Search for line-like and box-like features in the Galactic gamma-ray spectra with the Fermi LAT

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Introduction

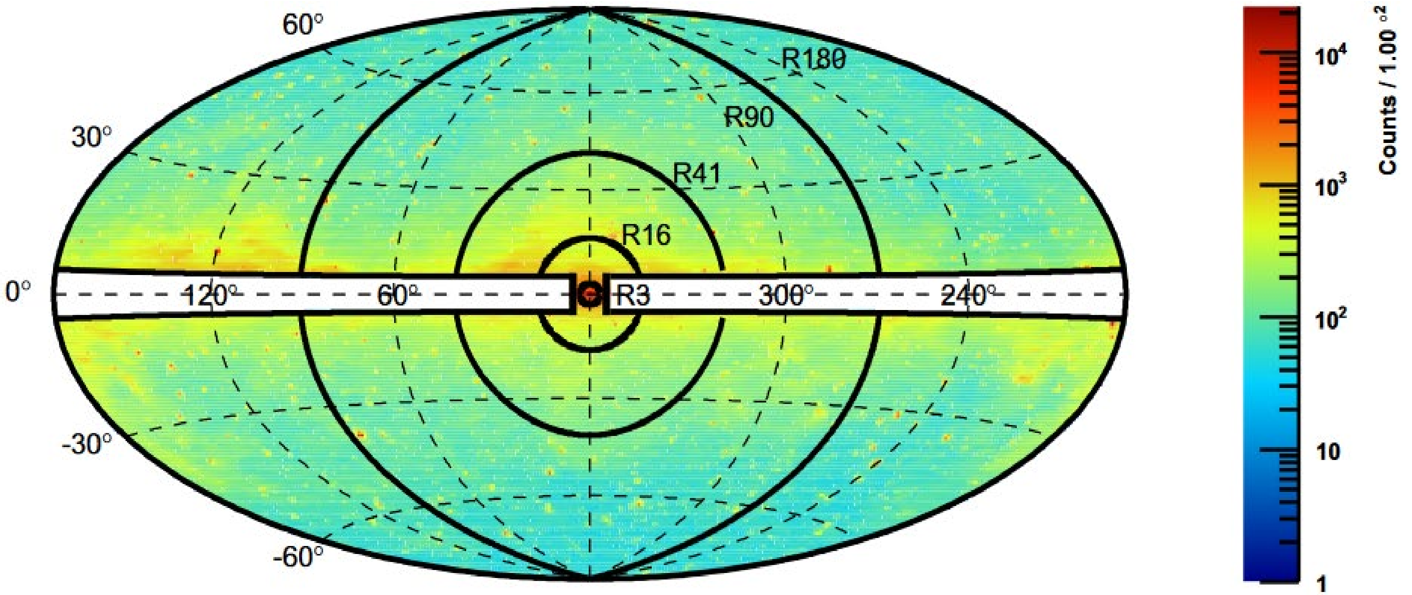
- Our Galaxy is an excellent target for dark matter (DM) searches with gamma rays
  - The disk of the Milky Way is thought to be embedded in a much larger, roughly spherical, DM halo
- Weakly Interacting Massive Particles (WIMPs) are among the most credited DM candidates
- WIMPs in the Milky Way halo can annihilate or decay into standard model particles, including gamma rays
  - Expected features in the energy spectrum of Galactic gamma rays
  - Direct production in WIMP annihilations ($\chi\chi \rightarrow \gamma\gamma$) or decays ($\chi \rightarrow \gamma\gamma$)
    - Both these processes yield monochromatic photons
    - Line-like features expected in the Galactic gamma-ray spectra
  - Indirect production with WIMPs annihilating ($\chi\chi \rightarrow \phi\phi$) or decaying ($\chi \rightarrow \phi\phi$) into light mediators, which in turn decay into pairs of photons ($\phi \rightarrow \gamma\gamma$)
    - Box-like features expected in the Galactic gamma-ray spectra

