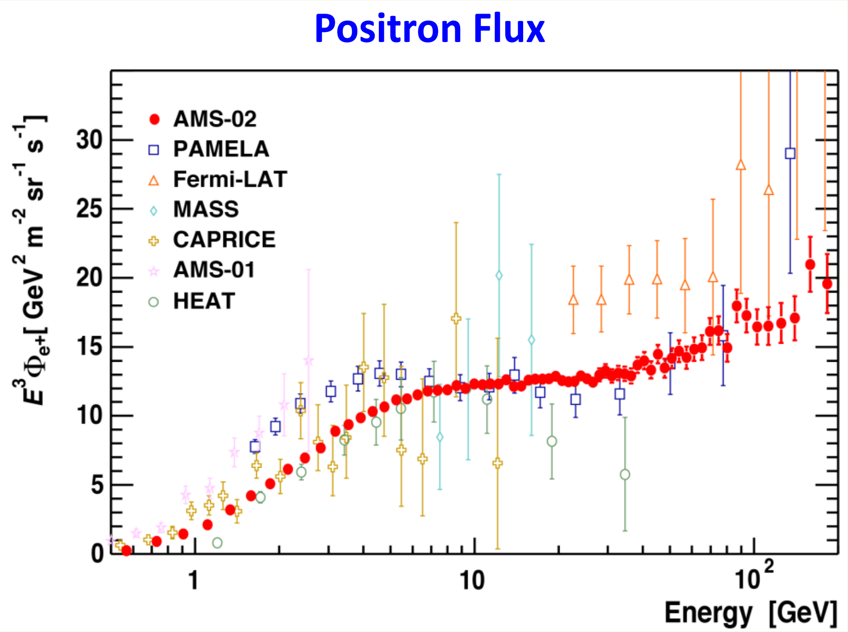
The CR positron excess

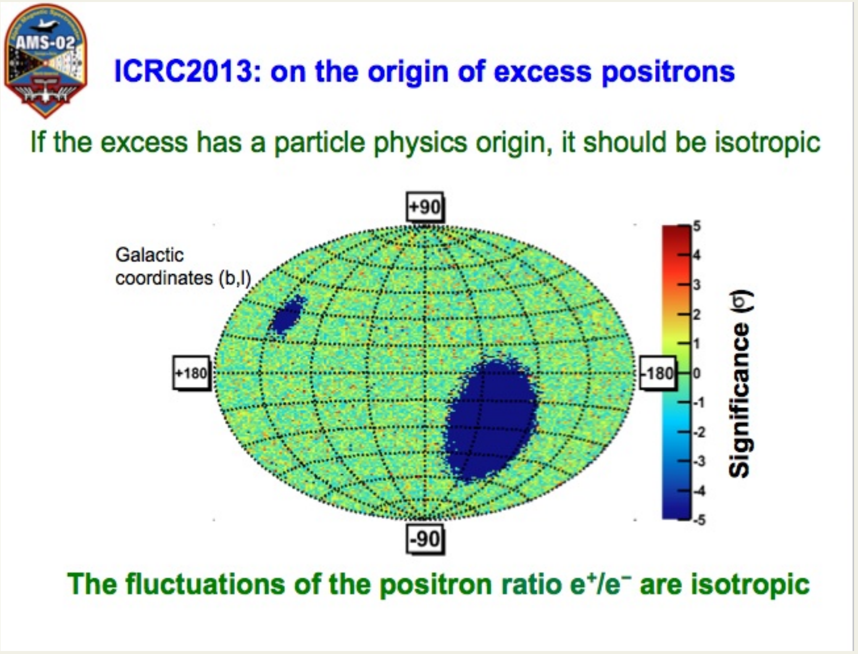


Phys.Rev.Lett. 113 (2014) 121101

- Positron fraction rises and reaches the maximal at energy ~270 GeV (expected to fall with energy, as secondaries)
- The high energy points set the scale of DM mass and annihilation cross section decay life-time

Positron flux and anisotropy





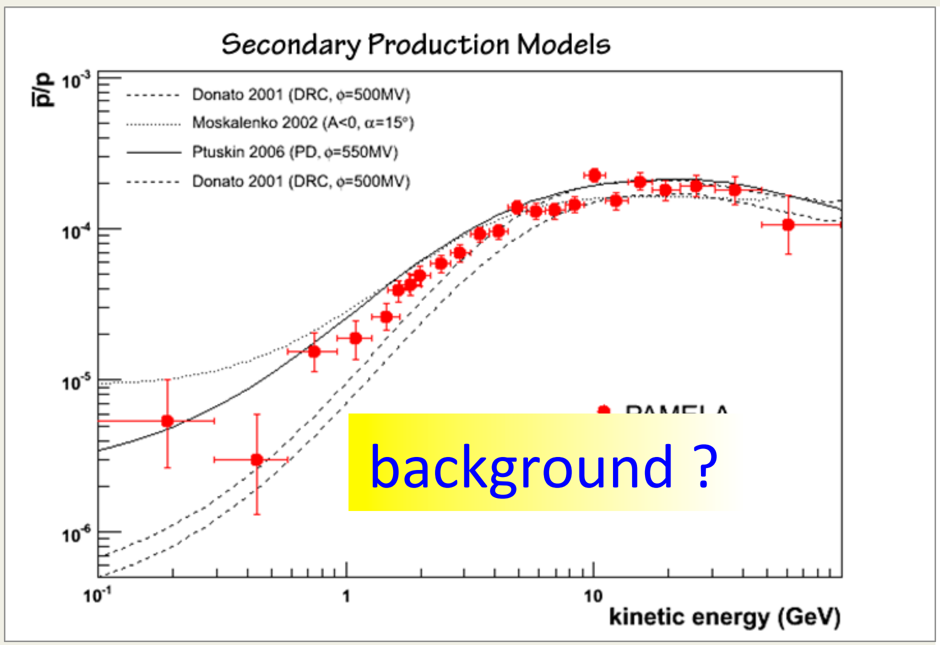
Phys.Rev.Lett. 113 (2014) 121102

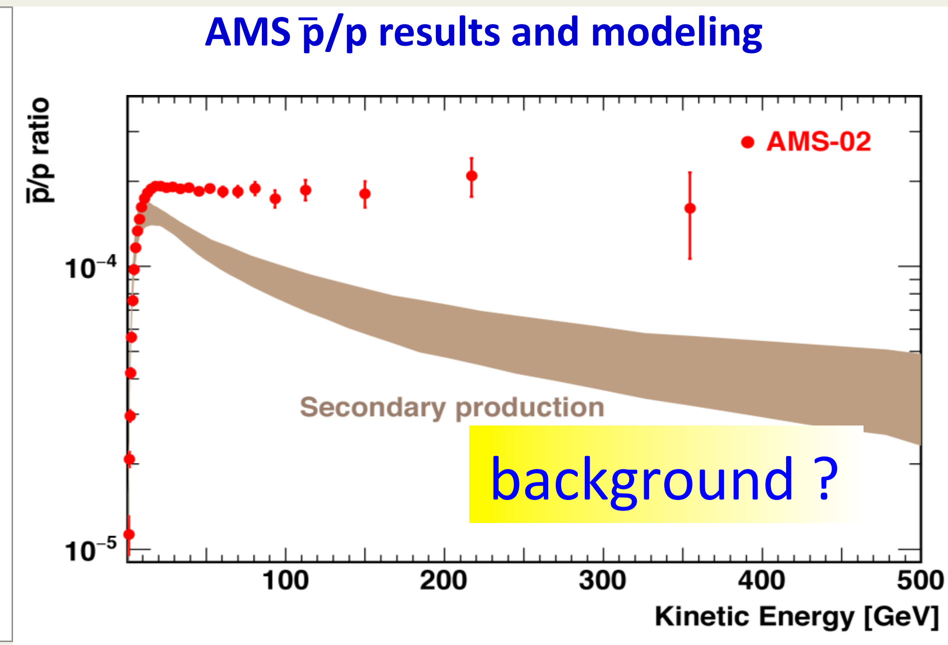
- The rise in positron fraction is due to more positrons rather than less electrons
- Limits on the amplitude of a dipole anisotropy <0.03 at 95% C.L
  consistent with DM interpretation, cannot ruled astrophysical contributions

Antiproton/proton ratio

CR antiproton flux

- Less likely to be created by pulsars
- much less energy losses during propagation
- More sensitive to propagation parameters, and DM profile





