



MadDM v.3.0

Luca Mantani

In collaboration with:

**C. Arina, M. Backovic, J. Heisig, F. Maltoni,
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Centre for Cosmology, Particle Physics and Phenomenology

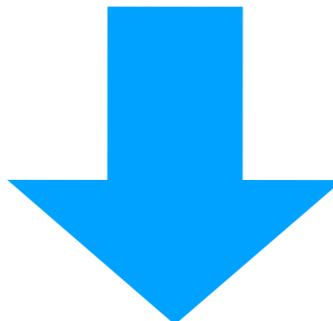


Outline

- ❖ **Introduction and motivations**
- ❖ **What is new?**
 - **Indirect detection module**
 - **Experimental constraints class**
 - **Model parameter space sampling**
- ❖ **Example of an application: internal bremsstrahlung**
- ❖ **Conclusions and outlook**

Dark Matter problem in a nutshell

- ❖ Indirect evidence
- ❖ Many experimental approaches
- ❖ Plethora of theoretical models
- ❖ No signal → understanding of DM properties limited



Demand for numerical tools

MadDM v.3.0: a Comprehensive Tool for Dark Matter Studies

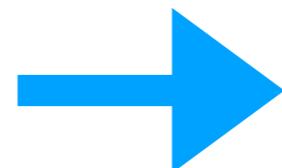
Federico Ambrogi, Chiara Arina, Mihailo Backovic, Jan Heisig, Fabio Maltoni, Luca Mantani, Olivier Mattelaer, Gopolang Mohlabeng

(Submitted on 30 Mar 2018)

arXiv:1804.00044v1

- ❖ MadDM is now a Madgraph plug-in
- ❖ Beta version available at <https://launchpad.net/maddm>
- ❖ New version of MG5_aMC_v2.6.2 needed

Easy to install



./bin/mg5_aMC

>install maddm

From the command line, execute maddm.py :

```
import model MyDMmodel
define darkmatter chi
generate relic_density
add direct_detection
add indirect_detection
output MyDMproject
launch
```

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The following switches determine which programs are run:

===== Description =====	===== values =====	===== other options =====
1. Compute the Relic Density	relic = ON	OFF
2. Compute direct(ional) detection	direct = directional	direct OFF
3. Compute indirect detection/flux	indirect = sigmav	flux_source flux_earth OFF
4. Run Multinest scan	nestscan = OFF	Please install module

You can also edit the various input card:

- * Enter the name/number to open the editor
- * Enter a path to a file to replace the card
- * Enter **set NAME value** to change any parameter to the requested value

5. Edit the model parameters	[<u>param</u>]
6. Edit the MadDM options	[<u>maddm</u>]

For a generic dark matter model with UFO files

MadDM capabilities

Relic density (MadDM v.1.0)

- Coannihilation
- Multi-component dark matter

Direct detection (MadDM v.2.0)

- Theoretical elastic spin-independent and spin-dependent cross section dark matter off nucleons
- Directional event rate (double differential event rate)
- LUX likelihood

Indirect detection (MadDM v.3.0)

- Theoretical prediction for the velocity averaged cross section at present time
- Generation of energy spectra from dark matter annihilation
- Computation of fluxes at source and detection
- Fermi-LAT likelihood for dwarf spheroidal galaxies

Model parameter space sampling (MadDM v.3.0)

- Sequential grid scan
- PyMultiNest interface

Experimental constraints module (MadDM v.3.0)

- compute DM annihilation cross section

Inclusive

Madevent

Reshuffling

- compute DM annihilation cross section

Inclusive

Madevent

Reshuffling

- calculate spectra of cosmic rays and fluxes at source

PPPC4DMID

Pythia8

- compute DM annihilation cross section

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- galactic positrons/antiprotons propagation

DRAGON



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- calculate spectra of cosmic rays and fluxes at source

PPPC4DMID

Pythia8

- galactic positrons/antiprotons propagation

DRAGON

- compare with experimental constraints

Experimental constraints module



The general expression is

$$\langle \sigma v \rangle = \int dv_{rel} \tilde{P}_r(v_{rel}) \sigma v_{rel}$$

Inclusive

Madevent

Reshuffling

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Reshuffling

Inclusive

- Very fast, only DM DM → 2-body at LO, good for scans
- $P(v) = \delta(v_{rel})$
- Numerical integration over the angle, no events generated



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Madevent

- Generic DM DM → n-body
- $P(v) = \delta(v_{rel})$
- Generates events for Pythia8



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Madevent

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- Generates events for Pythia8

Reshuffling

- Generic DM DM → n-body
- $P(v)$ Maxwell-Boltzmann
- Better for light DM or DM~SM

$$P(v) = \sqrt{\frac{2}{\pi}} \frac{v^2}{v_0^3} \exp\left(-\frac{v^2}{2v_0^2}\right)$$

DM can annihilate into all possible SM final states kinematically open

$\chi\chi \rightarrow gg, q\bar{q}, l^+l^-, \nu\bar{\nu}, ZZ, W^+W^-, hh$



$\gamma, e^+(e^-), \bar{p}(p), \nu, \bar{\nu}$

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PPPC4DMID

Pythia8

<http://www.marcocirelli.net/PPPC4DMID.html>

❖ Relic density : Ωh^2 Planck

❖ Direct detection :

