MadDM: Dark Matter Calculations using Madgraph 5

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University of Kansas

In collaboration with
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Collider Physics using MadGraph

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + i\bar{\Psi}\left(\not{D} - m\right)\Psi + \left(D^{\mu}\phi\right)^{*} D_{\mu}\phi + \ldots$$

Lagrangian

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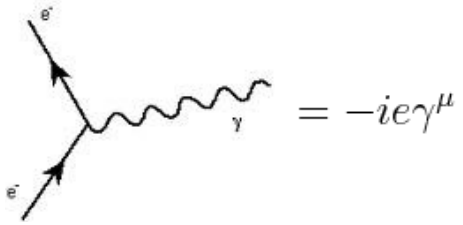
FeynRules

Model files



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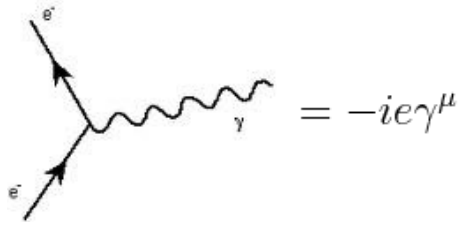

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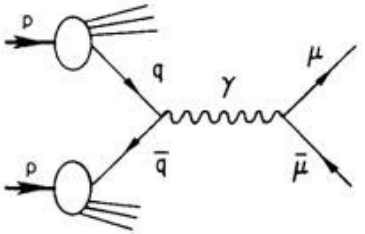

Model files

MadGraph/MadEvent

Parton Level Events

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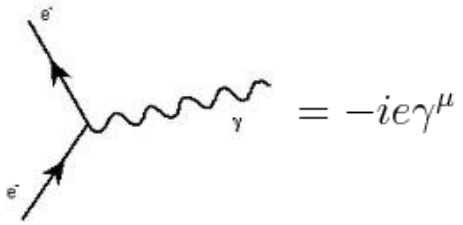

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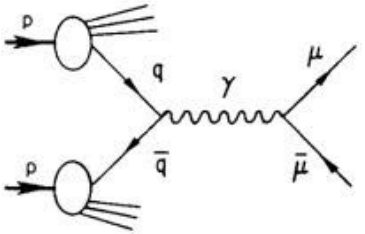

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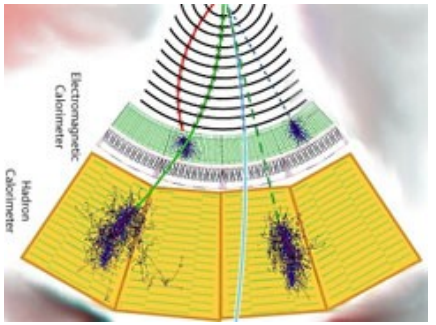

ISR / Parton Showering

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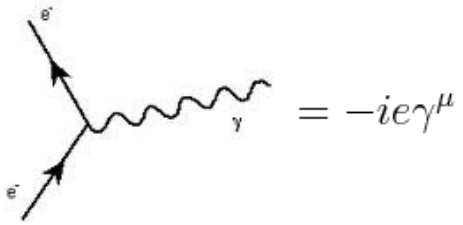

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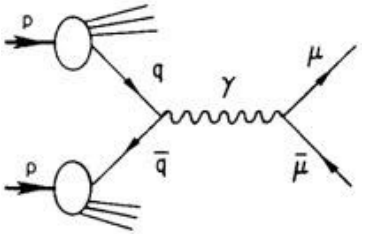

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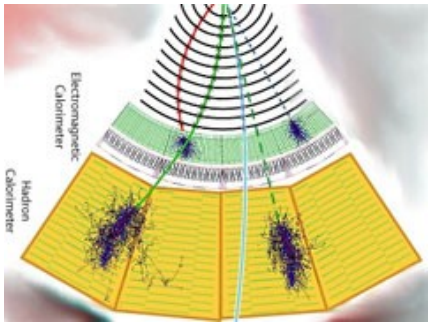