PAMELA, 0810.4994

S.Ting "AMS-02 days at CERN", April 15-17, CERN

The background modeling

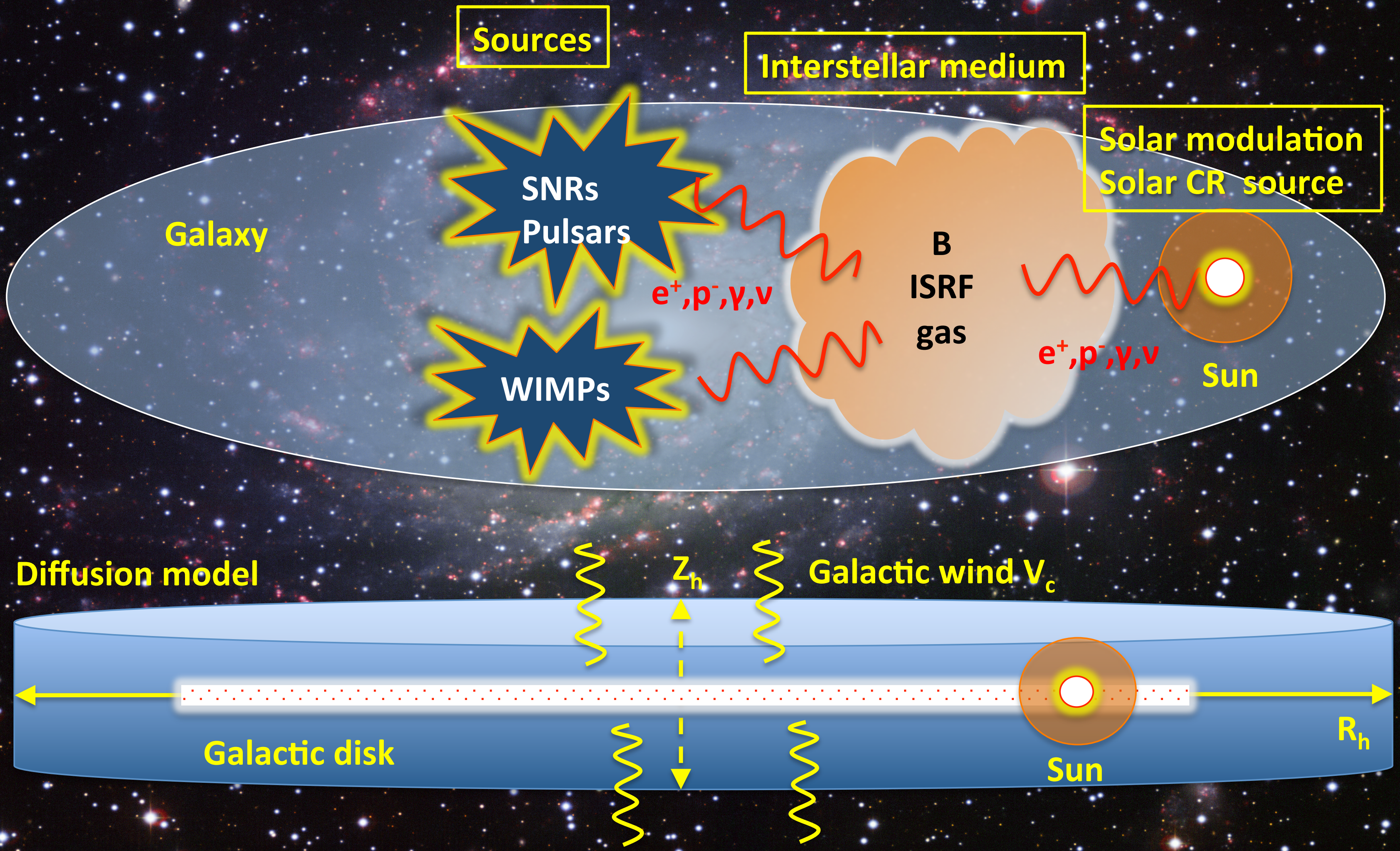
Background modeling is data driven

- Simplest approach: assume a “known” background
  (power-law in source term or flux after propagation)
- Fit the background to some “non-anomalous ” cosmic-ray data
  (“assume” no significant dark matter: p, e^-, B/C, $^{10}Be/^{9}Be$, etc.)
  and make predictions for DM contribution
- Fit simultaneously the “background” and DM contributions.
  (treat background as “unknown” as well)
  $e^+/(e^++e^-)$ actually has an impact on BG determination

Uncertainties in propagation parameters crucial for DM prediction

- Significant prop. parameter degeneration in B/C,
  not in DM → e^+ and pbar
- Primary source terms degenerate with prop. Parameters

Origin and propagation of CRs



Cosmic-ray transportation equation

diffusion | convection | E-loss

$$\frac{\partial\psi}{\partial t} = \nabla(D_{xx}\nabla\psi - \mathbf{V}_c\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla\cdot\mathbf{V}_c)\psi\right]$$
$$- \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi + q(\mathbf{r},p),$$

reaccelaration

spallation | decay | source

Sources of CRs

- Primary sources from SNR, pulsars
- Primary sources from WIMP
- Secondary source from CR fragmentation

Processes in Propagation

- Diffusion (random B field)
- Convection (galactic wind)
- Reacceleration (turbulence)
- Energy loss: Ionization, IC, Synchrotron, bremsstrahlung
- Fragmentation (inelastic scattering)
- Radioactive decay (unstable species)

Solar modulation

Uncertainties

- Distribution of primary sources
- Parameters in the diffusion equation
- Cross sections for nuclei fragmentation
- Distribution of B field
- Distribution of gas

Approaches

- Semi-analytical, two-zone diffusion model.
- Numerical solution using realistic astrophysical data. GALPROP/Dragon code

Sources of cosmic rays

- **Primary sources** (SNR)

Assume power low in rigidity

$$\frac{dq_A(p)}{dp} \propto \left(\frac{\rho}{\rho_{As}}\right)^{\gamma_A}$$

Spatial distribution (pulsar survey)

$$q_0 \left(\frac{R}{R_\odot}\right)^{\eta} \exp\left[-\xi \frac{R-R_\odot}{R_\odot} - \frac{|z|}{0.2\ \mathrm{kpc}}\right],$$

- **Secondary sources** (cross sections)

$$q(p) = \beta c n_i \sum_{i=\mathrm{H,He}} \int dp' \frac{\sigma_i(p,p')}{dp'} n_p(p')$$

only a few, very old pp-,pA-collision data

- **Primary DM sources** (spectrum)

$$q(\boldsymbol{r},p) = \frac{\rho(\boldsymbol{r})^2}{2m_\chi^2} \langle\sigma v\rangle \sum_X \eta_X \frac{dN^{(X)}}{dp},$$

DM profiles (N-body simulations)

$$\rho_\odot \left(\frac{r}{r_\odot}\right)^{-\gamma} \left(\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_\odot)^\alpha}\right)^{(\beta-\gamma)/\alpha}$$

	α	β	γ	r_s(kpc)
NFW	1.0	3.0	1.0	20
Isothermal	2.0	2.0	0	3.5
Moore	1.5	3.0	1.5	28.0

Cosmic-ray propagation processes

Diffusion (constant)

$$\hat{\mathcal{L}}_D \psi = \nabla (D_{xx} \nabla \psi)$$

Main source of uncertainty

$$D_{xx} = \beta D_0 \left(\frac{\rho}{\rho_0} \right)^{\delta_1, \delta_2},$$

In general D_0 should be spatial dependent (Dragon code)

e.g, larger diffusion const. at higher energy,

Kolmogorov: $\delta = 1/3$

Boundary Condition

flux vanishes at (R_h, Z_h)

Main source of uncertainty

Convection

$$\nabla V_c \psi(r,z) - \frac{\nabla V_c}{3} \frac{1}{p^2} \frac{\partial}{\partial p} (p^3 \psi(r,z))$$

$$\left(\frac{dE}{dt} \right)_{\rm Adiab} = -E \left(\frac{2m+E}{m+E} \right) \frac{V_c}{2h}$$

Reacceleration

$$\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi$$

Relation between Dpp and Dxx

$$D_{pp} = \frac{4 V_a^2 p^2}{3 D_{xx} \delta (4 - \delta^2)(4 - \delta) w},$$

determine the propagation models

Observables

1) Secondary/Primary

- B/C and sub-Fe(Sc+V+Ti)/Fe

  sensitive to combination D_0/Z_h

2) Radioactive species (cosmic clock)

- $^{10}Be/^{9}Be$, $^{36}Cl/Cl$, $^{26}Al/^{27}Al$

  sensitive to diffusive halo size

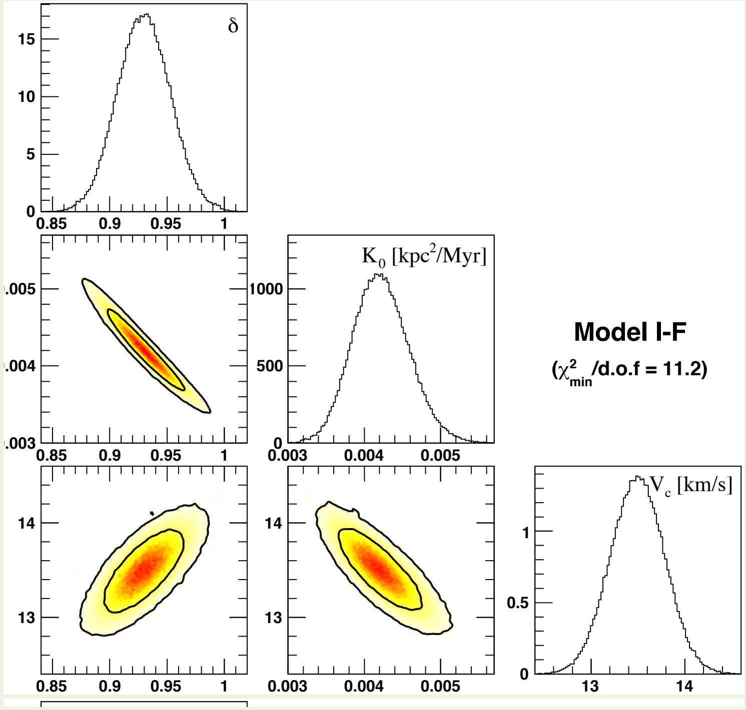
3) Stable primaries

- Proton and electron fluxes

  sensitive to primary sources

Degeneracies between parameters

1. D_0/Z_h, most relevant for DM !
2. $\delta + \gamma_{p2} = 2.7$
3. V_a scales as $(D_0)^{1/2}$



Trotta, etal, arXiv:1011.0037

Maurin, etal, astro-ph/0212111

An alternative analysis framework

Standard approach: B/C+ $^{10}Be/^{9}Be$

pros: B/C source independent, only constrain D_0/Z_h,

^{10}Be: τ_{Be10} =1.4 Myr, sensitive to D_0 only, break the D_0/Z_h degeneracy

corns: low precision $^{10}Be/^{9}Be$ data (from ACE, ISOMAX)