- Spin independent → XENON1T
- Spin dependent - neutrons → LUX
- Spin dependent - protons → PICO 60

❖ Indirect detection :

- Precomputed limits for DM DM → SM SM
- On the fly computation with the γ spectra → Fermi-LAT likelihood

The module can be loaded independently of MadDM and the user can update or add limits

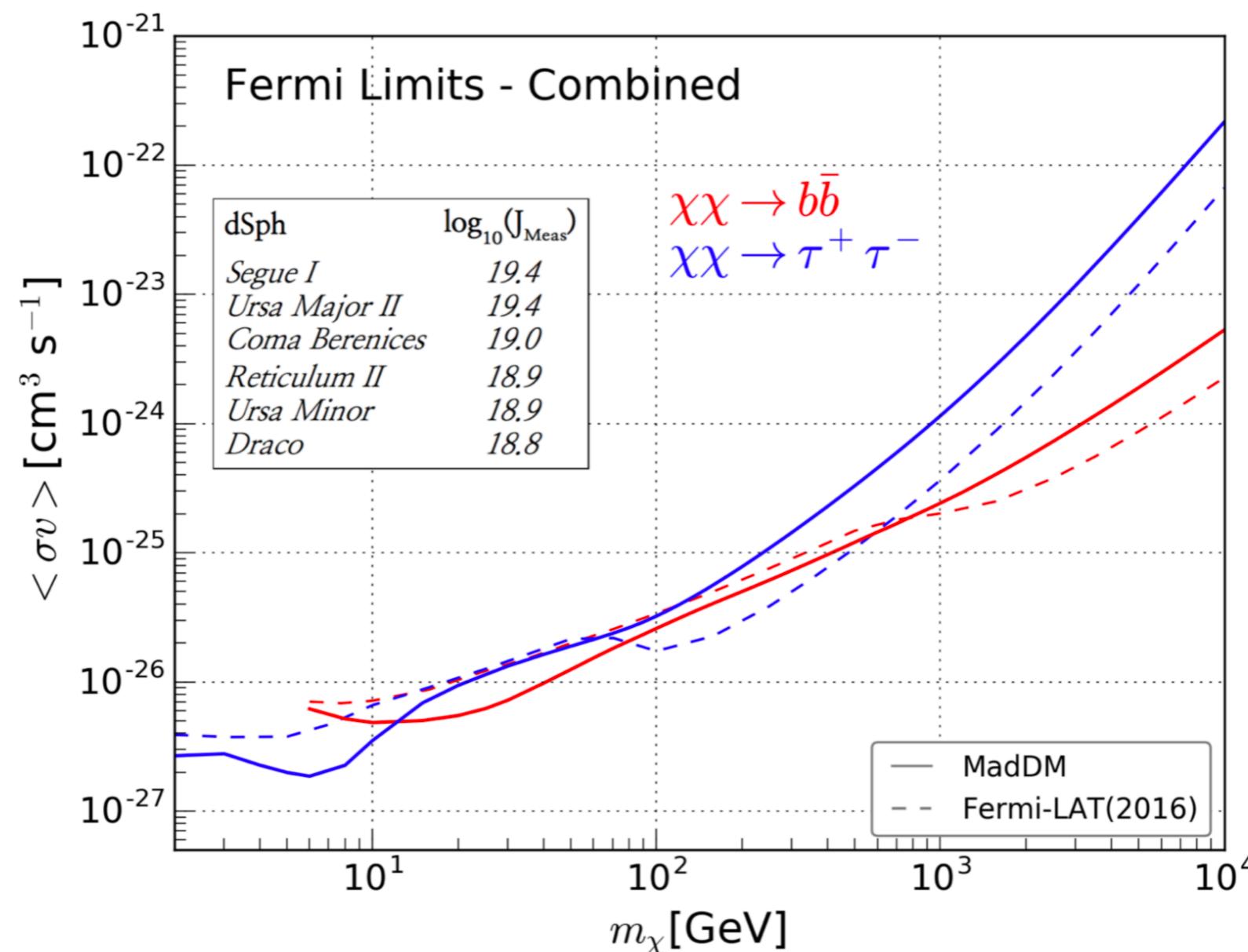


$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_\psi \frac{d\Omega}{\Delta\psi} \int_{\text{los}} \rho^2(\psi, l) dl.$$

J-Factor

- ❖ Non-observation of γ -rays from dSphs sets strong constraints
- ❖ Fermi collaboration made available likelihood profiles
- ❖ Chose 6 dSphs with higher J-factor as reference

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_{\psi} \frac{d\Omega}{\Delta\psi} \int_{\text{los}} \rho^2(\psi, l) dl.$$



