Studying dark matter with MadDM: Recent developments

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Based on arXiv:1804.00044, arXiv:2012.09016, arXiv:2107.04598

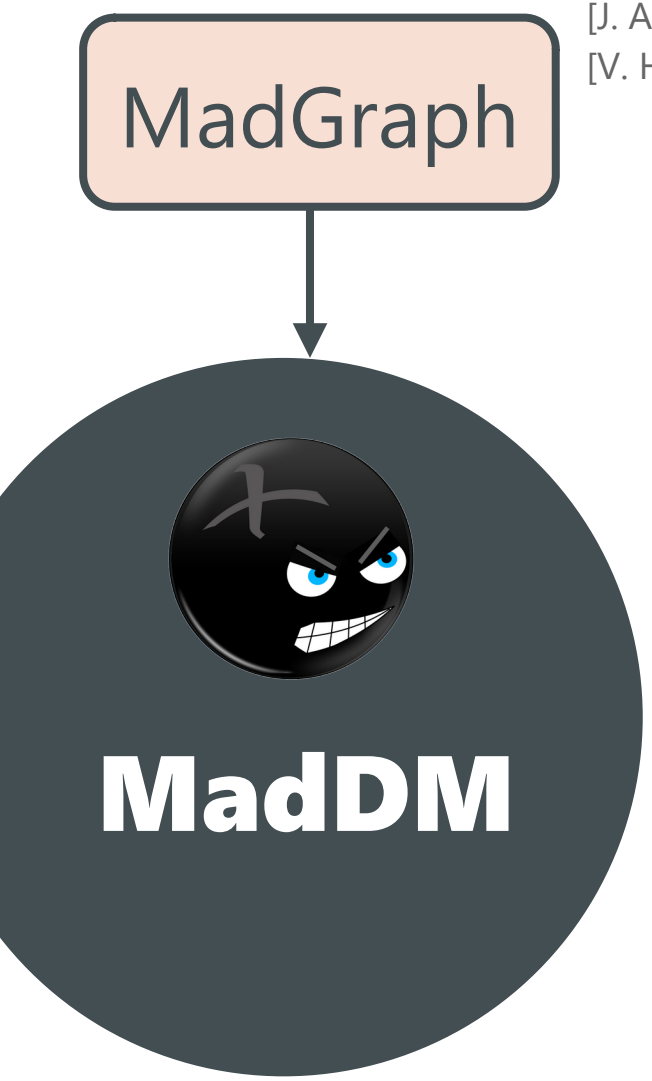
14th International Conference on Identification of Dark Matter (IDM 2022)

21 July 2022

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

UCLouvain


MadDM



[J. Alwall et al. JHEP 06 (2011) 128]
[V. Hirschi. JHEP 10 (2015) 146]

Automatic

MG5 plugin

User-friendly interface

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MG5_aMC>install maddm
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MadGraph

UFO model

[A. Alloul et al. Comput. Phys. Commun. 185 (2014) 2250–2300]

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Generic

Any UFO dark matter model

```
MadDM>import model IDM
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Comprehensive

Comparison with main experimental constraints

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Any UFO dark matter model

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Comprehensive

Comparison with main experimental constraints

Cool

Focused on WIMPs

MadDM computations

RELIC DENSITY

2 to 2 tree-level annihilations diagrams
freeze-out temperature

```
MadDM>generate relic_density
```

DIRECT DETECTION

Spin-dependent and independent nucleon-dm σ
Comparison with current constraints

```
MadDM>generate direct_detection
```

MadDM computations

INDIRECT DETECTION

```
MadDM>generate indirect_detection
```

MadDM v3.0

- Theoretical prediction for $\langle \sigma v \rangle$
- Generation of energy spectra (link to PPPC4DMID and Pythia 8)
- Computation of fluxes
- Fermi-LAT likelihoods for dwarf spheroidal galaxies

[F. Ambrogi et al. Phys. Dark Univ. 24 (2019) 100249]

MadDM computations

INDIRECT DETECTION