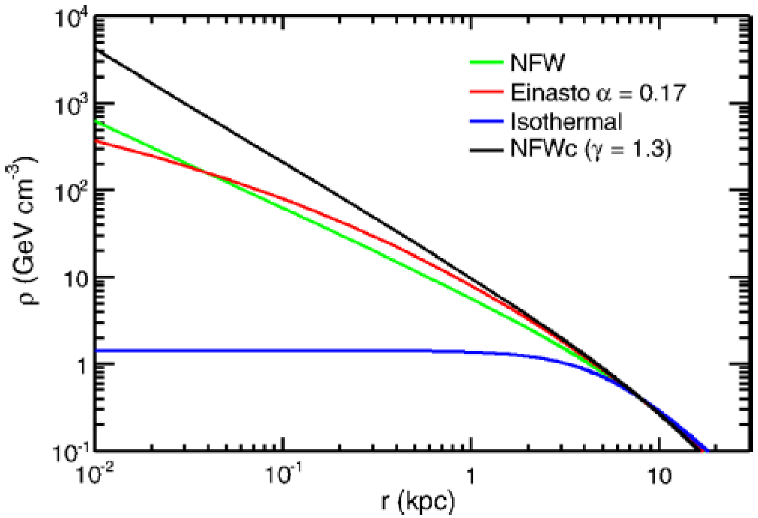
Data selection

- Dataset: August 2008 – April 2022
- Energy range: 100 MeV – 2 TeV
- Maximum zenith angle: 100°
- Standard selection cuts (DATA_QUAL==1, LAT_CONFIG==1, IN_SAA=!T)
- Event class: CLEAN
  - The event sample is partitioned in 4 subsamples, according to the LAT energy resolution (from EDISP0 worst, to EDISP3 best)
  - Different analyses performed for each EDISP sample
  - Combined analysis of all EDISP samples

Regions of Interest (ROIs)

- We follow the approach in the previous LAT papers
  - See PRD91, 122002 (2015)
- We select 5 different Regions of Interest (RoIs) corresponding to cones with the axis pointing towards the Galactic Center (GC), with different angular radii:
  - R3 ($3°$): optimized for NFWc DM density profile
  - R16 ($16°$): optimized for Einasto DM density profile
  - R41 ($41°$): optimized for NFW DM density profile
  - R90 ($90°$): optimized for Isothermal DM density profile
  - R180 (whole sky): optimized for decay searches only, NFW profile
- A mask, corresponding to the region $|b| < 5°$ $|l| > 6°$ (Galactic Plane, GP) is applied to all ROIs (with the exception of R3)
- The GP is used as control region





Plots from PRD 91, 122002 (2015)

Flux models

- **Flux in the ROI:**

$$\phi_{ROI}(E) = \phi_{sig}(E) + \phi_{ROI,bkg}(E)$$

- **Flux in the control region (GP):**

$$\phi_{GP}(E) = \phi_{GP,bkg}(E)$$

- **The signal flux is modeled either as a line ($\phi_{sig}(E) = s\delta(E - E_{fit})$) or as a box ($\phi_{sig}(E) = s\Theta\left(E - E_{fit}\right)$)**
  - **In both cases only one fit parameter ($s > 0$, corresponding to the intensity of the feature)**
- **The background flux is modeled as the sum of a smooth component and a possible feature with the same shape as the signal:**

$$\phi_{ROI,bkg}(E) = \phi_{ROI,smooth}(E) + \phi_{bkg,feature}(E)$$
$$\phi_{GP,bkg}(E) = \phi_{GP,smooth}(E) + \phi_{bkg,feature}(E)$$

- **The smooth component is modeled either as a log-parabola or as a power-law:**

$$\phi_{smooth}(E) = \begin{cases} k\left(\frac{E}{E_0}\right)^{-\Gamma-\beta\log\left(\frac{E}{E_0}\right)} & if\ E_{fit} < 10GeV \\ k\left(\frac{E}{E_0}\right)^{-\Gamma} & if\ E_{fit} > 10GeV \end{cases}$$

  - **Different smooth components in the ROI and in the GP ➔ Up to 6 fit parameters ($k_{ROI}, \Gamma_{ROI}, \beta_{ROI}, k_{GP}, \Gamma_{GP}, \beta_{GP}$)**
- **The feature component is either a line ($\phi_{bkg,feature}(E) = b\delta(E - E_{fit})$) or as a box ($\phi_{bkg,feature}(E) = b\Theta(E - E_{fit})$)**
  - **The feature component is the same in the ROI and in the control region ➔ Only 1 fit parameter (b)**