Example of the MadDM screen output

Luca Mantani

```
***** Relic Density
INFO: Relic Density      = 3.06e-03      ALLOWED
INFO: x_f                 = 2.60e+01
INFO: sigmav(xf)          = 3.96e-08
INFO: xsi                 = 2.56e-02
INFO:

***** Direct detection [cm^2]:
INFO: SigmaN_SI_p         Thermal = 9.76e-40    EXCLUDED    All DM = 3.82e-38    EXCLUDED    Xenon1ton ul   = 6.44e-46
INFO: SigmaN_SI_n         Thermal = 9.72e-40    EXCLUDED    All DM = 3.80e-38    EXCLUDED    Xenon1ton ul   = 6.44e-46
INFO: SigmaN_SD_p          Thermal = 1.01e-62    ALLOWED     All DM = 3.93e-61    ALLOWED     Pico60 ul     = 2.03e-40
INFO: SigmaN_SD_n          Thermal = 4.64e-62    ALLOWED     All DM = 1.81e-60    ALLOWED     Lux2017 ul   = 1.22e-40
INFO:

***** Indirect detection [cm^3/s]:
INFO: <sigma v> method: madevent
INFO: DM particle halo velocity: 2e-05/c
INFO: xxddxxdb_ccx          Thermal = 1.19e-28    ALLOWED     All DM = 1.83e-25    EXCLUDED    Fermi ul      = 1.19e-25
INFO: xxddxxdb_ddx          Thermal = 1.19e-28    ALLOWED     All DM = 1.83e-25    EXCLUDED    Fermi ul      = 1.20e-25
INFO: xxddxxdb_uux          Thermal = 1.19e-28    ALLOWED     All DM = 1.83e-25    EXCLUDED    Fermi ul      = 1.20e-25
INFO: xxddxxdb_bbx          Thermal = 1.19e-28    ALLOWED     All DM = 1.83e-25    EXCLUDED    Fermi ul      = 1.21e-25
INFO: xxddxxdb_ssx          Thermal = 1.19e-28    ALLOWED     All DM = 1.83e-25    EXCLUDED    Fermi ul      = 1.20e-25
INFO: xxddxxdb_ttx          Thermal = 1.19e-28    ALLOWED     All DM = 1.81e-25    EXCLUDED    Fermi ul      = 1.44e-25
INFO: xxddxxdb_y1y1         Thermal = 5.34e-28    NO LIMIT    All DM = 8.16e-25    NO LIMIT    Fermi ul      = -1.00e+00
INFO: Skipping zero cross section processes for: emep, mummup, xxcxxcb, vlvl, tamtap
INFO: Using generic Fermi limits for light quarks (u,d,s)
INFO: Total limits calculated with Fermi likelihood:
INFO: DM DM > all           Thermal = 1.25e-27    ALLOWED     All DM = 1.91e-24    EXCLUDED    Fermi ul      = 4.19e-25
```

Theory predictions

```
***** Relic Density
INFO: Relic Density = 3.06e-03
INFO: x_f = 2.60e+01
INFO: sigmav(xf) = 3.96e-08
INFO: xsi = 2.56e-02
INFO:

***** Direct detection [cm^2]:
INFO: SigmaN_SI_p Thermal = 9.76e-40 EXCLUDED
INFO: SigmaN_SI_n Thermal = 9.72e-40 EXCLUDED
INFO: SigmaN_SD_p Thermal = 1.01e-62 ALLOWED
INFO: SigmaN_SD_n Thermal = 4.64e-62 ALLOWED

***** Indirect detection [cm^3/s]:
INFO: <sigma v> method: madevent
INFO: DM particle halo velocity: 2e-05/c
INFO: xxddxxdb_ccx Thermal = 1.19e-28 ALLOWED
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INFO: xxddxxdb_ttx Thermal = 1.19e-28 ALLOWED
INFO: xxddxxdb_y1y1 Thermal = 5.34e-28 NO LIMIT
INFO: Skipping zero cross section processes for: emep, mummup,
INFO: Using generic Fermi limits for light quarks (u,d,s)
INFO: Total limits calculated with Fermi likelihood:
INFO: DM DM > all Thermal = 1.25e-27 ALLOWED
```

Limits stored in Exp. class

Xenon1ton ul	= 6.44e-46
Xenon1ton ul	= 6.44e-46
Pico60 ul	= 2.03e-40
Lux2017 ul	= 1.22e-40
Fermi ul	= 1.19e-25
Fermi ul	= 1.20e-25
Fermi ul	= 1.20e-25
Fermi ul	= 1.21e-25
Fermi ul	= 1.20e-25
Fermi ul	= 1.44e-25
Fermi ul	= -1.00e+00
Fermi ul	= 4.19e-25

Calculated on the fly with Pythia8/PPPC4DMID

Theory predictions

```
***** Relic Density
INFO: Relic Density = 3.06e-03
INFO: x_f = 2.60e+01
INFO: sigmav(xf) = 3.96e-08
INFO: xsi = 2.56e-02
INFO:
***** Direct detection [cm^2]:
INFO: SigmaN_SI_p Thermal = 9
INFO: SigmaN_SI_n Thermal = 9
INFO: SigmaN_SD_p Thermal = 1
INFO: SigmaN_SD_n Thermal = 4
INFO:
***** Indirect detection [cm^3/s]:
INFO: <sigma v> method: madevent
INFO: DM particle halo velocity: 2e-06
INFO: xxddxxdb_ccx Thermal = 1
INFO: xxddxxdb_ddx Thermal = 1
INFO: xxddxxdb_uux Thermal = 1
INFO: xxddxxdb_bbx Thermal = 1
INFO: xxddxxdb_ssx Thermal = 1
INFO: xxddxxdb_ttx Thermal = 1
INFO: xxddxxdb_y1y1 Thermal = 5
INFO: Skipping zero cross section pro...
INFO: Using generic Fermi limits for ...
INFO: Total limits calculated with Fe...
INFO: DM_DM > all Thermal = 1
```