data come from different exps., different solar activity periods,

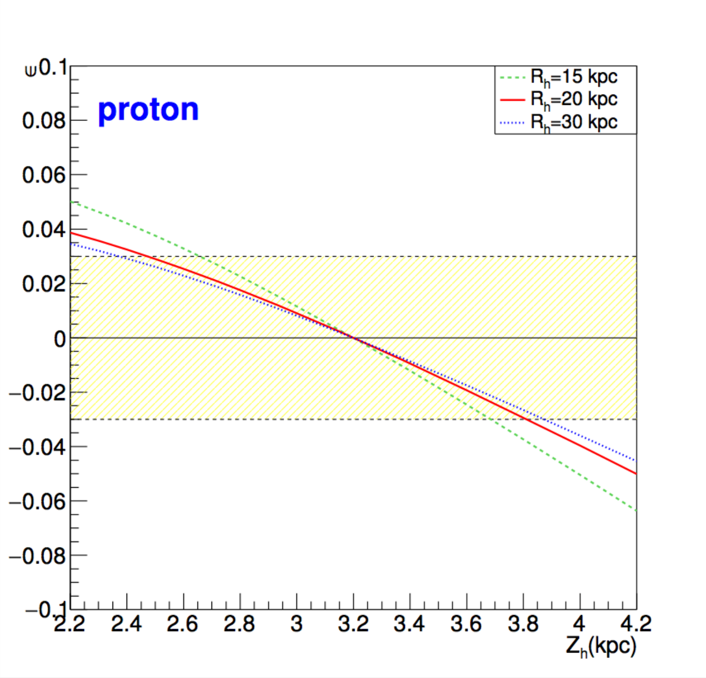
Alternative approach: B/C + Proton

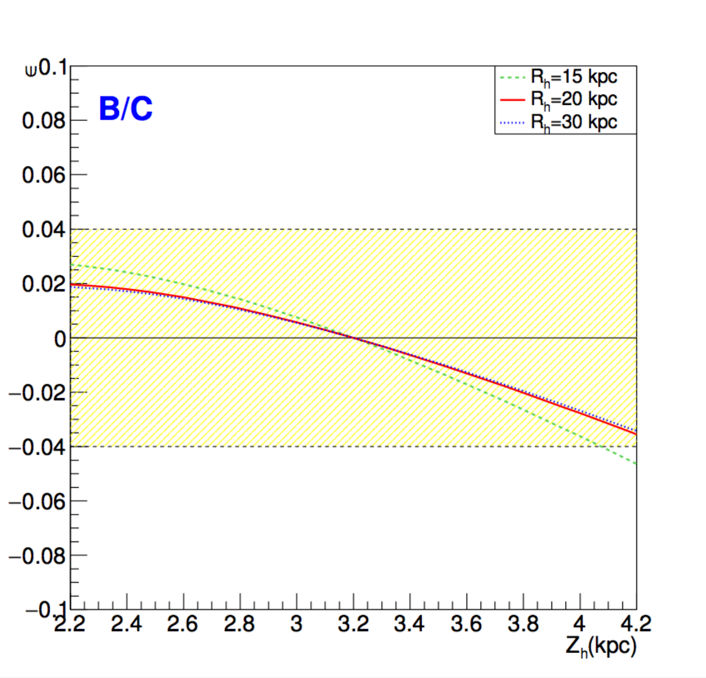
- B/C + Proton forms a complete set for determining all the propagation parameters.
- Both have been measured by AMS-02
  - Very precisely measured
  - Avoiding combination of syst. errors in different experiments
  - All data from the same period, easy to model solar modulation effects

H.B.Jin, Y.L.Wu, YFZ, JCAP 1509 (2015) 09, 04

Proton flux breaks the D_0/Z_h degeneracy in 2D diffusion model

Relative change with Z_h for fixed D_0/Z_h





Analytic solution in 2D two-zone model

$$\psi_i(0) = \frac{2hq_i}{V_c + 2h/\tau_f + D_{xx}S_i \coth(S_i Z_h/2)},$$

$$S_i^2 = \frac{V_c^2}{D_{xx}^2} + \frac{4}{D_{xx}\tau_r} + \frac{4\zeta_i^2}{R_h^2}.$$

Breaking term

$$D_{xx}S_i \coth(S_i Z_h/2) \approx \left(\frac{D_{xx}}{Z_h}\right)\left(2 + \frac{V_c^2 Z_h^2}{6D_{xx}^2} + \frac{2Z_h^2}{3D_{xx}\tau_r} + \boxed{\frac{2Z_h^2}{3R_h^2}\zeta_i^2}\right).$$

D0/Zh degeneracy is broken in stable CR fluxes

- For proton ~5%, data err ~3%
- For B/C ~2%, data error ~4%

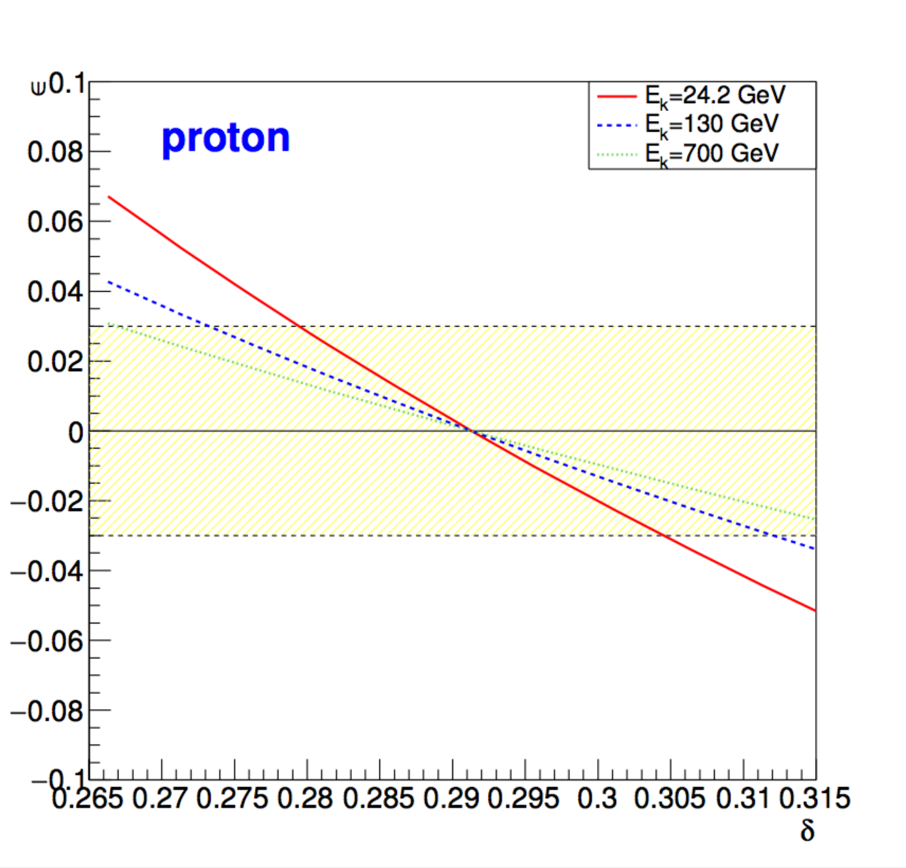
Thus

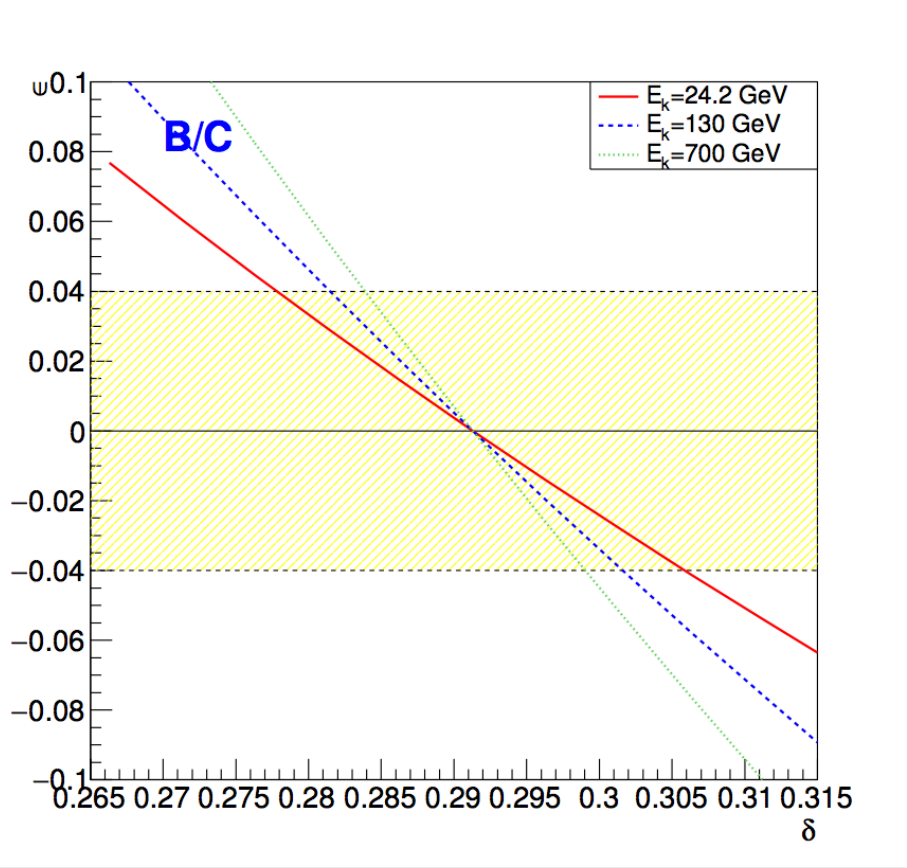
- B/C determines D0/Zh
- Proton flux determines Zh