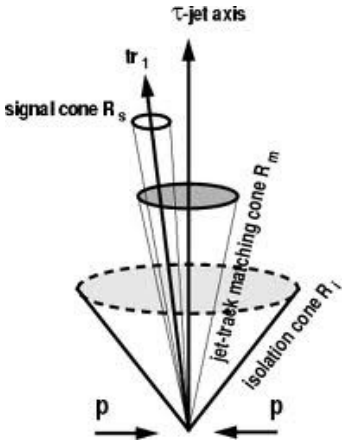

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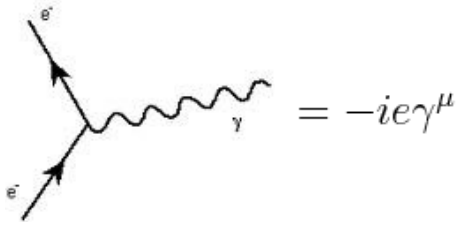

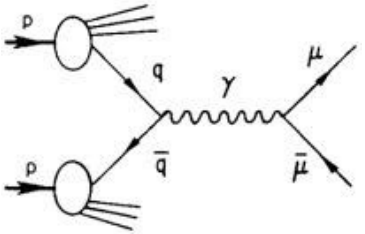

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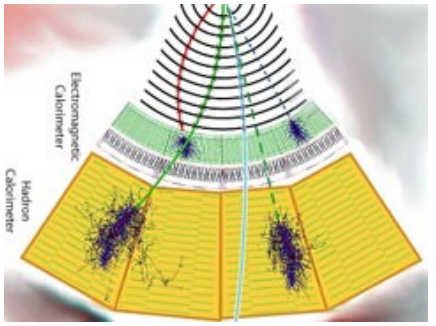

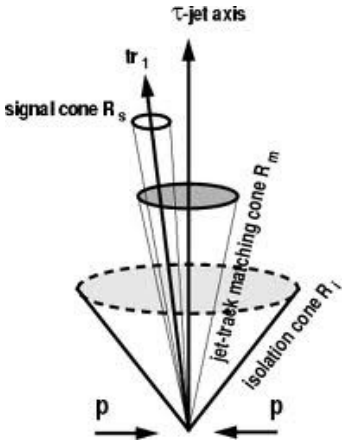

ISR / Parton Showering

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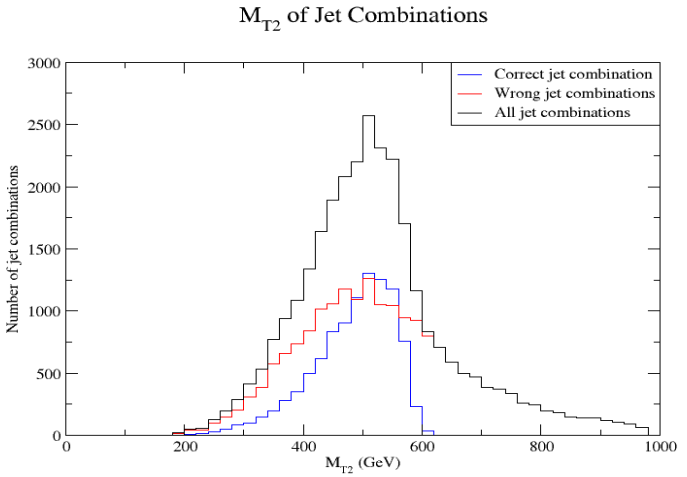
MadAnalysis
Root



Pretty Plots

Collider Physics using MadGraph

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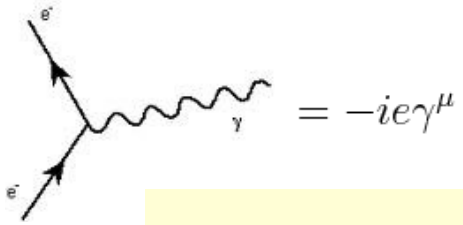