**EXCLUDED
EXCLUDED
ALLOWED
ALLOWED**

All DM = 3.82e-38
All DM = 3.80e-38
All DM = 3.93e-61
All DM = 1.81e-60

**EXCLUDED
EXCLUDED
ALLOWED
ALLOWED**

Xenon1ton ul	= 6.44e-46
Xenon1ton ul	= 6.44e-46
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Limits stored in Exp. class

EXCLUDED

Fermi ul = 4.19e-25

Calculated on the fly with Pythia8/PPPC4DMID

We consider a simplified t-channel model F3-S0-q

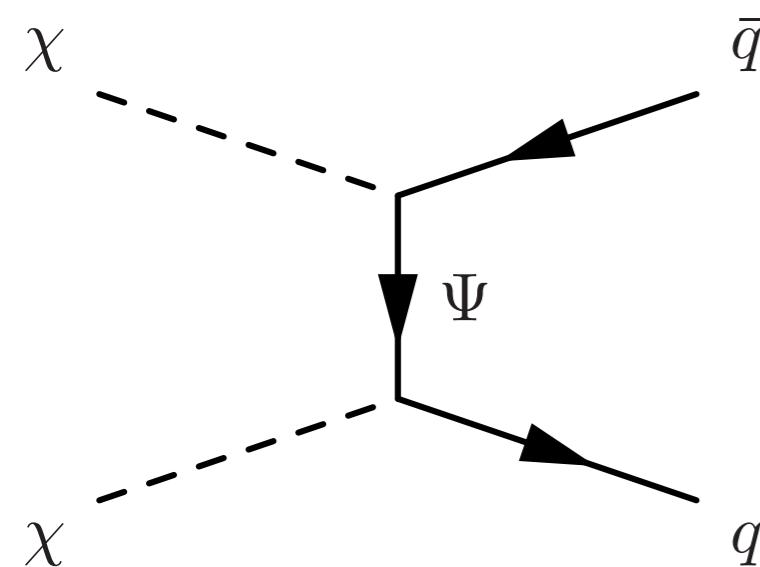
$$\mathcal{L} \supset y_R \chi_r \bar{\Psi}_R q_R + y_L \chi_r \bar{\Psi}_L Q_L + h.c.$$

- **x** : real scalar DM
 - **Ψ** : vector like fermion mediator, color triplet
-
- ❖ Restrict ourselves to interaction involving only right-handed quarks
 - ❖ Minimal Flavour Violation \rightarrow parameter space is {m, M, y}.
 - ❖ Stability of DM \rightarrow m < M

This and other t-channel models have been implemented with FeynRules and will be released to the public in the near future.

UFO model \rightarrow MadDM

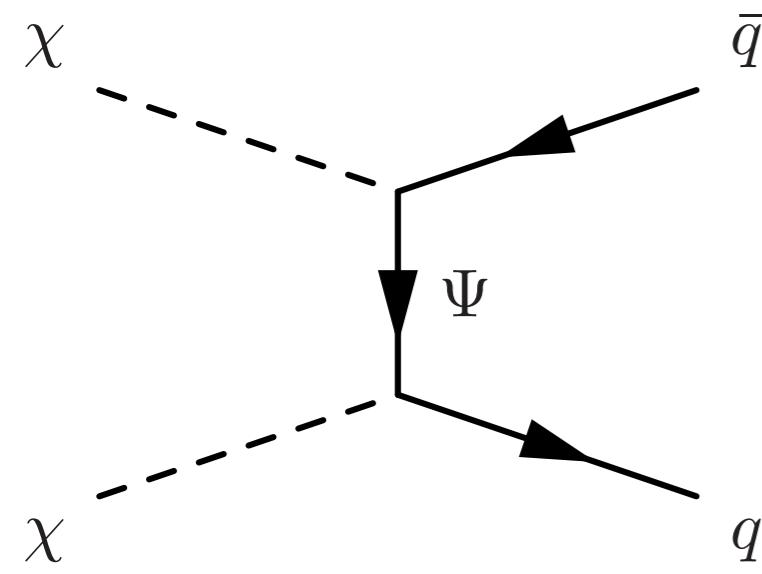




arXiv: 1307.6480 Giacchino et al.