H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

Proton flux also breaks the γ+δ degeneracy

Relative change with δ for γ+δ fixed at 2.7

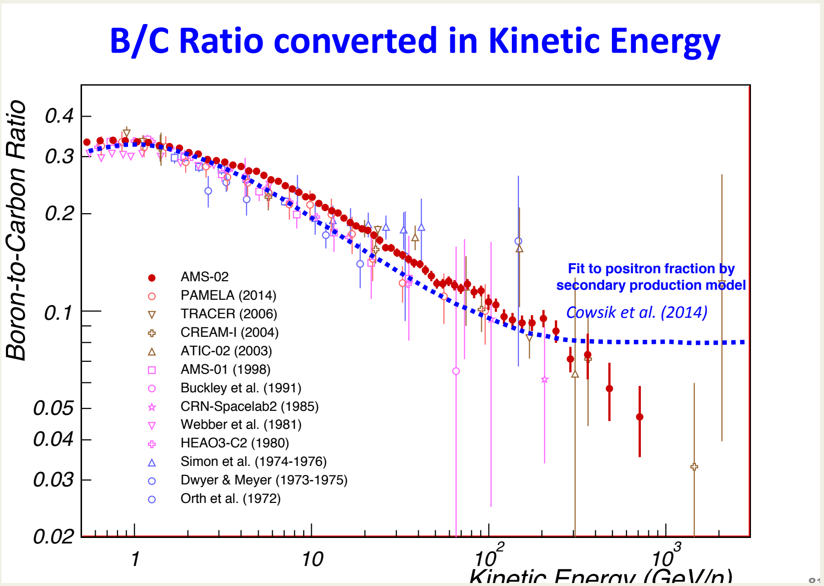


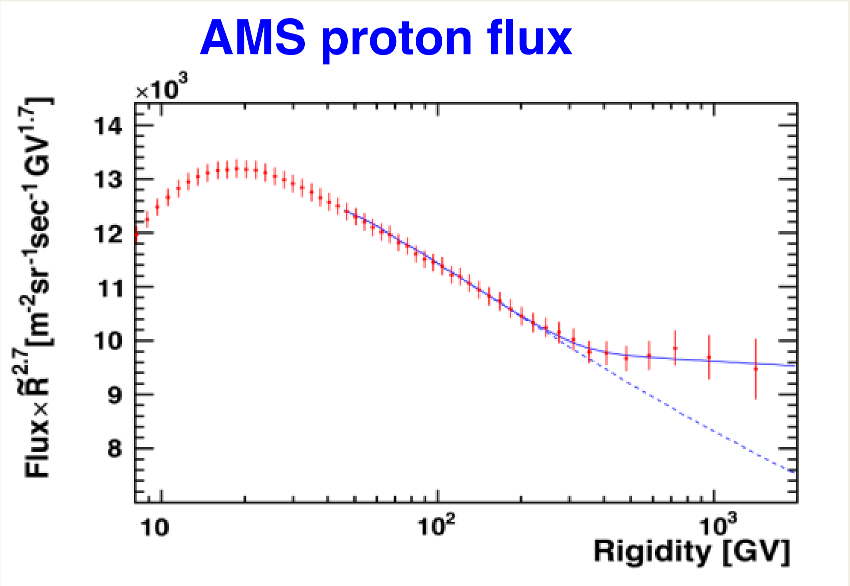


H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

A global Bayesian determination of propagation parameters

Input: AMS-02 data on B/C ratio and proton flux





Phys.Rev.Lett. 114 (2015) 171103

Approach: Bayesian statistic analysis + Markov Chain Monte Carlo

Results

(using data from AMS02, ICRC2013)

Trotta, 1011.0037
Fit B/C+^{10}Be/^{9}Be

Quantity	Prior range	Best-fit value	Posterior mean and Standard deviation	Posterior 95% range	Ref. [23]
Z_h(kpc)	[1, 11]	3.2	3.3±0.6	[2.1, 4.6]	5.4±1.4
D_0/Z_h	[1, 3]	2.02	2.00±0.07	[1.82, 2.18]	(1.54±0.48)
δ	[0.1, 0.6]	0.29	0.29±0.01	[0.27, 0.32]	0.31±0.02
$V_a(\mathrm{km \cdot s^{-1}})$	[20, 70]	44.7	44.6±1.2	[41.3, 47.5]	38.4±2.1
γ_{p1}	[1.5, 2.1]	1.79	1.78±0.01	[1.75, 1.81]	1.92±0.04
γ_{p2}	[2.2,2.6]	2.46	2.45±0.01	[2.43,2.47]	2.38±0.04

D_0/Z_h is precisely determined (err <5%)