```
MadDM>generate indirect_detection
MadDM>generate indirect_spectral_features
```

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- Generation of energy spectra (link to PPPC4DMID and Pythia 8)
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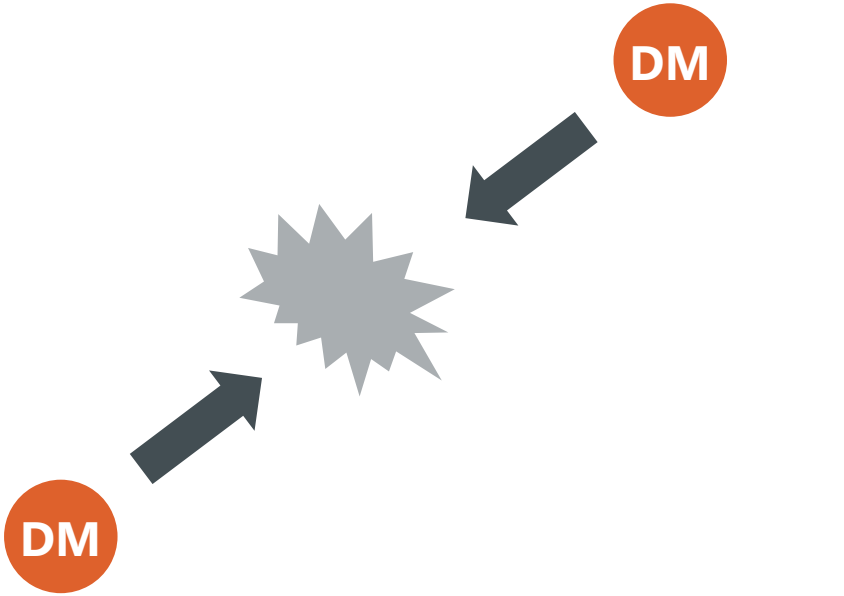
MadDM v3.2

- Loop-induced processes
- Gamma-line spectrum analysis
- Computation of astrophysical quantities
- New constraints implemented

[C. Arina, J. Heisig, F. Maltoni, DM and O. Mattelaer (July 2021). arXiv:2107.04598]

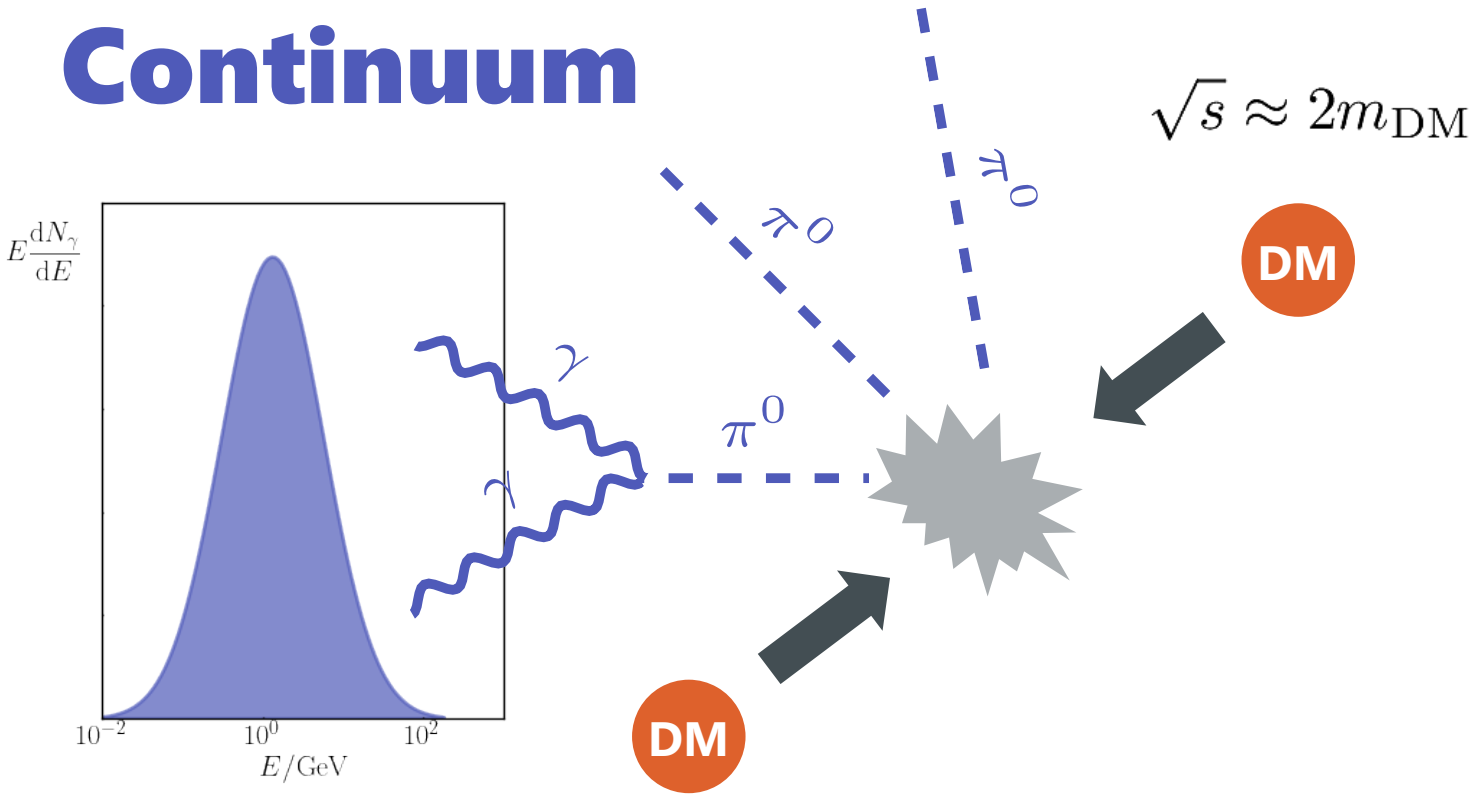
Gamma-ray spectra

$$\sqrt{s} \approx 2m_{\mathrm{DM}}$$



Gamma-ray spectra

Continuum



Gamma-ray spectra