d-wave suppressed

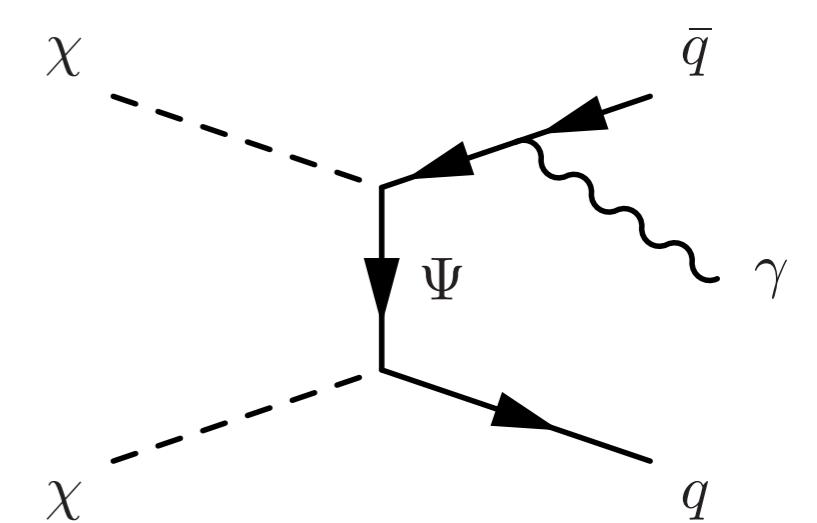
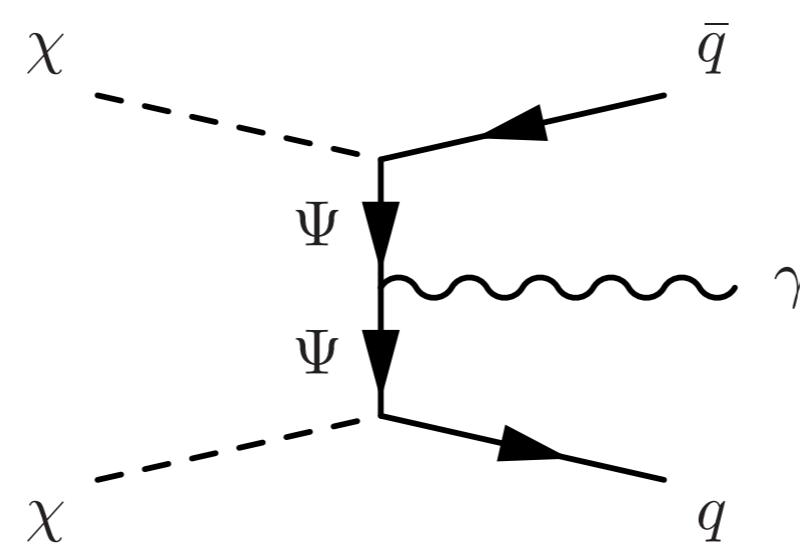
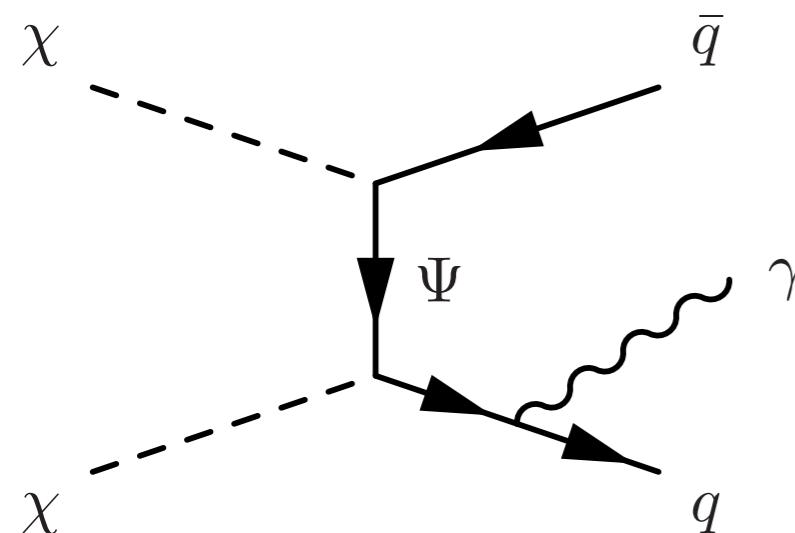
$$\sigma v \propto v^4$$



arXiv: 1307.6480 Giacchino et al.

$$\sigma v \propto v^4$$

d-wave suppressed



Helicity suppression lifted, cross-section enhancement

In order to generate the events and study the spectra of such model, one can simply give the following commands

```
import model DMsimp_t_f3
define darkmatter xr
generate indirect detection u u~ a
output test_uuxa
launch test_uuxa
```