Likelihood analysis

- For each ROI and for each event sample a maximum likelihood analysis in sliding energy windows has been implemented
  - Fit energy range from 1 GeV to 1 TeV
- Given the fit energy E_{fit}, the associated window is the interval $[E_{fit}(1-w), E_{fit}(1+w)]$
  - wE_{fit} is the half-width of the window
  - Analysis performed with $w = 0.40, 0.50, 0.60$
- The log-likelihood ratio is defined as:

$$\log \lambda(\vec{\theta}) = \log\left[\mathcal{L}\left(\vec{n}|\vec{\mu}(\vec{\theta})\right)/\mathcal{L}(\vec{n}|\vec{n})\right] = \sum_j \left[-(\mu_j + n_j) + n_j \log(\mu_j/n_j)\right]$$

  - $\vec{n} = (n_1, n_2 \dots)$ and $\vec{\mu} = (\mu_1, \mu_2 \dots)$ are the vectors of observed and expected counts
    - Expected counts are evaluated folding the flux models with the exposures:

$$\mu_{ROI}(E_j) = \int dE\, \varepsilon(E_j|E)\phi_{ROI}(E) \qquad \mu_{GP}(E_j) = \int dE\, \varepsilon(E_j|E)\phi_{GP}(E)$$

  - $\vec{\theta} = (k_{ROI}, \Gamma_{ROI}, \beta_{ROI}, k_{GP}, \Gamma_{GP}, \beta_{GP}, b, s)$ is the vector of the fit parameters
    - The strength of the signal feature s is allowed to take only positive values
      - The null hypothesis (no signal) is obtained when $s = 0$
    - The strength of the background feature b can take either positive or negative values
- The parameters $\vec{\theta}_{max} = \left(k_{ROI,max}, \Gamma_{ROI,max}, \beta_{ROI,max}, k_{GP,max}, \Gamma_{GP,max}, \beta_{GP,max}, b_{max}, s_{max}\right)$ which maximize the likelihood are obtained with a MINUIT fit and the corresponding maximum log-likelihood ratio $\log \lambda_{1,max}$ is evaluated

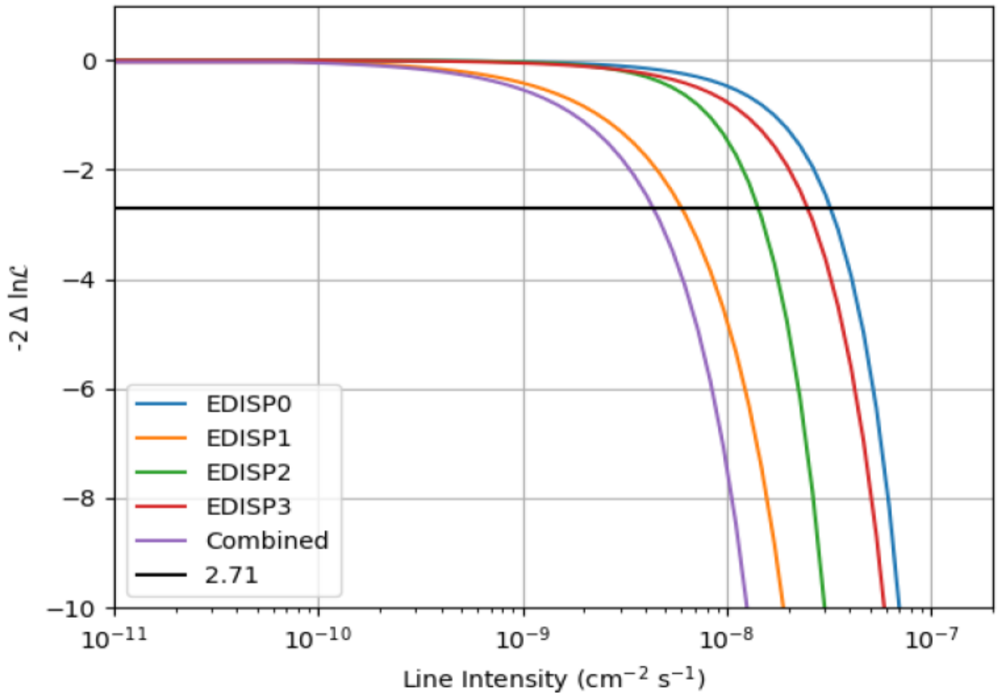
Test statistics and profile likelihood analysis

