# Cosmic-Ray Positrons Strongly Constrain Leptophilic Dark Matter

arXiv:2107.10261

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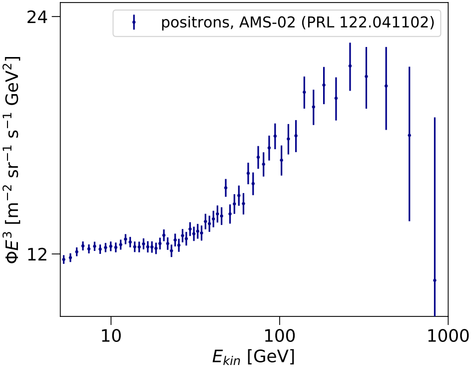
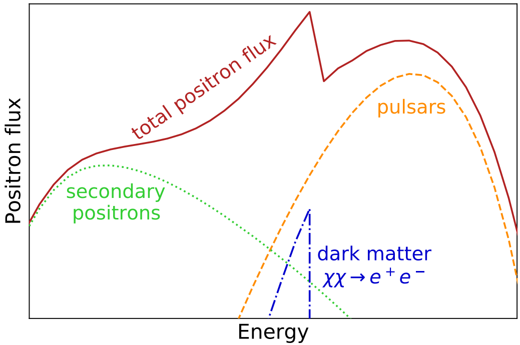
July 26, 2021
ICRC 2021

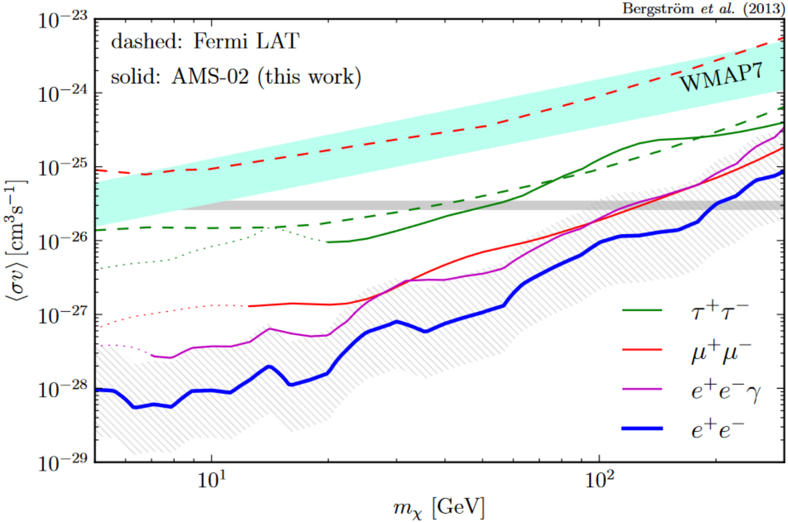
# Local Positron Flux

- Cosmic rays can constrain annihilating dark matter
- AMS-02 provides extremely precise cosmic-ray data
- Rising positron flux above 20 GeV: contribution from pulsars favoured over dark matter
- Constrain sharply peaked leptophilic dark matter



# Previous Dark Matter Constraints From Cosmic-Ray Positrons




arXiv:1306.3983

# In This Work

- Recent positron, proton and Helium data from AMS-02 with very high statistical precision:

| Particle | Energy range [GeV] | Time range | Ref. |
|---|---|---|---|
| Positrons | 2 – 1000 | May 2011 – Nov. 2017 | PRL 122.041102 |
| Protons | 2 – 60 | Feb. 2016 – May 2017 | PRL 121.051101 |
| | 60 – 1800 | May 2011 – Nov. 2013 | PRL 114.171103 |
| Helium | 2 – 1000 | May 2011 – Nov. 2013 | PRL 122.041102 |

- Simulating cosmic-ray propagation using Galprop v.56, with many free parameters to determine astrophysical background model fitting positrons, protons and Helium

- New solar modulation model: time-, charge- and rigidity-dependent model (arXiv:2007.00669)

# Astrophysical Background Model

**Galprop model:**

- many free parameters
- two halo heights:
  $z = 5.6$ kpc (default) and
  $z = 3$ kpc (conservative)
- include protons and Helium to constrain secondary positrons

**Fit to AMS-02 data for:**

- positrons
- protons
- Helium

**Minimisers:**

- iminuit
- multinest

**Pulsar model:**

- spectrum: Hooper et al. arXiv:0810.1527
- distribution: Lorimer et al. Mon. Not. Roy. Astron. Soc.372, 777
- free parameters: pulsar formation rate, energy cutoff, spectral index