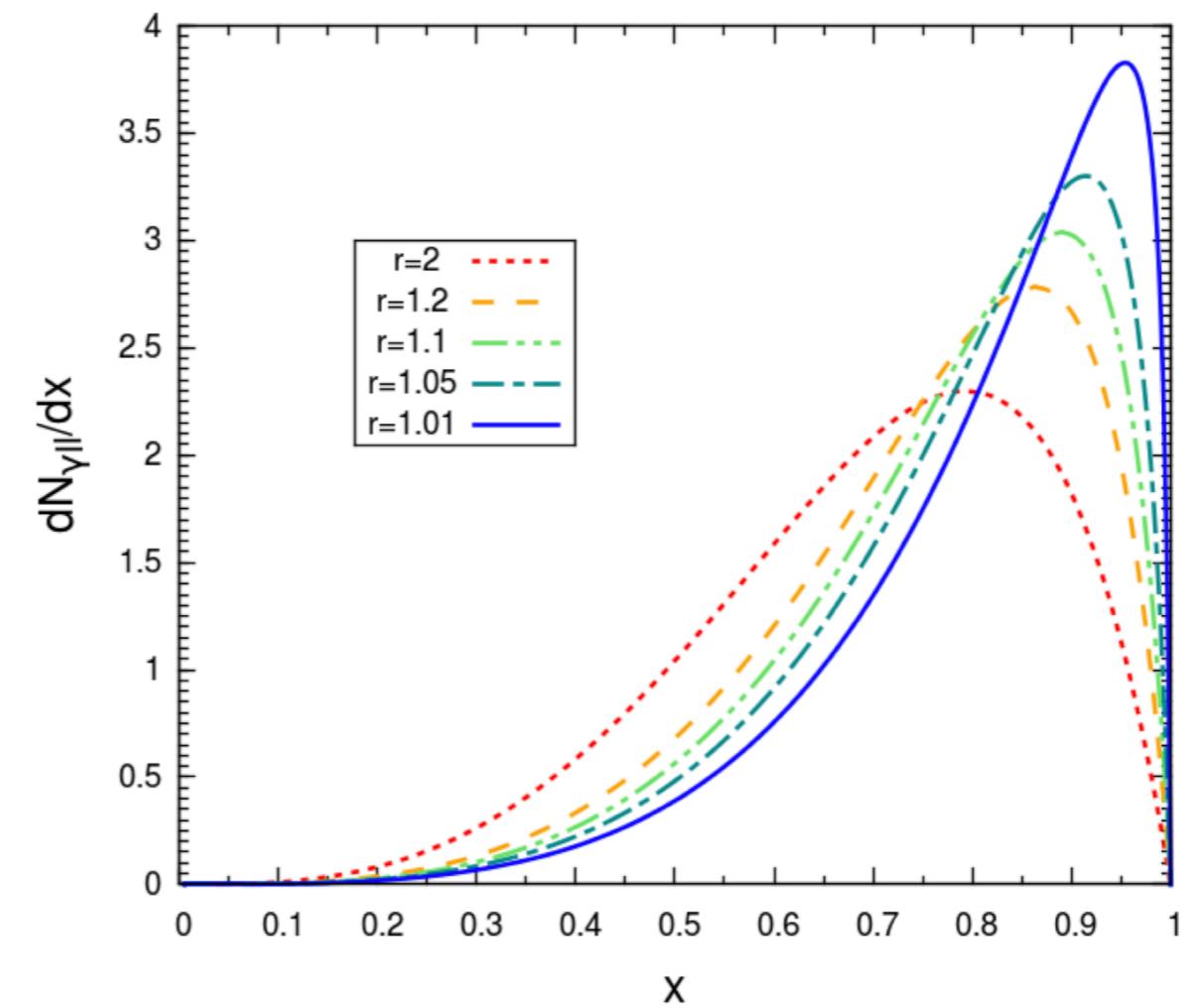
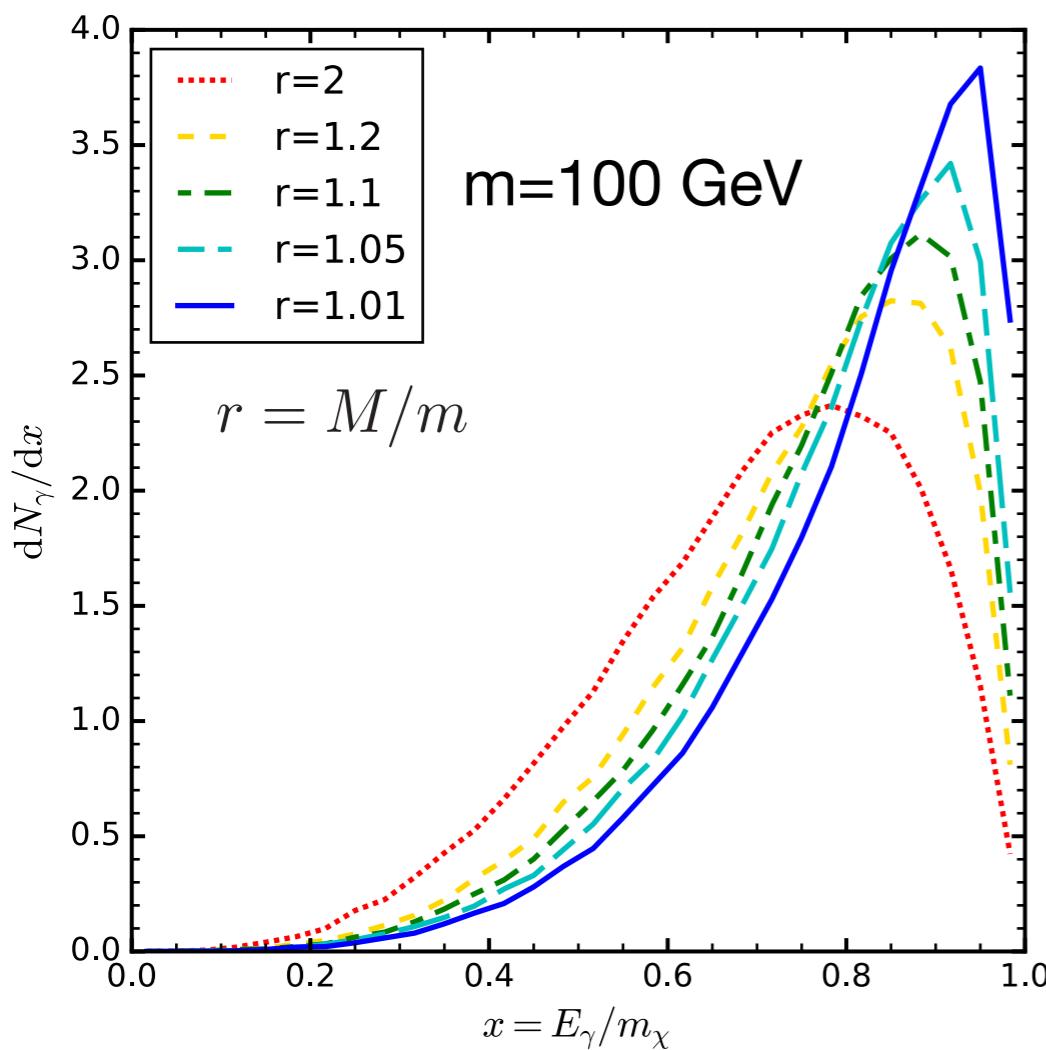
Generation