- The background parameters are fixed to the values obtained from the fit:
  - $\vec{\theta}_b = \vec{\theta}_{b,max} \equiv (k_{ROI,max}, \Gamma_{ROI,max}, \beta_{ROI,max}, k_{GP,max}, \Gamma_{GP,max}, \beta_{GP,max}, b_{max})$
- We evaluate the log-likelihood ratio for the null hypothesis ($s = 0$):
  - $\log \lambda_0 = \log \lambda(\vec{\theta}_{b,max}, s = 0)$
- Test statistics of the fit:

$$TS = 2[\log \lambda_{1,max} - \log \lambda_0]$$

  - TS is expected to obey a χ^2 distribution with 1 d.o.f.
  - The significance level of the feature (in σ units) is given by $\sqrt{TS}$
- If a feature is not significant, upper limits (ULs) on its strength s can be calculated
  - We study the variations of TS as a function of the signal parameter s
  - The UL on s at 95% confidence level (CL) is obtained by setting $TS = TS_{min} + 2.71$

Profile likelihood analysis



TS profiles evaluated for the different event types as a function of the line intensity s at $E_{fit} = 4.8 GeV$

- **The log-likelihood ratios used in the combined analysis are built from those used in the analysis of individual EDISP samples:**

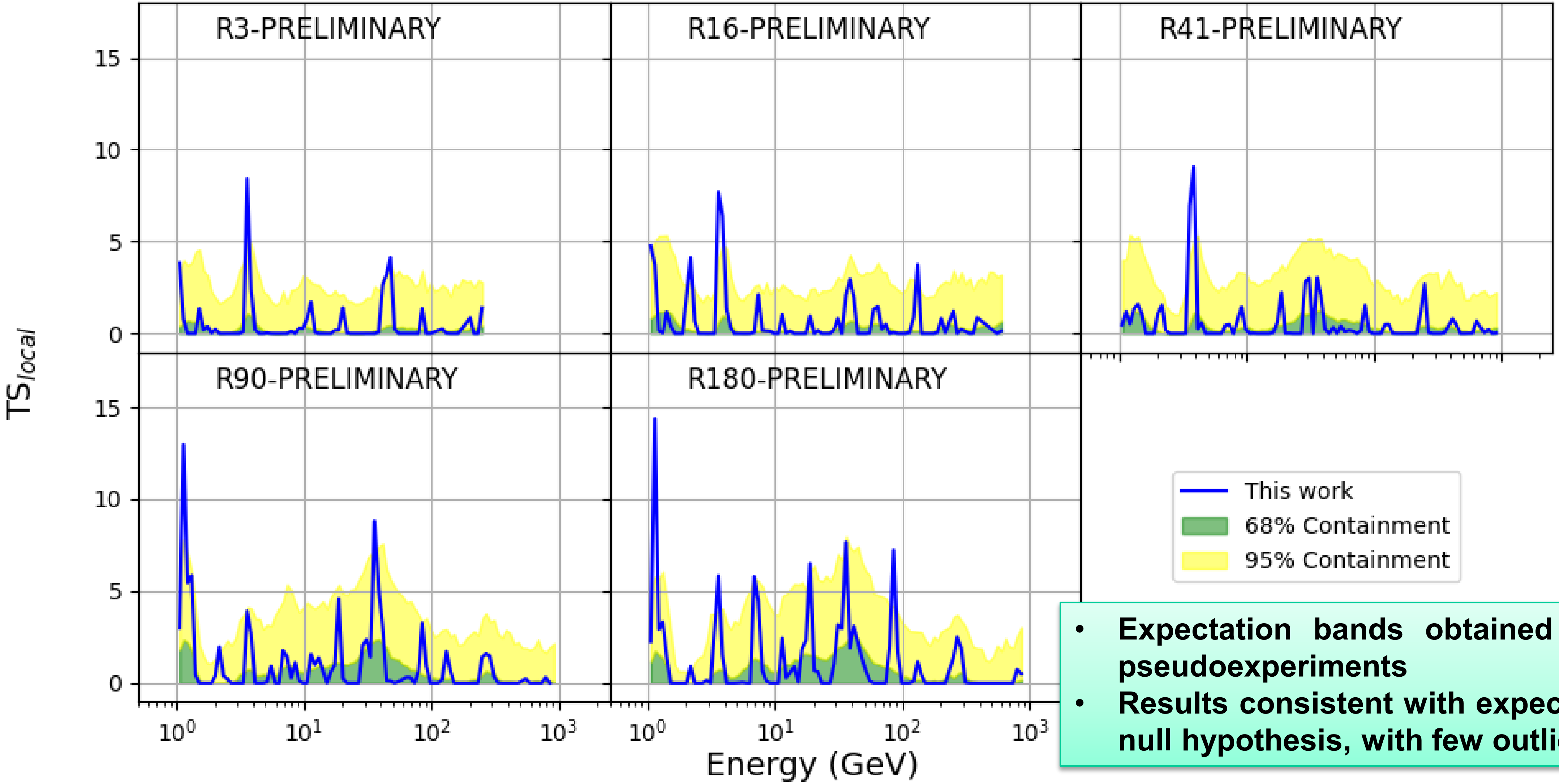
$$\log \lambda_{comb}(s) = \sum_{\alpha \in \{DISP\}} \log \lambda_\alpha(s)$$