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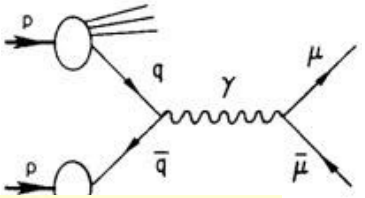

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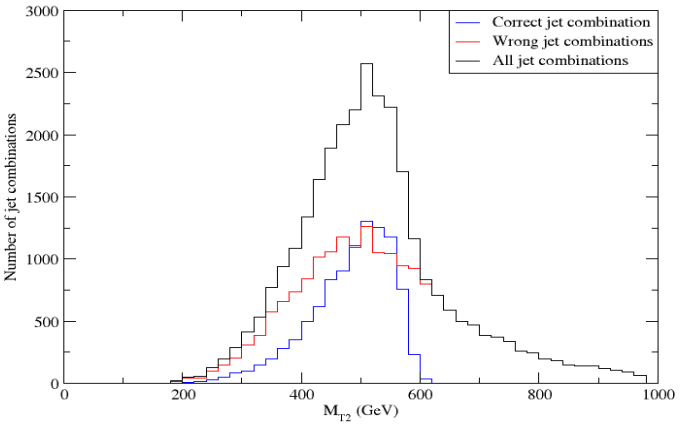


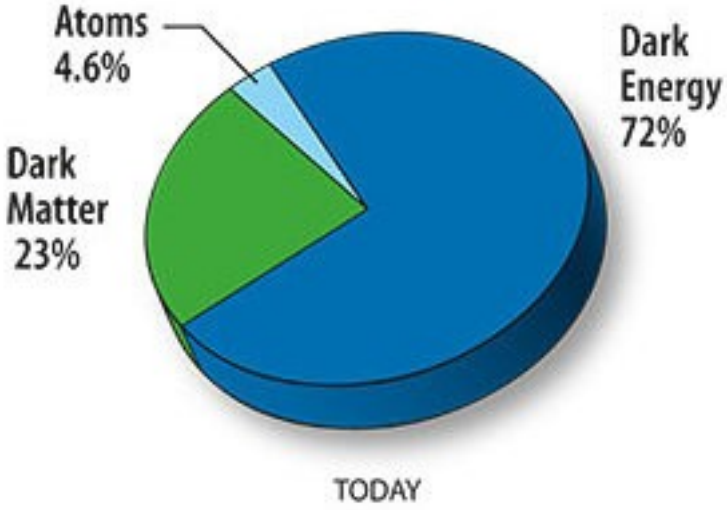
Pretty Plots

????

Profit

What about Dark Matter calculations?

- Many BSM models have a potential DM candidate
  - MSSM (neutralino)
  - UED (KK photon)
- Calculations use the matrix elements Madgraph provides.
  - Relic abundance
  - Direct detection cross sections
  - Indirect detection via DM annihilation



Motivation for Dark Matter Calculations in MadGraph

- MadGraph is very popular among theorists and experimentalists alike.
- Allows users to easily get Dark Matter information (relic density, scattering cross sections, annihilation rates) along with collider events.
- New models with complex DM processes can be easily calculated in the MadGraph framework.
- Cross check with other programs.
- Makes the MadGraph package more complete for doing collider physics.

MadGraph 5

- New python based interface.
- Loads all model information into memory
- Python structure allows for very fast generation of Feynman Diagrams and matrix elements.
- Even on the programming level the only necessary commands to calculate relic density
  - Loading a model with a DM candidate
    - Automatically creates a python object that determines which particle in the model is the DM candidate
  - Set a parameter card with approriate values
  - Run the relic density calculator

Determining the DM candidate

- Scans through the loaded model file and looks for the following criteria:
  - Non-SM particle (abs(particle ID) > 25)
  - No electric charge
  - No color charge
  - Zero width