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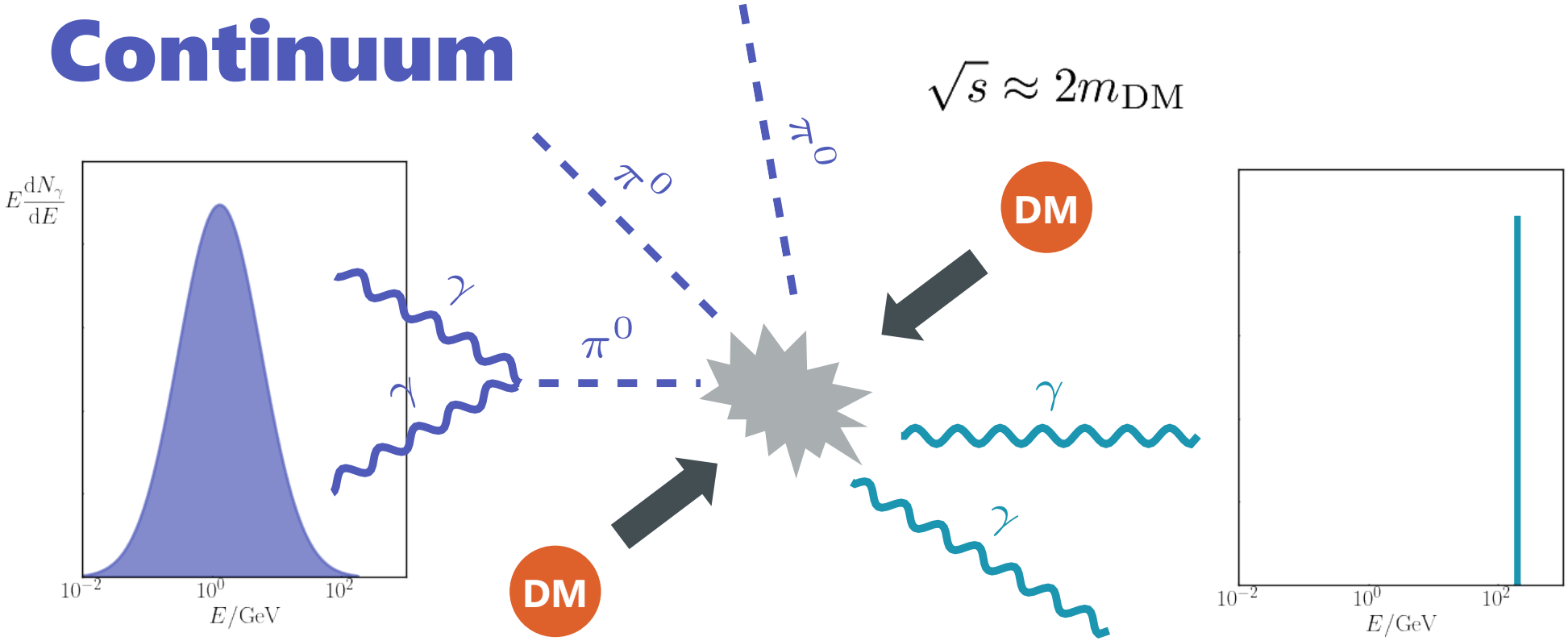
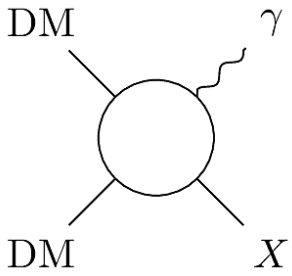


Loop-induced process

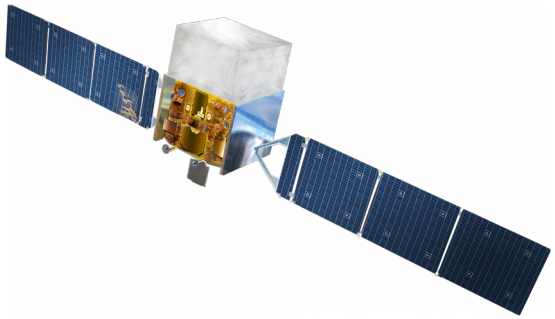


Line

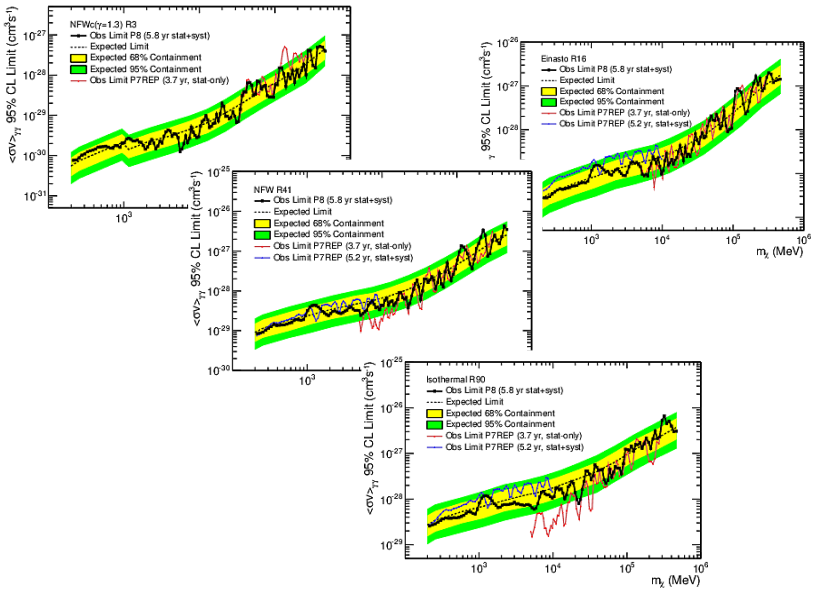
Smoking-gun signature
Hard to mimick with astrophysical background.

Gamma-ray line searches

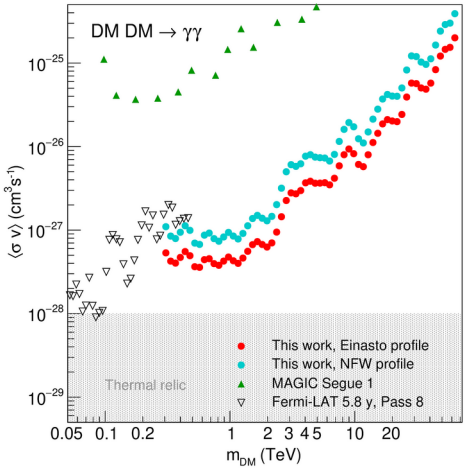
Fermi-LAT



Fermi-LAT © NASA



[M. Ackermann et al. Phys. Rev. D 91 (12) (2015) 122002]



H.E.S.S. © MPIK / Christian Föhr

H.E.S.S.

[H. Abdallah et al. Phys. Rev. Lett. 120 (20) (2018) 201101]

Gamma-ray flux

$$\frac{d\Phi}{dE} = \frac{1}{8\pi m_{\rm DM}^2} \sum_i \langle \sigma v \rangle_i \frac{dN_\gamma^i}{dE} \int_{\rm ROI} {\rm d}\Omega \int_{\rm l.o.s.} \rho^2(\boldsymbol{r})\, {\rm d}l$$