  - **The same analysis procedure as for individual EDISP samples is then implemented**

Monte Carlo simulations

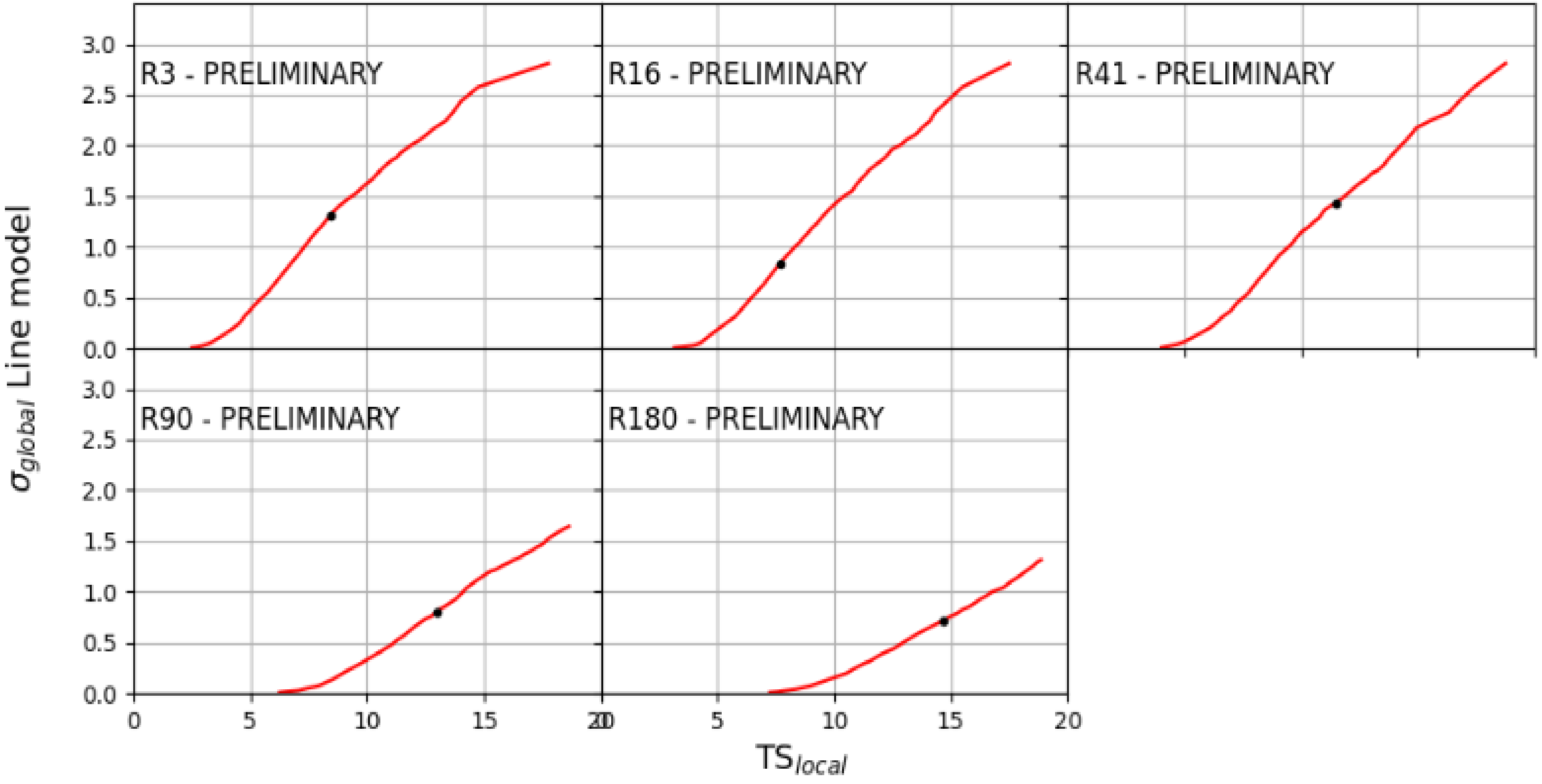
- A set of 1000 background-only Monte Carlo simulations (pseudoexperiments) is performed to study the sensitivity of the analysis to the null hypothesis
- Each pseudoexperiment is generated starting from a template of the count distributions corresponding to the null hypothesis
  - The counts in each energy bin are extracted from a Poisson distribution with its average value taken from the template model
- Simulated data are then processed with the same analysis chain as for real data
- The TS values and the ULs on the line intensities obtained from the pseudoexperiments are then compared with those obtained from real data