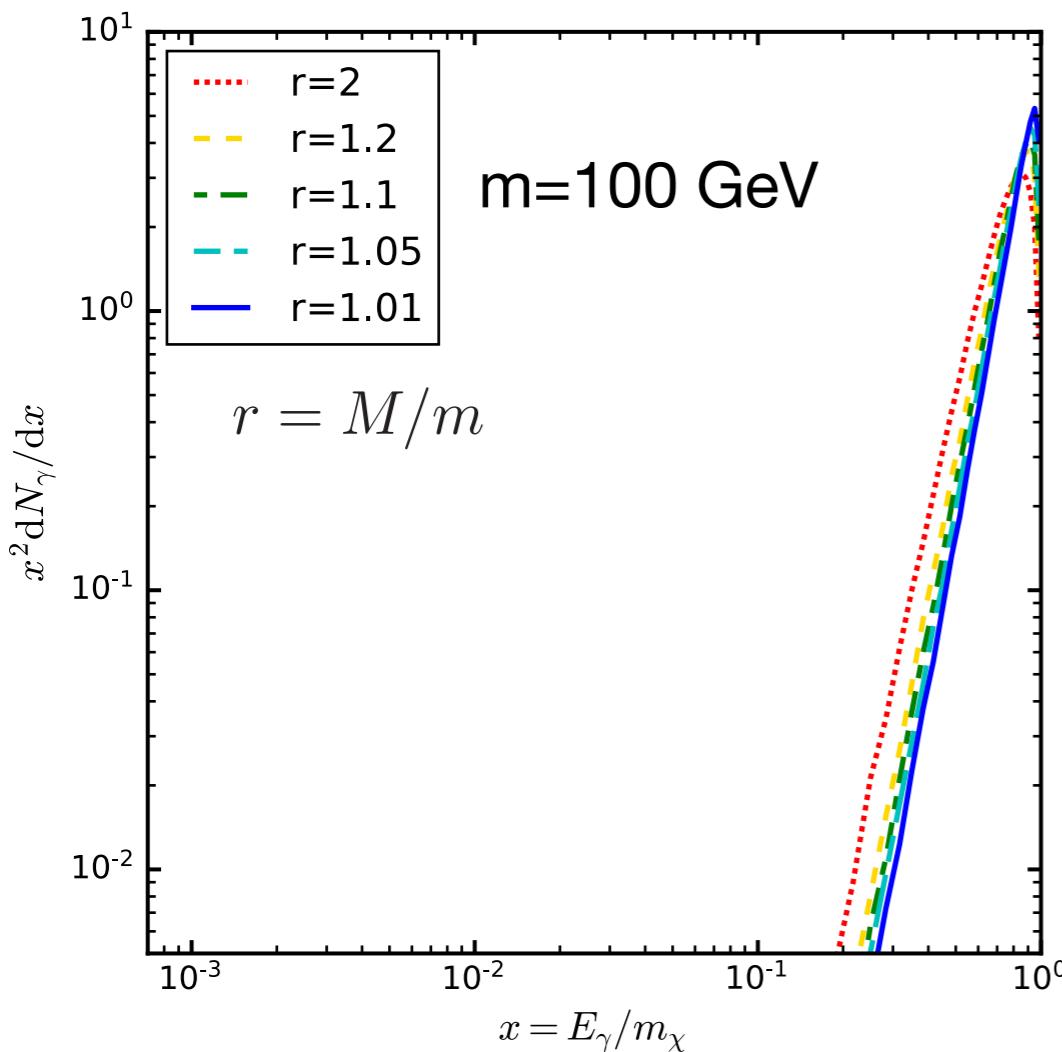
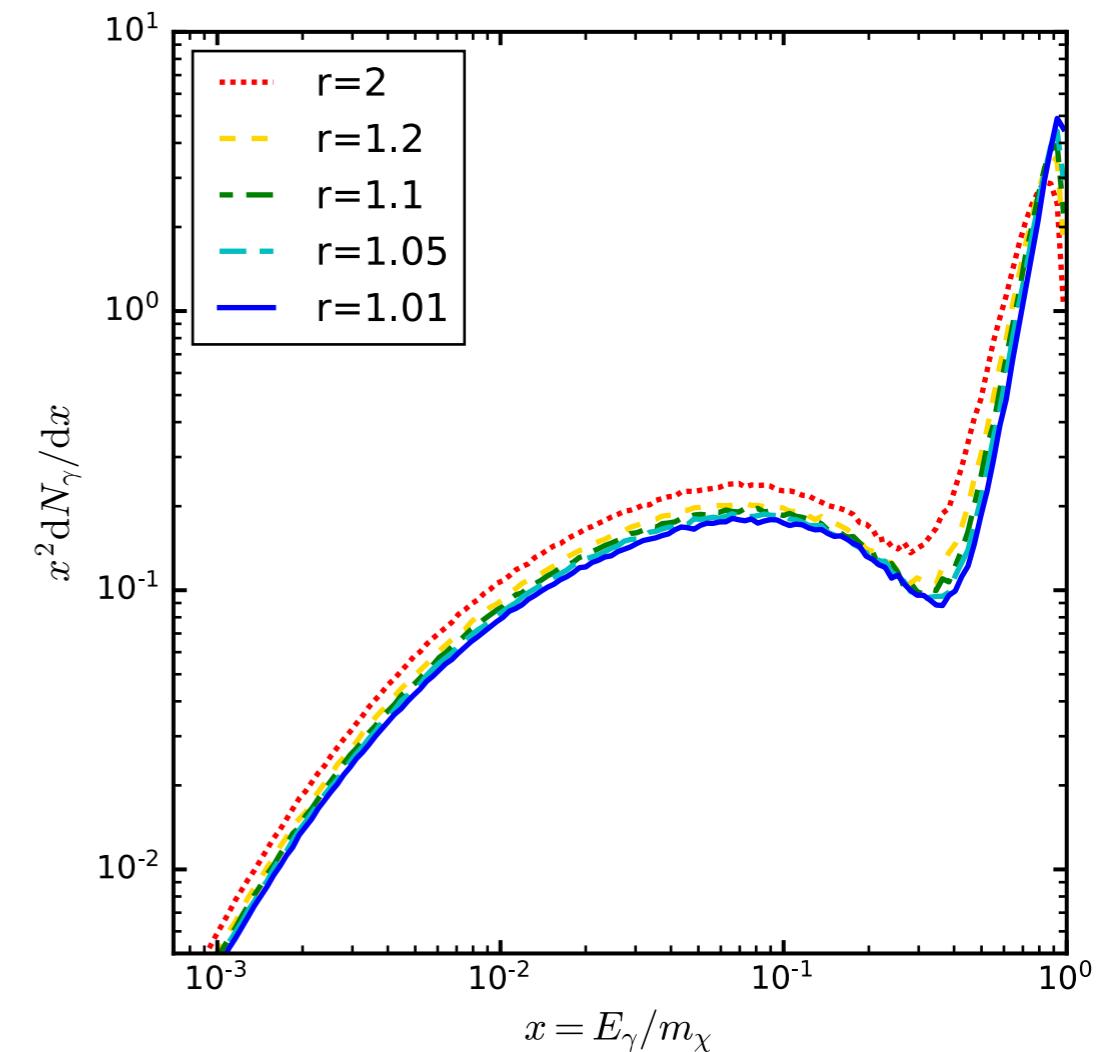
```
set sigmav_method madevent
set indirect_flux_source pythia8
set vave_indirect 1e-3
set nevents 100000
set Mxr 100
set MYur1 scan:[101,105,110,120,200]
set save_output all
```

Parameter setting

The events studied both at the parton level (MadAnalysis) and hadron level



Comparison between MadDM and analytical computation**MadDM v.3.0****arXiv: 1307.6480 Giacchino et al.****Validation OK**

Parton level spectrum**Pythia8**

In a nutshell

- ❖ **MadDM v.3.0 is out**
- ❖ **Welcome feedbacks from the users and we call for collaboration**
- ❖ **MadDM has caught up with other tools and has some unique features
(n-body scattering)**
- ❖ **In future release, improvement on both experimental side (adding further experimental likelihoods) and theoretical side (NLO computations, Sommerfeld enhancement)**



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Thank you!



BACKUP SLIDES



Fermi-LAT sensitive to γ in the energy range $\sim 0.5\text{-}500 \text{ GeV}$