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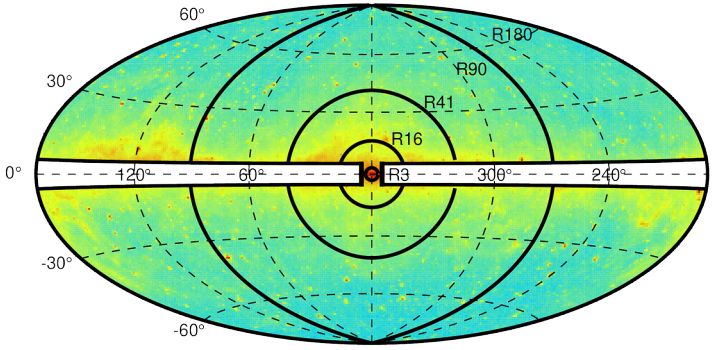
Line spectrum

$$\frac{dN_\gamma^i}{dE} = k \cdot \delta(E - E_\gamma)$$

$$E_\gamma = m_{\rm DM}\left(1 - \frac{m_X^2}{4m_{\rm DM}^2}\right)$$

Gamma-ray flux

[M. Ackermann et al. Phys. Rev. D 91 (12) (2015) 122002]



J-factor

ROI + mask
over galactic plane

$$\frac{d\Phi}{dE} = \frac{1}{8\pi m_{\rm DM}^2} \sum_i \langle \sigma v \rangle_i \frac{dN_\gamma^i}{dE} \int_{\rm ROI} {\rm d}\Omega \int_{\rm l.o.s.} \rho^2(\boldsymbol{r})\, {\rm d}l$$

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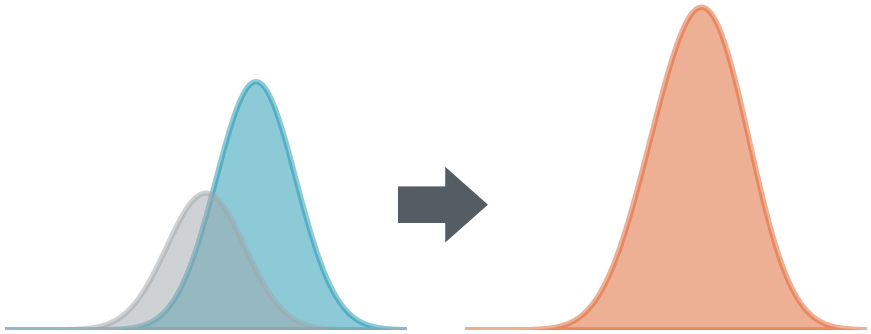