Local significance of possible line features



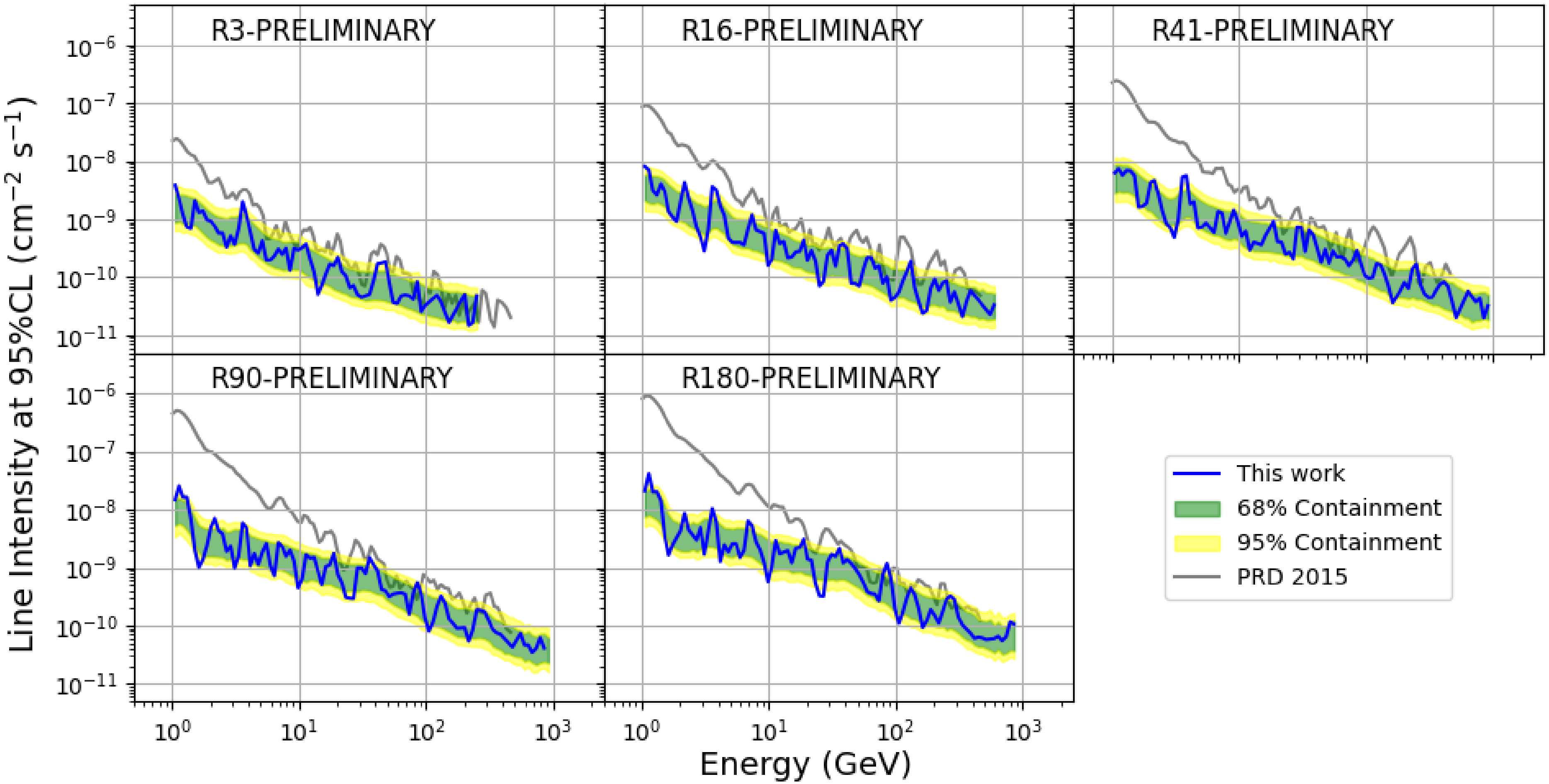
- **Expectation bands obtained from the 1000 pseudoexperiments**
- **Results consistent with expectations from the null hypothesis, with few outliers**