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Sample output: MSSM

```
mccaskey@Mathew-McCaskeys-MacBook-/madgraph5/maddm:
 python dm_class_test.py
DARK MATTER CANDIDATES:
----------------------
[{
    'name': 'n1',
    'antiname': 'n1',
    'spin': 2,
    'color': 1,
    'charge': 0.00,
    'mass': 'Mneu1',
    'width': 'Wneu1',
    'pdg_code': 1000022,
    'texname': 'n1',
    'antitexname': 'n1',
    'line': 'straight',
    'propagating': True,
    'is_part': True,
    'self_antipart': True
}]
------------------------------
```

Toy DM Model

$$V_{\rm DM} = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta}{2} H^\dagger H S^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4$$

- Add a real scalar singlet to the SM.
- S only talks to the rest of the SM through the Higgs.
- Only two parameters needed to set the DM mass and the interaction stength.
  - δ and m_S are free parameters
- We will take the study point:
  - Higgs mass = 120 GeV

Chemical Rate Equation

$$\frac{dn_\psi}{dt} + 3Hn_\psi = -\langle\sigma|v|\rangle(n_\psi^2 - (n_\psi^{EQ})^2)$$

- DM relic density is governed by the expansion of the universe and the pair annihilation or creation that keeps the DM in equilibrium.
- Transformation to simplify the equation is to use the number density per comoving volume.

$$Y \equiv n_\psi / s \qquad\qquad x \equiv m_\psi / T$$

$$\frac{dY}{dx} = -\sqrt{\frac{45}{4\pi^3}}\frac{m_{pl}\ x}{\sqrt{g_*}\ m^2}\langle\sigma_A|v|\rangle s[Y^2 - Y_{EQ}^2]$$

Thermally Averaged Annihilation Cross Section

- Kolb and Turner

$$\langle \sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle \equiv \left(n_{\psi}^{EQ}\right)^{-2} \int d\Pi_{\psi} d\Pi_{\bar{\psi}} d\Pi_{X} d\Pi_{\bar{X}} (2\pi)^{4}$$
$$\delta^{4}(p_{\psi} + p_{\bar{\psi}} - p_{X} - p_{\bar{X}}) |\mathcal{M}|^{2} \exp(-E_{\psi}/T) \exp(-E_{\bar{\psi}}/T)$$

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$$\delta^{4}(p_{\psi} + p_{\bar{\psi}} - p_{X} - p_{\bar{X}}) \overline{|\mathcal{M}|^{2}} \exp(-E_{\psi}/T) \exp(-E_{\bar{\psi}}/T)$$

— The thermal equlibrium density of DM

Thermally Averaged Annihilation Cross Section

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The thermal equlibrium density of DM

The matrix element integrated over the final state phase space. Matrix elements can be obtained by Madgraph and in a $2 \to 2$ process can be easily integrated manually.

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The thermal equlibrium density of DM