Density profile

NFW
Einasto
isothermal
Burkert

Gamma line spectrum

Line on spectrum: **Gaussian peak**

- $E_\gamma = m_{\mathrm{DM}}\left(1 - \frac{m_X^2}{4m_{\mathrm{DM}}^2}\right)$
- σ : energy resolution of experiment



Peak's analysis

- Close enough: **merge them**

Gamma line spectrum

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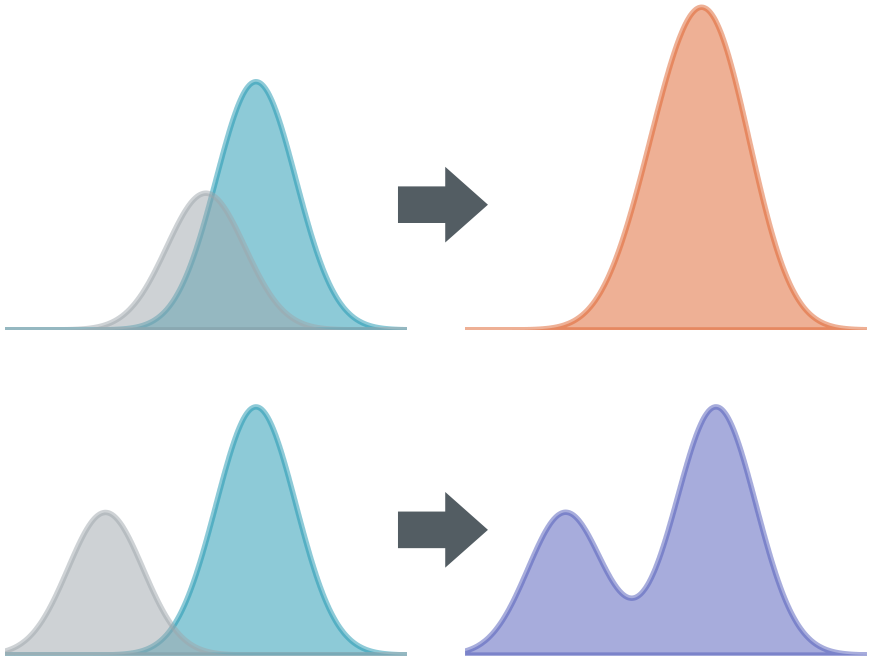

Peak's analysis

- Close enough: **merge them**
- Well-separated: **study each one separately**
- Not well-separated: **analysis is questionable**

Inert Doublet Model (IDM)

$$V = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + \text{h.c.}\right]$$

$$\Phi = \begin{pmatrix} H^\pm \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}$$