Global significance



- For each ROI, we build the distribution of the maximum TS values obtained in the pseudoexperiments, and we evaluate its quantiles
- Assuming that the global significance obeys a half-normal distribution, we associate a global significance to each value of TS
  - Conversion of the quantiles in units of σ
- In our data the potential feature with the highest global significance is found in R41, but its global significance is ~ 1.5σ
  - All features are globally insignificant

Upper limits at 95% confidence level on the line intensity



- **Improvement of one order of magnitude at low energies with respect to the previous LAT analysis**
- **Measured limits lie within the containment bands, and are therefore consistent with the expectations for the null hypothesis**

Constraints on the velocity-averaged DM annihilation cross section and decay time

- **Gamma-ray spectrum from DM self-annihilation:**

$$\left(\frac{d\Phi}{dE}\right)_{ann} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\left(\frac{dN_\gamma}{dE}\right)_{ann} J_{ann}(\Delta\Omega)$$

- **Gamma-ray spectrum from DM decay:**

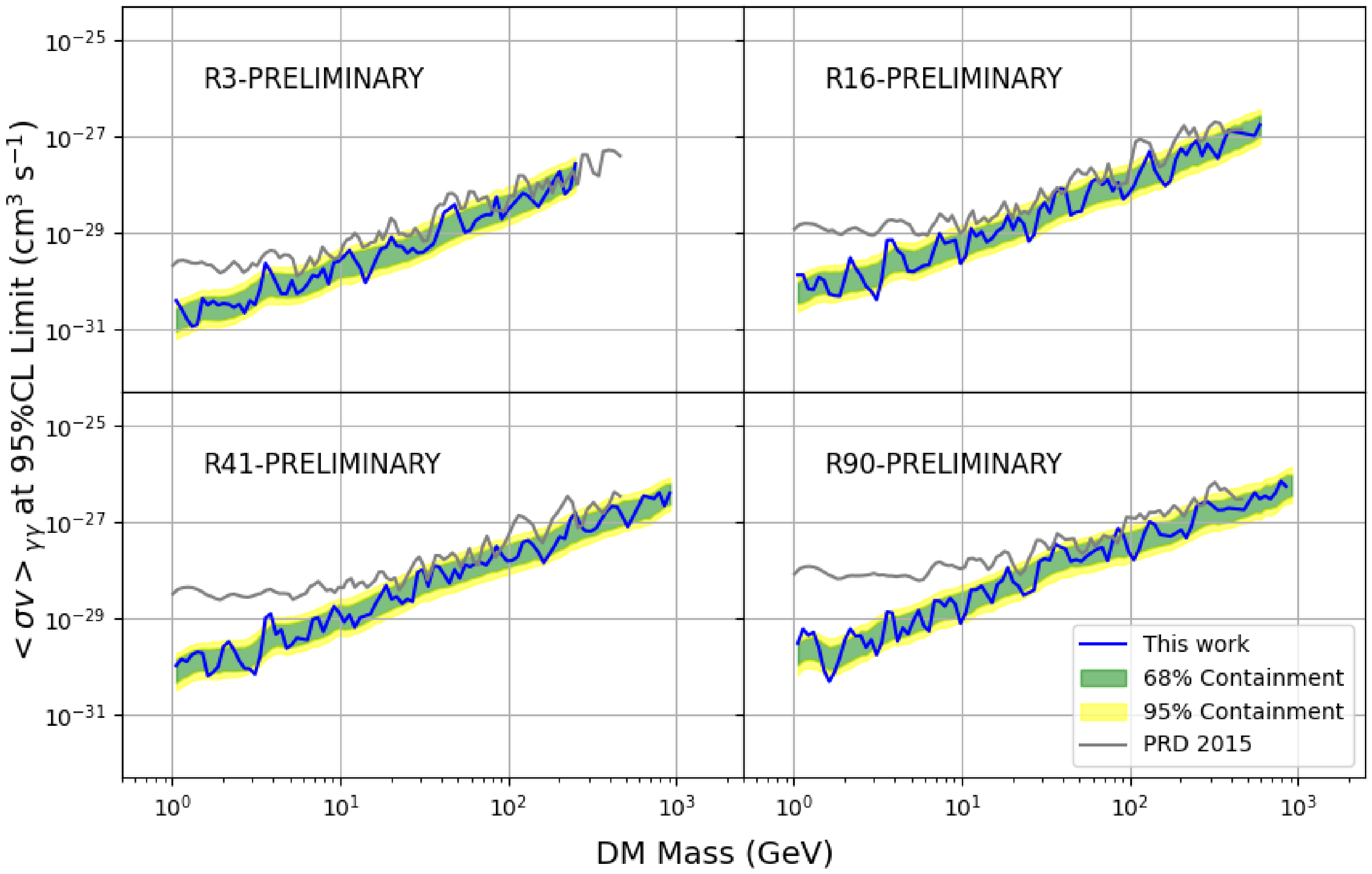
$$\left(\frac{d\Phi}{dE}\right)_{decay} = \frac{1}{4\pi}\frac{1}{m_\chi\tau}\left(\frac{dN_\gamma}{dE}\right)_{decay} J_{decay}(\Delta\Omega)$$