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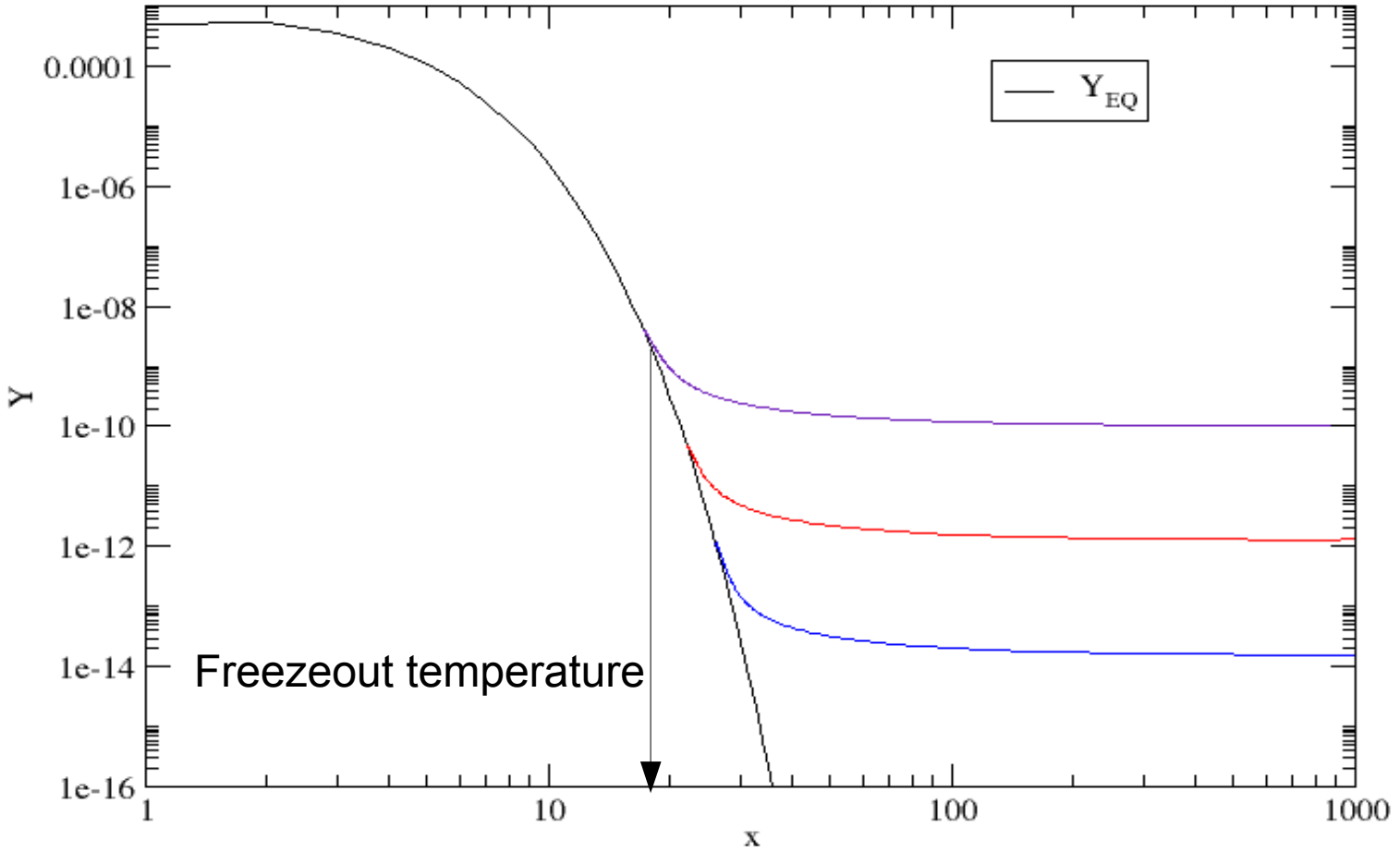
After a few pages of algebra and variable transformations, this part of the expression can be written in terms of the center of mass energy of the process, or more conveniently in terms of a relative velocity, beta.