- Scalar dark matter candidate
- 5 free parameters $m_{H^0}, m_{A^0}, m_{H^\pm}, \lambda_L, \lambda_2$
- [J. Heisig et al. Eur. Phys. J. C 77 (9) (2017) 624]: scan

Main constraints

Relic density
EW precision
New physics LEP-II
Continuum gamma-ray dSph
Unitarity, perturbativity, vacuum stability

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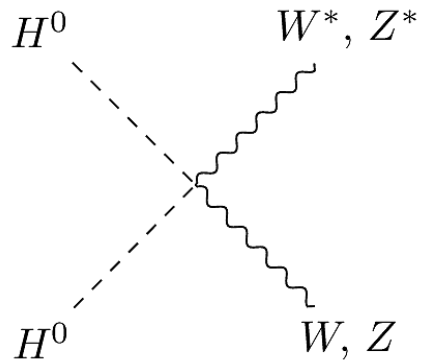
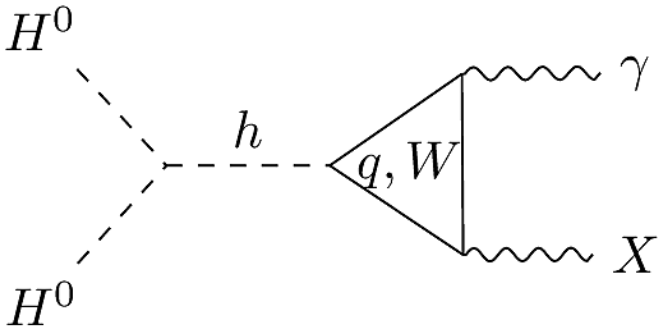
Low mass sweet spot $m_{H^0} \approx 72\,\text{GeV}$

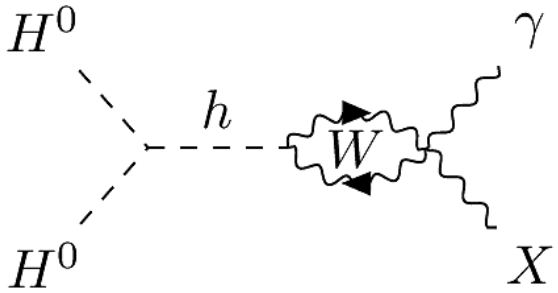
Reproduce relic density, without tuned coupling.

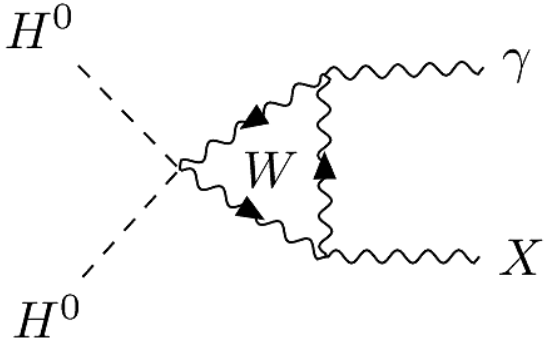
Not challenged by other constraints