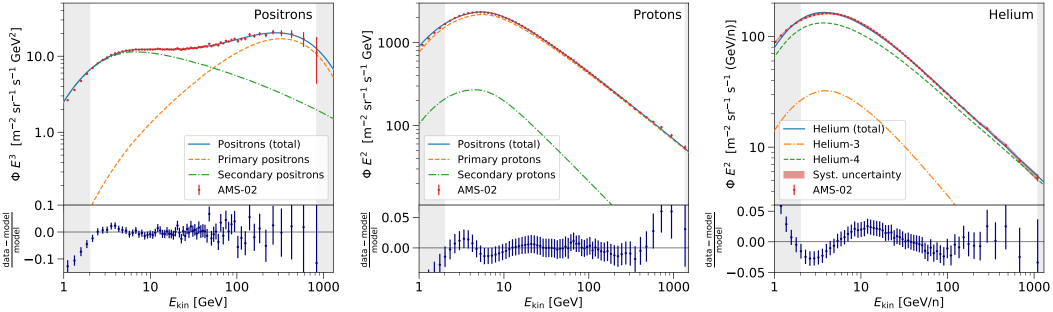
**Solar modulation:**

- free parameters: $\phi_0$, $\phi_1$ (heliospheric potential)

# Free Parameters and Best-Fit Values ($z = 5.6$ kpc)

| Parameter | Best fit | Uncertainty |
|---|---|---|
| Diffusion coefficient, $D_0$ [cm$^2$/s] | $1.636 \cdot 10^{28}$ | $2.786 \cdot 10^{25}$ |
| Diffusion spectrum break, $D_{\text{break}}$ [MV] | $6.067 \cdot 10^3$ | $0.339 \cdot 10^3$ |
| Spectral index below break, $\delta_1$ | 0.0527 | $6.489 \cdot 10^{-6}$ |
| Spectral index above break, $\delta_2$ | 0.361 | $0.138 \cdot 10^{-2}$ |
| Convection velocity, $v_c$ [km/(s kpc)] | 6.345 | $9.41 \cdot 10^{-4}$ |
| Alfvén velocity, $v_{\text{Alfvén}}$ [km/s] | 4.524 | $2.643 \cdot 10^{-3}$ |
| Proton injection spectrum break [MV] | $5.195 \cdot 10^2$ | 2.542 |
| Proton spectral index below break, $\gamma_1^p$ | 1.657 | 0.824 |
| Proton spectral index above break, $\gamma_2^p$ | 2.523 | $2.719 \cdot 10^{-4}$ |
| Pulsar spectral index, $\gamma_{\text{psr}}$ | 1.337 | $3.082 \cdot 10^{-2}$ |
| Pulsar cutoff energy, $E_{\text{cut}}^{\text{psr}}$ [GeV] | 535.587 | 17.998 |
| Pulsar formation rate, $\dot{N}_{100}$ [psr/century] | 0.0930 | 0.00128 |
| Solar modulation parameter, $\phi_0$ [GV] | 0.378 | $0.229 \cdot 10^{-2}$ |
| Solar modulation parameter, $\phi_1$ [GV] | 1.950 | 0.558 |
| Normalization (positrons, protons) | 0.815 | $0.178 \cdot 10^{-2}$ |
| Helium injection spectrum break [MV] | $305.303 \cdot 10^3$ | $56.095 \cdot 10^3$ |
| Helium spectral index below break, $\gamma_1^{\text{He}}$ | 2.505 | $2.917 \cdot 10^{-3}$ |
| Helium spectral index above break, $\gamma_2^{\text{He}}$ | 2.425 | $1.638 \cdot 10^{-2}$ |
| Normalization (Helium) | 1.100 | $3.866 \cdot 10^{-3}$ |

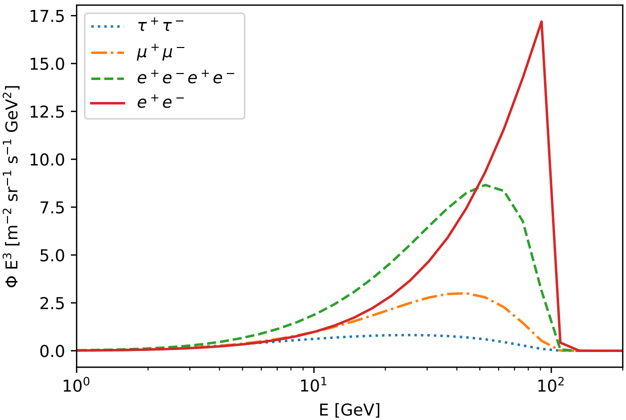
# Astrophysical Background Model ($z = 5.6$ kpc)




| Type | $\chi^2$/d.o.f. (d.o.f.) |
|---|---|
| total | 0.63 (141) |
| positrons | 0.88 (49) |
| protons | 0.43 (49) |
| Helium | 0.57 (43) |

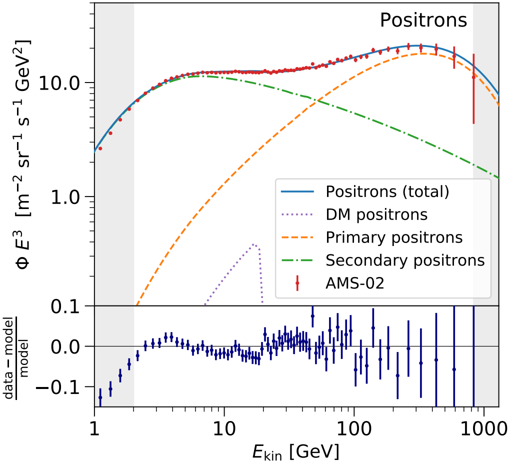
- Background model fits data to within few percent