$$\frac{D_0}{Z_h} = (2.00 \pm 0.07)\ \mathrm{cm^2 s^{-1} kpc^{-1}}.$$

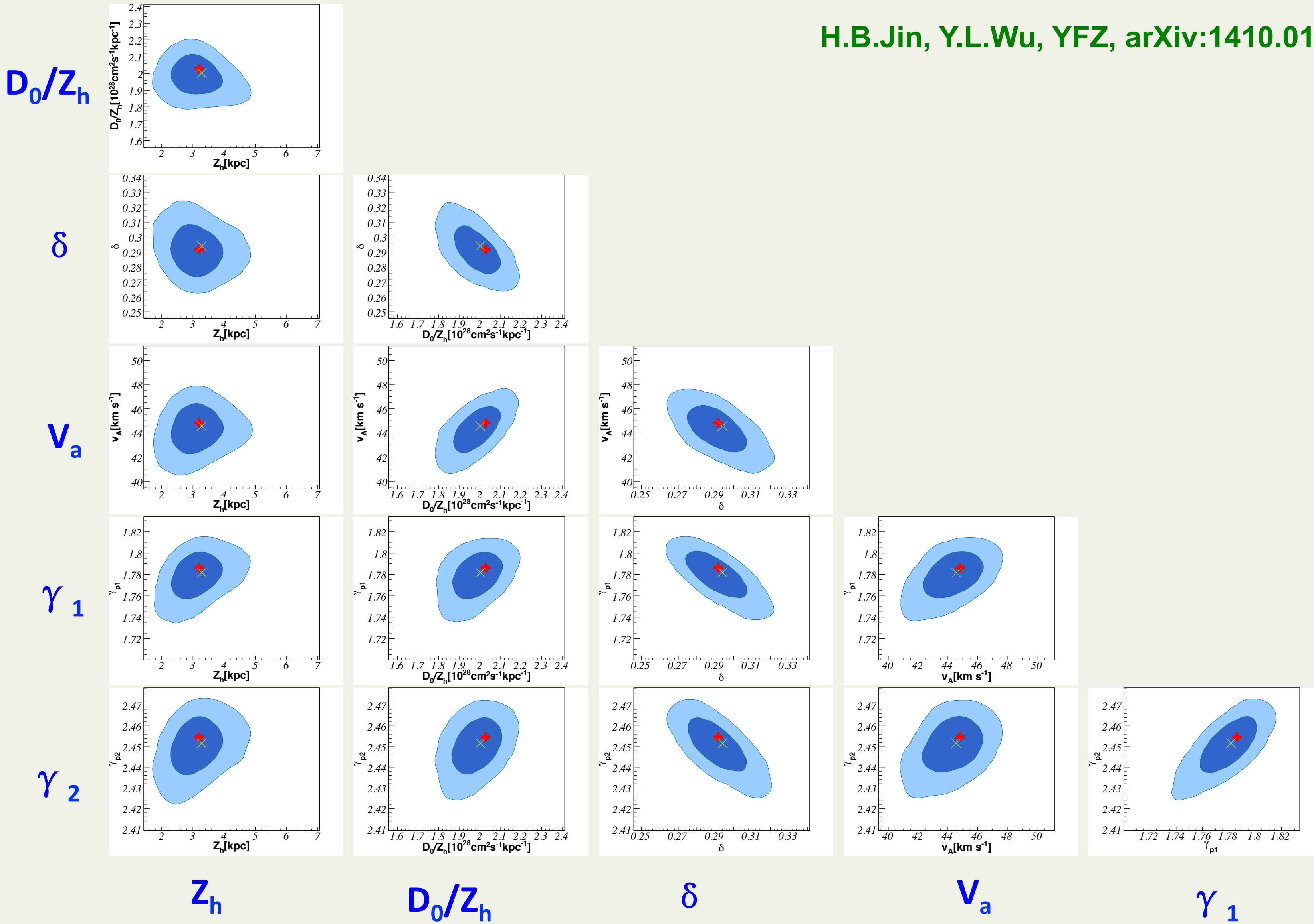
A lower Z_h favored

$$Z_h = 3.3 \pm 0.6\mathrm{kpc}$$

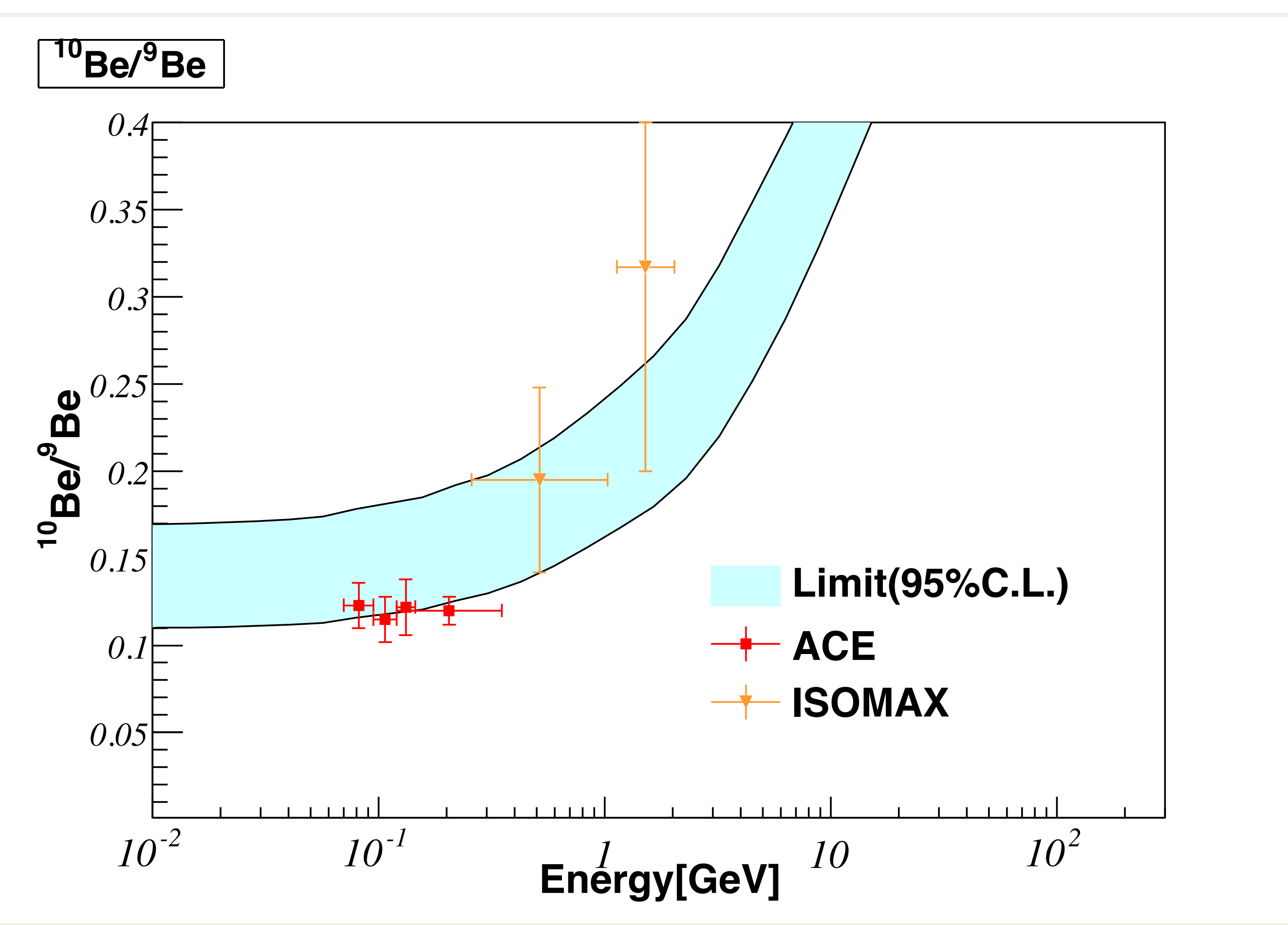
H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

Correlations between parameters

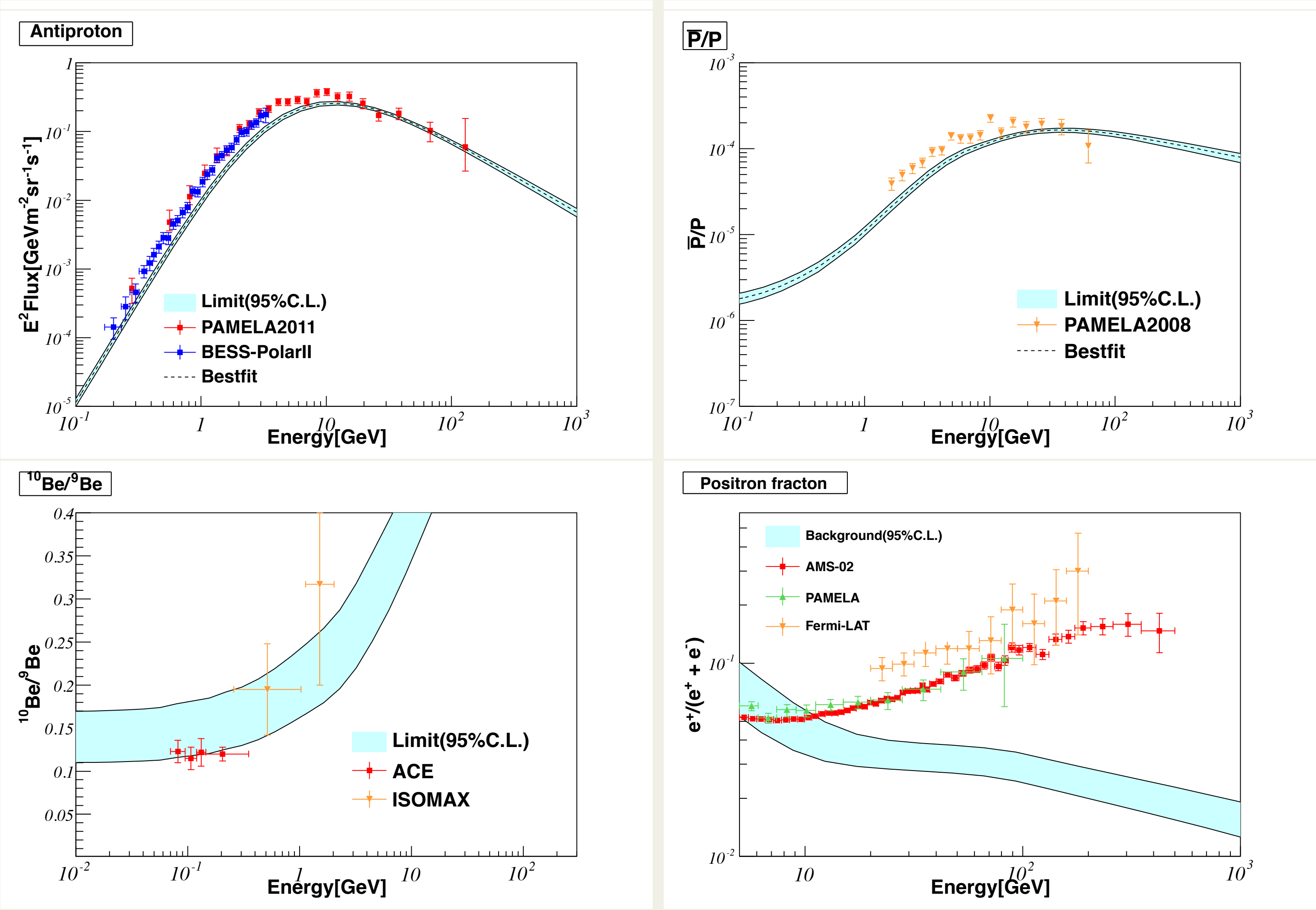
H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP



Prediction for $^{10}Be/^{9}Be$ consistent with data

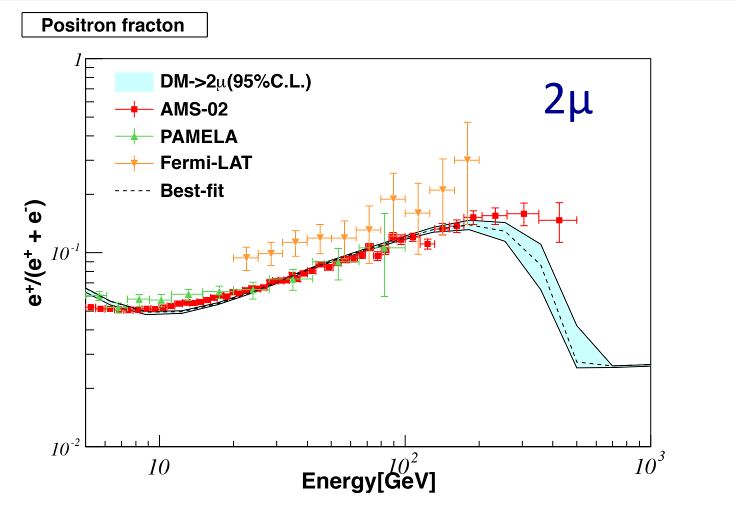


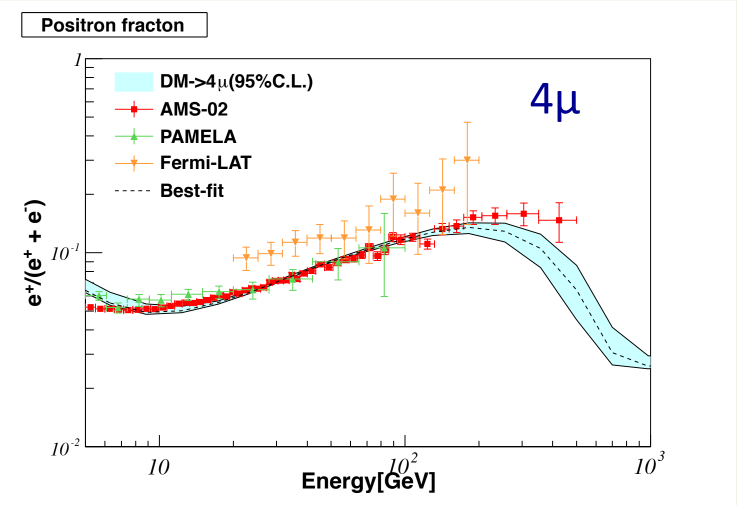
Predicted backgrounds

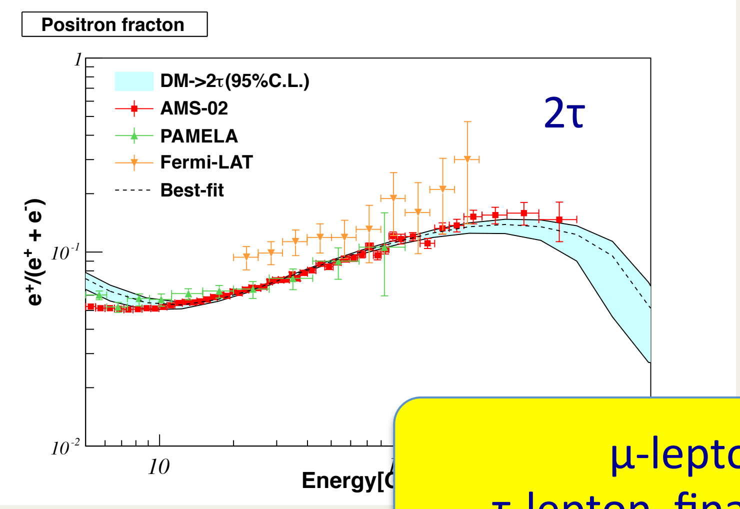


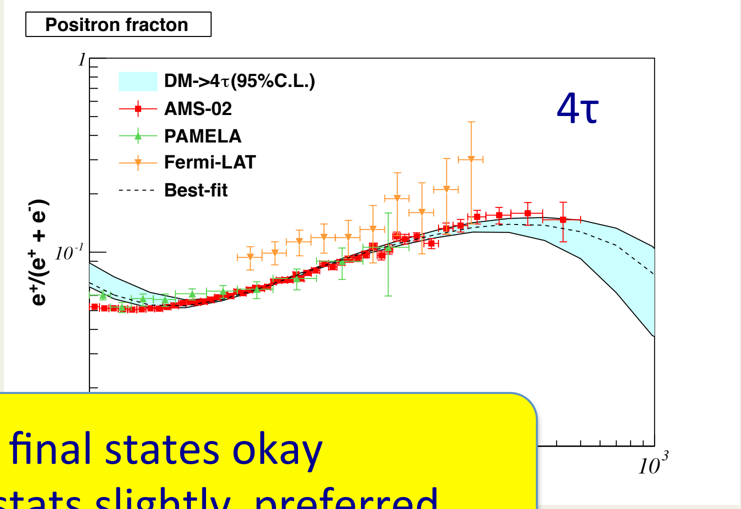
$e^+ / (e^+ + e^-)$ cannot be accommodated within uncertainties