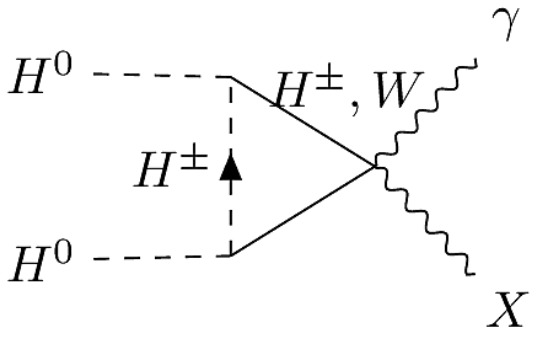


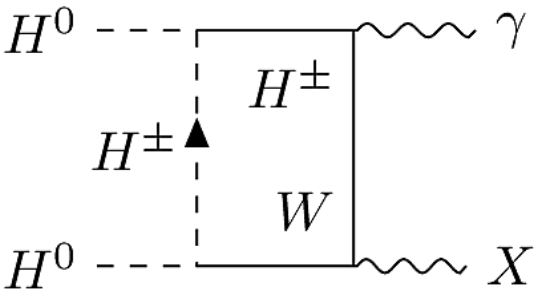
Diagrams in $\gamma\gamma$ (140) and γZ (172)

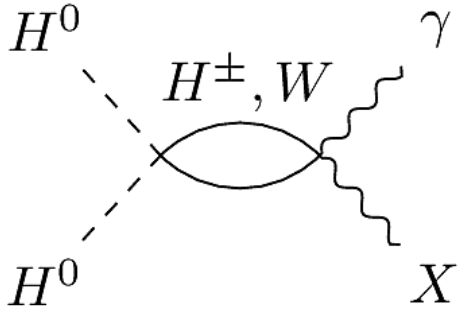




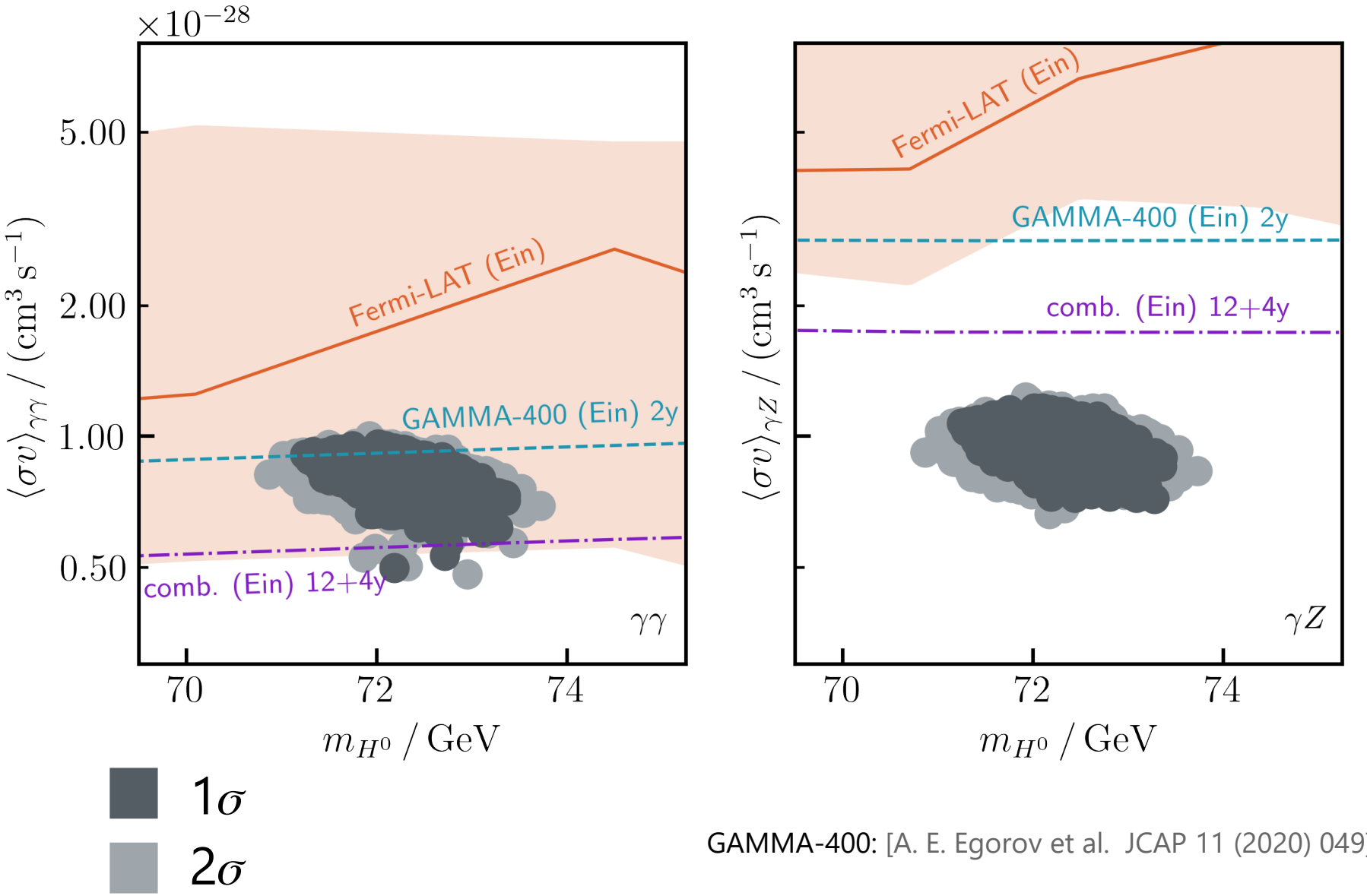








Parameter space



GAMMA-400: [A. E. Egorov et al. JCAP 11 (2020) 049]

Summary

- MadDM is MadGraph plug-in: inherits functionality
- Comprehensive tool for dark matter studies
- MadDM v3.2:
  - Loop-induced processes for indirect detection
  - important for gamma-lines
  - automatized reinterpretation of experimental results
- Beyond v3.2:
  - Direct detection: full NREFT operator basis and electron scattering
  - Dark matter genesis beyond WIMPs

launchpad.net/maddm

Backup