# Dark Matter Contributions



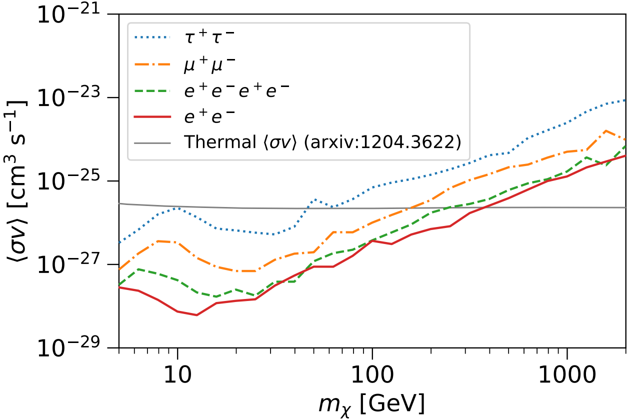

- Local positron flux for DM per annihilation
- DM mass 100 GeV, $\langle\sigma v\rangle = 3 \cdot 10^{-26}$ cm$^3$/s
- Four leptonic final states:
  - $\chi\chi \to \tau^+\tau^-$
  - $\chi\chi \to \mu^+\mu^-$
  - $\chi\chi \to \phi\phi \to e^+e^-e^+e^-$, where $\phi$ is a light mediator
  - $\chi\chi \to e^+e^-$

# Computing Dark Matter Constraints



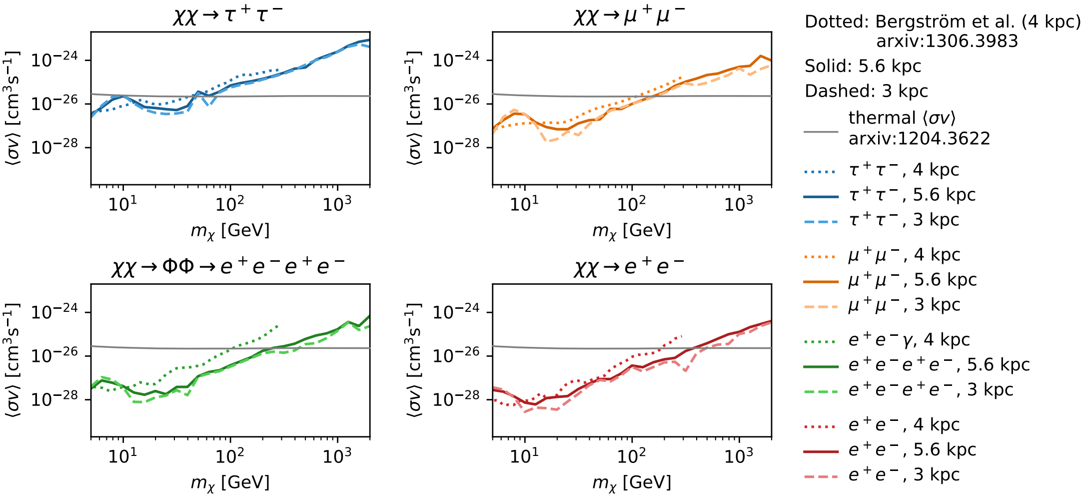

- Add DM contributions to positron flux from background model
- Fit with relevant parameters: $D_0$, $\delta_2$, pulsar parameters
- DM mass range from 5 to 2000 GeV
- Create grid on annihilation cross section $\langle \sigma v \rangle$ for each DM mass
- Compute $\chi^2$ profile for $\langle \sigma v \rangle$ to calculate limits at 95% upper CL

# Results: Dark Matter Limits ($z = 5.6$ kpc)




- Below thermal cross section for $\tau^+\tau^-$ below 60 GeV, for $\mu^+\mu^-$ below 160 GeV, for $e^+e^-e^+e^-$ below 240 GeV and for $e^+e^-$ below 380 GeV
- Excess at low energies $< 3\sigma$ due to larger uncertainties from being at energies close to lower limit of model (at 2 GeV)

# Comparison to Previous Limits




- Improvement on previous limits by a factor of $\approx 2$

# Summary and Conclusion

- Aim: set strong constraints on leptophilic dark matter in the local positron flux
- Very good agreement of background model with AMS-02 data
- At small masses ($\sim$ 30 GeV), constraints significantly below thermal cross section ($\sim 2.5\times10^{-28}$ cm$^3$/s) for annihilations into $e^+e^-$ $\rightarrow$ rule out even subdominant dark matter contributions
- Repeated analysis for conservative halo height of 3 kpc, which gives similar constraints
- Improvement on previous limits by a factor of $\approx 2$