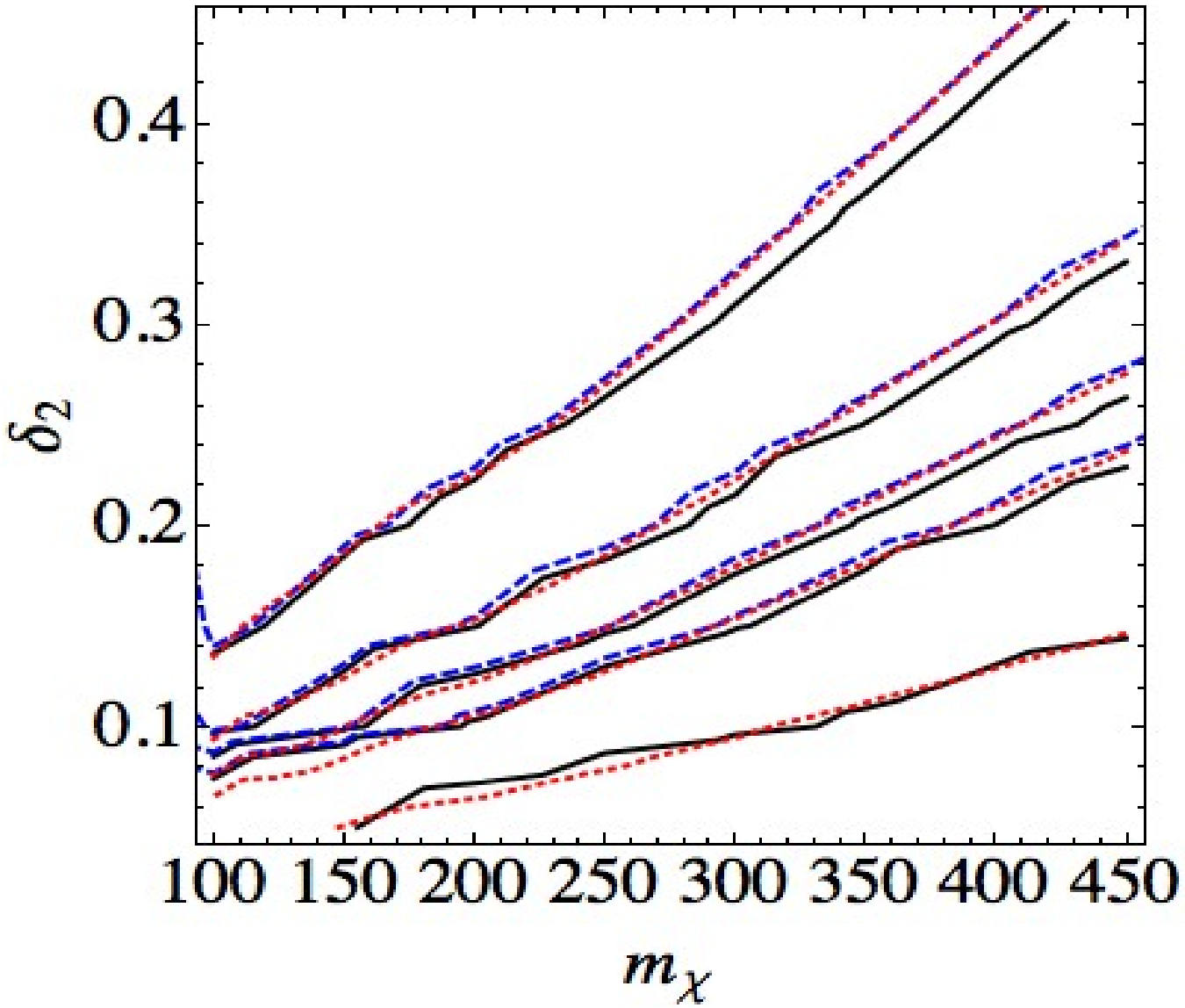
Integrated Chemical Rate Equation



Preliminary Comparison with micrOmegas

- We perform a parameter scan over the DM mass and interaction strength.
- Calculate relic density using our code and compare it with the results given by micrOmegas.
- For the most part there is very good agreement between the two programs.
  - The largest error being ~8%

Preliminary Comparison with micrOmegas



Additions and Improvements

- Annihilation cross sections
  - Take advantage of the various loop programs to calculate loop induced annihilation diagrams
- Spin-independent/Spin-dependent scattering cross sections.
  - Uses effectively the same diagrams as annihilation.
- Parameter scans.
- Relic density calculation is currently done entirely in python.
  - Possible to improve speed by evaluating the matrix element and do numerical calculations in Fortran.

Conclusions

- We have motivated the potential use of a DM calculations tool in the MadGraph framework.
- Have a pretty good relic density calculator that agrees well with other programs.
- Plans for more calculations to be implemented making MadDM and MadGraph as a whole a much more powerful tool for phenomenology.
- More updates to come!

The End

Thank you!