DM fits including propagation uncertainties



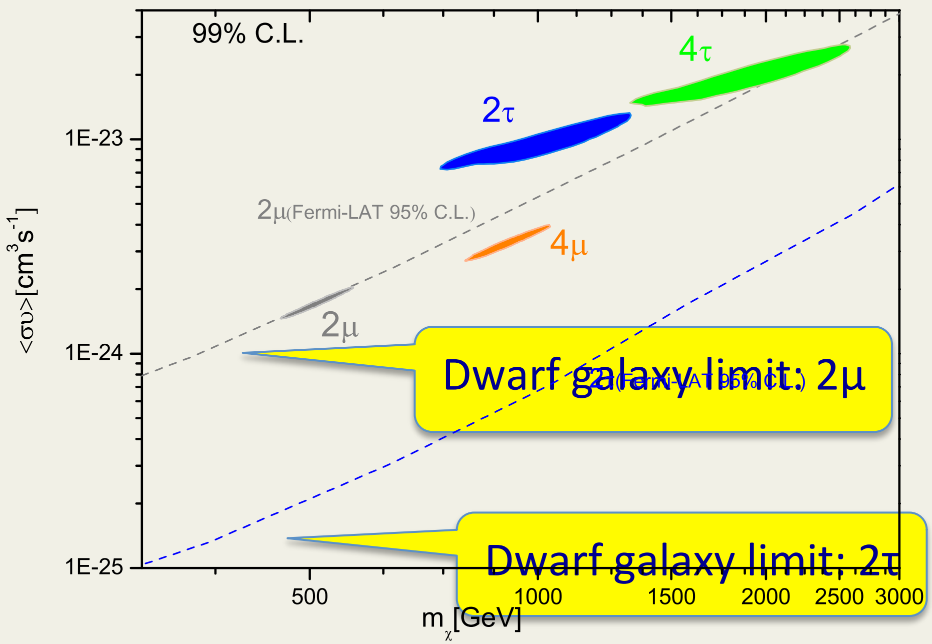




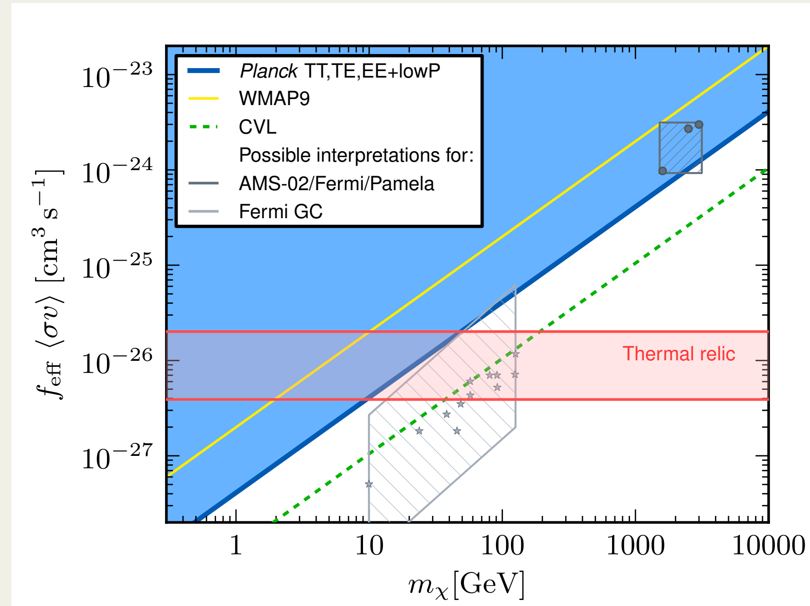


μ-lepton final states okay
τ-lepton final stats slightly preferred

Favored regions and limits



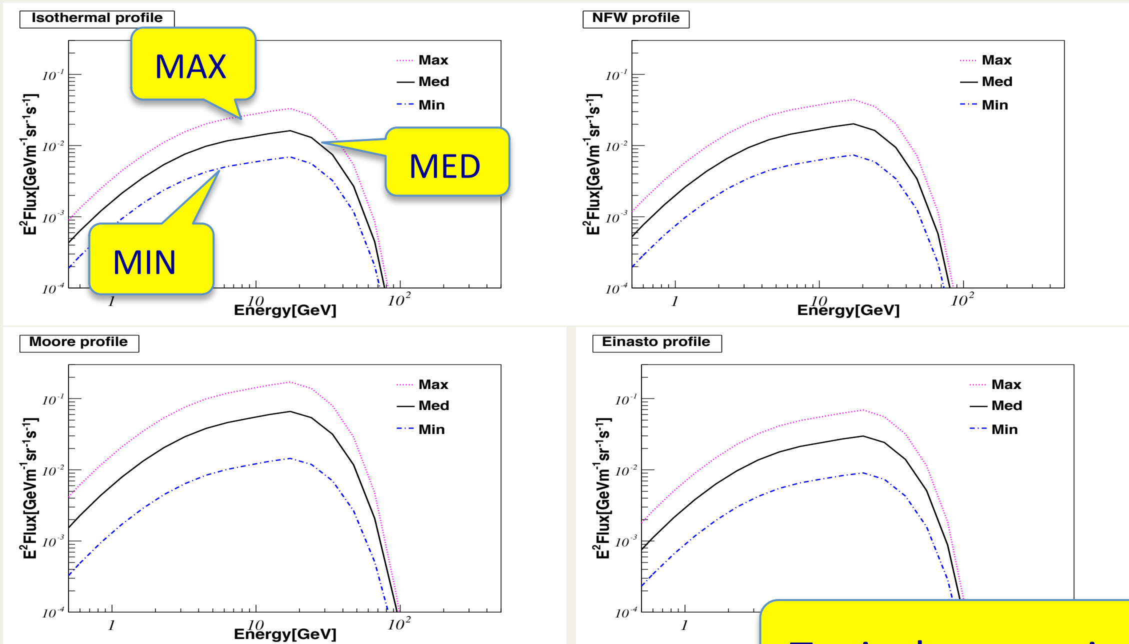
Fermi limits from dSphs



PLANK limits

H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

Typical uncertainties in antiproton flux

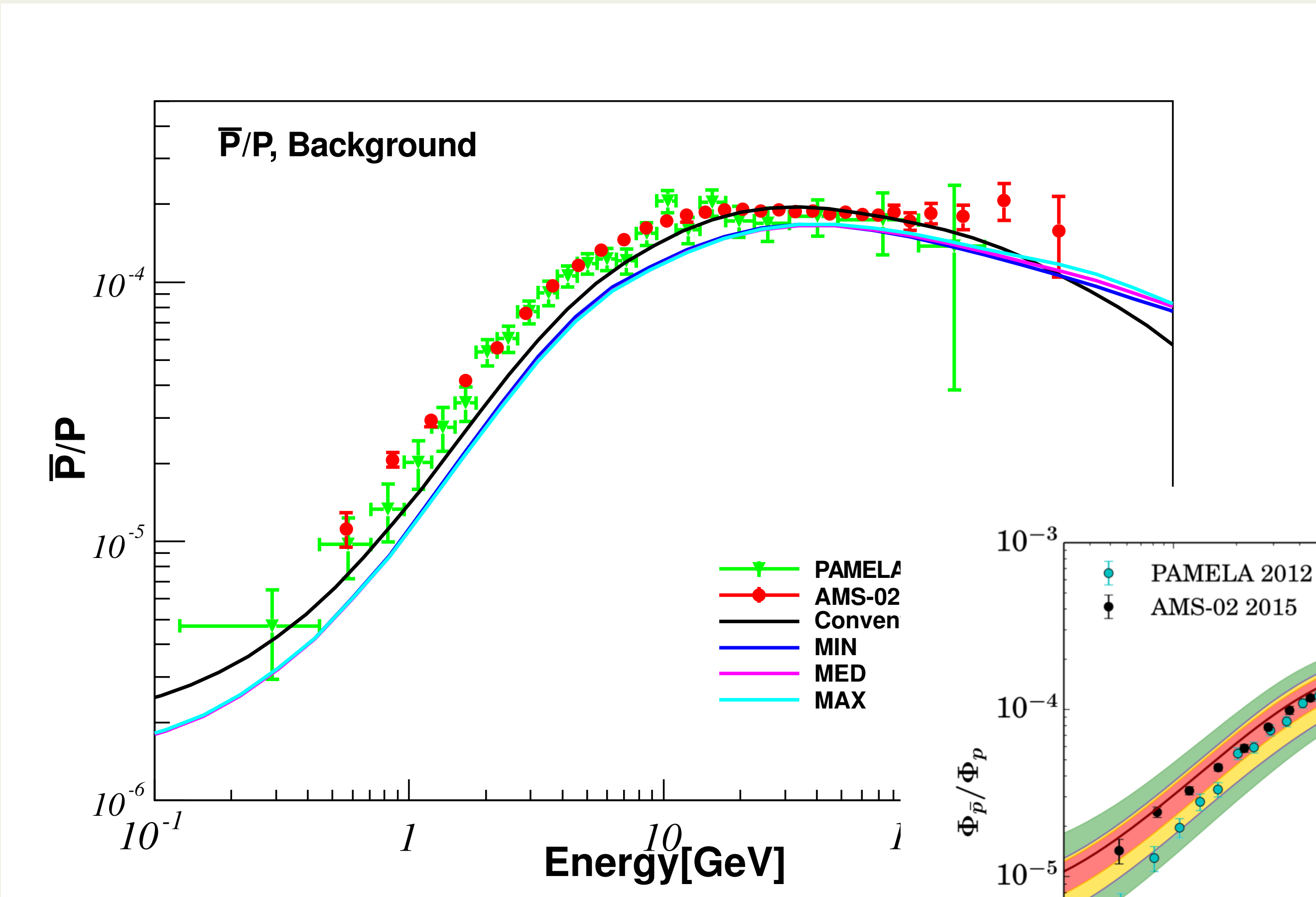


Typical uncertainty about a factor of 5

model	R(kpc)	Z_h(kpc)	D_0	ρ_0	δ_1/δ_2	V_a(km/s)	ρ_s	γ_{p1}/γ_{p2}
Conventional	20	4.0	5.75	4.0	0.34/0.34	36.0	9.0	1.82/2.36
MIN	20	1.8	3.53	4.0	0.3/0.3	42.7	10.0	1.75/2.44
MED	20	3.2	6.50	4.0	0.29/0.29	44.8	10.0	1.79/2.45
MAX	20	6.0	10.6	4.0	0.29/0.29	43.4	10.0	1.81/2.46

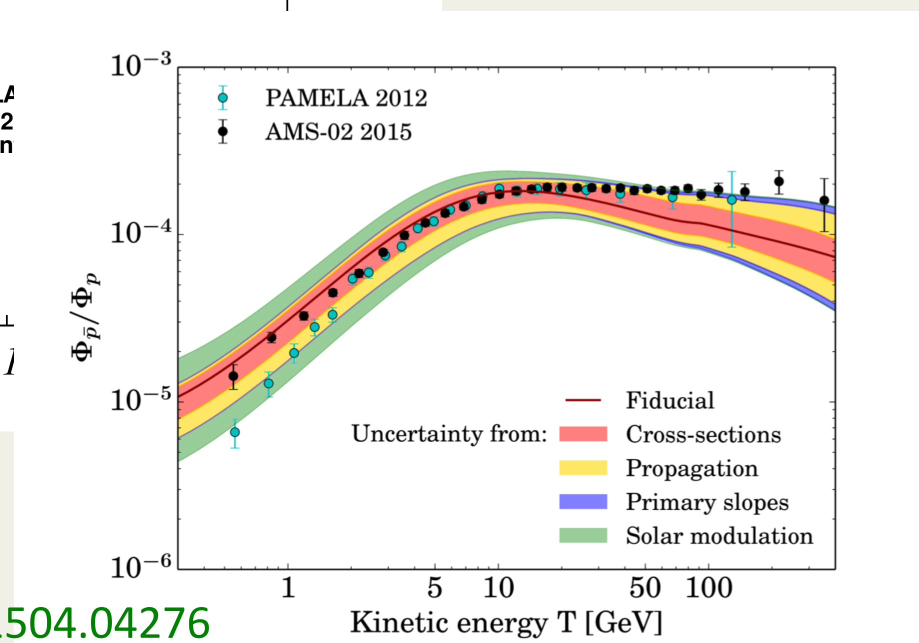
The “new” MIN, MED, MAX models in GALPROP approach

AMS-02 data (almost) consistent with background



H.B.Jin, Y.L.Wu, YFZ arXiv:1504.04601, PRD

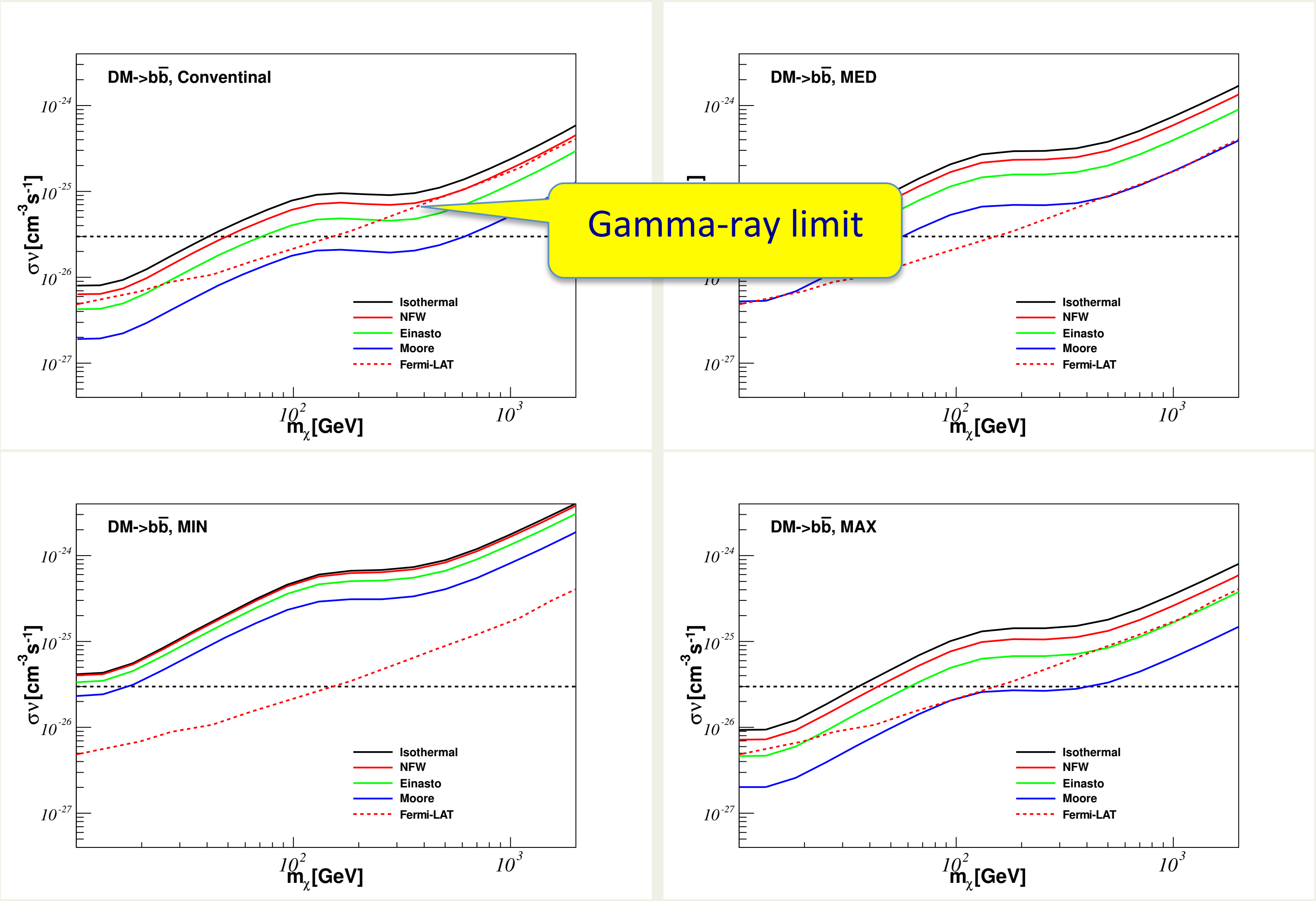
Giesen, 1504.04276
Ibe, 1504.05554
Hamaguchi, 1404.05937
Lin, 1504.07230
Chen, 1504.07848
Chen,1505.00134