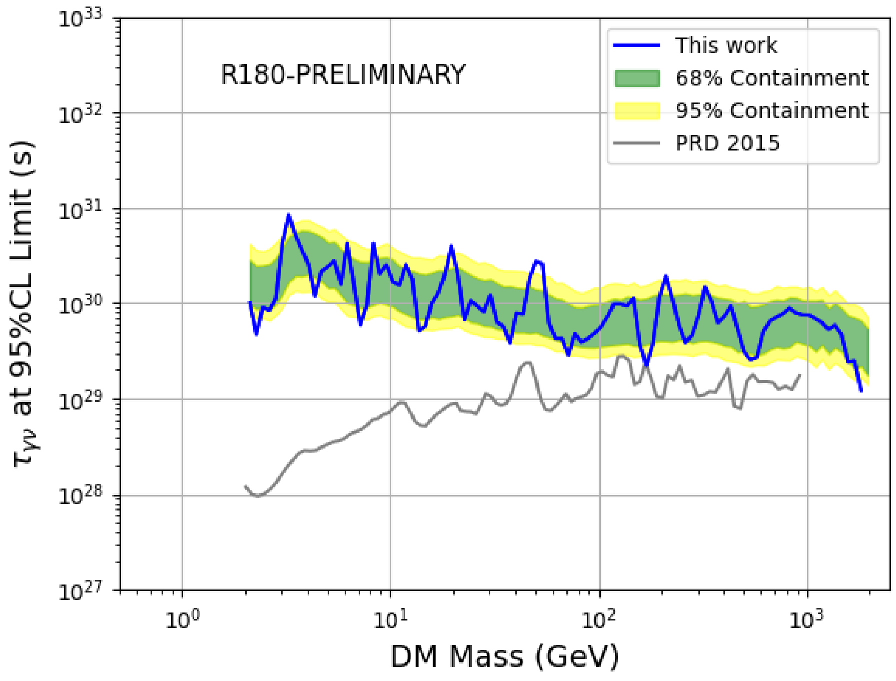
- **The astrophysics J-factors are evaluated from the DM density profile**
  - **J-factors taken from PRD91, 122002 (2015)**
- **In both cases**

$$\frac{dN_\gamma}{dE} = \delta(E - E_{line})$$

  - **The line energy depends on the process yielding the gamma-ray line**
    - **In the annihilation $\chi\chi \longrightarrow \gamma\gamma$ $E_{line} = m_\chi$ if both DM particles are nearly at rest**
    - **In the decay $\chi \longrightarrow \gamma\gamma$ $E_{line} = m_\chi/2$ if the parent DM particles is at rest**
    - **In the annihilation $\chi\chi \longrightarrow \gamma X$ $E_{line} = m_\chi\left(1 - \frac{m_X^2}{4m_\chi^2}\right)$**
    - **…**
- **The UL on the line intensity can be converted into constraints on $\langle\sigma v\rangle$ or τ**

Upper limits on the velocity-averaged DM annihilation cross section and on the DM decay time





Conclusions

- We have performed a search for possible line-like features in the Galactic gamma-ray energy spectra measured by the Fermi LAT
  - No signal detected
  - Constraints on the velocity-averaged DM annihilation cross section and on the DM lifetime
- The limits obtained in this analysis are a factor 10-100 stronger than those obtained in previous LAT analysis (see PRD91, 122022 (2015))
  - Significant improvement at low energies due to a more accurate modeling of the smooth component of the background flux
- The algorithm to search for box-like features has been also implemented