MadDM v3.2

1

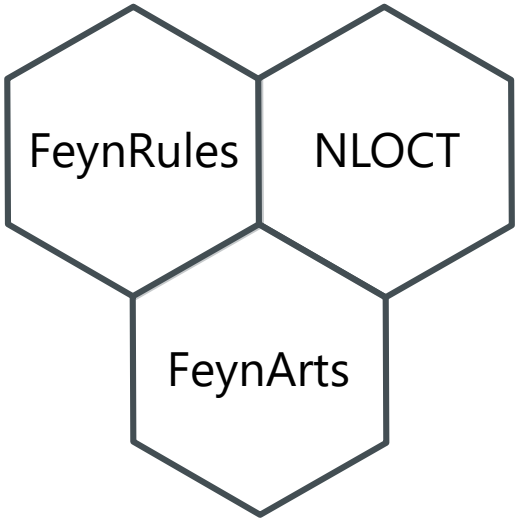
New command

```
MadDM>generate indirect_spectral_features
```

Automatic generation of annihilations into $\gamma X, X = \gamma, Z, h, Z_2-$even

2

Gamma-line spectrum analysis pipeline



- $\langle \sigma v \rangle$ computation (inherited from MadGraph)
- J-factor computation (ROIs and profiles)
- Flux predictions
- Gamma-line spectrum analysis
- Fermi-LAT and HESS UL comparison

[A. Alloul et al. Comput. Phys. Commun. 185 (2014) 2250–2300]
[T. Hahn. Comput. Phys. Commun. 140 (2001) 418–431]
[C. Degrande. Comput. Phys. Commun. 197 (2015) 239–262]

3

Features available for any UFO NLO model

4

Automatic detection of Z_2-odd/even particles