Giesen, 1504.04276

AMS-02 pbar data set stringent limits

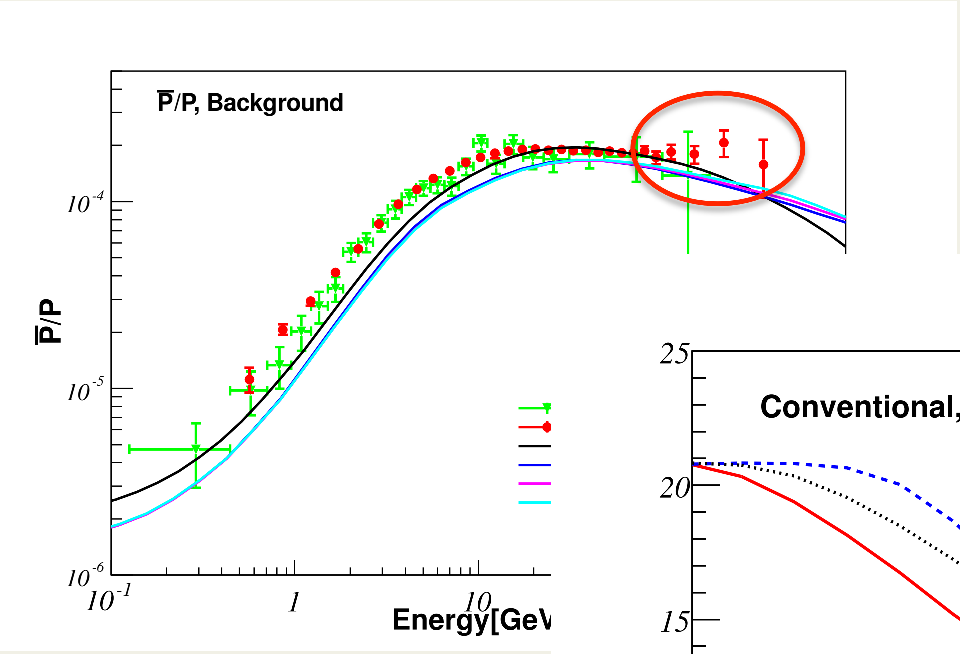
(bb channel)



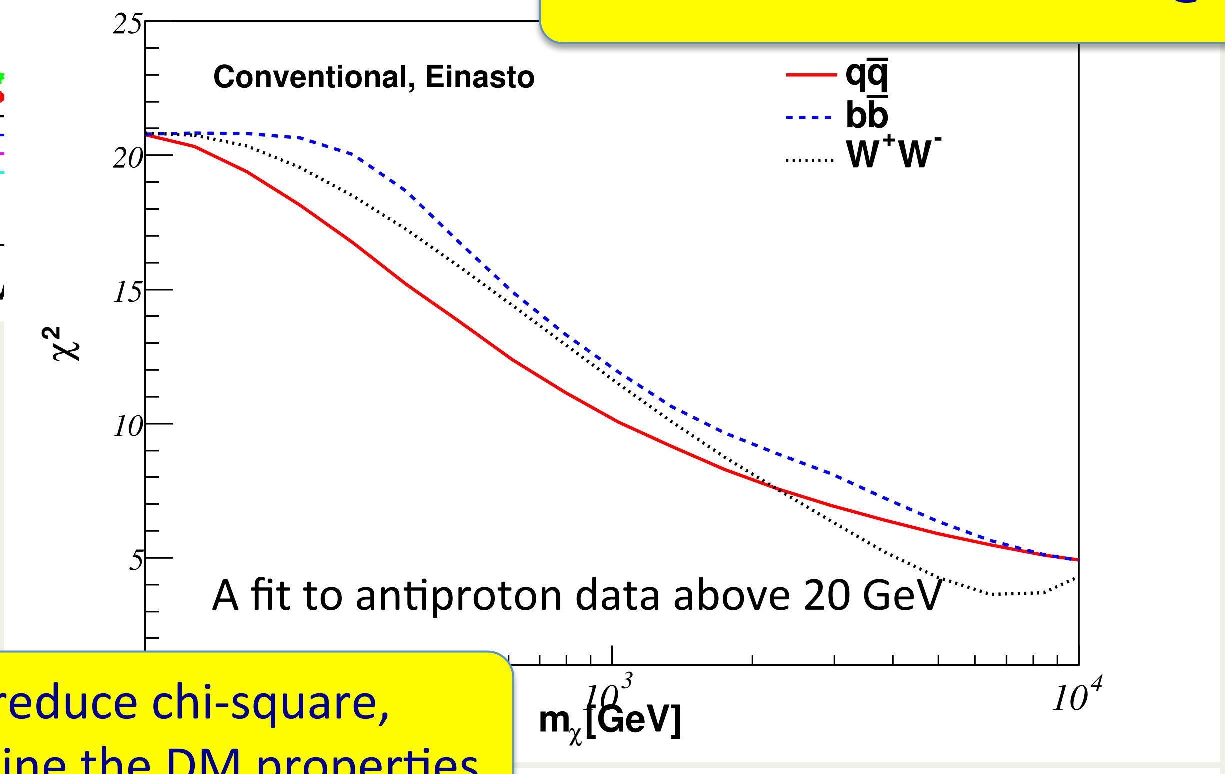
Upper limits from antiproton could be compatible with that from dwarf galaxies

AMS-02 data favor a heavy DM ?

H.B.Jin, Y.L.Wu, YFZ, arXiv:1504.04601,PRD



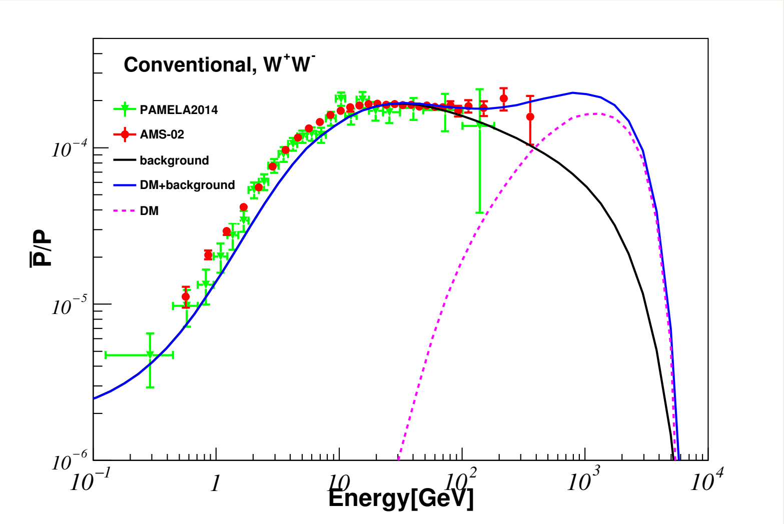
disfavor a DM mass <2 TeV @2σ

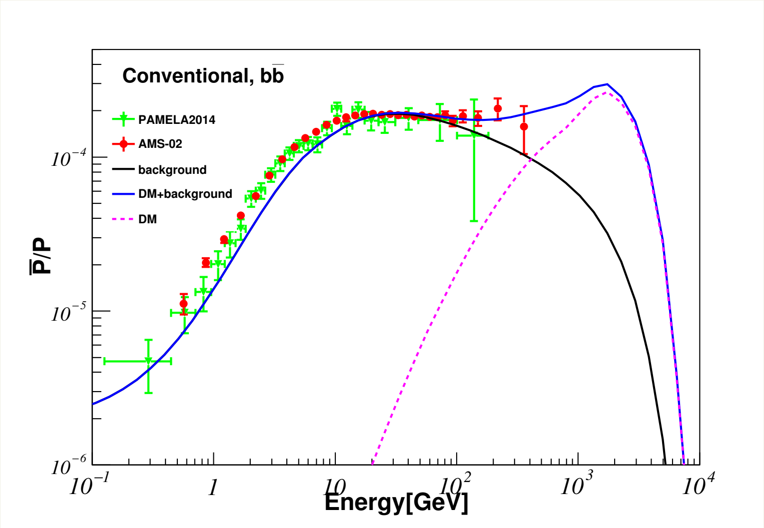


Introducing DM can reduce chi-square,
but so far cannot determine the DM properties

So far, a heavy DM is not excluded (yet)

H.B.Jin, Y.L.Wu, YFZ, arXiv:1504.04601, PRD





Eg. a 10 TeV DM contribution with Boost factor ~100

Antiproton data at high energies will be crucial
AMS-02 see ~one antiproton/month, due to limited acceptance & rigidity resolution
Call for next generation magnet spectrometer

Conclusions

- The AMS-02 experiment has measured the CRs with unprecedented precision.
- The cosmic ray propagation models can be more precisely determined by the new AMS-02 data on B/C and proton flux
- The positron anomaly favor DM annihilation into tau final states, which is in strong tension with Fermi-LAT gamma ray data.
- The first AMS-02 antiproton data can be used to set stringent limits on DM annihilation, compatible with that from the gamma ray data.

Thank you!